

SAFEGUARDS AS A DESIGN CRITERIA - GUIDANCE FOR REGULATORS

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INTRODUCTION

The nuclear non-proliferation regime rests on several complementary elements. The political commitment of States against possession of nuclear weapons is reinforced by institutional measures, the most important of which is IAEA safeguards. These measures provide a high level of assurance of compliance with obligations through international verification.

The political commitments and institutional barriers against proliferation, such as treaty regimes and associated verification arrangements, can be reinforced by technological barriers. At the very least, such barriers could make breakout from the non-proliferation regime more difficult and time-consuming, thereby providing enhanced deterrence against diversion and better opportunities for the international community to intervene should a State be found to be in breach of its commitments.

Following the application of the Model Additional Protocol (INFCIRC/540) and the subsequent move towards an integrated safeguards system, technological barriers to proliferation can be given additional weight in the overall national safeguards equation when establishing the system of safeguards to be applied in 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 constraining the growth in inspection effort and associated costs, allowing effort to be concentrated in areas of the nuclear fuel cycle of greatest proliferation concern.

This paper will examine some of those technological barriers which should be taken into account at the conceptual stage of fuel cycle design. Starting with a discussion of the strategic value of nuclear material and reactor-associated fissile material acquisition paths, this paper discusses three basic approaches to enhance the proliferation resistance of [nuclear

power] reactors, namely: (1) reduction of strategic value of materials involved in nuclear power generation; (2) incorporating reactor design features preventing diversion of material; and (3) facilitating safeguards implementation.

The views contained in this paper are the views of the authors and not necessarily those of the Australian Government.

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 in reprocessing plants or plutonium extraction facilities.

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

- 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 (RG-Pu) from the operation of LWRs is of around 25% Pu-240 or higher. Any attempt to utilise RG-Pu 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 i.e. its purity, could be an efficient barrier to proliferation because it relates directly to the relative difficulty of manufacturing a nuclear weapon.

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. As far as can be discerned from open literature, nuclear weapon states have used weapons-grade materials in the production of their nuclear arsenals indicating the unsuitability of lesser quality materials.

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 outputs of the material.

The chemical form of material can also serve as a proliferation barrier. This relates to the relative effort required to obtain materials of sufficient purity for weapons applications, that is: 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. 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 of ascending difficulty: 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 ASSOCIATED WITH REACTORS

There are a variety of paths available for States that might wish to acquire fissile material - for NPT non-nuclear weapons states 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 proliferants 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 measures to deal with that path 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" for each facility 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 unirradiated 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), uranium-233 and plutonium (of almost any isotopic composition) regardless of their chemical form.

Such material can be found as fresh fuel at Materials Testing Reactors (MTRs), Research Reactors (RRs), Critical Assemblies (CAs) and any facility which is using HEU fuel, Mixed Oxide (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 divert 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 other 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 here 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. 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. This is a significant weakness of the old system. 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 simplicity that makes it so difficult to prevent. If a facility has a sufficient quantity 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. Here 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 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.

Smaller reactor facilities generally have smaller fuel assemblies with lower fuel loadings per assembly - however, in general these factors do not greatly simplify the tasks that must be undertaken by a would be proliferator. Spent fuel from small power reactors, MTRs and the great majority of RRs is intensely hot and radioactive and requires comparable levels of shielding to large power reactor fuel in order to be handled safely.

In general, acquisition of IDU from small power reactors is much more complicated than an equivalent diversion from an MTR or RR. MTRs and RRs generally have means to introduce items into neutron beam lines or other irradiation stations. As these items also require the heavy shielding that is required to transport spent fuel they would provide a regular cover for potential diversion activities.

The IAEA considers all of the plausible "acquisition paths" or "diversion scenarios" in establishing a safeguards approach for a facility. The degree of difficulty inherent in the acquisition path is assessed, as well as the time required for successful completion. Where engineering controls have been established that limit the possibility for the successful completion of a particular diversion scenario it is possible to take account of this in establishing the safeguards approach (these engineering limitations will be discussed later in this paper). 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 and activities. 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 8kg of plutonium or uranium-233 within a twelve month period a reactor with a thermal power rating of at least 25 MW would be required. A similar minimum power level would apply to power reactors. For any power reactor with a thermal power output greater than 25 MW (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 MW). 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 covert acquisition of IDU.

In general, 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 to 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 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 susceptibility to proliferation exploitation 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), which includes some natural uranium fuelled graphite moderated reactors, pebble bed HTGRs and PHWRs. 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 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 the 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 and the State.

REDUCING THE STRATEGIC VALUE OF MATERIAL

As mentioned earlier, three basic approaches to enhance proliferation resistance of reactors, have been identified, namely: (1) reduction of the strategic value of the materials involved in nuclear power generation; (2) incorporation into reactor design features preventing diversion of material; and (3) facilitating at the design stage and through life safeguards implementation.

In general, any reduction in the strategic value of material will simplify the task of the design of a safeguards system for the facility and make safeguards less intrusive for the reactor operators.

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

- reducing the concentration of the fissile material (thereby increasing the quantity of spent fuel that must be diverted to obtain a significant quantity of IDU);
- increasing 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
- reducing the isotopic quality of the material (introduction of 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 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 to 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 barriers including security and access controls that limit access also.

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 AT REACTORS

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, thus ensuring 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.

CHOOSING THE BEST NUCLEAR FUEL CYCLE

Basic Criteria

There are at least three basic criteria, which are primary considerations

in the selection of a 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 have 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 in the future. 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.

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 and should influence the choice and development of technological options.

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.