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Proliferation Resistance and Physical Protection

Position Paper

Proliferation Resistance and Physical Protection

An assessment

Assessing the inherent Proliferation Resistance and Physical Protection (PRPP) characteristics of nuclear systems is an area that is becoming increasingly important internationally.

International efforts to stimulate the development of advanced nuclear systems, such as the Generation IV International Forum (GIF) and the IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) project, have identified the need to strengthen features that provide inherent PRPP.

The UK National Nuclear Laboratory (NNL) has been proactive in developing a PRPP assessment methodology in support of UK requirements in this area. Although PRPP assessment methods were developed primarily to guide decision making on advanced reactor and fuel cycle R&D, they can also be applied in other contexts, such as the management of historic UK liabilities.

This position paper explains the issues involved in PRPP assessments and highlights why NNL decided to develop its own methodology and why the new method is suited for real world application not just in the UK, but internationally.

Graham Fairhall

Graham Fairhall
Chief Science and Technology Officer

Introduction

Assessing the inherent Proliferation Resistance and Physical Protection (PRPP) characteristics of nuclear systems is an area that is becoming increasingly important internationally.

Proliferation Resistance is defined by IAEA as "… that characteristic of a nuclear energy system that impedes the diversion or undeclared production of nuclear material or misuse of technology by States in order to acquire nuclear weapons or other nuclear explosive devices"[1]. In the context of this report, Physical Protection refers to those features of the nuclear system that provide intrinsic protective barriers that help prevent nuclear materials being accessed by a terrorist group. This is the same as used by GIF[2], who define the threats under Physical Protection as originating from "… a sub-national group or other non-Host State adversary..." and involving "….either theft or sabotage….".

International efforts to stimulate the development of advanced nuclear systems, such as the GIF and the IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) project, have identified the need to strengthen features that provide inherent PRPP. Current reactor systems and their associated fuel cycles were not designed for inherent PRPP and in some instances they rely on institutional measures to control access to nuclear materials to prevent diversion or theft. It is not the intention that inherent physical characteristics would at any time lead to the introduction of additional nuclear safeguards and security. Instead, the aim is to be able to demonstrate inherent PRPP by design (such as avoiding the production or separation of high quality fissile material) and to help increase transparency and consistency in decisions on system development and ultimate selection. For the purpose of evaluating options against PRPP, no credit is assumed for safeguards and security measures, even though these will always be applied in full in practice.

The UK National Nuclear Laboratory (NNL) has been proactive in developing a PRPP assessment methodology in support of UK requirements in this area. Although PRPP assessment methods were developed primarily to guide decision making on advanced reactor and fuel cycle R&D, they can also be applied in other contexts, such as the management of historic UK liabilities. This position paper explains the issues involved in PRPP assessments and summarises some of the approaches that have been implemented by the international community. It concludes by highlighting the benefits and limitations of these previous PRPP assessments and highlights why NNL decided to develop its own methodology and why the new method is suited for real world application not just in the UK, but internationally.

Nuclear reactors and nuclear weapons both rely on fissile materials such as U-235, Pu-239 or U-233. These are nuclides with a strong propensity to undergo nuclear fission on interacting with fast or

"Although NNL's PRPP assessment methods were developed primarily as a guide to decision making on advanced reactor and fuel cycle R&D, they can also be applied in other contexts."

