IAEA-SM-367/15/07

PROLIFERATION-RESISTANCE AND SAFEGUARDABILITY OF INNOVATIVE NUCLEAR FUEL CYCLES

V.BRAGIN, J.CARLSON AND R.LESLIE
Australian Safeguards and Non-Proliferation Office
R G Casey Building, John McEwen Crescent
Barton, ACT 0221, Australia

R. SCHENKEL, J. MAGILL AND K. MAYER
Institute for Transuranium Elements, European Commission
Postfach 2340, 76125 Karlsruhe
Germany

Abstract

The nuclear non-proliferation regime rests on several elements that complement and reinforce each other. The political commitment of States against possession of nuclear weapons is reinforced by institutional measures, the most important being IAEA safeguards, which provide a high level of assurance of compliance with obligations through international verification. The institutional barriers against proliferation, such as treaty regimes and associated verification arrangements, can be effectively reinforced by technological barriers. This paper discusses basic approaches that could be taken to enhance the proliferation resistance of the nuclear fuel cycle. This general discussion is followed by illustrative examples of some topical concepts of proliferation-resistant nuclear fuel cycles that are being promoted by various experts and countries.

1. INTRODUCTION

The nuclear non-proliferation regime can be strengthened by the introduction of proliferation-resistant features at relevant stages of the nuclear fuel cycle that would serve as intrinsic technological barriers to proliferation. These technological barriers can be used to reinforce the existing institutional barriers to proliferation such as treaty regimes and associated verification arrangements. This has not been a priority to date, because institutional efforts at containing the spread of sensitive technology have been largely effective, and because nuclear power generation programs do not normally involve weapons-grade material. However, the possibility of increasing the use of plutonium fuels in future is prompting renewed interest in technological approaches in support of non-proliferation objectives.

While there is no such thing as a proliferation-proof nuclear fuel cycle, numerous concepts have been put forward by experts of various States with the aim of developing a fuel cycle with enhanced resistance to proliferation. Intrinsic technological elements of nuclear facilities can make it difficult to gain access to materials, or to misuse facilities to produce weapons-useable materials. The extent to which facilities, equipment and processes are resistant to the production of weapons-useable materials represents an important technological barrier to proliferation, independent from institutional barriers.

With the introduction of the Model Additional Protocol (INFCIRC/540) and the move towards integrated safeguards, technological barriers to proliferation can be given additional weight in the development and practical implementation of safeguards approaches to States as a whole. Hence this paper also addresses the safeguardability of the future nuclear fuel cycle, namely: what needs to be done to make the proposed innovative systems compatible with the requirements of the current, and anticipated future, verification approaches and technologies.

Starting with a brief discussion of the strategic value of the nuclear material, we proceed to a review of basic approaches to enhance proliferation resistance of the nuclear fuel cycle. This general discussion is followed by illustrative examples of some topical concepts of proliferation-resistant nuclear fuel cycles that are being promoted by various experts and countries.

2. THE STRATEGIC VALUE OF NUCLEAR MATERIAL

2.1. Weapons-Grade Materials

The strategic value of any particular form of nuclear material is determined by the effort that would be required to convert the material into a weapons-useable form. The manufacture of nuclear weapons requires either pure uranium metal at very high enrichment levels (though the HEU category starts at 20% U-235, *weapons-grade* uranium comprises 93% or more U-235) or pure plutonium metal preferably with a very high proportion of Pu-239 (*weapons-grade* plutonium comprises less than 7% Pu-240). Materials that are used or stored in a form suitable for weapons have the highest strategic value. Historically such material has been produced in facilities designed and operated for this particular purpose.

2.2. Materials in Civil Programs

These weapons-grade materials are very different to those normally produced in civil programs: low enriched uranium (LEU) typically used in light water reactors and reactor-grade plutonium. The utilisation of LEU as a source material for weapons would require chemical, isotope separation and metallurgical processes, increasing the time frame for the production of weapons-useable material significantly compared to the use of HEU as the source material. Any attempt to utilise reactor-grade plutonium for weapons would encounter substantial technological challenges compared to the use of weapons-grade plutonium. As discussed below, the strategic value of the materials involved in the civil fuel cycles can be reduced further by increases in the proliferation barriers associated with the isotopic composition and chemical form of the material.

