Report of the Fuel Cycle Research and Development Subcommittee of the Nuclear Energy Advisory Committee

Burton Richter (Chairman)
Margaret Chu
Darleane Hoffman
Ray Juzaitis
Sekazi Mtingwa
Ronald P. Omberg
Joy L. Rempe
Dominique Warin

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I. Introduction and Summary

The Fuel Cycle (FC) Subcommittee of NEAC met February 7-8, 2012 in Washington (Drs. Hoffmann and Juzaitis were unable to attend). While the meeting was originally scheduled to occur after the submission of the President's FY 2013 budget, the submission was delayed a week; thus, we could have no discussion on balance in the NE program. The Agenda is attached as Appendix A.

The main focus of the meeting was on accident tolerant fuels, an important post Fukushima issue, and on issues related to the report of the Blue Ribbon Commission on America's Nuclear Future (BRC) as related to the responsibility for used fuel disposal which was assigned to the FC program with the end of the Office of Civilian Radioactive Waste Management. In addition we heard an update on the systems study program which is aimed at helping chose the best options for advanced reactors, and possible new study on separation and waste form relevance to used fuel disposal (these two items are only discussed in this section of the report).

Fuels with Enhanced Accident Tolerance (Section II): The FC program has been thinking ahead. A call for proposals was sent out early in FY-2010. Twenty-one were received, and three were funded in Feb. 2010. In parallel with the specific R&D work, studies were carried out at EPRI on improving safety margins. Results to date are described in Section II of this report. We do note that there is potential overlap with the LWR Sustainability program (LWRS) where, for example, Silicon Carbide fuel rod tubes are being studied, and **recommend** that NE management assign roles and responsibilities to minimize duplication of effort,

While R&D to develop accident tolerant fuels can be conducted in a few years, the in-reactor testing required to license a new fuel can take a decade or more. Since we (and the world) have reactors with remaining lives that vary from a few to many decades, the timing of fuel improvements becomes important. Better fuels will not help those with only a short operating time remaining. Improvements in the balance of plant (BOP) can help all, and are particularly important for those reactors that are not seeking life extensions. Larger water reserves, better emergency power systems, accident-resistant instrumentation, etc. can help as well in reducing the effects of accidents.

As a result of the Fukushima accident last year, ongoing industry and U.S. Nuclear Regulatory Commission (US NRC) efforts have already identified and are addressing some of these improvements. DOE participation in a collaborative effort with industry and/or the US NRC could expedite evaluating and implementing other improvements under consideration, increasing the accident tolerance of the commercial fleet more rapidly than by just investigating accident tolerant fuels. We **recommend** that NE adopt an R&D approach that includes the fuel, the Nuclear Steam Supply System (NSSS), and BOP improvements with enhanced accident tolerance.

Used Fuel Disposition (Section III): The recent report of the BRC set a new course for the permanent disposition of used fuel from our nuclear reactors. There is as yet no official response to the BRC recommendations, but certain things are clear. We have now about 70,000 tons of civilian used fuel and will have about 120,000 tons when the present generation of reactors reaches the end of their lives. The BRC report endorses disposal in deep geological repositories that can keep the long lived radioactive material isolated from the biosphere as long as necessary and the DOE will have responsibility for the R&D necessary to implement whatever system ends up as our agreed future direction.

Even in advance of an official response there are some things that are clear that the DOE needs to address. Among these are generic site requirements that will aid in selection of specific sites, R&D in support of the validation of potential sites, technical systems related to packaging and transport of used fuel, etc. The International Atomic Energy Agency (IAEA) has a simple starting set of generic requirements which should be a useful starting point. Also, since the selection of Yucca Mountain nearly 25 years ago, it has become clear that reducing environments such as found in clay, salt and granite have great geochemical advantages. We **recommend** that DOE develop a preliminary set of site screening requirements.