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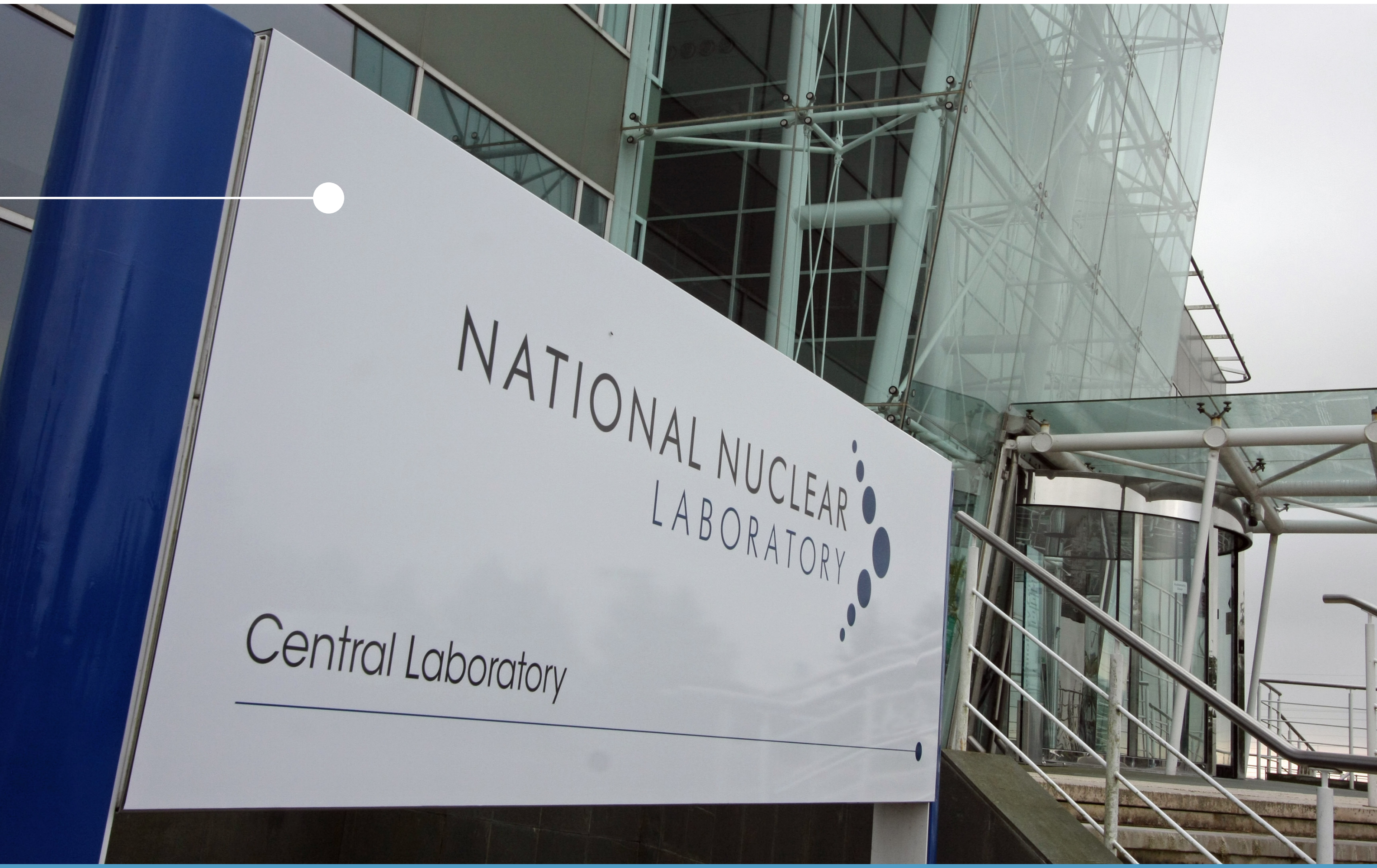
[1] "Proliferation Resistance Fundamentals for Future Nuclear Energy Systems", IAEA STR-332, December 2002.

[2] "Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems", Proliferation Resistance and Physical Protection Working Group Evaluation Methodology Expert Group of the Generation IV International Forum, GIF/PRPPWG/2006/005



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thermal neutrons. All reactors need to be supplied fissile material in fresh fuel and there is always some residual fissile material in the spent fuel. In principle, fissile materials could be diverted from fresh fuel or spent fuel and mis-used for nuclear weapons. Therein lies the risk of nuclear weapons proliferation which an ideal reactor system and its fuel cycle would be designed to minimise. This could be achieved by avoiding the use of high quality fissile materials, avoiding the separation of pure fissile materials in the fuel cycle or by building into the design of a reactor systems inherent features which would make it difficult to isolate high quality fissile materials or which would help ensure the early detection of any attempts to divert such materials. GIF and INPRO both have maximising inherent proliferation resistance as one of their design goals for advanced nuclear systems.

Given that inherent PRPP is one of the major goals of GIF and INPRO, it is important to have some objective means of assessing the relative strengths and weaknesses of different systems and their associated fuel cycles. For this purpose many different methods have been developed by the international community for assessing inherent PRPP. The different methods all have strengths and weaknesses and none can claim to be perfect. In particular, none of the methods available today can be regarded as completely objective in nature and all involve some greater or lesser degree of subjectivity. Nevertheless, despite their limitations, PRPP assessment methods do have a useful role to play in advanced reactor and fuel cycle development, not just in the final results of the assessment, but also out of the discussions and debate that takes part in reaching the consensus scoring.

This paper provides an independent, informed view of PRPP assessment methods worldwide, including those developed by NNL, and their potential usefulness in the UK, drawing on NNL's expertise built up from past involvement in the area fuel cycle and reactor technology.

Discussion

It is important to acknowledge that all fission reactors and their associated fuel cycle pose some degree of proliferation risk and there is no system which is completely proliferation resistant. There are two aspects of the fuel cycle which are relevant to proliferation:

At the front-end of the fuel cycle, the manufacturing route for fresh nuclear fuel poses varying degrees of proliferation risk from diversion or theft of the fissile material. Natural uranium and low enriched uranium fuels used in current commercial reactors are considered to pose minimal proliferation risk because the fissile material is not in weapons useable form and would need to be enriched to much higher levels to pose a viable threat. Historically, many research reactor fuels used high enriched uranium (HEU), with enrichments over 20 weight percent U-235, which is weapons useable. In response to pressure from USA, most research reactors have now been converted to use lower initial enrichments, which lessens the extent to which institutional controls are necessary to protect the fuel. It is worth noting that uranium enrichment technology is widely regarded as posing one of the major proliferation threats.

