IAEA Nuclear Energy Series

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Technical Approaches for the Management of Separated Civilian Plutonium

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TECHNICAL APPROACHES FOR THE MANAGEMENT OF SEPARATED CIVILIAN PLUTONIUM

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FOREWORD

The IAEA's statutory role is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world". Among other functions, the IAEA is authorized to "foster the exchange of scientific and technical information on peaceful uses of atomic energy". One way this is achieved is through a range of technical publications including the IAEA Nuclear Energy Series.

The IAEA Nuclear Energy Series comprises publications designed to further the use of nuclear technologies in support of sustainable development, to advance nuclear science and technology, catalyse innovation and build capacity to support the existing and expanded use of nuclear power and nuclear science applications. The publications include information covering all policy, technological and management aspects of the definition and implementation of activities involving the peaceful use of nuclear technology.

The IAEA Safety Standards establish fundamental principles, requirements and recommendations to ensure nuclear safety and serve as a global reference for protecting people and the environment from harmful effects of ionizing radiation.

When IAEA Nuclear Energy Series publications address safety, it is ensured that the IAEA Safety Standards are referred to as the current boundary conditions for the application of nuclear technology.

There are two main fuel cycle strategies for managing spent fuel from power reactors; the particular strategy adopted depends on whether spent fuel is considered an asset or a waste. Some Member States are deferring the decision on which fuel cycle strategy to implement (i.e. closed or open fuel cycle), which may indicate that a Member State does not have a fully defined spent fuel strategy or that it may be influenced at some point in the future by energy use, market prices or other factors.

Where spent nuclear fuel is considered an asset, it is reprocessed to recover the valuable materials (plutonium and uranium) for recycling in order to use the remaining energy. At the time of writing, plutonium reuse is achieved by the fabrication of mixed oxide (MOX) fuel from depleted uranium and reprocessed plutonium for irradiation in a light water reactor or a fast reactor. In some instances, a legacy stockpile of separated plutonium has been accumulated and stored pending future management owing to a reduced MOX fabrication capacity, fewer reactors licensed to use MOX than anticipated, and/or the unavailability of fast reactors in a given country.

This publication outlines credible technical options for managing separated plutonium, including information on when and how these options may become available.

In this publication there is no attempt to rank or rate any of the options; instead, the intent is to inform the reader of the various options, including what is involved for each, and the state of their development. Additionally, all options for managing separated plutonium, including storage and geological disposal, will likely require the application or continuation of international safeguards based upon the specific agreements between the Member States and the IAEA. This publication does not cover the safeguards or proliferation aspects of the materials and is only a review of the technical merits of the various options.

The IAEA would like to thank the consultancy meeting participants for their valuable input in developing the options, comparative analysis, and subsequent review of the findings. The IAEA officers responsible for this publication were L. McManniman, R. Robbins and P. Standring of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

This publication has been edited by the editorial staff of the IAEA to the extent considered necessary for the reader's assistance.

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The design basis for reprocessing plants currently in operation is to separate uranium and plutonium from other elements in spent fuel presently considered to be wastes (e.g., fission products and minor actinides) in the first process cycle. This is followed by further process cycles to separate the uranium and plutonium. It needs to be noted, however, that the latest processes incorporate co-management of uranium and plutonium. The separated plutonium may be considered a valuable energy source that originally was foreseen to be recycled in fast reactors (FRs); nevertheless, plutonium has mostly been recycled in thermal reactors and is an industrially mature technology with over 40 years of experience worldwide. Recycling strategies offer additional benefits, including reduction of the volume and long term overall toxicity of the high level waste (HLW) consigned for deep geological disposal, uranium resource savings, and the removal of heat generating materials. Recycling has the potential to reduce the overall footprint required for the deep geological repository. The IAEA has been organizing activities related to the use of separated plutonium and uranium since the early 1960s. Due to challenges in the widespread deployment of FR technologies, the emphasis on recycling shifted towards thermal reactors[1] [1]. As a result, the amount of plutonium and uranium that has been recycled in FRs to date is limited.

The supporting bibliography given in Annex I provides an account of the IAEA's activities in this area. The Nuclear Energy Agency of the Organisation for Economic Co-operation and Development has also published work on this topic [2]. In addition, significant national studies have been published in the past decade that identify and evaluate a wide variety of fuel cycle options and performance impacts (e.g., United States Department of Energy [3]).

1.2. OBJECTIVE

The aim of this publication is to provide Member States with information to support their decision making based upon their national circumstances. This publication identifies and describes the technical options under consideration for managing separated plutonium in the back end of the fuel cycle. The options for managing reprocessed uranium are reported in detail in an existing publication [4]. As these options described in the prior publication remain valid, the current publication is focused only on separated plutonium.

1.3. SCOPE

This publication is limited to technical options for managing separated plutonium arising from civilian activities.

Where recycling strategies are currently implemented, separated plutonium is recycled into mixed oxide (MOX) fuel. The MOX is then irradiated in existing light water reactors (LWRs) and FRs. Not all plutonium is suitable for efficient recycling; it may be low grade or contaminated. Therefore,

[1] For example, the United Kingdom Atomic Energy Authority predicted in the 1970s that 33 GW of installed capacity in the United Kingdom would be generated by fast reactors by the year 2000 [1].

processes to produce a stable conditioned product[2] that could be either recycled or disposed of have also been evaluated.

It may be that an overall approach to plutonium management is comprised of several of the technical options presented within this publication. The discussions presented here are only evaluated on their technical merits; no evaluations or statements about the safeguards aspects or proliferation potential of the paths will be made. It is likely that additional considerations with regards to the Member State's safeguards obligations related to plutonium bearing materials will need to be made for any of the disposal routes, up to and including safeguards approaches for deep geological disposal.

Throughout this publication, the terms MOX and ThMOX are used. This is to differentiate between MOX fuels prepared from uranium and plutonium, and those prepared from thorium and plutonium (ThMOX).

1.4. STRUCTURE

This publication identifies different technical options for plutonium recycling, plutonium conditioning, and waste disposal at various stages of development and implementation; these options are presented in isolation and are not ranked and rated against one another. It is intended that readers can draw their own conclusions based upon their Member State's specific considerations.

2. STRATEGIES FOR MANAGING SEPARATED PLUTONIUM

Figure 1 reflects the current position with respect to the management of separated plutonium in the framework of spent nuclear fuel recycling, where the material is recycled in either a thermal or fast neutron reactor. The recycling of separated plutonium more than once (multirecycling) is not currently practiced industrially, although there are ongoing developments and demonstrations in this area.

A small quantity of plutonium may be of unsuitable quality for recycling in reactors (e.g., residues contaminated with undesirable impurities, or scrap material from MOX fabrication). Complementary disposition options are therefore also required.

Due to a change of national fuel cycle strategy, there may be certain instances where the recycling of separated plutonium is on hiatus despite the continuation of reprocessing, which leads to the stockpiling of material. The following considerations are to be noted regarding the storage of separated plutonium:

— Some of the daughter products from the radioactive decay of plutonium are detrimental to the performance of plutonium based fuels and may cause issues during fuel fabrication and handling. This results in timing issues with respect to reuse if further refining is to be avoided.
— Separated plutonium may generate heat. Storage facility designs need to take this into account; modern storage facilities rely on passive cooling.
— Civilian plutonium contains many isotopes. A number of these isotopes are long lived and decay by alpha emission; these isotopes generate helium and may lead to container pressurization over time.

[2] A stable conditioned product being a specific matrix bearing radiological or nuclear material that is designed for either a storage facility and/or geological repository.

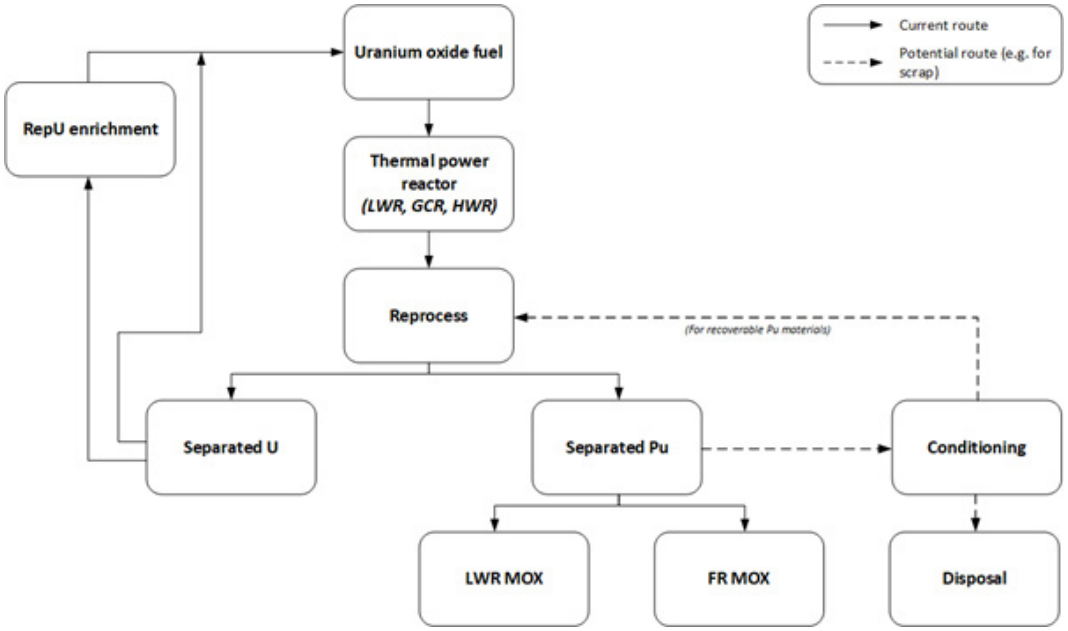

FIG. 1. Existing fuel cycle options for separated civilian plutonium (Pu) undertaken on a commercial scale. Uranium oxide fuel is irradiated and reprocessed to produce separated plutonium, which is currently reused as MOX fuel in LWRs and FRs. Plutonium material unsuitable for fuel fabrication (such as scrap or contaminated residues) can be conditioned for either future recycling or disposal; conditioning has only been undertaken on limited quantities of material to date. The separated uranium route is shown, but is outside of the scope of this publication. GCR = gas cooled reactor ; HWR = heavy water reactor ; RepU – reprocessed uranium.

The storage of separated plutonium requires physical protection measures at levels not lower than those stated in INFCIRC/225/Revision 5 [5], in addition to any safeguards requirements, according to agreements between Member States and the IAEA.

In conclusion, the ingrowth of daughter products creates timing issues related to the use of separated plutonium if the need for refining is to be avoided. Secondly, due to product container pressurization, separated plutonium cannot be stored indefinitely; at some point in time, a provision needs to be made for product recovery or, at a minimum, repackaging.

2.1. TERMINOLOGY

Throughout this publication, there are references to ‘conditioning’, ‘waste’, ‘waste forms’, ‘scrap’ and other terms for either unusable or unwanted materials for which recycling or disposal is planned. These terms are used in this publication with a focus on the economic use and future path of the materials, in accordance with the IAEA definitions below. Accordingly, any safeguards related obligations are not affected by this designation.

conditioning. “Those operations that produce a waste package suitable for handling, transport, storage and/or disposal. Conditioning may include the conversion of the waste to a solid waste form, enclosure of the waste in containers, and, if necessary, providing an overpack” [6].

scrap. “[R]ejected nuclear material removed from the process stream. Clean scrap comprises rejected process material that can be reintroduced into the process stream without the need for purification; dirty scrap requires separation of the nuclear material from contaminants, or chemical treatment to return the material to a state acceptable for subsequent processing” [7].

waste. “Material in gaseous, liquid or solid form for which no further use is foreseen” [6].

waste form. “Waste in its physical and chemical form after treatment and/or conditioning (resulting in a solid product) prior to packaging. The waste form is a component of the waste package” [6].

