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Technical Features to Enhance Proliferation Resistance of Nuclear Energy Systems

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TECHNICAL FEATURES TO ENHANCE PROLIFERATION RESISTANCE OF NUCLEAR ENERGY SYSTEMS

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FOREWORD

It is generally accepted that proliferation resistance is an essential issue for the continued development and sustainability of nuclear energy. Several comprehensive assessment activities on the proliferation resistance of the nuclear fuel cycle have previously been completed, notably the International Nuclear Fuel Cycle Evaluation (INFCE) carried out under the auspices of the IAEA, and the Non-proliferation Alternative Systems Assessment Program (NASAP) review carried out by the USA. There have been, however, relatively few comprehensive treatments of the issue following these efforts in the 1970s. However, interest in and concern about this issue have increased recently, particularly because of greater interest in innovative nuclear fuel cycles and systems. In 2000, the IAEA initiated the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) and the US Department of Energy initiated the Generation IV International Forum (GIF). These projects are aimed at the selection and development of concepts of innovative nuclear energy systems and fuel cycles. Proliferation resistance is one of the fundamental considerations for both projects.

In this context, the IAEA in 2001 initiated a study entitled 'Technical Aspects of Increasing Proliferation Resistance of the Nuclear Fuel Cycle'. This task is not intended as an effort to assess the merits of a particular fuel cycle system for the future, but to describe a qualitative framework for an examination of the proliferation resistance provided by the intrinsic features of an innovative nuclear energy system and fuel cycle. This task also seeks to provide a high level survey of a variety of innovative nuclear energy systems and fuel cycles with respect to that framework.

The concept of proliferation resistance is considered in terms of intrinsic features and extrinsic measures. The intrinsic features, sometimes referred to as the physical/technical aspects, are those features that result from the technical design of innovative nuclear energy system and fuel cycles, including those that facilitate the implementation of extrinsic measures. The extrinsic measures, also referred to as institutional aspects, are those measures that result from the decisions and undertakings of States related to nuclear energy systems. This publication focuses on the intrinsic features of proliferation resistance. In addition to the examples included in the report, an accompanying CD-ROM contains more detailed examples.

The IAEA expressed its thanks to all those who contributed to this publication. The IAEA officers responsible for this publication were K. Kawabata, Y. Hosokawa, H. Chayama and S. Sakaguchi of the Division of Nuclear Fuel Cycle and Waste Technology.

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1. INTRODUCTION

1.1. BACKGROUND

Several projects or initiatives for future nuclear energy systems and fuel cycles, which started around 2000, have included proliferation resistance assessment as one of their targets. These are the Generation IV International Forum (GIF) and the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), and national programmes in France and the USA. These programmes consider proliferation resistance as one of the fundamental considerations and study its assessment methodology. Since each carries out their studies separately, several different definitions and assessment methodologies now exist in the world [1]. However, most assessment methodologies share common considerations, in particular the technical considerations that affect the proliferation resistance of an innovative nuclear energy system and fuel cycle.

A proliferation resistance and physical protection expert group (PRPP) was formed in December 2002 under GIF [2]. This includes Canada, the European Union (EU), France, the IAEA (observer), Japan, the Republic of Korea, the United Kingdom and the USA. INPRO, initiated in the year 2000, seeks to provide guidance on incorporating proliferation resistance into innovative nuclear energy systems. Argentina, Brazil, Canada, France, Germany, India, the Republic of Korea and the Russian Federation have actively participated [3–4]. A French working group on Proliferation Resistance and Physical Protection (PR&PP) was created in January 2003 [5]. This PRPP working group consists of the main French nuclear stakeholders, including both ministries and industry. A proliferation resistance assessment methodology study, part of the AFCI (advanced fuel cycle initiative) began in the USA in 1999 [6]. They developed their methodology in collaboration with universities and US national laboratories.

1.2. OBJECTIVE

The purpose of this report is to provide technical readers with a description of a qualitative framework for examination of the proliferation resistance provided by the intrinsic features of innovative nuclear energy systems and fuel cycles, and to provide a high level survey of a number of innovative nuclear energy systems and fuel cycles with respect to that framework.

These results are not intended to be used for comparison or selection of particular systems, but rather to describe their technical features with respect to proliferation resistance. For a detailed proliferation assessment of these systems, the methodology being developed for INPRO or GIF could be used.

1.3. STRUCTURE

This report is divided into four sections. Following this introduction, Section 2 looks at the technical features of the materials involved in the nuclear fuel cycle. Section 3 provides the positive and negative aspects of various nuclear energy systems and fuel cycles. Section 4 concludes this report.

1.4. DEFINITION OF PROLIFERATION RESISTANCE

The definition of proliferation resistance used in this report is "that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by States in order to acquire nuclear weapons or other nuclear explosive devices" [7]. This is consistent with the definitions used in INPRO, GIF PR&PP, and is commonly used in other work on proliferation resistance.

Thus, the term 'proliferation resistance' refers in some measure to the degree of difficulty (technical difficulty, time, resources, etc.) associated with the development and/or construction of nuclear weapons or other

nuclear explosive devices involving acivilian nuclear fuel cycle. This involvement can be materials, equipment, processes, facilities and expertise that are associated with the fuel cycle.

While many technical features of an innovative nuclear energy system and fuel cycle that provide it with proliferation resistance also provide resistance against theft of nuclear material, the focus of this report is proliferation by a State, involving the nuclear facilities owned and operated by the State.

1.5. REVIEW OF PAST WORK

Consideration of proliferation resistance began in the 1970s with the International Nuclear Fuel Cycle Examination (INFCE) [8] carried out by the IAEA, and the Non-proliferation Alternative Systems Assessment Program (NASAP) [9] carried out by the USA. Both NASAP and INFCE were more focused on identifying positive directions for fuel cycle development with regard to minimizing proliferation risks, than with developing comprehensive means for evaluating such risks. The conclusion of these studies was that no technology alone would provide sufficient proliferation resistance, but in combination with extrinsic measures may help to ensure that the use of the civilian nuclear fuel cycle remains an unattractive mean to acquire material for a nuclear weapons programme.

Studies of proliferation resistance have covered a wide scope including consideration of dedicated and civilian facilities, and assessments of individual facilities and entire fuel cycles. A comprehensive review of past work and examination of proliferation resistance assessment can be found in recent documents by Jones [10], Joint Research Centre of the European Commission (EC JRC) [11], and the National Nuclear Security Administration [12]. Jones concludes that there does not appear to be any consensus approach to assessing proliferation resistance. Rather, past assessments had many different analytical objectives, resulting in a focus on different factors contributing to proliferation and application of different analytical methods.

Past analytical assessments of proliferation resistance were based on either a decision or risk analysis approach. Work occurred in two main phases. Following INFCE and NASAP, a round of early assessment work was conducted from the late 1970s through the 1980s. The present focus on proliferation resistance assessment follows a resurgence of interest in the mid-1990s during the US National Academy of Sciences (NAS) plutonium disposition studies.

In the most significant early analysis, Papazoglou [13] applied multi-attribute utility (MAU) analysis to examine proliferation by States with different nuclear capabilities and objectives. Further, Heising [14], [15], Silvennoinen [16] and Ahmed [17] also applied MAU approaches to rank alternative proliferation pathways. A more recent application of MAU analysis to proliferation resistance has been performed by Krakowski [18], which attempts to include additional dynamic and geopolitical considerations in the assessment, and by Ko [19], which draws an analogy between proliferation resistance and electrical resistance to suggest a novel heuristic for quantifying the proliferation resistance of nuclear fuel cycles.

Another form of decision analysis based on the assessment of barriers to proliferation emerged in 1996 with the Proliferation Vulnerability Red Team [20]. A similar approach was taken by the US Department of Energy's, Nuclear Energy Research Advisory Council (NERAC) Task Force on Technological Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS). The TOPS task force formulated a set of qualitative attributes (barriers) relevant to proliferation resistance but did not attempt to perform quantitative or comparative assessment based on these attributes [21], [22]. Hassberger and Wilson suggest an approach to quantification of proliferation resistance based on these barriers [23], [24].

A similar approach called Simplified Approach for Proliferation Resistance Analysis of Nuclear Systems (SAPRA) has been developed in France in the framework of the French PRPP working group mentioned above [25].

Although early probabilistic assessments of diversion of nuclear material were published in the late 1980s, systematic evaluations of threats and vulnerabilities utilizing probabilistic methods remained in the background until the latter half of the 1990s and formal probabilistic risk analysis approaches were not proposed until the turn of the century. Golay [26] describes the use of success trees to combine different aspects of proliferation in a structured and logical manner. Although the values of many of the probabilities in the success tree may only be assigned subjectively, the structured framework facilitates consistent integrated assessment. Elaborating on Safeguards Logic Trees developed by J. Hill [27], EC JRC carried out an investigation of the potential of the Fault

Tree technique as a means for addressing the identification of all possible acquisition pathways in a given nuclear fuel cycle and their quantification in terms of non-detection probability [28]. Rochau [29], [30] describes a probabilistic risk analysis approach based on: threat, preventative barriers, assets, mitigating barriers, and consequences, called Risk Informed Proliferation Analysis (RIPA), which identifies the pathways with the least proliferation resistance.

Recently, the Advanced Fuel Cycle Initiative (AFCI) Blue Ribbon Panel examined the proliferation resistance of a number of different alternative fuels and fuel cycle options (PUREX/MOX, UREX, DUPIC, Inert Matrix Fuel) involving current LWRs [31]. The assessment relied on a MAU assessment methodology developed at Texas A&M University by W.S. Charlton [6].

In parallel with these activities, complementary efforts aimed at assessing the effectiveness of international safeguards have been developed. Proliferation resistance evaluation and safeguards performance/effectiveness assessment are two different aspects that are both relevant for non-proliferation. A number of review studies on safeguards performance assessment have been carried out but most remain at the level of internal reports. A review study on Safeguard Assessment Methodologies [32] was carried out recently at EC JRC.

In addition to work on assessment, there has been considerable work on other aspects of proliferation resistance and proliferation risk. Some work has concentrated on the existence and availability of 'direct use' material, which is nuclear material that can be used for the manufacture of nuclear explosive devices without transmutation or further enrichment [33]. Koch [34] suggests that the following criteria are acceptable to provide a sufficient level of proliferation resistance for the export of an innovative nuclear energy system and fuel cycle: (1) the absence of separated direct use material in the fuel cycle, and (2) the absence of processes capable of producing direct use material. Plutonium and high enriched uranium are the most frequently cited examples of such direct use material [35]. Reductions in the amount of plutonium produced could be achieved by replacing uranium based cycle with thorium based cycle has been suggested by proponents of such approaches [36], [37]. The proliferation risks associated with the ^{233}U produced in thorium cycles must also be accounted for [38]. In addition, there may be some future concern over minor actinides [39] that could be made into a nuclear explosive and that are not currently subject to IAEA safeguards.

While material diversion is the most often discussed proliferation concern, as has often been pointed out, the availability of technologies for either isotope separation or chemical reprocessing also raise major proliferation concerns [40].

Kiriyama [41] reviewed a number of 'proliferation resistant technology' projects funded by the United States Nuclear Energy Research Initiative (US NERI) programme to infer a set of proliferation criteria. It was concluded that the three principal ways to increase proliferation resistance were to: reduce plutonium inventories, reduce materials separation, and reduce the number of steps in the fuel cycle.

The US National Academy of Sciences Committee on International Security and Arms Control [42] and the Panel on Reactor-Related Options for the Disposition of Excess Weapons Plutonium [43] developed a set of attributes to evaluate the proliferation resistance of the material forms resulting from the disposition of excess weapons materials. Their work and that of the more recent Interim Report by the Panel to Review the Spent Fuel Standard for Disposition of Excess Weapons Plutonium [44] developed a number of attributes associated with the various materials found in the civilian fuel cycle.

At present, there is no consensus on the best way to evaluate the proliferation resistance of an innovative nuclear energy system and fuel cycle. Each of the approaches examined in the past has its advantages and disadvantages. Despite the differences between the broad bases of past work on proliferation resistance, close examination suggests that there is some agreement as to what is important in examining the proliferation resistance of an innovative nuclear energy system and fuel cycle. While expressed in different ways, most historical attempts to evaluate proliferation resistance rely on characterizing:

— *Technical difficulty*
  The inherent difficulty in physically executing the proliferation steps of material acquisition/production, processing, and fabrication, an expression of the technical sophistication involved. This may be affected by, inter alia, the level of radiation, the physical and chemical form of nuclear material, and the amount of material required.
— *Detectability*
  Material features that allow the use of different detection systems for safeguards purposes.

— *Fissile material quality*
The utility of the fissile material (isotopic content/composition) for use in the fabrication of a nuclear explosive device.
— *Resources*
A measure of the level of effort and cost associated with the proliferation act.
— *Time*
Some notion of the total project time from preparation to completion or material conversion time.

1.6. THREATS

Proliferation resistance in the context of proliferation threats, and the definition of proliferation resistance depends, in part, on the nature of the threat. The common proliferation threats of concern include: (1) the misuse of material through its diversion or theft; (2) misuse of facilities, equipment, and technology; and (3) transfer of nuclear skills and knowledge — enabling a potential proliferator to make nuclear weapons or other nuclear explosive devices. Threats may be either overt or covert. The threat may also be posed by potential proliferators that have a very high technical level of nuclear technology and those that do not.

Our primary emphasis is on the State as an actor. Many of the proliferation resistant features discussed here may also be effective against sub-national threats (such as terrorist organizations, including those with international ties). Threats posed by a State can be considered fundamentally different from threats posed by a sub-national group in several important ways[1]. State threats can be assumed to occur in cooperation with plant operators and security forces, whereas sub-national threats are assumed to occur without cooperation of plant operators and security forces. State proliferation goals are likely aimed at the acquisition of a credible military capability, whereas the goals of the sub-national group are likely limited to the acquisition of one or two crude nuclear explosive devices or use of nuclear material for other terrorist applications (the so-called ‘dirty bomb’, which could use any kind of radioactive material). A State can also be assumed to have a higher level of technical expertise and resources than a subnational group.

