SAFEGUARDS-RELATED CONSIDERATION OF THE CONVERSION OF UNIRRADIATED PLUTONIUM IN MOX FUEL TO METALLIC FORM

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Abstract

A central premise in the development of integrated safeguards approaches has been that increased confidence in the absence of undeclared activities should allow commensurate changes to safeguards measures which have hitherto been applied to declared nuclear material. In this paper, publicly available information has been used in summarising likely requirements (including equipment, time and other resources) for the processing which could be used to obtain metallic plutonium from unirradiated MOX fuel. Potential indicators and the possible detectability of undeclared such processing are then considered in the context of integrated safeguards, specifically in terms of the kind of integrated safeguards approaches that could be applied to unirradiated MOX fuel assemblies. It is suggested that integrated safeguards approaches for MOX fuel assemblies in circumstances where the IAEA has been able to implement the additional protocol and draw a conclusion relating to the absence of undeclared activities could address (and match verification effort against) the full range of possible MOX fuel diversion and undeclared processing scenarios and, crucially, include a capability of detecting diversion within even worst case conversion scenarios.

Introduction

1. The process of developing integrated safeguards (IS) has included the re-examination of certain basic safeguards parameters, in particular those associated with timeliness. For example, a key factor in the development of IS approaches for irradiated fuel has been consideration of the IAEA’s increased capability to detect the processing which would be involved in obtaining plutonium from irradiated fuel in a State where the Agency has been able to implement the measures of the additional protocol. Such detection capability and the credible (but not absolute) assurance that comes from it means that less weight need be placed on the classical safeguards assumption that undeclared facilities may exist undetected. New IS approaches must however still recognise that there is some (albeit significantly reduced) chance that there might still be undeclared activities which have not been detected. It is important that the increased confidence in the absence of undeclared activities is commensurate with the proposed changes to existing traditional safeguards measures. In IS approaches for irradiated fuel this is characterised as a relaxation in the time within which the diversion of a significant quantity of material as feed to an undeclared processing plant should be detected (the timeliness goal) from 3 months to 12 – but with the important additional dimension that the approach must also retain some lesser capability of detecting diversion at times shorter than 12 months.

2. The use of mixed oxide (MOX) fuel in thermal reactors is now well established, and it is expected that this use will become more widespread in the future (although the rate of growth is perhaps uncertain). Current safeguards inspection criteria require that fresh MOX fuel assemblies are verified on a monthly basis (by evaluation of C/S measures and/or item counting, identification and gross defect measurement) and these inspections require...
considerable inspection effort (e.g. it has been reported that 16 out of a total of 167 LWRs inspected by the Agency in 1999 used MOX fuel, but that these 16 (10%) of the reactors consumed over 20% of the Agency’s inspection effort at LWRs). Increased use of MOX fuel clearly has potential significant implications for the Agency safeguards regime.

3. The aim of the studies described in this paper has been to examine whether and if so how the kind of considerations applied to date in the development of IS might be carried across into the development of IS approaches for unirradiated MOX fuel assemblies. The study has therefore involved the use of publicly available information in:

a) describing the kinds of process which could be used to recover plutonium from unirradiated MOX fuel;

b) assessing the requirements for these various processes, both in terms of the key equipment and non-nuclear materials that would be involved and also operational considerations;

c) estimating the time that would be required for such processing, the time taken for each individual process step and also, importantly, the time for the process as a whole to be completed successfully;

d) identifying possible indicators of undeclared such processing, in terms of the material, equipment and other resources required and also possible releases; and,

e) discussing the feasibility and possible detectability of the whole processing operation.

This assessment and its possible implications for IS approaches for unirradiated MOX fuel assemblies are then explored further.

4. It should be emphasised at the outset that this paper is concerned with safeguards issues relating to MOX fuel (i.e. measures to detect and deter its diversion). The paper does not attempt to address the measures which States themselves apply in order to prevent the theft of MOX fuel – and it is important to bear the distinction between safeguards and physical protection objectives and design capabilities in mind.