2.2. OPTIONS ANALYSIS

2.2.1. Assumptions

The different technical approaches considered within this publication were selected by subject matter experts and reviewed by the Technical Working Group on Nuclear Fuel Cycle Options and Spent Fuel Management. In addition to the approaches discussed here, there could be additional technologies that have not been captured or referenced.

All of the options will need criticality safety control, require physical protection measures no lower than those stated in INFCIRC/225/Revision 5 [5] and will be subject to safeguards as per the safeguards agreement between the Member State and the IAEA, in addition to meeting international and/or national safety standards.

It has been assumed that for the conditioning options, the material is in the oxide form (powder). It has also been assumed that all conditioned forms could be stored for 50 or more years pending the availability of a recycle route or deep geological disposal facility.

The technologies listed have been grouped to simply differentiate options that could be immediately available, those that could be available in the near to midterm, and those that still require significant development work before commercial scale can be realized and made available in the long term. The categories are:

— Commercially available — industrial scale processes available now for customers;
— Developing — advanced prototype or full scale process demonstration;
— Early stage — at proof of concept or proof of principle stage.

2.2.2. Factors for consideration

Sections 3–5 of this publication provide a basic description for each option, including the potential life cycle of the option and a summary of operating experience and/or technical development. For many of the plutonium ‘recycle options’, a given option could be split into two suboptions, depending upon the selected spent fuel management strategy:

— Monorecycle, where the plutonium is manufactured into fuel, irradiated and then disposed;
— Multirecycle, where the plutonium is manufactured into fuel, irradiated, and then reprocessed to produce fresh plutonium-based fuel.

There may be a delay between the irradiation of plutonium-based fuel and its subsequent reprocessing, or there may have been no decision made as to whether to implement multirecycling. In these cases, the infrastructure requirements are the same as for monorecycling in the interim.

More detailed information is given, where it is available, on each option in the Appendices on the following topics:

— Final conditioned form;
— Possible plutonium loading;
— Waste form durability (for waste options);
— Technology readiness;
— Advantages of the option — for example, the ability to use an existing plant and equipment, or enhanced safety benefits;
— Risks and uncertainties associated with this option — for example, ‘first of a kind’ technology that carries significant development costs and risks, or safety considerations.

2.3. SAFEGUARDS CONSIDERATIONS

While the goal of this publication is to evaluate the technical merits of various management options for separated plutonium, there are other factors that need to be considered. In addition to political, cultural, safety and security concerns, the Member States also need to be aware of the safeguards requirements for the various management options.

Every non-nuclear weapons state that is party to the Treaty on the Non-Proliferation of Nuclear Weapons has to conclude a safeguards agreement with the IAEA. A non-nuclear weapons state accepts safeguards on all nuclear material in the Member State in order to verify non-diversion of this material to a clandestine weapons programme. This includes both misuse of an existing facility and clandestine construction of a new facility for proliferation purposes.

On all issues regarding the application of IAEA safeguards to the various management options for separated plutonium, readers are strongly advised to refer to IAEA information circulars (INFCIRCs) available from the IAEA website, or to contact the national safeguards authorities concerned or the IAEA.

2.3.1. Safeguards by design

Safeguards by design (known by the acronym SBD) is the process in which facility designers and operators consider international safeguards requirements and features from the initial planning of a facility and through its design, construction, operation, and decommissioning. Safeguards by design encourages stakeholders to become familiar with the requirements of IAEA safeguards at an early stage in the design process and to address any potential challenges as soon as possible. Any facility with the possibility of having nuclear material in process or product streams, including waste, would benefit from including safeguards aspects in its design from inception. The ability to accurately account for the nuclear material masses and flows provides possibilities for the IAEA to verify nuclear materials in a facility as needed. Understanding the final form of the nuclear material and its storage location(s) is required in order to apply effective and efficient safeguards using proper measures over potentially long periods of time. Safeguards measures[3] can then be implemented.

3. PLUTONIUM RECYCLING OPTIONS

3.1. MOX OPTIONS

Currently, the only option deployed on a commercial scale for the recycling of plutonium is that of manufacturing MOX fuel for irradiation in an LWR or FR. Once the fuel has been irradiated, there may be additional suboptions for its management, as summarized in Fig. 2.

3.1.1. MOX in LWRs

Fabrication of MOX for LWRs is a mature technology; there is industrial manufacturing experience in Belgium, France, Germany and the United Kingdom. To date, around 10% of all operational power reactors globally were fuelled by MOX at some stage, with some reactors having now completed their

[3] Safeguards measures are methods available to the IAEA under safeguards agreements and additional protocols. A safeguards method is a specific technology used to implement a safeguards measure.

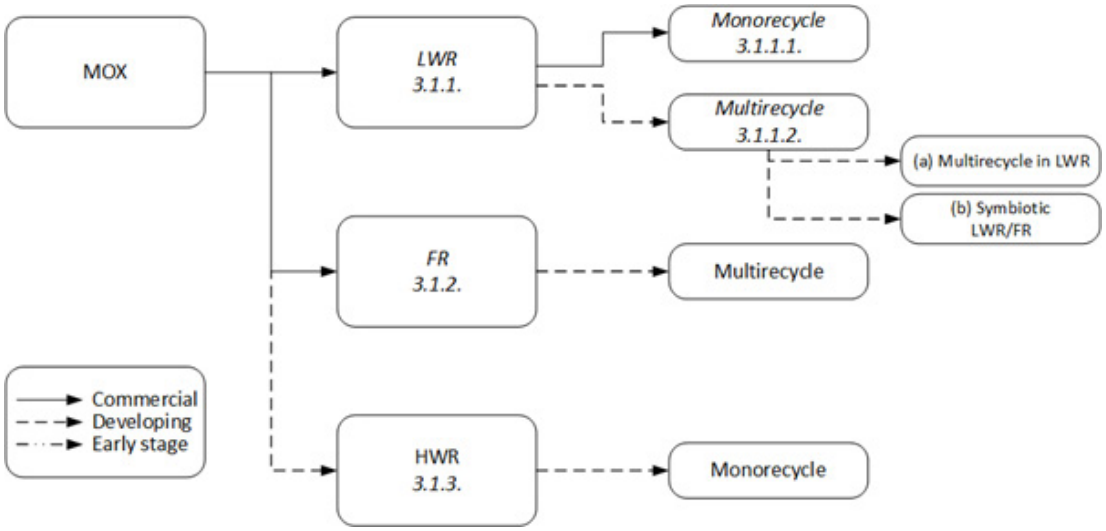

FIG. 2. Uranium MOX fuel options within LWRs, FRs and HWRs.

MOX fuel cycles. There is significant experience of loading MOX in Belgium, France, Germany, Japan, the Netherlands and Switzerland. Core loadings are commonly 25–50%, with core loadings of 100% MOX having been studied in Germany. Newer European pressurized reactors, advanced boiling water reactors, and AP1000 reactor designs have the potential to accommodate up to 100% MOX loading.

There are two potential options for the use of MOX in LWRs:

3.1.1.1. Monorecycle

This involves the irradiation of MOX in an LWR with the resulting spent MOX not considered for further use and stored in an appropriate facility prior to disposal. This option is currently in use, and usually forms part of a nuclear power strategy to minimize the plutonium inventory for disposal.

3.1.1.2. Multirecycle

This involves the irradiation of MOX in an LWR with the resulting spent MOX considered an asset for recycling to fabricate more fuel. This option involves the multiple recycling of plutonium and can be achieved either by multirecycling in an LWR or by symbiotic processing in an LWR/FR, as explained below.

(a) Multirecycling in LWRs

This option involves multiple recycling of the spent fuel and reuse of the recovered plutonium in an LWR. While it is feasible to multirecycle standard MOX fuel several times, each cycle reduces the fraction of fissionable plutonium, therefore requiring the percentage of plutonium to be increased after each cycle. This limits the total amount of plutonium that can be accommodated in the fuel. Fuel technologies using enriched uranium together with plutonium have been developed to increase the energy potential enabling multirecycling of plutonium in LWRs. This aside, reprocessing of spent MOX has been industrially demonstrated.

Multirecycling of plutonium in LWRs is under study in France with the optimization of concepts such as CORAIL and MIX[4] identified in the early 2000s. A technological road map gathering both

[4] CORAIL fuel assemblies contain both MOX and low enriched uranium fuel rods, MIX fuel assemblies contain fuel rods of plutonium and enriched uranium.

research and industrial studies is currently under preparation, aiming at potential industrial deployment in the 2040s [8].

In the Russian Federation, there is a development programme for a regenerated mixture (REMIX) fuel cycle concept aimed at multirecycling in a thermal reactor. A recovered mixture of regenerated uranium and plutonium (1–2%) will be blended with natural or reprocessed uranium in fuel fabrication. The level of uranium enrichment for REMIX fuel is selected so that its energy potential is identical to fresh fuel. The concept will allow for multiple recycling of all the recovered uranium and plutonium from spent fuel at 100% loading of water cooled, water moderated power reactor (WWER)-1000 type reactors. After irradiation, the fuel is cooled for five years in the storage pool prior to reprocessing. Approximately five to seven recycles of the REMIX fuel, containing 4% U-235 and 1–2% Pu, is foreseen with fresh batches of natural uranium and enriched reprocessed uranium [9]. No modification is required to the WWER to accept the REMIX fuel, and dedicated fabrication infrastructure is in the process of development. Three REMIX fuel assemblies were fabricated and loaded into the Balakovo nuclear power plant (WWER-1000 type, Russian Federation) in 2016 [10].

(b) Symbiotic LWR/FR MOX

This option involves first recycling the plutonium through an LWR as MOX fuel, with the resultant spent LWR MOX recycled into FR MOX fuel. Reprocessing of spent MOX is undertaken when the fuel is required for the second cycle.

This is part of the current fuel cycle strategy for Japan [11].

In France, a first recycling cycle of plutonium is implemented in 22 pressurized water reactors (PWRs) (24 are licensed). The latest multiannual energy plan identifies that the research and development programme to support the closure of the nuclear fuel cycle will focus on the multirecycling of spent fuels in PWRs in the medium term, maintaining the perspective of a potential industrial deployment of a fleet of sodium cooled FRs in the second half of the twenty-first century [12].

3.1.2. MOX in FRs

The method of processing MOX fuel in FRs is multirecycling. This involves the manufacture of FR-MOX from plutonium and subsequent irradiation in a sodium cooled FR[5]. The spent FR-MOX is then recycled multiple times, with experience already gained using existing aqueous reprocessing technology. The multirecycling of plutonium in FRs has been demonstrated in France using the Phénix reactor. During the transient phases between LWR fleet and FR fleet buildup, symbiotic fuel cycles could be considered. Plutonium recovered from spent FR fuel can be partially or totally recycled in an LWR (due to the higher fraction of fissionable isotopes after FR irradiation) and then reprocessed and recycled as FR fuel.