Hori [45] pointed out that the effectiveness of proliferation resistant technologies depends greatly on both when and where they are implemented. It is clear that proliferation resistant technologies will have little impact on nations that already possess enrichment and/or reprocessing technologies, but that they can have a very significant impact when implemented in countries without enrichment and reprocessing capabilities. He also pointed out that since the technological capabilities of all nations will continue to develop, their ability to overcome the barriers to proliferation will also increase and the effectiveness of any intrinsic feature as proliferation barrier is thus likely to decrease with time.

1.7. METHODOLOGY

This report does not attempt to develop a standard for proliferation resistance, but rather outlines a set of measures that may be used to help assess the impact the nuclear energy systems and fuel cycles might have on proliferation resistance. Proliferation resistance is a combination of intrinsic features and extrinsic measures, arranged to provide defence-in-depth against a broad range of proliferation-related threats. Implementation of technical options for increasing proliferation resistance can facilitate the implementation of extrinsic measures. Similarly, increments in overall proliferation resistance can also be accomplished by increments in the extrinsic measures. However, it is likely that no technical approach alone can remove the need for extrinsic measures. [3], [4], [7].

The goal of this report is to apply a TOPS[2] based analysis approach to assess qualitatively how technical concepts can influence proliferation resistance. It is not to evaluate the quantitative extent to which such concepts

[1] The distinctions described here are far from absolute, but serve to help define, in simple terms, the range of threats to be considered. Indeed, there may be considerable collusion between national and sub-national interests with regard to proliferation or terrorist threats.

[2] Technical Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power System, [21], [22].

increase proliferation resistance, nor is it to comparatively evaluate the various concepts against each other. In addition, this report does not attempt to determine what constitutes an **acceptable** level of proliferation resistance. Such a determination also requires careful consideration of the effectiveness of the extrinsic institutional measures, which is beyond the scope of this study. This analysis approach requires a set of attributes describing proliferation resistance sufficiently complete to evaluate qualitatively the impacts of technical concepts and options for increasing proliferation resistance. Table 1 illustrates proliferation barriers provided by the US TOPS effort [12].

As mentioned before, several definition and assessment methodologies in proliferation resistance now exist. Since the concept of 'increasing proliferation resistance' inherently involves comparison with some reference in order to determine if an increase potentially exists, and generally, proponents of particular technologies refer to the light water reactor (LWR) fuel cycle, we make comparisons between concepts for innovative nuclear energy systems and fuel cycles, and current LWR cycle in each proliferation resistance attribute. *It should be noted that any comparison we make here does not mean that some nuclear energy system and fuel cycle is superior or inferior to the reference LWR cycle in proliferation resistance aspect*. For instance, one nuclear energy system and fuel cycle might be superior in isotopic barrier but inferior in diversion detectability to the reference LWR cycle. We do not make a 'ranking' among attributes in overall proliferation resistance nor do we attempt to show how superior or inferior the attribute is. Thus we do not determine which nuclear energy system and fuel cycle is superior or inferior to the reference LWR cycle in proliferation resistance. How these factors in the attributes we indicate here determine its overall proliferation resistance is best left in the hands of the reader. One reader might assess a nuclear energy system and fuel cycle as superior to the reference LWR cycle in proliferation resistance aspect, even if only one attribute is superior and the others are inferior to the reference LWR cycle.

2. DEFINITION OF TECHNICAL ASPECTS

The civilian nuclear fuel cycle involves materials that could potentially be processed into weapons-usable material. All isotopes capable of being practically assembled into a critical mass are potentially weaponsusable and therefore of proliferation concern. It is important to note that the effort required to use any isotope depends on both the isotopic properties and the engineering and scientific skills of the potential proliferator. Another factor is the time needed to generate or separate a significant quantity of weapons usable material.

These materials exist in a variety of physical and chemical forms: they may be metals, gasses or liquids, compounds (e.g. an oxide), or mixtures. They may be in a form readily usable in nuclear explosive devices, or they may require complex chemical or isotopic separation processes to extract them for nuclear explosive devices. Table 2 summarizes some of the nuclear properties of fissile materials. For comparison, the table also includes the two major fertile materials, ^{232}Th and ^{238}U, which in the presence of neutrons can produce the fissionable isotopes ^{233}U and ^{239}Pu, respectively.

For the most part, the materials found in the civilian nuclear fuel cycle are not well suited for weapons purposes and therefore considered 'proliferation-resistant' to some degree. For example, low enriched uranium (LEU) fuel must be further enriched before it is weapons-usable and spent fuel must be reprocessed to extract weapons usable fissile materials. However, some aspects of the nuclear fuel cycle involve materials that either are weapons-usable or could be made weapons usable. HEU research reactor fuel[3] and separated plutonium from civilian spent fuel reprocessing are two examples.

As indicated in Table 2, a number of materials can physically be assembled into a fast critical mass, and are thus considered weapons-usable. Although Table 2 shows that ^{238}Pu is capable of sustaining a fast critical mass (and thus theoretically usable in a nuclear explosive device), on the advice of nuclear weapon States, the IAEA considers plutonium containing more than 80% ^{238}Pu not weapons-usable because of its high heat generation. The minor actinides, such as neptunium and americium, are also not currently included in the definition of 'special fissile

[3] HEU research reactor fuels can be of a special chemical composition (uranium-silicide compounds) making recovery/separation of HEU technically extremely difficult (example: FRM II Germany).

TABLE 1. PROLIFERATION BARRIERS AND EXAMPLE ATTRIBUTES [22]

Barrier type	Barrier	Attributes
Material barriers	Isotopic	Critical mass Degree of isotopic enrichment Rate of spontaneous neutron generation Rate of heat generation Difficulty presented by radiation to weapons design
	Chemical	Degree of difficulty in refining nuclear material to a form usable in a nuclear explosive
	Radiological (dose to humans)	Degree of remote handling normally required
	Mass and bulk	Concentration of material Ease of concealment
	Detectability	Degree of passive detection capability Active detection capability Hardness of radiation signature Uniqueness of material's signatures Uncertainties in detection equipment
Technical barriers	Facility unattractiveness (degree of difficulty of production of weapons material inherent in a facility)	Complexity of required modifications Cost of modifications Safety implications of modifications Time required to modify Facility throughput Effectiveness of observable environmental signatures
	Facility accessibility	Difficulty and time to perform operations Need for specialized equipment Manual versus automatic, remote operation Frequency of operational opportunity to divert
	Available mass	Amount of potentially weapons-usable material at a given point in a fuel cycle
	Diversion detectability	Type of material and processes with respect to accountability Uncertainties in detection equipment Form of material as amenable to counting
	Skills, expertise and knowledge	Dual-use skills and knowledge Applicability of dual-use skills Availability of dual-use information
	Time	Time materials in a facility or process are available to proliferator access
Extrinsic (institutional) barriers	Safeguards by IAEA	Availability and access to information Minimum detectability limits for material Ability to detect illicit activities Response time of detectors and monitors Precision and frequency of monitoring Degree of incorporation into process design and operation
	Access control and security[a]	Administrative steps for access Physical protection and security arrangements Existence of effective back-up support Effectiveness of access control and security
	Location	Remoteness and/or co-location of facilities

[a] Relative importance is low for diversion by a State.

TABLE 2. NUCLEAR PROPERTIES OF FISSILE AND FERTILE NUCLEAR MATERIALS [22], [46], [47][a]

Isotope	Half-life (a)	Neutron emissions (neutrons/sec-kg)	Decay heat (W/kg)	Critical mass[b] (kg)
^{231}Pa	32.8×10^3	Nil	1.3	162
^{232}Th	14.1×10^9	Nil	Nil	Infinite[c]
^{233}U	159×10^3	0.86*	0.281	16.4
^{235}U	700×10^6	0.364	6×10^{-5}	47.9
^{238}U	4.5×10^9	13.6*	8×10^{-6}	Infinite[c]
^{237}Np	2.1×10^6	0.139	0.021	59
^{238}Pu	88	2.67×10^6	560	10
^{239}Pu	24×10^3	21.8	2.0	10.2
^{240}Pu	6.54×10^3	1.03×10^6	7.0	36.8
^{241}Pu	14.7	49.3	3.41*	12.9
^{242}Pu	376×10^3	1.73×10^6	0.12	89
^{241}Am	433	1540**	115	57
^{243}Am	7.38×10^3	900	6.4	155
^{244}Cm	18.1	11×10^9	2.8×10^3	28
^{245}Cm	8.5×10^3	147×10^3	5.7	13
^{246}Cm	4.7×10^3	9×10^9	10	84
^{247}Bk	1.4×10^3	Nil	36	10
^{251}Cf	898	Nil	56	9

[a] Data in this table are mainly quoted from Ref. [22], data with * are quoted from Ref. [46]. There is some uncertainty with data of neutron emission rate of ^{241}Am (**). However, Ref. [22] says 1540 and Ref. [47] says 1180.

[b] Bare sphere.

[c] Not a potentially weapons usable material.

material' in the IAEA Statute: Article XX.1, although the Board of Governors of the IAEA has accepted that both are of concern.

The technologies, facilities and expertise inherent in the nuclear fuel cycle can also be used to support development of nuclear explosive devices. An enrichment facility might be used to produce weapons grade HEU directly, or its technology used to construct a dedicated, possible covert, enrichment facility for weapons material production. Several countries have pursued this HEU route for obtaining nuclear weapons. Similarly, civilian reprocessing plants or their technologies and designs could be used to obtain weapons-usable materials. Other countries pursued acquisition of weapons via the plutonium route, using the chemical processes and technologies essentially identical to those found in civilian reprocessing plants.

The technologies found in the nuclear fuel cycle can be used for proliferation purposes either directly (using a civil reprocessing plant to extract weapons-usable plutonium) or indirectly (using the expertise obtained from civilian enrichment activities to construct a covert enrichment plant for weapons use). While the most important associations between the technologies, facilities and expertise of the nuclear fuel cycle and the development of a nuclear explosive device are through the materials, other activities found in the civilian nuclear fuel cycle could contribute to the development of nuclear weapons or other nuclear explosive devices, such as neutron transport codes, criticality codes, and reactor design.

The existing civilian nuclear fuel cycle for power generation is not an ideal path for acquisition of nuclear explosive devices. It offers natural intrinsic features that impede the development of such nuclear explosive devices. For example, the LEU in the LWR fuel cycle is not directly usable in a weapon — it must be enriched much further. Similarly, most spent fuel from power reactors contains ^{240}Pu levels that make it less efficient for use in a nuclear explosive. The effectiveness of these intrinsic features depends on many features that must be considered and evaluated. Even with these intrinsic features, there is some risk that the civilian nuclear fuel cycle

can be used to further a potential proliferators goals. Thus, extrinsic (or institutional) measures are required to further reduce these risks.

Technologies may have higher proliferation resistance because of the effectiveness of either the intrinsic features or extrinsic measures. This report deals only with intrinsic features of different technologies. Extrinsic measures are considered only to help identify where technologies for increasing the intrinsic features might also impact the effectiveness of the extrinsic measures.

The point (in the fuel cycle) at which technical options for increasing the barriers to proliferation are introduced can impact the effectiveness of that option. For example, adding to the radiation barrier of spent fuel (which generally has a very high radiation barrier) will have little impact on proliferation resistance, whereas adding a radiation barrier to fresh MOX (as an example) could have a more significant impact on the proliferation resistance of the MOX.

The discussion of the various barriers to proliferation focuses on the qualitative assessment of proliferation resistance, and does not attempt to develop a quantitative scale, nor does it attempt to suggest that any barrier has some level of acceptability that must be achieved in order to ensure adequate proliferation resistance. For example, our definition of the isotopic barrier indicates that 50% enriched uranium has more proliferation-resistance than 90% enriched uranium. This does not imply that 50% enriched uranium somehow represents an acceptable proliferation risk, only that it is less risky than 90% enriched uranium. Similarly, the discussion below leads to the conclusion that plutonium recovered from 45 GW·d/t LEU spent fuel is more proliferation-resistant than that recovered from 33 GW·d/t LEU from the same reactor. This does not imply that the higher burnup plutonium cannot be used for nuclear weapons, only that it is less desirable in a nuclear weapon or nuclear explosive device.

Some parts of the following explanation of each barrier are referred to or cited from ‘TOPS’ [22].

2.1. MATERIAL BARRIERS

The civilian fuel cycle contains materials that could be used, with varying degrees of effort, in a nuclear explosive device. Thus, one role for technology is to reduce the utility (i.e. attractiveness) of the materials found in the nuclear fuel cycle for nuclear explosive devices. The material barriers are the inherent qualities of materials that affect how attractive a particular fissile material is for use in a nuclear explosive device.

The characteristics of the materials occurring in the nuclear fuel cycle can provide barriers to misuse. These barriers include the isotopic composition (isotopic barrier), chemical form (chemical barrier), radiation level (radiation barrier), volume and weight (bulk barrier), and material detectability (detectability barrier).

There are often many concepts that have been and can be proposed to increase the effectiveness of the various isotopic and technical barriers. Examples of some of these concepts are included in the discussion of each of the barriers below.

2.1.1. Isotopic barrier

Nuclear explosive devices can only be made with materials having appropriate nuclear properties. The isotopic barrier relates to how easily a particular fissile material can be used in a nuclear explosive device.

First, the material must be capable of sustaining a chain reaction on fast neutrons. Since one of the technical challenges in making a nuclear explosive device is to assemble the critical mass in the smallest possible time, the size of the critical mass is very important. In addition, a large critical mass leads to a large, heavy weapon, which becomes more difficult to handle and deliver. Thus, a material having an isotopic composition that leads to a large critical mass is somewhat more resistant to proliferation than one with a small critical mass[4].