Conversion Processes

5. The IAEA Safeguards Glossary defines conversion time as the time required to convert different forms of nuclear material into the metallic components of a nuclear explosive device. Clearly, identifying process routes which a proliferator might take in trying to obtain metallic plutonium from an unirradiated MOX fuel assembly is a matter of judgement and the processes which are the focus of this paper reflect the judgement that a proliferator is, to the extent possible, likely to try to minimise the risk of failure by careful operation of proven technologies (i.e. is less likely to take an approach involving the use of crude and/or untried processes and equipment, which could threaten safety and resources and also possibly increase the risk of detection). If safeguards arrangements could be defeated such that a MOX fuel assembly was successfully diverted and transported to a suitably equipped undeclared facility, it is our assessment that the basic processing steps could be as summarised in FIG. 1. (below)
Process Requirements – Equipment, Expertise and Time

6. It would be wrong to dismiss as trivial the process summarised in the figure above. But it would also be wrong to describe the equipment, reagents and consumables required as unique to the particular nuclear processes in question, for example:

- the equipment needed to extract MOX containing pins from a fuel assembly (and MOX pellets from those pins) could be of the kind employed in light engineering workshops;

- glove box containment facilities would be a feature common to many of the subsequent process stages. Some provision for inert gas supplies would also be necessary, for both safety (see below) and process reasons (e.g. preparations for the thermite reduction and metal alloying/casting activities would be done in an inert atmosphere). Suitable equipment is however now employed well beyond the nuclear industry (e.g. in pharmaceutical and related biochemical research, the semi-conductor industry and increasingly in ‘light’ chemical industries wherever increasing safety standards require increased attention to operator protection);

- specific equipment requirements for handling plutonium containing solutions (e.g. for dissolution, evaporation, centrifugation and filtration) would be a function of the scale of operations. A key, and potentially distinctive, feature might however be the size limitations needed to avoid inadvertent criticality excursions (see below);

- the hydro-fluorination, thermite reduction and subsequent metal casting processes would pose more significant technological challenges (e.g. the specialist equipment required would need to be carefully designed and constructed using corrosion resistant alloys if equipment failure and product contamination is to be avoided). By and large however, the processes and equipment involved are reasonably well documented in the open literature and are not unique to the nuclear industry.
7. Similar observations apply to most of the reagents and other process consumables involved, although the extra material employed during the R&D and plant commissioning stages could be regarded as significant (e.g. the material, possibly uranium, used to test the various process equipment – which would also have to be obtained and processed outside safeguards if the programme was to remain undetected by the Agency).

8. It is quite likely that usual safety and environmental considerations would not be an overriding concern for an aspiring proliferator. However, whilst standards might be relaxed, the process operators would still be concerned to avoid accidents which might inhibit progress (e.g. in terms of their effect on the personnel and equipment involved, and the diverted nuclear material being processed) or otherwise lessen the chances of success (e.g. inasmuch as they could result in the release of indicators of possible undeclared operations). This means that, in addition to the normal industrial and chemical hazards associated with any laboratory or industrial process, attention would also have to be paid to hazards which are peculiar to handling nuclear material, specifically:

- external radiation, the quantities of the higher plutonium isotopes and their decay products that could be present in plutonium from higher burn-up fuels would, over time, result in increased radiation levels;

- radioactive material ingestion, the containment used to prevent such ingestion of plutonium (either from surface contamination or breathing dust) is normally achieved by intrinsic features (e.g. the fuel canning), by equipment design, and by glove box working. It would seem to be in the proliferator’s interest to preserve such containment (and thus the process operators) and also to limit the extent to which any process indicators are released to the environment; and

- criticality control, a critical excursion could give rise to very high radiation levels such that exposed operators would become ill immediately and quite probably die within a short time and would also damage, if not write-off completely, the process equipment and materials (nuclear and non-nuclear) involved\(^1\). Such an excursion would therefore be a major concern and avoiding it would involve acquiring the specialist expertise necessary to perform criticality-related calculations and/or replicating equipment and processes (and thus possibly increasing the risk of detection and also the time required for processing) to work with batches containing material quantities which remain sub-critical under all possible process conditions.

9. Finally, the environmental impact of relatively small scale operations of the kind described in the preceding section, even if carried out in a most slovenly fashion, is likely to be minimal. That said, there is no shortage of evidence that, even when the kind of processing involved is conducted by well-practised States with technologically advanced nuclear industries, there have been lapses which lead to the release of small amounts of material to the environment.

\(^1\) criticality control is a matter of preventing the accumulation of sufficient nuclear material (a critical mass) in adverse geometry (near spherical), possibly exacerbated by the presence of moderators and reflectors (e.g. water).
10. Overall therefore the design, commissioning and operation of the kind of processes and equipment described above would demand expertise and skills across a range of scientific and engineering disciplines. Although the basic science and technology involved is widely reported in the open literature - and its deployment could, in principle, be within the reach of personnel with relevant scientific training and industrial and/or R&D experience – performing all the operations successfully and safely would be a considerable undertaking.