2.3. Proliferation Metric

A first estimate of the suitability of nuclear material for weapons use can be obtained from the proliferation metric developed at the Institute for Transuranium Elements [1]. This metric can be used to assess the proliferation potential of the uranium or plutonium isotope "vector" at any stage in the fuel cycle. The metric consists of four quantities relevant to the construction of a nuclear weapon: the bare critical mass (M), which gives an indication on the amount of material required to manufacture a weapon, and the radiation vector (**R**) consisting of the neutron emission rate (N), the heat generation rate (H) and the gamma dose rate (D) from this mass, which give an indication of the handling problems which can be expected. The proliferation metric can be written as:

$$(M; \mathbf{R}) = (M; D, H, N).$$

As an example we consider the proliferation metric applied to weapons- and reactor-grade plutonium. For weapons grade plutonium ((94% Pu-239, 6% Pu-240), the metric gives:

$$(M; D, H, N) = (9.6\text{kg}, 0, 22\text{W}, 7\text{x}10^{5}\text{neutrons/s}).$$

The same metric applied to reactor-grade plutonium in spent fuel (47.5 GWd/tHM) gives:

$$(M; D, H, N) = (11.9\text{kg}, 0, 217\text{W}, 6.7\text{x}10^{6}\text{neutrons/s}).$$

From this one can see that although the critical masses of weapons- and reactor-grade plutonium are similar in magnitude, the neutron emission and heat generation rates are an order of magnitude higher in reactor-grade plutonium that makes this material less suitable for use in weapons.

3. MATERIAL ACQUISITION PATHS AND TECHNOLOGICAL BARRIERS

There is a variety of paths available for States that might wish to attempt acquiring fissile material in violation of their international commitments. Safeguards provide the international community with means to deter or detect such violations. For there to be a high enough probability that any diversion of fissile material would be detected in a timely fashion, the IAEA considers each plausible acquisition path and introduces verification measures to deal with *all* feasible paths in an appropriate way. If the Agency devoted a great deal of resources to addressing some material acquisition paths at a facility but ignored others (even if only one is left uncovered), then the overall result would be less than satisfactory. Hence the Agency performs a thorough "diversion path analysis" and tailors the implementation of its safeguards efforts to address the real risks of diversion.

Technological barriers to proliferation have the potential to facilitate the development and implementation of safeguards approaches by rendering some of the material acquisition paths difficult or impossible to use, that would make safeguards more efficient and cost-effective. There are at least three basic approaches to enhance proliferation resistance of power reactors and associated fuel cycle facilities by technological means, namely:

- reduction of the strategic value of the materials involved in nuclear power generation at all stages of the nuclear fuel cycle;
- incorporating design features that would eliminate some (if not all) of the material acquisition paths and make weapons-useable material highly inaccessible; and
- incorporating design features that would facilitate practical safeguards implementation.

4. REDUCING THE STRATEGIC VALUE OF NUCLEAR MATERIAL

This could be achieved by eliminating or at least minimising the use of weapons-useable material at all stages of the nuclear fuel cycle. Conceptually there are at least two principal ways in which the strategic value of the material can be reduced:

- by changing the isotopic composition of the materials involved in the fuel cycle to ensure they are not (or are less) suitable for weapons purposes; and
- by increasing the chemical barriers to diversion that would make, for example, reprocessing and recovery of fissile material from irradiated material more difficult.

In general, any reduction in the strategic value of nuclear material will simplify the task of the design of a safeguards approach to the facility, and make safeguards both cheaper to the IAEA and less intrusive for the operator.

4.1. Reducing the Isotopic Quality of the Nuclear Material

The *isotopic composition* of the material intended for use in weapons directly relates to the relative difficulty of manufacturing a nuclear weapon with material of a specific isotopic composition or altering its isotopic composition to obtain weapons-useable material. In other words, materials with a higher isotopic proliferation barrier would require more advanced (and thus hopefully less available to would-be proliferators) weapon designs and technology for their processing into weapons-useable form.

As noted in section 2.3 the attributes that are important for determining the effectiveness of the isotopic proliferation barrier and which need to be taken into account when designing and manufacturing a nuclear device include:

- the critical mass of material, an attribute directly associated with its isotopic composition (M);
- the spontaneous neutron generation rate that might complicate design, and affect a weapon's yield and reliability; lower neutron generation rate represents lower proliferation barrier; for plutonium, this is strongly dependent on the concentration of Pu-240 and Pu-242 isotopes (N);
- the heat and radiation generation rates are other factors to be taken into account when designing and manufacturing nuclear device; the radiation released by the material itself interferes with the handling, processing and design of a nuclear device; lower radiation level represents lower barrier; for plutonium, this is dependent on the concentration of Pu-240 and Pu-242; for separated U-233 this is dependent on the presence of U-232; heating produced by nuclear decay of the material complicates device design; lower heat generation rate represents lower barrier; for plutonium, this is strongly dependent on the concentration of Pu-238 (D and H).

In terms of the proliferation metric, maximising the values of the scalar properties M, N, D and H will maximise the proliferation metric vector and minimise the attractiveness of any given quantity of material to a potential proliferator.

Currently safeguards give only a limited recognition of the importance of the isotopic composition of the material to its proliferation significance. In the case of plutonium, for example, the only isotopic distinction that the IAEA currently acknowledges relates to the proportion of Pu-238 within a given batch of plutonium. Plutonium comprising 80% or more Pu-238 is acknowledged as being unsuitable for explosive use. For uranium the Agency recognises that uranium that is less than 20% enriched is of less immediate use to a proliferator than uranium enriched to 20% or greater.

