PROLIFERATION RESISTANCE ASSESSMENT OF THE INTEGRAL FAST REACTOR

Harold F. McFarlane
Argonne National Laboratory
P. O. Box 2528
Idaho Falls, Idaho 83415, USA 208/533-7106

ABSTRACT

The Integral Fast Reactor (IFR) concept includes a sodium-cooled fast reactor collocated with an integrated pyroprocess fuel recycling facility. The pyrochemical processes and the inert atmosphere of the heavily shielded fuel cycle facility provide inherent proliferation-resistant features for this advanced technology. The reactor can be designed to operate with a number of different conversion factors, so that it could be used for excess plutonium consumption or as a breeder if needed for rapid expansion of energy supply. The system contains a large quantity of plutonium and minor actinides, which at all times remain in extremely hostile environments and in chemical and physical forms that would require additional processing to extract weapons-suitable material. The aqueous processing equipment and facilities to accomplish such separation would not be available on site. Transportation would not be required in the reference deployment scenario. Nevertheless, the proliferation-resistance of some parts of the system could be considerably strengthened by advanced safeguards technologies. In spite of its inherent features, international deployment of the system would probably be limited to stable countries with a strong existing nuclear infrastructure.

INTRODUCTION

Assessing the proliferation resistance of Argonne National Laboratory's Integral Fast Reactor (IFR) concept has been a relatively popular pastime activity for the past 16 years. [1,2,3,4,5] This particular assessment is based on the unpublished work that went into preparing a presentation for the Nuclear Energy Research Advisory Committee's (NERAC) Special Committee on Technical Opportunities for Proliferation-resistant Systems (TOPS) [6]. Speculation on the proliferation resistance of the concept endures because the technology continues to develop and mature, the assessment tools improve, and the possibility of applying elements of IFR technology to national problems continues to be raised.

As originally conceived [7], the Integral Fast Reactor comprised a fast-spectrum, sodium-cooled, metal-fuelled reactor and a collocated fuel recycling facility that employed pyroprocessing and fully remotized metal fuel casting and assembly. No transportation of nuclear materials would be required other than the initial shipment of fuel for startup. The system would be self-sustaining, i.e., producing as much plutonium as was consumed and lost to incidental waste streams. Because of the unique fuel cycle, plutonium would remain in a highly radioactive matrix at all times in facilities that were literally inaccessible to humans at all times. In designing the system during the post-International Nuclear Fuel Cycle Evaluation (INFCE) [8] era, robust proliferation resistance was a requirement. The fundamental assumption was that nuclear fuel recycle would be required and therefore the best approach to plutonium management was to avoid producing, storing or using it in any form that could be easily stolen or concealed, or that could be used without further refinement to fabricate a nuclear explosive. Furthermore, it was important that the process equipment and facilities could not be easily modified to produce a weapons-suitable product.

The reactor concept was not tied to a particular size, but rather was envisioned to work for any size, from small modular reactors to greater-than 1000 MWe systems. During the early development, industrial participants in the Advanced Liquid Metal Reactor (ALMR) program [9] adopted the concept. Smaller designs were favored, with General Electric advocating its rail-shippable PRISM system and Rockwell International favoring its barge-shippable SAFR system.

The common link was the U-Pu-Zr fuel—a radical departure from the traditional mixed-oxide (MOX) line of breeder reactor development—comprised of depleted uranium, nominally 20% plutonium and 10-wt% zirconium. The alloy components were melted in a ~1450 C furnace, electromagnetically stirred to a homogeneous mixture and simultaneously injection cast into multiple fuel-pin molds. The pins were removed from the molds, cut to length and placed in stainless-steel cladding that contained sufficient metallic sodium to provide a thermal bond in the gap between the cladding and the pin.

