INL/EXT-11-23975

Meeting Summary Advanced Light Water Reactor Fuels Industry Meeting Washington DC October 27-28, 2011

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November 2011

Idaho National Laboratory

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operated by Battelle Energy Alliance

INL/EXT-11-23975
FCRD-FUEL-2012-000029

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Prepared for the
U.S. Department of Energy
Office of Nuclear Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

ADVANCED LWR FUELS INDUSTRY MEETING

The Advanced LWR Fuels Industry Group first met in November of 2010 with the objective of looking 20 years ahead to the role that advanced fuels could play in improving light water reactor technology, such as waste reduction and economics. When the group met again in March 2011, the Fukushima incident was still unfolding. After the March meeting, the focus of the program changed to determining what could be done in the near term to improve fuel accident tolerance. Now that we have a better understanding of the consequences of a long station blackout, like Fukushima, it is becoming clear that changing the fuel alone probably can't solve the problem. We also need to remember to make decisions now that will benefit light water reactors two decades from now. DOE cannot develop a fuel that no one will use, and we have to determine how to move forward with a fuel that will provide benefits to both existing and advanced light water reactors.

Any discussion of fuels with enhanced accident tolerance will likely need to consider an advanced light water reactor with enhanced accident tolerance, along with the fuel. Today's reactor technology has evolved beyond those that had problems at Fukushima, but the accident was so severe, it isn't known that any plant could have survived. For example, some current reactors can survive for 72 hours without off-site power. NRC now requires 4 hours of battery backup. We should understand how Generation III+ reactors would have responded to a prolonged station blackout, and if fuel with enhanced accident tolerance would have helped to reduce the consequence of these accidents.

The viability of having a dual-path approach, including short-term and long-term objectives, was discussed. The potential issue is that the urgent needs always win out over the strategic needs. The path forward needs to be integrated and achieve short-term benefit without sacrificing important long-term objectives.

We should understand how the need for accident tolerant fuel designs and the incentive for economic improvement are coupled. We should also be careful about referring to testing beyond design basis conditions. These should be referred to as 'severe accident conditions.'

It is essential to maintain communication between DOE and the nuclear industry. DOE may need to find a more formal vehicle to continue to collaborate. The DOE components of an advanced LWR fuel program have to maintain the flavor of a federally funded program. The DOE funded parts of the program needs to work in the appropriate time frame.

The INL Advanced LWR Fuel Advisory Committee (referred to as Advisory Committee) presented their recommendations from the call for information on advanced LWR fuels. The Committee requested the information in a standard format that included a series of questions based on industry-valued fuel design objectives. The standard format was designed to:

- Provide Principal Investigators with information on desired design improvements and relative value from industry's perspective
- Provide a more complete understanding of the advantages and weaknesses of each concept
- Highlight the gaps in information related to commercial operation of the concept
- Promotes a more accurate assessment of the time necessary for development and testing
- Allow for a side-by-side comparison of concepts for resource allocation.

Industry-valued design objectives in order of importance are

- Improved normal performance and reliability

- Improved design basis accident performance
- Improved beyond design basis accident performance
- Manufacturability
- Same or higher power capacity
- Higher burnup and/or longer cycles
- Reprocessing capability
- Shipping and handling
- Storage and transport.

The Committee received information on 22 advanced fuel concepts (and one fuel-related concept). After evaluating the fuel concepts against the screening criteria, the Committee selected 7 concepts for oral presentations in September. The final recommendations of the Committee are to focus research in the following areas:

- MAX phase materials or other coatings that appear to have the potential to reduce or delay hydrogen generation at elevated temperatures
- Silicon carbide clad concepts
- Fully Ceramic Microencapsulated (FCM) Fuel
- The IAC opinion was divided on uranium nitride fuel
  - Compatibility with water is a key issue that must be solved
  - Large payoff if successful may warrant further investment to research water compatibility.

New fuels for future reactors still have to be tested or qualified in current reactors, so we have to keep in mind that there may be some operational limits during testing. In general, a lead test assembly of an advanced fuel has to fit within the envelope of an existing LWR assembly and have similar flow and neutronic characteristics.