The Used Fuel Disposition Campaign has three basic elements; storage, transportation, and disposal. Since it will probably take 20 to 30 years before a repository at a new site can be opened, storage is a major issue since storage times will be much longer than originally envisaged and regional or national interim storage facilities may be needed. New cladding, MOX, and higher burnup fuels may mean that storage and transport casks need recertification. Indeed, the NRC may be looking at long-term interim storage. We commend DOE efforts in the storage and transport areas and **recommend** that they continue efforts to determine how to validate casks for long-term storage and how to integrate storage and transport casks for cost effectiveness**.** However, it is not clear how relative funding allocations are decided upon.

In the disposal arena, much has been learned over the decades this topic has been under consideration. In the mediums now favored, the U.S. has experience in salt; Sweden has experience in granite; and France has experience in clay. We **recommend** a comprehensive review of national and international experiences to identify critical issue and places where advances in science and technology may address such issues.

System Study Issues: We reviewed this program last year. It aims to evaluate potential advanced fuel cycles against a set of generic criteria to aid in deciding which advanced options to support since the budget cannot come close to supporting them all. Selection criteria include safety, reliability, proliferation resistance, cost, ease of disposal of used fuel, etc. Our last report to NEAC commented on the criteria and on the sensitivity of the analysis results to the relative weights assigned to selection criteria (recognizing that this is a policy rather than a technical issue).

The program is in its second round. Criteria have been sharpened, though there is still no agreed upon definition of proliferation resistance. What might be called "dial a weight" has been added to allow policy makers to better understand the sensitivity of the outcome of the analysis to the weights of the criteria. We will review the program again when the second round is done. The program's progress is good, but we do **recommend** that NE and NNSA try once more to come to some agreement on how to evaluate relative proliferation resistance.

Separation and Waste Form Linkages to Disposal: The presentation materials focused on two activities – a relevancy review and a DOE workshop on Nuclear Separations Technologies. We were provided a report, "Nuclear Separations Technologies Workshop." This workshop, which was held July 27-28, 2011, brought together multiple DOE offices: Science, Environmental Management, National Nuclear Security Administration, and Nuclear Energy, to discuss their requirements for nuclear separations and areas of synergy. Nuclear separations are and will continue to be critical to multiple DOE missions. The report concluded with a recommendation to establish a "DOE Center of Knowledge for Nuclear Separations". This proposed center might improve coordination across DOE programs and create synergies among nuclear separations, waste management and fuel fabrication. The workshop appears to address many of the current issues and concerns. Since NE was only one of the DOE program participants in this workshop, the relation of the workshop with the Fuel Cycle R&D work is unclear to us. We **recommend** that follow-on actions from this workshop be provided to the Subcommittee.

A relevancy review of the separations and waste form campaigns is under discussion to provide strategic and programmatic recommendations on the near and longer term directions. The campaign is providing the science, research, development, enabling technologies, modeling and simulation, and systems engineering to enable advanced fuel cycles (modified and full-recycle) to be evaluated and considered in the U. S. Hence, the Fuel Cycle Systems Study is relying on input from this campaign. The justification for the separations and waste form study relevancy review is unclear to us, and we **recommend** that this justification should be examined prior to conducting this review.

Summary of Recommendations

1. In accident tolerant fuels work, there is overlap with the LWR Sustainability program (LWRS) and NE management should review roles and responsibilities to minimize duplication of effort.
2. Since older nuclear power plants may not benefit from more accident tolerant fuels, NE should adopt an R&D approach that includes fuel, NSSS, and BOP improvements to enhance accident tolerance.
3. Since a repository for used fuel will be needed, DOE should develop a preliminary set of generic site screening requirements that incorporate domestic and international experiences.
4. In the waste disposal arena, a comprehensive review of the national and international experiences is needed to identify critical technical issues and areas where advances in science and technology may resolve such issues.
5. Since development of a new repository is a long-term project, storage of used fuel for longer than originally anticipated is necessary. DOE should continue efforts to determine how to validate casks for long-term storage and how to integrate storage and transport casks for cost effectiveness.
6. Progress in the advanced systems study program is good, but NE and NNSA have not come to agreement on evaluating relative proliferation resistance and should try once again.

