GAIN-EPRI-NEI Advanced Fuels Workshop

Boise State University • March 5-6, 2019

NEI NUCLEAR ENERGY INSTITUTE

EPRI ELECTRIC POWER RESEARCH INSTITUTE

GAIN Gateway for Accelerated Innovation in Nuclear

GAIN-EPRI-NEI Advanced Fuels Workshop
Summary Report
March 5-6, 2019

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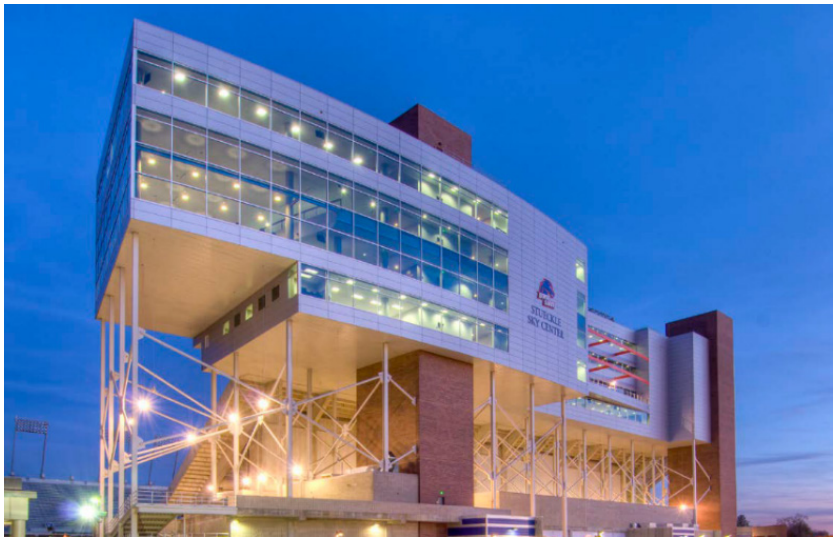
EXECUTIVE SUMMARY

The Gateway for Accelerated Innovation in Nuclear Initiative (GAIN), the Electric Power Research Institute, and the Nuclear Energy Institute hosted the Advanced Fuels Workshop to discuss the research and development needs of the advanced nuclear technology developers. The workshop was held on March 5-6, 2019, in the Stueckle Conference Facility, Boise State University, Boise, Idaho. Participants from the Fast Reactor, High Temperature Reactor, and Molten Salt Reactor Technology Working Groups presented their collective nuclear fuel research and development (R&D) needs to Department of Energy (DOE) national lab scientists and engineers. Together, they identified potential capabilities to meet their needs and the gaps that will need to be addressed by the applicable DOE programs.

GAIN is a private-public partnership and the organizing principle for the relevant DOE Office of Nuclear Energy programs. GAIN's mission is to provide the nuclear energy industry with access to technical, regulatory, and financial support necessary to move innovative nuclear energy technologies toward commercialization in an accelerated and cost-effective fashion.



The workshop achieved two desired outcomes. The first was an understanding of industry R&D needs to be used to inform the national laboratory strategy for developing and maintaining fuel development and qualification capabilities. The second was establishing the relationships needed to align advanced reactor designers and nuclear fuel leaders and researchers at the national labs. It is expected that discussions will continue between industry and the national labs to advance plans to meet industry needs.

We would like to thank Boise State University for the use of the Stueckle Sky Center meeting facility and for the support from their Nuclear Engineering Department.

TABLE OF CONTENTS

ACRONYMS

AFC	Advanced Fuels Campaign
AGR	Advanced Gas Reactor
ANL	Argonne National Laboratory
BWXT	Babcock and Wilcox Technologies
DOE-NE	Department of Energy Office of Nuclear Energy
EBR	Experimental Breeder Reactor
EPRI	Electric Power Research Institute
FFTF	Fast Flux Test Facility
FR	Fast Reactor
GAIN	Gateway for Accelerated Innovation in Nuclear
GFR	Gas-cooled Fast Reactor
HALEU	High Assay Low Enriched Uranium
HEU	High Enriched Uranium
HTR	High Temperature Reactor
INL	Idaho National Laboratory
LFR	Lead-cooled Fast Reactor
MSFR	Molten Salt Fast Reactor
MSR	Molten Salt Reactor
NEAMS	Nuclear Energy Advanced Modeling and Simulation
NEI	Nuclear Energy Institute
NRC	Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
R&D	Research and Development
SFR	Sodium-cooled Fast Reactor
SRNL	Savannah River National Laboratory
TWG	Technology Working Group
U.S.	United States
UNF	Used Nuclear Fuel
V&V	Verification and Validation
VTR	Virtual Test Reactor

Advanced Fuels Workshop Summary Report

INTRODUCTION

The Gateway for Accelerated Innovation in Nuclear (GAIN) Initiative, the Electric Power Research Institute (EPRI), and the Nuclear Energy Institute (NEI) hosted the Advanced Fuels Workshop to discuss the research and development (R&D) needs of advanced nuclear technology developers. The workshop was held on March 5-6, 2019, in the Stueckle Sky Center, Boise State University, Boise, Idaho.

GAIN is a private-public partnership and the organizing principle for the relevant DOE Office of Nuclear Energy (DOE-NE) programs. GAIN's mission is to provide the nuclear energy industry with access to technical, regulatory, and financial support necessary to move innovative nuclear energy technologies toward commercialization in an accelerated and cost-effective fashion.

