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INTRODUCTION TO THE CONCEPT OF PROLIFERATION RESISTANCE

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The views in this paper are those of the author, not necessarily those of the Australian Government.

EXECUTIVE SUMMARY

Proliferation resistance involves the establishment of impediments or barriers to the misuse of civil nuclear energy systems to produce fissile material for nuclear weapons. These impediments can be institutional or technical – this paper seeks to provide a general introduction to technical aspects.

Proliferation resistant measures are important to increasing the difficulties faced by proliferators. Although not specifically aimed at countering terrorist activity, measures taken for proliferation resistance may also reduce the risk of terrorists acquiring fissile material.

Currently, the principal barriers to nuclear proliferation consist of institutional measures, such as:

- treaty-level peaceful use commitments – principally the NPT;
- verification of performance of these commitments – especially by IAEA safeguards;
- national controls on supply of nuclear materials, equipment and technology – including those coordinated through the Nuclear Suppliers Group.

Further institutional measures under consideration include:

- fuel supply assurance schemes and "fuel leasing", to obviate any need for further states to develop the full fuel cycle;
- multilateralising proliferation-sensitive stages of the fuel cycle (i.e. enrichment and reprocessing).

Technical measures for proliferation resistance include:

- avoiding production of weapons grade material – and introducing technical barriers to producing such material;
- ensuring nuclear material is difficult to access (e.g. through high radiation levels) – increasing the difficulties of diversion by states or theft/seizure by terrorists;
- avoiding separation of plutonium.

Today the subject of proliferation resistance is receiving increasing attention in light of two major developments – the anticipated substantial growth in nuclear power programs, and the increasing interest in plutonium recycle, i.e. recovery of plutonium from spent fuel for re-use in reactors. Unless appropriately addressed, these developments, particularly plutonium recycle, potentially

present major challenges to the non-proliferation regime – and could also lead to increased risk of terrorist access to fissile material.

A key point to appreciate is that reactors have no proliferation capability in themselves. While all uranium-fueled reactors produce plutonium, this remains inaccessible unless the state has a facility for plutonium separation. Proliferation risk is presented primarily by the processes at the "front end" and the "back end" of the nuclear fuel cycle – uranium enrichment and reprocessing.

It is notable that to date proliferation violations have not been based on nuclear power programs, but have involved clandestine or otherwise unsafeguarded facilities, following one or both of the following acquisition paths:

- operation of reactors optimised for production of weapons grade plutonium – such as large "research" reactors – together with reprocessing plants or substantial hot cells for separation of plutonium; or
- operation of uranium enrichment plants – particularly based on illicitly acquired centrifuge technology.

Reflecting the experience of proliferation to date, non-proliferation effort is particularly focused on detecting clandestine nuclear activities and countering illicit procurement of sensitive equipment and materials. But an emerging issue is the risk of break-out by states that may acquire enrichment or reprocessing overtly but repudiate peaceful use commitments in the future.

The greater use of plutonium recycle and the prospective introduction of fast neutron reactors present non-proliferation challenges – but in view of the substantial advantages these reactors offer for efficiency of uranium utilization and management of spent fuel and radioactive waste, they are attracting interest by a growing number of states. These developments can be pursued in ways which will enhance non-proliferation objectives, e.g. through advanced spent fuel treatments that avoid production of separated plutonium. It is essential to ensure international commitment to appropriate conditions, especially proliferation resistance.

There is no magic bullet to eliminate all proliferation risk – no presently known nuclear fuel cycle is completely proliferation proof. But a combination of institutional and technical measures can give needed robustness to non-proliferation and counter-terrorism efforts.

Some suggestions are made at the end of this paper which Commissioners may wish to consider in their deliberations on this subject.

CONTENTS

1. INTRODUCTION

The present context for considering the subject of proliferation resistance is two-fold: the anticipated substantial growth in nuclear power programs – in terms of number of facilities and number of states – and the increasing interest in plutonium recycle, i.e. recovery of plutonium from spent fuel for re-use in reactors. These developments, particularly plutonium recycle, potentially present major challenges to the nuclear non-proliferation regime – and also potentially lead to increased risk of terrorist access to fissile material.

Successfully meeting these challenges will depend on developing institutional and technical measures to address the risks involved. The IAEA points out that both intrinsic (e.g. technical) features and extrinsic (e.g. institutional) measures are essential and neither should be considered sufficient by itself.

The main purpose of this paper is to provide a general introduction to technical aspects. It is anticipated that institutional aspects – including the development of new approaches such as fuel supply assurance schemes and multilateralisation of sensitive stages of the fuel cycle – will be covered in other papers.

Currently, the principal barriers to nuclear proliferation consist of institutional arrangements under the non-proliferation regime, such as:

- treaty-level peaceful use commitments – principally the NPT;
- verification of performance of these commitments – especially by IAEA safeguards;
- national controls on supply of nuclear materials, equipment and technology – including those coordinated through the Nuclear Suppliers Group.

The latter controls aim particularly to limit the availability of proliferation-sensitive technologies, especially enrichment and reprocessing. The non-proliferation regime benefits from the fact that, to date, enrichment and reprocessing – which provide the capabilities to produce highly enriched uranium (HEU) and separated plutonium, the materials required for nuclear weapons – are not widespread. The regime also benefits from HEU and separated plutonium not being widespread in civil programs.

In addition to these institutional arrangements, increasing attention is being given to reinforcing the non-proliferation regime at a technical level, through the development of proliferation resistant fuel cycle technologies. Proliferation resistance has been adopted as a key objective for new generation nuclear energy systems, by the two major international programs working in this area – the IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) and the Generation IV International Forum.

The need for both institutional and technical measures is reflected in the IAEA definition of proliferation resistance, namely:

> "That characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material or misuse of technology by [a state] seeking to acquire nuclear weapons or other nuclear explosive devices.
>
> The degree of proliferation resistance results from a combination of, *inter alia*, technical design features, operational modalities, institutional arrangements and safeguards measures."[1]

Thus, proliferation resistance involves the establishment of impediments to the misuse of civil nuclear energy systems to produce fissile material for nuclear weapons. These impediments can be described as being intrinsic (inherent, built-in) or extrinsic (external):

- **Intrinsic proliferation resistance** refers to technical characteristics of nuclear facilities, such as design features, that increase technological difficulties for diversion of fissile material and manufacture of nuclear weapons.
- **Extrinsic proliferation resistance** refers to institutional barriers, such as safeguards and international arrangements that limit the availability of sensitive technologies and materials.

The focus of proliferation resistance – reflected in the IAEA definition – is on possible misuse by states. However, measures taken for proliferation resistance can also contribute to the security of nuclear materials and facilities, protecting them against access and misuse by non-state actors. For example, avoidance/elimination of weapons grade materials in civil nuclear programs reduces the risk of terrorists being able to produce a workable nuclear explosive device.

Another key point is that proliferation resistance does not mean proliferation proof. No currently known nuclear fuel cycle is completely proliferation proof. Rather, proliferation resistance is a comparative term, a matter of degree. Proliferation resistance involves establishing impediments to misuse – to increase the difficulty, time, cost and detectability – as a disincentive, and to provide sufficient delay for the international community to have timely warning and opportunity for intervention.

Finally, it is noted that incorporation of proliferation resistant features can make a major contribution to the effectiveness and efficiency of performing safeguards: safeguards address proliferation risk – where this risk is lower, there can be a corresponding reduction in safeguards effort. The importance is now recognised of incorporating facility features to assist the safeguards task – what is termed "safeguards by design".

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1. IAEA, *Proliferation Resistance Fundamentals for Future Nuclear Energy Systems*, IAEA document STR-332, 2002.

2. NUCLEAR FUEL CYCLE CHARACTERISTICS AND DEVELOPMENTS

The nuclear fuel cycle involves the processing and use of nuclear materials – uranium, plutonium and thorium – to generate electricity using nuclear reactors. Fission (splitting) of nuclear material in a reactor produces energy in the form of heat, and this heat is used – usually as steam but with some reactor types as heated gas – to drive turbines to power electrical generators.

Reactors are described as thermal or fast, depending on the energy of the neutrons used to achieve fission in the reactor core. Thermal reactors use a *moderator* to slow down neutrons to an optimum speed for capture and fission. Today thermal reactors are almost universal. Fast neutron reactors remain at the development stage, but are likely to have an important place in the future (see section 5.D).

Light water reactors (LWR) are the predominant power reactor type today. These use light water (i.e. ordinary water) as both moderator and coolant. Because light water is an inefficient moderator, these reactors require low enriched uranium (LEU) fuel (see Annex A), to increase the fissile content compared with natural uranium.

Other thermal reactors in use today include heavy water reactors and graphite-moderated reactors.