II. Fuels with Enhanced Accident Tolerance

The Subcommittee heard several presentations on Accident Tolerant Fuel, or more properly said Fuels with Enhanced Accident Tolerance. The presentations involved research and development plans, specific proposals for improving safety margins, and innovative fuel components such as silicon carbide cladding. Each of these is addressed and the Subcommittee's views are articulated below.

Research and Development Plans: The Fuel Cycle Research and Development (FCRD) program has several research projects underway to explore fuel with both improved performance and enhanced accident tolerance. A call for proposals for fuel with improved performance characteristics was sent out in early FY-10, and twenty-one proposals were received. Of these, three were funded in February 2010, and it was later shown that these three also had enhanced accident tolerant characteristics.

The funded fuel concepts with both improved performance as well as enhanced accident tolerant characteristics are:

1. Metallic fuels for LWRs which have inherent thermo-physical properties capable of rejecting heat advantageously,
2. Micro-encapsulated fuels which have the capability of withstanding the higher temperatures which may occur with a loss of access to the heat sink,
3. Gettering concepts capable of absorbing fission gases which have the capability of reducing fission gas pressure and radionuclide release during an accident.

The Subcommittee commends the FCRD program for initiating this research and having its planning underway prior to the Fukushima event.

Specific Proposals for Improving Safety Margins: The EPRI representative presented a set of proposals for improving safety margins in a Fukushima type event. The presentation provided information on alternative cladding and coating materials to reduce hydrogen generation during events where cladding oxidizes due to elevated temperatures with degraded heat removal in the presence of steam. Of particular interest were the calculations indicating that a relatively small but continuous injection of water, on the order of ~ 40 gallons per minute assuming that it could be continuously maintained, would have a significant impact. Such a water injection would have the capability to limit cladding temperatures and preclude hydrogen generation, particularly with a non-zirconium cladding material. The research to date included a preliminary review of the performance of alternate cladding materials such as silicon carbide, molybdenum alloys, molybdenum-zirconium alloys, and Fe-Cr-Al alloys. Each of these has a higher melting temperature than currently deployed zircoloy-based cladding and could reduce hydrogen generation in a steam-bound core, and likewise provides an advantage with a minimal water injection rate as mentioned above. On the other hand, deployment of any of these alternatives would require a significant research and development effort, part of which will involve in-reactor testing. It should be noted that in-reactor testing involves a significant amount of time which is discussed below. In addition, we observe that other phenomena, such as materials interactions between control material and structural material, may relocate at temperatures equal to or lower than zircaloy-based cladding oxidation temperatures (thus, reducing the benefit of proposed enhancements that reduce hydrogen generation).

Silicon Carbide Cladding: Another part of DOE NE, the Light Water Reactor Sustainability (LWRS) program, is investigating silicon carbide cladding and composite coatings. The program has both a good understanding of the advantages of these materials and likewise a good understanding of the serious development issues which confront it. The advantages are: high temperature stability, low chemical reactivity, low neutron absorption rate, no exothermic hydrogen generation rate, and low corrosion rates, and the corresponding possibility of easing primary coolant water chemistry requirements.