Demonstration of remote fabrication of the fuel was not accomplished prior to cancellation of the IFR program by the Clinton Administration in 1994. However, all the processes were operated remotely in a glovebox environment and a complete set of equipment was fabricated and qualified for hot cell operation. Extensive test data were obtained on glovebox-fabricated metal fuels with irradiations in the Experimental Breeder Reactor-II (EBR-II) and the Fast Flux Test Facility (FFTF), and transient overpower tests in the TREAT facility. EBR-II operated for years with a U-Zr metal core and ternary experiments, while FFTF irradiated several whole metal fuel assemblies within its MOX core. The fuel demonstrated burnup to 20% without failure; transient testing indicated a major safety advantage over MOX.

In the IFR concept, the fuel would be recycled on site using a technique that has at various times been known as pyroprocessing, electrometallurgical treatment or dry reprocessing. Completely different from aqueous reprocessing that has been industrialized as PUREX, pyroprocessing uses a molten salt in the separations process. Various mixtures of chloride or fluoride salts have been used, but all must operate in high temperature (450 C and up) and in a dry argon atmosphere. Other differences include much higher concentrations and volumes of plutonium due to reduced criticality limitations and very poor (<10) separation factors for plutonium relative to other actinides and some rare earths. Sodium and zirconium are compatible with the process, whereas they are not with conventional PUREX processes. Also, no minimum fuel cooling time is required, since there are no organic solvents to be destroyed by intense radiation.

Spent fuel is chopped into short segments, arranged in a mesh basket and lowered into a molten salt electrorefiner. [A LiCl-KCl eutectic operating at 500 C has been the primary line of development.] The fuel basket becomes the anode for the electrorefining cell, with UCl_3 or CdCl used as an oxidant for the sodium and the active fission products. A small potential [<1 volt] is applied, which results in oxidation of uranium, transuranics and most fission products at the anode and reduction of uranium at the cathode. There is some carryover of zirconium and noble metal fission products, but uranium decontamination factors of 100 have been demonstrated.

When the ratio of plutonium to uranium becomes sufficiently high, the transuranics can be removed. This step has not been demonstrated with irradiated fuel due to policy restrictions during the 1990’s, but small-scale tests are now being planned. Various electrorefining, electrolysis and electrochemical techniques have been proposed, but with development arrested, no well-defined

flowsheet has emerged. This makes nonproliferation analysis more problematic, but only marginally so, since each technique would collect a witch's brew of transuranics in rough proportion to their relative concentration in the salt, uranium (~50%), and 1% or more of rare earth fission products. Throughout the 1990's, it was assumed that the material would be electrorefined into a liquid cadmium cathode, but that approach now seems to be losing favor because of the difficulty in scaling to industrial proportions. The salient characteristics of the transuranic product are intense heat, radiation and neutron emission.

Both the transuranic and the uranium products contain a high fraction (~20 wt.%) of adhering salt when removed from the electrorefining operation. A distillation furnace is used to separate the more volatile salt and subsequently to consolidate the metal into an ingot. These ingots from the uranium stream and the transuranic stream are broken into smaller pieces and used in proper proportion as charge to the fuel casting furnace, along with recycle scrap from previous castings.

In the classic IFR concept, the actinides are quantitatively removed from the salt prior to its disposition into the waste stream. However, during the treatment of the EBR-II fuel, the plutonium has been intentionally directed to the waste stream. The salt must be discarded when its heat generation rate reaches the design limit for the process vessels or when the composition of the salt reaches a point where it is no longer molten at a sufficient margin below the prescribed operating temperature for the process.

The salt, containing the bulk of the fission products, is mixed with zeolite particles at ~500 C to occlude the fission product chlorides in the zeolite structural cages. Twenty-five weight-percent glass frit is added as a binder and the resulting mixture is baked at about 900 C to transform the zeolite into sodalite, a rugged natural mineral found in some areas that would be considered potentially suitable geologic repositories. Very large monolithic waste forms—up to 50 tonnes—can be produced in this manner.