At the back-end of the fuel cycle, spent nuclear fuel contains residual quantities of fissile materials. Spent uranium fuel from commercial reactors contains up to 1.0 weight percent of residual U-235 and a similar concentration of plutonium generated by neutron captures in U-238 (this is the fertile conversion mechanism, whereby U-238 is converted to fissionable Pu-239 by neutron captures). The plutonium in spent nuclear fuel can be separated by reprocessing and thereby generates a source of potentially weapons useable fissile material. The physical bulk of spent nuclear fuel, combined with the need to chemically separate the plutonium and the presence of a strong irradiation field provides a certain degree of self-protection. Separating plutonium in reprocessing makes the fissile material more accessible, which implies that more reliance must be placed on institutional control measures (nuclear accountancy, safeguards and security) to guard against diversion or theft. Recycling the plutonium as mixed oxide (MOX) fuel is beneficial because, not only is a proportion of the plutonium actually destroyed (approximately 25%), but in addition, the plutonium becomes difficult to access once the MOX fuel has been loaded and irradiated in the reactor.

Similar questions as to the balance between inherent protection and institutional control occur throughout the nuclear fuel cycle and both GIF and INPRO have expressed a preference that future nuclear systems should lean more towards the former. This preference brings with it a clear need to be able to demonstrate that a system has a high degree of inherent PRPP and this is the reason why there has been increasing interest in PRPP assessment methods. The aim is to be able to compare the intrinsic PRPP characteristics of different reactor and fuel cycle systems in a

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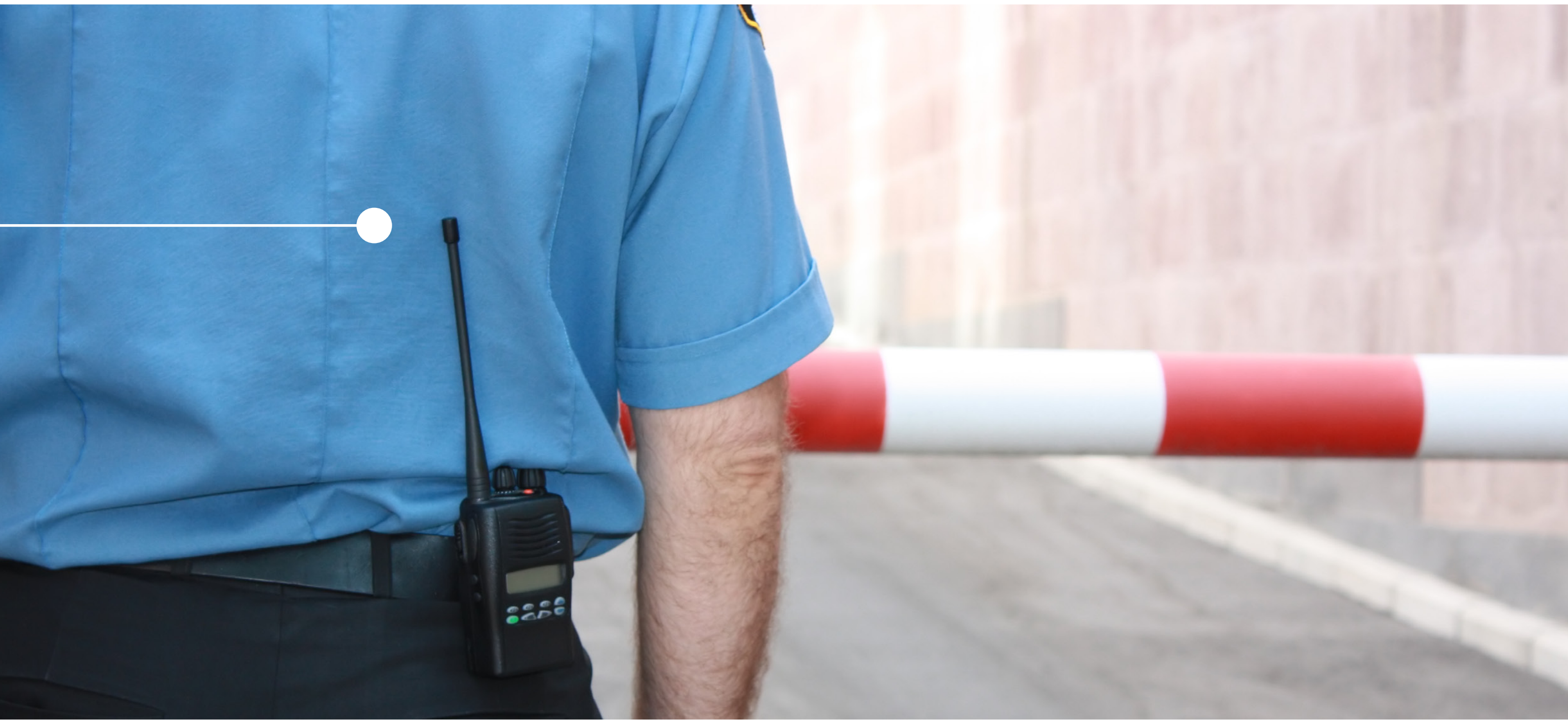


Security issues are of central importance

transparent and consistent way, in order to be able to demonstrate that PRPP aspects have been addressed in the selection process and identify those areas of the fuel cycle requiring improvement.

PRPP assessment methods have a broader role to play in the justification process for decisions involving the UK nuclear fuel cycle. It is a formal European Union requirement that any practice involving radioactive materials needs to undergo a justification process that demonstrates clearly that the benefits outweigh the detriments. This is a broad ranging process that addresses all the relevant aspects, including safety, environmental impact, radiological impact and others. PRPP is regarded as one of the aspects that need to be included.