11. So far as time requirements are concerned, the knowledge now openly available is such that it is conceivable that the necessary process/plant equipment could be designed, built and commissioned in somewhat less than a year. Estimates of the time then required for each stage of plutonium processing described above are shown in Table I (below), summation of which suggests that, in theory, the recovery of plutonium metal from an unirradiated MOX fuel assembly could take as little as two to four weeks (a figure that is consistent with the current IAEA estimate of a conversion time of the order of 1-3 weeks for plutonium in MOX - although it should also be recognised that were a proliferator able to operate in an environment which included ready access to substantial expertise supported by sufficiently extensive other resources, even this could be shortened).

**Table I – Estimated Timescales for the Processing of MOX Fuel to Produce Plutonium Metal**

<table>
<thead>
<tr>
<th>Possible Process Stages (assuming input which includes 1 Significant Quantity of plutonium)</th>
<th>Time (days – assuming that the necessary facilities, materials and equipment are available and operate immediately at optimum efficiency)</th>
</tr>
</thead>
<tbody>
<tr>
<td>remove fuel pins (~100) from the fuel assembly and pellets from these pins</td>
<td>1.5 – 5</td>
</tr>
<tr>
<td>crush pellets</td>
<td>0.5 – 1</td>
</tr>
<tr>
<td>dissolve MOX (in solid solution form)</td>
<td>2 – 3</td>
</tr>
<tr>
<td>Separate plutonium from uranium (nitrate) - by precipitation (repeated)$^2$</td>
<td>3 – 4</td>
</tr>
<tr>
<td>Precipitate plutonium oxalate</td>
<td>1 – 2</td>
</tr>
<tr>
<td>Ignite oxalate to PuO$_2$</td>
<td>1 – 2</td>
</tr>
<tr>
<td>Fluorinate PuO$_2$ to PuF$_4$</td>
<td>1 – 4</td>
</tr>
<tr>
<td>Reduction</td>
<td>2 – 4</td>
</tr>
<tr>
<td>Metal casting</td>
<td>1.5 – 3</td>
</tr>
</tbody>
</table>

12. These timings and their simple summation do however include a number of major assumptions, for example:

- that sufficient nuclear material input (including one significant quantity of plutonium) is available, i.e. the material has been successfully diverted and transported to the undeclared processing facility (activities which might take some time, e.g. depending on whether or not the undeclared processing facility was co-located with the declared location of the MOX fuel assembly);

$^2$ it is estimated that alternative separation processes (e.g. solvent extraction) would take significantly more time.
- that the necessary plant and equipment is available, suitably tested, and that all this equipment operates successfully first time; and

- that the undeclared plant has, for example, chemical separation and finishing stages which are of a sufficient scale, and/or sufficiently replicated, to produce about 1kg plutonium oxide per day (i.e. to process in the region of 12kg MOX each day, assuming the plutonium content of the MOX is about 8%), a figure which equates to an annual process throughput of several tonnes of heavy metal – and is therefore not trivial.

13. Such straightforward summation would also be at odds with experiences in the nuclear industry and elsewhere. Difficulties with the operation of equipment and processes are not unknown\(^3\); indeed it is likely that almost any bulk chemical process (however simple the basic chemistry) will run into unexpected snags during its initial operation. A more realistic scenario might reasonably be expected to involve a somewhat longer process – perhaps to the extent of doubling the time needed.

14. The possible implications of these assumptions and the resulting timelines with respect to the formulation of IS approaches in States where the Agency is successfully applying the measures of the Additional Protocol are considered further below.

Possible Process Indicators and Detectability

15. As is evident from the preceding section, possible indicators of processing to produce plutonium metal can be divided into two basic categories. First there are the equipment, material and personnel resources required to support the process (i.e. input) and secondly the outputs from the process (e.g. releases to the environment of radioactive and/or other contaminants). Many of the possible indicators that fall into the first category are equipment or materials that are used outwith the nuclear industry (e.g. in pharmaceutical and related biochemical research, the semi-conductor and metallurgical industries). It is not possible to describe any of the process requirements as both an outstanding indicator and essential to the process. However, the more specialist requirements in respect of which the scope for a plausible non-nuclear ‘cover’ is more limited, and which could therefore be regarded as better indicators of possible plutonium processing, include the corrosion resistant alloys used in construction of equipment for the hydro-fluorination of plutonium oxide, the specialist calorimeters required for the thermite reduction process and some of the materials and equipment used in casting the metallic plutonium (e.g. gallium, tantalum crucibles or graphite moulds). Plant commissioning activities with uranium may also provide indicators (particularly if the uranium has been diverted). And evidence of the (re)deployment of potentially relevant personnel (e.g. health physicists, radio-chemists, physicists/criticality experts, and operators with nuclear fuel cycle process experience) must also be considered as a possible indicator.

