LA-UR- 10-00016

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Intended for: International Conference on Fast Reactors and Related Fuel Cycles (FR09)

Los Alamos NATIONAL LABORATORY EST. 1943

Proliferation Resistance for Fast Reactors and Related Fuel Cycles: Issues and Impacts

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Abstract

The prospects for a dramatic growth in nuclear power may depend to a significant degree on the effectiveness of, and the resources devoted to, plans to develop and implement technologies and approaches that strengthen proliferation resistance and nuclear materials accountability. The challenges for fast reactors and related fuel cycles are especially critical. They are being explored in the Generation IV International Forum (GIF) and the International Atomic Energy Agency's (IAEA's) International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) initiative, as well as by many states that are looking to these systems for the efficient use of uranium resources and long-term energy security. How do any proliferation risks they may pose compare to other reactors, both existing and under development, and their fuel cycles? Can they be designed with intrinsic (technological) features to make these systems more proliferation resistant? What roles can extrinsic (institutional) features play in proliferation resistance? What are the anticipated safeguards requirements, and will new technologies and approaches need to be developed? How can safeguards be facilitated by the design process? These and other questions require a rethinking of proliferation resistance and the prospects for new technologies and other intrinsic and extrinsic features being developed that are responsive to specific issues for fast reactors and related fuel cycles and to the broader threat environment in which these systems will have to operate. There are no technologies that can wholly eliminate the risk of proliferation by a determined state, but technology and design can play a role in reducing state threats and perhaps in eliminating non-state threats. There will be a significant role for

[1] The views expressed are the author's own and not those of the Los Alamos National Laboratory, the National Nuclear Security Administration, the Department of Energy or any other agency.

extrinsic factors, especially the various measures—from safeguards and physical protection to export controls—embodied in the international nuclear nonproliferation regime. This paper will offer an assessment of the issues surrounding, and the prospects for, efforts to develop proliferation resistance for fast reactors and related fuel cycles in the context of a nuclear renaissance. The focus of the analysis is on fast reactors.

Introduction

The prospects for a dramatic growth in nuclear power may depend to a significant degree on the effectiveness of, and the resources devoted to, plans to develop and implement technologies and approaches that strengthen proliferation resistance and nuclear materials accountability. The challenges for fast reactors and related fuel cycles are especially critical. They are being explored in the Generation IV International Forum (GIF) and the International Atomic Energy Agency's (IAEA's) International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) initiative, as well as by many states that are looking to these systems for the efficient use of uranium resources and long-term energy security. How do any proliferation risks they may pose compare to other reactors, both existing and under development, and their fuel cycles? Can they be designed with intrinsic (technological) features to make these systems more proliferation resistant? What roles can extrinsic (institutional) features play in proliferation resistance? What are the anticipated safeguards requirements, and will new technologies and approaches need to be developed? How can safeguards be facilitated by the design process? These and other questions require a rethinking of proliferation resistance and the prospects for new technologies and other intrinsic and extrinsic features being developed that are responsive to specific issues for fast reactors and related fuel cycles and to the broader threat environment in which these systems will have to operate. This paper will offer an assessment of the issues surrounding, and the prospects for, efforts to develop proliferation resistance for fast reactors and related fuel cycles in the context of a nuclear renaissance.

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Proliferation Resistance: General Considerations

Proliferation resistance is an old concept that was first raised in the Acheson-Lilienthal report's discussion of "denaturing."[2] The report recognized that denaturing could be reversed, but held that doing so would pose major technological challenges.[3] The authors of the report were overly hopeful of denaturing, but the pursuit of a technological way to make the peaceful uses of nuclear energy resistant to proliferation appears and reappears in the history of nuclear power.

Although there has been some controversy and continued debate over the meaning of proliferation resistance, the International Atomic Energy Agency (IAEA) developed a widely accepted definition at a meeting in Como in 2002. According to the IAEA: "Proliferation resistance is that characteristic of the nuclear energy system that impedes the diversion or undeclared production of nuclear materials, or misuse of technology, by the host state in order to acquire nuclear weapons or other nuclear explosive devices."[4] The IAEA further defined both intrinsic and extrinsic elements of the definition. On intrinsic features, it stated: "Extrinsic proliferation resistance features are those features that result from the decisions and undertakings of states related to nuclear energy system."[5] As for intrinsic features, the IAEA stated: "Intrinsic proliferation resistance features are those features that result from the technical design of nuclear energy systems, including those that facilitate the implementation of the extrinsic measures."[6]

As we look at nonproliferation efforts in the current threat environment, it is especially important to recognize that no proliferation resistant measures can prevent a state from acquiring nuclear weapons if it makes a decision to do so. Proliferation resistance does not

[2] *A Report on the International Control of Atomic Energy, Prepared for the Secretary of State's Committee on Atomic Energy* (Washington, D.C.: U.S. Government Printing Office, March 16, 1946, pp. 26-27.
[3] Ibid., p. 27.