Developers from the Fast Reactor (FR), High Temperature Reactor (HTR), and Molten Salt Reactor (MSR) Technology Working Groups (TWGs) presented their collective nuclear fuel R&D needs to (DOE) national laboratory researchers and program management. Together, they identified potential capabilities to meet their development needs and gaps that will be evaluated by applicable DOE programs. Over 90 people representing the commercial nuclear industry, national laboratories, and the Department of Energy (DOE) attended.

The objectives of the workshop were to:

- Promote interaction between advanced reactor designers and nuclear fuels researchers.
- Understand fuel development and qualification needs of advanced reactor designers.
- Update advanced reactor designers on capabilities at DOE laboratories.
- Identify gaps between designer needs and DOE capabilities.

It is expected that discussions will continue between industry and the national labs to advance plans to meet industry needs.

Prior to the workshop, advanced nuclear technology developers were asked to complete a survey to collect fuel development data for their reactor concepts. The request included fuel type, licensing and modeling needs, and demonstration. In addition, the survey asked if they needed assistance from the national laboratories with R&D of those advanced fuels. Survey information is provided in the body of the report under each specific technology.

The survey results were evaluated by the national laboratories to identity capabilities currently available to meet industry R&D needs. In addition, gaps in laboratory capabilities were of interest and may require strategic investments to meet industry needs. The national laboratories presented the results of their gap assessment at the workshop.

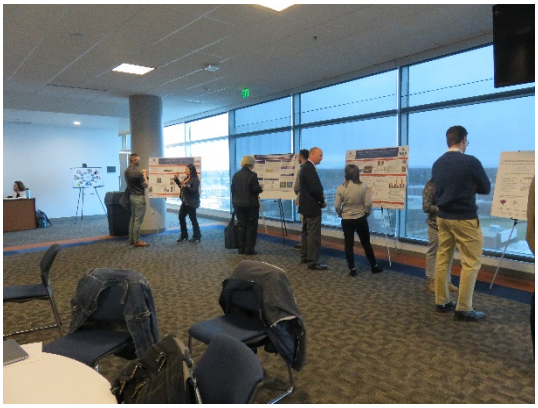
Cross-cutting fuel development R&D needs were categorized into the following five areas.

- Assembling, organizing and making available legacy data
- Addressing gaps in existing data through separate effects and integral testing, advanced modeling and international collaborations
- Investigating fabrication methods
- Performing safety and licensing calculations
- Generating data for fuel performance validation.

Overviews of fuel development capabilities were provided by DOE's Advanced Reactor Technologies (ART) program and Advanced Fuels Campaign (AFC). DOE and the advanced fuels programs will use the information generated in the workshop to inform R&D planning and priorities in fiscal year 2020 and beyond.

Three technology specific breakout sessions were organized to facilitate deeper understanding of industry areas of interest, R&D needs, laboratory capabilities, gaps, and a sense of priority for filling the gaps. Each session was co-led by an industry representative and a national laboratory technical expert. Breakout session reports were provided at the conclusion of the workshop on the second day.

Additionally, means to facilitate private-public partnerships (e.g., contracting with DOE) were extensively discussed, and workshop participants identified activities that could help commercialization efforts of the advanced nuclear industry.