As the safeguards system develops, there may be scope for recognising further distinctions in the isotopic composition of nuclear material. The proliferation metric provides a quantifiable means of ranking the attractiveness of material to proliferators. Consideration of the proliferation metric also provides a framework in which consideration of the effectiveness of any proposed method to address proliferation concerns (e.g. spiking, isotopic dilution etc.).

For example, if the material in question would require extensive processing facilities it will clearly be less desirable for a proliferator than material that is more readily applicable for weapons use, and there may be scope to reflect this in some reduction in inspection effort. This line of reasoning can be applied to the production of fuel for new reactor designs. As one example, if a particular proportion of Pu-238 degrades the utility of plutonium for explosive use, then introduction of appropriate (possibly quite small) quantities of Pu-238 at the fabrication stage may render the resulting fresh (in the case of MOX) and spent fuel unattractive to potential proliferators. While the "spiking" of fuel would complicate the storage and handling of fresh fuel and have some effect upon the reactivity of the reactor, associated costs may be acceptable if they result in spent fuel that has a high intrinsic proliferation resistance. It may be possible to reduce the safeguards applied to such material to a much lower level than would otherwise be possible.

4.2. Increasing the Chemical Barrier

The *chemical form* of material can also serve as a proliferation barrier. This relates to the relative effort required to refine materials into the appropriate form or chemically process fissile material to separate it from accompanying diluents, contaminants or any other admixtures that might be incorporated to frustrate chemical separation, in order to obtain materials of sufficient purity for weapons applications. The chemical barrier effectiveness of some of the more common materials involved in the nuclear fuel cycle can be roughly classified in the following order (from simplest to most difficult): pure metals, conventional compounds (for example, oxides, nitrides), mixed compounds (for example, fresh MOX fuel), spent fuel, non-conventional compounds (for example, carbides and silicides), and vitrified wastes (borosilicate glasses and titanium oxide forms).

If the fuel at a facility has features that render it unsuitable for reprocessing and fissile material recovery there is a case to be made for substantially decreasing the intrusiveness of the safeguards applied to the facility as part of the application of an integrated safeguards regime. Silicide (and to a lesser extent carbide) fuels present substantial difficulties for existing reprocessing technologies when compared with oxide or metal fuels. The material is not completely intractable, but the processing of this material to recover fissile material is substantially more difficult than for most other fuel forms and, in general, it would require far longer conversion times to produce useable weapons components.

Under an integrated safeguards system the longer conversion times required for fuels which cannot readily be reprocessed can be taken into consideration in determining the inspection frequency and the intrusiveness of the inspection measures applied to the facility. It should be noted that choosing an intractable fuel form might have substantial fuel management implications and it would have to be considered in the context of an overall fuel cycle strategy.

5. DESIGN FEATURES PREVENTING DIVERSION OF MATERIAL

5.1. Use of Radiation Field

The radiation hazard associated with nuclear material is a substantial proliferation barrier due to the external dose potential to humans and the damage the radiation field could inflict on the equipment and non-nuclear materials needed to manufacture a complete operational nuclear device. The effectiveness of radiological barriers could be characterised by the associated dose rates or the time required for the accumulation of a lethal dose. Thus materials could be categorised by the degree of remote handling required: starting with those suitable for unlimited hands-on handling and ending up with materials requiring fully remote and/or shielded facilities.

5.2. Facility Unattractiveness

The extent to which civil nuclear fuel cycle facilities are resistant to modifications required to convert them to the production of weapons-useable materials is another important intrinsic proliferation barrier. Those facilities, equipment and processes that cannot be modified to produce weapons-useable material would have a higher proliferation barrier. A number of attributes can be used to characterise facilities by this criterion: the complexity of modifications needed to convert the facility to production of weapon-useable materials, including the need for additional specialised equipment, materials and technical knowledge; the availability of such specialised skills, material and knowledge to the country of proliferation concern; the safety implications of the facility's modification; the time and effort required to perform such modifications; facility throughput or, in the case of reactors, power level; and environmental signatures associated with facility modification and misuse.

5.3. Access to Material

The extent to which facilities and equipment inherently restrict access to fissile materials represents an important barrier independent from institutional barrier including security and access controls that limit access. Limiting, for example, the lifting capacity of cranes in the pond area and designing the structural limitations of the reactor area to ensure that there are only a limited number of possible paths for spent fuel to follow can serve as a useful adjunct to other proliferation limitation strategies.