Threat scenarios

The scope of the threats considered in this paper is restricted to two scenarios involving the diversion or theft of fissile materials:
Diversion: In this scenario the threat is postulated to come from state-sponsored diversion of fissile material from safeguarded civil nuclear facilities. The eventual aim would be to divert sufficient fissile material to assemble into one or more viable fission explosion devices. The intended purpose of such devices might range from a reliable high yield strategic or tactical weapon, to a low yield device. For a high yield device, high quality fissile material would be considered preferable by the diverting state, but it is widely acknowledged that poor quality fissile material is potentially usable, though it would present additional technical difficulties. For a low yield device, fissile quality is not considered a limitation and any fissile material would be considered to pose a threat. In the limit, mere possession of diverted fissile material without any attempt to assemble a fissile explosion device might suffice to pose a serious threat.

Theft: In this scenario the threat is postulated to come from the theft of fissile materials from safeguarded civil nuclear facilities by a sub-national organisation. Nuclear security measures are designed to protect against this threat, but the scenario assumes that these have been circumvented. A sub-national organisation might then intend the nuclear material to be used for the assembly of a viable fissile explosion device. A high yield device is likely to be beyond the capabilities of a sub-national group, but cannot be ruled out and a low-yield device is more likely. Again, mere possession of fissile material would in itself constitute a serious threat.

Technical Issues

Assessing the inherent PRPP characteristics of a reactor system and its associated fuel cycle is a complex inter-disciplinary task, but it can be broken down into two major technical areas, which are fissile material quality and fissile material accessibility:

Fissile material quality

The physics properties of fissile material determine whether it is weapons usable. The main requirements are:

1. Neutron multiplication factor: To be weapons usable, fissile material should have a neutron multiplication factor well in excess of 1.0 when assembled into critical geometry. A high multiplication factor reduces the number of neutron generations needed to achieve a full yield and thereby strongly affects the viability of a fission device. High Enriched Uranium (HEU), normally defined as uranium enriched in U-235 to >20 weight percent, plutonium with a high content of Pu-239 and U-233 all satisfy this requirement.

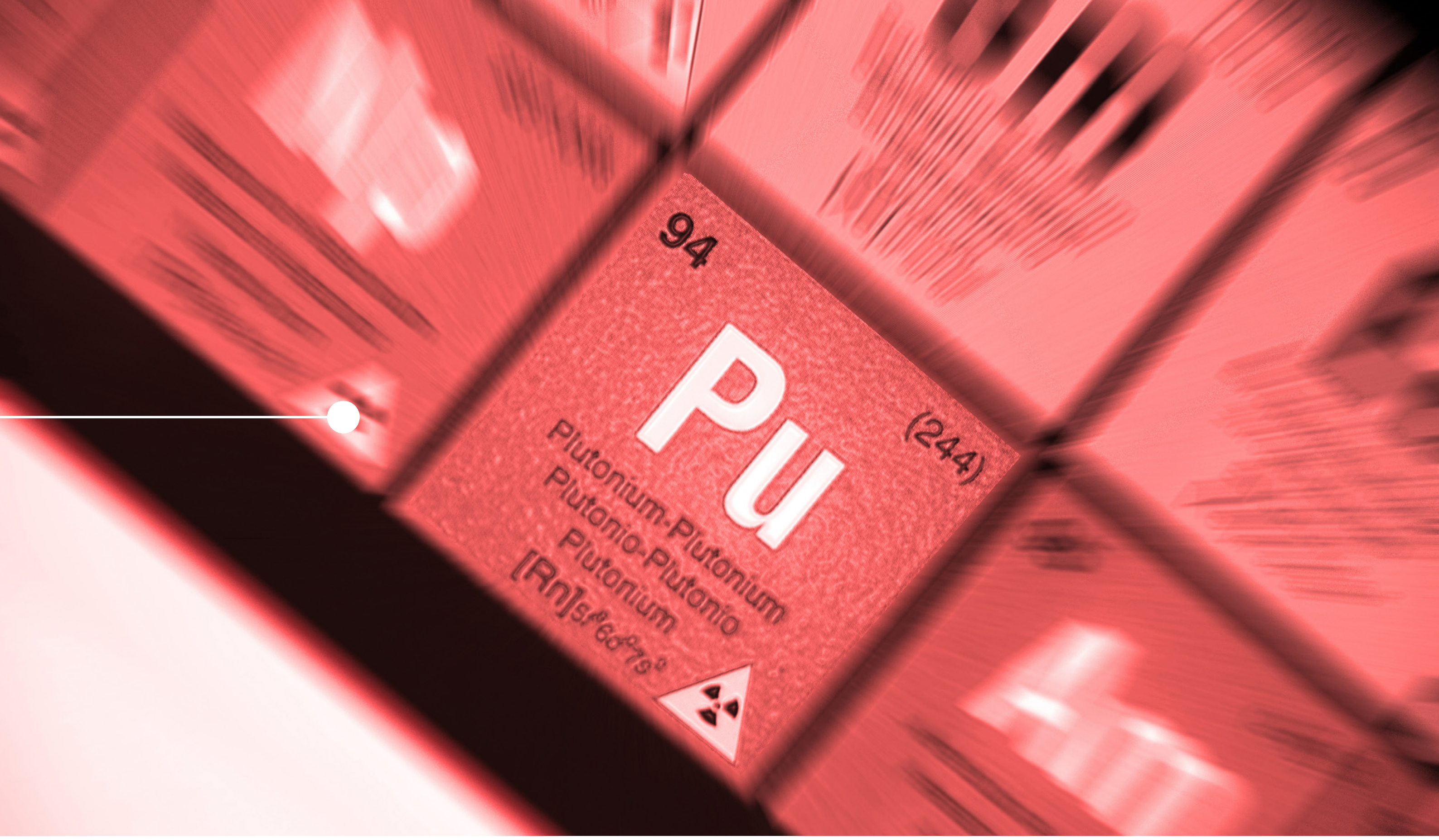
2. Fissile mass. The fissile mass determines how compact a fission device needs to be and is also a major factor in determining its viability. High Enriched Uranium (HEU), plutonium with a high content of Pu-239 or U-233 all have low critical masses.

