Final Report of the International MOX Assessment

COMPREHENSIVE SOCIAL IMPACT ASSESSMENT OF MOX USE IN LIGHT WATER REACTORS

J. Takagi, M. Schneider, F. Barnaby, I. Hokimoto, K. Hosokawa,
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November, 1997

IMA Project
Citizens' Nuclear Information Center

COMPREHENSIVE SOCIAL IMPACT ASSESSMENT OF MOX USE IN LIGHT WATER REACTORS

Published by Citizens' Nuclear Information Center, November 1997.

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Structure of the IMA Project

November 1. 1995 - October 31. 1997

Title: Comprehensive Social Impact Assessment of MOX (uranium-plutonium mixed oxide) Use in Light Water Reactors

For short: **IMA** (International MOX Assessment)

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Funders of IMA Project:

Toyota Foundation, W. Alton Jones Foundation,
John Merck Fund, Ploughshares Fund

Acknowledgement

This project was only made possible by the generous financial support of Toyota Foundation as well as W. Alton Jones Foundation, Ploughshares Fund and John Merck Fund who also later joined the funding. We would like to express our sincere gratitude to these foundations. Thanks are also due to Takagi Psychiatric Clinic for Funding.

Many people helped us conduct the project and prepare this report. Our thanks go to all contributors, advisors and reviewers, whose names are found in the *Structure of the IMA Project*. We iterate the names of Ross Hesketh, Bernard Laponche, Yukio Yamaguchi and David Lowry to express our special gratitude to their very careful review and proof-reading. Thanks go to WISE-Paris, Oeko-Institut(Darmstat-Buero), Greenpeace International, Committee to Endorse IMA Kyoto Conference, Masafumi Takubo, Aileen Mioko Smith. Lastly but not the least, thanks are due to almost innumerable number of individuals and groups, whose names are not given here but who supported and encouraged us.

IMA Project

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Acronyms

ACE	Advisory Committee on Energy (Japan)
AEC	Atomic Energy Commission (USA)
AEC J	Atomic Energy Corporation (Japan)
AFR	Away from the reactor
ANRE	Agency of Natural Resources and Energy, MITI (Japan)
ATR	Advanced thermal reactor
AVLIS	Atomic Vapor Laser Isotope Separation Project (USA)
BNFL	British Nuclear Fuels Ltd (now plc)
BWR	Boiling water reactor
CD	Conference on Disarmament
CEA	Commissariat a l'Energie Atomique (France)
CNIC	Citizens' Nuclear Information Center
COGEMA	Compagnie Generale des Matieres Nucleaires (France)
COMARE	Committee on Medical Aspects of Radiation in the Environment
CORE	Cumbrians Opposed to A Radioactive Environment
CTBT	Comprehensive Nuclear Test Ban Treaty
DFD	Direct fuel disposal
DOE	Department of Energy (USA)
DTI	Department of Trade and Industry (UK)
EC	European Community
EdF	Electricite de France
EIS	Environmental impact statement
EU	European Union
Euratom	European Atomic Energy Community
FBR	Fast breeder reactor
FEPCO	Federation of Electric Power Companies (Japan)
FMCT	Fissile Material Cut-Off Treaty
GCR	Gas-cooled reactor
GPI	Greenpeace International
HEU	Highly enriched uranium
HLW	High level radioactive waste

IAEA	International Atomic Energy Agency
ILW	Intermediate level radioactive waste
JNFL	Japan Nuclear Fuel Ltd.
LEU	Low-enriched uranium
LI S	Laser isotope separation
LLW	Low level radioactive waste
LWR	Light water reactor
Magnox	Magnesium oxide
MBA	Material Balance Area
MDF	MOX Demonstration Facility
MdI	Secretary of State for Industry (France)
Minatom	Ministry of Atomic Energy (Russia)
MITI	Ministry of International Trade and Industry (Japan)
MOX	Mixed oxide fuel
MUF	Material unaccounted for
MWD/t	Megawatt day per ton (fuel burnup)
NAS	National Academy of Science (USA)
NEA	Nuclear Energy Agency, OECD
NERSA	Groupement Central Nucléaire Européen a Neutrons Rapides
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NRC	Nuclear Regulatory Commission (USA)
NRTA	Near real time accountancy
OECD	Organization for Economic Co-operation and Development
ORC	Overseas Reprocessing Committee (Japan)
OTA	Office of Technology Assessment
NSC	Nuclear Safety Commission (Japan)
PCI	Pellet clad interaction
PFPF	Plutonium Fuel Production Facility (Tokai, Japan)
PNC	Power Reactor and Nuclear Fuel Development Corporation (Japan)
Pu	Plutonium
Purex	Plutonium-uranium extraction
PWR	Pressurized water reactor
R&D	Research and development

RepU	Reprocessed uranium
RIA	Reactivity initiated accident
SMP	Sellafield MOX plant
SQ	Significant quantity
STA	Science and Technology Agency
START	Strategic Arms Reduction Talks/Treaty
SWU	Separative work units
TEPCO	Tokyo Electric Power Company
tHM	Ton heavy metal
THORP	Thermal Oxide Reprocessing Plant (UK)
U	Uranium
UCS	Union of Concerned Scientists
UKAEA	United Kingdom Atomic Energy Authority
VHLW	Vitrified high level waste
WISE-Paris	World Information Service on Energy-Paris

FOREWORD

Having been long involved in issues of Japanese and world-wide civil plutonium programs -- sharing worldwide concerns over safety, security, economics and social aspects of plutonium utilization--the Citizens' Nuclear Information Center felt it urgent to conduct an independent full scale impact assessment of MOX (mixed oxide of uranium and plutonium) use in light water reactors and applied for research grant of the Toyota Foundation in 1995. As the proposal was approved by Toyota, the International MOX Assessment (IMA) Project --was started in November 1995 as a two year project until the end of October 1997. The full title of the project is ***Comprehensive Social Impact Assessment of MOX (uranium-plutonium mixed oxide) Use in Light Water Reactors.***

An international study group was organized with JinzaburoTakagi (Japan) and Mycle Schneider (France) serving respectively as the Project Director and Assistant Director and by inviting seven other people from Germany, the U.K. and Japan as the coresearchers and, another four from Germany, Russia and the U.S. as the contributors. The names of co-researchers who wrote the seven *Chapters* of this report and contributors who contributed papers to the *annex* are seen in *Structure of the IMA Project* . In addition, many people from various countries helped as the advisors to the project by taking part in workshops, formal and informal discussions, advising and supplying up-to-date information to the co-researchers, as well as reviewing draft reports. Furthermore we needed help of numerous people for organizing the project and preparing the final report. Only the names of people to whom we owe our work most significantly are found in the *Acknowledgements*.

The project was only made possible by the support of Toyota Foundation as well as W.Alton Jones Foundation, Ploughshares Fund and John Merck Fund who also later joined the funding.

The co-researchers and advisors met frequently in various parts of the world formally and informally; the most important events were the starting workshops at Hochhausen, Germany in January and at Amsterdam, Holland in February 1996, the interim report workshop and public meeting at Kyoto, Japan in October 1996.

Although the chapters are reviewed internally by co-researchers, contributors and other advisors as well as externally by Ross Hesketh, Bernard Laponche and Yukio Yamaguchi, the author(s) of each chapter are responsible for the final content of the

chapter. While the directors (J.T and M.S) are responsible for the *Summary Report*, the *Conclusions and Recommendations* are signed by all the co-researchers and thus the responsibility for these parts rests jointly with the nine co-researchers.

I hope that this report will contribute to a democratic decision-making process on MOX and related nuclear programs by presenting useful information and arguments to the public at large and to those who are involved in the governmental, local governmental and industrial decision-making.

Jinzaburo Takagi
Director of IMA
October 1997

Summary Report

The following summary report pulls together the main findings of the different co-researchers and contributors. We have decided to maintain essentially the structure of the full report, which allows the reader to easily identify the relevant location in the full report if he wishes to get more in depth information on one or other aspect. We have integrated to some extent information supplied by the contributors into the structure of the full report. In some exceptional cases additional information has been added to the full papers prepared by the co-researchers and contributors, if the directors of the IMA project felt it important to update specific points. Therefore the directors (J.T and M.S) are responsible for the executive summary.

The directors have drawn from the findings the conclusions and recommendations. They have been reviewed and signed by all co-researchers of the project (authors of chapters), and thus the responsibility for the global conclusions and recommendations stays jointly with them. The readers can find the source of references to this executive summary generally in the list of references attached to the relevant chapters, while references additionally introduced by the directors are detailed in this summary.

Chapter 1 Introduction into General, Environmental and Health Aspects

(Chapter written by Jinzaburo Takagi)

1.1 What Is MOX?

Plutonium, a man-made element

Plutonium was discovered in February 1941 by Glenn Seaborg at the University of California. Soon after its discovery it was found that an isotope of plutonium could undergo fission and its study was entirely incorporated into the secret Manhattan project that enabled mass production of plutonium for use in atomic bombs.

It was a fabulous coincidence in the history of science that the element which turned Nagasaki into hell in a flash four years after its discovery was named after what has become the synonym of the ruler of the underworld. Fifteen isotopes of plutonium with mass numbers from 232 to 246 are known but the most important one is plutonium-239 with a half life of over 24,000 years, a fissile nuclide which was used for the Nagasaki bomb and can basically be burned in a nuclear reactor to produce energy.

Pu-239 is produced in a conventional uranium-fueled reactor as a result of

neutron capture of U-238, which takes place alongside the main heat-generating fission reaction of the fissile isotope of uranium, U-235. U-235 constitutes only 0.7% of natural uranium and is usually enriched to about 3-4% U-235 content for use in a light water reactor (LWR), the most prevalent type of nuclear reactor. Around 150 kg of Pu-239 and 200 kg of total plutonium accumulate after one year operation of a typical 1000 MW light water reactor.

Weapon-grade and reactor-grade plutonium

Thus in a reactor various isotopes of plutonium are accumulated in uranium fuel in varying amounts depending upon the degree of fuel burn-up. Of the five main isotopes produced, the two odd mass number isotopes, Pu-239 and -241, are fissile (fissionable upon reaction with thermal [slow] neutrons) and can in principle be used as reactor fuel. Therefore, for reactor fuel purposes, only the quantity of Pu-239 plus Pu-241 is important.

For the nuclear weapon design, nearly pure Pu-239 is favored, because neutron emitting Pu-240 and Pu-238 could trigger a "pre-ignition" which would substantially reduce the explosive yield. Therefore, a distinction between different "grades" of plutonium is usually made according to the isotopic composition of plutonium. [Albright 1997]

Super-grade plutonium:	nearly pure Pu-239, less than 3% of non-fissile Pu-240 content;
Weapon-grade plutonium:	less than 7% Pu-240;
Fuel-grade plutonium:	7% to 18% Pu-240;
Reactor grade-plutonium:	more than 18% Pu-240.

In Japan and some European countries, plutonium proponents still maintain that reactor-grade plutonium should be considered a virtually non-weapons usable material and thus the plutonium program in these countries, which are mainly based on separation and use of reactor-grade plutonium, could be regarded as essentially "peaceful".

The assertion of the "peacefulness" of reactor-grade plutonium is, however, contrary to the internationally-established scientific knowledge and evidence. The 1994 US National Academy of Sciences report on the disposition of nuclear weapons concludes [NAS 1994]: "Virtually any combination of plutonium isotopes can be used to make a nuclear weapon."

There are further scientific and technical arguments in support of the weapons-

usability of reactor-grade plutonium. (See Chapter 2 for details on the property of different qualities of plutonium as weapons material).

Military-civil dual use character of plutonium

Because of the weapons-usability of plutonium, every civil plutonium utilization program is essentially vulnerable to diversion for military purposes. Reactor-grade plutonium could be directly built into a crude nuclear bomb or used to fuel a fast breeder whose blanket can produce substantial amounts of super-grade plutonium for weapons-use.

The military-civil dual character is not only related to the weapons-usability of the material but to the whole technological system of plutonium use. A full scale civil plutonium program could under political directives be used to build up a military nuclear capability. Even without military intention and with strict international control, merely possessing a plutonium stockpile and plutonium-related facilities could be regarded as having a nuclear option by other countries and trigger a counter program in those countries which could well be of military nature. Concerning Japan's plutonium program, to some extent this might actually be the case in the future.

A number of international and security-related problems arise therefore from this dual-potential of plutonium programs and they should be addressed as one of the central issues in an assessment of every plutonium utilization program. This study deals with these issues in Chapters 2 and 6 in particular.

Toxicity of plutonium

Plutonium is known as one of the most toxic elements. Most of the plutonium isotopes are alpha emitters. The high energy of the alpha particles lead to a high ionizing capacity and makes alpha-emitting plutonium extremely harmful when uptaken into the human body, whereas external exposure to alpha-emitters does not usually give rise to serious health problems due to the short range of alpha radiation.

Another cause of the high toxicity of plutonium is its long retention in the body once uptaken by inhalation or ingestion. A fraction of plutonium inhaled will reach the lungs and then part of it is absorbed into the blood, finally finding its way mainly to liver and bones and to a lesser extent to the reproductive glands. A smaller fraction of ingested plutonium would also be absorbed into the blood and reach similar organs. Plutonium incorporated in these organs would stay there for a long period ranging from years to the entire lifetime of the human being, exposing the respective organs to alpha radiation. Various studies suggest that the sustained irradiation by low levels of alpha radiation causes cancers and genetic injuries.

The comparison of the annual limits of intake (ALI) of Pu-239 oxide as compared to those of U-238 gives a good idea of the frightening toxicity of plutonium. The current Japanese occupational limit for the inhalation (oxide) of Pu-239 is 0.26

micrograms or 460,000 times smaller than that of U-238 (120,000 micrograms). This order of magnitude should be kept in mind while discussing plutonium production and stocks in the order of dozens of metric tons.

Furthermore, ALI values for reactor grade plutonium are far smaller when measured by weight than those for pure Pu-239. Typical reactor grade plutonium is eight to ten times as toxic as Pu-239 and one gram of reactor grade plutonium oxide corresponds to the cumulated annual limit of inhalation for as many as 40 million people.

Thus plutonium is a health concern to workers at nuclear facilities handling plutonium at sub-microgram levels and to the member of the public at nanogram levels.

The use of plutonium therefore poses a new dimension of environment, safety and health concerns, which are dealt with in particular in Chapter 3.

MOX fuel

The most common chemical form of plutonium for reactor fuel use is the dioxide PuO_2 mixed with uranium dioxide UO_2. The mixed oxide fuel or MOX (PuO_2+UO_2) can be used usually to fuel two types of reactors, fast breeder (FBR) and light water reactors.

Technical difficulties of FBRs and the fuel chain have led to poor economics of the system, and these two major drawbacks -- technical and economical -- have forced the United States and all of the Western European countries to scrap their FBR programs. Japan, which was once thought the most ambitious country in FBR development, now seems to follow suit or, to say the least, to defer its FBR program substantially in particular due to the accident of the prototype FBR Monju in December 1995.

Another way of fueling a reactor with MOX is to use a commercial light water reactor (LWR). Usually, MOX containing 5 to 8% plutonium is used to fuel PWR (pressurized water reactors) and BWR (boiling water reactors), the two major types of LWRs. Although using MOX in LWRs essentially designed to burn low enriched uranium oxide poses various problems which are central issues being dealt with in this project, the nuclear industry pretends replacing a third of an LWR core with MOX does not constitute a major reactor safety problem and is implementing it in some German, French, Belgian and Swiss LWRs (see Annex 1). Japan has also an ambitious plan to use MOX in LWRs, and irradiating MOX in LWRs is now considered, by some experts, to be an effective option for the disposition of plutonium from dismantled nuclear weapons by the atomic authorities in the US and Russia.

1.2 Japan's Plutonium Program

Focus on Japan

We deal here only with the nuclear fuel cycle / plutonium policy associated with light water reactors and MOX use, which has been adopted in West-European countries and Japan, as we think it is currently of key international concern as far as civil use of plutonium is concerned. Particularly, we focus on the Japanese case to understand the full scope implications and associated problems of a country's plutonium program, because it is one of the world's most extensive plutonium programs and we believe that the future of the world plutonium industry may be largely dependent on the success or failure of Japan's program. Also, recent developments indicate that the choice of MOX use in LWRs will be subject to considerable public attention and controversial debate in Japan.

Japan's plutonium strategy

Japan's current plutonium program is based on the 1994 version of the Long Term Program for Research Development and Utilization of Nuclear Energy [JAEC 1994], published by the Japan Atomic Energy Commission (JAEC). Many observers had expected that the plutonium program might be drastically scaled down in the revision, but in fact the whole plan was only delayed by some 10 years, and the projected plutonium demand and supply level by the year 2010, was reduced to 100-110 tons (all amounts are given in total plutonium) from the previous plan of 110-130 tons. Officially, all of the separated plutonium except for a small running stock should in principle be consumed. However, while the long term program and the associated supply and demand plan were decided only two years ago, rapid changes in the situation surrounding Japan's plutonium program have made the figures and plans almost meaningless.

Implications of the Monju and Tokai Accidents

The sodium leakage accident which occurred at Monju on December 8, 1995 had far more serious impacts than first thought by PNC (Power Reactor and Nuclear Fuel Development Corporation), the operator and owner of Monju. As a result, PNC and the Science and Technology Agency, responsible for supervising PNC, have lost public confidence utterly. The strong feeling of distrust and concern over the government's energy policy is reflected very clearly in the joint statement of the governors of Fukushima, Niigata and Fukui, the Prefectures (local government regions) where 60% of Japanese power reactors are located. In their statement published on January 23, 1996, the governors urged the prime minister to review Japan's nuclear policy, in particular the plutonium program, thoroughly and also the way the policy was forced upon the local populations. They stated further that, without the review process, they

would refuse to accept not only the restart of Monju but also MOX use in light water reactors which the utilities were about to propose in their districts.

In response to the proposal JAEC sponsored 11 meetings of the first series of Nuclear Energy Policy Roundtable Talks inviting many people from all over Japan. As the outcome of the discussions, JAEC organized an advisory committee on the review of the FBR program and the second series of the Roundtable was also supposed to be held in 1997. But the latter seems to be indefinitely postponed because another accident, a fire which led finally to explosion, occurred on March 11, 1997 to the low level radioactive waste bituminization facility of PNC's Tokai Reprocessing Plant exercerbated the post-Monju confusions.

At the time of writing of this summary (October 1997), the FBR Advisory Committee is about to issue its final report, which will probably advise the government to scale down the current FBR program while leaving Monju operable for research purpose. Nobody knows yet, however, where these confusions will finally lead to. One can say at this moment, however, that it is highly unlikely that the restart of Monju will get approved by the local governments in the foreseeable future and without approval, Monju can never be restarted; and without operation of Monju Japan will not be able to take any further step in its FBR program.

If the Japanese government insists on its reprocessing policy, this leaves Japan with MOX use in light water reactors as the only official option for the consumption of separated plutonium. Indeed at the beginning of 1997, the government confirmed anew its MOX use policy and made public the whole program of MOX use in LWRs, starting from Fukushima I-3 BWR reactor in 1999 and loading MOX to 16-18 reactors by 2010 involving all Japanese utilities. Local governments and residents have just started to consider the utilities' proposal to use MOX at their areas, but did not seem to be prepared to accept the proposal as of the end of October 1997.

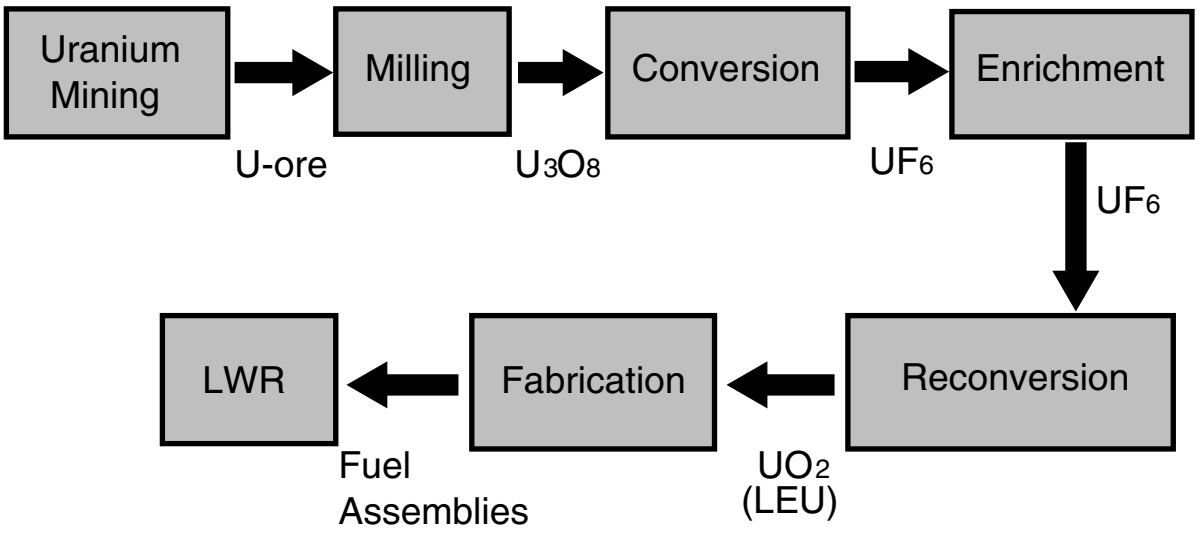
1.3 MOX Use in Light Water Reactors--Scope and Issues

MOX fuel cycle and issues to be addressed

The flow of nuclear fuel[1] and radioactive substances for an LWR is usually separated into two main parts: the upper stream which originates from uranium mining and ends in loading of low enriched UO_2 in a reactor core (Fig. 1-2); and the downstream which covers the stages from the discharge of spent fuel to the final storage / disposal of radioactive waste (Fig. 1-3).

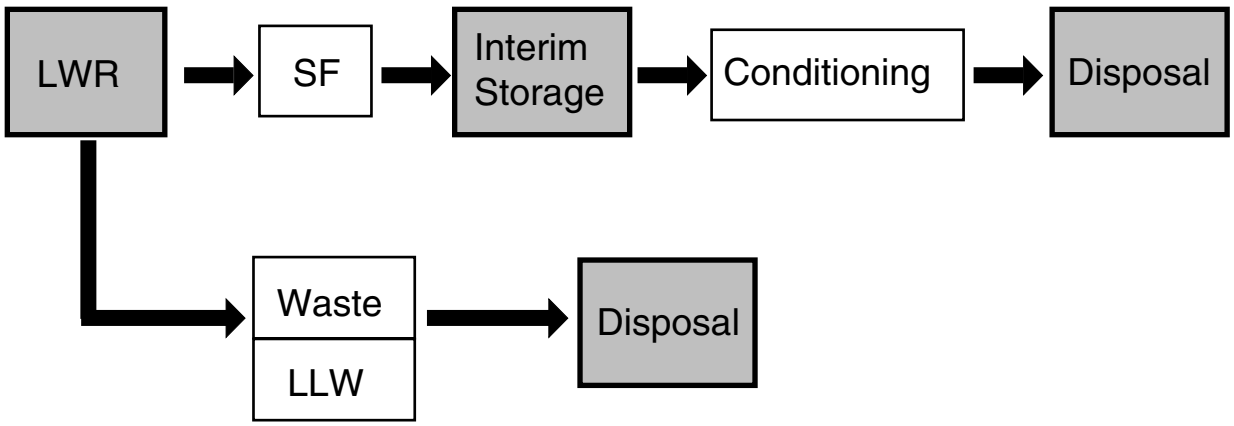
1. As a matter of fact, a "nuclear fuel cycle" never closes in the strict literal sense, because a substantial part of the fuel materials remains as waste as well as radioactive waste emerging from each step of the processes. A more appropriate term may be the "nuclear fuel chain".

Fig.1-2 Upper Stream of LWR Fuel Flow



LEU:Low Enriched Uranium

Fig.1-3 Once-Through LWR Downstream



SF : Spent Fuel

The "once-through" flow on the chart already contains one of the most difficult and controversial parts of nuclear technology -- the shipment, storage and disposal of highly radioactive materials. But the fuel flow involving MOX or the "closed fuel cycle" is far more complicated. The original spent fuel is transported from the reactor site to the reprocessing plant, where plutonium is separated from uranium and other radioactive products and then transported to the MOX fabrication plant. The MOX fuel assemblies produced in the fabrication plant are then shipped to the reactor for reloading. The spent MOX may or may not be reprocessed. Even in the case where spent MOX is not reprocessed ---which is the most likely case under current conditions---, its transportation, storage and disposal will give rise to special safety, security and economic considerations, owing to the increased content of plutonium and transuranic nuclides compared to traditional LWR spent fuel.

An overview of a full MOX fuel cycle and related issues covered in this report is illustrated in Fig. 1-4.

1.4 Implications of MOX Use in a Changing World

Plutonium in the post Cold War era and the plutonium surplus problem

With the end of the cold war the possibility of a full scale nuclear war has been greatly reduced. But a new threat to the world has arisen -- the proliferation and environmental risks of rapidly accumulating weapons-usable fissile materials from dismantled nuclear weapons of the United States and former Soviet Union.

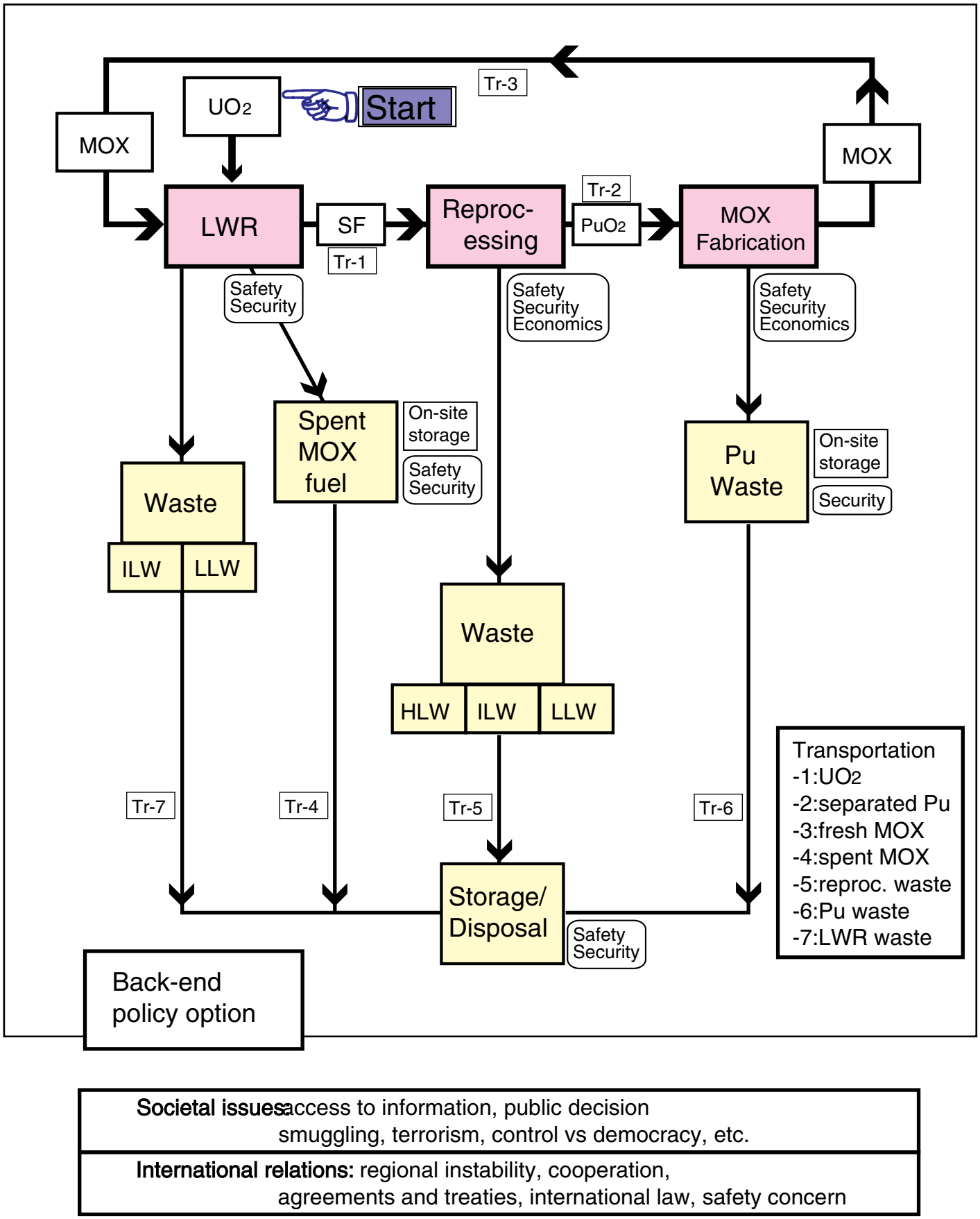
The question of the disposition of fissile materials arising from the tens of thousands of nuclear weapons to be dismantled has become an urgent problem to the international community as a whole.

While the US DOE recently decided to take the so-called dual-track option for plutonium disposition allowing two thirds of US weapons' plutonium to be irradiated in commercial thermal reactors as MOX [US DOE 1996], the decision should not be taken as to open the way for the US to commercialize weapons plutonium.

The issue of the weapons plutonium surplus should raise concern over the civil plutonium stockpile as well.

The surplus problem appears to be becoming much more serious now in Western European countries and in Japan, since these countries maintain the reprocessing policies despite many arguments and moves against them. In the European reprocessing centers at La Hague in France and Sellafield in the U.K., there are already large amounts of separated plutonium stockpiled: 43.6 tons of plutonium in France (mainly at La Hague) as of the end of 1996 **[MdI1997]** and 53.5 t at Sellafield as of March 31, 1997**[DTI1997]**, a large proportion of which can be attributed to the two largest foreign customers, Japan and Germany.

Fig.1-4 Problem areas of MOX use in LWR



Societal issues: access to information, public decision
smuggling, terrorism, control vs democracy, etc.

International relations: regional instability, cooperation,
agreements and treaties, international law, safety concern

A large surplus of Japanese plutonium also already exists [Takagi 1996]. According to the inventory data at the end of 1995 given by the government, Japan has a stock of 16 tons of plutonium, of which 14.7 tons are stored at the reprocessing and MOX fabrication facilities without any imminent use and thus can be regarded as surplus. Of this surplus, 1.42 and 9.96 tons are stored in the U.K. and France, respectively. If the reprocessing in Europe, and Tokai and then in Rokkasho in Japan proceeds as planned -- and with the FBR and ATR[2] research and development program beyond Joyo and Fugen indefinitely deferred and the MOX use in LWRs delayed substantially -- we estimate that the surplus will exceed 30 metric tons by 2000 and 70 tons in 2010, even if MOX use is partially realized. The authors' estimation of cumulative surplus by 2010 for two scenarios, (a) no MOX use and (b) MOX use in up to ten LWRs is given in Fig. 1-5.

The figures represent a very curious but serious situation. MOX use in LWR seems now to provide the justification for reprocessing on the grounds that it might contribute to reduce plutonium stockpiles, but the reality is that the reprocessing policy is actually *increasing* the plutonium surplus as a whole even though MOX use could consume a part of it.

Basic approach of the IMA project

There have been many well-founded arguments raised against plutonium utilization mainly by independent researchers and authors. Some of them include an environmental impact assessment of the kind we are aiming at in this project but they are neither comprehensive nor dedicated to issues specific to MOX use in LWRs. In addition some are out-of-date today, given the striking changes in the international arena after the end of the cold war.

It goes without saying that an independent assessment of a big industrial program is essential for a healthy society. This is particularly so, concerning a modern big science and technology project such as the MOX program at issue with its immense social, political, environmental and health implications. Assessments free of industrial or governmental conflicts of interest are of absolute necessity for the public to make its own decision. In the public interest, a democratic government should in principle encourage independent groups to conduct such assessments. In Japan, in contradistinction to other countries, there has been hardly any effort by public bodies to encourage independent assessments.

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2. The ATR is a heavy water moderated- light water cooled thermal reactor (BWR type) of Japan's own design which can be fueled by MOX of low plutonium content (up to 2%). A prototype reactor Fugen (165 MWe) is operating at Tsuruga, Fukui. A demonstration reactor (600 MWe) was planned at Ohma, Aomori by government-owned Electric Power Development Corporation but canceled in August 1995. Fugen is supposed to be decommissioned in near future.

We are deeply convinced that an independent comprehensive assessment of a nuclear program in a form understandable to the public is vital not only for clarifying or assuring safety and security, but also for the democratization of society.

Implications of plutonium policy in a changing world

At the turn of a century of science and technology, or more specifically the age of nuclear technology, we are confronted with a series of difficulties on a global scale which humanity has never experienced before nor even anticipated. Amongst the most urgent issues we find environmental deterioration due to the discharge and accumulation of noxious wastes, climate change, global ecological crisis in such forms as decertification and endangering of biological species, and last not but least the threat of nuclear war and fear of Chernobyl-like accidents due to military and civil nuclear activities.

Discussing the international efforts for environmental protection, whether in the framework of the UN or not, is certainly beyond the scope of this study, but we think that it is essential to learn basic lessons from past experiences and set up a series of working principles on the basis of lessons learned.

What we have in mind is a sort of set of global ethical principles on which we are to base our assessment on MOX. They are:

- Efforts towards a world free of fear of nuclear war and man-made disaster;
- Fairness to future generations;
- Priority to international environmental and human rights concerns over national industrial interests;
- Conservation of resources and ecological systems;
- Decisions on such issues to be taken with international public participation.

We need not much to say here on these principles. While the position based on these principles are maintained in our whole project, special attention will be paid in Chapter 6 with respect to these ethical prerequisites.

References added to this summary

DTI 1997:Department of Trade and Industry (U.K.), Press Release, 31 July, 1997.

MdI 1997: Secretary of State for Industry, Press release, 5 September 1997.

Chapter 2 The Security Aspects of the Use of MOX as Nuclear Fuel

(Chapter written by Frank Barnaby)

2.1 Introduction

If the end of the Cold War has reduced the risk of a nuclear world war to virtually zero, the risk of diversion of weapon usable fissile materials by governments or subnational groups in particular has taken its place. While it is unlikely that a new full scale nuclear weapon power besides the "official" nuclear weapon states (USA, Russia, China, France and the UK) and "unofficial" ones (Israel, Pakistan, India) will emerge over the next 10 or 15 years, we believe the evidence suggests that "divertable" civil nuclear facilities and ballistic missiles will have spread widely. This in return will then lead to a significant proliferation risk.

Proliferation will also destabilize the region in which it occurs. Even the acquisition of the capability to acquire nuclear weapons will affect the security of the region. It will encourage other countries in the region to acquire nuclear weapons of their own. Thus, if Japan, for example, was to move towards a nuclear-weapon capability, North and South Korea would be under pressure to do the same and China may increase its nuclear-weapon force.

The other risk is subnational proliferation. Nuclear terrorism has replaced a nuclear world war as the most serious military nuclear threat in the post Cold-War world, at least in the short and medium terms.

Terrorist groups need to continually move to higher levels of violence. Recently, we have seen the level escalate from blowing up jumbo jets to the Tokyo nerve gas attack. The Tokyo incident shows that some of the leaders of these groups have considered the pros and cons of using weapons of mass destruction -- nuclear, chemical, and biological. The next rung on the terrorist ladder of escalation may well be the acquisition and use of a nuclear or radiation weapon.

The use of MOX fuel, and the consequent separation of plutonium from spent nuclear-power reactor fuel elements, will considerably increase the risk of nuclear proliferation to governments and terrorists. The aim of this section is to put these issues into perspective.

2.2 The Attraction of MOX for Those Wishing to Fabricate Nuclear Weapons

The use of reactor-grade plutonium in nuclear weapons

Although reactor-grade plutonium can be used to fabricate nuclear weapons, as

proved when the Americans exploded such a weapon in 1962, nuclear-weapon designers prefer weapons-grade plutonium. The latter contains less of the isotope Pu-240 than reactor-grade plutonium. A nuclear explosive device can be built with plutonium of various qualities.

The critical mass -- which is the minimum amount of a fissile material that will result in a chain reaction-- of reactor grade plutonium is a little higher than that of weapon grade plutonium, respectively 13 kg and 11 kg for a bare metal sphere. However, the use of a reflector reduces the critical mass significantly, e.g. to less than 4.4 kg - with 3.3 cm radius (the size of an orange) - in the case of a weapons grade plutonium sphere surrounded by a reflector of natural uranium. A modern nuclear-fission weapon would typically use 3-4 kg of weapon-grade plutonium surrounded by an efficient neutron reflector and tamper and about 100 or so kg of high explosive. The entire volume of device would be about that of a football and its total weight roughly 200 kg.

However, the actual amount of weapons-grade plutonium used in an implosion-type nuclear-fission weapon varies considerably, according to the explosive yield required and the technology used. A designer with access to high technology, particularly to achieve very fast implosion, could design a nuclear-fission weapon with an explosive yield of 1 kt with as little as 1 kg of weapons-grade plutonium. With 2 kg, he could design a nuclear-fission weapon with a 10 kt yield; and with 3 kg he could design a 20-kt weapon. If only low technology is available, a designer would require about 6 kg of weapons-grade plutonium to design a 20-kt weapon. With 3 kg of weapon-grade plutonium he could design a 1-kt weapon [Cochran and Paine, 1994].

Nuclear terrorism

Terrorist groups have shown themselves to be sophisticated and skilled. The construction of the explosive device that destroyed the PanAm jumbo jet over Lockerbie, for example, required considerable skill, as did the construction of the nerve gas weapon used in the Tokyo underground. Sub-national groups now have access to professional scientific and technical skills, as well as to large sums of money.

The combination of these with the increasing availability of the fissile materials which can be used to fabricate nuclear explosives; the relatively small amounts of fissile material, particularly plutonium, needed for a nuclear explosive; the availability in the open literature of the technical information needed to design and fabricate a nuclear explosive; and the small number of competent people necessary to fabricate a primitive nuclear explosive device are reasons for considerable concern.

There is no need for terrorist groups willing to manufacture a nuclear weapon to

get access to weapon-grade plutonium. Hans Blix, then director general of the IAEA, stated : "The Agency considers high burn-up reactor-grade plutonium and in general plutonium of any isotopic composition [...] to be capable of use in a nuclear explosive device. There is no debate on the matter in the Agency's Department of Safeguards" [Blix 1990].

At the June 1997 IAEA plutonium conference in Vienna, Matthew Bunn, assistent director of the Science, Technology and Public Policy Program at the John F. Kennedy School of Government, at Harvard University who chaired the National Academy of Sciences investigation into weapons plutonium disposition options, made a stunning statement based on recently declassified materials "of unprecedented detail on this subject":

"For an unsophisticated proliferator, making a crude bomb with a reliable, assured yield of a kiloton or more - and hence a destructive radius about one-third to one-half that of the Hiroshima bomb - from reactor grade plutonium would require no more sophistication than making a bomb from weapon-grade plutonium. [...] And major weapon states like the United States and Russia could, if they chose to do so, make bombs from reactor-grade plutonium with yield, weight, and reliability characteristics similar to those made from weapon-grade plutonium. That they have not chosen to do so in the past has to do with convenience and a desire to avoid radiation doses to workers and military personnel, not the difficulty of accomplishing the job. […] Indeed, one Russian weapons-designer who has focused on this issue in detail criticized the information declassified by DOE [US Department of Energy] for failing to point out that in some respects it would actually be *easier* for an unsophisticated proliferator to make a bomb from reactor-grade plutonium (as no neutron generator would be required)." (emphasis in the original) **[Bunn 1997].**

A nuclear explosive device could be constructed using plutonium either in metal form or as plutonium oxide (PuO_2). The latter is the most common form in the plutonium industry, whether reprocessing plant, plutonium stores or MOX fuel manufacturing plants. The transformation into metal, which would guarantee a significantly higher yield, is a straight-forward chemical process. However, the use of plutonium oxide is much simpler and safer to handle. The disadvantage is the much higher critical mass as compared to plutonium metal. Reactor grade plutonium in the form of oxide crystals in spherical shape has a critical mass of about 35 kg. The radius of this sphere would be about 9 cm, the size of a cantaloupe. In order to manufacture the device, besides the fissile material, a group would need to place a spherical vessel containing the plutonium oxide in the center of a large mass of a conventional high explosive. A number of detonators would be used to set off the explosive. The shockwave from the explosion could compress the plutonium enough to produce

some energy from nuclear fission and set off the chain reaction. The size of the nuclear explosion from such a crude device is impossible to predict, but it would have an excellent chance of exploding with an explosive power of at least 100 tones of TNT. Even if it was only equivalent to the explosion of a few tens of tones of TNT it would completely devastate the center of a large city.

The addition of incendiary materials would lead even a very small nuclear explosion to widespread dispersion of plutonium. The dispersal of many kg of plutonium over an area of a city would make the area uninhabitable until it was decontaminated, which could take many months. The threat of dispersion is perhaps the most serious danger that would arise from the acquisition of plutonium by a terrorist group. In fact, this danger is so great that the mere possession of significant quantities of plutonium by a terrorist group is a threat in itself. If a terrorist group proved to a government that it had plutonium in its possession it could blackmail the government.

The government would not need to be convinced that the group had the expertise to design and construct an effective nuclear explosive device. Even if there was no fission yield, the conventional explosive in the device would scatter plutonium over a large area: this would be threat enough for the terrorists' purposes.

The group would not need access to highly specialized classified data, all the necessary data can be found in the public domain, no inaccessible equipment would be needed. The Office of Technology Assessment (OTA) of the US Congress concluded that "only modest machine-shop facilities that could be contracted for without arousing suspicion would be required. The financial resources for the acquisition of necessary equipment on open markets need not exceed a fraction of a million dollars. The group would have to include at a minimum, a person capable of researching and understanding the literature in several fields and a jack-of-all trades technician. There is a clear possibility that a clever and competent group could design and construct a device which would produce a significant nuclear yield [OTA 1977]".

Which terrorists groups are likely to escalate to nuclear terrorism?

There are about 50 known terrorist groups operating today. Six types of terrorist groups can be usefully identified, each of which has distinct characteristics. First, there is terrorism by an individual. Second, there is terrorism by religious fundamentalists. Third, there is political terrorism - usually with nationalist aims. Four, there is terrorism by extreme political groups, both right wing and left wing. Five, there is terrorism by millennial groups which are getting more prominent as the year 2000, an actual millennium, approaches. Six, there is terrorism carried out by single issue groups, such as anti-abortionists and radical ecologists.

Whereas political terrorism seems to be on the decrease, religious and millennial terrorism is on the increase. These trends influence the probability of the use by terrorists of nuclear explosives.

The Oklahoma bombing by right wing activists on 19 April 1995 where a federal building was entirely destroyed, 168 people lost their lives and 850 injured went like a shock wave through the United States in particular because it was widely believed impossible that the country could be subject to devastating terrorist attacks.

The repeated bombings in the Paris Metro in the summer of 1996 where several people got killed and dozens were severely injured showed the capacity of Algerian islamic fundamentalist terrorist groups to act even in the middle of the capital of an industrialized country. The same group's attitude in their own country is characterized by limitless violence and cruelty causing tens of thousands of victims over the last few years.

2.3 The Effectiveness of International Safeguards in Plutonium Bulk-Handling Facilities

The purpose of a nuclear safeguards system is to provide assurance that nuclear materials are not being diverted from peaceful purposes to nuclear-weapon programmes. International nuclear safeguards are implemented by the International Atomic Energy Agency (IAEA) [IAEA, 1995]. Because of the danger that plutonium may be stolen or otherwise illegally acquired, and used to produce nuclear weapons illegally by governments or sub-national groups, the question of whether safeguards can be effectively applied to facilities which handle large amounts of plutonium is of crucial importance.

Commercial size plutonium bulk handling facilities like reprocessing plants and MOX fuel fabrication facilities are the most difficult sites to safeguard. This is because of the very large quantities of plutonium handled in such a plant (typically 7,000 kg or more per year for a large reprocessing plant).

The measurement uncertainties in bulk handling facilities of fissile materials are given as material unaccounted for or MUF. Under normal circumstances (in the absence of a diversion of material) the MUF figure might be positive or negative, depending on the deviation. The safeguards goal is to keep the MUF lower than a significant quantity (SQ) of fissile material. A significant quantity is defined by the IAEA as the amount of nuclear material for which the possibility of manufacturing a nuclear explosive device cannot be excluded. For plutonium an SQ is given as 8 kg. However, the safeguards system is currently not able to achieve such a performance. Independent experts have calculated that, in the case of the British THORP plant, even

if the error margin in the operator's computer calculations is as low as 1%, the minimum amount of diverted plutonium which could be detected with a probability of 95 % and a false alarm probability of 5 % is about 220 kg, equivalent to about 28 SQs.

Further one must note that even if the diversion of an SQ could be effectively detected, the IAEA's timeliness goal for plutonium could not be satisfied currently. Assuming that the THORP reprocessing plant operates for 250 days in the year, the rest of the time being used for routine maintenance, an average of about 35 kg, or 4 SQs, of plutonium will be separated each day. Conversion time --time required for conversion to weapons-usable chemical form--for plutonium oxide is one to three weeks. To achieve a minimum diversion of an SQ detected with a 90 to 95 % probability and with a false-alarm rate of no more than 5 %, assuming that σ-(MUF)-- MUF measurement error standard deviation-- is 1 %, a material balance measurement must be made when about 240 kg of plutonium have been separated.

This means that, for THORP, which on the average separates about 35 kg of plutonium per working day, a material balance measurement must be made weekly to detect the diversion of an SQ. But to satisfy the timeliness requirement the period must be significantly shorter than this. This means that, for THORP, a material balance measurement must be made *every two days* or so instead of *every year* as practiced today. Such a frequency would not be acceptable for the operator from a commercial point of view.

The Office of Technology Assessment of the US Congress, concludes that: "The conventional 'material accountancy' safeguards methods now in use by the IAEA appear unable to assure that the diversion of a bomb's worth of plutonium per year from a large reprocessing facility - e.g., one processing much over about 100 t of spent fuel per year - would be detected with high confidence." [OTA, 1995)].

A problem linked to the manufacturing of MOX fuel is the plutonium hold-up in the fuel pellet production sections in particular of first generation facilities. In May 1994, it was disclosed that a major discrepancy in the inventory had occurred at the Plutonium Fuel Production Facility, a MOX fabrication plant, at Tokai, Japan. It turns out that about 70 kg of plutonium was held up - that is, stuck to surfaces - in the remote-handling equipment. The measurement of held-up plutonium is subject to a wide range of error. Hold-up has considerable consequences for safeguards. Of particular concern is hold-up in parts of the plant which are inaccessible. When some of the contamination occurs in inaccessible places, the requirement of timely detection obviously cannot be fulfilled.

The verification of fresh MOX fuel at reactor sites has also proven extremely difficult. Various problems have been raised at the IAEA already 10 years ago [SIR 1988], but seem to persist at least to some degree until today [Pellaud 1996]. In fact, to

the technical problems one has to add the historical difficulties between the IAEA and EURATOM, as witnessed by the assistent director general of the IAEA and head of the safeguards department, Bruno Pellaud: "EURATOM and/or the German government denies access to the IAEA for some additional verification of MOX fuel in the German power plant of Unterweser, the fuel having been received from the UK. We are asked to simply accept EURATOM verification. This is accompanied by a stern lecture, that we should have and we should in the future perform our verification at the shipping end in the Nuclear Weapon States France and UK. (...) If the issue cannot be resolved, the IAEA will have to report an 'anomaly' in the next Safeguards Implementation Report". [Pellaud 96]

The document clearly shows that none of the problems with the safeguarding of fresh MOX have been solved in spite of the fact that they have been rated "high priority" almost ten years ago.

Physical protection systems

Safeguards systems are not designed to protect fissile materials but rather to control whether the physical protection is efficient. Detailed description of current physical protection concepts are, for obvious security reasons, not in the public domain. However, independent experts have had a good insight into containment and surveillance systems and estimate that these systems can be defeated or rendered non-conclusive [Leventhal 1994].

The physical protection of separated plutonium and fresh MOX in transit is of particular concern. The increasing production and use of MOX fuel leads to a sharp increase of transport of plutonium bearing materials. An analysis for France carried out by WISE-Paris showed that by the year 2000 one can expect two plutonium or fresh MOX transports per week travelling through the country by road **[WISE-Paris 1995]**. Tight safety control and security surveillance are fundamental. Beyond the dangers of traffic accidents, the danger of an armed attack on one of these transports is far from negligible. A US Department of Energy report suggests that a special protection system guarded with "deadly forces" be necessary for MOX burning of weapons plutonium in commercial reactors [US DOE 1996].

2.4 The Consequences of the Use of MOX for Negotiation of a Ban on the Production of Fissile Materials for Use in Nuclear Weapons

After the CTBT (Comprehensive Test Ban Treaty), the most important arms control measure is the negotiation of a treaty prohibiting the production of fissile material for nuclear weapons (often called a fissile material cut-off treaty).

The current negotiating mandate of the Conference on Disarmament is a

compromise and does not clearly define the scope of a future treaty. Whether it would include existing stocks of materials and "civil" plutonium production and stocks remains to be seen. However, the exclusion of "civil" plutonium would render such a treaty quite useless given the technical possibilities to use reactor grade plutonium for the manufacturing of nuclear weapons (see above) and the available current and future stocks of "civil" plutonium. According to Hans Blix, then director general of the IAEA, currently the world's nuclear reactors produce about 50 tons of plutonium every year[3]. In 1996 about 22 tons of plutonium were separated and only 8 tons were used as MOX and in FBR programs. The total stock was estimated by the IAEA to be about 160 tons at the end of 1996[4]. The stock would continue to increase over the coming years **[Blix 1997].**

The current MOX strategies, on the contrary of what their proponents claim to achieve, obviously lead to further increase of plutonium stocks and not to their reduction. This is all the more obvious since the plutonium stocks increase in particular in the countries which stand for plutonium production and/or MOX production and use: France, the UK and Japan.

Besides the technical possibility to use reactor grade plutonium even for sophisticated weapon design with high reliability, the upcoming technology of atomic vapor laser isotope separation (AVLIS), which is applicable to plutonium as well as to uranium, renders the differentiation between reactor and weapon grade all the more superficial. In fact, AVLIS will allow to transform reactor grade plutonium into weapon grade plutonium with unprecedented efficiency probably in pilot plants in various countries in less than ten years time.

The disposal of weapon-grade plutonium as MOX

Weapon-grade plutonium removed from nuclear weapons can either be stored or permanently disposed of. There are only two feasible ways under active consideration for the disposition of this military plutonium. One is to use it as MOX fuel in existing or modified nuclear reactors. The other is to vitrify it, with or without high-level radioactive wastes, and permanently dispose of it in deep bore holes or geological repositories. Although US DOE has decided to take both alternatives for

3. The difficulty to establish reliable figures is well demonstrated by the fact, that whereas the IAEA's most recent evaluation is about 50 t of additional plutonium in spent fuel, another evaluation [Albright et al. 1997] puts the figure at 75 t. We have not done our own calculation, but we do not consider that a difference of 50% for this figure is scientifically justifiable.

4. 132 t according to [Albright et al. 1997] by the end of 1995. Albright et al. project the plutonium stock to increase to 150 to 200 tons by 2000. The IAEA figure of 160 t for the end of 1996 outweighs already the low scenario for the year 2000 of Albright et al.

weapons plutonium disposition [US DOE 1997], the MOX route is certainly not the preferable method for disposing of military plutonium. The main reasons are the problems arising from the transportation of plutonium, increased radiation hazards for workers in the nuclear fuel-cycle, the long time taken to dispose of the plutonium, the financial costs involved compared with other methods, the impossibility of safeguarding adequately plutonium bulk-handling facilities, the encouragement it will give for civil reprocessing, and the irrationality of use of MOX as reactor fuel.

MOX fuel would typically contain about 45 grams of weapons-grade plutonium per kg. In a 900-MW(e) light-water reactor which can use MOX in a third of the core, about 170 kg of plutonium could be consumed (i.e. converted to reactor-grade plutonium) a year. It would take 30 of these reactors operating for at least 30 years (i.e. their lifetime) to handle the 140 t of military plutonium to be removed from dismantled nuclear weapons in the next ten years. In other words, about 25,000 MW(e) of reactor capacity would have to be used.

The use of military plutonium in MOX fuel will not assist nuclear disarmament. To the contrary. It will encourage the proliferation of nuclear weapons.

References added to this summary

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Bunn 1997: Matthew Bunn, The U.S. Program for Disposition of Excess Weapons Plutonium, IAEA-SM-346/102, Vienna, 3-6 June 1997

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Chapter 3 Safety Aspects of MOX Use in LWRs

(Chapter written by Jinzaburo Takagi and Chihiro Kamisawa)

It is often stated by MOX-use advocates that, since plutonium is produced and consumed partially in uranium dioxide (UO_2) fuel operated light water reactors (LWRs), burning MOX in LWRs basically designed for UO_2 fuel does not pose any

major safety problem.

However, there are significant differences of chemical and physical properties between UO_2 and MOX. While in a typical UO_2 fuel of up to 30-40 MWd/kg burn-up, plutonium accumulation in the fuel is 0.8-1.0 per cent after one year's operation (see Fig. 1- 1 in Chapter 1), the plutonium content of a fresh MOX fueled core can be an order of magnitude higher than that (5 to 10 %, or even higher).

The industrial experience with MOX is very limited as compared to UO_2 fuel. The number of MOX fuel assemblies used represents only less than 0.2% of the total LWR fuel assemblies and even in Germany which, besides Japan, is the largest foreign reprocessing client of the French and British plutonium industries, the share does not exceed 4% (200 t of MOX against 5,000 t of UO_2 fuel).

3.1 Safety-Related Properties of MOX as Compared to UO_2

3.1.1 Fabrication of MOX and physical-chemical properties

One of the important differences of MOX as compared to UO_2 is lowering of the melting point. The melting point of UO_2-PuO_2 lowers nearly proportionally to the PuO_2 content from the 2,840 C for pure UO_2 to 2,390 C for pure PuO_2. Also, the thermal conductivity of MOX fuel decreases systematically with increasing plutonium content, which can have a negative impact in certain transients.

3.1.2 Nuclear Characteristics of MOX fuel

The nuclear properties of plutonium isotopes are very much different from those of uranium isotopes. The remarkable differences in neutron induced-nuclear reaction behaviors (fission and capture) of Pu-239, -240 and -241 as compared to U-235 result mainly in the following changes of safety concern in MOX-based core:

- Reduction of neutron absorbing capacity of the control rods (control rod value);
- Making certain reactivity coefficients more negative at low plutonium enrichment;
- Increased power peaks;
- Reduction of delayed neutron fraction. The delayed neutron fraction of Pu-239 isabout one third of U-235, making the control more difficult, particularly for plutonium with high Pu-239 isotopic content.
- Hardening of the neutron spectrum: the nuclear property of plutonium isotopes makes the average neutron energy in the MOX-fueled core shift to higher energy regions. This effect is called hardening of the neutron spectrum.

3.1.3 Radiological properties

Plutonium is, generally speaking, radiologically a very hazardous substance and even the fuel material and unirradiated MOX fuel poses serious risks that would never be met in fresh uranium fuel. The irradiated MOX fuel presents additional radiological risks as compared to irradiated UO_2 fuel due to increased contents of plutonium and other transuranic nuclides.

Three aspects of radiological risks should be taken into consideration:

-Internal exposure to plutonium and other transuranic isotopes;
-External exposure to gamma rays from Am-241: MOX fuel also emits gamma radiation which contributes to external radiation exposure mainly of MOX facility workers. One of the major sources of gamma radiation is Am-241, which is a decay product of Pu-241 (half life:14.4 years).
-Neutron radiation: For typical MOX fuel, the neutrons from spontaneous fission of Pu-240 and from (alpha, neutron) reactions of Pu-238 alpha particles are most important.

3.2 Reactor Safety Aspects of MOX Use in LWRs

3.2.1 Summary of key factors affecting reactor safety

Most of the changes mentioned above such as lowering of the melting point, decrease of heat conductivity, decrease of control rod value, increase of absolute values of certain reactivity coefficients, reduction of delayed neutron fraction and hardening of neutron spectrum might not give rise to any serious safety problem in the operation of an LWR, as long as each effect appears separately. But the question remains open whether several factors combined could appear and significantly affect the operational safety margin under certain unfavorable conditions and, in the worst case, could lead to severe accidents which would have been avoided in a UO_2 core.

Physical-chemical irradiation behavior of MOX fuel is not quite equal to UO_2 due, above all, to the fact that plutonium has much higher fission probability (cross-section) and neutron capture reactions and that alpha particles from decay of plutonium isotopes will accumulate in MOX.

One area for concern is inhomogeneity. Even in the case of perfectly elaborated MOX, with state-of-the-art technology, PuO_2-UO_2 tends to exist rather inhomogeneously as agglomerates surrounded by UO_2 matrix in a fuel pellet and the local

burn-up of the agglomerates enriched in plutonium are usually much higher than the fuel-averaged typical burn-up of 30-40 GWd/t. This inhomogeneity along with the change of physical-chemical properties of MOX after irradiation tends to deteriorate safety features of the fuel. The effect of increased fission gas release is known and release of non-gaseous radionuclides like cesium could also be enhanced.[Walker 1991]

There are quite a few factors affecting the safety of MOX fueled reactors in the adverse direction. Factors considered relevant to operational safety are listed in Table 3-2 below.

Table 3-2 Safety Related Characteristics of MOX as Compared to UO_2

Characteristic Item	Change from UO_2	Effect
Physical-Chemical		
Melting point	Lowers by 20-40 C	Adverse effect
Heat conductivity	Decreases	Adverse effect
Fission gas release	Increased release	Adverse effect
(Non-gaseous element release)	(possible increase)	(cesium and some others)
Nuclear		
Fission/absorption cross section	Larger; strong resonance above thermal energy	Reduced control rod/boron worth
Power peaking	Increased peak ratio	Complicated MOX rod configuration needed
Reactivity coefficient	Change of absolute value	
At low Pu enrichment:		
Doppler coefficient	More negative	More rapid reactivity change in case of transient;reduced reactor shutdown margin
Void Coefficient	More negative (BWR)	
Moderator temperature coefficient	More negative (PWR)	
Fission yield and actinide production	Increased iodine, tritium and actinide production	Increased hazard in accident
Decay heat	Increased(moderately)	Negative effect on residual heat control and long term waste management
Delayed neutron fraction	Reduced fraction	Difficulty in reactor control
Prompt neutron	Shorter life time	Difficulty in reactor control

3.2.2 BWR specific problems and credible accident scenarios

For a BWR the key factor threatening the safety is considered to be the increase of the absolute value (becoming more negative) of the void reactivity coefficient of the coolant (water), which has the potential to make the change of reactivity dangerously sharp under certain conditions. The voids (steam bubbles) in the core of a BWR decreases the fission reaction rate because slowing down of neutron energy by the moderator (water) is reduced. If the void reactivity coefficient becomes more negative, the rise of power due to decrease (or collapse) of voids becomes sharper.

Feedwater transient

Loss of feed water heating or malfunction of feedwater control valve may lead to power rise due to reduced coolant temperature (the so-called increased subcooling), which would be enhanced by use of MOX fuel.

Recirculation flow transient

Increase of recirculation water flow due to malfunction of the flow control valve or inadvertent start-up of a recirculation pump increases the reactor power (inserts positive reactivity) because it pushes the voids in the primary coolant out of the core. This effect is serious even in a UO_2-based core under certain circumstances, and MOX introduction exacerbates the transient situation.

Main steam-related transient

A transient directly related to blocking of, or flow reduction in, the main steam line would be one of the most serious transients in a BWR which could lead to a power excursion in case, for example, the control rods fail to respond correctly. But, even if the functioning of control rods is assured, replacement of, say, one third of UO_2 fuel with MOX containing 4-6 per cent fissile plutonium, could be fatal because it could make the void coefficient up to 20 per cent more negative, which would result in the insertion of additional reactivity of up to 1 dollar and could lead to power excursion.

The estimate above involves uncertainties because we do not have the full information on details of various parameters. It can be justified , however, to state at least, that there are uncertainties large enough to raise well-based safety concerns over MOX fueled cores particularly in regard to response to transient changes.

3.2.3 PWR specific problems

For the operation and control of a PWR, the kinds of transient events most relevant to safety are those caused by insertion of reactivity due to change in the primary coolant density, temperature and pressure. These transient situations would

be worsened by insertion of a larger reactivity due to more negative coolant temperature coefficient of MOX.

Perhaps the most serious of such events would be a main steam line break. The severest situation will result when a main steam pipe ruptures in the reactor's hot shut down state, where the largest reactivity insertion occurs due to rapid core cooling. MOX fuel will surely worsen the situation with a larger response to rapid core cooling and the reactor shutdown margin is substantially reduced because of the large negative coolant temperature coefficient.

3.2.4 Other transient and accident cases

There are yet other transient and accident cases of light water reactors, e.g. fuel drop, fuel withdrawal and loss of coolant accidents which could be affected adversely. The reduced heat conductivity and lower melting point of MOX would adversely affect fuel behavior in such transient conditions.

It could be argued that replacement of UO_2 by MOX would contribute to better performances in some safety-related features, nevertheless negative effects and uncertainties introduced by MOX should be given weight in a safety review of MOX fuel.

3.3 Assessment of Severe Accident Consequences of MOX-fueled reactor

In view of the fact that non-negligible additional risk and uncertainty would be introduced by a MOX-based reactor core, an assessment of consequences of major accidents has been carried out both for BWR and PWR assuming the release of plutonium and MOX-associated actinides (americium and curium isotopes). This is believed worthwhile, particularly because Japanese authorities have decided that the applicants of relicensing for MOX use in LWRs do not need to assume release of plutonium in their assessment of accident consequences in relicensing application. This "MOX-LWR exempt" is a very controversial decision, because the Japanese Nuclear Safety Commission's Guideline for Plutonium Dose for Siting of Plutonium Fueled Reactor (hereafter Pu Reactor Guideline) stipulates that a dose assessment due to internal exposure to plutonium should be carried out in the siting assessment of a "plutonium-fueled reactor". The term "plutonium-fueled reactor" is somewhat vague, but there is no further definition in the text, and it should be applied, from the literal reading of the guideline, to every MOX-fueled reactor including the LWRs, needless to say of fast breeder reactors.

Therefore we have conducted assessments of accident consequences assuming release of significant amounts of plutonium and associated actinides, and calculating

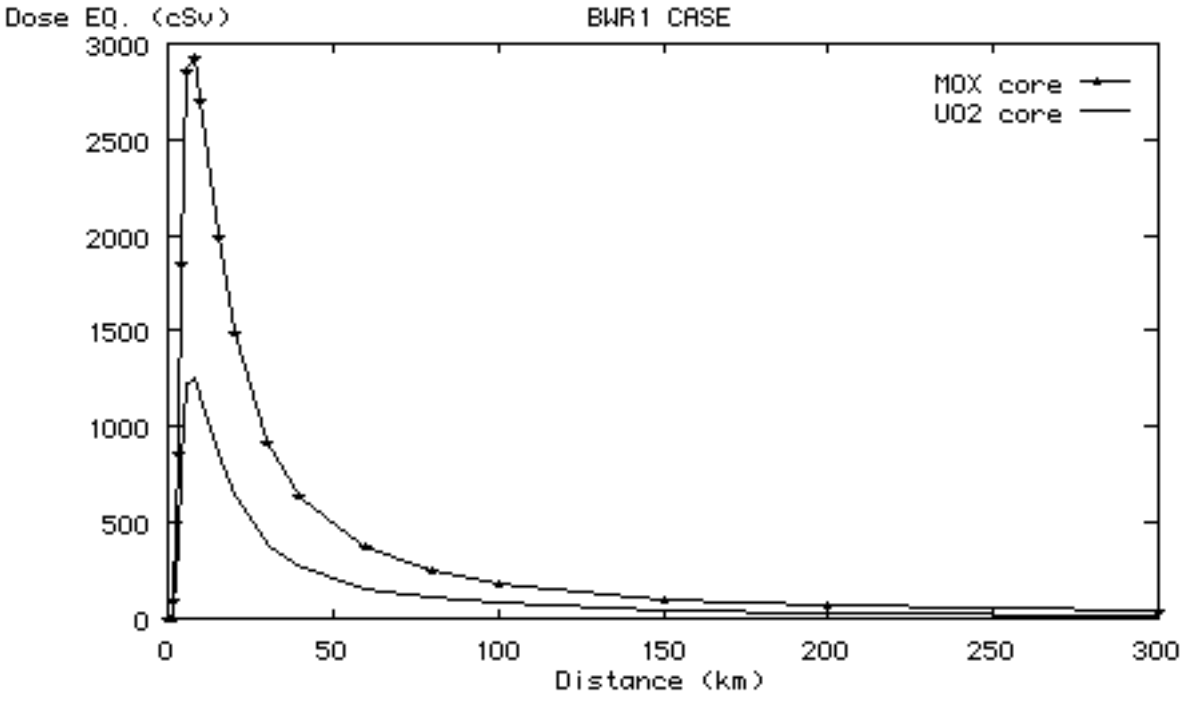
the internal exposure dose due to inhalation of isotopes of these nuclides in addition to doses by fission products by using standard LWR simulation schemes. The results have then been compared to accident consequences of similar type accidents of a UO_2 based BWR and PWR in order to assess the additional health and environmental effects caused by the use of MOX fuel.

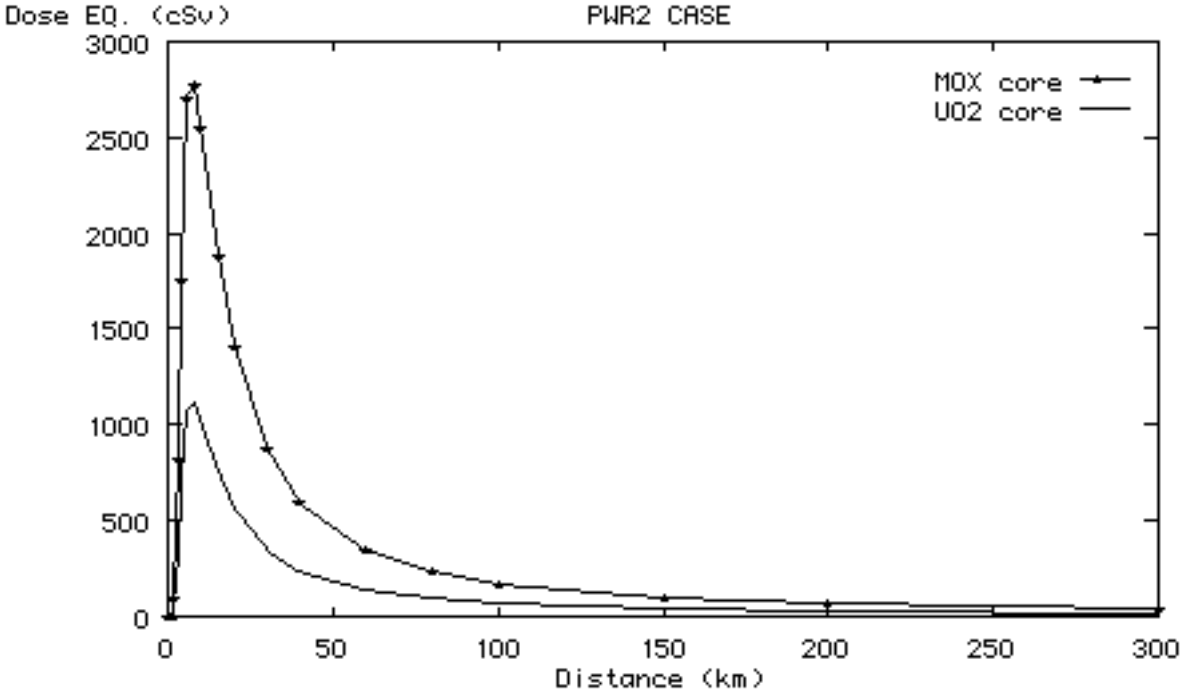
The details of the accident assumptions are given in the full report, we sum up here only the key parameters and the results of the calculations. The modelling is based on the BWR-1 type and the PWR-2 type core melt accidents involving containment failure according to the 1975 US Reactor Safety Study (WASH-1400)[USNRC 1975]. the plutonium release fraction is estimated to be 4% corresponding to the release of 67 and 69 kg of total plutonium respectively for the BWR and PWR accidents assumed.

The evaluation of internal exposure due to plutonium intake is based on current Japanese legal basis. Figure 3-1 indicates the whole body dose estimates as a function of distance from the reactor. While the effect is already catastrophic in the case of a UO_2 fueled reactor, the results clearly show the effect of actinide (plutonium, americium and curium) release in the case of a severe accident at a MOX loaded reactor. The dose is generally 2.3 to 2.5 higher at a given distance in the case of the MOX fueled reactor, implying that health effects of the radioactivity release would increase by the same factor. In other terms, the distance of various health impacts increases so that the actual increase in social impacts would be 3.2 to 4 times higher if social impact is assumed to be proportional to the affected area (since the area is proportional to the square of the distance).

In case of a smaller release of actinides, the impact of MOX use is naturally expected to be less significant. Even for very moderate releases of actinides of 0.5-1%, however, our calculations show that the exposure rate at a given place is 1.1 to 1.5 times higher for a MOX core as compared to a UO_2 core, implying that the large actinide inventories of the MOX-fueled core could worsen accident consequences significantly for any major accident scenario.

Fig.3-2 Whole Body Dose Due to LWR Accident





3.4 Safety Aspects of the MOX Fabrication Plant

3.4.1 MOX fabrication processes and workers' exposure

For MOX fabrication, PuO_2 and UO_2 are first co-milled to form a master (primary) blend, which is further blended with UO_2 to produce MOX powder of high homogeneity and with specific Pu/U ratio. The blended MOX is pressed/pelletized, sintered in inert atmosphere and packed into fuel rods. Most of these processes take place in an advanced MOX fabrication plant in an automated sealed glove box system that is designed to minimize risks associated with the handling of large amounts of plutonium. Indeed, newly built automated MOX plants have reduced the radiation exposure level of workers substantially.

However, some of the processes still need manual work and there are possibilities of workers being internally exposed to plutonium, mostly by inhalation, spilled from a hole in a damaged glove or packing. A more general cause of worker's exposure is external irradiation by gamma-rays. Am-241 accumulating in MOX as the decay product of Pu-241 is the main source of gamma radiation and in order to limit individual exposure, the time period from separation of plutonium in a reprocessing plant to MOX fabrication is limited to about three to five years.

The actual level of average individual dose experienced in European MOX fabrication plants ranges from 2 to 12 mSv per year, while the collective personnel doses are in the range of 600 to 2,700 person-mSv per year. [OECD/NEA 1993]

3.4.2 Plutonium release accident in MOX fabrication plant

Accident possibilities

Among several accidental events which would provide pathways to release of plutonium to the environment, fire and criticality are considered to give most serious consequences. Although a MOX fabrication plant is built mostly of fire-resisting and non-flammable materials and MOX itself is not flammable, combustible materials like glove box panels, organic additives, paper and plastics or hydrogen gas are used in the plant.

Criticality is perhaps the most frequently experienced type of severe events in plutonium processing plants, and a plutonium plant should, in principle, be designed to prevent the occurrence of criticality status under any conceivable plant condition.

Consequences of plutonium release

The maximum credible accident case may be an explosion caused by a criticality excursion or by a large fire inside the plant. If 100 kg of plutonium is involved in a big fire inside the plant, then a ground level plutonium release of the order of 100 g fine

aerosol particles can be expected. A calculation of internal exposure to plutonium similar to that conducted for reactor accidents in the preceding section shows that the 10 cSv evacuation zone extends to 3.5 km from the plant.

3.4.3 Plutonium waste from MOX fabrication plant

Plutonium bearing wastes and scrap pose security and safety concerns. Significant quantities of plutonium can be withheld in the piping and gloveboxes of MOX fabrication facilities as was demonstrated with the stunning 68 kg of plutonium identified at PNC's PFPF (Plutonium Fuel Production Facility) plant at Tokai. Even after extensive clean-up 9.5 kg remained unrecovered.

Treatment of scrap materials and waste including the clean-up process would result in increased workers' radiation exposure. Plutonium wastes contained in plastic bags and used gloves are flammable and could catch fire to release plutonium aerosols. Furthermore, the whole process of scrap treatment comprises very complicated chemical procedures.

3.5 Risks of Reprocessing Plants

With its large spent fuel storage and chemical processing capacities, a full scale reprocessing plant is a central facility for a MOX fuel cycle where largest amount of radioactive materials and nuclear materials contained in spent nuclear fuel assemblies amass. In addition, highly radioactive spent fuel rods are dissolved and subjected to a long series of chemical procedures. All of the commercial reprocessing plants had significant accidents including radioactive releases in the past. However, the detailed discussion of these aspects would go beyond the scope of this study. Also other reports have covered this subject quite extensively [UCS 1975; Takagi 1990; OECD / NEA 1993, IAEA 1996].

A significant matter of concern is the routine radioactive discharge of reprocessing plants, by far the largest release of any given element of the nuclear fuel chain. If compared with a standard French PWR, the radioactive release of the La Hague reprocessing plant is more than 1,000 times higher. The comparison between the discharges of different plutonium production facilities is also quite interesting. One of the most hazardous component is the liquid beta-gamma discharge because it is directly related to the contamination of marine organisms. The total beta liquid discharge (except tritium) of UP2+UP3 (usine plutonium = plutonium factory) is about 50 times higher than that of Thorp at Sellafield, which is itself about 50 times larger than that of the Rokkasho project. Accidentally or not, the planned Rokkasho liquid beta discharges are just 50 times higher than envisaged for the Wackersdorf

reprocessing project in Germany now canceled.

The discharge of radioactive Iodine-129 with half life of 15.7 million years is of particular concern. It accumulates in the thyroid when inhaled or digested to cause thyroid injuries including thyroid tumor. Obviously, given the extraordinarily long half-life, Iodine-129, once released, will stay in the environment virtually forever. It is already identifiable in significant concentrations in seawater, marine organisms and moss around reprocessing plants and at significant distances from these facilities.

The issue of increased childhood leukemia near reprocessing facilities has been raised in the UK since 1983 and, more recently in France. The publication in the British Medical Journal [Pobel 1997] of a study raising the potential link between the La Hague plant and a leukemia cluster identified lately in the vicinity of the plant has led to considerable concern in the French population. The discovery of exceptionally high levels of radiation at the plant's discharge pipe which was found uncovered over significant length on the beach in March 1997 and subsequent sample analysis by various laboratories on behalf of Greenpeace and COGEMA client country's authorities led to additional agitation. In fact, unexpectedly, the plutonium issue has been on the top news agenda for most of 1997 in France.

Chapter 4 Economics of MOX Use in LWRs

-An Analysis Based on Japanese Realities

(Chapter written by Baku Nishio)

4.1 Introduction

Economy is obviously another key factor in judging whether the MOX- LWR program is justified. Our main interest here is in the economics of MOX in Japan. Although there have been a certain number of analyses addressing the economics of the plutonium fuel cycle or MOX in Europe and America, most of them are not directly applicable to Japan, because costs of various fuel cycle-related industrial activities are substantially different in Japan from those in Europe and America.

We have elaborated two scenarios, one which considers that plutonium is already available, so its production cost is taken as zero and a second scenario which takes the plutonium production costs into account.

4.2 Fuel Cost Estimate: Case 1 -- The Free Plutonium Scenario

The total annual fuel costs for a Japanese 1,000 MWe LWR loaded with MOX for a third of core is estimated, under the assumption of sunken reprocessing costs or "free plutonium", to be 5.3 to 6.3 billion yen ($48-57 million), as compared to 4,4 billion for a full UO_2 core. The result clearly indicates that the costs for 1/3 core MOX fuel utilization are 20 to 40 % higher even under the most optimistic assumption for MOX program promoters of free plutonium.

The unit cost of MOX is 260 to 370 million yen/tHM or $2.4 to 3.3 million/tHM, which is 1.7 to 2.5 times the cost of uranium fuel (150 million yen/tHM). The fuel cost per kWh power generation is calculated for a capacity factor of 75% to be 0.80-0.94 and 0.67 yen, respectively for 1/3 MOX loading and full UO_2 loading.

4.3 Fuel Costs Estimate: Case 2 -- Taking Reprocessing Costs into Account

1/3 core MOX fuel utilization will cost 2.2 to 2.7 times as much as that of the conventional UO_2-based core, when the costs associated with reprocessing are to be taken into account. Doubtlessly MOX fuel utilization should largely increase the nuclear fuel cost. If the AECJ's long term program - to adopt a one-third of a core MOX plan for 10 Japanese thermal reactors by the year 2000 - is implemented, it will lead to an extra fuel cost of 54-73 billion yen every year.

If we compare fuel costs per tHM, MOX fuel costs 770-870 million yen as compared to 150 million yen for uranium fuel. Thus MOX is more than 5 times as costly as the UO_2 fuel. Assuming a reactor capacity factor of 75%, fuel costs per unit power generation (per kWh) will be:

uranium fuel: 0.67 yen/kWh
1/3 MOX fuel: 1.5-1.8 yen/kwh

Official figures of power generation cost per kWh in Japan as given by the Agency of National Resources and Energy (ANRE) for 1992 are 9 yen for nuclear reactors, as compared to 10 yen for oil/coal fired power plants. While this low cost estimate for nuclear energy is highly questionable in view of recent trends , 1/3-MOX fueling will push up the nuclear power cost by 0.8 to 1.1 yen per kWh, which would offset even the alleged "economic advantage" of nuclear power.

4.4 Other Factors to Be Considered

There are yet many factors which were not considered above but would push up the MOX costs even further. They include:

Transportation costs

The 1992-93 maritime transportation of plutonium oxide by the Akatsuki Maru required not merely the direct cost of shipment (1.2 billion yen), but an additional 5.1 billion yen for the construction of a cask, renovation of the carrier ship (to be a fully-equipped plutonium freighter) and other related costs .

Physical protection costs

Akatsuki Maru was escorted by Shikishima, a lightly armed coast guard cutter, the construction of which costed the Maritime Safety Agency of Japan 20.3 billion yen, plus the yet undisclosed cost of voyage. In addition, 69 patrol vessels, 5 aircraft, and 5,000 police and coast guard officers had to be mobilized to secure the arrival of Akatsuki Maru.

PR/PA costs

A large sum of money has to be spent, both in Japan and overseas, in order to raise public acceptance for plutonium shipments, HLW shipments, and construction of new nuclear fuel cycle facilities. Every year, the Science and Technology Agency (STA) alone spends five billion yen advertising its plutonium program [18].

Research and development (R&D) costs

Considerable technological uncertainties remain as to MOX fuel utilization in light water reactors and disposal of HLW and other kinds of waste. A large investment on research and development is still required, which can be very costly. In the 1996-97 budget of the Japanese Government, approximately 50 billion yen ($455 million) is estimated to be allocated to the back-end and MOX research (excluding FBR and ATR funding) .

Reprocessed uranium

We have assumed that uranium recovered by reprocessing can be used free of charge in fuel fabrication. If this is not the case, the cost of shipment of waste uranium from the reprocessing plants in Europe back to Japan and the cost of domestic storage and disposal have to be added to the bill.

If one estimates the total of the additional costs between 2000 and 2010, we have to count 5.1 billion yen for transportation expenses, 20.3 billion yen for the physical protection, half of 5 billion/y x 10 years for the PR/PA costs and tentatively 10 % of the

annual R&D (50 + 9.1 + 6.8 billion yen) x 10 years for the R&D funding. These add up to 116 billion yen which will be spent on the use of total 70 tons of plutonium. Thus the additional cost is about 1.7 million yen/kg plutonium or 57 million yen/tHM MOX, which would raise the total fuel cost by several percent.

The deterioration issue aside, the uranium savings by the current Japanese MOX programs is considered to be less than 10 % for the foreseeable future [Skornikoff et al. 1995], which cannot thus offer a persuasive justification for the MOX program in this age of surplus uranium and buyer's market for uranium that is predicted by industry analysts to last for a long time to come.

4.5 Conclusions

The introduction of MOX to a third of core will raise the fuel costs of LWRs by a factor of about 2.5. There is no economic justification for the MOX use in light water reactors.

Some cost overruns in Japan, if compared to other countries, can be attributed mainly to high construction costs in Japan. While this disadvantage can be avoided by commissioning reprocessing and MOX fabrication from European companies, this would not result in net cost reduction since the long distance shipments of radioactive materials push up the costs.

There are still many uncertainties in figures used for the calculation, particularly for the back-end and transportation costs, some of which are due to lack of transparency of the plutonium industry and the utilities.

Chapter 5 MOX and Back-end Policy

(Chapter written by Michael Sailer and Jinzaburo Takagi)

5.1 Introduction

This chapter is dedicated to examining the wisdom of MOX use in the light of back-end policy options. Nuclear fuel cycle policy has to be decided on the basis of two main aspects, the fuel strategy and the back-end strategy (nuclear waste or spent fuel management policy). Historically, the main emphasis in the rationale for the reprocessing and MOX use policy has been in the effective reactor fueling strategy, that is using uranium resources efficiently by recycling and breeding plutonium and also by

recovering uranium for reuse. However, disadvantages, uncertainties and complications associated with the MOX use appear to far outweigh the potential advantage of plutonium "recycling."

While a lot of nuclear experts initially expressed great concern over the lack of uranium resources and uranium prices which showed a soaring trend in the 1970s, the situation has dramatically changed since. Uranium prices have stabilized at a very low level and today's world uranium market has a potential for a long term supply since the current number of some 430 operating reactors is set to decrease rather than increase in the future. Furthermore, uranium savings by reprocessing and MOX use are estimated to be small.

The examination of the rationale for reprocessing-MOX use option, as compared to the once-through option from the back-end policy point of view seems to be becoming increasingly important under the current situation, whereby the main justification for the reprocessing/MOX fuel cycle option is shifting from the fueling policy to the alleged advantage in spent fuel and radioactive waste management.

5.2 Direct Interim and Final Storage: Technical Description of the Process

5.2.1 Direct management of spent nuclear fuel

The fuel strategy without reprocessing (and use of plutonium) is called once-through nuclear fuel cycle, but from the back-end policy point of view, it can be called a "direct fuel disposal" (DFD) option, since this path is generally regarded as leading to final disposal of spent nuclear fuel. A back-end policy aiming at DFD, in spite of many uncertainties concerning the siting of final disposal facilities, is now the world mainstream for the management of spent nuclear fuel of light water reactors (see Annex 1).

The DFD path needs the following steps from a purely technical point of view:
- Interim storage of spent fuel for a time span of 25 to 30 years;
- Conditioning of spent fuel for final disposal;
- Final disposal at a high level nuclear waste repository;
- Transports necessary to carry out the steps above.