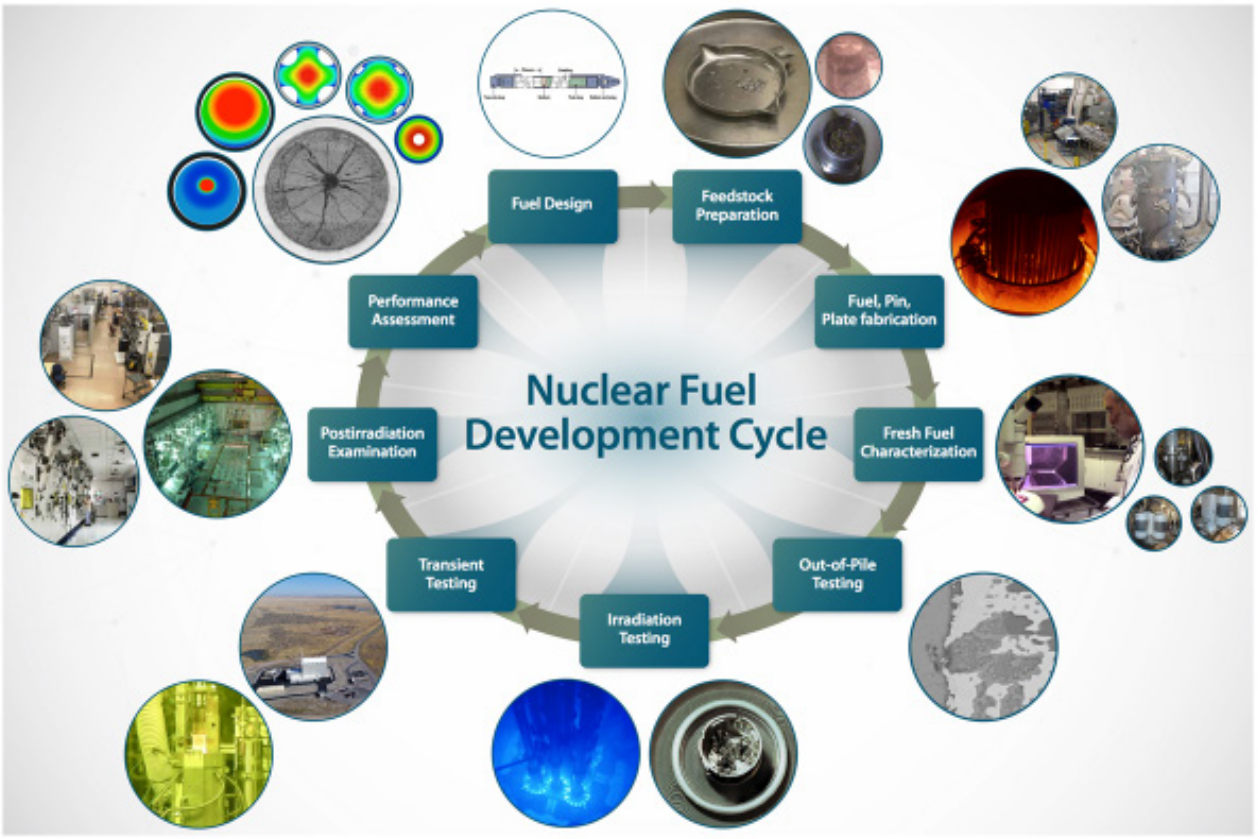


Boise State University featured their students and university capabilities during a poster session after the meeting on March 5, 2019.

The Advanced Fuels Workshop Summary Report provides a high-level overview of the workshop and detailed lists of advanced fuel developers R&D needs by technology. The agenda and attendee list are provided in Appendix A. Presentations are located on the GAIN website at gain.inl.gov/workshops.
https://gain.inl.gov/2019AdvFuelsWorkshopPresentations/Forms/AllItems.aspx#InplviewHash3fae9788-13b3-4742-86de-0292764b1422=SortField%3DLinkFilename-SortDir%3DAsc

ADVANCED NUCLEAR FUEL DEVELOPMENT NEEDS

The sections that follow contain lists of fuel development R&D needs by technology (Fast Reactor, High Temperature Reactor, and Molten Salt Reactor). The information is general and may pertain to one industry company or several. General stages of nuclear fuel development are provided in the figure below.



Fast Reactor Nuclear Fuel Development Needs

The Fast Reactor TWG is large and broad. Nuclear fuel makes the reactor concepts unique and is fundamental to proving the safety case for a new reactor. The advanced nuclear industry wants consistent, well-funded DOE programs to maintain capability at the national laboratories. For example, the metal fuel database needs funding and focus to complete.

Fast Reactor Technology Nuclear Fuel Development Needs
Areas of Interest
Fuels for Sodium Fast Reactor (SFR), Lead-cooled Fast Reactor (LFR), Gas-cooled Fast Reactor (GFR), and Molten Salt Fast Reactors (MSFR) • Metallic Fuel (SFR, LFR) • Oxide (LFR) • Nitride (LFR) • Carbide (GFR) • Chloride Salt (MSFR)
Industry Needs
Thermophysical properties of fresh fuels.
Quantify degradation of thermal conductivity with burnup, swelling (especially for metallic fuel). Need MARMOT (i.e., mechanistic, microstructure-based) modeling, with experimental validation. This is especially important to understand in the first few percent burnup, then long-term, high burnup as well.
Irradiation performance of fuels is needed up to terminal burnups. This is mostly steady-state testing, but transient testing is of interest as well. Transient-over-power (TOP) events are probably more interesting than loss-of-flow (LOF). Need sodium loop, lead loop, gas loop/pass through (for GFR) for transient tests.
For nitride fuel, irradiation performance, chemical compatibility between liquid lead (and to a lesser degree lead-bismuth), and UN, UO_2, MOX fuels.
For carbide fuel, properties and performance data is needed. The previous data was poorly characterized, and specification was usually not provided. Need to understand swelling behavior to high burnup (30%), diffusion, release of fission gas, and PCMI between carbide fuel and ceramic (SiC) cladding.
Pu-bearing fuels are of much more interest to industry in the longer-term (not as initial or startup cores) due to the lack of availability of HEU. It is assumed that we will eventually get to a fast recycle economy. Industry wants to send message to DOE that it is interested in fast recycle.
For cladding, SFRs can use austenitic stainless steel for low burnup and Ferritic Martensitic Stainless Steel (FMSS) for high burnup. LFR interest is in Al-forming steels (e.g., FeCrAl). Can FMSS be used in lead-cooled systems? There is interest in coatings or other ways of addressing corrosion-resistance in lead. Also, long-term interest in SiC. The GFR is only interested in SiC. Generally, more data is needed on HT9 regarding how high in dose it can go and if it is compatible with lead.