This approach is already implemented in the Russian Federation[6] on an industrial scale, with two FRs in operation. For the sodium cooled FR BN-600, 40 fuel assemblies have been fabricated, irradiated and reprocessed. For the first core loading of the sodium cooled FR BN-800, fuel assemblies comprising different types of uranium-plutonium oxide fuel, both pellets and vibro-packing, were fabricated and irradiated. An industrial fuel fabrication plant for BN-800 MOX pellet fuel has been constructed and is now in operation [9].

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[5] Other FR options are explored in option B, which follows in the next section.

[6] They have an installed thermal neutron reactor capacity of 25.6 GW, and an installed fast neutron reactor capacity of 1.4 GW.

3.1.3. MOX in HWRs

This option involves the manufacture of heavy water reactor (HWR) MOX and irradiation of it in an HWR. As for LWRs, the resulting spent fuel is stored, pending the next step of the fuel cycle. Reported work has focused on monorecycling, where MOX is irradiated in an HWR and then stored for disposal.

The use of MOX in HWRs has been trialled in India and Canada. At the Bhabha Atomic Research Centre (BARC), 50 fuel assemblies (0.4% Pu) have been fabricated and irradiated at Kakrapar atomic power station (KAPS-1) in India, with burnup up to 15 GWd/tHM [13]. Experience of MOX irradiation in research Canada deuterium–uranium (CANDU) reactors dates back to the 1970s, at which time six MOX fuel bundles with a plutonium content of 3 wt% were irradiated in the Nuclear Power Demonstration (NPD) reactor in Canada, to a burnup of 49 MWd/kgHM. More recent work has involved the irradiation of 18 bundles of MOX fuel with a varied plutonium content up to 5 wt% in the National Research Universal (NRU) reactor, Canada, to a burnup of 35 MWd/kgHM [14].

3.2. ADVANCED FUEL OPTIONS

There are several options for managing plutonium that involve the use of advanced fuels, as summarized in Fig. 3. None yet exist at a commercial scale, but development work is under way at varying stages.

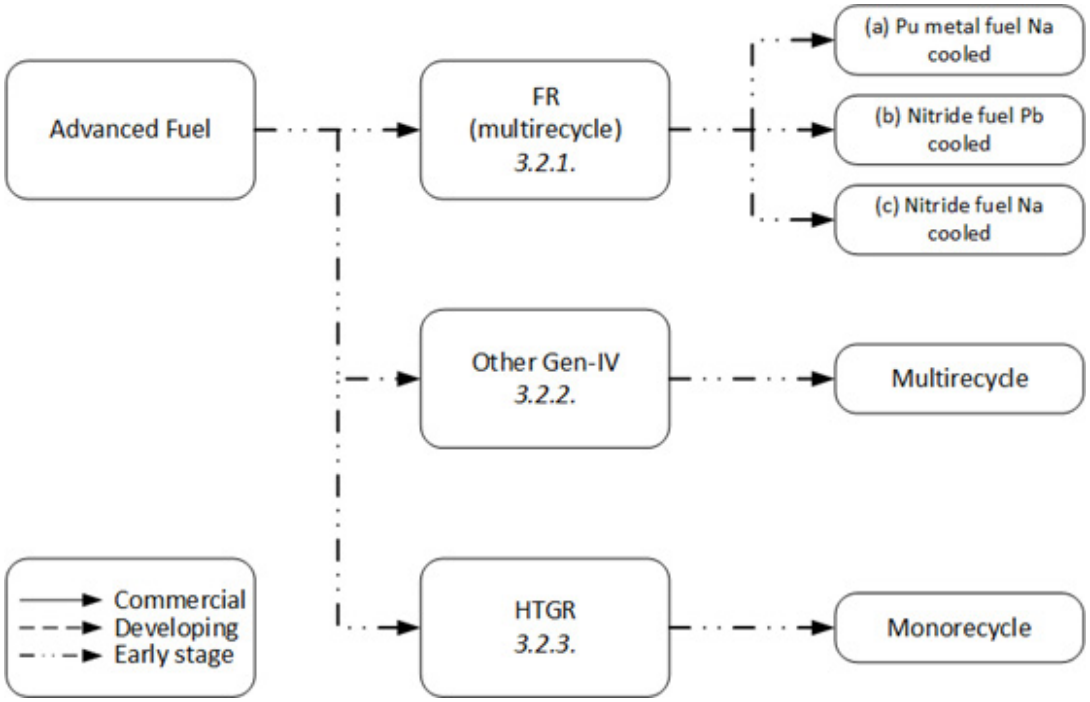

FIG. 3. Advanced fuel recycling options available using FRs with advanced fuels multirecycling, within other Generation IV technologies and within high temperature gas reactors.

3.2.1. Advanced fuels in fast reactors

There are currently three variations using advanced fuels in FRs, which involve the manufacture of FR fuels that are irradiated and the resultant spent fuel recycled continuously after one year of cooling:

(a) Plutonium metal fuel, sodium cooled FR — FR-metal fuel is fabricated and irradiated in a sodium cooled FR;
(b) Nitride fuel, lead cooled — FR-nitride fuel is fabricated and irradiated in a lead cooled FR;
(c) Nitride fuel, sodium cooled FR — FR-nitride fuel is fabricated and irradiated in a sodium cooled FR.

The first option for advanced fuels in FRs (a) is at the most advanced stage of development. To implement it, an integrated FR and back end facility including fuel manufacture is required, and the reprocessing stage is assumed to use pyroprocessing technologies. Demonstration programmes relating to metallic U-Pu-Zr fuels were undertaken at the EBR-II reactor (United States of America) including fabrication, irradiation and recycling [15, 16]. The fuels fabricated involved both U–8Pu–10Zr and U–19Pu–10Zr (wt%) compositions. As part of the demonstration programme, approximately 10 000 pins were electro-refined and recycled back to the reactor, with an average turnaround time of two months from discharge to reload. Although the basic process techniques have been demonstrated at EBR-II, adaptations are required for modern fuel characteristics and to serve at power reactor scale. More sophisticated processing equipment has been developed and demonstrated for more modern fuels at a bench scale.

Development work is under way on the second option (b) in the Russian Federation using the BREST-OD-300 pilot demonstration reactor, part of an energy complex including a power unit and fuel fabrication and refabrication modules. This option is a prototype system in the seventh stage of development. There is combined pyro and hydro reprocessing technology for reprocessing of spent nitride FR fuel under development [17].

The third option (c) uses the same fuel as in the second option (b), but it is irradiated in a conventional sodium cooled FR. Plutonium-nitride fuel has been irradiated in the BN-600 FR (Russian Federation). At the end of 2017, 16 fuel assemblies had been irradiated, with 7 removed and subjected to post-irradiation examination. The full test programme includes the irradiation of plutonium-nitride fuel in both the BN-600 and BOR-60 reactors with reactor and post-irradiation testing [18]. This option is a prototype system in the seventh stage of development.

3.2.2. Other Generation IV reactors

This option includes all other advanced reactor systems — for example, molten salt reactors (MSRs) — but has not been developed in detail. As new concepts in reactors and reprocessing are considered, the full requirements of the fuel cycle are unknown. There has been a theoretical consideration of placing plutonium into molten salt reactors, but the focus is currently on using enriched uranium.

3.2.3. High temperature gas reactors

This option involves the manufacture of graphite-based fuels containing plutonium for deep burnup irradiated within a HTGR or very high temperature reactor in a once through cycle. Compared to standard fuels, the fuel manufacture infrastructure is considered to be more expensive, although the Japan Atomic Energy Agency estimates that power generation costs for an HTGR could be 30% lower than for an LWR [19].

HTGR operating data are available, although experience to date has been based upon using uranium and thorium based fuels — for example, the Japanese system uses 15% U-235. Design readiness has been prepared, but to date there is no experimental validation.

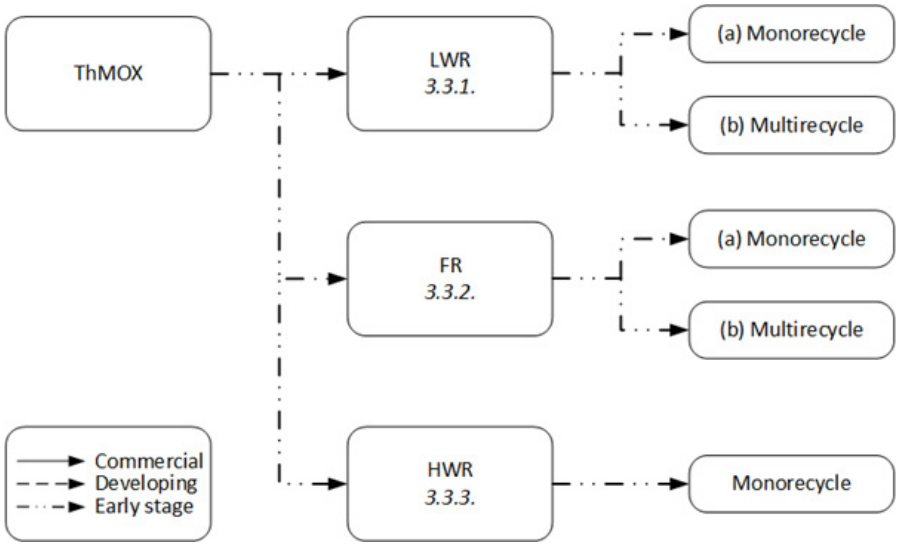

FIG. 4. ThMOX fuel recycling options within LWRs, within HWRs and within FRs.

3.3. ThMOX OPTIONS

Thorium based (Th-Pu) MOX fuels have been investigated for a number of reactor types and are summarized in Fig. 4. All are at an early stage of development.

3.3.1. ThMOX in LWRs

As with MOX, the two options for recycling ThMOX in an LWR involve fabrication of the fuel, irradiation within an LWR and subsequent storage of the spent fuel prior to its disposal or recycling:

(a) Monorecycle — ThMOX is irradiated in an LWR and then stored pending packaging for disposal;
(b) Multirecycle — ThMOX is irradiated in an LWR and the plutonium is then recycled to fabricate more fuel.

ThMOX fuels would require a manufacturing capability similar to that of conventional MOX fuel with an alpha sintering facility. Target burnups for the fuel are in the region of 50–60 GWd/tHM.

Part pins have been irradiated in Obrigheim (Germany), BR2 (Belgium), HFR-MTR (high flux reactor — materials test reactor in the Netherlands) and Halden Reactor (Norway) under LWR conditions, achieving burnups up to 40 GWd/tHM [20, 21]. Halden was loaded in 2017 with fuel pins containing Th-12% MOX pellets fabricated using an industrial type co-milled/micronized master (MIMAS) type process [22]. The CIRUS research reactor in India has used Th-4% Pu MOX in a boiling water reactor (BWR) assembly design from the Tarapur Atomic Power Station, also in India [23].

3.3.2. ThMOX in FRs

This option involves the manufacture of FR-ThMOX fuel from thorium and plutonium and subsequent irradiation in a sodium cooled FR. The resultant spent fuel is then recycled multiple times.

This option is in very early stages of development, so no further detail will be given here, other than to say there are two types:

(a) Monorecycle — ThMOX is irradiated in an FR and then stored pending packaging for disposal;
(b) Multirecycle — ThMOX is irradiated in an FR and the plutonium is then recycled to fabricate more fuel.

