Proliferation-Resistant Fuel Cycle Strategies

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The views expressed in this presentation are those of the authors and not necessarily the views of the Australian Government.

Introduction

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.

It has been argued by the authors [i] (and many others) that the political commitments and institutional barriers against proliferation, such as treaty regimes and associated verification arrangements, can be effectively reinforced by technological barriers. At the very least, those barriers could make breakout from the non-proliferation regime more difficult and time-consuming, thus providing enhanced deterrence against diversion and better opportunity for the international community to intervene should a State be found to be in breach of its commitments.

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 establishing a system of safeguards to be applied to a State. For the State this could have the benefit of lowering the overall intrusiveness of the international safeguards inspection regime while still allowing the State to demonstrate its compliance with its international commitments. For the IAEA it could have the benefit of slowing the growth in inspection effort and associated costs, allowing effort to be concentrated in areas of the fuel cycle of greatest proliferation concern.

Starting with a brief discussion of the status and trends of the nuclear power, we proceed to the discussion of the strategic value of the nuclear material, fissile material acquisition paths potentially available to a would-be proliferator, and 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. We precede our conclusions with a discussion of the criteria, which are primary considerations in the selection of the future reactor system and associated nuclear fuel cycle.

Status and Trends of the Nuclear Power

In the 1960s, the closed fuel cycle was perceived to be the best option for nuclear energy development. With the anticipation of a rapid growth of installed nuclear capacity and the deployment of Fast Breeder Reactors (FBRs), commercial reprocessing plants were constructed and operated by several States. However, in 1997, at the IAEA Symposium on Nuclear Fuel Cycle and Reactor Technologies, world nuclear experts recognised the new realities [ii] that had brought about a *significant imbalance between the rate of the plutonium separation and utilisation*:

- the lower than expected growth of nuclear electricity generation and the associated rapid fall in natural uranium production and price,
- the delay of fast breeder reactors' commercialisation and the associated accumulation of separated plutonium that has triggered utilisation of MOX fuel in thermal reactors,
- the growing inventory of spent fuel caused by emerging open fuel cycle policies and deferred decision on fuel cycle options, and
- the need to dispose of large inventories of ex-weapons plutonium and HEU.

What kind of developments in power reactors and associated fuel cycle technologies are we going to see during the time period up to the year 2050? Looking at such a long time period is speculative. Nevertheless, a consensus was reached at the aforementioned 1997 Symposium in Vienna that the next 50 years will be dominated by thermal reactors and the number of fast reactors will grow steadily after the year 2050. We will see a large number of advanced concepts of thermal light water and heavy water reactors. Innovative reactor concepts will continue to be proposed and promoted. However, due to the inertia of nuclear technology it might be difficult for the innovative concepts to succeed in the near future.

A fundamental issue remains whether plutonium recycle is desirable, or necessary. Some of the arguments of this debate are as follows:

- the open fuel cycle, involving direct disposal of spent fuel, is an extremely inefficient use of uranium resources, whereas the closed fuel cycle, based on fast neutron reactors, offers the efficient use of uranium resources, including the depleted uranium tails that are currently essentially a waste product,
- the open cycle will eventually lead to the establishment of large-scale plutonium repositories spent fuel might present a proliferation risk in the future, as radiation levels decline and recovery of the plutonium becomes more and more feasible,

- with the closed cycle, on the other hand, large accumulations of plutonium can be avoided and plutonium inventories can be stabilised over time,
- although current circumstances appear to favour the open cycle, this cycle is not viable in the longer term,
- promoting the open cycle as the most acceptable policy option ignores the realities, that nuclear energy will have an important role in meeting environmental and other policy objectives, and that future programs will almost certainly be based on the closed cycle.

We believe, now is the time to address how the nuclear fuel cycle development can proceed in ways that are consistent with and if possible enhance non-proliferation objectives. A challenge for the industry is to assure that proliferation does not occur when advanced plutonium recycle systems are deployed.

THE Strategic Value of Nuclear Material

The strategic value of any particular form of nuclear material is determined by the degree of difficulty that would be experienced in converting the material into a weapons-useable form. Materials that are used or stored in a form suitable for weapons have the highest strategic value.