Since spent nuclear fuel contains huge amounts of radioactive substances, every step of the DFD path is influenced by the basic safety problems. Gamma and neutron radiation in particular necessitate massive radiation shielding. Highly reliable barriers against radioactive release are an absolute necessity and have to be maintained during a very long period of interim and final storage (disposal). The radioactive decay also

generates thermal energy. Therefore, the spent fuel has to be cooled for a long time period.

5.2.2 Interim storage of spent fuel: technical basis and requirements

Technology of interim storage

A typical light water reactor of 1,000 MWe discharges 25 to 30 tHM (tons of heavy metal) spent fuel annually. The intensive decay heat of the initial spent fuel has to be cooled down for 25 to 30 years. Heat generation decreases very slowly after this time period.

The available technical options for the interim storage include wet storage in a pool and dry storage either in casks or canister systems.

Wet storage

Every nuclear power plant has a water-cooled (wet) storage pool to cool down spent nuclear fuel removed from the core. The rather limited capacity of storage facilities, a few hundred tons in the case of a typical Japanese LWR, reflects partly the concern of local governments which do not want the accumulation of spent fuel on site as well as the initial government policy to reprocess spent fuel as early as possible after discharge.

The shortage of wet on site storage capacity is countered firstly by so-called "compact racking" or reracking, and secondly by the construction of new pools. The reracking, which is to apply a redesigned compact rack with smaller distances between the fuel assemblies, poses criticality problems, and thus special additional measures like using borated steel or borocarbide layers for racks are necessary. For the expansion, the current tendency in Japan is to build an additional storage facility common to more than one reactor at the site. Safety issues aside, expanding the storage capacity in one of these ways is now facing difficulties in securing approval by local residents.

In addition to the on-site storage facility, there are away from reactor (AFR) storage facilities. The most typical facility is the entrance storage facility at reprocessing plants with a large capacity, in some cases as large as over 13,700 tHM (La Hague) as compared to 3,000 tHM in the case of the planned Rokkasho Reprocessing Plant in Japan.

A wet storage facility needs a lot of engineered safety features. These include active cooling systems to remove residual heat, water cleaning systems, redundant power supply systems, control systems for the operation of the storage facility, and protective systems against impacts from outside of the building housing the pool (and related safety systems have to provide protection against an air crash, the greatest possible earthquake shock and sabotage).

An additional problem is corrosion of the metallic fuel claddings which would

also pose handling difficulties in a conditioning plant after the interim storage period is over.

Cask storage

Spent fuel storage in dry state is already put to practical use in some countries such as the USA, Germany, Czech Republic and Lithuania. TEPCO has got permission for dry storage and started to store some 400 BWR spent fuel assemblies in 1995. The technology basically consists of a container of steel or cast iron with a wall thickness of 30 to 40 cm, along with a cap system which serves as the key barrier against radioactive releases into the environment and needs essentially no active components. A leak control system needs active features like a control room and active components. The decay heat of the spent fuel will be air-cooled and needs essentially no additional cooling.

Storage in cans

Storage in cans is a type of dry storage for spent fuel implemented in countries such as the USA, Scotland and Hungary. The spent fuel is encapsulated in steel canisters with relatively thin wall thickness (several millimeters typically). The cans (canisters) are weld-sealed and stored in storage channels housed in a concrete storage building. The channel and the building are basically designed to be cooled by natural air convection and thus constitute a passive cooling system. A control system assures leak-tightness of the facility. The building should be designed to resist the maximum credible impact and to serve as shielding of gamma and neutron radiation. There are still many uncertainties in the long term leak-tightness of canisters, especially due to corrosion potential.

Technical requirements for siting

Interim storage can be in a in a central facility on the reactor site, or in decentralized facilities, some or all of which can be off-site. The most basic technical conditions for siting is that the site should exclude the possibility of external impacts such as aircraft crash and earthquake shock.

Best available interim direct storage option

Cask storage seems to be the best technical option for the direct storage strategy from the safety point of view, because it relies mostly on relatively simple and cheap passive safety features. This does not mean that dry storage in casks would not pose any risk. Long term assurance of leak-tightness and diversity of safety control need to be further improved; also there is concern over the adequacy of existing casks in regard to shielding against neutron radiation. However, cask storage appears to be the best available option, if the direct spent fuel management policy is adopted.

5.2.3 Conditioning and Final Disposal

A brief description of the technical aspects of the DFD path would seem of particular interest to the Japanese public because the non-reprocessing option has not been subject to large scale public debate in Japan.

The key advantage of the DFD path may be in that the spent fuel can be put to final disposal without intensive processing, although conditioning is still necessary to bring the spent fuel into a disposable form. The package or cask for the final disposal has to be designed to remain intact for 10,000 years or longer under the geological conditions of the final storage facilities. The technology for conditioning for final disposal is still immature and specifications of the packaging for it are yet to be established.

Final disposal

The most probable way of final disposal would be burial in a geological repository 500 to 1,000 meters deep underground. Key factors to be taken into account should be heat generation, the long term integrity of the package and the geological characteristics of the surrounding rocks such as the tectonic stability and water permeability. While these factors are strongly affected by the amount of radioactivity (heat, radiation), they do not depend much on the type of specific nuclear fuel path because the amount of radioactivity is determined by the amount of original spent fuel generated.

5.3 Reprocessing Path as Back-end Policy Option

5.3.1. Technical steps for reprocessing

The spent fuel is transported, after a cooling period of usually one to several years, to the reprocessing plant where it may be further stored for some time before being subjected to an extensive chemical separation process (reprocessing). Usually, the radioactive substances contained in spent fuel are chemically separated through a wet chemical process (PUREX) based on solvent extraction into three major fractions, uranium (around 96%), plutonium (1%) and fission products, including actinides (3%). Recovered uranium and plutonium is stored and could be put to use as fuel or could be dealt with as waste. The major part of highly radioactive substances in aqueous solution is solidified into borosilicate glass logs in a process called vitrification. The vitrified high level waste (VHLW) will be stored for an interim period of 30 years (or longer) and is planned to be shipped to a final disposal facility

after the interim storage period. The packaging and process for final disposal are basically similar to that of the DFD path.

Difficulties of the reprocessing industry

In Table 5-1 listed are the industrial-scale civil reprocessing plants now operating in the world. There are only five plants operable industrially for light water oxide fuel, two in France and one each in the UK, Japan and Russia. Even if these plants were booked out and operating at full capacity they could only process about one third of the spent fuel discharged annually world-wide. The record of the existing five plants reveal technical and environmental difficulties and the latest explosion at the Tokai reprocessing plant shows that the technology is far from being mastered.

5.3.2 Radioactive waste from reprocessing

Essentially, three categories of radioactive wastes are produced by reprocessing, although classification systems and therefore regulations differ from country to country:

Vitrified high level waste (VHLW): Most of the fission products and actinides in the spent fuel will be contained in these glass logs (0.1 - 0.15 m^3 per ton of light water spent fuel according to industry sources).

Intermediate level waste (ILW): Usually ILW indicates hulls, nozzles, bituminized sludge and other medium level radioactive wastes (1.3 to 2.6 m^3 per ton, according to industry sources) with radioactive concentrations of around 1 MBq/g, but the definition for "intermediate" is rather vague. It can contain actinides.

Low level waste (LLW): The low level waste from the process stream mainly comprises concentrates of various kinds of waste liquid solidified with bitumen, cement or polyester as well as miscellaneous solid low level wastes arising from the daily reprocessing plant operation (3.8 to 6.8 m^3 per ton according to industry sources).

Other wastes from the reprocessing path

Spent MOX fuel and plutonium waste: In addition the reprocessing-MOX path produces spent MOX fuel and MOX fabrication plant wastes. While spent MOX fuel could be put to further reprocessing in theory, it is usually regarded as a variation of spent nuclear fuel which is to be treated as HLW for direct disposal.

Decommissioning waste: The wastes emerging from decommissioning a reprocessing plant should also be regarded as reprocessing wastes, because they are wastes

exclusively associated with the reprocessing path. The most voluminous part of the decommissioning wastes is the concrete which is considered to be of very low level, but decommissioning also generates wastes of much higher degrees of radioactivity, up to intermediate level. Some estimates suggest that the waste volume associated with decommissioning would be as much as 30 to 80 m^3 per ton of spent fuel [Large 1993].

Radioactive discharges and "virtual waste": Radioactive gaseous and liquid discharges due to the normal operation of a reprocessing plant are substantial. They are radioactive waste which is directly dumped into the environment. Homberg et al. regard these discharges as "virtual waste" and estimate the corresponding volume of "waste" for the La Hague reprocessing plant, assuming the emissions were to be solidified into low level waste packages.[Homberg 1995] Their estimate is 23.7 and 11.9 m^3, respectively for gaseous and liquid discharges.

5.3.3 Transport of radioactive wastes

The most difficult and controversial shipments are those for return of radioactive wastes from a foreign reprocessor to the client country like the ones now taking place from France to Japan.

French legislation on radioactive waste stipulates that the storage of foreign radioactive wastes in France is prohibited beyond the time frame technically necessary to carry out reprocessing. This is understood as covering the period necessary for the HLW to cool down enough to be returned to the country of origin.

CNIC estimates the amounts of waste to be sent back to Japan from France to be about 30,000 containers and 7,600 from the U.K. as a result of reprocessing with return clause contracts at La Hague (LWR: 2,774 tHM) and Sellafield (GCR spent fuel: 920 tHM; LWR: 1,998 tHM).[Takagi 1994]

While the VHLW is being transported and stored in the storage facility at Rokkasho, there is no plan to build a storage/disposal facility for the wastes in the other waste categories which are also supposed to be stored at Rokkasho. Recent information obtained by WISE-Paris indicates that there is a secret agreement between the reprocessing company COGEMA and its foreign clients to send back none of the low level wastes and only a minor part of the intermediate level waste. In addition, compacted intermediate level waste should not be sent back before 2008. However, such an agreement would be illegal under current French law. The return of reprocessing wastes to Japan from Sellafield is similarly surrounded by secrecy and uncertainty.

5.4 Comparison of Reprocessing and Direct Storage/Disposal Path

5.4.1 Decay heat

The main advantage of the reprocessing path as claimed by the plutonium industry is that it would result in vitrified high level waste of smaller volume with less decay heat and toxicity for final disposal and thus would present a smaller environmental burden than the DFD path. This is an over-simplified argument from the overall back-end policy point of view because it ignores the fact that the reprocessing-MOX use path generates also spent fuel (MOX spent fuel) and actinides.

If one is to compare the volume and thermal output of the high level waste from the reprocessing-MOX path and DFD-once through path, the total high level wastes generated should be compared:

- The high level waste from the DFD path is basically the spent fuel itself.
- The high level waste from the reprocessing path is
  - (a) vitrified high level waste plus
  - (b) spent MOX fuel whose decay heat is always much higher than that of the UO_2 spent fuel with the difference increasing with the fuel burn-up.

It is evident that the specific decay heat as well as radiation and toxicity, per unit electricity generated, of the reprocessing path, as it adds vitrified high level waste to spent MOX fuel, is far higher and more difficult to handle than that of DFD path. The thermal output of spent MOX fuel is by a factor of two higher than that of UO_2 spent fuel at moderate fuel burn up rates and by about factor three or more at higher burn-up rates due to the increased build up of heat generating long-lived actinides.

In conclusion, the DFD path is preferable to the reprocessing path from the viewpoint of overall waste heat management. The same holds true for the radiotoxicity involved.

5.4.2 Total waste comparison

It may still be argued that the discussion given above would not be valid, if the reprocessing policy was adopted from a purely back-end policy point of view and no use of plutonium was made.

The Japanese reprocessor at Rokkasho, JNFL, indicates a total waste volume generated per ton of spent fuel processed of 2.7 m^3. The figure is far less than COGEMA's original value for La Hague of 6.65 m^3, which can itself be regarded as excessively optimistic. But, when the figure of 2.7 m^3, without conditioning and packaging for management/disposal, is compared to the bare volume of spent fuel (0.4

and 0.5 m^3, respectively per ton of PWR and BWR fuel), the waste volume generated by reprocessing is still about six times that of the original spent fuel.

It is interesting to note that the past operation of the Tokai reprocessing plant produced as of the end of March 1996 about 13,000 m^3 solid waste equivalent of liquid and solid low and intermediate level radioactive wastes after having reprocessed 813 tons of spent fuel. This indicates that on the average about 16 m^3 of low plus intermediate level waste was generated by the reprocessing of a ton of spent fuel, which is more than six times the projection for Rokkasho. The only official statement by the Japanese government on the issue stated that: "The volume of waste would be probably 20 to 30 times of the original spent fuel volume" [Ishida 1993].

WISE-Paris gives a much higher estimate of reprocessing waste volumes. The amount of low, intermediate and high level radioactive wastes adds up to about 17 m^3 per ton of fuel without the decommissioning waste.

If we compare the total estimated volume of wastes from the direct disposal and reprocessing paths with the package for disposal included and without counting the decommissioning of related facilities and plutonium disposition, the former may be around 2.7 m^3 while the latter is at least 17 m^3, indicating that the reprocessing path generates at least six times more waste than the direct disposal path.

5.4.3 Radioactive discharges

The large environmental radioactive discharges associated with reprocessing constitute obviously a great disadvantage of the reprocessing path as compared to the DFD path which has no comparable emissions (see Chapter 3).

5.4.4 Transport and other related nuclear activities

Large amounts of wastes have to be sent back from Europe to Japan in accordance with the reprocessing agreements in addition to the shipments of spent nuclear fuel from Japan to Europe. More than 200 shipments are expected to take place in the coming decade (Figure 5-4), while one plutonium and two VHLW shipments carried out in the past five years already raised worldwide concerns. The reprocessing path obviously increases transport -- especially demanding international transit -- of highly radioactive wastes greatly as compared to the DFD path.

5.4.5 Reprocessing vs interim storage

The main reason for continued, though limited, interest in reprocessing, is that storage capacity for spent nuclear fuel assemblies is running out soon at some reactor sites and sending the spent fuel to an existing reprocessing plant with extra storage

capacity could avert the difficulty for some time.

This is going to be exactly the case in Japan. The total generation of spent fuel under the present nuclear generating capacity of 45 GW from 52 commercially operating reactors is about 1,100 - 1,200 t (HM) per year. The existing on-site storage pool capacity totals around 15,000 t with about one third already occupied. Even if the 3,000 tHM storage capacity at the Rokkasho reprocessing site is added, the storage capacity will probably run short around 2010. While the capacity shortage is therefore not so impending in Japan as a whole, it is becoming serious for *some* reactor-side spent fuel pools and reracking has already been implemented.

Furthermore, it should be noted that storage at reactor sites is accepted by local governments only as temporary spent fuel management and not as general interim storage scheme for Japan. However, Zengenkyou (the National Association of Nuclear Power Plant Site Cities, Towns and Villages) partially modified its strict "no storage principle" to allow on-site interim storage when the relevant local government judges it unavoidable.

Reprocessing or spent fuel storage at reprocessing sites is merely buying time. Aside from the reprocessing wastes to be returned, the spent fuel sent to a reprocessing plant will sooner or later be sent back as MOX fuel and stay at the reactor site as spent MOX fuel. Thus, reprocessing will not solve any of the problems in the longer term. It may put off an urgent difficulty, which will return even in a more serious form. Thus it will leave serious problems for future generations to resolve.

5.4.6 Rational back-end Policy -- conclusion

The direct management and disposal of spent fuel is doubtlessly the preferable option, since the enormous volume and types of radioactive substances -- which are the central hazard of nuclear energy -- can be kept confined in principle in fuel elements. There is no need to separate them out and subject them to additional processing which has no positive effect on the back-end management.

VHLW from reprocessing, as spent fuel in the DFD path, needs conditioning for final disposal and if MOX use is implemented, the spent MOX fuel needs conditioning for long term management and final storage.

Nuclear activities should be kept as simple as possible, since that minimizes the potential for accidental radioactive releases and nuclear proliferation as well as control on information. From this point of "simplicity principle", the best option is the DFD path. For interim storage along the DFD path, dry storage is preferred to wet storage as the storage technology option since the former requires fewer active safety features and is thus less vulnerable to failure.

5.5 Future Handling of Spent fuel and Plutonium

5.5.1 Canceling the reprocessing contracts

If there remains no justification for reprocessing and MOX use, further plutonium separation should be halted and corresponding reprocessing contracts be canceled. This is an appropriate moment for Japan to do this, because the Tokai Reprocessing Plant is expected to be out of operation due to the March 1997 accident for at least three to four years to come, and the plutonium program is being reconsidered. While as of 1 March 1997 about 75% of the spent fuel under contract with COGEMA was already reprocessed, most of the Japanese spent fuel under contract by BNFL has not been reprocessed yet.

It is widely said and believed that cancellation of overseas reprocessing is impossible. This is not true. Typically commercial contracts contain a clause, which allows cancellation under unavoidable situations. A political decision by the Japanese government supported by a parliamentary resolution is enough to be treated as the unavoidable condition. **Even if the clients were forced to pay all of the amount fixed under the commercial contract plus the additional cost of returning the spent fuel, the total cost would be almost certainly lower than the MOX option**.

Steps after cancellation

The following types of spent fuel and associated radioactive materials must first be distinguished:

(1) Spent fuel included in the contracts but not yet shipped;
(2) Spent fuel transported to overseas reprocessing plants, but not yet reprocessed;
(3) Wastes from reprocessed spent fuel;
(4) Plutonium already separated and existing in store in European plants.

Legal and technical steps

(1) The shipment of Japanese spent fuel to European reprocessors should be stopped immediately. Because more than 97% of the total of 5,598 tHM of LWR spent fuel have already been sent to Europe, canceling further shipments would cause no major problem.

(2) The spent fuel stored at European reprocessing plant sites has to be sent back to Japan immediately after cancellation of the contracts. Therefore there is an urgent need of establishing an interim storage capacity in Japan with a given size and in a given time frame in accordance with the cancellation of the respective contracts.

(3) Wastes generated until the cessation of reprocessing should be sent back to Japan. There are still unsolved safety problems and large international and domestic

concerns over the safety, based on solid technical arguments. But, as in the case of unreprocessed spent fuel, there is no other choice for the reprocessors to return Japanese wastes and for Japanese utilities to accept them. There should be however an in depth impact assessment prior to any further shipments.
(4) According to the Japanese government, as of the end of 1995, almost 10 tons and 1.4 tons of separated Japanese plutonium were stockpiled respectively at La Hague and Sellafield. The amount at the time of this writing (April 1997) may be respectively over 11 and 2 tons.

From the results of our analyses, it is concluded that separated plutonium should be treated as waste and discarded as such in a proliferation resistant form. This is believed to be achieved either by immobilization techniques or storage pin technology [Kueppers 1994].

A possible choice may be to mix Japanese plutonium with Japanese origin high level liquid waste to produce vitrified high level-plutonium waste and send it back to Japan. This certainly needs further technical developments. but it is believed that adding plutonium to the high level waste before vitrification into glass log -- at a concentration of up to 2% -- would not give rise to serious additional difficulties beyond the safety problems inherent to the usual vitrified high level waste. The amount of available high level waste is considered to be sufficient to incorporate all the separated plutonium.

5.5.2 Shutting down reprocessing at Tokai forever and scrapping Rokkasho

Reprocessing at the Tokai Reprocessing Plant is now virtually suspended. It should remain so. The construction of the main parts of the Rokkasho Reprocessing Plant has not yet been started and the completion, if ever, will be many years behind the official time table of 2003. Under current circumstances, it would be a good choice for the Japanese utilities to cancel their contracts with JNFL and order the utilities-owned JNFL to halt construction of the plant.

5.5.3 Some thoughts on interim storage

From a purely technical and economical perspective, expansion of total storage capacity in the form of a dry storage facility, say by 100%, would be feasible at Japanese reactor sites or at some central storage facility. However, heads of the local governments as well as residents have clearly expressed almost unanimous concern over the expansion of storage capacity at their respective sites.

Under the current situation , it is recommended that discussions are started immediately on the back-end policy, in particular on the interim storage issue, with

participation of a wide spectrum of residents and the nation-wide public. There is still time to discuss the options in depth.

In view of the extreme difficulty in finding a suitable geological site or formation for final disposal which is compounded by political problems which internationally affect decision on nuclear waste disposal, expansion of interim storage capacity and prolonged storage are likely to be unavoidable. The authors feel that a scenario for nuclear power phase out should be elaborated in order to facilitate a certain level of consensus on the back-end policy.

5.6 MOX Iradiation as Weapon Plutonium Disposition Option

A full scale analysis of the weapons plutonium disposition issue would go beyond the scope of this study. But, since a decision in the nuclear superpowers would have large impacts on the civil plutonium program in these and other countries, some comments seem to be highly significant.

The US government decided to take the so-called dual-track option, which allows for about two thirds of the plutonium from dismantled nuclear warheads to be irradiated as MOX and one third to be immobilized. The Russian MINATOM(Ministry of Atomic Power)'s intention to opt for MOX, not only for weapons disposition purposes but also for commercial use, differs significantly from the US position which explicitly limits plutonium use to disposition-dedicated MOX irradiation.

Therefore, the US decision in favor of a partial MOX option will rather stimulate the Russian civil plutonium industry. It will also stimulate the civil plutonium industry in Japan and Europe, and threatens to reactivate the once-dead US plutonium industry. It is now becoming evident that European plutonium industrial corporations like Siemens and COGEMA are trying hard to use the US decision in favor of the MOX option for the survival of their own plutonium activities.

The key aim of plutonium disposition is to bring weapons plutonium into a proliferation resistant form, the so-called spent fuel standard, but the MOX option needs a very complicated path to achieve the goal with many plutonium related facilities and transport activities which are proliferation vulnerable as we have analyzed for the civil MOX program in this study. In addition, a full MOX core strategy with a relatively high plutonium concentration, necessary to implement the disposition option in a reasonable time frame, is open to crucial safety questions.

The MOX option is thus very unrealistic at least in the short term, particularly so, if it is to be implemented with Russia and the United States keeping in pace, because of the large political / social instabilities and financial difficulties of Russia.

Chapter 6 Societal and Legal Implications of Mox Use

Part 1 Legal Aspects of MOX Use - A Japanese Perspective

(Part 1 written by Ichiro Hokimoto)

6-1. 1 Current Status of the Rights of Residents in Regard to Nuclear Issues in Japan

Freedom of information

The principle of public access to information in Japanese nuclear policy, to "publicize the results of nuclear energy research, development and utilization to the public", was stipulated in Article 2 of Japan's Atomic Energy Basic Law Act together with two other basic principles - democracy and independence. At that time, during the 1950s military aspects of nuclear energy were the main concern of Japanese scientists and the public at large, and the principle was introduced as a key device for prevention of military diversion.

This principle should have now a broader implication as the right to know, constituting a part of the citizens' rights of self-defence. It should also be in accordance with the worldwide trend to guarantee fairness, transparency and accountability by breaking the secrecy of the administrative process on nuclear issues.

In the aftermath of the Monju accident, JAEC was forced to hold a series of Roundtable Talks on nuclear energy policy and at the end of the 11 meetings of the first series, JAEC issued a statement in which it recognizes the principle of freedom of information and will accordingly open AEC-sponsored committees to the public with possible exceptions of meetings related to proliferation, physical protection, diplomatic negotiations etc.. In order to reflect public opinions more effectively in the government decision-making, the committees of JAEC, in deciding important policies, will first publish a draft report to solicit opinions from the public and adopt them when judged relevant. The rejected opinions will be published in the final report along with the reasons for their rejections.

Legal aspects of public participation

The traditional legal system applicable to nuclear facilities provides for the administrative agency to first grant the applicant for construction of a nuclear plant a license, which may be followed by a lawsuit demanding the nullification of the license filed by residents or opponents. In this system, the judicial review as to whether the facility satisfies the safety standards set by the positive law or not is conducted ex post facto.

Therefore, a public participation procedure is recommended in which the resident (group) is assured to exchange information and discuss with the would-be operator of the plant over minimization of residual risks and details of the project before a license was granted.

The internal contradiction is that on one hand, the would-be operator seeks acceleration and simplification of the procedure while on the other hand, "legal hearing" of substantial duration should be guaranteed, as a part of the residents' rights to defend.

The ideal structure of a procedural law presupposes real equality between the two parties. In the licensing procedure of a nuclear facility, however, the enterprise in charge of the project has an enormous advantage of information. Adequate information and materials - even those related to commercial secrets should be disclosed to the citizens and experts assisting them. Sufficient time should be spent for a trial-type hearing so that refutation and rebuttal are guaranteed in a cross-examination process based on the materials prepared by the enterprise (proponents) and the citizens (opponents). It is also necessary to prevent the participation procedure from turning into a mechanism of "engineering of consent" which serves as an "alibi function" to justify the project as a result.

Role of local governments

Currently, the citizens in Japan are virtually deprived of the rights and power to intervene effectively as an equal party in legal procedure and decision making process. Recent developments indicate that through the administration of local governments, the public participation could perform an effective function.

The basic principle is that the local administration should be carried out by the head of the local government and the local assembly which represent the residents. When the head of the local government and the assembly fail to fulfill the duty to protect the residents thereby leading to a doubt whether they represent the will and interests of the people, however, the only thing to do is to rely on "direct democracy". The Japanese Local Government Act allows residents to make direct requests for various actions. These include requests for the recall of the head of local government and members of the local assembly, the dissolution of the assembly, and the enactment or amendment of an ordinance.

The requests with a required number of signatures may be followed by a voting in the assembly or a popular voting in accordance with the stipulation in the law. In the town of Maki in Niigata Prefecture, the first referendum of its kind in Japan was held on August 4, 1996 and the population massively rejected a nuclear power plant project.

6-1. 2 Societal Concern over MOX Use

Difficulty in public participation

When it comes to the issue of present concern in particular, i.e. legal aspects of MOX use, the two conditions mentioned above should be satisfied not only in the decision making process over the plutonium policy but also in the process of the licensing of reprocessing facilities and MOX fuel fabrication facilities and the decision making and re-licensing of light water reactors for the use of MOX fuel.

Assuring equality between the two parties is, however, thought to be nearly impossible with regard to a MOX program, because commercial and security-related secrets possessed by the enterprise are always justified for the "safety and security of the public". Our conclusion therefore is that a MOX program which requires the large scale use of weapons-usable and highly sensitive nuclear materials is inimical to the principle of public participation.

International concerns

Japan's MOX program raises international concern because the MOX program requires international shipments of highly toxic and weapons-usable materials. Also, the large scale utilization and trade of weapons-usable materials poses international security problems.

In 1988 Japan acceded to the Convention on the Physical Protection of Nuclear Material (PP Convention), which entered into force in 1987. In accordance with the Convention, the Law for the Regulations of Nuclear Source Materials, Nuclear Fuel Materials and Reactors was substantially revised and regulatory measures against the so called "nuclear hijack" (nuclear terrorism) were included. The Convention also applies to nuclear materials in domestic use, storage, and transport. It stipulates that the information concerning the details of the protection of nuclear material and transportation plans should not be disseminated unnecessarily. In case of robbery, embezzlement, or extortion in relation to nuclear materials, the Convention sets forth the duty of informing the countries involved, recovering the materials, and punishing the offenses.

Despite the Convention, until 1992 the residents along the route of nuclear fuel transports in Japan had had relatively free access to information on the transport, because the local governments have to prepare for contingency. On April 18, 1992, just prior to the plutonium shipment from France to Japan, the Science and Technology Agency (STA) sent a notification to operators of nuclear facilities and a letter of request to local governments urging them not to make public information on transports of nuclear materials. STA explained that this was necessitated by the PP Convention. This policy has since been applied to the transportation of every kind of nuclear materials including the compounds of natural uranium - an obvious stretching of the

meaning of the PP Convention. This is the actual effect of Japan's plutonium program. The MOX program is used to justify control of information related to nuclear energy in general at domestic as well as international level.

6-1.3 Duty to Share the Earth with Future Generations and Other Living Organisms

Perspective for future generations

Because of the safety problems associated with the use of plutonium and the fact that the introduction of plutonium will change the social structure of the community, it is essential to introduce a system of participation of the local residents in the decision making process of the plutonium policy. This is a very urgent task for the legislative system. The plutonium policy, however, could also have a national and global effect. Therefore, it is necessary to have the participation of the citizens not only of the particular country but also of an international community of the whole world as members of the human race.

The use of plutonium poses the question of our responsibility for generations stretching into the distant future because of its long half-life (assuming one bears a child at the age of 30, a half of the present radioactivity of Pu-239 will still remain even 803 generations later). For example, the German Constitutional Law stipulated in its new provision in Article 20a, that the government should protect the living environment from the stand point of responsibility for the future generations (Verantwortung fuer die kuenftigen Generationen).

Furthermore, the concept of fairness between generations and a bill of rights for the future generations are now discussed [Weiss 1988]. There exists a view that the future generations have the right to a clean earth. The present generation should have an "inter-generational ethic" to prohibit environmentally disruptive actions taking into consideration injuries that would be inflicted upon future generations. The present generation should control its desires and refrain from passing the cost to the future generations.

Rights of every living organism

In Japan, various lawsuits have been introduced to courts on several levels calling for the legalization of standing to sue on behalf of animals. The whole question of the legal framework of animal rights has just started and is still open to debate. However, it should be pointed out here that the discussion of the legal aspects of a MOX program entails, in particular, a consideration of fairness to future generations and other creatures-- a newly developing consciousness in relation to the future law system. The author's basic position is that, so far as the basic right of remaining unharmed is an acknowledged right of every living organism, all the

living creatures should be given the standing to sue.

Part 2 MOX and Society

(Part 2 written by Alexander Rossnagel)

Jeopardizing civil liberties

Any national energy policy should providefor the necessary energy supply at reasonable costs, promote international cooperation and protect the environment but it should also be compatible with the basic values of the constitution. Whereas all other criteria are open to debate, compatibility with the constitution should be an indisputable criteria. Society has formally agreed on these basic values. They are legally binding. In particular the effects of energy policy on civil basic rights must be heeded.

The German example is of particular interest in this regard because it is essentially transferable to Japan, which has a similar constitution with comparable civil rights and alternatives in atomic energy policies comparable to those in Germany a few years ago.

Plutonium - Target and Means of Threats

MOX and plutonium can be misused as radioactive poisons or for an atomic explosive device. There are always people or groups which are fanatical, crazy, greedy, disgruntled or revengeful enough to divert plutonium and to blackmail society by its misuse. The main constraint at present, the deficit of motivation, could change in the future for many reasons. We must consider nuclear terrorism as a "real threat to civilization" with increasing probability. In particular plutonium and MOX transports represent targets for assault, sabotage and diversion.

Objects to be protected

The 1994 Long Term Program for Research Development and Utilization of Nuclear Energy of the Atomic Energy Commission of Japan shall serve as the basis for a scenario of plutonium and MOX use to determine the objects threatened and to be protected. By 2010 Japan was planned to operate 70 LWRs and several FBRs and ATRs. Besides the Tokai plant, two additional reprocessing plants would be operating in Rokkasho. Around 90 plants, including plutonium stocks and fuel fabrication plants, would have to be protected. About 400 shipments of MOX fuel, maybe 40% of them from Europe, would be needed. 30 to 60 shipments of HLW from Europe to Japan

would also have to be protected.

The protection of the 90 plants would need about 5,400 security guards (15 guards in 4 shifts around the clock). Each transport on road needs 7 guards.

Inadequate security measures

A security concept of "delayed action" combines physical barriers and armed guards which should resist an attack on a plant or a shipment long enough for the local police force to arrive on the scene. Although this is perhaps adequate to cope with the officially defined threat on which it is based, the threat definition itself is not adequate. Violent groups acting different parts of the world have demonstrated that they are able to assemble up to ten or more well-trained people to carry out sophisticated attacks, seizures or kidnapping. The implementation of the concept of delayed action does not appear capable of coping with well organized sophisticated types of attacks.

Security measures against hidden diversion or other insider threats are mainly based on the international control system of nuclear material movements, enclosure and access control measures, as well as surveillance of plant personnel which is also subject to security clearances. However, as outlined in Chapter 2, this system cannot guarantee sufficient security either. Material losses, diversions and infiltrations have been reported many times (more than 70 reported cases in [Rossnagel 1987b]).

The reason for the inadequacy of security measures is obvious: adequate measures would be too expensive. The provided measures are oriented to the financial and organizational priorities of the companies.

Social costs of improvements

Any society using plutonium and MOX will not accept the hazards of misuse and will feel forced eventually to enhance security measures, once the threats are recognized. Physical protection could be upgraded to the extent that the protection forces are able to provide adequate defense without dependence on outside support. Private security forces would be replaced by police forces to introduce a security element independent of the licensees. For example, as has been demonstrated in the so called "Hanau case", not only employees but also plant management could divert special nuclear material.

Nevertheless, all the protection costs should be paid by the operator not by the taxpayer, since it is the licensee who causes specific dangers to the public and government funding should not distort competitiveness in the energy market.

The surveillance and background checks could be significantly increased to prevent insider misuse. These measures can only be adequate if they deeply invade the privacy of applicants, employees, their relatives and their acquaintances. Threat reduction measures against potential or suspected actors will include wire tapping,

post surveillance or infiltration of suspected groups. The line of defense will be transferred into society. All improvements can only be achieved at the cost of civil liberties - not only of suspects but also of innocents.

Social costs of emergency and recovery actions

If plutonium or MOX is stolen or diverted it must be recovered very quickly. In the case of nuclear blackmailing, recovery of the device and arrest of the actors will have to be achieved very quickly. Temptation will be great in such cases to hold suspects for hard interrogation for hours, even days --probably without a lawyer. Media control might also be seen as crucial to those in charge of the search operation. All of these measures would need restrictions of civil liberties even if there is only a credible threat.

Reactive steps to a nuclear crisis have to be planned well ahead of an emergency and special technical units have to be established. Additional police forces have to be trained in particular to deal with such a nuclear emergency.

Pressure to security

In the absence of fear of assaults and diversions, and social conflicts, security measures may remain on a socially tolerable level, but this will change dramatically with the occurrence of any particular crisis situation. This kind of evolution is beyond control of society. If society uses plutonium, it will come under pressure to intensify security. If the threats beyond its control increase, the society has no choice. Its security measures will restrict civil liberties.

Silent change of constitution

The legal constitution will rather encourage such a development since life and health, rule of law and the sovereignty of the State have to be weighed against civil liberties. Security measures will constitutionally be in the right proportion, as long as they are considered necessary to combat the threat. But since only the security agencies are in a position to assess the threat, they will get an uncontrolled discretion to decide about security measures. Therefore in an emergency situation all security measures could always be legal and constitutional, but still have a severe impact on civil liberties.

Like the German constitution the Japanese constitution guarantees civil liberties in Article 10-40. Although there are no restrictions to most liberties in the text of the constitution, the supreme court has recognized that the constitution allows restrictions of civil liberties if they are necessary to protect public welfare and are the less restrictive alternatives to match this aim. A civic norm in favor of civil liberties cannot resist the strong pressure to implement draconian security if thousands of lives are at stake. In such circumstances the words in the constitution will still be the same

but its intrinsic value will have altered. Perhaps nobody will even notice the change because the standards of evaluation will have changed together with the meaning of constitutional terms.

Conclusion

Even if the security in a plutonium based MOX fuel system is enhanced steadily, it is impossible to reach an adequate level on an economically viable basis. At the same time society exposes itself to a pressure to tighten security beyond its control which can lead to restrictions or loss of civil liberties. Atomic energy, and a MOX fuel economy in particular, is the only energy resource which needs armed guards, broad surveillance measures and intelligence gathering. Society can choose less dangerous ways of energy supply and thus can avoid jeopardizing civil liberties by an intelligent energy policy.

Chapter 7 Transportation of Radioactive Materials in MOX Utilization

(Chapter written by Komei Hosokawa and Jinzaburo Takagi)

7.1 Overview of MOX-Related Transport Activities

Japan's MOX program requires a number of different types of transport activities, including relatively short-distance land transport and global-scale shipments by sea or possibly by air. Expanded shipments of plutonium, either in the form of dioxide (PuO_2) or mixed oxide (PuO_2-UO_2), inevitably increases risks both in security and safety.

The case of the planned MOX program for Fukushima I-3 illustrates well a typical case of transport scheme. The spent fuel is first transported from Eastern Japan to the French reprocessing plant at La Hague. Plutonium oxide is shipped in two lots to the Belgian MOX fabrication plant at Dessel. In parallel, low enriched UO_2 fuel rods are shipped from Japan to Dessel to be fabricated into MOX fuel assemblies. The MOX fuel assemblies are then shipped back to La Hague before they go on their return trip to Japan by sea. While COGEMA plans to ship the MOX by sea, its British counterpart BNFL considers air transport as well. Radioactive wastes will also be transported from Sellafield and La Hague to Japan. After the MOX use at the Fukushima reactor, the spent MOX will have to be shipped to an intermediate storage site yet to be determined. Even if one considers only one transport per type of shipment, the distance to be travelled by nuclear materials totals some 100,000 km or more than twice around the world.

Radioactive material transports are the most exposed link of nuclear energy systems. There are neither anywhere near the same level of containment nor emergency cooling as in the case of nuclear facilities.

7.2 Safety Aspects of MOX Transports and Related Activities

The IAEA Transport Regulations, in particular Safety Series No.6 and, since 1996, the "Safety Standard Series No. ST-1", generally govern transport of radioactive materials within and between most IAEA member countries. The IAEA classifies the packages into six categories (1996 edition), Excepted Package (very low active material like empty packagings), Industrial Packages (material with low specific activity like uranium ore), Type A (medium activity material like unirradiated uranium fuel), Type B (highly active material like irradiated fuel, separated plutonium, HLW), Type C (high active material for air transport) and UF_6 (low enriched uranium hexafluoride). Under IAEA regulations, unirradiated MOX fuel shall be transported in a Type B cask. This package is designed to ensure shielding so that the radiation level can be kept below the "acceptable level" in case it is exposed to an impact of a nine meter drop onto an unyielding surface followed by a fire of 800 C for 30 minutes.

Criticism of the IAEA standards has a long history. In particular it has been questioned whether they can represent "reality" adequately well, since numerous cases of accident conditions which exceed the reference case have been reported. The "graceful failure principle" -- as called by Lyman [Annex 2-b] -- has been sharply criticized. IAEA considers that the cask design has been carried out with such a high level of conservatism that the casks could actually withstand far more severe conditions than those under which they are tested. Also outstanding is the question whether a MOX fuel cask can actually be designed as to meet the IAEA Standards (see Lyman:Annex 2-b).

Technical details of the transport casks to be used for shipment of unirradiated MOX from Europe to Japan are not public. However, some "educated guess" on the basis of other existing casks is perfectly possible. MOX casks will have rather thin shielding as compared to spent fuel casks, and thus would be less able to withstand impact and heat. MOX fuel pellets, due to their brittle nature, might shatter into small particles when exposed to high energy impacts. Such small particles can escape from the cask's containment system. Should a transport freighter sink somewhere in the open seas, the probability would be high that the cask, designed for a maximum immersion of 200 meters depth, would rupture. In addition, a sunken shipment is not planned to be recovered, since the IAEA claims that there will be only "negligible harm to the environment and minimal radiation exposure to man". But there has been no published assessment for such an optimistic claim.

Air shipment of fresh MOX has been carried out in Europe in particular between Britain and Switzerland. The USA is very unlikely to allow any plutonium or plutonium containing MOX fuel to fly over their territory.

Currently one can assume that the MOX shipments from Europe to Japan would be carried out by sea. Air shipment stays however very attractive because it avoids conflicts with enroute states, keeps costs down and makes physical protection easier. BNFL is considering air transport for spent fuel from Japan, Switzerland and Germany to the UK as well as for separated plutonium or fresh MOX from the UK to the client countries. MOX containers for air shipment would be categorized as Type C according to the new IAEA regulations. Type C casks are to withstand a 324 km/h impact and a one hour fire at 800 C separately (not consecutively). But these "enhanced accident conditions" cover only 85-90% of air crashes, so that the *regulations versus reality* problem arises here again. Also the impact speed is less strict than the one required for ordinary aircraft flight recorders (black box) which is to survive a crash speed of 496 km/h and a one hour fire at 1,100 C *consecutively*. The US standard for plutonium air transport containers is 1,015 km/h.

The Type C cask has not even been developed yet and the plutonium industry aims at a generalized approval of Type B casks for MOX transports. The IAEA granted that exception on the grounds that transporters have to demonstrate that the nuclear substances are in the form of Low Dispersable Materials (LDM) and that radionuclides will not be dispersed following a severe accident. It is unclear yet on how the industry could prove that condition.

In the short term, MOX is unlikely to be transported by land in Japan, but it is shipped by land between Belgium, France[5] and Germany [STA 1997]. Later there could be land MOX transports from a MOX fabrication plant (possibly at Rokkasho-mura) to nuclear power plants in Japan.

Emergency response plans are virtually non-existent in Japan, whether for land, sea or air accident scenarios involving nuclear materials, let alone MOX fuel elements.

An additional weakness of the Japanese situation is the absence of a thorough environmental impact assessment procedure (EIA). Safety assessments carried out by STA and MITI (Ministry of International Trade and Industry) are not public, but are thought to be no more than a certification ceremony. The lack of independent access to relevant data is obvious. However, EIA of a potential accident involving a MOX transport cask has never been carried out. A study carried out by CNIC suggests that such an accident even under conservative assumptions could cause over 500 cancer

5. According to the latest Japanese government information, 220 kg of plutonium had already been transferred from La Hague to Dessel for Japanese MOX fabrication as of the end of May 1997[STA 1997].

deaths if it took place in Kawasaki City or over 400 if it happened in Yokohama City [Kamisawa 1996].

7.3 International and Social Aspects of Transport of Radioactive Materials

International concern over shipments of radiotoxic materials is growing rapidly. Plutonium and HLW shipments from France to Japan met intense protests, not only by NGOs but also by governments of en route States. Massive transports of MOX fuel would no doubt lead to additional opposition and concern over Japan's plutonium program.

MOX shipments by sea would be conducted under the so-called right of "innocent passage", i.e. the freedom of navigation, which by itself is fully guaranteed by international laws. Whereas existing international legislation in general gives little means to oppose the shipments, the UN Convention of the Sea which came into force in 1994 stipulates the right of coastal States to elaborate contingency plans and environmental assessment. It is obvious that such measures can only be applied under the condition of prior notification and consultation on emergency planning, EIA and liability requirements as requested in a declaration by 13 coastal States at the Special Consultative Meeting of the IMO (International Maritime Organization) on the INF Code in March 1996.

It is self evident that the same transparency should apply on the national level for en route representatives of the public.

The radiological protection of transport workers is to be greatly increased. In fact, shipments of radioactive materials are carried out most often by subcontractors who do not have appropriate radiation monitoring and follow-up. Also radiation exposure induced by MOX fuel shipments are higher than for standard uranium fuel, not only because of the higher specific activity, but also because e.g. additional police forces have to protect the casks closely.

The increased security forces for plutonium fuel transports lead to large additional economic costs. To date there seems to have been no appropriate evaluation of these extra costs.

Finally, the liabilities are enormous and in the absence of third-party liability, the claims for compensation by en route countries, land owners or professional unions would be an unbearable burden to the industry in case of a major accident.

Reference added to this summary:

STA 1997: Answer to Inquiry by Sumiko Shimizu, Member of House of Councilors, Science and Technology Agency, Sept 10, 1997.

Chapter 1
Introduction into General, Environmental and Health Aspects

Jinzaburo Takagi

1.1 What Is MOX

1.1.1 Plutonium, a man-made element

In February 1941, Glenn Seaborg and his colleagues at the University of California, Berkeley, synthesized a new transuranic (beyond uranium) element by bombarding uranium with deuterons and confirmed it to be element 94. This was the second synthesis / discovery of elements beyond uranium (element 92), the heaviest naturally occurring element. The element 94 was named plutonium (symbol Pu) after the planet Pluto, just as the element 93 was named after Neptune since it was just next to in sequence after uranium -the element of Uranus.

Soon after its discovery it was found that an isotope of plutonium could undergo fission and its study was entirely incorporated into a secret project with a military purpose, this later evolved to the Manhattan project that enabled mass production of plutonium for use in atomic bombs.

It was a bitterly ironic coincidence in the history of science that the element which turned Nagasaki into hell in a flash just four years after its discovery was named after the ruler of the underworld.

Fifteen isotopes of plutonium with mass numbers from 232 to 246 are known but the most important one is plutonium-239 with a half life of 24,000 years, a fissile nuclide which was used for the Nagasaki bomb and can basically be used in a nuclear reactor to produce energy.

U-235 constitutes only 0.7% of natural uranium and is usually enriched(i.e. concentrated) to about 3 % U-235 content for use in a light water reactor (LWR), the most prevalent type of nuclear reactor both in Japan and worldwide. The remaining 97 % is U-238. Pu-239 is produced in an uranium-fuelled reactor as a result of neutron capture of U-238, which takes place alongside the main heat-generating fission reaction of the fissile isotope of uranium, U-235.

U-238 + n = U-239 $\xrightarrow{\beta \text{ decay; } 23.5\text{m}}$ Np-239 $\xrightarrow{\beta \text{ decay; } 2.35\text{d}}$ Pu-239

Since the decay of U-239 to Np-239 and then to Pu-239 takes place in a matter of

days, Pu-239 is accumulated in a uranium-fueled power reactor. Around 150 kg of Pu-239 accumulates after one year's operation of a typical 1000MW light water reactor.

Some part of Pu-239 produced in a reactor undergoes further neutron capture reactions to produce higher isotopes of plutonium such as Pu-240, 241 and 242, while small amount of Pu-238 is also produced through other nuclear reactions of uranium. Importantly, Pu-239 also undergoes neutron-induced fission.

Pu-238 + n = fission products

1.1.2 Weapon-grade and reactor-grade plutonium

Thus in a reactor various isotopes of plutonium are accumulated in the uranium fuel. The quantity vary depending upon the degree of fuel burning (burn-up) as illustrated in Fig.1-1 for a typical LWR [OECD 1966]. Of the five main isotopes produced, the two odd mass number isotopes, Pu-239 and -241, are fissile (fissionable upon reaction with thermal [slow] neutron) and can in principle be used as reactor fuel. Therefore, for reactor fuel purposes, only the quantity of Pu-239 plus Pu-241 is important and this is often denoted as Puf (plutonium fissile) while Pu-tot or simply Put is used to mean the total quantity of plutonium.

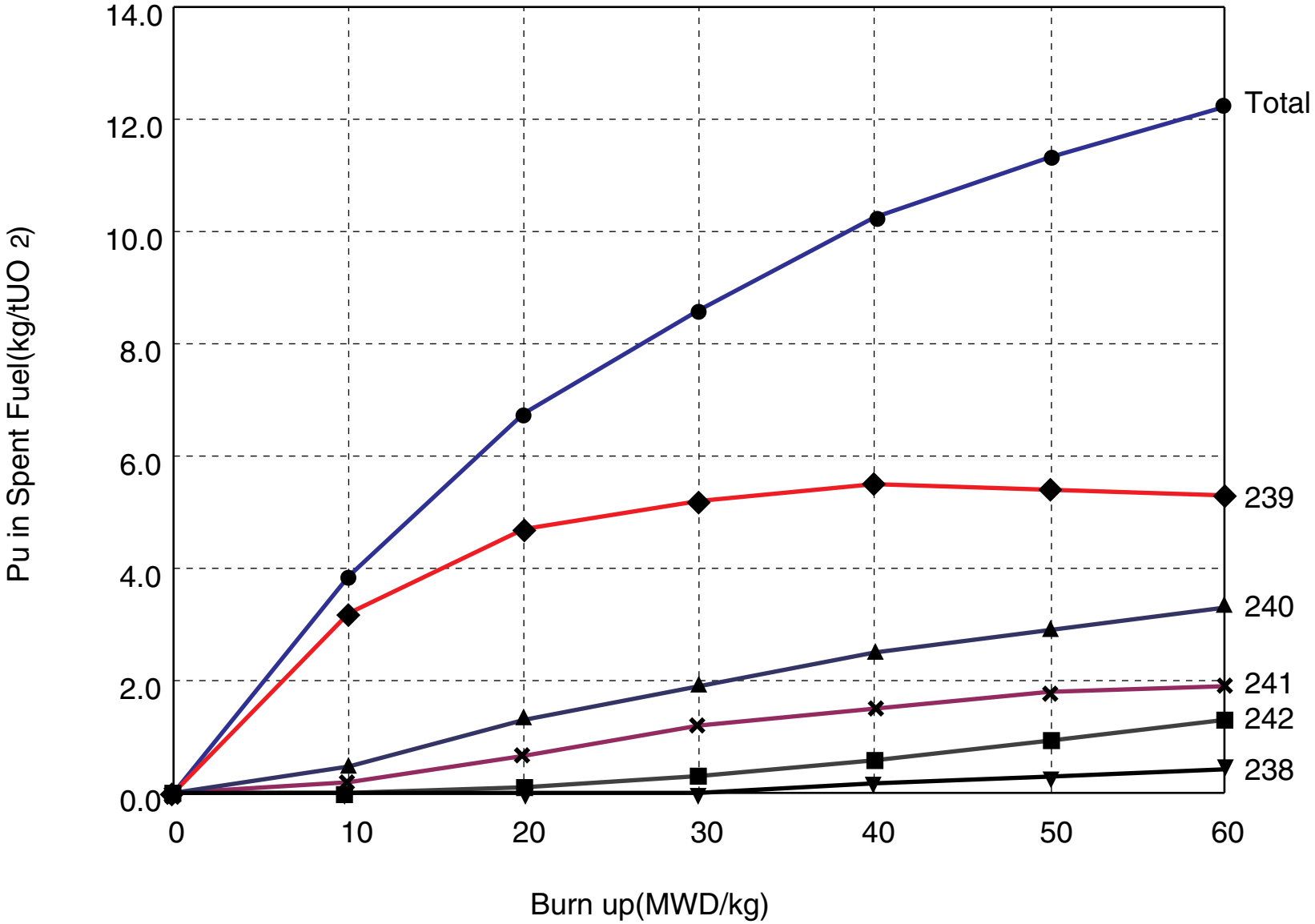
For the nuclear weapon design, nearly pure Pu-239 is favored, because neutron emitting Pu-240 and Pu-238 could trigger a "pre-ignition which would reduce the explosive yield. Therefore, a distinction between different "grades" of plutonium is usually made according to the isotopic composition of plutonium[Albright et al. 1997].[1]

Super-grade plutonium:	nearly pure Pu-239, containing less than 2-3 percent of non-fissile Pu-240
Weapon-grade plutonium:	plutonium with Pu-240 content less than 7 percent
Fuel-grade plutonium:	plutonium with Pu-240 content between 7 to 18
Reactor- grade plutonium:	plutonium containing over 18 per cent Pu-240

Although the pre-ignition may reduce the explosive yield of a nuclear warhead made of reactor-grade plutonium, " the explosive yield of a relatively simple device (using reactor-grade plutonium) similar Nagasaki bomb would be on the order of one or a few kilotons" (well with in the nuclear explosion range) "even if the pre-ignition occurs at the worst possible moment"[NAS 1994; USDOE/OACN 1997]. In Japan and some European countries, plutonium proponents still persist in putting forward

1. Prior to 1970, fuel-grade and reactor grade were both labelled "reactor-grade" (Source: DOE-Facts, 27 June 1994)

Fig.1-1 Accumulation of Pu isotopes in UO2 Fuel



arguments that reactor-grade plutonium, with pre-ignition difficulties, should be considered a virtually non-usable explosive material, and thus the plutonium program in these countries -- which are mainly based on separation and use of reactor-grade plutonium -- could be regarded as essentially "peaceful". The assertion of the "peacefulness" of reactor-grade plutonium is, however, contrary to the internationally-established scientific knowledge and evidence. The 1994 US National Academy of Sciences report on the disposition of nuclear weapons [NAS 1994] says :

> "Virtually any combination of plutonium isotopes can be used to make a nuclear weapon."

There are further scientific arguments [DOE/OACN 1997; Bunn 1997; Carson-Mark 1993; Kankeleit et al. 1989] in support of the weapons-usability of reactor-grade plutonium and we base our arguments in this report on this recognition (See Chapter 2 for further discussions on the property of plutonium as weapons material).

Table 1-1 Isotopic Composition of Reactor-Grade Plutonium (Burn-up:30-40MWd/kg)

Isotope	weight per cent	half life(y)	decay mode	thermal fission
plutonium-238	0-2	87.7	alpha	non-fissile
-239	55-65	24,100	alpha	fissile
-240	20-25	6560	alpha	non-fissile
-241	10-15	14.4	beta	fissile
-242	3-7	373,000	alpha	non-fissile

1.1.3 Military-civil dual use character of plutonium

Because of the weapons-usability of plutonium, every civil plutonium utilization program is essentially vulnerable to diversion for military purposes. Reactor-grade plutonium could be directly built into a crude nuclear bomb or used to fuel a fast breeder whose blanket can produce substantial amount of super-grade plutonium for weapons-use.

The military-civil dual character is not only related to the weapons-usability of the material but to the whole technology system of plutonium use. A full scale civil plutonium program needs a full cycle of plutonium production in a reactor, separation at a reprocessing plant and fuel fabrication, which could under political directives be used to build up a military nuclear capability. Even if a state with a civil plutonium program had no military intention and was under strict international

control, merely possessing a plutonium stockpile and plutonium-related facilities such as a reprocessing plant could be regarded as having a "nuclear option" by other countries, particular those in the same region, and trigger a counter program in those countries which could well be military. In regrd to Japan's plutonium program, to some extent this might actually be the case in the future.

A number of international and security-related problems arise therefore from this dual-character of plutonium programs and they should be addressed as one of the central issues in an assessment of every plutonium utilization program. This study deals with these issues mainly in Chapters 2 and 6.

1.1.4 Toxicity of plutonium

Plutonium is one of the most toxic elements. Most of plutonium isotopes are alpha emitters. The high energy (over 5 MeV) alpha particles emitted in the decay of plutonium-239 and other plutonium isotopes strongly interact with other materials, thus causing intense ionization which has harmful biological effects. The high ionizing capacity makes alpha-emitting plutonium extremely harmful when taken up inside the human body, whereas external exposure to alpha-emitters like Pu-239 does not usually give rise to serious health problems due to short range of alpha radiation.

Another cause of the high toxicity of plutonium is its long retention in the body once taken in by inhalation or digestion. A fraction of plutonium inhaled will reach the lungs (depending on the plutonium aerosol particle size); and then part of it is absorbed into the blood, finally finding its way mainly to liver and bones and to a lesser extent to the reproductive glands. A smaller fraction of digested plutonium would also be absorbed into the blood and reach similar organs. Plutonium incorporated in these organs would stay there for a long period ranging from a few years to many years, exposing the respective organs to alpha radiation. The sustained irradiation by low levels of alpha radiation can well be the cause of cancers and genetic injuries.

Table1-2 shows the annual limits of intake (ALI) for inhalation and digestion of Pu-239 oxide as compared to those of U-238. The ALIs given in the table are values currently adopted by Japanese regulatory authorities for Pu-239 in commonly-used oxide form, in accordance with the 1977 ICRP (International Commission for Radiological Protection) recommendations [ICRP 30].

There are varying opinions in regard to the adequacy of the 1977 ICRP ALI recommendations and the ICRP itself has made revised recommendations [ICRP 48, 61 and 68]. But the arguments aside, Table 2 is useful to illustrate the frightening toxicity of plutonium.

Furthermore, ALI values for reactor grade plutonium are far smaller when measured by weight than those for pure Pu-239, since short-lived isotopes of

plutonium contained in the reactor grade plutonium are more toxic than Pu-239 as compared per unit weight. A typical reactor-grade plutonium is 8 to 10 times as toxic as Pu-239 and **one gram of reactor grade plutonium oxide corresponds to the annual limits of inhalation for as many as 40 million people.**

It should further be noted that the ALI values correspond only to annual occupational dose limit of 50 mSv, while the annual dose limit for the general public is 1 mSv (Japan still bases its regulations on the old 1977 ICRP values for occupational and public exposure limit. The adoption of the 1990 recommendations is now discuused by the government). If we define the annual limit of intake for the general public (ALI-GP), it should be a 50 th of the ALI mentioned above. This means that, for members of the general public, less than a billionth of a gram (or <0.000000001 gram) of plutonium oxide should be considered as the limit of intake by inhalation. Thus plutonium is a health concern to workers at nuclear facilities dealing with plutonium at sub-microgram levels and to the member of the public at nanogram levels. External exposure to reactor grade plutonium is also a serious health problem, especially for workers of plutonium industry, since it contains appreciable amounts of gamma-ray and neutron emitting isotopes.

Table 1-2 Annual Limits of Intake (ALI) for Pu-239 and U-238 (For oxide) (Japanese regulations)

	ALI for Inhalation		ALI for Ingestion	
	Becquerel	microgram	Becquerel	microgram
Plutonium-239	590	0.26	2.7E6	1190
Uranium-238	1,500	120,000	8.1E6	6.5E8
(Reference) Typical Reactor-grade Pu*	160,000 #	0.028	8.1E7#	140

*Plutonium in LWR spent fuel of 33 MWD/kg burn-up(cf Fig.1-1)
#Specific radioactivity is high due to beta-ray of short-lived Pu-241

Reactor grade plutonium also poses external exposure risks, since gamma-rays from some isotopes of plutonium, particularly americium-241 produced as the decay product of plutonium-241, are hazardous to workers handling plutonium (see Chapter 3).

The use of plutonium therefore poses a unique dimension of ES&H (environment, safety and health) concerns, which is dealt in this report in Chapter 3.

1.1.5 MOX fuel

Since the reactor grade plutonium as well as higher grade plutonium is mostly composed of fissile materials, it can be used in principle as reactor fuel. The most common chemical form of plutonium for reactor fuel use is the dioxide PuO_2 mixed with uranium dioxide UO_2. The mixed oxide fuel or MOX (PuO_2-UO_2) can be used usually to fuel two types of reactors, fast breeder reactors or light water reactors.

A fast breeder reactor (or FBR) is a reactor which can produce plutonium by neutron capture reaction of fertile U-238 in the core and surrounding blanket while burning plutonium (20-30% plutonium enriched MOX) in the core. The reactor is called a breeder because it is designed to produce more plutonium than it consumes. The rationale for the breeder is that it could enhance the efficiency of uranium resource utilization theoretically by as much as 60 times, as it can convert much of the otherwise useless U-238 into fissile plutonium while generating electric power. Because of this theoretical potential of breeding, the FBR was believed from the very beginning of nuclear development to be the ultimate dream of nuclear industry, the energy perpetuum mobile.

The history of nuclear development, however, seems to be proving that the technology of breeding is a nightmare rather than a dream. In order to make breeding possible, the fission reactions in a FBR are maintained by the use of fast (high energy) neutrons, in contrast to the conventional light water reactor (LWR) which uses thermal neutrons. Since a moderating coolant cannot be used, the core of an FBR has to be cooled by molten sodium metal, a highly reactive substance which burns explosively in air and in contact with water and thus a potential source of hazard. Another fatal difficulty of the FBR is that the possibility of a catastrophic nuclear excursion accident, which is very unlikely in a LWR, can not be ruled out.

Furthermore, even if plutonium breeding is possible, the doubling time , i.e., the time it takes to produce enough surplus plutonium with one breeder reactor to fuel a second one, is far more than the lifetime of the first reactor. While the life of a FBR is expected to be no longer than 30 years, the plutonium doubling time for a FBR is estimated to be no shorter than 40 years even under optimistic assumptions [Takagi 1997]. This points to another key problem of the breeder reactor; one has to keep in mind that eventually it has to be based on a full scale system with reprocessing and thus plutonium production, up to fuelling the breeder reactors and the eventual reprocessing of the irradiated breeder fuel and the blanket.

These and other technical difficulties of FBRs have also led to a poor economic performance of the reactor, and these two major drawbacks --technical and economic-- have forced the United States and all of the Western European countries to scrap their FBR programs. Japan, which was once thought most ambitious in FBR development, now seems likely to follow suit or, to say the least, defer its FBR program substantially

due to the accident of the prototype FBR Monju in December 1995.

Another way utilizing MOX is to useit as fuel for a commercial LWR. Usually, MOX containing 5 to 8 % plutonium is used to fuel PWRs (pressurized water reactor) and BWRs (boiling water reactor), the two major types of LWRs. Although using MOX in LWRs essentially designed to burn low enriched uranium (LEU) oxide poses various problems -- which are central issues being dealt with in this project -- the nuclear industry believes replacing up to a third of a LWR core with MOX[2] does not constitute a major reactor safety problem and is implementing it in some German, French, Belgian and Swiss LWRs (see Annex 1). Moreover, the nuclear industry is thinking of operating LWRs with a full MOX core [Nedderman 1996]. Japan also has an ambitious plan to use MOX in LWRs, and irradiating MOX in LWRs is now considered, by some experts in the US in particular, to be an effective option for the disposition of plutonium from dismantled nuclear weapons in the US and Russia.

1.2 Japan's Plutonium Program

1.2.1 Civil plutonium program and nuclear fuel cycle policy

While countries like the United States, Sweden and Canada have abandoned or do not have civil plutonium utilization programs, there are many countries which still plan to separate and use plutonium. Although they maintain their plutonium programs on varying grounds and in varying sizes (see Annex 1), plutonium has to be chemically separated from spent nuclear fuel in order to be used. This chemical process called reprocessing is a key element for any plutonium program and the nuclear fuel chain based on reprocessing and use of plutonium is often called a "closed nuclear fuel cycle"[3]. Some countries favor reprocessing as a back-end nuclear policy rather than to obtain separated plutonium, on the grounds that it would make treatment of spent fuel easier, but this justification should now be critically reviewed (see Chapter 5).

According to Kueppers and Sailer [1994], reprocessing-based nuclear fuel systems in the world can be classified into three types. The first one is Western European/Japanese system which is basically associated with LWRs. Then there is the

2. Now there are also plans to replace full core of LWR with MOX.

3. As a matter of fact, a nuclear fuel cycle never closes in the strict literal sense, because a substantial part of the fuel materials as well as radioactive waste emerging from each step of the processes remains as waste. A more appropriate term may be the "nuclear fuel chain".

UK system related to the fuel cycle of gas cooled graphite reactor (GCR) whose Magnox spent fuel usually needs to be reprocessed quickly because of cladding degradation, while a third power reactor/reprocessing system has been developed in the former Soviet bloc. In addition countries like India have their own reprocessing capacity on smaller scales. It should also be noted that reprocessing technology emerged from nuclear-weapon programs and is still institutionally connected to military programs in many countries. The country by country nuclear fuel cycle facts and figures are presented in the Annex1 of this report.

We deal here only with the nuclear fuel chain/plutonium policy associated with light water reactors and MOX use, which has been adopted in Westren European countries and Japan, as we think it is currently the key international concern so far as civil use of plutonium is concerned. In particularly, we focus on Japan's plutonium program to understand the full scope and associated problems of the country's plutonium program. Japan is centrally important as it has the world's most extensive plutonium program; and we believe that the future of the world plutonium industry may be largely dependent on the success or failure of the Japan's program. Moreover, recent developments indicate that the choice of MOX use in LWRs will be subject to considerable public attention and controversies in Japan.

1.2.2 Japan's plutonium strategy

Japan's current plutonium program is based on the 1994 version of Long Term Program for Research Development and Utilization of Nuclear Energy [JAEC 1994], published by the Atomic Energy Commission of Japan (hereafter JAEC). The 1994 Program is a much-debated revision of the 1987 Program whose full-scale plutonium utilization program had been a focus of intense international criticism and skepticism. The criticism was especially harsh with regard to proliferation concerns, when a shipment of 1.5 metric tons of plutonium took place from France to Japan on board Akatsuki-maru from the end of 1992 to the beginning of 1993 and also when the prototype fast breeder reactor Monju went critical in April 1994, against the world-wide trend of withdrawing from fast breeder programs.

Many observers therefore had expected that the plutonium program might be drastically scaled down in the revision, but in fact, the whole plan was only set back by some 10 years, and the projected plutonium demand and supply level by the year 2010, was reduced to 100-110 tons (all plutonium amounts are given in total plutonium base) from the previous plan of 110-130 tons. Main plutonium-related items in the long term program are given in Table1-3. As the government has pledged to maintain the "no-stockpile policy" in response to the international concern over Japan being a "plutonium giant", all of the separated plutonium -- except a small running stock -- should, in principle, be consumed. The supply and demand balance

Table 1-3 Japan's Plutonium Program [JAEC 1994]

Item	Target year of realization
Nuclear power capacity(GWe)	2010:70 ; 2030:100
Demonstration FBR(660MWe)	constr. start:early2000s
Commercialization of FBR	around 2030
FBR reprocessing test plant	mid-2010s
Operation of demonstration ATR	early 2000s
MOX use in LWR (1/4 to 1/3 core)	late 90s:a few PWRs and BWRs around 2000:10 reactors(PWR+BWR)
MOX fabrication	Fabrication in Europe for Pu separated in Europe Rokkasho plant(100 tHM):after 2000
Rokkasho reprocessing plant	1st plant(800 t):operable after 2000 2nd plant: decision suspended

Table 1-4 Japan's Plutonium Supply and Demand Projection(1994-2010)

Supply (ton Pu_{tot})	Demand (ton Pu_{tot})
Pu recovered in Japan 1994-99 From Tokai repro. plant: 5 (incl. Pu returned from Europe) [2000-2010] From Tokai and Rokkasho Plant: 50-65	 Joyo, Monju, Fugen: 5 Joyo, Monju, DFBR, Fugen and DATR: 20-30 LWR: 30-35
Pu recovered in Europe [1994-2010] From La Hague and Sellafield: 40	 FBR and ATR: a few tons LWR: most of 40
Total: 95-110	Total: 95-110

of plutonium as projected by JAEC in 1994 is shown in Table1- 4.

While the long term program and the associated supply and demand plan as given in the tables below were decided only two years ago, rapid changes in the situation surrounding Japan's plutonium program has made the figures and plans in the tables almost meaningless. Among others, the government had to scrap the construction of the demonstration ATR (advanced thermal reactor) in August 1995 in the face of utilities' unwillingness to pay the extra cost for the MOX-fuelled uneconomic reactor of Japanese design[4]. Then followed two accidents of great significance at the Monju fast breeder reactor (December 8, 1995) and Tokai Reprocessing Plant (March 1997), which are both operated by the government-owned Power Reactor and Nuclear Fuel Cycle Development Corporation (PNC) and are the central facilities for Japan's plutonium program. Furthermore, another tritium leakage incident took place on April 14, 1997 at PNC's prototype ATR Fugen. All these incidents have made the future of almost every plutonium-related project in the long term program very uncertain.

1.2.3 Implications of Monju and Tokai Accidents

The sodium leakage accident which occurred to Monju on December 8, 1995 had far more serious impacts than first thought by PNC. 700 kg of sodium leaked from a broken thermometer well inserted into the main secondary sodium piping loop C, and burnt in the secondary piping room vehemently reacting with oxygen and water in the ambient air. The rupture of the thermometer well was found to be caused by a very basic design fault combined with a lack of a system for checking such design faults. The failure of the PNC operators to quickly shut down the reactor and minimize the effect of sodium fire showed a surprising weakness of PNC's sodium handling technology.

Furthermore, it was revealed that PNC attempted many times to cover up the seriousness of the accident by editing video footages, hiding records of the investigation conducted immediately after the leakage and so on. PNC also failed to report the accident quickly to the relevant local governments. All in all, PNC and STA which is responsible for supervising PNC have lost utterly the public confidence. The strong feeling of distrust and concern over the government's energy policy is reflected very clearly in the joint proposal of the governors of Fukushima, Niigata and Fukui, the Prefectures where 60 % of Japanese power reactors are situated. In the proposal --

4. The ATR is a heavy water moderated- light water cooled thermal reactor of Japan's own design which can be fuelled by MOX of low plutonium content (up to 2 %). A prototype reactor Fugen (165 MWe) is operating at Tsuruga, Fukui. A demonstration reactor (600 MWe) was planned at Ohma, Aomori by government-owned Electric Power Development Corporation but cancelled in August 1995. Fugen is supposed to be decommissioned in near future.

made on January 23, 1996 -- the governors urged the Prime Minister to review thoroughly Japan's nuclear policy, in particular, the plutonium program, and also the way the policy was forced on the local people. They further stated that, without the review process, they will refuse to accept not only the restart of Monju but also MOX burning in light water reactors which the utilities were about just going to propose in their districts.

In response to the proposal, JAEC sponsored 11 meetings of the first series of Nuclear Energy Policy "Roundtable Talks" inviting many people from all over Japan. As the outcome of the discussions, JAEC has organized an advisory committee on review of the FBR program and the second series of the Roundtable was also planned to be held in 1997. But, just as the discussion at the FBR committee just started, another accident occurred at the Low level Radioactive Waste Bituminization Facility at PNC's Tokai Reprocessing Plant and the planned Roundtable was suspended. In the Tokai accident, drums with bitumen-waste sludge mixture auto-ignited at round 10 a.m. and, without an effective fire fighting response, the fire led to an explosion of substantial scale. 37 workers were internally exposed to radioactive cesium and 10 billion bequerrels or more of radionuclides were released to the environment [NIT 1997]. The accident was followed by inadequate emergency measures as well as false and delayed reports, which were almost like an exact reproduction of the way the nuclear industry responded to Monju accident. In addition another tritium leakage accident at ATR Fugen which took place one month after the Tokai accident has further increased the distrust of PNC and STA.

The government had to start various new panels and committees to relieve its plutonium program from the current confusion, but nobody yet knows where these discussions will lead to. We can say at this moment, however, that it is highly unlikely that the restart of Monju will get approved in the foreseeable future by the prefectural government and people of Fukui. Without the approval, Monju can never be started and without operation of Monju Japan will not be able to take any further step in its FBR program. Also, Fugen will probably be decommissioned soon. Operation of the Tokai reprocessing plant will be suspended for many years and PNC will be substantially restructured (See also Chapter 5 for future of Japan's fuel policy).

Nonetheless, Japan seems likely to keep its reprocessing policy, since it has become like a prerequisite for the spent fuel treatment policy. This leaves MOX use in Japanese light water reactors as the only option for the consumption of separated plutonium. This situation has recently been confirmed by the government in the report of the Nuclear Energy Subcommittee of Advisory Committee for Energy [ACE 1997]. The government's report made public the whole program of MOX use in LWRs, starting from Fukushima I-3 BWR in 1999 and burning MOX in 16-18 reactors by 2010 involving all Japanese utilities. Local governments and residents have just started to consider the utilities' proposal to burn MOX at their areas, but did not seem

to be prepared to accept the proposal as of the end of September 1997.

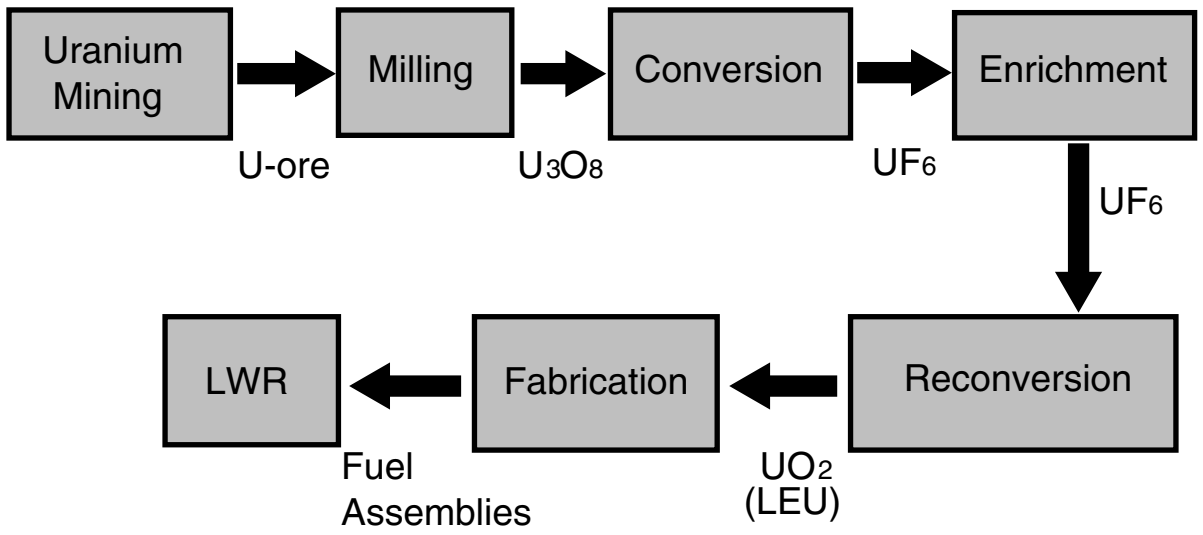
This situation of a failed FBR program and large plutonium surplus resulting from reprocessing is more or less the case with Western-European countries, and has led to plans currently being developed for the large-scale MOX burning program in LWRs.

1.3 MOX Use in Light Water Reactors--Scope and Issues

1.3.1 MOX fuel cycle and issues to be addressed

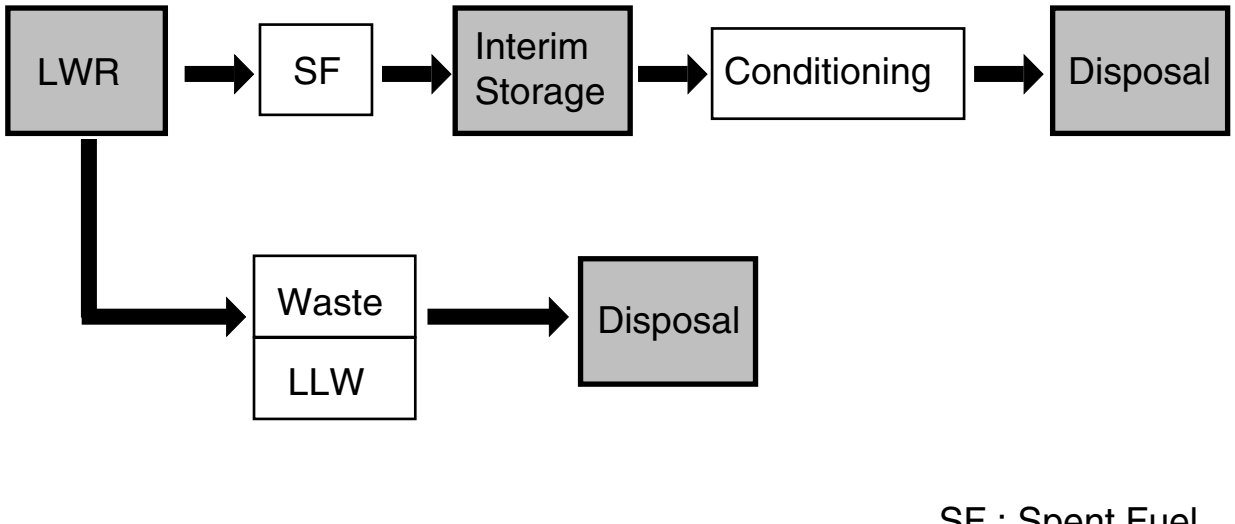
The flow of nuclear fuel and radioactive substances (the nuclear fuel "cycle") for an LWR is usually separated into two main parts, the upper stream which originates from uranium mining and ends in loading of low enriched UO_2 in a reactor core (Fig. 1-2) and the downstream which covers the stages from the discharge of spent fuel from the core up to the final storage/disposal of radioactive waste (Fig. 1-3).

Fig.1-2 Upper Stream of LWR Fuel Flow



LEU:Low Enriched Uranium

Fig.1-3 Once-Through LWR Downstream



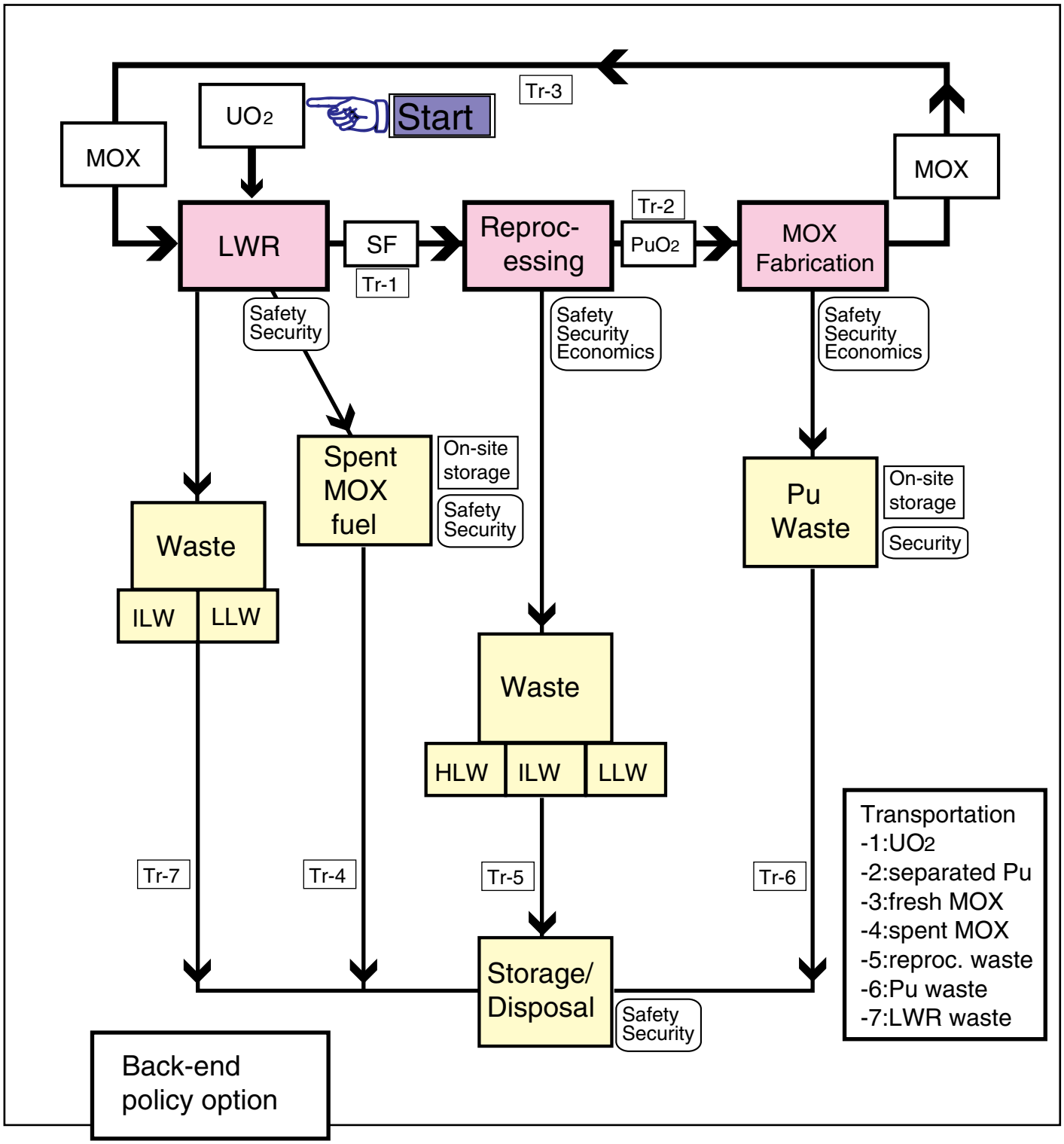
SF : Spent Fuel

Though the entire stream is related to the flow of nuclear fuel and radioactive materials, and hence poses safety and security concerns from start to finish, the focus of our concern here is the downstream. In case uranium fuel used is not reprocessed, the spent fuel removed from the reactor core is stored for an intermediate period in a dry or wet storage facility on reactor site, or else at an away-from-reactor (AFR) facility and would finally be buried probably in a geological-layer for final disposal.

Although this is a relatively simple "once-through" flow on a chart, it already contains one of the most difficult and controversial parts of nuclear technology, the shipment, storage and disposal of highly radioactive materials.

The fuel flow involving MOX or the "closed fuel cycle" is far more complicated. The spent fuel is transported from the reactor site to the reprocessing plant, where plutonium is separated from uranium and other radioactive products and then transported to the MOX fabrication plant. The MOX fuel assemblies produced in the fabrication plant are then shipped to reactor for reloading. The spent MOX may or may not be reprocessed. Even if spent MOX is not reprocessed --which is the most likely case--, its transportation, storage and disposal will give rise to special safety, security and economic considerations, owing to the increased content of plutonium and transuranic nuclides. If the spent MOX is further reprocessed (multiple plutonium recycle), it will go through another whole fuel cycle(s), each time with increasing complexities due to complex combinations of radionuclides involved.

Fig.1-4 Problem areas of MOX use in LWR



Societal issues: access to information, public decision
smuggling, terrorism, control vs democracy, etc.

International relations: regional instability, cooperation,
agreements and treaties, international law, safety concern

An overview of a full MOX fuel cycle and related issues to be dealt in this report is illustrated in Fig. 1-4. Any nuclear industrial activity, as a big science and technology project, will have a large impact on the various aspects of human life, but the use of MOX use in LWR and the associated fuel cycle as illustrated in Fig. 1-4 poses a quite new dimension of issues and concerns.

Before going into the details of the issues in the succeeding chapters, it seems useful to comment briefly on our basic approach. The present project aims at the identification and analysis of the additional *social* burdens that are expected to be introduced by use of MOX fuel in LWRs in regards to safety, security, economy and societal fairness. This background analysis then provides a basis for a proper review of the *rationales* for MOX use in LWRs, and the comparison of the back-end policy options to find out what is the most preferable spent nuclear fuel management strategy.

Security

The term SECURITY, as dealt with in Chapter 2, is used in a rather broad sense covering problems ranging from physical protection of weapons-usable materials and safeguarding of MOX-related facilities, to political implications of MOX use in the international community. Societal implications of the MOX use and security system associated with it will be addressed in Chapter 6.

Safety

SAFETY as dealt with in Chapter 3 covers a broad spectrum of concerns related to the environment, safety and health (the so-called ES&H), and thereby to closely related to social interests. The environmental concern is not limited to the area of the MOX-related facilities but spreads through international reprocessing, fuel fabrication contracts and trasportation of spent fuel and MOX fuel, to the whole world. Safety and health issues are dealt with not only in regard to the engineering safety of MOX-related facilities (reactor, reprocessing and fabrication), but also in regard to the health of workers. In addition, consequences of major radiation release accidents are assessed.

Economy

The ECONOMY of MOX use is dealt with in Chapter 4.