3.3.3. ThMOX in HWRs

This option involves fabrication of ThMOX fuel, irradiation in an HWR and storage pending packaging for disposal.

ThMOX fuels have been test irradiated in the pressurized water loop of the CIRUS reactor and the Dhruva research reactor using both pressurized HWR (Th-6.75% Pu MOX) and advanced HWR (Th-8% Pu MOX and Th-1% Pu MOX) designs [24]. There has also been a test irradiation in the High Flux Isotope Reactor in Romania. ThMOX fuels have been assessed as part of advanced fuel materials studies completed by CANDU researchers [25]. China has an outline development scheme for ThMOX fuels.

4. PLUTONIUM CONDITIONING OPTIONS

4.1. CONDITIONING OPTIONS

Figure 5 shows the potential conditioning options for plutonium not compatible with direct reuse. With the exception of fabricating sintered MOX pellets (D1), there are currently no conditioning options in common use for plutonium. Several conditioning options are being investigated to immobilize plutonium as a waste form and are at various stages of development. Disposal of any of these conditioned forms has yet to be demonstrated.

The infrastructure requirements for each of the options are outlined in Table 1 and an overview of the technical information is found in Annex IV.

TABLE 1. INFRASTRUCTURE REQUIREMENTS FOR PLUTONIUM CONDITIONING OPTIONS

	Option						
	Sintered MOX pellets	Vitrification	Spiked HLW	Cold pressing and sintering	High pressure process	Ceramic in glass	Mixing
Additives	×			×	×	×	
Assay equipment	×	×	×	×	×	×	×
Blender	×	×	×				
Bulk handling facility	×	×	×	×	×	×	×
Cold press	×			×			
Canister / container	×	×	×	×	×	×	×
Evaporator		×	×				

TABLE 1. INFRASTRUCTURE REQUIREMENTS FOR PLUTONIUM CONDITIONING OPTIONS (cont.)

	Option						
	Sintered MOX pellets	Vitrification	Spiked HLW	Cold pressing and sintering	High pressure process	Ceramic in glass	Mixing
Furnace	×			×			
Glass former		×	×				
Glovebox	×	×	×	×	×	×	×
Granulator				×			
HIP / HUP[a]					×	×	
Melter		×	×				
Milling / mixing	×			×	×	×	×
Neutron poison		×	×				×
Off-gas	×	×	×	×			
Sorting capability							×

[a] A consideration depending in the additives used.
Note: Each option will also have transport, storage and disposal considerations.

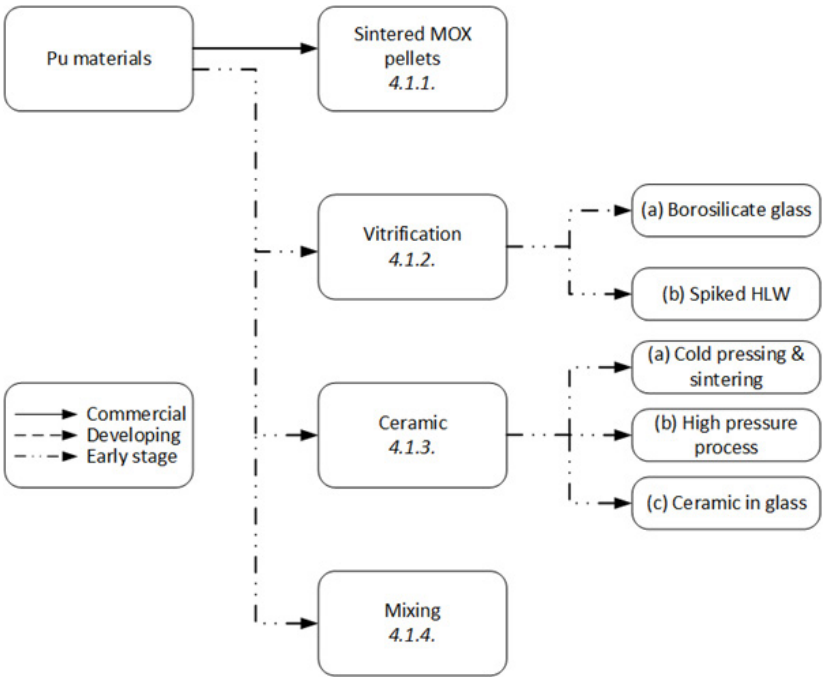

FIG. 5. Conditioning options in various stages of development for plutonium oxide in the powder form.

4.1.1. Sintered MOX pellets

This option for conditioning plutonium involves manufacturing sintered uranium and plutonium MOX pellets using an adaptation of the process for MOX fuel pellet fabrication. The process includes a sintering step to remove moisture and volatile elements, and results in a high density ceramic pellet. The process can allow for the addition of neutron poison components, such as gadolinium, if required, as is the case in standard fuel pellet production.

This method was used to process scrap and glovebox residues during post-operational clean out of the Atelier de technologie du plutonium MOX fabrication plant in Cadarache, France. It resulted in a waste form satisfying both the transportation constraints and technical specifications for storage pending future recycling or disposal. By using a simplified route of the master process, minimal new equipment was required to perform the operations. Over the three year period of conditioning operations, 5 tHM of PuO_2 pellets were conditioned in rods of various lengths, and 2 tHM of pellets containing a plutonium and uranium mixture (between 12.5–20%) were packaged in stainless steel boxes.

4.1.2. Vitrification

Vitrification involves incorporating the plutonium into a glass matrix. Options include:

(a) Borosilicate glass — Plutonium is homogenously incorporated into a ‘clean’ borosilicate glass matrix (i.e. in the absence of any other radionuclides);
(b) Spiked HLW — Small amounts of plutonium are homogenously incorporated into a glass matrix containing HLW from uranium/plutonium reprocessing.

Both options involve similar infrastructure. However, it is anticipated that the second option (b) would use existing HLW vitrification infrastructure, which would limit the amount of plutonium that could be incorporated per batch due to criticality concerns. For the borosilicate glass option (a), a specially designed melter would be needed to ensure criticality safe geometry, or a premixing phase could be implemented to ensure homogenization of the blend.

Both options have been investigated on a small scale, although developments in the first option (borosilicate glass) are more advanced.

4.1.3. Ceramic

The ceramic process involves incorporating plutonium into a ceramic matrix. There are currently three options for doing so:

(a) Cold pressing and sintering — High energy milling process incorporates plutonium into a ceramic matrix. This is similar to option D1 (sintered MOX pellets), but the product produced is a larger puck rather than fuel pellets and it is produced in a batch operation.
(b) High pressure process — High pressure processes such as hot isostatic pressure (HIP) or hot uniaxial pressing (HUP) incorporate plutonium into a ceramic matrix.
(c) Ceramic in glass — Uses a glass ceramic matrix, whereby the plutonium is incorporated into a ceramic phase surrounded by a glassy matrix.

Each of these techniques has been tested at a small scale using plutonium [26–31], with full scale demonstrations reported using simulants [29].

4.1.4. Mixing

Technically, this mixing option is not based on the immobilization of the plutonium in a waste form. Instead it involves the addition of an adulterant to the plutonium prior to disposal with the aim of making recovery more technically challenging. It has been demonstrated at a small scale, but its use is limited to specific disposal circumstances where the disposal safety case does not require a waste form with specific characteristics, such as waste not in a solid conditioned form [32].

5. WASTE DISPOSAL OPTIONS

5.1. DISPOSAL OPTIONS

Two options (Fig. 6) are being pursued by many Member States for the disposal of spent fuel and HLW from reprocessing activities and are currently under consideration for immobilized plutonium, however none of them are yet operational.

Generic safety assessments of geological disposal are available but cannot yet be implemented as no facilities are currently available for any spent nuclear fuel or HLW disposal. The operating licence for the first spent fuel repository was submitted to the regulator in 2021 [33].

The safeguards requirements for waste following disposal are under consideration.

The infrastructure requirements for each of the options are outlined in Table 2.

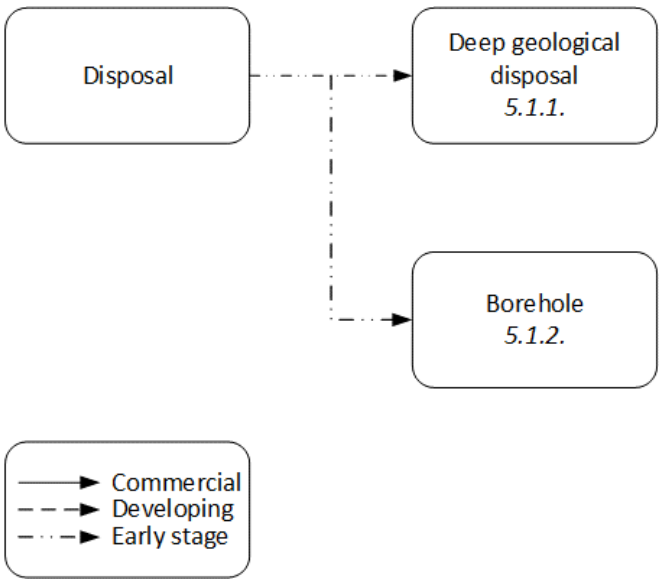

FIG. 6. Disposal options for immobilized plutonium.

TABLE 2. INFRASTRUCTURE REQUIREMENTS FOR DISPOSAL OPTIONS

	Options	
	Deep geological disposal	Borehole
Packaging system	×	×
Engineered containers	×	×
Transport	×	×
Disposal site	×	×
Plug / backfill system	×	×

5.1.1. Deep geological disposal

Deep geological disposal is the reference end point for spent fuel declared as HLW. Several concepts (using a variety of geologies) have been developed and licence applications are under way in a number of Member States. A deep geological disposal facility for transuranic waste (TRU) is operational in the United States of America[7] (using a salt geology). This option involves using a deep geological facility for disposition of immobilized plutonium.

5.1.2. Borehole disposal

Deep boreholes are currently conceptual and would be used for the disposal of waste. This option involves emplacing immobilized plutonium into a deep borehole (minimum depth 1000 metres).

6. SUMMARY

The current generation of reprocessing plants leads to product streams, namely reprocessed uranium, and plutonium, and waste products. In some instances, changes in fuel cycle strategy can lead to a legacy stockpile of separated plutonium.

The management approaches for reprocessed uranium are detailed in Ref. [4] and are not reported in this publication.

To date, spent fuel recycling strategies lead to the reuse of separated plutonium mainly through the commercialized process of MOX fabrication and irradiation in a thermal (LWR) reactor, or the fabrication of MOX FR fuel for irradiation in FRs. Around 10% of thermal nuclear power reactors worldwide have been routinely loaded with MOX. Based on significant industrial recycling experience so far, a

[7] The Waste Isolation Pilot Plant was designed for the disposal of transuranic wastes. These wastes are a by-product of the nuclear defence programme and consist of materials contaminated with transuranic elements, mainly plutonium.

very limited quantity of separated plutonium, incompatible with direct reuse in LWR or FR, has been conditioned for future management.

This publication looks at the potential technical options for managing separated plutonium. In total, 24 options have been identified. The overall approach to plutonium management may consist of a combination of technical options, depending upon the circumstances.