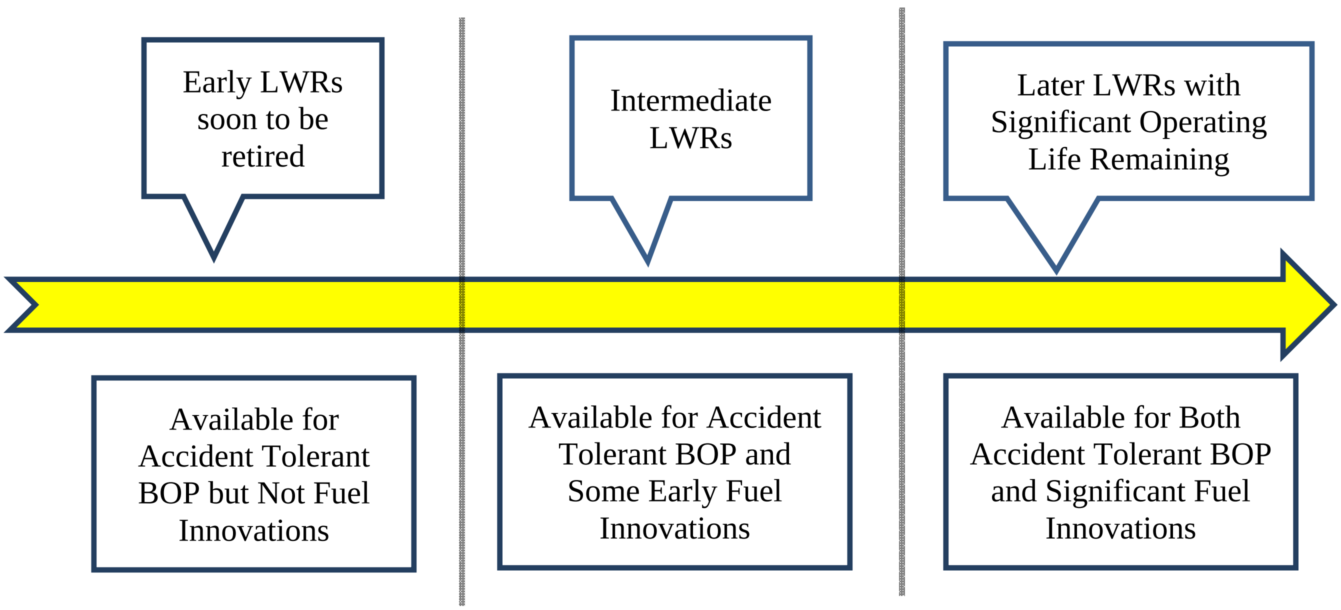
Examples of development issues are: the need for a robust end-cap bonding method, brittle behavior in contrast to the ductile behavior of zirconium cladding, manufacturing capability and the cost thereof, SiC degradation at temperatures lower than 'run-away' oxidation temperatures, and pellet to clad interaction in both steady state and accident modes.

The current LWRS fuel program is oriented toward performing research with experiments to answer these questions and anticipates answers, either favorable or unfavorable, in the next four years.

Timing of Research to Develop Fuels with Improved Accident Tolerance: Ex-reactor testing of fuel and cladding materials can be performed relatively quickly, e.g. on the order of a few years. In contrast, in-reactor testing which is the *sine quo non* for the development of a new fuel system can easily require a decade or possibly two before a new fuel system is ready for extensive use. This is because either a Lead Test Rod (LTR) or a Lead Test Assembly (LTA) must be inserted into a commercial Light Water Reactor (LWR) before a new fuel system can be validated for commercial procurement and extensive use. Prior to insertion into a commercial reactor, the fuel is very likely to require testing in a test reactor such as the Advanced Test Reactor (ATR) in Idaho. Extensive commercial use requires both letting a long-term contract by a utility and acceptance of this contract by a fuel manufacturer; and such contracts can often run for eight or so reloads, or eight years.

Given the extensive duration required for fuel development and deployment, it is important to note that improved accident tolerance can be obtained by improvements in the reactor plant. For example, improved accident tolerance can alternatively be obtained by ensuring access to the heat sink, e.g., by ensuring a minimal but reliable flow of water to the core as mentioned in the section on *Specific Proposals for Improving Safety Margins* above. This is equivalent to ensuring a minimal degraded Emergency Core Cooling System (ECCS) capability. Likewise, accident resistant instrumentation in the vessel and containment building could improve the ability of operators to diagnose any off-normal conditions and assess the effectiveness of any mitigating actions that they take. Other considerations that can favorably affect plant performance include longer life batteries, more reliable deployment of backup diesel generators, hardened hydrogen venting systems, and ensuring safety class pumping capability.