6. DESIGN FEATURES FACILITATING SAFEGUARDS IMPLEMENTATION

Safeguards are most easily applied to facilities in which movements of fuel and all other general maintenance activities are conducted exclusively during refuelling outages. Any equipment hatches must be able to be readily sealed and remain sealed for the entire time between refuelling outages. Provision of suitable locations for the attachment of seals should be incorporated into hatch design. Personnel hatches should be designed so that it is impossible for them to be used as an exit point for fresh or spent fuel.

If spent fuel is to remain on the reactor site between refuelling operations, it should be stored either in spent fuel ponds inside the reactor containment building or transferred to separate storage ponds outside the reactor containment by a transfer channel designed so that it can be readily sealed between refuellings. Provision of suitable locations for the attachment of seals should be incorporated in the design of the transfer channel – many existing facilities are difficult to safeguard satisfactorily because the transfer channel cannot be sealed effectively.

If spent fuel is stored outside of the reactor containment the engineering design of the transfer channel should be such that the only possible path for spent fuel is between the reactor and the storage ponds. The external storage pond area should be designed so that the only time its cask transfer hatches need to be unsealed is when an offsite transfer of spent fuel is taking place. Additional "safeguards-friendly" engineering measures include ensuring that cask transfer hatches can only be opened if the transfer channel from the reactor containment has been closed and sealed (this ensures that there is no path for the removal of unreported fissile material from the core).

During refuelling operations, the IAEA generally maintains continuity of knowledge on the material in the core and covers the "unreported production" scenario by the use of surveillance systems. Provision of suitable places for the mounting of cameras and placement of recording equipment should be included in the design of the reactor hall.

In addition to the design features discussed above future nuclear power generating systems could be designed in ways that would facilitate the application of advanced verification techniques and minimise the interference with routine facility operations. Design features could facilitate a move from inspector-carried and -operated verification instruments towards stationary, integrated and computercontrolled systems used by both the IAEA and the operator. This would include built-in systems for unattended measurement, remote monitoring and secure data transmission to the IAEA Headquarters. This could also incorporate built-in systems to conduct real time analysis of the information resulting from all verification activities at the facility, including measurements of material characteristics and facility operating parameters. Future verification systems could probably enable the IAEA to arrive at safeguards implementation conclusions much faster than the currently technology allows. This would make safeguards implementation more flexible and effective. A useful practical example would be the development and installation at future reactors of built-in systems providing and transmitting to Vienna real-time information on reactor operations, including outages, power levels, abnormal regimes of operation. Another example would be improved monitoring systems for storage, processing and use of fissile material.

7. SOME TOPICAL CONCEPTS OF PROLIFERATION-RESISTANT FUEL CYCLES

In this section we discuss very briefly selected topical concepts of proliferation-resistant fuel cycles that are being promoted by various experts and countries.

7.1. Direct Use of Spent PWR Fuel in CANDU Reactors (DUPIC)

An interesting example is the proposed DUPIC process that is being developed through collaboration between KAERI, AECL and LANL [2] and that can reduce uranium requirements and spent fuel arisings by direct re-fabrication of spent PWR fuel into CANDU reactor fuel. Several features of this process enhance its proliferation resistance relative to fuel cycles employing separated plutonium. The dry thermal-mechanical fuel processing contrasts with conventional wet reprocessing, in which spent fuel is separated into uranium, plutonium and fission products or actinides. The plutonium concentration remains dilute throughout the entire fabrication process, making it difficult to divert a significant quantity of plutonium. All stages of the fabrication process, as well as final fuel itself, are highly radioactive. Thus all processing and handling must be done in a shielded facility, making diversion difficult. The processing facility is entirely self-contained: spent PWR fuel is an input to the facility, and finished DUPIC fuel bundles are the product. There is no transport of any intermediate products.

7.2. Plutonium Multi-Recycling in Conventional PWRs

Currently, only partial mono-recycling of plutonium in the form of mixed uranium and plutonium oxide (MOX) is applied to PWRs. However, French studies have shown the feasibility of multi-recycling in conventional PWRs, if a new type of fuel based on plutonium combined with enriched uranium is developed. The Advanced Plutonium fuel Assembly (APA) [3], compatible with the internals of PWRs, which enables complete multi-recycling of plutonium and potentially of minor actinides in PWRs. The design is based on a large annular rod consisting of thin plutonium rings on an inert support, cooled on both sides like plate fuel. The absence of plutonium generation and the relatively low fuel temperature, reducing the release of fission gases, translate into very high achievable burnups. The high moderation ratio, favours plutonium consumption, improves heat removal, minimises the production of minor actinides.