DOE won't be licensing the fuel, but will be involved in LTRs and LTAs, and needs to understand the process. The Advisory Committee should be able to provide some input in general terms. More specific information might result from a funded industry task.

The conclusions of industry Task #5 evaluations of advanced fuel concepts were presented by the three Task 5 teams: AREVA, Global Nuclear Fuels, and Westinghouse. Presentations and reports from the teams will be made available on the INL FCRD LWR portal. General conclusions:

- Advanced LWR fuel concepts that offer enhanced accident tolerance may have a lower heavy metal density
  - Increasing ^{235}U density can be achieved either by using a high-density fuel phase or by increasing enrichment
- Increasing the density of the fuel phase appears to be more straightforward than increasing enrichment

- There are only a few candidate materials (for example UN and UC)
- Water corrosion resistance has to be improved before these will be acceptable
- Additives may be an effective way to increase corrosion resistance
- The potential for hydrogen generation from these materials at high temperature should be addressed

- An effective path for increased enrichment may be the introduction of integral burnable poisons into the fuel early in the production cycle.
  - Burnable poisons would reduce the need for major changes in fabrication, handling, and storage, if the equivalent reactivity and criticality behavior can be attained
- Silicon carbide cladding was suggested as a revolutionary fuel concept by all three teams
  - Opportunities for improvement in BWR fuel performance are dictated by the cladding (e.g., critical power, reliability, LOCA, temperatures)
  - Structural stability at high temperature is better
  - There is a reduction in the hydrogen generation rate
  - There is a reduction in the energy release rate
  - BWR channels may be the best entry point for use of silicon carbide composites in reactors

A discussion was held on the value and timing of increased enrichment, based on the following questions:

- Is it desirable to go above 5% enrichment?
- Is it doable?
- When should NRC be involved?
- What approach should be taken?
- What is the role of DOE?

There was not a clear consensus on the question of desirability for increased enrichment. Utilities operating plants with current fuels would take advantage of increased enrichment it if it was available, but it is not a big driver. Higher enrichment might allow more flexibility in fuel management, and allow most PWRs to go to 24 month cycles, which would result in one less outage every six years. Note that 24 month cycles also depend on increasing the allowable cladding burnup limits. Some advanced claddings like M5 Zirlo+ and Axiom may be able to achieve longer cycles. Other issues such as CIPs must alos be overcome for the more active assemblies. BWRs may not get the same benefit as PWRs, because they are already capable of 24 month cycles. Economically, the 'sweet spot' for enrichment depends on the discount rate, but is in the range 7-10 wt.% ^{235}U. The same net benefit in ^{235}U density at 7 % enrichment can be obtained by using a high-density fuel such as UN, if the water corrosion issue can be solved. The economics for a high-density fuel are better than for increasing enrichment. This logic would change if the cost of enrichment decreased dramatically. Note that this conclusion also depends on the discount rate that is applied to the uranium purchase.

High-density fuels also tend to have high thermal conductivity, which helps reduce centerline temperature. Currently UO_2 fuel is on the edge of its performance capability because of centerline melting concerns during transients. Extending burnup further to take advantage of higher enrichment may mean that plants will have to decrease fuel operating power. This could also be addressed by methods which increase the thermal conductivity of UO_2 fuels, such as high conductivity fibers.

Two of the three vendors viewed the enrichment question as dependent on the outcome of advanced LWR fuel development. As development and testing of advanced fuels proceeds, and results in the conclusion that breakthroughs in fuel technology may require higher enrichment, it should then be pursued. The third vendor indicated that fuel technology would not advance without some increase in enrichment.

It was agreed that increases in enrichment were technically feasible. The current enrichment level is assumed in the regulatory framework, and may require rule making to untangle.

The correct timing for interfacing with the NRC was discussed. NRC research is ready to discuss this topic. There was no clear consensus from industry on timing, with logic along the lines as described above.