As a result of the Fukushima accident last year, ongoing industry and U.S. Nuclear Regulatory Commission (US NRC) efforts have already identified and are addressing some of these improvements. DOE participation in a collaborative effort with industry and/or the US NRC could expedite evaluating and implementing other improvements under consideration, increasing the accident tolerance of the commercial fleet more rapidly than by just investigating accident tolerant fuels. While this will benefit all reactors, it is especially important for reactors that are older and not seeking life extension. Reactors with significant operational life remaining, on the other hand, can benefit from fuels with enhanced accident tolerance as indicated in the figure below.



Recommendations: The conclusions of the Subcommittee can be summarized as follows:

1. The Subcommittee commends the FCRD program for initiating research on fuels with enhanced accident tolerance in FY-10 well prior to the Fukushima event,
2. The Subcommittee notes that the goals listed in the LWRS fuel program have the potential to overlap with those in the FCRD program on enhanced accident tolerant fuel development, and the Subcommittee recommends that NE management assign roles and responsibilities to minimize duplication of effort,
3. And finally, the Subcommittee recommends that NE adopt an approach that includes the fuel, NSSS, and BOP improvements with enhanced accident tolerance and consider the relative balance of these improvement approaches by appropriately assigning R&D tasks.

III. Used Fuel Disposition:

During the Subcommittee meeting, four presentations were provided under the "Used Fuel Disposition Campaign". They included 1) an overview, 2) compatibility of commercial storage containers with waste management system, 3) generic repository concepts and thermal analysis, and 4) integrated research project of used fuel storage. No presentation on transportation was included in this meeting.

Current Used Fuel Disposition R&D activities include three areas:

1. Crosscut activities including management and integration, international collaborations, and perspectives on nuclear waste management;
2. Disposal Research including generic Engineered Barrier System (EBS), generic natural systems, generic system-level modeling, thermal load management and design concepts, inventory, and low level waste (LLW) disposition;
3. Storage and Transportation Research including test and evaluation capability development, storage R&D, transportation, security, engineering analysis, and engineered materials.

The U.S. nuclear waste policy is still highly uncertain at this stage, and the President's Blue Ribbon Commission on America's Nuclear Future recently recommended prompt efforts in the development of one or more geologic repositories in the U.S. Consequently, all disposal options are back on the table and geologic media other than tuff (Yucca Mountain) are also being considered. To develop a meaningful and fruitful disposal R&D program in this highly uncertain environment can be quite difficult. No site-specific activities can be performed, and only activities on generic geologic media can be conducted. This being the case, it seems reasonable that the development of initial siting criteria does not need to be overly detailed. The subcommittee finds that the generic siting criterion of the International Atomic Energy Agency (IAEA) seems to be reasonable. They consist of the following:

1. Long-term (millions of years) geologic stability in terms of major earth movements and deformations, faulting, seismicity and heat flow (for material that includes long lived components)
2. Low groundwater content and flow at repository depths, which can be shown to have been stable for periods of at least tens of thousands of years
3. Stable geochemical or hydrochemical conditions at the prescribed depth, mainly characterized by a reducing environment and a composition controlled by equilibrium between water and rock forming minerals
4. Good engineering properties that readily allow construction of a repository, as well as operation for periods that may be measured in decades.1

A good repository site also should be located far from population centers yet close to accessible transportation routes, and have minimal potential for future human intrusion in search of resources. No doubt that the Yucca Mountain site, which is not a reducing environment, could provide the needed long-term safety; however, the advantages afforded by a reducing

[1] "*Scientific and Technical Basis for Geologic Disposal of Radioactive Waste,*" Technical Report Series no. 413, International Atomic Energy Agency, p. 6, Vienna, Austria, 2003.

environment in the natural system cannot be underestimated. Since the repository program appears to be starting over, there is a chance now to take full advantage of the IAEA criteria.

