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N. W. Brown
J. Hassberger
E. Greenspan
E. Elias

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Lawrence Livermore National Laboratory

PROLIFERATION RESISTANT FISSION ENERGY SYSTEMS[1]

Neil W. Brown, James Hassberger
Lawrence Livermore National Laboratory
6000 East Avenue, Livermore California, 94550
Tel: 510-424-4019 Fax: 510-422-5497 E-mail: brown93@llnl.gov

Ehud Greenspan, Ezra Elias
University of California, Nuclear Engineering Department
Berkeley, California
Tel: Fax: E-mail: gehud@nuc.berkeley.edu

ABSTRACT

Fission energy systems that significantly reduce the need for the user country to be involved in the nuclear operations and technology could simplify implementation and reduce the proliferation potential. Conceptual system designs with improved (relative to the once-through LWR fuel cycle) proliferation resistance for application in developing countries are being evaluated. The fission energy systems being studied include all activities and equipment necessary to produce energy, recycle selected materials, and dispose of the waste. The systems currently being studied are required to function with no refueling of the reactors on the user site. These requirements are being used to initiate the study, on the assumption that removal of these operations from within the developing countries will improve the proliferation resistance. Preliminary evaluations of a small fast reactor core cooled either by sodium or lead-bismuth are provided.

I. INTRODUCTION AND BACKGROUND

Use of recycled Pu is increasing in those countries that consider it likely to be an important source of energy early in the next century. The following factors are likely to cause this use to continue to increase: existing long-term commitments to reprocessing facilities and programs, the excess plutonium inventories from reduction of nuclear weapon stockpiles, increasing use of electric energy, uncertainty about the impact of energy growth on the global climate change, the desire not to waste the fission energy resources, and the expectation that recycled plutonium will become competitively priced early in the next century.

Although the spread of nuclear technology and increased use of Pu is not likely to occur very rapidly in the near term, the world-wide demand for clean electric energy will continue to press for the use of this technology. If the current trend in use of light water reactors (LWRs) and the development of the sodium cooled fast breeder reactors were to continue in developing countries, it could lead to large inventories of Pu, demanding inspection and accountability requirements that are not easily achieved. Alternatives to the breeder reactor are very conceptual, such as fusion-fission systems or accelerator-based systems, or are approaches directed toward restricting the use of fission energy in one form or another. Such restrictions could limit use of fission energy in developing countries, or be found to be unacceptable. Therefore, it is desirable to identify improvements to the proliferation resistance of fission energy systems that are compatible with their use in developing countries.

The fission energy systems being studied are defined to include all activities and equipment necessary to produce energy, recycle selected materials, and dispose of the waste. The systems currently being studied are required to function with no refueling of the reactors on the user site, thus reducing the need for user involvement in the nuclear technology.

The U.S. policy on nonproliferation and export controls includes the following major principle stated by the President:[2]

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"We need to build a new consensus—embracing the Executive and Legislative branches, industry and the public, and friends abroad—to promote effective nonproliferation efforts and integrate our nonproliferation and economic goals."

The policy also includes the following key elements directed toward the growing accumulation of fissile material from dismantled nuclear weapons and within civil nuclear programs:

"– Explore means to limit the stockpiling of plutonium from civil nuclear programs, and seek to minimize the civil use of highly-enriched uranium."

"– Initiate a comprehensive review of long-term options for plutonium disposition, taking into account technical, nonproliferation, environmental, budgetary and economic considerations. Russia and other nations with relevant interests and experience will be invited to participate in this study."

Although the U.S. over the last 20 years has not encouraged the use of fission energy, the above statements are being interpreted to encourage the type of effort being undertaken in this study.

II. PROLIFERATION

Nuclear proliferation is the growth in the number of states, institutions, or organizations possessing nuclear explosives. Proliferation requires essentially two components: access to adequate quantities of fissile materials with suitable properties for making nuclear weapons, and the technical means and infrastructure to construct an explosive device. An activity related to proliferation is the diversion or clandestine acquisition of materials (or hardware) used to manufacture and assemble nuclear explosives, or to otherwise use these in a terrorist act. As used in this paper, the term proliferation includes activities to divert fissionable material for other than its intended use. Proliferation controls are technical or institutional features that are directed toward controlling proliferation.

Access to nuclear technology is inherent in the approach that countries have used to implement nuclear power. They have acquired not only the fuel and equipment but have established the institutions to educate the technologists needed to operate and regulate the industry. And with this knowledge it is possible to establish programs for acquisition of materials for nuclear weapons. Institutional controls are implemented to ensure that these peaceful programs, including nuclear power programs, do not lead to proliferation. The institutional controls are implemented through the IAEA. These institutional controls are extremely important in establishing international confidence that countries possessing nuclear technology are not contributing to proliferation. If a country were to be a user of nuclear power without developing the nuclear technology infrastructure, the proliferation potential might be reduced. Such an approach would have to develop new mechanisms to assure adequate safety since minimal internal expertise would be available. This approach is being evaluated using several systems.