- Heavy water reactors use heavy water (D_2O)[2] as moderator and coolant. Because D_2O is an efficient moderator these reactors can operate on natural uranium fuel. The most widespread heavy water power reactor is the Canadian CANDU.

- Graphite reactors use graphite (a pure form of carbon) as moderator. The most common type of graphite reactor uses gas − CO_2 or helium − as the coolant. Graphite is also an efficient moderator, so these reactors can operate on natural uranium fuel. Examples of this reactor type are the UK Magnox and Advanced Gas-cooled Reactor (AGR).[3] The Russian RBMK is graphite-moderated and water-cooled − these were operated with natural uranium but now use slightly enriched uranium.

  A promising new type of graphite-moderated reactor under development is the pebble-bed reactor (discussed in section 5.A.3). This operates on LEU.

Another type of thermal reactor is seen with the thorium fuel cycle, based on the production and recycle of uranium-233 from thorium, which is a *fertile* material. The thorium fuel cycle still requires substantial development (see section 5.C).

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2. D_2O has a heavier hydrogen isotope, deuterium (having one proton and one neutron), which exists naturally in the proportion of around 1:6400 of hydrogen in water.
3. Magnox reactors are fueled by natural uranium, AGRs by slightly enriched uranium (i.e. enrichment lower than for LWR fuel).

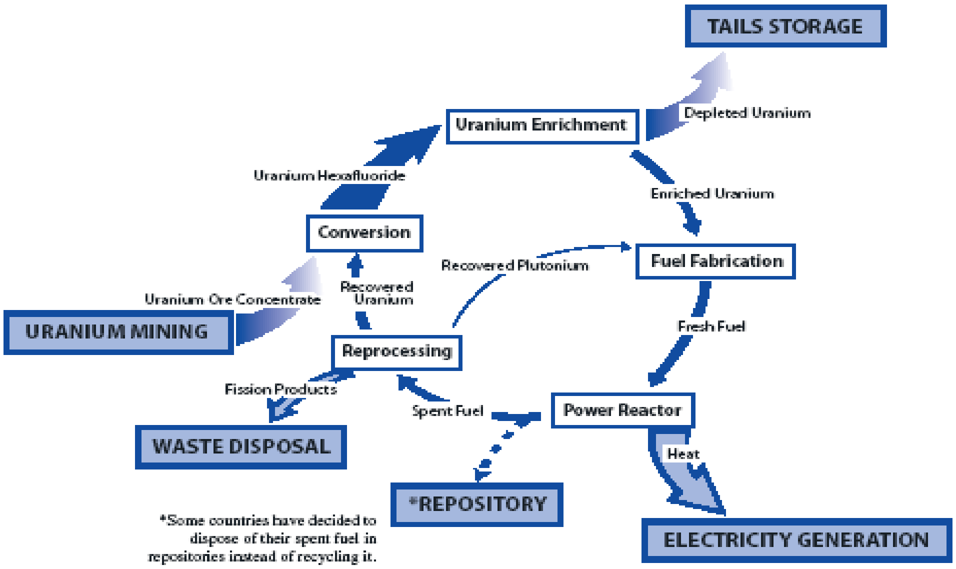

Figure 1. Nuclear fuel cycle

2.A "Open" or "once through" fuel cycle

Today most nuclear power programs are based on thermal reactors, operated on a "once through" basis. With the once through cycle, spent fuel assemblies are intended for eventual disposal as nuclear waste. In practice most states have not taken a firm decision on final disposition, and spent fuel is being stored indefinitely, keeping open the option of reprocessing/recycle if the economics favour this in the future.

The once through cycle is inefficient in the use of uranium resources, and if the anticipated expansion in nuclear energy eventuates the once through cycle is not expected to be sustainable as uranium becomes scarcer and prices rise. With thermal reactors the principal source of energy is the splitting (fission) of the fissile uranium isotope, uranium-235, which constitutes only <u>0.71%</u> (i.e. $1/140^{th}$) of natural uranium. On this basis presently identified global uranium resources are sufficient to sustain only <u>50 years</u> of nuclear power programs at their <u>current</u> scale. No doubt exploration will result in further uranium resources – and if necessary uranium can be recovered from sea water (albeit at substantial cost) – but uranium is expected to become increasingly expensive.

The once through cycle also has the disadvantage of generating substantial volumes of high level radioactive waste – all the spent fuel has to be disposed of as waste – and it does not allow treatment to reduce the life-span of high level waste (see following).

It should be noted that the once-through cycle is not entirely free of proliferation concern. Apart from the possibility of diversion of spent fuel (discussed later), the once-through cycle would result in large plutonium concentrations in spent fuel repositories, which present a potential proliferation risk to later generations as "<u>plutonium mines</u>". Over some decades radiation levels will reduce, making spent fuel more accessible. Over a period of centuries the higher plutonium isotopes decay[4], so that the plutonium in repositories will gradually become more suitable for weapons use.

2.B "Closed" fuel cycle

The "closed" fuel cycle involves recovery of plutonium from spent fuel and re-use as reactor fuel –termed plutonium recycle. Plutonium recycle is attracting increasing interest because of its advantages for spent fuel and radioactive waste management and optimising uranium resource utilization. With currently used technologies, plutonium recycle requires that plutonium is separated from spent fuel by reprocessing.

The basis of recycle is to convert the predominant, "fertile", uranium isotope, uranium-238 (which constitutes over 99% of natural uranium) to plutonium, and to generate energy through fissioning plutonium. In principle, using fast neutron reactors, energy production from uranium can be extended by a factor of 60 or more.

When the nuclear power industry first underwent expansion in the 1960s, it was envisaged that thermal reactors would be phased out in favour of fast breeder reactors[5], which would produce more plutonium than they consume. When nuclear growth slowed, fast breeder reactors did not eventuate in any significant number, and states with reprocessing programs turned to plutonium recycle through light water reactors (what the Japanese term the "pluthermal" program).

However, recycle through light water reactors is not efficient – typically less than 70% of plutonium can be fissioned in a thermal reactor[6] – and the waste management benefits of transmutation are not available. The combination of reprocessing and light water reactors can be seen as an interim phase, pending the introduction of fast neutron reactors.

2.C Fast neutron reactors

Plutonium recycle is most effective with use of fast neutron reactors (also known as fast reactors). Fast reactors use a core with a higher fissile density, relative to thermal reactors – typically the fuel is MOX (mixed uranium/plutonium oxide) comprising around 20% plutonium – so high energy ("fast") neutrons do not need to be slowed down by a moderator. Fast neutrons will fission all plutonium isotopes. In addition, fast neutrons can fission other transuranics (such as neptunium, americium and curium), and can be used to transmute fission products[7] – thus having a major potential application in the management of high level waste.

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4. Plutonium isotopics are discussed in section 4.C and Annex A.
5. Fast breeder reactors are a particular type of fast neutron reactor.
6. Plutonium recovered from light water reactor fuel (reactor grade) comprises more than 30% of isotopes which will not fission with thermal neutrons.
7. Fission products are essentially waste materials formed through the fission of nuclear material.

Fast reactors can be designed and operated in the following modes:

- to consume more plutonium than they produce – termed a "burner" reactor;
- to produce the same quantity of plutonium as they consume – an equilibrium core; or
- to produce slightly more plutonium than they consume – termed a "breeder" reactor. NB as will be discussed, the term "fast breeder reactor" (FBR) refers to a particular type of fast reactor designed to produce plutonium in a uranium "blanket" surrounding the core.

Operated in equilibrium or breeder mode, fast reactors can maximise the energy utilisation of uranium by allowing extensive recycle – in principle, over many fueling cycles all the U-238 present in natural uranium (i.e. 99.3% of natural uranium) can be converted to plutonium and fissioned to produce energy. In theory, a fast reactor would never require newly produced uranium – for a 1,000 MWe fast reactor, the annual requirement for fresh uranium, additional to recycled fuel, would be less than 2 tonnes (compared with around 180 tonnes for a thermal reactor). This can be supplied by depleted uranium from enrichment tails, global stocks of which are at least 1.5 million tonnes – a virtually unlimited source of fuel.

Recycle substantially reduces the quantity of high level waste – materials constituting high level waste comprise only 3-4% of spent fuel, compared with the once through cycle, where the whole of the spent fuel has to be disposed of as waste. Recycle through fast neutron reactors also allows for transmutation of longer-lived radioactive materials from spent fuel to materials having much shorter half-lives. The period over which most high level waste must be isolated from the environment can be substantially reduced, from some 100,000 years to 300-500 years.[8]

The potential advantages of fast neutron reactors has led to increasing interest in developing the fast neutron fuel cycle. These reactors are now the subject of research in a number of states, and through international coordination by the Generation IV International Forum (GIF).[9]

Six reactor types have been selected for development under GIF − three are fast neutron reactors and one can be operated as a fast reactor:

- gas-cooled fast reactors;
- lead-cooled fast reactors;
- sodium-cooled fast reactors;
- super-critical water-cooled reactors – can be thermal or fast;
- molten salt reactors – thermal;
- very high temperature gas-cooled reactors – thermal.