Second, the heat released by the nuclear material can interfere with the design, manufacture and operation of the nuclear explosive device. Too much heat makes the materials and parts difficult to handle, damages the high

[4] Many point out that the size of the critical mass is much more important for a weapon than for a crude nuclear explosive device. While this may be correct, it does not change the fundamental point that in general (and all other things being equal) it will be easier to design and develop either a weapon or a crude nuclear explosive device from a material with a lower critical mass than from a material with a higher critical mass.

explosive components, and can even melt the nuclear material itself. Thus, materials that emit more heat offer a more effective isotopic barrier than those with lesser emissions.

Third, the radiation (especially gamma radiation) released by the nuclear material interferes with handling, processing, and design of a nuclear explosive device. A lower radiation level represents a lower barrier than a higher level.

Fourth, the spontaneous neutron emission rate of the material greatly affects nuclear explosive device design. HEU, with a very low neutron emission rate, can be made into a 'gun assembled' device, which is considered less technically challenging than the 'implosion' system required for a nuclear explosive device made from plutonium that has a higher neutron emission rate. Other things being equal, materials that can be used in a gun-assembled design can be considered less proliferation resistant than those requiring an implosion design. Besides necessitating the more complicated implosion design, excessive neutron emission can cause the nuclear explosive device to 'pre-initiate' rendering it almost useless. This is a particular issue when considering the proliferation resistance of plutonium, for the rate of spontaneous neutron emission increases significantly with increasing burnup of reactor fuel.

All these properties — heat, radiation and neutron emission — affect the level of technology required to develop a nuclear explosive device from a given material.

There are a number of ways that the isotopic barrier can be increased. For thermal reactors operating on LEU fuel, the material with the lowest isotopic barrier is generally considered the ^{239}Pu in the spent fuel. Increasing the burnup of these fuels degrades the isotopics of the plutonium. However, unlike the situation with uranium, which at low enrichments cannot sustain a fast chain reaction, all isotopic mixes of plutonium can sustain a fast chain reaction and therefore can be used in principle to make a nuclear explosive device. In practice, the neutron emissions, heat output and radiation emissions from even numbered isotopes can cause sufficient complications as to make the engineering of such a nuclear explosive device extremely difficult and perhaps a practical impossibility. Thus constructing an effective weapon using plutonium generated in thermal reactors is more difficult with increasing burnup. Although there is no well defined burnup threshold above which the plutonium becomes unusable and the working hypothesis is that all grades of plutonium are considered as posing a threat[5], there is clear benefit in degrading plutonium isotopics where possible.

Thus, any technology that increases burnup beyond current practice increases the isotopic barrier of the plutonium in spent fuel. This includes increased burnups by advancing current fuel technologies; the burnup increases potentially available through the denatured thorium cycle (thorium cycles can potentially achieve higher conversion ratios than the uranium cycle), and use of high temperature gas cooled reactors (HTGR) that appear more tolerant of higher burnup fuels. MOX (mixed oxide) recycle and 'reburning' spent fuel, such as proposed by the DUPIC (Direct use of Spent PWR Fuel in CANDU Reactor) process, also effectively increase the burnup of the plutonium coming from spent fuel, increasing its isotopic barrier. It should be noted that many of these approaches to increased burnup require increases in the enrichment of the initial uranium fuel charge, resulting in a decrease in the effectiveness of the isotopic barrier of the fresh fuel.

Greatly increasing the content of ^{238}Pu also degrades the attractiveness of plutonium. A possible way to do so may be adding minor actinides such as neptunium or americium into the LEU fresh fuel mix to increase the amount of ^{238}Pu in the spent fuel and thus increase the isotopic barrier of the spent fuel. However, since neptunium is usable in a nuclear explosive device, the benefits of enhanced ^{238}Pu in the spent fuel must be balanced against the addition of the separable neptunium in the fresh fuel.

2.1.2. Chemical barrier

The chemical barrier refers to the extent and difficulty of chemical processing required to separate the weapons usable material(s) from accompanying diluents and contaminants. Attributes of the chemical barrier generally relate to the degree of technical difficulty needed to refine materials into the appropriate form, be they metals or compounds. Other possible attributes include the existence of admixtures (such as those incorporated to frustrate chemical separation or denaturing), the number of separate processing steps needed to obtain materials of sufficient purity for weapons applications, and the general availability of the necessary processing techniques [22].

[5] A State may request that plutonium containing in excess of 80% of the isotope ^{238}Pu be exempted from IAEA safeguards.

The chemical barrier is frequently a major element of the overall proliferation resistance of materials having a low isotopic barrier, such as the plutonium in spent fuel or HEU in some research reactor fuels. A number of concepts offer promise of increasing the chemical barrier, particularly related to that of either LWR spent fuel or plutonium in separated or MOX forms.

The use of so-called inert matrix fuels (fuels using plutonium as the fissile material in a difficult to separate matrix, with no fertile material) is proposed as an alternative to the use of MOX fuel as a vehicle for plutonium recycle and for disposition of excess weapons plutonium. The plutonium is bound in a chemical form that is much more difficult to chemically separate than the plutonium oxide portion of the MOX fuel, thus providing an increased chemical barrier.

The coated particulate fuel used in various gas cooled reactor concepts is substantially more difficult to reprocess to recover plutonium (or ^{233}U in some concepts) than conventional LWR fuel using reprocessing technologies available today.

Advanced aqueous processing technologies are being developed that do not extract pure plutonium and this can increase the chemical barrier for diversion thus making the extraction of plutonium more difficult. Pyroprocessing uses materials difficult to handle that make diversion difficult, increasing the chemical barrier.

Some have suggested that chemical additives can be introduced that will interfere with subsequent chemical processing and thus increase the chemical barrier. Evaluation of the impact of such concepts requires careful analysis of the particular concept and potential separation technologies before such claims can be verified.

2.1.3. Radiation barrier

The radiation barrier affects both the ease of theft or diversion and can complicate chemical processing. One might select many attributes to describe the effectiveness of radiological barriers, among them, the specific dose rates (for example, at the surface of the material or container) or the time required to accumulate a significant dose (the mean lethal dose). Other possible attributes could categorize the materials by the degree of remote handling required: for example (in order of increasing severity), unlimited hands-on access, limited or occasionally hands-on, long handled tools and/or isolation and/or remote manipulation (such as in glove boxes), and fully remote and/or shielded facilities [22].

It is important to recognize that some materials have a high radiation barrier in their elemental form, while other materials have a radiation barrier only due to admixtures. For instance, the radiation barrier generally attributed to ^{233}U is primarily due to the decay of ^{232}U daughter products. While the ^{232}U itself can only be eliminated potentially by laser isotopic separation, its daughter products can be eliminated by subsequent chemical processing, providing a time window of one or two years during which the gamma activity is low. On the other hand, the radiation barrier associated with spent fuel can be substantially eliminated through chemical processing. Although important for materials such as ^{233}U, this does not constitute an additional barrier, but represents the interaction of the radiological barrier with the isotopic and/or chemical barriers [22].

There are ways to increase the radiation barrier of materials found in the nuclear fuel cycle. The benefits of the implementation of such suggestions depend partly on the effectiveness of the other barriers, particularly the isotopic and chemical barriers. , There is little incentive for increasing the radiation barrier of materials that already enjoy effective isotopic barrier.

Some of the concepts proposed for increasing the radiation barriers of materials include mixing fission products into otherwise attractive separated materials, such as either separated plutonium oxide or MOX fuel. Pyroprocessing technologies and some advanced aqueous processes proposed for advanced fuel cycles produce products that may have a more effective radiation barrier than that of current LWR-MOX products and fuels produced using PUREX technologies, although some consider the process to have reduced diversion detectability.

Increasing the burnup of conventional fuels also increases slightly the radiation barrier of the spent fuel. The ^{233}U produced in the various thorium cycles develops a higher radiation barrier than the plutonium produced in the normal LWR fuel cycles.

2.1.4. Mass and bulk barrier

If the material is dilute, then the total amount of material to obtain, transport, and process in order to have sufficient material for a weapon is large, and the mass barrier could be significant. Conversely, if the material is

concentrated, then less bulk is needed and the barrier is considerably lower. Other attributes besides the concentration of the material itself are important. Although fissile material is often in relatively concentrated forms, it is frequently incorporated into bulky items or configurations that are themselves not easy to obtain or transport (such as MOX fuel in a complete fuel assembly). The shear bulk and unwieldy character of the MOX fuel assembly acts as a barrier to theft or diversion. Another attribute of the mass and bulk barrier is the ease of concealing the material being diverted or stolen. Materials that are easily transported and concealed represent a more significant risk [22].

An example would be high temperature reactors that increase the mass and bulk barriers because these reactors use very dilute fuels.

Some technical options that increase the mass and bulk barrier do so as a side effect, as opposed to a primary effect. For example, approaches that increase the radiation barrier, especially those that provide enough radiation to meet the 'self-protection standard' effectively increase the mass and bulk barrier by requiring massive shielding.

2.1.5. Detectability barrier

Nuclear materials are inherently detectable, and this detectability facilitates proliferation resistance through various safeguards and security arrangements. The easier a material is to detect and identify, the more difficult it is to remove without detection, thus a greater level of proliferation resistance. For intrinsic detectability to be meaningful, it must be supported by a safeguards and security system (extrinsic measures) capable of detecting specific materials [22].

One concept that increases the detectability barrier is to add radionuclides to fresh fuels or to reprocessing products that increase the detectability of the materials. While similar to concepts for increasing the radiation barrier, this concept would selectively add radionuclides that would be easily detected, but not intrusively interfere with handling and other operations.

2.2. INTRINSIC TECHNICAL FEATURES

Technical barriers are the intrinsic technical elements of the fuel cycle, its facilities, processes, and equipment that serve to make it difficult to gain access to materials and/or to use or misuse facilities to obtain weapons-usable materials. Misuse of facilities includes the replication of facilities, processes, and technologies to support weapons development. Some of the intrinsic technical features include the attractiveness (utility for weapons use) of facilities, equipment, and processes for producing potentially weapons-usable material; the extent to which facilities and equipment inherently restrict access to fissile materials; the amount of attractive material potentially available; materials accountability; applicability of skills, expertise, and knowledge; and timing [22].

2.2.1. Facility attractiveness

The extent to which facilities, equipment, and processes are resistant to the production of weapons-usable materials is an important intrinsic feature. Those that cannot be modified to produce weapons material have a high barrier, and those that can directly produce weapons-usable materials have a negligible barrier to proliferation threats. A number of attributes can be used to describe the difficulty associated with obtaining weapons materials from facilities:

— The complexity of modifications needed to obtain potentially weapons-usable materials, including the need for specialized equipment, materials, and knowledge, and the general availability of such specialized skills, material, and knowledge;
— The cost of modifying a facility or process to obtain potentially weapons usable materials;
— The safety implications of such modifications;
— The time required performing such modifications;
— Facility throughput;
— Existence and effectiveness of 'observables' (e.g. environmental signatures that can be remotely sensed or observed) associated with facility modification and misuse [22].

With the large number of types of nuclear facilities and technologies, it is difficult to discuss a comprehensive list of examples. However, broad classes include enrichment, reprocessing, and remote handling fuel fabrication facilities.

2.2.2. Facility accessibility

The extent to which facilities and equipment inherently restrict access to fissile materials represents an important barrier independent from institutional barriers including security and access controls that limit access. For example, reactors with on-line refuelling (especially those involving manual fuel handling) are considered to have a lower proliferation barrier than those designed for operation without refuelling over the entire life of the reactor, or those designated for replacement of entire cores with no direct access to the fuel itself. Similarly, facilities with a high degree of remote, autonomous processes and operations generally present a higher barrier to proliferation than those with more hands-on operations [22].

Attributes that help describe the effectiveness of inherent accessibility barriers might include:

— The difficulty and time necessary to perform operations leading to access to materials, equipment and processes of concern (such as the time required to remove a reactor head for refuelling). Difficult and time consuming operations represent a higher barrier than quick and simple operations;
— The extent of manual vs. automatic, remote or autonomous operation, with remote, autonomous operations representing a higher barrier than manual operations; and
— The frequency of operations potentially supporting a proliferator's end (such as refuelling, which may provide access to fuel) with infrequent operations representing a higher barrier and frequent operations a lower barrier [22].

A number of concepts have been proposed to limit the access to fissile materials within facilities and processes. Several concepts for long life cores enabling reactors to operate for their entire lifetime without refuelling can significantly increase the accessibility barrier associated with fuel in the core, and potentially eliminates the need to store spent fuel on-site. Concepts such as the IFR (Integral Fast Reactor) and DOVITA (Dry reprocessing, Oxide fuel, Vibropac, Integral, Transmutation of Actinides), that recycle fuel without off-site transport of either spent fuel or fresh fuel potentially increase the accessibility barrier associated with transport operations[6].

2.2.3. Available mass

To construct a nuclear explosive device, proliferators must obtain a sufficient mass of an appropriate weapons-usable material[7]. If there is insufficient material available in a process or at a facility to represent an attractive target for diversion, theft, or other misuse, then material must be obtained from multiple sources, resulting in a larger barrier to proliferation than for cases where large amounts of materials are available. Material availability in general is affected by the physical characteristics of the process, technology, and facility, and by the security and safeguards measures implemented. These aspects of availability are discussed under the intrinsic facility features and the extrinsic institutional measures described later. The available mass barrier specifically treats the amount of material in existence at a point in the nuclear fuel cycle [22].

[6] It should be noted that transport offers the possibility of an efficient control of material being shipped while on site processing may make nuclear material more difficult to track. In addition, few large reprocessing centres may be assets to limit the diffusion of sensitive technology.

[7] Implosion designs require less material than the 'bare-sphere critical mass' noted in Table 2 since they compress the fissile material. A potential proliferator likely needs to obtain considerably more than the minimum mass required by design, however, to accommodate losses during processing, machining, and other operations during the weapon development and manufacturing process, particularly when considering the amount of material needed to produce the first nuclear explosive device.

The attribute associated with available mass is the amount of potentially weapons-usable material, expressed in terms of critical masses[8] (see Table 2). For the purposes of this barrier, the available mass must be considered the material potentially extractable from diluents or other materials present [22].