Fast Reactor Technology Nuclear Fuel Development Needs
DOE/Laboratory Gaps
Assembling, organizing, and making available legacy data. Includes metallic fuel, nitride fuel, and carbide fuel. Industry expressed strong interest in making this effort a major initiative to complete in a rapid fashion. Rather than attacking piece meal, need to do all the major fuel technologies of interest simultaneously (else we will basically be picking winners/losers by "our" prioritization).
In area of fuel fabrication, need access to facilities to explore fuel fabrication and work on scale-up issues prior to standing up a commercial fuel fabrication facility (for multiple fuel types). Need a "fuel fabrication user facility" available for industry use.
Strong consensus that a fast test reactor (i.e., Virtual Test Reactor [VTR]) is needed for prototypic testing of cladding and fuel-cladding integral effects.
Lead compatibility testing capabilities.
Need fresh fuel canisters for storage and shipping to address FR fuels. Interest in feedstock forms other than UF_6, such as metallic feedstock.
In the area of nuclear data needs: 1) U-238 (capture and scatter), 2) Pu isotopes, 3) Th isotopes, 4) Zr. On the fast salt side, Cl isotopes are a big missing gap. Scattering on one of the Pb isotopes for lead-cooled reactors.
Recommendations
Expand GAIN Legacy Document project to collect, archive, organize, and preserve legacy data.
Focused physical characterization programs for advanced fuels.
Appropriately scaled and targeted irradiation campaigns for advanced fuels.
Recommendations (continued)
Modeling and simulation efforts to support advanced fuels, including a focus on codes usable for licensing.
Development of an advanced fuel cycle including the necessary front-end infrastructure.

General Survey Results for Fast Reactor Fuel Development

Data Needs

What are your data needs for licensing your reactors and fuels?

- Irradiation data (including condition) is needed to demonstrate that the fuels would be stable during reactor use and storage.
- Operating conditions and materials different from light water reactors result in new phenomena coming into play, for which no or limited licensing experience exists.
- High temperature (600-800°C) creep data for monolith material options (stainless steel, ZrC, Nb:1Zr, graphite).
- Evaluation of irradiation effects on the monolith material after 10-year reactor operation without outage.
- Suitability of ion irradiation to reproduce neutron irradiation conditions; when an equivalency exists and when it does not.
- Data needs on interaction between the cladding/monolith materials and fuel (U-10Mo, U3Si2).
- Codes and standards applicable to high-temperature heat-pipe reactors.
- Legacy Data: There is an extensive collection of public and proprietary fuel performance data. New data will likely be needed to extend data for long-term, economically optimized operation but not for plant startup.
- For LFR specifically:
    - High-temperature creep data for key components such as fuel rod cladding and reactor vessel. Particularly, required duration of creep tests for licensing purposes.
    - Data needs regarding the performance of coatings that could potentially be used to enhance corrosion resistance of certain components, e.g. fuel rod cladding.
    - Suitability of thermal neutron irradiation to reproduce fast neutron irradiation conditions; when an equivalency exists and when it does not. Provisions are needed to maximize applicability of irradiation data collected in (mostly) thermal spectrum to fast reactor applications.
    - Codes and standards applicable to high-temperature liquid metal reactors. We are aware of some but knowing whether a compendium exists would be beneficial.

How can the national labs assist with collecting and utilizing the existing, legacy fuel data?

- The national lab infrastructure is key in providing the data especially on new fuel concepts since it is the only entity that has the infrastructure and resources to do so.

- Cross-section data for 5% enriched U material.
- There were a series of carbide fuel irradiation tests in 1970s. There are two issues with those in open literature; most of them are mixed carbide and characterization data is incomplete. Labs can search for uranium carbide fuel with further specifications that can be used for simulation.
- Specifically, data from Systems Nuclear Auxiliary Power Program (SNAP) reactor and Hanford Fast Flux Test Facility (FFTF) on UN. UO2. We have an extensive collection of public and proprietary fuel performance data. New data will likely be needed to extend data for long-term, economically optimized operation but not for plant startup.
- The labs have been doing substantial work on this front, but there's a lot to do. However, the legacy data work seems to be a frequent casualty of national programmatic funding decisions. Therefore, I think GAIN would be a great home for a mini data moonshot initiative to sprint through and appropriately collect this data in a 3- to 4-year timeframe. There's a tremendous amount of data out there, and much that we don't know and it's important to do that work ASAP.
- Access and awareness of ad-hoc databases; for fuel (UO2, MOX, UN) and cladding (D9, HT-9) in fast spectrum up to 150-200 DPA.
- Access to documents, both domestic and international, containing irradiation data for fuel (U3Si2, U-10Mo, TRISO fuel) and monolith materials (stainless steel, ZrC, Nb:1Zr, graphite).
- SFR will utilize existing data along with PIE of archive fuel. TREAT tests of FFTF/MFF pins is highly desirable.

Do you have additional fuel data needs or are there gaps in the existing data?

- We need to obtain a better understanding of the mechanical properties of fuel to understand cracking and degradation.
- Integrated testing of fuel response to accident/severe conditions.
- The legacy data are mostly for mixed carbide. New data are needed for the carbide fuel with full characterization.
- There are high burnup fuel performance data and reactor physics data that would be useful in getting to full deployment. But it is not expected that there will be significant data required to enable initial deployment if UO_2 is used. Need swelling, thermal conductivity with burnup, fission gas release for UN in particular, added data for U3Si2, and likely some U-10Mo.
- Not for early units, but as we look at fuel design evolution, it would be great to see more data to support these efforts.
- Gaps are associated with materials for which limited irradiation performance data exist, or for which existing data may not have adequate pedigree. Examples are:

- Fast neutron irradiation performance data for UN and high-DPA data for SiC. Moreover, since available literature only provides statements on chemical compatibility between liquid lead and fuels of interest (oxide fuel, UN), access is needed to associated data or to generate new ones by running new fuel and lead compatibility tests.
- Data gaps exist for U-10Mo and U3Si2. Also, there are knowledge gaps on interactions and methods to mitigate interactions between U-10Mo fuel and cladding and monolith materials.

How can the national labs assist in addressing your data needs or gaps in the existing data?