The Used Fuel Disposition program completed a Disposal R&D Roadmap in March of 2011. The objective of the R&D Roadmap is to develop information that could ultimately be applied to a site-specific application. The Roadmap contains logical and high-level priorities for disposal R&D activities. Based on the Roadmap, the program developed a list of Disposal R&D activities some of which were carried out in FY11 and some proposed for FY12. Examples are experimental work on Pu colloid behavior in the presence of goethite (an iron-bearing mineral in soil), effect of spatial heterogeneity in the sorption coefficient (Kd) on radionuclide transport, radionuclide transport in clay, experimental and model development for engineered materials performance.

Presentation on generic repository concepts and thermal analysis were provided to illustrate results on alternative disposal concepts, different waste types, and geologic settings.

An informative presentation was given to discuss the compatibility of commercial storage containers with the waste management system. It points to the importance of integrating commercial storage containers with transportation and disposal strategy. However, disposal canister design depends on the repository. The Swedes use copper, while the French use glass. There is a need for systems studies to optimize cask designs, although it is recognized that the answer may depend on the repository

Finally, an excellent presentation was given on an integrated research project on accelerated characterization and performance assessment of used fuel storage systems. These mostly-universities research teams have clear objectives and metrics, and focus on novel ideas. This is a good example of effective use of resources.

With the repository program in halt, interim storage has been the focus for R&D, and funding for R&D in storage and transportation activities has rightly been increased.

Scope of Disposal R&D: The program completed a Disposal R&D Roadmap in March of 2011. The Roadmap contains logical and high-level priorities for disposal R&D activities. However, it is not apparent how the detailed current and future activities “flowed down” from the Roadmap. In other words, the roadmap is a conceptual high-level guideline, but how the actual specific R&D activities were chosen is not clear to the Subcommittee members. Analyses are being performed for alternative disposal concepts, thermal effects, peak temperatures, etc. in different rock types. Except for deep borehole concept, we believe that many similar analyses had been conducted in the past; and the additional knowledge gained at generic site level needs to be justified.

Strategy of Disposal R&D: The Blue Ribbon Commission (BRC) recently concluded that for permanent disposal of spent nuclear fuel and high-level waste, geologic repositories were needed. It is estimated that it will take at least 20 - 30 years to develop a new geologic repository in the U.S. Given the long time horizon, a strategic R&D objective should be such that innovative and large improvements are achieved when the next repository is ready to be developed. This approach should include the following considerations:

1. From the vast amount of experience and information gathered in the U.S. and internationally in geologic disposal, identify the fundamental technical issues that have existed throughout the past decades
2. Identify potential improvements/solutions to the above issues.
3. The R&D implementation should contain a portfolio that encourages innovative, “think outside the box” solutions.

Implementation of Disposal R&D: To gain the full benefits of R&D, it is imperative that the most advanced concepts/technologies are explored. Given the long history of repository science, we want to avoid being limited by prior thinking. Many technologies have made quantum leaps in the past 20 years; a prime example is the advancement of materials science. We suspect new technologies/scientific discoveries have not been fully explored for nuclear waste management area applications.

Examples of R&D ideas:

1. New approach to tackle the quantification of retardation (transfer) of radionuclides in a natural system. The traditional concept of using equilibrium sorption coefficient (Kd) to quantify retardation has always been problematic; alternative (non-equilibrium) mechanistic concepts should be pursued.
2. Incorporating advanced materials science into R&D of Engineered Barrier System and storage containers
3. Innovative approaches to control the source term from SNF and HLW degradations in the repository
4. Advanced technologies in characterizing geologic sites, material behavior, etc.