For a plutonium-based nuclear fuel cycle (a "closed fuel cycle" or plutonium economy") to make sense in terms of resource efficiency and energy security, FBRs should still be the central pillar of a plutonium program in any country, despite the mounting difficulties of the FBR technology. MOX use in light water reactors can never contribute significantly to uranium resource conservation. A recent MIT report

[Skornikoff et al. 1995] estimates uranium savings due to Japan's LWR MOX use by 2010 to be only 9.6 % and by 2020 to be 8.5 %. Situations in Europe may be much the same.

But there are arguments suggesting economic advantage of MOX use in LWRs over UO_2 once-through use at least until the FBR technology becomes mature. The 1989 OECD / NEA economic analysis [OECD / NEA 1989] presents a typical case in favor of MOX fuel cycle. But the OECD study appears to be far from the current realities, especially as related to Japan, and thus we have conducted our own economic analysis in this study. A comparison was carried out between the fuel costs for one reactor-year of MOX and UO_2 fuel. In the former case the fuel overall costs were evaluated both by taking into account the reprocessing cost and by assuming that plutonium is obtained free (sunken plutonium cost case). The methodology is essentially the same as that used by the OECD study, but we have carried out the evaluation in light of most realistic costs of materials and labor in Japan to get an up-to-date cost analysis for Japanese MOX. Consideration will also be given to external factors which are not generally included in cost analyses.

Back-end policy

The choice of the BACK-END of nuclear fuel cycle, in other words, the question of how to deal with the spent fuel will be the central issue in terms of nuclear fuel policy regarding MOX. Based on the finding of this study, a critical review of MOX use policy is conducted in Chapter 5, in light of a rational fuel and waste policy. The chapter is closely related to the question of rationales of MOX use and the alternative for MOX use policy.

Societal, legal and political implications

The introduction of a "plutonium economy" would further raise special societal, legal and political questions such as indicated at the bottom of Fig. 1-4. These are discussed in Chapter 7. Some of these are issues already discussed by a number of authors [Jungk 1977; Rossnagel 1983] and are not new to MOX use. But with the development of the international MOX industry and possible adoption of MOX option for the disposition of US and Russian weapons plutonium, it may be worthwhile analyzing the implications of a "plutonium economy" anew. This may be of special concern to the Japanese public after the sodium leakage accident at Monju, as well as the Tokai fire, when not only technical difficulties, but a series of cover-ups by PNC, aroused public concerns over lack of access to information and the way policy decisions are made in Japan concerning, above all, the plutonium program.

Transportation of radioactive materials

As illustrated in Fig. 1-4, the use of MOX fuel necessitates a number of different

types of transportation of highly radioactive materials. These range from relatively short-distance land transportation to very long distance transnational sea and air shipments of highly radioactive and deadly toxic materials, which arouse worldwide concern over safety. The shipments of plutonium and MOX could increase substantially the proliferation/diversion risks. The consequences of these safety and security issues associated with the introduction of MOX fuel are analyzed in Chapter 7.

1.4 Implications of MOX Use in a Changing World

1.4.1 Plutonium in the post Cold War era and the plutonium surplus

With the end of the Cold War the possibility of a full scale nuclear war has been greatly reduced. But a new threat to the world has arisen-- the proliferation and environmental risks of rapidly accumulating weapons-usable fissile materials from dismantled nuclear weapons of the United States and former Soviet Union.

The question of the disposition of fissile materials arising from the tens of thousands of nuclear weapons to be dismantled has become an urgent problem to the international community as a whole. Of these weapon-grade fissile materials, plutonium is considered to pose a far more serious problem than highly-enriched uranium(HEU)[5]. While the latter can be converted to a relatively proliferation-resistant form by diluting with natural uranium and can be consumed in conventional reactors, no similar method is available to plutonium because "virtually any combination of plutonium isotopes can be used to make a nuclear weapon."

While US DOE (Department of Energy) recently decided to take the so-called dual-track option for plutonium disposition allowing two thirds of US weapons' plutonium to be burned in commercial thermal reactors as MOX [DOE/OFMD 1996], the decision should not be taken as to open the way for US to commercialize weapons plutonium. It can still be said that the fundamental change in value systems that occurred with the end of Cold War has also affected the evaluation of plutonium. Plutonium is now generally regarded as a liability rather than an asset, as a 1994 NAS report puts it[NAS 1994]:

> "In short, in strictly economic terms, excess weapons plutonium is more a liability than an asset. No matter what approach is taken to long-term

5. Highly enriched uranium: Uranium with fissile U-235 content of 20 percent or more is defined as highly enriched uranium (HEU), which is of importance for weapns-usable fissile material control. Weapons-grade uranium contains more than 90 percent of U-235.

disposition, the process is likely to involve a net economic cost, rather than a benefit."

The issue of a weapons plutonium surplus should arouse a concern over civil plutonium stockpile as well. The concern over civil plutonium surplus was raised at the 1992 annual assembly of the Japan Atomic Industrial Forum (JAIF) by William Dircks [Dircks 1992], then Deputy Director General of International Atomic Energy Agency (IAEA):

> "Even if one disregards the fissile materials from nuclear warheads, the excess of isolated fissile plutonium from civilian nuclear programs poses a major political and security problem worldwide.
>
> As a result of nuclear fuel reprocessing, and potentially as a result of nuclear weapons dismantling, in the foreseeable future the supply of plutonium will far exceed the industrial capacity to absorb plutonium into peaceful, commercial nuclear industrial activities."

The surplus problem appears to be becoming much more serious now in Western European countries and in Japan, since they maintain their reprocessing policicies despite many arguments and subsurface moves against it. In the European reprocessing centers at La Hague in France and Sellafield in the U.K., there are already large amounts of separated plutonium stockpiled: 43.6 t at La Hague as of the end of 1996 [MDI 1997] and 44.0 t at Sellafield as of March 31 1995 [DTI 1995]. At least a large fraction of the French stockpile can be attributed to the two largest customers, Japan and Germany.

Let us have a closer look at the Japanese surplus. It can be determined that a large surplus of Japanese plutonium already exists [Takagi 1996]. According to the inventory data at the end of 1995 given by the government, Japan has a stock of 16 tons of plutonium (Pu tot), of which 14.7 tons are stored at the reprocessing and MOX fabrication facilities without any imminent needs and thus can be regarded as surplus. Of this surplus, 1.42 and 9.96 tons are stored in the U.K. and France respectively. If the reprocessing in Europe and at Tokai, followed by Rokkasho in Japan proceeds as planned and with the FBR program beyond Joyo indefinitely deferred and the MOX burning in LWRs delayed substantially, we estimate that the surplus will exceed 30 metric tons by 2000 and 70 tons in 2010 *even if MOX use is partially realized.* The author's estimate of cumulative surplus by 2010 for two scenarios, (a) no MOX use and (b) MOX use in up to ten reactors mostly according to the latest Japanese

government plan[6] is given in Fig. 1-5.

The figure represents a very curious but serious situation. MOX use in LWR seems now to provide the justification for reprocessing on the grounds that it might contribute to reducing plutonium stockpiles, but the reality is that the reprocessing policy is actually increasing the separated plutonium surplus as a whole even though MOX burning could consume a part of plutonium.

The military and civil plutonium surplus is therefore one of the greatest threats to humanity in the post-Cold War period and this should be kept in mind throughout this assessment project.

1.4.2 Basic position of IMA project

In mid-seventies, the US planned to introduce MOX use in commercial LWRs on a large scale and the Nuclear Regulatory Commission (NRC) conducted a full-scale environmental impact assessment of MOX use in LWRs [NRC 1976]. As the Carter administration then decided to scrap the reprocessing and MOX burning program in accordance with its non-proliferation policy, not much has since been done scientifically in the United States on this subject. Now after 20 years, there is a lot of discussion about the "MOX option" or "reactor-related option" for disposition of excess weapons plutonium[NAS 1995; DOE/OFMD 1996;DOE/ OACN 1997], but little seems to be said about the potential impact of this MOX option on the world civil plutonium program.

INFCE (International Nuclear Fuel Cycle Evaluation) which was started in October 1978 on the proposal of US President Jimmy Carter and ended in February 1980 focused on the various options of nuclear fuel cycles but did not address the environmental impact of MOX use. Since that time there have been arguments supporting MOX use in LWRs in European countries, but they only deal with individual technical aspects of MOX production and use in LWRs and are therefore not much help to the general public to comprehensively evaluate the social impacts of MOX use.

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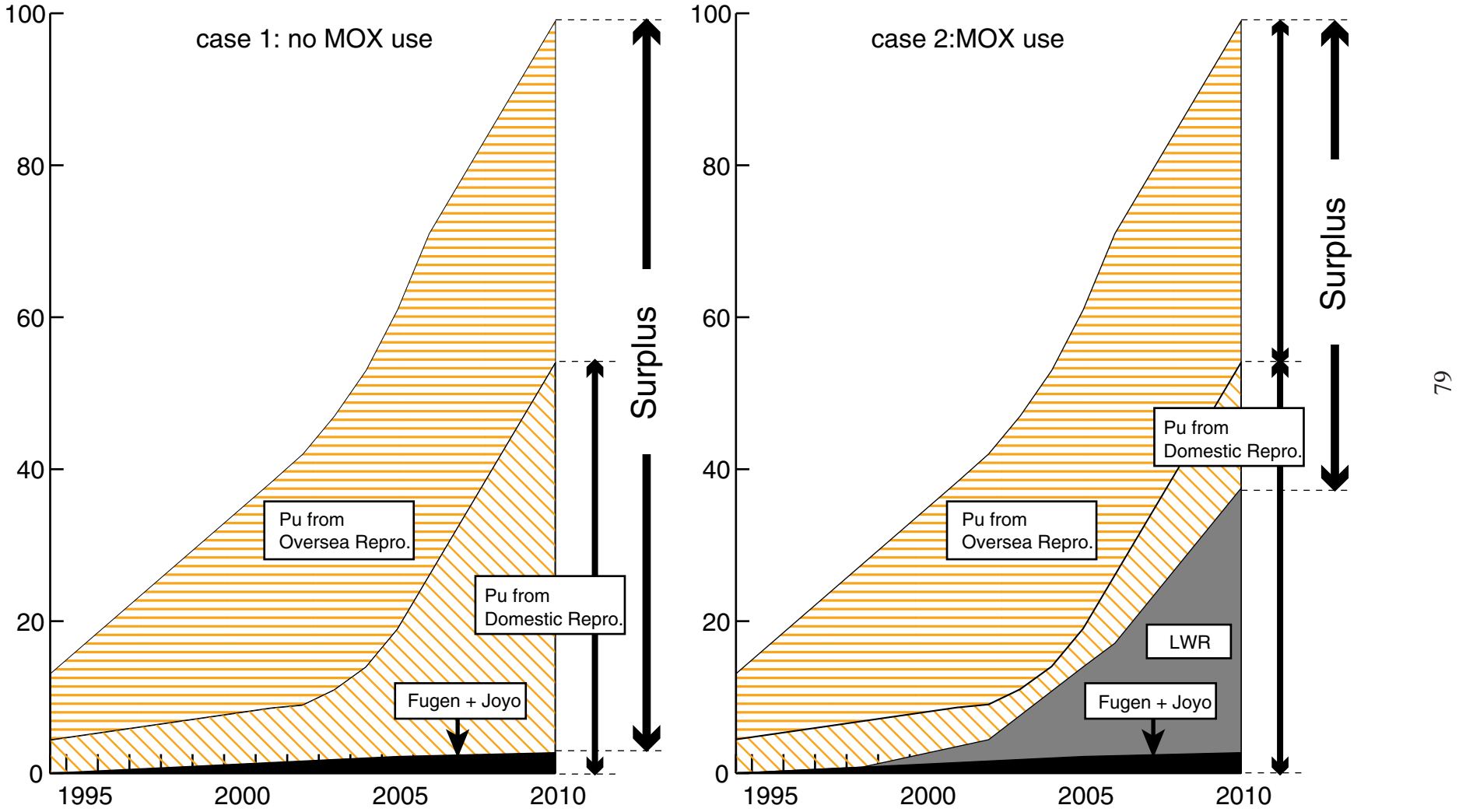
6. The interim Report issued in January 1997[ACE/NES 1997] by Japan's Advisory Committee on Energy envisages starting MOX burning in 3-4 LWRs by early 2000 s and increasing the number of reactors to over 10 by 2010.

Fig.1-5 Pu Supply and Demand Projection

Pu TOT in MT [tones, Put]



[Citizens' Nuclear Information Center 1996]

There have been many well-founded arguments against plutonium utilization mostly by independent researchers and authors. Some of them include environmental impact assessment of the kind we are aiming at in this project but they are neither comprehensive nor dedicated to issues specific to MOX use in LWR. In addition some are much out of date today, given the striking changes in the international sphere after the end of the Cold War. The most comprehensive independent assessment on MOX may be the one conducted by one of the present co-researchers and his colleague [Kueppers and Sailer]. Another in-depth analysis of the MOX strategy has been carried out by the assistant director of the project [Schneider 1993]. We have to continue along those lines to obtain a more comprehensive as well as in-depth assessment with particular focus on the Japanese MOX program.

We strongly believe that an independent assessment of a big industrial program is essential for a healthy society, particularly a modern big science and technology project like the MOX program. Immense social, political, environmental and health implications are at issue, and assessments free from industrial or governmental interests are of absolute necessity for the public to make its own decision.

In the public interest, a democratic government should in principle encourage independent groups to conduct such assessments on government and industry projects, offering resources and opportunities, but in reality this is usually not the case. In some countries, the parliaments play an important role to make independent assessment available to the public. Local (state) governments also contribute much to assure independent evaluation of the central government's projects. In Japan, however, there has been hardly any effort by the public bodies to encourage independent assessments.

We are deeply convinced that an independent comprehensive assessment of a nuclear program in a form understandable to the public is vital not only for assuring safety and security but for proper democratic accountability of a society. The nuclear industry has been developed under the strong patronage of mighty political powers and has built up a unique centralized structure, which makes the public feel that the nuclear technology is inaccessible and something beyond their judgement. On the other hand, central governments, in the interest of power politics, tend to prefer centralized energy systems - nuclear power is one par excellence - to other alternatives without conducting an objective assessment. Those governments and their technocratic administration have taken full advantage of the "public inaccessibility" of the nuclear issue to draw up and carry out their own plans with little or no public scrutiny. This was the case at least until the accident at Monju in Japan. But the Monju accident raised questions of democracy and transparency in Japan and led to the implementation of a referendum at Maki Town, in Niigata and to a majority voting of "No"to build a new reactor in the community. We believe that the situation surrounding nuclear programs are more or less similar in other countries and

therefore an independent comprehensive assessment with emphasis on Japan as an example will be of help to the public worldwide.

1.4.3 Implications of plutonium policy in a changing world

At the turn of a century of science and technology, or more specifically the age of nuclear technology, we are confronting a series of difficulties in a global scale which the human kind had never experienced nor even anticipated. In the context of energy and nuclear policy, the following may be the most urgent:
(1) Environmental deterioration due to discharge and accumulation of noxious wastes from energy production and related industrial activities, including among others radioactive wastes, ozone-layer depleting agents and other pollutants;
(2) Climate changes due to excessive consumption of energy leading above all to rapid buildup of greenhouse gases;
(3) Global ecological crisis in such forms as desertification and endangering of biological species due to uncontrolled development;
(4) Ever-existing threat of nuclear war and fear of another Chernobyl-scale accident due to military and civil nuclear activities.

In order to cope with the crisis,

> "Hundreds of agreements, declarations, action plans, and traditional treaties on the environment have now been negotiated covering such shared concerns as acid rain contamination, ocean pollution, endangered species protection, hazardous waste trade, and the preservation of Antarctica-many of them under U.N. auspices."
>
> " Despite all of these efforts, however, the health of the earth's natural systems has declined precipitously in the decades since the United Nations was created, and the pace of the reversal so far shows no signs of letting up."[French 1995]

Discussing the international efforts for environmental protection whether in the framework of UN is certainly beyond the scope of this study, but we think that it is very important to learn basic lesson from past experience and set up a series of working principle on the basis of lessons learned.

What we have in mind is a set of global ethical principles on which we are to base our assessment on MOX. They are:

- Efforts towards a world free of fear of nuclear war and disasters arising from nuclear activities
- Fairness to future generations

- Priority of international environmental and human rights concerns over national industrial interests
- Conservation of resources and ecological system
- Decision-making involving international public participation

We need not say much here on these principles. While the position based on these principles is maintained in our whole project, special attention will be paid in Chapter 6 to these ethical prerequisites.

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Chapter 2
The Security Aspects of the Use of MOX as Nuclear Fuel

Frank Barnaby

The end of the Cold War has reduced the risk of a nuclear world war to virtually zero. But other nuclear risks have taken its place. These are related to the diversion of weapon-usable fissile materials -- highly-enriched uranium or plutonium-- by governments or sub-national groups for the fabrication of nuclear weapons or other nuclear explosive devices.

2.1 Introduction

Many commentators argue that the main nuclear threat to global security now arises from the spread of nuclear weapons to new countries. Like other nuclear-weapon powers, the British want to keep their own nuclear weapons while preventing all other countries from acquiring them. Today's world contains seven or eight nuclear-weapon powers -- China, France, Russia, the USA, the UK, Israel, India and Pakistan.

The current American operational nuclear arsenal contains 9,500 nuclear warheads. The current Russian operational nuclear arsenal contains about 10,500 nuclear warheads. If current disarmament proposals are carried through, the Russians and Americans will reduce their nuclear arsenals to about 5,000 nuclear warheads each by the year 2003. Even though these reductions represent significant nuclear disarmament, the Russians and Americans will still have massive nuclear arsenals for a long time to come.

Britain currently deploys about 400 nuclear warheads; France about 500 nuclear warheads; China may have about 400; Israel about 200; India about 60; and Pakistan about 7 nuclear weapons. And some believe that Iran, Iraq, and North Korea have ambitions to become nuclear-weapon powers.

But, in practice, it is unlikely that a new nuclear-weapon power will emerge in the next ten or fifteen years. During this period, civil nuclear technologies (which could be diverted to nuclear-weapon programmes) will spread far and wide, as will the technologies for the production of ballistic missiles. This combination of nuclear and ballistic-missile technologies will be a very dangerous one. When this happens, in 10 or 15 years, the danger of nuclear-weapon proliferation will then become a real one

and nuclear weapons may spread at a fast rate.

Bearing in mind that the nuclear-weapon powers are continuing to modernize their nuclear arsenals, so that 'vertical proliferation' continues, the risks arising from the eventual spread of nuclear weapons to countries which do not now have them, 'horizontal proliferation', should not be underestimated. Any proliferation of nuclear weapons to countries which do not now have them will increase the risk that nuclear weapons will be used in a future war in an unstable region.

Proliferation will also destabilize the region in which it occurs. Even the acquisition of the capability to acquire nuclear weapons will affect the security of the region. It will encourage other countries in the region to acquire nuclear weapons of their own. Thus, if Japan, for example, was to move towards a nuclear-weapon capability, North and South Korea would be encouraged to do the same and China may increase its nuclear-weapon force.

Although it is unlikely that further governments will take the political decision to acquire nuclear weapons in the short term, the risk that terrorist groups will acquire nuclear explosives is increasing. Nuclear terrorism has replaced a nuclear world war as the most serious nuclear threat in the post Cold-War world, at least in the short and medium terms.

Terrorist groups need to continually move to higher levels of violence. Recently, we have seen the level escalate from blowing up jumbo jets to the Tokyo nerve gas attack. The Tokyo incident shows that some of the leaders of these groups have considered the pros and cons of using weapons of mass destruction-- nuclear, chemical, and biological. The next rung on the terrorist ladder of escalation may well be the acquisition and use of a nuclear weapon.

The use of MOX fuel, and the consequent separation of plutonium from spent nuclear-power reactor fuel elements, will considerably increase the risk of nuclear proliferation to governments and terrorists. The aim of this section is to put these issues into perspective.

A useful debate on these issues requires some knowledge of the types of nuclear weapons likely to be of interest to horizontal proliferators, particularly smaller countries and sub-national groups. The first part will, therefore, describe the main components required to assemble a basic nuclear-fission weapon, which obtains all its explosive energy from nuclear fission.

The implosion type of nuclear weapon, using plutonium, will be described. The designers of basic nuclear weapons would be so confident that their weapons would work that they would be satisfied with non-nuclear testing. The weapons could, therefore, be fabricated and deployed clandestinely.

2.2 The Attraction of MOX for Those Wishing to Fabricate Nuclear Weapons

2.2.1 The use of reactor-grade plutonium in nuclear weapons

There are various grades of plutonium, having different isotopic compositions, according to the way in which the plutonium is produced. Plutonium produced in commercial nuclear-power reactors operated for the most economical production of electricity is called reactor-grade plutonium. Plutonium produced in military plutonium-production reactors, specifically for use in nuclear weapons, is called weapons-grade plutonium.

Although reactor-grade plutonium can be used to fabricate nuclear weapons, as proved when the Americans exploded such a weapon in 1962, nuclear-weapon designers prefer weapons-grade plutonium. The latter contains less of the isotope Pu-240 than reactor-grade plutonium. In fact, the less Pu-240 there is the better pleased nuclear-weapon designers are.

The isotopic composition of reactor-grade plutonium (produced in civil nuclear-power reactor fuel elements exposed to about 33,000 megawatt-days per ton (MWD/t) of uranium fuel) is about:

1.4 % Pu-238; 56.5 % Pu-239; 23.4 % Pu-240; 13.9 % Pu-241; and 4.8 % Pu-242.

Weapons-grade plutonium contains about:

0.05 % Pu-238; 93.0 % Pu-239; 6.4 % Pu-240; 0.5 % Pu-241; and 0.05 % Pu-242.

The plutonium in typical mixed-oxide (MOX) fuel contains about:

2 % Pu-238; 42 per cent Pu-239; 31 % Pu-240; 14% Pu-241; and 11 % Pu-242 [Mark, 1990].

Whereas Pu-239 undergoes fission when it captures a neutron, Pu-240 undergoes fission spontaneously; it does not need an extra neutron. This means that in plutonium containing Pu-240 there is a flux of neutrons from spontaneous fission. For weapons-grade plutonium, the number of neutrons from spontaneous fission is 66 neutrons per second per gram; and for reactor-grade plutonium, it is 360 neutrons per second per gram. The higher the number of spontaneous-fission neutrons the greater the probability that the weapon will pre-detonate and explode with an unpredictable explosive yield. However, this can be compensated for by using faster implosion to compress a subcritical mass to a supercritical one (the implosion technique is described below). The faster the implosion the more predictable the yield of the nuclear explosion.

2.2.2 Critical mass

The critical mass of a fissile material, like plutonium, is the minimum amount of the substance that will result in a self-sustaining chain reaction. It depends on a

number of factors. Firstly, the nuclear properties of the fissile material used - whether it is plutonium or highly-enriched uranium. Secondly, the shape of the material. A sphere is the optimum shape because for a given mass the surface area is minimized which, in turn, minimizes the number of neutrons escaping through the surface per unit time and thereby lost to the fission process. Thirdly, the density of the fissile material. The higher the density, the shorter the average distance travelled by a neutron before it causes another fission and, therefore, the smaller the critical mass. Fourthly, the purity of the fissile material. If materials other than the one used for fission are present, some neutrons may be captured by their nuclei instead of causing fission. Fifthly, the physical surrounding of the material used for fission. If the fissile material is surrounded by a medium, such as beryllium, which efficiently reflects neutrons back into the fissile material, some of the reflected neutrons may cause fissions. These neutrons would otherwise have been lost. The use of a neutron reflector reduces the critical mass.

Plutonium metal occurs in six phases, or crystalline forms, depending on how it is produced. Each form has a different density, ranging from 15.92 to 19.80 grammes per cubic centimetre. As normally produced, plutonium metal is brittle and hard to machine into precise shapes. For use in nuclear weapons, plutonium is usually alloyed with gallium or indium. This makes it more machinable and prevents it changing from one phase to another.

It is important to prevent a phase change because the new phase will have a different density. The volume of the plutonium will then change and the shape may distort. This is, to say the least, a very undesirable thing to happen in a nuclear weapon. In nuclear weapons, plutonium metal in the delta-phase (density = 15.8 grams per cubic centimetre) is often used. Delta-phase plutonium is more stable, less likely to change phase, and more easily compressed than alpha-phase.

The critical mass of reactor-grade plutonium is a little greater than that of weapons-grade plutonium. But the difference is not large. For alpha-phase plutonium, the critical mass is 13 kilograms for a bare metal sphere of reactor-grade plutonium compared with 11 kilograms for weapons-grade plutonium. For delta-phase, plutonium the figures are 20 kilograms and 17 kilograms respectively [Mark, 1990].

For plutonium produced in the blanket of a breeder reactor, the critical mass for alpha-phase metal is 10 kilograms; for delta-phase it is 16 kilograms.

Another difference is the amount of heat generated by the absorption of alpha particles produced by the radioactive decay of Pu-240. Weapons-grade plutonium generates about 2.5 watts per kilogram. A sphere of weapons-grade plutonium weighing about 4 or 5 kilograms, a typical weight used in a basic nuclear-fission weapon, will have a temperature slightly higher than normal room temperature. It will feel slightly warm to the touch.

Reactor-grade plutonium generates about 11 watts per kilogram. This means that measures must be taken to dissipate the excess heat if the material is used to fabricate a nuclear weapon. One possibility would be to use shells of plutonium rather than a solid sphere. The shells would have a lower thermal capacity and become less hot. When the high explosives explode (to compress the plutonium by implosion, see below) the shells would be forced together to form a super-critical mass.

2.2.3 Design of nuclear weapons

The main components required to assemble a nuclear weapon, which obtains all its explosive yield from nuclear fission, using the implosion design include:

* very high quality conventional high explosives;
* reliable detonators for these explosives;
* electronic circuits to fire the detonators in a precise time sequence;
* a tamper and a neutron reflector;
* a core of fissile material in the form of a sphere of plutonium or highly-enriched uranium; and
* a neutron source to initiate the fission chain reaction.

The sphere of plutonium, for example, is surrounded by conventional high explosives. When exploded, the high explosive uniformly compress the sphere of plutonium. The compression reduces the volume of the sphere of the plutonium and increases its density.

The critical mass is inversely proportional to the square of the density. The original less-than-critical mass of fissile material will, after compression, become super-critical, a fission chain reaction will take place and a nuclear explosion take place.

The plutonium in the spherical core of the weapon is surrounded by a spherical shell of beryllium or uranium to reflect back into the fissile material some of the neutrons which escaped through the surface of the sphere without causing fission. The use of a neutron reflector significantly reduces the amount of fissile material needed.

For example, a bare sphere of weapons-grade plutonium, in the alpha-phase, has a critical mass of 11 kilograms; the radius of a sphere of this weight is about 5 centimetres, about the size of a small grapefruit. If the plutonium sphere is surrounded by a natural uranium reflector, about 10 centimetres thick, the critical mass is reduced to about 4.4 kilograms, a sphere of radius of about 3.6 centimetres, about the size of an orange.

The beryllium shell is surrounded, in turn, with a shell of a heavy material, like natural or depleted uranium, which acts as a tamper. When the high explosives around the tamper are detonated, the shock wave causes the tamper to collapse

inwards. Its inertia helps hold together the plutonium during the explosion to prevent the premature disintegration of the fissioning material and thereby obtain a larger explosion.

The mass of the plutonium in the core of the weapon expands at very high speeds when the weapon explodes, initially at speeds of about 1,000 kilometres per second. In much less than a millionth of a second the size and density of the fissile material have changed so that it becomes less than critical and the fission chain reaction stops. The task of the designer is to keep the fissioning material together, against its tendency to fly apart, long enough to produce a nuclear explosion with an explosive yield appropriate for his purpose.

The timing of the detonations of the chemical explosives to produce the shock wave is crucial for the efficient operation of the weapon. Normally, the more explosive lenses there are the more symmetrical the shock wave. Forty or so detonators would be typical. Getting the timing of the detonation sequence right is crucial - milli-microsecond (a thousandth of a millionth of a second) precision is required.

The shapes of the explosive segments (called explosive lenses) are rather complex and must be carefully calculated. The high explosive, such as HMX (cyclotetramethylenetetranitramine), must be chemically extremely pure and of constant constituency throughout its volume.

For maximum efficiency, the fission chain reaction in a nuclear weapon must be initiated at precisely the moment of maximum super-criticality, i.e., the moment of maximum compression. The initiation is achieved by a burst of neutrons. In a modern weapon, the neutrons are produced by a small electronic device called a 'neutron gun' placed outside the conventional high explosives.

In a neutron gun, a high voltage is used to accelerate small amounts of deuterium down a cylindrical tube. A zirconium-tritide (a mixture of zirconium and tritium) target is placed at the bottom of the tube. When deuterium nuclei collide with tritium nuclei in the target they fuse together and nuclear fusion process occur, producing high-energy fusion neutrons. When the high voltage is applied, a shower of neutrons penetrates into the compressed plutonium core and initiates the fission chain reaction.

In the nuclear explosion very high temperatures, of hundreds of millions of degrees centigrade, and very high pressures, of millions of atmospheres, build up in a very short time, of about a half a millionth of a second. In this time, about 55 generations of fission take place. In less than a millionth of a second, the size and density of the fissile material have changed so that it becomes less than critical and the chain reaction stops.

The actual amount of weapons-grade plutonium used in an implosion-type nuclear-fission weapon varies considerably, according to the explosive yield required

and the technology used. A designer with access to high technology, particularly to achieve very fast implosion, could design a nuclear-fission weapon with an explosive yield of 1 kt with as little as 1 kilogram of weapons-grade plutonium. With 2 kilograms, he could design a nuclear-fission weapon with a 10 kt yield; and with 3 kilograms he could design a 20-kt weapon. If only low technology is available, a designer would require about 6 kilograms of weapons-grade plutonium to design a 20-kt weapon. With 3 kilograms of weapon-grade plutonium he could design a 1-kt weapon [Cochran and Paine 1994].

The complete fission of one kilogram of Pu-239 would produce an explosion equivalent to that of 18,000 tons (18 kilotons or kt) of TNT. Modern fission weapons have efficiencies approaching 45 per cent, giving explosive yields of about 7 kt per kilogram of plutonium present.

A typical modern nuclear-fission weapon would typically use three or four kilograms of weapon-grade plutonium surrounded by an efficient neutron reflector and tamper and about 100 or so kilograms of high explosive. The entire volume of device would be about that of a football and its total weight roughly 200 kilograms.

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2.2.4 Nuclear terrorism

Terrorist groups have shown themselves to be sophisticated and skilled. The construction of the explosive device that destroyed the PanAm jumbo jet over Lockerbie, for example, required considerable skill, as did the construction of the nerve gas weapon used in the Tokyo underground. Sub-national groups now have access to professional scientific and technical skills and to large sums of money.

The combination of these with the increasing availability of the fissile materials which can be used to fabricate nuclear explosives; the relatively small amounts of fissile material, particularly plutonium, needed for a nuclear explosive; the availability in the open literature of the technical information needed to design and fabricate a nuclear explosive; and the small number of competent people necessary to fabricate a primitive nuclear explosive are reasons for considerable concern.

2.2.5 Terrorist use of plutonium

Some statements imply that plutonium produced in nuclear-power reactors cannot be used in nuclear weapons or nuclear explosive devices. For example, Ambassador Ryukichi Imai, former Japanese Ambassador for Non-Proliferation,

stated in *Plutonium*: "Reactor-grade plutonium is of a nature quite different from what goes into the making of weapons...Whatever the details of this plutonium, it is quite unfit to make a bomb" [Imai 1994]

This statement is totally incorrect. The actual situation is the one expressed by Robert Selden, Lawrence Livermore Laboratory: "All plutonium can be used directly in nuclear explosives. The concept of ....plutonium which is not suitable for explosives is fallacious. A high content of the plutonium 240 isotope (reactor-grade plutonium) is a complication, but not a preventative" [Selden 1976].

And in the words of Hans Blix, the Director General of the International Atomic Energy Agency: "The Agency considers high burn-up reactor-grade plutonium and in general plutonium of any isotopic composition...to be capable of use in a nuclear explosive device. There is no debate on the matter in the Agency's Department of Safeguards" [Blix 1990]. That reactor-grade plutonium can be used to fabricate nuclear weapons was, as mentioned above, proved by the Americans who exploded at least one such device in the 1960s.

A nuclear device could be constructed using plutonium either in metal form or as plutonium oxide (PuO_2). After plutonium has been removed from spent reactor fuel element in a reprocessing plant it is normally stored as the oxide rather than plutonium metal. If plutonium is stolen from a reprocessing plant it is, therefore, likely to be in the oxide form. But the oxide could be chemically converted to plutonium metal without much difficulty.

A sub-national group intent on fabricating a nuclear explosive from plutonium would not need to have access to classified literature. Amory B. Lovins, for example, published all the physics data needed, by a competent nuclear physicist, to design a crude nuclear device [Lovins 1980]. The group would need access to machine-shop facilities, which could be hired. The machining of plutonium metal, to shape it into a sphere, for example, should be done in a fume cupboard, preferably in an atmosphere of an inert gas, like argon.

A sub-national group would probably use an amount of plutonium close to the critical mass - say, about eight kilograms of plutonium metal. This plutonium would be surrounded by conventional high explosives. Because the mass of plutonium is close to the critical mass, it would not be necessary to use shaped charges to compress the plutonium to produce a super-critical mass. It would be sufficient to stack the explosives around the plutonium.

A number of detonators would be positioned in the conventional high explosive. If a large number of detonators, say, 50 or 60, are used, the shock wave is likely to be symmetrical enough to compress the plutonium satisfactorily. The detonators should be fired as simultaneously as possible. This can be done using an electronic circuit which generates a high-voltage square wave. The detonators could be fired by remote control.

The construction of a nuclear explosive device using plutonium oxide would be much simpler than one using plutonium metal. The oxide is much simpler and safer to handle. Plutonium metal may, for example, burst into flames in air, as sodium may do. Also, a sub-national group is likely to want to avoid the stage of conversion from the oxide to the metal.

The disadvantage with plutonium oxide is that the critical mass is much higher than that of the metal. The critical mass of reactor-grade plutonium in the form of plutonium-oxide crystals is about 35 kilograms, if in spherical shape. The radius of this sphere of plutonium oxide would be about 9 centimetres.

In a crude nuclear explosive device, the plutonium oxide could be contained in a spherical vessel placed in the centre of a large mass of a conventional high explosive. A number of detonators would be used to set off the explosive, probably by remote control. The shock wave from the explosion could compress the plutonium enough to produce some energy from nuclear fission.

To maximize the probability of getting a significant amount of fission energy, the amount of plutonium oxide used should be close to the critical mass. This could be achieved by using a neutron counter close to the vessel containing the oxide as it was being poured in. As soon as the neutron counter indicated the presence of neutrons the pouring would be stopped. The mass of plutonium oxide would then be close to critical and a relatively small amount of compression could produce fission energy.

The size of the nuclear explosion from such a crude device is impossible to predict. But even if it was only equivalent to the explosion of a few tens of tons of TNT it would completely devastate the centre of a large city. Such a device would, however, have an excellent chance of exploding with an explosive power of at least a hundred tons of TNT. Even one thousand-tons or more equivalent is not impossible, but it is not likely.

The explosive power of the device will depend mainly on how close to critical the mass of the plutonium oxide is. This, in turn, will depend on the risk the people making the device are prepared to take. If they get to close to criticality they may be exposed to a strong burst of neutrons. Irradiation by neutrons is a major health hazard.

The explosive power will also depend on how effectively the explosion of the conventional high explosives surrounding the plutonium oxide sphere compresses it. Some of the energy released by the explosion will go into the plutonium oxide; the rest will go in other directions. Of the energy which goes in, some will compress the sphere and the rest will heat up the plutonium oxide. The more energy which goes into compression, the more powerful the nuclear explosion is likely to be.

Also, the more symmetrical the compression, the larger the nuclear explosion will be. And the larger the number of detonators used to set off the high explosives, the more symmetrical the explosion will be. The detonators could, again, be fired

simultaneously by a circuit generating a high-voltage square wave with a fast rise time.

A crude nuclear device constructed by a terrorist group could be contained in a vehicle such as a van. The van could be positioned so that, even if the device, when detonated, did not produce a significant nuclear explosion, the explosion of the chemical high explosives would widely disperse the plutonium. If incendiary materials were mixed with the high explosives, the explosion would be accompanied by a fierce fire.

The plutonium would burn in the fire, producing small particles. These would be taken up into the atmosphere in the fire-ball and scattered far and wide downwind. A large fraction of the particles would be small enough to be inhaled into the lung. These particles would become embedded in the lung and would irradiate the surrounding tissue with alpha-particles, given off when plutonium nuclei underwent radioactive decay. Irradiation by alpha-particles is very likely to cause lung cancer. This is why plutonium, when inhaled, has a very high toxicity.

The threat of dispersion makes a crude nuclear explosive device using plutonium a particularly attractive weapon for nuclear terrorists. The dispersal of many kilograms of plutonium over an area of a city would make the area uninhabitable until it was decontaminated, a procedure which could take many months. The great fear of radioactivity by the general population considerably enhances the threat.

The threat of dispersion is perhaps the most serious danger that would arise from the acquisition of plutonium by a terrorist group. In fact, *this danger is so great that the mere possession of significant quantities of plutonium by a terrorist group is a threat in itself.* If a terrorist group proved to a government that it had plutonium in its possession it could blackmail the government.

The government would not need to be convinced that the group had the expertise to design and construct an effective nuclear explosive device. It would know that even an ineffective nuclear device would scatter plutonium over a large area. And this would be threat enough for the terrorists' purposes.

2.2.6 Could a terrorist group make a nuclear explosive?

This question has been addressed by the scientists at the Office of Technology Assessment (OTA) of the US Congress. The OTA's conclusion is that:

> "A small group of people, none of whom have ever had access to the classified literature, could possibly design and build a crude nuclear explosive device. They would not necessarily require a great deal of technological equipment or have to undertake any experiments. Only modest machine-shop facilities that could be contracted for without arousing suspicion would be required. The financial

resources for the acquisition of necessary equipment on open markets need not exceed a fraction of a million dollars. The group would have to include at a minimum, a person capable of researching and understanding the literature in several fields and a jack-of-all trades technician. There is a clear possibility that a clever and competent group could design and construct a device which would produce a significant nuclear yield (i.e.,a yield much greater than the yield of an equal mass of high explosive)" [OTA 1977].

Similar conclusions were drawn by a group of American nuclear-weapon designers. They pointed out that there are some potential hazards in constructing a crude nuclear explosive device. They include:

"Those arising in the handling of a high explosive; the possibility of inadvertently inducing a critical configuration of the fissile material at some stage in the procedure; and the chemical toxicity or radiological hazards inherent in the materials used" [Mark et al. 1987].

Lovins argues that the hazards should not be exaggerated. He shows that the radiation dose rates from plutonium - including reactor-grade plutonium oxide - are such that they would not deter a person from handling it. And he concludes that, given sensible precautions against achieving criticality accidentally (by, for example, using a neutron counter to detect any neutrons emitted during the assembly of the plutonium) a terrorist group constructing a nuclear explosive would not face serious radiological hazards. In any case, such a group would probably be prepared to take some risks to achieve their purposes.

The explosive yield of a crude nuclear device using reactor-grade plutonium as the fissile material would be unpredictable. But this is not likely to bother a terrorist group. It is likely to be satisfied with any yield above the equivalent of ten tons of TNT or so. And because such a device would disperse plutonium, even if there was no nuclear explosion, unpredictability is not an issue.

2.2.7 Effects of the explosion of a primitive nuclear explosion

A 100-ton nuclear explosion

The largest conventional bombs used in warfare so far had explosive powers equivalent to about 10 tons of TNT. The largest terrorist explosion so far has been equivalent to about one ton of TNT. A nuclear explosion equivalent to that of 100 tons of TNT in an urban area would be a catastrophic event, with which the emergency services would be unable to cope effectively.

Exploded on or near the ground, such a nuclear explosive would produce a crater,

in dry soil or dry soft rock, about 30 metres across. For small nuclear explosions, with explosive powers less than a few kilotons, the lethal action of radiation covers a larger area than that affected by blast and heat. The area of lethal damage from the blast produced by a 100-ton nuclear explosion would be roughly 0.4 square kilometres; the lethal area for heat would be about square 0.1 kilometres; and that for radiation would be roughly 1.2 square kilometres.

Persons in the open within 600 metres of such an explosion would very probably be killed by the direct effects of radiation, blast, or heat [Rotblat, 1981]. Many other deaths would occur, particularly from indirect blast effects - from the collapse of buildings, from being thrown into objects or from falling debris. And a large number of people would be seriously injured by blast, heat, and radiation effects. Heat and blast will cause fires, from broken gas pipes, petrol in cars, and so on. The area and extent of damage from fires may well exceed those from the direct effects of heat.

A nuclear explosion at or near ground level will produce a relatively large amount of early radioactive fall-out. Heat from fires will cause the radioactive particles to rise into the air; they will then be blown downwind, eventually falling to the ground under gravity at rates and distances depending on the velocity of the wind and the weather conditions. The area significantly contaminated with radioactive fall-out will be uninhabitable until decontaminated.

The area concerned may be many square kilometres and it is likely to take a long time to decontaminate it to a level sufficiently free of radioactivity to be acceptable to the public. If one kilogram of plutonium is uniformly distributed it will contaminate about 600 square kilometres to a level of one micro-curie per square metre, the maximum permissible level allowed for plutonium by international regulations.

An explosion of this size, involving many hundreds of deaths and injuries, would paralyse the emergency services. They would find it difficult even to deal effectively with the dead. Many, if not most, of the seriously injured would die from lack of medical care. In the UK, for example, there are only a few hundred burn beds in the whole National Health Service. There would be considerable delays in releasing injured people trapped in buildings, for example.

And, even for those not trapped, it would take a significant time to get ambulances through to them and then to transport them to hospital. Therefore, a high proportion of the seriously injured would not get medical attention in time to save them. Experience shows that, when large explosions occur in an urban area, panic sets in which also affects the trained emergency personnel. This would be considerably enhanced by the radioactive fall-out accompanying a nuclear explosion.

A 1000-ton nuclear explosion

The British Cabinet Office has calculated the effects of a primitive nuclear explosive detonated at ground level in a typical city. The explosion was equivalent to

that produced by 1,000 tons of TNT. Within one minute, people outdoors on near windows inside houses would be killed by thermal radiation (heat) up to a distance of 200 metres from the point of detonation. Within one minute, blast would kill people up to a distance of 800 metres, and initial nuclear radiation would kill people up to a distance of 1 kilometre.

People within 2 kilometres would be injured by blast and those within 1 kilometre would be injured by heat. Communications equipment would be damaged by the nuclear electromagnetic pulse up to a distance of about 2 kilometres and electronic equipment would be damaged or disrupted up to a distance of about 10 kilometres, with severe consequences for fire services, police headquarters, and hospitals. The electromagnetic pulse would affect motor vehicles out to about 10 kilometres.

Assuming a 24 kilometre per hour wind, ionising radiation levels from radioactive fallout within an area of about 15 square kilometres would be high enough to cause radiation sickness in the short term to those exposed in the open, and in some cases to those in buildings. This area would extend some 10 kilometres downwind and would have a maximum width of about 2 kilometres.

Furthermore, radiation levels in an area of about 400 square kilometres would be such that certain counter-measures would have to be taken to protect people from the long-term effects of exposure to radiation - for example, fatal cancers. This area would extend some 80 kilometres downwind.

2.3 The Effectiveness of International Safeguards in Plutonium Bulk-Handling Facilities

The purpose of the nuclear safeguards system of the International Atomic Energy Agency (IAEA) is to provide assurance that nuclear materials are not being diverted from peaceful purposes to nuclear-weapon programmes [IAEA 1995]. Because of the danger that plutonium may be stolen or otherwise illegally acquired, and used to produce nuclear weapons illegally by governments or sub-national groups, the question of whether safeguards can be effectively applied to facilities which handle large amounts of plutonium is of crucial importance.

The safeguarding of plutonium in spent reactor fuel elements is relatively simple, even spent MOX fuel elements. All that is required is to count the number of elements in the area in which they are stored - in the cooling pound at the reactor, for example. Even after many years the fuel elements are so highly radioactive that they can only be handled with heavy remote-handling equipment. Safeguarding them is a matter of unit accountancy plus, possibly, surveillance with video cameras. The

safeguarding of fresh MOX reactor fuel elements is more complicated, as will be described later.

But commercial facilities for the bulk handling of plutonium - specifically, plants for reprocessing plutonium (separating plutonium from unused uranium and fission products in spent nuclear-power reactor fuel elements) and for the fabrication of fuel elements from mixed (plutonium and uranium) oxides (MOX) - cannot be effectively safeguarded [Miller 1990].

For example, because of measurement uncertainties and the large amount of plutonium handled in a commercial reprocessing plant, conventional safeguards techniques are not sufficiently precise to ensure, in a timely way, that the diversion of an amount of plutonium sufficient for the fabrication of a nuclear weapon would be detected [Leventhal 1994]. This has nothing to do with inefficiency or incompetence. Even using the best available and foreseeable safeguards technologies and accountancy techniques, the safeguards on plutonium bulk-handling facilities are ineffective. The plants most difficult to safeguard effectively are large reprocessing plants.

2.3.1 Material balance areas

The most important safeguards measure used for the timely detection of the diversion of nuclear materials from peaceful to military uses is material accountancy. As applied to a nuclear facility, material accountancy is similar to any audit. The operator of the facility prepares a material balance covering a specific part of the facility (called the material balance area - MBA) and covering a specified period of time. The balance should show whether or not all the nuclear material which has passed through the MBA for the specified period can be accounted for.

If safeguards are to be effective, it must be possible to establish accurately the amount of nuclear material in it and to measure the flows of nuclear materials into and out of it [Johnson and Islam 1991]. In a reprocessing plant, for example, the MBAs are normally: the part of the plant into which spent reactor fuel elements are received and stored; the part in which the cladding on the fuel elements is removed and elements dissolved in nitric acid; the part after the dissolver in which the reprocessing chemistry takes place; and the store in which the separated plutonium is kept. The idea is that the amounts of nuclear materials passing into and out of these areas are monitored.

In practice, material accountancy using MBAs in bulk handling facilities faces a number of problems. Moreover, safeguards inspections at these facilities are exceedingly difficult. The operators of the plants understandably want to operate with as little interruption and intrusion as possible. The nature of the operation is such that the inspectors have to rely on data supplied by the operator with no possibility of independently checking it. Reprocessing and MOX-fabrication are dynamic processes

and significant fluctuations in the operations are inevitable. To follow them continually and sufficiently precisely to ensure that diversion has not taken place is, to say the least, exceedingly difficult.

The nature of the operations at commercial reprocessing and MOX-fabrication plants adds to the problems of safeguarding them [Berkhout and Walker 1992; Shea et al. 1993]. The plants are largely automated. The computers deal with huge amounts of data. Because the items and materials involved are normally highly radioactive they have to be handled with remote-handling equipment. The radiation shielding around much of the plant makes large areas inaccessible while the plant is operating.

The chemical composition of the nuclear materials is complex and there are many changes during the process in the chemical composition and concentrations of the materials. The nuclear materials occur in complex and changing mixtures of nuclear and non-nuclear materials.

The most difficult MBAs to safeguard are the input section (the so-called head-end) and the reprocessing section (in which the plutonium, uranium, and fission products are chemically separated) in a reprocessing plant. The problems of safeguarding a reprocessing plant are discussed below.

It should be noted that the design and operation of commercial reprocessing plants are very closely guarded secrets. There is, therefore, very little information in the literature about the effectiveness of safeguards at the plants or about possible diversion pathways. What information there is relates to very limited operational periods at the small reprocessing plant at Tokai (still in operation), Dounreay (still in operation) and Karlsruhe (closed down in 1991).

2.3.2 Material unaccounted for

If the amount of nuclear material going into the MBA is A, B is the amount leaving the MBA, and R is the total amount of nuclear material removed (legally) from A, then, if no material is lost,

$$B = A - R.$$

But if an amount, X, has been lost or is otherwise unaccounted for,

$$B = A - R - X.$$

Hence,

$$X = A - B - R.$$

If X = 0, and the values of A, B, and R given by the operator are authenticated by the IAEA inspector, then the Agency will conclude that no diversion has taken place. A positive value of X indicates that an illegal diversion has occurred. The value of X is called the "material unaccounted for" or MUF.

In some cases, it is possible to measure A, B, and R reasonably accurately. For example, if the MBA is the cooling pond of a reactor, then these values are simply

numbers of fuel assemblies and X can be determined exactly. But in facilities in which plutonium is handled in large quantities, specifically in reprocessing plants and MOX-fuel fabrication plants, only approximate measurements are possible.

The first measurement, as opposed to an estimate based on calculations, of plutonium in a reprocessing plant is made in an accountancy tank. The problem is that the amount of plutonium is not measured directly. A small sample is taken from the tank and, using mass spectrometric methods, the ratio of the amount of plutonium to the amount of uranium is measured.

The amount of uranium in the spent reactor fuel elements introduced into the plant is calculated by the reactor operators from their knowledge of the amount of uranium originally in the reactor fuel elements and of the way in which the reactor was operated (particularly the amount of heat produced by the fuel). From the amount of uranium and the uranium/plutonium ratio the amount of plutonium is determined. But there are errors in each of the steps in this operation.

For example, the spent fuel is chopped up and dissolved in nitric acid. Some plutonium remains in the undissolved portions of the fuel elements (the "hulls") and is very difficult to measure.

Because of the errors involved, even if no illegal diversion of plutonium has taken place, the value of the MUF will generally not be zero. Its value may be either positive or negative. Put another way, *the operator will not know whether or not an amount of plutonium up to the value of the MUF has been illegally removed.* Statistical methods must be used to work out the probability that a positive MUF means that plutonium has been illegally diverted or arises because of a chance combination of errors in A and/or B and/or R.

The magnitude of the errors are specified by the square root of the measurement error variance of MUF, σ-(MUF), or the measurement error standard deviation. The goal of the IAEA is to verify that for a given period "no significant quantity of nuclear material has been diverted or that no other items subject to safeguards have been misused by the State". A 'significant quantity' (SQ) is the amount of nuclear material for which "the possibility of manufacturing a nuclear explosive device cannot be excluded". For plutonium, SQ is defined by the IAEA as 8 kilograms.

If σ-(MUF) is large compared with SQ, then the minimum diversion which can be detected by safeguards measures with high confidence and a low false alarm probability will be much greater than a SQ. In other words, safeguards will be ineffective[OTA 1995].

The British Thermal Oxide Reprocessing Plant (THORP), at Sellafield, England, for example, will separate about 7,000 kilograms of plutonium a year. The reactor operators which send their spent fuel elements to THORP for reprocessing cannot measure the amount of plutonium in the fuel elements (they are too radioactive to

allow measurements to be made); they calculate the amount of plutonium instead. These computer calculations are done from the operator's knowledge of how the reactor operated while the fuel elements were in the core - the heat generated, and so on.

The amount of plutonium going into the reprocessing plant (i.e., the term A above) is calculated from these computer calculations. The reactor operators have not stated the error in their calculations. But independent experts calculate it to be about 5 per cent [Barnham 1992].

If the material balance is done once a year, as it normally is, then the value of σ-(MUF) is 350 kilograms. The minimum amount of diverted plutonium which could be detected with a probability of 95 per cent and a false alarm probability of 5 per cent is 3.3 σ-(MUF), or about 1,100 kilograms [Miller 1990].

Even if the error in the reactor-operator's computer calculations is as low as 1 per cent, the minimum amount of diverted plutonium which could be detected with a probability of 95 per cent and a false alarm probability of 5 per cent is about 220 kilograms, equivalent to about 28 SQs. Clearly, the THORP reprocessing plant cannot be effectively safeguarded using current techniques.

Based on such calculations, the Office of Technology Assessment of the US Congress, concludes that:

> "barring acquisition of additional measurements and use of more sophisticated statistical analysis - many analysts have concluded that measurements are incapable of reliably detecting diversions of one or even several significant quantities of safeguarded material from large reprocessing plants."

The report goes on to say:

> "actual IAEA experience in safeguarding large plants is minimal, so that it is not known how well routine measurements will compare with their predicted performance" [OTA 1995].

Even if the diversion of an SQ could be effectively detected, the IAEA's timeliness goal for plutonium could not be satisfied currently. Assuming that the THORP reprocessing plant operates for 250 days in the year, the rest of the time being used for routine maintenance, an average of about 35 kilograms, or 4 SQs, of plutonium will be separated each day.

The IAEA's guidelines for effective safeguards were that the diversion of a significant quantity should be detected, with a 90 to 95 per cent probability and with a false-alarm rate of no more than 5 per cent within a 'conversion time'. The concept of

a conversion time is based on the time likely to be required to convert diverted fissile material into a form that could be used in a nuclear weapon. For plutonium in the forms of the oxide or nitrate, the products produced in a reprocessing plant, the conversion time is 1 to 3 weeks.

If the detection of an illegal diversion is to be timely enough to allow action to be taken to prevent the use of the plutonium in, say, a nuclear explosive device, the detection time must be significantly shorter than the conversion time so that a response can be made. To achieve a minimum diversion of an SQ detected with a 90 to 95 per cent probability and with a false-alarm rate of no more than 5 per cent, assuming that σ-(MUF) is 1 per cent, a material balance measurement must be made when about 240 kilograms of plutonium have been separated.

This means that, for THORP, which on average separates about 35 kilograms of plutonium per working day, a material balance measurement must be made weekly to detect the diversion of an SQ. But to satisfy the timeliness requirement the period must be significantly shorter than this. This means that, for THORP, a material balance measurement must be made every two days or so; this is a much greater frequency than that in conventional materials accountancy. Could it be achieved in practice?

2.3.3 Near-real time accountancy

Material accountancy with material balance measurements taken at this sort of frequency is called Near-Real-Time Accountancy (NRTA). Direct measurements using instruments built into the plant, analyses using models of the plant operations, and indirect calculations using computer simulations of the chemical processes are used to provide data [Shea and Chitumbo 1993]. In the case of THORP, direct measurements are taken only in the main buffer tanks and the accountancy tanks. Elsewhere, models have to be used.

NRTA depends on a series of MUF values being obtained when no diversion takes place, to calibrate the system. It is assumed that the deviations in this series of MUF values are caused by measurement errors and plant losses, such as plutonium retained in pipes, tanks, and so on. Systematic measurement errors are obtained from the series. These can then be subtracted from a series of MUF values being investigated to see if diversion has taken place to build up a standardized set of MUF values. [Walker 1995].

Over time, the magnitude of σ-(MUF) can be reduced and the detection sensitivity increased. The statistics involved in these sequential tests are very complex. The snag is that no single statistical method can deal effectively with all possible means of diversion.

A problem with NRTA is that small amounts of plutonium may be illegally diverted now and again so that the total diverted over a relatively long period exceeds an SQ. Whether a diversion is a single one or a number of smaller ones is not an issue for conventional materials accountancy because measurements are made over a long period, of say a year.

Because NRTA depends on repeated calibrations, plutonium could be systematically put into or taken out of the plant during a calibration period so that the value of normal MUF values are falsified. This is one example of the way in which a determined diverter could succeed in his purpose even when the most sophisticated safeguards technique available is used.

The Office of Technology Assessment of the US Congress, concludes that:

> "The conventional "material accountancy" safeguards methods now in use by the IAEA appear unable to assure that the diversion of a bomb's worth of plutonium per year from a large reprocessing facility - e.g., one processing much over about 100 tons of spent fuel per year - would be detected with high confidence." [OTA 1995].

And goes on to say:

> "New techniques such as "near-real-time accountancy" -- unproven at this scale by the IAEA -- must be adopted for large reprocessing plants, and even these techniques may not be able to measure material flows and inventories accurate enough to detect the absence of one bomb's worth of plutonium per year. In that case, if the IAEA could not demonstrate that safeguards methods other than the material accountancy techniques that form the core of its current safeguards approach can be relied on to detect diversion with a high degree of confidence, it would have to conclude that it could not safeguard such a plant to the same standards it applies at smaller facilities." [OTA 1995]

2.3.4 Physical protection of facilities handling MOX

It would be extremely easy, even for a sub-national group, to chemically separate the plutonium from the uranium in MOX and use the plutonium to fabricate a nuclear explosive. The protection of facilities handling MOX require, therefore, special consideration.

Countries operating nuclear facilities try to prevent nuclear thefts and illicit activities by operating a safeguards system, as described above, and a physical protection system. These two systems are meant to be complementary. The safeguards system should, in theory *detect* the disappearance of nuclear material if the physical

protection system fails to *prevent* such a disappearance. The physical protection system should then *recover* the stolen material. Because it is not possible to adequately safeguard plutonium bulk-handling facilities, the effectiveness of the physical protection of plutonium in such plants is crucially important.

The IAEA has published general recommendations for a national physical protection system for nuclear material which are meant to set minimum standards. Normally, national systems are based on these recommendations. The responsibility for establishing and operating a physical protection systems rests solely with the government of the country in which the nuclear facility is operated.

The main aids to physical protection are the use of security devices, guards, and security procedures. A major aim should be to limit access to significant amounts of nuclear material to a minimum number of people. These people should be selected for their trustworthiness.

All significant amounts of plutonium, except that with isotopic concentration exceeding 80 per cent in Pu-238, should be stored within an inner area which is itself within a protected area. Only specially chosen people should be allowed to enter the protected area and access should be kept to the minimum necessary.

All people and packages moving into or out of inner areas should be searched for stolen nuclear material or articles of sabotage. People inside an inner area should be under constant surveillance. The area should be guarded day and night with guards reporting to the local police at regular intervals during non-working hours. If the guards are unarmed, arrangements should be made to bring in armed people very rapidly indeed to deal with an armed attack. Adequate communications between guards, their central headquarters, and reserve forces are essential.

Significant amounts of plutonium should be stored in special strong rooms inside inner areas. Access to storage areas should be carefully controlled and limited to specially selected people. People and articles entering protected and inner areas should be screened for articles of sabotage, guns and explosives with, for example, fixed metal detectors backed up by hand-held detectors. To detect the theft of plutonium, people leaving an inner area should be screened with a fixed radiation monitor sensitive to gamma-rays and neutrons, and with a fixed metal detector. In addition, frequent random searches should be made with, at least, very sensitive hand-held monitors.

An emergency force must be prepared to recover any stolen plutonium very rapidly. This implies a large force of highly-trained well-armed commandos with a wide range of detection equipment, including airborne equipment.

According to the IAEA, containment and surveillance techniques, the use of tamper-indicating seals, video cameras, and on-site inspections make up for the shortfalls in the safeguards system. But for facilities for the bulk-handling of plutonium this is not true. Even if the most modern and intrusive containment and surveillance systems are used, and they are often not, they can be defeated or rendered

non-conclusive [Leventhal 1994].

Seals can be broken or cut and the view of cameras can be blocked or obscured during normal operations or in response to emergencies without necessarily indicating an attempt to conceal a diversion. Consequently, containment and surveillance cannot be regarded as adequately complementing safeguards on plutonium bulk-handling facilities.

2.3.5 Physical protection of plutonium, including MOX, in transit

The use of MOX fuel inevitably involves much transportation of plutonium. The plutonium has to be transported from the plutonium store at the reprocessing plant to the fuel-fabrication plant. The MOX fuel elements will then be transported from the plant to the reactors in which it is to be used.

A typical MOX fuel fabrication plant with a capacity of producing 100 tons of MOX fuel year will use about 4 tons of plutonium a year. If the MOX is fabricated at a distance from the plutonium store, it would probably be transported by road. Each lorry load to the MOX-fabrication plant would probably carry about 60 kilograms of plutonium so that about 70 transports - one every five days - will be needed.

Plutonium is very, perhaps most, vulnerable to theft and sabotage when it is being transported. A widespread use of MOX could involve the transportation, using all forms of international transport, of thousands of kilograms of plutonium a year. This transportation should be protected to a degree which minimises the possibility that just a few kilograms of plutonium, in metal or oxide form, falls into the wrong hands. In addition, many thousands of tons of spent reactor fuel elements may be transported internationally from nuclear-power reactors to reprocessing plants. And a large number of fresh fuel elements may be transported from MOX fabrication plants to nuclear-power reactors.

The IAEA has issued recommendations for the protection of nuclear material in transit; recommendations which are meant to be minimum standards. The recommendations include general rules, similar to those covering dangerous or valuable cargoes. For the transport of plutonium, guards should accompany each shipment and there should be provision for continuous two-way radio or frequent telephone communication between shipper and receiver. The surveillance of road and rail transports by guards should be continuous.

There should be frequent examination of seals and continuous surveillance of the cargo-hold when the vehicle is stationary. The most modern communications systems should be used so that there is adequate contact between the vehicle carrying the nuclear material, the escorting vehicle, and between these vehicles and the shipper and receiver. The vehicle carrying the nuclear material should be fitted with a vehicle disabling system and during an overnight stop it should be immobilised or parked in a

guarded and locked building or compound. Similar arrangements should apply to shipments by rail and sea.

Adequately sized and trained teams should be ready to deal with any emergencies arising during the transport of significant amounts of plutonium. The teams should be able to reach the scene of an incident in transit either while the illicit action is in progress, or at worst immediately afterwards when the possibility of recovering any stolen plutonium is greatest. For this purpose, the emergency teams should be sited at a number of strategic locations within the countries through which nuclear transport pass.

Today's terrorists may be armed with automatic weapons and will become armed with stand-off missiles and other weapons of great fire-power. An attack on a nuclear transport may, therefore, be a formidable one, requiring an equally, or better armed defensive force to defeat it.

A large commercial reprocessing plant employs some 500 workers with jobs requiring security clearance to ensure trustworthiness. Because people enter and leave the plant daily, there will be hundreds of thousands of opportunities each year for the illegal removal of plutonium from a plant. Similar considerations apply to a large MOX fabrication plant.

Because of the impossibility of applying adequate safeguards to plutonium bulk-handling facilities, physical protection is the only security safeguard. Measures of physical protection must take into account the easiest way to obtain illicitly plutonium from such a facility would be to bribe, seduce or blackmail an employee who may otherwise be above suspicion.

The severity of searches and surveillance at a plutonium bulk-handling facility would have to be exceptionally high to deter or detect the theft of gram quantities of plutonium. Security investigations and surveillance would have to extend far beyond the worker in the facility or the nuclear transport worker -- family, friends and associates would also be involved.

The severity of physical protection measures will inevitably increase in severity as incidents occur, a ratchet effect will apply. A time will arrive when trade unions, civil liberties and citizen groups, and so on will find the protection measures necessary in facilities and for nuclear transportation intolerable. Moreover, the draconian emergency measures eventually adopted to deal with nuclear incidents in facilities and nuclear transportation, involving heavily armed guards and commando teams with massive fire-power stationed at many locations, will be intolerable in democratic societies.

It can be concluded that: in an open society, operating under the rule of law, it is extremely doubtful whether the procedures required to protect a plutonium economy adequately would be legally, politically and socially acceptable. In short, it is reasonable to question whether a democracy could survive a plutonium economy based on the

large-scale use of MOX fuel. (See Chapter 6 for further discussion).

Most radioactive materials should be protected against theft or unauthorised use. But plutonium needs special protection because it may be stolen by criminal or terrorist groups to make nuclear explosives or diverted clandestinely and/or illegally to fabricate nuclear weapons. Plutonium, possible in the form of MOX, may also be stolen to radioactively contaminate an urban area. A terrorist group may also hi-jack a shipment of plutonium or MOX - for example, on the way to and from a reprocessing plant.

Fresh MOX fuel elements may be stolen from a nuclear-power reactor. With the use of MOX, reactors will become stores of weapon-usable plutonium. This will require them to be guarded with very much greater thoroughness than they are today and provided with much physical protection with all that implies for the surveillance of workers on the reactor site.

2.3.6 Hold-up of plutonium in MOX fuel-fabrication plants

A typical MOX fuel-fabrication plant consists of four main plant areas: fuel pellet production; fuel rod production; fuel rod inspection; fuel assembly manufacture and inspection. Based on the experience of hold-up in the Japanese Tokai-Mura MOX plant it can be assumed that all first-generation MOX plants retain (hold-up) plutonium when they are operated normally, particularly in the fuel pellet production sections.

In May 1994, it was disclosed that a major discrepancy in the inventory had occurred at the Plutonium Fuel Production Facility, a modern MOX fabrication plant, at Tokai, Japan. It turns out that about 70 kilograms of plutonium was held up - that is, stuck to surfaces - in the remote-handling equipment. The measurement of held-up plutonium, made using neutron coincidence counting, is subject to a wide range of error. This makes adequate safeguards on MOX fabrication plants even more difficult to implement.

Hold-up has considerable consequences for safeguards. Of particular concern is hold-up in parts of the plant which are inaccessible, as some are in early plants. When some of the contamination occurs in inaccessible places, the requirement of timely detection obviously cannot be fulfilled. Therefore, safeguards cannot be applied. This is yet another example of why adequately safeguarding plutonium bulk-handling facilities is not possible.

It should be emphasised that the main reason given for reprocessing spent reactor fuel elements today is to provide plutonium oxide for the fabrication of MOX fuel. The reason given for producing MOX is to dispose of an embarrassing surplus of plutonium. This situation is, of course, absurd. It would be better not to separate the plutonium from spent nuclear fuel elements in the first place.

As described above, the fact that reprocessing plants cannot be safeguarded effectively is the most serious nuclear safeguards issue. This problem will only be solved if the use of MOX and the reprocessing of plutonium are stopped.

2.4 The Consequences of the Use of MOX for the Negotiation of a Ban on the Production of Fissile Materials for Use in Nuclear Weapons

2.4.1 Fissile cut-off

Commitments made at the 1995 NPT Extension Conference require the negotiation of a treaty prohibiting the production of fissile material for nuclear weapons (often called a fissile material cut-off treaty). The concept of a fissile material cut-off was first suggested 50 years or so ago in the 1946 American Baruch Plan. During the 1960s, when the negotiations for an NPT were in progress, a cut-off was included in a group of measures recommended by the non-aligned countries for urgent negotiation. After 1978, cut-off resolutions have been regularly passed by the General Assembly but there was little hope of progress while the Cold War was on.

With the end of the Cold War, the concept in its own right was given a considerable impetus by President Bill Clinton, in his speech to the General Assembly in September 1993: "We will pursue new steps to control the materials for nuclear weapons. Growing global stockpiles of plutonium and highly enriched uranium are raising the danger of nuclear terrorism in all nations. We will press for international agreement that would ban production of these materials for ever." Strong American support made a cut-off realistic and attainable.

In 1993, General Assembly Resolution 48/75, adopted by consensus, recommended the negotiation of a non-discriminatory, multilateral, and internationally and effectively verifiable treaty banning the production of fissile material for nuclear weapons and other nuclear explosive devices. The treaty described in Resolution would ban future production but it says nothing about existing stocks of fissile materials.

On 25 January, 1994, the members of the Conference on Disarmament (CD) in Geneva agreed to appoint a Special Co-ordinator to "seek the views of its members on the most appropriate arrangement to negotiate" a cut-off. It was soon apparent to the Special Co-ordinator, Canadian Ambassador Shannon, that a crucial political issue was the scope of the cut-off treaty. Would it include the past production as well as the future production of fissile materials for nuclear weapons?

It was not until 23 March, 1995 that Ambassador Shannon was able to report consensus on the negotiating mandate for the cut-off and the establishment of an "Ad

hoc Committee to negotiate a non-discriminatory, multilateral and internationally and effectively verifiable treaty banning the production of fissile material for nuclear weapons or other explosive devices." The difficulty about defining the scope of the cut-off was not solved but the adoption of the mandate was achieved by a compromise (some would say a fudge). In the words of Ambassador Shannon: "During the course of my consultations...some delegations expressed the view that this mandate would permit consideration in the committee only of the future production of fissile material. Other delegations were of the view that the mandate would permit consideration not only of future but also of past production. ..... It has been agreed by delegations that the mandate for the establishment of the Ad Hoc Committee does not preclude any delegation from raising for consideration in the Ad Hoc Committee any of the above noted issues" [Bishop 1995].

2.4.2 The scope of a fissile material cut-off treaty

The scope of a cut-off is not only a matter of whether or not past as well as future production of fissile materials should be included. There is also the issue of whether civil fissile materials should be included as well as military ones. As defined in Resolution 48/75 a treaty banning the production of fissile materials would, at a minimum, cover the production of weapon-grade plutonium (plutonium containing more than 93 per cent of the isotope plutonium-239), weapon-grade highly-enriched uranium (uranium enriched to over 90 per cent uranium-235), and uranium-233 for nuclear weapons or other nuclear explosive devices, or outside of international safeguards.

A more comprehensive and effective cut-off than this minimum one would include: plutonium of all isotopic compositions, except plutonium containing more than 80 per cent of the isotope plutonium-238; uranium enriched to over 20 per cent in the isotope uranium-235; and uranium-233. This would include all the weapon-usable fissile materials.

A treaty banning the further production of just military plutonium and highly-enriched uranium for use in nuclear weapons - i.e., the production of weapon-grade materials in designated military facilities - should, on first sight, be easy to negotiate. In all of the five declared nuclear-weapon states - the USA, Russia, the UK, China, and France - the production of weapon-grade plutonium and highly-enriched uranium is coming or has come to an end [Berkhout et al. 1994]. This is why these powers are willing to ban future production.

2.4.3 Current stocks of weapon-usable fissile materials

Plutonium

The extent of the existing stocks of weapon-grade and weapon-usable fissile materials is important when considering the need for a cut-off treaty. The world's total stock of plutonium, civilian and military, by the end of 1996 is about 1,300 tons (excluding the plutonium in the cores of the world's nuclear-power reactors). Of this, more than 1,000 tons are civil plutonium. The world's nuclear-power reactors are currently producing about 70 tons of plutonium a year [Albright et al. 1997]; by the year 2000 the total amount of plutonium in the world will be about 1,500 tons.

About 200 tons of civil plutonium have been separated from spent nuclear-power reactor fuel elements in reprocessing plants. An additional 30 tons are being reprocessed a year so that by the end of 1996 there must have been as much separated civil plutonium as military plutonium. By the year 2000, there will be some 280 tons of separated civil plutonium; if current reprocessing plans go ahead, by the year 2010 there will be about 440 tons of separated civil plutonium. This means that the amount of civil plutonium as a percentage of total (civil plus military) plutonium will have increased from about 30 per cent in 1990 to about 60 per cent in 2010.

By the year 2000, the amount of civil plutonium in store will have increased to about 250 tons. Of this, about 80 tons will be in France, about 50 tons will be in the UK, about 50 tons in Japan, and about 40 tons in each of Germany and Russia. Smaller amount (less than 8 tons) will be in each of Belgium, India, Italy, the Netherlands, Spain, Switzerland, and the USA [Leventhal 1995].

There are about 230 tons are military plutonium in the world's stockpile. A small amount of military plutonium is still being produced in Russia in two reactors which are also used for domestic heating purposes; they will be shut down when their heating function can be replaced, probably before the end of the 1990s. No military plutonium is being produced in the USA, the UK, and France. The amount of military plutonium that China plans to produce in the future is not publicly known. India and Israel are probably still producing plutonium but in relatively small amounts. The world's stock of military plutonium is, therefore, unlikely to increase very much.

The amount of military plutonium in the USA is about 110 tons. About 40 tons of this plutonium are outside nuclear weapons. The USA is currently dismantling about 1,800 nuclear weapons a year, probably containing about 7 tons of plutonium. As of mid-1995, the USA had in store the fissile cores of about 8,000 dismantled nuclear weapons. These contain a total of about 32 tons of plutonium.

The amount of military plutonium in the former Soviet Union is probably about 125 tons. The amount outside weapons is probably about 50 tons. Russia is apparently dismantling about 1,800 nuclear weapons a year, probably containing about 7 tons of

plutonium, the same as the USA.

The U.K. has probably produced about 10 tons of military plutonium of which about 3 tons are in weapons. France may have produced roughly 6 tons of military plutonium. China probably has about 2 tons in its weapons. Israel may have produced about 950 kilograms of military plutonium and India between 200 and 300 kilograms.

It is reasonable to assume that about 70 tons of the world's 250 tons of military plutonium are currently in nuclear weapons. About 14 tons of this plutonium are removed each year from dismantled nuclear weapons. By the year 2000, the total amount of military plutonium outside nuclear weapons may have increased to about 160 tons, or about 60 per cent of the world's total military plutonium.

Highly-enriched uranium

The situation with highly-enriched uranium is different from that with plutonium. The bulk of the world's stock of highly-enriched uranium is military; only about 1 per cent is civil. Moreover, the highly-enriched uranium removed from dismantled weapons can be disposed of more easily by mixing it with natural or depleted uranium to produce low enriched uranium for nuclear-power reactor fuel. Low enriched uranium is not usable in nuclear weapons.

There are about 1,800 tons of highly-enriched uranium in the world - about 700 tons in the USA; about 1,000 tons in the ex-Soviet Union; about 20 tons in each of the France and China and 10 tons in U.K.. Pakistan has probably produced about 150 kilograms of highly-enriched uranium and South Africa about 360 kilograms. About 20 tons of highly-enriched uranium is used in civil facilities, almost all of it as fuel in civil research reactors.

About 1,300 tons of highly-enriched uranium are outside nuclear weapons and about 410 tons in active nuclear weapons (160 in the USA, 230 in Russia, 8 in France, 3 in the UK, and 7 in China). Highly-enriched uranium is also used to fuel the reactors in nuclear-powered warships. The reactors in, for example, American nuclear-powered warships have so far consumed about 100 tons of highly-enriched uranium as fuel and about the same amount will be needed for future fuel.

On average, a nuclear weapon contains about 15 kilograms of highly-enriched uranium. The dismantling of nuclear weapons will produce about 30 tons of highly enriched uranium a year in each of the USA and Russia.

2.4.4 Need to include civil plutonium in a convention banning the production of fissile material

If surplus military plutonium remains outside international safeguards it will, to say the least, considerably reduce the effectiveness of a fissile material cut-off treaty.

Hence the argument for including existing stockpiles (i.e., past production as well as future production) in a cut-off treaty. Similarly, given that the world stock of separated civil plutonium will soon exceed the world stock of military plutonium and that this civil plutonium can be used to fabricate efficient nuclear weapons, the effectiveness of a fissile material cut-off will be, to put it mildly, much reduced if civil plutonium is excluded. Nuclear weapons can be manufactured from plutonium containing almost any combination of plutonium isotopes, although plutonium containing high percentages of the isotope plutonium-239 is more suitable than plutonium containing more than 10 per cent or so of the isotope plutonium-240. Except for plutonium containing 80 per cent or more of the isotope plutonium-238, all plutonium must be considered to be potentially weapon-usable [DOE/OACN 1997].

A ban on the production of fissile materials for nuclear weapons will, therefore, be effective only if it puts under international safeguards the military plutonium and highly-enriched uranium already produced as well as banning all future production of these materials. Moreover, such a ban will not be effective unless it includes civil fissile materials which can be used in nuclear weapons. It can only include civil plutonium if the use of MOX is banned.

2.4.5 The disposal of weapon-grade plutonium as MOX

Weapon-grade plutonium removed from nuclear weapons can either be stored or permanently disposed of. There are only two feasible ways of disposing of this military plutonium. One is to use it as MOX fuel in existing or modified nuclear reactors. The other is to vitrify it, with or without high-level radioactive wastes, and permanently dispose of it in deep bore holes or geological repositories.

The MOX route is certainly not the preferable method for disposing of military plutonium. The main reasons are the problems arising from the transportation of plutonium, increased radiation hazards for workers in the nuclear fuel-cycle, the long time taken to dispose of the plutonium, the financial costs involved compared with other methods, the impossibility of safeguarding adequately plutonium bulk-handling facilities, the encouragement it will give for civil reprocessing, and the irrationality of use of MOX as reactor fuel.

To dispose of weapon-grade plutonium by using it in MOX fuel inevitably involves much transportation of plutonium. The plutonium has to be transported from the plutonium store to the fuel-fabrication plant. The MOX fuel elements will then be transported from the plant to the reactors in which it is to be used.

The details of the design of Russian and American nuclear warheads are close-guarded secrets. In particular, the sizes, shapes, and isotopic content of the fissile-material components will not be divulged to any other power. This means that the plutonium pits from dismantled weapons will be melted down before released for

disposal to hide the details of their size and shape.

Because of the presence of radioactive decay products, such as isotopes of americium; non-nuclear alloy metal, such as gallium; and the non-nuclear material used to coat, and make airtight, the plutonium, such as copper or gold, the pits will have to be chemically processed to separate out and purify the plutonium before it can be used in MOX fuel. This adds a stage to the process.

The Pu-241 in weapons-grade plutonium will decay to americium-241 with a half life of 14.4 years. If the weapons-grade plutonium is, for example, 10 years old, 0.13 per cent will be americium-241. Americium-241 emits 1,200 neutrons per second per kilogram and is a strong gamma-ray emitter.

If the plutonium were used to fabricate MOX fuel elements, the americium would present a significant radiation hazard for those working in the MOX-fuel fabrication plants. The older the weapon-grade plutonium, the more the radiation hazard.

The suggestion that weapon-grade plutonium can be disposed of as MOX in a timely way is not true. Because the nuclear properties of plutonium differ from those of uranium, the amount of MOX which can be used in the cores of most current light-water reactors is limited to about a third of the core. More MOX could be used only if the cores were modified by using more control rods of higher efficiency. Even if this were possible, the costs would be considerable.

MOX fuel would typically contain about 45 grams of weapons-grade plutonium per kilogram. In a 900-MW(e) light-water reactor which can use MOX in a third of the core, about 170 kilograms of plutonium could be consumed (i.e. converted to reactor-grade plutonium) a year. It would take 30 of these reactors operating for at least 30 years (i.e. their lifetime) to handle the 140 tons of military plutonium to be removed from dismantled nuclear weapons in the next ten years. In other words, about 25,000 MW(e) of reactor capacity would have to be used.

Some reactors, such as the US System-80 reactor, are designed with the inherent capability to use a full core of MOX fuel, although they are not licensed to operate in this way and the safety of the design is not yet known.

It would, of course, take a long time to obtain the necessary approvals and licenses to use military plutonium in civil MOX fuel. If American civil light-water reactors, for example, are used, the licensing process would probably take 10 years or more, adding this period to the time taken to recycle the plutonium.

It is reasonable to assume that the total number of nuclear warheads in the world's nuclear arsenals will continue to decrease, eventually to a few hundred or even zero. It would take several decades to process all the weapons-grade plutonium removed from dismantled nuclear weapons as MOX fuel. All in all, the rate of disposal of weapon-grade plutonium is of necessity so slow that the use of the MOX route is impracticable.

The cost of putting 130 tons of military plutonium through civil light-water nuclear-power reactors would be between $1 billion and $6 billion. Bearing in mind that contract charges can reach $3,000 per kilogram of MOX if the MOX fabrication plant runs significantly below capacity, the cost of recycling military plutonium as MOX may be very much higher.

Civil reactor operators would demand a subsidy to use military plutonium in MOX fuel rather than uranium. This could amount to many hundreds of millions of dollars. In addition, there are the costs of modifying the reactors and the additional costs of spent fuel disposal.

It is useful to compare the costs of storing military plutonium, until an acceptable way of permanently disposing of it is found, with the costs of disposing of it using the MOX route. The costs of plutonium stores at Sellafield and La Hague have not been publicly revealed but costs of about $2 per gram of plutonium a year are a reasonable estimate although it appears that utilities may be charged as much as $4 per gram a year. A cost of $3 per gram a year would probably be an upper limit.

It is estimated that the cost of building a large storage facility, with a 90 ton capacity, would be about $1.5 billion, suggesting a storage cost of about $1.5 per gram of plutonium a year. This means that the cost of storing the 130 tons of plutonium to be removed from dismantled Soviet and American weapons is about $200 million a year. Cost is, therefore, not a valid argument against storing military plutonium.

MOX spent fuel will contain more plutonium than ordinary spent fuel. Eventual permanent disposal of such spent fuel in geological repositories raises concern about possible criticality. It will also emit more heat for a longer time than ordinary spent fuel so that larger repositories would be needed. Also possible differences in the release of radioactivity in the repository and possible eventual release into the environment would have to be investigated.

Also uncertain are the safety and safeguards issues involved with the large-scale processing of the plutonium cores of nuclear weapons and the conversion of the weapons-grade plutonium metal to plutonium oxide. Until these are solved, the plutonium should be stored as cores.

So far, the world's civil nuclear-power reactors have discharged about 152,000 tons of spent fuel containing about 860 tons of civil plutonium. About 190 tons, or about 20 per cent, of this plutonium have been separated in commercial civil reprocessing plants. This percentage is unlikely to significantly increase in the foreseeable future.

This means that 75 or 80 per cent of the plutonium produced in civil nuclear-power reactors will have to be permanently disposed of without reprocessing. The rational thing to do would be to add the military plutonium removed from dismantled nuclear warheads to this civil plutonium for permanent disposal. The surplus military plutonium could be mixed with high-level waste so that the material

disposed of would be a similar radiation hazard - and therefore self-protected against theft - as spent fuel.

The use of military plutonium in MOX fuel would simply convert weapons-grade plutonium to reactor-grade plutonium; it would not destroy the plutonium. Reactor-grade plutonium is less desirable than weapons-grade for the manufacture of nuclear weapons but it is weapon-usable and can be used in nuclear weapons. After it has been through a reactor the MOX fuel would either have to be reprocessed or permanently disposed of. As described above, reprocessing capacity is so limited that merely producing more spent fuel makes no sense.

The use of military plutonium in MOX fuel will not assist nuclear disarmament. To the contrary, it will encourage the proliferation of nuclear weapons. The most sensitive activity insofar as nuclear-weapon proliferation is concerned is plutonium reprocessing. The use of MOX fuel requires large-scale reprocessing. If military plutonium is used to fabricate MOX fuel, civil reprocessing will be much encouraged to support the large-scale use of MOX.

Given the enthusiasm of the nuclear industry for MOX fuel, it is naive to suggest that the use of military plutonium for MOX would allow civil reprocessing to be phased out. The nuclear industry sees the use of MOX fuel as a way of maintaining the momentum of nuclear technology, leading to the widespread commercial use of breeder reactors. The preferred fuel for breeder reactors is weapon-grade plutonium. The consequence of a breeder economy for nuclear-weapon proliferation is obvious.

2.4.6 Laser isotope separation

Reactor-grade plutonium can be converted to weapon-grade plutonium using lasers in a process known as Laser Isotope Separation(LIS). LIS will completely eliminate any remaining difference between civil and military plutonium for those countries with access to it.