[4] IAEA, STR-332, "Proliferation Resistance Fundamentals for Future Nuclear Energy Systems," Report on COMO meeting held in Como, Italy, October 28-31, 2002.
[5] Ibid.
[6] Ibid.

and cannot mean "proliferation-proof." There are no simple technological fixes or "silver bullets." Proliferation resistance can in principle increase the technical difficulty, cost and time needed by the proliferators. This can be an important objective, but it is limited especially for advanced nuclear states.

Although the discussion of proliferation resistance measures has focused primarily on states, they may be more important for non-state actors and could complement current physical protection practices. This may lead to new approaches to nuclear security in the future. Moreover, even though the current approaches are directed against state threats, they arguably have some utility for non-state threats and need to be evaluated from that perspective.

Despite its clear limits, improving proliferation resistance will be essential if nuclear power is to expand in the United States and abroad without increasing proliferation or terrorism risks. As the US debate over President Bush's Global Nuclear Energy Partnership demonstrated, however, we must be clear about the limits and the benefits of proliferation resistance in public discussions.

As we look ahead, if proliferation resistance is to be real, it will need to be pursued through an integrated strategy involving intrinsic and extrinsic features. Extrinsic features are most important in assuring meaningful proliferation resistance, and with improved IAEA safeguards could change the terms of the debate. But there is value in pursuing intrinsic features as well. It is important to pursue the potential benefits that may yet be realized from reactors and other facilities designed to minimize risks coupled with effective safeguards and other nonproliferation measures. Proliferation-resistant small reactors and other new ideas for addressing underlying proliferation concerns must continue to be pursued. However, those efforts that focus on material quality appear especially limited, and those that rely on radiation protection are likely to have significant negative impacts on operations and on safeguards that may or may not be ameliorated through further R&D.

Given the importance of safeguards, efforts to design new plants with enhanced safeguardability are critical. For fast reactors and related fuel cycles, this offers a great opportunity. The application of safeguards by design (SBD) in conjunction with R&D on novel safeguards technologies and approaches will be needed to meet formidable challenges and can improve the proliferation resistance of fast reactors. In principle, advances and alternative approaches can make safeguards comparable to existing light water reactors (LWRs).

Proliferation Resistance for Fast Reactors and Related Fuel Cycles

Proliferation concerns about fast reactors have a long history, which has been colored by the fact that they were originally seen exclusively as "breeder" reactors and tied to closed fuel cycles. This lineage was a response to concerns about the availability of uranium, which was thought at the beginnings of the nuclear age to be exceedingly scarce. Both of these issues are at the forefront of the debate today, albeit not in the same way as the past. Today, the ability of fast reactors to transmute actinide elements has led to interest in their possible role as "burners," a role that has the potential to address proliferation concerns about the stockpiles of separated plutonium around the globe as well as waste management issues.

Reflecting these interests, especially in recent years, the proliferation resistance of fast reactors has largely been seen in terms of concepts marked by the presence of TRU in the fresh fuel. This was driven by waste management, especially the goals of reducing the volume and radiotoxicity of nuclear waste, but it has been highlighted as a proliferation resistance feature of all three GenIV fast reactor concepts.

The implications for proliferation resistance, however, are not decisive. The fresh fuel is slightly less attractive than unirradiated reactor-grade plutonium, but it remains attractive. On the other hand, the need for shielding and remote handling of the fuel makes detection of diversion easier in principle due to limited entry and exit points for fresh fuel. (The shielding and remote handling offers some benefits against non-state actors.) If high burnup can be achieved, which is a goal of advanced fuel research, it can reduce the frequency of fuel handling and create a higher radiation barrier for the material. Both have proliferation resistance benefits.

Beyond such considerations, the goal of burning separated plutonium, minor actinides and fission products also enter the calculation. Although burners can in principle mitigate proliferation concerns to some degree, they can be changed in a reactor to a breeder configuration. Moreover, the expected growth in nuclear power production globally raises anew the issues of resource utilization, sustainability and energy security that have long been the driver for thinking about breeders.