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8. A very small proportion of the fission products, e.g. technetium-99 and iodine-129 (less than 1% of total fission products), will be difficult to transmute and would be separated for storage and later treatment.
9. GIF currently comprises Argentina, Brazil, Canada, China, France, Japan, ROK, Russia, South Africa, Switzerland, UK and US, and also the EU.

3. PROLIFERATION AND TERRORISM RISKS ASSOCIATED WITH NUCLEAR POWER

The currently established nuclear fuel cycle uses processes at the "front end" and the "back end" that were originally developed for nuclear weapons programs, namely, enrichment of uranium and reprocessing of spent fuel:

- most power reactors today require low enriched uranium (LEU) fuel – so there is a requirement for uranium enrichment;
- plutonium is produced during the operation of all uranium-fueled reactors, but is retained within spent fuel unless it is separated by reprocessing.

Depending on how these processes are operated, enrichment and reprocessing can be used to produce fissile material for nuclear power or for nuclear weapons – hence the need for the nuclear fuel cycle to be rigorously controlled.

A key point to appreciate is that reactors have no proliferation capability in themselves. An inevitable consequence of operating uranium-fueled reactors is that they produce plutonium in the fuel – but this plutonium remains inaccessible unless the state has a facility for plutonium separation – a reprocessing plant or large-scale hot cells.[10]

Thus proliferation risk primarily relates to the "front end" or the "back end" of the fuel cycle – the potential for risk depends, in the first instance, on what facilities the state has in these areas of the fuel cycle. While a reactor is a prerequisite for plutonium production, if the state has only reactors, then – provided the state does not have a clandestine reprocessing facility or establish reprocessing in the future – the reactors in themselves do not present a proliferation risk.

There are two basic scenarios for development of enrichment and/or reprocessing capabilities:

- Acquisition openly, as part of a declared nuclear program. In this case, the risk is that capabilities acquired ostensibly for "civil" purposes could subsequently be used – through diversion or break-out (see below) – to produce fissile material for nuclear weapons.

- Acquisition clandestinely. Since these activities are secret, the state does not need a nuclear power program to provide legitimacy.

Historically, proliferation violations have not been based on nuclear power programs, but have involved clandestine or otherwise unsafeguarded facilities, following one or both of the following fissile material acquisition paths:

- Operation of reactors optimised for production of low burn-up plutonium – such as large natural uranium fueled "research" reactors – together with reprocessing plants or substantial hot cells for separation of plutonium; or

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10. Hot cells are areas with radiation shielding where highly radioactive materials such as spent fuel can be safely processed.

- Operation of uranium enrichment plants – particularly based on illicitly acquired centrifuge technology.[11]

3.A Proliferation paths

Broadly speaking, there are two basic proliferation paths – diversion and break-out.

Diversion involves the misuse of nuclear facilities or materials that are subject to peaceful use commitments – e.g. under the NPT – including operation of undeclared facilities. Diversion therefore implies attempted evasion of safeguards.

Break-out involves abrogation of peaceful use commitments, and use for military purposes of facilities acquired while under peaceful use commitments. While preparations for break-out may be made in secret, break-out implies willingness to withdraw from relevant treaty commitments – e.g. formal withdrawal from the NPT – or to openly breach these commitments.

Specific proliferation scenarios will depend on the circumstances of the state. An outline of the main scenarios relevant to this paper is given in Annex B.

3.B IAEA safeguards

The role of the IAEA safeguards system is to verify compliance with treaty commitments – principally under the NPT – to use nuclear material and facilities for exclusively peaceful purposes.

Non-nuclear-weapon states party to the NPT are obliged to declare all nuclear material to the IAEA so safeguards can be applied. States' declarations are verified through measures such as nuclear accountancy, inspections and monitoring.

A key objective of IAEA safeguards is to detect diversion. "Diversion" includes removal of nuclear material from safeguards coverage, and undeclared production of nuclear material, including through use of undeclared nuclear facilities. The principal examples of diversion are outlined in Annex B. Safeguards aim to deter diversion through the risk of detection.

Safeguards have proven highly effective at verifying non-diversion from declared facilities. However, detection of undeclared facilities, particularly small-scale centrifuge enrichment plants, has emerged as a major challenge.

Technically speaking, all nuclear activities (if declared by the state) can be effectively safeguarded – all that is needed is a well-designed safeguards approach and the application of the necessary safeguards resources. However, incorporation of

11. Both these fissile material acquisition paths are illustrated in the case of Iran, which is building a large heavy-water moderated natural uranium reactor, ideally suited for producing weapons grade plutonium, and is expanding a uranium enrichment program, which was originally clandestine and is now under safeguards. Iran is continuing these activities in defiance of IAEA and Security Council resolutions.

proliferation resistant features can make a major contribution to the effectiveness and efficiency of performing safeguards – reference has already been made to the importance of “safeguards by design”.

Safeguards can only verify the present and the past, there is no way to verify the future. Thus safeguards cannot provide an effective counter to the risk of break-out, where by definition the state no longer accepts safeguards. At the technical level, the most effective counter to the risk of break-out is to limit the opportunity for states to acquire militarily useful nuclear facilities and materials. In this regard, the incorporation of proliferation-resistant features in nuclear facilities is particularly important – as well as institutional measures to address technology acquisition.

3.C Plutonium recycle

The recovery of plutonium and use of plutonium-based fuels, if not conducted on sound non-proliferation principles, can present substantial proliferation risks.

From a non-proliferation perspective, current reprocessing technology has a major disadvantage – it gives a state the capability to separate plutonium for military use, if it decides to abrogate peaceful use commitments. And from a terrorism perspective, having increasing quantities of separated plutonium in commercial use could lead to an increasing risk that terrorists may succeed in acquiring plutonium. Opponents of the closed cycle argue that plutonium is least accessible for diversion (by states) or theft or seizure (by terrorists) if it remains locked in spent fuel.

On the other hand, if plutonium recycle *is* conducted on sound non-proliferation principles − especially without plutonium separation (see section 5.D.3) − it has significant non-proliferation advantages. As noted earlier, the once-through cycle creates potential “plutonium mines”. Recycle consumes plutonium, and in the process degrades its isotopic quality.[12]

3.D Terrorist risks

In the context of this paper, the following discussion is in terms of the risk of terrorists acquiring fissile material, rather than the risk of sabotage of nuclear facilities.

It is generally considered unlikely that non-state actors would be capable of producing fissile material, i.e. establishing or operating a uranium enrichment facility or operating a reactor and reprocessing facility. These activities would be difficult to conceal from state authorities and require substantial expertise and resources.

Nor is it likely that terrorists could steal or seize spent fuel for reprocessing − power reactor spent fuel has very high radiation levels, making it self-protecting against unauthorized access and handling (this also applies to the possibility of spent fuel being

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12. Recycle of plutonium in reactor fuel increases the proportion of Pu-240 and higher isotopes, making plutonium increasingly impracticable for weapons use.

used in a radiation dispersion device or "dirty bomb" – the risk of dirty bombs lies with radioactive materials outside the nuclear fuel cycle, rather than nuclear material).

A qualification on the last point is with respect to spent research reactor fuel, some of which has only low levels of radioactivity and could be vulnerable to theft. Most research reactor fuel contains very little plutonium, but some such fuel is made from HEU, and even after use in a reactor the HEU could be still at enrichment levels attractive for explosive use – hence the international program to eliminate HEU from civil use (see section 4.A).

While it might be possible to steal unirradiated LEU, for example as fuel pellets from a fuel fabrication plant, this is only of terrorism concern if there is a capability to re-enrich the LEU to higher HEU levels. As noted, operation of an enrichment plant is likely to be beyond the capabilities of a sub-state group.

The principal terrorist concern is with the possible theft or seizure of plutonium fuel. Plutonium is not used in nuclear power programs in pure form, but in MOX, a mixture with uranium. However, small-scale chemical processing of unirradiated MOX to separate plutonium would not be beyond the capabilities of a well organized and resourced sub-state group.

Theft or seizure of MOX fuel assemblies would be a considerable challenge – typically fuel assemblies are objects 4-5 metres long weighing of the order of one tonne. The most vulnerable source of MOX would probably be at a fuel fabrication plant, where prior to fabrication MOX is in the form of fuel pellets.

It is not possible to entirely eliminate the risk of terrorists acquiring MOX while MOX fuel is used in nuclear power programs. As use of MOX and the facilities handling MOX become more widespread, this risk could increase, although this does not necessarily follow – it depends on maintaining the highest levels of security. It should be pointed out that MOX has been in commercial use since the 1980s without incident. To date over 2,000 tonnes of MOX fuel have been fabricated and loaded into power reactors. Currently MOX is used in over 30 power reactors, mostly in Europe.