Concepts that reduce the attractiveness of fissile materials, especially those potentially usable in nuclear explosive devices, can serve to increase the available mass barrier. Many of the modular graphite moderated HTGRs have low inventories of fissile material. Other systems minimize the amount of fissile material that might be considered 'available' by reducing, for example, on-site material storage. Systems such as IFR and DOVITA maintain a minimum inventory of either spent or fresh fuel by use of continuous refuelling and on-site reprocessing, minimizing the need to store large amounts of either spent or fresh fuel. Spent fuel is stored only long enough to enter the processing system and fresh fuel is quickly reintroduced into the reactor, if the original concepts of them are implemented properly.

2.2.4. Diversion detectability

Diversion detectability is a measure of the extent to which diversion or theft of materials from processes and facilities can be detected. This concept differs from material detectability because diversion detectability accounts for the barriers that the various facilities, technologies, and processes themselves present to diversion and theft. Diversion detectability differs from safeguards in that it relates to those features intrinsic to a technology, process, or facility that make diversion (and/or theft) inherently detectable, whereas safeguards are extrinsic measures added institutionally to actually effect the detection of diversion. Facility detectability describes the extent to which undesirable modifications to the facilities can themselves be detected and is included in the definition of the attributes for facility unattractiveness [22].

Most processes and operations incur uncertainties in materials accountability and process control, and these uncertainties can mask the diversion or theft of material. The amount of material that could be accepted as 'unaccounted for' because of these uncertainties increases with the throughput. As for the accountability systems for process materials, it should be noted that highly precise material accountability is only possible with relatively pure material where spurious radiation signatures are small. Processes with high uncertainties represent a lower barrier to proliferation than those with low uncertainties [22].

Attributes that characterize the facility detectability barrier include:

— The type of material and processes involved and the extent to which the process supports accurate materials accountability;
— Uncertainties in detection equipment, including screening for dummy items; and
— The form of the material is amenable to item counting [22].

2.2.5. Skills, expertise, and knowledge

Most nuclear fuel cycle facilities, operations, and processes involve skills, expertise, and knowledge that may be applied to support a weapons development programme, although not equally in different parts of the fuel cycle. Some attributes that might apply to determining the extent to which such information could support a weapons development programme might be:

— The level of specialized skills and knowledge necessary to support specific elements of the fuel cycle (the availability of 'dual use' skills — skills that can serve both peaceful and weapons programmes). In general, the absence of specialized skills presents a higher barrier than the requirement for such skills;
— The extent to which such information is directly applicable to weapons development and the applicability of dual use skills. Systems and process requiring skills with little or no applicability to weapons development present a higher barrier than otherwise; and

[8] For safeguards purposes, the IAEA uses the term 'significant quantity' to characterize the amount of material representing particular proliferation concerns. However, since the definition of significant quantity does not capture some of the potentially important differences in the critical masses of various fissionable materials, we recommend that critical mass be used as one of the measures to characterize the available mass barrier.

— The extent to which such information is generally available (alternate sources of skills). The time required to achieve some level of expertise from available sources may be part of this attribute [22].

2.2.6. Time

The time that materials (and to some extent facilities and technologies) are available to potential proliferators is an important element in determining the overall effectiveness of the barriers to proliferation. To a first approximation, the storage of materials and equipment represents the greatest time-related proliferation threat. In general, long storage times for materials and equipment provide potential proliferators with plenty of opportunities for access (and thus a very small proliferation barrier), while materials with a very short or no storage represent less of a proliferation risk and therefore a higher barrier to proliferation [22]. Time can also impact the effectiveness of other barriers. As an example, the radiation barrier associated with spent fuel decays with time.

2.3. IMPACT ON EXTRINSIC/INSTITUTIONAL MEASURES

Technology may impact institutional barriers that provide proliferation resistance; in particular, technology can improve the effectiveness and efficiency of safeguards e.g. by enhancing material control and accountability. While extrinsic measures are the essence of the diplomatic and legal dimensions of the international non-proliferation regime and are thus critical to the success of preventing further proliferation, this report does not consider the institutional mechanisms for improving safeguards or other extrinsic measures against proliferation.

Technical options for enhancing intrinsic features can impact extrinsic measures both positively and negatively. For example, adding fission products to fresh fuel can add a radiation barrier and increase the detectability of such fuels. However, the fission products can adversely impact safeguards and increase the normal radiation hazards associated with that material as well as its potential use by terrorists in radiological dispersal devices.

Technological options for increased proliferation resistance need to accomplish their intended aims while having minimal adverse impact on other security interests (like sabotage or theft), as well as safety and economic interests.

Safeguardability is the degree of ease with which a nuclear system can be effectively and efficiently put under international safeguards. Safeguardability is a property of the whole nuclear system and is dependent on the characteristics of the nuclear material, process implementation and facility design. It relies basically on intrinsic characteristics of the nuclear energy system, and is independent of the implemented extrinsic/institutional characteristics. Safeguardability provides insight into whether a nuclear system contains intrinsic features that are likely to support the implementation of safeguards.

A preliminary list of characteristics related to safeguardability is contained in Table 3, together with a preliminary definition for each identified characteristic. In assessing the impact of the intrinsic features of a nuclear system on the extrinsic/institutional characteristics, it is necessary to examine the impact of all of the intrinsic features listed in Table 3 on the following high level features that are important for the implementation of international safeguards;

— Detectability of nuclear material;
— Accountability of nuclear material;
— Traceability of nuclear material;
— Difficulty to modify/misuse the process;
— Difficulty to modify the facility design.

It is important to recognize that some of the characteristics can support some aspects of safeguards and hinder others. For example, processes conducted within shielded facilities may be very amenable to containment/surveillance (C/S) measures because the shielding provides a natural containment boundary, but may impede verification of the material because it is inaccessible. Similarly, hard radiation signatures may facilitate detection of undeclared material removal, but may impede detection of radiation signatures that are unique to the nuclear material.

TABLE 3. NUCLEAR SYSTEM CHARACTERISTICS AFFECTING SAFEGUARDABILITY [48]

Characteristic	Definition
Uniqueness of material signature	The intrinsic material characteristics that contribute to the ease of identifying/recognizing the nuclear material type and composition.
Hardness of radiation signature	An intrinsic material characteristic that contributes to the difficulty of concealing a nuclear material radiation signature for identification purposes.
Possibility of applying passive measurement methods	The intrinsic material characteristics that facilitate characterization of the nuclear material using passive measurement methods instead of requiring active measurement methods.
Radiation field	Radiological hazard that impacts accessibility to areas where nuclear material is stored.
Item/Bulk	Whether the nuclear material is stored/handled/processed in item or in bulk form. This affects the accuracy of nuclear material accounting.
Uncertainties of detection equipment	The intrinsic features that contribute to uncertainties in detection equipment.
Throughput inventory	The amount of nuclear material produced by the process in a given period of time. This affects the absolute uncertainty of the material accountancy.
Extent of automation	The extent to which procedures are carried out without the need of human intervention. This may affect transparency and convertibility of the process.
Availability of data	Availability of sufficient information to trace nuclear material in the process.
'Authentication' of data	The extent to which the authenticity of information provided about the process can be verified.
Operational practice	The procedures to be followed during the functioning of the nuclear energy system. This may affect traceability, accessibility etc.
Batch/continuous/ process	Whether the foreseen process will be carried out in a batch or in a continuous manner. This affects traceability of nuclear material and measurement accuracy.
Applicability of C/S measures	The intrinsic features that contribute to the ease of implementing effective C/S techniques.
Transparency of facility design	The intrinsic feature that contributes to the ease of detecting design modifications and traceability of materials etc.
Un-convertibility of the process	The intrinsic features that contribute to the difficulty of converting the process for use in a nuclear weapons programme. e.g. to separate plutonium.

3. ASSESSMENT ON NUCLEAR ENERGY SYSTEMS AND FUEL CYCLES

Many technical alternatives for future reactor, fuel cycle and supporting technologies have been offered which may increase the proliferation resistance of current and future nuclear energy systems and fuel cycles. This section briefly describes some of those technologies and identifies which barriers the technologies increase (thus increasing proliferation resistance) and which barriers they may degrade (potentially reducing proliferation resistance).

Since the framework for evaluation is qualitative, a comparative assessment among the various nuclear energy systems and fuel cycles discussed is not performed. Additionally indications that any nuclear energy system and fuel cycle in fact increases (or degrades) proliferation resistance are not done. Only the possible impacts and the tradeoffs (if any) that should be carefully evaluated in deciding what technologies merit further consideration are identified.

The concept of increasing proliferation resistance, however, inherently involves comparison with some reference in order to evaluate the effect of the changes. Generally, proponents of particular technologies refer to the light water reactor (LWR) fuel cycle, and this is also done here. For nuclear energy systems and fuel cycles not involving recycle, the once-through LWR fuel cycle (LWR–OT) will be used for comparison; for those featuring recycle, the LWR fuel cycle using PUREX reprocessing and recycle in LWRs with MOX fuel (LWR-MOX) will be referred.

A large number of innovative nuclear energy systems and fuel cycles have been proposed in the world. These proposals include different combinations of fuel cycles (e.g. once-through, closed cycle, thorium cycle), reactor types (e.g. sodium cooled fast reactor, advanced heavy water reactor, high pressure water reactor, high temperature gas cooled reactor, lead fast reactor, molten salt reactor, accelerator driven system, small reactor with extended life core), fuel types (liquid, metal, oxide, nitride, carbide, ceramics), reprocessing types (e.g. aqueous processing, dry processing), fabrication types (e.g. powder–pellet process, sol–gel process), location of the facilities (e.g. on-site fabrication and reprocessing, no on-site refuelling) and so on. Since it is impossible to discuss all of these proposals here, some innovative nuclear energy systems and cycles have been selected for the discussion that follows.

If some proposals have similar intrinsic features in proliferation resistance, one of them is selected as a representative for purposes of discussion. For example, whereas there are many proposals on innovative nuclear energy systems and cycles with small reactors with extended life core, they have similar intrinsic features in proliferation resistance if they do not plan to refuel it on-site. In order to make an assessment of an innovative nuclear energy system and cycle on intrinsic features in proliferation resistance, the proposal should include a specific plan on all fuel cycle aspects. Otherwise, it cannot be discussed at the same level with other proposals. Proposals that are only ‘desk plans’ are not discussed. If the proposal is receiving strong national commitments, it is more likely to be discussed. Only ‘innovative’ nuclear energy systems and cycles are discussed. Nuclear energy systems and cycles that will be commercially deployed in the near future and do not have ‘innovative’ features are out of the scope of this study.

Based on the above considerations, the following nuclear energy systems and cycles were selected for our discussion:

— Synergistic fuel cycles utilizing PHWRs and LWRs;
— DUPIC nuclear energy systems and fuel cycles;
— Fast reactor nuclear energy systems and fuel cycles with pyrometallurgical reprocessing (IFR, DOVITA);
— Thorium nuclear energy systems and fuel cycles (Radkowsky, ‘denatured’);
— Sodium cooled fast breeder reactor system with advanced aqueous reprocessing;
— Nuclear energy systems and fuel cycles with small reactors with extended life core;
— Nuclear energy systems and fuel cycles with International Reactor Innovative and Secure (IRIS);
— Nuclear energy systems and fuel cycles with HTGR/PBMR reactors (both U and Th cycles);
— Molten-salt reactor systems and fuel cycles;
— Accelerator driven systems;
— Nuclear energy systems and fuel cycles with other fuels.

The following sections of this report briefly describe these nuclear energy systems and fuel cycles and some of the implications these nuclear energy systems and fuel cycles might have on proliferation resistance. In some cases, proliferation resistance advantages result from limitations of current technologies. For example, carbide fuels are currently considered more proliferation resistant than oxide fuels because they are more difficult to reprocess using today’s reprocessing technologies. Future technologies will likely be developed that can overcome the limitations of today’s technologies are recognized. Thus, this and any other discussions of proliferation resistance must be viewed as snapshots in time, taken from the perspective of the moment and subject to change as future technologies evolve.

3.1. REFERENCE NUCLEAR ENERGY SYSTEMS AND FUEL CYCLES

3.1.1. Light water reactor, once-through system

Since the LWR–OT system represents the most prevalent system in use today, it is selected as the reference for assessing potential changes in proliferation resistance brought by other once-through nuclear systems. The LWR–OT system uses water cooled reactors operating with low enriched uranium fuel. Refuelling occurs in batches, with a portion (usually 1/3 of the core) replaced every year to year-and-a-half. Current systems achieve burnups on the order of 33–45 GW·d/t, producing approximately 10–12 kg plutonium/tonne spent fuel. At this burnup, the plutonium contains on the order of 60–65% fissile isotopics. In the once-through fuel cycle, spent fuel is neither reprocessed nor recycled, but is placed in interim storage awaiting ultimate disposition, usually planned as a geologic repository. There are currently no such repositories in operation.

Proliferation resistant features of the LWR fuel cycle focus on the facts that no separated weapons-usable materials exist in the system, and that the potentially weapons-usable plutonium in the spent fuel is protected by the radiation of the spent fuel. The reactors themselves are poorly suited for production of low burnup, weapons grade plutonium. Fuel assemblies are large and item accountable. However, the necessity for enrichment represents a proliferation risk. Significant global expansion of enrichment facilities could represent an increased proliferation risk in the future. However, this risk could be reduced through international arrangements that are under consideration today.

3.1.2. Light water reactor with MOX recycle

The use of mixed oxide (uranium oxide + plutonium oxide) in LWRs is the only fuel cycle in broad use that recycles the fissile materials remaining in spent fuel. The LWR–MOX system is very similar to the LWR–OT system with the exception that part of the fuel is made from plutonium recovered from spent uranium fuel. The reactors are the same as used in the LWR–OT system, and the front end of the fuel cycle is essentially the same, with the exception that fuel uses recycled plutonium in place of enriched uranium as the fissile material in at least part of the fresh fuel. The recycled plutonium is recovered by reprocessing spent uranium fuel, the same type of fuel discharged in the LWR–OT system. Current civilian reprocessing uses the aqueous (PUREX) process that produces a very pure plutonium product. While some reactors can be fuelled completely with MOX, most reactors are fuelled with a mix of MOX (1/3) and normal uranium (2/3) fuel. Although spent MOX fuel can be, and has been reprocessed, the reprocessing of spent MOX fuel is economically less attractive than that of spent uranium (LWR–OT) fuel, and spent MOX is currently stored similarly to the storage of LWR–OT spent fuel.

