Report to NEAC
Fuel Cycle Subcommittee
Meeting of April 23, 2013

Washington D.C.
June 13, 2013

Burton Richter (Chair), Margaret Chu, Darleane Hoffman, Raymond Juzaitis, Sekazi K Mtingwa, Ronald P Omberg, Joy L Rempe, Dominique Warin

I Introduction and Summary

The Fuel Cycle Subcommittee of NEAC met in Washington on April 23, 2013. The meeting focused on issues relating to the NE advanced reactor program (sections II, III, and IV), and on storage and transportation issues (section V) related to a possible interim storage program that is the first step in moving toward a new permanent repository as recommended by the Blue Ribbon Commission (BRC) and discussed in the recent response by DOE to Congress on the BRC report[1]. The agenda is given in Appendix A

The DOE advanced reactor program is not in good shape. It starts much, finishes little, and throws away what it does accomplish in various fits of changing program direction and budget savings as administrations come and go. Though the US led the world in the development of commercial nuclear power, we now are behind almost everyone else including, for example, China, India, France, Japan, Russia, and possibly even South Korea.

Section II of this report discusses what we heard about advanced reactors themselves. The briefing was divided into three parts:

- International advanced reactor development programs where the rest of the world is far ahead of the US with prototypes and demonstration facilities of many types under construction or already working.
- Advanced Small Modular Reactor programs (not to be confused with LWR SMRs) being proposed in the US – it is to be noted that we had one in the FFTF at Hanford, a 400 MWt sodium-cooled reactor which is now shut down after running for 10years. It could be restarted, but plugging the hole in it and bringing it back on line is expensive and the budget will not support it.
- An effective program on materials, modeling and simulation, fuels research, and international collaborations aimed at bringing down the cost of advanced systems (restart of TREAT is discussed separately in section IV).

We conclude that the third element describes what seems to be an effective program, but that current budgets are inadequate to support the development of advanced reactor prototypes.

Recommendation: An effort should be initiated to reduce the number of Advanced Reactor Technology concepts under investigation in order to focus US research funding on achieving the ultimate goal of deploying an advanced reactor prototype within the

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[1] Due to organizational conflict of interest, Dr. Joy Rempe limited her participation in the discussion and formulation of recommendations on topics affecting the Idaho National Laboratory.

next decade as is being done in other countries, such as Japan, India, Russia, and China.

Section III focuses on the Systems Study program which aims to develop a methodology to facilitate the selection of a path ahead that best suits the US objectives for future systems. These objectives include both technical and policy ones (safety criteria and proliferation resistance are examples of the two). The criteria are given in Appendix A.

It is taking longer to develop the analysis system than we hoped when we first heard of the program in 2011. The final report is not due until March 2014. Even then, a further evaluation will be required to sort out which of the many paths forward is most appropriate to US goals.

Recommendation: A few simple clear options should be identified as soon as possible by the systems study and necessary follow-on studies.

Section IV focuses on the future of the transient testing of possible future reactor fuels. These tests are needed for new types of LWR fuels (accident tolerant fuels) as well as fuels for advanced systems. There are two facilities in the US that can be used for testing; the Annular Core Research Reactor (ACRR) at Sandia national Laboratory and the Transient Reactor Test Facility (TREAT) at the Idaho National Laboratory. TREAT can do tests that cannot be done with ACRR and world class hot cell facilities are co-located at INL are for analysis of the results of tests. Simply put, it is a much more advanced facility

It is worth noting that other countries have expressed an interest in using TREAT for tests of their fuels. This opens the possibility that major test facilities do not have to be duplicated in each country interested in developing new reactors. This mode of operation can save all time and money. The International Subcommittee of NEAC makes similar comments.

Recommendations:

1. Proceed with the restart of TREAT so that it can be available for transient testing by 2018, matching the time scale for evaluation of DOE down-selected more accident tolerant LWR fuels.
2. While TREAT upgrades/modifications (such as a change from HEU to LEU fuel) may be desirable, DOE should not let such changes delay the restart of TREAT. TREAT should resume operations with its original HEU fuel and qualify the LEU replacement fuel in TREAT after it is operational.