In the short term, many of the technical options for plutonium recycling are at varying stages of technical development. Monorecycling of plutonium in LWRs is currently industrially implemented in several countries. Subsequent recycling stages for plutonium multirecycling in LWRs are under development and demonstration, with some concepts reaching industrial implementation. This will enable a transition to symbiotic LWR/FR fuel cycle options in the longer term. A closed fuel cycle using FRs has been demonstrated, and the use of commercial sized FRs is currently being progressed in the Russian Federation and India, with the loading of MOX fuel into one of these reactors.

A number of options have been identified for immobilizing separated plutonium declared as unsuitable for direct reuse (such as scraps/residues, material that has been contaminated, or material that is out of specification for fuel fabrication). With the exception of using a uranium and plutonium ceramic matrix to form sintered pellets, as implemented in France for conditioning limited plutonium quantities following the closure of the Cadarache MOX fabrication plant, the other conditioning options are at an early stage of development.

Disposal of all final waste forms will be contingent on the availability of a suitable deep geological repository.

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Annex I

RELATED IAEA PUBLICATIONS

This annex provides a summary of the publications produced by the IAEA related to plutonium management (Table I–1.).

TABLE I–1. PLUTONIUM RELATED PUBLICATIONS PRODUCED BY THE IAEA

Area/reference	Scope
Use of plutonium in nuclear reactors	
INTERNATIONAL ATOMIC ENERGY AGENCY, Use of Plutonium for Power Production, Technical Reports Series No. 49, IAEA, Vienna (1966).	Mostly of historical interest, this results from the first of the panels looking into plutonium use from civilian nuclear power. Discussions relate to: — FR physics; — Plutonium physics in thermal reactors; — Irradiation experience with plutonium fuel; — Fabrication and reprocessing of plutonium bearing fuel; — Economic aspects of plutonium; — Physical, technological and economic aspects of recycling thorium and plutonium.
INTERNATIONAL ATOMIC ENERGY AGENCY, Plutonium as a Reactor Fuel — Brussels, 13–17 March 1967, Proceedings Series No. 85, IAEA, Vienna (1967).	Mostly of historical interest. From a time at which the expectation was that low cost uranium resources would be fully used, hence there was a need to use separated plutonium. Sessions covered: — Physics of plutonium fuelled systems; — Fabrication of plutonium fuels and fuel elements; — Irradiation behaviour of plutonium fuels; — Reprocessing of irradiated plutonium fuels; — Prospects and economics of plutonium fuelled systems.
INTERNATIONAL ATOMIC ENERGY AGENCY, Plutonium Utilization, (Vienna, 2–6 September 1968), IAEA-TECDOC-112, IAEA, Vienna (1969).	Mostly of historical interest, this 1969 panel focused on the recycling of plutonium in thermal reactors. The main areas discussed were: — Review of plutonium fuel programmes; — Recycling of plutonium in thermal reactors; — Economics of plutonium fuel cycles.
INTERNATIONAL ATOMIC ENERGY AGENCY, Plutonium recycling in thermal power reactors (Proc. of a panel on plutonium recycling in thermal power reactors, in Vienna 21–25 June 1971, IAEA-TECDOC-143, IAEA, Vienna (1972).	Mostly of historical interest, this is the output from the third panel discussions on plutonium use. The main focus was on: — Status reports on national programmes, including demonstration programmes and plutonium availability; — Technology of low enriched plutonium fuel, including fuel fabrication, fuel and core design and performance; — Economics of plutonium use approach.

TABLE I–1. PLUTONIUM RELATED PUBLICATIONS PRODUCED BY THE IAEA (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Plutonium utilization in thermal power reactors (Proc. of a panel in Karlsruhe, 25–29 Nov. 1974), IAEA-TECDOC-175, IAEA, Vienna (1975).	Mostly of historical interest from a time when plutonium was considered too valuable a fuel not to be used. The current initiative built upon a symposium in 1967 and the three panels held in 1964, 1968 and 1971 with a focus on thermal reactor use including: — Status reports on national programmes, including demonstration programmes and plutonium availability: — Technology of low enriched plutonium fuel, including fuel fabrication, fuel and core design and performance; — Economics of plutonium use approach.
INTERNATIONAL ATOMIC ENERGY AGENCY, Unconventional options for plutonium disposition (Proc. of a technical committee meeting held in Obninsk, Russian Federation, 7–11 November 1994) IAEA-TECDOC-840, IAEA, Vienna (1995).	Unconventional uses of plutonium are considered in terms of evolution of fuel designs and reactor technology. The publication reflects the position in the early 1990s and the then recent decision to dismantle nuclear warheads. The main difference between weapons grade Pu and reprocessed Pu is that it can be stored almost indefinitely. Topical sessions included: — Gas cooled reactors and thorium aspects; — CANDU and LWR; — Molten salts; — FRs; — Weapons grade plutonium.
INTERNATIONAL ATOMIC ENERGY AGENCY, Recycling of plutonium and uranium in water reactor fuel (Proc. of a technical committee meeting held in Newby Bridge, United Kingdom, 3–7 July 1995) IAEA-TECDOC-941, IAEA, Vienna (1997).	The publication primarily focuses on MOX use in LWR reactors. The use of weapons grade plutonium as MOX in an LWR and PHWR reactor is also covered. The technical sessions covered: — MOX recycled uranium fuel use; — MOX fabrication and reprocessing; — MOX fuel design; — Plutonium disposal (in-reactor); — Fuel performance.
INTERNATIONAL ATOMIC ENERGY AGENCY, MOX fuel cycle technologies for medium and long term deployment (Proc. of an international symposium held in Vienna, Austria, 17–21 May 1999) IAEA-CSP-3/P, IAEA, Vienna (2000).	The technical sessions covered: — Overview of the current status of and prospects for Pu management and MOX use; — MOX fuel fabrication; — Fuel design, performance and testing under normal and off-normal conditions; — In-core fuel management and advanced fuel cycle options; — Management of the MOX fuel cycle.

TABLE I–1. PLUTONIUM RELATED PUBLICATIONS PRODUCED BY THE IAEA (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Potential of thorium based fuel cycles to constrain plutonium and reduce long lived waste toxicity, IAEA-TECDOC-1349, IAEA, Vienna (2003).	Report of the reactor core modelling studies for the burning of plutonium (civil and weapons grade) in LWR, HWR, HTR and MSR systems. Weapons grade plutonium incineration is generally more effective than LWR plutonium burning. LWR reactors were the least effective system in burning plutonium. HTR was the most effective mainly due to the burnups which can potentially be achieved in such systems. Radiotoxicity of the resultant waste is also evaluated.
INTERNATIONAL ATOMIC ENERGY AGENCY, Status and advances in MOX fuel technology, Technical Reports Series No. 415, IAEA, Vienna (2003).	An overview of the status of plutonium fuel development as of December 2000. The areas covered include: — Strategic considerations; — Plutonium feed production, handling and a storage; — MOX fuel fabrication; — LWR fuel assembly design, in-core fuel management and licensing; — LWR MOX fuel design and performance; — Transportation; — Spent MOX fuel management; — Waste treatment and decommissioning; — Applications of safeguards and physical protection to MOX fuel; — Specific aspects of FR MOX fuel; — Alternative approaches.
INTERNATIONAL ATOMIC ENERGY AGENCY, Viability of inert matrix fuel in reducing plutonium amounts in reactors, IAEA-TECDOC-1516, IAEA, Vienna (2006).	Interest in the application of inert matrix fuels (IMF) to reduce plutonium stockpiles and other transuranic elements was the subject of some interest in the 1990s. This publication reviews the progress in this area up to the early 2000s. Areas covered include: — Overview; — National programmes; — International programmes; — Results and outlook. The publication concludes that strategies have been identified for the implementation of IMF in existing reactors in the short term and new reactor systems in the longer term, but more work is required to underpin this technology.
INTERNATIONAL ATOMIC ENERGY AGENCY, Impact of high burnup uranium oxide and mixed uranium-plutonium oxide water reactor fuel on spent fuel management, IAEA Nuclear Energy Series NF-T-3.8, IAEA, Vienna (2011).	The focus of this publication is on the back end of the fuel cycle and application of high burnup uranium oxide (UOX) in LWR or HWR systems/introduction of MOX into those systems. Areas covered include: — UOX and MOX fuel burnup; — Components of the analysis; — Characteristics of spent fuel; — Analysis of effects of high burnup and MOX on spent fuel management.

TABLE I–1. PLUTONIUM RELATED PUBLICATIONS PRODUCED BY THE IAEA (cont.)

Area/reference	Scope
Specific safety related publications	
INTERNATIONAL ATOMIC ENERGY AGENCY, Safe handling and storage of plutonium, Safety Reports Series No. 9, IAEA, Vienna (1998).	Areas covered: — Existing and future plutonium activities and inventories; — Nuclear, physical and chemical properties of plutonium; — Plutonium in the environment; — Pathways to humans and the biological effects of plutonium; — Licensing, controls and regulatory limits; — Safety aspects of design; — Operational safety.
INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of uranium and plutonium mixed oxide fuel fabrication facilities, IAEA Safety Standards Series No. SSG-7, IAEA, Vienna (2010).	This publication provides guidance related to the safety of MOX fuel fabrication facilities all stages of facility lifetime from site selection through to decommissioning, with a focus on design and operational phases. It describes how the safety requirements related to the handling, processing and storage of plutonium oxide, depleted, natural or reprocessed uranium oxide or mixed oxide fuel feed stock for MOX fuel rods can be met.
INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Fuel Reprocessing Facilities, IAEA Safety Standards Series No. SSG-42, IAEA, Vienna (2017).	This publication provides guidance related to the safety of nuclear fuel reprocessing facilities, including spent fuel handling, mechanical treatment and dissolution of spent fuel, separation of products from fission product waste, separation of Pu and U and the production and storage of feed material for fresh fuel. It covers all stages of facility lifetime from site selection through to decommissioning, with a focus on design and operational phases.
INTERNATIONAL ATOMIC ENERGY AGENCY, Storage of Spent Nuclear Fuel (Specific Safety Guide), Safety Standards Series No. SSG-15 (Rev. 1), Vienna (2020).	This publication provides guidance on the storage of spent nuclear fuel for all types of storage facility and all types of spent fuel from NPPs and research reactors. Areas covered: — All stages in spent fuel storage facility lifetime, from planning through siting and design, to operation and decommissioning; — Storage periods exceeding the original design lifetime of the storage facility; — Developments associated with nuclear fuel, such as higher enrichment, MOX fuels and higher burnup.
Alpha bearing wastes publications	