The plutonium currently used in MOX fuel is reactor grade (see section 4.C and Annex A). It would be difficult for a sub-state group to successfully explode a device made from this material, and the yield would be uncertain. A much higher risk would be presented if MOX was produced from weapons grade plutonium – from the terrorism as well as the proliferation perspective, production of weapons grade plutonium in civil programs should be avoided. If weapons grade plutonium released from military programs is to be used in power programs, very careful thought needs be given to how its security can be ensured.

For the future, plutonium recycle using electro-processing (see section 5.D.3) has major security advantages, avoiding plutonium separation and ensuring plutonium is always in a highly radioactive mix self-protecting against theft.

3.E A proliferation resistant fuel cycle?

There are many concepts for a proliferation-resistant fuel cycle, but the basic issue can be stated as follows:

> ***Can a fuel cycle be developed which produces nuclear fuel without using enrichment, and enables plutonium recycle without plutonium separation?***

The necessity for enrichment can be avoided altogether by the use of reactors fueled by natural uranium, but these raise other issues − discussed in section 5.A.2. Enrichment could also be avoided through novel technologies such as accelerator-driven systems, but so far these remain theoretical.[13]

In principle, another route for avoiding the need for enrichment is the thorium fuel cycle, but as will be discussed in section 5.C, a thorium reactor requires enriched uranium or plutonium for the initial operating cycles, and current thorium reactor types also require reprocessing. Although reprocessing is for recovery of uranium-233 rather than plutonium, U-233 can also be used in nuclear weapons. A liquid fuel reactor concept is being considered which would avoid the need for U-233 separation.

Enrichment is not required for fast neutron reactors, which are fueled through plutonium recycle. However, for most of this century the light water reactor is likely to remain the predominant reactor type, possibly supplemented by high temperature gas-cooled reactors (such as the pebble bed reactor), so there will be a continuing – indeed, growing – need for uranium enrichment.

Reprocessing can be avoided altogether through using the “open” or “once-through” fuel cycle. However, as discussed earlier, the “closed” fuel cycle has a number of advantages and is attracting increasing interest. It is essential to develop an approach to plutonium recycle that avoids adding to, and if possible reduces, proliferation and terrorism risks. This requires moving away from current reprocessing technologies, producing separated plutonium, to new technologies where plutonium can be made into reactor fuel without separation from highly radioactive materials. This is discussed further in section 5.D.3.

4. AVOIDING WEAPONS GRADE MATERIALS IN CIVIL PROGRAMS

For an outline of fissile material grades and burn-up levels, see section 4.C and Annex A.

Nuclear materials at or near weapons grade are unusual in civil programs. Currently the only such material in widespread use is HEU as research reactor fuel. With the exception of fast breeder reactors, which are very limited in number, weapons grade plutonium is not produced and used in civil programs, but the situation could change in the future if steps are not taken to ensure this remains the case.

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13. Accelerator-driven systems are not necessarily free of proliferation implications.

4.A Highly enriched uranium

HEU is not used in power reactors, but historically has been widely used to fuel research reactors. Since 1978 there has been an international program – the Reduced Enrichment for Research and Test Reactors (RERTR) – to convert HEU-fueled reactors to LEU, or to shut them down, and to return HEU fuel to the US or Russia (most of the research reactors involved had been supplied by these states). World-wide, to date 62 research reactors have been converted to LEU or shut down under this program.

However, some 130 research reactors or critical assemblies in over 40 countries are still operating on HEU fuel – totaling some 20 tonnes of HEU. In many cases these facilities are operating with a life-time core, i.e. they do not require refueling so there is no incentive for the operators to convert them to LEU. While in such facilities the HEU is irradiated – hence to some extent protected against terrorist access by radiation – these radiation levels are relatively low, in many cases minimal.

Clearly the completion of the RERTR program and the withdrawal of HEU from civil programs remains a matter of the highest priority.

4.B Plutonium

As already noted, plutonium is produced in the fuel of all uranium-fueled reactors, but remains in spent fuel unless separated by reprocessing. Where plutonium is recycled as fuel, this is not in the form of pure plutonium but as <u>MOX</u> (mixed oxide) – fuel comprising a mixture of plutonium and uranium oxides. MOX fuel for light water reactors typically contains around 8% plutonium and 92% uranium.[14] Few states hold significant quantities of reprocessed plutonium, although the use of MOX fuel in light water reactors is increasing.[15]

The plutonium produced and used in civil programs today is reactor grade. This situation could change in the future, if numbers of <u>fast breeder reactors</u> enter service. These reactors produce weapons grade plutonium in a *breeder blanket* – discussed in section 5.D.1. Another potential source of weapons grade plutonium for civil programs is <u>plutonium released from military programs</u> as a result of disarmament measures.

4.C Differentiating plutonium grades

For non-proliferation and safeguards purposes, plutonium of *any* isotopic composition is regarded as presenting a potential proliferation (and terrorist) risk. This reflects the fact that all isotopes of plutonium are fissionable by fast neutrons, and theoretically a nuclear explosive device − albeit perhaps of unpredictable yield − could be made using even high

14. MOX containing 8% plutonium has a similar fissile content to LEU fuel containing 5% U-235.
15. Although recycle of plutonium has caused some public concern about safety in some countries, it is noted that in normal operation of a uranium-fueled reactor, as U-235 is consumed an increasing proportion of the energy produced is due to fissioning of plutonium being produced in the fuel. Towards the end of the fuel's lifetime in the reactor (3-4 years), around half of the energy produced is due to fission of plutonium.

burn-up plutonium. The diversion or theft of a significant quantity of separated plutonium would be a major concern, regardless of the isotopic quality.

Accordingly, the safeguards system does not formally distinguish between plutonium of different grades, apart from an exemption from safeguards for plutonium containing 80% or more of the isotope Pu-238.[16] To date this has not been a practical issue because almost all plutonium in civil programs is reactor grade. But with the possibility of weapons grade plutonium entering civil programs, it is necessary to consider whether the policy of regarding all plutonium as alike has an unintended consequence − that insufficient attention is being given to the dangers of plutonium of higher fissile composition.

History shows that all the states with plutonium-based nuclear weapons have specifically produced weapons grade plutonium for this purpose. Discussion of the possible use of reactor grade plutonium for nuclear explosives reinforces the need to ensure that reactor grade plutonium is properly dealt with – but this should not distract from the fact that this material is sub-optimal for weapons use, and has never been so used. There is no doubt that the material of choice for both proliferators and terrorists would be weapons grade plutonium if it were available.

Paralleling international efforts to eliminate HEU from civil programs, steps should be considered now, while there is time, to keep weapons grade plutonium out of civil programs. In fact this issue has been recognized and action is being taken at the technical level. The problems associated with the established fast breeder reactor model are now well understood internationally, and a number of states are engaged in developing alternative, proliferation-resistant, technical approaches.

In the international program to coordinate R&D on new reactor designs – the Generation IV International Forum – the *fast breeder* design has been replaced by fast neutron reactors where there is no breeding *blanket*, but rather, plutonium production takes place in the core where burn-up levels will always be very high. In conjunction with the new fast reactor designs, advanced spent fuel treatments are being developed, to enable plutonium to be recycled without separation. This is discussed further in section 5.D.3.

Thus, the potential problems of fast breeder reactors and production and use of weapons grade plutonium in civil programs are being addressed through technical development. However, this should be reinforced through policy decisions and institutional arrangements, to ensure that technical development continues in this direction.

The other area to be addressed is the use of ex-military plutonium – plutonium released from military programs through disarmament. This plutonium represents a major energy resource, and will be needed for power generation in the future. In addition to the energy produced, use in reactors will have the important benefit of degrading the isotopic quality

16. Safeguards *do* distinguish between plutonium grades in one case – the application of substitution under INFCIRC/66 safeguards agreements (i.e. the agreements applying to non-NPT states). INFCIRC/66 takes isotopic composition into account, and does not allow lower-fissile material to be substituted for higher-fissile material.

of this plutonium – through irradiation, low burn-up, weapons grade plutonium will become high burn-up, reactor grade.

However, the question is how to minimize proliferation and terrorist risks when weapons grade plutonium first enters civil programs. Measures at both the institutional and technical level should be considered. It is essential to keep weapons grade plutonium under high security, limiting the states and the facilities involved. At the technical level, it may be possible to denature or degrade the plutonium in some way, e.g. through blending with reactor grade plutonium at an appropriate ratio[17], or blending with Pu-238, to make explosive use more difficult. The practicability of denaturing weapons grade plutonium warrants further study.