Finally, there are safeguards challenges involved with such approaches to proliferation resistance. The capability of the Non-Destructive Assay (NDA) will be an issue for the fast reactor concepts now under discussion. NDA may not be able to verify plutonium in fuel with TRU due to the presence of high concentrations of minor actinides. This is complicated by the fact that verification will be difficult due to the opaque nature of sodium or lead coolants.[7] To meet these challenges will require, inter alia, developing advanced instrumentation and methodologies for materials detection, measurement, accounting and tracking; novel radiation and visual monitoring systems; improved process design verification and monitoring; and integrated process monitoring and materials accountancy to provide near real time accounting.[8] Under Sodium Viewing (USV) or a variant may also be required.

[7] This is not an issue for gas-cooled concepts.

[8] For a discussion of fast reactor safeguards challenges, see Philip C. Durst, Ike Therios, Robert Bean, A. Dougan, Brian Boyer, Rick L. Wallace, Michael H. Ehinger, Don N. Kovacic and K. Tolk, *Advanced Safeguards Approaches for New Fast Reactors*, PNNL-17168, December 15, 2007.

Greater dependence on containment and surveillance (C/S) will also be required, especially because of the difficulties of precisely measuring plutonium in fast reactors. C/S can be improved by such means as greater utilization of: automation; remote data collection, authentication and transmission; and remote handling of fresh and spent fuel.[9] The move to greter dependence on C/S does not remove the need for more effective NDA.

If safeguards challenges can be addressed, overall proliferation resistance does not appear fundamentally different from other reactors in use or on the drawing table, and can be enhanced by design choices and further safeguards improvements. Additional institutional measures such as multinationalized fuel cycle facilities may also be useful, but require extensive analyses, which should include attention to feasibility, effectiveness, cost and operational impacts.

Fast reactors are associated with closed fuel cycles, which have been argued to be less proliferation resistant than once-through fuel cycles primarily because of the separation and use of plutonium, and the difficulty of safeguarding large plants. The arguments of critics may be challenged and the relative risks of once-through and closed fuel cycles debated. However, for closed fuel cycles to become more proliferation resistant, it will be necessary to address the issues surrounding closed fuel cycles. Efforts to avoid brreding or the separation of pure plutonium are a feature of many current concepts designed to do just that.[10] There is also a recognized need to meet difficult safeguards challenges through integrated facility design, advanced safeguards technologies and techniques and other means. The prospect over time of greatly reducing the need for enrichment via closed fuel cycles is attractive, but this is not likely to be realized in the short or medium terms and possibly not at all.

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[9] Ibid.

[10] See, e.g., Y. Kuno, M. Senzaki, M.Seya and N. Inoue, "Role of Safeguards in Proliferation Resistance for the Future Nuclear Fuel Cycle Systems," paper presented at the International Conference on Fast Reactors and Related Fuel Cycles: Challenges and Opportunities, Kyoto, Japan, December 7-11, 2009.

Assessing Proliferation Resistance: Fast Reactors

Given these concerns and uncertainties, can fast reactors be made proliferation resistant? A look at two representative, high level pathways to nuclear weapons using fast reactors illustrates the nature of the challenges to proliferation resistance and some possible solutions.[11]

One scenario involves clandestine plutonium production in the fast reactor using uranium targets in the blanket.

The cost and technical difficulty of implementation would not be significant for state actors. The time needed is not great, but the time depends on the number of targets utilized.

Indictors of insertion and removal of targets may be small. It will rely almost entirely on the ability to interrogate material movements into and out of the reactor. If there are a large number of fuel movements during refueling, it may be difficult to follow target movements.

This is a concern for safeguards at existing LWRs and might be more difficult in fast reactors where it is more difficult to survey the core. However, the fuel loading/unloading operation may provide opportunities for process monitoring however that could be effective.

[11] The analysis is based on an expert elicitation using the PR&PP methodology from which this section is drawn. See Kory W. Budlong Sylvester, Charles D. Ferguson, Eduardo Garcia, Gordon D. Jarvinen, Joseph F. Pilat and James W. Tape, *Report of an Elicitation on an Example Sodium Fast Reactor (ESFR) System in Support of the Proliferation Resistance and Physical Protection (PR&PP) Working Group*, Los Alamos National Laboratory White Paper, Los Alamos, NM, October 1, 2008.

As suggested, nondestructive assay (NDA) may not be able to verify plutonium in fuel with TRU due to the presence of high concentrations of minor actinides. Greater dependence on C/S certainly would be required and USV may be useful.