TABLE I–1. PLUTONIUM RELATED PUBLICATIONS PRODUCED BY THE IAEA (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Treatment of Alpha Bearing Wastes, Technical Reports Series No. 287, IAEA, Vienna (1988).	The publication focuses on the treatment of wastes coming from reprocessing, fuel manufacturing facilities, decommissioning and research and development. Areas covered: — Sources, types and volume of alpha bearing wastes; — Waste management strategies; — Treatment of solid alpha bearing wastes; — Treatment of liquid alpha bearing wastes; — Alpha bearing waste treatment facilities.
INTERNATIONAL ATOMIC ENERGY AGENCY, Conditioning of alpha bearing wastes, Technical Reports Series No. 326, IAEA, Vienna (1991).	Follow-up publication to (TRS No. 287). Areas covered: — Alpha bearing wastes: types and characteristics; — Matrix materials; — Immobilization processes; — Waste form properties; — Packaging the final waste form; — Integrated alpha bearing waste conditioning facilities.
Fast reactor/Fast reactor fuel cycle publications	
INTERNATIONAL ATOMIC ENERGY AGENCY, Fast reactor database, IAEA-TECDOC-866, IAEA, Vienna (1996).	Provides detailed information on the materials of construction and design of FRs.
INTERNATIONAL ATOMIC ENERGY AGENCY, Status of liquid metal cooled fast reactor technology, IAEA-TECDOC-1083, IAEA, Vienna (1999).	Captures the experiences and learning from operating, building, etc. LMFRs for the period up to 1985–1998.
INTERNATIONAL ATOMIC ENERGY AGENCY, Fast reactor database 2006 update, IAEA-TECDOC-1531, IAEA, Vienna (2006).	Update of IAEA-TECDOC-866.
INTERNATIONAL ATOMIC ENERGY AGENCY, Status and trends of nuclear fuels technology for sodium cooled fast reactors, IAEA Nuclear Energy Series No. NF-T-4.1, IAEA, Vienna (2011).	Subjects covered: — Sodium cooled fast reactors and its fuel cycle activities in Member States; — Oxide fuel; — Carbides and nitrides; — Metallic fuels; — Thermophysical properties.
INTERNATIONAL ATOMIC ENERGY AGENCY, Status of developments in the back end of the fast reactor fuel cycle, IAEA Nuclear Energy Series No. NF-T-4.2, IAEA, Vienna (2011).	Publications the results of an evaluation of nuclear energy systems based on a closed nuclear fuel cycle with fast reactors using the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) methodology.
INTERNATIONAL ATOMIC ENERGY AGENCY, Assessment of nuclear energy systems based on a closed nuclear fuel cycle with fast reactors, IAEA-TECDOC-1639 Rev. 1, IAEA, Vienna (2012).	Section 2: Overview of the basic processes in FR fuel reprocessing; Section 6: An account of the status of spent FR fuel reprocessing and waste treatment is provided for France, Germany, India, Japan, Republic of Korea, Russian Federation, United Kingdom and United States of America.

TABLE I–1. PLUTONIUM RELATED PUBLICATIONS PRODUCED BY THE IAEA (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Fast reactors and related fuel cycles: Safe technologies and sustainable scenarios (FR13) (Proc. of an international conference, held in Paris, France, 4–7 March 2013, STI/PUB/1665, IAEA, Vienna (2015).	Status of fast reactor technology. Track relevant to this publication: Technical track 5: FR fuel cycle: processes and demonstrations, including partitioning and transmutation.
INTERNATIONAL ATOMIC ENERGY AGENCY, Fast Reactors and Related Fuel Cycles: Next Generation Nuclear Systems for Sustainable Development (FR17), Proceedings Series - International Atomic Energy Agency , IAEA, Vienna (2018).	Status of fast reactor technology. Track relevant to this publication: Technical track 4: Fuel Cycle Sustainability, Environmental Considerations and Waste Management.
INTERNATIONAL ATOMIC ENERGY AGENCY, Fast Reactors and Related Fuel Cycles: Sustainable Clean Energy for the Future (FR22), Proceedings Series - International Atomic Energy Agency, IAEA, Vienna (In print)	Status of fast reactor technology. Track relevant to this publication: Technical track 3. Fuels, Fuel Cycles and Waste Management.
Other relevant publications	
INTERNATIONAL ATOMIC ENERGY AGENCY, Problems concerning the accumulation of separated plutonium, IAEA-TECDOC-765, IAEA, Vienna (1994).	The publication provides the status and forward projections at the time of the advisory group meeting April 1993. The world has moved on since this publication was produced and the situation in a number of participating Member States has changed and some proposed facilities have not been provided on the timescales indicated or have subsequently been shut down.
INTERNATIONAL ATOMIC ENERGY AGENCY, Thorium based fuel options the generation of electricity: Developments in the 1990s, IAEA-TECDOC-1155, IAEA, Vienna (2000).	Although this publication is now dated, Section 3.4 is of interest and provides a comparison between those fuel cycles using pure thorium with those where thorium is combined with plutonium.
INTERNATIONAL ATOMIC ENERGY AGENCY, Technological implications of international safeguards for geological disposal of spent fuel and radioactive waste, Nuclear Energy Series No. NW-T-1.21, IAEA, Vienna (2010).	Compilation of challenges and potential solutions to the task of safeguarding a deep geological repository.
INTERNATIONAL ATOMIC ENERGY AGENCY, Role of thorium to supplement fuel cycles of future nuclear energy systems, IAEA Nuclear Energy Series No. NF-T-2.4, IAEA, Vienna (2012).	The most up to date information on the application of mixed thorium-plutonium oxide fuels.
INTERNATIONAL ATOMIC ENERGY AGENCY, International safeguards in the nuclear facility design and construction, IAEA Nuclear Energy Series No. NP-T-2.8, IAEA, Vienna (2013).	An overview of safeguards required on nuclear facilities with an emphasis on the safeguards by design philosophy. It covers general principles and the roles and responsibilities for various stakeholders.
INTERNATIONAL ATOMIC ENERGY AGENCY, International safeguards in the design of facilities for long term spent fuel management, IAEA Nuclear Energy Series No. NF-T-3.1, IAEA, Vienna (2018).	Exemplary safeguards measures that can be used for long term storage facilities; complimentary to NP-T-2.8.

TABLE I–1. PLUTONIUM RELATED PUBLICATIONS PRODUCED BY THE IAEA (cont.)

Area/reference	Scope
INTERNATIONAL ATOMIC ENERGY AGENCY, Status and Trends in Pyroprocessing of Spent Nuclear Fuels, IAEA-TECDOC-1967, IAEA, Vienna (2021).	Reviews the status and trends in the development of pyrometallurgical processes and technologies for processing spent nuclear fuel and identifies gap areas requiring further development.

Note: HTR = high temperature reactor; LMFR = liquid metal cooled fast reactor; PHWR = pressurized heavy water reactor.

Annex II

SUPPORTING INFORMATION

II–1. INFRASTRUCTURE

The following section gives an indication of the infrastructure requirements in support of fuel cycles. Parts of these requirements are readily available from the marketplace or are provided by service providers.

II–1.1. Recycling

II–1.1.1. Monorecycling

The following infrastructure elements will be required to deliver a monorecycling fuel cycle strategy. Some of the elements may already exist for uranium oxide (UOX) fuel cycles but will require safety assessments and licence extension to be incorporated into applications for MOX or alternative fuel applications not in the original design scope.

(a) Transport of raw materials to a fuel manufacturing facility using approved service providers and transport packages via one or more transport modes (road, rail, ship):
- Fuel manufacturing facility for MOX manufacture (more complex than UOX manufacture due to need for full or partial automation, and parts will be in glove boxes and or shielded cells);
- Currently there is one service provider for MOX fabrication;

(b) Transport of fresh fuel to the utility using an approved transport package via one or more transport modes (road, rail, ship);

(c) If using an existing reactor system, review and modify safety assessment and operating licence, and modify the fuel route and reactor system if required;

(d) At reactor spent fuel storage:
   (i) Review and modify safety assessments, if not covered;

(e) Transport of spent fuel to away from reactor storage or conditioning plant for disposal via an approved transport package and one or more transport modes (road, rail, ship);
- Away from reactor spent fuel storage (dependent on time to next stage) is available;
- Spent fuel conditioning (or repackaging) plant is available;

(f) Transport of spent fuel to repository via an approved transport package and one or more transport modes (road, rail, ship);

(g) Deep geological disposal facility:
   (i) Requires safety assessment and modification of operating licence, if not included.

II–1.1.2. Multirecycling

Multirecycling of fuel requires the same elements as for monorecycling with some additions:

(a) Transport of spent fuel to reprocessing via an approved transport package and one or more transport mode (road, rail, ship);

(b) Reprocessing facilities for MOX fuel, either through;
   (i) Service providers that are available for small volumes of LWR MOX with initial waste storage;
   (ii) Development of a reprocessing plant;

(c) Front end facilities with capability to handle reprocessed uranium (where reprocessed uranium forms part of the option);
(d) Design services available to develop a reprocessing plant[1];
(e) Transport of waste to long term storage facility (including the return of wastes from a reprocessing service provider) using an approved transport package and one or more transport modes (road, rail, ship);
(f) Storage of waste within a suitable facility;
(g) Transport of waste to a conditioning plant using an approved transport package and one or more transport modes (road, rail, ship);
(h) Waste conditioning (or repackaging) within a conditioning plant;
(i) Transport of waste to repository using an approved transport package and one or more transport modes (road, rail, ship);
(j) Deep geological disposal facility.

It is to be noted that fuel cycles using pyroprocessing are based on having integrated buffer storage for spent fuel, a pyroprocessing facility and a fuel manufacturing facility alongside the reactor system. These options will remove a number of transport elements.

II–2. REACTOR SYSTEM EXPERIENCE

II–2.1. Thermal reactors (LWR)

Thermal reactor experience at LWRs in the use of MOX fuel is detailed in Table II–1. In Belgium, Germany, and Switzerland, MOX loading to reactors has either been completed or will be completed in the near future. The situation reflects that the separated plutonium from contracted reprocessing activities has been either all fabricated into MOX, then irradiated, or its management has been taken over by the service provider. France and the Netherlands are the only Member States routinely loading fresh MOX, with 22 reactors in France routinely loaded with one-third MOX. MOX has been loaded in selected reactors in Japan, however many reactors are currently shut down, pending reactor upgrades to meet new safety requirements.

II–2.2. Fast reactors

FR experience is detailed in Table II–2. Currently, there are two operational power FRs; both are in the Russian Federation and only one of these reactors has MOX loaded.

The Russian Federation is the current leader in terms of operating FR technology[2]. It is unclear whether this technology will be exported outside of the Russian Federation. FR research is also at an advanced stage in France and Japan.

[1] Reprocessing of FR MOX has been demonstrated in France and commercial operations in the United Kingdom (10 tHM/year scale).

[2] A review of FR development in the Russian Federation is provided in NUCLEAR ENGINEERING INTERNATIONAL, “Fast Reactor Progress at Beloyarsk,” NEI Magazine **61** 738 (2016) 20–21.

TABLE II–1. THERMAL REACTOR (LWR) MOX ROUTINE LOADING EXPERIENCE

Reactor name	Location	Type	Power (MW(e))	Maximum core loading	Status
DOEL-3	Belgium	PWR	1000	25%	Completed
TIHANGE-2					
BLAYAIS-1	France	PWR	900	30%	Loaded
BLAYAIS-2					
CHINON-B1					
CHINON-B2					
CHINON-B3					
CHINON-B4					
DAMPIERRE-1					
DAMPIERRE-2					
DAMPIERRE-3					
DAMPIERRE-4					
GRAVELINES B-1					
GRAVELINES B-2					
GRAVELINES B-3					
GRAVELINES B-4					
GRAVELINES B-5					
GRAVELINES B-6					
ST LAURENT B-1					
ST LAURENT B-2					
TRICASTIN-1					
TRICASTIN-2					
TRICASTIN-3					
TRICASTIN-4					
BROKDORF	Germany	PWR	1410	Variable up to 50%	Shutdown
GRAFENRHEINFELD		PWR	1275		Shutdown
GROHNDE		PWR	1360		Shutdown
GUNDREMMINGEN B		BWR	1284		Shutdown
GUNDREMMINGEN C		BWR	1288		Shutdown
ISAR-2		PWR	1410		Shutdown
NECKARWESTHEIM-2		PWR	1310		Shutdown
PHILIPPSBURG-2		PWR	1402		Shutdown
UNTERWESER		PWR	1345		Shutdown

TABLE II–1. THERMAL REACTOR (LWR) MOX ROUTINE LOADING EXPERIENCE (cont.)