3. Spontaneous neutron source: Emissions of spontaneous neutrons can cause the premature initiation of neutron multiplication. HEU, Pu-239 and U-233 all have very low spontaneous neutron emissions. The unavoidable presence of Pu-240 at varying concentrations in plutonium introduces a large spontaneous neutron source that may affect the reliability of achieving high yields.

4. Heat output: The presence of heat producing nuclides, such as Pu-238 will cause the temperature of the components of a fission device to increase, possibly beyond the workable limits. Heat output is a major complicating factor that may, in some circumstances demand assembly of a fission device be carried out very shortly before use. HEU and U-233 have low heat outputs, while reactor grade plutonium has a significant heat output because of the presence of Pu-238.

5. Dose rate: The radiological dose rate of the nuclear material is an important consideration in fabricating fissile material into a fissile device. With some fissile materials, the presence of gamma emitters may require radiological protection measures. HEU has a low radiological dose, while plutonium and U-233 can both have significant radiological emissions, depending on their isotopic makeup.

To protect against the diversion scenario, it is preferable to have poor quality fissile materials in the civil nuclear fuel cycle. Material with a high critical mass, high spontaneous neutron source and high heat output would complicate weaponisation and lower the probability of a successful outcome for the proliferator. It is widely agreed that, within reason, a state with access to sophisticated weapons expertise could overcome any such difficulties and all plutonium is therefore considered to pose some degree of threat. Because of the obvious sensitivities, the detailed assessments are not available for open discussion.



In the context of the theft scenario, the physics properties of the fissile material are largely irrelevant, because the mere possession of fissile material or the assembly of a low-yield device already poses an unacceptable threat.

Fissile material accessibility

Spent nuclear fuel typically contains just 1 or 2 weight percent of fissile material dispersed (uranium plus plutonium primarily) in the fuel matrix. Separating the fissile material in reprocessing requires shielded handling of the spent fuel assemblies (a task normally carried out in a pond with several metres of water covering the top of the assembly). The fuel assembly then needs to be sheared mechanically and then dissolved in acid. The fissile materials (uranium and plutonium) are separated from the fission products and other heavy elements and from each other and then purified to remove all residual radioactive contaminants.

All these steps represent physical barriers to accessibility. A would-be clandestine proliferator needs to construct and operate complicated large scale industrial facilities in order to be able to accomplish them. Building such a facility represents major technical and cost barriers, which also require time to implement. The existence of such facilities and the various physical, chemical and radiological signatures associated with operating them put the entire process at risk of detection.

Spent fuel can therefore be regarded as having a high degree of inherent PRPP. GIF and INPRO both recognise the need to increase the inherent PRPP of reprocessing by ensuring that the separation of pure fissile material for recycle is avoided. Possibilities being considered include the production of a mix of uranium and plutonium rather than pure plutonium.

In NNL's experience, fissile material accessibility has been the main determinant of PRPP. In future, there needs to be increased attention on material accessibility in designing reactors and fuel cycles to maximise inherent PRPP.

International PRPP methodologies

In the past 10 years several major international research projects have addressed PRPP either as their principal focus or as part of the broader requirements of the development of future nuclear systems, eg, TOPS, JAEA, INPRO and Generation IV. All four of these have developed what are loosely referred to as PRPP methodologies. However, these so-called methodologies could perhaps be more accurately regarded as providing general guidelines or frameworks for PRPP assessment, rather than prescriptive methodologies.

The U.S. Department of Energy (DOE) Office of Nuclear Energy, Science, and Technology and DOE's Nuclear Energy Research Advisory Committee (NERAC), established a special Task Force in 1999 to review the technological opportunities to improve PRPP for global civilian nuclear power systems (TOPS)[1]. The TOPS report was one of the first international studies to consider how civil nuclear systems design might be directed towards enhanced PRPP. The PRPP approach adopted was entirely qualitative, based on breaking down the fuel cycle into stages and using a tabular method whereby the barriers applicable at each stage (both institutional barriers and inherent technical barriers) are listed and ranked according to a five-point scale from Ineffective, Low, Medium, High and Very High. The tables so constructed can then be used to identify priority areas for maximising overall effectiveness. Its purpose was not so much to arrive at a definitive assessment, which was considered unrealistic at that time, but to use the comparative analysis to highlight the key technical questions that a fully developed methodology would need to address.