Proliferation resistant features of the LWR–MOX system are similar to the LWR–OT system with a few notable exceptions. The recycling of plutonium (as currently practiced) involves the complete separation of plutonium, a potentially weapons usable material. In addition, the use of MOX involves considerable transport of the plutonium-containing MOX, and the plutonium in fresh MOX fuel can be separated for potential weapons use. These are considered significant proliferation risks compared to the LWR–OT system, and these additional steps are carried out under strict safeguards and security arrangements. Once the MOX fuel has been irradiated in the reactor, the spent fuel is similar to spent uranium fuel, but has a slightly increased isotopic barrier because of the additional burnup.

However, the recycle of plutonium as MOX fuel has advantages from a long term proliferation perspective. In particular, the recycle of plutonium reduces the continuing accumulation of plutonium in spent fuel that occurs in the LWR–OT system. Additionally, use of recycled plutonium also reduces — but does not eliminate — the requirement for enrichment. The additional irradiation received by the plutonium in MOX also degrades the isotopics of the plutonium in spent MOX fuel as compared to that of ‘normal’ LWR–OT spent fuel.

To date, there is no generally accepted methodology to assess the relative proliferation risks versus benefits of the LWR–MOX and LWR–OT systems. Both are considered acceptably proliferation resistant as currently implemented under appropriate safeguards.

3.2. ANALYSED NUCLEAR ENERGY SYSTEMS AND FUEL CYCLES

3.2.1. Synergistic fuel cycles utilizing PHWRs and LWRs

The PHWR's high neutron economy, fuel channel design, online refuelling capability, and small, simple fuel bundle make it ideally suited to exploiting the energy content of recycled, spent LWR fuel utilizing fuel cycles that provide enhanced proliferation resistance. The high neutron economy of a PHWR allows the use of fuels that are inherently less reactive, such as natural uranium or fuels with large neutron poison loading. It also permits extending the burnup of moderately reactive fuels to maximize any gains from producing fissile material, or from burning off neutron poisons. The fuel channel design of a PHWR provides separation of the moderator from the coolant and some degree of neutronic decoupling between the reactivity control devices (in the low pressure moderator region) and the fuel. This decoupling helps to preserve the worth of the reactivity devices in the presence of plutonium bearing fuels, and eliminates the class of accidents that is associated with rapid ejection of control rods.

On-power refuelling provides flexibility in fuel management, including the ability to shape the axial and radial power distributions in the core. A simple, bi-directional refuelling scheme results in similar axial power profiles for a wide range of enriched fuels, with the power peaking at the inlet end of the channel (where fuel burnup is low), and decreasing towards the outlet end. On-power refuelling allows reactivity control to be achieved for a wide variety of fuels, simply by varying the number of bundles that are added during refuelling. The small, simple CANDU fuel bundle (just one-half metre long and ten centimetres in diameter) greatly simplifies and reduces the cost of fabricating and handling active fuels, such as those made from recycled material.

CANDU PHWRs typically use natural uranium as fresh fuel and burn the fissile content down to 0.2% ^{235}U and 0.25% Pu. A LWR uses uranium oxide fuel with a starting enrichment of 3.5% to 4.5% ^{235}U; the residual fissile component in the spent LWR fuel is typically 0.9% ^{235}U and 0.6–0.65% fissile Pu. This residual fissile content is higher than natural uranium.

Many closed fuel cycles generate a stockpile of recovered uranium that must be re-enriched before it can be used as new fuel. Recovered uranium (RU) is an excellent source of fuel for a PHWR, providing about twice as high a burnup as natural uranium fuel. Fuel cycles in which the RU is used to fuel a PHWR provide more energy per SWU of enrichment. This provides proliferation resistance for the overall fuel cycle by reducing the demand for enrichment facilities.

High thermal neutron flux provides a CANDU PHWR with a capability for actinide destruction. Mixtures of plutonium and actinide wastes in an inert matrix can be used to fuel a PHWR. Work to date indicates that such fuel could destroy about 65% of the Pu (including 97% of the ^{239}Pu) and 38% of the minor actinides. Inert matrix fuel is discussed further in Section 3.2.11.3 of this report. The use of inert matrix fuel containing plutonium and actinide wastes provides proliferation resistance in several ways: it provides the highest possible rate of plutonium destruction by consuming plutonium without generating any additional plutonium or other fissile material; the inert matrix is designed such that the plutonium is more difficult to extract; and the plutonium remains mixed with minor actinides.

A key benefit of fuel cycles involving PHWRs and LWRs is that Pu does not need to be separated from other transuranics and fission products. The resultant fuel has both a high fissile content and a high fission product poison content. Examples of fuel cycles involving such technology are DUPIC, fluoride volatility, and UREX+. These fuel cycles produce highly radioactive new PHWR fuel from spent LWR fuel. The new PHWR fuel typically provides several times as much burnup as conventional natural uranium fuel. These fuel cycles achieve enhanced proliferation resistance in a number of ways. (1) The fuel cycle facilities can be designed so that separation of the plutonium is difficult if not impossible. (2) The fuel itself is highly radioactive and extraction of the plutonium from the recycled fuel would be similar in terms of technical difficulty and proliferation cost to separation of the plutonium from spent fuel. (3) The isotopic composition of the plutonium is degraded through additional burning in the PHWR, and (4) because these fuel cycles provide additional energy from a given initial fuel mass, the overall amount of spent fuel per MW(e)-h generated is reduced. (5) In addition, intrinsic design features required to handle the high radiation fields enhance the safeguardability of the fuel cycle; for example, shielded facilities limit access to the nuclear material whilst providing structural features that can be used for strong containment and surveillance measures, and the fresh fuel has a hard radiation signature that facilitates safeguards monitoring.

3.2.2. DUPIC nuclear energy systems and fuel cycles

Development of the DUPIC (Direct Use of spent PWR fuel in CANDU reactor) process is a joint project involving Canada, the Republic of Korea, the USA and the IAEA. DUPIC is a dry process that converts spent LWR fuel into 'fresh' fuel for a CANDU reactor. The LWR spent fuel is fabricated into CANDU fuel assemblies without chemical separation of plutonium, thus avoiding the possibility for separation of potentially weapons usable materials and maintaining the bulk of the radiation barrier inherent in spent fuel. CANDU fuel is either natural or very light enriched uranium, and is subject to quite low burnup. There is little plutonium in a single spent CANDU fuel element, but that plutonium has a slightly higher ^{239}Pu content than spent fuel from the LWR–OT fuel system, with about 67% ^{239}Pu. The CANDU reactors themselves operate differently from LWR systems. The reactors are refuelled on-line, with the reactors operating, as opposed to the off-line, batch refuelling used in the LWR systems.

The DUPIC system offers three increases in proliferation resistance relative to the existing LWR fuel cycle, and one relative to the normal CANDU fuel cycle.

First, it obtains additional energy from a given initial fuel mass, effectively reducing the overall amount of spent fuel per MW(e)-h generation relative to the LWR–OT system. Second, the higher burnup reached in the spent fuel degrades the isotopics of the plutonium in the spent fuel (again, relative to the LWR–OT system)[9]. Third, in avoiding the separation of plutonium, it inhibits access to potentially weapons usable materials relative to that of the LWR-MOX fuel cycle. Spent fuel from the DUPIC system, with its higher overall burnup, also has degraded isotopics as compared with normal CANDU spent fuel, and thus a higher barrier to proliferation.

Compared to the LWR spent fuel from which the DUPIC fuel is fabricated, the radiation barrier in the DUPIC fuel is reduced with the release of the gaseous fission products. However it is still strong enough to satisfy the spent fuel standard for proliferation resistance as DUPIC was designed to remove a minimum of fission products and the reduction in radiation due to fission product release is probably less than that of any other fuel recycle process. In addition, the CANDU fuel elements are smaller than LWR spent fuel assemblies, and thus have a less effective mass and bulk barrier than the LWR spent fuel. However, since the diversion of a full fuel assembly is easily detectable and the protracted diversion of material in the bulk accounting facility seems to be more likely, the development of a precise material accounting method is recommended. Although the spent fuel arising from the DUPIC system has plutonium of degraded isotopics, there is more plutonium in the spent fuel than that arising from the LWR–OT fuel cycle. On the other hand, relative to the LWR-MOX fuel cycle, the plutonium content is similar.

3.2.3. Fast reactor nuclear energy systems and fuel cycles with pyrometallurgical reprocessing

The two fast reactor fuel cycle variants considered here both involve recycling of spent fuel, but differ from the LWR-MOX fuel cycle in important ways. The fast reactor uses more concentrated cores, requiring either HEU or plutonium in its initial fuel load. The fast reactor converts the ^{238}U in the fuel or blanket to plutonium that is recovered and used to refuel the reactor.

Two main variants of fast reactor fuel cycles featuring pyroprocessing have been widely discussed. These are the IFR system from the USA and the DOVITA cycle from the Russian Federation. The IFR fuel cycle uses a metal fuel, the DOVITA fuel cycle features vibro-packed oxide fuel. Both systems use closely integrated on-site reprocessing and fuel fabrication facilities. Their pyrometallurgical reprocessing avoids separation of plutonium and complete decontamination from fission products, in particular the short half-life highly active fission products. The IFR uses an off-line batch refuelling system, while the DOVITA uses an on-line continuous refuelling scheme.

Compared with the LWR–OT fuel cycle, the IFR/DOVITA fuel cycles significantly reduce the amounts of plutonium requiring eventual disposition. Compared with the LWR-MOX fuel cycle, the IFR/DOVITA fuel cycles eliminate complete separation of potentially weapons-usable materials and avoid off-site shipment of such materials. In addition, due to the ability to reprocess after a short cooling time, the out-of-reactor inventory is small. These fuel cycles can also be used to reduce existing stocks of plutonium and (depending on the specific reactor design) may be capable of doing so more efficiently than many nuclear energy systems and fuel cycles.

[9] It should be pointed out that the first two of these increments in proliferation resistance are shared by the LWR-MOX fuel cycle.

Potential proliferation disadvantages relative to the LWR–OT fuel cycle occur because the IFR/DOVITA cycles incorporate a level of reprocessing that removes some of the radiation barrier from spent fuel. This may aid in the spread of reprocessing technology that, while not easily capable of providing well-separated potentially weapons-usable materials, can serve as a preliminary process in the separation of such materials. In addition, fast reactors can produce more fissile material than they consume, resulting in less proliferation resistance. One way to overcome this is to denature the fuel with fission products or minor actinides.

Fast reactor systems, since they can burn most actinides, including those that do not burn effectively in thermal systems, generally produce wastes having lower actinide content[10], and reduce the total amount of actinides that go to the waste stream. In fact, these systems have also been proposed as actinide burners for waste management applications particularly when integrated with pyroprocessing technologies as described here, which inherently separate minor actinides together with plutonium.

3.2.4. Thorium nuclear energy systems and fuel cycles

Because of the abundance of thorium and the fact that ^{233}U has excellent thermal neutronic properties (which allows a thermal breeder cycle as demonstrated in the Shippingport LWR), the thorium fuel cycle was originally envisaged as a closed fuel cycle, with separation and recycle of the fissile ^{233}U, analogous to the recycle of plutonium in LWR-MOX. While India is still pursuing recycle of ^{233}U, there are other approaches currently being pursued that can eliminate the need to recover ^{233}U. Both variants discussed here are optimized to burn the ^{233}U in situ, and thus avoid reprocessing.

The thorium fuel cycles considered here are all designed to use standard LWR reactors and a once-through fuel cycle system. For the purposes of this report, most reactor and fuel cycle operations of 'modern' thorium fuel cycles are nearly identical to the LWR–OT fuel system, and the main difference between these fuel systems is the fact that the thorium fuel requires so-called 'driver' fuel since the thorium itself is fertile and not fissile. This driver fuel is generally at the high end of the LEU enrichment category, nearly 20%. The reactor is refuelled off-line in batches, similar to fuel management in the LWR–OT system, although there are some minor variations in the details of fuel management, particularly with the seed-blanket concept.

Several varieties of thorium fuel cycles offer promise of increasing the proliferation resistance of thermal reactor fuel cycles. In the so-called Radkowsky (or seed-blanket) concept, driver fuel assemblies (containing enriched uranium fuel) sustain the nuclear chain reaction and provide neutrons to blanket assemblies containing thorium, converting some of the thorium to ^{233}U that sustains the reaction. In the so-called 'denatured' thorium fuel cycle, the uranium fuel and thorium are blended. Both concepts tend to operate with cores containing about 1/3 uranium and 2/3 thorium. In both concepts, the uranium portion of the fuel is enriched to nearly 20%.

The primary proliferation resistance advantage of these thorium fuel cycles is a significant reduction in plutonium generation: the thorium cycle generates about 1/3 as much plutonium as a comparable uranium-based fuel, and potentially even less as the thorium cycle may achieve higher burnups, further reducing plutonium arising (on a per MW(e)-a basis). In addition, the potentially higher burnups can result in degraded plutonium isotopics, increasing the isotopic barrier. Furthermore, the thorium fuel cycle could be operated with reactor grade Pu or ^{233}U replacing the LEU fuel. If there is no ^{238}U, the thorium cycle would generate no plutonium.

There are some disadvantages of the thorium fuel cycles. Both require the use of high enrichment uranium (approaching 20%) than comparable LWR fuel cycles that operate on LEU fuel generally under 5% enrichment. The higher enrichment of the fresh fuel represents a lower proliferation barrier than the lower enrichment of the fuel normally found in the LWR fuel cycles.