Weapons-Useable Material

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), produced in enrichment plants designed and operated for this purpose, or
- pure plutonium metal preferably with a very high proportion of Pu-239 (*weapons-grade* plutonium comprises less than 7% Pu-240), produced in reactors designed and operated to produce low burn-up plutonium, and separated from spent fuel or irradiation targets.

These weapons-useable materials are very different to those normally produced in civil programs:

- low enriched uranium (LEU) typically used in light water reactors (LWRs) is in the range of 3-5% U-235; the utilisation of LEU as a source material for weapons would require chemical, enrichment 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,
- reactor-grade plutonium from the operation of LWRs is of around 25% Pu-240 or higher; any attempt to utilise reactor-grade plutonium for weapons would encounter substantial technological challenges compared to the use of weapons-grade plutonium.

Material Features Affecting Its Strategic Value

The *isotopic composition* of the material intended for the use in weapons could be an efficient barrier to proliferation as it 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) weapon designs and technology for their processing into weapons-useable form.

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,
- *the spontaneous neutron generation rate* that might complicate design, and affect a weapon's yield and reliability,
- *the heat and radiation generation rates* are other factors to be taken into account when designing and manufacturing nuclear device.

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 (eg oxides, nitrides), mixed compounds (eg fresh MOX fuel), spent fuel, non-conventional compounds (eg carbides and silicides), and vitrified wastes (borosilicate glasses and titanium oxide forms).

Fissile Material Acquisition Paths

There are a variety of paths available for States that might wish to try to acquire fissile material in violation of their international commitments. One of the most important reasons for the existence of the international safeguards regime is to have the capability to detect such violations and to deter them by placing an element of risk that the acquisition would be detected in a timely fashion. In order for there to be an appreciable risk of detection, the IAEA has to consider each plausible acquisition path and introduce verification measures to deal with all paths in an appropriate way. If the Agency devotes a great deal of resources to addressing one particular material acquisition path at a facility but ignores others, then the overall result will be less than satisfactory. The Agency must perform a thorough "diversion path analysis" and tailor the implementation of its safeguards efforts to address the real risks of diversion.

Diversion of Unirradiated Direct-Use Material

There are many nuclear facilities in the world that have material that for safeguards purposes at least is considered to be in a form directly useable by would -be proliferators. Such material is generally referred to as *Unirradiated Direct-Use Material* (UDU). This description is applied to high enriched uranium (HEU containing 20% or more U -235), and separated uranium-233 and plutonium (of almost any isotopic composition) regardless of their chemical form.

Such material can be found in bulk form at enrichment, conversion, fuel fabrication and reprocessing facilities, and as fresh fuel at MOX-fuelled power reactors, materials testing reactors (MTRs), research reactors (RRs), critical assemblies (CAs) and any other facilities that use HEU fuel, MOX fuel or any other plutonium or U-233 fuel. UDU is the most sensitive and closely controlled material in the international safeguards system.

There are many possible ways for a State to attempt a diversion of UDU material the most obvious (and the most difficult to counter) is described as a *"crash through" approach*. Under this scenario a proliferator would simply take the material from its safeguarded storage area as soon as the IAEA inspector had finished performing one inspection. The intention would be to have processed the material into a form suitable for use in a weapon before the next inspection falls due. At this point the proliferator could declare itself to be in possession of a nuclear weapon (or weapons) and the whole world would know that it was in breach of its safeguards obligations.

There are also certain *less dramatic scenarios* for the acquisition of UDU for a State with facilities containing material of that type. For example the operator could replace one or more items either with inactive dummies or with dummies which in some way mimic the material taken (such as borrowing equivalent material from another facility within the State). The aim would be to take the risk that the statistical sampling plan applied to the population of fresh fuel assemblies by the IAEA would fail to note the substitution. An alternative is to take small amounts of material from many items or facilities. The expectation would be that the small loss from many items would be within the statistically accuracy limits of the measurement system used by the IAEA during the inspection and consequently the overall diversion would be undetected.

Other acquisition paths for UDU include *the undeclared import of the material or manufacturing the material from undeclared source material using indigenous enrichment technology*. Under the classical safeguards system, formal consideration was only given to the paths that involved acquisition from declared sources with the advent of the Additional Protocol, measures are increasingly in place to deal with acquisitions from any source not just declared sources.