5. COMPARISON OF VARIOUS REACTOR SYSTEMS

A qualitative comparison of proliferation resistance for the various reactor types discussed here is shown in Table 1, at page 28.

As noted earlier, reactors have no proliferation capability in themselves. The plutonium in spent fuel remains inaccessible unless the state has a facility for plutonium separation. The proliferation issues with reactors, therefore, are:

- whether the reactor can be readily used to produce proliferation-attractive (i.e. low burn-up) plutonium; and
- whether the state has – or can readily develop – reprocessing capabilities.

5.A "Thermal" reactors

5.A.1 Light water reactors

Because light water reactors are the predominant power reactor today, they will be considered here as the reference or base case, against which the relative proliferation resistance of other reactor types can be compared.

Light water reactors operate on LEU fuel, using water as moderator and coolant. A feature of these reactors is a substantial pressure vessel, and they operate under very high pressure (for a PWR[18], typically around 150 times atmospheric pressure), so when the reactor is operating the fuel is inaccessible. The normal operating cycle is 12-18 months, at the end of which the reactor is shut down and refueled. The shut-down and refueling process takes some 4-6 weeks. When the pressure and temperature have dropped, the top of the pressure vessel is removed so the fuel can be accessed. Depending on the

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17. Blending weapons grade plutonium with reactor grade would have the advantage of concealing the original isotopics, regarded by nuclear-weapon states as a matter of national security.
18. Light water reactors have two basic variants, the boiling water reactor (BWR), in which steam is drawn directly from the pressure vessel to drive turbines, and the pressurised water reactor (PWR), in which the turbines are driven via a secondary cooling circuit. PWRs are more widespread than BWRs.

operating mode, typically a quarter or a third of the fuel assemblies will be replaced by fresh fuel.

With light water reactors, the principal proliferation vulnerability is with spent fuel which has been removed from the reactor and is stored in the reactor spent fuel pond. Typically all spent fuel from the reactor (which could be many years worth) will be in the spent fuel pond. This fuel is accessible at any time (i.e. access is independent of reactor shut-down), but spent fuel is highly radioactive and would require a heavily shielded container to move (so theft by terrorists is not practical).

Fuel which has gone through a normal operating life – 3 or 4 refueling cycles – will be of high burn-up, so of limited interest for weapons use. However, when a light water reactor is refueled after its very first operating period, a quarter or a third of the fuel assemblies will be permanently removed from the core and stored – this "initial core load" fuel has an appreciably lower burn-up level (albeit still above weapons grade), and is potentially more attractive to a proliferator. Where proliferation risk is a concern, it should be a priority to remove such initial core load fuel from the state.

There is another sense in which light water reactors have good proliferation resistance − in case of break-out, a state without enrichment capabilities will be dependent on imported fuel. If – as would be expected in case of break-out – suppliers cease supply of fuel, the state would be unable to continue operating these reactors beyond whatever fresh fuel it has on hand. Interruption of fuel supply, however, would not prevent the state from reprocessing accumulated spent fuel.

Plutonium recycle using light water reactors

Some operators are recycling recovered plutonium as MOX fuel for light water reactors. While MOX itself is not weapons-usable, it would not be a major challenge for a state or even non-state actors to chemically process MOX to separate the plutonium, so MOX presents some proliferation and terrorist risk. While the plutonium in today's MOX fuel is derived from light water reactor fuel and so is high burn-up, it would still be of considerable concern if such plutonium came into the wrong hands.

Summary Because of the extended period between shut-downs, the inaccessibility of the reactor core during operation, and the practical difficulties in producing low burn-up fuel[19], light water reactors have good proliferation resistance.

The proliferation resistance of light water reactors would be enhanced by institutional measures, such as "fuel leasing" (supply of fuel under lease arrangements) combined with spent fuel take-back by suppliers in order to avoid accumulation of spent fuel. Any take-back scheme should give priority to initial core load fuel and other relatively low burn-up fuel (such as damaged fuel removed after one operating period).

19. It would be possible to produce very low burn-up fuel by shutting down a LWR within weeks of start-up, but this would be abnormal and obvious to safeguards inspectors/outside observers. Further, there would be a significant economic cost − the state would lose substantial electricity output during the shut-down period.

5.A.2 Natural uranium reactors

Because these reactors do not require enrichment, they have been attractive in the past to states without enrichment technology that were seeking energy independence. A disadvantage of natural uranium reactors is that they require much more fuel than a light water reactor of similar power, and produce a correspondingly larger quantity of spent fuel. As the commercial nuclear industry has matured, and low enriched uranium fuel has proven to be readily available, the more efficient light water reactor has consolidated its position as the predominant power reactor. The only natural uranium reactor being marketed today is the CANDU.

Because natural uranium reactors do not require enrichment, it might be thought that a fuel cycle based on these reactors would be preferable from the non-proliferation perspective. However, this is not the case. Most natural uranium reactors are based on <u>on-load refueling</u> (OLR) designs[20] − that is, the reactor can be refueled without the need to shut it down. This has two major non-proliferation disadvantages:

- Fuel can be readily discharged after short residence time in the reactor, i.e. while still at low burn-up levels, hence containing plutonium that is predominantly Pu-239 (weapons grade).[21]
- Fuel can be discharged at any time in the operating cycle, requiring continual intensive safeguards monitoring.[22] IAEA figures indicate that on average the safeguards effort for an on-load refueling reactor is some <u>eight times</u> the effort required for a light water reactor.[23]

Independence from the need to import LEU − which made natural uranium reactors attractive in the first place − can be a disadvantage from the non-proliferation perspective. Natural uranium is more readily available than LEU, and if cost is no object uranium could be recovered by most states, at least in the quantities required for a nuclear weapon program.

Of course, a reactor by itself cannot be misused without a reprocessing plant or large hot cells also being available for separation of plutonium from spent fuel. For natural uranium reactors using uranium dioxide fuel − such as the CANDU − reprocessing is not part of the commercial fuel cycle, and a proliferator would have to establish this capability covertly or following break-out. With earlier types of natural uranium reactors, which used uranium metal fuel (e.g. the Magnox), reprocessing was a necessary part of

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20. E.g. with the CANDU reactor, the fuel is contained in a series of pressure tubes. Individual pressure tubes can be refueled without interrupting the operation of the entire reactor. Other examples of OLRs include Magnox reactors and RBMKs.
21. With some types of OLR (e.g. CANDUs), there can be technical complications in moving fuel through the core quickly – but obtaining low burn-up fuel is far easier than with LWRs.
22. By contrast, as discussed earlier, when a LWR is operating, fuel in the core is inaccessible. LWRs must undergo a lengthy shut down process before fuel can be removed, and the normal time between shut downs is 12-18 months.
23. In 2007 20 OLRs accounted for 16% of the IAEA's total inspection effort, compared with 171 LWRs which accounted for 17% of total inspection effort.

the fuel cycle, because spent fuel would quickly deteriorate and could not be stored for any significant length of time. The natural uranium fuel cycle based on this type of reactor and fuel would be anything but proliferation-resistant − it is no coincidence that the DPRK based its nuclear program on Magnox-type reactors.

As with light water reactors, accumulation of large quantities of spent fuel is also a potential proliferation issue with natural uranium fueled reactors. Much of this fuel will be of lower burn-up compared with light water reactor fuel. With fuel stored for longer periods (30 + years) radiation levels will have declined, making handling of fuel for reprocessing easier.

Summary A combination of fuel independence and the ability to produce weapons grade plutonium could make a natural uranium reactor attractive for a state wanting to maintain a break-out option. With on-load fueling reactors the primary technical proliferation barrier is the need to establish reprocessing capability.

5.A.3 Pebble bed reactors

The PBMR (Pebble Bed Modular Reactor) is a gas-cooled, graphite-moderated reactor in which the fuel comprises, not fuel assemblies, but graphite/uranium spheres.[24] The reactor is a vertical cylinder, lined with graphite, through which fuel spheres are circulated:

- these spheres (roughly tennis-ball size) comprise a graphite matrix in which small particles of <u>LEU</u> are embedded – in the ESKOM design the reactor core contains some 330,000 such spheres;
- the spheres are introduced through the top of the reactor and gradually move by gravity to an exit at the bottom, where they are sorted and returned to the reactor (each sphere will move through the reactor 6 times) or sent to spent fuel storage – thus the PMBR is a type of on-load refueling reactor;
- heat from the nuclear reaction is removed by circulating helium through the core. In the ESKOM design the heated helium (around 900°C) is passed directly through a turbine to generate electricity (i.e. unlike other reactor systems, there is no steam production).