The technical controls have focused on limiting nuclear reactors to low enriched uranium and seeking advanced fuels that incorporate radioisotopes that make it more difficult to use the fissionable isotopes in a nuclear explosive. Plutonium is considered the most sensitive proliferation-prone nuclear material for two reasons:

1. As a by-product in power reactor fuel an abundance of Pu may be available.

2. Chemically refining Pu from reactor fuel is considered to be easier than the isotopic enrichment required to obtained suitable uranium.

Various processes and operational schemes have been developed attempting to make its isotopic content throughout the fuel cycle unsuitable for nuclear explosives. These proposed practices will be included in this study.

III. MEASURING SYSTEM VALUE

Conceptual systems designs are being developed, based largely on published information and input from manufacturers and developers. A utility metric consisting of important attributes is also being developed for measuring and ranking each system. This metric will be used in selecting preferred systems for further evaluation and will ultimately be used to rank the systems retained for detailed study. Table I provides the preliminary list of attributes to be used in ranking systems, and indicates how two factors—proliferation resistance and suitability for use in developing countries—will be measured. Development of the weighting factors is in process, and the scoring of the systems will be completed by various expert groups once the system descriptions are available. The list of attributes and weighting is expected to be revised as the candidate systems descriptions mature.

The preliminary list of attributes is based on experience and judgment, and at this stage has had relatively little peer review. An initial round of peer review by industrial participants and experts within Lawrence Livermore National Laboratory is scheduled for completion in FY97, and the measuring scheme will be adjusted following that round of review. The interactions with industry are part of an outreach effort to develop consensus concerning the potential value for any of the systems achieving the program objective. Ultimately, scoring of the systems will be completed by the group of peer reviewers that is developed as part of the outreach communications. The process selecting the systems for continued evaluation will not be based entirely on the performance metric scores. Sensitivity evaluations of the metric to changes of the importance weighting factors will be completed and used to assess the robustness of the measurement scheme.

IV. IMPROVING PROLIFERATION RESISTANCE

Initially, it was thought that it would be possible to identify a detailed set of parameters related to fission energy systems, both institutional and technical, that could be measured or rated as to their importance to proliferation control. However, it was later recognized that technical and institutional factors involved in defining proliferation resistance are often mixed together. This has lead to an approach based on identifying what appears to be a suitable target for proliferation resistance, namely the once-through LWR fuel cycle. The LWR once-through fuel cycle provides a suitable target for an acceptable level of proliferation resistance, and it can be rated using the attribute list and scoring to be developed. The candidate system scores can be compared to the LWR once-through scores to determine if improvement and suitability for use in developing countries has been achieved.

V. CANDIDATE SYSTEMS

In addition to the LWR once-through system, the following systems are being developed and evaluated: LWR with recycle, sodium-cooled fast reactor with recycle, lead-bismuth cooled fast reactor with recycle, gas-cooled reactor with gas turbine, molten-salt reactor system and a thorium fuel cycle in the most suitable reactor. Specific industrial designs for the molten salt and thorium fueled systems are not available and therefore these systems are more speculative. Some uncertainty exists regarding the level of evaluation that will be completed for these systems.

The technical evaluations to date have focused on fast reactors based on parameters and design concepts summarized in Reference 3. These systems appear to have the potential to achieve long life without refueling.[3] The feasibility of fueling a 4S-like reactor with uranium enriched to up to 20 weight % ^{235}U rather than with plutonium was assessed because of the potential for improving proliferation resistance. Realizing that, in a hard spectrum, the neutron economy of ^{235}U is significantly inferior to that of ^{239}Pu and ^{241}Pu, the possibility of improving the neutron economy by replacing the sodium coolant by lead (or lead-bismuth) was evaluated. Two additional incentives led to the consideration of lead:

1. Enhanced safety—as lead is chemically inert to reactions with air and water.

2. Potentially improved economics—as with lead-cooled reactors it might be feasible to eliminate the secondary coolant system altogether, to simplify the steam generators design, and to simplify the reactor safety systems.[4,5]

Table I. Evaluation Attribute Scoring

Evaluation Attributes	Proliferation Resistance		Suitability	
	Weighting	Score	Weighting	Score
1. No onsite refueling	Must		Must	
2. No planned maintenance of nuclear components	Must		Must	
3. Autonomous control of nuclear systems	Must		Must	
4. Environmental impact of system life cycle				
5. Fissionable material attractiveness for subversive use				
6. Ease in accounting for fissionable material throughout fuel cycle				
7. Intrusiveness of international safeguards				
8. Extent of passive safety				
9. Size of exclusion area impacted by postulated severe accidents				
10. Weight of largest assembly				
11. Number of major assemblies				
12. Estimated reliability				
13. Probability of successful demonstration				
14. Estimated cost of demonstration program				
15. Capital cost				
16. Operating cost				
17. Manufacturer and user interest in system				

Although the preferred coolant might be a Pb-Bi alloy, pure lead was used in the neutronic analysis. Since Bi is neutronically similar to Pb, the conclusions derived from this study also apply to a Pb-Bi coolant.