LIS increases the proportion of one isotope in a mixture of isotopes. For example, the concentration of Pu-239 in reactor-grade plutonium - containing a mixture of plutonium isotopes (Pu-238, -239, -240, -241, and -242) - can be increased to make the reactor-grade Pu more suitable for the fabrication of nuclear weapons. Another use for LIS is to increase the proportion of uranium-235 in natural uranium.

LIS increases the proportion of Pu-239 or U-235 by preferentially ionizing the atoms of the isotope by laser excitation (a process called photoionization) and then removing the ionized isotope. The conventional methods of separating isotopes rely on small differences in the masses of molecules containing the isotopes. For example, U-235 is separated from U-238 in natural uranium by gaseous diffusion or gas centrifuge technologies. Because the mass differences between the isotopes is so small (about 0.01 for U-235 and U-238), these methods are inefficient.

LIS separates isotopes more efficiently than gaseous diffusion or centrifuges because it is based on the fact that each isotope of an element has a unique set of electronic energy states. Consequently, electrons of atoms of each isotope will absorb light of a specific colour (i.e., of a specific energy level). If illuminated by a laser beam containing light of this precise energy, electrons of atoms of the selected isotope will absorb photons and become excited. An atom may give up its excited electron, and become a positively-charged ion.

The atoms of the other isotopes will not absorb photons, because they do not have the appropriate energy, and will not be ionized. The ionized atoms can be separated from the neutral ones by an electromagnetic field.

An example of this method of separating isotopes is the Atomic Vapor Laser Isotope Separation (AVLIS) system developed by the Lawrence Livermore Laboratory, California, USA. AVLIS consists of two main units - a separator and a laser. When used to separate uranium isotopes, natural uranium metal is vaporized in the separator, using an intense electron beam that creates a uranium vapour stream in a vacuum chamber which rapidly moves away from the uranium metal. The vapour contains atoms of U-235 and U-238. Researchers at the Lawrence Livermore Laboratory recently completed a 400-hour test run of the AVLIS separator equipment, bringing AVLIS "significantly closer to commercial feasibility" [Nuclear Fuel 1997].

The laser unit uses powerful copper-vapour lasers which emit beams of green-yellow light. This light energizes (excites) 'dye' lasers which emit beams of red-orange light of precisely the right energy (i.e., frequency) to photoionize preferentially U-235 atoms. The red-orange beams are passed through the vapour of uranium atoms.

U-235 atoms absorb photons of the red-orange light whereas U-238 atoms do not. The excited U-235 atoms eject the excited electrons, becoming ionized; the U-238 atoms remain untouched. An electromagnetic field moves the positively charged U-235 atoms to a collecting plate where they condense. The enriched U-235 can then be removed. The remaining uranium vapour, containing a much greater proportion of U-238 than natural uranium, flows on through the separator chamber and is removed.

The AVLIS process has an atomic selectivity of more than 10,000 - only one ion of U-238 is produced for every 10,000 ions of U-235. This high enrichment efficiency, combined with the fact that relatively little energy is needed to operate the separator and laser systems, makes the operating and capital costs of the AVLIS process relatively low. This makes laser-isotope separation considerably more attractive than other enrichment technologies.

The AVLIS process can also be used to increase the proportion of Pu-239 in plutonium for use in nuclear weapons. For the separation of Pu isotopes, copper-vapour and dye lasers are used. The dye laser is tuned to a slightly different frequency. There are also some differences in the techniques in the separator unit and the method of collecting the separated Pu isotope.

An AVLIS commercial-scale enrichment plant may be in operation in the USA by the late 1990s. The first major industrial scale application will be the production of low-cost enriched uranium for fuel for nuclear-power reactors. But the plant it could also be used to increase the proportion of Pu-239 in reactor-grade plutonium for use in nuclear weapons.

LIS research and development activities are also underway in Russia, France, Japan, Germany, the UK, Israel, China, Brazil, India. The use of LIS systems capable of separating plutonium isotopes and enriching uranium will require the development of more sophisticated safeguards technologies and methods. The spread of LIS technology has serious consequences for the proliferation of nuclear weapons.

2.4.7 The regional security consequences of the use of MOX fuel

Any country operating reactors - power or research - will build up a cadre of trained nuclear scientists and engineers which could be employed to design and fabricate nuclear weapons. Nuclear-power reactors or large research reactors could be used to produce plutonium which could be used to fabricate nuclear weapons. A country's 'civil' nuclear programme is, therefore, a measure of its capability to produce nuclear weapons.

The use of MOX fuel will encourage the proliferation of nuclear weapons. The most sensitive activity insofar as nuclear-weapon proliferation is concerned is plutonium reprocessing. The use of MOX fuel requires large-scale reprocessing and, therefore, makes more likely the spread of nuclear weapons.

If a country uses MOX to fuel its nuclear-power reactors, or some of them, it will have a supply of weapon-usable plutonium on its territory. Japan, for example, is accumulating an increasing amount of plutonium, thereby acquiring a growing capability to produce nuclear weapons.

Countries acquire nuclear weapons for a number of reasons. The most important are to solve real or perceived security needs and prestige. There may also be a 'domino' effect; if one country acquires nuclear weapons, then neighbouring ones will feel obliged to follow suit. Political leaders may also want nuclear weapons for internal political reasons, to boost their domestic prestige or to distract the attention of the population from internal social or economic problems.

The acquisition by Japan, for example, of the capability to build nuclear weapons may be one of the reasons why North Korea initiated a programme to make its own nuclear weapons. It may also encourage South Korea eventually to initiate a nuclear-weapon programme.

Nuclear weapons, or the option to manufacture them rapidly, are perceived by some political leaders to add to the prestige of a country within its region. Any competition between China and Japan for hegemony in the Asia-Pacific region will,

therefore, be affected by the nuclear status of the two powers. Consequently, China is likely to feel obliged to react to a growing Japanese nuclear capability by, for example, increasing the size of its nuclear arsenal.

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Chapter 3
Safety Aspects of MOX Use in LWRs

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It is often stated by the MOX-use advocates that, since plutonium is produced and partially consumed in uranium dioxide (UO_2) fueled light water reactors, burning MOX in LWRs basically designed for UO_2 fuel does not pose any major safety problem. For example, the Advisory Committee on Reactor Safety Standards of Japan's Nuclear Safety Commission (NSC) states in its May 1995 report, which is generally regarded to have given the "go ahead" in regard to safety to Japan's MOX use in LWRs[ACRSS 1995]:

> "Even in a UO_2 fueled LWR, plutonium produced during operation contributes cumulatively to a total of about one third of fissions, and when seen at a fuel cycle end, the contribution of plutonium is generally more than that of uranium. This means that plutonium is already used *de facto* in LWRs and utilizing plutonium fissions in LWRs does not constitutes any new problem."

It is also frequently claimed that worldwide experiences of MOX use in LWRs already serve as a guarantee for the safety of LWR MOX use[AECJ 1994].

> "Use of MOX fuel in light water reactors have been widely tried and proven abroad, and considering that in Japan, good results regarding fuel behavior and other parameters have been obtained in demonstration programs with small quantities, it is fair to say that there are no particularly serious technological problems standing in the way of use of MOX fuel in present light water reactors in Japan as well."

But these claims are lopsided and misleading. The nuclear properties of plutonium isotopes are very much different from those of uranium isotopes. In addition there are no small differences of chemical and physical properties between UO_2 and MOX. While in a typical UO_2 fuel of up to 30,000-40,000 MWd/t burn-up, plutonium accumulation in the fuel is 0.8-1.0 per cent after the end of a usual fuel cycle (see Fig. 1-1 in Chapter 1), the plutonium content of a fresh MOX fueled core can be an order of magnitude higher than that (5 to 10 %, or even higher). Burning of this high plutonium content fuel in LWRs should be of major safety concern in respect of

reactor physics.

Even the NSC's advisory Committee report mentioned above points out the basic differences in nuclear characteristics, physical-chemical properties and irradiation behavior and admits the necessity to take the differences into account in reviewing the safety of MOX use[ACRSS 1995].

The number of MOX fuel assemblies used represents only less than 0.2 % of the total LWR fuel assemblies and this can hardly be considered to be a good safety assurance in view of the fact that even UO_2-based LWRs are still posing various safety problems worldwide.

In addition there are safety concerns arising from the more hazardous radiological properties of plutonium isotopes as compared to uranium isotopes. Furthermore, as already mentioned in Chapter 1, the much complicated transports and fuel chain activities associated with MOX use in LWRs raises new safety problems.

The purpose of this chapter is to present a general idea of what new problems would arise from MOX burning and introduction of MOX fuel into nuclear fuel cycle, as compared to once-through burning of UO_2. Our intention is not to go too much into technical details, but to try to clarify what are the important safety problems introduced by MOX use and what additional risks should be taken into consideration if a society adopts the MOX use option as the fuel chain/energy policy. Our emphasis is thus the safety issues of MOX use as seen qualitatively from its impact on the society, but we will also deal some quantitative aspects concerning the analysis of accident consequences of a MOX fueled reactor as this may be of importance for social impact assessments. Further considerations relevant to the safety will be given by two contributors in the Annex-2 concerning reactor physics and transportation of MOX.

3.1 Safety-Related Properties of MOX as Compared to UO_2

3.1.1 Fabrication of MOX and physical-chemical properties

Usually prepared pure PuO_2 is chemically very stable and difficult to dissolve in nitric acid. So the first generation MOX fuel presented significant difficulties in reprocessing. But the MOX fabrication industry claims that it has overcome this solubility difficulty[1]. The basic procedure for preparing MOX is to mix UO_2 and PuO_2 powder intensively to produce a virtual UO_2-PuO_2 chemical compound, called often a master blend, which will then be subjected to plutonium enrichment adjustment by

1. The ease of dissolving raises, however, a security problem, because MOX can be more easily subjected to further chemical procedure to produce weapons-usable plutonium metal.

diluting with UO_2 for use in reactor[2]. The adjusted powder is compressed and sintered to form pellets, which are then packed to fuel rods (pins) and finally assembled into fuel assemblies[MacLeod and Yates 1993; Krellmann 1993; Haas et al. 1994; T. Mishima 1995].

One of the important differences of MOX as compared to UO_2 is lowering of melting point. According to the observations by Lyon and Baily[Lyon and Bailey 1967], the melting point of UO_2-PuO_2 lowers nearly proportionally to the PuO_2 content from the 2840 C for pure UO_2 to 2390 C for pure PuO_2, indicating that a lowering of 20-40 degree could result for MOX of typical plutonium content. A further lowering could be realized at higher burn-ups[Anderson et al. 1985]. Although this level of melting point lowering, though not desirable, may not be serious in general, the effect when combined with other adverse effects could be of significance in some transient situations.

It is also known that the thermal conductivity of MOX fuel decreases systematically with increasing plutonium content[Gibby 1971]. While the extent of decrease is also not large, this could have a significant adverse effect on the thermohydraulic behavior of reactor core under some critical conditions.

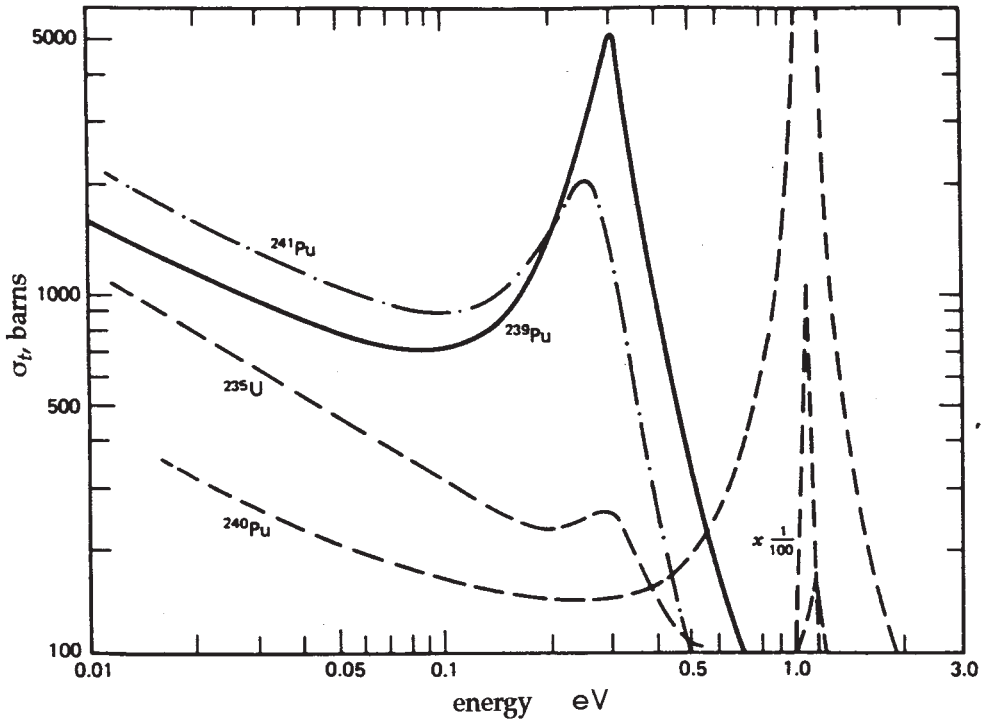
There are some other changes in physical-mechanical properties such as Poisson's ratio and Young's modules, which are however, beyond the scope of this report. One thing which deserves mentioning is increase of fission gas release from MOX fuel as compared to UO_2 and the effect becomes remarkable with high burn-ups[Goll et al. 1993; Blanpain et al. 1994; Haas et al. 1995].

3.1.2 Nuclear characteristics of MOX fuel

The nuclear properties of plutonium isotopes are very much different from those of uranium isotopes. The nuclear reaction characteristics --neutron reaction cross sections-- of uranium-235 and major plutonium isotopes are illustrated in Fig. 3-1 [Graves 1979]. The remarkable differences in neutron induced-nuclear reaction behavior (i.e. fission and capture) of Pu-239, -240 and-241 as compared to U-235, resulting mainly in the following changes of safety concern in MOX-based core:

-*Reduction of neutron absorbing capacity (control rod worth) of the control rods* : this is due to the high neutron absorption of MOX fuel at low neutron energy, which makes the averages energy of neutron in the core higher and thus more difficult to be absorbed by the control rods. Owing to the same reason, the boron worth--the neutron

2. The MOX preparation techniques are different from company to company and called in different acronyms: MIMAS for Belgonucleaire process, OCOM-AUPuC for Hanau process, SBR for Sellafield process and MH method for Tokai, PNC. We do not deal with the details of these processes, but detailed descriptions can be found in the references[Haas et al 1994; Krellmann 1993; Lyon and Bailey 1967; Mishima 1995].



H.W. Graves, Jr.:Nuclear Fuel Management, John Wiley & Sons, 1979

Fig. 3-1 Absorption Cross Section of U-235 and Plutonium Isotopes

absorption ability of boron which is introduced in the coolant of PWR to control reactions and also in BWR in case of emergency, is decreased. Because of this change in neutron absorption, it is usually necessary to avoid placing control rods close to MOX-fuel assemblies and this is the main reason to limit loading of MOX fuel to one third of the originally UO_2-based core.

-Making certain reactivity coefficients more negative at low plutonium enrichment the reactivity coefficient is a parameter related to the degree of changes of fission reaction rates--reactivity (hence power output) responding to various changes introduced to the core; there are a number of coefficients related specifically to the Doppler effect of fuel, voids in the coolant, temperature of moderator(water), temperature of fuel etc. The negative increase of the void coefficient poses a specific safety problem in a void collapsing transient in a BWR, while a more negative moderator temperature reactivity coefficient could be a safety concern in a PWR under certain transient conditions. These will be mentioned in the next section.

-Increased peaking of power Due to intense absorption of thermal neutrons by plutonium, there is a tendency that an irregular power distribution results inside the core, producing in particular a large power peak at the UO_2-MOX boundary, especially at the water-MOX fuel interface. The effect is usually mitigated by adopting special core configurations with multiply-graded plutonium enrichment levels in a fuel

assembly, which results however in a very complicated fuel fabrication / assembling process and thus any confusion in the process could be a safety concern [Gouffon and Merle 1990].

-*Reduction of delayed neutron fraction* : This is a technically important issue which is dealt with in R. Donderer's contribution in Annex 2 of this report. But a short description of the problem at this point may be useful. There are two kinds of neutron emission: prompt emission and delayed emission. Prompt neutrons which are emitted directly from fissioning nuclei constitute the major fraction (99.3 % or more) and have a very short life time of less than l micro second, while delayed neutrons are emitted in the course of radioactive decay of short-lived fission products with a delay time of a few tenths of a second to several tens of second. Although the fraction of delayed neutron is around 0.7 % or less, the control of chain reactions in a core with the use of mechanically-driven control rods can only be achieved by using the delayed neutrons effectively. The delayed neutron fraction of Pu-239 is about one third of U-235, making the control more difficult, particularly for plutonium with high Pu-239 isotopic content.

-*Hardening of neutron spectrum*: as mentioned above the nuclear property of plutonium isotopes makes the average neutron energy in the MOX-fueled core shift to higher energy region. This effect is called hardening of the neutron spectrum. The possible consequence of this result is "to increase the rate of radiation damage(by fast neutrons) to structural materials in and around the core, which can bear on the operating lifetime of these materials and, in some circumstances, on safety" [NAS 1995].

3.1.3 Radiological properties

As already mentioned in Chapter l, the plutonium is in general radiologically a very hazardous substance and even the fuel material used in unirradiated MOX fuel poses serious risks that would never be met in fresh uranium fuel. The irradiated MOX fuel presents additional radiological risks as compared to irradiated UO_2 fuel due to increased contents of plutonium and other transuranic nuclides.

Three aspects of radiological risks should be taken into consideration:

-*Internal exposure to plutonium and other transuranic isotopes* : We have mentioned the radiological toxicity and hazard caused by internal exposure due to intake of plutonium, particularly the inhalation hazard. Attention has been paid also to the increased toxicity of reactor grade plutonium as compared to pure Pu-239. The inhalation hazard will be of special concern for workers in MOX fabrication facilities and for the general public in case of a major plutonium release accident of a plutonium-related facility like a MOX-fueled reactor. The latter case will be treated quantitatively later in this Chapter.

-*External exposure to gamma rays from Am-241* : MOX fuel also radiates gamma radiations which contribute to external radiation exposures mainly of MOX facility workers. One of the major sources of gamma radiation is Am-241, which is a decay product of 14.4 year Pu-241. Since usual reactor grade plutonium contains 10-15 % Pu-241, about 0.5 to 0.7 % of the total plutonium transforms to Am-241 per year resulting in increased gamma ray emissions. Therefore the gamma ray dose rate from the surface of a separated plutonium sample increases with the time period after the reprocessing due to accumulation of Am-241, but decreases with the time period prior to reprocessing due to decay of Pu-241. A calculation of the change of gamma ray dose[Kueppers and Sailer 1994] is shown in Table. 3-1.

-*Neutron radiation* : Emission of fast neutrons from MOX is also of safety concern because the high energy (fast) neutron is one of the most hazardous ionizing radiations. Plutonium emits neutrons through two different processes; the neutron emission associated with spontaneous fission of isotopes of even mass numbers (Pu-238, Pu-240 and Pu-242) and the (alpha, neutron) reactions of alpha particles from decay of plutonium isotopes on light elements like oxygen. For a typical MOX fuel, the neutrons from spontaneous fission of Pu-240 and from (α, n) reactions of Pu-238 alpha particles are most important. Table 3-2 shows an estimate of neutron emission for plutonium with a typical reactor grade isotopic composition.

Table 3-1 Dose Rate from X and Gamma Radiation from Am-241 in Plutonium

Dose rate at the surface of a 1 kg metallic plutonium sphere of reactor grade (in mSv / h)

	Storage time after reprocessing (years)				
Period prior to reprocessing(years)	1	2	3	4	5
2	308	484	651	812	964
3	299	466	627	778	923
5	283	435	580	719	852
7	268	407	540	664	803

Table 3-1 suggests that a PWR MOX fuel assembly containing about 20kg of plutonium emits about 10^7 neutrons per second, which could be of health concern to workers handling the MOX fuel even under shielding. Neutron emissions from irradiated MOX fuel is much higher.

Table 3-2 Neutrons from Reactor Grade Plutonium*

Pu isotope	content(%)	neutrons /gPu /sec	surface dose of 1kg Pu sphere (mSv/h)
Pu-238	1	(α, n):140 SF:30	66
Pu-239	55	(α, n):25	9
Pu-240	22	(α, n):37 SF:220	82
Pu-241	15	_	(beta:18)
Pu-242	7	SF:119	22
Total		571	180(+18)

* Estimated with reference to [NRC 1976] and [Swahn 1992].

3.2 Reactor Safety Aspects of MOX Use in LWRs

3.2.1 Summary of key factors affecting reactor safety

We have given a general overview of characteristic changes which the introduction of MOX would entail in regard to MOX--related industrial activities. A few more considerations may be helpful at this point to understand the risks associated with the operational safety of a LWR fueled up to 1/3 of core with MOX.

Most of the changes mentioned above such as, lowering of melting point, decrease of heat conductivity, decrease of control rod worth, increase of absolute values of certain reactivity coefficients, reduction of delayed neutron fraction and hardening of neutron spectrum might not give rise to any serious safety problem in the operation of a light water reactor, as long as each effect appears separately. But the question remains open whether several factors combined could appear and significantly affect the operational safety margin under certain unfavorable conditions and could, in the worst case, lead to severe accidents which would have been avoided in a UO_2 core.

The only public assurance supporting the safety of MOX use in LWRs is that "many" fuel assemblies were already used in Europe without significant safety

problems. We do not have for the moment any means to affirm or negate this claim, but granted this is true, total number of MOX fuel assemblies used (around 1600 by the end of 1996 worldwide and only 6 in Japan[ACE 1997]) would not be a good assurance in view of the fact it is less than 0.2 per cent of the total fuel assemblies used in LWRs worldwide and LWRs nevertheless continue to represent a significant safety concerns worldwide. MOX use will certainly add new elements to these concerns.

It should also be pointed out that there are still considerable uncertainties in the safety evaluation of MOX burning in light water reactors in the case of high MOX loading portion and at high burn-up[MOXFRG 1993] (see also Annex 2-a).

Another aspect worth considering is the irradiation behavior of MOX fuel. While there are abundant experiences in fabricating and using UO_2 based PWR and BWR fuels and the industry claims that much of the initial troubles with UO_2 fuel and fuel claddings like cladding failure, deformations and pellet-clad interactions (PCI) have now been solved, we do not think that the experiences with MOX fuel is enough to assure a similar level of performance.

As easily conceivable, physical-chemical irradiation behavior of MOX fuel is not quite equal to UO_2 due, above all, to the facts that plutonium has much higher possibility (cross-section) of fission and neutron capture reactions and that alpha particles from decay of plutonium isotopes will accumulated in MOX.

One area of concern is inhomogeneity. Even in MOX, prepared with the state-of-the-art technology, PuO_2-UO_2 tends to exist rather inhomogeneously as agglomerates surrounded by UO_2 matrix in a fuel pellet and the local burn-up of the agglomerates enriched in plutonium are usually much higher than the fuel-averaged typical burn-up of 30,000-40,000 MWd/t. This inhomogeneity along with the change of physical-chemical properties of MOX after irradiation tend to make the safety features of the fuel deteriorate. We have already mentioned the effect of increased fission gas release but release of non-gaseous radionuclides like cesium can also be enhanced[Walker et al. 1991].

While the fission yields of fission products of Pu-239 fission are somewhat different from those of uranium, the total beta-gamma radioactivity of spent MOX fuel is said not to be significantly different from that of UO_2[Thomas 1992] and we have not taken the difference specially into consideration in our accident analysis. But increase of production of certain nuclides like iodine isotopes and tritium may be of some safety concern. Also the increased long lived actinides would exacerbate the radioactive waste management problems.

It could also be argued that the MOX fuel would behave differently in a reactivity

accident[3] and that the fuel might be destroyed below the designed UO_2 enthalpy limit due to power peaking at the pellet surface[MOXFRG 1993].

To summarize this section, there are quite a few adverse factors affecting the safety of MOX fueled reactors. Factors considered relevant to operational safety are listed in Table 3-3 below.

Table 3-3 Safety Related Characteristics of MOX as Compared to UO_2

Characteristic Item	Change from UO_2	Effect
Physical-Chemical		
Melting point	Lowers by 20-40 C	Adverse effect
Heat conductivity	Decreases	Adverse effect
Fission gas release (Non-gaseous element release)	Increased release (possible increase)	Adverse effect (cesium and some others)
Nuclear		
Fission/absorption cross section	Larger: strong resonance above thermal energy	Reduced control rod/boron worth
Power peaking	Increased peak ratio	Complicated MOX rod configuration needed
Reactivity coefficient	Change of absolute value	
At low Pu enrichment:		
Doppler coefficient	More negative	More rapid reactivity change in case of transient;reduced reactor shutdown margin
Void Coefficient	More negative (BWR)	
Moderator temperature coefficient	More negative (PWR)	
Fission yield and actinide production	Increased iodine, tritium and actinide production	Increased hazard in accident
Decay heat	Increased(moderately)	Negative effect on residual heat control and long term waste management
Delayed neutron fraction	Reduced fraction	Difficulty in reactor control
Prompt neutron	Shorter life time	Difficulty in reactor control

3. When a large reactivity is inserted to fuel in a RIA(reactivity insertion accident), the fuel would be fragmented to create a pressure wave. According to the Japanese Guideline for Evaluation of Power Reactor Reactivity Accident, the enthalpy threshold for the generation of pressure wave caused by fragmentation of fuel is set to 230 cal/g. This value maybe lower for MOX.

3.2.2 BWR specific problems and credible accident scenarios

Given the general problems of MOX fuel as mentioned above, we have to step further to question what are the possible crucial safety problems for BWR and PWR operation and control.

For a BWR the key factor threatening the safety is considered to be above all the increase of the absolute value (becoming more negative) of the void reactivity coefficient of coolant (water), which has the potential to make the change of reactivity dangerously sharp under certain conditions. The voids (steam bubbles) in the core of a BWR decreases the fission reaction rate because slowing down of neutron energy by the moderator (water) is reduced. If the void reactivity coefficient becomes more negative, the rise of power due to decrease (or collapse) of voids becomes sharper.

The following may be the typical BWR transients where change of void reactivity coefficient due to introduction of MOX fuel might worsen the transient situations.

Feedwater transient

Loss of feed water heating or malfunction of feedwater control valve may lead to power rise due to reduced coolant temperature (the co-called increased subcooling), which would be enhanced by use of MOX fuel. But the effect may not usually be serious.

Recirculation flow transient

Increase of recirculation water flow due to malfunction of flow control valve or inadvertent start-up of a recirculation pump increases the reactor power (inserts positive reactivity) because it pushes the voids in the primary coolant out of core. This effect is serious even in UO_2-based core under certain circumstances and MOX introduction exacerbates the transient situation.

Main steam-related transient

A transient directly related to blocking of or reduction in the main steam line would be one of the most serious transients in a BWR which could lead to power excursion in case, for example, the control rods fail to respond rightly. The disturbance of main steam flow can be caused by a turbine trip or erroneous activation of the main steam isolation valve (MSIV). In either case, the closure of MSIV leads to a pressure surge in the UO_2 based reactor core, collapsing the voids and hence resulting in a rapid power increase.

In the usual reactor transient/accident scenario for a licensing safety review, a power excursion would be prevented by an adequate functioning of control rods and pressure relief valves, but questions remain whether proper functioning of control rods could always be assured[Webb 1976]. As there seems to be no publicly available

report specially dedicated to this type of transient with MOX-based core, while it might probably be a transient that would be most seriously affected by introduction of MOX, let us consider here the possibility of the transient developing into a severe accident.

Let us consider a typical transient event caused by a turbine trip. According to a typical transient analysis for a UO_2 fueled 1,100 MWe BWR (Kashiwazaki-Kariwa 1)[TEPCO 1975], the severest situation arises when a turbine trips at a power level of 30 % or more with the functioning of the turbine bypass valve failed. The analysis states that the power rises to 186 % of the rated power in about 0.7 sec due to reactor pressure rise and subsequent collapse of voids, but then falls down quickly due to the effect of control rods insertion actuated by the main steam valve position signal. The safety guarantee by this rapid functioning of control rods is questionable even for UO_2 core[Ito 1990]. But, even if the functioning of control rods is assured, replacement of, say, one third of UO_2 fuel with MOX containing 4-6 % plutonium, could be fatal because it could make the void coefficient up to 20 per cent more negative, which would result in insertion of additional reactivity of up to 1 dollar (reactivity equal to delayed neutron fraction) and could lead to power excursion.

The estimate above involves uncertainties because we do not have the full information on details of various parameters. It can be justified , however, to state at least, that there are uncertainties large enough to raise well-based safety concerns over MOX fueled core particularly in regard to response to transient changes.

3.2.3 PWR specific problems and credible accident scenarios

For the operation and control of a PWR, the kinds of transient events most relevant to safety are those caused by insertion of reactivity due to change in the primary coolant density, temperature and pressure. These includes sudden introduction of cold coolant into the core by an inadvertent operation of a primary coolant pump or valve in the steam lines, and abnormal pressure reduction in the primary or secondary coolant system caused by erroneous operation of a valve such as the pressurizer relief valve, or by malfunction of a steam generator. These transient situations would be worsened by insertion of a larger reactivity due to more negative coolant temperature coefficient of MOX.

Perhaps the most serious of such events would be the main steam pipe rupture accident. According to a typical accident analysis of a 1,180 MWe PWR(Ohi 3 and 4)[KEPCO 1985], the severest situation will result when a main steam pipe ruptures under the reactor's hot shut down state, where the largest reactivity insertion occurs due to rapid cooling of the core. For a UO_2 core, the analysis suggests that a return to criticality occurs due to insertion of positive reactivity with the power rising to 21 % of the rated value, but the reactor will then be cooled down by the action of borated emergency coolant injection. While MOX fuel will surely worsen the situation with a

larger response to rapid cooling of the core, we do not have sufficient information again to make a more qualitative analysis of the transient. It can be said, however, that the reactor shutdown margin is substantially reduced because of the large negative coolant temperature coefficient.

3.2.4 Other transient and accident cases

There are yet other transient and accident cases of light water reactors which would be affected adversely or at least cause uncertainties which might work in the direction of increasing the accident possibilities and accident consequences. Among these are fuel drop accident, fuel withdrawal accident and loss of coolant accident.

Furthermore, in the transient conditions mentioned above, the decreased heat conductivity and lower melting point would adversely affect fuel behavior. Further argument on reactor safety implications of MOX fuel will be found in Annex 2-a.

While it could be argued that replacement of UO_2 by MOX would contribute to better performances in some safety-related features, nevertheless negative effects and uncertainties introduced by MOX should also be given due weight in a safety review of MOX fuel.

3.3 Assessment of Severe Accident Consequences of MOX-Fueled Reactor

In view of the fact that non-negligible additional risks and uncertainties in safety would be introduced by a MOX-based reactor core, an assessment of consequences of major accidents has been conducted both for a BWR and PWR by assuming release of plutonium and MOX-associated actinides (americium and curium isotopes). This is believed worthwhile, particularly because Japanese authorities have decided that the applicants of relicensing for MOX use in LWRs do not need to assume release of plutonium in their assessment of accident consequences in relicensing application. This "MOX-LWR exempt" is a very controversial decision, because the Japanese Nuclear Safety Commission's Guideline for Plutonium Dose for Siting of Plutonium Fueled Reactor (hereafter Pu Reactor Guideline) stipulates that an assessment of dose due to internal exposure to plutonium should be done in the siting assessment of a "plutonium-fueled reactor". The word "plutonium-fueled reactor" is somewhat vague, but there is no further definition in the text, and it should be applied, from the literal reading of the guideline, to every MOX-fueled reactor including the LWRs, needless to say of fast breeder reactors. The guideline was indeed applied, although without the appropriate degree of commitment to Monju.

Therefore we have conducted assessments of accident consequences assuming release of significant amounts of plutonium and associated actinides, and calculated the internal exposure dose due to inhalation of isotopes of these nuclides in addition to doses by fission products by using standard LWR simulation schemes. The results have then been compared to accident consequences of similar type accidents of a UO_2 based BWR and PWR in order to assess any additional health and environmental effects caused by the use of MOX fuel.

3.3.1 Accident assumptions

Fuel and reactor data

Estimation of actinide production was essentially based on Wiese's calculation for the fuel M2[Wiese 1993]. Isotopic composition of plutonium for fresh fuel and the fuel inventory data used for the calculation are given, respectively in Tables 3-4 and 3-5.

Table 3-4 Isotopic Composition of Plutonium in MOX

Nuclide	percent(wt)
Pu-238	1.8
Pu-239	59.0
Pu-240	23.0
Pu-241	12.2
Pu-242	4.0

Table 3-5 Fuel Data Used for Calculation

	BWR	PWR
Power Output	1,100 MWe	1,180 MWe
Fuel Inventory	132 tHM	86 tHM
Fraction of MOX	1/3	1/3
Puf enrichment	2.6 %	4.0 %
Put core 1st load	1.58 t	1.63 t
Put content(total core-averaged)	1.2 %	1.9 %
U-235 in uranium	0.25 %	0.25 %

(HM: heavy metal)

Accident scenarios and radioactive releases

The calculation of air-borne spread of radionuclides from the reactor and resulting residents' exposure doses was made by applying basically the methodology of WASH-1400[NRC 1975], assuming the following accident types and meteorological conditions for BWR and PWR (Table 3-6). The calculation of dispersion is essentially based on the usual Pasquill's model. The accident types chosen, namely BWR-1 and PWR-2 of WASH-1400 are those in which largest release of refractory elements like plutonium would be expected.

Table 3-6 Accident Assumptions

	BWR(1,100MWe)	PWR(1,180MWe)
Accident type	BWR-1*	PWR-2#
Height of release	200 m	200 m
Pasquill stability	D	D
Wind speed	4.0 m/s	4.0 m/s
Spread of plume	15 degrees	15 degrees

* BWR-1 type accident in WASH-1400

The core cooling systems including the ECCS (emergency core cooling system) fail and the core melts down. The molten core falls to the reactor bottom and reacts with remaining water to cause a steam explosion. The containment is ruptured and a substantial amount of molten fuel is ejected into the atmosphere. The duration of release is here taken to be 30 minutes instead of WASH-1400's 2 hours for BWR-1 type accident in order to assume a sustained plume angle of 15 degrees. A fuel burnup of 40,000 MWd/t at the time of the accident is assumed for source term calculation for a third of core loaded with MOX.

The WASH-1400 values of release of main fission products for various fission products groups (fraction of core inventory):
Rare gases: 100 % ; Te:70% ; I, Ru:50 % ; Cs: 40% ; Sr:5.0 %;
lanthanides(including actinides):0.5 %

#PWR-2 type accident in WASH-1400

The core cooling systems fail and the core melts down. The containment spray and residual heat removal systems also fail, and the failure of the containment barrier occurs through the overpressure causing a substantial fraction of the containment

atmosphere to be released in a "puff" from containment. The assumed fuel burn-up at the time of accident is also 40 MWD/kg (a third of core loaded with MOX).
Assumed releases: Rare gases:90 % ; I:70% ; Cs:50% ; Te:30% ; Sr:5.0% ;
lanthanide (including actinides) :0.4%

Release of actinides

Radionuclides of actinides which are relevant in terms of health effect are plutonium isotopes, Am-241 (alpha emitter, 433 y) which is mainly a decay product of Pu-241 and curium isotopes Cm-242 (alpha emitter, 163 d) and Cm-244 (alpha emitter, 18.1 y). Release of 4 % of the total core inventory[4] was assumed for these isotopes as the initial assumption. This results in release of 67 and 69 kg of Pu tot, respectively for the BWR and PWR accidents assumed.

The assumed release fraction of 4 % may be regarded as too high in the light of WASH-1400 figure of 0.4-0.5 % for actinide release. A severe accident in a MOX fueled reactor is, however, likely to involve a large reactivity insertion, thus leading to serious fragmentation and partial atomization of the fuel mass, where a larger fraction of actinides could be released into the environment. Indeed in the case of the Chernobyl accident which was a power excursion, the estimated release percentage was 4 % for plutonium[USSR-SCUAE 1986] and a German official risk study also postulates 4% release for plutonium and other actinides[GRS 1990]. A much higher release could be expected under certain hypothetical conditions[Kueppers and Sailer 1994]. Therefore, we adopted the value of 4 % as our initial assumption in order to get the maximum credible consequences of plutonium and other actinide release from a MOX fueled reactor. Calculations were also conducted for different actinide release fractions and results are compared.

Evaluation of internal exposure dose due to plutonium inhalation

For the assessment of radiation doses due to plutonium, the doses from inhalation of aerosol particles to bone surface, lung, liver and effective dose resulting from these organ doses are important. Therefore, the calculation of these internal exposure doses were performed in accordance with the dose assessment model provided in the current Japanese Guidelines for Plutonium Dose mentioned above, which is based on ICRP Publication 30. While new models for metabolism of actinides and therefore new dose coefficients for intake have now been recommended in recent ICRP publications (ICRP Publications 61[ICRP 61] and 68[ICRP 68]), we have based our calculation on the ICRP 30 dose coefficients because they are still effective legally in Japan and many

4. Core inventory values of actinides calculated for 40,000 MWd/t fuel burn-up (ref. [Wiese 1993]) were used as base data for the present calculation with adaptation to 1/3 MOX core and with necessary corrections for decay.

other countries.

Results of dose calculations

The results of whole body dose[5] estimations are plotted in Fig. 3-2(a) 1,100 MWe BWR and in Fig. 3-2 (b) for 1,180 MWe PWR as a function of distance from the reactor. The upper curve of each figure corresponds to the MOX-fueled core case, while the lower one to the UO_2 based core case. The difference of two curves is solely due to whole body dose commitment by inhalation of actinides.

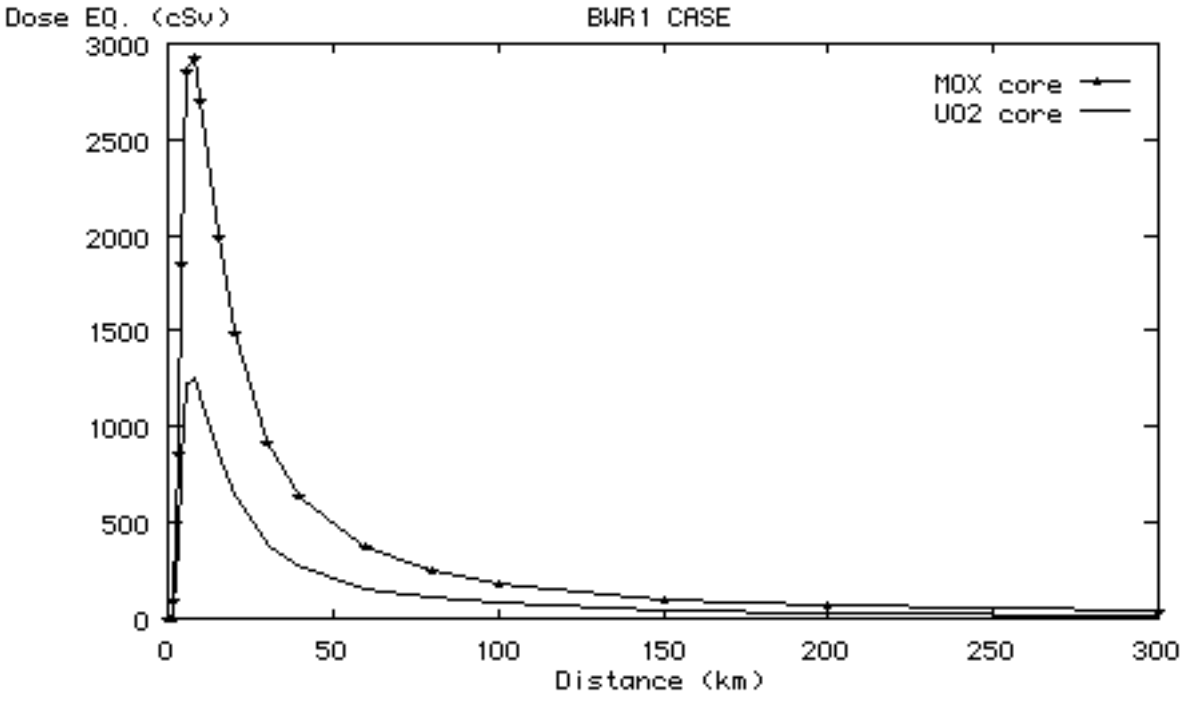
While the distance-dose curve showing the consequences of major reactor accidents such as the assumed BWR-1 and PWR-2 are already catastrophic even for UO_2 fueled reactors, the results clearly shows the marked effects of actinide release in MOX-fueled reactor accidents. For the same distance from the reactor, the dose is generally 2.3 -2.5 times higher in the case of MOX based reactor, implying that health effects of the radioactive release would increase by the same factor.

Implications of dose evaluations

The implications of the dose evaluations shown in Fig. 3-3 may be better understood by comparing distances of various dose levels as listed in Table 3-7 below. The distances of various impacts on human health increases with the use of MOX fuel by 80 to 100 % as can be clearly seen in the Table 3-7. The increase in distance means that the actual increase in social impacts would be 3.2 to 4 times higher if the social impact is assumed to be proportional to the affected area, since the area is proportional to the square of the distance. Furthermore, the real impacts are likely to be far more serious than that, because with extended distances more densely populated urban zones could be included.

5. While the word dose is simply used throughout this work, the calculated dose is, strictly saying, the committed dose equivalent (50 years) unless otherwise stated.

Fig.3-2 Whole Body Dose Due to LWR Accident



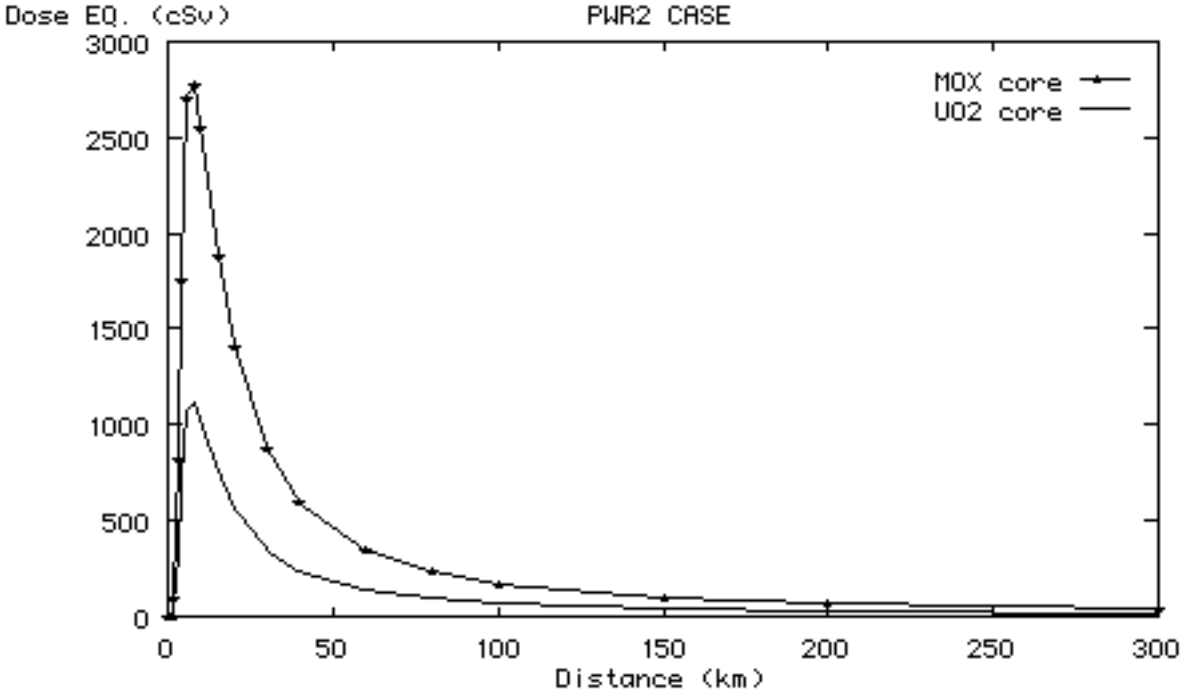


Table 3-7 Significant Dose Levels and Distances

Dose equivalent (cSv)	Distance (km)		Distance (km)	
	BWR(UO_2)	BWR(MOX)	PWR(UO_2)	PWR(MOX)
600 (100% lethal)	22	43	19	40
300 (50% lethal)	38	72	34	69
100	84	154	76	148
25 (exclusion area)	225	395	196	382
10 (evacuation zone)	400	730	366	683
5 (annual dose limit for occupational exposure)	617	1133	573	1072

To illustrate the effect, let us imagine accident scenarios in Japanese LWRs. If we assume that the accident occurs at TEPCO's Fukushima II-4 BWR (1,100MW) which is considered to be a candidate for MOX use and the wind direction is towards Mito and Tokyo (SSW), the population inside the 100 cSv (centi-Sievert=rem) dose zone increases with the use of MOX by as much as factor 3.7 (from 410,000 to 1,500,000). The increase would be of very serious social concern, since 100 cSv dose commitment (50 years) could certainly have various adverse effects on human health (acute injuries, later death etc.) and the society. If the accident occurs at TEPCO's Kashiwazaki-Kariwa-1 (1,100MWe) which is also a candidate for MOX use and the wind blows towards Maebashi and Tokyo (SSE), the affected population due to MOX use in the same radiation zone is larger by an order of magnitude as compared to UO_2 use (2,500,000 as compared to 220,000). These striking increases are due to the fact that the extended areas now include the densely populated cities in the suburbs of Tokyo.

As a PWR example, let us imagine an accident at KEPCO's Ohi 4 (1,180MWe) which is also a candidate for MOX use. If the wind blows southward (in the direction of Kyoto and Osaka), the affected population inside the 100 cSv zone increases by as much as factor 5.1 from 2.0 million to 10.3 million. It should be noted that in this Ohi accident case, the 100 cSv zone population is already 2 million for an assumed UO_2 core accident because the zone includes big cities like Kyoto and Takatsuki and increases to more than 10 million because of Osaka and neighboring urban areas being also affected.

It might be argued that the accident scales assumed is too big to be realistic. The

WASH-1400 probability estimates are 9 in ten million and 5 in a million, respectively for BWR-1 and PWR-2. These probability values of WASH-1400 are, however, highly questionable. It can also be argued from the analysis presented in this chapter that the accident probability would be increased by introduction of MOX fuel for certain accident sequences and therefore the assumption of severe accidents and assessment of consequences based on the assumption in the present work is meaningful for the assessment of MOX.

It should be noted that the accident scenarios are not necessarily based on the worst cases. They are chosen in order to make a comparison of accident consequences of a MOX-based core with significant actinide releases and UO_2-based core with moderate actinide release (0.4-0.5 % as assumed in WASH-1400). The accident consequences could be much more serious in case of more adverse weather conditions or for larger actinide releases.

In case of a smaller release of actinides, the impact of MOX use is naturally expected to be less significant. Even for very moderate releases of actinide of 0.5-1%, however, our calculations show that the exposure dose at a place is 1.1 to 1.5 times higher for a MOX core as compared to UO_2 core, implying that the large actinide inventories of the MOX-fueled core could worsen accident consequences significantly for any major accident scenario.

3.4 Safety Aspects of MOX Fabrication Plant

3.4.1 MOX fabrication processes and workers' exposure

In a usual MOX fabrication plant, the fabrication starts either from dry UO_2 and PuO_2 powder feed or from wet nitrate solution from which plutonium is coprecipitated with uranium as ammonium uranyl/plutonyl carbonate (AUPuC) and then converted to dry oxide.

In either case, PuO_2 and UO_2 are co-milled to form a master(primary) blend, which is further blended with free-flowing UO_2 to produce MOX powder of high homogeneity and with specific Pu/U ratio. The blended MOX is pressed/pelletized, sintered in H_2/argon atmosphere and packed into fuel rods. Most of these processes take place in an advanced MOX fabrication plant in an automated sealed glove box system that is designed to minimize risks associated with handling of large amounts of plutonium. Indeed, newly constructed automated MOX plants have reduced the radiation exposure level of workers substantially.

However, some of the processes still need manual work and there are

possibilities of workers being internally exposed to plutonium mostly by inhalation spilled from a hole of a damaged glove or packing. A more general cause of workers' exposure is external irradiation by gamma-rays. Am-241 accumulating in MOX as the decay product of Pu-241 is the main source of gamma radiation and in order to limit individual exposure to a design level of say 5 mSv/yr[Haas et al 1994], the time period from separation of plutonium in a reprocessing plant to MOX fabrication should be limited to three to five years to avoid excessive build up of Am-241[Bairiot and Vandenberg 1989]. The actual level of average individual dose experienced in European MOX fabrication plants ranges from 2 to 12 mSv per year, while the collective personnel doses lie in the range of 600 to 2,700 person-mSv per year[OECD/NEA 1993].

As an example of actual records, the collective annual personnel dose and average individual dose at the Siemens MOX Fabrication Plant at Hanau, Germany are compared in Table 3-8 with those at the UO_2 fuel fabrication plant of the same company at the same site for 1989-1992. The table has been compiled from plural sources[Krellmann 1993; Thomas 1993; OECD/NEA 1993] and it has to be noted that the figures in the table include uncertainties because some are based on reading of graphical presentations and also because some inconsistencies were identified amongst different source materials [IANUS 1996].

Despite these small uncertainties, the increased exposure level at MOX plant as compared to UO_2 plant is very significant, particularly when annual exposure is compared per ton of fuel produced. As the table shows, production of a ton of MOX fuel costs 100 person-mSv or more of the collective dose and 100 μSv or more of average individual dose, which are 50-100 times higher than the dose burden for the production of the same amount of UO_2 fuel.

Table 3-8 Comparison of Workers' Exposure Dose of MOX and UO_2 Fabrication at Siemens plants at Hanau 1989-1992

(a) Collective Annual Dose (person-mSv)

	MOX Plant			UO_2 Plant*	
year	prod.(tHM/y)	coll. dose/y	coll. dose/tHM	coll. dose/y	coll. dose/t
1989	22	2400	109	1534	1.7
1990	26	2500	96	1504	1.7
1991	13	1400	107	1342	1.5
1992	1	750	750	1117	1.3

* No yearly throughput figure was available. A throughput was assumed to be nearly equal to the plant capacity of 900 ton/y each year.

(b) Individual Average Dose (μSv / y)

	MOX Plant			UO_2 Plant	
year	prod.(tHM / y)	ind. dose / y	ind. dose / tHM	ind. dose / y	ind. dose / t
1989	22	3100	141	2240	2.5
1990	26	3300	127	2780	3.1
1991	13	950	73	1230	1.4
1992	1	400	400	1000	1.1

In other words, if we apply a risk factor value of one fatal cancer per 10 person- Sv [Takagi 1994] to the data above, one fatal cancer results from a production of 100 ton MOX which is about the annual production scale of new plants like MELOX (Marcoule, France) and SMP (Sellafield, U.K.) , while production of the same amount of UO_2 fuel creates around 0.015 fatal cancers. In this sense, the MOX fuel is an extremely "costly" fuel.

While reduction of exposure dose can be expected for the new fully automated large-scale plants, trend of burn-up increase of LWR UO_2 fuel would probably offset the reduction because higher burn-up makes plutonium more hazardous due to increased neutron radiation and increase of short-lived Pu-236 content which decays into gamma-emitting U-232.

3.4.2 Plutonium release accident in MOX fabrication plant

Accident possibilities

Among several accidental events which would provide pathways to release of plutonium to the environment, fire and criticality are considered to threaten the most serious consequences. Although a MOX fabrication plant is built mostly of fire-resisting and inflammable materials and MOX itself is non-flammable, combustible materials like glove box panels are used in the plant. Organic additives like lubricant and poreformer used in the pellet preparation process are also flammable. Waste storage facilities usually relies heavily on papers and plastics and contain also combustible solid and liquid wastes. Hydrogen gas usually used for the sintering process together with argon could also trigger a fire or explosion.

Another possible cause of fire or chemical explosion is the exothermic chemical reaction of plutonium containing solution, solvent and resin. MOX fabrication is basically a dry process, but various wet chemical reactions are also involved in a MOX

plant since plutonium is brought into the plant often in the form of nitrate solution, refuses (scraps) are treated by wet-chemistry to be returned into the process and chemical analysis are also necessary to monitor the processes. Some plants are equipped with americium extraction system. Uncontrolled chemical reactions in these wet systems could result in fire, overpressurization and explosion.

A criticality accident is perhaps the most frequently experienced severe event in plutonium processing plants, and a plutonium plant should in principle be designed to prevent the occurrence of criticality under any conceivable plant condition. There are nonetheless possibilities of criticality accidents, because the amount of plutonium treated in a full scale MOX plant corresponds to tens to hundreds of critical masses and there remain equipments and processes which can not be completely brought under designed anti-criticality control.

Typical situations which could potentially trigger a criticality excursion are excessive moderation and/or reflection by water and inadvertent excessive concentration of plutonium.

It is said that a criticality excursion of 5×10^{18} corresponding to a total energy of 40 kWh or less is a reasonable maximum credible hypothesis but this could not give serious physical consequences[OECD/NEA 1993]. 5×10^{18} fissions correspond, however, to fissions of only about 2 mg Pu-239 and a larger excursion event can well be conceived [Takagi 1991]. A criticality excursion of 10^{19} fissions would generate 2×10^{14}Bq iodine isotopes and 9×10^{15} Bq rare gases which could be of serious health concern. If the HEPA (high efficiency particulate) filters are intact, plutonium and fission products other than the rare gases can be confined inside the plant. But the possibility of the HEPA filters working inefficiently, being damaged or being involved in a fire can not be ruled out.

Other external cause of accidents like flooding, earthquake and airplane crash could also cause a major release. Various smaller release scenarios can be considered [Kling et al. 1994].

Consequences of plutonium release

The maximum credible accident case may be an explosion caused by a criticality excursion or by a large fire inside the plant. As long as the basic building structures and HEPA filters remain intact, the accident inside the plant would not result in serious consequences for the environment. But in the worst case the confinement structure of the central buildings might be destroyed thereby providing direct plutonium release to outside the plant. Alternately, filters could be destroyed or burned out if an explosion or fire were to take place not so far from where they are installed. If not destroyed, a substantial deterioration of filter efficiency due to fumes or steams could well result under severe fire/accident conditions. In such a case, up to 0.1 % of the plutonium powder under processing could be expected to be released into the environment, if we

assume that maximum 1 % of plutonium in a MOX mass becomes airborne in a fire, based on experimental observations[Mishima and Schwendiman 1973a; Mishima and Schwendiman 1973b; Kling et al. 1994], and that 10 % of it is released from a deteriorated filter system.

If 100 kg of plutonium is involved in a big fire inside the plant, then a ground level plutonium release of the order of 100 g fine aerosol particles can be expected. A calculation of internal exposure to plutonium similar to that conducted for reactor accidents in the preceding section shows that 10 cSv evacuation zone extends to 3.5km from the plant[6]. Although this consequence is far smaller than that of a major reactor accident, the result is yet of concern to nearby residents. A larger release would be expected in a bigger fire, explosion, airplane crash or earthquake which would paralyze the confinement functions of a large-scale MOX plant. A larger plutonium release accident would be expected for fire or collision accident involving MOX during transportation, which will be discussed in Chapter 6.

3.4.3 Plutonium waste from MOX fabrication plant

Scrap and waste management is a very important part of a MOX plant. The complicated powder transfer through piping, mechanical milling/blending, and grinding steps produce fairly large amount of scraps. Up to 20-30 % may result as the initial scraps which should then be recovered and recycled. But no small amount should remain unrecovered as was actually the case in the PNC's Tokai PFPF MOX fabrication plant[Usui 1994]. As much as 68 kg of scrap plutonium was found scattered inside glove boxes as "hold up" and even after extensive clean up 9.5 kg remained unrecovered [PNC 1996]. The amount is more than the significant quantity defined by IAEA of 8 kg and this case indicates that strict management of plutonium scrap and waste is extremely difficult, posing the security problem as discussed in Chapter 2.

The waste and scrap also pose safety concern. Treatment of scraps and waste including the cleanup process would result in increased workers' radiation exposure. Plutonium wastes contained in plastic bags and used gloves are flammable and could catch fire to release plutonium aerosols. Furthermore, the whole process of scrap treatment comprises very complicated chemical procedures, an example of the CFCa plant at Cadarache being shown in Fig.3-3[Haas et al. 1994].

What are the final volume and amount of plutonium-contaminated waste from a MOX plant? According to the DEMOX (Dessel MOX Plant) statistics[Haas et al. 1994], the plant produced in total 724 fuel assemblies (111,788 rods) by July 1, 1993 and the following wastes were produced (Table 3-9).

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6. This estimation is for reactor grade plutonium reprocessed 4 years after discharge from a reactor and decayed further for 3 years before and during the fabrication.

The volume of solid and liquid wastes are not small in view of the fact that they are contaminated with significant amounts of plutonium. This waste plutonium could be a source of worker's radiation exposure, leakage and accidental release as well as an object of security concern.

Fig. 3-3 MOX Scrap Treatment Flow at CFCa Plant

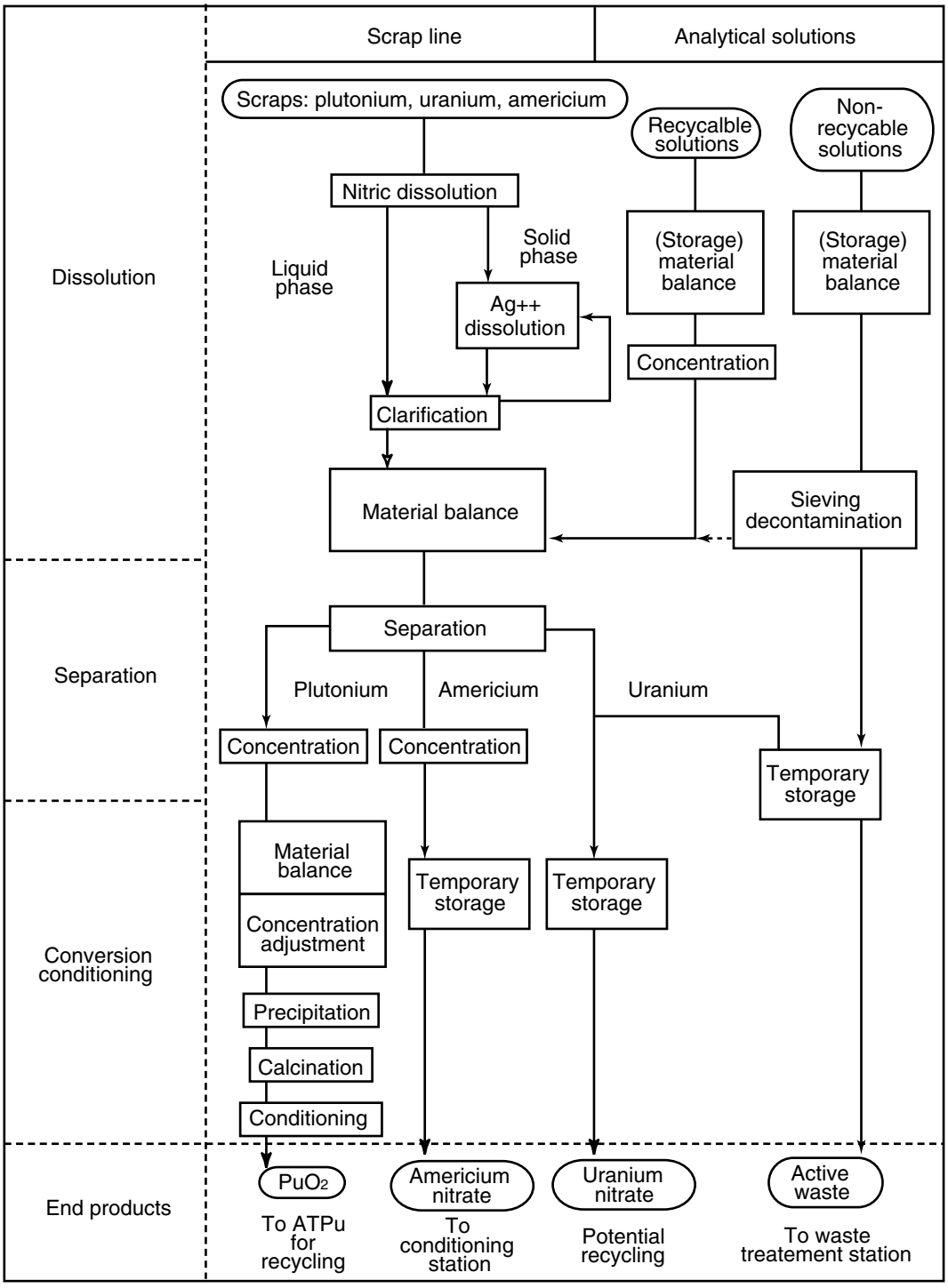


Table 3-9 DEMOX Plutonium Waste up to 1992

Total plutonium processed (kg)	9,400
Solid wastes	
Suspect (m^3)	230
Contaminated(m^3)	198
Plutonium(kg)	14.5
Liquid wastes	
Volume (m^3)	7.4
Plutonium(g)	199

3.5 Risks of Reprocessing

3.5.1 Safety aspects of reprocessing plants

With its large spent fuel storage and chemical processing capacities, a full scale reprocessing plant is a central facility for a MOX fuel chain where largest amount of radioactive materials and nuclear materials contained in spent nuclear fuel assemblies amass. In addition, highly radioactive spent fuel rods are dissolved and subjected to a long series of chemical procedures. Associated with these activities, we can give a long list of potential hazards ranging from daily radioactive discharges and workers' radiation exposure to accident hazards with varying degrees of impacts to the environment, safety and human health (ES & H).

Although reprocessing is the key activity whose risks should fully be taken into consideration in an assessment of MOX use in light water reactors, addressing the issue fully is beyond the scope of this project. In addition, there are already a number of qualified assessment works also by independent researchers [UCS 1975; Hatzfield et al. 1979; Berstermann et al. 1983; Takagi 1991].

We will therefore give a short review of accident hazards of a reprocessing plant and thereafter focus our concern on the daily radioactive discharge of a reprocessing plant, which most conspicuously distinguishes the facility from other nuclear facilities and activities.

Accident hazards of reprocessing plant

Because of the enormous concentration of radioactive materials in a reprocessing

plant, the potential consequences of a catastrophic radioactive release event in a reprocessing plant could be far more serious that in a nuclear reactor and could affect tens of millions of people [Bacher et al. 1975; Greenpeace 1989]. The following possibilities are considered to be the severest among the probable events.

-criticality due to excessive concentration of plutonium containing solution
-fire caused by ignition of organic solvent, degradation products (red oil), combustible gas and by external causes
-explosion due to uncontrolled chemical reactions, overpressurization, overheating and erroneous chemical operations
-loss of cooling due to coolant loss and power failure
-containment failure caused by leakage of piping, valves, tanks etc. due to corrosion and mechanical damage

Accidents caused by reasons given above were experienced in commercial-scale civil and military reprocessing plants in the past [OECD / NEA 1993, IAEA 1996] with consequences of varying degrees. Significant events include:

*Kyshtym, Southern Urals: 29.9.1957. About 74 PBq of fission products was released due to chemical explosion of high level radioactive liquid waste from reprocessing.
*Windscale (now Sellafield) :26.9.1976. Ru-106 was released due to uncontrolled exothermic reactions of dissolution residues at the head-end equipment of the reprocessing plant. 31 workers were exposed to Ru-106 above permissible lung burden.
*La Hague: 15.4.1980 : Total loss of power supply caused by fire at the site power distribution board put the plant in a huge mess, paralyzing among others key safety functions such as the cooling of high level waste storage tanks and criticality control.
*Tomsk, Siberia: 6.4.1993. An explosion occurred to a uranium solution tank due to overpressure caused by uncontrolled nitric acid / organic solvent reaction. Released radioactive nuclides contaminated downwind areas 10-20 km from the plant.
*Tokai: 11.3.1997 : A fire and then explosion occurred to the low level radioactive waste bitumenization facility. 37 workers were internally exposed to cesium-137 and around 10 billion Bq of radioactive nuclides was released.

Radioactive discharges from reprocessing plant

It is often claimed by the reprocessing advocates that reprocessing is a nuclear back-end policy with less environmental burden, because it reduces the volume and radioactivity of high level radioactive waste to be finally disposed of. While the claim might have had some rationale twenty years ago, no reliable arguments can justify this claim now (see Chapter 5). In regard to the environmental aspect of reprocessing, it should be pointed out that the reprocessing is the nuclear industrial activity whose daily aerial and liquid radioactive discharges of radionuclides into the environment by far outweigh other facilities and activities. In this sense, a reprocessing plant is the

"dirtiest part" of the nuclear fuel chain. This can be easily demonstrated by a comparison of regulated discharges from various plants -- at the time of licensing of the respective plants -- given in Table 3-10. As a comparison, the regulation and observed values of discharge from a nuclear power plant (1,100 MWe Tokai II BWR) are given in the last column.

Table 3-10 Radioactive Discharges from Reprocessing Plant
(Annual regulation in TBq)

Plant	UP2+UP3	THORP	Rokkasho	Wackersdorf	Tokai-II NPP
Capacity (tHM)	1600	700	800	500	1,100MWe
Aerial discharge					
krypton	480,000	370,000	330,000	160,000	1,400 (0.15[a])
tritium	2,200	21.6	2,000	1,500	(0.00012[b])
iodine-129	0.11[c]	0.022	0.013	0.0018	
(iodine-131)					(0.00007[d])
Liquid discharge					
tritium	37,000	13,900	18,000	37	(1.6[e])
all beta(except tritium)	1,700	34.2	0.7	0.013	0.037 (0.00012[f])
all alpha	1.7	0.14	0.0098	0.00044	N.D.
iodine-129	n.a.	1.4	0.026	0.0001	N.D.

Table 3-10 compiled mainly from official documents and statistics, see also [Kueppers et al. 1990; Homberg et al. 1995].
Figures are official limits of discharge at the time of plant licensing;
figures in the parentheses are actual releases:
a. Official measurement in 1987;releases were below detection limit since 1988 .
b. Official measurement in 1986; releases were below detection limit since 1987.
c. French regulation is for "halogens", which means regulation I-129 + I-131, of which I-129 is predominant in a usual reprocessing plant because of short half life of I-131.
d. Iodine-129 from power plant is not detectable; I-131 value is for 1987; from 1988 on below detection limit.
e. Official measurement in 1991; lower measured values in other years.
f. Official measurement in 1986; releases have been below detection limit since 1987.
n.a.: Regulation value is not available. It seems French authority has no regulation for discharge of iodine-129,131 to see.
N.D.: Below detection limit.

The implications of the table are almost self-evident. The most striking fact is the

large differences between the discharge regulation values for the reprocessing plant and nuclear power plant. For every kind of environmental discharges, discharge from a reprocessing plant is larger by several orders of magnitude. This is one of the central reason why the "closed nuclear fuel cycle" is not favorable from the environmental point of view.

Another remarkable trend is the substantial differences of discharge values among various reprocessing plants. The discharge of krypton is similar, being proportional to the plant throughput, since no elimination of krypton is implemented anywhere. As to the other discharges, in general La Hague's discharges are by far the largest, followed by THORP. Rokkasho's discharges are much smaller than the two European plants, while the abandoned Wackersdorf plant set the most strict control of radioactive discharges. The reason of Wackersdorf plant's strict control- which is however by far looser than that of power reactors- is partly because the plant is an inland facility in contrast to the usual reprocessing plants which are sited along the sea coast. But the strong public opposition in Germany had also affected the safety features to achieve a stiff limitation of discharges and this in return affected the construction costs of the plant substantially, which was one of the reasons why the plant had to be scrapped.

Now the soaring cost estimates of Rokkasho plant is at issue [NIT 1995] and might kill the whole project. For German and Japanese utilities, commissioning reprocessing to UP3 and Thorp will be far cheaper, the reprocessing cost per unit HM being probably about one third in these plants than in Wackersdorf or Rokkasho and thus overseas rather than indigenous reprocessing contracts make comparative economic sense.

French and British reprocessors which are so influential to affect their authorization of regulations are running the plants not to support the nation's back-end policy but in order to obtain foreign currency; but they are doing so at the cost of their environment and public health. If we look into the details of Table 3-10, we find that the emission of La Hague plant is much higher than that of Sellafield in many respects and that there is an interesting trend. One of the most hazardous component is the liquid beta-gamma discharge because it is directly related to the contamination of marine organisms. The total beta liquid discharge (except tritium) of UP2 + UP3 is about 50 times more than that of Thorp, which is itself about 50 times larger than that of the Rokkasho project. Accidentally or not, the planned Rokkasho liquid beta discharge is just 50 times higher than envisaged for the Wackersdorf project.

Rational consideration might suggest that, however different the meteorological, geographical, demographical conditions, and eating habits are around different sites, those plants have passed essentially similar licensing procedure, judged by the relevant authorities as "environmentally harmless" and therefore the level of discharges are much the same, but the truth is totally different. This raises a strong suspicion about the credibility of environmental impact assessment procedures of

these plants, especially the two European plants.

There is now ever-increasing concern over accumulation of iodine-129 around European reprocessing plants. Iodine-129 is an extremely long-lived (half life:15.7 million years) beta-gamma emitter and accumulates in thyroid when inhaled or ingested to cause thyroid injuries including thyroid tumor. Yiou et al.[Yiou et al. 1994] recently detected large concentrations of I-129 in sea water and marine organism samples taken in the Irish Sea and English Channels. French independent research group CRII-RAD[CRII-RAD 1995] have detected high levels of I-129 in moss samples taken around the La Hague plant. The observed levels of I-129 are far above the level attributable to past atmospheric nuclear testing and seem certain to be due to emissions from La Hague and Sellafield. It is feared that the expected increased amount of reprocessed fuel and increase of spent fuel burnup handled in these plant will exacerbate the situations. I-129 release from Tokai reprocessing plant [Muramatsu and Ohmomo 1986] once posed concern also in Japan.

Large emission of tritium and krypton is also of serious concern in view of the adverse environmental effects of tritium[Fairlie 1992] and krypton[Kollert and Butzin 1989] being possibly larger than previously thought. Emission of another long-lived radionuclide, carbon-14, from reprocessing plant should also attract more attention. Although the long-term global effects of these cumulating long-lived radionuclides are yet to be accurately assessed on full scientific evidence, almost uncontrolled emission of these nuclides from a number of large scale commercial reprocessing plants poses serious concerns. After the end of nuclear testing now the only major sources of this type of radioactive global contamination are four or five commercial reprocessing plants. The MOX program should be reviewed also from this global environmental aspect.

Incidence of childhood leukemia

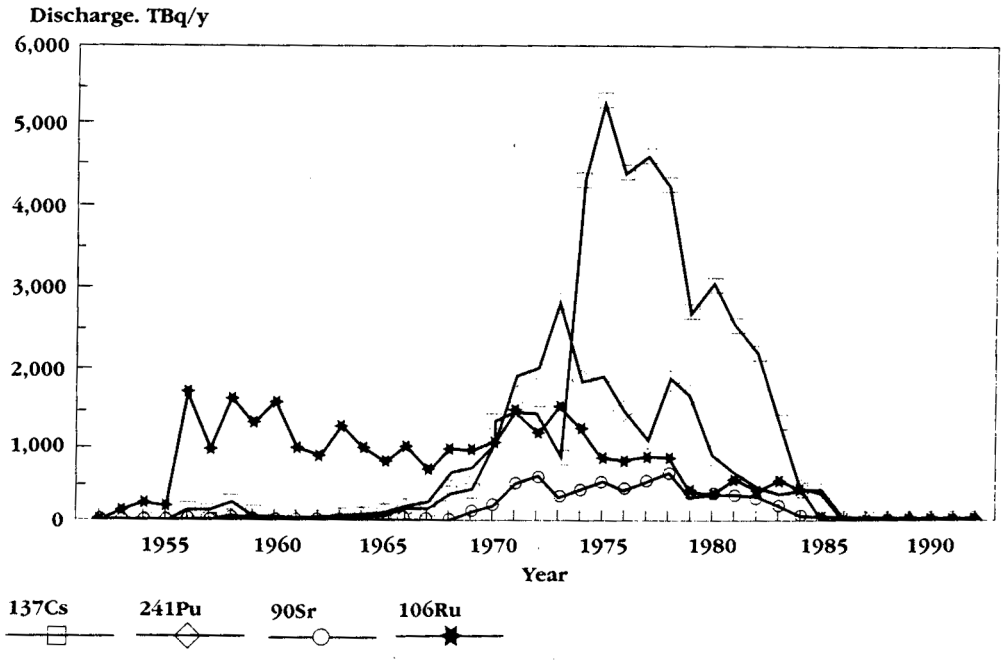
The level of radioactive discharges in European reprocessing plants was very much higher in the past [COMARE 1996; Homberg et al. 1995]. The past liquid discharges from the Sellafield site is shown in Fig. 3-4. The past enormous emissions as well as the current regulation level which is still significant are enough to raise concerns over the possible adverse health effects.

The issue of increased incidence of childhood leukemia near British reprocessing plants has been and is still a subject of controversy to say the least. The issue came to the fore when a 1983 TV program aroused public concern about the possible association of leukemia with the reprocessing plant at Sellafield, West Cumbria.

The results of epidemiological study by Gardener et al as published in 1990 [Gardner et al. 1990] presented a convincing evidence for the correlation of paternal exposure at the plant to the increased childhood leukemia/lymphoma incidence,

while another study[Urquhart et al. 1992] suggested a possible association of childhood leukemia at near the Dounreay reprocessing plant in Scotland.

Fig. 3-4 Liquid Discharges at Sellafield Site



The Committee on Medical Aspects of Radiation in the Environment (COMARE) organized by the U. K. Department of Health has been reviewing the issue since mid-1980s. Its second report[COMARE 1988] published in 1988 and fourth report [COMARE 1996] in 1996 confirmed the increased incidences of childhood leukemia, respectively in areas near Dounreay and Sellafield. COMARE's position is, however, that the observed increase of childhood leukemia can not be attributed to radiation from the nuclear installations on grounds that the estimated exposure doses of residents and workers are too small to cause the observed effects. The committee thus asserts that all the increased incidences near nuclear installations are "clusters" whose causes are yet to be explained by some non-radiological theory.

But, this argument by COMARE is not persuasive. There were actually not insignificant radioactive discharges to the environment as well as exposure to radiation inside the installations. Also, the increased incidence of childhood leukemia was confirmed. These are unrefutable facts, and epidemiological studies strongly suggest incidence of radiation induced effects. It is only natural and reasonable to assume that these are real associations and therefore COMARE's basic assumptions of exposure dose and/or risk factors of ionizing radiation for leukemia incidence should rather be reviewed in the light of facts.

More recently, increase of childhood leukemia was also reported in area downwind of the La Hague reprocessing plant [Viel et al. 1995] and has been attributed

to use of contaminated beach near the plant[Pobel and Viel 1997].

Uncertainties are still very large, but there are good reasons for continuing concerns over contamination due to radioactive discharges from the reprocessing plants and the adverse health effects which may be caused by the contamination.

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Chapter 4
Economics of MOX Use in LWRs
--An Analysis Based on Japanese Realities

Baku Nishio

4.1 Introduction

The potential or comparative economic benefits is obviously another key factor in judging whether the MOX-LWR program is justified. Our main interest here is again in the economics of MOX in Japan. Although there have been a certain number of analyses that have addressed the economics of plutonium fuel cycle or MOX in Europe and America, most of them are not directly applicable to Japan, because costs of various fuel cycle-related industrial activities are substantially different in Japan from those in Europe and America.

There are also a few Japanese studies [Deguchi et al. 1982; Nagano et al. 1989] but they have become outdated and are not based on the current Japanese cost realities. Therefore, we have conducted our own economic analysis based as far as possible on the latest information publicly available in Japan to get the latest realistic estimation of the costs of using MOX in light water reactors.

A detailed study on the economy of MOX fuel utilization in thermal reactors was presented in an 1989 OECD/NEA(Nuclear Energy Agency) report entitled "Plutonium fuel: An Assessment" [OECD/NEA 1989]. Two cases are considered in the study as the basis for economic analysis:

(1) the so-called "free plutonium scenario", where plutonium is treated as already separated and the reprocessing cost as sunken,
(2) "reprocessing scenario", where the cost of recovering plutonium out of spent fuel is taken into consideration.

In its actual calculation, however, the OECD/NEA report deals only with the "free plutonium" scenario. The report acknowledges that:

> "The situation where plutonium has not been separated and there is no existing commitment to its separation is both more complex and subject to greater uncertainty. There is no clear international consensus on the future costs of some stages of the nuclear fuel cycle, particularly the back-end, and for some of

them there is no established commercial service in prospect. "[p.88]

Nonetheless, it eventually claims the following:

> "In such a case the costs of reprocessing and conversion of the plutonium to oxide would be an additional charge to the MOX fuel, offset by any savings on spent uranium fuel storage charges and any credit for the recovered uranium, taking due account of any difference in the conditioning and disposal costs of spent fuel and reprocessing wastes." [p. 71]

Such an argument is based on the once-taken-for-granted view that spent fuel should unquestionably be reprocessed, a view which is now highly questionable.

By assuming a "free plutonium" scenario, the OECD/NEA report concluded that MOX fuel utilization would notably reduce nuclear fuel cost. The report, however, is based on incredibly inadequate cost figures such as $80/kgU for uranium purchase (far too high) and $800/kgHM (HM: heavy metal) for MOX fuel fabrication (far too low). This is enough to make us suspect that the calculation has been carried out only for the sake of demonstrating the alleged cost performance of MOX utilization. The realistic figures that must be employed for a reasonable economic assessment are, however, a uranium price of $34.7/kgU in the international market [IEE 1991], and $1,300~1,600/kgHM for fabrication of MOX fuel assemblies in Europe [Berkhout et al. 1993].

It should further be pointed out that prices and wages in Japan are generally 2 to 4 times as much as those in Europe[1] or US, heavily affecting almost every aspect of nuclear fuel cycle costs. MOX fuel, for example, can be 2.5 to 3 times more expensive if assembled in a Japanese plant(the implications will explained in a later paragraph).

In the present paper, therefore, the economics of MOX fuel are analyzed by estimating the costs of reactor fuel for one year use with a third of core loaded with MOX fuel and by comparing it with those of uranium (UO_2) fuel-a methodology adopted by the 1989 OECD/NEA report. Calculations are made for the two cases (scenario 1 and 2) mentioned above separately, based on most realistic cost estimates for the several activities related to fuel fabrication in Japan. It should be noted that, for the first scenario, the MOX fuel costs includes the fuel cycle costs up to the loading of fresh fuel into the reactor, but not the costs of the back-end of the fuel cycle.

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1. We are chiefly concerned here with costs in France and the U.K., because Japanese utilities are commissioning reprocessing and MOX fabrication basically to companies in these countries. Costs in Germany may be in between Japan and France/U.K..

The cost calculations in two cases should result in the same cost estimates so far as the reprocessing cost could be offset by the spent fuel storage cost plus credit for recovered uranium, as claimed in the OECD/NEA report quoted above. According to our calculation in the present paper, however, annual fuel cost for a 1,000MW light water reactor (LWR) loaded with MOX fuel (1/3 core MOX loading) has been estimated as follows:

Case 1: 5.3 to 6.3 billion yen (= $48 to 57 million) /GWy reactor fuel
Case 2: 10.6 to 12.6 billion yen (= $96 to 114 million) /GWy reactor fuel

UO_2: 4.4 billion yen (=$40 million)/GWy reactor fuel

Our results indicate that the reprocessing costs are far higher than the spent fuel storage cost plus uranium credit and hence the "free plutonium" scenario is not justified. The results for cases 1 and 2 are both substantially higher than that for UO_2 implying that the introduction of MOX would lead to a large fuel cost increase.

4.2 Fuel Costs Estimation: Case 1

4.2.1"Free-plutonium" scenario

Here we follow the assumption of the 1989 OECD/NEA report that MOX utilization takes the form of "1/3-core loading", i.e., a thermal reactor is loaded one-third with mixed oxide (plutonium-uranium) fuel assemblies and two-thirds with uranium oxide fuel assemblies. What is compared are (i) the cost of refueling the reactor for one year's operation by applying MOX fuel to one third of the reload and (ii) that of refueling with 100% UO_2 fuel. Those are equivalent to the annual fuel costs of a power reactor with and without MOX, respectively.

The following figures are used as the basis of calculation for the amounts of nuclear materials and output from enrichment works needed to run a 1,000 MWe LWR using basically the figures given by Atsuyuki Suzuki [Suzuki 1985]. Some other figures such as those for enrichment services necessary for calculation but not indicated clearly can be found in sources given in reference [Leventhal and Dolley 1993; Cochran et al. 1996; Suzuki and Kiyose 1981; Hensing and Schulz 1995a; Hensing and Schulz 1995b].