Advantages offered by the PBMR concept include:

- low cost – expected to be around 2/3 that of a light water reactor on an electricity output basis;
- safety, ease of operation – the concept is simple, operation would be largely automated, and in the event of a loss of coolant accident (e.g. break in helium

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24. The PBMR concept was developed in Germany over the period mid-1960s to early-1980s, but due to political factors never progressed to commercial deployment. Now the concept has been substantially progressed by a South African company, ESKOM. China is also very interested in PBMR technology – China acquired the right to the German patents, and has been operating a small pebble bed reactor since 2000.

pipes, or pump failure), the core would be passively cooled (i.e. would cool by natural convection without need for pumps);

- small size – the ESKOM design is 165 MWe, compared with common light water reactor output of 1,000 MWe. This makes it attractive to states with small power grids, such as developing countries. The modular part of the name refers to the reactors being designed so up to 10 units can be linked together and operated from a common control room – so a power utility can start small and expand later at marginal cost;
- proliferation resistance – due to the graphite, there would be major technical difficulties in reprocessing the spent fuel. In addition, the burn-up levels from normal operation are very high, and there is no excess reactivity that would permit irradiation of uranium targets for illicit plutonium production.

Summary The pebble bed reactor has a number of inherent proliferation resistant characteristics. This has been recognized through inclusion of this reactor concept in the international Generation IV reactor development program (i.e. very high temperature gas-cooled reactor concept).

5.A.4 Proliferation resistant fuel designs

To round off this discussion of thermal reactor types, it is worth mentioning some concepts for new types of fuels for use with existing reactors. These remain experimental – and it is not clear whether they could be sufficiently attractive economically to enter into widespread use.

Proliferation resistant fuels (PRFs) PRFs have been proposed in several countries, including France, Italy, Switzerland, Japan and the US, as a means of disposing of excess military and civil plutonium. PRFs would encapsulate plutonium and burnable poisons in a non-uranium matrix. PRFs are designed to behave like standard LEU fuel, able to be used in standard light water reactor fuel cycles without reactor modification. Because they do not contain uranium or thorium, PRFs do not produce plutonium or U-233. Consequently, PRFs can consume more plutonium than MOX over identical reactor cycles. The results of extensive theoretical studies are promising. However, deployment of PRFs will require a significant fuel development and qualification program.

Radkowsky Thorium Fuel (RTF) concept This is another approach to a proliferation-resistant fuel. The RTF concept assumes a once-through fuel cycle with no reprocessing. The fuel comprises uranium enriched to a maximum of 20% and a thorium blanket, incorporated in a “seed-blanket unit” fuel assembly. Compared to a light water reactor, the partial replacement of uranium by thorium results in a major reduction in plutonium production. U-233 produced through irradiation of the thorium is mostly consumed in the reactor, and residual U-233 in the spent fuel is denatured by non-fissile uranium isotopes.

5.B The "front end" and "back end" of the fuel cycle – enrichment and reprocessing

As already noted, in themselves reactors do not present a proliferation risk. Producing fissile material for nuclear weapons use requires uranium enrichment or reprocessing.

5.B.1 Uranium enrichment

In principle no uranium enrichment technique can be regarded as proliferation resistant. The currently established processes of gaseous diffusion and gaseous centrifuge have been used for producing HEU. The Argentinean firm INVAP has developed an innovative form of gaseous diffusion, named SIGMA, which is claimed to be proliferation resistant. However, the advantages of SIGMA seem to relate to safeguardability, rather than proliferation resistance in any absolute sense – while it might be difficult to modify a SIGMA facility to produce HEU, there seems no in-principle technical barrier to doing so.

A technology which appears to be more validly described as proliferation resistant is the French Chemex (chemical exchange) process. Because this is an aqueous process, the danger of accidental criticality appears to rule out any possibility of high enrichment.

Even here, however, the process cannot be considered benign from a non-proliferation perspective − it is a fact that (with any enrichment process) attaining an enrichment of 5% U-235 (a normal level for LEU fuel) accounts for over 70% of the separative (enrichment) effort required to reach weapons grade. To proceed beyond LEU to weapons grade HEU involves enriching only around 10% of the volume of material processed to get to 5% LEU, and about 30% of the separative effort. LEU is thus an extremely attractive feedstock for high enrichment: either for diversion – a proliferator producing LEU in a safeguarded facility (whichever process) can, using suitable technology (e.g. centrifuge), upgrade the LEU to weapons grade in a much smaller clandestine plant – or for break-out.

Thus enrichment, whichever process, must be regarded as proliferation-sensitive. There is no practical technical solution − rather, effective international institutional mechanisms are needed. A desirable direction for the future is away from national enrichment programs to programs conducted on a multilateral basis.

5.B.2 Reprocessing

The currently established reprocessing technology – Purex[25] – is an aqueous process, involving water-based chemicals. Spent fuel is chopped and dissolved in hot nitric acid, and the resulting solution is treated with solvents to separate plutonium from residual uranium and from the highly radioactive fission products formed during irradiation.

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25. Plutonium and Uranium Recovery by Extraction.

In typical light water reactor spent fuel, the U-235 content has reduced to around 1% due to fission, and the residual plutonium content is around 0.8 - 0.9% (a significant proportion of the plutonium formed in the fuel is fissioned in the reactor before the fuel is discharged). The residual U-238 content is about 95%, and the fission products are about 3%.

Purex has three output streams – plutonium, uranium and fission products (most of the transuranic elements, apart from plutonium and uranium, are included in the fission product stream). Plutonium and uranium recovered through reprocessing are recycled as fresh fuel (typically the uranium has a residual U-235 content of below 1% and will require re-enrichment). The fission products are immobilised in borosilicate glass for disposal as high level waste.

There is no technical method for making aqueous reprocessing proliferation resistant. In some cases uranium and plutonium are blended at the facility (say, 50-50), to avoid having pure plutonium in storage and in subsequent transport and processing operations (e.g. transport to and handling in a fuel fabrication plant). Some processes are designed to produce plutonium and uranium as a co-product – so plutonium, rather than being pure, will be in a mix with between 20% and 80% uranium. Blending or co-processing however does not result in significant proliferation resistance – it is not difficult to further process the product to separate the plutonium, and the plant itself can be modified to produce a pure plutonium product.

For the next generation of nuclear energy technology, alternative reprocessing technologies, in particular electro-metallurgical processing, are being developed which do not produce separated plutonium, hence have intrinsic proliferation resistance. Electro-processing is discussed in section 5.D.3.

5.B.3 Plutonium recycle without reprocessing

An interesting example of plutonium recycle without separation is the DUPIC process[26] being developed through collaboration between the ROK, Canada, and the US. DUPIC involves direct re-fabrication of spent PWR (pressurised water reactor) fuel into CANDU reactor fuel, thereby reducing natural uranium requirements and the overall quantity of spent fuel.

The basis of DUPIC is that the fissile content of spent PWR fuel (residual U-235 and produced plutonium) is well suited for use in heavy-water moderated CANDU reactors. No separation of plutonium is involved: dry thermal-mechanical processes are used to reduce spent PWR fuel to a fine powder, which is subject to high temperature to drive off volatile fission products (around 40% of total fission products), pressed into pellets, and fabricated into CANDU fuel bundles.

Since there is no plutonium separation, DUPIC is inherently proliferation resistant.

26. DUPIC stands for Direct Use of spent PWR fuel in CANDU reactors.

5.C Thorium fuel cycle

The thorium fuel cycle has similarities to the fast neutron fuel cycle – it depends on breeding fissile material (U-233) in the reactor, and reprocessing to recover this fissile material for recycle.

Thorium is not a fissile material, so cannot be used as reactor fuel. The basis of the thorium fuel cycle is irradiation of the fertile thorium isotope, Th-232, to produce the fissile material U-233 through neutron capture (rather like production of plutonium from U-238). The thorium fuel cycle requires separation – i.e. reprocessing – of U-233 produced in the fuel, and the recycle of U-233 as fresh fuel.

Proponents argue that the thorium fuel cycle is proliferation resistant because it does not produce plutonium. Proponents claim that it is not practicable to use U-233 for nuclear weapons.

There is no doubt that use of U-233 for nuclear weapons would present significant technical difficulties, due to the high gamma radiation and heat output arising from decay of U-232 which is unavoidably produced with U-233. Heat levels would become excessive within a few weeks, degrading the high explosive and electronic components of a weapon and making use of U-233 impracticable for stockpiled weapons. However, it would be possible to develop strategies to deal with these drawbacks, e.g. designing weapons where the fissile "pit"[27] is not inserted until required, and where ongoing production and treatment of U-233 allows for pits to be continually replaced. This might not be practical for a large arsenal, but could certainly be done on a small scale.