The metal cladding hulls, containing some zirconium, noble metal fission products, and a small fraction of uranium (plutonium is preferentially oxidized) are collected and mixed with additional zirconium if necessary to be melted at a favorable eutectic ratio (15% Zr). The metallic waste ingot produced in this way is also considered to be high-level waste and has proven to be extraordinarily corrosion resistant. Significantly for geologic disposal, the ingot contains most of the technetium, which is insoluble in metal form.

PREVIOUS PROLIFERATION ASSESSMENTS

As one of the cornerstones of the IFR concept, affirmation of proliferation resistance has been necessary to the continued, albeit erratic, development of the fuel cycle technology. The envisioned system relies on active plutonium management, maintaining a large inventory of plutonium, but only as much as needed to maintain a nuclear island with power plants and a fuel cycle facility. The material would remain continuously in a sequence of highly radioactive matrices within inaccessible facilities. The cost of safeguarding the material would be compensated by the sale of electricity.

Three independent assessments were critical in gaining authorization to advance the technology to the next level: Bengelsdorf (1986) when development was just getting started, Wymer (1992) as the

technology was being readied for the demonstration phase, and the 1999 assessment by the Department of Energy's Office of Arms Control and Nonproliferation when a negative report would have killed the little remaining development of the technology in the U.S. The early assessments acknowledged that the technology appeared to be interesting, but until it was developed and demonstrated there would be gaps in the analysis. One firm conclusion was that containment and surveillance would have to play a larger role than in established fuel cycles because of the difficulty in confirming the composition of the spent fuel. However, since the fuel cycle facility would contain few portals and no pipes, containment would be a natural advantage. The more recent Department of Energy report was positive in most respects, but expressed concern about general technology transfer (hot cell operations, metal melting and casting, etc.)

THE TOPS EXERCISE

The TOPS exercise used a barrier approach to nonproliferation assessment. For each fuel cycle, three sets of barriers—material, technical and institutional were considered relative to six potential proliferation threats. Three phases of each fuel cycle were considered: mining through fresh fuel fabrication, initial core loading, and equilibrium operations. Of the six potential proliferation threats, that from existing nuclear weapons states was dropped because only treaties and international safeguards agreements would have any effect, rendering the analysis uninteresting. The potential threats for unsophisticated states with or without nuclear operations were considered largely degenerate and collapsed into a single threat. That left the overt threat from a sophisticated state with a full range of fuel cycle facilities, the covert threat from the same, and the threat from sub-national or terrorist groups.

From a proliferation resistance viewpoint, most intrinsic barriers are ineffective against a state with ample resources bent on overt proliferation, leaving only the extrinsic barriers that are largely independent of fuel cycle technology. For the same state attempting covert proliferation, facility characteristics and ease of detecting diversion can be troublesome barriers. The more interesting cases are the terrorist threat and the covert threat from a state with no other nuclear capability. In these cases, the materials barriers (isotopic, chemical, radiological, detectability and mass and bulk) and the technical barriers (facility unattractiveness, accessibility, available fissile mass, diversion detectability, time required, and skills, expertise and knowledge) can be effective. There is not room here to repeat all the barrier assessments done for different scenarios in the TOPS exercise. Rather I have attempted to describe the dimensions of some of the intrinsic barriers and then to provide some context for international deployment and future development that would enhance the proliferation-resistance of pyroprocessing-based fuel cycles.

BARRIER ANALYSIS

Isotopics: Unlike thermal reactors, fast-spectrum systems are relatively insensitive to the isotopic vector of the charged fuel. There are two extreme cases of interest—the first is to have the system operate as classic breeder reactor, in which weapons-grade plutonium would be discharged in the blanket elements. At the other extreme, the reactor could operate as the second tier of a transmutation system in which the charged fuel comprises minor actinides and once-recycled plutonium from MOX cores. In this case the discharged fuel would be highly undesirable as source material for a weapons program.