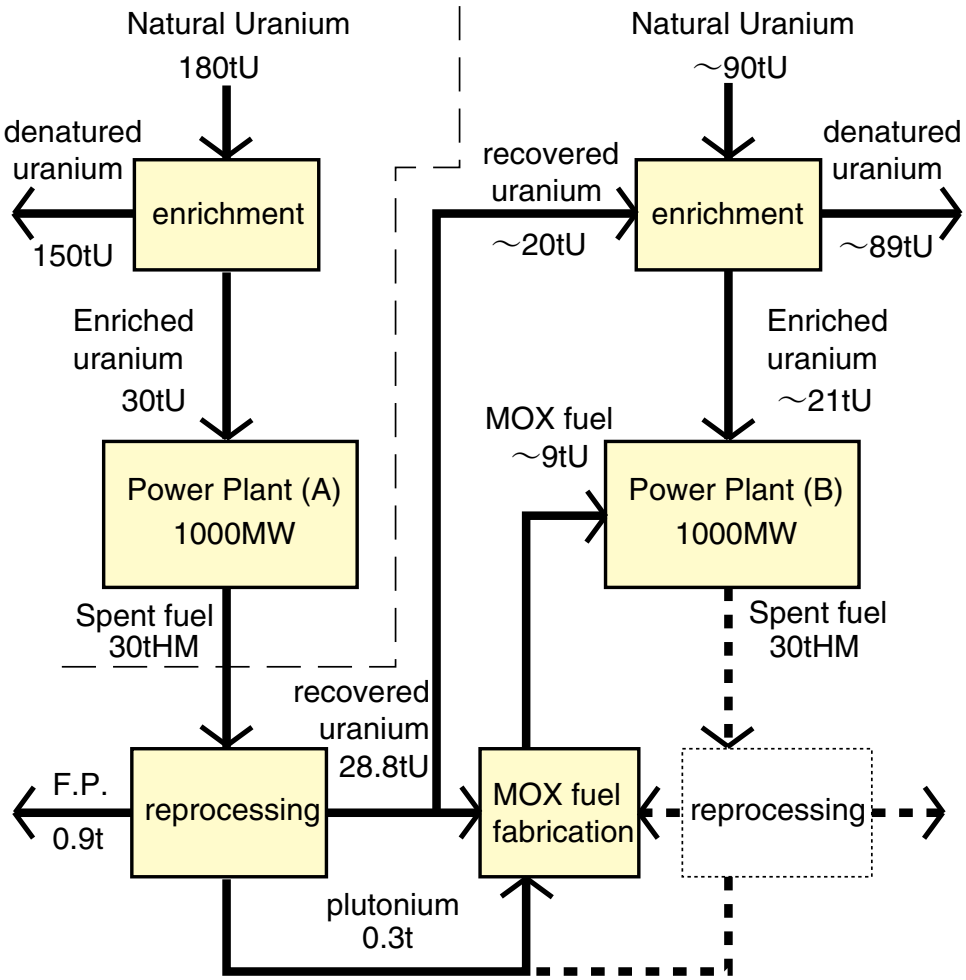
- 100% UO_2 loading

natural uranium:	180 tU	conversion:	180 tU
enrichment:	100 tSWU	fuel fabrication:	30 tU

-1/3-MOX loading

natural uranium:	90 tU
reprocessed uranium:	20 tU
conversion of natural uranium:	90 tU
conversion of reprocessed uranium:	20 tU
enrichment of natural uranium:	50 tSWU
enrichment of reprocessed uranium:	20 tSWU
uranium-oxide fuel fabrication:	21 tU
MOX fuel fabrication:	9 tHM

Fig. 4-1 Flow of Nuclear Materials per 1,000 MWy



According to [IEE 1991], unit prices for the material listed above are given as follows:
purchase of uranium: \$29.4 / kgU_3O_8 (= \$34.7 / kgU)= 3,800 yen / kgU
conversion: \$6.5 / kgU = 720 yen / kgU
enrichment: \$95 / kgSWU = 10,000 yen / kgSWU
UO_2 fuel fabrication: 88,000 yen / kgU

These prices are 3 to 4 times as high as the corresponding figures in Europe and USA, reflecting the general trend of high costs in Japan. Since the cost for MOX fabrication is not given in IEE, we have assumed here that it will fall in the range of 4 to 6 times the uranium fuel fabrication cost[2]. Our estimation is thus at 350,000 - 530,000 yen / kgHM for fabrication of MOX in Japan..

It should be noted here that fabrication for Japanese MOX will actually take place largely in Europe. According to the Japanese Government's 1995 version of the official plutonium supply and demand projection, which is a slight modification of the 1994 Long Term Program[AECJ 1994], plutonium to be consumed as LWR-MOX comprises 25-30 tons recovered from domestic reprocessing and 30 tons from overseas. For the sake of calculation, we have to take the difference of costs in Japan and Europe into consideration. We here assume that half of MOX fuel is fabricated abroad and half in Japan. As for the MOX fuel fabrication cost in Europe, we adopt a value of \$1,300 - 1,600 / kgHM based on [Berkhout et al. 1993]. This estimate is 5 to 8 times the cost of uranium fabrication but is likely to be an underestimate because Japanese stricter fuel performance demands could push up the fabrication cost further. Hensing and Schulz[Hensing and Schulz 1995a; Hensing and Schulz 1995b] assumes a MOX fabrication cost of 4,000DM / kgHM in their analysis of German backend costs, which corresponds to \$2,400 / kgHM or 280,000 yen / kgHM, a value just between the French / U.K. and Japanese (our estimate) values and thus the intercorrelation seems reasonable.

Thus the MOX fabrication costs assumed are:
overseas: \$1,300 to \$1,600 / kgHM = 140,000 to 180,000 yen / kgHM
domestic: 350,000 to 530,000 yen / kgHM (=\$3,200 to \$4,800)

Conversion / enrichment cost of recovered uranium (i.e.product from reprocessing) is

2. We have used this MOX / UO_2 fabrication costs ratio based on the assumption that the ratio in Japan is essentially similar to that in Western countries. The ratio calculated from the cost figures in references [Berkhout et al 1993;Chow and Solomon 1993] ranges from 4 to 8.

taken as 1 to 1.5 times as much as that of natural uranium.[3] Thus, we estimate:

conversion of recovered uranium: $6.5-9.8 / kgU = 720-1,100 yen / kgU
enrichment of recovered uranium: $95~140 / kgSWU = 10,000-15,000 yen / kgSWU

In overseas reprocessing, additional transportation costs should be taken into account. These are (i) shipment of plutonium from the reprocessing plant to the MOX fabrication plant, for example from Cap La Hague, France to Dessel, Belgium; and (ii) shipment of MOX fuel from Europe to nuclear power plants in Japan. Regarding that (i) is included in the fabrication cost cited earlier, we consider below the cost for (ii) alone.

Although there has been no sea shipment of MOX fuel from Europe to Japan, the amount of MOX to be carried in one shipment is expected to be around 50 tMOX (= 2 t as plutonium). If one shipment from Europe to Japan is to require the same expenditures as those spent in the sea transportation of plutonium oxide on board Akatsuki Maru (November 1992 to January 1993), namely 1.2 billion yen[Ishida 1992], then the estimated cost per unit weight for MOX transportation would be:

MOX fuel shipment cost: 24,000 yen / kgHM

The cost for each item in fuel fabrication is thus:

For 100%-UO_2 reloading
purchase of uranium: 180 ,000kgU x 3,800 yen / kgU =680 million yen
conversion: 180 ,000kgU x 720 yen / kgU =130 million yen
enrichment: 100,000kgSWU x 10,000 yen / kgSWU =1,000 million yen
fabrication: 30,000kgU x 88,000 yen / kgU =2,600 million yen
TOTAL = 4.4 billion yen ($40 million) for a year of 1,000 MW LWR fuel

For 1 / 3 MOX and 2 / 3 UO_2 reloading
purchase of uranium: 90,000kgU x 3,800 yen / kgU =340 million yen
(Uranium recovered from reprocessing is assumed free.)
conversion of natural uranium: 90,000kgU x 720 yen / kgU =65 million yen
conversion of reproc. uranium: 20,000kgU x 720-1,100 yen / kgU=14-20 million yen
enrichment of natural uranium: 50,000kgSWU x 10,000 yen / kgSWU
=500 million yen

3. In reality, reprocessed uranium needs a higher enrichment effort and is not carried out in every enrichment plant because of the presence of neutron absorbing and significantly more radioactive uranium isotopes (like U-236) which are not present in natural uranium.

enrichment of reproc. uranium: 20,000 kgSWU x 10,000-150,000 yen / kgSWU
=200-300 million yen
UO_2 fuel fabrication: 21,000 kgU x 88,000 yen / kgU = 1,800 million yen
MOX fabrication (in Europe):4,500kgHM x 140,000-180,000 yen / kgHM
=630-810 million yen
MOX fabrication (in Japan):4,500kgHM x 350,000-530,000 yen / kgHM
=1,600-2,400 million yen;
MOX shipment (from Europe):4,500kgHM x 24,000 yen / kgHM =108 million yen

TOTAL = 5.3 - 6.3 billion yen ($ 48 - 57 million) per year of 1,000MW LWR fuel

4.2.2 Summary of Case 1

To summarize, the total annual fuel costs for a Japanese 1,000 MWe LWR loaded with MOX for a third of core is estimated, under the assumption of sunken reprocessing cost or "free plutonium", to be 5.3 to 6.3 billion yen($48-57 million), as compared to 4,4 billion for a full UO_2 core. The results clearly indicates that the expenditures for 1/3 core MOX fuel utilization are 20 to 40 % higher *even under the most optimistic assumption for MOX program promoters of free plutonium*.

The unit cost of MOX is 260 to 370 million yen / tHM or $2.4 to 3.3 million / tHM, which is 1.7 to 2.5 times the cost of uranium fuel (150 million yen / tHM). The fuel cost per kWh power generation is calculated for a capacity factor of 75% to be 0.80-0.94 and 0.67, respectively for 1/3 MOX loading and full UO_2 loading.

As suggested by the present calculations, the results of the 1989 OECD / NEA estimation which claims that 1/3 core MOX use is slightly cheaper than using full UO_2 is attributable to its supposition of unrealistically expensive uranium price and cheap MOX fabrication cost. Simply applying the current market uranium price of $40 / kgU instead of $80 / kgU of the OECD report and the MOX fabrication of $1,100 / kgHM given in the new OECD / NEA report [OECD / NEA 1993] instead of $800 / kgHM shows that the MOX option is 5% more expensive than the exclusive uranium use.

4.3 Fuel Costs Estimation: Case 2

4.3.1 A scenario taking reprocessing costs into account

In order to calculate the fuel cost for case 2, the cost of plutonium should be added to the costs obtained above for the scenario assuming free plutonium. The cost of

plutonium consists of reprocessing cost and high-level radioactive waste (HLW) treatment/disposal cost, while the costs of spent fuel (irradiated uranium fuel) storage and direct disposal are to be deducted from the plutonium cost because spent fuel direct storage/disposal is avoided in this scenario.

Thus, we define here the "net plutonium cost" as:

For overseas reprocessing: cost of spent fuel transport + cost of reprocessing
+ cost of reprocessing wastes shipment + cost of HLW storage and disposal
- cost of spent fuel direct storage and disposal

For reprocessing in Japan: cost of reprocessing + cost of HLW storage and disposal
-cost of spent fuel direct storage and disposal

We assume here that reprocessed uranium is "recycled" free of charge into fabrication of UO_2 and MOX fuel. It is assumed as before that half of plutonium is supplied from overseas reprocessing and the remaining from reprocessing in Japan.

According to the 1991 IEE report cited earlier, the transportation cost of spent fuel from Japan to Europe is 130£/kgHM(22,000yen/kgHM) while the reprocessing cost is given as 6,740FF/kgHM(140,000yen/kgHM)for the La Hague plant.[4]

As for domestic reprocessing, the construction cost of Rokkasho Reprocessing Plant, Aomori, is estimated by Chow and Solomon[Chow and Solomon 1993] at $1,000/kgHM. These authors also estimated that the plant operating cost per kgHM at Rokkasho would be almost the same as the construction cost. If this is the case, then the total reprocessing costs (construction + operation) would be $2,000/kgHM.

This estimate, however, is based on the original estimation of the construction cost of the Rokkasho plant, i.e. 840 billion yen. The estimation has since been more than doubled to 1,880 billion yen. This is considered to indicate that the original estimation was far too optimistic and the operating cost would also rise by the same factor. On a hopeful assumption that operating cost will remain at the same level as that of the original estimation ($1,000/kgHM), and taking into account the 120 % increase of construction expenditure alone, the total costs would be $3,200/kgHM. The operating costs could also rise, say by 50%, leading to total reprocessing costs of $3,700/kgHM. Thus, our provisional cost estimation for the domestic reprocessing can be taken in the range of $3,200- 3,700 (350,000-410,000 yen)/kgHM.

The construction cost of the Rokkasho HLW Temporary Storage Facility with a capacity of 1,440 vitrified canisters, is officially set at 60 billion yen[JNFL 1997]. Assuming that the operational cost will be half the construction cost per unit weight, the total storage cost is estimated to be 63,000 yen per kgHM of spent fuel. As for the cost of final disposal of vitrified high level waste, the Preparatory Committee for HLW

4. Throughout this paper, the currency exchange rate is taken as 170 yen /£ (British pound) and 21 yen/FF (French franc).

Disposal gives a maximum value of 97 million yen per canister [PCHLWD 1996], which can be converted to 97,000 yen/kgHM spent fuel. Without having any alternative estimate, this is used here as the disposal cost, though the official estimation of the final disposal costs might also be too optimistic.

For overseas reprocessing, further expense on transportation of reprocessing waste (high-, intermediate- and low-level radwaste) back to Japan should be taken into account. We assume here that reprocessing of one ton of spent fuel yields one canister of vitrified high-level radwaste (VHLW) and eighty 200-liter drums of intermediate- and low-level radwaste (ILW/LLW) based on our estimation of reprocessing waste [Nishio 1994; F. Homberg et al. 1995].

To estimate the transportation costs of waste, it is assumed that one typical shipment can carry an amount of VHLW corresponding to 100 tHM of spent fuel or that of ILW/LLW corresponding to 40 tHM. Suppose that one shipment costs 1.2 billion yen as in the case of Akatsuki-Maru, the HLW transportation cost from Europe to Japan is estimated as 12,000 yen per kgHM of original spent fuel and that for ILW/LLW as 30,000 yen/kgHM.

The disposal cost of LLW/ILW is estimated to be around 450,000 to 600,000 yen per 200 l drum based on JNFL accounts[JNFL 1995] for 1994 and 1995, which corresponds to 36,000 - 48,000 yen/kgHM spent fuel. This should be taken as the lowest cost estimate, because the JNFL figures are for burial of low level waste only and disposal costs for intermediate waste would certainly be higher.

On the other hand, the costs of storage and direct disposal of spent fuel, as given in the 1989 OECD/NEA report, are, respectively, $230 (=25,300 yen)/kgHM and $610 (= 67,100 yen)/kgHM, corresponding to a total cost of $840 (=92,400 yen)/kgHM. As judged from comparison of other prices, the cost in Japan should be taken three times as much. Therefore, we assume here a storage/disposal cost of $2,500 (= 280,000 yen) per kgHM of spent fuel, which should be deducted from the plutonium cost as mentioned above.

Taking everything into account, the net plutonium cost as defined above is estimated to be 79,000 - 80,000 yen/kgHM spent fuel for overseas reprocessing and 270,000 - 340,000 yen /kgHM spent fuel for domestic reprocessing. If we assume a plutonium recovery from spent fuel as 1 %, the net cost per kg of plutonium is, respectively for overseas and domestic reprocessing 7.9 - 8.0 million and 27 - 34 million yen.

The overall fuel costs for 1/3 core MOX reloading can be calculated by assuming as before that half of the total 300 kg plutonium is supplied from overseas and the latter half from domestic reprocessing as:

Costs for free plutonium scenario:5.3-6.3 billion yen

Plutonium cost:

overseas reproc. 150kgPu x 7.9-8.0 million yen / kgPu =1.2 billion yen
domestic reproc. 150kgPu x 27-34 million yen / kgPu =4.1-5.1 billion yen
TOTAL:10.6-12.6 billion yen ($96-115) per year of 1000MW LWR fuel

4.3.2 Summary of Case 2

To summarize, if one-third of a reactor core is to be loaded with MOX fuel assemblies, then its economic burden for the whole core will be 2.4 to 2.9 times as much as that of conventional UO_2-based core, when the costs associated with reprocessing are to be taken into account. Therefore there is little doubt that MOX fuel utilization would result in a large increase of the nuclear fuel cost. If the AECJ's long term program that 10 thermal reactors in Japan should be loaded to one-third of core with MOX around the year 2000 is implemented, it will lead to an extra fuel cost of 62 - 83 billion yen every year.

If we compare fuel cost per tHM, MOX fuel costs 840-1,100 million yen against the cost of 150 million yen for uranium fuel. Thus MOX is more than 5 times as costly as the UO_2 fuel. Assuming a reactor capacity factor of 75%, fuel cost of unit power generation (per kWh) will be:
uranium fuel: 0.67 yen / kWh
1 / 3 MOX fuel: 1.6-1.9 yen / kwh

Official figures of power generation cost per kWh in Japan as given by the Agency of National Resources and Energy (ANRE) for 1992 are: 9 yen for nuclear, as against 10 yen for petro / coal-thermal[ACEI 1994]. While this low cost estimate of nuclear energy is highly questionable in view of the recent trend[Denki Shinbun 1996], 1 / 3-MOX loading will push up the nuclear power cost by 0.9 to 1.2 yen per kWh, which would offset the alleged "economic advantage" of nuclear power.

4.4 Other Factors to Be Considered

4.4.1 Additional Factors

There are yet many factors which were not considered above but would push up the MOX costs further. They include:

Transportation costs
The 1992-93 maritime transportation of plutonium oxide by Akatsuki Maru

required not merely the direct costed of shipment (1.2 billion yen), but additional 5.1 billion yen for the construction of cask, renovation of the carrier ship (to be a fully-equipped plutonium freighter) and other related costs[Ishida 1992]. This suggests that the cost of MOX fuel shipment given earlier in this paper may actually be an underestimation.

Physical protection costs

Akatsuki Maru was escorted by Shikishima, a lightly armed coast guard cutter, the construction of which cost the Maritime Safety Agency of Japan 20.3 billion yen, plus the yet undisclosed cost of voyage. In addition, 69 patrol vessels, 5 aircraft, and 5,000 police and coast guard officers had to be mobilized to secure the arrival of Akatsuki Maru. Taking all these expenses into account, the cost of MOX utilization would be raised accordingly.

PR/PA costs

A large sum of money has to be spent, both in Japan and overseas, in order to obtain public acceptance for plutonium shipment, HLW shipment, and construction of the nuclear fuel cycle facilities. In 1994, the Science and Technology Agency (STA) alone spent 5 billion yen advertising its plutonium program [Gen San 1991]. This figure does not include the taxpayers' money poured into the public relations efforts of nuclear energy in general.

Research and development (R&D) costs

Considerable technological uncertainties remain as to MOX fuel utilization in light water reactors and disposal of HLW and other kinds of waste. A large investment on research and development is still required, which could prove very costly. In the 1996-97 budget of the Japanese Government, approximately 50 billion yen ($455 million) is estimated to be allocated to the back-end and MOX research (excluding FBR and ATR funding)[Gen San 1996]. Utilities also spend quite a large sum in R&D: the 1996-97 budget of utilities includes 9.1 billion yen for nuclear fuel cycle R&D, and 6.8 billion yen for back-end R&D[FEPCO/CEPC 1996]. Some of these research expenditures should have to be included in the cost estimates as they constitute an essential part of the MOX program costs.

Reprocessed uranium

We have assumed that uranium recovered by reprocessing can be used free of charge in fuel fabrication. If this is not the case, the cost of shipment of waste uranium from the reprocessing plants in Europe back to Japan, and the cost of domestic storage and disposal should be taken into account.

Let us estimate the additional costs due to the factors mentioned above. The period we have to take into account may be 10 years from around 2000 to 2010, when according to the AECJ program 70 tons of separated plutonium should be consumed as MOX. For this period and for MOX program, we have to count 5.1 billion yen for transportation expenses, 20.3 billion yen for the physical protection half of 5 billion/y x 10 years for the PR/PA costs and tentatively 10 % of the annual R&D (50 + 9.1 + 6.8 billion yen) x 10 years for the R&D funding. These add up to 116 billion yen which will be spent on use of total 70 tons of plutonium. Thus the additional cost is about 1.7 million yen/kg plutonium or 51 million yen/tHM MOX, which would raise the total fuel cost by several percent.

It should be noted that the additional costs estimated above are only those which can be estimated numerically however uncertain they may be, but there are further uncountable costs such as social and environmental costs and risks associated with the large scale use of weapons-usable materials, which are central subjects of other chapters of this study. An economic analysis should contain analysis of these factors, including above all the costs of long term storage/disposal of surplus plutonium and associated nuclear wastes, which could well be astronomical, based on projections from our current knowledge.

4.4.2 Uranium savings?

One argument, though not a major one, for justification of the "closed fuel cycle" is that by using the recovered uranium there can be savings of uranium. It is not certain, however, whether it would make sense economically to recycle uranium recovered from reprocessing, because the recovered uranium contains undesirable isotopes like uranium-236 and -232 and hence if used would lead to a deterioration of fuel quality. Even if they are no major problems for recycling as reactor fuel, the increased radiation would require additional protection, leading to an increased costs of transportation, conversion and enrichment, as suggested already.

The deterioration issue aside, the uranium savings by the current Japanese MOX programs may be considered to be less than 10 % for the foreseeable future [Skornikoff et al. 1995]. This cannot offer a persuasive justification for a MOX use program in this age of surplus plutonium coupled with a buyer's market for uranium that is predicted to last for a long time to come.

4.5 Conclusions

The results of the present analyses are summarized in Table 4-1. In short, the introduction of MOX to a third of core will raise the fuel cost of LWR by about 2.5

times. There is no economic justification for the MOX use in light water reactors.

When the result of this study is compared with the results of previous estimations conducted in foreign countries, the present cost estimate is much higher than the others. However, if we take into account the general differences of costs in different countries as we have mentioned, most of the other results[5] are quite consistent with the present one (except the OECD/NEA results), and demonstrate the diseconomics of a MOX program. Table 4-2 shows the comparison of the present estimations with those by Nuclear Control Institute in 1994[Leventhal and Dolley 1993]. The present fuel cost estimation is higher by a factor 1.2 to 1.4 for UO_2, 1.8 to 2.1 for the free plutonium case (Case 1) and 1.3 to 1.7 for the case with reprocessing cost taken into consideration (Case 2).

Table 4-1 Estimated Fuel Costs

Fuel	Fuel cost /1GW year (billion yen)	Fuel cost per kWh* (yen)
UO_2	4.4	0.67
1/3 core MOX:Case 1#	5.3-6.3	0.80-0.94
Case 2(a)	10.6-12.6	1.6-1.9
Case 2(b)	11.1-13.1	1.7-2.0

* A load factor of 75 % is assumed.

Case 1 is for free plutonium scenario and case 2 is for scenarios with reprocessing cost taken into consideration. The case 2(a) scenario does not take into account the "additional costs" as mentioned in the text and 2(b) includes the "additional costs".

The higher Japanese costs can be attributed mainly to high construction costs in Japan. While this disadvantage can be avoided by commissioning reprocessing and MOX fabrication to European companies, this would not result in net cost reduction since the long distance shipments of radioactive materials push up the costs.

There are still many uncertainties in figures used for the calculation, particularly for the back end and transportation costs. However, as we have adopted always conservative (lowest) cost estimates for MOX-associated activities for in case there are great uncertainties, the actual costs of MOX use will most probably be higher than the figures given by the present analysis. While some figures are uncertain, even to the

5. The results of similar analyses are given in papers given in [Leventhal and Dolley 1993; Cochran et al. 1996; Suzuki and Kiyose 1981; Hensing and Schulz 1995a; Hensing and Schulz 1995b].

electric utilities who are planning the program, the largest cause of the uncertainties comes from the fact that the nuclear industry continues to conceal those details of contracts which are necessary for a precise economic analysis.

Table 4-2 Comparison of Cost Estimates

Fuel cost in $/kgHM

Author	UO_2 fuel	MOX (Case 1)*	MOX (Case 2)*
NCI #	1,000-1,200	1,300-1,600	5,700-6,000
This study	1,400	2,400-3,400	7,600-10,000

*Case 1 is for sunken reprocessing cost and case 2 is for reprocessing cost included in the fuel cost. See text.
See [Leventhal and Dolley 1993].

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Chapter 5
MOX and Back-end Policy

Michael Sailer and Jinzaburo Takagi

5.1 Introduction

The question of MOX use as light water reactor (LWR) fuel is closely related to the strategy of nuclear fuel cycle, that is, the fueling and back-end (waste management) policies of light water reactors, as has been briefly outlined in Chapter 1. The present chapter is dedicated to examining the wisdom of MOX use in the light of the back-end policy.

The present day fuel and waste management strategies for nuclear power reactors have a long history. Much of the "received wisdom" in this field is the result of historical steps and developments, some of which are still valid; but others remain only as historical legacy or inertia, after having lost their rational grounds. Therefore, an assessment of the needs based on the current realities is necessary.

The nuclear fuel cycle policy has to be decided on the basis of two main aspects, the fuel strategy and the back-end strategy (i.e. nuclear waste or spent fuel management policy). Historically, the emphasis in the rationale for the reprocessing and MOX use policy has been in the effective reactor fueling strategy, that is, using uranium resources efficiently by recycling and breeding plutonium and also by recovering uranium for reuse. We have already reviewed in detail the security, safety and economic aspects of the MOX use policy in the preceding chapters. The societal and legal aspects will be covered in Chapter 6 and issues associated with transport of MOX and related radioactive materials in Chapter 7.

From the analyses and considerations given in those chapters, it looks extremely difficult to justify the reprocessing/MOX use option as the fuelling strategy for light water reactors. Disadvantages, uncertainties and complications associated with MOX use appear to far outweigh the potential advantage of plutonium "recycling". A better, more rational fuel policy would be based on once-through use of uranium fuel. Initially, a lot of nuclear experts feared lack of uranium resources and uranium price showed a trend of soaring in the seventies, the situations have changed dramatically since then [Chow and Solomon 1993]. The price of uranium is low and stable; moreover today's world market has a potential for a long range supply. In addition, the current number of some 430 operating reactors is likely to decrease rather than

increase, because the number of reactors to be decommissioned in Western countries would most likely exceed the number of possible new reactors constructed in Far East countries. Furthermore, uranium savings by reprocessing and MOX use are estimated to be small [Skornikoff et al. 1995].

However, we have still to examine the other aspect of the nuclear fuel cycle policy, that is, the rationale promoted for the reprocessing-MOX use option as compared to the once-through option. This seems to be becoming more and more important under the current situations, where the main justification for the reprocessing-MOX fuel cycle option is shifting from the fueling policy to the alleged advantage gained in spent fuel and radioactive waste management. For example, a recent Japanese government report which is regarded as having given a final official go-ahead to MOX use in Japanese light water reactors stresses the advantage of reprocessing-MOX use policy as the preferred back-end policy option, while admitting unfavorable economics of MOX fuel [ACE 1997].

The main justification, as given by the ACE report, is that reprocessing is a more rational option for spent fuel management than the direct storage / disposal option and it is also claimed that MOX burning in light water reactors can be justified to reduce the stockpile of separated plutonium. The prospective lack of on-site spent fuel storage capacity is used by the government to support the reprocessing policy.

It is therefore crucial to examine the wisdom of reprocessing / MOX use policy as the back-end policy in comparison with the direct storage and disposal option. The present chapter is dedicated to addressing the issue.

5.2 Direct Interim and Final Storage: Technical Description of the Process

5.2.1 Direct management of spent nuclear fuel

Because of the important implication of each management option, it may be worthwhile here identifying the technical steps for the direct storage and disposal of spent nuclear fuel. While the direct path is going to be the main option chosen across the world, the technical feasibility of this path is not well known in countries such as Japan, where the reprocessing path had been, until very recently, thought to be the only option.

The fuel strategy without reprocessing (and use of plutonium) is called once-through nuclear fuel cycle, but from the point of back-end policy, it can be called a "direct fuel disposal" (DFD) option since this path is generally regarded as leading to final disposal of spent nuclear fuel without substantial processing after discharge from a reactor. Although there are still large uncertainties about how, where and when the

direct final disposal in geological layers could take place, a back-end policy aiming at DFD is now the world mainstream for the management of the spent nuclear fuel of light water reactors (see Annex 1).

The DFD path needs to implement the following technical steps:

-Interim storage of spent fuel for a time span of 25 to 30 years at a interim storage facility;
-Conditioning of spent fuel for final disposal;
-Final disposal of conditioned spent fuel at a high level nuclear waste repository (heat generating nuclear waste disposal facility);
-Transports necessary to carry out the above steps.

Since spent nuclear fuel contains huge amounts of radioactive substances, every step of the DFD path is influenced by the basic safety problems associated with these substances.

Firstly, the extremely high level of external radiation due to high radioactivity, particularly gamma and neutron rays necessitate massive radiation shielding.

Secondly, there exists always a potential for release of radioactive materials. Therefore a highly reliable barriers against radioactive release are an absolute necessity. The reliability will have to be maintained during a very long period of interim storage and final disposal.

Thirdly, the radioactive decay also generates thermal energy, which poses serious safety problem during storage and disposal. Therefore, the spent fuel has to be cooled for a long time period of interim storage. The heat generation remaining after the interim storage determines volume of the final disposal facility and the quantities and types of spent fuel that can be placed in it.

5.2.2 Interim storage of spent fuel: technical basis and requirements

Technology of interim storage

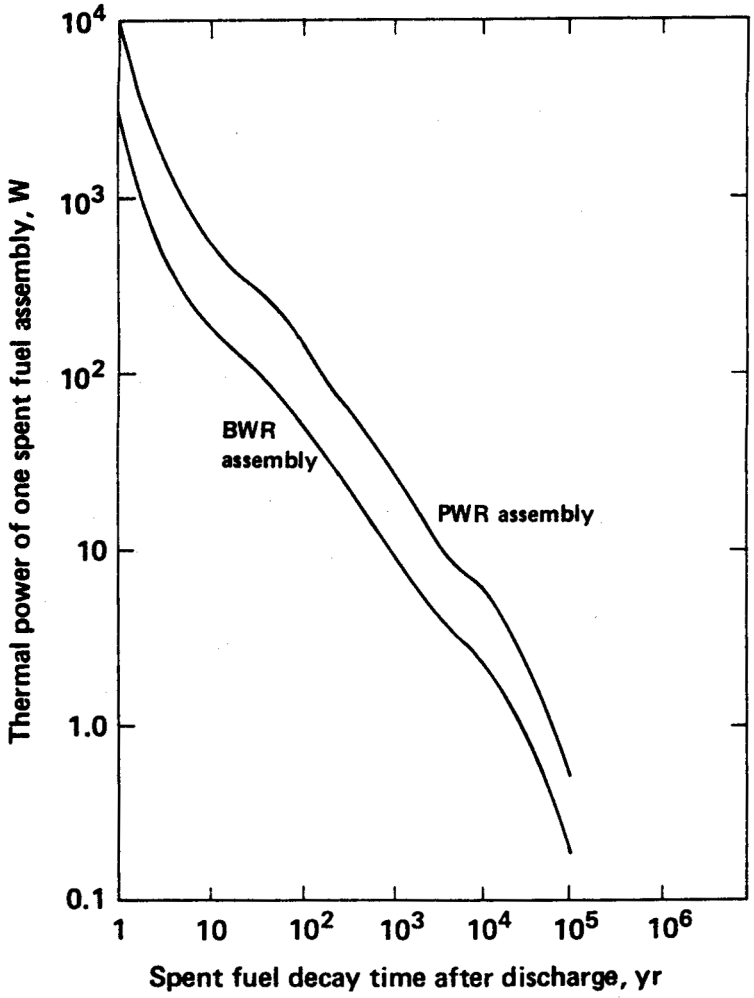
A typical light water reactor of 1,000 MWe discharges 25 to 30 tHM (tons heavy metal, see Chapter 4) and interim storage is the first step of direct spent fuel management. The intensive decay heat of the initial spent fuel has to be cooled down for 25 to 30 years, which is the technically meaningful cooling time. Although heat generation must be reduced to as low as possible, before the final disposal (storage), it would not make much sense from purely technical point of view to extend the interim storage period further by a few tens of years, since the heat generation decreases very slowly after this time period (see Fig. 5-1). It should be noted here, however, that the above technical argument does not necessarily mean that a decision

on the final disposal site can be politically reached in that time frame.

The available technical options for the interim storage include:

-wet storage in storage pool
-dry storage in storage cask
-dry storage in storage canisters

Fig. 5-1 Decay Heat of Typical Light Water Spent Fuel [NRC 1983]



Wet storage

Every nuclear power plant has a water-cooled (wet) storage pool to cool spent nuclear fuel removed from the core. In the case of typical Japanese light water nuclear power plants, a pool with a storage capacity of a few hundred tons (heavy metal) of

spent fuel is installed just outside the reactor containment[1]. The capacity and design of the pool is aimed at short-term temporary storage of discharged spent fuel before it is transported to the reprocessing plant, rather than for a long-term intermediate storage. The rather limited capacity of the storage facilities reflects partly the concern of local governments, which do not want accumulation of spent fuel on site, as well as the initial government policy to reprocess spent fuel as early as possible, although reprocessing programs now appear to be being delayed substantially.

There are now attempts to avoid -- at least temporarily -- the shortage of wet on-site storage capacity: firstly by the so-called compact racking or reracking and secondly by constructing new pools. The reracking, which is to apply a redesigned compact rack with smaller distances between the fuel assembles, poses criticality problems, and thus special additional measures like using borated steel or borocarbide layers for racks are necessary. Reracked pools also need a somewhat improved cooling capacity , caused by the heat load of the additional spent fuel to be stored. For the expansion, the current Japanese tendency is to build an additional storage facility common to more than one reactors at the site[2] (see also [NSC 1994]). Safety issues aside, expanding the storage capacity in one of these ways is now also facing difficulty in getting approval by local residents.

In addition to the on-site storage facility, there are away from reactor(AFR) storage facilities. A large facility in this class, with a capacity of 13,700 tons, is the receipt storage facility at La Hague. The planned Rokkasho Reprocessing Plant in Japan has a storage pool of 3000 tHM capacity. This serves for temporary storage before reprocessing and is not basically meant to be used for long term interim storage.

The wet storage facility needs a lot of engineered safety features. These include:

-Active cooling system to remove heat, particularly water circulation pumps, piping and heat exchange system. Failure of one of these subsystems could lead to loss of cooling ability problems. Therefore redundant cooling systems are essential (comprising perhaps a two-fold or three-fold set of cooling systems).
-Water cleaning systems. There is a permanent leakage of small amounts of radioactivity from spent fuel to the cooling water. Therefore a cleaning system is necessary to keep the radioactive concentration of the cooling water in the pond below

1. For example, the first licensed capacity of the spent fuel pool at the Kashiwazaki- Kariwa 1 reactor is about 200 tHM (140 % of core fuel inventory), assuring maximum storage capacity for 7-8 years equivalent of spent fuel.

2. A common wet storage pool was licensed in 1994 for Fukushima I Plant with six BWR reactors. The capacity for the common pool is about 200 % of the total core inventory of six reactors corresponding to 1200 tHM.

licensed or permitted limits.
-Ventilation and air filter system:there is a continuous release of radioactivity out of the contaminated cooling water into the air inside the storage building. Therefore, ventilation systems are necessary to hold air pressure to below the atmospheric pressure, to lead the contaminated air to filter systems and controlled exhausts. These systems also need active components like fans and valves.
-Control systems for the operation of the storage facility is also necessary.
-Power supply: The features described need electric power supply and a reliable redundant power supply system is necessary to assure operation of engineered safety features.
-The building housing the pool and related safety systems has to be protected against impacts from outside. The building is not usually designed to resist against air crash, greatest possible earthquake shock or sabotage. Although Japanese on-site storage facilities are classified as A class[3] facility in regard to antiseisemic design [NSC 1981], it is not specially designed against air-craft crash and sabotage.

To summarize, the wet storage in a water pool requires many active safety features to assure safety and this means that there are many potential failure modes. An additional problem is corrosion of the metallic fuel claddings, particularly when the storage in pool is used for a relatively long period of intermediate storage. Corroded fuel would also pose handling difficulties in a conditioning plant after the interim storage period is over.

Cask storage

Spent fuel storage in dry state is now available by several suppliers and already put to practical use in some western countries such as the USA, Germany Czech Republic and Lithuania[NEI 1997]. While Japan was slow to introduce dry storage, TEPCO has got permission for dry storage and started to store some 400 BWR spent fuel assemblies in 1995 [Iwaki 1996]. The basic features of the technology are:

-The spent fuel is housed in a container of steel or cast iron with a wall thickness of 30 to 40 cm. The cask consists of a container body and a cap system, which normally comprises two caps and different sealings for each cap. So two separate spaces are created :the space inside the inner cap which is the storage space itself filled with spent nuclear fuel and the small space between the inner and outer caps which is used for monitoring. The sealing systems for both caps should be leak-proof for more than

3. The class A facilities is classified as next important to As class facilities like reactor containment and the design criteria, in short, is that the A class facility should resist against the maximum credible earthquake shock according to the Japanese guidelines.

forty years.
-The cask itself including the cap system serves as the key barrier against radioactive releases into the environment and essentially needs no active components. To control the leak tightness, the pressure inside the inner cap is set to a level below the atmospheric pressure. On the other hand the pressure of the space between the two caps is set to a level higher than the atmospheric, and is always monitored by remote pressure control. A drop of the monitored pressure level means a leakage either from inside the inner cap or outside from the outer cap. A radioactive leakage to the atmosphere is possible after both of the caps and/or their related sealings failed. So a detection of sealing failure is possible before leakage to environment actually takes place[4], providing that a pressure drop is announced. This pressure monitoring system is the only one that needs active features, a control room and active components with related energy supply.
-The thick wall of the storage cask serves as the protection against radiation as well as heavy external impacts. The radiation on the outer surface of the container is lowered to a level allowed by the international transport guidelines. The cask can withstand heavy impacts according to its design parameters which officially should follow at least the type B(U) transport cask parameters of IAEA regulations (see Chapter 7).
-The decay heat of the spent fuel will be air-cooled and needs essentially no additional cooling. To ensure better cooling , most of the storage casks have cooling fins to have a greater surface for transfer of the heat from the surface of the cask to the air around.
-Basically the storage of spent fuel in a dry cask can be done without further housing as in the case for some US utilities. In most cases, however, the casks are stored in a storage building, which has air inlet and outlet to assure natural ventilation. The building can also reduce the intensity of gamma and neutron radiations to the environment by providing additional distance between the cask and the environment.

To summarize, the dry storage in cask is in large part based on passive safety features, which, in general, have low failure probability. It still relies on the active control system, which should be improved to assure higher reliability, by adding a second control system with the diverse capability for a safe and on time detection of sealing problems.

Storage in cans

Storage in cans is another type of dry storage for spent fuel implemented in countries such as the USA, Scotland and Hungary. The main features are:

4. In the case of the Fukushima 1 dry storage cask, the helium-filled design pressure inside the primary cap is 0.8 atm and the pressure difference of the space between the two caps is designed to be 4 atm. An alarm system is to be signaled when the pressure difference reduces to 3 atm [NSC 1994].

-The spent fuel is encapsulated in steel canisters with relatively thin wall thickness (several millimeters typically). The cans (canisters) are weld-sealed. Because of the thin walls of the cans the radiation level on the surface of the can is very high. Therefore, it is necessary to handle the cans by remote control. For transportation the cans have to be put into "overpack" transport containers with thick walls.
-The cans are then stored in the storage channels housed in a concrete storage building. The channel and the building are basically designed to be cooled by natural circulation of air and thus constitutes a passive cooling system.
-A control system is also necessary to assure leak-tightness of the system.
-The building should be designed to resist the maximum credible external impact and to serve as the shielding of gamma and neutron radiation. The design parameters depend on the levels required by licensing authorities.

While the storage in can system is based on the basic concept of passive cooling, there is much uncertainty in the long term leak-tightness of canisters, especially due to corrosion potential. Furthermore, the assurance of safety of the system relies largely on the integrity of the building, against impacts like airplane crash and earthquake shock, which is open to question in regard to effectiveness.

Technical requirements for siting

Interim storage can be in a central facility on the reactor site, or in decentralized facilities, some or all of which can be off-site. A basic technical condition for siting is that the site should exclude the possibility of external impacts such as aircraft crash and earthquake shock. Naturally, the political acceptability of siting of long term storage site is a separate issue and will be discussed later in this chapter.

Best available interim direct storage option

The considerations above suggest that, as far as technical conditions are concerned, the cask storage would be the best option for the direct storage strategy in terms of safety, because it relies mostly on a relatively simple passive safety features. The relative simplicity of the system will also make the system economically attractive in the long run.

This does not mean that the dry storage in cask will not pose any risk. On the contrary, the long term assurance of leak-tightness and diversity of the safety control should be further improved. Also, there is concern over the adequacy of existing casks in regard to shielding from neutrons [Kuni 1996]. But as a matter of comparison, it can be concluded that storage in cask is comparatively the best available option if the direct spent fuel management policy should be adopted.

5.2.3 Conditioning and final disposal

Although addressing all of the issues concerning final disposal of radioactive waste is beyond the scope of this MOX study, a description of the technical aspects of DFD path is still relevant for the assessment of a MOX program's implications for the back-end policy. This would be particularly of interest to the Japanese public because the non-reprocessing option has not been much discussed in Japan.

Conditioning

The key advantage of the DFD path may be in that the spent fuel can be put to final disposal (storage) without intensive processing. But a step called conditioning is necessary after interim storage to bring the spent fuel into a disposable form, because the cask for final disposal has to satisfy a number of technical criteria, which differ from those for interim storage. While it is undoubtedly clear that much has to be done to the spent fuel which comes from wet storage, it should not be overlooked that spent fuel stored in a dry cask also has to be subjected to a conditioning process.

The package or cask for the final disposal(storage) has to be designed to remain intact for 10,000 years or longer under the geological conditions of the final facilities. The technology for conditioning for final disposal is immature and specifications of the package and therefore the packaging procedure are yet to be established. The details will depend on the conditions posed by the specific final disposal facility adopted. It is therefore not possible to define the final technical criteria for conditioning before the definite design for the final disposal facility has been decided. But the basic processes for conditioning of spent fuel in a conditioning plant would include:

-removing the spent fuel from the interim storage cask or can, or from the transport cask in the case of wet interim storage. Due to the high radiation of spent fuel this has to be done by remote control in a properly-shielded room with control facilities, ventilation systems and filter systems.
-conditioning spent fuel assemblies: there are two basic options. The first is based on using the fuel assembly as it is, while the second is based on disassembling to fuel rods; the first option needs less handling in the conditioning plant, but more space in the final disposal casks. In the second option, the spent fuel assemblies have to be disassembled, which would include cutting fuel top fittings and removing all other fittings to the fuel assembly (e.g. spacers) so that the pure fuel rods remain. The second concept has the benefit of saving space in the final disposal casks, but needs more handling.
-loading of fuel rods or fuel assemblies in a can and closing the can by welding or some other means.
-filling the can into the final disposal cask and applying overpack to form the final

package.

After these conditioning procedures the packed spent fuel can be brought immediately to the final disposal facility. It has to be remarked that the conditioning is not necessary before the final disposal facility becomes operable. Up to that time the spent fuel has to remain in the interim storage facility.

Final disposal

The most probable way of final disposal, if ever a public decision is made, would be burial in a rock layer 500 to 1000 meters deep underground. As mentioned above, however, we will not address the issues of final waste disposal itself (feasibility, survey, research and assessment of specific geological site, structure of repository, safety criteria etc.). It has to be pointed out here only that the key factors to be taken into account should be heat generation of the waste package, long term integrity of the package and the geological characteristics of the surrounding rocks such as the tectonic stability and water permeability. While these factors are strongly affected by the amount of radioactivity (heat, radiation), they do not depend much on the type of specific nuclear fuel path because the amount of radioactivity is determined by the amount and burn-up of original spent fuel generated. Recognition of this basic point is essential to the comparison between the direct and reprocessing paths.

5.3 Reprocessing Path as the Back-end Policy Option

5.3.1 Technical steps for reprocessing

Reprocessing is not a process which makes radioactivity disappear. Reprocessing is only a chemical process for separating different radioactive materials. These materials need further handling. Therefore the Reprocessing Path actually consists of far more facilities and steps of handling than needed only for the mere reprocessing process:

-Spent nuclear fuel is first taken out of reactor and stored in a pool at the site to cool down its radioactivity. Transport to the reprocessing plant is physically possible after a cooling period of 1-2 years. Due to logistical reasons a lot of spent fuel assemblies in practice stay longer at the reactor site.
-Then the spent fuel is transported to the reprocessing plant. Transportation may involve long distance shipment such as from Japan to Europe.
-At the reprocessing plant, the fuel will be stored for some time in the receipt storage

facility pools. The storage time depends on the process schedule of the reprocessor. It can last several years.
-Then the fuel is subjected to an extensive chemical separation process, the reprocessing itself. In the most common process (applied in La Hague as well as in Sellafield), the radioactive substances contained in spent fuel are chemically separated through a wet chemical process (more specifically the PUREX process) based on solvent extraction into three major fractions, uranium (around 96%), plutonium(1%) and fission products (inclusive of actinides). The operation of the process leads to the release of high amounts of radioactivity to the environment (see Chapter 3 Section 3.5.1 for a detailed analysis). There is also the potential risk of major radiation accidents which could contaminate thousands of square kilometers of land.
-Reprocessed uranium (RepU) is stored and could finally be put to use as fuel after processing, or could well be dealt as waste, depending upon the policy.
The necessary processing for reuse as fuel includes:
-Chemical conversion
-Re-enrichment in a enrichment plant, which is able to deal with the higher radioactivity of RepU
-Fuel fabrication in an uranium fuel fabrication plant, which is willing to deal with the higher radioactivity of RepU
-Necessary transports (e.g. from and to Russia, since re-enrichment of RepU is often done there, probably because of low enrichment cost and less stringent radiation regulations.)
-Recovered plutonium would be stored and could finally be put to use as fuel, the so called mixed oxide (MOX) after processing, or could well be dealt as waste, depending upon the policy.
For reuse following steps are necessary:
-Transport of the plutonium to a MOX fuel fabrication facility
-MOX fuel fabrication
-Transport of MOX fuel back to Japan
-Residual main body of highly radioactive substances in nitric acid solution will finally be solidified into borosilicate glass logs in a process called vitrification. Then the vitrified high level waste (VHLW) will be sent back to the customer.
-The VHLW has to be stored for a period of 30 years (or longer) in an interim storage facility suitable for VHLW.
-After the interim storage it has to be conditioned for final disposal.
-Final disposal of conditioned VHLW at a high level nuclear waste repository (heat generating nuclear waste disposal facility). The conditioning and the process for final disposal are basically similar to that of DFD path (see 5.2.3).

Difficulties of reprocessing industry

Table 5-1 lists the industrial-scale civil reprocessing plants now operating in the world [Albright et al. 1997; IEER 1997]. As shown in the table, there are only five plants operable industrially for light water oxide fuel , two in France and one each in the UK Japan and Russia, whereas there are some 340 light water power reactors in the world.

Table 5-1 LWR Reprocessing Plant in the World

Location	Plant	Owner/ Operator	Design Capacity (tHM /y)	Year of operation
La Hague(F)	UP2-800	COGEMA	800	1994
La Hague(F)	UP-3	COGEMA	800	1990
Sellafield(UK)	THORP	BNFL	1500	1994
Tokai-mura(J)	Tokai	PNC	(100)	1977
Chelyabinsk(R)	RT-1	Minatom	600	1976

The contrast already suggests the difficulty of industrializing reprocessing. The records of the existing five plants show technical and environmental difficulties some of which have been described in Chapter 3, but the latest explosion of the low level waste bituminization plant [NIT 1997] at the Tokai reprocessing plant reinforced our impression that reprocessing is an yet unproven technology. The Tokai plant will have to be kept out of operation for many years [JT 1997] and the plants in France and the U.K. suffer from their own problems [Hibbs 1997; CORE 1996].

5.3.2 Radioactive waste from reprocessing

Essentially, three categories of radioactive wastes are produced by reprocessing, although classification systems and therefore regulations are somewhat different from country to country.

-Liquid or vitrified high level waste (VHLW)

Most of the fission products and actinides in the spent fuel will be contained in this fraction (typically in the form of 170 l glass log contained in a stainless-steel canister). The volume of the VHLW will be in the range of 0.1-0.15 m^3 per ton of light water spent fuel according to industry sources[COGEMA 1993; Homberg et al. 1995; Takagi 1994].

-Intermediate level waste (ILW)

Although this category usually indicates hulls[5] and medium level radioactive waste with radioactive concentration of around 1 MBq/g, the definition for "intermediate" is rather vague and would in practice include all wastes between high and low level[6]. Waste containing relatively large concentration of alpha-emitters (alpha-waste or TRU) should be treated separately from other waste but is usually included in this category. The volume of ILW as given by the reprocessors ranges from 1.3 to 2.6 m^3 per ton of light water spent fuel [Homberg et al. 1995].

-Low level waste (LLW)

The low level waste from the process stream of the reprocessing plant mainly comprises concentrates of various kinds of low level waste liquid solidified into bitumen, cement or polyester as well as miscellaneous solid low level wastes arising from the daily reprocessing plant operation such as gloves, coats etc.. The definition of "low level" is again not so clear and differs from country to country. In Japan, "low level" can be interpreted as "allowed to be put to surface repository", for which upper limit of radioactive concentration for certain radio-nuclides are regulated [NSC 1986]. The estimated volume of LLW as given by the reprocessors ranges from 3.8 to 6.8 m^3 per ton of light water spent fuel.

Other wastes from reprocessing-MOX path

- Uranium waste

Important amounts of wastes stem from the reprocessed uranium and its handling. The biggest amount is depleted uranium stemming from the reenrichment of the RepU (more than 3/4 of the original uranium mass). Others are production wastes of the steps of RepU handling.

-Spent MOX and plutonium waste

As shown in Fig.1-4, the reprocessing-MOX path also produces various kinds of radioactive wastes outside the reprocessing plant including the spent MOX fuel and MOX fabrication plant wastes. The radiation and heat associated with this spent fuel are much higherwith UO_2 (see Section 5.4.1). The waste from the MOX fabrication plant containing significant levels of plutonium needs careful management and safeguard (see Chapter 3).

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5. Undissolved residues from reprocessing such as fuel cladding

6. Currently, there is no official regulation in Japan for the intermediate level waste and therefore all the waste not classified as low level (to be disposed of shallow underground) and TRU should be treated as high level.

-Decommissioning waste

Although usually not done, the wastes emerging from decommissioning a reprocessing plant should also be regarded as the reprocessing wastes, because they are apparently wastes only associated with the reprocessing path. The most voluminous part of the decommissioning wastes is the concrete waste which is considered to be of very low level, but decommissioning also generates wastes of much higher level up to intermediate level.

The estimation of volume of radioactive waste corresponding to one metric ton of spent fuel reprocessed depends upon the total amount of spent fuel reprocessed during the life of a reprocessing plant and therefore is open to uncertainties. It is evident, however, that the volume of radioactive waste to be disposed of would increase strikingly with the decommissioning. Some estimations suggest that the waste volume associated with decommissioning would be as much as 30 to 80 m^3 per ton of spent fuel [Large 1993]. It should also be noted that the feasibility of decomissioning a large reprocessing plant is highly questionable.

-Radioactive discharges and "virtual waste"

As has been described in Chapter 3, radioactive aerial and liquid discharges due to normal operation of the reprocessing plant are substantial. Although these are not usually treated as waste, they are a sort of radioactive waste directly dumped into the environment. [Homberg et al. 1995] call these discharges as "virtual waste" and estimate the corresponding volume of "waste" for the La-Hague reprocessing plant, assuming the emissions are to be solidified into low level waste packages. Their estimate is 23.7 and 11.9 m^3, respectively for aerial and liquid discharges, but the ability to retain these environmental discharges and solidify them, rather than dispersing them, has yet to be seriously examined.

5.3.3 Transport of radioactive wastes

While the reprocessing path necessitates various types of radioactive transports as has been described, the most difficult and controversial shipments are those for return of radioactive wastes from a foreign reprocessor to the home country, such as the ones now taking place from France to Japan in regard to VHLW.

With the exception of the first generation of contracts between the French reprocessor, COGEMA, and their British counterpart, BNFL, and foreign clients covering a relatively small quantity of fuel, all reprocessing contracts contain the options to send back the wastes arising from reprocessing. French law on radioactive

waste[7] stipulates that the storage of foreign radioactive wastes is prohibited beyond the time frame technically necessary to carry out reprocessing. This is understood as covering the period necessary for the HLW to cool down enough to be returned to the country of origin. Also recent reprocessing contracts usually contain the "return clause" which obliges the country sending the spent fuel to take back in principle all the reprocessing wastes[8]. CNIC's estimates [Takagi 1994] of the amounts of waste to be sent back from France and the U.K. to Japan as a result of reprocessing with return clause contracts at La Hague (LWR spent fuel: 2774 tHM) and Sellafield (GCR spent fuel:920 tHM; LWR spent fuel:1998 tHM) are given in Table 5-2. The estimates are largely based on the yet-unpublished internal documents by the Japanese utilities, which are based on figures presented by the European reprocessors.

While the VHLW is being transported and stored in the storage facility at Rokkasho, there is no plant to build a storage/disposal facility for the wastes in the other category groups (ILW, LLW and TRU) which are also planned to be stored at Rokkasho [STA 1994].

7. 30 December 1991 Act on the Research and Management of Radioactive Waste (France)

8. There are discussions inside the U.K. about the so called swapping of wastes, which means substitution of a small quantity of additional HLW for a large quantity of LLW and ILW equivalent in toxicity and radioactive inventory. This is therefore also called Curie-Swap. Sending back only HLW would be cheaper because of the greatly reduced volume and therefore the greatly reduced number of necessary shipments. The prospect for this swapping plan is , however, now not clear after the failure of NIREX in the beginning of 1997 to get the Rock Characterization Facility at Sellafield licensed , because the ILW and LLW supposed to be buried at Sellafield may now have to be returned to generating countries due to lack of diposal facility in the U.K.

Table 5-2(a) Wastes To be Returned from France to Japan

Waste type	Medium	Container	Containders /ton HM	Total Number of containders	Radioactivity /container (Bq)
HLW	glass	material: stainless steel size: 0.4mΦ x 1.3m high volume: 170 ℓ	0.73	2,030	α 1.4E14 βγ 2.8E16 wattage:2.0kW
Low & Interim.					
Hulls	cement	material: stainless steel size: 1.1mΦ x 1.7m high volume: 1,300 ℓ	0.4	1,110	α 2.4E12 βγ 1.4E15
α waste	cement	material: asbestos cement size: 1mΦ x 1.5m high inner canister: 400 ℓ	1.4	3,880	α 7.4E10 βγ 7.4E11
non-α waste	cement	material: asbestos cement size:0.9mΦ x 1.2m high inner drum: 200 ℓ	5.4	15,000	βγ 3.7E9
chemical precipitates	bitumen	material: stainless steel size:0.6mΦ x 0.9m high volume: 210 ℓ	3	8,320	α 1.9E10 βγ 3.7E12
Total				30,300	(8,020m^3;2.9m^3/ton)

Table 5-2(b) Wastes To be Returned from the U.K. to Japan

Waste type	Medium	Container	Containders /ton HM	Total Number of containders	Radioactivity /container (Bq)
HLW	glass	material: stainless steel size: 0.4mΦ x 1.3m high volume: 170 ℓ	LWR 0.54 MGX 0.12	LWR 1,080 MGX 110	LWR α 3.5E14, βγ 4.5E16 MGX α 6.1E13, βγ 4.5E16 wattage:2.5kW
Intermediate					
Hulls	cement	material: stainless steel size: 0.8mΦ x 1.2m high volume: 500 ℓ	0.77	2,250	BWR α 4.2E10, βγ 6.8E13 PWR α 8.0E10, βγ 1.6E14
Centrifuge slurry	cement	ditto	0.45	1,310	PWR α 1.5E11, βγ 6.3E13
Others	cement	ditto	0.044	260	α 6.0E7, βγ 2.6E11
Pu contaminated waste					
flammable	cement	material: stainless steel volume: 500 ℓ	0.05	150	α 7.5E10, βγ 2.7E12
inflammable	cement	ditto	0.1	290	α 4.2E10, βγ 1.5E12
LLW	cement	material: steel size: 2.1mH x 3.8mL x 1.8mW volume: 9,000 ℓ	0.75	2,190	α 1.1E8, βγ 1.9E9
Total				7,640	(22,000m^3;7.6m^3/ton)

5.4 Comparison of Reprocessing and Direct Storage-Disposal Path

The purpose of this chapter is to examine the justifications for the reprocessing/MOX path as compared to the once-through option in so far as they impact upon the back-end policy point of view. As briefly mentioned in the beginning of this chapter, this seems to be becoming more and more important under the current situation, whereby the main motivation for the reprocessing/MOX fuel cycle option is shifting in many countries from the fuelling policy to the alleged advantages in spent fuel and radioactive waste management.

5.4.1 Decay heat

The decay heat of the vitrified high-level waste after reprocessing is about 95% of the decay heat in the reprocessed spent fuel. The decay heat is a crucial factor limiting the useable capacities of interim storage and final disposal. Therefore, reprocessing cannot efficiently reduce the need of storage capacities compared to the DFD path. It should also be emphasized that plutonium is not the most toxic and long living radionuclide in spent fuel. There are other isotopes of actinides, especially Neptunium-237 with a half life of 2.14 million years, that are more mobile in the long term and will dominate the future radiation exposures caused by a final disposal facility.

Ignoring these facts, the nuclear industry claims that the reprocessing path results in vitrified high level waste of smaller volume with less decay heat and toxicity for final disposal and thus presents less environmental burden than the DFD path [ACE]. This is claimed on grounds that VHLW package for final disposal can be less voluminous, toxic and heat generating than the direct storage/disposal package and because plutonium and other actinide isotopes are assumed to be removed by reprocessing from the VHLW package. There are typical figures in nuclear industry literatures demonstrating reduced heat of VHLW as compared to direct spent fuel [OECD/NEA 1993], but this is an over-simplified argument from the overall perspective of back-end because it ignores the fact that reprocessing/MOX use path generates also spent fuel (MOX spent fuel) and actinides.

If one is to compare the volume and thermal output of the high level waste from the reprocessing/MOX path and DFD/once through path, the total high level wastes generated should be compared.

-The high level waste from DFD path is basically spent fuel itself.
-The high level waste from reprocessing path is

(a) vitrified high level waste, whose thermal output is, as discussed, essentially

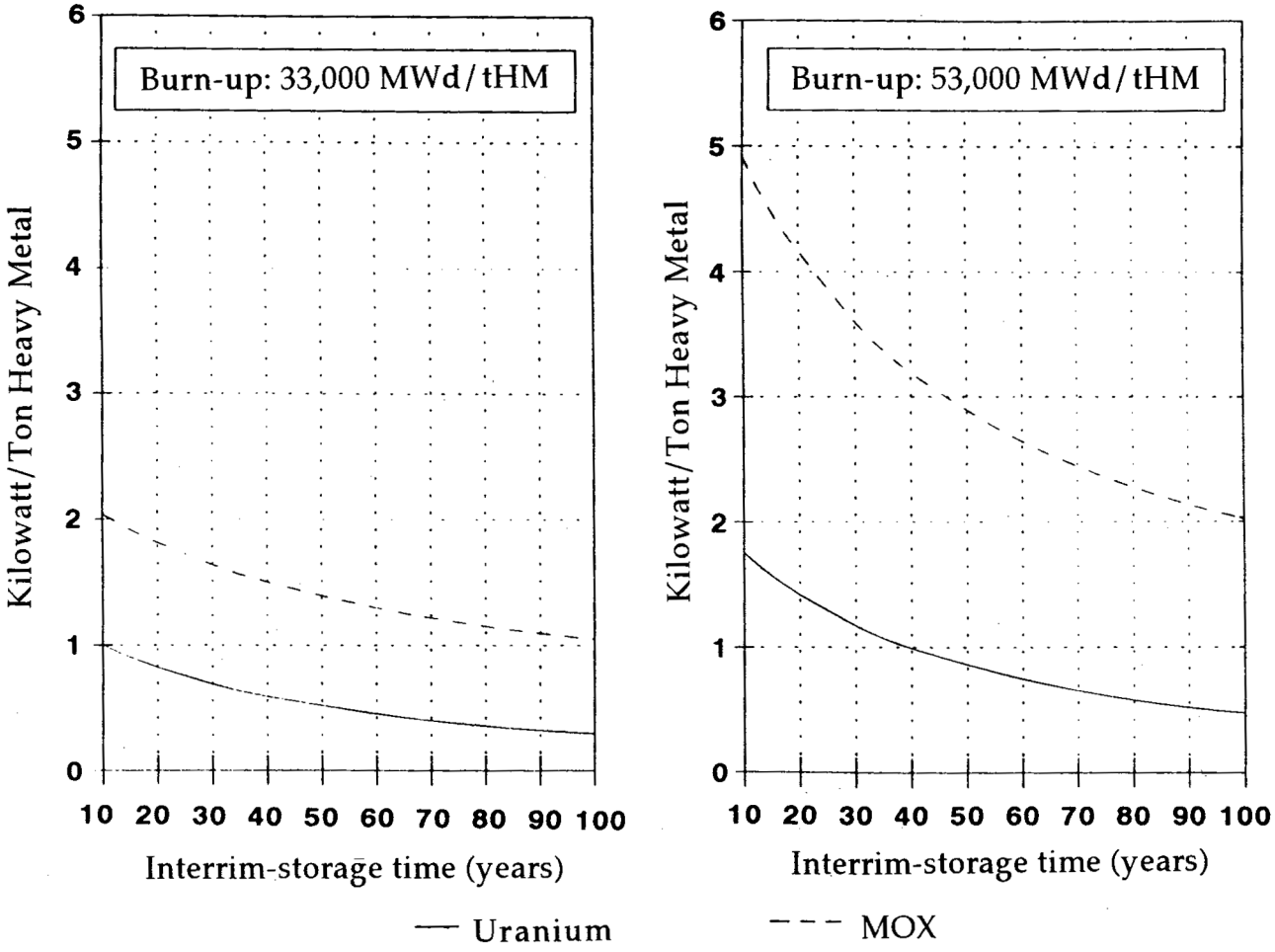
the same as the original spent fuel,
and

(b)spent MOX fuel whose decay heat is always much higher than that of the UO2 spent fuel with the difference increasing with the fuel burn-up [Wiese 1993;Thomas 1991].

Fig. 5-2 shows a comparison of the thermal output of UO_2 and MOX spent fuel [Kueppers and Sailer 1994]. As the figure shows, the thermal output of spent MOX fuel is higher by factor 2 than that of UO_2 spent fuel at moderate fuel burn-up and by about factor 3 or more at higher burn-up due to build up of heat generating long-lived actinides. This implies that the decay heat per unit electricity production is always far larger in the case of MOX fuel as compared to $_2$UO

In summary, DFD path is preferable from the standpoint of overall heat management to the reprocessing path. The same holds true for the radiotoxicity involved. It is logical to add that reprocessing the spent MOX fuel for multiple recycling of plutonium can never contribute to clearing the difficulty of reprocessing path in regard to high level waste management.

Fig. 5-2 Heat Generation of Spent UO_2 and MOX Fuel



5.4.2 Total waste comparison

It may be still argued that the discussion given above would not be valid, if the reprocessing policy was adopted purely as a management strategy for back-end policy and no use of plutonium was made. While this policy leaves aside the question of what to do with separated plutonium, conducting the comparison of waste arising from the DFD path and reprocessing path -- without waste from plutonium utilization or disposition -- would be worthwhile.

Let us first start the comparison by using the very optimistic figures given by the Japanese reprocessor at Rokkasho, JNFL. Table 5-3 compiled by CNIC and --based on the company's official figures [JNFL 1989] -- gives the volumes of various waste categories.

Table 5-3 Estimated Waste Volumes from Rokkasho Reprocessing Plant [CNIC 1994]

Waste group	Generation / year	Solidified volume (m^3) / tHM SF
HL liquid	560 m^3	0.21 in VHLW canister
LL liquid concentrate	2,200 m^3	0.7 in 200 l drum
Organic solvent waste Resins and sludge	160 m^3 10 m^3	0.075 in 200 l
Hulls and FA fittings	300 tons	0.5 in 1,000 l container
Channel boxes and BP	100 tons	0.14 in 200 l drum
Miscellaneous solid	1,000 tons	1.1 in 200 l
TOTAL		2.7

SF: spent fuel; FA: fuel assembly; BP: burnable poison

The figures are only *projections* based on the industry's optimistic expectations. The total volume is far less than COGEMA's value for La Hague of 6.65 m^3, which some analysts regard as excessively optimistic calculations [Homberg et al. 1995]. But, when the total volume of 2.7 m^3 without packages for management / disposal is compared with the bare volume of spent fuel (0.4 and 0.5 m^3, respectively for ton of PWR and BWR fuel), the waste volume from the reprocessing is about 6 times than that of the original spent fuel.

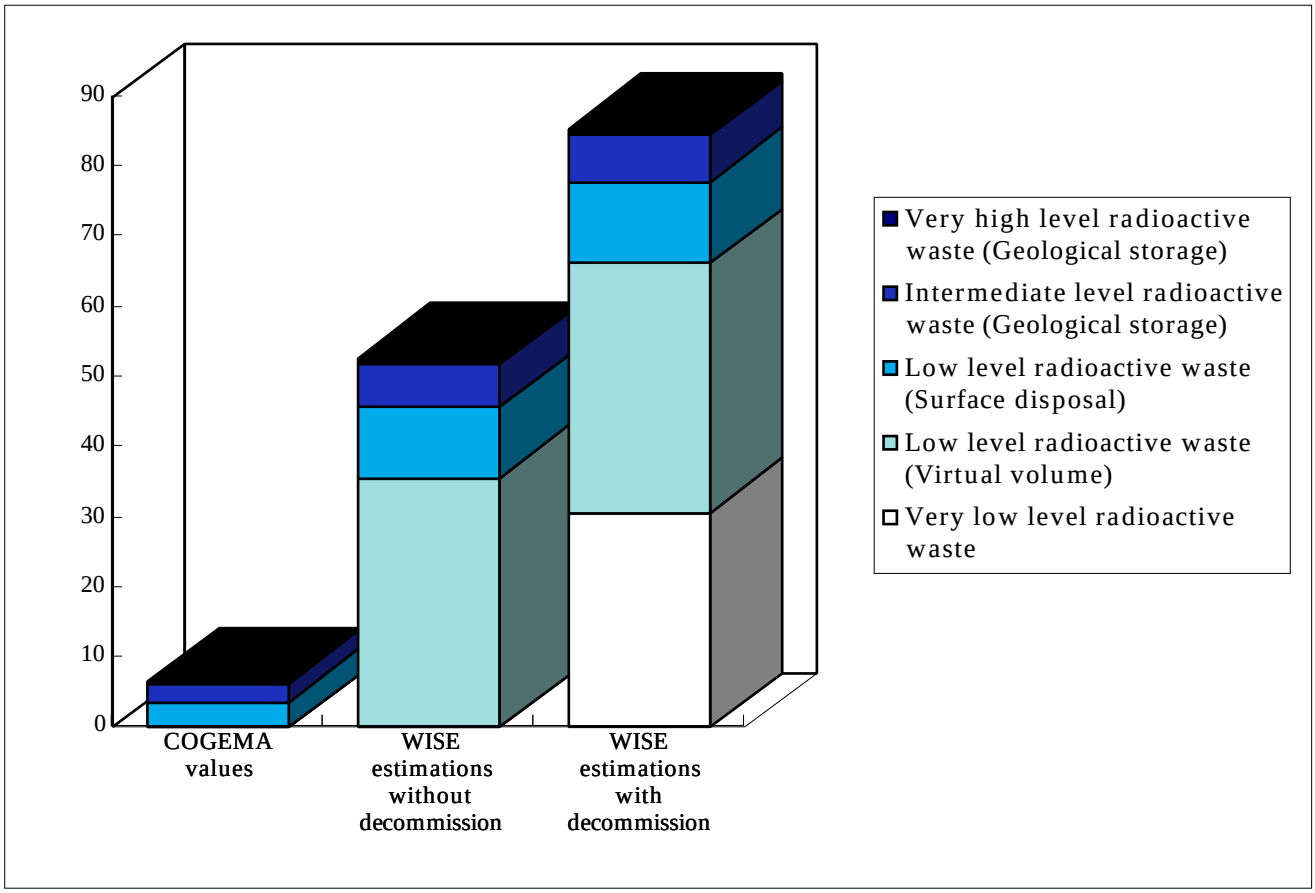
It is interesting to note that as of the end of March 1996 the historic operation of the Tokai reprocessing plant produced about 13,000 m^3 solid waste equivalent of liquid and solid radioactive wastes, after having reprocessed 813 tons of spent fuel [NSC

1996]. This indicates that about 16 m^3 waste was generated from a ton of spent fuel reprocessed, which is more than 6 times the projection for Rokkasho.

The only official public statement by the Japanese government for the reprocessing waste volumes is that given in a Diet session in 1993 by H.Ishida, a top government official in charge: "the volume of waste would be probably 20 to 30 times that of the original spent fuel volume"[Ishida 1993].

WISE-Paris gives a much higher estimate of reprocessing wastes, which is reproduced graphically below in Fig. 5-3 from its report. Their figures include the "virtual waste" (environmental discharge as converted to solid waste) as discussed in 5.3.2 above, but the issue of "virtual waste" set aside, we regard the estimate as very realistic. The amount of low, intermediate and high level radioactive wastes adds up to 17.2 m^3 per ton of spent fuel without the decommissioning waste, and this is in general agreement with the performances of Tokai plant (16 m^3).

Fig. 5-3 Reprocessing Wastes per Ton of Spent Fuel [Homberg et al. 1995]



To summarize this section, if we compare the total estimated volume of wastes from the direct disposal and reprocessing paths respectively with the package for disposal included but without counting the decommissioning of related facilities and plutonium disposition, the former may be up to 2.67 m^3 [Schaller 1990] while the latter is 17.2 m^3, indicating that the reprocessing path generates at least 6 times more wastes than the direct disposal path. These may be regarded as the most conservative values, and more realistic estimates for the reprocessing waste suggest that it would be at least 10 times larger.

WISE-Paris estimations are given below reproduced below [Homberg et al. 1995 p 100].

Table 5-4 Waste Produced by Direct Disposal or Reprocessing[9] (waste volumes in m^3/t HM, including packaging)

Waste category	Direct disposal - Option B		Reprocessing	
	Without decommisioning	With decommisioning	Without decommisioning	With decommisioning
High level radioactive waste (Geological disposal)	1.58	1.58	0.91	0.91
Intermediate level radioactive waste (Geological disposal)	0.65	0.76	6.09	6.59
Lowlevel radioactive waste (Surface disposal)	0.44	0.75	10.24	11.64
Very low level radioactive waste (concrete)		6.65		30.70
Virtual wastes (discharges)			35.62	35.62
Total wastes	**2.67**	**9.74**	**52.86**	**85.46**
		WISE-Paris estimation		

9. There can be a number of conceivable options for the packaging of direct disposal wastes and in option B only containers holding rods are placed in a Pollux heavy container. Decommissioning here means that for conditioning plant for direct disposal (see for details [Homberg et al. 1995]).

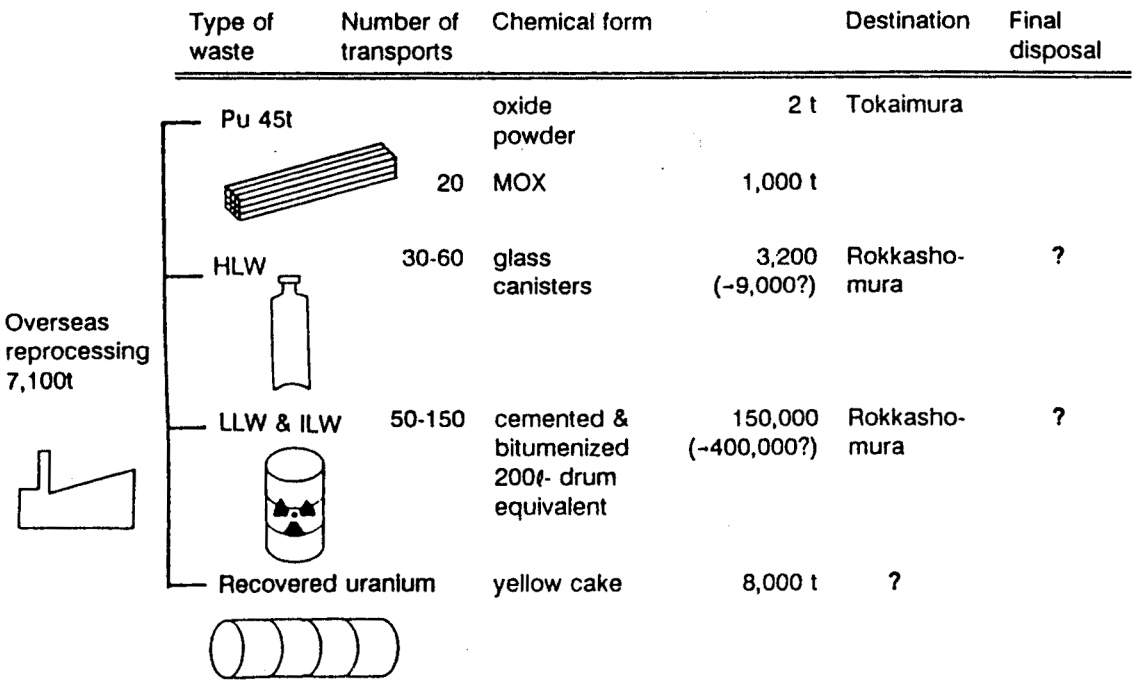
5.4.3 Radioactive discharge

The large environmental radioactive discharge associated with reprocessing is obviously a great disadvantage of reprocessing path as compared to the DFD path, which has no counterpart emission. Radioactive discharges from reprocessing have been dealt with in Chapter 3.

5.4.4 Transport and other related nuclear activities

The issue of increased transports and related industrial activities associated with reprocessing/MOX use path has been discussed in preceding chapters and will further be detailed in Chapter 7. While not much needs to be added, a reference to the transports of radioactive materials associated with overseas reprocessing of Japanese spent fuel would be worthwhile.

Fig. 5-4 Wastes to Be Returned from Europe to Japan



As described in 5.2, large amounts of wastes have to be sent back from Europe to Japan in accordance with the reprocessing contracts in addition to the shipments of spent nuclear fuel from Japan to Europe[10]. The types and number of shipments as estimated by [Takagi 1994] is illustrated in Fig. 5-4. More than 200 shipments are

10. More than 97 % of the shipments with a total of 7,100 tons of Japanese spent fuel from Japan to Europe have already been carried out as of September 1997.

expected to take place in the coming decade, while one plutonium and two VHLW shipments carried out in the past five years aroused world wide concerns. There are still serious uncertainties about how all these expected shipments could be carried out safely.

5.4.5 Reprocessing vs interim storage

Though the original motivations for plutonium separation and use appear to have disappeared worldwide for reasons already mentioned, reprocessing is still practiced in many countries and is still being pursued in East Asian countries like South Korea [Hibbs 1997b], as the best nuclear fuel back-end policy. The reason is that the storage capacity of spent nuclear fuel assemblies is going to run out soon at many sites and sending them to an existing reprocessing plant which has still an extra storage capacity could avert the difficulty for some time. This may be the last remaining "justification" for reprocessing.

It is going to be exactly the case in Japan. The total generation of spent fuel under the present nuclear generating capacity of 40.27 GW at 51 commercially operating reactors is about 1,100 - 1,200t (HM) per year. The existing on-site storage pool capacity totals around 15,000 t with about one third already occupied [ACE-att 1997]. When the 3,000 t storage capacity at the Rokkasho reprocessing site is added, the storage capacity will probably run short in around 2010 (see Table 5-5). While the capacity shortage is therefore not so impending in Japan as a whole, it is becoming serious for some reactor-site spent fuel pools and re-racking has been implemented.

Furthermore, it should be noted that the storage at reactor sites is only accepted by the local governments as temporary management and not as interim storage in Japan. The official position of Zengenkyou (the National Association of Nuclear Power Plant Site Cities, Towns and Villages[11]) is that the local governments at the sites do not admit "any interim on site storage"; and therefore all the spent fuel should be removed from the site as quickly as possible. However, Zengenkyou partially modified its strict "no storage principle" to allow interim on-site interim storage in cases when the relevant local government judges it unavoidable [Asahi 1997]. The decision of Zengenkyou was made at its 1997 Annual Assembly which took place just after the Tokai accident (in March) and Aomori Prefecture's resistance to accept spent fuel from reactor sites at the newly-completed storage pool at the Rokkasho Reprocessing Plant site.

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11. Zengenkyou (Zenkoku Genshiryoku Hatudensho Shozai Shichoson Kyogikai) (currently headed by I. Kawase, the major of Tsuruga, Fukui) is an ad hoc organization with no legal power, but, organizing all the 24 municipalities of nuclear plant sites and 10 neighboring local governments, it has a very influential role in Japanese nuclear policy decision making.

This type of situation may be more or less common to every country with a nuclear energy program. While we will address the political aspect of this back-end policy issue briefly later in this Chapter, the issue of spent fuel storage problems and opposition of local residents to on-site storage has its roots in the difficulties of radioactive waste management and disposal. This fundamental problem lies at the very heart of the nuclear energy debate and no back-end policy can solve these basic difficulties. Moreover, the in-depth analysis of these issues is obviously beyond the scope of this study.

However, it must be emphasized here that using the reprocessing or storage at the reprocessing site is nothing more than going to an emergency refuge. Aside from the reprocessing wastes to be returned, the spent fuel sent to a reprocessing plant will sooner or later be sent back as MOX fuel and stay at the site as spent MOX fuel[12]. Thus, reprocessing will not solve problems. It may put off the urgent difficulty, which will without a doubt however return even in a more serious form.

5.4.6 Rational back-end policy --- conclusion

To conclude this section, we can now clearly state that the direct management/disposal of spent fuel is definitely a better option than the reprocessing (and MOX use) path as a back-end strategy. The choice of the back-end policy is, in short, to opt for the most rational way of handling, managing and disposing of radioactive substances produced in spent nuclear fuel.

Our conclusion is, at least in regard to the back-end policy for the light water reactor fuel, that the direct management and disposal of spent fuel is doubtlessly the preferred option, since in this way the enormous range of radioactive substances which are obviously the central hazard of nuclear energy can be principally confined in fuel elements; and so there is no need to take them out and subject them to additional processing. It has been shown above that the additional handling and processing of spent fuel necessitated by the reprocessing path have no positive effect on the back-end management.

Insofar as any argument against DFD it might be pointed out that the DFD path needs still a conditioning plant before producing the final disposal package. But VHLW from reprocessing would also need conditioning for the final; disposal and if MOX use is implemented, the spent MOX fuel needs also to be conditioned for long term management and later again for final storage. Conditioning requirements are therefore common to each option.

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12. The Japanese government policy is very vague on construction of spent MOX fuel reprocessing facility and we can reasonably assume that reprocessing of spent MOX fuel will not take place for the foreseeable future.

To summarize our conclusion in other words, the nuclear activities, if ever necessary, should be kept as simple as possible, since that minimizes the potential for accidental radioactive release and nuclear proliferation as well as control on information and limits to civil liberties. From this point of "simplicity principle", the best option is the DFD path.

Also, from the same view point, for the interim storage along the DFD path, dry storage is preferred to wet storage as the storage technology option since the former requires fewer active safety features and thus less vulnerable to failure.

5.5 Future Handling of Spent Fuel and Plutonium

5.5.1 Cancelling the reprocessing contracts

Following the analyses developed in this and preceding chapters, there remains no logical justification for MOX use and reprocessing. The analyses set out above clearly leads to support for the direct management / disposal of spent fuel. Therefore, further plutonium separation should be halted and the corresponding reprocessing contracts be cancelled. Now is an appropriate moment for Japan to do this, because the Tokai Reprocessing Plant is expected to be out of operation due to the March 1997 explosion accident at least for a few years to come, and the plutonium program is being reconsidered. Furthermore, THORP and UP3 where Japanese spent fuel are being reprocessed have their own problems. THORP has so far hardly reprocessed any of the contracted Japanese spent fuel.

It is widely said and believed that the cancellation of overseas reprocessing contracts is impossible. This is not true. Although the details of the reprocessing contracts between the Japanese utilities (under the coordination of ORC = Overseas Reprocessing Committee) are not published, typically commercial contracts contain a clause, which allows cancellation under unavoidable situations. *Even if the client utilities were forced to pay all of the amount fixed under the commercial contract plus the additional cost of returning the spent fuel, the total cost would be almost certainly lower than the MOX option.*

A political decision by the Japanese government, supported by a parliamentary resolution, is enough to be treated as the unavoidable conditions. It cannot be exaggerated that a national political decision takes always priority over a commercial contract. This may cause some difficulties between the contracted parties and the respective countries involved, but so far as it is a nation's decision, the difficulties can be overcome by determined diplomacy.

Cancellation can thus be effected and should be implemented as early as possible. To say the least, a public discussion should now be started supported by unrestricted access to the details of the reprocessing contracts, which will assure a precise evaluation of losses and gains of such cancellation. Refusal to disclose details of contracts on the grounds of commercial confidentiality should not be acceptable in the context of such an important public policy decision.

Steps after cancellation

After cancellation a number of steps have to be taken. Although details of the technical and political procedures are out of the scope of this study, the basic prospect for the post-cancellation steps will be discussed. Again, we focus our discussions here on the Japanese overseas contracts, because it is an issue of greatest interest to this study, but the basic thrust of discussion could also be applicable to other contracts.

For the ease of discussion, the following types of spent fuel and associated radioactive materials must first be distinguished.

(1) Spent fuel included in the contracts but not yet shipped from Japan to Europe
(2) Spent fuel transported to overseas reprocessing plants, but not yet reprocessed
(3) Wastes from reprocessed spent fuel
(4) Plutonium already separated and existing in European plants

Also in order to make clear the relevant issues and necessary steps, discussions of political decision-making procedures in the relevant countries will be dealt with separately from purely legal(moral) obligations and technical necessities.

Legal and technical steps

(1) The shipment of Japanese spent fuel to European reprocessors has to be stopped immediately. Because more than 97 % of the total 5,598 tons HM of LWR spent fuel are considered to have already been sent to Europe[13] with the planned remaining shipment of some 200 tons or less, to stop further shipment would cause practically no major problem. Of course there still exists the issue of prospective shortage of spent fuel storage capacity as mentioned in the preceding section, but this comes mainly from spent fuel arising in the future, which must be handled inside Japan in any case.

(2) The spent fuel existing at European reprocessing plants has to be sent back to Japan immediately after cancellation: this is the contractual obligations. Therefore there is a

13. Latest information publicly available is that about 96 % (5,350 t of total 5598 t) of the spent fuel to be reprocessed in Europe according to the contracts had already been shipped as of September 1995:Answer by the Government to Member of House of Representative Osami Imamura, January 31,1996.

need of establishing an interim storage capability in Japan with a capacity and in a time frame in accordance with the cancelling of the respective contracts .

The time frame of cancelling each individual contract must fit in with the time frame of planned reprocessing. The reprocessing schedule is usually announced to the customers 2 years in advance. So the Japanese utilities should have known in Summer 1997 the reprocessing schedule for 1998 and 1999. These amounts must first be taken into account in implementing cancellation of contracts and preparing for the interim storage. Implementing this return of spent fuel and finding the capacity and site for the interim storage in Japan as well as obtaining the international understanding is one of the most difficult parts of the cancellation scenario, but it should nevertheless be carried out. The key issue is mostly political and will be addressed in section 5.5.3.