- See above; the national labs have the infrastructure.
- Labs can conduct differential and integral tests to build the carbide fuel data base. Labs can utilize their international collaboration to possibly collect data from foreign laboratories. Labs can also apply advanced modeling techniques to fill the data gap.
- The national labs can be helpful in providing access to hot cells and test reactors for the measurement, development and testing of fuel materials in prototypical, high burnup exposures. The cost and logistics of these services will be critical in how the work is assigned.
- They have unique facilities and capabilities and are frequently the home for legacy data. We simply need to make data collection a priority and not something we twiddle around with and let wither away. We cannot afford to lose the data or let it set on the shelf while the experts needed to help qualify the data retire or move on. This information simply cannot be regenerated at this point.
- In addition to referring to databases that we may not be aware of, assuming proper funding schemes are put in place labs can assist in activities such as:
    - UN pellets process development for subsequent testing, including irradiation
    - U-10Mo process development for subsequent testing, including irradiation
    - Diffusion couple experiments to assess fuel-cladding compatibility
    - Test compatibility between liquid lead and fuels of interest for the LFR. Argonne National Laboratory (ANL) performed similar experiments for assessing metal fuel-sodium interaction
    - Assisting in designing irradiation experiments, including irradiation of cladding material in lead environment as to assess effect of irradiation on corrosion rate.

Fabrication

Have you identified commercial fuel fabrication capabilities to meet your development needs?

- We have significant fuel fabrication capability as well as a willingness to work with third parties where it makes business sense.
- Work with existing suppliers and add capabilities.

How can the national labs help in developing new fuel fabrication methods?

- New fuels will need new fabrication methods and those must be developed.
- The laboratory fuel fabrication method and procedure have been established. A commercial scale fabrication procedure needs to be developed.
- Nothing significant for the projected fuel forms being envisioned by the reactor design team.
- Do not need to but may want to be even more efficient and effective.
- Optimization of UN fuel manufacture, which may or may not be through carbothermic route.

How can the national labs help in addressing the need for new fuel fabrication methods?

- The national labs have the required infrastructure; it is cost prohibitive to do it anywhere else.
- Labs can investigate the optimum (time and cost) fabrication procedure.
- Labs have unique capabilities to do this kind of work. More facilities are needed.
- Advising on UN, U-10Mo and TRISO fuel fabrication process development.

Modeling and Simulation

Do you have the simulation codes/tools needed to analyze your specific fuel design and the required safety and licensing calculations?

- Legacy and Nuclear Energy Advanced Modeling and Simulation (NEAMS) capabilities.
- The fuel code was updated for advanced fuels. Safety/licensing calculations were not done.
- In fact, they have already been helpful and continue to be helpful through projects such as GAIN.
- We would benefit from consultancy from BISON developers for properly using, and identifying modeling gaps, for the fuel systems and operating conditions of interest. For the latter, we are interested to understand the limitations of this code in analyzing high-burnup fast reactor fuel systems.

What additional data is needed for validation of the fuel performance codes and tools that you will use?

- The property data being used for advanced fuel needs to be updated for the specific fuel design (i.e., different from legacy fuels). Thermal mechanical performance measurements are required to confirm the models.
- The first category of data is that which is necessary to deploy a new reactor and fuel material. Beyond the dataset necessary for initial deployment, there is always a need for additional data to validate fuel performance codes and tools to enable optimizing operation or dealing with unexpected performance issues. The tradeoff for gathering additional data is always the expense of obtaining the data versus the benefit for having the being able to use the data. At some point, the cost/benefit analysis concludes that the point of diminishing return has been reached.
- Atomistic simulations to answer fundament questions on fuel behavior and fuel-cladding interactions need to be pursued both from a schedule as well as cost point of view. This will hopefully reduce the need for reactor data and help direct the in-reactor testing to minimize it.
- Legacy data, some of which has been appropriately archived, some has not yet.

Please provide any additional comments you may have.

- First, carbide fuel data needs to be updated. Second, the safety/licensing cases should be identified for each advanced reactor/fuel type. Third, confirmation tests are required for the selected cases.
- It's difficult to overstate the important and urgency that we need with respect to managing our wealth of legacy data.
- The national move toward metal fuel for sodium cooled reactors may have a problem if the reactor is very big. It appears that the lack of Doppler in metal fuel leads to small or zero power defect in even a 1500 MwT core which makes it rather difficult to operate safely. The only obvious cure is to have a pancake core which may require double the number fuel assemblies, which leads to a core that is not cost effective.

Molten Salt Reactor Fuel Development Needs

The Molten Salt Reactor TWG has a varied group of developers with a wide range of nuclear fuel needs. Not all need HALEU. Salt chemistry is unique to each concept. National lab testing will need to be tailored to each concept.