Chemical: The presence of 10 weight percent zirconium in the fresh fuel and the sodium thermal bond pose problems for "textbook" PUREX reprocessing if the fuel were to be diverted. Samples of uranium-zirconium alloy have exploded when being dissolved in nitric acid. The process was never developed for EBR-II fuel, although it was known to be feasible with some development work. If instead the target of diversion were to be the recovered actinide product from the pyroprocess, separation would still be problematic because the product contains a mixture of elements that are the most chemically similar. Modification of the pyroprocesses to effect better separation would require changes in equipment and in operating parameters, especially temperature which would affect the vessel design. The result would likely be at best a product more concentrated in plutonium, but far from pure.

Radiological: In equilibrium, plutonium is maintained in a lethal radiation matrix throughout the closed fuel cycle. Americium, curium and carry-over rare earth fission products provide an intense gamma and neutron source that would exceed the highest current safeguards level of self-protection. The fuel must be remotely fabricated and inspected. Further, the intense heat generated by alpha decay and spontaneous fission presents a daunting engineering challenge for anyone who would wish to fashion the actinide product alloy into a weapon.

Mass and bulk: The fuel assemblies are massive and bulky, but the actinide product would be small, less that 10 kg, to prevent inadvertent criticality.

Detectability: Because of heat, neutron and gamma signatures, the locations of the fuel and the fuel cycle products are easily detected.

Facility Unattractiveness: Imagine a long, windowless hot cell of high-density concrete, filled with incapacitating argon gas. The only penetrations are portals at each end to move spent fuel in and fresh fuel and waste products out, perhaps an additional portal for equipment transfer, and a rabbit system to shuttle samples to the analytical laboratory. Process equipment is operating at temperatures ranging from 500 C to 1700 C. All systems are automated to the extent possible. Cameras continuously view processing equipment and staging areas. Monitors relentless sniff for oxygen and water vapor, anathema to pyroprocesses, but necessary if clandestine plutonium separation is to be carried out in the facility. At other times the fuel is in the reactor, which is completely inaccessible, or in a spent fuel holding cell. Since long cooling times are not required, the fuel is unlikely to be stored for more than three years.

Facility Accessibility: Radiation and an inert atmosphere make the interior of the process hot cell completely inaccessible. The reactor is inaccessible. The spent fuel storage area might be accessible, but only if there is massive shielding, such as a cask, between the fuel and humans. Transportation is eliminated or minimized.

Available Mass: This metric can be used in two very different ways. As intended in the TOPS exercise, fewer "significant quantities" (~10 kg) of plutonium in the system make it a less likely target for proliferation. But that argument can be flipped around. Plutonium is building up continuously in the present system and separated plutonium continues to accumulate due to commercial reprocessing and military weapon dismantlement. If the source plutonium for the initial fueling of the system reduces the stockpile, there may be an advantage in having many significant quantities in a contained, safeguarded, revenue-generating system. Assuming that each reactor

required two or three core loadings of fuel, a 1000 MWe plant could tie up about 10 tonnes of plutonium. A system of four power plants and a fuel recycle plant could tie up as much as 40 tonnes of plutonium, more than enough to supply an entire military capability.

Diversion Detectability: Pyroprocessing is an inherently heterogeneous batch process. This can be a plus because of unit accountability, but it makes precise measurement of the plutonium in the system difficult—a circumstance that concerns some safeguards experts. However, because of the limited number of portals and movement of materials, containment and surveillance should be effective if properly implemented as the system is developed.

Skills, Expertise and Knowledge: Development and deployment of new fuel cycle systems anywhere will, to some level, increase the level of skills, expertise and knowledge throughout the world. Expertise in hot cell operations and actinide metal fabrication could be useful to a potential weapons program.

Time: The time factors include the time necessary to divert the material, time to set up an aqueous processing facility in order to obtain weapons-suitable material, and the time to fabricate the plutonium into a weapon. Sufficient time allows the institutional barriers to work.