Both concepts produce ^{233}U, a fissile material that is usable as a nuclear explosive material. In the Radkowsky concept, with its separate blanket assemblies, the ^{233}U can be relatively isotopically pure and potentially recoverable similar to the way plutonium can be recovered. In the denatured thorium concept, the uranium-thorium fuel blend is designed so that the ^{233}U is always sufficiently diluted (by ^{238}U) so that the ^{233}U does not exceed the limits of so categorized LEU[11].

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[10] Although the primary justification for actinide burning has been to reduce the long term heat load in geologic repositories, designers of various actinide burning systems point out that reducing the inventories of most of the actinides also reduces the inventories of potentially weapons usable materials.

[11] There is no ^{233}U definition of LEU; current practice is to consider less than 12% ^{233}U to be equivalent to LEU.

3.2.5. Sodium cooled fast breeder reactor system with advanced aqueous reprocessing

The traditional fast breeder reactor (FBR) fuel cycle concept involves the conventional aqueous reprocessing (PUREX process) of discharged core and blanket spent fuels to recover uranium (U) and plutonium (Pu). Since in an FBR the fissile material is produced in quantity more than the amount of consumed fissile material, and the recovered U and Pu can be used as fuels for additional reactors, the FBR cycle has enough sustainability to supply energy from identified resources for more than one thousand years. Since the Pu compound recovered in the PUREX process is highly decontaminated; it might be considered an attractive material for nuclear proliferation purposes.

The Japan Atomic Energy Agency (JAEA) and electric utilities initiated the Feasibility Study (FS) in July 1999, in cooperation with the Central Research Institute of Electric Power Industry (CRIEPI) and manufacturers, in order to effectively use the knowledge accumulated in designing the demonstration FBR, as well as the construction/operation experience from an experimental fast reactor, JOYO, and a prototype FBR, MONJU. The objective of the FS was "to present a promising picture both of the commercialization of the FBR cycle and the research and development programmes leading up to the commercialization" in approximately 2015. Because the enhancement of nuclear non-proliferation was counted as one of the development targets of the FS, the proliferation resistance aspects of the FBR cycle were taken into consideration in the design studies.

As a result of the FS Phase II (from April 2001 to March 2006), the advanced sodium cooled FBR fuel cycle featuring the advanced aqueous reprocessing based on a single-cycle co-extraction process and the simplified pelletizing fuel fabrication process was selected as the principal concept. In addition to being very promising in many respects (economics, environment, technical feasibility, etc.); the FBR cycle system also complies with the design requirements and evaluation criteria in the area of non-proliferation. The current level of safeguards and physical protection, which efficiently utilize remote surveillance and automation, could be applied to the FBR cycle system; and separated Pu is not produced in the fuel cycle. The advanced aqueous reprocessing utilizes a crystallization step for the purpose of separating a major part of uranium from the dissolver solution of spent fuel. This in principle makes it difficult to isolate Pu, so that Pu with U and neptunium can be recovered.

Some other ideas to enhance proliferation resistance were also investigated under the FS. For instance, one of them was a concept of an FBR system that generates low-grade Pu in discharged blankets ('No weapon-grade Pu in the system') and a technique to recover all actinides in reprocessing to increase the material accompanying Pu.

The Ministry of Education, Culture, Sports, Science and Technology (MEXT) reviewed the result of FS Phase II. Its advisory council proposed Research and Development Policy on FBR Cycle Technology which in October 2006 provided a new research and development plan for the period until 2015. This policy provided for proceeding with research and development activities for the sodium cooled fast breeder reactor system with advanced aqueous reprocessing. Some targets of research and development activities related to the proliferation resistance were set to refrain from the production of separated Pu in the fuel cycle, and to accept low decontaminated TRU fuel in order to limit its accessibility. MEXT accepted this policy and in December 2006 the Japan Atomic Energy Commission decided on Basic Policy on Research and Development of FBR Cycle Technologies over the Next Decade for the whole of Japan with respect to the above mentioned policy and studies.

3.2.6. Nuclear energy systems and fuel cycles with small reactors with extended life cores

While there are many concepts for small, transportable autonomous reactors, they all tend to share several important features, including long core life with no on-site refuelling, low enriched uranium fuel, highly autonomous operation and reduced maintenance. The long-life core designs eliminate the need to refuel the reactor, thus eliminating all 'in-country' fuel handling and storage operations. Fresh and spent-fuel handling is limited to the actual installation and replacement of the entire reactor unit, presumably under strict international control. The concepts also strive to eliminate reactor maintenance, simplify reactor operations, and severely restrict access to the reactor itself. Of particular note is the assumption[12] that all fuel cycle operations occur under strict international

[12] It should be noted that this assumption is an extrinsic measure, although many discuss about this nuclear energy system and fuel cycle on the basis of this assumption. In the case where the assumption is not fulfilled, some proliferation resistance attributes discussed here are not applicable.

control, presumably in States with fuel cycle facilities. These combine to increase the skills and access barriers relative to the reference LWR–OT case.

The front end and back end operations normally associated with the fuel cycle are presumed to be provided under strict international control. Because there is no in-country storage of fresh or spent fuel, and no related fuel handling operations, proliferation resistance is considerably increased relative to the LWR–OT reference, specifically for those States in which such a type of reactor is used for power generation.

Generally, these long life cores will be operated to achieve high burnups, thus increasing the isotopic and radiation barriers. The fresh fuel for these concepts and variants generally use higher enrichments than standard LWRs (some approaching 20%) and thus the fresh fuel may have reduced proliferation resistance than the reference LWR–OT case. In contrast, the long life, high-burnup core design means that the ^{239}Pu content of the spent fuel is low, possibly as low as 40%, increasing proliferation resistance of the spent fuel (relative to the LWR–OT case).

The fact that the entire reactor could be transported fully fuelled increases the mass and bulk barriers associated with fresh and spent-fuel transport. Because the core is designed for unrefuelled operation and the reactor systems are designed to inhibit access (in principle, the reactor can be designed with a non-removable head, and does not require an in-containment crane or handling equipment), both of these proliferation resistance barriers could increase relative to the LWR reference cases. In addition, the small size of these systems may result in lower overall available masses, suggesting a possible increase in this barrier compared to the reference LWR–OT case. The design specifically adopts features minimizing the requirements for the specialized skills needed to operate more conventional nuclear plants. Thus, this barrier is also increased.

In effect, all these long life small reactor concepts increase proliferation resistance by use of a combination of intrinsic features at the reactor sites to reduce the requirements for costly on-site institutional controls. This however needs to be balanced against the increased enrichment.

3.2.7. Nuclear energy systems and fuel cycles with IRIS

The International Reactor Innovative and Secure is an integral configuration modular LWR, rated at 1000 MW(th) (~ 335 MW(e))/module. The emphasis of its design is simplicity and the safety-by-design™ approach where accidents are eliminated by design, together with the would-be associated safety systems.

As discussed in Annex VIII, the fuel design of the first IRIS generation, to be deployed in the next decade, is almost identical to that of advanced Westinghouse PWR, but with an enhanced moderation due to the increase in the coolant volume fraction. With an enrichment still below 5%, both the fuel burnup (50–75 GW·d/t) and the fuel cycle length (2.4–4 years) are increased in respect to current LWR–OT systems. Thus improving proliferation resistance because of: (1) reduced access to the fuel; (2) higher burnup and consequent degradation of Pu isotopes; (3) reduced at-reactor safeguards efforts in respect of core fuel verification (these are the same characteristics as small long life reactors).

In subsequent IRIS upgrades, the core lifetime can be increased to 8–10 years with an increase in fissile enrichment to 8–12%. Note that ten years is considered as an upper limit for the actual feasibility of a straight burn fuel and thus no consideration is presently given to longer lifetimes.

Thus, IRIS will have in the first generation an increase in proliferation resistance in respect to current LWR–OT, without the adverse effects due to a higher enrichment. In subsequent upgrades the further enhanced proliferation resistance is tempered by the increase in enrichment, which however remains lower than for small reactors with assumed core lifetimes in excess of ten years.

3.2.8. Nuclear energy systems and fuel cycles with HTGR/PBMR

The high temperature gas cooled reactor (HTGR), as the name implies, is cooled by gas (current designs use helium) heated to higher temperatures than achievable in any other reactor concept. Since the gas is not an effective moderator, a separate moderator is required, and in the case of the reactors considered here, the moderator (carbon) is part of the fuel design itself. By achieving higher temperatures than water cooled reactors, the HTGR can achieve higher thermal efficiencies, and since the moderator is part of the fuel and cannot leak out (or boil away), HTGR's claim potential safety advantages over the LWRs.

Like many other reactor concepts, the HTGR concepts can also be used to burn existing stocks of plutonium.

3.2.8.1. Nuclear energy systems and fuel cycles with prismatic-fuelled HTGR

The prismatic fuel HTGRs use a once-through, high burnup fuel using a low-fissile-density carbide fuel blocks inserted into hexagonal graphite structures arranged and handled similarly to fuel assemblies in common LWRs.

The prismatic high temperature gas cooled reactor (HTGR) isotopics achieve very high burnups, producing spent fuel with ^{239}Pu content[13] on the order of only 40%, representing an increased isotopic barrier as compared to the once-through LWR reference (which has ^{239}Pu content on the order of 60% at current burnups of ~45 GW·d/t). However, it accomplishes this high burnup using LEU fuel enriched to nearly 20%, which decreases the proliferation resistance of the fresh fuel relative to the LWR reference. Other non-proliferation advantages (relative to the previously discussed cases) include higher burnup, and lower fissile material density.

Since the prismatic HTGR achieves high burnup, the spent fuel has a slightly higher radiation barrier than spent LWR fuel. However, this may be somewhat offset by the smaller size of individual fuel assemblies implying a lower level of radiation. Overall, the combination of these effects is not considered significantly different from those for other spent fuel.

The chemical barriers associated with reprocessing spent prismatic fuel appear substantially increased relative to LWR spent fuels. The combination of the chemical processing required for the carbide forms, the mechanical processing required, the dilute nature of both fresh and spent fuel, and the fact that there is currently no commercially demonstrated technology for processing the fuel supports the higher chemical barrier noted here.

Fresh fuel assemblies for the prismatic-HTGR weigh approximately 118 kg (approximately 260 lb and can be handled with only a few people or a single person with a handcart, but nearly 100 are required to obtain a significant quantity of ^{235}U. Thus, the mass and bulk barrier for fresh fuel is somewhat increased from that for LWR fuel. Because of the very low plutonium density in the spent fuel, a significant fraction of the entire core must be diverted to obtain roughly a critical mass of plutonium. This contributes to an increased barrier mass and bulk barrier for spent fuel as compared with LWR spent fuel. Thus, a core of spent fuel is very dilute in plutonium, and an entire spent core contains only on the order of a few critical masses and the available mass barrier for this concept is increased relative to that of the LWR.

3.2.8.2. Nuclear energy systems and fuel cycles with pebble bed modular reactor

The pebble bed modular reactor (PBMR) is very similar in many aspects to the prismatic HTGR, with the main difference being that the fuel is in the form of thousands of individual tennis-ball-sized spheres that slowly move downward through the reactor, like grains of sand in an hourglass. The reactor is refuelled on-line. The pebble-bed fuelled HTGR uses a low density carbide-based fuel using approximately 8% enriched ^{235}U and achieves very high burnups (slightly higher than the prismatic-HTGR). The reactor features a higher degree of automatic refuelling, but is refuelled continuously and on line. Two variants of this concept have been mainly discussed: one using uranium fuel, the other using a mixed uranium-thorium fuel. Here, the uranium case will primarily be discussed. The thorium case would be similar, but both the isotopic and available mass barriers of the spent fuel would be further increased through the use of a mixed uranium–thorium fuel.

Nearly all of the increments in proliferation resistance described for the prismatic-fuelled HTGR apply to the PBMR. The following discussion focuses only on those barriers where some difference may apply to the PBMR.

The small size of the individual pebbles suggests that individual spent pebbles may be more easily shielded than other spent fuel forms. Thus, the detectability barrier for spent pebbles is considered to be slightly less effective than that for other spent fuel forms.

In one design, individual fuel pebbles move through the reactor relatively quickly and remain in the reactor for only about 60 days at a time. Pebbles make many passes (~10) through the reactor before being fully spent. There is a sophisticated automatic fuel monitoring and handling system that routes individual pebbles either back to the reactor for additional irradiation, to a spent fuel holding tank, or to a defective fuel holding tank. The rapid

[13] Plutonium content, as discussed here, is simplified to describing the amount of the isotope ^{239}Pu in the total Pu mix. Most of the remaining Pu is in the isotopes ^{238}Pu, ^{240}Pu and ^{242}Pu, all of which have higher heat, radiation and neutron emissions than ^{239}Pu. Thus, lower ^{239}Pu concentrations result in an overall mix of plutonium less useful for a weapon, yielding a higher proliferation barrier.

transit through the reactor suggests that the system, particularly if modified, could provide a possible vehicle for producing weapons usable material[14]. Thus, the facility unattractiveness barrier for the PBMR reactor may be lower than for the reference LWR–OT system. On the other hand, careful design of the fuel handling and storage system, supported by appropriate inspections during construction and installation, can impede access to the irradiated pebbles and ensure that the diversion of significant quantities of fissile material is likely to be detectable. Furthermore, the small mass of fissile material per pebbles (both as uranium in unirradiated fuel and as plutonium in irradiated fuel) means that a large number and large masses of pebbles would need to be handled to access a significant quantity of fissile material, resulting in a somewhat more effective mass barrier than that of the reference LWR–OT case.

The facilities access barriers associated with the at-reactor operations of the PBMR have advantages and disadvantages relative to the LWR–OT system. On the one hand, reduced need for hands-on operations suggests increased proliferation resistance compared to the reference LWR–OT case. On the other hand, the small pebble size, the fact that the system is continuously refuelled, and the system for sorting various pebbles (especially 'defective' pebbles) suggest that a lower set of access barriers may be appropriate.