The role of DOE funded programs could be to develop a road map for the process (or review existing roadmaps and reports to ensure that they correctly identify all required actions), possibly to initiate some studies on nuclear cross sections, and to determine the adequacy of criticality data. The cost of increasing enrichment to 6% would be on the order of $10's M (per the AREVA task 5 report), and $1.3 B - $1.7 B to go to 20% enrichment, and cannot be funded by DOE. DOE is committed to studying the feasibility of advanced LWR fuels for the next two years, and we need utilities, vendors, and regulators to analyze this and ensure that the right long-term decision is made.

EPRI has a Breakthrough Fuel Technology program. EPRI's current activity is in understanding severe accident conditions and in looking at alternative refractory materials for cladding. EPRI goals are to have a fuel ready for demonstration in 5-10 years. EPRI priorities for breakthrough fuels parallel DOE's:

- Maintain majority of good attributes under normal operations
- Reduce/delay hydrogen generation (total and rate)
- Reduce heat generation rate
- Increase strength at higher temperature (maintain fuel integrity)

EPRI is currently fabricating SiC BWR channels for testing. Refractory metals may also be an option, but there are several potential barriers, including fabrication, irradiation embrittlement, and steam reaction. Molybdenum and niobium are potential candidates, and have neutronic performance similar to steel. EPRI recommends the development of a high-pressure, high-temperature steam testing facility. They would also like advice on fabricating Mo and Nb.

A draft definition of accident tolerant fuel was offered for comment:

> "In comparison with the standard UO_2 + zirconium alloy system, fuels (system or plant) that can tolerate higher temperatures for longer durations while maintaining a coolable geometry and retaining its fission products and a safe shutdown."

Meeting attendees were requested to provide comments on this definition to Kemal Pasamehmetoglu.

The potential attributes of accident tolerant fuel were discussed. These include:

- Slower oxidation kinetics when exposed to steam at high temperatures
  - Lower enthalpy of reaction
  - Slower rate and/or smaller amount of hydrogen release
- Reduced hydrogen intake or reduced hydrogen embrittlement
- Smaller deformation at high temperatures
  - Ballooning, warping, bowing, swelling…
- Higher failure temperature for cladding
- Reduced internal oxidation of the cladding
- Higher temperature for fuel dispersion
- Reduced fission product release after clad breach
- Higher melting temperatures (clad & fuel)
- Longer time to reach critical temperatures – increased response time
- Thermal-shock resistance
- Reliable large-scale manufacturing
- Reduced fission product release

Industry should consider whether the attributes of new fuels should be based on performance requirements, rather than focused on comparing behavior to current zirconium alloy clad fuel. If the definition is based on comparison to current fuel, key attributes may be overlooked. It was suggested that safe shutdown be included.

The advanced fuel program believes that NRC should be involved in defining the attributes of accident tolerant fuel.

At the research laboratory level, our international contacts are concerned that the U.S. will charge forward on actions that impact the rest of the world. Utilities and Industry should work with their international counterparts to define accident tolerance. EPRI would have to help with this coordination.

A brief overview of the economics of LWR systems was provided. It was emphasized that decreases in heavy metal density negatively impact economics of current plants. These impacts can be offset by increases in power density. Increases in enrichment using current fuels can have a significant impact on LWR economics, if increased power can be extracted from the fuel from increased burnup. The benefit is around 1-2%, so (hypothetically) if 100 plants with revenue of $500 M each were to benefit, the net value would be > $500 M per year.

The program is generating maps of several variables to make it easier to understand the relationships between cost of electricity and fuel design parameters. The program wishes to benchmark it’s analysis against others, to continue to improve economic analysis as a decision making tool.

The second panel session discussed the path forward for the program. The following questions were discussed.

1. Are these the correct areas for fuel development (including addressing feasibility)?

- SiC cladding
- Alternative metal cladding alloys
- Coatings on cladding
- High density, corrosion resistant fuel pellets (UN)
- Very robust fuels (microencapsulated, FCM, etc.)
- Other components, such as control rods?

The consensus was that we should focus on fuel, and understand the implications for control rod melting. The control rods will melt before the fuel, but it is probable that when the core dries out and fuel melts, more robust control rods offer no additional benefit.

2. At what level should industry be involved in review of technology development?

The Advisory Committee is valued by the program. The Committee wants to remain engaged and interested. They will revisit the group charter to determine more precisely on how best to provide feedback on new concepts and on the development of concepts.