DISCUSSION

In spite of all the effort that has gone into developing quantitative proliferation-resistance methodology (expert group Delphi, multi-attribute analysis, probabilistic risk assessment, mass vulnerability analysis, etc.) [10], subjective judgment remains an essential ingredient. The weighting factors that one assigns to barriers or attributes of a fuel cycle system always depend on context, which can vary tremendously depending on the perspective of the evaluator. Further, the dynamics of proliferation resistance remain elusive. For example, the once-through system has become the de facto standard [11], but some evaluators worry about the improbability of the costly safeguarding of waste in some 30 countries for thousands of years as the plutonium becomes ever more accessible. Further, even in today's context, neither this standard nor any other that we could devise would be 100%, i.e., proliferation proof.

We have to be realistic about what technology can and cannot do. The history of nuclear proliferation makes it clear that any country with sufficient economic resources and motivation can develop a nuclear weapons capability within a decade. Further, the linkage to the civilian nuclear fuel cycle has not been strong because in the end, a dedicated military program simply makes more sense. In the case of Iraq and North Korea, where nuclear aspirations have apparently been thwarted, it is the institutional measures that have made the difference, more so than the difficulty of the technology. To be sure, controls on export of critical technologies have played an important role, but again this is primarily an institutional undertaking. Technology alone cannot prevent nuclear proliferation, but technology can play a strong role in supporting international monitoring and in blocking access to plutonium by terrorist organizations.

In the most basic analysis, only extrinsic barriers are effective against national proliferation, whether overt or covert. By extrinsic barriers, we mean the international nuclear nonproliferation regime that includes a collection of treaties, agreements, national policies and laws, multilateral inspections, and export control practices. The host country is responsible for safeguarding and securing the nuclear materials in the fuel cycle from sub-national or terrorist groups, again through

such extrinsic barriers as access control, a protective force, and an effective nuclear materials accountancy program. Intrinsic barriers such as high radiation fields potentially can make this task easier and perhaps less costly. However, some traditionalists dislike inherent proliferation-resistant characteristics because they make precise measurements more difficult due to high background signals and the problem of obtaining a representative sample from a heterogeneous matrix. This argument, which when carried to its extreme would seem to favor pure plutonium metal, fails to consider the effect on the overall system of safeguards or the potential for new developments.

International deployment is a key issue in nonproliferation analysis. But the idea that to be developed, a technology must be deployable anywhere simply doesn't pass muster. Performing a proliferation-resistance assessment for deployment of an IFR nuclear park in a country that otherwise does not possess a significant nuclear infrastructure is not a particularly useful exercise—in spit of the fact that its intrinsic barriers would be relatively effective in such a situation. Advanced closed fuel cycles in today's context would only seem to make sense in countries with a substantial nuclear energy investment and where nuclear waste management and national energy security are priorities.

The key to objectively assessing the proliferation resistance of the IFR concept is to recall that much of what Bengelsdorf and Wymer said years ago still pertains in large measure today, i.e., that some elements of the technology still remain to be developed and demonstrated. The reactor aside, neither the recovery of transuranics from the molten salt system nor the remote fabrication of fuel has been demonstrated. Even the concept for transuranic recovery has evolved through two generations since those early assessments were done. For every chemist worried about degradation of proliferation-resistant characteristics, there is another worried about obtaining a product sufficiently decontaminated to be useful in fuel fabrication. The assessment of this fuel cycle should be an ongoing analysis that keeps up with the research rather than one based on the presumptions of either the advocates or the critics.

CONCLUSIONS

The TOPS exercise identified several research opportunities to enhance the proliferation resistance of advanced nuclear fuel cycles including those based on pyroprocessing. One of the first opportunities identified was to complete the R&D on the extraction of the transuranic-bearing product from the electrorefining process in order to characterize its physical and chemical characteristics. Most of the other suggestions dealt with technologies that could enhance the effectiveness of the extrinsic barriers to proliferation. Perhaps the key suggestion was to develop the means of incorporating safeguards technologies into the facility design in order to improve process transparency. As the fuel cycle technology develops, there should be a complementary activity to integrate technologies that will enhance extrinsic safeguards barriers.