3.2.9. Molten Salt Reactor systems and fuel cycles

The Molten Salt Reactor (MSR) represents a promising non-classical reactor type assigned to advanced reactor systems. MSR can be operated either as thorium breeder within the ^{232}Th – ^{233}U fuel cycle or as actinide transmuter incinerating transuranium fuel. The reactor exhibits some very specific features coming out from the use of liquid fuel circulating in the MSR primary circuit. This principle should allow very effective extraction of freshly constituted fissile material (^{233}U) or its precursor (^{233}Pa). Besides, the on-line fuel salt clean up is necessary within a long run to keep the reactor in operation. As a matter of principle, it permits to clear away fission products — typical reactor poisons like xenon, krypton, lanthanides etc. and possibly also other products of burned plutonium and transmuted minor actinides. The fuel salt clean up technology should be linked with the fresh MSR fuel processing to continuously refill the new fuel (thorium or transuranics) into the reactor system.

Main fuel processing and reprocessing technologies proposed for MSR fuel cycle are generally pyrochemical, majority of them are fluoride technologies. This is caused by the fact that MSR fuel is constituted by the mixture of molten fluorides. There are three main pyrochemical partitioning techniques proposed for processing of MSR fresh transuranium fuel and/or on-line reprocessing of MSR spent fuel: fluoride volatilization processes, molten salt/liquid metal extraction processes and electrochemical separation processes. All mentioned separation technologies are in present time under intensive technological development [49].

Whereas the fuel cycle of MSR working as actinide burner (incinerating transuranium fuel) brings no exceptional requirements regarding to proliferation resistance, the MSR operated as Th-breeder requires special vigilance dedicated to the ^{233}U non-proliferation. As pure ^{233}U is produced from ^{233}Pa, the only way, how to increase proliferation resistance of the fuel cycle is via denaturing the separated protactinium by the 'dirty' uranium from the MSR fuel circuit containing in addition to ^{233}U also ^{232}U and ^{234}U, which decrease the proliferation risk by increasing the isotopic barrier and the radiation barrier, the latter is caused by their decay products of ^{232}U.

3.2.10. Accelerator driven system

The accelerator driven system (ADS) uses an accelerator driven neutron source to irradiate spent fuel arising from nuclear reactors to extract additional energy from the spent fuel and to destroy the plutonium (and other actinides) remaining in the spent fuel. In addition, the ADS is capable of burning some of the fission material or irradiating Th for production of ^{233}U. Since the ADS is a 'driven' system (i.e. it does not maintain a critical chain reaction) it can tolerate a variety of spent fuels and other waste materials. In addition, some of the safety issues associated with normal nuclear reactors are somewhat alleviated.

From a 'proliferation resistance' perspective, this ADS concept resembles a fast reactor preferably using pyroprocessing of the spent fuel, and has similar proliferation resistance features. Since the ADS eliminates fertile

[14] Several scenarios for covertly introducing Pu-breeding pellets have been suggested that will require review to determine their practicality and detectability before a complete assessment of the facility access and diversion detectability barriers can be made.

material from its core, it is more efficient at eliminating plutonium, therefore reducing stocks of accumulated plutonium and minor actinides (in either spent fuel or separated forms) in less time than the fast reactor systems, providing some additional overall proliferation resistance. This potential for rapidly reducing accumulated stocks of plutonium and minor actinides is the principle proliferation resistance attribute of the ADS concept.

3.2.11. Nuclear energy systems and fuel cycles with other fuels

3.2.11.1. Nuclear energy systems and fuel cycles with high burnup fuel

All high burnup low enriched uranium fuels offer proliferation resistance advantages relative to lower burnup LEU fuels. In thermal reactor, higher burnup fuels produce plutonium in the spent fuel with a higher fraction of the even isotopes, which offer a higher isotopic barrier to proliferation. In addition, the total amount of plutonium produced for each unit (GW(e)-a) of output power is reduced, lowering the total plutonium inventories relative to that produced by lower burnup fuels. In fast reactor burners, the isotopic content is less affected, but the total amount of plutonium consumed increases. Higher burnup also allows for longer cycle times, reducing the frequency of refuelling and thereby reducing access to the reactor. This also increases the facility access barrier.

Generally, high burnup is achieved, in part, by increasing the enrichment of the fresh fuel[15] (an enrichment of approximately 7% would be required in a LWR to achieve a mean discharge burnup of 80 GW·d/t, while an enrichment of approximately 9% would be necessary for 100 GW·d/t, assuming quarter-core refuelling). This will result in fresh fuel with a somewhat reduced proliferation resistance compared to lower burnup fuels. Furthermore, this would require additional enrichment capacity, which would also result in lower proliferation resistance for the whole fuel cycle.

3.2.11.2. Nuclear energy systems and fuel cycles with spiked fuel

Several ways to spike fresh fuel have been discussed as increased proliferation resistance.

Spiking fresh fuel with radioactive nuclides to provide a radiation barrier has been suggested to increase the radiation barrier. Such an approach would have clear value for designs using fresh fuel with low isotopic or chemical barriers, such as in the MOX fuel for thermal reactors, or for enriched or plutonium-bearing fuels for fast reactors, but less of an impact for LEU-based fuels.

Adding nuclides to fresh uranium fuel to increase the proliferation resistance of the spent fuel has also been considered for the thermal reactors. For example, adding the small amount of minor actinides (MAs) such as ^{237}Np or ^{241}Am to enhance the production of ^{238}Pu, which is high spontaneous fission neutron source to deteriorate the quality of the nuclear explosive and also has high decay heat to make the process of the nuclear weapon or other nuclear explosive device manufacture and maintenance technologically difficult, can be effective for increasing the isotopic barrier of the plutonium in the spent fuel. Adding MAs to MOX fuel or inert matrix fuel (IMF) in the thermal reactors is also effective for the denaturing of the plutonium from LWR spent fuels or weapon grade plutonium. Adding MAs in the blanket fuels is attractive for the breeding of the protected plutonium with enhanced content of ^{238}Pu in the fast breeder reactors. Since the protected plutonium with enhanced content of ^{238}Pu can be burnt effectively in the fast reactors, the advanced fuel cycles with the fast breeder reactors to produce the protected plutonium in the blanket, of course, without the enrichment process of the uranium, have a potential to increase the proliferation resistance.

However, since ^{237}Np and ^{241}Am are fissionable material and is potentially usable in a nuclear explosive device, the benefits of enhancing the ^{238}Pu content of the spent fuel must be weighed against the increased proliferation risk associated with the separation, storage, and handling of neptunium, as well as the increased proliferation risk of the fresh fuel containing neptunium. Therefore, neptunium should be not separated alone but should be recovered together with other minor actinides and uranium or plutonium to reduce its proliferation risk. It is also required to improve the fuel cycle technologies in the storage, reprocessing and fabrication of the fuels with the protected plutonium with enhanced content of ^{238}Pu.

[15] Current LWR fuels reach approximately 45 GW·d/MTU from enrichments of about 4.5%. Current fuel designs may be capable of burnups reaching 75–90 GW·d/MTU with enrichments from 8 to 10%.

Spiking fresh fuel to increase its detectability or to provide a way to trace material to its source has been discussed as a way to increase the safeguardability of both fresh and spent fuel. This is considered an extrinsic approach and it outside the scope of this report, which is to look at increased intrinsic features.

3.2.11.3. Nuclear energy systems and fuel cycles with inert matrix fuels

Inert matrix fuels, which are fuels containing no fertile material, can increase proliferation resistance by avoiding the generation of plutonium during irradiation, thus increasing the effective rate of plutonium consumption and reducing overall plutonium stocks. The inert matrix is designed such that the plutonium is far more difficult to extract than that from conventional MOX fuels. Thus, relative to the LWR–MOX reference case; these fuels can have higher chemical barriers than those of conventional MOX in addition to the increased proliferation resistance gained by more rapidly reducing total stocks of plutonium. However, development of a technology for easily separating plutonium from the inert matrix would essentially eliminate the chemical barrier, and the higher plutonium content of the fresh fuel would represent a decreased proliferation barrier compared to fresh MOX fuel.

3.3. SUMMARY

The following table summarizes the *apparent* proliferation resistant features of the nuclear energy systems and fuel cycles reviewed as compared to the reference LWR fuel cycles in previous sections. These results are included here for readers' understandings to highlight the technical features of each nuclear energy system and fuel cycle. It is noted that this table does not present complete sets of proliferation resistance features and is not intended to be used for comparison or selection of particular systems. To fully evaluate the proliferation resistance of a system, an INPRO or GIF style analysis should be performed.

TABLE 4. APPARENT PROLIFERATION RESISTANT FEATURES AND POSSIBLE RISKS ASSOCIATED WITH INNOVATIVE NUCLEAR ENERGY SYSTEMS

Nuclear energy systems and fuel cycles	Proliferation resistant features	Possible proliferation risks
Synergistic PHWR/LWR fuel cycles	Reduces enrichment activity Avoids completely separated Pu Degraded Pu isotopics Increased radiation barrier of fresh fuel Pu difficult to extract Reduces growing Pu and minor actinide stocks	Expands reprocessing activities Partially separates Pu
DUPIC	High burnup degrades Pu isotopics Avoids completely separated Pu Reduces growing Pu and minor actinide stocks	Increased Pu content in spent fuel
FR – pyro processing	Reduces enrichment activity Avoids completely separated Pu Reduces growing Pu and minor actinide stocks	Expands reprocessing activities Partially separates Pu
Thorium nuclear energy systems and fuel cycles	High burnup degrades Pu isotopics No separated direct-use material Reduces growing Pu and minor actinide stocks	Higher enrichment levels required Potentially recoverable ^{233}U
Sodium cooled fast breeder reactor system with advanced aqueous reprocessing	Reduces enrichment activity Avoids completely separated Pu Reduces growing Pu and minor actinide stocks	Expands reprocessing activities Partially separates Pu
Nuclear energy systems and fuel cycles with IRIS	Higher burnup and fuel cycle length at same enrichment as reference LWR–OT	Similar to reference LWR–OT
Nuclear energy systems and fuel cycles with small long life reactors	Reduced access to fresh/spent fuel High burnup degrades Pu isotopics Reduced at-reactor safeguards efforts	Higher enrichment levels required

TABLE 4. APPARENT PROLIFERATION RESISTANT FEATURES AND POSSIBLE RISKS ASSOCIATED WITH INNOVATIVE NUCLEAR ENERGY SYSTEMS (cont.)

Nuclear energy systems and fuel cycles	Proliferation resistant features	Possible proliferation risks
Nuclear energy systems and fuel cycles with HTGR/PBMR	High burnup degrades Pu isotopics Low available fissile mass Spent fuel difficult to reprocess Reduces growing Pu and minor actinide stocks	Higher enrichment levels required Smaller "easily handled" fuel element On-line refuelling (PBMR)
MSR systems and fuel cycles–MSR-An-burners	Reduces enrichment activity Avoids completely separated Pu Direct connection of reprocessing with the reactor Reduces growing Pu and minor actinide stocks	Expands reprocessing activities (TRU-processing and "on-line" reprocessing on reactor site)
MSR systems and fuel cycles–MSR–Th breeder	Reduces enrichment activity Avoids completely separated Pu Direct connection of reprocessing with the reactor Reduces growing Pu and minor actinide stocks	Expands reprocessing activities ("on-line" reprocessing on reactor site) Separates U with high content of ^{233}U
ADS, as described in Section 3.2.10	Reduces enrichment activity Avoids completely separated Pu Reduces growing Pu and minor actinide stocks	Expands reprocessing activities Partially separates Pu
Nuclear energy systems and fuel cycles with high burnup fuel	High burnup degrades Pu isotopics	Higher enrichment levels required
Nuclear energy systems and fuel cycles with spiked fuel	Increased radiation barrier of fresh fuel and isotopic barrier of plutonium in spent fuel	May interfere with safeguards, material accounting, Separation of Np alone
Nuclear energy systems and fuel cycles with inert matrix fuel	Pu difficult to extract Reduces growing Pu and minor actinide stocks	Separated Pu Pu potentially separable from fresh fuel

4. CONCLUSION

Improved proliferation resistance can be achieved by a combination of the intrinsic features and extrinsic measures, arranged to provide *defence in depth* against a broad range of proliferation-related threats. Implementation of technical options for increasing proliferation resistance can reduce the reliance on extrinsic measures. Similarly, increments in overall proliferation resistance can also be accomplished by increments in the extrinsic measures. However, technical approaches alone cannot eliminate the need for extrinsic measures. While future nuclear energy systems and fuel cycles may have the potential to be more intrinsically proliferation resistant, the actual proliferation resistance will depend on details such as where the facilities are located, how they are implemented (engineering detail), what safeguards are applied, and the objective, strategies and capabilities of the adversary.

Technical options for increasing proliferation resistance may impact economics, safety of nuclear installations, environment, waste management, and national, regional, and international infrastructure [3], [4]. Thus, the implementation of any technology option or system for increasing proliferation resistance should consider these impacts. All of these impacts should be carefully evaluated to determine the best path forward for the future development of nuclear power. Proliferation resistance will play an important role in the determination of the future path for nuclear power. Better understanding of what proliferation resistance is and how technology can impact proliferation resistance as well as the other issues affecting nuclear power will help frame a better understanding of the related vulnerabilities and the remaining risks. How these factors determine the pace and direction of nuclear power development in the future is best left in the hands of the individual States which will develop and deploy nuclear power in the future and which, therefore, must make their own assessment of this balance within the context of their own situation.

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GLOSSARY

acquisition. The set of activities carried out to acquire nuclear material in any form. Acquisition starts with the decision to acquire nuclear material and ends with the availability of nuclear material, in any form.

actinides. Elements with atomic numbers ranging from 90 to 103.

advanced gas cooled reactor (AGR). A graphite moderated, CO_2 cooled, thermal reactor with slightly enriched uranium as a fuel.

barrier. A characteristic of a nuclear energy system that impedes proliferation, sabotage or theft of nuclear material/information.

burnup. (1) Induced nuclear transformation of atoms during reactor operation. (2) The total energy released per initial unit mass of fuel as a result of irradiation. Commonly used units are gigawatt-days per tonne (GW·d/t).