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3 for example, the thermite reduction of plutonium fluoride can, and has been known to, be incomplete and result not in plutonium metal and calcium slag, but in a heterogeneous mess - from which recovery of plutonium would require re-dissolution, precipitation etc, and the success of each of the chemical processing steps, in terms of product yield and purity, will be very much dependent on achieving the correct reaction conditions.
16. The presence of indicators in the second category, i.e. environmental evidence of processing, would be a function of, amongst other things, the scale of operations and the extent of efforts to control releases (i.e. the kind of abatement measures mentioned above). However, as noted above, such releases are likely to be limited, especially where the operations concerned are on a relatively small scale.

17. Regarding detectability, the measures of the additional protocol are primarily intended to increase the Agency’s capability to detect indicators of possible undeclared nuclear activities. In general terms, a State where a protocol was being implemented but which was nevertheless intent on undertaking undeclared processing of the kind outlined above would have to do so against the background of:

- its provision to the Secretariat of detailed declarations on its nuclear fuel cycle-related activities;
- the Secretariat’s evaluation of both these declarations and other available information relevant to them; and also
- the Secretariat’s use of complementary access, in particular in pursuit of inconsistencies and questions arising this evaluation.

Protocol measures which relate more specifically to undeclared plutonium processing include, for example, the requirement that States report on the relevant R&D activities, on the manufacture of criticality safe tanks and vessels, and the export/import (on request) of equipment both for plutonium processing and for its conversion to metallic component form – and the accompanying provisions for complementary access, both at declared nuclear sites and, given cause, elsewhere in the State.

18. Overall, the Secretariat is expected to draw a conclusion relating to the absence or otherwise of undeclared activities in a State where an additional protocol is successfully implemented. Within this, it is recognised that implementation of additional protocol measures will provide the Secretariat with a significant capability to detect undeclared activities at or near declared nuclear sites. Given such a capability it would seem unlikely that the totality of plutonium processing activities described above could go un-remarked and undetected were they undertaken at a declared site. Equally, it is also acknowledged that, even with implementation of the additional protocol, detection of undeclared activities (plutonium processing or otherwise) elsewhere in a State will be more difficult - just how much so remains a matter of considerable debate and is, ultimately, a matter of judgement. Once again however the totality of the processing which would be involved in the undeclared production of metallic plutonium must be borne in mind. Although there is no single process stage which can be said to pose potentially insurmountable technical difficulties and/or provide an unambiguous indicator of undeclared activities, for a proliferator’s activities to remain undetected, each one of the stages must be designed, built, commissioned and then operated successfully without the release and identification of a sufficient accumulation of indicators. Whilst individually inconclusive, such indicators when taken together could prompt interest, investigation and possibly eventual detection. Put another way, an undetected whole on a scale capable of successful processing of sufficient MOX fuel to yield a significant quantity of plutonium in a 2-4 week time-scale will pose more of a challenge than simply the sum of its parts.
Possible Implications for IS

19. The analysis above suggests that the time required for processing MOX fuel to obtain plutonium in metallic form could be as little as 2-4 weeks – an outcome which is very much consistent with existing estimates of conversion time for such material. It is however also clear from the analysis that this estimate of conversion time is based on conservative assumptions about the processing plant concerned; that it has been designed and built without detection, that plant testing and commissioning either does not take place or is also performed without detection, and that the plant as a whole then operates immediately at optimum efficiency.

20. The key issue for the development of IS (specifically for MOX fuel, but also more generally) is whether and/or to what extent it is reasonable for judgements on the timeliness-related component of future IS approaches to be based largely on multiple pessimistic (or worst case) estimates and assumptions of the time required for a proliferator to succeed and also remain undetected in a given set of actions. A shift of emphasis - recognition that the ‘credible worst case scenario’ for the clandestine recovery of metallic plutonium is at one end of a spectrum of possible outcomes – is, as noted in the introduction to this paper, already evident in IS proposals for irradiated fuel. These approaches are characterised as involving a relaxation in the timeliness goal, but retain a capability to detect diversion within this 12 month goal (i.e. recognising that even with implementation of the additional protocol, there cannot be an absolute guarantee that the Agency will detect all undeclared processing). In other words, it is acknowledged that as the ability to detect undeclared activities increases, there can be less reliance on the timely detection of diversion of declared material, i.e. that the IS approach to timeliness should better reflect the spectrum of possible conversion scenarios rather than fixing on a single point at one end of that spectrum.