(3) Waste generated until the cessation of reprocessing should be sent back to Japan according to the contracts. There are still unsolved safety problems concerning the transport and well justified international and domestic concerns over the safety as will be discussed in Chapter 7. But, as in the case of unreprocessed spent fuel, there is no other choice but for the reprocessors to return Japanese wastes and for Japanese utilities to accept them. There should be however an in depth impact assessment conducted prior to any further shipments, as demanded by CNIC, WISE-Paris, Nuclear Control Institute and Greenpeace International in an open letter to the concerned authorities dated September 14, 1994 [NIT 1994].

(4) As of the end of 1995, 9.96 and 1.42 tons of separated Japanese plutonium are stockpiled respectively at La Hague and Sellafield as announced by the Japanese government [AECJ 1996]. At the time of writing this chapter (August 1997) the amount may be respectively over 11 and 2 tons. Part of this was supposed to be fabricated first in Dessel, and then in Sellafield, into MOX fuel to be shipped back to Japan. But under current political conditions in Japan the fabrication will probably be substantially delayed. Therefore, we will think only of plutonium stored in the form of plutonium oxide.

From the results of our analyses, it is concluded that separated plutonium should be treated as waste and discarded as such in a proliferation resistant form. This can be achieved either by immobilization techniques[DOE/OFMD 1996; DOE/OACN 1997] or storage pin technology [Kueppers and Sailer]. Whatever route is chosen, the large amount of separated plutonium in La Hague has to be carefully dealt with.

Given that vitrified high level waste will have to be transported back to Japan, a possible choice may be to mix Japanese plutonium with Japanese high level liquid waste to produce vitrified high level-plutonium waste and send it back to Japan, particularly. This certainly needs further technical development, but there is already

evidence to suggest that adding plutonium to the high level glass log at a concentration of around 2 % would not give rise to serious additional difficulties to the safety problems inherent to the usual vitrified high level waste [DOE/OACN 1997]. The quantities of high level waste are considered by current assessments to be sufficient to incorporate all the separated plutonium.

5.5.2 Shutting down Tokai and scrapping Rokkasho

Reprocessing at the Tokai Reprocessing Plant is now virtually indefinitely suspended.

Immediately after the explosion at the bituminization plant of the Tokai plant, it was revealed that the ten Japanese utilities with nuclear power plants had concluded reprocessing contracts with JNFL [To-oh Nippo 1997]. Although details of the contracts are not known, this information may have been released by the utilities in order to show that they are still sticking to the reprocessing policy despite strong opposing voices. At any rate, the construction of the main parts of Rokkasho Reprocessing Plant has not yet been started, and the completion, if ever, will be many years behind the official time table of 2003. Under the circumstances, it would be a good choice for the Japanese utilities to cancel the contracts and urge the utilities-owned JNFL to halt construction of the plant.

5.5.3 Some thoughts on interim storage

As has been argued above, the direct interim storage is far better as the back-end policy option than the reprocessing path. Also, it has been argued that reprocessing path does not contribute at all to solving the spent fuel storage predicament.

However, Japan will face shortage of spent fuel interim storage facilities in near future and the proposed choice of direct interim/final storage/disposal would surely trigger the discussion on expanding the interim storage facility in Japan as described in 5.4.5).

Taking into account purely technical and economic considerations, expansion of the total storage capacity in the form of dry storage facilities, say by 100 %, would be feasible either at reactor sites or at some central storage facility. But the most important question is whether the expansion is acceptable to the nearby residents. Heads of the local governments as well as individual residents who took part in the Japanese nuclear energy policy roundtable talks in 1996 expressed almost unanimously concern over expansion of storage capacity in their sites.

As a background to the recent roundtable talks is a long history of undemocratic Japanese nuclear administration, with-decision making conducted without popular participation as will be discussed in the next Chapter. The residents fear that, if they

were to accept the idea of interim storage, this would likely result in an indefinite storage, and if they approved the expansion of storage capacity, it might open the way for indefinite expansion or almost limitless accumulation of spent fuel at their site. This is a well-founded concern and nobody can ignore it.

Table 5-5 Spent Fuel Stored and Storage Capacity in Japanese LWR Nuclear Power Plants

(as of the end of March 1996)

company	plant	full core loading (tU)	yearly reloading	spent fuel stored	storage capacity
Hokkaido	Tomari	100	30	140	550
Tohoku	Onagawa	160	40	70	570
Tokyo	Fukushima I Fukushima II Kashiwazaki-Kariwa	580 520 660	150 140 170	680 840 660	1,510 1,700 2,030
Chubu	Hamaoka	420	110	430	1,290
Hokuriku	Shika	60	20	30	180
Kansai	Mihama Takahama Ohi	160 290 360	50 100 120	150 510 270	510 1490 1320
Chugoku	Shimane	170	40	140	600
Shikoku	Ikata	170	60	170	700
Kyushu	Genkai Sendai	190 140	60 50	130 430	770 760
JAPCO	Tsuruga Tokai II	140 130	40 30	320 160	630 420
	Total	4,240	1,210	5,120	15,010

Under the current situation, it would be best to immediately start discussions on the back-end policy, in particular on the interim storage issue, with participation of a wide spectrum of residents and the nation-wide public. This can only be done with unrestricted access to information and the discussions may take a long time. Since the on-site storage capacity, although temporary in nature, will not run out in the short term (Table 5-5), there is still sufficient time to discuss the options in depth.

In view of the extreme scientific difficulty in finding a suitable geological layer for

final disposal -- and in reaching a decision politically as well -- expansion of interim storage capacity and prolonged storage are likely to be unavoidable. But the authors feel that a scenario for nuclear power phase out must be necessary in order to develop a certain level of consensus on the back-end policy, or even to start a calm discussion on the issue. Without a scenario based on the prospects for the end of production of spent fuel, there will always remain the fear over any interim storage facility that there would be indefinite incoming flow of spent fuel, which would be unacceptable to residents.

5.6 MOX Irradiation as Weapon Plutonium Disposition Option

We have made clear that we are strongly in favor of the direct management path as compared to the reprocessing/MOX path as the nuclear back-end policy. Based on the arguments in this report, we are equally opposed to the so-called MOX option for the disposition of weapons plutonium, although we will not fully address the weapons plutonium disposition issue in this study. But, since the decision of the nuclear superpowers would have large impacts on the civil plutonium program in these and other countries, some comments seem to be highly significant.

US government decided to take the so-called "dual-track" option [DOE 1997], which allows about two thirds of plutonium from dismantled nuclear warheads to be irradiated in MOX, and one third to be immobilized. The main justification for the MOX option is that only the MOX option could be adopted by the Russian government with whom the US, as the government claims, has to work in close cooperation and keep pace in the disposition process. But in reality the Russian government through its atomic agency (Minatom) is in favor of a civil plutonium program including MOX use (see A.Dmitriev's contribution in the Annex), and has no intention to restrict its MOX option to disposition of plutonium.

Therefore, the US decision in favor of the MOX option will rather lead to the stimulation of the Russian civil plutonium industry. It will also stimulate the civil plutonium industry in Japan and Europe, and could finally reactivate the once-dead US plutonium program (see the contribution by Leventhal and Dolley in the Annex 2). It is now evident that European plutonium industrial corporations like Siemens and COGEMA are trying hard to use US decision in favor of the MOX option for the survival of their plutonium activities.

The key interest of plutonium disposition is to bring dismantled weapons plutonium into a proliferation resistant form, the so-called spent fuel standard [NAS 1994, NAS 1995], but the MOX option needs a very complicated path to achieve the goal, with many plutonium related facilities and transport activities, which are

proliferation- vulnerable, as we have analyzed for civil MOX program in this study. In addition full core MOX burning with relatively high plutonium concentration which will be necessitated in order to implement the disposition in a reasonable time frame, is open to crucial safety questions and doubts (See Donderer's contribution in the Annex 2).

The MOX option is thus extremely unrealistic, at least in the short term, and is particularly so if it has to be implemented with Russia and United States keeping pace, because of the large political / social instability and financial difficulties of Russia.

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Chapter 6
Societal and Legal Implications of MOX Use

Part 1 Legal Aspects of MOX Use
-A Japanese Perspective

Ichiro Hokimoto

6-1.1 Current Status of the Rights of Residents in Regard to Nuclear Issues in Japan

6-1.1.1 Freedom of information

The history of the principle of "openness", or public access to information, in the Japanese nuclear policy began with the budget proposal -- suddenly announced and large in scope -- for nuclear energy R & D in 1954, and the subsequent critical reaction to it by the Science Council of Japan. The principle openness to "publicize the results of nuclear energy research, development and utilization to the public" was stipulated in the Article 2 of the Atomic Energy Basic Law Act[1] together with two other basic principles -- democracy and independence. At that time military aspects of nuclear energy were the main concern of Japanese scientists and the public at large, and the principle was introduced as a key device for prevention of military diversion.

However, the principle should now have a broader application as the "right to know", constituting a part of the citizens' rights of self-defence, in particular the right to protect the life and health of the residents living near nuclear facilities and more generally, the public at large. It should also be in accordance with the worldwide trend to guarantee fairness, transparency and accountability by breaking the secrecy of the administrative process in the licensing of nuclear plants, and assuring popular participation in the administration of nuclear energy through the use of administrative procedure laws and freedom-of-information acts.

Despite the general trends toward the freedom of information, there is no law in Japan like the Freedom of Information Act (FoIA) in the United States and what is guaranteed by the Japanese law regime is only the access to the "results", as mentioned above. This state is going to be improved, to a certain extent, in the

1. Atomic Energy Basic Law, first enacted in 1955, major amendment in 1980.

aftermath of the Monju accident, AECJ was forced to hold a series of Roundtable Talks on nuclear energy policy and at the end of the 11 meetings of the first series, AECJ issued a statement[AECJ 1996] which can be summarized as follows[NIT 1996b]:

> "AEC recognizes the principle of freedom of information and will accordingly open AEC-sponsored committees to the public with possible exceptions of meetings related to proliferation, physical protection, diplomatic negotiations etc. In order to reflect public opinions more effectively in the government decision-making, the committees of AEC, in deciding important policies, will first publish a draft report to solicit opinions from the public and adopt them when judged relevant. The rejected opinions will be published in the final report along with the reasons for their rejections."

This decision is generally regarded as progress because now the access to information on the *process* of decision making, not only *result* is basically recognized by the Commission. It is, when implemented, really a step toward popular participation in decision making, but it should be noted that the AECJ statement mentions only "reflect public opinions in government decision-making". This is just the current status in Japan of the citizens' rights on nuclear energy decision making.

6-1.1.2 Legal aspects of popular participation

What kind of legal regulations would be appropriate for a potentially highly hazardous entity such as a nuclear facility? Besides the large potential risks, it should also be taken into consideration that there is generally a sharp difference of opinions and values amongst the public regarding the very necessity of such a facility, and that those holding political power always tend to back such facilities but only taking account issues of energy security.

For nuclear facilities, of course there exists a traditional legal system[2] where the administrative agency first grants the applicant for construction of, for example, a nuclear power plant (i.e. an electric power company) a license, which may be followed by a lawsuit demanding the nullification of the license filed by residents or opponents. In this system, the judicial review as to whether the facility satisfies the safety standards set by the positive law or not is conducted *ex post facto*.

The ability of the court to judge, however, is extremely limited in regard to the highly technical discretion related to the licensing of the plant. Even when the court requests expert opinions in the process and gives consideration to them, there is a

2. The central Japanese law for regulation of nuclear energy is "Law for Regulation of Nuclear Raw Materials, Nuclear Fuel Materials and Reactors (first enacted in 1957).

marked tendency for the court to only confirm the licensing decision already given. The lawsuits related to nuclear power plants in Japan have all followed this pattern and led to loss on the part of the residents.

Therefore, a popular participation procedure is recommended in which the resident (group) is assured an exchange of information and documents, and discussion with the would-be operator of the plant over minimization of residual risks, the location and size of the facility, safety systems, etc. before a license was granted.

The kind of administrative procedure which should be introduced would have the following internal contradictions.

(a) On the one hand, there is a demand by the proponents to prevent delays almost inherent in the popular participation procedure. It is mainly the would-be operator which seeks the acceleration and simplification of the procedure. Similarly, residents do not want a long procedure, if it can be avoided.

(b) On the other hand, "legal hearings" of substantial duration should be guaranteed, as a part of the residents' rights to defend their community, to those whose life and health might be threatened by the construction and operation of the facility including possible accidents. The knowledge gained by the participation of local residents and the discovery, of facts overlooked by the would-be operator is sometimes extremely influential in the formation of the opinion concerning the administrative decision.

This is a conflict which arises particularly in the popular participation procedure when a large number of residents take part in or seek to participate. If a priority is given to the acceleration of the procedure at the expense of the full participation of the residents, it will only hinder the public acceptance of the final decision.

Keeping this situation in mind, let us now examine two issues related to bringing into being a system for popular participation.

First, the ideal structure of a procedural law presupposes real equality between the two parties. In the licensing procedure for a nuclear facility, however, the enterprise in charge of the project has an enormous advantage of proprietary information. If a perfunctory procedure is allowed without correcting this situation, there is no way for the citizens to obtain enough accurate information in support of their objections, and arguments they put tend to be insufficiently based and emotional in tone.

Therefore sufficient information and documentation -- even those related to commercial secrets -- should be disclosed to the citizens and experts assisting them. Enough time should be set aside for a trial-type public hearing so that opportunity to refute and rebut is guaranteed in a cross-examining process based on the documentation prepared both by the nuclear industry applicants and the concerned citizens. The final administrative decision should only be made having taken into consideration of the result of such a process. Unless equality of information between the "enterprise" and the citizens -- based on free access to information -- is guaranteed, the administrative decision cannot have the "legitimacy by way of the procedure."

Secondly, it is necessary to prevent the participation procedure from turning into a mechanism of "engineering of consent", which serves as an "alibi function" to justify the project as a result. A hearing held after all the preparations have proceeded on the assumption that the project would go through is an act of "administrative involvement", which is nothing more than a ceremony that gives false authorization of the project. For a hearing to be a procedure involving real public participation, it should be held at a stage where the project is still being planned, or at least before any administrative decision has been made so that there is a room for the objections raised by the residents to be reflected in the final decision and the administrative decision-making process itself.

6-1.1.3 Role of local governments

In real terms, under the current situations in Japan, the citizens are virtually deprived of the rights and power to intervene effectively as a equal party in the legal procedure and decision-making.

The recent developments in Japan, however, indicate that through the administration of local government the public's participation could perform an effective function. In Japan, the heads of local governments are chosen by direct election by residents unlike the prime minister of the country. This leads to residents placing strong expectation on local government which they feel are "nearer" to them. The heads of local governments thus have a heavy responsibility of fulfilling the duty of guaranteeing the safety of residents.

In fact, at the time of the recent accident at Monju, the on-the-spot inspections carried out by Fukui Prefecture and Tsuruga City based on the Nuclear Safety Agreement[3] led to the disclosure of the intentional cover-up[4] of the details of the accident on the part of the Power Reactor and Nuclear Fuel Development Corporation (PNC). Furthermore, after this sodium fire accident, the three governors of the prefectures of Fukui, Niigata, and Fukushima declared their refusal to agree to the use

3. In the legal system of Japan, the local governments have no legal powers in licensing and inspecting nuclear power plants. In order to make up for the deficiencies, a safety agreement is concluded between the relevant local governments and operator of the plant. The agreement is nothing more than a "gentleman's agreement" but usually provides clauses establishing local government's power to inspect and operator's duty to present relevant information in case of anomalous incidents and emergency.

4. PNC has tended and still tends to keep information secret as much as possible and cover-up facts. One of the findings of the Committee for General Evaluation of Monju Accident organized by CNIC is that this marked tendency of PNC comes from the very intrinsic nature of Japan's plutonium program for which PNC is exclusively responsible.

of MOX fuel in the light water reactors located in their prefectures until full discussions and deliberations were guaranteed, in an attempt to improve the safety of the residents [NIT 1996a].

The basic principle is that the local administration should be carried out by the head of the local government and the local assembly which represent the residents. Therefore,if the head of the local government and the assembly fail to fulfil their duty to protect the residents, thereby leading to a doubt whether they represent the will and interests of the people, the only recourse for residents is to rely on the direct democracy. The Japanese Local Government Act allows residents to make direct requests for various actions. These include requests for the recall of the head of local government and members of the local assembly, the dissolution of the assembly, and the enactment or amendment of an ordinance.

Such requests supported by the required number of signatures may be followed by a vote in the assembly, or a popular voting in accordance with the stipulation in the law, i.e. a referendum. In the town of Maki in Niigata prefecture, after a movement to recall the former mayor and the enactment of an ordinance calling for a referendum on the nuclear power plant planned in the town, the first referendum of its kind in Japan was held in August 1996. The residents voted against the siting of the power plant in the town (The town owns a piece of land inside the planned site of the power plant). Although the referendum system may have disadvantages as well as advantages, the referendum in Maki was carried out calmly. Even though the voting is affected by the national energy policy to satisfy the demand for electricity in the area with a huge consumption, the right to self-determination of the local residents should be respected.

6-1.2 Societal Concern over MOX Use

6-1.2.1 Difficulty in popular participation

When it comes specially to the issue of present concern i.e. legal aspects of MOX use, the two conditions mentioned above should be satisfied not only in the decision-making process of the plutonium policy but also in the process of the licensing of reprocessing facilities and MOX fuel fabrication facilities and the decision making and relicensing of the use of MOX fuel in light water reactors. Assuring equality between the two parties is, however, thought to be nearly impossible with regard to a MOX program, because commercial and security-related secrets possessed by the enterprise are always justified for the "safety and security of the public", even from the constitutional point of view, as A. Rossnagel points out in the succeeding part of this chapter: MOX and Society. This suggests a basic contradiction between the principle of

popular participation and the operation of a MOX program--which necessarily makes large-scale use of weapons-usable (and therefore highly sensitive) material.

6-1.2.2 International concerns

Japan's MOX program arouses international concerns mainly for two reasons. First, as argued in Chapter 1 by Takagi, the MOX program requires international shipments of highly toxic and weapons-usable materials. Secondly, the large scale utilization and trading of weapons-usable materials poses international security problems.

The issues associated with security is addressed in Chapter 2 by F. Barnaby, while the transportation-related issues will be dealt with by K. Hosokawa and J. Takagi in Chapter 7. But a few additional points worth mentioning from the legal viewpoint.

In 1988 Japan acceded to the Convention on the Physical Protection of Nuclear Material (PP Convention), which entered into force in 1987. In accordance with the Convention, the Law for the Regulations of Nuclear Source Materials, Nuclear Fuel Materials and Reactors was substantially revised and regulatory measures against the so called "nuclear hijack" (nuclear terrorism) were included. While the Convention should principally apply to nuclear materials for peaceful uses during international transport, it also applies to nuclear materials in domestic use, storage, and transport. The Convention stipulates that the information concerning the details of the protection of nuclear material and transportation plans should not be disseminated unnecessarily. In case of robbery, embezzlement, or extortion in relation to nuclear materials, the Convention sets forth the duty of informing the countries involved, recovering the materials, and punishing the offenders.

Despite the Convention, the residents along the overland route of nuclear fuel (UO_2 fuel, uranium hexafluoride etc.) transportation have had relatively free access to information on the transport -- because the local governments have to prepare for emergency -- until April 1992, when the government announced a change of policy. On April 18, the Science and Technology Agency (STA) sent a notification to operators of nuclear facilities and a letter of request to local governments urging them not to make information on transportation of nuclear materials publicly available. STA explained that this was necessitated by the PP Convention.

The new information policy was adopted just in advance to the planned international shipment of plutonium on board Akatsuki-maru from France to Japan and the land transport of MOX fuel assemblies from Tokai to Tsuruga (Monju). This non-disclosure policy was actually applied not only to on land domestic transport of plutonium but also to the international transport, which aroused international protests from over 40 countries and regions along the plutonium shipment route.

What is more, the policy has since been applied to transportation of every kind

of nuclear material -- including the compounds of natural uranium--an obvious stretching of the meaning of the PP Convention. This is the actual effect of Japan's plutonium program. The MOX program is being used in practice to justify control of information related to nuclear energy in general at domestic as well as international level.

6-1.3 Duty to Share the Earth with Future Generations and Other Living Organisms

6-1.3.1 Perspective from future generations

Because of the safety problems associated with the use of plutonium and the fact that the introduction of plutonium will change the social structure of the community, it is essential to introduce a system of participation that engages the local residents in the decision-making process covering plutonium policy. This is an extremely urgent task for the legislative system. The plutonium policy , however, also has a national and global effect. Therefore, it is necessary to have the participation of the citizens not only of the country, but also of the international community across of the whole world as members of the human race.

The use of plutonium poses the question of our responsibility for distant generations because of its long half-life (Pu-239 has a half-life of 24,100 years; assuming one bears a child at the age of 30, a half of the present radioactivity will still remain even after 803 generations later). The German Constitutional Law stipulated in its new provision in Article 20a [Grundgesetz 1994], that the government should protect the living environment from the stand point of the responsibility for the future generations (Verantowortung fuer die kuenftigen Generationen). this is a general principle of sustainable developments.

Furthermore, the concept of fairness between generations and a bill of rights for the future generations are now intensively discussed [Weiss 1989]. Increasingly, the public hold to the view that the future generations have the right to a clean earth. In a meeting of the Japan Association of Legal Philosophy [JALP 1995], a question was raised:"When the present generation does not have information concerning the values and the technological level of the future generations, is it allowed to carry out a policy which would give some benefits to the present generation but might possibly bring about a disaster for the generation 200 years from now on?"

The belief based on the historical view of progressivism that the future generations will always enjoy a wealthier and more pleasant life has collapsed because of the emergence of environmental disruptions, e.g. climate change, and nuclear

wastes which need absolute isolation from the biosphere for hundreds of thousands of years. This means that the present generation should have an "inter-generational ethic" to prohibit environmentally disruptive actions, taking into consideration injuries that would be inflicted upon the future generations. The present generation should control its desires and refrain from passing the cost to the future generations. This is the principle of inter-generational equity.

6-1.3.2 Rights of every living organism

Nor are natural rights for present and future generations confined to humankind.

In Japan, a lawsuit calling for the nullification of the permit of the forest development for the construction of a golf course planned on the Amami Ohshima island, granted by the governor of Kagoshima Prefecture, was filed at the Kagoshima district court: interestingly with the endangered and threatened species in the area including the Amami hare (Pentalagus furnessi) were named as the plaintiffs [Ryuzaki 1994]. The case was dismissed when the request by the district court to have the name and address of the plaintiffs written on the complaint was turned down. The case was resubmitted with " Mr. So and So, alias the Amami hare," etc. as the plaintiffs and is now pending in court.

A lawsuit was filed at the Mito district court claiming that it is illegal for the Ibaraki Prefecture not to preserve the winter habitat of the ohhishikui (large bean goose), a migratory bird designated as a Natural Monument of the nation, with the ohhishikui and a citizens' group as the plaintiffs. In February 1996 the district court decided that the wild life did not have standing to sue and dismissed this portion of the case [Mainichi 1996a]. The group appealed to the Tokyo high court maintaining that even the fetus has been admitted standing to sue, attaching a warrant of attorney with a footprint of a ohhishikui stamped on it [Yomiuri 1996].

A lawsuit was filed at the Nagasaki district court demanding the suspension of the construction work by the national government in the land reclamation work at the Isahaya Bay in Nagasaki Prefecture with the Isahaya Bay itself, five species living in the tideland including the mudskipper (Boleophthalmus pectinirostris), and their representatives (residents) as the plaintiffs [Mainichi 1996b]. In Hokkaido, there emerged the possibility of a case being filed demanding the suspension of the tunnel construction work in the Daisetsuzan national park, with the ezonakiusagi (Ezo area Asiatic pike) living in the area as the plaintiff [Nikkei 1996].

Obviously, the whole question of animal rights should be addressed elsewhere. However, the author would like to draw attention of the readers of this report to the issue. The discussion of the legal aspects of a MOX program entails, in particular, a consideration of fairness to future generations and other creatures, which is a newly

developing consciousness in relation to the future law system. The author's basic position is that, so far as the basic right of remaining unharmed is an acknowledged "right" of every living organism, all the living creatures should be given the standing to sue. There should remain much to be discussed, however, on who could really represent the rights of animals in a court and in what way.

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Chapter 6
Societal and Legal Implications of MOX Use

Part 2 MOX and Society

Alexander Rossnagel

Any energy policy should provide the necessary energy supply at reasonable costs, promote international cooperation and protect the environment, but it should also be compatible with the basic values of the constitution. Whereas all other criteria are controversial compatibility with the constitution should be an indisputable criterion. Society has formally agreed on these basic values. They are legally binding. All policies -- energy policy included -- have to match these aims. In particular, the effects of energy policy on basic civil rights must be heeded.

With regard to this demand, this part chapter reports some arguments which have been important in the energy debate in Germany[1] especially in the debate on the legal regulation of MOX or the plutonium fuel cycle.[2] These arguments are largely transferable to Japan as it has a similar constitution with comparable civil rights, corresponding atomic energy laws[3] and has comparable alternatives in atomic energy policies such as those Germany had some years ago.

Plutonium - target and means of threats

MOX and especially separated plutonium can be misused as poison or as basis for an atomic explosive device.[4] If they poses reactor-grade plutonium even a small group of well informed and trained individuals would be able to construct a crude atomic

1. The energy suppliers in Germany have abandoned fast breeder reactors, nuclear fuel reprocessing and fabrication of MOX fuel, above all for economic reasons but also due to public disquiet and regulatory problems.
2. See SPD (1987) and GRUENE (1984). Both bills have prohibited the use of plutonium. They are not in force, because they have not gained the majority. Nevertheless renewed versions of these bills could pass the legislative bodies after the next elections.
3. See Matsunaga (1995) p. 39; Yasuda (1995), p. 53; Uemura (1995), p. 93; Hokimoto (1985), p. 45; Narita (1983), pp. 63.
4. The weapons-usability was proved in a test conducted in the US in 1962. For further references see for instance Kollert (1995), p. 490; NAS (1994), p. 36; Kankeleit et al. (1989); Shea / Chitumbo (1993), p. 23; see also Chapter 2.

device providing a yield high enough to blackmail or fight a government (see Chapter 2). What would have happened if the lunatics in Oklahoma City had had a crude atomic device instead of their fuel oil-and-fertilizer bomb, with which they killed 169 people in April 1995. What would have been the outcome if the Aum sect in Japan had had not only brilliant chemists, but also nuclear physicists and technicians and could use a home-made atomic device instead of nerve gas, when they injured more than five thousands and killed twelve people in March 1995.[5]

And there are always people who are fanatical, crazy, greedy, disgruntled or revengeful enough to rob, steal or divert plutonium and to blackmail the society by misusing it.[6] There are always foreign agents, members of organized crime or actors in an international nuclear black market[7] who are interested in disrupting society or in developing or defending of their illegal activities. The main constraint at present, i.e. the lack of motivation[8], could disappear in the future for many reasons. Therefore nuclear terrorism is a "real threat to civilization" and its probability is increasing[9] [ITF 1987; .

If Japan transports separated plutonium from France and United Kingdom by ship, or gains it by reprocessing spent fuel in Tokai and Rokkasho, stores it in a stockpile, transports it from the storage to the fuel element fabrication plant, converts it to MOX and implants it into fuel elements [Kueppers and Sailer 1994; Takagi 1996], it creates targets for assaults, sabotage and diversion.

Objects to be protected

Although social implications of MOX use is a matter of principle, the importance of these implications is also a matter of degree. Therefore the problems depend on the magnitude and the multitude of objects threatened and to be protected. To determine these objects and the need of protectionary efforts I will try to extrapolate a scenario of future MOX use in Japan - according to the hope of its proponents. For this reason the Long Term Program for Research Development and Utilization of Nuclear Energy of the Atomic Energy Commission of Japan (see Chapter 1 and 4) is recognized as a

5. See Kamp (1996), p. 30, who asks whether these two attacks mark a turning point in the violence and in the use of technical assistance by terrorists.

6. See Rossnagel (1990a); see for the former Soviet-Union Bukharin (1993), p. 43; Krause (1995), p. 51.

7. See for examples Rossnagel (1990b); for the case of smuggling 408 grams of weapongrade plutonium from Russia to Munich in August 1994 and the intransparent role of German Intelligence Service see Hibbs (1994), pp. 24. The Bundeskriminalamt, the German Federal Bureau of Investigation, recorded 41 cases of nuclear black market activities in 1991 and 241 cases in 1993 - see Hibbs (1994), p. 25.

8. See Rossnagel (1987b), p. 62.

9. International Task Force (1987), p.8, 17; see also Kamp (1996), p.34.

serious prospect for the next decade[10] but its desirability and acceptability should be questioned.

In 2010 Japan is supposed to produce about 70 GWe by atomic energy. Let us assume this energy would be provided by about 70 LWRs, most of them of the 1000 MW class, and about 10 FBRs. Besides the Tokai reprocessing plant two additional reprocessing plants with an annual throughput of 800 tHM and two fuel fabrication plants would be operating in Rokkasho. Together with stockpiles for plutonium, MOX fuel and enriched uranium fuel and interim storage facilities for spent nuclear fuel around 90 plants would need to be protected.

Eighty reactors would need to be supplied with nuclear fuel. Assumed each of these reactors would need about 30 tHM fresh fuel per year and assuming again that 1/3 of the fuel would be MOX, 800 t MOX would have to be shipped by road annually. Transport casks have an average payload of about 2 tHM. Therefore in approximately 2010 about 400 shipments would be needed every year to supply the reactors.[11] Each shipment would have to be protected.

MOX fuel would be produced either in the United Kingdom, Belgium and France[12], or in Rokkasho and Tokai. Between today and 2010 about 60 t plutonium would be recovered in Japan and about 40 t plutonium[13] in Europe. The plutonium from Europe would be fabricated into about 1.000 t MOX fuel there (see Chapter 1). In order to transport the fuel to Japan, around 20 shipments would be necessary each with a 50 t MOX payload. The return of the Japanese high-level nuclear waste would require about 30 to 60 shipments (see Chapter 5). It might be realistically assumed that each shipment will be protected in the same way as was the shipment of Akatsuki Maru in 1992/93.[14]

For each plant an average of 15 guards would be necessary to work in four shifts around the clock.[15] With 90 plants to be protected about 5,400 security guards would be needed. Additionally each shipment by road will need an average security force of 7 guards.

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10. For this purpose it is unimportant whether the following figures would be reached some years earlier or later.

11. A similar multitude of transports of spent nuclear fuel have to be added. They are not specially considered because they are also needed in a nuclear power program without MOX.

12. See for the next future plans of the fuel fabrication enterprises for instance MacLachlan (1996), p. 10.

13. The Nuclear Control Institute estimates about 70 t plutonium and about 1500 t vitrified nuclear waste are to be transported in 15 to 30 shipments back to Japan - see Tanzer (1997).

14. See for the expenditures Footnote 40.

15. See for details Rossnagel (1983a), pp 111.

Inadequate security measures

Although various security measures against these threats exist in practice, these measures are inadequate.

To prevent successful *assaults* against plants or transports a special security concept called the "concept of delayed action"will need to be established.[16] This concept has three components: firstly, physical barriers secondly, armed guards should resist an attack long enough for thirdly, the local police force, to arrive on the scene and to overcome the attackers. The security measures in force are designed to resist an assault from one or a small number of adversaries armed with sophisticated weapons, with knowledge of local conditions and the technical aspects of the plant or the transportation shipment (see for details [Rossnagel 1987a]).

Although the current security system is perhaps adequate to cope with the "officially-defined threat" on which it is based, that threat itself is an inadequate representation of reality. In practice, the officially defined threat does not correspond at all to the maximum credible threat. On the contrary, violent groups acting in Europe and other parts of the world have demonstrated that they are able to assemble up to ten or more well-trained people to carry out sophisticated attacks, seizures, or kidnappings. There may be only a small probability of an attack on a nuclear facility or nuclear materials in transport, but if a group chose this course, its actions would most likely succeed.[17] The "concept of delayed action" and its implementation do not appear capable of coping with well organized sophisticated types of attacks [Rossnagel 1987a].
Security measures against a hidden diversion or other *insider threats* are the following: Firstly, there is a control system accounting for the flow of nuclear material; it is also a requirement under the international safeguards of the International Atomic Energy Agency [IAEA INFCIRC/153; Schleicher 1990]. Secondly, there are the enclosures and access control measures (see Chapter 2). Thirdly, plant personnel at work are surveilled, principally by means of a television system and the two-man rule, and fourthly, they are subject to security clearances [Rossnagel 1987a].

Neither the system that protects against diversion of special nuclear material ensure sufficient security.[18] Material accountings take place over too long an interval in too large material balance areas and the tolerances for material unaccounted for are

16. The IAEA has published in INFCIRC/225 general recommendations for a national physical protection system for nuclear materials in plants and in transit. The recommendations are meant to set minimum standards. The German physical protection system - reported in the following text - is based on these recommendations and designed and maintained far beyond them.

17. See International Task Force (1987), pp. 20; Mueller (1989a), p. 2; Mueller (1989b), p. 159.

18. See Schleicher 1990; Rossnagel (1990c), pp. 345; Miller (1990); OTA (1995).

too wide, with the result that major diversions would be undetected or detected too late. In a commercial reprocessing and fuel fabrication facility the minimum diversion which can be detected by safeguards -- with high confidence and low false alarm probability -- is much greater than the quantity of plutonium needed for the construction of a crude atomic device (see Chapter 2). If the "material unaccounted for" in the 800 t Rokkasho plant were to be just 2% and the material balance were to be done only twice a year[19], a diverted quantity of 80 kg plutonium could go undetected -- the quantity enough to make 4 to 8 atomic devices.[20] Also near-real time accountancy using computer simulations of the plant operations is ineffective if plutonium is illegally diverted in small amounts time and again (see Chapter 2 for further references). In addition, the remaining security measure, i.e. surveillance at workplaces and the access controls are as insufficient as the security checks. Examples of diversions and infiltrations are reported again and again (see more than 70 cases in [Rossnagel 1987b]).

The reason for the inadequacy of security measures is obvious: adequate measures would be too expensive. The security system is designed to provide the financially affordable security not the adequate security needed to prevent the maximum credible threats. The measures provided are oriented to the financial and organizational priorities of the companies.[21] If the measures to protect special nuclear material are not based on a relatively likely average threat but on a less likely maximum credible threat, it will be necessary to continue maintaining a very high level of security which is very expensive and seldom needed. If, for instance, material accounting intervals were close enough, if material balance areas were small enough and if alarm levels were deep enough to detect the diversion of even a small amount of special nuclear material, the plant wouldn't be economically viable. The principles of sufficient security and of economic operation of a plant are incompatible objectives.

These plants and transports should never be allowed to become a means of extortion in a serious political conflict or even in a civil war. However, nobody can exclude such developments. Those who possess or protect plutonium will gain strong power to influence the results of social conflicts. Who can guarantee the persistent peace needed for the peaceful use of plutonium?[22] Do we need a "nuclear priesthood"

19. These are very optimistic assumptions.

20. For comparison the IAEA is reported to have measured a "material unaccounted for" of 70 kg plutonium in 1994 in the Tokai reprocessing plant. This plant has a nominal annual throughput of only 90 t - see Frankfurter Rundschau, May 11, 1994.

21. See Nuclear Regulatory Commission (1987), USDOD(1987); Hirsch (1987), p. 207, 216; Mueller (1989b), pp. 159, 169.

22. See Rossnagel (1983a), p. 237; Rossnagel (1987b), p. 140.

for operating and protecting nuclear energy?[23]

Social costs of improvements

Any society using MOX and plutonium will not accept these hazards of misuse. Once it recognizes the threats, it will feel forced to enhance the security measures. Improvements are possible but expensive. *Physical protection* could be enhanced if the plant is again and again adequately backfitted and always protected by armed numerous guards sufficient to cover even sophisticated types of attacks by any well-trained and equipped teams of intruders. The protection force should provide the capacity of self-defense without dependence on support by additional forces from outside.[24] Today, the protection forces are private individuals who have no special legal authority and are not subject to special legal restraints as are armed forces such as soldiers or police officers.

Therefore outside security companies which are engaged to provide the prescribed security measures should be replaced by police forces (see for details [Rossnagel 1983b]. In this way a security element independent of the licensees would be established. Such an element may be necessary as it has been demonstrated in the so called "Hanau case" that not only the employees but also the plant management could divert special nuclear material.[25] Nevertheless all the costs of necessary protection should be payed by the licensee not by the public.[26] There are two reasons. First, the licensee causes specific dangers to the public; the public doesn't create them. Second, payments by the public must not distort competition conditions among competitive actors in the energy market.[27]

To *prevent insider misuse* additional measures will be seen necessary, directed

23. To this potential, fundamentally undemocratic necessity see Weinberg, 1973, p. 269.

24. See International Task Force (1987), pp. 21; Dixon (1987), p. 201; Mueller (1989a), p.4; Lowry (1984). To the problem of use of deadly force see International Task Force (1987), pp. 28.; Rossnagel (1984), p. 133.

25. See Mueller (1989a), p. 4; Mueller (1989b), p. 167; Rossnagel (1988), p. 15.

26. There could be considerable costs of physical protection especially for shipments. For instance the Akatsuki Maru shipment from France to Japan in 1992/93 was escorted by Shikishima, a lightly armed coast guard cutter. Additionally 69 patrol vessels, 5 airplanes and 5000 police and coast guard officers were mobilized to secure the arrival of Akatsuki Maru - see Chapter 4. In Germany the transport of one Castor cask from La Hague to the interim storage facility in Gorleben required the protection by 5,900 police officers, with security costs for the shipment totalling 55 million DM - see Nuclear News, June 1995, p. 59. The transport of one Castor cask from Philippsburg to Gorleben in May 1996 had to be protected by 19,000 police officers and created security costs for the shipment totalling about 66 million DM. The transport of six Castor casks from LaHague, Neckarwestheim and Gundremmingen to Gorleben in March 1997 is to be guarded by more than 30,000 police officers - see Frankfurter Rundschau, February 28, 1997.

27. See also International Task Force (1987), p. 18; see for details Rossnagel (1983b), p. 63.

against the employees of the plants.[28] Responsible persons could attempt to address the threat of an insider diverting special nuclear material or sabotage by strengthening the scope and depth of the background checks of applicants and employees and the permanent work controls. The severity of searches and surveillance would have to be exceptionally high to deter or detect the theft of gram quantities of plutonium. The repeated background checks would even have to guarantee that an employee could not be bribed, seduced or blackmailed to divert special nuclear material or information (see Chapter 2). Therefore the checks must cover all possible motives for misuse and all social contacts.[29] They can only be adequate if they deeply invade the privacy of applicants, employees, their relatives and their acquaintances. And the checks must recur in a short space of time [Dixon 1987]. All improvements are only to be achieved at the cost of civil liberties.[30]

In addition, the responsible persons are likely to combat the threats of insider misuse by taking measures against potential actors. Various forms of intelligence gathering will be established like wire tapping, post surveillance or infiltration of suspected individuals and groups. Those with responsibility must be vigilant to detect possible actors and planned attempts at the earliest juncture.[31] The line of defense will inevitably spread into civil society [Rossnagel 1983a]. All these measures will conflict with civil liberties[32] - not only of suspects but also of innocents. The mere existence of government surveillance programs discourages some people from engaging in legal political activity since they fear that, despite their innocence, information might still be gathered and misused.

Social costs of emergency and recovery actions

In a nuclear emergency all possible efforts would have to be undertaken to prevent or to minimize harm to the public. If plutonium or MOX is diverted or stolen it must be recovered very rapidly. If nuclear backmailing occurs the nuclear material or device must be found -- and the perpetrators must be arrested -- as soon as possible. Therefore large-scale and massive search operations might be necessary starting

28. See Rossnagel (1990c), p. 352; International Task Force (1987), p. 22, p28.

29. See for details Rossnagel (1983a), p. 178; Rossnagel (1987), p. 142.

30. For instance at the cost of the right to the pursuit of happiness, to privacy, freedom of assembly and association, of speech and other forms of expression and the secrecy of any means of communication, see Art. 13, 21 of the Constitution of Japan.

31. See International Task Force (1987), p. 25; Ne'eman (1987), p. 335; Despres (1987), p. 325; Rossnagel (1990c), p. 353.

32. For instance conflicts with the right to privacy, to be secure in the homes, the freedom of assembly and association, of speech, press and other forms of expression and the secrecy of any means of communication, see Art. 21, 35 of the Constitution of Japan.

immediately after having received the information - with or without a warrant. All suspects must be detained and vigorously questioned. In such a crisis, it might be tempting to hold suspects for interrogation for hours and days without letting them see anyone, even a lawyer. The possibility should not be excluded that responsible officers could torture a suspect to gain the decisive information. Additionally, it may be in the interests of those seeking to recover nuclear materials or to detect the nuclear device, to keep their efforts secret, both to avoid public panic and to increase the odds of success. They would try to control the media reporting the crisis.[33] All these measures would need severe restrictions upon civil liberties.[34] They would be adopted even if there were to be only a credible threat, lacking verifiable proof of the blackmailer's claims.

Possible acts of nuclear terrorism cannot be ignored until there is a crisis. In contrast to its approach to proliferation by states, the international community has no organized program for responding to a violent nuclear crime by a group not under state control [Kamp 1996]. Reactive steps taken if there are indications of a nuclear emergency must be planned in advance by each state. Special technical units must be established such as the "Nuclear Emergency Search Team"(NEST) in the United States. They have to be situated at a number of strategic locations to be able to move to any place at very short notice. They should have special equipment to measure radiation, identify materials, defuse nuclear devices, limit damage if an explosion or dispersal of radioactive materials occurs and decontaminate irradiated areas. In addition special police units have to be ready to organize search operations, seek suspects and witness, and question them in order to find the hidden material or device in a very short space of time. To be prepared for a crisis they need continuous training in handling nuclear emergencies and acts of nuclear terrorism [Kamp 1996, see also Chapter 2].

Pressure to security

In the absence of fear of assaults and diversions, as long as there is no escalation of social conflicts, the security measures will remain on a socially tolerable level. But if social conflicts escalate, if assaults or diversions occur or are suspected, those responsible will strengthen their efforts and enhance the level of surveillance.

Society cannot effectively influence the escalation of conflicts or the development of radical groups or be confident of breaking-up black markets for special nuclear

33. See for details Rossnagel (1983a), p. 210, p219; Goldberg (1987), p. 410.

34. For instance restrictions of the freedom of assembly and association, of speech, press and other forms of expression and the secrecy of any means of communication, the right to liberty, to be secure in the homes, of the constitutional procedure of arresting and detaining, the prohibition of torture and of compelling any person to testify against himself, see Art. 21, 31, 33, 34, 35, 36 and 38 of the Constitution of Japan

materials. If society uses plutonium, it will come under pressure to intensify security. If the threats beyond its control increase, society will have no choice: Its security measures will restrict civil liberties. Plutonium and democratic society are incompatible.

Silent change of constitution

The legal constitution will not prevent such a development.[35] On the contrary, it will encourage it. There are always different constitutional values at stake - on the one hand, for instance, the life and health of potential victims, the rule of law and the sovereignty of the state and on the other hand civil liberties. All restrictions of basic civil rights have to be weighed against the importance of -- and the threat to -- defended constitutional values. Security measures will constitutionally be in the right proportion, as long as they are considered necessary to combat the threat. But only the security agencies will be able to assess the threat and the necessity of security measures. They will enjoy an uncontrolled discretion to decide about security measures.

Therefore, in such a situation, all security measures will always be legal and constitutional. But although they will be legal they will have a severe impact on civil liberties [Goldberg 1987]. It should be borne in mind that a constitution consists of words on paper: its interpretation and its implementation is decisive. In case of conflict the defence of public welfare will always take preference over the civil rights of individuals. In an escalation of misuse or suspected misuse the values of the constitution will be interpreted separately and then weighed against each other to legalize and to legitimate the measures which the security agencies consider to be necessary.

Like the German constitution the Japanese constitution guarantees civil liberties in Article 10 - 40. Although there are no restrictions to most liberties, and only very few restrictions to certain liberties in the text of the constitution, the supreme court has recognized that the constitution allows restrictions of civil liberties if they are necessary to protect public welfare and are the least restrictive alternatives to match this aim.[36] Therefore in a critical situation the conflict between public welfare and individual liberties will be solved in favor of public welfare in Japan too. A civic norm in favor of civil liberties cannot resist the strong pressure to maintain security if thousands of lives are at stake.

After such a development the face value of the words in the constitution will still

35. See details in respect of the following Rossnagel (1984); see also Goldberg (1987), p. 403.

36. See Igarashi (1990), p. 23; for the example of the freedom of free speech, press and all other forms of expression see Matsui (1991).

be the same but its intrinsic value will have altered.[37] Citizens will still continue living in a democracy and in a constitutional state but the meaning of these words will have changed. And perhaps, nobody will notice the change because the standards of evaluation will have changed together with the meaning of constitutional terms [Rossnagel 1993].

In conclusion: In a MOX fuel cycle it will be impossible to ensure an adequate security level on an economically viable basis. But it may be necessary to enhance the possible level of security more and more, if circumstances seem to need it. By using plutonium as a fuel, society exposes itself to a pressure to tighten security beyond its control;this pressure can give rise to restrictions or the loss of civil liberties. [38] The only way to keep this pressure under control is by developing a wise energy policy. Atomic energy and especially a MOX fuel cycle is the only energy resource which needs armed guards, permanent work controls, mandatory background checks, broad surveillance measures and continuous intelligence gathering. Society can choose less dangerous ways of energy supply.[39] It can avoid jeopardizing civil liberties by its chosen energy policy. And it should do so.

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37. There is also a silent change in the constitution of Japan, see Neumann (1983), p. 179 with references to judgements of the supreme court.

38. This is one of the disadvantages of the Faustian bargain which society is forced to contract if it want to use plutonium - for this bargain see Weinberg, Science 1972, 33.

39. There is no necessity to recover plutonium from spent fuel - see Chapter 5, and there is no necessity to use separated (military) plutonium in nuclear power reactors - see for instance Lyman (1996) and also Chapter 2.

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Chapter 7
Transportation of Radioactive Materials (RAM) in MOX Utilization

Komei Hosokawa and Jinzaburo Takagi

7.1 Overview of MOX-Related Transport Activities

7.1.1 Expansion and complication of transport activities with particular reference to Japan's MOX program

It was pointed out in Chapter 1 that complicated transportation involving a huge amount of radiotoxic and weapon-usable materials would be vital to complete the nuclear fuel cycle (see Fig. 1-4). Japan's program of MOX fuel utilization particularly requires a number of different types of transport activities, including relatively short-distance land transport and global-scale shipments by sea or possibly by air. Expanded shipments of plutonium, either in the form of dioxide (PuO_2) or mixed oxide (PuO_2-UO_2), inevitably increases risks both in security and safety.

To illustrate the complicated transport activities that comprise the Japanese MOX program, let us examine the case of the proposed MOX use program in Fukushima I-3 plant (784MWe BWR) operated by Tokyo Electric Power Company (TEPCO). In order to extract plutonium from irradiated uranium fuel, first the spent fuel assemblies have to be transported from TEPCO's LWR (BWR) sites in east Japan to the reprocessing plant in La Hague, France. Most of this transport and part of the reprocessing have already been carried out. A recent Japanese Government document [Gov. 1997] reports that a certain amount of separated plutonium has already been moved on land from La Hague to Belgonucleare's MOX plant in Dessel, Belgium, where the oxide material will be fabricated and assembled for BWR use.

According to the 1995 contract between Commox and Toshiba (for TEPCO), a total of 483kg of plutonium will be transported to Dessel on land in the form of PuO_2 by 1998 [STA 1997]. The diplomatic document exchanged among the governments of Japan, Belgium and the Commission of the European Community (CEC) in February 1997 specifies that the material in question will be transported by two lots: first 221kg by

autumn 1997, and the remaining 262kg by July 1998[1]. Then, after having been manufactured in Dessel, 60 assemblies of fresh MOX fuel rods will have to be brought back to the French naval base of Cherbourg near La Hague, from where they will be shipped to Japan by sea. The use of the military port, rather than other ports closer to Dessel, is necessary for physical protection purposes. Intriguingly, it has been also made clear that UO_2 pin portions (3,088kgU of LEU with less than 10% of U-235 composition) are to be fabricated in Japan and transported all the way to Dessel, where they will be used, with PuO_2 loaded pins, in the manufacture of integral assemblies of MOX fuel. The fuel assemblies will then be transported back to Japan [MITI 1997].

As in the cases of the 1992-93 PuO_2 shipment by Akatsuki-maru and the 1995 and 1997 shipments of vitrified high level waste (VHLW) by BNFL freighters (see 7.3.1), the MOX fuel will have to make a very long voyage, either around South Africa or around South America, since the shorter and smoother route through the Canal of Panama will probably be unavailable given the strong opposition of the en-route countries, i.e. Caribbean countries and Panama.

Things are less clear as regards the reprocessing and MOX fabrication at Sellafield plant (SMP) for PWR use. Kansai Electric Power Company (KEPCO), which operates PWRs in Mihama and other sites in mid-western Japan, placed a contract with Mitsubishi Heavy Industry in December 1995, and Mitsubishi then promptly worked out a contract with BNFL for 16 MOX assemblies. The necessary plutonium should in principle be separated at THORP, Sellafield, but there is a slight possibility that the plutonium already separated at La Hague from Japanese spent fuel might be used for the BNFL-Mitsubishi-KEPCO deal, since La Hague has a much larger stockpile of Japanese plutonium. In that case, an extra transport of plutonium oxide from France to UK (probably by sea) would be necessary.

While Cogema seems to be more committed to sea shipment rather than transportation by air, BNFL considers air shipment as a conceivable alternative. As a matter of fact, MOX fuel for Swiss PWRs has been fabricated at Sellafield and taken to the nearby small airport at Carlisle, from where it is carried by aircraft to Zurich. Air transport of MOX from UK to Japan remains an odds-on probability (see 7.2.2.3 for more on this matter).

In addition to the shipment of fresh MOX, reprocessing waste generated at La Hague plant will also have to be transported back to Japan. This will include varieties of low-level, intermediate-level and high-level radioactive waste (LLW, ILW and HLW), and eventually the plant decommissioning wastes as well. The shipments of VHLW (vitrified HLW) are already going on. It should be noted that BNFL is

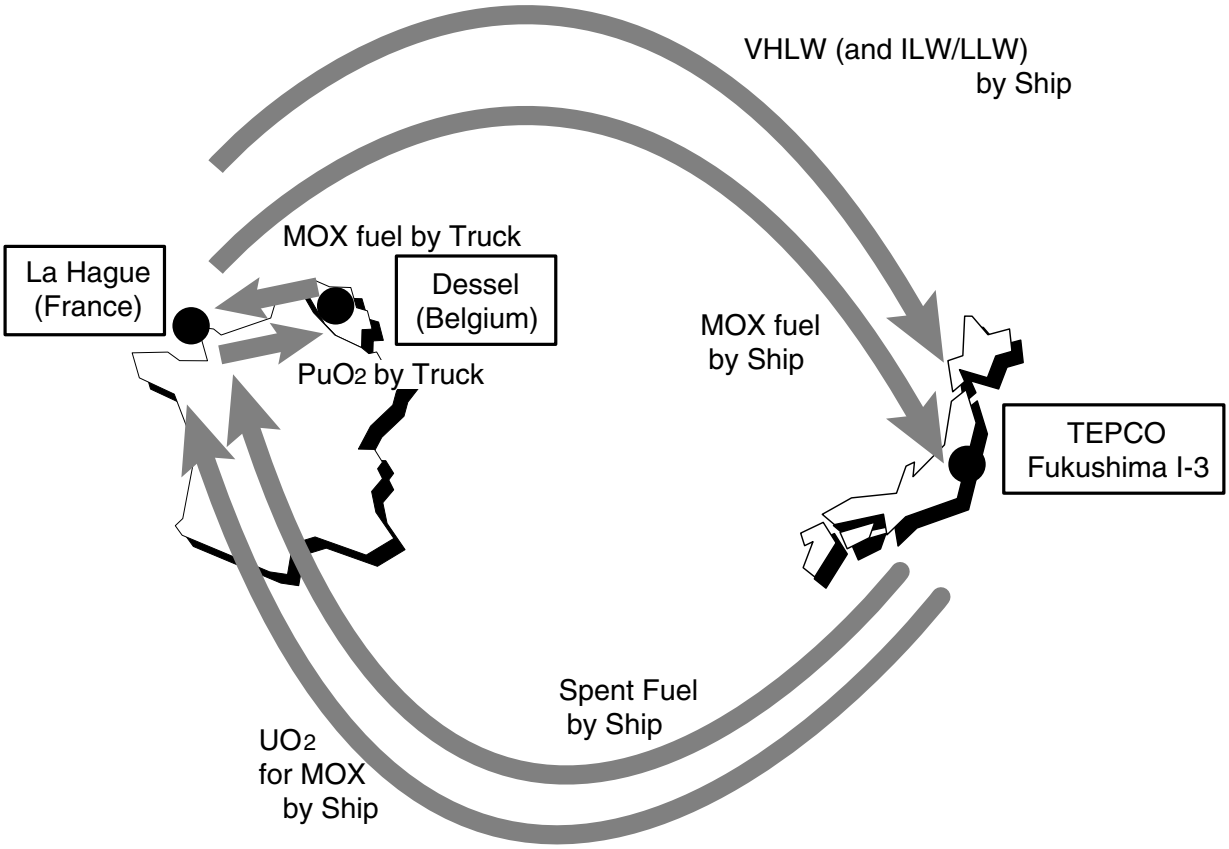
1. According to the latest Japanese government information, 220 kg of plutonium had already been transferred from La Hague to Dessel for Japanese MOX fabrication as of the end of May 1997[STA 1997].

considering what is called "curie-equivalent substitition" as a method of waste management, i.e. returning HLW instead of ILW and LLW so as to offset the absolute quantity of radioactivity (curies) to be transported [RWMAC 1997]. Although such practice would reduce the total volume of the radioactive waste to be brought back to Japan, the danger of the voyage could be much higher with increased volumes of HLW.

It is also highly possible that, if MOX utilization is realized in Japan, then spent MOX fuel will have to be transported to a yet-to-be-decided site of intermediate storage facility either by sea or land.

With all these transport activities put together, the distance required for transportation of radioactive materials for MOX utilization approaches 100,000km (Fig. 7-1), which is more than twice round the world. (Here the calculation is based on the assumption that one shipment for each kind of cargo is necessary for reloading a reactor core once.)

Fig. 7-1 Transportation of RAM Associated with Japan's MOX Use at Fukushima (schematic)



7.1.2 Issues to be addressed

Although the nuclear industry claims that there have been thousands of successful shipments of highly toxic radioactive materials (RAM), transportation should be regarded still as the most controversial links of the nuclear fuel cycle, in terms of both safety and security. Transportation of RAM, unlike its management at usual nuclear facilities, has no such "defense-in-depth" safety features as containment building and emergency cooling system. Nor is any concept of population exclusion zones and site emergency measures applicable to it. The recent French incidence of derailment of the train carrying spent nuclear fuel has reminded us anew of the vulnerable nature of nuclear transport.

Because of the essential safety disadvantage pointed out above, transportation of RAM should follow "the proximity principle" as proposed by [Lowry and Blowers 1996]. The principle states that nuclear waste should be managed as close to the point of arising as possible. Obviously, the expansion and complication of transport activities in MOX program are contrary to this principle.

The central question, therefore, is whether or not the MOX utilization justifies the cost. This question has been partly dealth with in Chapter 4 in terms of the realistic cost of reprocessing and transportation, and in Chapter 5 in terms of the choice of back-end policy, and it will further be discussed in the final chapter of this report.

The purpose of the present chapter is to point out specific problems associated with the transport activities that would be required for MOX fuel utilization. The issues relate to safety, security, economics, international relations and other societal matters. Since the problems of the MOX fuel cycle have already been addressed in a general way in previous chapters, we shall in this chapter focus on the specific safety issues (in 7.2) and social issues (in 7.3) that arise from transportation of fresh MOX (i.e. unirradiated MOX fuel assemblies), again with particular reference to Japan's MOX program.

7.2 Safety Aspect of MOX Transport and Related Activities

7.2.1 Framework of regulations and its problems

The IAEA Transport Regulations, specifically the Safety Series No.6 (SS6), of which the 1985 edition (as revised in 1990) is currently in effect, generally govern transportations of radioactive materials within and between most IAEA member countries. The Regulations themselves are advisory and require transposition into national law. The new version of the IAEA Transport Regulations issued in December

1996 will be adopted by IAEA member countries after certain review procedures, which may take several years (for a general backgraound briefing, see [Price 1996].

The IAEA classifies the packages of radioactive material (RAM) into six categories (Type C and UF_6 packages were added in the 1996 edition):

- Excepted packages (called "Type L" in Japan): to carry low activity material, e.g. radioisotopes and empty packagings
- Industrial packages: to carry low specific activity material or surface contaminated objects, e.g. uranium and thorium ore, solid natural uranium, various kinds of low-level radioactive waste
- Type A packages: to carry medium acitivity material, e.g. unirradiated uranium fuel
- Type B packages: to carry high activity material, e.g. irradiated fuel, separated plutonium, HLW
- Type C packages: high activity packages for air transport[2]
- UF_6 packages: to carry low-enriched uranium hexafluoride (before and after conversion)

These categories are specified with different safety test conditions.

Under the 1985 edition of SS6, unirradiated MOX fuel is designed and transported in a "Type B package", which is designed so as not to lose its radioactive contents beyond the "acceptable" amount, known as "A2" per week. The Type B package is also designed so as to keep its shielding capability within the "acceptable" radiation level in case it is exposed to accident conditions equivalent to an impact of 9-meter drop onto an unyielding surface (the equivalent of a 13m/s = 46.8km/h crash) followed by a fire of 800 degrees C for 30 minutes[3] .

One of the key questions raised against SS6 is whether the Regulations can cover the "reality" well [Lyman 1994]. There is a certain probability of occurrence of accidents which would exceed the "accident conditions" defined in SS6, and in fact there were numerous accidents reported exceeding such "accident conditions" [Lyman 1994]. There also are criticisms over the "graceful failure" principle of SS6, as called by Lyman (Annex 2-b) meaning that RAM packages are designed and constructed with

2. At the moment, Type C exists only as a conceptual design and actual containers are yet to be developed (see further discussion in 7.2.2.3).

3. IAEA, Regulations for the transport of radioactive material (Safety Series No.6). The impact test and thermal test are consecutive, in which the same package undergoes the two test (cf. the discussion on the non-consecutive Type C test in 7.2.2.3).

such a high degree of conservatism that they will be able to withstand accident conditions far severer than those under which they are tested. Against these criticisms, the IAEA seems to have made an effort to relate its defined "accident conditions" to reality [Clark et al. 1976; Dennis et al. 1978; Colton and Romander 1980; McLure 1981; Jefferson and McLure 1983] but, inherently, the requirements for the "accident conditions" have never been derived directly from any reasonable accident scenarios; they have only been justified by the history of "safe transport", as the IAEA has itself explained.[4]

Another key issue is whether or not a MOX fuel cask can be designed and fabricated so as to meet SS6. This issue is further discussed by Lyman (Annex 2-b, re: Westinghouse model MO-1 and Transnucleaire models FS-69 and FS-47). An unirradiated MOX fuel cask will have characteristics somewhat different from those of conventional spent fuel (i.e. irradiated uranium fuel) casks, which are also designed as Type B package. MOX casks tend to have less shielding capability, which would mean less mechanical strength against an impact and less thermal resistance against a fire. They also has different characteristics in their containment and criticality control system. All these safety concerns about MOX cask are further discussed below.

The 1996 edition of IAEA Transport Regulations, now called "Safety Standard Series No. ST-1" instead of "SS6", has several new provisions: Type C package for air transport of a certain quantity of radioactive materials; UF6 package; a wider application of 200-meter water immersion test; and enhanced tests for the package containing fissile materials transported by air [IAEA 1996]. The new edition, however, maintains the same principle of the "graceful failure" and the same assumptions for accident conditions. Thus it faces the same criticism as directed at SS6 (the1985 edition) concerning safety:

• There is no change in the radiation level around the package, i.e. 0.1 mSv/h at one meter from the package and 2 mSv/h on its surface, whereas the ICRP recommendation for radiological protection principle has been revised in 1990;

• There is no revision of the "allowable" leakage rate of radioactive material from the package, again despite the relevant revision of the ICRP recommendation [ICRP 1990];

• The adoption of enhanced "accident conditions" for Type C package, which would carry MOX fuel in case of air transport, has brought the new question of "regulations vs reality" (see Annex 2-b);

• The introduction of "LDM (the low dispersible material)" exemption from Type C package in the 1996 edition would make things complex as also discussed in the ANNEX report (Annex 2-b).

4. Para. E-627.1 of IAEA Safety Series No.7 [IAEA 1987].

Although the adoption of "enhanced accident conditions" for fissile material packages carried by air is progress from the point of view of safety, they are still insufficient in that the water in-leakage factor is left out when evaluating criticality. The possibility of water entering into the damaged cask is excluded from the assessment, although that could be a crutial factor in the maintenance of subcriticality when transporting plutonium.

The new IAEA regulations are also insufficient because the evaluation under the so-called "enhanced accident conditions" is based merely on an individual package in isolation, not for package arrays. The earlier version(SS6), by contrast, considered package arrays in the assessment of criticality accident possibility, both under normal and (unenhanced) accident conditions. This should be regarded as not only inconsistency in the safety regulations, but neglect of the reality that the fissile material package in question would be carried by air in arrays.

7.2.2 Safety aspects of various MOX transport modes

Fuel casks for unirradiated MOX have serious packaging problems in each mode of transport: sea, air or land. See the contribution by Edwin Lyman (Annex 2-b) for details. The main points of his assessment are summarized here, with some additional discussion.

7.2.2.1 MOX fuel cask

Although any technical specifications of the MOX casks for transport from France to Japan have not been made available so far, we can make some reasonable guessess from existing casks. The MOX casks (i.e. containers of fresh MOX fuel assemblies) will have rather thinner shielding than the casks for spent fuel assemblies, which is often made of steel 25cm thick. This means less ability to withstand impact and heat. Fresh MOX pellets, due to their brittle nature, might shatter into small particles when subjected to high-energy impacts that may damage the assembled zirconium rods in which the pellets are packed. Such small particles can escape from the cask’s containment system. Also, should the fuel cladding be breached, the volatility of Americium-241 in the MOX pellets would be enhanced at temperatures as low as 250C [Annex 2-b].

A total review of containment safety of MOX cask is imperative in order not merely to consider phenomena such as those mentioned above, which seem to have never been assessed, but also to evaluate the methodology of assessment itself since the current method is based on the US standard ANSI N14.5, which is basically

applicable only to leakage of liquid and gaseous materials.[5]

7.2.2.2 MOX transport by sea

There are numerous historical examples of shipboard fires which continued for days or even weeks, i.e. much longer than the thermal test conditons for Type B casks, which is only 30 minutes. Also, the temperature of a fire by hydrocarbon could be over 1,300 degrees C, i.e. much higher than that of the Type B fire test, which is only 800 degrees. If a MOX transport vessel experiences such an accident with greater severity than that of Type B requirements, then the loss of shielding, containment and heat resistance due to the long-duration fire could be followed by substantial oxidization and possible rupture of fuel rods since the safety margin for the MOX casks is rather small compared to that of uranium fuel casks.

The MOX cask may be designed -- if it is designed under the 1996 edition guidelines-- so as to withstand the outer pressure equivalent to 200-meter water depth (water immersion test). In the case of a freighter carrying fresh MOX sinking somewhere in the open sea between France and Japan, where the depth is mostly far over 200 meters, the cask could hardly withstand rupture by outer pressure. The IAEA does not intend to recover the cask sunk down over 200 meters depth, claiming there will be only "negligible harm to the environment and minimal radiation exposure to man"[6], but there has been no assessment for MOX fuel transport proving such an optimistic assumption. Even if a MOX transport vessel sinks where the depth is less than 200 meters, it is likely to take a longer period than expected to recover it. Consider the Japanese Government's inadequate response to the tanker Nakhodka, which sunk not far from the San'in (Shimane-Tottori) coast of western Japan (approximately 100km off the Oki Islands) in January 1997.

7.2.2.3 MOX transport by air

Air shipment ispresently by no means a rarity in MOX transports within Europe. Swiss MOX rods assembled in UK are flown from an airport in Carlisle (in northern England near Scottish border) to Zurich. There were also MOX transports by air from Germany to Scotland. The practice is not free from controversy, however. In 1993, German authorities announced a ban on MOX transport by air from UK to Germany

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5. See para A-548.7 of IAEA Safety Series No.7 [IAEA 1987] This paragraph refers to the American National Standard for Leakage Tests on Packages for Shipment of Radioactive Material (ANSI N14.5-1977), American National Standard Institute, New York (1977).

6. Para E-550.2 of IAEA Safety Series No.7 [IAEA 1987]

[WISE 1994]. Flights from Belgium to Scotland were stopped in 1996.

The USA has a stricter safety standard (NUREG-0360) on air transport of RAM in general and is rather unlikely to allow plutonium or Pu-containing MOX fuel to fly over its territory. It was disclosed in 1987 that the air shipment plutonium container that had been developed by Japan's PNC jointly with the U.S. Battelle-Columbus failed the crash tests conducted at the Sandia National Laboratory. This led to a hot debate in the US Congress. Senator F. Murkowski of Alaska and Senator W. Proxmire of Wisconsin proposed to upgrade the NRC safety criteria for licensing transport packages for air transport of plutonium so that the packages could withstand even the worst aircraft accident, virtually laying a ban on foreign plutonium overflight from US airspace.[7]

For the time being, we assume that MOX fuel is to be carried from France to Japan by sea, not by air. This is currently the Japanese Government policy as confirmed by the STA official responsible for nuclear fuel affairs [STA 1997]. Air transport, however, could be an alternative to sea shipment from Europe to Japan should much greater opposition come from the en-route countries of proposed sea shipment, or considering other merits such as far easier time management and physical protection.

It was revealed recently (Kyodo News, 10 June 1997) that BNFL is considering a possiblity of air shipment of spent fuel from Japan, Switzerland and Germany to THORP, Sellafield, sending processed plutonium back to these countries also by air. BNFL says that air shipment is one of the possibilities and that the choice is to be made primarily by the overseas utilities with which they are contracted.

MOX containers for air transport would be categorized as Type C, which was newly introduced in the 1996 edition of the IAEA Transport Regulations.[8] A cask of Type C is supposed to withstand the "enhanced accident conditions", including 90 m/s (= 324 km/h) impact and one-hour fire at 800 degrees C *separately* (not in succession). But it has been pointed out that these "enhanced accident conditions" cover only 85-90% of air crashes, so the "regulations vs reality" problems arise here again. In a preliminary draft of the Advisory Material, the IAEA asserts that the 90 m/s standard would cover 95% of air crashes, whereas Greenpeace claims that 50% of air crashes exceed the 90m/s impact. It is recognized in IAEA's data that 10% of aircraft fire lasted over 60 minutes. Notice also that the IAEA Type C standard is even less strict than the

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7. This was legislated into what is known as Murkowski Amendment to the Budget Reconciliation Act, which passed the US Congress and became effective on 22 December 1987. In the Pacific Southwest Airlines flight 1771 accident on December 7, 1987, which is the worst-case crash referred to by NRC, the impact speed was 282 m/s (see discussion in 7.2.2.3).

8. It should be noted that STA, as the Japanese representative to IAEA, voted for the approval of the new regulations at the IAEA board meeting in Geneva, September 1996.

one required for ordinary aircraft flight recorders, which are to survive a crash speed of 138m/s (= 496km/h) and one-hour fire at 1,100°C (not separately, but the crash being directly followed by fire: i.e. the same piece of black box should undergo an impact test and a thermal test consecutively, which is not the case with IAEA's Type C test). Needless to say, black boxes (and/or flight recorders inside them) did get destroyed in a number of actual aircraft accidents. The US standards for a Pu container in air transport is 282 m/s (= 1,015km/h). Neither Type B nor Type C containers as specified by the IAEA meet the US standards.[9]

Type C packages are yet to be developed, and obviously the use of Type C would greatly increase the cost of MOX transport. It is thus not surprising that nuclear fuel industry pressed for MOX fuel to be exempt from Type C packaging in air shipment. The 1996 revision of the IAEA safety standards mentioned above introduced an exemption from Type C package: the so-called "low dispersible materials" (LDM) exemption. Apparently, MOX fuel assemblies are regarded as a strong candidate for the LDM category, which means that plutonium in the form of MOX fuel may be assumed less likely to get dispersed in the environment because it is firmly sintered into the pellets and the pellets are contained in fuel rods made of solid alloy. The point is that LDM may be allowed to fly in Type B packages, rather than Type C. It does not follow straighforwardly, however, that the existing Type B casks may be used to transport MOX by air. The revised edition of the safe transport regulations in question, approved by the IAEA Board Meeting in September 1996, allows the use of Type B casks for plutonium and MOX shipments, provided transporters can demonstrate that radionuclides will not be dispersed following a severe accident that ruptures the cask [WISE 1997; Tanzer 1996]. This is a fairly high threshold test, since the enhanced accident conditions similar to those for testing Type C packages would be applied to LDM cargo itself, rather than its casks. At the moment, it seems quite difficult for the nuclear industry to meet this condition.

Furthermore, LDM exemption of MOX fuel from Type C packaging in air shipment will have to be approved by the International Civil Aviation Organization (ICAO). But none of the IAEA Type B containers has ever been tested in a plane crash.

Packages for air transport containing fissile materials (such as MOX) will also be subject to "enhanced accident conditions" similar to those for Type C, and will be required to maintain subcriticality. This involves problems as explained above.

9. The 282 m/s test is a requirement for international overflights of U.S. territory. For domestic plutonium packages, U.S. requires that the casks should survive an impact of 129 m/s (= 464 km/h), which is still stricter than the IAEA requirement [Tanzer 1996].

7.2.2.4 MOX transport by land

Since MOX fuel is supposed to be transported by sea directly from France to the sites of nuclear power plants in Japan such as TEPCO's Fukushima I-3, it is rather unlikely that the transport will involve land transit outside plant boundaries in Japan. But it is planned to be transported on land (probably by railway) between France and Belgium. In future, it is also highly possible that MOX fuel be transported on land from a MOX fabrication plant in Japan (possibly sited in Rokkasho-mura) to the country's nuclear power stations licensed for MOX.

In regard to land transport of MOX fuel, we should first consider the problem of radiation exposure of transport workers. Serious consequences could also occur in severe accidents that go beyond the test conditions required for Type B cask, as discussed further below. Highways in Japan have so many bridges: almost 10% of the total distance of national highways is elevated, more than half of them being higher than 9 meters.[10] To consider "hypothetical" accident conditions exceeding the IAEA standards for Type B cask, therefore, is a prudent approach to adopt.

7.2.3 Accident scenarios and emergency response

The IAEA recommends that each of the member states should establish their own emergency planning for transportation accidents, however arising, involving radioactive material. In elaborating emergency response plans, it is recommended to assume a hypothetical accident scenario that goes beyond the design base of the package in question.*[11] This means that an emergency plan should be developed for MOX fuel transportation as well, assuming the possibility of such accidents in which considerable lowering of the cask's safety level may occur. One such accident is a fire affecting a transport vessel for a much longer duration and at a higher temperature than prescribed in the IAEA regulations. Another may be the case ion which the carrier vessel sinks down below the depth of 200 meters, but still within territorial waters of a certain country. Still another scenario would be a collision on a city highway, followed by a fire, and release of MOX particles into atmosphere.

Neither the Japanese Government, nor any other competent agency for MOX

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10. According to Japan Highway Public Corporation (Nihon Doro Kodan), total length of major highways in Japan, namely Tomei, Meishin, Chugoku and Tohoku Highways, is approximately 98,000 km, with 5.6% of it, or 1,700 km, being elevated. Of those elevated sections, 60 % is over 9m high, 10 % over 20m and 5 % over 30m.

11. Para 4.03, 4.10 and 4.19 of IAEA Safety Series No.87 [IAEA 1988]

transport, has ever taken serious account of emergencies such as suggested above. The only emergency response plan prepared by STA (Science and Technology Agency of the Japanese Government) in 1986 is for incidents involving Type A package. STA, however, has been totally neglectful of even imagining the possibility of hypothetical accidents beyond IAEA Regulations. The Agency insists that the Regulations cover all the realistic possibilities [NSRA 1986].[12] However, a desperate lack of emergency response capability of the Japanese administration was revealed in the recent accident of the tanker Nakhodka (January 1997) which caused massive crude oil spill in the Sea of Japan, not to mention the catastrophic Kobe earthquake in January 1995.

It is the responsibility of the Japanese Government, not merely for the protection of the Japanese public, but to the international community as well, to make clear what practical measures could be taken in case of an emergency involving such highly dangerous material as plutonium and related radiotoxic materials, whether in mixed oxide or any other form, during transport.

7.2.4 Safety aspects of domestic MOX transport in Japan

All the points discussed so far would apply to the safety aspect of domestic MOX transport within Japan. In addition, Japan's socio-political peculiarity brings further problems to the society and less safety to MOX transport. There is no legislation in Japan assuring freedom of information, so that little, if any, of information held by governmental agencies tends to be disclosed. Japan was the last member country of OECD to have legislated the rules of environmental impact assessment (EIA), and the recently-passed EIA law of Japan is often criticized for its weakness.

Science and Technology Agency (STA) and the Ministry of Transport (MOT) have their respective committees on safety assessment of transport packages. Since both committees are closed, however, very little information on safety assessment of the transport packages is available outside these agencies, making an independent review almost impossible. Lack of third party scrutiny leads to such unexpected consequences as the recent series of accidents in PNC facilities: the sodium fire in FBR Monju (December 1995), the explosion at the Tokai reprocessing plant (March 1997), the leakage of radioactive heavy water at ATR Fugen (April 1997), and leakage of uranium waste due to many years of bad management of underground pits, again at the Tokai reprocessing plant (as revealed in August 1997).

Apart from the study of safety features of the MOX cask itself, the Japanese Government have never done any environmental impact assessments of MOX

12. In the preface of this report by the Nuclear Safety Research Association, STA claims that type B and fissile packages are guaranteered to retain their radioactive contents and not to lose their shielding ability if they suffers an accidnet, based on the safety regulatory conditions.

transportation, particularly an assessment of the possible consequences of a hypothetical accident involving a MOX cask. The Nakhodka accident mentioned earlier caused $200 million damage to the fishing industries around the coast of the Sea of Japan. If it were not crude oil but plutonium-based nuclear fuel, not only would the economic damage be much larger, but also serious long-term radiological consequences could occur.

It is the inherent duty of the Government, which is charged with the duty to protect the peace and safety of the public, to allow independent third parties to assess the impact of MOX transport, to disclose the assessment report, and to entrust to public and political discussion whether or not the MOX transport is safe enough; and whether it is economically viable and socially justifiable. A study by CNIC suggests that hypothetical accidents in Japan involving a MOX transport cask, even with the conservative assumption of release of only 0.1 % of plutonium contained in the cask, could have a large impact on society: over 500 people would die of cancer if such accident takes place in Kawasaki City; over 400 people if it takes place in Yokohama City [Kamisawa et al. 1997]. Total evacuation would be required within a 1.5 km radius of the accident spot, and children and pregnant women within a radius of 3 km would have to be evacuated. Additionally, as a wind of only 2 m/s would carry the released plutonium a distance of 1.5km in only 13 minutes, this would render evacuation of the population practically impossible.

7.3 International and Social Aspects of Transport of RAM

7.3.1 International concern over shipments of Japanese plutonium and vitrified HLW

International concern over shipments of radiotoxic materials is growing rapidly. The plutonium shipment from France to Japan (November 1992 - January 1993), the first HLW shipment from France to Japan in 1995 and the second HLW shipment in 1997 were all met by intense protests, not only of NGOs internationally but of the governments of the en-route countries as well.[13] Some countries, namely Argentina,

13. Protests by NGOs are described in Lowry and Blowers (1996) --- see note (3) above. Governments of 32 countries (including 3 autonomous regions and a British colony) protested against the first HLW transport (Asahi News Paper, 22 April 1995), and more than 20 governments protested against the second HLW transport (Kyodo News, 18 February 1997). Those are: Bahamas, Antigua and Barbuda, Belize, Jamaica, St. Lucia, Dominican Republic, Commonwealth of Dominica, St. Vincent and the Grenadines, Guyana, St. Christopher and Nevis, Barbados, Trinidad and Tobago, Grenada, Honduras, Columbia, Brazil, Uruguay, Argentine, Chile, Puerto Rico, Martinique, Virgin Islands, New Zealand, Nauru, Micronesia, Fiji, Kiribati, Northern Mariana Islands, Philippines, Taiwan, Ethiopia and South Africa. The following 43

Brazil, Chile and Uruguay, stated they would demand compensation in case of accident causing environmental contamination, and others (e.g. South Africa, New Zealand, Solomon Islands, Nauru and Philippines) requested that the freighter(s) in question should not go through their exclusive economic water zone (EEZ). Certain countries, such as Nauru and Chile, even warned that they would refuse to offer a port of emergency call for the plutonium/HLW freighters. Transport of MOX fuel will certainly invite further international concerns and criticism on Japan's plutonium program [Skornikoff et al 1995:Harrison 1996].[14]

In spite of the raised conflict and stresses on international relations, however, no reasonable justification has been made by the Japanese Government regarding the plutonium and HLW shipments, to say nothing of the proposed MOX transportation. It seems to be very difficult for the relevant Japanese electricity companies to justify their MOX transport against the prevailing international concerns and opposition. It would be relevant to point out here that Japanese utilities, despite the fact that they are stock companies, are not in a straightfoward way commercial enterprises, but are to be regarded as public statutory bodies under the current regional monopoly system of electricity supply in Japan, and therefore it is rather unlikely (or at least it has been so to date) for utilities to defy the nuclear policy as set out by the Government.[15]

7.3.2 International laws

The nuclear industry intend that MOX shipments would be conducted under the so-called rights for "innocent passage", i.e. the freedom of navigation, which by itself is fully guaranteed in international laws. This was actually the case both with the

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countries/regions officially expressed their concern to the 1992-93 plutonium shipment: Panama, Columbia, Venezuela, Ecuador, Peru, the Caribbean Community (composed of 13 countries), Brazil, Uruguay, Argentine, Chile, Marshall Islands, Micronesia, Northern Mariana Islands, Kiribati, Tubalu, Nauru, Western Samoa, Tonga, Fiji, Vanuatu, Solomon Islands, Paupa New Guinea, Cook Islands, Niue, New Zealand, Australia, Philippoines, Indonesia, Malaysia, Singapore, and South Africa. Also the Association of the Western States Governors (representing 21 states) of USA, as well as the state Parliament of Hawaii, lodged their opposition to the plutonium shipment.

14. It is rather ironic to note, in this regard, that a high-profile politician of the ruling Liberal Democratic Party of Japan, who supports Japan's nuclear policy, recently opposed to the radioactive waste shipment from Taiwan to North Korea for safety and moralistic reasons (Jiji-Tsushin News on 3 February1997).

15. Things, however, seem to be slightly changing because of the recent moves for deregulation of power generation and transmission in Japan.

Japanese plutonium shipment in 1992-93 and with the HLW shipments in 1995 and 1997. The Basel Convention of the Control of Transboundary Movements of Hazardous Wastes and Their Disposal (1989), which is the first comprehensive global legal regime for the regulation of trade in hazardous materials and disposal of them, does not prohibit transboundary movements of hazardous materials under certain conditions; neither does it cover radioactive wastes. Another international regime, the INF code of International Maritime Organization (IMO), adopted in November 1993, is entirely in harmony with the IAEA Regulations.[16]

A recent trend, however, is that the right of the coastal states to protect their marine safety and environment is given a higher priority than the "innocent passage" rights. The United Nation's Convention on the Law of the Sea (1982), which came into force in November 1994, covers nuclear substances and stipulates that the coastal states have the right to have contingency plans and environmental assessment.

A number of developing countries are party to regional treaties which control --- or try to control --- transboundary movement of some types of nuclear materials.[17] The declaration by 13 coastal states at the Special Consultive Meeting of the IMO on the INF Code in March 1996 demanded that, among other things, en-route countries be given prior notification and consultation on emergency planning, environmental impact assessment and liability requirements concerning RAM freight.

7.3.3 Social aspects

As the impacts of MOX utilization on society in general have already been discussed in Chapter 6, some social issues associated with MOX transport in particular are briefly recapitulated in this section.

Even today, fresh and spent uranium fuel transportation to and from Japanese reactors is conducted under unreasonably strict information closure and with firm security arrangement involving the police force -- althoug strangely, without involvement of fire brigades or any other emergency professionals. MOX transport, which means plutonium transportation in terms of the physical protection arrangement, would further increase the security pressure, and could result in restricted civil liberties (see the argument in the previous chapter).

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16. The INF (irradiated nuclear fuel) code is an IMO voluntary code of practice for the safe carriage of irradiated nuclear fuel, plutonium and high-level radioactive waste on board ships. The code forms a part of the International Maritime Dangerous Goods Regulations.

17. For example, *Lomé IV Convention* between EC and sixty-nine African, Caribbean, and Pacific states; and the 1991 *Bamako Convention on the Ban of the Import into Africa and the Control of Transboundary Movements of Hazardous Wastes Within Africa* explicitly include radioactive wastes.

Another issue that should not be left out in evaluating MOX fuel handling is transport workers' exposure to the radiation levels higher than those in the case of handling uranium fuel. Radiological protection of site workers is not merely a technical issue, but rather a matter of social justice, especially in Japan, since the country has a poor record in radiological protection of subcontract workers (in most cases, as a matter of fact, sub-sub-sub-subcontracters) [Kaito 1993]. Most of the workers actually engaging in the transport activities of radioactive materials are not classified in Japan as "transport workers" in the sense defined by the IAEA Regulations. Transport workers, in strict IAEA terms, are supposed to be well monitored for radiation doses and must be educated in radiological protection prior to any handling of radiotoxic substances, irrespective of the fact that the material to be handled is in hard casks or containers. Such measures are omitted in Japan for political as well as economical reasons. The reality of the Japanese nuclear fuel cycle is that the workers' radiation risk is quite high because freight operations, wharf labor, land transport, and related peripheral work are all carried out under radiologically uncontrolled conditions, often without any knowledge of radiation hazards on the part of the workers. This is also the case with the considerable number of police officers who are ordered to be "on the alert", standing very close (i.e. within half a meter) to the casks contaning nuclear fuel assemblies or nuclear fuel materials while the lorries are parking. Such scenes have been common in the domestic transport of FBR MOX fuel from the fabrication plant in Tokai-mura to the reactor Monju in Tsuruga.