Section V discusses used fuel storage and transportation issues associated with the development of any repository, including the pilot interim storage facility recommended by the Blue Ribbon Commission (BRC) that is included in the DOE response to Congress on implementing BRC recommendations (Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Waste, Jan. 2013). R&D on storage and transport issues is allowed under current legislation while creation of an interim storage facility is not.

A problem for the program is that there are no standard storage or transport casks, and there is no approved rail-car for transportation to whatever site for interim storage is eventually chosen. The pilot interim storage facility is supposed to take used fuel from shutdown reactor sites. However, these sites use 16 different storage canister designs and 8 different storage overpack designs. Out of a total about 400 casks in the shut-down reactor sites, only five casks (at Humboldt Bay) are “transportation ready”, and seven different transport overpack designs are needed to transport all casks. Also, there are no railcars that have been designed, developed, and fully tested to meet the American Association of Railroads (AAR) Standard S-2043. It is estimated it may take at least five years to complete the process and have an AAR S-2043 compliant railcar.

There are even more canister types in use at active power plants, and for economic reasons utilities have chosen canisters that have many more fuel assemblies than are appropriate for any of the designs of repositories now being considered. In planning for the interim storage facilities, some consideration has to be given to the facility where used fuel will be moved to containers designed for permanent disposal.

Recommendations:

1. A new standardized storage, transport and disposal canister design should be developed for the large amount of used fuel still in cooling pools, and the roughly 70,000 tons of used fuel still to come over the remaining life of the existing reactor fleet.
2. DOE should carefully and systematically evaluate the features and requirements of the pilot interim storage that are linked to the future bigger consolidated interim storage facility.

Summary of all Recommendations

Recommendation (section II): An effort should be initiated to reduce the number of Advanced Reactor Technology concepts under investigation in order to focus US research funding on achieving the ultimate goal of deploying an advanced reactor prototype within the next decade as is being done in other countries, such as Japan, India, Russia, and China.

Recommendation (section III): A few simple clear options should be identified as soon as possible by the systems study and necessary follow-ons studies.

Recommendations (section IV):

1. Proceed with the restart of TREAT so that it can be available for transient testing by 2018, matching the time scale for evaluation of DOE down-selected more accident tolerant LWR fuels.
2. While TREAT upgrades/modifications (such as a change from HEU to LEU fuel) may be desirable, DOE should not let such changes delay the restart of TREAT. TREAT should resume operations with its original HEU fuel and qualify the LEU replacement fuel in TREAT after it is operational.

Recommendations (section V):

1. A new standardized storage, transport and disposal canister design should be developed for the large amount of used fuel still in cooling pools, and the roughly 70,000 tons of used fuel still to come over the remaining life of the existing reactor fleet.
2. DOE should carefully and systematically evaluate the features and requirements of the pilot interim storage that are linked to the future bigger consolidated interim storage facility.

II Advanced Reactors

Because of limited research funding in the NE program, it is important to prioritize the needs of the existing fleet and the new reactor concepts considered for deployment. DOE-NE is funding research on several advanced reactor designs, including concepts cooled by inert gas, supercritical water, lead bismuth eutectics (LBE), sodium, etc. During our subcommittee meeting, we received briefings on the status of DOE-NE funded research related to Advanced Reactor Technologies (ART). The briefing focused upon three topics: (1) international progress in the development and deployment of advanced reactor concepts (ARCs), (2) advanced small modular reactor (SMR) concepts being proposed in the US and (3) current focus of US ART research.

Recognizing the benefit of closing the fuel cycle, several foreign countries are focused upon deploying sodium-cooled fast spectrum reactors (SFRs). In 2011, the 20 MWe Chinese Experimental Fast Reactor began operation, allowing China to gain valuable operating experience to support their current effort to design a larger (600 to 800 MWe) sodium-cooled demonstration reactor plant. France, a well-established leader in the design and operation of SFRs, is developing a 4th generation 600 MWe SFR with several supporting research and development facilities for large component testing, severe accident testing, and fuel fabrication. In addition to their 40 MWt SFR that began operation in 1985, India will start up a 1250 MWt/500 MWe Prototype Fast Breeder Reactor (PBFR) this year. Japan continues to fund activities to support restart of their 741 MWt/280 MWe Monju demonstration and 140 MWt Joyo test SFRs. However, Monju restart efforts are currently waiting for approval by the new Japanese regulatory authority. South Korea is engaged in an effort to design and deploy a SFR by 2028. Russia also continues to advance their SFR capabilities with the BN-800 (2100 MWt/880 MWe) reactor that is under construction (with plans for startup in 2014), their efforts to develop a larger BN-1200 that is cost-competitive with LWRs, and the MBIR test reactor which is to replace the BOR-60.