21. It is perhaps also worth recalling that even current timeliness goals are not based solely on estimates of the time required to convert the material concerned into the metallic components of a nuclear explosive device, but also take account of non-technical factors such as the practicability of performing routine inspections at the frequency that rigid such linkage would demand. Thus, for example, the estimated conversion time for MOX and other mixtures containing unirradiated plutonium is ‘of the order of weeks’ – because, as described above, the production of truly ‘direct-use’ material from it would require non-trivial processing. In contrast, the estimated conversion time for plutonium metal is ‘of the order of days’, but the current timeliness goal for both types of material is set at 1 month.

22. In drawing these considerations together it has been suggested that the timeliness-related elements of future IS approaches could be characterised in a number of ways. For example, one option would be to change the timeliness goal from 1 month to 3, but include a capability to detect diversion at shorter times (i.e. akin to the way the IS approach for irradiated fuel has been described). Another option would be to define the timeliness goal in terms of an ‘average time to detection’, based on a given number of randomised inspections, of say 3 months - or a ‘range of timeliness’ of say 2 weeks to 3 months, with increasing probability of detecting diversion over that range.

23. Ultimately however, what is more important than how the regime is described is the way that safeguards measures for the timely detection of diversion are implemented in practice – and thus the assurance that this implementation yields. It is our view that, where the implementation of the Additional Protocol provides credible assurance of the absence of
undeclared activities, a regime involving three to five interim inspections per year and which
included an element of randomisation would be reasonable for unirradiated MOX fuel
assemblies. There are a number of options which could be considered, for example, 3 (or
more) interim inspections per year, all performed at random or alternatively perhaps interim
inspections at set intervals (either three or four months) but supplemented by 1 or 2
randomised interim inspections. As is the case with irradiated fuel however, the capability of
detecting diversion at times shorter than a nominal timeliness goal of 3 months should be an
important part of the IS approach for MOX fuel.

24. Whilst inspection frequencies are one aspect of an IS approach, the activities
performed during these inspections are another. The assumption underlying the possible
interim inspection regimes outlined above is that these inspections will deliver the same
chance of detecting MOX fuel diversion as is provided by current inspections for timeliness
purposes. This in turn implies that the inspections will comprise the same timeliness-related
activities as are performed at present, i.e. that comparable C/S measures are applied to MOX
fuel receipt, storage and core transfers or there is provision for re-measurement of MOX fuel
(although this is understood to be a somewhat less practicable proposition – at least where
reactor locations are concerned). It is however for consideration whether the increased
confidence provided by full implementation of additional protocol measures could allow for
modification of the detail of these activities.

25. In any case, the combination of inspection measures that is most effective and efficient
will depend on circumstances at the particular facilities concerned. For example, factors such
as:

- the availability of suitable C/S equipment (e.g. the scope for remote access to retrieve and
  review data from surveillance and other C/S equipment, and the recording capacity for
  surveillance data);
- the practicability and utility (i.e. with respect to specific diversion scenarios) of short or
  no-notice inspections;
- likely limitations in terms of being able to re-measure MOX fuel at a reactor facility.

26. In conclusion, IS provides an opportunity to develop safeguards approaches which
could perhaps be described as more ‘sophisticated’ than those used hitherto, in better
addressing (and matching verification effort against) the full range of possible diversion and
undeclared processing scenarios. More specifically, the climate of successful implementation
of the additional protocol would allow for re-assessment of the safeguards measures applied to
MOX fuel, suitably constructed IS approaches for which should include some (albeit limited)
capability of detecting diversion within even the worst case conversion scenario described in
this paper. An important aspect of these and other IS approaches is the widespread
recognition that their implementation and evaluation (e.g. in the resolution of inconclusive
results from surveillance equipment) will demand still greater use of qualitative information
with associated judgement. Key to allowing for and encouraging such use of judgement will
be the development of suitably flexible (i.e. less mechanistic) guidelines for IS activities. As
suggested above, such so-called ‘performance-based safeguards criteria’ could, for MOX fuel,
provide for a degree of latitude in exactly how verification is performed, but with the over-
riding requirement that the objective must be demonstrable confidence in the absence of
diversion (i.e. ‘credible assurance’).