7.3. Proliferation-Resistant Fuels (PRFs)

PRFs have been proposed by researchers in several countries [4] including France, Italy, Switzerland, Japan and the United States as an effective means to dispose of excess plutonium. PRFs are designed to behave like standard, low-enriched uranium fuel, enabling them to be used in standard LWRs without reactor modification. PRFs encapsulate plutonium and burnable poisons in a non-uranium matrix. Because they do not contain uranium or thorium, PRFs do not produce plutonium or uranium-233 as opposed to MOX or thorium fuels. Consequently, PRFs can destroy more of their plutonium charge than MOX over identical reactor cycles. Thus burning plutonium in PRFs will enhance the proliferation resistance of the commercial fuel cycle. Spent PRF is less attractive than spent MOX as a source for weapons plutonium. In the absence of the *in situ* production of Pu-239 or U-233 found in MOX and thorium fuels, respectively, an extremely deep burn-up of the plutonium is possible, producing a spent fuel that goes well beyond the spent-fuel standard. In place of the UO_2 in MOX, PRFs blend a non-fertile-oxide-diluent and burnable poisons with PuO_2. The resultant ceramic is more chemically durable than MOX. Consequently, none of the proposed PRF inert matrices can be processed by conventional PUREX reprocessing. In short, more spent PRF would have to be processed to recover the same amount of plutonium than could be recovered from spent MOX, it would take longer to fabricate a weapon from spent PRF, the weapon design would be more complex, and its performance would be much less reliable.

7.4. Radkowsky Thorium Fuel

A novel fuel-cycle concept has been developed [5] to address the proliferation issues. The concept assumes a once-through fuel cycle without reprocessing. The U-233 that is bred is mostly burnt *in situ,* and the fuel rods that contain the U-233 (which is denatured by non-fissile uranium isotopes) are then disposed of. The main idea of the proposed concept is the utilisation of the seed-blanket unit (SBU) fuel assembly geometry that allows a spatial separation of the uranium (mostly in the seed) and thorium (blanket) parts of the fuel. The central region of the assembly (seed) includes uranium enriched to a maximum of 20%. The external region of the assembly (blanket) includes natural thorium spiked by a small amount of 20%-enriched uranium. One of the novel features of the RTF concept is its in-core fuel management scheme. The standard multi-batch fuel management of a PWR is replaced by a scheme, based on two separate (seed and blanket) fuel flow routes. Seeds are treated similarly to standard PWR assemblies, ie one-third of seeds are replaced periodically by "fresh" seeds, and the remaining seeds are reshuffled together with partially depleted blankets to form a reload configuration for the next cycle. For reasons of fuel economy, the thorium blanket in-core residence time is about 10 years to achieve an accumulated burnup of 100 GWd/t for the thorium part of the fuel. The main design objective of the RTF concept is a reduction in the spent fuel storage requirement and in its long-term toxicity. These objectives are achieved by a partial replacement of uranium by thorium, and consequently a major reduction in the amount of Pu and other transuranic isotopes. The total discharged fuel inventory is approximately one third compared with the PWR inventory.

7.5. Gas Turbine – Gas Cooled Reactors

General Atomics is the industrial pioneer of the Gas Turbine – Modular Helium Reactor (GT-MHR), an ultra-safe, meltdown-proof, helium-cooled reactor, to meet the need for safe and economical nuclear-generated electricity and process heat. The reactor is characterised by inert helium coolant, graphite as the core structural material and refractory-coated particle fuel, which retains fission products at very high temperatures. In the GT-MHR, the high temperature helium coolant directly drives a gas turbine coupled to an electric generator. The efficiency of the system is about 48%. This is about 50% more efficient than today's first generation reactors. A typical GT-MHR module yields a net output of about 285 MWe. The reactor can be fuelled with uranium or plutonium. This system permits sequential construction of modules to match the user's growth requirements. In early 1995, General Atomics and Russia's MINATOM began a joint program to design and develop a GT-MHR for use in Russia for destruction of weapons-grade plutonium.

South African Pebble Bed Modular Reactor (PBMR) is another high-temperature helium-cooled reactor using a direct cycle gas turbine. Helium is used as the coolant and energy transfer medium to a closed cycle gas turbine and generator. Essentially it is a nuclear plant which is inherently safe, presents lower-cost options and facilitates problem-free siting. This nuclear power plant uses uranium elements (pebbles) encased in graphite to form a fuel sphere (about the size of a tennis ball). About 400,000 of these fuel balls will lie within a graphite-lined silo that will be 10m high and 3.5m in diameter. Helium at a temperature of about 500°C is introduced into the top of the reactor. After the gas passes between the fuel balls, it leaves at the bottom at a temperature of about 900°C. This gas passes through three turbines. The first two turbines drive compressors and the third the generator, from where the power emerges. At that stage the gas is about 600°C. It then goes into a recuperator where it loses excess energy and leaves at about 140°C. A water-cooled pre-cooler takes it down further to about 30°C. The gas is then re-pressurised in a turbo-compressor before moving back to the regenerator heat-exchanger, where it picks up the residual energy and goes back into the reactor. Spent fuel balls are passed pneumatically to large storage tanks at the base of the plant where there is enough storage capacity to store all spent fuel throughout the life of the plant. The tanks are also designed to hold the spent fuel for 40 to 50 years after shutdown. About 2.5-million fuel balls will be required over the 40-year life of a 100 MW reactor.