The acquisition of fissile material from fresh fuel is a relatively straightforward exercise and it is its very simplicity that makes it so difficult to prevent. If a facility has a significant quantity or more of UDU material the IAEA will generally conduct inspections on a monthly or biweekly basis. If facility conditions make it practical, a large part of the inventory will be covered by containment or surveillance measures and the remaining inventory will be subject to frequent re-measurement. The aim is to provide a heightened level of deterrence by ensuring that any diversion would be detected in a short enough interval that even a "crash through" scenario is unlikely to be successful before it is detected.

Diversion of Irradiated Direct-Use Material

Material that has been irradiated in a reactor (or any other intensive neutron source) normally has a high output of heat and radiation and requires heavy shielding and special tools to be handled or processed. Because of these special factors it is acknowledged that *acquiring material suitable for weapons from Irradiated Direct-Use Material (IDU) is much more complicated than a similar acquisition from UDU.*

To acquire fissile material from the declared irradiated fuel from a reactor, a proliferator would need to take either an adequate number of complete spent fuel assemblies or a very large number of irradiated fuel pins from a large number of assemblies. This material would need to be transported away from the reactor in heavily shielded casks in order to deal with both the heat and radiation generated by the assemblies or pins. The reprocessing of the spent fuel or irradiated pins has to take place behind massive shielding and all of the necessary equipment must be operated remotely.

A "crash through" scenario for IDU material involves diverting the material immediately after an IAEA inspection, but unlike the case for UDU, the material must be reprocessed before it can be used for weapons. Reprocessing appreciable quantities of spent nuclear fuel and producing UDU from IDU is not something that can be accomplished very quickly. UDU can theoretically be processed into weapons components in a matter of days, while, even under the best of circumstances it would take some months to process IDU to produce UDU.

There are many possible diversion scenarios for spent fuel, but as all of these scenarios require the special handling equipment and extensive shielding that were mentioned earlier, there are relatively simple measures that can address a whole range of diversion scenarios. The frequency and intensity of inspection effort is set to ensure that every reasonably achievable acquisition path is covered by appropriate safeguards measures. Most commonly, this involves inspections at regular intervals with either some form of verification activity or with the review of some form of containment and surveillance measures to ensure that continuity of knowledge on the spent fuel items has been maintained.

At power reactors in countries subject to the new Integrated Safeguards regime, current plans are to remove surveillance measures from the spent fuel pond area and rely on annual reverification of the spent fuel as the major safeguards measure. This practical step is being taken in countries in which the IAEA has been able to derive credible assurance as to the absence of undeclared facilities. The fissile material in spent fuel is accessible only after reprocessing and the assurance that there is no undeclared reprocessing capability within a State makes unnecessary the current quarterly inspections for spent fuel.

Undeclared Irradiation

IDU material can also be produced at a range of nuclear facilities by irradiating fertile material in the neutron flux of the core. Plutonium can be bred from natural or depleted uranium and uranium-233 can be bred from thorium. The degree to which this is a realistic acquisition path depends heavily on the power output of the reactor and on the configuration of the reactor core. In the case of MTRs and RRs it has been calculated that in order to produce 8 kg of plutonium within a twelve month period a reactor with a thermal power rating of at least 25 MWt would be required [[iii]]. A similar minimum power level would apply to small power reactors. For any power reactor with a thermal power output greater than 25 MWt (which is effectively all power reactors), some consideration must be given to addressing the possibility of unreported fissile material production.

Unreported fissile material production is a difficult acquisition path to cover for MTRs and RRs (most especially those with thermal power outputs in excess of 25 MWt). The purpose of such reactors is generally to gain access to the neutron flux on a regular basis such activities are entirely legitimate but they would also provide the perfect cover for undeclared acquisition of IDU.

In general, small power reactors present fewer possible acquisition paths for the undeclared production of fissile material than MTRs and RRs. As the principal purpose of a power reactor is produce power (or in special cases, heat and/or desalinated water) rather than neutron beams, there are, in general, greater complications involved in using such a reactor for unreported production of fissile material.