Our subcommittee was introduced to the types of advanced SMR concepts proposed by vendors, such as Gen4Energy, Toshiba, General Atomics, Terrapower, GE, and Westinghouse. (These should not be confused with the LWR versions of SMRs now under development.) Although vendors indicate that there are many attractive safety and economic features associated with their proposed designs, research is needed to demonstrate the viability of the fuels, coolants, and materials in their designs.

An important objective of FCRD advanced reactor fuel research is to enable deployment of the results of ART research. To assess if the FCRD program is meeting this objective, we were briefed on current research being performed by the ART program, which is focused upon the following areas and objectives:

- *Fast Reactor Research* – This program has made the decision to focus on activities that will reduce the capital cost of SFRs by applying innovative technology solutions; exploring improved conceptual designs, new high temperature materials, energy conversion enhancements, advanced modeling and simulation, and advanced techniques to enhance component reliability and maintenance. Some of the activities described to the Subcommittee, such as efforts to develop more accurate modeling and simulation tools, are funded by the Nuclear Energy Advanced Modeling and Simulation (NEAMS) program.
- *Fuels Research* – This effort continues to evaluate the relative merits and characterize the properties of candidate fuels. Currently, irradiations are planned to continue through at least 2017.
- *International Collaborations* – These activities allow US researchers to retain a limited amount of expertise by collaborating in some aspects of international efforts to deploy ARCs. This includes US laboratory collaboration with CEA to perform analyses to support safety and performance parameters for the new French reactor design, the Advanced Sodium Technological Reactor for Industrial Demonstration (ASTRID). However, DOE funding allocations limit such participation.

Clearly, on-going FCRD research, such as the AFC irradiations and efforts to restart TREAT support US efforts to deploy advanced systems. However, FCRD activities must support other DOE initiatives, as discussed in this report. Hence, we caution that current ART funding levels are inadequate for the US program to deploy any advanced reactor design. Although it is important for the US to be cognizant of international efforts, collaborating activities are not a substitute for our own advanced reactor prototype.

Recommendation: An effort should be initiated to reduce the number of ART concepts under investigation in order to focus US research funding on achieving the ultimate goal of deploying an advanced reactor prototype within the next decade as is being done in other countries, such as Japan, India, Russia, and China.

III Fuel Cycle Options Update

An update on the status of the Fuel Cycle Options Study was provided to the Subcommittee. The presentation was in response to questions asked by the Subcommittee regarding the purpose of the Fuel Cycle Options Study and the use of its results. The Subcommittee had previously noted that there are both technical and policy aspects to the criteria used to evaluate different fuel cycle options. This, in the Subcommittee's mind raised the following questions:

1. How will policy criteria be handled, especially as some of these are not easily subject to quantification, e.g. economics and nonproliferation?
2. Does the study enable the weights applied to the criteria to be changed?
3. To what extent is the study still relevant, given that the world has moved on while the US has remained largely stationary?

To deal effectively with these questions, the presentation to the Subcommittee took the view of a user of the results of the study. In particular, the presentation first clarified what the Fuel Cycle Options Study does do and what it does not do. This view and the table summarizing it, is thought sufficiently important that the table is replicated in its entirety here.