The high temperature gas cooled reactors (both GT-MHR and PBMR) serve as good examples of systems that provide technical barriers to proliferation.

The nature of the fuel is such that each fuel item contains only a very small quantity of fissile material. In the case of the PBMR it is planned to have 9g of LEU per assembly – the design of the fuel has the fissile material dispersed in a relatively large volume of inert matrix material. A proliferating State will have to divert a very large number of fuel elements (tens of thousands) in order to obtain a significant quantity of fissile material – the inert matrix material will substantially increase of the bulk of the material to be diverted and will complicate the handling and storage of the diverted material and makes the mechanical crushing of the material physically more difficult.

The fuel forms chosen for these reactors feature carbides and silicides, which provide natural barriers to reprocessing and recovery of fissile material. The fuel itself is not impossible to reprocess – but it presents substantial difficulties for all existing, commercial scale reprocessing technologies and may allow for relaxation of existing timeliness limits (in the context of integrated safeguards) due to the difficulties inherent in reprocessing such fuel. This inert matrix material complicates the acid dissolution of the assemblies because the different chemical forms present within each assembly are difficult to treat chemically when placed in combination.

The planned operating cycles of the reactors result in extremely high burn-up for the fuel (typically 100 GWd/tU) raising the isotopic barrier for proliferation on spent fuel. The plutonium contained in PBMR fuel is likely to be less than 55% Pu-239 ensuring that the fissile material within each assembly has a heat output level and a high spontaneous fission rate. While the Agency gives little recognition of the importance of the Pu isotopics to a proliferator there are clearly additional complications involved in designing a weapon using fissile material that is a significant source of both heat and unwanted neutrons. In terms of the proliferation metric – M, H, D and N have been maximised and this substantially reduces the attractiveness of the spent fuel material to would-be proliferators.

As a result of the high burnup of the fuel the radiation barrier to proliferation is very high. Each individual pebble will have a radiation output that ensures that it can only be handled from behind massive shielding and via remote means. Any equipment required for the diversion of the spent fuel has to be similarly shielded and managed remotely, complicating diversion scenarios and increasing the likelihood of the discovery of the preparations for diversion.

The designs of the facilities are such that they provide clear points at which fuel flows can be measured and safeguarded. The use of LEU fuel will require limited controls on the fresh fuel and the centralized nature of the spent fuel handing operations are well suited to the use of unattended monitoring systems.

7.6. BREST Reactor

Fast neutron reactors are largely on hold at the moment, mainly for economic reasons (depressed uranium prices), but also because of engineering complications and public concerns. If nuclear energy is to realise its potential as a major source of electricity, however, the efficient use of uranium reserves will require programs based on plutonium breeding and recycle. Moscow Research and Development Institute of Power Engineering is working on an innovative concept of a fast lead-cooled reactor BREST with UN-PuN fuel [6]. The proposed reactor has a number of design features that make it proliferation-resistant. The reactor features full plutonium reproduction in the core. There is no use of uranium blankets, precluding production of weapons-grade plutonium. The isotopic composition of plutonium in fresh fuel and spent fuel will be similar. Plutonium is neither extracted nor added to the fuel, to adjust fuel composition U-238 is added to the core to compensate for the fuel burnup. With small reactivity margin in the core, it is not possible to load into the proposed reactor source material for undeclared Pu production. The design eliminates the need for plutonium separation from spent fuel. Spent fuel reprocessing will be reduced to removing the bulk of fission products from spent fuel. The remaining transmuted actinides and 1 to 10% of fission products still remaining in the fuel after incomplete purification create a radiation barrier against diversion at all stages of the cycle. Spent fuel can be cooled for 3 to 12 months in an in-vessel storage facility and then sent directly for reprocessing and re-fabrication at the power plant site. This eliminates long-distance shipments of fuel.

7.7. Modular Liquid Sodium-Cooled Fast Reactor

General Electric is developing a modular liquid sodium-cooled fast reactor called Super-PRISM [7]. Utilising in this concept a dry pyro-processing system that does not separate plutonium from minor actinides enhances the proliferation resistance of the proposed fuel cycle. Due to the compact nature of the dry pyro-processing system, on site processing of the spent metal fuel is a design option. In this case, the fresh and spent fuel storage and receiving facilities would be replaced by a compact co-located Spent Fuel Recycle Facility that integrates spent fuel storage, processing and waste storage and conditioning operations into a single facility. As S-PRISM fuel assemblies can be fabricated and recycled in the SFRF, they do not need to be shipped off-site.