There are some forms of power reactor that present additional opportunities for unreported fissile material production that must be addressed when designing a safeguards approach for the reactor.

Attention must be paid to multi-purpose small reactor designs that are principally designed for power production but also allow access to neutron beam ports for irradiation studies and isotope production. The Argentine designed CAREM reactor is an example of the multi-purpose small reactor it has the potential to be an extremely valuable contribution to the nuclear industry but its utility needs to be taken into account in the design of the safeguards systems applied to this new reactor type.

Special attention is paid to reactors that can be fuelled while on-line (OLRs) these include some natural uranium fuelled graphite moderated reactors, pebble bed HTGRs and CANDU reactors. The capacity to move fuel through the core at a faster rate than has been declared opens a fissile material acquisition path that is not readily available to more conventional reactors and the advantage of more favourable isotopic composition from lower burnups. The regular movements of spent fuel from the reactor also provide cover for the movement of undeclared material (e.g. by the production of a transfer flask with the same external appearance as a declared flask but with a greater capacity to allow for the removal of undeclared material).

While it is clear that that some reactor designs are especially suited to unreported production of fissile material (OLRs, multi-purpose reactors, reactors with declared dummy assemblies and any reactor with open structural areas within the reactor pressure vessel), there does not appear to be any practical reactor design in which it is possible to eliminate the possibility for unreported fissile material production entirely.

The scenario of unreported fissile material production is somewhat less complicated in the case of reactors which only allow access to the core during refuelling. The use of containment and surveillance measures can allow the IAEA to derive a credible assurance that there has been no opportunity to remove unreported fissile material from the facility and therefore, when the inventory of spent fuel at the facility is verified, the IAEA can indirectly derive assurance that there has been no unreported production of fissile material.

As there are inherent difficulties involved in any attempt to "prove a negative" the IAEA has always found the unreported production of fissile material to be a difficult scenario to cover effectively at a number of facilities. Relatively minor problems have to potential to prevent the IAEA from being able to derive an independent assurance that there has been no such unreported production of fissile material at a given facility. Any steps taken at the design phase of the reactor to limit the opportunity to misuse a reactor in this way will have substantial benefits for the IAEA and, in the long run, for the operator.

ReducING THE Strategic Value of MATERIAL

We see at least three basic approaches to enhance proliferation resistance of reactors and associated fuel cycle facilities, namely: (1) by reduction of the strategic value of the materials involved in nuclear power generation, (2) by incorporating reactor design features preventing diversion of material, and (3) facilitating safeguards implementation. In general, any reduction in the strategic value of material will simplify the task of the design of a safeguards approach to the facility and make safeguards less intrusive for the operator.

Conceptually there are a number of ways in which the strategic value of the material can be controlled:

- reduce the concentration of the fissile material (thereby increasing the quantity of spent fuel that must be diverted to obtain a significant quantity of IDU);
- increase the chemical barriers to the diversion of the material (producing fuel of a form that has features that present difficulties for reprocessing and recovery); and
- reduce the isotopic quality of the material (introduce features into the fuel that ensure that the final isotopic composition of the irradiated material is unsuitable for weapons purposes).

Reducing Concentration

Most power reactors are considered by the IAEA to be *item* facilities. This means that when the IAEA is designing the safeguards approach for the facility it considers that the fuel assemblies are to be accounted for as discrete, identifiable, individual items. Spent fuel items that contain less (preferably much less) than one *significant quantity* (SQ) of IDU [[iv]] are subject to less intrusive safeguards than items that contain more than one SQ. In general safeguards on a large number of items with a low fissile material content will be less intrusive and simpler than safeguards on a small number of items with a high fissile material content. For example CANDU fuel bundles contain very little IDU per assembly and, once discharged, are subject to only limited safeguards (the major complication arising from the safeguarding of CANDU reactors relates to the fact that fuel can be discharged while the reactor is operating).

Increasing the Chemical Barrier

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.

Reducing the Isotopic Quality of the Material

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. 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 for some reduction in inspection effort.

This line of reasoning can also 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 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 these 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.

Design Features Preventing Diversion of Material

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 the 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.

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,
- environmental signatures associated with facility modification and misuse.

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 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.

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.