CANDU. A reactor of Canadian design, which uses natural or slightly enriched uranium as fuel and heavy water as moderator and coolant.

critical mass. The minimum mass of a fertile material that can be made to undergo a sustained nuclear chain reaction with a specified geometrical arrangement and material composition.

critical reaction. A sustainable sequence of nuclear fission reactions in which the fissions are induced by neutrons emerging from proceeding fissions.

detectability. A measure of the vulnerability of the proliferation action to external intervention.

detection probability. A measure that expresses the probability that undeclared proliferation activity is detected by verification authorities.

detection resources. A measure describing the manpower, equipment, and funding required to apply international safeguards for the nuclear energy system.

direct use material. Nuclear material that can be used for the manufacture of nuclear explosive devices without transmutation or further enrichment. It includes plutonium containing less than 80% ^{238}Pu, HEU and ^{233}U.

deuterium. A hydrogen atom with a nucleus of mass number 2.

enrichment. The process by which the content of a particular isotope in an element is increased, e.g. *enrich* natural uranium from less than 1% ^{235}U to 4% ^{235}U.

extrinsic (institutional). Relating to States commitments, obligations, and policies with regard to nuclear non-proliferation; bilateral agreements between exporting and importing States; commercial, legal or institutional arrangements that control access to nuclear material and nuclear energy systems; verification activities (including IAEA, regional, bilateral and national); and arrangements to address violations of nuclear non-proliferation undertakings. Hence, extrinsic includes treaties, agreements, the application of IAEA safeguards, and security forces and equipment to impede proliferation, sabotage and theft.

fabrication. The set of activities carried out to manufacture and assemble one or more nuclear explosive devices. Fabrication starts with the availability of nuclear weapons material ready for use in a nuclear weapon (e.g. Pu

in metallic form) resulting from the processing stage or from direct acquisition, and ends with a number of nuclear weapons devices.

facility. 1. A reactor, a critical facility, a conversion plant, an enrichment plant, a fabrication plant, a reprocessing plant, an isotope separation plant or a separate storage installation; or 2. Any location where nuclear material in amounts greater than one effective kilogram is customarily used.

fast critical mass. A mass of fissile material that can maintain a critical reaction on fast neutrons.

fast neutrons. Neutrons with a kinetic energy greater than a specified value, usually greater than 0.1 MeV.

fertile material. A nuclear material that can be converted into a special fissionable material through capture of one neutron per nucleus. There are two naturally occurring fertile materials: ^{238}U and ^{232}Th. Through the capture of neutrons followed by two beta decays, these fertile materials are converted to fissionable ^{239}Pu and ^{233}U, respectively.

fissile material quality. The degree to which the characteristics of the material affects its utility for use in nuclear explosives.

fissile materials. Isotopes that undergo fission by neutrons of all energies, including slow (thermal) neutrons, are usually referred to as fissile materials or fissile isotopes. For example, isotopes ^{233}U, ^{235}U, ^{239}Pu and ^{241}Pu are referred to as both fissionable and fissile, while ^{238}U and ^{240}Pu are fissionable but not fissile.

fission. The process by which a neutron strikes a nucleus and splits it into fragments or 'fission products'. During the process of nuclear fission, several neutrons are emitted at high speed and radiation is released. Fissions can occur spontaneously but usually are caused by absorption of neutrons.

fission products. Nuclides produced either by fission or by the subsequent radioactive decay of the nuclides thus formed.

fissionable material. Material whose nuclei can be induced to fission by a neutron.

fuel. Fissile material used or usable to produce energy in a reactor. Also applied to a mixture, such as natural uranium, in which only part of the atoms are fissile, if the mixture can be made to sustain a chain reaction.

fuel assembly. A collection of fuel elements that is not taken apart during fuelling and refuelling of a reactor core.

fuel cycle. The series of steps involved in preparation and disposal of fuel for nuclear reactors. It includes mining, refining the ore, fabrication of fuel elements, their use in a reactor, chemical processing to recover the fissile material remaining in the spent fuel, re-enrichment of the fuel material, and refabrication into new fuel elements.

fuel element. The smallest structurally discrete part of a reactor or fuel assembly that has nuclear fuel as its principal constituent.

gigawatt days/tonne. A common unit of specific burnup. The burnup is determined by dividing the total energy generated by the fuel (in gigawatt-days) by the original mass of the actinide components of the fuel in metric tonnes.

gigawatt electric GW(e). The amount of power, in gigawatts, generated by a reactor in the form of electricity.

gigawatt thermal GW(th). The amount of power, in gigawatts, generated by a reactor in the form of heat.

half-life. The time in which half of the atoms in a given amount of a specific radioactive substance disintegrate.

heavy water. Water in which the ordinary hydrogen is replaced by deuterium.

heavy water moderated reactor. A reactor that uses heavy water as its moderator. Heavy water is an excellent moderator that permits the use of natural uranium as a fuel.

high enriched uranium (HEU). Uranium in which the percentage of ^{235}U nuclei has been increased from the natural level of 0.7% to 20%, or more.

hot cells. Lead shielded rooms with remote handling equipment for examining and processing radioactive materials. In particular, hot cells are used for examining spent reactor fuel.

intrinsic. Relating to physical design features of a nuclear energy system; hence, intrinsic relates to physical design features that impede proliferation, sabotage or theft.

irradiation. Exposure to a radioactive source; usually in the case of materials being placed in an operating nuclear reactor.

isotopes. Nuclides of the same chemical element but different atomic weight, that is with the same number of protons but different numbers of neutrons.

low enriched uranium. Enriched uranium containing less than 20% of the isotope ^{235}U.

material attractiveness. The extent to which the material is readily usable for weapons applications.

measures. High level parameters that can be used to express Proliferation Resistance robustness. The usage of this term must not be confused with another frequent use (e.g. safeguards measures) to indicate the set of extrinsic actions or procedures applied to material and facility control and protection.

metric. A quantitative or qualitative scale and method that can be used to estimate the value of a system characteristic or of a measure.

minor actinides. Actinides other than uranium, plutonium or thorium.

moderator. A material, such as ordinary water, heavy water, or graphite used in a reactor to slow down fast neutrons to thermal energies.

natural uranium. Uranium as found in nature, containing 0.7% of ^{235}U, 99.3% of ^{238}U, and a trace of ^{234}U.

non-weapons grade material. A material containing fissile nuclides but at a concentration so low as to make it unsuitable for nuclear weapons.

nuclear fuel. Material containing fissile material that when placed in a reactor can achieve a chain reaction.

nuclear fuel cycle. A system of nuclear installations and activities interconnected by streams of nuclear material. Such a system may consist of uranium mines and concentration (ore processing) plans, thorium concentration plants, conversion plants, enrichment (isotope separation) plants, fuel fabrication plants, reactors, spent fuel reprocessing plants, and associated storage installations. The fuel cycle can be ‘closed’ in various ways, for example by the recycling of enriched uranium and plutonium through thermal reactors, by the re-enrichment of the uranium recovered as a result of spent fuel reprocessing or by the use of plutonium in a fast breeder reactor.

proliferation resistance. That characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material, or misuse of technology, by states in order to acquire nuclear weapons or nuclear explosive devices.

proliferation resources. The economic and human resources required to overcome the multiple barriers that impede completion of the proliferation process.

proliferation technical difficulty. The inherent difficulty, arising from the need for technical sophistication and materials handling capabilities, required for a proliferation process to succeed.

proliferation threats. (1) The potential misuse of material through its diversion or theft; (2) The misuse of facilities, equipment, and technology; and (3) transfer of nuclear skills and knowledge — all for a potential proliferator to make nuclear weapons. Threats may be either overt or covert. The threat may also be posed by potential proliferators that have very high technical levels of nuclear sophistication and those that do not.

proliferation time. The time necessary to complete the proliferation process.

pyrometallurgical or pyrochemical processing. Fuel reprocessing based on chemical or electrochemical reactions involving molten salts, liquid metals and inorganic fluorinating agents at high temperatures.

safeguardability. The degree of ease with which a system can be effectively (and efficiently) put under international safeguards. Safeguardability is a property of the whole nuclear system and is estimated on targets on the basis of characteristics related to the involved nuclear material, process implementation and facility design.

safeguards. Activities conducted by an independent agency to verify that commitments made by States under safeguards agreements are fulfilled.

significant quantity (SQ). The approximate amount of nuclear material from which the possibility of manufacturing a nuclear explosive device cannot be excluded. Significant quantities take into account unavoidable losses due to conversion and manufacturing processes and should not be confused with critical masses.

spent fuel standard. A form of plutonium that is at least as inaccessible for weapons use as plutonium that exists in spent fuel from commercial nuclear reactors.

target. Nuclear material that can be diverted, or equipment that can be misused to process undeclared nuclear materials or can be replicated in an undeclared facility.

technical difficulty. The inherent difficulty in physically executing the proliferation steps of material acquisition/production, processing, and fabrication, an expression of the technical sophistication involved. This may be affected by characteristics like radiation level, the physical and chemical form of nuclear material, and the amount of material required.

theft. Unlawful removal of nuclear material, radioactive material or information.

threat. A description of a potential menace consisting of information both about the proliferator, and about the proliferators' strategy. A proliferation threat can be described by defining the objectives, capabilities, and strategy of a proliferating State.

weapons usable material. All materials capable of being assembled into a fast critical mass.

ABBREVIATIONS

Am	americium
Bk	berkelium
CANFLEX	CANDU FLEXible fuel bundles
Cf	californium
Cm	curium
DUPIC	direct use of Plutonium in CANDU reactors
GW·d/t U	gigawatt-days/tonnea uranium
GW(e)-h	gigawatt (electric)-hour
GW(e)-a	gigawatt (electric)-year
IMF	inert matrix fuel
MW(e)-hr	megawatt (electric)-hour
MW(e)-a	megawatt (electric)-year
Np	neptunium
OT	once-through
Pa	protactinium
PR	proliferation resistance
Pu	plutonium
PUREX	plutonium/uranium extraction process
s	second(s)
Th	thorium
U	uranium
UREX	uranium extraction process

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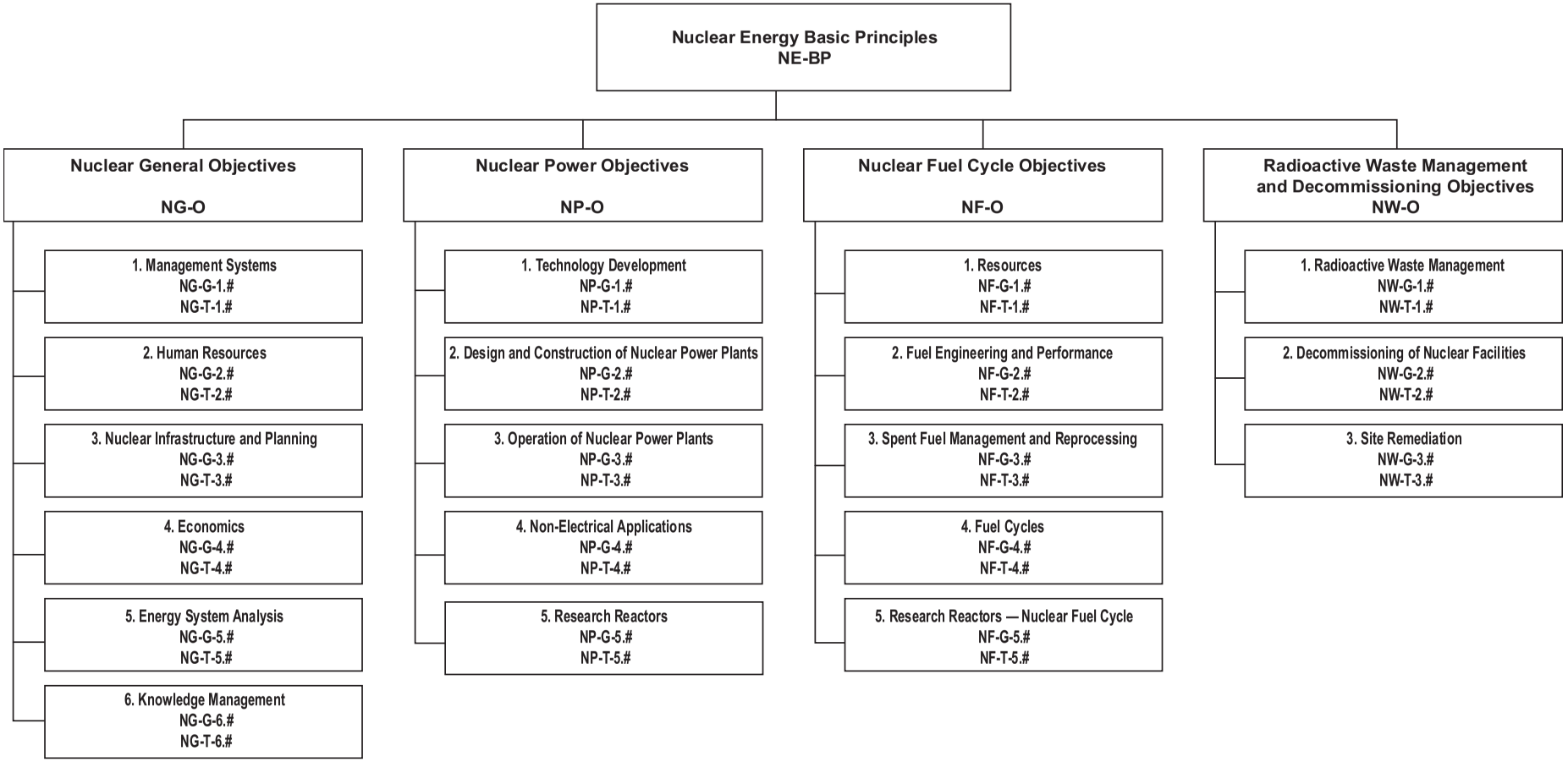

Key

BP: Basic Principles
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Nos. 1-6: Topic designations
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Examples

NG-G-3.1: Nuclear General (**NG**), **G**uide, Nuclear Infrastructure and Planning (topic **3**), **#1**
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