7.8. Encapsulated Nuclear Heat Source

Motivated by the goal to develop an encapsulated nuclear heat source (ENHS) which could be delivered and retrieved unopened after a long core lifetime, a novel reactor concept of an autonomous long-life lead (or lead-bismuth) cooled core was proposed by the University of California at Berkeley (UCB) [8]. This concept appears to be highly suitable for the ENHS that would be inserted into, and later removed from an in-place power plant comprised of a secondary heat transfer circuit and the balance of plant energy conversion equipment. The ENHS would, in fact, constitute a totally new refuelling concept. The ENHS is expected to be highly proliferation resistant, as a consequence of the following features: once for life core and no refuelling operations throughout life.

7.9. Secure, Transportable, Autonomous Reactor (STAR)

LLNL, with the support of ANL, LANL, MIT and others has been working on the concept of a Secure, Transportable, Autonomous Reactor (STAR) [9]. It uses small nuclear power stations with the aim of reducing the proliferation concern associated with the introduction of nuclear power in developing countries. The following features enhance STAR's proliferation resistance: the reactor is delivered pre-assembled and pre-fuelled, hence there is no access to fresh fuel, that eliminates access to fissile materials; highly autonomous operation; reduced requirements for local nuclear infrastructure; reduced containment size; and the concept eliminates much ancillary equipment.

7.10. Double Strata Fuel Cycle

As a way of reducing the amounts and radiotoxicities of nuclear waste, and thereby reducing the burden of nuclear waste repositories, various partitioning and transmutation (P&T) concepts are being investigated worldwide. Both advanced aqueous and pyro-processing schemes are being developed in which minor actinides (MA) and selected fission products are separated from the waste in addition to plutonium. Following separation, the MAs can be fabricated into fuels or targets for transmutation.

In the transmutation scenario, there are two options. The waste can be recycled and transmuted in available conventional reactors (homogeneous fuel cycle option – Pu and MAs kept together), or in dedicated burner reactors (heterogeneous fuel cycle option – Pu and MAs are separated). This latter option is generally referred to as the *Double Strata* fuel cycle. In this context, the European Technical Working Group on ADS has recently published "A European Roadmap for the Developing Accelerator Driven Systems (ADS) for Nuclear Waste Incineration".

In the Double Strata, the first stratum is based on a conventional fuel cycle. Recovered plutonium is recycled as mixed oxide (MOX) fuel in power reactors. The second stratum is primarily devoted to waste reduction where rest Pu, MAs, and long-lived fission products are fabricated into fuels and targets for transmutation in dedicated accelerator driven systems (ADS). In this Double Strata fuel cycle, particularly in the second stratum, there are various proliferation and safeguards issues which need to be addressed related to the new reprocessing schemes, the availability of MAs possibly in separated form, and the misuse of accelerator and spallation sources for fissile material production.

With regard to pyro-processing, it is believed at present that this results in impure plutonium, which is not suitable for making nuclear weapons. The plutonium removed from the salt contains some uranium, other transuranic elements and some fission product contamination, it is so impure and highly radioactive that it would not be suitable for the construction of a nuclear weapon.

Minor actinides at present do not come under international safeguards. However, in 1999, the IAEA Board of Governors issued a recommendation concerning the proliferation risk arising from the minor actinides neptunium and americium. Neptunium monitoring is implemented on a voluntary basis (regarding the production and transfer of separated neptunium). The monitoring of americium is deferred until a later date. Although little has been separated, neptunium and americium are contained in spent fuel or reprocessing waste. In the European Union alone, about 4 metric tons are expected to be produced each year in discharged fuel from reactors. Consequently, the envisaged controls are facing basically two challenges: controls on separated quantities of neptunium and verification that neptunium is not clandestinely separated from spent fuel or reprocessing waste. Techniques are being actively developed for these purposes.

Finally, the accelerators and spallation sources foreseen for the dedicated burner reactors present some new challenges with regard to non-proliferation. Accelerators and spallation sources do not, at present, come under safeguards. It can be shown, however, that even commercially available cyclotrons may be able to produce about 100 g Pu per year. The very much more powerful accelerators foreseen for ADS do, therefore, present a proliferation problem in this respect. For this reason the safeguardability of accelerators and spallation sources is currently under investigation.

8. CONCLUSIONS

Developments in the nuclear industry and in nuclear technology should be considered in the context that the overwhelming majority of countries have given political and legal commitments against the acquisition of nuclear weapons. These commitments are reinforced by the institutional arrangements of the non-proliferation regime, especially by IAEA safeguards, and also by limits on the supply of sensitive technology. Institutional aspects of the non-proliferation regime continue to evolve, for example, through strengthened safeguards, enhanced transparency and current progress towards integrated safeguards regimes as more States bring the Additional Protocol into effect.