Does	**Does Not**
Provide a framework and process to allow decision makers to evaluate the impact of policy decisions	Make policy decisions
Provide a screening tool to identify those options with significant benefits so that	Decide on the preferred fuel cycle or cycles

they may be explored in more detail	
Provide information for R&D prioritization	Decide what R&D will or will not be conducted or how it will be conducted
Evaluate fuel cycle options as groups based on differentiating attributes	Evaluate engineering design of fuel cycle facilities
Base the evaluation on fundamental characteristics (e.g. fast versus thermal spectrum)	Differentiate a specific technology (e.g. gas-cooled fast reactor versus lead cooled fast reactor)
Assume a deep geologic repository is a viable, socially acceptable option	Differentiate among repository types (engineering solutions)
Provide extensive documentation for transparency and understanding of methods and applicability of conclusions	Preclude incorporation of future data and knowledge

To evaluate the relative merits of different fuel cycle options, the study used nine metrics and twenty-four criteria, which are listed in Appendix B. Recognizing the uncertainty associated with some of these criteria, e.g. economics and nonproliferation, the study will attempt to identify the more robust solutions that are relatively immune to changes in these criteria. This approach will attempt to guard against engaging in programs that are too fragile, i.e. such that minor changes in economics or policy require major program changes. More importantly, this approach allows the identification of broad solution options and supporting programs, which will prevent the premature down-selection to a specific narrow option and fragile supporting program. Even though some attributes are not easily quantifiable, the focus on broad and robust solution options provides the answer to the first question above.

In addition to giving both NE and the Department the maximum input when selecting among policy and program alternatives, this approach also provides the possibility of making the model available to a wide range of users. This is appealing in that others will be able to examine the basis for US policies, options, and supporting programs.

As the situation in each nation state is different, use of this model will provide transparency and allow others to differentiate between the policy drivers that do in fact make the differences in the nuclear programs, and do so such that they are unique to each nation state. As an example, a nation state with a small amount of spent fuel, ready access to an accelerator-driven burning technology, and little land for use as a geologic repository, would be likely to adopt a different policy and program than the US. The model offers the possibility of being used in consultation with stakeholders, including nuclear agencies in other governments, such that the rationale for different policies and programs becomes transparent to all interested parties. In answer to the second question above, weights of course will differ from nation state to nation state and can be changed accordingly. The United States, with its own policy drivers will have its own unique solution, and the fact that this model with this approach will help in clarifying it, answers the third question above.

Given this as background and guidance for a path forward, it is necessary that a follow-on round of analyses be performed as soon as possible to identify a more specific research and development path forward. The Subcommittee is concerned with the slow nature of progress which prevents the identification of a main thrust for nuclear energy research and development in the United States. Of concern is the schedule that was presented to the Subcommittee which implied that the program would not be completed until late 2013 and that the final report would not be available until March 2014. Of concern to the Subcommittee is the rate of closure on this study. It is essential to keep the top-level objectives in mind which are to provide a methodology which will allow DOE to (1) identify and justify R&D needs, (2) allow it to accelerate progress by focusing program funds in critical areas, and (3) permit adaptability for future policy changes.

Recommendation: A few simple clear options should be identified as soon as possible.

IV Transient Testing

DOE is sponsoring a wide range of fuel development programs that are meant to support a variety of objectives, including the following:

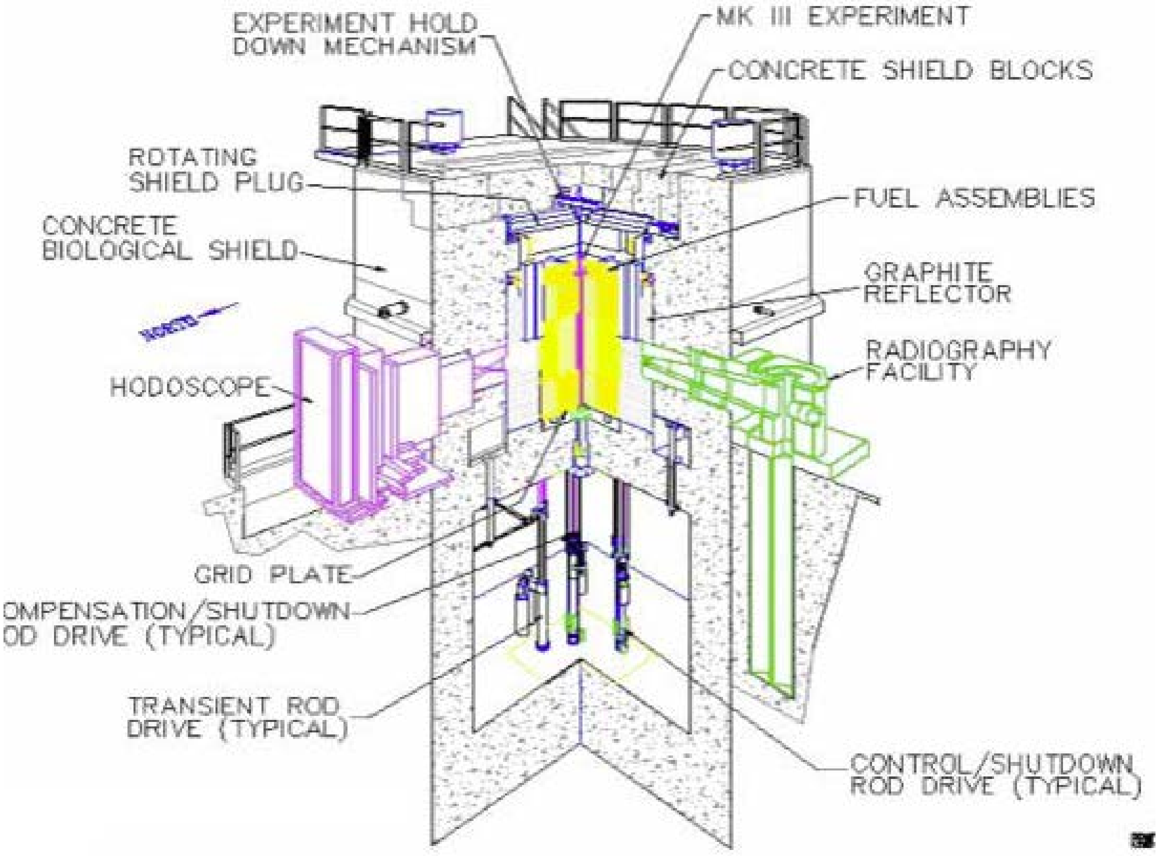
1. Accident tolerant LWR fuel
2. Fast reactor actinide transmutation fuels
3. Coated particle fuels for high temperature gas reactors
4. Research reactor fuel
5. High burn-up LWR fuel.

For this work, it is of utmost importance to perform transient testing to obtain data on fuel failure mechanisms and failure margins for combinations of fuel, cladding, and burn-up for which the current database is deficient. Many codes that model such processes exist and others are under development; however, it will be crucial to validate the codes with experimental tests. In fact, in DOE’s Fuel Development Program, without such transient tests, new concepts will not be able to pass Technology Readiness Level Six (TRL-6), which involves the study of prototypic rod/compact and assembly/element irradiation in representative environments, under the full range of relevant normal and off-normal conditions. In its fuel down-selection timeline, DOE wants to select down to a few accident-tolerant LWR fuel concepts by 2016, followed by the start of transient irradiation tests in 2018. Thus, appropriate transient testing facilities should be operational five (5) years from now.

In the US, there are two major possibilities under consideration for reactor transient testing: the Annular Core Research Reactor (ACRR) at Sandia National Laboratory and the Transient Reactor Test Facility (TREAT) at Idaho National Laboratory. While the ACRR is currently operational, TREAT is in standby mode.

Sandia's ACRR is a water-moderated, pool-type research reactor capable of steady-state, pulsed and tailored transient operations, and it maintains a large, dry, 9-inch irradiation cavity at the center of its core. The neutron flux at the center of the central cavity is about 4×10^{13} n/cm^2-s in an unmoderated condition at a steady-state reactor power level of 2 MW. About 45% of the neutron flux is above 100 keV and 56% above 10 keV. Assembled in its current configuration in 1978, it provides irradiation testing where a high neutron flux is required for a short period of time and has performed experiments for a wide variety of applications, including weapons testing, nuclear fuels testing, nuclear pumped laser experiments, space nuclear thermal propulsion testing, and medical isotope production. With regard to fuels testing, the ACRR has been used to investigate fuel pin design limitations and clad and fuel relocation for the fast reactor safety program.