As already discussed in Chapter 4 (re: MOX economics), increased social cost is another problem that goes inevitably with MOX transportation. In addition to the direct cost of shipment and cask manufacture, and apart from management and administrative costs -- including the costs of extra diplomatic and public relations--, MOX transportation would require physical protection expenditures including the cost for escort ships (see Chapter 4.4) and other security costs all along the long-distance voyage. The fact that the physical protection requirements dealing with plutonium, even in MOX form, is much greater than those dealing with conventional uranium fuel have a substantial influence on the economics of MOX. Neither the Japanese Goverment nor the electricity industries seem to have made a serious calculation of the *indirect* costs of MOX transportation.

Furthermore, a huge amount of compensation claims could be made by en-route countries, and/or by private companies, fishermen's unions, landowners and so on in those countries or regions, should they suffer from radioactive contamination or any other serious consequences caused by MOX traffic accidents. With the absence of any third-party liability insurances, such compensation would be a tremendous burden on the MOX carriers and the government of the responsible state(s). It would be quite unreasonable for utilities to commit themselves and their shareholders to such economically unjustifiable risks in light of combination of problems explained in this

report concerning the use of MOX.

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Chapter 8
CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Plutonium is essentially a man-made radioelement which occurs in nature only in very minor quantities in a handful of locations on this planet. Every uranium fuelled commercial size nuclear reactor (1,000MW) produces roughly 200 kg of plutonium per year. Initially, plutonium-239, the most important fissile isotope of plutonium with a half life of 24,000 years, had been produced in a sizable quantity to fabricate weapons of mass destruction, which showed its terrible efficiency at Nagasaki in 1945.

One of the Most Toxic Elements Known to Man

Plutonium-239 is a well-known carcinogenic (cancer-causing) substance, but reactor grade plutonium, which consists of a combination of various isotopes of plutonium and is commonly used in civil plutonium programs, is eight to ten times more toxic by weight than pure plutonium-239.

One gram of reactor grade plutonium oxide corresponds to the cumulated annual **limit of inhalation** for as many as **40 million people**.

This order of magnitude should be kept in mind when discussing plutonium production and stocks in the order of dozens of metric tons.

Fast Breeder Reactors Abandoned -- MOX Fuel Prompted

Beyond military uses, plutonium separation had been originally justified by the development of fast breeder reactors. However, fast breeder reactor programs have been abandoned entirely in the USA and Europe. The French government has acknowledged the failure of the program and shut down definitely the Western world's only industrial scale fast breeder reactor Superphenix. In Japan the Monju reactor has been shut down since a sodium fire devastated the plant in December 1995. There are no realistic perspectives for any significant future breeder program in Japan. As a consequence, MOX (uranium-plutonium mixed oxide fuel) is being prompted to absorb vast plutonium stocks arising as a consequence of earlier decisions on plutonium separation.

Plutonium Stockpiles Still Growing

By year 2000 the US-Russian **stockpile of separated weapons plutonium** (outside weapons) will be roughly **160 tons**. In addition, the civil plutonium stocks continue

to rise, especially in Europe. In 1996, worldwide about 22 tons of plutonium were separated and only 8 tons were used as MOX and in FBR programs. The total **stock** was estimated by the IAEA to be about **160 tons** at the end of 1996. The Japanese stockpile was about 16 tons at the end of 1995, according to the Japanese government, or roughly **10% of the world's stockpile**, it will increase its share and reach 30 tons and 70 tons in 2000 and 2010 respectively, according to an estimate by the Group.

Any Plutonium is Potential Primary Bomb Ingredient

There are various "qualities" of plutonium. However, the Group's analysis has clearly established that:

Plutonium of almost any isotopic composition, and in particular plutonium separated from spent fuel of **any nuclear reactor** currently operating in Japan, can be used for the manufacturing of a **nuclear explosive device**. Reactor grade plutonium in the form of oxide crystals in spherical shape has a critical mass of about 35 kg. The radius of this sphere would be about 9 cm, the **size of a cantaloupe**. The transformation of plutonium oxide into metal - a straightforward chemical process - reduces the critical mass to 13 kg which would be still reduced if a neutron reflector like natural uranium was used.

Persistent statements by the plutonium industry as to the inadequacy of reactor grade plutonium for the manufacturing of an explosive device are misleading and scientifically incorrect.

Weapons Plutonium to MOX: A Counterproductive Proposal

In a 900-MW(e) light-water reactor which can use MOX in a third of the core, about 170 kg of weapons plutonium could be absorbed a year. Besides the build-up of an entire plutonium alloy conversion and MOX fabrication infrastructure, it would take 30 of these reactors operating for at least 30 years to handle the 140 t of military plutonium to be removed from dismantled nuclear weapons in the next ten years.

This activity would contribute to the dispersion of plutonium to a large number of facilities over a long time span and thus encourage nuclear proliferation rather than prevent it.

Safeguards: Not up to the Challenge

Independent experts have calculated that, in the case of a large reprocessing plant (capacity of 800 tons of spent fuel per year), even if the error margin in the operator's computer calculation is as low as 1%, the minimum amount of diverted plutonium which could be detected with a probability of 95% and a false alarm probability of 5% is about 220 kg, enough to produce 6 to 10 crude nuclear bombs.

Problems of safeguarding of MOX fuel fabrication plants and fresh MOX fuel at reactor sites have been rated "high priority" by the IAEA as early as 1987. However, in

1994 it was disclosed that 70 kg of plutonium were held-up (stuck to surface) in remote-handling equipment at the Tokai Plutonium Fuel Production Facility.

It is chemically of no difficulty to extract plutonium from fresh MOX fuel. With the storage of fresh MOX fuel, the reactor sites thus become direct weapons use material storage sites. In 1996, the IAEA was confronted with the problem of the refusal by the operator of a German nuclear power plant of MOX fuel verification.

Physical Protection: Defeatable

Detailed descriptions of current physical protection concepts are, for obvious security reasons, not in the public domain. However, independent experts have had a good insight into containment and surveillance systems and estimate that these systems can be defeated or circumvented. In particular the spectacular increase in plutonium and fresh MOX transports as well as MOX storage at reactor sites is of great security concern. The US Department of Energy suggests that a special protection system guarded with "deadly forces" be necessary for MOX irradiation of weapons plutonium in commercial reactors.

Nuclear Terrorism: An Increasing Threat

Increasing availability of plutonium and the existence of highly trained terrorist organizations make the escalation to nuclear terrorism more likely than ever. Some of these organizations have shown an unprecedented level of cruelty and the use of means of mass destruction. There can be no doubt that some of these groups would be in a position to manufacture a crude nuclear device or to deliver a credible equivalent threat.

Safety of MOX Fuel Production and Use Questionable

The industrial experience with MOX is very limited as compared to UO_2 fuel. The number of MOX assemblies used worldwide represents less than 0.2% of the total LWR fuel assemblies and even in Germany which, besides Japan, is the largest foreign reprocessing client of the French and English plutonium industries, the share does not exceed 4% (200 t of MOX against 5,000 t of UO_2 fuel).

Certain properties of MOX fuel can have a negative impact in the reactor use, in particular in case of certain transients:

- The melting point of MOX is lower by 20-40 C as compared to uranium fuel.
- The thermal conductivity of MOX fuel decreases systematically with increasing plutonium content.
- Reduction of neutron absorbing capacity of the control rods.
- Change of certain reactivity coefficients takes place, making a MOX-loaded reactor core more difficult to control under certain conditions.
- Power peaks are increased.

- The delayed neutron fraction is reduced, making the control more difficult.
- The neutron spectrum is hardened.

In general, MOX fuel lowers the safety margin of a light water reactor. In addition, there are considerable uncertainties in regard to safety-related aspects of MOX burning in light water reactors, particularly at large plutonium enrichment and high fuel burn-up.

MOX Would Make a Severe Accidents Even Worse

In case of a severe reactor accident with containment failure, the dose at a given distance **would generally be 2.3 to 2.5 higher in the case of the MOX fuelled reactor** (a third of core loaded with MOX), implying that health effects of the radioactivity release would increase by the same factor. In other terms, the distance of various health impacts increases so that the actual increase in social impacts would be 3.2 to 4 times higher if social impact is assumed to be proportional to the affected area (since the area is proportional to the square of the distance).

MOX Fuel Chain Introduces Risks at All Steps

The necessary manipulation of plutonium in all steps of the MOX fuel chain including reprocessing, fuel fabrication and handling of spent fuel makes each operation potentially more hazardous than in the case of the uranium fuel chain. Particularly, intensive radioactive discharges from a reprocessing plant cannot compare with other nuclear facilities and pose serious environmental and health risks.

MOX Increases Fuel Costs Significantly

The Group's own economic analysis shows that the introduction of **MOX** to a third of core **will raise the fuel costs of LWRs by a factor of about 2.5**. There is no economic justification for the MOX use in light water reactors. Some cost overrun in Japan can be attributed mainly to high construction costs in Japan. While this disadvantage can be avoided by commissioning reprocessing and MOX fabrication to European companies, this would not result in net cost reduction since the long distance shipments of radioactive materials have a net negative economic effect.

Cask Dry Storage Best Available Interim Storage Option

As far as technical conditions are concerned and if compared with wet pool type and can type storage systems, the cask storage is considered to be the best option for the direct storage strategy from the safety point of view, because it relies mostly on relatively simple and cheap passive safety features.

Direct Fuel Disposal Preferable Option for an Optimum Backend Policy

The direct spent fuel storage option is the preferable path if compared to reprocessing for a large number of reasons, and in particular according to the following criteria:

- **Waste volumes**: The reprocessing path generates at least six times more waste than the direct disposal path, probably even significantly more.
- **Radioactive discharges**: Reprocessing facilities release very large quantities of liquid and gaseous discharges, the Direct Disposal option virtually none.
- **Transports of radioactive materials**: More than 200 waste shipments between Europe and Japan associated with the reprocessing option are expected to be carried out in the coming decade.
- **Interim storage**: Reprocessing is certainly not a credible path to combat insufficient interim storage capacity; technically it can be increased without difficulty.
- **Waste heat management**: The thermal output of spent MOX fuel is by a factor of two to more than three higher than that of UO_2 spent fuel.

Severe Societal and Legal Implications of MOX Use

Currently, the citizens in Japan are virtually deprived of the rights and power to intervene effectively as an equal party in legal procedure and decision-making process in regard to nuclear issues and freedom of information is not guaranteed. Recent developments indicate that through the administration of local governments the public participation could perform an effective function. However, because commercial and security-related secrets possessed by the enterprise are always justified in regard to a plutonium program on the ground of "safety and security of the public" and thus contradict with any principle of public participation, a MOX program will always tend to contradict democratic, participatory and transparent decision-making processes.

What if the Japanese Official Plutonium Long Term Plan Went Ahead? --- A Security Scenario

If the Japanese Long Term Program on plutonium went ahead, around 90 plants including plutonium stocks and fuel fabrication plants would have to be protected. About 400 shipments of MOX fuel, may be 40% of them from Europe, would be needed. Roughly 30 to 60 shipments of HLW from Europe to Japan also have to be protected. The protection of the 90 plants would need about 5,400 security guards (15 guards in 4 shifts around the clock).

Reactive steps to a nuclear crisis have to be planned well ahead. Technical elite units like the Nuclear Emergency Search Team in the US have to be established. Additional police forces have to be trained in particular to deal with such a nuclear

emergency.

If society uses plutonium, it will come under pressure to intensify security. If the threats beyond its control increase society has no choice. Its security measures will restrict civil liberties.

Plutonium and MOX Transports - Security and Safety at Stake

The case of the planned MOX program for Fukushima I-3 illustrates well a typical case of transport scheme. Nuclear materials and wastes go several times back and forth between Europe and Japan. Even if one considers only one transport per type of shipment, the distance to be travelled by nuclear materials totals some 100,000 km or more than twice around the world: a nightmare for security officials and insurance companies.

The Co-Researchers of the IMA-Project conclude that the disadvantages of the Plutonium-MOX path versus the Direct Fuel Disposal option are overwhelming whether on the level of industrial, economic, security, safety, waste management and societal implications. In other words, there is no reasonable justification or identifiable social benefit in the continuation of plutonium separation and the launch of a MOX fuel program for light water reactors.

RECOMMENDATIONS

On Transparency

The classification of information concerning nuclear matters should be entirely reviewed by a Commission, set up under the auspices of the Diet, its members should stem from civil society and be independent of any nuclear interests. The Commission should elaborate recommendations as to relevant future restrictions of access to information. The principle to be achieved is that information on nuclear matters is a priori public, and confidentiality, if ever necessary, has to be justified on a case by case basis.

On the Weapons Usability of Reactor Grade Plutonium

The Japanese Government should make a solemn statement recognizing the weapons usability of light water reactor plutonium thus ending any further misleading speculations.

On Reprocessing

Considering the strategic value as well as the extreme toxicity of plutonium and taking into account the fact that the total stockpile of "civil" plutonium was about 160 tons at the end of 1996 of which more than 10% belonged to Japanese utilities, further separation of plutonium should be immediately halted.

Existing reprocessing contracts with foreign reprocessors should be cancelled. This implies:

* The non-reprocessed spent fuel - 800 tons or 27% of the LWR (light water reactor) spent fuel under contract with COGEMA and 2,300 tons or 90% of the spent fuel under contract with BNFL (exact figures not available from BNFL) have to be shipped back to Japan. Only about 1% of the spent fuel under contract has not been shipped yet and should of course be kept in Japan(all figures as of March 1997).
* The reprocessing wastes corresponding to the throughput already carried out under Japanese contracts have to be shipped back from Europe to Japan. Prior to any further shipments there should be an in depth impact assessment and potential adaptation of the shipment mode.
* The Japanese utilities and the Japanese government should make a public statement that Japan will take back *all* corresponding wastes, category by category as they are conditioned by the reprocessing service, and to cancel any other potential agreement with European reprocessors. They should also make public the calculation according to which Japan takes back what quantities of what kind of waste.
* Plutonium already separated should stay at European plants for the time being. The Japanese Government should immediately enter negotiations with the French and

British Governments as to the possibility of conditioning the plutonium with high level radioactive waste into a final waste package - transforming plutonium separation into plutonium conditioning services. These plutonium bearing waste packages could then be shipped back to Japan.

* The Japanese Government should announce the permanent closure of the Tokai Reprocessing plant, whose operation is jeopardized by the fire/explosion in March 1997.

* The Japanese Government should announce the abandoning of the Rokkasho Reprocessing plant, which is still in its early construction phase, before any significant capital is wasted (as was the case in the late abandoning of the German Wackersdorf plant).

On the Fast Breeder Reactor Program

The Fast Breeder Reactor Program should be abandoned. The Monju reactor should be shut down forever. The Japanese Government and industry should consult with their French counterparts - France took the decision to shut down the Western world's only industrial scale fast breeder reactor Superphenix - as to the final shut down and dismantling procedures.

On Plutonium and MOX Transports

Current plutonium and MOX fuel transport schemes lead to unacceptable risks. These transports should be minimized to the level necessary for conditioning and final disposal as waste.

On Interim Storage of Spent Fuel

Consultations should be engaged immediately with local governments and residents of potential intermediate storage sites for spent fuel. These locations include reactor sites as well as away-from-reactor facilities. The prior aim of the consultations should be the evaluation of the conditions for the acceptability of interim storage for spent fuel currently covered by reprocessing contracts.

Additional intermediate spent fuel storage capacity should be evaluated in a second step preceded by the elaboration of alternative energy scenarios, including the phase out of the operation of a given nuclear plant.

On Nuclear Material Accountancy and Physical Protection

The standards of nuclear material accountancy and control should be significantly increased, in particular in Japanese plutonium handling facilities.

The standards of physical protection for plutonium handling facilities should be upgraded at least to the US standards.

On MOX Fuel Fabrication

The Japanese utilities have signed contracts with European MOX fabricators *before* any impact assessment of its use in Japanese light water reactors has been accomplished and *before* any license for its use has been granted. These agreements should be cancelled, the utilities should not be permitted to build up a fait accompli in the debate over plutonium production and use in Japan.

On MOX Fuel Use

The Japanese utilities are invited to publish a comprehensive analysis of MOX use in light water reactor covering technical, economic and social issues. Such a report should make all the basic assumptions public and be subject to a full check and review process involving a wide spectrum of the general public.

On the Present Report

We invite the Japanese Government, utilities and industry to analyze the present report and submit their comments to the director of the project.

The members of the Group are ready to give evidence on the results of the report to the Japanese Parliament, Government and any committee dealing with the issues raised.

We also invite the government, utilities and industry of any country, which is engaged in, has plans for or has a concern over using MOX in light water reactors, to analyze the present report and review its nuclear policy on the basis of the present findings.

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Annex 1

Annex 1

Plutonium Fuels at Crossroads

MOX as the Ultimate Justification for the Production of Plutonium --- for How Long Yet ?

Mycle Schneider and Mathieu Pavageau

Introduction

Fifty years after the first separation of plutonium, twenty years after the first commercial agreements on plutonium production, the plutonium industry is at crossroads. Currently negotiations are being carried out at various stages in various countries about the future production and use of plutonium. It is clear that the question of the development of the plutonium fuel industry is central to the future perspectives of the overall plutonium industries.

Significant opposition to plutonium use - from the civil society as well as from the power industry - in the key countries of the plutonium industry, service providers and clients, has led to a tense situation. Unfortunately, much of the debate takes place behind closed doors, without providing any opportunity for input from the whole range of concerned citizens and experts. However, it is clear that the further production of plutonium cannot be justified industrially unless plutonium absorption capacities match those of plutonium production.

The plutonium produced today adds on to the very large stockpile of weapon usable plutonium in the world. It does not need an experts' quarrel to conclude that it is irresponsible to continue the production of plutonium under these conditions. Therefore the plutonium fuel producers hold a key position today in the debate. Plutonium fuel production constitutes the industrial bottleneck of the full scale plutonium economy in the absence of the plutonium fast breeder reactor. The industrial experience with MOX fuels is very limited as compared to uranium fuels (roughly two orders of magnitude difference in the quantities produced). Will the MOX fuel industry be able to provide long term industrial answers to the problems of the nuclear power reactor operating industry?

This paper does not deal with the full scope of concerns connected with the production and use of plutonium like safety, proliferation and legal issues, which are

dealt with in other papers of the IMA Project. This paper attempts rather to give an overview of the current industrial situation and to highlight certain key facts linked to upcoming decisions and developments in the area.

Whereas the plutonium question is still often discussed in terms of a "dogmatic conflict", today ***all*** nuclear countries have effectively abandoned the "one hundred percent reprocessing" option and have either decided for direct disposal of all their spent fuel or developed a mixed reprocessing / direct disposal strategy.

Whereas the first generation of plutonium production facilities was initiated by the nuclear weapons industry, the second generation of industrial facilities (in operation in France, Britain and the Russian Republic) was motivated mainly by the perspective of a full scale plutonium breeder based nuclear electricity production infrastructure. At that time socio-political, technical and legal problems led certain countries to transfer the management of their spent nuclear fuel to other countries (France, Britain, Russia for commercial fuel) which in return were able to finance the build up of their commercial facilities. During the 1970s, Germany, Japan and to some extent Belgium subcontracted the reprocessing of spent fuel to France and Britain - expecting to build their own large facilities soon after. The nuclear industries in other countries (Spain, Sweden, Switzerland, Italy, the Netherlands, Finland, Hungary) were too small to justify plans for national plutonium production facilities. The USA provided worldwide reprocessing services for highly enriched uranium research reactor fuels but this initiative was regarded widely as targeting non-proliferation purposes.

Today the situation radically changed. Italy phased out nuclear power by referendum in 1987. The Netherlands and Sweden have firm shut down dates in 2004 and 2010 respectively. Germany, Switzerland, Spain, Finland and Hungary do not have any firm commitments to increase or even replace their current nuclear generating capacity. Only Japan and Russia are building plutonium separation facilities, although the construction of RT2 at Krasnoyarsk (Siberia) was halted in 1993 and the construction of the plant at Rokkasho-mura (Aomori Prefecture) has experienced very significant delays.

However, fundamental decisions are to be taken over the coming years as whether to build new MOX production facilities or complete the ones under construction and whether to license the use of MOX fuel for a large number of reactors in Japan and France. Also the fate of the reprocessing plants in Britain and France, once the current firm contracts terminate by the end of the century, is of primary impor-

tance. Further plutonium production will be intrinsically linked to the success of the MOX fuel industry to convince an increasingly skeptical public opinion of its benefits.

Reprocessing

Today there are six commercial reprocessing plants operated in the Western world, three in France, two in the UK and one in Japan.

The B205 and the **THORP** plant at **Sellafield**, **United Kingdom**, are operated by British Nuclear Fuels. B205 processes only MAGNOX fuels and is planned to reprocess all the magnox fuel yet to be produced in the UK. Japanese magnox spent fuel has been and will be reprocessed at the B205 plant. Since it started operations, the B205 plant has reprocessed over 35,000 MT of magnox spent fuel, of which 1,590 from March 1995 to March 1996[1].

Table 1: Operating Commercial Reprocessing plants and Nominal Annual Throughputs up to 1996

Country	Operator	Name and/or site	Nominal annual throughput (MT)	Active operation
France	COGEMA	UP1 (Marcoule)	*400 metal*	To be shut down before the end of 1997
France	COGEMA	UP2+UP3 (La Hague)	1,600 oxide	yes
Japan	PNC	Tokai-mura	90 oxide	yes
UK	BNFL	Sellafield	*1,500 metal*	yes
UK	BNFL	THORP (Sellafield)	900 oxide	yes
Russia	Minatom	Cheliabinsk-65	400 oxide*	yes

(Source: WISE-Paris, Naudet94)

[1] BNFL, personnal communication, 9 July 1997.

It was estimated by British Nuclear Fuels that the THORP plant, which started active operations in 1994, would take five years to reach a nominal throughput of 900 MT per year. Reprocessing throughputs for the first two years of operation of the THORP plant were 63 MT for 1994 and 208 MT for 1995. As of March 1997, the THORP plant had reprocessed a cumulated 680 MT of spent fuel[2]. Also British Nuclear Fuels maintains some ambiguity as to the "nominal" peak throughput. The discharge licenses presently consider an annual throughput of up to 1,200 MT. BNFL only received a full operating licence from the Nuclear Installation Inspectorate on 22 August 1997.

The **UP2** and **UP3** reprocessing plants at **La Hague, France,** are operated by COGEMA. They both have a 800-850 MT annual nominal capacity (through-puts for 1996 were 862 MT for UP2 and 819 MT for UP3). The UP3 plant currently reprocesses exclusively foreign spent fuel while the UP2 plant now processes only French fuel. The only exception to this separation of activities between UP2 and UP3, since the extension of the UP2 plant from 400 MT to 800 MT per year and restart in 1990, is a small batch of German MOX fuel which was reprocessed in UP2 for demonstration purposes.

The following tables and corresponding charts show the evolution of the quantities of spent fuel reprocessed for customers from different counties. About 60% of the LWR spent fuel reprocessed at La Hague is foreign spent fuel.

[2] BNFL, idem, 1997.

Table 2: LWR Fuel Reprocessing at La Hague

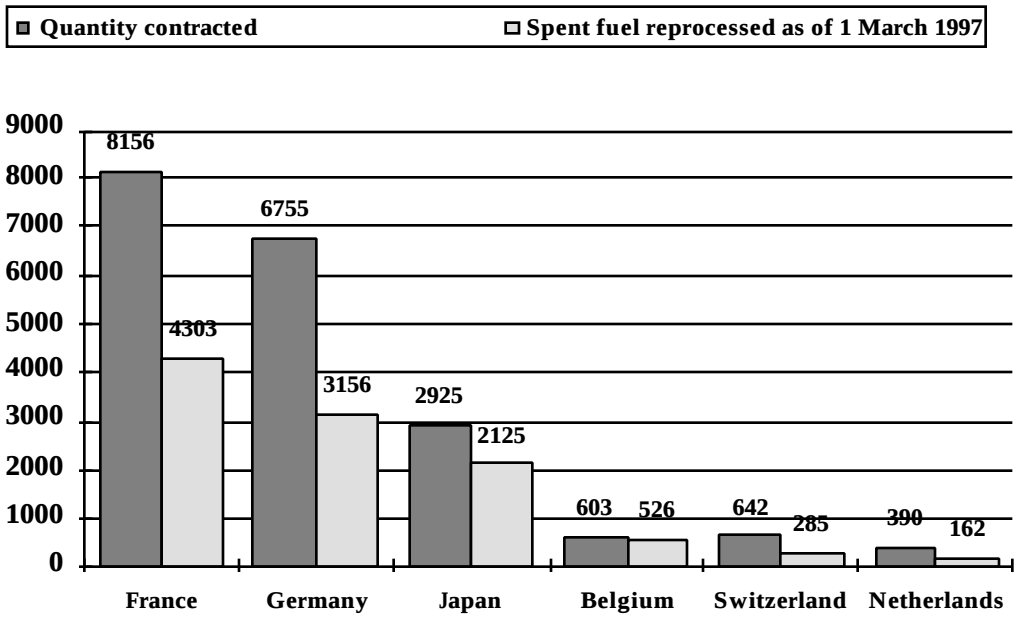
Quantities contracted and quantities reprocessed as of 1 March 1997

Origin of spent fuel and type of contract	*Quantity contracted (MT)*	Spent fuel reprocessed as of 1 March 1997 (MT)	Share of total spent fuel reprocessed as of 1 March 1997
TOTAL France	**8,156**	**4,303**	**40.8%**
Germany UP2	1,643	1,643	15.6%
Germany UP3	3,112	1,513	14.3%
Germany post-2000	2,000	0	0.0%
TOTAL Germany	**6,755**	**3,156**	**29.9%**
Japan UP2	151	151	1.4%
Japan UP3	2,774	1,974	18.7%
TOTAL Japan	**2,925**	**2,125**	**20.1%**
Belgium UP2	139	139	1.3%
Belgium UP3	464	387	3.7%
TOTAL Belgium	**603**	**526**	**5.0%**
Switzerland UP2	132	132	1.3%
Switzerland UP3	510	153	1.4%
TOTAL Switzerland	**642**	**285**	**2.7%**
Netherlands UP2	85	85	0.8%
Netherlands UP3	140	77	0.7%
Netherlands Post-2000	165	0	0.0%
TOTAL Netherlands	**390**	**162**	**1.5%**
TOTAL non French customers	**11,315**	**6,254**	**59.2%**
TOTAL ALL COUNTRIES	**19,471**	**10,557**	**100.0%**

(Source: COGEMA97, WISE-Paris97)

Chart 1: LWR Spent Fuel Reprocessing at La Hague

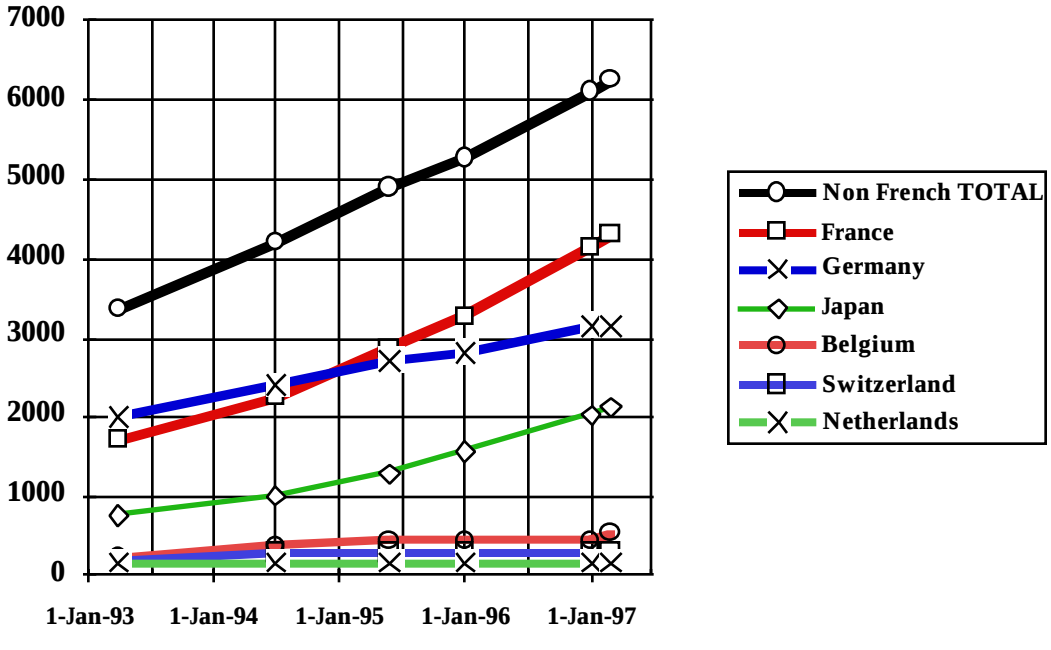
Quantities and origin of spent fuel contracted and reprocessed as of 1 March 1997



(Source: COGEMA97, WISE-Paris97)

Chart 2: LWR Spent Fuel Reprocessing at La Hague

Quantities reprocessed for ustomers from different countries since 1993



(Source: COGEMA93, COGEMA97)

Magnox (*UNGG*) Reprocessing in France

The **UP1** reprocessing plant for metallic fuel at **Marcoule, France**, which produced military plutonium for the French weapons programme, is due to be shut down by the end of 1997 after the total quantity of unloaded spent graphite reactor fuel has been processed. Dismantling operations will then follow.

The MOX Fuel Industry and Recent Developments

Most of the MOX produced up to now in **Western Europe** has come from the German Siemens plant at Hanau (now definitively shut down), the French CEA plant in Cadarache (now operated by COGEMA under the responsibility of the German director from the abandoned Siemens **Hanau** plant) and the Belgonucléaire plant at **Dessel/Mol**. These plants are limited in scale and produce between about 25 and 35 MT of MOX fuel annually. Between 1973 and 1992 (when it was shut down), the German Hanau plant produced a cumulated 158 MT of MOX fuel.[3] Between 1984 and the end of 1995, Belgonucléair manufactured more than 270 tons of MOX fuel.[4]

COGEMA is making efforts to adapt to German requirements for MOX fuel and has invested over $100-million to upgrade the **Cadarache** MOX plant in anticipation of MOX contracts with German utilities. The Union of German electricity (VDEW) utilities announced at the beginning of 1996 that the production of about 300 tonnes of MOX fuel had been ordered, mainly from COGEMA[5]. In fact, the Cadarache plant is expected to be operated with an annual throughput of 25 MT of MOX from 1997 onwards exclusively for the needs of the German utilities until after the turn of the century. However, according to the French safety authorities, the Cadarache plant will be shut down shortly after the turn of the century.

The **MELOX** plant at Marcoule is the first large scale MOX plant and is designed for a 100 MT annual throughput. Its active operation began in 1995 but at a significantly slower pace than initially planned. At the beginning of 1996, COGEMA was aiming at an annual throughput of 85 MT for the Melox MOX plant.[6] COGEMA did not even

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3 Mycle Schneider, Jochen Schulz, Mathieu Pavageau, "Deutsches Plutonium und das französische Atomwaffenprogramm", WISE-Paris, commissioned by IPPNW-Germany, 1997

4 J. van Vliet, D. Haas, Y. Vanderborck, M. Lippens, Cl. Vandenberg, "MIMAS MOX Fuel Fabrication & Irradiation Performance", Belgonucleaire, International Seminar on MOX Fuel: Electricity Generation from Pu Recycling (June 1996, UK), quoted in Yurika's E-mail Pu-Update, "Fissile Material Disposition & Civil Use of Plutonium", Issue No.2, October 3, 1996.

5 *Revue générale nucléaire*, March-April 1996.

6 *NuclearFuel*, 1 January 1996.

produce half of the planned quantity. It is only in the first 6 months of 1997 that MELOX achieved a throughput of over 45 MT.[7]

COGEMA's engineering subsidiary SGN is currently working on an "arrangement" for the MOX plant to adapt to foreign MOX fuel requirements[8]. This involves, in particular, adjusting plant equipment for the production of MOX for boiling water reactors (BWR).

The **British nuclear industry** is not considering the production of MOX fuel for domestic use. British Energy in a recent statement declared that: "It would be thoroughly uneconomic for us to convert our AGR reactors to use the new MOX fuel. It is not just a cost issue either. It would require a lot of extra shielding and protection for our workers. It would be difficult, if not impossible for us to use MOX fuel."[9] As a consequence, BNFL currently_produces MOX in its demonstration plant exclusively for a Swiss client and plans to use its new Sellafield MOX Plant (SMP) mainly for Japanese customers.

During 1995 the **German plutonium industry**, backed by officials in the German Foreign Office, decided to follow up on an idea put forward by a senior researcher at the Frankfurt Peace Research Institute to use the second German MOX plant in Hanau, (a plant under construction with a design throughput of 120 MT per year which has never been licensed to operate), for the production of MOX fuel incorporating Russian plutonium from the dismantling of nuclear weapons. This option was officially abandoned for obvious political and technical reasons[10] and the operator Siemens-KWU is planning to dismantle the plant.

Instead of the Hanau MOX option, COGEMA, Siemens and the British BNFL are now competing to propose technology for a domestic MOX plant to the Russians. Siemens is particularly interested in selling off parts of the Hanau plant. Belgonucléaire has also finalised design studies to adapt a MOX plant (P1) (which was never licensed in Belgium) for the Russians.

The **French CEA** (Commissariat à l'énergie atomique) cooperates with the Russian Federation under the AIDA programme. This programme aims at the promotion of French MOX fuel technology for the management of plutonium from

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7 *NuclearFuel*, 6 October 1997

8 *NuclearFuel,* 23 September 1996.

9 *Whitehaven News,* 20 August 1997

10 e.g. several dozen plutonium transports would have to be carried out each year from Russia to Germany and the plutonium would have to be processed according to Siemens specifications, besides the fact that the Russian government never indicated any interest to export its weapons plutonium in whatever form to whatever destination...

weapons dismantling in Russia. In the framework of the second phase of the AIDA programme, a pilot MOX fabrication plant is planned to be built in Russia[11].

Similarly, during the Moscow Nuclear Safety Summit in April 1996, the **Canadian government** signed an agreement with the Russian Federation to carry out a feasibility study for the introduction of MOX fuel containing Russian weapons plutonium in Canadian CANDU reactors.

A similar agreement has been signed with the US government and irradiation tests are to be carried out in early 1998 at the Canadian Chalk River research reactor on a small sample of MOX fuel containing weapons grade plutonium.

However, political and economic conditions remain unfavourable to any such option concerning Russian plutonium. For the time being, there are no concrete signals from the Russian side to go ahead with the MOX option. On the contrary, the Russian breeder lobby seems to push for plutonium stocks to be kept for some (highly unlikely) future use in breeder reactors.

The **US Department of Energy** has not excluded either the use of MOX fuel containing weapons grade plutonium or the disposal of plutonium through vitrification with high-level radioactive waste. The DOE has decided to pursue both options and has initiated procedures to build demonstration plants for both technical solutions. By March 1996, representatives from industry and fifteen utilities had shown interest in the use of MOX in US plants to dispose of US weapons plutonium. However, it is clear that they request compensation payments for the use of MOX in their reactors and DOE has already budgeted several hundred million dollars for such payments.

Table 3 shows the planned development of the international MOX industry's commercial fabrication capacities as outlined by the plutonium industry. However, certain assumptions appear very optimistic as to the probability of their realisation, at least within the indicated time framework. Whereas the P0 plants in Belgium, the CFCa plant in France and the MDF plant in Britain are currently operating roughly at indicated capacities and the slow capacity increase for CFCa seems realistic given past experience, some comments seem to be appropriate as to indications on the other plants:

11 *Enerpresse*, 8 July 1996.

Table 3: MOX Fuel Fabrication Plants Nominal Capacities

According to Industry Estimates

State of the plants	Country	Company	Name or site	1996	2000	2010
Shut down	Germany	Siemens	Hanau (35 MT)	-	-	-
Abandoned construction	Germany	Siemens	Hanau (120 MT)	-	-	-
Active	Belgium	Belgonucléaire	Dessel (P0)	35	35	35
Active	France	COGEMA	Cadarache (CFCa)	25	30	35
Active	France	MELOX	Marcoule	50	100	160
Active	United Kingdom	B.N.F.L.	Sellafield (MDF)	8	8	8
Active	Japan	P.N.C.	Tokai-mura	6	6	15
Construction	United Kingdom	B.N.F.L.	Sellafield (SMP)	-	120	120
Planned	France	COGEMA		-	40	40
	Japan		Rokkasho-mura	-	100	100
TOTAL				**124**	**439**	**513**

(Sources: COGEMA95, Naudet94, Fournier94, Kishimoto94)

- **MELOX** is far behind its original start up schedule. However, the plant produced over 45 metric tonnes of fuel pins between January 1 and June 30, 1997, more than the number produced during the entire 1996 period.. If no more technical problems occur, it should now reach the design throughput of about 100 MT per year by 2000. However, plans to increase the throughput to 160 t/year or even 200 t/year as outlined in recent COGEMA documents, have been abandoned by the present French Government, as announced by Christian Pierret, Secretary of State of Industry, on 21 October 1997.[12]

- The additional **40 MT** planned French annual fabrication capacity (most likely at **La Hague**) will certainly not be available by the year 2000 given the fact that the plant is not yet under construction or subject to any licensing procedure. Also, as in the case of the MELOX extension, the plan is likely to be abandoned by the French government.

[12] Press conference, Paris, 21 October 1997

- The French Safety Authorities (Direction de la Sûreté des Installations Nucléaires) stated in 1997 that it has ordered the CFCa plant at Cadarache to be shut down shortly after year 2000 (for instance 2002). COGEMA will either have to close down the plant or make costly upgradings to satisfy the safety authorities. We think that it is unlikely that these upgradings will be made.

- Given the current experience with the start up of the MELOX plant, it seems highly unlikely, if not impossible for the British **SMP** to reach its nominal throughput by the year 2000. An annual throughput in the start up phase of about 50 MT seems more likely, or even optimistic. The plant is currently still under construction, but has not yet been awarded its full operating license.

- The **Rokkasho-mura** plant will certainly not be available by 2000. Given the current set-back in the Japanese plutonium programme, it is unlikely that the plant even will be available by 2010.

Table 4: MOX Fuel Fabrication Plants Capacities

According to WISE-Paris Estimates

State of the plants	Country	Company	Name or site	2000	2010
	Belgium	Belgonucléaire	Dessel (P0)	35	35
	France	COGEMA	Cadarache (CFCa)	30	0
Active	France	MELOX	Marcoule	100	100
operations	United Kingdom	B.N.F.L.	Sellafield (MDF)	8	8
	Japan	P.N.C.	Tokai-mura	6	15
Construction	United Kingdom	B.N.F.L.	Sellafield (SMP)	50	120
Planned	Japan		Rokkasho-mura	-	100?
TOTAL				**229**	**378**

The WISE-Paris estimates in table 4 give a significantly less optimistic picture concerning the development of MOX fuel fabrication capacities as compared to industrial expectations. However, the figures indicate that even with this moderate scenario, the international MOX fuel fabrication capacity will double by the year 2000 (from 124 MT to 229 MT) and might increase by another 65% from 2000 up to 2010 to 378MT per year. The biggest single unknown factor in this scenario is the planned 100MT Rokkasho plant.

The Plutonium Balance

The interesting question is obviously what the plutonium balance will look like in the future. According to current planning, by 2000 commercial plutonium production in the Western world will correspond to the output of the French UP2, UP3 and British THORP plants, roughly 25 MT per year. With an average plutonium content of 7.5% - this is higher than the current 5% average content - by 2000, the 243 MT of **MOX would absorb** about 18 MT, thus **less than three quarters of the output of the plutonium production plants**. Until 2000, the stocks will increase even faster since the plutonium production output will increase faster than the MOX production capacities.

By 2010, if the MOX production capacities really increase as outlined and reach about 380MT per year, the plutonium absorption capacity will finally start to match the output of the continuous plutonium production. But by that time the stock of separated plutonium will have increased to unprecedented levels. If for economic or technical reasons the MOX production capacities do not increase by 2010 as currently planned, the stock of separated plutonium will be even greater. The continued delays in the start up of the French MELOX plant, the construction of the British SMP and the development of the Japanese Rokkasho plant indicate that our scenario is very conservative and that plutonium stocks might well continue to increase beyond 2010.

The stock of French separated plutonium alone increased between the end of 1994 and the end of 1996 from 13.7 MT to 35.6 MT, while the **stock of French and foreign separated plutonium in France increased by 22.5 MT** to 65.4 MT (see hereafter for details).

There is clearly **little possibility** with current MOX fabrication capacity forecasts that commercial plutonium **stocks** will **start decreasing over the next 20 years** if plutonium production continues at given throughput capacities.

Reprocessed Uranium

Another byproduct of reprocessing is the uranium which is separated during the plutonium separation process. A different isotopic content makes reprocessed uranium more complicated to re-enrich and to use as, fuel because of necessary additional radiological measures and of the different behaviour of the fuel in the reactor core.

Reprocessed uranium must be re-converted to uranium hexafluoride before it can be re-enriched to produce new fuel. The only plant which allows this operation at the moment is the Comurhex demonstration plant operated by COGEMA. British Nuclear Fuels has just started the construction of a large scale, 1,200 MT, nominal capacity plant at Sellafield[13].

[13] *NuclearFuel*, 26 February 1996.

A few reactors in France and Belgium are now being partly fuelled with reprocessed uranium. Theoretically the material can be re-enriched or used for the fabrication of MOX fuel. However, the lack of economic incentive to re-enrich reprocessed uranium has led to the accumulation of very large stocks since the reprocessing began.

Since the beginning of reprocessing activities, and as of end of 1995, 230 fuel assemblies containing reprocessed uranium have been loaded into French and Belgian reactors. The fuel assemblies correspond to about 120 MT of heavy metal. This corresponds to **less than a tenth of the quantity of fuel which is loaded each year** into reactors in **France and Belgium**. Most of the reprocessed uranium has been re-enriched to enrichment rates higher than for ordinary enriched uranium from natural uranium (3.6-4,2%)[14] to balance the higher neutron absorption of reprocessed uranium.

Table 5: Use of Reprocessed Uranium in France and Belgium, as of the end of 1995

Destination and year	Number of fuel assemblies	Comments
Cruas-Meysse-4 (1986-1987)	8	The fuel assemblies have been irradiated up to 33,000 MW.d / MT. Four of the fuel elements also contained natural uranium.
Two reactors in Belgium (1990)	88	The fuel assemblies were irradiated up to 48,000 MW.d / MT.
Two reactors in France and one reactor in Belgium (1994 and 1995)	134	
TOTAL	**230**	

(Source: Magnin, Framatome, Revue Générale Nucléaire, March-April 1996)

Only very limited quantities of reprocessed uranium are used as nuclear fuel. During 1994 and 1995, 134 fuel elements containing reprocessed uranium were loaded into reactors in France and Belgium, while a total of about 2,500 fuel elements were loaded into reactors in these two countries during the same period. Reprocessed uranium fuel thus represented hardly more than 5% of the total nuclear fuel consumption.

[14] *Revue Générale Nucléaire*, March-April 1996.

National Spent Fuel Management and Plutonium Fuel Policies

In the mid-seventies, reprocessing and plutonium separation were considered to be the priority option for spent fuel management by Belgium, France, Germany, the Netherlands, Sweden, Switzerland, the United Kingdom and Japan. Electricity utilities committed themselves to long term reprocessing agreements with reprocessing companies (COGEMA in France and BNFL in the UK). Today the direct disposal of spent fuel option is being considered by all of the utilities but to various degrees.

An overview of the spent fuel and plutonium management policies in Belgium, Germany, Italy, Japan, the Netherlands, Spain, Sweden and Switzerland is now presented. French policy is analysed in a subsequent separate case study.

The **Belgian** national electricity utility Electrabel operates seven reactors. The reactors produced 41.4 TWh in 1996, which accounted for 57% of the country's electricity generation.

The Belgian fuel management company, Synatom has contracted reprocessing agreements with COGEMA for 530 MT of spent fuel. In 1993, the Belgian Parliament voted a five year moratorium on further reprocessing contracts, delaying any further contracts to beyond the year 2010. The parliament is to rediscuss the issue in 1998.

Currently, two of Electrabel's reactors are loaded with 20% of MOX fuel. There are no plans to increase the number of reactors loaded with MOX fuel.

The **German** electricity utilities operate twenty commercial reactors. Nuclear electricity generation was 152.8 TWh in 1996, which accounted for 30% of the country's electricity generation.

Due to significant opposition, a reprocessing plant under construction (Wackersdorf), a fast breeder reactor (Kalkar) and a MOX fuel fabrication plant (Hanau) were never licensed for active operations. This led German utilities to continue to send spent fuel abroad for reprocessing. German utilities are the largest foreign customers of COGEMA. However, in 1994, the "Atomic Law" was amended, enabling electricity utilities to officially choose between reprocessing and direct disposal options. Two utilities subsequently cancelled contracts with BNFL for post-2000 reprocessing.

Twelve reactors are licensed for MOX fuelling. Nevertheless, whereas a MOX fuelling demonstration was already made back in 1970, the lack of incentives has resulted in only seven reactors being, at present, loaded with this fuel.

Table 6: Plutonium in Hanau, Germany

State of plutonium	kg total plutonium
Pu in MOX	1,090
Other reactor fuel	250
Plutonium nitrate	70
Plutonium oxide	490
MOX powder	500
Total	**2,400**

(Source: German Government quoted in Nucleonics Week, 15 August 1996)

The **Japanese** electric utilities operate 53 commercial reactors. Nuclear electricity generation was 287 TWh in 1996, which accounted for about 33% of the country's electricity generation.

Japanese utilities are the largest customers of British Nuclear Fuels (outstripping British utilities), and are the second largest foreign customers of COGEMA after Germany. Today, because of the construction of the Rokkasho-mura reprocessing plant, utilities are no longer interested in making post-2000 reprocessing commitments abroad. However, persistent delays in the construction schedule and current limitations in spent fuel storage capacity as well as opposition to additional storage capacity might change this situation.

Commercial fuelling with MOX is not planned before the year 1999. Two reactors have already been partly fuelled with MOX for demonstration purposes. On 28 April 1995, TEPCO signed a MOX fabrication contract with the French-Belgian MOX broker Commox[15] through the Japanese industrial group Toshiba[16].

Though the Japanese Atomic Energy Commission stated in 1994 that it was "basic nuclear energy policy" in Japan to reprocess spent fuel, the picture has significantly changed since the Monju Accident in december 1995, and the fire in the bitumen waste facility of the Tokai reprocessing plant in march 1997.

The **Dutch** electricity utilities operate one commercial reactor, the only other reactor was definitively shut down at the end of March 1997. Nuclear electricity generation was 3.9 TWh in 1996, which accounted for 5% of the country's electricity

15 60% COGEMA, 40% BELGONUCLÉAIRE

16 *"Memo of April 24 meeting of Tokyo-based NGO groups with TEPCO on the MOX fabrication contract"*, memo and translation by Dr. Jinzaburo Takagi, 24 April 1996.

generation. The commercially operating reactor is due to be shut down by 2004 and no additional reactors are planned.

Reprocessing contracts with the French COGEMA are under increasing attack, in particular because no use is envisaged for MOX fuels in the Netherlands. The Dutch have a share[17] in the French Superphénix fast breeder reactor which is not operating at the moment. The plutonium recovered from reprocessing at La Hague has therefore no use in any Dutch operated or owned reactor. The destination of this plutonium is still unclear.

According to a top EDF official, some time ago, the Dutch utilities asked EDF to take possession of Dutch plutonium. EDF did not agree to do so.

The **British** electricity utilities operate 35 commercial reactors, of which 20 are Magnox reactors, the others being Advanced Gas Reactors (AGR) of British design and one PWR. Nuclear electricity generation was 85.9 TWh in 1996, which accounted for 26% of the country's total electricity production.

Magnox spent fuel is difficult to store for long periods of time and reprocessing is generally considered necessary because of corrosion of the fuel cladding. Nevertheless, dry storage of metal fuel has been demonstrated. Utilities have also reprocessed minor quantities of spent fuel from other types of reactors.

British utilities only operate one PWR (Sizewell-B), which technically could be fuelled with MOX (although this option is not currently envisaged. Therefore British utilities are not interested in the future Sellafield MOX fabrication Plant (SMP), currently under construction. The builder-operator British Nuclear Fuels is looking for foreign clients to fill up its order books. Precise information on the state of negotiations has not been published.

The presently operated MOX Demonstration Facility at Sellafield only produces about one reload (7 to 8 MT) per year and for the time being delivers all of this fuel to Switzerland.

The following two tables give the official British plutonium inventory as of 31 March 1997. We only give here the information concerning the inventories of plutonium which are located at BNFL and UK Atomic Energy Authority (UKAEA) sites;, this means we are not considering spent fuel which is stored after being unloaded from reactors which has not yet been sent to either BNFL or the UKAEA for reprocessing or storage.

[17] The Dutch utilities hold 14,75% of the German Consortium SBK, besides German, Belgian and British utilities, which holds 16% in the capital of the Superphénix builder/operator NERSA.

Table 7: Stocks of plutonium held by BNFL on 31 March 1997

Location of plutonium	Quantity (MT)
Unextracted plutonium in irradiated fuel	41.0
In the process of extraction / fuel fabrication or in other intermediate forms (eg. nitrate)	2.0
Stored as plutonium oxide	53.5
TOTAL	**96.5**

(Source: UK Department of Trade and Industry Press Notice, 31 July 1997)

Table 8: Stocks of plutonium held at UKAEA sites on 31 March 1997

Location of plutonium	Quantity (MT)
Being processed, stored or in irradiated fuel	2.5
Non-irradiated mixed oxide fuels	1.5
TOTAL	**4.0**

(Source: UK Department of Trade and Industry Press Notice, 31 July 1997)

The **Swedish** electricity utilities operate twelve commercial reactors. Nuclear electricity generation was 71.4 TWh in 1996, which accounted for 52.4% of the country's electricity generation. A referendum in 1980 prompted the Government to commit itself to shut down all plants by 2010. According to a government decision in spring 1997, the first reactor is to be shut down by July 1998.

In the 1970s, utilities signed reprocessing contracts with COGEMA. Following the 1980 referendum to phase out nuclear power, these utilities have tried to disengage themselves from these reprocessing contracts. They have exchanged spent fuel with German utilities. Today, the utility is still formally a reprocessing client of COGEMA ("base load customer"), even though the utility no longer appears in any of the published contract tables, the German utilities are, however still responsible for the corresponding nuclear materials. The plutonium from corresponding quantities of Swedish spent fuel reprocessing will thus be attributed to the German utilities.

The **Swiss** electric utilities operate five commercial reactors. Nuclear electricity generation was 23.7 TWh in 1996, which accounted for 44.5% of the country's electricity generation.

During the 1970s, Swiss utilities signed reprocessing contracts with both British Nuclear Fuels and COGEMA. However, the utilities no longer seem to be interested in post-2000 contracts with either of these plutonium companies.

MOX fuel has been loaded into two reactors on a demonstration basis. Some MOX fuel has been transferred by air from the British pilot plant to Switzerland. It is planned to partly fuel two more reactors with MOX before the end of the century.

French Plutonium Policy

The **French** national electricity utility Electricité de France (EDF) operates fifty-six commercial reactors, of which the last two were connected to the grid in 1997. Two more reactors are under construction, the last reactors to be constructed since the beginning of the massive construction programme in 1973. Nuclear electricity generation was 378.2 TWh in 1996, which accounted for 77% of the country's electricity generation.

COGEMA has been negotiating over the last few years - without much success - a follow up to its previous long-term reprocessing contract with EDF. The current contract covers spent fuel to be reprocessed up until the year 2000-2001. The follow-up contract should cover fuel to be reprocessed from 2001 to 2010. EDF is taking its time to negotiate the best possible post-2000 reprocessing contracts it can get at a lower cost than it obtained with COGEMA for the current ten year cost-plus-fee contract.

For the year 1996, EDF has asked COGEMA to reprocess 870 MT of its spent fuel[18]. EDF had 862 MT reprocessed in 1996, thus right on target.

Because of low storage capacity for fresh MOX fuel on the MELOX MOX fabrication site, the French electricity utility EDF is looking into the possibility of building dedicated storage compartments for MOX fuels on nuclear power plant sites . For safeguards reasons, MOX fuel cannot be stored in uranium fuel storage compartments.

However, the single most important recent event - which took place in 1996 - in the French plutonium industry is EDF's officialised decision not to reprocess the total quantity of fuel unloaded from French reactors. Although plans have never existed to reprocess the total quantity of spent fuel, it has been officially argued that spent fuel stocks would only constitute buffer quantities, which would eventually have to be reprocessed after the turn of the century[19]. It is not yet sure how long this plant will be operated after the turn of the century.

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18 *NuclearFuel,* 26 February 1996.

19 In a paper presented to the Omiya International Plutonium Conference in 1991, Mycle Schneider argued already that France has de facto already a mixed spent fuel management because the spent fuel stock would be 10,000 to 12,000 MT by the turn of the century. This would mean that at an annual discharge rate of 1,200 MT, an annual available capacity of 1,600 MT, and without any foreign contracts after 2000, it would have taken up to 30 years to absorb the stocks.

This fundamental decision is not the result of a national consultation process, but the result of the French National Assembly discovering EDF's plans in consultations about high level waste. Christian Bataille, a socialist member of parliament and government appointed waste negotiator drafted a report for the Parliamentary Office for the Evaluation of Scientific and Technological Options[20]:

"Over the last few months, what was formerly considered a hypothesis is becoming a certitude: EDF is not going to reprocess the total quantity of spent fuel unloaded from its nuclear power plants, at least in the immediate future. [...] During the hearings for the purpose of this report, representatives of EDF were perfectly clear on the issue:

- "All the nuclear fuel used by EDF in its plants is 'reprocessable', the choice of not reprocessing is not due to a technical impossibility. Moreover safety authorities have imposed the condition that all the fuel loaded into reactors must be reprocessable at the end of the cycle.
- "On average, each year, 1,200 MT of spent fuel are unloaded from EDF reactors. Of these 1,200 MT, it has been decided to reprocess only 850 MT. (...)"

In fact EDF has considered a "high-level scenario" with the reprocessingat of 1,200 MT per year, and a "low-level scenario" with the reprocessing of no more than 400 MT per year. EDF has also submitted a "medium-level scenario" with a rate of 650 MT per year to the National Commission on the Evaluation of high-level waste policy implementation. Details of the scenarios have not been made public.[21] It is clear, (and top EDF officials confirm this in private discussions), that EDF would prefer not to be involved in the production and use of plutonium. The main reasons for this position are related to economic, technical fuel management and operational considerations. But it is also clear that State control - and protection - not only applies to EDF but to the plutonium fuel industry as well.

According to information obtained by WISE-Paris, the former French Minister of Industry Franck Borotra, in a classified letter, obliged the French utility EDF to increase the number of reactors to be "moxed". In fact, the plan to increase the number of reactors to be loaded with MOX fuel from 8 to 14 from the beginning of 1996 to the end of 1997 seems to be already a consequence of this ministerial obligation. EDF management was firmly opposed to this development. WISE-Paris has requested this letter from the ministry but has not received a reply up to now. WISE-Paris therefore requested intervention of the Access to Administrative Documents Commission; this Commission has informed, WISE-Paris that it is "favorable" to access being given to this document. However, this administrations opinion can not counteract the

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[20] Bataille, Ch., Député, "Rapport sur l'évolution de la recherche sur la gestion des déchets nucléaires à haute activité", Office parlementaire d'évaluation des choix scientifiques et technologiques, Edition provisoire 18 mars 1996, pp. 77-78 (translated by the authors).

[21] Commission Nationale d'Evaluation relative aux recherches sur la gestion des déchets radioactifs, "Rapport d'évaluation n°2", juin 1996.

ministry's refusal. WISE-Paris has recently written to Prime Minister Lionel Jospin on this matter and envisages to take the issue to Court.

The Second National Commission for Evaluation report states: "In 1996, EDF informed the Commission that its industrial policy involved the reprocessing of 850 MT/year of spent fuel starting from the year 2000 (out of the 1,200 MT/year unloaded from its reactors) and the "monocycling" of the plutonium recovered in MOX fuel. The non reprocessed 350 MT/year of spent fuel, 215 MT of standard uranium fuel and 135 MT of MOX fuel, will be stored under water awaiting a final destination decision (delayed reprocessing or final storage) [...]"

The EDF rationale according to the Bataille Report: "
- The figure 850 MT corresponds to the throughput of the UP2 plant at La Hague.
- From these 850 MT of spent fuel, reprocessing produces 8.5 MT of plutonium.
- These 8.5 MT of plutonium allow for the production of 120-135 MT of MOX fuel, which corresponds to the throughput of the MELOX plant.
- These 120-135 MT of MOX fuel then correspond to the planned possibilities to use this fuel in the 900 MWe CP1 and CP2, i.e. all the reactors which are [will be] licensed to use this fuel."[22]

The Second Report of the National Commission for the Evaluation of high-level waste policy implementation adds in a footnote that the 350 MT of spent fuel not reprocessed under this scenario would be composed of 215 MT_of uranium fuel and 135 MT of MOX.

As of October 1997, twelve French reactors were partly (30% of the core) fuelled with MOX, while 16 (the CP1 reactors)[23] are licensed for MOX use. EDF had been planning to enlarge MOX fuelling licences to 12 additional reactors (the CP2 reactors). Accordingly, licensing amendments for using MOX in the four Chinon reactors have been submitted and the necessary public enquiry organised. Safety authorities plan to make a decision before the end of 1997. However, EDF has interrupted its licensing procedures for the reactors going beyond the Chinon reactors which would limit the total number of reactors licensed for MOX to 20.

The MELOX plant has a nominal capacity of roughly 120 MT of oxide. The average heavy metal weight of a MOX fuel reload for a reactor is around 7.5 MT. Therefore the 120 MT appear to correspond to the 16 licensed reactors for MOX use. Additional licensed reactors are needed because the management of the full output of the UP2 and MELOX plants is not realistic without a reasonable reserve capacity on the reactor side.

However, Christian Pierret, Secretary of State for Industry, declared in a press conference on 21 October 1997: "We do not envisage loading all the 28 reactors

22 ibidem.

23 CP stands for contrat de programme.

designed for use with MOX with this fuel." Consequently, licensing procedures beyond the 4 additional reactors at Chinon have been abandoned.

Table 9: Plutonium in France

	As of 31 Dec. 1994	As of 31 Dec. 1995	As of 31 Dec. 1996
Separated plutonium at French reprocessing plants	27.8	36.1	43.6
Separated plutonium at other French plants	4.6	5.5	5.5
Separated plutonium undergoing processing ("in the system") in France	8.7	10.1	11.3
Separated plutonium in MOX or other fuels in France	1.8	3.6	5.0
Plutonium in spent fuel on French reactors sites (estimate)	60.0	63.6	64.9
Plutonium in spent fuel at reprocessing plants or undergoing reprocessing in France	89.0	87.1	87.6
Separated plutonium in France attributed to Foreign countries	21.6	25.7	30.0
French plutonium abroad	0.6	0.2	0.2

(Source: L'énergie nucléaire en 113 questions, ministère de l'Industrie, France, March 1996, Ministère de l'Industrie, 5 septembre 1997)

Reactors are currently fuelled on a "hybrid" pattern, with different burnup rates for uranium and MOX fuels, which complicates fuel management significantly.

EDF has stated that savings must be made in the medium term to bring MOX costs in line with reference uranium fuel management. While more constraints are imposed on MOX use in France as compared to MOX use in Belgium and in Germany (plutonium content and burnup) more MOX has been used in France than in other countries. One of the factors which put constraints on MOX use in French reactors is fission gas release during operation.

Table 10: French Separated Plutonium Stocks

	As of 31 Dec. 1994	As of 31 Dec. 1995	As of 31 Dec. 1996
French separated plutonium, stored, "in the system" or in fresh plutonium fuel, in France and abroad	**21.9**	**29.8**	**35.6**

(Source: L'énergie nucléaire en 113 questions, ministère de l'Industrie, France, March 1996, Ministère de l'Industrie, 5 septembre 1997)

According to the official French plutonium inventory, as of 31 December 1996, there was a total of 65.4 MT of separated plutonium (or fresh MOX) in France, of which up to 30.0 MT were attributed to foreign countries. Another 0.2 MT of French plutonium were abroad at the time, part of which is separated plutonium. French separated plutonium (stored, "in the system" or in fresh plutonium fuel) increased by 13.7 MT to 35.6 MT during 1995-1996.

According to our estimate, French plutonium stocks will further increase to over 40 MT by the end of year 2000. A more limited consumption of MOX in French plants would, of course, lead to even further increases in stocks.

Conclusion

Commercial reprocessing plants in France and Britain are today_producing quantities of plutonium of the order of 20 tons per year, but the plutonium industry which is supposed to use this plutonium is not developing as planned. Technical, legal and financial constraints are making utilities reconsider previous commitments to reprocessing. However, plutonium stockpiles are increasing and will continue to increase if the currently planned scenarios become reality.

The dilemma is that the utilities do not seem to be free in their choice. They consider the separated plutonium or the plutonium under contract to be separated as a *fait accompli*. The major political and industrial challenge over the coming years will be to reopen options. The plutonium industry is at crossroads: it will either succeed extending the *fait accompli* logic into the next century or will cease to exist as a possible consequence of a fully open comprehensive impact assessment on the production and use of plutonium.

The most striking case is France. Over the past 20 years the plutonium industry has imposed its own pace of development on the French utility and on the political level. Now the establishment is committed to fighting over the strategy to be chosen for the beginning of next century. The dilemma - or scandal - is that, given the

overwhelming significance of the plutonium issue for the French population, the debate is not being carried out in a transparent democratic way.

The situation in other countries might backfire on France. It would be a significant step backwards if the current debate, in Germany and Japan in particular, merely leads the power industries in these countries sliding back to the situation in the 1970s of transfering their spent fuel management to France and Britain. In the past, this strategy has led to buying time, the reprocessing waste returning to its country of origin 20 years later. The problem is that the reprocessed fuel waste management dilemma is no closer to being solved today than in the past and also that an unacceptable pattern of "nuclear risk export" is automatically involved.

It is quite clear that neither the French nor the British populations will accept being exposed in the long term to the risks of plutonium production, storage and transport for the mere purpose of earning Yens or Deutsch Marks. It is also obvious that the plutonium industries would not have survived the 1970s either in France or in Britain without the massive capital input from other countries - Japan and Germany in particular.

It is time that client countries face up to their responsibilities for the management of their own nuclear waste. This simple ethical rule is being considered basic in any other sector of our Society. The nuclear sector is lagging behind. It should be encouraged to catch up.

NOTE

. However, while the design throughput is often given even as 400 MT per year, real throughput is rather roughly 100 MT/ a over last years, according to Russian sources.

Annex 2

Contribution Papers to the IMA Project

Annex 2-a
Contribution

Core Physics related Safety Aspects of MOX Fuel Burning in Light Water Reactors

Richard Donderer

1. Introduction

The use of plutonium from reprocessed irradiated fuel of Light Water Reactors (LWRs) mixed with uranium in oxide fuel to reload LWRs is currently being practiced or in preparation in Belgium, France, Germany, Switzerland and, to a minor extent, in Japan.

Mostly due to economic reasons, these mixed-oxide (MOX) fuel programmes are intended to be extended in the future by utilizing a larger percentage of MOX fuel assemblies in a given reactor, by increasing the burn-up levels (up to 60 GWd/t) and by starting with higher initial Pu-enrichment levels. In particular, the feasibility of new light water reactor concepts loaded with up to 100 % MOX assemblies made out of dismantled weapons grade plutonium is actually evaluated in various countries. However, such new reactor concepts will not be available during the next 10 years.

Most of the so far available experiences with MOX fueled reactor cores have been made in pressurized water reactors (PWRs), e.g. 350 MOX fuel assemblies have been used in German PWRs, 450 MOX assemblies in French ones [BURTAK 96b]. The MOX usage in boiling water reactors (BWRs) is currently practiced in a lesser extent.

In Germany, the current usage of MOX fuel covers MOX loading percentages between 10 and 50 %, averaged fissionable Pu-enrichments between 2.2 and 4.8 w/o and burn-up levels of up to 50 GWd/t [SCHLOSSER 95; BURTAK 96a].

In this paper, the safety aspects of the MOX fuel usage in LWRs are addressed, in particular those aspects which are related with the different reactor core physics characteristics of the MOX fuel compared with conventional UO_2 cores. Chapter 2 lists the potential safety relevant implications. Chapter 3 summarizes informations of separate effect studies taken from literature data on these aspects as well as on design measures which are proposed or already utilized to counteract safety relevant implications of the MOX usage. Chapter 4 compiles literature information on coupled accident analysis for special MOX core scenarios. Chapter 5 discusses general safety aspects of MOX fuel usage, and chapter 6 summarizes the discussion from the authors viewpoint.

2. Safety related Implications of MOX-fuel Utilization

Basically, the utilization of MOX fuel in LWRs means that the content of Pu-isotopes within the reactor core will be increased compared to an operational regime with pure UO_2 fuel. Due to

the thus changed isotopic composition of the reactor core, the neutron physical behavior of the reactor will change because of some different neutronical features of the plutonium isotopes. The safety relevant implications of these changes is the main topic of this chapter.

In addition to these core neutronics aspects however, some thermo-physical, mechanical and chemical characteristics of the mixed PuO_2/UO_2 fuel also are different compared to the pure UO_2 fuel. Furthermore, there may be differences in the thermalhydraulic and mechanical design of the MOX fuel assembly and MOX fuel rod. Of course, the implications of these different characteristics and design features must be taken into account when analysing the integral accident behavior of MOX-fueled cores.

Furthermore, the fission product and actinides inventory of a MOX-fueled core will be different from that of a pure UO_2 core. This also may be of safety relevance in terms of a different radiological source term in cases of radioactivity release events. This aspect as well as the safety relevance of the different nuclide inventories for the fuel reprocessing, refabrication, short-term and long-term waste disposal steps of the fuel cycle will not be discussed in this paper.

Thus, the following safety related implications of MOX-fueled reactor cores are identified and addressed here:

- principally, due to the higher capture and fission cross section of Pu-239 and Pu-241 in the thermal energy range[1], the thermal neutron absorption in a MOX-fueled core is significantly increased; this leads to
  - a considerable neutron spectrum hardening and thus to
  - a substantial reduction in xenon and control rod worths because neutron absorption mainly takes place in the thermal neutron region;
  - a substantial reduction in boron worth, and
  - changes in the most important reactivity coefficients, as there are: the moderator temperatur coefficient, the moderator density coefficient or void coefficient, and the fuel temperatur coefficient or Doppler coefficient;
  - a decrase in prompt neutron lifetime;
- these effects are intensified by an additionally spectrum hardening effect due to a faster neutron fission spectrum of the fissionable Pu isotopes and the other fissionable actinides present in MOX fuel;
- due to different fission product distribution, especially of Pu-239, a lower delayed neutron yield is obtained compared to a pure U-235 fueled core;
- except for 100 % MOX utilization concepts, which are currently discussed in the literature, the MOX elements will be neighboured by UO_2 elements; due to the inflow of thermal neutrons from the UO_2 into the MOX assemblies, a significant power peaking at the MOX assembly boundaries may be caused;
- the different fission product and/or actinide inventories, which built up during MOX fueled

1. the absorption cross sections of Pu-239 and Pu-241 are about twice higher than for U-235; the fission cross sections are about 3 times higher; also, the absorption cross sections of Pu-238, -240, -242 and Am-241 are relatively high [GUYOT 95].

reactor operation, may further enhance the safety implications mentioned above; in any case,
  - the decay heat production will be changed, as well as
  - the thermal conductance of the fuel pin rod gap;
- due to different thermophysical features of PuO_2-containing fuel (i.e. melting temperature, thermal conductivity of the fuel, oxygen reduction potential of PuO_2, fission gas relase rates) the detailed operational and transient behavior of the reactor may be changed;
- as a secondary effect of the spectrum hardening (larger fraction of fast neutrons), accelerated damages to the reactor structural materials (especially the reactor pressure vessel) may occur.

Of course, the quantitative extent of safety-related impacts of these aspects depends on the specific design of the MOX fuel assembly, fuel rods and the Pu utilization concept envisaged for the reactor core. In particular, the fraction of the MOX fuel percentage in the reactor core and the Pu-enrichment within the MOX fuel are of major importance, as well as the isotopic composition of the used Pu. The different percentages of MOX usage discussed in the literature range from a low percentage to 100 % MOX loading.

In general, however, it can be concluded that the safety related implications of the different MOX fuel utilization concepts will become more important with:
- an increasing percentage of MOX fuel loading,
- an increasing Pu-enrichment level,
- the usage of weapons-grade Pu (due to the different isotopic composition),
- an increased level of burn-up and
- an additional enrichment of the fuel with minor actinides.

In the next chapter quantitative data on the separate MOX implications are compiled, taken from the literature. However, for a final evaluation and judgement of the safety impacts of MOX usage reactor core concepts, it is not sufficient to quantify the values of the various MOX induced core physics effects separately. Rather, the coupled accident behavior of the specific reactor design has to be investigated explicitly, analysing the whole spectrum of the operational and transient accident regimes known from the UO_2 cores and those which may be additionally important for the specific MOX core designs. Results from accident analyses presented in the literature for different MOX fueled reactors are compiled in the forth chapter.

3. Quantitative Results of separate Effect Studies

This chapter summarizes literature information on the quantitative effects of safety related implications of the MOX fuel usage in LWRs, and on proposed design measures to counteract these implications. Table 1 gives on overview over some MOX fueled PWR data found in the literature.

Control Rod Worth/Shutdown Margin/Boron and Xenon Worth

In general, the effectiveness of the control rods, designed for conventional LWRs, is significantly reduced when used in MOX fueled cores. However, [SCHLOSSER 93] states that it will be possible to load a conventional PWR core with up to 50 % MOX fuel, without the need for

Table 1. Comparison of Core Physics Related Parameters for Differently Fueled PWRs (examples)

parameter / reference	units	PWR fueling		
		UO_2 100 %	MOX 30-40 % reactor Pu	MOX 100 % weapons Pu
moderator temperature coefficient	1.e-4 / C			
BOL [ROHR 94]		-1.06		-1.80 to -2.12
EOL [ROHR 94]		-5.83		-5.58 to -2.74
EOL [THOMAS 86]		-5.19	-5.61	
EOL [SCHLOSSER 93]			-5.95 to -7.85	
EOL [NISAN 91]		-4.0	-5.5	-5.5 to -6.0
fuel temperature coefficient	1.e-5 / C			
EOL [ROHR 94]		-2.25		-1.96 to -2.99
[THOMAS 86]		-2.77	-2.76	
critical boron concentration	ppm			
BOL [ROHR 94]		1170		1775 - 2100
BOL [SCHLOSSER 93]			1085 - 1996	
inverse boron worth	ppm / %			
EOL [ROHR 94]				241 - 331
EOL [THOMAS 86]		101	121	
BOL [SCHLOSSER 93]		102	135 - 298	
effective delayed neutron fraction				
EOL [ROHR 94]		0.0055		0.0034 - 0.0045
EOL [THOMAS 86]		0.0057	0.0050	
prompt neutron lifetime	1.e-6s			
EOL [ROHR 94]		24.8		7.9 - 10.7
EOL [THOMAS 86]		24.1	20.3	

(BOL: full power beginning of life; EOL: fill power end of life)

additional control rods or redesigned ones. In French PWRs, some additional control rods have been implemented to counterbalance the reduced rod worths [GOUFFON 90]. According to [RIZVI 94], MOX fuel is generally not placed in control rod locations as a standard design practice, to minimize the effect of reduced rod worths.

In the conventional French PWR, loaded with 30 % MOX assemblies, the soluble boron concentration in the safety injection water reserves has been increased [GOUFFON 90], [SCHLOSSER 93].

According to [MUROGOV 93] the control and safety rod efficiency in a MOX fueled PWR with weapons-grade Pu becomes lower up to 30 %, compared to the UO_2 core. A unique feature of the use of weapons-grade MOX fuel is that the rod worth increases with burnup. This behavior is opposite to that of pure UO_2 cores, and has to be observed carefully [ROHR 94].

With regard to 100 % MOX usage concepts in PWRs, it is considered as necessary to add more control rods and / or rods with a more effective isotopic composition into the cores, to obtain the requested shutdown margins and to fulfil the necessary shutdown reactivity requirements ([BISWAS 94; BISWAS 95; BARBRAULT 94]). [NISAN 91] proposes to increase the overall control rod worth by a suitable choice of the control material (enriched B_4C and hollowed hafnium or Eu_2O_3 rods) and by an appropriate number of these rods to obtain a sufficient reactivity margin.

In BWRs, more gadolinium-poisoned rods are needed in the MOX assemblies because of the reduced absorption efficiency [SCHLOSSER 93].
The xenon worth in a 100 % MOX fueled PWR core decreases by a factor of two, boron worths even more [BISWAS 94]. It is proposed to increase the B-10 enrichment within these core concepts in an adequate magnitude [BARBRAULT 94].

Reactivity Coefficients

There is agreement with regard to the trend of the void reactivity effect in PWRs which becomes more positive as the Pu content of the MOX region increases [OECD 95]. Infinte lattice calculations show that the void reactivity of MOX assemblies becomes positive somewhere between 10 and 14 weight percentage total Pu content. This value will depend on the specific Pu isotopic composition used [OECD 95].

Furthermore, the calculational results presented in [OECD 95] show, that in case of local voiding of a MOX assembly, even the low-enriched MOX assembly (5.4 % Pu) may result in a positive void effect. These results have been unexpected. In [OECD 95], it is considered as not possible in a real reactor that one assembly is fully voided while its neighbours are fully moderated. However, the existence of a positive reactivity coefficient generally increases the risk of additional accident initiators (in this specific case, positive reactivity may be introduced by local voiding effects, e.g. local overheating scenarios, fission gas releases), and it is not yet clear wether the consequences of such a local positive reactivity insertion into a PWR core could lead to fuel rod failures. It is one of the main safety criteria of the French new MOX core designs, that under no circumstances the partial (i.e. local) void coefficient should become positive [NISAN 91].

According to [YAMASHITA 91], [BRITTINGHAM 94], the void coefficient is slightly more negative in the MOX core of an advanced boiling water reactor (ABWR) concept.

With regard to the moderator temperature coefficient, it is commonly stated that this coefficient becomes more negative, particular at the beginning of the PWR fuel cycle ([THOMAS 86; KREBS 90; NISAN 91; ARKISCH 94]). However, for end of life conditions in some 100 % MOX PWR designs, the coefficient may be less negative [ROHR94]. For a 100 % MOX fueled PWR core, it is said that moderator temperature coefficients similar to the ones of uranium fueled cores can be achieved by balancing burnable absorbers (erbium) and soluble boron [BISWAS 94], [ROHR 94]. However, [NISAN91] states that it will not be realistic to reduce the negative extent of the moderator temperature coefficient for some 100 % MOX core concepts to a level below -30 pcm / C.

The fuel temperature (Doppler) coefficient is stated to be more negative in a 100% MOX fueled PWR core [BISWAS 94; ROHR 94; GARKISCH 94]. In conventional pressurized water reactors with a maximum MOX loading of 30 %, the Doppler coefficient is slightly less negative than in pure UO_2 fuel [THOMAS 86].

Delayed Neutron Fraction

The values of the reduction in the fraction of the delayed neutrons due to the MOX usage range from 10 - 25 %, compared to pure UO_2 cores (see Table 1, and [KUEPPERS 92]).

Power and Neutron Flux Distribution

At the interface between MOX and UO_2 assemblies, the neutrons will be strongly absorbed by the plutonium in the MOX assemblies. These absorptions risk to give fission and power peaks at the periphery of the MOX assembly unacceptable for plant operational safety [GUYOT 95]. Therefore, it was decided to reduce the fission rate in this region by using intrasubassembly zones of varying Pu content. Usually 3 zones with different enriched fuel rods are used in pressurized water reactors, and 6 zones in boiling water reactors [THOMAS 92; SCHLOSSER 93; KRAMER 88].

However, such a design leads to an undermoderation effect of the centered rods within the zoned MOX assembly. This effect has to be corrected as well and it is commonly proposed to use so-called water rods in the assembly center, which can raise the moderation in this region and improve the power distribution. Care must be taken in the choice of the position of these rods: if they are too close to a guide tube the fuel rod between this water rod and the guide tube may become overmoderated [GUYOT 95].

According to [THOMAS 87], the Pu content within the different zoning regions of the PWR MOX assembly range from 2 - 3.5 w/o Pu-fissionable, according to [SCHLOSSER 93] 1.9 - 4.6 w/o. For higher burnups, these concentrations will be increased [CLEMENTE 91]. For the BWR rods, 0.8 -5.7 w/o are mentioned [SCHLOSSER 93].

Despite the intrasubassembly zoning efforts to smoothen the local power distribution, the local power peaking is still slightly higher than in pure UO_2 assemblies [GOUFFON 90].

In addition, there are specific problems with MOX elements for boiling water reactors: due to the non-boiling of the moderator in the gaps between the assemblies, very strong thermal neutron flux gradients occur, especially at the element boundaries, and, the thermal neutron in-flow from the UO_2 assemblies into the MOX assemblies is more pronounced than in the pressurized water reactors (due to the smaller element widths) [KAAS 88]. Thus, special MOX assembly concepts are discussed for BWRs to additionally reduce the effects of thermal flux peakings by using pure UO_2 rods at the boundary of the element, or, as in PWRs, water-rods in the center of the element. Both cases will lead to an highly inhomogeneous assembly configuration [KAAS 88].

As an additional measure for the purpose of reduction of PWR MOX fuel power peaking, the use of lumped burnable poison rods (with gadolinia Gd_2O_3) is proposed [YAMATE 95].

In general, the significantly increased complexity and heterogenity of the zoned MOX assemblies, including the centered water rods, increases the calculational uncertainties on the rod power peaking factor and other safety relevant parameters. Thus, the heterogenity of the MOX assembly design has to be considered as a principle disadvantage in terms of reactor safety [BARBRAULT 94].

It should be further added, that the problem of local power peaking poses also higher requirements on the fuel fabrication accuracy, especially with regard to the Pu content, isotopic composition and mixture homogeneity [THOMET 90].

Thermo-Physical/Thermo-Mechanical and Chemical Aspects

Due to the different isotopic composition and/or concentration of non-shortlived fission products within the MOX fuel, the decay heat generation is approximately 3 % higher than for UO_2 cores (24 hours after the end of the irradiation period), and ~100 % higher after a period of 10 years [THOMAS 92].

Due to the more flattened reactivity development with increasing burn-up, MOX elements have higher powers at higher burnups than UO_2 cores. This results in increased fission gas releases [KREBS 93]. According to [YAMATE 95], the internal pressures of MOX rods become higher than

that of UO_2 rods because of higher relase ratios of fission gases (see also [THOMAS 92]).

According to [MISHIMA 90], the increased release of helium into the gap between the fuel pellet and the fuel rod cladding may change the thermal conductance of the gap, compared to UO_2 rods. This effect has to be taken into account in the thermal-hydraulic calculations of the assembly design and accident analysis.

According to [THOMAS 92], the importance of the pellet-clad mechanical interaction (PCMI) which controls fuel rod failure mechanisms during transients increases for MOX rods.

According to [RENARD 78], the potential presence of Pu microheterogenities in MOX fuels introduces safety problems in some particular conditions, because modifications of local power distributions can occur due to large Pu particles or aggregates. Moreover, in transient conditions, the influence of those fissile aggregates near the pellet surface is important for the risk of clad failure. Problems with hot Pu spots at the surface of the pellets, which may induce clad damage especially under transient conditions, are also mentioned in [GOUFFON 90]. Therefore, the safety requirements, which have to be realized during the fabrication process of MOX rods have to be increased. It must be prevented with a high accuracy that confusion between pellets or rods having different Pu contents or isotopic concentrations occurs. This increases the risk of errors at the fabrication stage a well as of core physics validation calculations [GOUFFON 90] (see also [GUYOT 95; THOMET 90]).

Furthermore, PuO_2 has a stronger oxygen reduction potential than UO_2. This may have disadvantageous effects on the corrosion of the inner clad surface and thus on the clad behavior (fission gas release) during transients [BAIRIOT 90].

All these effects as well as those listed in chapter 2 but not mentioned here explicitly (i.e. the lower melting point and thermal conductivity of MOX fuel) have to be included in the investigations of the accidental behavior of MOX fueled cores. In addition, the potentially different fuel failure characteristic of MOX fuel rods during transients or accidents, caused by the different thermo-mechanical, chemical and neutronical features (e.g. by local power peaking effects at the pellet surface), has to be reminded. However, the experimental data base, available for the failure behavior of MOX fuel, may be very limited, particularily for irradiated conditions, and thus, potentially large uncertainties of the MOX fuel failure thresholds has to be taken into account in the analyses.

Neutron induced Material Damages

The spectrum hardening effect in MOX fueled cores increases the risk of potential neutron induced material damages due to the larger fraction of fast neutrons. Therefore, placement of MOX fuel assemblies at the core periphery should be limited because of its higher fast flux and resulting accelerated damage to the pressure vessel (for fresh and lower burnup MOX fuel) [RIZVI 94].

4. Results of Accident Analyses for MOX fueled Cores

The evaluation and final judgment of the safety of MOX fuel usage in light water reactors has to be based on an explicit and plant-specific analysis of the operational and accidental behavior of the reactor. It is not possible to judge the safety of a certain MOX design a priori, i.e. based on the consideration of some isolated safety parameters, since some of the MOX-specific safety characteristics may be beneficial for a given transient from the safety point of view, others not, and this behavior may be different for different core conditions. In addition, the details of the design of the fuel rods, fuel assemblies, of the core loading pattern and fuel cycle state will be of importance for the accident analysis.

Thus, before the licensing of the loading of MOX assemblies into LWR cores, the impact of

the coupled behavior of the relevant MOX safety features on the whole spectrum of core related accidents has to be investigated. It is only on the basis of these analyses that a judgement can be made wether the safety criteria are met, or wether the usage of MOX fuel increases the probability of a given reactor design to initiate transients and/or accidents, and if those transients/accidents may reach safety limits easier.

However, there are some MOX-specific features that apparently tend to deteriorate the safety behavior of the reactor cores. Thus, it is expected, that due to the smaller delayed neutron fraction and the smaller prompt neutron lifetime in MOX fueled cores, the accident kinetics in uncontrolled rod withdrawal or excessive cooling accidents will be faster than in pure UO_2 cores (i.e. the flux increases will be faster also) [GOUFFON 90].