The non-proliferation regime can be further strengthened through technological barriers, such as proliferation-resistant features at relevant stages of the fuel cycle. This has not been a priority to date, because containing the spread of sensitive technology has been largely effective, and because there is very little weapons-grade material in civil nuclear programs. However, the possibility of increasing use of plutonium fuels in future, and particularly the development of the plutonium breeding cycle, is prompting renewed interest in technological approaches in support of non-proliferation objectives.

Introduction of the plutonium breeding cycle has been delayed by a number of factors, especially economics, brought about by the slowdown in the growth of nuclear energy and by depressed uranium prices. This delay provides an important opportunity for the international community to ensure that non-proliferation aspects are properly addressed at an early stage in the development of new fuel cycle concepts. While plutonium recycle could present a substantial challenge to non-proliferation objectives, some of the approaches outlined in this paper indicate that, if developed in an appropriate way, plutonium recycle could actually bring major non-proliferation advantages. Consideration of safeguards issues at the design stage of power reactors can produce benefits for both the operator and the IAEA. In an appropriately designed nuclear facility, a simple system of unobtrusive safeguards should provide confidence to the international community that the facility does not represent a risk of proliferation.

Currently there are several national approaches to these issues – this paper has touched on just some of these. While national efforts in this area are indispensable, clearly there is also a need for international co-ordination. To a significant extent this will result from existing and prospective co-operation between national programs, but there is also an important role for the IAEA. This July the IAEA organised in Como, Italy a topical workshop on proliferation-resistance in innovative reactors and fuel cycles. The Workshop was undertaken to define future activities related to proliferation resistance and to consider the broader non-proliferation issues and opportunities that would arise with the introduction of innovative reactors and nuclear fuel cycles. The authors consider it is important that the Agency should continue to work in the direction of assuring that proliferation-resistance and safeguardability are fully taken into account in the development of new technologies, for example, as a part of the IAEA project on innovative reactors and fuel cycles (INPRO), and in support of other initiatives under way by IAEA Member States. It is important for the IAEA's own work in this area to closely involve the Department of Safeguards, and for non-proliferation aspects to be one of the key elements in future work.

---

[1] MAGILL, J., "Non-Proliferation and Safeguards Activities at ITU - Recent Publications", Technical Report, JRC-ITU-TN-2000/19

[2] SULLIVAN, J.D., et al., "Benefits of the DUPIC Fuel Cycle Strategy", Proc. of the Int. Conf. on Future Nuclear Systems, 1999, Jackson Hole, Wyoming; KEIL, H., et al., "Direct Use of Spent PWR Fuel in CANDU: The DUPIC Fuel Cycle", Proceedings of the Global 1993 Conference, Seattle, Washington, USA (1993); RIM, C.S., "Burning LWR Spent Fuel in Heavy Water Reactors", presented at the Scientific Program, Advanced Nuclear Fuel Cycle: New Concepts for the Future, 40th General Conference of the IAEA, September 1996.

[3] PUILL, A., BERGERON, J. AND ROHART, M., "Mastery of the Plutonium Inventory in PWRs: the APA Concept", Proc. of the Int. Conf. on Future Nuclear Systems, 1999, Jackson Hole, Wyoming.

[4] CHODAK III, P. "Using Proliferation-Resistant Fuels to Manage Global Plutonium Inventories: Going Well Beyond the Spent-Fuel Standard", Proc. of the Int. Conf. on Future Nuclear Systems, 1999, Jackson Hole, Wyoming.

[5] GALPERIN, A., et al., "A Thorium-Based Seed-Blanket Fuel Assembly Concept to Enhance PWR Proliferation Resistance", Proc. of the Int. Conf. on Future Nuclear Systems, 1999, Jackson Hole, Wyoming.

[6] LOPATKIN, A.V., ORLOV, V.V., " Fuel cycle of BREST-1200 with non-proliferation of plutonium and equivalent disposal of radioactive waste", Proc. of the Int. Conf. on Future Nuclear Systems, 1999, Jackson Hole, Wyoming; FILIN, A.I., et al., "Design Features of BREST Reactors. Experimental Work to Advance the Concept of BREST Reactors: Results and Plans", Proc. of the Int. Conf. on Future Nuclear Systems, 1999, Jackson Hole, Wyoming.

[7] BOARDMAN, C.E., HUI, M.,"A Competitive Integral Fast Reactor with Enhanced Diversion Resistance (S-PRISM)", Proc. of the Int. Conf. on Future Nuclear Systems, 1999, Jackson Hole, Wyoming.

[8] BOLOORI, A.S., et al., "Once-for-Life Fueled, Highly Modular, Simple, Super-Safe, Pb-Cooled Reactors", Proc. of the Int. Conf. on Future Nuclear Systems, 1999, Jackson Hole, Wyoming.

[9] BROWN, N.W., et al., "The Secure, Transportable, Autonomous Reactor System", Proc. of the Int. Conf. on Future Nuclear Systems, 1999, Jackson Hole, Wyoming.