Thermal Reactors

In this and the following sections we discuss some of the topical concepts of proliferation-resistant fuel cycles that are being promoted by various experts and countries. It is very difficult in a short presentation to give detailed account of all technical aspects and features of the proposed nuclear power generating systems. So our discussion will take a necessarily superficial view of the topic, as discussion of each concept would probably need a separate presentation.

Direct Use of Spent PWR Fuel in CANDU Reactors

An interesting example is the DUPIC process that is being developed through collaboration between Korea (KAERI), Canada (AECL), and the US (LANL). DUPIC fuel cycle [v] can reduce natural uranium requirements and spent fuel arisings by direct re-fabrication of spent PWR fuel into fresh CANDU reactor fuel. The heart of the DUPIC fuel cycle is the OREOX (Oxidation and Reduction of Oxide fuels) process. During this dry process, uranium from spent PWR fuel is oxidised and reduced to a fine powder, which forms the starting material for fabrication of DUPIC fuel pellets.

Several features of the DUPIC process significantly enhance its proliferation resistance relative to fuel cycles employing separated plutonium:

- The fuel processing does not involve any wet chemistry. The employed dry thermal-mechanical processes contrast with conventional wet reprocessing, in which spent fuel is separated into uranium, plutonium and fission products or actinides.
- With no selective separation, 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 the final DUPIC fuel bundles themselves, are highly radioactive. Thus all processing and handling must be done in a shielded facility, making physical entry into the facility, and diversion of material 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. Transportation of the spent PWR fuel into the DUPIC processing facility and of DUPIC fuel to the CANDU reactor involves highly radioactive materials.

Proliferation-Resistant Fuels

Proliferation-Resistant Fuels (PRFs) have been proposed by researchers in several countries [vi] including France, Italy, Switzerland, Japan and the United States as an effective means to dispose of excess military and civil plutonium. PRFs are designed to behave like standard, low-enriched uranium fuel, enabling them to be used in standard LWR fuel cycles without reactor modification. Because PRFs contain no uranium, burnable poisons are used to tailor their neutronic properties. The inert matrix material is a neutronically inert diluent.

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 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 by enabling a substantial reduction in plutonium inventories with one-third core LWR cycles.

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 mixed uranium-plutonium dioxide (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.

Radkowsky Thorium Fuel

A novel fuel-cycle concept Radkowsky Thorium Fuel (RTF) has been developed to address the proliferation issues. [vii] The RTF is a new fuel concept, not a new reactor. It is based on the experiences of the Bettis Atomic Power Laboratory's Light Water Breeder Reactor (LWBR) program as demonstrated at the Shippingport reactor in the 1980s. However, in contrast to the LWBR, the RTF concept assumes a once-through fuel cycle with no 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. Basically, seeds are treated similarly to the standard PWR assemblies, ie approximately one-third of the seeds are replaced periodically by "fresh" seeds, and the remaining, partially depleted, 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.

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) [[viii]], 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.

Fast Reactors

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.

Russian Reactor BREST

Of potentially greater importance, because it involves plutonium breeding, is the Russian concept of a "transmutational" fuel cycle. Moscow Research and Development Institute of Power Engineering (RDIPE) is working on an innovative concept of a fast lead-cooled reactor BREST with UN-PuN fuel [ix]. The proposed reactor has quite a few design features that make it proliferation-resistant.

- The reactor features full plutonium reproduction in the core. Thus there is no need to use uranium blankets to breed plutonium, which precludes production of weapon-grade plutonium. Spent fuel composition is close to that of fresh fuel plutonium is neither extracted nor added to the fuel. To adjust fuel composition, just another portion of 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 that facilitates fuel protection against possible diversion at all stages of the fuel 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. Hence with fuel cycle facilities arranged at the power plant site, it becomes possible to do without out-of-pile storage for spent and fresh fuel. This eliminates the danger of diversion associated long-distance shipments of fuel.