According to [BRITTINGHAM 94], Generel Electric evaluated the entire spectrum of events for the advanced BWR safety analysis for MOX fuel, including the anticipated transient without scram scenarios (ATWS). Typically, with the lower delayed neutron fraction associated with the MOX core, events that produce reactivity increases are considered as more severe than for UO_2 cores. For boiling water reactors for example, such an event is the collapse of void during pressurization. Also, the BWR neutron flux stability problem is affected and this accident type has to be evaluated explicitly analysing the consequences of the MOX fuel utilization.

According to [NISAN 91], the lower control rod worth and the more negative moderator temperature coefficient are quite beneficial for PWR core heating accidents but these two parameters may have serious consequences with regard to reactor control in core cooling accidents such as a secondary valve opening or a steam line rupture. Thus, breaks on the secondary side and valve opening events have to be analysed carefully. Furthermore, subcriticality has to be demonstrated for the whole range of core loadings and irradiation cycle conditions.

Specific Accident Analysis

For conventional pressurized water reactors (PWRs) with a MOX loading of up to 30 %, [FERRIER 90] states, that because of the lower boron worth and the more negative moderator temperature coefficient, the double-ended steamline break accident results in higher power peaks for the MOX core, and the inadvertent secondary valve opening accident shows a lesser margin to criticality in the MOX case compared to the UO_2 core. According to [SCHLOSSER 93], an interim return to criticality may occur during a main steamline break accident in a PWR, with approximatelly 40 % MOX usage, due to the introduction of cold coolant and the more negative coolant temperature coefficient of the MOX fuel. However, the author states that the conditions for burnout, film boiling or centerline melting were not reached.

On the other side, the low boron worth is considered as beneficial for boron dilution accidents, and it is stated that early indications do not reveal any impact of the low boron worth on the steamline break accident for a 100 % MOX fueled PWR core [BISWAS 94].

The rod drop accident in a MOX fueled BWR is said to develop very similar as in the pure UO_2 core, despite the less favorable neutronic characteristics of the MOX fuel [SCHLOSSER 93]. However, during a BWR pressurization transient (e.g. inadvertent bclosure of the main steam isolation valve, MSIV, or other void reduction transients), the more negative void coefficient in the MOX core leads to an increased power. This requires an additional safety margin in the minimum critical power ratio [SCHLOSSER 93].

An analysis of the rod ejection accident in a 30 % MOX loaded PWR showed that the safety margins are reduced compared to the UO_2 core, safety limits however are not reached [GOUFFON 90]. For a 100 % MOX fueled PWR core, the control rod ejection accident was analysed, in particular because of the low delayed neutron fraction of that core. Far less limiting results have been obtained than for a typical standard plant design. The primary reason for this is said to be

the reduced worth of the individual fuel rods [BISWAS 94].

During loss of coolant (LOCA) analysis in MOX fueled pressurized water reactors, it was demonstrated that for certain piping breaks, water went into the core and steam was removed. Such a process would lead to high boron concentrations in the core and a low concentration in the sump water. Therefore, it has to be assured by additional accident management measures that the required minimum boron levels in the sump water, which must be higher for the MOX fueled cores, will be maintained [GOUFFON 90].

Due to the low xenon worth in MOX cores, less problems are expected with xenon instabilities [GOUFFON 90; BISWAS 94].

As already mentioned above, the analysis of a hypothetical single MOX assembly voiding within a watered UO_2 assemblies environment yielded positive void reactivity effects [OECD 95]. According to the authors of [OECD 95], it is not considered as possible in a real reactor that one single assembly is fully voided while its neighbours are fully moderated. However, the existence of a positive reactivity coefficient increases generally the risk of additional accident initiators. Thus, it has to be proven that there may not be any possibilities of local voiding events (e.g. local overheating scenarios, fission gas releases) which may cause local positive reactivity insertions into a PWR core, and which may be severe enough to cause fuel rod failures and the loss of core coolability. Therefore, it is strongly recommended to strictly request as a design requirement, that under no circumstances the global or partial (i.e. local) void coefficient should become positive (see e.g. [NISAN 91]).

As a further aspect, it has to be mentioned that because of the higher enrichment of fissionable material, MOX fueled cores have a higher risk of achieving recriticality conditions after the partial meltdown of the core [THOMAS 92].

With regard to the French 100 % MOX fueled PWR concepts, it was concluded in [THOMET 90], that there are still difficulties in core control in various cold and hot shutdown, normal and accidental situations. These problems are connected with the important control rod worth decrease and notable variations in the kinetic coefficients, the reactor pressure vessel fluences and power distribution factors. In addition, it is said that further analysis of the fuel rod and clad behavior during loss of coolant accidents are needed.

Furthermore, it must be added that the potentially adverse safety implications of the MOX fuel usage will be further enhanced by increasing the level of burn-up, because an increase in burn-up essentially has the same adverse effect on core neutronics as the MOX usage alone (see [CLEMENTE 91]).

Finally, fuel concepts where the MOX fuel is additionally enriched with minor actinides (neptunium and/or americium) are also discussed in the literature. The admixture of minor actinides will change the reacitivity characteristics (coefficients) of the core. The quantiative extent of these changes will depend on the neutron spectrum envisaged and the admixture composition. For example, according to [KIMURA 94], only an overmoderated PWR core concept has a negative void coefficient, whereas the standard or undermoderated ones result in positive void coefficients. Compared to the pure MOX standard-moderated core, the void coefficient in the overmoderated core with minor actinides is approximatelly 50 % more negative.

5. Generic Aspects

Heterogenity

Compared to pure UO_2 fuel, MOX fuel is a more heteregeneous product. The main Pu isotopes generated during the operational periods in light water reactors range from isotope

number 238 to 242. In addition, americium is present due to the decay of Pu-241. The plutonium isotopic composition cannot be considered as stable, it depends on the type of reactor which the spent fuel comes from, on the initial enrichment and on the discharge burnup of the uranium fuel which is processed, on the time between the end of irradiation and the reprocessing, and finally on the time between reprocessing and fuel manufacturing [GUYOT 95].

This heterogenity, which is further enhanced by the current heterogeneous MOX assembly design and core loading patterns, increases the magnitude of uncertainties, poses new challenges on the calculational requirements (see below) and increases the risk of errors. For example, it must be prevented with a high accuracy during the fabrication process of MOX rods, that confusion occurs between pellets or rods having different Pu contents or isotopic concentrations (the problem of hot Pu spots at the surface of the pellets has already been mentioned).

Calculational Uncertainty

According to [FOUGERAS 94], the uncertainties of the reactor physics calculations of Pu fueled pressurized water reactor (PWR) cores are not yet on the same level which has been obtained so far for the traditional UO_2 fuel calculations. Results produced with the standard PWR calculational scheme are unsatisfactory. Thus, the EPICURE experimental programme has been initiated with the main objective to evaluate and to reduce these calculational uncertainties. It is stated that there are particular problems with the power distribution modelling. Some of the conventionally used calculational schemes gave disappointing results. The discrepancies resulted from the numerical approximations used, in particular at the MOX/UO_2 interface (e.g. the homogenization of the complicated geometrical conditions, and the collapsing of the neutron energy spectrum into discrete energy groups). Furthermore, the use of the diffusion theory approximation and the numerical method of the `finite differences' contributed to the observed discrepancies. These approximations are widely used calculational methods, and thus, it can be concluded that specific care has to be taken when choosing calculational tools for MOX reactor physics calculations, especially in the quantification process of the related calculational accuracy.

These problems are confirmed by [OECD 95]: the use of MOX fuel in standard PWRs introduces inhomogeneities into the core, which cause difficulties with the calculation of the power distribution around the interfaces between UO_2 and MOX assemblies. A correct treatment needs improvements of the calculational models.

Another problem arises from the behavior of the void coefficient for different MOX fuel types: in a benchmark calculation, specified to check computer code results and nuclear data, significant spreads in the calculated multiplication factors have been obtained, especially for the voided cases. In particular, the so-called deterministic calculational methods which rely on homogenization procedures, are questionable at the MOX/UO_2 boundary. According to [OECD 95], it is considered necessary to improve the calculational accuracy significantly.

According to [MOSTELLER 91], care must also be taken when choosing the methods for the Doppler coefficient calculation in MOX fuel. [BAIRIOT 90] confirms that due to the heterogeneous MOX assembly design, there exists a significant higher level of neutronical complexity than in conventional UO_2 cores. This complexity requires a higher level of calculational efforts. [GOUFFON 90] states that the calculational validation of the use of MOX assemblies in PWRs has to be confirmed.

6. Summary

The usage of MOX fuel in light water reactor cores introduces various safety relevant neutron physical changes which influence the core behavior during the operational and accidental regime significantly. Thus, it has to be demonstrated within the national licensing procedure wether the loading of MOX assemblies into a reactor core meets the safety criteria. To achieve this, core-

specific analyses of the whole spectrum of accidents have to be performed taking into account the current state of knowledge.

Since some of the MOX-specific safety characteristic changes may be beneficial from the safety point of view during a given transient or accident, and others not, and since this behavior may be different for different accidental conditions, it is not possible to judge the safety of a certain MOX usage design a priori, i.e. based on the consideration of some isolated safety parameters. In addition, the specific core loading and/or cycle conditions may be important for the results of the accident analysis.

Typically, with the lower delayed neutron fraction and in combination with more disadvantageous reactivity coefficients associated with the MOX core, events that produce reactivity increases are considered as more severe than for UO_2 cores. For boiling water reactors for example, such an event is the void collapse during pressurization transients. For pressurized water reactors, core cooling events such as main steam line breaks are most important.

According to results presented in the literature for specific accident types, the safety margins of MOX cores are smaller when compared to pure UO_2 core accidents. This is already true for conventional light water reactor cores with a MOX usage of up to 40 % and a plutonium enrichment between 3 and 5 w/o. However, these results, taken from the literature, do not yet cover the whole spectrum of accidents nor the spectrum of MOX usage concepts (e.g. 100 % MOX loading concepts).

Independently of reactor specific analyses however, some of the characteristical features of the MOX fuel may in principle be considered as a deterioration of the safety behavior compared to pure UO_2 fueled cores. These features are:

- due to the smaller delayed neutron fraction and prompt neutron lifetime in MOX fueled cores, the kinetics of some accidents (as the uncontrolled rod withdrawal or the excessive cooling accident) will be faster, i.e. the flux increases will be accelerated compared to pure UO_2. This behavior will be intensified by using an increased percentage of MOX fuel, an increased Pu-enrichment and also with increased burnup levels.

  Thus, MOX fueled light water reactors approach the neutronics characteristics of fast reactor cores. For these type of cores, the risk of power excursion accidents (core disruptive accidents) predominates.

- For high plutonium contents in the MOX fuel, there is a clear tendency for getting positive void coefficients. This feature also increases the risk of power excursion type accidents as it has been the case in design of the Chernobyl-4 reactor core. Therefore, the quantitative determination of the acceptable Pu levels is of importance and it has to be demonstrated, that these levels are safe under all operational and accidental conditions, including very exotic core states (as the one in Chernobyl-4 has been).

- Due to the strongly increased heterogenity of the MOX fuel, fuel assemblies and the whole core, compared to UO_2 fueled cores, the magnitude of uncertainties increases significantly, as well as the risk of additional error sources, in particular during fuel fabrication, core loading and core physics calculations.

  The uncertainties of the reactor physics calculations of Pu fueled reactor cores are not yet on the same level as for the traditional UO_2 fuel calculations. In particular, the use of MOX fuel introduces inhomogeneities in the core, which cause difficulties in the calculation of the power distribution around the interfaces between UO_2 and MOX assemblies. Further calculational uncertainties are related with the quantification of the void effect for different

MOX fuel types. The calculational spread between the different methods is considered as excessive and a correct treatment needs improvements of the calculational models.

These MOX related disadvantages apply to all the MOX usage concepts, currently in practice or in preparation, e.g. for the conventional PWR cores with a load of ~30 % MOX assemblies as well as for higher MOX usage concepts. However, it has to be emphasized that, the risk augmenting features of the MOX fuel usage will be further increased separately by

- increasing the fraction of MOX fuel in the core,
- increasing the plutonium enrichment in the MOX fuel,
- utilization of weapons-grade plutonium,
- increasing burn-up levels,
- recycling of minor actinides in the MOX fuel,

and even more if combinations of these measures will be realized.

Thus, the usage of MOX fuel apparently has the potential to increase the risks of accidents compared to pure UO_2 fueled cores by introducing new accident initiatiors and accident paths. Therefore, before any MOX usage is licensed, it has to be demonstrated that all relevant safety criteria are met.

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Annex 2-b
Contribution

Safety Aspects of Unirradiated MOX Fuel Transport

Edwin S. Lyman

Introduction

As a result of several factors, it is becoming increasingly likely that in the future, large quantities of commercial plutonium will be shipped internationally not in the form of oxide powder, as was the case during the controversial sea shipments of 1984 and 1992, but in the form of finished mixed-oxide (MOX) fuel assemblies. These factors include: (1) the delay or cancellation of MOX fuel fabrication facilities in the nations which are foreign customers of reprocessing companies, such as Germany and Japan; (2) the expansion of MOX fabrication capacity in the countries that provide reprocessing services; (3) the reprocessing industry's hope that the transport of plutonium in the form of MOX fuel will be perceived by the public as posing less severe environmental and security risks than the transport of plutonium oxide, and will therefore generate less controversy.

Will transport of unirradiated MOX fuel (U-MOX), as currently conceived, be less dangerous than transport of plutonium oxide? In general, the answer is yes -- the risk that a large fraction of the contents of a shipping package will be dispersed as a result of a transport accident is smaller if the material is shipped in consolidated form rather than as a powder, if all other aspects of the transport are identical. However, if one considers the actual packaging systems for transport of U-MOX that are now in use or will be used in the future, it is apparent that U-MOX package designs tend to exploit the less dispersible nature of the contents through omission of one of the multiple containment barriers that would be present in a plutonium oxide transport cask. For example, US domestic regulations require that plutonium in dispersible forms be shipped (by land) in packages with two independent containment barriers, but shipping packages for " nondispersible" forms, including U-MOX, need only have one.

In this article, I will argue that the current regulations governing transport of U-MOX provide inadequate assurance that the risks of such transports will be acceptably low. The recently approved 1996 revision of the IAEA's Safety Series No. 6 (SS6), which promulgates international standards for the shipment of radioactive materials (RAM), was carefully constructed to legitimate the risky practices now utilized for transport of U-MOX. These standards are not intended to provide protection in the event of very severe transport accidents, which could result in a widespread dispersal of plutonium from a cargo of U-MOX. The revised IAEA regulations will do little to alleviate the serious safety concerns associated with sea and air shipment of radioactive materials in general, and U-MOX in particular.

Type B Package Standards and the Notion of "Graceful Failure"

Under the 1985 (revised 1990) edition of SS6, which will remain in effect until the 1996 version is adopted by individual IAEA member states (a process that can take years), unlimited quantities of plutonium in any form can be transported by land, sea or air in so-called "Type B" casks. Type B casks are designed so that they will lose only a fraction of their contents (a radionuclide-specific quantity known as "A_2" per week, an amount deemed "acceptable" by the IAEA and which is tabulated in SS6) if they are exposed to accident conditions equivalent to an impact of 13.2 meters per second (m/s) on an unyielding surface, followed by an fire with a flame temperature of 800°C for 30 minutes.

It has been pointed out by many observers on many occasions that the conditions that a RAM package may encounter in the course of an accident at sea or the crash of an aircraft can be far more severe than those simulated by the Type B test. One of the chief arguments invoked by the IAEA in response is the notion of "graceful failure": namely, the claim that RAM packages are designed and constructed with such a high degree of conservatism that they will be able to withstand accident conditions far more severe than those under which they are tested.

The "graceful failure" principle is central to the philosophy on which the 1996 version of SS6 is based, as will be discussed further below. However, there is hardly any experimental evidence for it, as the IAEA freely admits.[1] Package manufacturers have little incentive to carry out testing to a severity beyond what the standards require; such tests are expensive and difficult, and they present the risk of embarrassment should the package fail abruptly rather than gracefully.[2] In the absence of experimental verification, "graceful failure" is based entirely on expectation.

While the graceful failure concept may have limited validity in the case of spent fuel casks, for which the shielding requirements mandate very thick (25 cm) metal walls that also provide mechanical strength and thermal insulation, the Type B packages used for transport of U-MOX require far less shielding. A review of available information on U-MOX transport cask designs does not provide confidence that they can withstand mechanical and thermal loads far in excess of those for which they were designed.

A typical Type B U-MOX fuel cask design is the Westinghouse Model No. MO-1. Although the 1976 NRC license for this design was allowed to lapse, it is considered representative of the type of package that will be used in the US for the transport of U-MOX, should the US carry out its plan to dispose of some excess weapon plutonium by fabricating it into MOX and irradiating it in reactors.[3] The MO-1 is designed to transport 2 MOX assemblies containing about 45 kg of

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1. International Atomic Energy Agency, "The Air Transport of Radioactive Material in Large Quantities or With High Activity," IAEA-TECDOC-702, April 1993.

2. Even attempts to design casks to withstand more severe accident conditions than the Type B test have not been successful; for example, when Japan in 1987 tested a cask specifically developed to meet the stricter US domestic air transport standards, it failed to survive the impact test [P. Leventhal, M. Hoenig and A. Kuperman, "Air Transport of Plutonium Obtained by the Japanese from Nuclear Fuel Controlled by the United States," March 3, 1987, p.5].

3. Westinghouse Electric Corporation, "Plutonium Disposition in Existing Pressurized Water Reactors," report prepared for the U.S. Department of Energy, DOE/SF/19683--6, June 1, 1994, p. 2.7-2.

plutonium. The package weighs 3.9 tonnes and has outer dimensions 1.143 m x 1.194 m x 5.23 m. It consists of two concentric steel shells, each around 3 mm thick. The volume between the shells is filled with an 18-cm thick layer of rigid polyurethane foam to provide shock and thermal insulation. The MOX assemblies are separated by borated stainless steel plates for criticality control. Because of the importance of insulating the assemblies from shocks during routine transport, they are shock-mounted inside the package with clamps.

Less information is publicly available about the Transnucléaire FS-69, the Type B package currently used in France to transport U-MOX assemblies by road, and presumably the same one that will be used for international shipments. The FS-69 is a Type B package licensed for the transport of U-MOX containing plutonium with up to 30,000 parts per million (approximately 3 weight-percent) americium-241 (Am-241). This corresponds to plutonium obtained from spent fuel of 45,000 MWD/t burnup and aged for six years, which is the plutonium composition used in the design of the MELOX plant.

Details of the FS-47 are considered proprietary. However, from the general descriptions that can be found in the open literature, the cask can be seen to have many similarities to the MO-1: it carries two assemblies held in place by a borated aluminum basket, weighs 5 tonnes when loaded and consists of two concentric steel shells separated by a neutron-absorbing material.[4] On the basis of the weight similarity with the MO-1, the FS-69 must contain a comparable amount of structural metal.

It is reasonable to assume that with respect to the construction materials and overall design philosophy, the FS-69 is similar to the FS-47, the container that was used to transport cans of plutonium oxide by sea in 1993. The FS-47 structure, like that of the MO-1, is based on two thin concentric steel shells (outer shell a few millimeters thick; inner shell about 1 cm thick) separated by a 5-cm thick layer of heat insulation ("wet", or hydrated, gypsum) and a 15-cm thick layer of a (proprietary) neutron absorber material.[5]

No information on the type of seal used in the FS-69 could be located. The ability of a cask to maintain containment if exposed to a beyond-design-basis fire depends crucially on the seal material. For instance, the elastomer seals used in the Transnucléaire TN 28 VT cask for vitrified high-level radioactive waste (VHLW) will fail if they are heated to a temperature above about 250 °C, which could occur if the cask were exposed to an 800°C fire for a couple of hours. According to COGEMA, the seal of the FS-47 cask failed after it was exposed to a 1000°C fire for 1.5 hours;[6] if the FS-69 uses the same type of seal it can be expected to behave similarly.

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4. J. Charles and O. Konirsch, "Transportation by Road of Plutonium as a Reusable Product," Proceedings of the 11th International Conference on the Packaging and Transportation of Radioactive Materials (PATRAM '95) (December 3-8, 1995, Las Vegas, Nevada), p. 777.

5. Science and Technology Agency of Japan, "Application for Design Change Approval of Nuclear Fuel Transport Cask, FS-47 (in Japanese).

6. COGEMA, "Le Retour Au Japon Du Plutonium," 1992.

Even less information is available about the "mystery" package now used by BNFL to transport MOX by air to Switzerland. A recent request for details about this cask was denied by BNFL, on the grounds that "disclosure of package types and capabilities would result in a breach of customer confidentiality."[7] However, according to BNFL, "... all packages for MOX transport fulfil the requirements of all the appropriate transport regulations." All this means at present is that the package used to ship MOX by air is Type B, the significance of which will be discussed below. However, one would expect that the package would not be more robust than the FS-69 used by BNFL's commercial competitor, Cogema. BNFL had attempted in the past to design a package specifically for air transport of plutonium oxide, known as the 1680. However, "due to changing commercial priorities ... it has not yet been used."[8]

It is apparent from what little is publicly known of these package designs that their structural strength and thermal resistance is provided primarily by the filler material between the two steel shells, which are themselves too thin to provide much strength. However, materials such as rigid polyurethane foam typically are not capable of providing resistance to mechanical or thermal stresses well in excess of design stresses. If the energy of an impact is significantly higher than the design energy, the foam will be crushed without causing any deceleration of the package. However, increasing the resistance of the package to high energy impacts by using a denser foam would increase the risk that the package could not withstand lower energy impacts, since the foam will not compress (and therefore act as a rigid surface) if the energy is too low.[9] In other words, for any foam density, there is a fairly narrow "window" of impact energies for which the foam is capable of providing protection.

"Wet" (hydrated) gypsum is a material used in boards for building construction. It is not capable of load-bearing and therefore cannot provide the FS-47 cask with significant impact resistance.

With regard to thermal resistance, organic materials such as polyurethane foams function primarily via *ablation* -- that is, they absorb heat energy by burning and carry heat away from the payload by dispersal of combustion products. Therefore, they can only continue to protect against a fire until they are completely consumed. After this point, the contents of the cask will quickly achieve thermal equilibrium with the fire temperature. In thermal tests of a polyurethane foam shielded by a metal lid, more than 25% had degraded after exposure to a flame of approximately 980°C for fifteen minutes.[10] Thus the "graceful failure" margin for casks that rely on ablative media for thermal protection is rather slim.

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7. Alan Hughes, BNFL Public Affairs Division, letter to Fred Barker, 24 January 1997.

8. *Ibid*.

9. F. Henry and C. Williamson, "Rigid Polyurethane Foam for Impact and Thermal Protection," Proceedings of the 11th International PATRAM Conference, December 3-8, 1995, Las Vegas, Nevada, p. 1161.

10. *Ibid.*

In the FS-47 cask, thermal protection is provided by the layer of hydrated gypsum, which has a low thermal conductivity at temperatures around 40°C. However, hydrated gypsum can decompose at temperatures as low as 150°C, and it cannot be expected to provide a significant margin of safety against fires of greater severity than the design basis fire.

Behavior of Unirradiated MOX Fuel Under Accident Conditions

Thermal: Although U-MOX is a refractory material with a very high melting point (around 2700°C), if it is heated in the presence of oxygen it readily oxidizes, expands and undergoes comminution (production of fine particles). This process can take place at temperatures as low as 250°C, so that significant oxidation and comminution is possible even in thermal conditions of moderate severity.[11] In particular, prolonged thermal exposure at relatively low temperature, as is characteristic of smoldering conditions following a severe fire, could result in substantial particulate formation.

Oxidation can only occur, by definition, if the fuel pellets themselves are exposed to oxygen. Therefore, for oxidation to occur mechanisms must exist for failure of the cladding of fuel rods and for the cask seal (if the casks are filled with inert gas; otherwise, oxygen will be present in the cask even if the seals initially remain intact). Fuel rod cladding can be ruptured either by mechanical impact during the accident or by bursting as a result of thermally induced overpressure. The latter has been observed to occur in spent fuel rods after exposure to temperatures over 725°C for a four-hour period.[12] Extrapolation of this result to unirradiated fuel rods is not straightforward, because they contain no fission gas and their cladding has not undergone wastage from interaction with fuel and coolant during reactor operation. However, the former will not make much difference for PWR fuel rods, since they are pressurized with helium fill gas, and fission gas would only increase the internal pressure by a few percent.

If the cladding is breached due to mechanical impact, oxidation of the fuel will cause it to expand and exert additional pressure on the cladding, which will cause further ruptures and exposure of the fuel pellets to air.

If oxygen access to the fuel pellet surfaces is limited, then there will be little particulate formation. However, the volatility of americium-241 in the fuel will be greatly enhanced in reducing conditions, which could result in the release of highly radiotoxic americium vapor from the fuel during a fire, even if the fuel matrix itself is not dispersed. Transport safety literature has paid no attention to this phenomenon. In contrast, volatilization of plutonium (e.g. gaseous release) is not likely to occur to a significant extent for the range of temperatures that would be encountered in a transport accident.

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11. T. Sanders *et al.*, "A Method for Determining the Spent-Fuel Contribution to Transport Cask Containment Requirements," Sandia Report SAND90-2406, Sandia National Laboratories, November 1992, p. IV-23.

12. *Ibid*, p. III-6.

Mechanical: Uranium oxide ceramic pellets are brittle materials, and shatter when exposed to high-energy impacts. The size distribution of particles produced by such impacts is typically log-normal. For example, experiments on depleted uranium pellets subjected to an impact of energy 0.1 J/g, corresponding to an impact on an unyielding surface of 14.1 m/s (slightly higher than the IAEA Type B impact speed) have found that the pellets will release approximately 1% of their mass as particles with diameters less than 100 microns (called the "dispersible fraction"), and 0.01% as particles with diameters less than 10 microns (called the "respirable fraction") [Fig 1].[13] Higher impact speeds shift the distribution in the direction of smaller average particle size [Fig 2], and thus in the direction of increasing hazard.[14] (The "dispersible fraction" denotes particles that can be transported easily in the form of aerosols; larger ones tend to settle rapidly. The "respirable fraction" denotes particles that tend to remain deep in the lung once inhaled.)

One must rely on uranium oxide impact data because there is little or no information available on actual MOX pellets. However, differences in the microstructure of the two fuel materials may affect the impact behavior.

Transport of U-MOX by Sea

There are numerous historical examples of shipboard fires of much greater duration than that represented by the SS 6 Type B test. For instance, some fires have burned for days or even weeks. It has also been noted that the combustion of hydrocarbon fuels can result in considerably higher maximum temperatures --- as high as 1300°C --- than are simulated by the 800°C test.[15]

After enduring years of criticism by outside experts, IAEA recently initiated a Coordinated Research Program (CRP) to analyze whether the Type B test indeed provides adequate protection for RAM transport by sea. However, it is questionable whether the CRP will provide an objective evaluation of the situation, because its underlying premise is not to question, but rather to confirm, the adequacy of the IAEA standards, according to one of the participants in the project.[16]

It is worth noting that the international marine transport of RAM is essentially an unregulated practice. RAM transport was intentionally excluded (as a result of IAEA intervention) from the Safety of Life at Sea (SOLAS) convention, which is a binding international

13. *Ibid.*

14. *Ibid*, p. IV-12 -- IV-16.

15. ECO Engineering, Inc (Annapolis, Maryland, USA), "A Review of the Proposed Marine Transport of Reprocessed Plutonium from Europe to Japan, March 1992; E. Lyman, "Safety Issues in the Sea Transport of Vitrified High-Level Radioactive Wastes to Japan," Center for Energy and Environmental Studies, Princeton University, prepared for the Nuclear Control Institute, Greenpeace International and CNIC Tokyo, December 1994.

16. See discussion in E. Lyman, "Addressing Safety Issues in the Sea Transport of Radioactive Materials," presentation to the International Maritime Organization (IMO) Special Consultative Meeting, 4-6 March 1996, London, p.8.

agreement mandating design specifications for ships carrying dangerous goods. The "Irradiated Nuclear Fuel" (INF) Code, which was adopted by the International Maritime Organization (IMO) in an attempt to narrow this RAM loophole, is a voluntary agreement only. Even under this non-binding code, it is acceptable to transport as much as about one tonne of reactor-grade plutonium (e.g. about 40 U-MOX assemblies) on non-purpose-built passenger (INF 2 class) vessels.

In the event that a MOX transport vessel experiences an accident of greater severity than a Type B package is designed to withstand, the amount of material released will be determined by the "graceful failure" behavior of the package. As discussed above, U-MOX packages that use ablative materials for fire protection will not be able to withstand a prolonged fire (greater than a few hours). Of special concern is an accident which first causes the rupture of many fuel rods and is then followed by a long-duration fire. Even if the fire smolders at a low temperature, substantial oxidation of the fuel rods can take place if the package is ruptured or the seals fail. The amount of fuel oxidized would be limited only by the duration of the fire and the availability of oxygen.

Transport of U-MOX by Air: The Low Dispersible Material (LDM) Exemption

An alternative to sea shipment of U-MOX fuel from Europe to Japan is air shipment. Air shipment of plutonium and other radioactive materials has been a controversial practice, largely because of the inadequacy of the IAEA air transport standards. Past versions of SS6 were essentially "mode-independent": the same package standards (Type B) applied for both ground and air transport, despite the fact that the mechanical and thermal stresses encountered in a plane crash would be far greater than those simulated by the Type B test. This deficiency was highlighted most forcefully by the United States, which unilaterally adopted very stringent domestic regulations on air transport of RAM.

In response to public criticism and the disparity between SS6 and U.S. domestic regulations, the IAEA made a feeble attempt to increase the credibility of its standards. The 1996 revision of SS6 defines requirements for packages, called "Type C," which are intended for the air transport of large quantities of RAM. The Type C test includes an impact of 90 m/s on an unyielding surface, and a *non-sequential* 800°C, 1-hour fire. Although the Type C standards appear to be more rigorous than the Type B standards, they fall far short of the US domestic regulations, and in fact were intentionally chosen so that Type C casks would only survive 85-90% of air crashes (the so-called "knee of the curve" point beyond which significant improvements would come at too great a cost to industry, in the IAEA's judgement).

Having introduced a new but still inadequate standard for air shipment of RAM, IAEA then proceeded to include an exemption from the Type C requirement for so-called "low dispersible material" (LDM). While the actual text makes no mention of specific materials which may fit the LDM criteria, it is widely understood that the primary beneficiary of this exemption will be transporters of U-MOX assemblies, who would be free to transport unlimited quantities of U-MOX in Type B casks should it be demonstrated that U-MOX meets the LDM criteria.

One strong indication that plutonium shippers fully expect that they will be able to transport U-MOX by air in Type B casks is the noticeable lack of development work in recent years by the nuclear transport industry on the Type C cask, even though introduction of the regulation was anticipated as long as a decade ago. For instance, at the 1995 PATRAM (Packaging and Transport of Radioactive Materials) Conference, there was not a single paper on RAM air transport packaging, in stark contrast to the 1989 and 1992 meetings, at which there were entire panels on the subject. One suspects that attempts to develop Type C packaging for plutonium were abandoned once it became clear that an exemption applicable to U-MOX would be included in the revised regulations.

This has been confirmed in a recent letter from BNFL, which stated that "BNFL has undertaken some provisional tests to establish whether MOX fuel might be classified as Low Dispersible Material. The results of these test [sic] were encouraging ...".[17]
BNFL gives no further details or references to support their claim.

The certification process for LDM is as follows: the test material will be subjected to the Type C impact and fire tests (also non-sequentially), without the protection of any packaging. The material qualifies as LDM if it then does not release an amount of activity greater than 100 A_2 in gaseous and particulate forms of up to 100 microns in diameter. As is the case with package tests, compliance can be shown by "direct physical tests, analytical methods or a proper combination of these."

This precision of this definition, which was originally introduced by Germany, falsely gives the impression that it was derived from detailed technical analysis. In fact, a review of the supporting documents shows that the technical basis of the LDM definition is obscure. The radiological arguments advanced in the German working papers on the subject seem crude and arbitrary.[18] There is some evidence, however, that the definition may have been constructed from German data on the oxidation behavior of MOX fuel pellets so that U-MOX would qualify automatically.

The first odd aspect of the LDM definition is that it appears to be inconsistent with the radiation protection standards upon which the remainder of the SS6 is based. For instance, following an accident, a Type B or Type C package is supposed to release an amount of activity no greater than A_2 in one week (with no restriction on particle size). However, material qualified as LDM can release more than one hundred times that amount (100 A_2 in particles with diameters less than 100 microns, plus an unlimited amount of activity in particles greater than 100 microns). Therefore, in order for the transport of LDM to be consistent with this standard, the Type B package must be in sufficiently good shape following a plane crash that it can prevent more than 99% of the activity released from the LDM from escaping into the environment. This invocation of the "graceful failure" hypothesis requires that one believe that a Type B cask will remain largely

17. Alan Hughes, BNFL Public Affairs Division, *op cit*.

18. F. Lange, F. Nitsche, F-W. Collin and M. Cosack, "Requirements for Very Low Dispersible Material (VLDM), TC-946, Working Paper No. 11, IAEA Technical Committee Meeting, Vienna, 15-19 May 1995.

intact if it is subjected to an impact energy 50-100 times greater than that which it was designed to withstand.

The German working group papers on LDM are vague on exactly why they believe their criterion provides an acceptable standard. At one point, they make reference to "graceful failure"; at another, they cite the low rate of aircraft accidents; at another, they cite the effect of atmospheric dilution of the release. None of these explanations provides a convincing rationale for adopting release rates for LDM that are inconsistent with Type B and Type C release rates.

The definition of the LDM test proposed by Germany also underwent a significant change. Originally, the German proposal suggested that the impact and fire tests be conducted sequentially, because they realized that the fire test alone conducted on a sample such as a MOX fuel rod would probably cause little or no dispersal, whereas a fire following an impact which ruptured the fuel rod would cause a much greater release; thus, use of a non-sequential test would give a misleading impression of the non-dispersibility of the material. However, they proposed that the fire test in the sequence be limited to only 10 minutes at 800°C.[19] In later versions of their proposal, the recommendation that the impact and fire tests be performed sequentially was omitted.

A 1982 German paper on the oxidation behavior of MOX fuel pellets in a kerosene fire may shed some light on the mysterious origins of the LDM standard.[20] In this paper, it was found that exposing MOX pellets to an 800°C fire for 15 minutes in an air atmosphere led to a release of 0.01% of the initial material. The particles formed were all well below 100 microns in diameter. Therefore, for a Type B cask carrying about 45 kg of plutonium in two MOX assemblies, this release fraction would correspond to a release of 4.5 grams of plutonium, which is very close to 100 A_2 = 5 grams (for a typical reactor-grade plutonium composition). Thus it is possible that a release of 100 A_2 was proposed by Germany based on their expectation of how a MOX fuel rod would perform with respect to the initial LDM test proposal (e.g. an impact test, which would cause the fuel pellets to be exposed but might not itself lead to a significant release, followed by a 10-minute fire test). Even though the test specifications later changed, the original LDM definition was retained, probably because of the initial observation that the fire test alone would probably not lead to release of any material from a MOX fuel rod, even for a duration of one hour.

Despite this apparent effort to work backward from the known properties of MOX fuel to devise a definition of LDM, it remains highly uncertain whether U-MOX will be able to meet the LDM standard, especially with regard to its impact resistance. An impact of 90 m/s corresponds to an energy input of around 4 J/g, which, based on depleted uranium oxide impact tests, would cause the release of more than 0.5% of the material as particulates with diameters less than 100 microns. For the 2-assembly package, this would be equivalent to a release of 225 grams, well in

19. F. Lange and F. Nitsche, "Contribution to Technical Committee Meeting," Working Paper 8, IAEA, Vienna, 29 August - 2 September 1994.

20. H. Seehars and D. Hochrainer, "Durchführung von Experimenten zur Unterstützung der Annahmen zur Freisetzung von Plutonium bei einem Flugzeugabsturz," (in German), Fraunhofer-Institute, SR 0205A, March 1982.

excess of 100 A_2. Only if the assembly structural materials and fuel rod cladding provide a great deal of impact resistance will a MOX assembly be able to meet the LDM impact test.

Another large source of uncertainty comes from the LDM qualification test itself. The feasibility and potential environmental consequences of carrying out these tests on actual MOX fuel have not been seriously considered. It is possible that the industry will resort to demonstrating LDM with simulant materials or relying entirely on computer modeling. Neither of these methods will provide assurance that the behavior of actual MOX pellets is being accurately represented. France's Institute of Nuclear Safety and Protection (IPSN) recently voiced its concern about the feasibility and reproducibility of LDM qualification tests.[21]

Nonetheless, BNFL has indicated that it is moving ahead on qualification of U-MOX as LDM, and that "together with other European nuclear companies, [BNFL] has embarked on a full development of an LDM test facility in line with the requirements of the published LDM regulations."[22]

If the industry finds a way to qualify U-MOX as LDM, clearing the way for large-scale U-MOX air shipments in Type B casks, the consequences could be disastrous. For a crash at the not inconceivable speed of 140 m/s, it is unreasonable to assume that a Type B cask would retain any containment ability whatsoever. Such an impact could cause a dispersible release on the order of 1% for particles smaller than 10 microns (corresponding to 450 grams of plutonium per cask) and 10% for particles smaller than 100 microns (corresponding to 4.5 kg of plutonium per cask). A typical cargo could consist of several casks, all of which must be presumed to fail under such severe conditions. These releases are enormous from a radiological perspective. Dose rates at ten miles from the crash site could well exceed 50 milliSievert per hour and could result in as many as tens of thousands of latent cancers if the crash were to occur in a densely populated area. The crash and prolonged fire of an El Al jet at an apartment complex in Amsterdam in 1992 serves as a stark reminder that this type of accident is very much in the realm of possibility.

21. A. MacLachlan and G. Seneviratne, "France's ISPN Raises Concerns About New IAEA Transport Standards," *Inside N.R.C.*, September 16, 1996, p. 12.

22. Alan Hughes, BNFL Public Affairs Division, *op cit*.

FIG. 1 Fracture Particle Size Distribution for Depleted UO_2

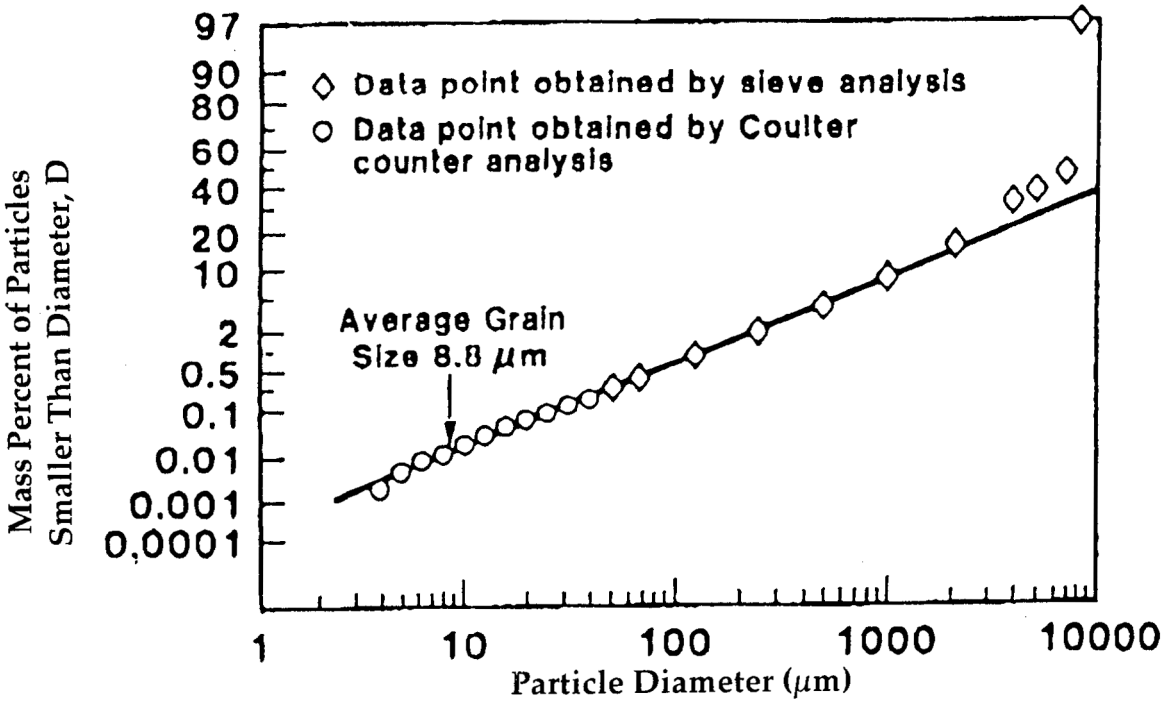
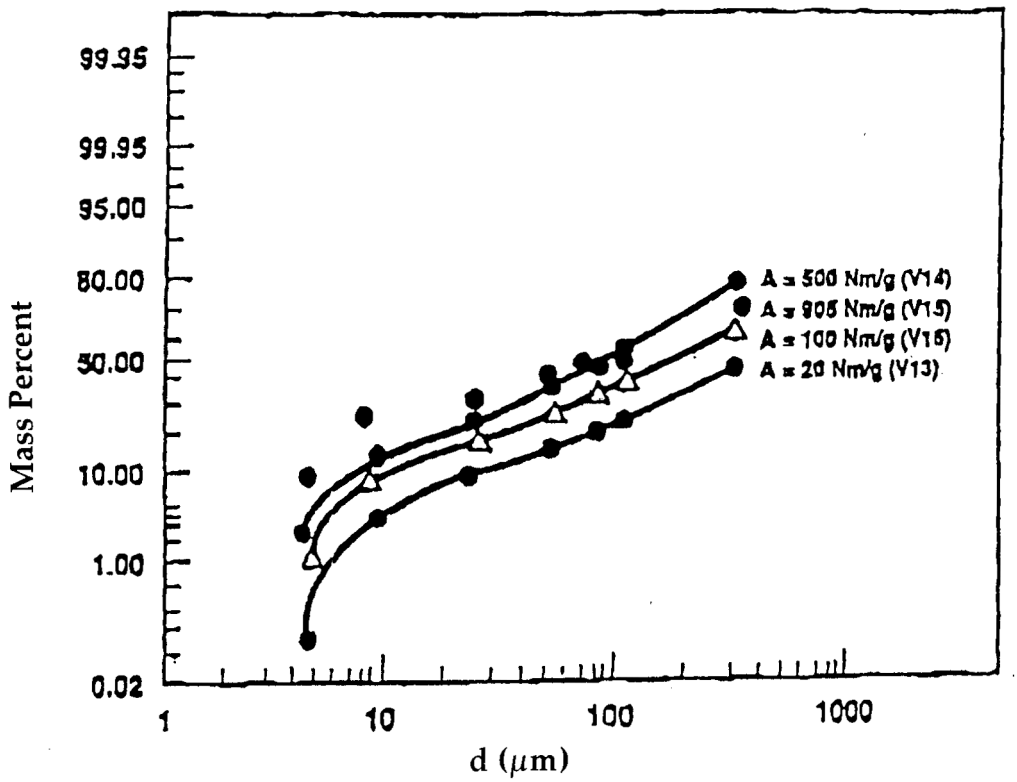


FIG. 2 Size Distribution of Depleted UO_2 Fragments After Impact with Various Energy Densities



Annex 2-c
Contribution

Current State and Perspectives for MOX-fuel Use in Russia

Alexander Dmitriev

20-30 years ago the concept of nuclear energy development in the Soviet Union was heavily based on plutonium. Plutonium was considered as the main fuel for nuclear industry. It was well believed that the lack of large stocks of uranium must necessarily lead to breeding of nuclear fuel in fast breeder reactors in order to increase the potential of nuclear energy. It was suggested to build certain number of fast breeder reactors and radiochemical facilities and thus practically put aside a question about stocks of natural uranium. Use of plutonium in either a metal or oxide form in breeders should be a priority for nuclear industry. The fast breeder reactor BR-1 with zero capacity, which was put into operation in 1955, allowed experimentally approve the idea of fuel cycle. An experimental breeder reactor BOR-60 with thermal power about 50 MWt was built at the Institute of Nuclear Reactors in Dimitrovgrad and put into operation in 1969. As it was partially fueled with the mixture of uranium and plutonium oxides, it was the first experience of the use of MOX-fuel in fast breeder reactors.

The first industrial fast-breed reactor with projected electrical capacity 350 MWt was put into operation in 1973. This reactor is located near the city Ak Tau in Kazakhstan. Then a sodium cooled reactor BN-600 with integral layout was constructed at Beloyarskaya NPP in Urals in 1980. The thermal power of this reactor is approximately 1500 MWt. These reactors were supposed to be fueled with uranium dioxide with further shift to MOX-fuel. The current load of BN-600 reactor consists of about 7% of MOX-fuel and there are plans to increase the nuclear core load with MOX-fuel up to 15%. The question of further increase of MOX-fuel load of the nuclear core. MOX-fuel for breeder reactors is fabricated at the chemical combine Mayak where they have facilities to fabricate MOX-powder, pellets and fuel rods. Weapons-grade plutonium is used as plutonium component.

The reprocessing plant RT-1 for chemical separation of plutonium from the spent fuel of pressurized water type reactors (Soviet design VVER-440) and storage-facility for reactor-grade plutonium has been operating at "Mayak" since 1976. Currently there is approximately 30,000 tones of plutonium in dioxide form in this storage-facility. Plans existed to build a plant of big capacity for MOX-fuel fabrication for fast breeder reactors of Soviet design at RT-1. It was supposed to fabricate fuel both from weapons grade and reactor grade plutonium there. But the construction has never been completed because of several reasons. The program for fast-breeder reactors construction was postponed several times, the initial amount of fast breeder reactors had been decreasing several times because of their high cost. Also proposed fuel burn up for this type reactors (up to 15%) has not been reached yet and the share of MOX fuel in a BN-600 nuclear core is much lower than it was expected to achieve. For the last years Gosatomnadzor of Russia received only one proposal to build a new nuclear power plant with three fast breeder sodium cooled reactors. This is South-Urals (Yuzhno Uralskaya) NPP with BN-800 type reactors, thermal power of each of them must be approximately 2,000 MWt.

The construction of South-Urals NPP has begun 8 years ago near Mayak. It should be a part of Mayak's infrastructure. But the construction is going on very slowly - and is expected to be this

way in nearest future - because of insufficient financing. Long-term focus on utilization of plutonium in fast breeder reactors in Russia led to the lack of experience of MOX fuel production for and use in PWR type reactors. Neither has Russia installations for acquiring this experience. Since 1985 the construction of big nuclear facility RT-2 for reprocessing spent fuel from PWR VVER-1000 type reactors is under way. This facility is a part of Krasnoyarsk Mining Chemical Combine which is located near the city of Krasnoyarsk in the center of Siberia. A design of this facility has been changed several times. In the last version of it construction of a unit for MOX-fuel production from reactor-grade plutonium to fuel VVER-1000 type reactors is envisaged. Capacity of this unit is expected to be up to 300 tones of MOX fuel per year for PWR type reactors. But one can hardly expect RT-2 and MOX plant to be put into operation before 2005-2010 due to unreadiness of the project and financial difficulties. Although the idea of burning plutonium as MOX fuel in PWR reactors of Russian design (in case of VVER-1000) has been discussed for the last few years from the view of both physical and technical characteristics of these reactors, there is no any practical realization of this idea yet.

As reactor-grade and weapons-grade plutonium have defferent physical characteristics, it is important to clearly understand which kind of plutonium is more preferable for to be used as fuel. Despite all the intentions to develop so called closed nuclear fuel cycle, this idea was realized to a very limited extent. First of all, it was decided uneconomical and technically quite difficult to reprocess irradiated fuel from RBMK reactors. Until now the spent fuel of 15 units that have been built is stored in cooling water pools at NPPs in situ. There are plans to shift this fuel to dry storages which have to be built. Thus, one comes to the conclusion that plutonium accumulated in spent fuel of graphic RBMK reactors should be classified as waste. But for a long time Western experts believed that plutonium produced in RBMK reactors could be considered as weapons-grade by its characteristics.

Currently cooling pools for spent fuel at all the NPPs with RBMK reactors are overfilled, and this problem raises a question of construction of a centralized storage-facility with further shift to dry storage, as mentioned above. Similar situation is with another type of nuclear reactors -- VVER-1000. Perspective of completion of the construction of RT-2 is very unclear because of economic uncertainties. All attempts to get credits for the construction of this plant from potential customers have failed.

Up to now only a storage-facility for spent fuel as part of RT-2 was built and put into operation. Approximately 1,200 tones of spent fuel from Ukranian and Russian VVER-1000 reactors are being stored in this storage-facility. Only spent fuel from VVER-440 (PWR type), which accounts for 15-20 % of all the spent fuel from NPPs in Russia, is reprocessed now. These reactors produce around 30 % of electricity in Russia (for comparison, fuel burn-up of RBMK reactors is 15,000-18,000 MWt-days per tone, which means that fuel consumption per 1 unit of energy in RBMK is twice bigger than in VVER-440 reactors). The bottomline of the said above is that instead of closed fuel cycle we have "almost open" fuel cycle. The amount of reactor-grade plutonium separated from spent fuel at RT-1 is around 30 tones. The amount of excess weapons-grade plutonium which can be used as a fuel is 80-100 tones. Three uranium-grade reactors in Seversk (former Tomsk-7), 20 kilometers away from Tomsk, and Zheleznogorsk (former Krasnoyarsk-26), 65 kilometers away from Krasnoyarsk, still produce weapons-grade plutonium (approximately 2 tones per year). Under agreement with United States plutonium from these reactors is not used in weapons since October 1994 and is stored in a form of plutonium oxide. These reactors can not be shut down immediately because in addition to plutonium they also

produce heat for residential houses in Tomsk, population of which is around 400,000 people, and Zhelznogorsk, a home for 60,000 workers of Krasnoyarsk Mining Chemical Combine and their families. Because of international concern of nuclear weapons proliferation and for the reactors that stock of weapons-grade plutonium is larger than that of reactor-grade one, that weapons-grade plutonium is stored in metal form, which is less safer than plutonium dioxide, also due to the fact that it is technically easier to handle weapons-grade plutonium, it is preferable to find technical options to burn first of all weapons-grade plutonium. Ministry of Atomic Power (Minatom) is taking firm position on plutonium as a valuable source of energy. But one can hardly agree with this statement as total amount of plutonium currently available in Russia is not sufficient for nuclear power development on a large scale and long-term basis. Besides, equipment for fuel fabrication from plutonium requires large capital investments.

Russian Gosatomnadzor has a different view: it is necessary to destroy surplus plutonium as soon as possible. But it can not be done through vitrification or disposal in underground bores. Vitrification can guarantee safety of glass with plutonium only for 100 years and after this time the problem will be even more serious. Underground geochemical processes are so complicated that nobody can guarantee that we do not face any unpredictable consequences in the future. The most preferable way to destroy plutonium is to transmutate it into fission products which have much shorter half-lives and are not so highly-active. Thus, Gosatomnadzor also stands for burning plutonium but for different reasons. In order to escape a vicious circle of plutonium production and use, certain measures for reduction plutonium breeding in all types reactors must be undertaken. This is no more than a clearly technological problem. Both in Russia and worldwide scientists are looking for technology which allows to use nuclear fuel with lower concentration of 238U. Of course it might lead to the losses in economy of nuclear reactors but economic advantages could be won through higher safety of spent fuel and reduction of expenses for regenerated plutonium storage and safeguards.

In the last years the project of disposition of surplus Russian and American plutonium in Canadian heavy water reactors CANDU received a real impetus. The United States promised to produce first portion of MOX fuel from weapons-grade plutonium in Los Alamos. Under this project Russia must produce 5 kilograms of MOX fuel from weapons-grade plutonium at the Institute for Nonorganic Materials by the end of 1996.

Then, if the first experiment is successful, MOX fuel for Canadian reactors in the amount of tens of kilograms per year must be produced at Mayak. Large stock of surplus plutonium in Russia made France and Germany interested in taking part in solution of the problem of plutonium disposition together with Russian specialists. In both cases a pilot unit for uranium-plutonium fuel production has to be built, supposedly at Mayak or Krasnoyarsk Mining Chemical Combine. It will be possible to produce MOX-fuel from weapons-grade plutonium in the amount sufficient for making 20 fuel assemblies per year for VVER-1000 and 40 fuel assemblies per year for BN-600 at this installation (1 tone of plutonium per year). 239Pu rate in MOX-fuel for BN-600 is 20-30 %, for VVER-1000 - 3-5 %. Although MOX-fuel had never been used in VVER reactors, in numerous scientific papers this option was considered and theoretically it was proved. But it is important to begin on a small-scale basis, like an experiment, in order to be sure that this technology works well.

It is supposed that the pilot unit will have a line to partially utilize its own spoilage and tails which will allow to more efficiently use nuclear materials and preprocess solid waste that can not be utilized for further long-term disposal. Plutonium and uranium for MOX-fuel will be used in a form of either of nitrite solutions or of dioxide powder. MOX-fuel can be produced from both

weapons-grade plutonium extracted from nuclear warheads in the process of disarmament or weapons-grade plutonium that had never been used in weapons and also from reactor-grade separated from spent fuel at the reprocessing plants.

Conclusion

1. Russian stock of plutonium, that has been chemically separated at the reprocessing plants, mainly consists of weapons-grade plutonium.

2. For a long time MOX-fuel was considered in Russia as duel for fast breeder reactors. Units for small scale MOX-fuel production for fast breeder reactors exist. Currently in Russia there is no technology for MOX-fuel production for PWR reactors.

3. Only one commercial fast breeder reactor BN-600 with 7-10 % of MOX fuel core load is currently operated in Russia. Three more breeders are supposed to be built. This means that fast breeder reactors can not substantially decrease stock of weapons-grade plutonium by the year 2010.

4. There are projects to build a pilot unit for MOX fuel production for fast breeder and PWR reactors with a capacity of 1 tone of plutonium per year and a bigger unit with a capacity of 300 tones for PWR reactors.

5. There is a proposal to burn weapons-grade plutonium in Canadian CANDU reactors. Whether this plan could be realized will be clear after the first set of fuel rods with MOX fuel is produced and tested in CANDU.

6. Realistically one can expect substantial reduction of the stock of surplus weapons-grade plutonium no earlier than after 2010, as technologies and installations for MOX fuel production are not ready yet.

7. Disposition of plutonium in nuclear reactors is the most preferable option. Measures to reduce accumulation of plutonium in nuclear reactors of power plants shooed be undertaken.

Annex 2-d
Contribution

IMPACT OF U.S. PLUTONIUM DECISION-MAKING ON JAPAN'S PLUTONIUM PROGRAM

Paul Leventhal and Steven Dolley

As citizens of democratic societies, Americans and Japanese share a common privilege and responsibility---to educate themselves on important issues and thereby ensure that their participation in decisions is informed and well-reasoned. Both Japanese and Americans have learned from experience that abdicating control over nuclear power and weapons to corporate and bureaucratic interests can be highly dangerous.

Today, it is all the more important for both societies to be actively engaged in nuclear decision-making and to be asking tough questions of those making the decisions. Japan is at the threshold of a civilian plutonium economy that threatens to burden its citizens and the world with more plutonium than is now contained in all of the nuclear arsenals. The United States is at the threshold of disposing of tons of surplus warhead plutonium and must find a way, in cooperation with Russia, that does not impose new dangers on the world.

The nuclear challenges facing Japan and the United States are closely related and interconnected. In particular, a decision by the United States to dispose of most of its military plutonium by using it as fuel in civilian nuclear power reactors could unduly influence Japan to continue with its civilian plutonium fuel program at the very time when the substantial safety, security and economic liabilities are becoming apparent and forcing a major national debate and reassessment of the program.

This paper reviews the history of the U.S.-Japan plutonium relationship, explores the impact of current developments in the plutonium industry, and concludes with some suggestions for plotting a future course that avoids the pitfalls of plutonium for both nations.

I. Brief History of the U.S.-Japan Plutonium Relationship

From the violent beginnings of the nuclear age in the 1940s, there has always been a close connection between plutonium developments in the United States and in Japan.

In the 1950s, the U.S. "Atoms for Peace" initiative, which was intended to steer the world away from military applications, produced a strange paradox: the declassification of military reprocessing (PUREX) technology, which had been used to produce the first plutonium bombs, for the purpose of launching both the United States and Japan on a civilian nuclear course of recovering and recycling weapons-usable plutonium for use as fuel to produce electricity. In fact, the United States informed Japan during this early period that Japan could obtain low-enriched uranium (LEU) fuel for its power program from the United States only on condition that Japan agreed to recycle plutonium. Thus, it was the United States that pressured Japan into its initial

commitment to plutonium, even though Japanese government and industry officials are now fond of characterizing this program as an exercise of Japanese sovereignty in pursuit of "energy independence."

In the 1960s, the United States, anticipating the construction of several hundred nuclear power plants domestically and more than 1,000 worldwide by the turn of the century, pressed ahead with commercial breeder and plutonium fuel-cycle development, further stimulating plans for application of these technologies in Japan.

In the 1970s, when it became apparent that original projections about nuclear-power growth and original assumptions about preventing military applications of civilian plutonium were unduly optimistic, the United States reversed course for both economic and non-proliferation reasons. It halted domestic licensing of plutonium recycling in light-water reactors and enacted the Nuclear Non-Proliferation Act of 1978 (NNPA) to impose tighter controls over overseas processing and use of plutonium originating in U.S.-supplied nuclear fuel. These tighter controls caused severe political frictions with both Japanese and European allies, who insisted on continuing their plutonium programs with or without U.S. support.

In the 1980s, the United States abandoned its domestic commercial breeder, reprocessing and mixed-oxide (MOX) plutonium fuel industries, but backed away from further confrontation with Japan and Europe over theirs. The 1980 final report of the International Nuclear Fuel Cycle Evaluation (INFCE), a three-year review by the United States and other nuclear industrial nations, concluded that MOX-fuel development was necessary for long-term breeder development. The 1988 U.S.-Japan nuclear cooperation agreement gave Japan the green light to reprocess all U.S.-origin spent fuel over the next 30 years. Thus, the United States made clear that regarding plutonium it was prepared to look the other way, and concentrated instead on winning European and Japanese support for other non-proliferation initiatives such as strengthening the export controls of the Nuclear Suppliers Group (NSG) and the safeguards of the International Atomic Energy Agency (IAEA), and shoring up support for extending the Nuclear Non-Proliferation Treaty (NPT). But at U.S. insistence, the agreement with Japan at least foreclosed air shipments of plutonium from Europe to Japan for safety reasons, and established security requirements that set the stage for the global controversy sparked by Japan's 1992 shipment of plutonium by sea from France.

Now in the 1990s, the end of the Cold War has opened a crucial new chapter. The need to dispose of tons of plutonium recovered from dismantled warheads in the United States and Russia is providing an important opening to American, European and Japanese plutonium advocates to seek a reversal of the U.S. domestic ban on commercial use of plutonium and thereby undermine U.S. non-proliferation policy aimed at not encouraging civilian plutonium applications abroad.[1] This development comes at a time when the plutonium industry in Japan and Europe is under mounting pressure because of a succession of failures of the fast breeder reactor, the prohibitive costs of MOX fuel, and growing public opposition to transports and storage of

1. The Clinton Administration's 1993 non-proliferation policy stated that "[t]he United States does not encourage the civil use of plutonium, and, accordingly, does not itself engage in plutonium reprocessing for either nuclear power or nuclear explosive purposes. The United States, however, will maintain its existing commitments regarding the use of plutonium in civil nuclear programs in Western Europe and Japan." White House, "Nonproliferation and Export Control Policy," September 27, 1993.

plutonium and its highly radioactive waste byproducts. Warhead plutonium disposal is one of several current developments that are serving to breathe new life into a declining industry.

II. Current Developments: Industry's Attempt to Turn Adversity to Advantage

The great American author Mark Twain once responded to rumors of his demise with typical acerbic humor: "Reports of my death are greatly exaggerated," he declared. We hear similar rumors today about the demise of the plutonium industry worldwide, but invariably such reports have proven to be greatly exaggerated. Remarkably, major setbacks to the plutonium industry actually have worked to its advantage.

Frans Berkhout of the University of Sussex identifies three "perversities" that have had the effect of buoying up the plutonium industry.[2] First, major setbacks to breeder programs have led to the development of new missions for fast reactors, especially so-called "actinide partitioning" for waste-management purposes, that serve to keep these dangerous programs alive. Second, the success of anti-nuclear activists in protesting interim storage of spent fuel, most notably in Germany, has served to throw desperate utility companies into the hands of reprocessors who are only too happy to take the spent fuel from the utilities for reprocessing. Third, as noted above, the need to dispose of surplus military plutonium is fueling a major drive by plutonium advocates to "dispose" of the plutonium in the form of MOX fuel in reactors, rather than to dispose of it directly as waste.

To Berkhout's three perverse developments, we add a fourth: The successful shutting down of the commercial plutonium industry in the United States in the 1980s has served to shift American public interest and political attention away from plutonium proliferation concerns, and this has resulted in a "free ride" for Japanese and European plutonium fuel-cycle programs that are based mostly on reprocessing of U.S.-supplied nuclear fuel.

We now address each of these perverse developments.

The Near-Death of the Fast Breeder Reactor

Every major industrial nation, except Japan and Russia, has abandoned the original vision of the fast breeder reactor (FBR) as an infinite source of energy that would create more plutonium fuel than it consumed and would lead to a "plutonium economy" with electricity "too cheap to meter." The breeder has fallen victim to hard reality: Electricity demand and nuclear-power growth have proceeded much more slowly than projected, and uranium, far from being exhausted by the end of the century, has turned out to be abundant and cheap. Electricity generated by FBRs will not be economically competitive with electricity generated by conventional nuclear-power plants fueled by low-enriched uranium for at least five decades.[3] In addition, the proliferation risks of fast

2. Frans Berkhout, University of Sussex, presentation to NGO Meeting on Reprocessing, Washington, DC, October 4, 1996.

3. Brian Chow and Kenneth Solomon, Limiting the Spread of Weapon-Usable Fissile Material, Rand Corporation, November 1993, p. 49. Even using mixed-oxide (MOX) plutonium fuel in conventional light-water reactors would be four to eight times more expensive than standard low-enriched uranium fuel. Paul Leventhal and Steven Dolley, "A Japanese

reactors producing enough nuclear-bomb material each year for thousands of weapons have been too great to ignore, as have the safety problems that have curtailed operations or forced the shutdown of every breeder started up.

As a result, the United States, Germany, Great Britain, and even France have cancelled ambitious plans for commercial FBR fuel cycles. The sodium spill and fire at the Monju fast breeder reactor in December 1995 (in combination with the recent fire and explosion at the Tokai-mura reprocessing plant) has put the future of the Japanese FBR program, and perhaps the entire plutonium program, into question.[4] These major setbacks, however, have prompted fast-reactor technocrats to invent new missions for their obsolete reactor designs, such as "partitioning and transmutation" and other so-called "waste-management" research.

France is in the process of relicensing its accident-prone and uneconomic Superphenix FBR as a research reactor for experiments on actinide burning.[5] A similar situation occurred in the United States, when in 1994 Congress cancelled the Advanced Liquid Metal Reactor (ALMR), the last vestige of the U.S. breeder reactor program. Argonne National Laboratory, however, managed to muster political support for continued R&D on "pyroprocessing," a reprocessing technology developed specifically for the ALMR but re-cast as a new approach to "waste management" even though the end-product is a new waste form with unexplored characteristics that may not be suitable for disposal in a repository.[6]

Anti-nuclear Opposition to the Interim Storage of Spent Fuel

Opposition by anti-nuclear groups to utilities' attempts to deal with spent fuel (dry storage, interim storage, etc.) has ground progress on permanent disposal options nearly to a halt in some nations, such as Germany and the United States. In Germany, utilities have begun seriously to consider reprocessing additional spent fuel even though they are no longer interested in burning MOX fuel. In the wake of violent opposition to spent-fuel storage at Gorleben, German nuclear electric utilities are considering contracts for long-term storage of their spent fuel in France, with

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Strategic Uranium Reserve: A Safe and Economic Alternative to Plutonium," Science and Global Security, 1994, Volume 5, Table 3, p. 6.

4. Pamela Newman, "Will Monju Become Japan's TMI?," Energy Daily, May 7, 1996, p. 1.

5. The Environment Minister wanted to shut down Superphenix while the Industry Minister wanted to operate it primarily as a research reactor. The Prime Minister recently sided with the Industry Minister by deciding to allow the relicensing of Superphenix in a combined research and power reactor role, without holding a public hearing. However, shutdown of Superphenix is high on the Green Party's list of priorities if it comes to power in next year's elections in coalition with the Socialists. Ann MacLachlan, "No New Public Inquiry Planned for Superphenix's Relicensing," Nucleonics Week, March 20, 1997, p. 16.

6. Committee on International Security and Arms Control, Management and Disposition of Excess Weapons Plutonium: Reactor-Related Options, 1995, pp. 219-221; p. 412.

eventual reprocessing by Cogema.[7]

In the United States, the spent-fuel dilemma is also having perverse effects. An early version of the Nuclear Waste Policy Bill proposed in the U.S. Senate in 1995 provided for "urgent relief," including reprocessing options, for U.S. nuclear utilities running out of storage space for spent fuel. This provision was removed last year only after vigorous opposition a coalition of public interest organizations.[8] But it is possible that a similiar provision, backed vigorously by British and French reprocessing interests, will be offered as an amendment to nuclear waste legislation before Congress this year.

Disposition of Plutonium from Dismantled Nuclear Weapons

If disposition efforts take the form of MOX fuel cycles, rather than immobilization of plutonium in glass for direct disposal as waste, they could activate a civilian plutonium economy in the United States, further stimulate plutonium fuel use in Japan and Europe, and give a new lease on life to Russia's plutonium program.

John Holum, director of the Arms Control and Disarmament Agency (ACDA) and the U.S. government's top arms control adviser, had such concerns in mind when he wrote to Energy Secretary Hazel O'Leary in November 1996, advising that the U.S. Department of Energy (DOE) "reject the hybrid option and select immobilization," and warning that the MOX option "would set a very damaging precedent for U.S. nonproliferation policy" and "would be contrary" to this policy "and our long-term interests."[9] A coalition of 14 national public-interest groups also urged O'Leary to foreswear the MOX disposition approach unless immobilization were proven incapable of dealing with all surplus plutonium.[10] Despite these warnings, DOE announced a decision in January 1997 to proceed with a "dual-track" or "hybrid" option, using both MOX and immobilization, which will likely lead to the majority of surplus warhead plutonium being fabricated into MOX fuel for U.S. nuclear-power plants.[11]

The United States is also making it clear it will not oppose Russia's goal of using warhead plutonium disposition to save its sinking plutonium fuel cycle. At a technical summit on warhead plutonium disposition sponsored by the G-7 nations and Russia, held in Paris last October,

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7. Mark Hibbs, "German Utilities Said Close to Deal on Storage Contracts with Cogema," NuclearFuel, January 15, 1996, pp. 5-6.

8. Letter from Nuclear Control Institute and 23 other public-interest groups to members of the U.S. Senate, April 22, 1996; Letter from Nuclear Control Institute to members of the U.S. Senate, April 25, 1996.

9. John Holum, "Memorandum for the Secretary of Energy," November 1, 1996; Peter Passell, "U.S. Set to Allow Reactors to Use Plutonium from Disarmed Bombs," New York Times, November 22, 1996, p. 1.

10. Letter from 14 public-interest groups to Hazel O'Leary, Secretary of Energy, December 20, 1996; Matthew Wald, "Groups Protest a Proposal for Disposing of Bomb Fuel," New York Times, December 23, 1996.

11. Matthew Wald, "Plan to Convert U.S. Plutonium is Announced," New York Times, January 15, 1997, p. A13.

Germany and France proposed construction of a pilot mixed-oxide (MOX) plutonium fuel plant in Russia. Far from rejecting the plan, the United States expressed tentative support, subject to a pledge by Russia that it would not use the pilot MOX plant to fabricate fuel from civilian plutonium, and that MOX fuel produced in the plant would not be reprocessed---conditions the Russian side has thus far refused to accept.[12]

A coalition of 12 U.S. public interest groups had urged Secretary of State Christopher to propose a pilot plant in Russia for the demonstration of vitrification of plutonium for direct disposal as waste,[13] but the United States has not floated such a proposal, and it seems unlikely that the United States will express support for such a project unless an effective constituency for immobilization emerges. The G-7 summit to be held in Denver this June is not expected to ratify the Russian pilot MOX plant because of a lack of funding from the G-7 and a refusal by Russia to accept U.S. conditions, but the proposal remains under active consideration.

Meanwhile, Cogema and British Nuclear Fuels Limited (BNFL) are actively pushing the MOX option in the U.S. disposition decision process. For example, they are proposing to build a MOX fuel plant at the Pantex nuclear-weapon dismantlement facility in Texas, where all surplus plutonium cores, known as "pits," are being stored. This so-called "swords-to-plowshares" approach also threatens to resurrect civilian spent-fuel reprocessing and recycle in the United States by providing a domestic MOX plant which could then be used for separated civilian plutonium after completion of the disposition mission. Indeed, Westinghouse has prepared a study proposing large-scale reprocessing of U.S. commercial spent fuel in the canyons of the Savannah River Site it operates for the U.S. Department of Energy in South Carolina. If this plan were to come into operation, Pantex could become a "plutonium magnet," eventually drawing in up to 300 tons of plutonium separated from power-reactor spent fuel.

Also, the Energy Department released a skewed economic analysis of plutonium disposition options that minimized costs of the MOX option.[14] This analysis failed to include the "incentive" fees---essentially hidden subsidies for uncompetitive electricity generation---that U.S. nuclear electric utilities are certain to demand in exchange for use of warhead-plutonium MOX fuel in their reactors. These incentives, in the form of free MOX fuel and/or direct cash payments, could cost as much as several billion dollars over the life of the disposition program.[15] Eleven public-interest organizations wrote to Energy Secretary O'Leary to request that the economic analysis be revised

12. Anne MacLachlan, "Paris Meeting on Military Pu Disposition Says No Option Should Be Totally Ruled Out," NuclearFuel, November 4, 1996, p. 1.

13. Letter from Nuclear Control Institute and 11 other public interest groups to Secretary of State Warren Christopher, October 3, 1996.

14. Office of Fissile Materials Disposition, U.S. Department of Energy, Technical Summary Report for Surplus Weapons-Usable Plutonium Disposition, DOE/MD-0003, July 17, 1996.

15. Paul Leventhal, "Comments on Technical Summary Report for Surplus Weapons-Usable Plutonium," Nuclear Control Institute, August 30, 1996.

to reflect the true cost of MOX options.[16] DOE did revise the report to include fees that would have to be paid to utilities for using MOX---estimated by DOE to be as much as $500 million. But these fees were classified as "cost uncertainties" and not included in the final overall cost estimate for MOX options.[17] DOE also assumed that utilities would be willing to pay as much for MOX fuel as they would otherwise pay for low enriched uranium fuel. If utilities insist on free or reduced-price MOX, the cost of the MOX option could increase by up to $820 million.[18]

On yet another MOX front, Atomic Energy of Canada Limited (AECL) is lobbying for the export of U.S. weapons plutonium to fuel CANDU reactors in Canada. The Los Alamos National Laboratory has applied for a license from the U.S. Nuclear Regulatory Commission to export MOX fuel pellets to Canada for testing even before the Department of Energy has made a decision on what disposition technologies to employ. The Nuclear Control Institute, the Natural Resources Defense Council, and Greenpeace International petitioned NRC to reject this export license on the grounds that it is premature and runs counter to U.S. non-proliferation policy.[19] DOE agreed to withdraw the export license application pending completion of the final environmental impact statement, but a DOE officials recently indicated that the application might be re-submitted soon.

In our petition, we emphasized a special danger in demonstrating the feasibility of MOX use in CANDU reactors---the type of power reactors developed by Canada for domestic use and for export. CANDUS are operated in Argentina, India, Romania, and South Korea, each of which at some point had an active program to develop nuclear weapons. Non-Canadian CANDU operators are likely to seize on the MOX demonstration in Canada as a precedent to justify their own use of plutonium. The proposed export should not be examined simply as an isolated export of a small amount of plutonium for experimental purposes but considered within the larger framework of U.S. plutonium disposition and nuclear non-proliferation policy. Unless and until a formal trilateral agreement on the use of CANDU reactors for warhead plutonium disposition is concluded among the governments of the United States, Canada and Russia, any MOX export to Canada would be premature and would create proliferation risks that outweigh any research benefits.

The Department of Energy has failed to take proliferation risks seriously. In particular, DOE's "Non-Proliferation Assessment" of plutonium disposition technologies[20] attempts to

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16. Letter from Nuclear Control Institute and 10 other public-interest groups to Energy Secretary O'Leary, September 25, 1996.

17. Office of Fissile Materials Disposition, U.S. Department of Energy, Technical Summary Report for Surplus Weapons-Usable Plutonium Disposition, Rev. 1, October 31, 1996 ["Revised TSR"], Table 6-1, p. 6-3; George Lobsenz, "DOE Estimates Utility Fees for Plutonium Disposal at $500 Million," Energy Daily, November 6, 1996, p. 1.

18. Revised TSR, Table 4-1, p. 4-5.

19. Nuclear Control Institute, Natural Resources Defense Council, and Greenpeace International, In the Matter of Los Alamos National Laboratory (Export of MOX Fuel to Canada), Petition to the U.S. Nuclear Regulatory Commission, October 3, 1996.

20. U.S. Department of Energy, Office of Arms Control and Nonproliferation, Nonproliferation and Arms Control Assessment of Weapons-Usable Fissile Material Storage and Plutonium Disposition Alternatives, DOEINN-0007, January 1997, ("Non-Proliferation Assessment").

rationalize and wish away the adverse "fuel cycle policy signal" that would be sent to the rest of the world if the United States implemented the MOX disposal option. The U.S. National Academy of Sciences' 1994 study on warhead plutonium disposition warned that

> ... policymakers will have to take into account the fact that choosing to use weapons plutonium in reactors would be perceived by some as representing generalized U.S. approval of separated plutonium fuel cycles, thereby compromising the ability of the U.S. government to oppose such fuel cycles elsewhere. Conversely, choosing to dispose of weapons plutonium without extracting any energy from it could be interpreted as reflecting a generalized U.S. government opposition to plutonium recycle. Either choice could have an impact on fuel cycle debates now underway in Japan, Europe, and Russia.[21]

ACDA Director Holum, the top U.S. arms control advisor, also warned the Secretary of Energy that

> If the hybrid option is chosen, these countries [Russia, South Korea, and others] would hear only one message for the next 25 years: that plutonium use for generating commercial power is now being blessed by the United States. No matter how much effort we take in reducing these risks ... the overriding message that we will convey is that civil plutonium use is acceptable."[22]

However, the Department of Energy assessment cavalierly dismissed these concerns:

> It is unlikely . . . that a decision to use MOX fuel in the United States would, in and of itself, result in substantial additional reprocessing and use of MOX fuel in other countries. . . . Use of MOX by the United States might, in some rare cases, provide modest cover for would-be proliferant states to pursue and justify plutonium production capabilities. Such cases are likely to be rare, and the impact of a U.S. MOX disposition program rather modest. . . . The potential impact of encouraging plutonium use could be mitigated by several steps. If this alternative is chosen, high-level U.S. officials should clearly outline how this approach fits within broader U.S. fuel cycle and nonproliferation policies.[23]

MOX advocates in Japan and Europe can be expected to scoff at efforts by the United States to "spin" a decision to use MOX and almost certainly will seize upon such a decision to provide further justification for their own programs. Indeed, the French government declared that

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21. Committee on International Security and Arms Control, National Academy of Sciences, Management and Disposition of Excess Weapons Plutonium, 1994, p. 149.

22. Holum, "Memorandum for the Secretary of Energy," November 1, 1996, p. 2.

23. Non-Proliferation Assessment, pp. 97-98.

U.S. support for a Russian MOX plant "would definitely be a symbolic success for France."[24] In short, a noble effort to reduce the proliferation dangers of warhead plutonium is at risk of being captured for the ignoble purpose of reinvigorating civilian plutonium fuel cycles, with the net effect of increasing proliferation risks over the long term.

Washington: Turning a Blind Eye to Commercial Plutonium

Success in eliminating the commercial plutonium industry in the United States in the 1980s has had the paradoxical result of shifting interest and attention away from fuel-cycle proliferation concerns. Congress, the Clinton Administration, and even some public-interest arms control groups today view non-proliferation as exclusively a matter of supporting the Nuclear Non-Proliferation Treaty and the International Atomic Energy Agency and denying nuclear assistance to "rogue states." There is no longer a strong political base in Congress or the U.S. Government for actively pushing U.S. non-proliferation efforts to discourage commercial plutonium fuel cycles abroad, or for fighting off attempts to restore a plutonium industry in the United States.

A glaring example of this situation is the recent conclusion of the new U.S.-EURATOM nuclear cooperation agreement in 1996.[25] This 30-year agreement effectively abdicates U.S. control over U.S.-origin nuclear material in the European Community and even allows it to flow freely into former East Bloc nations when they join the European Union. The United States will not be informed (let alone consulted) about future transfers of U.S.-origin material among nations within Euratom, including weapon-usable plutonium and highly-enriched uranium.

The Clinton Administration simply did not consider fuel-cycle proliferation risks to be an issue in the EURATOM agreement, despite the fact that the nine nations with applications pending for EU membership all have experienced incidents of nuclear materials smuggling since the breakup of the Soviet Union. A Western European intelligence report "said that in 1992 there were 53 successful or attempted cases of nuclear smuggling from formerly communist countries reported to Western governments, while in 1993 there were 56 cases and in 1994, 124 cases. Seventy-seven of the 1994 cases involved plutonium or uranium."[26]

The U.S. Energy Department also recently authorized a list of European MOX fuel plants to fabricate fuel for Japan using U.S.-origin plutonium---despite the fact that Japan had not demonstrated a need for this fuel and despite an appeal by a coalition of public-interest organizations that a DOE decision be deferred until completion of the major reassessment of plutonium programs underway in Japan following the Monju accident.[27]

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24. Nuclear Notes from France (French Embassy, Washington, DC), No. 43, Oct-Nov 1996.

25. Paul Leventhal, Testimony before the Committee on Governmental Affairs, U.S. Senate, U.S.-EURATOMAgreement for Peaceful Nuclear Cooperation, Senate Hearing 104-481, February 28, 1996, pp. 291-300; Steven Dolley, "EURATOM's Nuclear Proliferation Record," Nuclear Control Institute, February 9, 1996.

26. Craig Whitney, "Smuggling of Radioactive Material Said to Double in a Year," New York Times, February 18, 1995, p. A2.

27. Letter from Nuclear Control Institute, Natural Resources Defense Council, and Greenpeace International to Energy Secretary Hazel O'Leary, March 1, 1996.

Fortunately, at the urging of the chairman of the House Foreign Affairs Committee, the U.S. State Department provided formal assurance that "the physical protection for MOX shipments [from Europe to Japan] will be no less rigorous than the measures applied to Japan's 1992 shipment of bulk plutonium oxide," and that the Clinton Administration would require an armed escort vessel for such shipments unless a satisfactory alternative arrangement, not yet envisioned, were developed.[28]

Although the United States is prepared to acquiesce in Japanese and European cooperation to promote commercial use of plutonium, the question remains: What will Japan do with the MOX fuel to be fabricated in and shipped from Europe, other than add to the dangerous domestic plutonium surplus Japan is already accumulating? Some Japanese electric utilities and prefectural governments are beginning to question seriously whether there is any need for the program to recycle plutonium in light-water reactors.[29] Yet, earlier this year, MITI announced a policy to accelerate the introduction of MOX fuel into Japan's LWRs, and the Federation of Electric Power Companies (FEPC) agreed to load MOX in four LWRs by 2000, and as many as 18 LWRs by 2010.[30] However, neither prefectural governments nor key nuclear electric utilities have agreed to this plan.

IV. Conclusion: Plotting a Future Course

How can we improve the chances of Japanese and American citizens' controlling the destiny of their nuclear energy programs to avoid further separation and use of plutonium?

First, there is a need for more Japanese interest and engagement in U.S. developments related to plutonium policy. U.S. plutonium policies which may not seem to relate directly to Japan can have major repercussions on the course of the Japanese plutonium program. Surely, a U.S. decision to dispose of warhead plutonium by use of MOX fuel would give significant aid and comfort to plutonium advocates in Japan and around the world. And a decision by any U.S. utility to reprocess spent nuclear fuel would break a 20-year moratorium and undermine the strongest counter-example to use of civilian plutonium.

Second, there is a need for more Japanese citizens' involvement in Japan's plutonium activities overseas. Japanese utilities are signing contracts with European MOX fuel fabricators, and making transportation arrangements with the cooperation of the British, French, and U.S. governments to ship MOX fuel back to Japan---whether that fuel is needed or not. All these

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28. Letter from Nuclear Control Institute to Secretary of Energy Hazel O'Leary, July 23, 1996; Letter from Representative Benjamin Gilman to Secretary of State Warren Christopher, August 1, 1996; Letter from Strobe Talbott, Acting Secretary of State, to Representative Benjamin Gilman, September 6, 1996; Letter from Secretary of Energy Hazel O'Leary to Nuclear Control Institute, October 16, 1996.

29. "Utilities to Delay Plutonium Use in Light-Water Reactors," Asahi Evening News, January 24, 1996; David Hamilton, "Japan's Plutonium Program Won't Die," Wall Street Journal, April 2, 1996, p. A11.

30. Naoaki Usui, "Japan Utilities Plan to Burn MOX in Up to 18 LWRs by 2010," Nucleonics Week, February 27, 1997, p. 3.

activities are being paid for and should be subject to close scrutiny by Japanese electricity consumers.

Third, concerned U.S. and Japanese citizens need to coordinate their efforts on plutonium issues on a global basis. Energy policy decisions are largely domestic, but decisions about plutonium carry global implications, making any nation's plutonium program a concern for every other nation. Plutonium advocates staunchly support one another worldwide, attempting to forward their common commercial interests. Public-interest groups and citizens concerned with plutonium issues must show similar solidarity in resisting plutonium use. In this regard, the Citizens Nuclear Information Center is to be commended for organizing and pursuing its International MOX Assessment Project to provide policymakers and individual citizens the information needed to make intelligent decisions to avoid this ultrahazardous material.

Note: Many of the documents cited in this paper can be downloaded from the Nuclear Control Institute's site on the World Wide Web [http://www.nci.org/nci/].

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