Japan Atomic Energy Agency (JAEA) developed the TOPS approach further[2],[3] to introduce an element of consensus. It uses the TOPS tabular approach, but the barrier scoring is carried out by a panel of experts whose scores are then averaged to arrive at a numerical ranking. This is an attempt to make the process less affected by individual subjectivity. Although the outcome is a numerical score, the method is still qualitative and therefore unable to provide reliable relative rankings between options or sensitivities. It is, however, generally applicable to any stage of the fuel cycle and like TOPS can highlight where the vulnerabilities are.

The IAEA's INPRO[4], has developed a set of guidelines to assist developers of new nuclear systems with all aspects of system design. The areas covered are: safety; infrastructure; environment; waste management; physical protection; economics and PRPP. The aim of INPRO is essentially to establish best practice for nuclear system designers to follow when developing new reactors and their associated fuel cycles.

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[1] "Report by the TOPS Task Force of the Nuclear Energy Research Advisory Committee (NERAC)", October 2000, www.ne.doe.gov/pdfFiles/TOPS-Final.pdf

[2] Naoko Inoue, Masato Hori, and Keiichiro Hori, "Methodologies of nuclear proliferation resistance assessment", Proceedijgs of 44th Annual Meeting of the Institute of Nuclear Materials Management, Phoenix Arizona, July 13-17 2003

[3] Naoko Inoue and Junichi Kurakami & Hiroshi Takeda, "Review of JNC's study on Assessment Methodology of Nuclear Proliferation Resistance", Proceedings of 45th Annual Meeting of the Institute of Nuclear Materials Management, Orlando Florida, July 18-22 2004

[4] "Methodology for the assessment of innovative nuclear reactors and fuel cycles Report of Phase 1B (first part) of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)", IAEA-TECDOC-1434, ISBN 92–0–116304–5, ISSN 1011–4289, December 2004

International PRPP methodologies

For all of the technical areas covered by INPRO, a set of Basic Principles and User Requirements are defined[6]. For PRPP the basic principle is:
Proliferation resistance intrinsic features and extrinsic measures shall be implemented throughout the full life cycle for innovative nuclear energy systems to help ensure that innovative nuclear systems (INS) will continue to be an unattractive means to acquire fissile material for a nuclear weapons program. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.

The Generation IV Forum (GIF) was set up to encourage the development of new reactor systems and, in a similar way to INPRO, has developed best practices for designers to follow. One of the areas covered is PRPP, where an assessment methodology has been developed[5]. This has some similarities to the INPRO methodology, being largely qualitative and based on prescriptive categorisations, but is currently more developed, provides a semi-quantitative outcome and is perhaps somewhat less subjective. It can also be used to analyse different threat scenarios.

The Gen IV PRPP methodology is a rigorous process that is intended to be carried out by a large team of people, possibly from different organisations. Once the threat pathway has been defined, the Gen IV PRPP methodology involves analysing the proliferation risk based on a set of six metrics (or measures) each of which assigns a nuclear system into one of five categories. The six metrics are: Technical Difficulty (TD); Proliferation Cost (PC); Proliferation Time (PT); Fissile Material Type (MT); Detection Probability (DP) and Detection Resource Efficiency (DE), all of which are assigned into one of five pre-defined categories, which simplifies the assessment process.

Assigning scores against each of the six metrics is necessarily a subjective activity, though the degree of subjectivity is minimised by providing clear guidelines as to which category is applicable given the materials in the fuel cycle. The results can be presented in tabular form and/or graphically, with the columns in the table recording the scoring against each of the six metrics. The table and graph provide a qualitative guide to comparing different proliferation pathways for a given reactor/fuel cycle. The method does not use weighting functions to aggregate the different metrics, so that no single overall numerical score is provided.

World-wide, a large number of PRPP methodologies have been developed, influenced by and designed to be consistent with one or more of the frameworks above. Their distinguishing feature is that they aim to combine all the different metrics to provide a single quantitative figure of merit with which to compare different systems. In principle, this also allows sensitivity and uncertainty analysis to be performed, which is difficult to do in any meaningful way with the qualitative approaches. However, care is required because, though these quantitative methods may give the appearance of being rigorously objective, in many cases the process still involves a degree of subjectivity. Examples summarised below are the multi-attribute utility analysis (MAUA), Markovian

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[5] Evaluation Methodology for Proliferation Resistance and Physical Protection of Generation IV Nuclear Energy Systems, Rev 5, Nov 30 2006, GIF/PRPPWG/2006/005, Gen IV International Forum.

International PRPP methodologies

methods and Risk Informed Probabilistic Analysis (RIPA):
Multi-Attribute Utility Analysis (MAUA) is a long standing method that has been used to aggregate the assessment of multiple attributes. For proliferation resistance analysis, MAUA has been developed most fully by Texas A&M University (TAMU)[6] [7].