The study has focused on beginning-of-life (BOL) characteristics. All the calculations were performed with the MCNP Monte Carlo code using cross-sections derived from the ENDF-B/V and ENDF-B/VI libraries. This computational tool enables accurate accounting for neutron spectral effects resulting from composition variations. It can also accurately account for the system geometry.

The 4S reactor adopted as the reference for this study is the 50 MWe (125 MWt) version described in Reference 3. Its effective core height is 4 meters; effective cylindrical core diameter is 83 cm. Five core variants have been examined so far; they differ in the type of coolant and type of fuel used. Table II summarizes selected calculated BOL characteristics of the five cores.

The substitution of Pb for Na positively affects three neutronic characteristics:

1. It changes the reactivity effect due to loss of coolant from positive to negative. This is consistent with the findings in previous studies for different reactor concepts.[5,7,8]

2. It requires a lower fissile fuel content for attaining criticality.

3. It offers a somewhat higher conversion ratio. The higher the conversion ratio, the higher will be the attainable burnup and core lifetime.

Table II. Selected Characteristics of Five Variants of 4S Reactor Cores

	Core Type				
Characteristics	**1**	**2**	**3**	**4**	**5**
Fuel Type	MOx	MOx	UO_2	U-Zr[a]	Pu-U-Zr[a]
Coolant	Na	Pb	Pb	Pb	Pb
Pu[b] weight % of HM	20.0	18.5	–	–	10.6
^{235}U weight % of U	0.25	0.25	25.4	21.0	0.25
^{239}Pu Inventory (kg)	1,470	1,334	–	–	1,399
^{235}U Inventory (kg)	15	15	1,975	2,252	23
Void Reactivity[c] (%)	+0.9	-1.1	-2.0	-3.6	-0.5
Conversion Ratio	0.53	0.59	0.32	0.37	0.67

[a] Zr contents is 10 weight %.

[b] Pu contains 93.5 weight % ^{239}Pu, 6 weight % ^{240}Pu, and 0.5 weight % ^{241}Pu.

[c] Due to removal of all of the coolant from the core only; core is reflected.

Fueling the 4S reactor with enriched uranium was found to require enrichment in excess of 20 weight %, and the enrichment required when U-Zr alloy is used for the fuel is a few percent lower than that required for UO_2. It is expected that with modest design modifications (for example, reducing the B_4C contents in the shield) it will be possible to design a U-Zr fueled 4S-like reactor with 20 weight % enriched uranium. The conversion ratio of uranium-fueled cores is significantly smaller than of the corresponding cores using plutonium as the primary fissile fuel. This implies that uranium-fueled cores will have significantly smaller burnup (hence, shorter lifetimes) than the corresponding plutonium-fueled cores. The quantification of the attainable burnup, as well as means for maximizing the core lifetime, are the subjects of ongoing study.

VI. CONCLUSIONS

A set of attributes for measuring the suitability and proliferation resistance of fission energy systems has been developed. The scheme will serve to help identify if there are systems that are more desirable for application in developing countries.

Based on the preliminary nuclear analysis, it should be possible to design a 4S-like reactor with 20 weight % enriched uranium. However, the attainable burnup and core life are expected to be significantly smaller than those of the corresponding plutonium-fueled reactor. The analysis also confirmed that, neutronically, lead is preferred over sodium and metallic fuel is preferred over oxide fuel.

REFERENCES

1. A. WEINBERG et al., *The Second Nuclear Era,* Praeger Publishers (1985).

2. Press Release, The White House, Fact Sheet Nonproliferation and Export Control Policy (September 27, 1993).

3. K. AOKI and S. HATTORI, "Long Term Pu Storage and MA Burning in a Small Fast Reactor," *Proc. Int. Conf. on Advances in Fuel Cycle, GLOBAL '95*, Versailles, France (Sept. 11–14, 1995).

4. E. ADAMOV, V. ORLOV et al., "The Concept of the High Safe Economical Fast Lead-Cooled Reactor," *Proc. Int. Conf. on Fast Reactors and Related Fuel Cycles*, Kyoto, Japan (Oct. 28–Nov. 1, 1991).

5. G. TOSHINSKY, "LMFBR Operation in the Nuclear Cycle Without Fuel Reprocessing," *Proc. Topical Mtg. on Advanced Reactor Safety*, Orlando, Florida (June 1–5, 1997).

6. J. BRIESMEISTER, "MCNP—A General Monte Carlo N-Particle Transport Code, Version 4A," Los Alamos National Laboratory Report LA-12625 (1993).

7. J. LIAW, E. FUJITA and D. WADE, "Comparative Neutronic Analysis of Pb- Versus Na-Cooled LMR Cores," *Proc. Topical Meeting on Advances in Reactor Physics, 2*, 578, Charleston, South Carolina, (March 1992).

8. C. RUBBIA et al., "Conceptual Design of a Fast Neutron Operated High Power Energy Amplifier," European Organization for Nuclear Research Report CERN/AT/95-44(ET) (1995).

Technical Information Department • **Lawrence Livermore National Laboratory**
University of California • Livermore, California 94551