Reactor name	Location	Type	Power (MW(e))	Maximum core loading	Status
FUKUSHIMA-I-2	Japan	BWR	760	15%	Shutdown
FUKUSHIMA-I-3		BWR	760		Shutdown
FUKUSHIMA-I-4		BWR	760		Shutdown
GENKAI-3		PWR	1127		Loaded
IKATA-2		PWR	538		Shutdown
IKATA-3		PWR	846		Loaded
TAKAHAMA-3		PWR	830		Loaded
BORSSELE	Netherlands	PWR	482	40%	Loaded
BEZNAU-1	Switzerland	PWR	365	40%	Loaded
BEZNAU-2			365		Loaded
GOESGEN			1010		Loaded

Note: For power data, see the IAEA Power Reactor Information System Database.

TABLE II–2. FAST REACTOR EXPERIENCE

Reactor name	Location	Classification	Power (MW(th) / MW(e))	Fuel properties		Operating years
				Form	Pu loaded	
EBR-I	United States of America	Experimental	1.2/0.2	Alloy	Core 4	1951–1963
BR5, BR10	Russian Federation	Experimental	5/0 8/0	Oxide/ Carbide	Yes	1959–1971 1973–2002
DFR (Dounreay FRs)	United Kingdom	Experimental	60/15	Alloy	No	1962–1977
FERMI-1	United States of America	Experimental	200/60	Alloy	No	1962–1972
EBR-II	United States of America	Experimental	62.5/20	Alloy	Limited trail	1963–1994
Rapsodie	France	Experimental	20–40/0	Oxide	Yes	1967–1983
BOR-60	Russian Federation	Experimental	55/-	Oxide	Yes	1968
PFR (Prototype FR Dounreay)	United Kingdom	Prototype	600/270	Oxide	Yes	1976–1994
KNK II	Germany	Experimental	58/21	Oxide	Only in test core	1979–1991

TABLE II–2. FAST REACTOR EXPERIENCE (cont.)

Reactor name	Location	Classification	Power (MW(th) / MW(e))	Fuel properties		Operating years
				Form	Pu loaded	
PHÉNIX	France	Prototype	565/255	Oxide	Yes	1973–2010
BN-350 (AKTAU)	Kazakhstan	Prototype	700/130	Oxide + expt MOX	No	1973–1999
Joyo	Japan	Experimental	140/0	Oxide	Yes	1977–present
BN-600	Russian Federation	Prototype	1470/600	Oxide	Limited trial	1980–present
FBTR	India	Experimental	40/15	Carbide	Yes	1985–present
SUPERPHÉNIX	France	Commercial sized	2990/1242	Oxide	Yes	1986–1998
MONJU	Japan	Prototype	714/280	Oxide	Yes	1994–2016
CEFR	China	Experimental	65/25	Oxide	No	2011–present
BN-800	Russian Federation	Commercial sized	2100/800	Oxide	Yes	2015–present

II–2.3. High temperature gas reactors

HTGR experience is provided in Table II–3. The fuel for HTGRs is composed of a complex structure comprised of a fuel kernel and one or two coatings, shown in Fig. II–1.

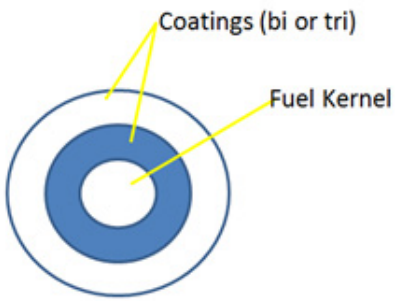

FIG. II–1. HTGR fuel composition (particle diameter typically ~0.9 mm).

TABLE II–3. HTGR EXPERIENCE

Reactor name	Location	Power (MW(th)/ MW(e))	Connected to the grid	Fuel properties				Operating years
				Type	Coating	Kernel	Enrichment	
Dragon	United Kingdom	20/-	No		TRISO[a]	Carbide	<20% ^{235}U >20% ^{235}U	1965–1975
Peach Bottom	United States of America	115/40	Yes	Fixed	BISO[b]	Carbide	>20% ^{235}U	1967–1974
AVR	Germany	46/15	Yes	Pebbles	TRISO[c]	Oxide	>20% ^{235}U	1968–1988
Fort St Vrain	United States of America	842/330	Yes	Fixed	TRISO	HEU carbide & thorium carbide	>90% ^{235}U	1979–1989
THTR	Germany	750/300	Yes	Pebbles	BISO	HEU oxide & thorium oxide or carbide	>90% ^{235}U	1985–1989
HTTR	Japan	30/-	No		TRISO	Oxide	<20% ^{235}U	1998–present
HTR-10	China	10/-	No		TRISO	Oxide	<20% ^{235}U	1998–present
HTR-PM	China							Under construction[d]
GTMHR	Russian Federation	-/600						Under development

[a] TRISO (tri-coated isotropic) fuel has three types of coatings around the internal fuel kernel, low density pyrolytic carbon, high density pyrolytical carbon and silicon carbide.

[b] BISO (bicoated isotropic) fuel has two types of coatings around the around the internal fuel kernel. Low density pyrolytic carbon and high density pyrolytic carbon.

[c] AVR (Arbeitsgemeinschaft Versuchsreaktor, Germany) tested a variety of pebbles from BISO HEU (highly enriched uranium) carbide, BISO thorium carbide to the final LEU (low enriched uranium) TRISO.

[d.] Functional testing of the HTR-PM began in October 2020.

Note: Experience quoted here relates to uranium and thorium fuels only; THTR = thorium high temperature reactor.

Annex III

TECHNICAL INFORMATION — RECYCLING OPTIONS

TABLE III–1. TECHNICAL INFORMATION ON RECYCLING OPTIONS FOR MOX IN LWRs

Option	Ultimate waste type	Pu loading	Technology readiness	Advantages	Risks/Uncertainties
MOX monorecycling in LWRs (3.1.1.1.)	Spent fuel	8–12 wt% total Pu(HM) per FA; PWR: up to 6 t(Pu) for a 1300 MW(e) NPP at 50% loading; BWR: Up to 9 t(Pu) for a 1150 MW(e) NPP at 50% loading.	Commercially available	Proven technology; 2700 tHM MOX produced by Melox plant at the end of 2018; Approximately 10% of natural U is saved by using MOX in the current French fuel cycle; ~30% of Pu is burned when irradiating MOX fuel.	
Multirecycling in LWRs (3.1.1.2.(a))	Vitrified waste	2–12 wt% total Pu (HM) per FA	Under development	MIX/CORAIL fuel technologies would allow to multirecycling Pu in LWR, with partial or 100% core loading. Technologies are burning Pu through irradiation. REMIX fuel enables multiple recycling of the entire quantity of U and Pu from spent nuclear fuel, with the 100% core charge and 25–30% saving of natural uranium in each cycle[2].	
		Up to 2%, depending on recycling option adapted	Under development; Pilot loading of 3 REMIX FAs in Balakovo-3 NPP, July 2016[1].		
Symbiotic LWR/FR MOX (3.1.1.2. (b))	Vitrified waste	Second cycle: up to 19.5–24.7 wt% per FA; Up to 3.6 t (Pu) for an 800 MW(e) FR at 100% loading.	French experience with Superphénix fast breeder reactor Russian experience with Russian Federation BN-800.	Target burnup for the second cycle likely to be 150 GWd/tHM; Reduces waste in back end by at least 75% and reduces DGR footprint required; Reprocessing when required minimizes rework to remove daughter products.	Cost associated with FR technology.

TABLE III–1. TECHNICAL INFORMATION ON RECYCLING OPTIONS FOR MOX IN LWRs (cont.)

Option	Ultimate waste type	Pu loading	Technology readiness	Advantages	Risks/Uncertainties
MOX in FR (3.1.2.)	Vitrified waste	Up to 19.5–24.7 wt% per FA; Up to 3.6 t (Pu) for an 800 MW(e) FR at 100% loading.		Increased use of Pu and U energy; Fuel burnups estimated to be 80–100 GWd/tHM; Significant waste reduction and potential to consume minor actinides; Not sensitive to isotopic composition of fuel.	Limited supply (both fuel manufacturing and reactor technology); Potentially more complex fuel route in comparison to UOX or LWR MOX.
MOX in HWR (3.1.3.)	Spent fuel	Up to 5 wt%; Up to 6 t (Pu) at 100% core loading.	Burnup demonstrated to 20 GWd/tHM in KAPS-1[3]	Storage duration reduced compared with standard MOX before it can be disposed of; Savings in natural uranium.	No industrial scale fuel manufacturing plant
Pu metal, Na cooled FR (3.2.1.(a))	Ceramic and metal wastes	15 wt%	Experience at EBR-II	Core safety — low reactivity maintained throughout cycle; Can be configured for actinide consumption / waste minimization; Near 100% fuel use; Can keep virtually all TRU in the reactor, only fission products in the waste stream.	Potentially more challenging fuel production due to inclusion of minor actinides with remote fabrication and need for atmospheric controls due to pyrophoric materials; Sodium coolant handling and destruction require specific safety considerations.

TABLE III–1. TECHNICAL INFORMATION ON RECYCLING OPTIONS FOR MOX IN LWRs (cont.)

Option	Ultimate waste type	Pu loading	Technology readiness	Advantages	Risks/Uncertainties
Nitride fuel, Pb cooled FR (3.2.1. (b))	100 litre canisters (<80/year produced by BREST-OD-300)	14 wt% in equilibrium active zones 20 wt% in non-equilibrium active zones	Experience of operating BREST-OD-300 in Russian Federation[4].	Inherently safe — low reactivity maintained throughout the cycle Better thermal conductivity as high density High power ratings Option for minor actinide consumption Complete reduction of Pu in the equilibrium core No requirement to separate U & Pu in reprocessing Fuel fabricated from depleted U	'First of a kind' technology Lower burnup than MOX (PCI limited) Greater coolant circuit erosion properties Decommissioning issue with lead disposal Fuel isotopic composition sensitive Further work required on reprocessing of nitride fuel (chemical behaviour)
Nitride fuel in Na cooled FR (3.2.1. (c))	As option B1.2	As option B1.2	FR proof of principle	As option B1.2	As option B1.2; Also, sodium coolant handling and destruction require specific safety considerations.

TABLE III–1. TECHNICAL INFORMATION ON RECYCLING OPTIONS FOR MOX IN LWRs (cont.)