In addition, there are other considerations. A thorium reactor requires initial core fuel – LEU or plutonium – until it reaches the point where it is producing sufficient U-233 for self-sustainability, so the cycle is not entirely free of issues applying to the uranium fuel cycle (i.e. requirement for enrichment or reprocessing). Further, while the thorium cycle can be self-sustaining on produced U-233, it is much more efficient if the U-233 is supplemented by additional "driver" fuel, such as LEU or plutonium. For example, India, which has spent some decades developing a comprehensive thorium fuel cycle concept, is proposing production of weapons grade plutonium in fast breeder reactors specifically for use as driver fuel for thorium reactors. This approach has obvious problems in terms of proliferation and terrorism risks.

A concept for a liquid fuel thorium reactor is under consideration (in which the thorium/uranium fuel would be dissolved in molten fluoride salts), which would avoid the need for reprocessing to separate U-233. If it proceeds, this concept would have non-proliferation advantages.

Finally, it cannot be excluded that a thorium reactor – as in the case of other reactors – could be used for plutonium production through irradiation of uranium targets.

27. The core of the nuclear nuclear weapon.

Summary Arguments that the thorium fuel cycle is inherently proliferation resistant are overstated. In some circumstances the thorium cycle could involve significant proliferation risks.

5.D Fast Neutron Reactors

5.D.1 Fast breeder reactors

In the established "fast breeder reactor" design, the reactor core, containing the fuel, is surrounded by a uranium "blanket" in which neutrons are captured to produce further plutonium. The plutonium produced in the blanket (as well as in the core) is recovered by reprocessing, and made into fresh fuel. The reactor produces more plutonium than it consumes − the surplus is to be used for fueling further reactors (enabling a gradual expansion in the number of reactors).

A major issue from the non-proliferation perspective however is that plutonium produced in fast breeder reactor blankets has a very high proportion of the isotope Pu-239, well within the weapons grade range. This combination of producing weapons grade plutonium and reprocessing presents obvious proliferation concerns. Further, use of separated weapons grade plutonium on a commercial scale could present a major terrorism risk.

5.D.2 New fast neutron reactor concepts

The problems associated with the established fast breeder reactor model are now well understood internationally, and a number of states are engaged in developing alternative, proliferation-resistant, technical approaches, e.g. through the Generation IV International Forum.

The conventional fast breeder reactor is being replaced by new fast neutron reactor designs, in which there is no "blanket" – all plutonium is produced in the fuel core where burn-up levels are high, making it even less attractive for explosive use than the plutonium produced in today's light water reactors.

Of vital importance, advanced spent fuel treatments − such as electro-processing (see 5.D.3 following) − are under development which will enable plutonium recycle without separation – plutonium will not be produced as a purified material. Plutonium will not be separated, but will remain in a highly radioactive mix with fission products and other spent fuel materials. This highly radioactive mix will be made into new fuel using robotic equipment.

Plutonium will at all times be in a mix having high radiation levels, similar to spent fuel, self-protecting against diversion and theft. A would-be diverter or terrorist could only handle this material with substantial shielding – as with spent fuel – and reprocessing would still be required for plutonium separation – again, just like spent fuel.

Thus, these fast reactor designs will incorporate a number of important proliferation-resistant features:

- use of a "hot" fuel (plutonium mixed with fission products as well as minor actinides);
- high burn-up, absence of a breeding blanket – all plutonium production occurs in the core, at all times plutonium from the reactor has an isotopic composition unfavourable for weapons;
- in addition, spent fuel treatment avoids any separation of pure plutonium.

It is possible to incorporate further proliferation resistant features. For example, because most fast reactor designs operate under no or low pressure and the core is readily accessible, a potential misuse scenario is undeclared plutonium production through irradiation of uranium targets. The Russian BREST lead-cooled fast reactor concept specifically addresses this scenario. In addition to the proliferation resistant features outlined above, the BREST reactor is designed with an equilibrium core − so there are no excess neutrons available for illicit target irradiation. If a target is introduced into the core, there will be insufficient neutrons to maintain the chain reaction, bringing the reactor to a stop.

Possible in-built proliferation barriers of this kind should be studied further. Clearly it would be a major non-proliferation benefit if it were possible to design fast reactors where the core could not be modified, e.g. where it was not possible to reconfigure the reactor as a conventional fast breeder (i.e. with a blanket), or to increase neutron density to allow for target irradiation.

5.D.3 Electro-metallurgical processing

Because fast neutrons can be used to fission or transmute a range of elements, plutonium can be recycled without, as is the case with current reprocessing, being fully separated. Electro-metallurgical processing is an advanced spent fuel treatment, in which spent fuel will be melted in a molten salt mix, and uranium separated through electrolysis (electro-refining). Plutonium, uranium, actinides and some fission products would remain mixed together and fabricated as "fresh" fuel. This mix cannot be used in nuclear weapons, and the high radioactivity levels ensure it is self-protecting against theft.

Electro-processing is not a theoretical concept, but has already been demonstrated at a practical scale in the US.[28]

Subject to the need to conduct further research, it appears that electro-processing does not allow for plutonium separation. It is not clear whether it might be possible to arrive at a relatively pure plutonium product through repeated passes through the process, but it would seem easier for a proliferator to obtain separated plutonium by treating the product of electro-processing with aqueous reprocessing. Further, if electro-processing is used in

28. Electro-processing was used at the Argonne National Laboratory for spent fuel from the EBR-II experimental fast reactor.

conjunction with fast neutron reactors as discussed here, the plutonium isotopics would be very unattractive for nuclear weapons use, providing no incentive to attempt plutonium separation.

Thus electro-processing used by itself appears to have high proliferation resistance. However, in analysing proliferation risk it is necessary to consider the potential fissile material acquisition path as a whole. As noted above, a proliferators could use electro-processing in tandem with aqueous reprocessing – either a clandestine facility or following break-out. In this scenario, the product of electro-processing − the plutonium/uranium/actinide/fission product mix − represents a very substantial quantitative reduction compared with the spent fuel from which it was processed.[29] If a state were planning illicit separation of plutonium (by aqueous reprocessing), electro-processing would reduce the volume of material to be reprocessed illicitly, compared with spent fuel, by a factor of around 10 to 25 − a very considerable advantage.

If electro-processing were to be used as part of a proliferation strategy, it should be assumed that the state would seek to use it with more attractive (i.e. lower burn-up) fuel. As noted above, it is to be hoped that proliferation resistant features are possible for fast neutron reactors to exclude the possibility of operating them to produce weapons grade plutonium (e.g. with a breeder blanket or uranium targets).

This discussion highlights the need to minimise proliferation risk through limiting the spread of potentially sensitive technologies.

5.D.4 Some conclusions regarding fast neutron reactors

In principle, the general use of fast reactors would make <u>uranium enrichment</u> obsolete. However, establishing fast reactors on an industrial basis will take some decades, and may be constrained by availability of fuel for initial core loads (i.e. until self-sustainability is achieved). For most of this century, light water reactors are expected to have an important role (with other thermal reactors such as pebble bed reactors also having a place), so there will be a continuing need for enrichment for the foreseeable future. An increase in global enrichment capacity will be needed from as early as the coming decade.

As regards <u>reprocessing</u>, however, the development of fast reactors together with advanced spent fuel treatments such as electro-metallurgical processing could make the current aqueous reprocessing technology obsolete in the foreseeable future. If the viability of these new technologies is proven – and dependent on the timing of introduction of fast neutron reactors – there should be no requirement to build new plutonium separation plants. Instead, management of spent fuel from light water reactors would be based on advanced spent fuel treatment and recycle through fast reactors. However, for safeguards purposes there will be an ongoing need to counter the possibility of clandestine plutonium separation.

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29. Depending on the type of fuel and the proportion of uranium and other materials retained with the plutonium etc, the electro-processing product will be between around 4% and 10% of the initial spent fuel.

Table 1: Proliferation resistance of various reactor systems

The following is an indicative qualitative comparison of proliferation resistance for various reactor types and fuelling arrangements, relative to a light water reactor operated on the once-through cycle (the base case).

Proliferation resistance is shown in descending order, from most resistant to least resistant. This is a simplified representation, there are many complexities that cannot readily be taken into account in a summary table of this kind. Some of these are touched on in the notes.

Reactor type	Produces weapons grade material, or can be readily operated to do so	Independent of imported uranium [1] or thorium	Uses separated Pu or U-233
Light water reactor [LWR] with fuel leasing [2]	no	no	no
Pebble bed reactor	no	no	no
Base case: **LWR with once-through cycle**	no	no	no
Fast neutron reactor, with recycle using electro-processing [3]	no	yes	no
On load refueling reactor – natural uranium [4]	yes	yes	no
LWR with MOX fuel [5]	no	no	yes
Thorium reactor [6]	yes	yes	yes
“Traditional” fast breeder reactor [7]	yes	yes	yes

Notes:

1. Assumes state does not have enrichment.
2. Fuel supplied on “as needed” basis, spent fuel removed from state.
3. No breeding “blanket”, all Pu production in core (with resultant high burn-up), no Pu separation.
4. Historically some OLR types have been operated to produce Pu for military use. For some other OLR types, operation to produce weapons grade Pu could be complicated – but OLRs are more readily useable for this purpose than LWRs.
5. Assumes imported MOX, no reprocessing by state. The proliferation risk here is with diversion of fresh MOX fuel and separation of Pu content.
6. Where reprocessing required for separation of U-233. The liquid fuel reactor concept, if it proceeds, would avoid this requirement.
7. With breeding blanket, and reprocessing to separate Pu.