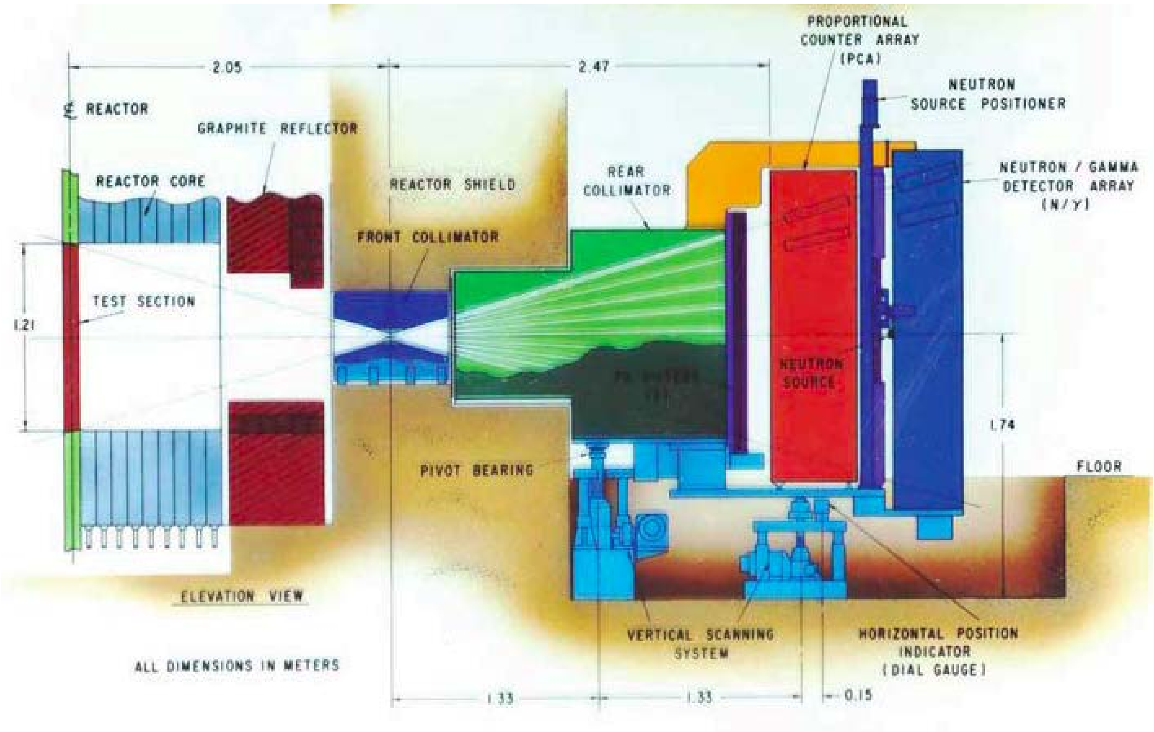
Schematically shown in Fig. 1, TREAT is a large air-cooled thermal test reactor that was constructed in the late 1950s and operated for almost forty (40) years. Since 1994, it has been in standby mode, and the cost for a restart is estimated to be on the order of $100 million. If a decision is made to restart, it can be made available for research by 2018. It nominally operates at 100 kW steady-state power, and can go up to about 19 GW peak transient power for times of approximately 100 msec. Its core measures 4-ft high x roughly 6-ft diameter and is surrounded by a 2-ft graphite reflector. It consists of a 19 x 19 array of 4-in x 4-in. fuel and reflector assemblies. The fuel is 0.2 wt. % of highly enriched UO_2 dispersed in graphite with 12 steady state and 8 transient control rods.



Schematic of TREAT
Figure 1

Although ACRR is still operational, TREAT enjoys several advantages over ACRR, including the following:

1. The core volume available for irradiating samples is considerably larger in TREAT than in ACRR.
2. Unlike ACRR, TREAT has a view directly into the core so that a hodoscope can track fuel motion in real time during irradiation to understand failure mechanisms and feedback to overall reactor response. Fig. 2 shows a schematic of the fast neutron hodoscope.
3. Researchers at TREAT have access to a world-class hot cell called the Hot Fuel Examination Facility (HFEF), which is one of the largest hot cells dedicated to radioactive materials research at Idaho National Laboratory. It can be utilized during fuel fabrication and post irradiation testing. A comparable facility is not available at ACRR.