US Super-PRISM Reactor

While the Russian concept looks particularly attractive, there are other concepts, which have been advanced in the past or are currently under development. Based on the success of previous DOE sponsored Advanced Liquid Metal Reactor (ALMR) program General Electric is developing a modular liquid sodium-cooled fast reactor called Super-PRISM (or S-PRISM) [x]. Utilising in this concept a dry pyro-processing system that does not separate plutonium from minor actinides enhances the proliferation resistance of the S-PRISM 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 (SFRF) that integrates spent fuel storage, processing and waste storage and conditioning operations into a single facility. It would be located in a dedicated area of the plant within its own security area. As S-PRISM fuel assemblies can be fabricated and recycled in the SFRF, they do not need to be shipped off-site.

Transportable Power Reactors

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 was proposed by the University of California at Berkeley (UCB) [xi]. The UCB study resulted in the conception of an autonomous long-life lead (or lead-bismuth) cooled core that appears to be highly suitable for the ENHS. The ENHS 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 single most unique feature of the ENHS is that the fission-generated heat is transferred from the primary coolant to the secondary coolant through the reactor vessel wall. This enables the reactor module to have a very simple design and to be free of any mechanical connections to the power plant components. 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.

Secure, Transportable, Autonomous Reactor (STAR) System

A new concept for a nuclear power system to specifically address the needs of the developing world was first presented at Global 97. Lawrence Livermore National Laboratory (LLNL), with the support of Argonne National Laboratory (ANL), Los Alamos National Laboratory (LANL), Westinghouse Science and Technology Center, the University of California at Berkeley (UCB), Texas A&M University (TAMU), and the Massachusetts Institute of Technology (MIT), has further evaluated this nuclear power system concept and named it the Secure, Transportable, Autonomous Reactor (STAR) [xii]. 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:

- 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.
- Concept eliminates much ancillary equipment.

The STAR system approach is continuing to be discussed with the US Department of Energy and with those in the international community who have expressed interest. The STAR-Light Water and the highly innovative concept for the ENHS (using liquid metal coolant) have been selected for further study under the Nuclear Energy Research Initiative (NERI).

Choosing the Best Nuclear Fuel Cycle

There are at least three basic criteria, which are primary considerations in the selection of the future reactor system and associated nuclear fuel cycle:

- *strategic considerations* such as the State's independence of external energy suppliers, technological capabilities;
- *economics*, involving all costs, not just the cost of generating electricity, but the consideration of financial risks that could affect the investment as well;
- *public acceptance factors* incorporating safety, environmental considerations, and proliferation-resistance.

As US experts [xiii] have recently pointed out, economics will, by far, be the principal consideration in future decisions to build new nuclear plants. Considerations related to public acceptance would probably be secondary to, and influenced by, those related to economics. Commercial plant buyers are unlikely to view proliferation resistance as a high priority, relative to economic factors.

For the large capacity nuclear generating plants that have been favoured throughout the developed world, the capital costs of building plants and their associated infra-structure have tended to dominate the decision making process. The input cost of fuel has been a relatively small component of running costs of a plant, the capital cost tends to dominate all considerations. As these are major capital works it becomes difficult for any concern, beyond immediate economics, to influence design considerations delay and expense are seen as impossible barriers to changes in plants' designs.

Plans for smaller more modular designs, with emphasis on distributed production and responsiveness to end-consumer needs, could drastically change these considerations as time goes forward. Physically small units, with small power outputs and lower overall costs (though not necessarily cheaper on a per kilowatt basis) could dominate the future deployment of nuclear power plants. As noted earlier, the costs associated with long distance electricity transmission and attendant transmission infrastructure tend to limit the per kilowatt advantage that large centralised plants have over smaller plants in the vicinity of demand centres.

With smaller capital costs and shorter deployment cycles, the concentration of risk is less significant and the chance for concepts of proliferation resistance to influence the overall design may become greater.

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, eg 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 increasing use of plutonium fuels, 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 show 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 greatly benefit the safeguards that are applied by the IAEA to the facility. 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. It is particularly encouraging that the US, which has sought to discourage plutonium recycle, appears to be starting to focus on how the closed fuel cycle can be undertaken consistent with non-proliferation objectives. A task force (TOPS) has been established under USDOE auspices to identify technical opportunities to further increase the proliferation resistance of nuclear power systems, and to recommend specific research areas.

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. The IAEA has organised valuable conferences on new fuel cycle technologies, but to date these have not had a major non-proliferation focus. 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.

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