MAUA is useful because it generates a single figure of merit for the entire system, but is limited because the weights and utility functions used in the method are subjective and it is difficult to know how much the overall result is affected by this subjectivity. MAUA can be used to determine the time dependence of proliferation risk – any time dependence of an individual attribute (for example, due to radioactive decay) affects the individual utility functions and propagates to the overall utility function.

Markovian methods can be used for the analysis of a specific system against a specific threat scenario and the use of such methods is therefore a scenario-based approach. It relies on constructing a Markov chain to represent the pathways from the normal flow of fissile materials through the fuel cycle and also postulated diversion pathways where a proliferator attempts to acquire weapons usable fissile material. The method has been developed by Brookhaven National Laboratory[8] [9] and is designed to calculate the probability of detection of covert diversion activities or, conversely, the probability of diversion succeeding. Provided that the detection probabilities are evaluated rigorously, it is potentially a very useful tool for assessing the effectiveness of safeguards measures and in particular of highlighting where potential vulnerabilities may lie so that the safeguards measures can be strengthened where they are most needed.

Risk-Informed Probabilistic Analysis (RIPA)[10] is a method based on Probabilistic Risk Assessment (PRA). RIPA is designed to determine the most probable path towards acquisition of a nuclear weapon and thus to show how the fuel cycle can best be modified to minimise the probability of proliferation success. RIPA accounts for the time and cost of each stage in the proliferation chain (evaluated taking account of the proliferator's available resources), the probability of detection, the probability of technical success and the materials throughput. RIPA gives an objective, quantitative assessment of the proliferation risk and in principle can be used to carry out sensitivity analyses. It does not require the use of weighting factors as in MAUA, avoiding this source of subjectivity. However, there are still subjective elements because not all the elements of the analysis may necessarily be quantifiable. For example, the probability of detection of different proliferation options might need to be estimated by an expert panel, introducing a degree of subjectivity.

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[6] D D J Giannangeli III, "Development of the fundamental attributes and inputs for proliferation resistance assessments of nuclear fuel cycles", MSc thesis, Texas A&M University, May 2007

[7] W S Charlton et al "Proliferation resistance assessment methodology for nuclear fuel cycles", Nuclear Technology, Vol 157, Feb 2007, pp 143-156.

[8] Meng Yue, Lap-Yan Cheng and Robert A Bari, "A Markov model approach to proliferation resistance assessment of nuclear energy systems", Nuclear Technology, Vol 162, April 2008, pp 26-44.

[9] Meng Yue, Lap-Yan Cheng and Robert A Bari, "Relative proliferation risks for different fuel cycle arrangements", Nuclear Technology, Vol 165, Jan 2009, pp 1-17.

[10] "Guidelines for the Performance of Non-proliferation Assessments", PNNL-14294, May 2003, Appendix D. The Risk-Informed Proliferation Analysis Methodology

NNL Methodology

NNL has reviewed the potential suitability of the various approaches described above for application in the UK and carried out a comparative assessment for this purpose. The conclusion of the assessment is that none of these approaches were ideally suited for the applications envisaged in the UK, though there were elements in the INPRO and GIF methodologies which were potentially usable. Limitations of these approaches that emerged from the assessment included:

- Many of the approaches are qualitative in nature (TOPS, JAEA, SAPRA and INPRO) and therefore not able to provide sensitivity analysis or uncertainty analysis.
- Only some of the approaches incorporate time dependence (INPRO, MAUA and the Markovian).
- None of the methods is entirely free of subjectivity. However, some of the methods involve a higher degree of subjectivity than others.
- Some of the methods are better suited to assessing a specific proliferation scenario and are less well suited for assessing the generic risk posed by a particular system against multiple possible threats.
- The MAUA, Markovian and RIPA methods are not straightforward to implement, requiring specialist software and sometimes requiring very time consuming and demanding inputs from users.

On the basis of this survey, the TOPS, JAEA, SAPRA and INPRO methodologies all have major shortcomings, especially their failure to provide quantitative results. This is partly because they are really high level frameworks that are intended to direct more detailed work. Also, the INPRO methodology, as currently published, is not complete and the finished version may address some of its weak points.

NNL therefore decided to develop its own approach, that incorporates some of the best features of the available international methodologies and attempts to avoid their limitations as far as possible. NNL's approach is designed to be flexible enough to be applicable to the various different UK applications and easy enough to allow relatively fast turnaround on application. More specifically, the following user requirements have driven the development of NNL's PRPP assessment methods:

- To be as objective as possible and to provide a numerical relative ranking of different reactor and fuels cycle systems (though there is no requirement for the numerical ranking to have any absolute quantitative meaning).
- To be applicable to any reactor and fuel cycle system and any proliferation pathway.
- To be sufficiently general to be able to incorporate different approaches to treating the various metrics adopted and to allow easy inter-comparison.
- To be simple to implement and to be capable of being presented graphically very clearly.

> **"During the application of the PRPP methods, NNL has identified that it is during the discussion and debate within a group of experts where the real value is added and the methodology facilitates that process and this approach is actively encouraged."**

NNL Methodology

- Preferably, to use input parameters that are easily obtainable without requiring complex shielding or critical mass calculations.
- To be usable without reliance on knowledge of sensitive site-specific information, such as details of the security measures in place at a nuclear plant and an assessment of their effectiveness. Such information is understandably kept confidential and its use would not allow the methodology to be used in open publications.