Schematic of TREAT Fast Neutron Hodoscope
Figure 2

As for the necessity and urgency of TREAT, we note that there are several new fuels proposed by the LWR industry (for improved accident tolerance and for higher burnup) and by designers proposing advanced reactor concepts, using sodium coolant, fluoride salt, etc.). Prior interactions with the Nuclear Regulatory Commission indicate that transient testing is required for licensing[2]. Among the tests needed are investigations of fuel damage, cladding failure, and pre-failure fuel expansion.

Finally, it is not sufficient for the US to use facilities in other countries without establishing a reciprocal international user facility at home. International partners already have expressed interest in utilizing TREAT and thus it could serve that purpose.

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[2] *Preapplication Safety Evaluation Report for the Power Reactor Innovative Small Module (PRISM)*, Final Report, US Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, NUREG-1368, February 1994.

Recommendations:

1. Proceed with the restart of TREAT so that it can be available for transient testing of DOE down-selected fuel type(s) by 2018.
2. While TREAT upgrades/modifications (such as a change from HEU to LEU fuel) may be desirable, DOE should not let such changes delay the restart of TREAT. TREAT should resume operations with its original HEU fuel and qualify the LEU replacement fuel in TREAT after it is operational.

V Nuclear Waste Storage and Transportation

A comprehensive presentation was provided to the Subcommittee on the status and technical issues associated with DOE's plans on nuclear fuels storage and transportation. DOE has published the "Strategy for the Management and Disposal of Used Nuclear Fuel and High-Level Waste" in January, 2013. The strategy adopts many of the recommendations of the Blue Ribbon Commission and it includes a plan to implement a program over the next ten years that:

- Sites, designs, licenses, constructs, and begins operation of a pilot interim storage facility by 2021 with used fuel from shut-down reactor sites.
- Sites and licenses a larger consolidated interim storage facility by 2025 with sufficient capacity to accept enough used fuel to reduce government liabilities; and
- Makes demonstrable progress on the development of a geologic repository.

Phased interim storage development (pilot to large consolidated) is appealing because it can start relieving the burden from current used fuel owners, can test out systems, technologies and logistics by DOE for the future large-scale storage, and can reduce the government's liability for failure to meet its contractual obligations. However, there are many issues that need to be resolved.

The presentation focused on the current dry storage practices used by the utilities. Due to the continued delays of waste acceptance by the DOE over the years and the necessity of moving spent fuels from pools to storage, utilities have been using large dry storage systems with canister capacities up to 37 PWR or 89 BWR assemblies. These large storage systems have been selected by the utilities because of economic and operational considerations at the reactor sites. There are two basic cask designs: bare-fuel casks and canister-based casks, which can be licensed for either single (storage only) or dual purpose use (storage and transportation), depending on their design. Currently, most of the casks are welded metal canisters. There are 26 different welded metal canister designs that have been licensed; some are for storage only and others for storage and transportation.

Since thermal constraints are more stringent for transportation than for storage, large and hot storage canisters need to stay at utility sites longer to cool down before they can be transported. An additional complication of large casks relates to disposal requirements. Current international and domestic repository design concepts call for relatively small canisters for disposal packages mainly for thermal management. Large capacity storage canisters currently used at utilities may not be able to be accepted in a geologic repository. Although efforts are underway to study this issue, it is reasonable to assume that re-packaging of the fuel assemblies in these large canisters is most likely required for disposal. Since more than 80% of existing storage casks uses metal canisters with welded lids, re-packaging of these welded canisters can be cumbersome and would require special facility/equipment/operations.

The transportation of existing storage casks will require railcars. However, at this point there are no railcars that have been designed, developed, and fully tested to meet the American Association of Railroads (AAR) Standard S-2043. It is estimated that it may take at least five years to complete the process and have an AAR S-2043 compliant railcar. In addition, rail shipment will require rail access to an interim storage facility.

It is clear that the current used fuel management system is neither optimized nor integrated. As recommended by the BRC, it is important for DOE to perform the systems analyses and design studies to develop a conceptual design for a highly flexible, initial federal spent fuel storage facility. This study needs to consider alternatives to the continued use of existing storage systems.