Finally, the Subcommittee is concerned about the phase out of funding for actinide cross section measurements. That work is fundamental to advanced fuel cycles and should be revived. Computationally derived cross sections based on models needs to be rooted in data and cross checked with actual experiments. This is an ideal topic for national laboratory partnerships with universities.

Future Interim Storage Facilities: One of the key ingredients for the successful development of a nuclear waste facility involves public confidence and public support. In the past, oftentimes the “fear of anything nuclear” by the public was not fully appreciated and therefore underestimated. We believe a facility with design features of ultra-high levels of safety and security needs to be incorporated into the conceptual design of any interim storage facility. Technical experts may argue that it is unnecessary to “overdesign” a facility; however, the benefits gained from such extra protection features on public comfort will most likely prove to be cost-effective in the long run. These extra-protection features can be achieved through current and future technologies.

It is important to move swiftly with ascertaining the lifetime of interim dry cask storage technologies. Such information is crucial for the NRC to make informed decisions in formulating its licensing guidelines. Currently, the NRC plans to develop an EIS to analyze the impacts of interim storage from approximately the middle of this century for a period of 200 years. Any research to support that effort would be most advantageous. Moreover, national laboratory researchers' partnering with university materials scientists and engineers could lead to transformative breakthroughs in the understanding and implementation of dry cask storage.

Funding Allocation within the Used Fuel Disposition Campaign: The Used Fuel Disposition Campaign basically has three elements; storage, transportation, and disposal. It appears that storage of used fuel should be the most urgent topic because it has never been anticipated that used fuel would be stored for very long period of time. Potential technical issues associated with long-term storage of used fuel should be addressed with high priority. On the other end, there have been plenty of scientific studies and investigations associated with deep geologic repositories; further R&D should focus on new, innovative ideas that can advance disposal technologies to the next level. The basis of funding allocation among disposal, storage and transportation in the Used Fuel Disposition Campaign is not clear to the subcommittee.

We believe this is an area that new innovative ideas should be explored. Many new scientific frontier research may be applied to the separations and waste forms R&D.

Appendix A

Final Agenda
Nuclear Energy Advisor Committee
Fuel Cycle Research and Development Sub-Committee
February 7-8, 2012
Forrestal GH-019
Washington, D.C
Chair: Dr. B. Richter

<u>Executive Session:</u> Closed Meeting

9:00	General Remarks/Welcome	Dr. Richter/Monica Regalbuto

<u>Presentation Session:</u>

9:20	Used Fuel Disposition R&D – Path Forward	William Boyle (DOE)
10:00	Compatibility of Commercial Storage Containers with Waste Management System	Jeff Williams (DOE)
10:45	Break	
11:00	Generic Repository Concepts and Thermal Analysis	Ernest Hardin (SNL)
12:00	Lunch	
1:00	Integrated Research Project – Used Fuel Storage ***"Fuel Aging in Storage and Transportation (FAST): Accelerated Characterization and Performance Assessment of the Used Nuclear Fuel Storage System"*** Texas A&M University	Sean McDevitt (Texas A&M)
2:00	Fuel Cycle Options – Update on Metrics	Rob Price (DOE)
3:45	Break	
4:00	Programmatic Integration	Phillip Finck (INL)
4:20	U.S. Republic of Korea Joint Feasibility Study	John Herczeg
5:00	Open Discussion	
5:30	Adjourn	
6:00	Dinner	

February 8, 2012

8:30	Accident Tolerant Fuel (ATF) R&D Plans	K. Pasamehmetoglu (INL)
9:30	ATF Plans & Proposals	Bo Cheng (EPRI)
10:00	ATF Strategy and Plans	K. Pasamehmetoglu
10:30	Break	
10:45	LWRs SiC Cladding R&D	R. Reister (DOE)
11:15	Separations &Waste Forms Relevance Review – Charter	Andy Griffith (DOE)

Executive Session: Closed Meeting

12:00	Lunch
1:00	Sub-Committee
3:00	Adjourn