Design efforts to minimize the number of entry and exit points for fuel transfer between system elements would enhance both NDA and C/S and improve detection probability. To the extent it does so, it would compensate in part for the inability to conduct visual inspections during fuel transfers.

Designs that minimized the time the fuel spent under sodium could allow more chances to verify and re-verify TRU fuel, especially if Continuity of Knowledge (CofK) is lost. Design modifications to limit the space available in the core for target insertion would be desirable, but it is not clear whether this could be achieved and verified on a continuous basis.

There are efforts to address these and other issues via design in some GenIV and other fast reactor concepts, including efforts to allow continuous visual monitoring of fuel assemblies and to prevent dummy fuel assemblies from being introduced.

Another scenario involves abrogation of nonproliferation obligations, namely withdrawal from the Nonproliferation Treaty with production of plutonium in the fast reactor.

Should a state decide to withdraw from the NPT, the issues of technical difficulty, cost and time would not present any major impediments to obtaining the material needed for a weapon. The time could be higher or lower depending on the number of targets utilized, their location, etc.

Unless there were operational problems, a fast reactor with sufficient capacity would work well as a weapon-grade plutonium producer. A blanket of fertile material would be added, unless the design precluded this possibility.

The issue of whether material type is germane to this scenario to some degree dependent on time sensitivity. If the proliferator views rapid acquisition of weapon material as urgent, available material will be used. In this case, unless targets had been introduced clandestinely prior to abrogation, fast reactors offer some degree of proliferation resistance because all fuel is either irradiated or freshly recycled, which would produce relatively high-burnup plutonium. If time is not sensitive for the proliferator, it can be assumed that production will be optimized to produce high-quality weapon-grade material.

Safeguards questions are not central to the case of abrogation to the extent the State is choosing to disregard detection concerns. However, they can be relevant in scenarios where there are illicit actions are undertaken before abrogation.

There may be some proliferation resistance value in designs that physically reduced the capacity for production of weapon-grade plutonium, and were not easily reversed.

It should be noted that these and other scenarios are not unique to fast reactors, but can be especially challenging with fast reactors. Analysis is required.

Proliferation Resistance: Related Fuel Cycles

While this paper focuses on fast reactors themselves, it appears that the proliferation resistance of the reactors, which are generally comparable to current reactors and to other rector concepts assuming safeguards challenges are met, is less an issue than their related fuel cycles. Fast reactors are planned with closed fuel cycles. To the extent that those fuel cycles envisage no separation of plutonium and minor actinides, no radial blanket, limited access and other such measures, they should have some limited proliferation resistance. There is a real need for further analyses of these and other proliferation resistance measures, taking into account attendant safeguards costs as well as the ease with which they can be reversed or otherwise contravened by states. Ultimately, the proliferation resistance of these fuel cycles will depend on their ability to address safeguards challenges. For reprocessing facilities, key challenges include traditional safeguards issues such as measurement uncertainties in large bulk material handling facilities, accuracy of plutonium accountability data and process holdup inventories, as well as issues raised by the use of TRU fuels and other new developments..

In some cases, efforts to increase proliferation resistance can be in conflict with other objectives. For example, the high radiation fields created by not separating plutonium from minor actinides and possibly fission products can make material somewhat less attractive and provide important barriers to material theft, but it can hamper accurate materials accounting designed to deal with material diversion and adversely affect facility operations.

Conclusions

There are no technologies that can wholly eliminate the risk of proliferation by a determined state, but designs with intrinsic proliferation resistance features need to be further studied to determine what role they may be able to play in reducing proliferation risks and non-state threats as well. There will be a more significant role for extrinsic factors, especially the various measures—from safeguards to export controls—embodied in the international nuclear nonproliferation regime. One promising area involves benefits that may be realized from reactors and other facilities designed to minimize proliferation risks coupled with effective safeguards and other nonproliferation measures that likely will offer the highest degree of proliferation resistance. In this context, there is growing interest in improving the application of safeguards by developing facility designs that would improve the efficiency and effectiveness of safeguards, reduce or eliminate diversion or misuse pathways or increase the prospects for detection along pathways by facilitating verification. This approach can in principle benefit fast reactor development, especially if SBD is combined with a directed safeguards R&D effort that focuses on well characterized as well as on anticipated safeguards challenges. If such activities are successful, and there is no reason to believe they will not be, the proliferation resistance of fast reactors will likely be comparable to current and future reactor systems. Safeguards are also key to the future proliferation resistance of related fuel cycles. If these safeguards advances are realized, the vast promise of fast reactors for sustainability, energy security, waste management and other objectives will be more likely to be achieved.