Option	Ultimate waste type	Pu loading	Technology readiness	Advantages	Risks/Uncertainties
HTGR (3.2.3.)	Waste form to be defined (dependent upon fuel type); THTR & AVR fuel can be disposed of in CASTOR THTR/AVR cask; Prismatic fuel dismantling options likely to yield similar volumes to LWR for equivalent burnup; Undismantled pebble fuel disposal volume expected to be 10–30× that of LWR for equivalent burnup; Pebble fuel dismantling options likely to yield comparable volume to LWR for equivalent burnup but would be more complex than for prismatic fuel	0.5 g 239Pu per FA optimal (based on studies) 260 kg/year 239Pu required for a 200 MW reactor		Can withstand temperatures in excess of 2000°C without failure; Uses inert gas coolant; Target burnup 120 GWd/tHM; Could reduce waste in back end and repository footprint, but fuel type dependent; High Pu consumption, with up to 93% claimed.	New concept in terms of licensing; Fuel production more complex compared with UOX.
ThMOX monorecycling in LWRs (3.3.1.(a))	Spent fuel	Up to 20 wt% (fabricated & simulated); PWR: up to 10 t(Pu) for a 1300 MW(e) NPP at 50% core loading; BWR: up to 15 t(Pu) for a 1150 MW(e) NPP at 50% core loading.		Improved in-core safety performance compared with UOX & MOX; Does not produce any new Pu; Waste form has high leach resistance and is non-oxidizable.	Low price of uranium does not promote non-U based fuel development Produces fissile U-233 Potential for additional shielding requirements

TABLE III–1. TECHNICAL INFORMATION ON RECYCLING OPTIONS FOR MOX IN LWRs (cont.)

Option	Ultimate waste type	Pu loading	Technology readiness	Advantages	Risks/Uncertainties
ThMOX in HWR monorecycle (3.3.3.)	Spent fuel	Up to 5 wt% Up to 6 t(Pu) for 100% core loading		Storage duration reduced compared with MOX before it can be disposed of; Simpler manufacturing process compared with MOX; Savings in natural uranium Burnup up to 15 GWd/tHM.	No industrial scale fuel manufacturing plant; Potential for additional shielding requirements.

Note. FA = fuel assembly ; DGR = deep geological repository ; NPP = nuclear power plant ; PCI = pellet-cladding interaction.

[1] NUCLEAR ENGINEERING INTERNATIONAL, Russia loads REMIX fuel ready for pilot operation at Balakovo NPP, Nuclear Engineering International (5 July 2016), https://www.neimagazine.com/news/newsrussia-loads-remix-fuel-ready-for-pilot-operation-at-balakovo-npp-4941371.

[2] KOVALEV, N.V., GOLETSKY, N.D., ZILBERMAN, B.Ya., SINYUKHIN, A.B., A new approach to nuclear fuel recycling for LWR REMIX fuel concept: Status and trends, Management of Spent Fuel from Nuclear Power Reactors: Learning from the past, enabling the future (Proc. of an Int. Conf. held in Vienna, Austria, 24–28 June 2019) IAEA, Vienna (2020) Paper 55.

[3] SONI, R., PRASAD, P.N., VIJAYAKUMAR, S., CHHATRE, A.G., DWIVEDI, K.P., "Fuel Technology Evolution for Indian PHWRs," (Proc. 6th International Conference on WWER Fuel Performance, Modelling and Experimental Support, Albena, Bulgaria, 19–23 Sept. 2005) Bulgaria (2006), https://inis.iaea.org/collection/NCLCollectionStore/_Public/37/098/37098316.pdf.

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Annex IV

TECHNICAL INFORMATION — CONDITIONING OPTIONS

TABLE IV–1. CONDITIONING OPTIONS FOR PLUTONIUM

Option	Type/volume of final disposal package	Pu loading	Conditioned form durability	Technology readiness	Advantages	Risks/uncertainties
Sintered MOX pellets[1] (4.1.1.)	Similar to spent fuel	Expected to be at least 10 wt% PuO_2; Maximum uncertain due to long term stability considerations.	Good	Commercial	MOX fabrication is mature technology; Using Th may enhance durability/reduce leaching.	Maximum Pu loadings uncertain due to long term stability considerations; MOX requires reducing conditions in the repository.
Vitrification — borosilicate glass[2] (4.1.2.(a))	Unknown	Up to 10 wt%; Loading obtained in trials with LaBS glass[3].	Good	Early stage	Vitrification of HLW is a mature technology; Criticality precluded as leach rate of neutron absorbers congruent to Pu.	Special melter design required to prevent criticality; Premixing step required to ensure homogenization; Maximum Pu loadings uncertain due to long term stability considerations; Shielded containment required due to high radiation rates from α & n reactions in borosilicate glass; Industrial production using LaBS glass may be challenging due to high melt temperatures required (1500°C); Criticality control in short term from B, but leaching may require the addition of Hf for the long term[4].

TABLE IV–1. CONDITIONING OPTIONS FOR PLUTONIUM (cont.)

Option	Type/volume of final disposal package	Pu loading	Conditioned form durability	Technology readiness	Advantages	Risks/uncertainties
Vitrification — spiked HLW (4.1.2.(b))	Typical HLW canister	Up to 2 wt%	Good	Early stage	Vitrification of HLW is a mature technology.	Dependent upon sufficient HLW feed to accommodate Pu inventory; Pu density separation over time in melter will necessitate good mixing; Maximum Pu loadings uncertain due to long term stability considerations.
Ceramic — cold pressing & sintering (4.1.3.(a))	Unknown	Expected to be at least 10 wt% PuO_2; Maximum uncertain due to long term stability considerations.	Very good	Early stage	High waste loading; Criticality precluded as leach rate of neutron absorbers congruent to Pu.	Maximum Pu loadings uncertain due to long term stability considerations; For an industrial scale process, a homogenized well characterized feed is likely to be required[3].
Ceramic — high pressure process (4.1.3.(b))	Unknown	Expected to be at least 10 wt% PuO_2; Maximum uncertain due to long term stability considerations.	Very good	Early stage	High waste loading; Criticality precluded as leach rate of neutron absorbers congruent to Pu.	Maximum Pu loadings uncertain due to long term stability considerations; Need to make safety case for high pressure operations; For an industrial scale process, a homogenized well characterized feed is likely to be required[3].

TABLE IV–1. CONDITIONING OPTIONS FOR PLUTONIUM (cont.)

Option	Type/volume of final disposal package	Pu loading	Conditioned form durability	Technology readiness	Advantages	Risks/uncertainties
Ceramic in glass (4.1.3.(c))	Unknown	Expected to be at least 10 wt% PuO_2; Maximum uncertain due to long term stability considerations.	Very good	Early stage	High waste loading; Criticality precluded as leach rate of neutron absorbers congruent to Pu; Can accommodate impurities.	Maximum Pu loadings uncertain due to long term stability considerations; Need to make safety case for high pressure operations.
Mixing (4.1.4.)	200 L drum	Up to 10 wt% (for the inside container) 100–300 g PuO_2 per 200 L disposal package	Low (to be confirmed by future development work)	Early stage	Low infrastructure requirements; Simple process once repository is available.	Reliance on a repository whose safety case does not require an engineered waste form; Effectiveness of chosen additive is unknown; Presence of waste and moisture will present a safety challenge.

Note: LaBS = lanthanide borosilicate.

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LIST OF ABBREVIATIONS

BWR	boiling water reactor
CANDU	Canada deuterium–uranium
FR	fast reactor
HLW	high level waste
HTGR	high temperature gas reactor
HTR	high temperature reactor
HWR	heavy water reactor
LaBS	lanthanide borosilicate
LWR	light water reactor
MOX	mixed oxide fuel
MSR	molten salt reactor
PWR	pressurized water reactor
REMIX	regenerated mixture
ThMOX	thorium based mixed oxide
UOX	uranium oxide
WWER	water-water energetic reactor

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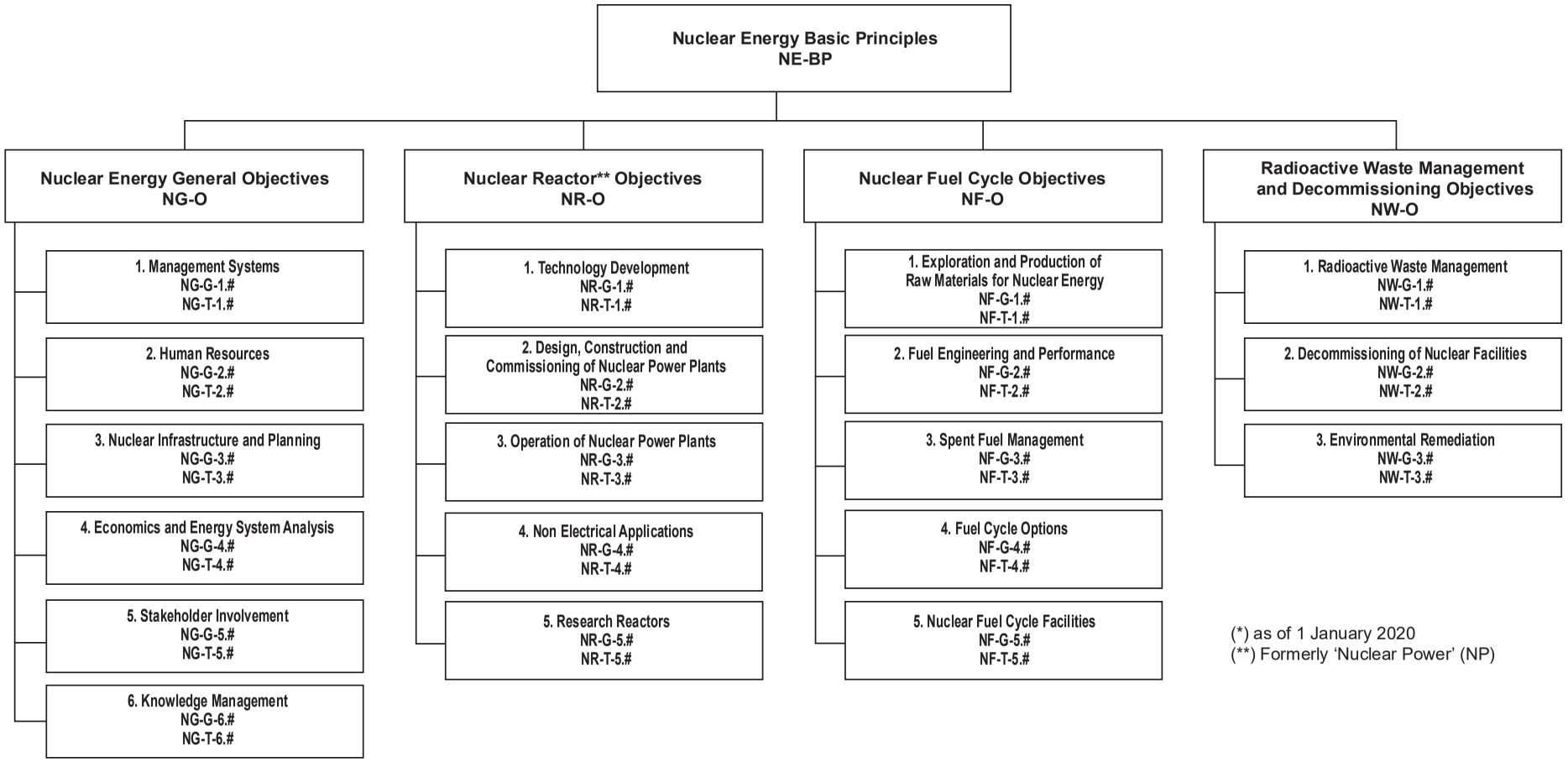

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