Molten Salt Reactor Technology Nuclear Fuel Development Needs
Areas of Interest
• Validated fuel salt property model (current campaign activity) • Validated baseline fuel salt property measurements (current campaign activity) • Validated measurement techniques that can be employed at plant sites • Design basis accident set (licensing basis event workshop planned) • Accident progression modeling tools (radionuclide releases, especially off gas system)
Industry Needs
Physical properties measured
Fuel “qualification” and licensing path
New techniques for salt production and producing products at scale
Suitable liquid fuel performance codes
Cross section data
Data for severe accident response conditions
Chloride salt data from pyro-processing efforts and others
Conversion of Used Nuclear Fuel (UNF)
Radiation effects on solidified salts
Fully coupled THD and neutronics, 3d, transient, chemistry modeling
Test data to validate computational fluid dynamics (CFD) data
Materials characterizations, including high temperature molten salts
Approach to critical and critical experiments
Reduced uncertainty in temperature coefficients of reactivity
Thermochemical and thermophysical property measurements of salt over the range of composition and operation conditions (including non-reactor operations)
Information on fission product behaviors in molten salts

Molten Salt Reactor Technology Nuclear Fuel Development Needs
Industry Needs (continued)
Enrichment of isotopes as needed
Speciation and transport of significant radionuclides in solid fuels and/or primary system salts
DOE/Laboratory Gaps
General capability is available within the labs to test radioactive salts. However, a well-funded coordinated effort is needed to ensure efficiency.
Recommendations
Work with reactor developers to understand design approaches and time lines. The government needs to be prepared to support in a timely manner.

General Survey Results for Molten Salt Reactor Fuel Development

Data Needs

Do you understand the data needs for licensing your reactors and fuels?

- Fluid fuels have a lot of questions around their eventual fuel licensing.
- Irradiation data (including condition) to demonstrate that the fuels would be stable during reactor use and storage.
- Some information is understood but still some gaps remain. SFR is better understood. MSR has fundamental questions.

How can the national labs assist with collecting and utilizing the existing, legacy fuel data?

- Some of our fuel has legacy data but other formulations need physical properties measured. In some cases (like plutonium-bearing fuel) this can only be done at a national lab.
- The national lab infrastructure is key in providing the data especially on new fuel concepts since it is the only entity that has the infrastructure and resources to do so.
- There is a lot of chloride salt and corrosion data from pyro-processing that could be shared.
- There is a vast amount of data that can be used in modeling.
- To a limited extent, legacy data may be relied on, the extent of the reliance will be based primarily on the final correlation between the existing legacy data and laboratory testing and confirmation results.

Do you have additional fuel data needs or are there gaps in the existing data?

- Physical properties, primarily.
- We need to obtain a better understanding of the mechanical properties of fuel to understand cracking and degradation.
- Actual testing is needed (currently utilizing German testing).
- Swelling data for HT-9.
- The additional data associated with the specific fuel type that is needed is being obtained now from external sources.
- Chloride form plutonium dose conversion factors, thermal physical properties of high uranium content chloride salts, thermal conductivity, viscosity, irradiation stability, plutonium solubility in chloride salts, fission product mobility.

How can the national labs assist in addressing your data needs or gaps in the existing data?

- Only the national labs can handle some of the materials that will make up our fuel formulations, for instance: NaCl-ThCl4-PuCl3.
- Labs have the modeling and real testing results they can input into the model for best accuracy.
- Need new test reactor or restart FFTF.
- Qualification of existing data to support use in licensing applications.
- Continue to measure thermal physical properties of chloride salts.

Fabrication

Have you identified commercial fuel fabrication capabilities to meet your development needs?

- Savannah River National Laboratory (SRNL), ANL, Idaho National Laboratory (INL), Pacific Northwest National Laboratory (PNNL), Oak Ridge National Laboratory (ORNL) have lots of experience in chloride fuel chemistry.
- Venders have said they would produce the salts.
- Fabrication, in the traditional sense of solid fuel fabrication is not necessarily required for a liquid fuel; however, commercial suppliers have been identified who can supply the constituent parts necessary to make up the complete liquid fuel system (U + Salts).

Do you need to develop new fuel fabrication methods?

- Making up the batches of molten salt will require development of new techniques.
- New fuels will call for new fabrication methods and those must be developed.

- Conversion of UNF, Pu, and UNF U extraction to concentrate Pu.
- Optimized manufacturing process.
- Salt in quantity and purity needs ramp up and commercialization.
- HALEU material, capable fabrication facilities, bulk metal supply, chlorine enrichment capabilities, fuel salt synthesis, and purification, for example.

Can the national labs help in addressing the need for new fuel fabrication methods?

- Preparing the molten salt mixtures could benefit from national lab involvement.
- The national labs have the required infrastructure; it is cost prohibitive to do it anywhere else.
- Large scale fuel salt purification methods that can be scaled up to successful (economically) commercial scale that is replicable for installation at each reactor site could be useful.

Modeling and Simulation

Do you have the simulation codes/tools needed to analyze your specific fuel design and the required safety and licensing calculations?

- We can't even begin to model some of the fuel compositions until we get basic physical properties on them, otherwise its "garbage-in, garbage-out" to the modeling approach.
- We lack suitable liquid fuel performance codes.
- Legacy and NEAMS capabilities.
- Fuel ratio determination needs knowledge of input fuel? As well as chemistry.
- Need fully coupled THD and neutronics 2D axi-symmetrical and 3D.
- Development is needed for MSR applications.

What additional data is needed for validation of the fuel performance codes and tools that you will use?

- We need physical properties first before we can even begin performance modeling on some of our design approaches.
- Radio chemistry effects on properties of salt.
- Could use some real test-based data and materials characterizations to back up computational fluid dynamics (CFD) predictions.
- Simulation codes and tools are in place but identification of other external independent verification methods and code to code validation aids may be available but possibly unknown to vendors. Neutron cross sections of some elements could be improved,

especially those not common in current reactors such as Fluorine. It is also highly likely that experimental facilities will be needed for the verification of reactivity coefficient calculations. This may be from modest test sections in existing experimental reactors but likely that dedicated sub-critical or zero-power facilities will be utilized. Confidence and accuracy of reactivity coefficients (mainly of temperature) are vital for all reactors employing passive response and lower safety reliance on shutdown mechanisms.