There has been a recent prominence placed on the development of advanced fuel cycles through the National Energy Policy [12] and the recent White House press announcement [13] during the Russian summit that "*…we will establish expert groups…to recommend collaborative research and development efforts on advanced, proliferation-resistant nuclear reactor and fuel cycle technologies.*" There may be a near-term opportunity to begin to integrate safeguards enhancements with advanced fuel cycle development as has been advocated. [14] The logical place to begin the

integrated demonstration in the U.S. is in Argonne's Fuel Conditioning Facility, where pilot-scale pyroprocessing is ongoing.

As R&D moves ahead, it is important to keep proliferation resistance in perspective. Technology characteristics are only one part of the total nonproliferation regime. Regardless of these characteristics, the host country still has a responsibility to provide physical security as well as materials control and accountancy. And ultimately only the international community can be effective in discouraging nations that aspire to join the nuclear weapons club. Technology's role is to improve the effectiveness of traditional extrinsic safeguards measures and perhaps to provide a level of transparency that will help enable the expansion of nuclear energy.

ACKNOWLEDGMENT
This work was supported under U.S. Department of Energy contract W-31-109-Eng-38.

REFERENCES

[1] Bengelsdorf, Harold, "Nonproliferation Risks and Benefits of the Integral Fast Reactor," IEAL-R/86-100, International Energy Associates Limited, Fairfax, VA (Dec. 1986)
[2] Carbon, M. W., Frank Baronowski, Hans Bethe, Melvin Coops and Myron Kratzer "Proliferation Aspects of the Integral Fast Reactor," Special Advisory Committee for the Integral Fast Reactor, University of Chicago (May 1991)
[3] Wymer, R. G. et al, "An Assessment of the Proliferation Potential and International Implications of the Proliferation Potential and International Implications of the Integral Fast Reactor," Martin Marietta (May 1992)
[4] Hannum, W. H., D. C. Wade and H. F. McFarlane, "Nonproliferation and Safeguards Aspects of the IFR, *Progress in Nuclear Energy*, Vol. 31, No. 1,2 pp. 203-217 (1997)
[5] "Nonproliferation Impacts Assessment for the Treatment and Management of Sodium-Bonded Spent Nuclear Fuel, US Department of Energy Office of Arms Control and Nonproliferation (1999)
[6] TOPS Task Force on the Nuclear Energy Research Advisory Committee, "Technical Opportunities to Increase the Proliferation Resistance of Global Civilian Nuclear Power Systems (TOPS), U.S. Department of Energy (Oct. 2000)
[7] Till, C. E.,.Y. I. Chang and W. H. Hannum, "The Integral Fast Reactor—an Overview," Progress in Nuclear Energy 31:3-11 (1997)
[8] International Nuclear Fuel Cycle Evaluation, INFCE Working Group Reports 1-8, International Atomic Energy Agency, Vienna (1980)
[9] "The New Reactors," Nuclear News, 88-90 Vol. 35, No. 12 (September 1992)
[10] Krakowski, R. A., Los Alamos National Laboratory, personal communication (2002)
[11] Committee on International Security and Arms Control, National Academy of Sciences, "The Spent Fuel Standard for Disposition of Excess Weapon Plutonium: Application to Current DOE Options, National Academy Press (2000)
[12] Report of the National Energy Policy Development Group, "Reliable, Affordable and Environmentally Sound Energy for America's Future," The White House (2001)
[13] White House press release, "The President's Trip to Europe and Russia," May 24, 2002
[14] Stanboro, W. D. and C. T. Olinger, "Proliferation Resistance: New Visibility and Myths," Journal of Nuclear Materials Management, 39-43 (Spring 2002)