Although NNL's methodology addresses all of these user requirements, it does not completely avoid subjectivity, as the assessments are completed by individuals or groups of individuals expert in their respective fields. The methodology is based on calculating a "utility function" that represents how useful a nuclear fuel cycle might be to a potential proliferator and in which the multiple parameters that characterise the fuel cycle are captured. The utility function is the product of a "value function" that measures the amount of fissile material in the fuel cycle and its fissile quality and an "access function" that measures how accessible the fissile material is. These functions are generally applicable to both the front-end and the back-end of the fuel cycle. Since it is the access function that is the main controlling parameter, it is informative to plot the utility function as a function of the access function, as this visualises where the inherent PRPP attributes of a system come from and the method is therefore known as the U-A methodology. The U-A methodology incorporates aspects of MAUA, but in a manner which is much simpler and easier to implement. The U-A methodology also uses the GIF metrics to determine the value and access functions, so that it is automatically links in with the GIF framework.

To provide confidence in NNL's methodology, having taken on board the lessons learned outlined above, NNL has benchmarked its U-A methodology against the various international approaches discussed earlier . Applied to analysing different fuel cycles, the U-A methodology gives relative rankings that agree very well with other approaches. One of the main conclusions of the benchmarking was that there was a high degree of correspondence between the various different methods, which adds confidence that the results from the different approaches are meaningful even though none of the methods can give an absolute measure of PRPP.

NNL has applied the U-A methodology to a number of different applications in the UK and there are plans to extend its application further. Applications to date include an assessment of the inherent PRPP characteristics of different options to manage the UK's stocks of separated plutonium, immobilised waste forms options, spent fuel management and reprocessing options. These applications of the U-A methodology are sufficient to demonstrate that it is possible to rank different fuel cycle options relative to each other in a manner which is transparent and to a large extent objective and reproducible.

"NNL has developed its own PRPP approach based on lessons learnt from international methodologies. It is designed to be flexible enough to be applicable to the various UK applications and easy enough to allow fast turnaround."

Conclusions

On the basis of NNL's experience of having reviewed international PRPP assessment methods and having developed and applied its own U-A method to UK fuel cycle options, NNL has reached the following conclusions:

- Underlying the entire approach to PRPP assessment is an implicit acceptance that no option is completely free of proliferation risk. The method has no formal role in security assessment and in determining the measures that are required to safeguard nuclear material. However, the method can identify options which are preferred because, for example, a favoured option might be more reliant on intrinsic rather than extrinsic measures.
- PRPP assessment methods are only able to indicate relative risks and it is not feasible to quantify the absolute risk of proliferation, nor is it sensible to attempt to define any kind of go/no-go criterion.
- Accepting that there is no perfect method for comparing the proliferation risk posed by different options, there is still merit for the UK in applying the methodology and presenting and recording the results as part of due process in a consultation system that is intended to be consistent, open and transparent.
- Given the shortcomings in the international methods developed to date, NNL has learnt from international best practice and developed its own approach, which is designed to be flexible enough to be applicable to the various different UK and international applications and easy enough to allow relatively fast turnaround on application.
- NNL's methodology demonstrates a simple and practical means to combine PRRP metrics such as those defined by GIF into a single figure of merit that can be used to rank different fuel cycle options. Using the GIF PRRP metrics as the starting point automatically ties in the NNL methodology with international practice.
- The need to assess options against the GIF PRPP metrics has, of itself, proved very valuable, automatically focusing the discussion to ask the right questions and facilitating the agreement of a consensus view when completing the analyses. It is during the discussion and debate within a group of experts where the real value is added and the methodology facilitates that process. This approach is actively encouraged.
- Successful applications of the NNL methodology to date include an assessment of the inherent PRPP of options to manage the UK's stocks of separated plutonium, immobilised waste forms options, spent fuel management and reprocessing options. These applications of the NNL methodology are sufficient to demonstrate that it is possible to rank different fuel cycle options relative to each other in a manner which is transparent and to a large extent objective and reproducible to assist policy and decision makers from a PRPP perspective.
- NNL's experience is that fissile material accessibility is the key determinant of inherent proliferation resistance and though fissile material quality is important, it plays a secondary role.

More detailed information regarding NNL's PRPP methodology, its comparison with international alternatives and its application to the UK's plutonium management options is available in published literature[1] [2] as is further background information regarding how NNL supported the recent Royal Society project on nuclear non-proliferation.[3]

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[1] K W Hesketh, A Worrall, "A Review of International Proliferation Risk Assessment Methodologies and Application By the UK National Nuclear Laboratory", INMM 2011, Palm Springs, CA, USA, July 2011

[2] "Management of the UK's Plutonium Stocks: A consultation on the long term management of UK owned separated civil plutonium", Department of Energy and Climate Change, February 2011

[3] "Fuel cycle stewardship in a nuclear renaissance", Royal Society, October 2011.

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5th Floor
Chadwick House
Warrington Road
Birchwood Park
Warrington
WA3 6AE

T. +44 (0) 1925 289800
E. customers@nnl.co.uk

W. www.nnl.co.uk

@UKNNL

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