- Thermal physical properties of chloride salt fuel, corrosion test data, etc.

Please provide any additional comments you may have.

- Identify a pathway to measure physical properties on certain salt formulations (such as those with plutonium) that can only be done by a national lab. This would really be enabling.
- Liquid fuel offers the potential for dramatically simpler fuel development and fuel qualification. As the fluoride salt fuel form has been shown impervious to irradiation damage when operating as a liquid, most needs are on the properties of the liquid that can be studied using fission product surrogates in a non-radioactive state. That said, even basic property measurement capability for molten salts at high temperatures are currently difficult to source commercially and increased aid from the national lab sector would be most beneficial.
- Development of licensing and fuel qualification approach for MSRs is needed.

High Temperature Reactor Fuel Development Needs

The High Temperature Reactor TWG's primary need from DOE is the completion of the Advanced Gas Reactor (AGR) testing program for NRC licensing.

High Temperature Reactor Technology Nuclear Fuel Development Needs
Areas of Interest
• Enrichment • Licensing data • Data for fuel design; National Laboratory data assistance with obtaining legacy fuel data or acquiring new data • Fuel for development • Simulation codes and tools • Fuel development, with additional development of new fuel fabrication methods
Industry Needs
Source of HALEU source material
Collaboration on creation of simulation codes for safety and licensing
Help with forming international agreements
Subsidizing or eliminating the cost share for small businesses
DOE/Laboratory Gaps
Updating or creating reactor modeling codes to better resemble advanced reactor designs
Development of new fuel fabrication methods
Physical property data for all liquid fuels
Recommendations
Complete Advanced Gas Reactor fuel program and summarize data
Summarize and distribute relevant legacy fuel data

General Survey Results for High Temperature Reactor Fuel Development

Data Needs

Can the national labs assist with collecting and utilizing the existing, legacy fuel data?

- We believe that there is enough data on TRISO fuel resulting from the Advanced Gas Reactor (AGR) program, but it will need to be organized and presented in a way that will satisfy regulators, whether in US, UK, Canada or elsewhere. The national labs could play a vital role.
- The national lab infrastructure is key in providing the data, especially on new fuel concepts, since it is the only entity that has the infrastructure and resources to do so.
- Cross-section data for 5% enriched uranium material.
- Fuel licensing relies on the AGR TRISO fuel irradiation data including PIE and safety testing results. The timely completion of this work and documentation and issuing of reports is both helpful and critical to the licensing requirements. This includes the AGR-5,6,7 fuel qualification data that will be generated through the AGR campaign.

Do you have additional fuel data needs or are there gaps in the existing data?

- We need to obtain a better understanding of the mechanical properties of fuel to understand cracking and degradation.
- We have an early summary report from Babcock and Wilcox Technologies (BWXT) on their experience with TRISO and their manufacturing process and quality control which will be vital to all regulators given that there is little possibility of inspection, but we will be asked for a lot more detail.
- Integrated testing of fuel response to accident/severe conditions.
- Some legacy data can be used but new data may be required by the NRC.

Fuel Fabrication

Have you identified commercial fuel fabrication capabilities to meet your development needs?

- The TRISO particle fuel supply chain will be developed in a boot-strap fashion. The must be a market for our reactor before a commercial supply chain for fuel can be developed.
- Our expectation is to continue to work with BWXT, but we believe that collaboration with the US national labs and, potentially, with the national labs in UK and Canada would enhance development.
- Parallels that currently underway with in conjunction with other firms that have obtained grant money from DOE.

Do you need to develop new fuel fabrication methods?

- We know how make good TRISO fuel. However, the market demand must be created first before commercial availability of the fuel can be created.
- New fuels will call for new fabrication methods and those must be developed
- There are always ways to optimize fuel fabrication and automating and optimizing what has been done at BWXT would be a development activity.
- The AGR uranium oxycarbide (UCO) TRISO fuel particle design and fuel fabrication methods will be used, in particular from the AGR-5,6,7 fuel particle design. However different fuel pebble fabrication methods will be needed for various designs. The laboratories capabilities may be very helpful in developing these methods.

How can the national labs help in addressing the need for new fuel fabrication methods?

- During commercialization, areas of improvement can be supported by national labs
- The national labs have the required infrastructure; it is cost prohibitive to do it anywhere else.
- The national labs can leverage their expertise and current capabilities in fuel pebble fabrication methods.

Modeling and Simulation

Do you have the simulation codes and tools needed to analyze your specific fuel design and the required safety/licensing calculations?

- We need an efficient code to simulate fission product generation and transport from the particle to the environment. There may not be a single code, but a suite or codes must be available to model the fission product generation and transport.
- We are only beginning discussion with the regulators in UK and Canada about what they need from us. We have not engaged with NRC.
- Legacy and NEAMS capabilities.
- Leverage the NEAMS fuel performance modeling tool BISON in order to develop a fuel performance code.

What additional data is needed for validation of the fuel performance codes and tools that you will use?