6. Suggestions to Commissioners

Commissioners may wish to consider the following issues:

- Endorsement of proliferation resistance as an essential objective in the design and operation of nuclear facilities.

- Importance of institutional and technical proliferation resistance measures to be used together – institutional measures will be discussed in further papers.

- Support for further steps to eliminate weapons grade materials in civil programs, and to avoid production and use of these materials. Issue of civil use of weapons grade plutonium released from military programs to be further considered (how to avoid proliferation and terrorist risks).

- Increasing use of plutonium recycle, and prospective introduction of fast neutron reactors, present particular non-proliferation challenges – essential for these developments to be pursued in ways which enhance non-proliferation objectives and avoid adding to proliferation and terrorism risks.

ANNEX A

FISSILE MATERIAL

While proliferation resistance is usually discussed in the context of technology, proliferation concerns relate to proliferation-sensitive nuclear materials. A key part of reducing proliferation and terrorism risk in civil programs is to minimise the use of sensitive nuclear materials, especially weapons grade materials.

Fissile materials consist of isotopes[30] whose nuclei fission (split) after capturing a neutron of any energy. In practical terms, only one fissile material exists in nature, the isotope uranium-235. However, natural uranium contains only 0.711% of this isotope – over 99% of natural uranium consists of the non-fissile isotope U-238.

Nuclear weapons require either highly enriched uranium (HEU) or separated plutonium, i.e. plutonium separated from spent fuel or irradiated targets.[31] Production of HEU and separated plutonium requires the use of suitable nuclear facilities.

A. Highly enriched uranium

Enriched uranium is uranium in which the proportion of the fissile isotope uranium-235 has been concentrated above the 0.711% found in nature. This requires the use of a uranium enrichment facility. Uranium enrichment is a physical process for increasing the proportion of the fissile isotope U-235 in a given quantity of uranium.

For the operation of the currently predominant type of power reactor − the light water reactor − the proportion of U-235 must be increased typically to between 3% and 5%. This is described as low enriched uranium (LEU). The upper limit of the LEU category is just under 20% U-235.

Table 2 – Uranium isotopic compositions

	U-235 %	**U-238 %**
Natural uranium	0.7	99.3
Typical LEU fuel	4	96
HEU	≥ 20	≤ 80
Weapons grade	≥ 90	≤ 10

Highly enriched uranium is uranium in which the U-235 content is 20% or above. In theory a nuclear explosive device could be made from HEU at 20% enrichment, but this

30. Isotopes are variations in the atoms of a particular chemical element. The atomic number of an element is defined by the number of protons in its nucleus, e.g. in the case of uranium, 92. Where atoms of the same element have different numbers of neutrons, these variations are known as isotopes. For example, uranium-235 has 92 protons and 143 neutrons, uranium-238 has 92 protons and 146 neutrons.
31. In this context, targets are items, other than fuel, made from uranium and intended to be placed in a reactor to produce plutonium.

is not practical (because of the mass of material involved). While nuclear weapons have been made from HEU at around 80% enrichment[32], weapons grade uranium is usually described as having an enrichment level of 90% and above.

B. Plutonium

Plutonium is produced in the fuel of all uranium-fueled reactors, but is retained within spent fuel unless separated through a chemical process known as reprocessing. Thus, to obtain separated plutonium requires both a reactor and a reprocessing (or plutonium extraction) facility.

Plutonium is formed through neutron capture. The predominant uranium isotope U-238 is described as *fertile*, i.e. when irradiated in a reactor it can capture a neutron and transform into a new element, plutonium. The initial plutonium isotope formed is plutonium-239, which is fissile. Higher irradiation levels (usually equating to longer periods in the reactor) result in additional neutron capture, producing higher plutonium isotopes, e.g. Pu-240, Pu-241 and Pu-242. Increased irradiation also produces quantities of a lower plutonium isotope, Pu-238.[33]

Pu-239 is the plutonium isotope of primary interest for nuclear weapons. Pu-238 and the plutonium isotopes higher than Pu-239 have properties which present technical difficulties for weapons use (high spontaneous fission rate, radiation and heat levels). Weapons grade plutonium is defined as comprising no more than 7% of the isotope Pu-240, i.e. around 93% Pu-239.

Table 3 – Plutonium isotopic compositions[34]

	Pu-239 %	**Pu-240 %**
Weapons grade	≥ 93	≤ 7
Reactor grade	≤ 77	≥ 19
Typical light water reactor fuel	56	24

Plutonium intended for nuclear weapons use (weapons grade) is produced in reactors designed so that fuel can be readily removed after only a short time in the reactor. The object is to produce "low burn-up" fuel, fuel that can be removed after only a few weeks, before too high a proportion of higher plutonium isotopes is produced. By contrast, "reactor grade" plutonium − plutonium produced through the normal operation of a power reactor − is defined as having 19% or more Pu-240. In fact, typically reactor grade

32. The "Little Boy" bomb dropped on Hiroshima used HEU enriched to slightly more than 80% U-235.
33. The isotope Pu-241 is fissile, while the isotopes Pu-238, Pu-240 and Pu-242 are fissionable, i.e. they can be fissioned only by high energy ("fast") neutrons. In addition to the higher plutonium isotopes, the isotope Pu-238 is produced through a chain of neutron absorptions and radioactive decays starting from U-235.
34. Table does not show Pu-238, Pu-241 and Pu-242 content.

plutonium has around 25% Pu-240, which equates to less than 60% Pu-239. Such plutonium results from fuel spending 3-4 years in a reactor ("high burn-up" fuel).

Once plutonium is formed in reactor fuel, to be available for use in nuclear weapons it has to be separated from the fuel through reprocessing.

C. Uranium-233

U-233 is another fissile material. U-233 is produced in the thorium fuel cycle, through neutron capture by the fertile thorium isotope, Th-232 (similar to the production of plutonium from U-238). The thorium fuel cycle requires separation – i.e. reprocessing – of U-233 produced in the fuel, and the recycle of U-233 as fresh fuel.

Because to date the thorium fuel cycle remains experimental, quantities of U-233 are limited, and in practical terms U-233 is not currently considered a significant proliferation concern. The situation could change, however, if thorium reactors entered into service. The thorium fuel cycle is discussed further in section 5.C.

ANNEX B

OUTLINE OF PROLIFERATION SCENARIOS

The main proliferation scenarios relevant to this paper are as follows.

1. Uranium enrichment

(a) Operating declared plant to produce HEU;

(b) Diversion of LEU from declared plant – i.e. undeclared removal of LEU – for use as feed in undeclared enrichment plant (d);

(c) Undeclared production of LEU using declared plant – i.e. introduction of undeclared feed and removal of resulting LEU product – for use as feed in undeclared enrichment plant (d);

(d) Establishment of undeclared plant to produce HEU – using as feed undeclared uranium, or diverted LEU as per (b) or (c);

(e) Break-out scenario – operating declared plant to produce HEU, likely using accumulated LEU as feed.

2. Fuel fabrication

Diversion of LEU, to use as feed for undeclared enrichment facility.[35]

3. Power reactors

(a) Operation of reactor to produce plutonium at or near weapons grade – diversion as per (b) or (c), reprocessing per (e);

(b) Diversion of spent fuel from reactor – possibly in association with (a) – reprocessing per (e);

(c) Diversion of spent fuel from spent fuel storage – possibly in association with (a) – reprocessing per (e);

(d) Irradiation of undeclared uranium targets[36] – reprocessing per (e);

(e) Establishment of undeclared reprocessing plant or large-scale hot cells to separate plutonium from spent fuel or targets obtained as above;

(f) Break-out scenario – optimizing operation of reactors to produce weapons grade plutonium, reprocessing as per (e) or 5.(b).

4. Where MOX fuel used

Diversion of fresh MOX[37], processing to separate plutonium.

5. Reprocessing (declared plant)

(a) Diversion of plutonium product.

(b) Break-out scenario – dedicated reprocessing to recover weapons grade plutonium.

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35. Fuel fabrication cannot *produce* fissile material – so fuel fabrication is not classed as a sensitive activity – but a fuel fabrication facility could present risk of diversion.

36. In this context, targets are items, other than fuel, made from uranium placed in a reactor to produce plutonium.

37. MOX is mixed oxides of plutonium and uranium.