The program could continue to improve the performance of UO_2 through technologies that improve thermal conductivity and use higher enrichment.

As development and feasibility studies proceed, we need to ensure that the technologies make sense in the aggregate. There may not always be an improvement in every area.

It was suggested that we meet in January to discuss in detail progress on advanced fuel concepts. The program will consider this. The meeting will include presentations from industry to DOE to clarify the playing field to narrow scope and field.

The program may also want to consider small modular reactors and how advanced fuels may apply to them.

Industry wants DOE to support small, incremental improvements for industry. These are still very expensive. This is not DOEs typical role, but will be discussed at DOE.

3. Enrichment

- Is there a consensus?
- Is the time right to map out and take the initial steps toward increasing enrichment?
- Industry/DOE involvement?

Industry needs more assessment of the benefit of increased enrichment in the absence of a compelling reason to do so. There are several documents that consider increased enrichment. The first step may be to mine these documents from IAEA and OECD/NEA, and consider whether we should we conduct additional evaluations or road mapping. OECD is considering an expert group to look at higher enrichment, and the implications to infrastructure and safeguards. We should also engage designers of next generation reactors, such as small modular reactors and NGNP. Enhanced accident tolerance may require the potential for higher enrichment. There is no compelling industry case to increase enrichment for current plants, so DOE should lead the effort.

The discussion on enrichment will continue at the industry meetings with DOE on November 3.

4. New IDIQ Industry Tasks

Potential new IDIQ contract tasks were discussed, including the following:

- Design requirements for non-Zry fuel?
- What severe accident should we be using as a benchmark?
- How should we work together on analysis of the fuel/reactor system?
- Industry involvement in screening new concepts submitted to DOE
- Implementation strategy for lead test rods and lead test assemblies
- Industry involvement in program planning
- Leverage industry test facilities and procedures to evaluate advanced fuel concepts
- Industry participation in international collaborations
- Joint working group with NRC R&D on advanced fuel concepts

NRC commented that it is useful to know what is in the pipeline and welcomes dialog. Industry would have to know which concept and what application to start dialog with NRC.

ACTIONS

1. At the next Advanced LWR Fuels Industry Meeting, discuss whole plant performance in severe accident scenarios.
2. Determine if it is worthwhile to hold a working group meeting in January to discuss progress on advanced fuel concepts in detail.
3. Advisory Committee will reevaluate their charter after this first round of proposal reviews.
4. Advisory Committee will provide a report to the PIs from the first call for information in late November.
5. Coordinate breakthrough fuels session with EPRI for the Fuel Reliability Program meeting on February 22 in Tucson, Arizona.

AGENDA

Thursday, October 27, 2011

1:00	Opening Remarks/Current DOE Perspective	Frank Goldner
1:30	INL Advanced LWR Fuels Industry Advisory Committee Recommendations	Rose Montgomery
2:30	***Break***	
	Task 5 Advanced Fuel Concepts: Presentation and Discussion	
3:00	• AREVA	Richard Kochendarfer
3:30	• GE Hitachi	Russ Fawcett
4:00	• Westinghouse	Ed Lahoda
4:30	Round Table Discussion on Increased Enrichment in LWRs (Short presentations from each industry team with discussion) • Westinghouse • GE Hitachi • AREVA	Frank Goldner Panel: Task 5/NRC
5:30	***Adjourn***	

Friday, October 28, 2011

8:00	"Accident Tolerant Fuel" Definition	Kemal Pasamehmetoglu
9:00	Accident Tolerant Fuel Program Planning	Lance Snead
9:30	EPRI Breakthrough Fuel Technology Program	Bo Cheng
10:10	***Break***	
10:30	Economics of Advanced LWR Fuels	Francesco Ganda
11:30	Round Table: Path Forward for AFC LWR Fuel Development • What is the next step for AFC/Industry Cooperation? • What advanced fuels should we pursue? • Transition to qualification	Mitch Meyer Panel: vendors, utilities, NRC
Noon	Summary and Path Forward	Lori Braase
12:30	***Adjourn Meeting***	

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