- There are several fission product transport phenomena that must be identified, ranked, and the most important ones modeled.
- The fuel qualification data coming from the AGR fuel irradiation campaign is especially important developers using the AGR UCO TRISO fuel particle. It is extremely important

for the AGR fuel irradiation test data to be fully analyzed, documented, and issued in timely reports to make use of this fuel performance data.

- It would be very helpful to have some agreement between, the US, UK and Canada, that the needs will be the same or similar or that they are willing to consider approvals of each other. The Office for Nuclear Regulation and Environment Agency in UK just announced that the updated Generic Design Assessment process will do just that. The announcement was made at a Nuclear Institute Seminar at URENCO's Capenhurst facility on 14 November 2018 and will be published in January 2019.

SUMMARY

The recommendations from the workshop are being considered in national laboratory and DOE program planning for fiscal year 2020 and beyond. Select activities that address industry needs have been included in next year's work packages.

GAIN will continue to coordinate the legacy data needs identified in the report and work with DOE, national labs, and the TWGs to provide access to priority data needs.

Appendix A contains the agenda and list of attendees. Presentations are provided on the GAIN website at gain.inl.gov under the "Workshops" tab.

Appendix A

Agenda and Attendees

GAIN-EPRI-NEI Advanced Fuels Workshop

Boise State University • March 5-6, 2019

NEI Nuclear Energy Institute | EPRI Electric Power Research Institute | GAIN Gateway for Accelerated Innovation in Nuclear

Agenda

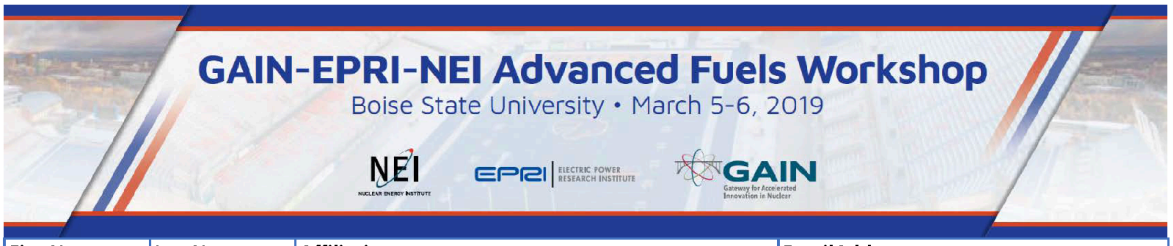
March 5, 2019

	Overview/Advanced Reactor Industry Needs	
8:00	Welcome	Rita Baranwal, GAIN
8:05	BSU Nuclear Perspective	Dr. Brian Jaques, BSU
8:20	Welcome to Idaho from the Director of Intergovernmental Affairs, Office of Idaho Governor Brad Little	Bobbi-Jo Meuleman
8:40	Introductions and Workshop Overview	Steve Hayes, INL
	TWG Reports on Fuel RD&D Needs (informed by Survey)	
9:00	• High Temperature Reactor	Dan Brown, X-Energy Micah Hackett, Kairos Power
9:45	Break	
10:00	• Molten Salt Reactor	Matt Lish, Flibe Energy
10:45	• Fast Reactor	Jake DeWitte, Oklo
11:30	Lunch on your own	
	Nuclear Fuel Development Capabilities	
	Overview of Fuel Development Capabilities	**Session Leads**
1:00	High Temperature Reactors	Paul Demkowicz, INL
2:00	Break	
2:15	Molten Salt Reactors	Lou Qualls, ORNL
3:15	Break	
	Fast Reactors	Steve Hayes, INL
3:30	• Fabrication and Characterization	Randy Fielding, INL
3:50	• Irradiation Testing	Dan Wachs, INL
4:15	• PIE and Out-Of-Pile Testing	Jason Harp, INL
4:40	• Performance Assessment	Pavel Medvedev, INL
5:00	BSU Student Poster Session	
6:00	Adjourn	

Agenda

March 6, 2019

	Future Capability / Breakout Sessions	
8:00	Fast Spectrum Testing: VTR	Doug Crawford, INL
8:20	NSUF: Fuel & Materials Development	Rory Kennedy, INL
8:40	HALEU: Status	Monica Regalbuto, INL Everett Redmond, NEI
9:10	X-Energy Fuel Production Capabilities	Dan Brown, X-Energy
9:30	***Breakout Sessions: What is needed to fill the gaps?***	**Session Leads**
	• High Temperature Reactor / 15 minute Q&A	Micah Hackett, Kairos Power Paul Demkowicz, INL
	• Molten Salt Reactor / 15 minute Q&A	Matt Lish, Flibe Energy Lou Qualls, ORNL
	• Fast Reactor	Jake DeWitte, Oklo Doug Porter, INL Steve Hayes, INL
Noon	Lunch on your own	
	Overview/Advanced Reactor Industry Needs	
	Breakout Sessions Reports and Discussion	**Session Leads**
1:30	• High Temperature Reactor / 15 minute Q&A	Micah Hackett, Kairos Power Paul Demkowicz, INL
2:00	• Molten Salt Reactor / 15 minute Q&A	Matt Lish, Flibe Energy Lou Qualls, ORNL
2:30	• Fast Reactor / 15 minute Q&A	Jake DeWitte, Oklo Doug Porter, INL Steve Hayes, INL
3:00	Break	
3:15	Engagement Opportunities	John Jackson, GAIN
3:30	Summary Discussion / Path Forward	Steve Hayes, INL
4:00	BSU Tour	
5:00	Adjourn	



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