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As for the pilot interim storage facility, DOE intends to focus on removing fuels from the shutdown reactors. These shutdown reactor sites use 16 different storage canister designs and 8 different storage overpack designs. Out of a total about 400 casks in the shutdown reactor sites, only 5 casks (at Humboldt Bay) are “transportation ready”, and 7 different transport overpack designs are needed to transport all casks. Furthermore, the shutdown reactors are located in 10 states across the country, requiring vastly different routes and logistics. These facts only point to the complexity of removing used fuels from the shutdown reactors and the complexity of the “pilot” program.

Given the complex situation of current storage practices used by utilities, DOE is faced with a fragmented and un-integrated waste management system. It is important that a consolidated interim storage facility implemented in phases needs to be considered in the context of the total waste management system that integrates current utility practices, storage, transportation, and waste disposal. The system-wide implications need to be considered and analyzed as part of a detailed evaluation of existing dry cask storage practices and alternatives to these systems. For example, the continued use of large dry cask storage systems will only lead to sub-optimization for the waste management system; alternatives should be actively pursued. For future used nuclear fuels in pools, a new standardized storage, transport and disposal canister design should be considered and developed. Furthermore, DOE needs to carefully and systematically evaluate the features and requirements of the pilot interim storage that are linked to the future bigger consolidated interim storage facility. A set of “pilot features” needs to be identified or developed so they can benefit the development of the larger facility.

Recommendations:

1. A new standardized storage, transport and disposal canister design should be developed for the large amount of used fuel still in cooling pools, and the roughly 70,000 tons of used fuel still to come over the remaining life of the existing reactor fleet.
2. DOE should carefully and systematically evaluate the features and requirements of the pilot interim storage that are linked to the future bigger consolidated interim storage facility.

Appendix A

Agenda
Nuclear Energy Advisory Committee
Fuel Cycle Sub-Committee
April 23, 2013

Chair: Dr. Burton Richter

Location: DOE Forrestal Building, Room 6A-092

8:30	Executive Session	Members & DOE
9:00	Nuclear Waste Policy/Introduction	Chris Hanson
9:15	Nuclear Waste Storage & Transportation: Technical Issues	Jeff Williams
10:30	Break	
11:00	Advanced Reactors-Applicable to the Fuel Cycle (U.S. & International)	Robert Hill
12:00	Lunch	
1:00	Transient Testing Overview	Griffith/ Pasamehmetoglu
1:15	TREAT	Kemal Pasamehmetoglu
2:00	Fuel Cycle Options – Update	Kemal Pasamehmetoglu
3:30	Break	
3:45	Executive Session	
5:30	Adjourn	

Appendix B

Nine Criteria and Twenty-four Metrics Used in the Fuel Cycle Options Study

Development and Deployment Risk • Development time • Development cost • Deployment cost from prototype validation to FOAK commercial • Compatibility with the existing infrastructure • Existence of regulations for the fuel cycle and familiarity with licensing • Existence of market incentives and/or barriers to commercial implementation of fuel cycle processes	**Financial Risk and Economics** • Levelized cost of electricity at equilibrium
Environmental Impact • Land use per energy generated • Water use per energy generated • Radiological exposure – total estimated worker dose per energy generated (as leading indicator for public dose potential) • Carbon emission – CO2 released per energy generated	**Nuclear Waste Management** • Mass SNF+HLW disposed per energy generated • Activity of SNF+HLW (@ 100 years) per energy generated • Activity of SNF+HLW (@ 100,000 years) per energy generated • Mass of DU + RU + RTh disposed per energy generated • Volume of LLW per energy generated
Institutional Issues • Compatibility with the existing infrastructure • Existence of regulations for the fuel cycle and familiarity with licensing • Existence of market incentives and/or barriers to commercial implementation of fuel cycle processes	**Proliferation Risk** • Maximum FOM1 (nominal fuel cycle material) • Maximum FOM1 (material with misuse of technology included in the fuel cycle) • Maximum FOM1 (material with clandestine use of any technology)
	Nuclear Material Security • Maximum FOM1 (nominal fuel cycle material) • Activity of SNF + HLW (@ 10 years) per energy generated
	Resource Utilization • Natural uranium required per energy generated

	• Natural thorium required per energy generated
	Safety • Challenges of meeting safety requirement • Safety of deployed system