Report to NEAC

Nuclear Technology R&D Subcommittee

Meeting of May 10, 2017

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I. Introduction

The agenda for the May 10, 2017 Nuclear Technology R&D Subcommittee meeting is shown below. The meeting provided members an overview of several research efforts funded by the DOE Office of Nuclear Energy's Nuclear Technology Research and Development Office (NE-4), and related research that is coordinated with NE-4. This meeting started with an overview of the FY17 Budget and the DOE-NE and NE-4 reorganizations. One member of the Subcommittee, *viz*., Ron Omberg, was absent. Ron was able to phone in for part of the morning session.

Agenda
Chair: Dr. Alfred P. Sattelberger
Location: DOE Germantown, Conference Room A410

8:30	Light breakfast
9:00	Executive Committee – Closed Session
9:15	Budget Update
9:30	NE-4 Organizational Overview
9:45	Advanced Reactor Programmatic Overview
10:15	Break
10:30	Advanced Materials R&D
11:00	Fast Reactor R&D and Future Direction
12:00	Lunch
12:45	Gas Cooled Reactor R&D and Future Direction
1:45	Molten Salt Reactor R&D and Future Direction
2:30	Energy Conversion R&D and Future Direction
3:00	Break
3:15	Office of Science "Basic Research Needs for Future Nuclear Energy"
3:45	Test Reactor – R&D Path Forward
4:00	Spent Fuel and Waste Disposition – Update
4:45	Closed Session - Committee Members
5:45	Adjourn

As usual, our report is organized more or less along the lines of the agenda.

II. Budget Update

The 2017 Omnibus bill provided NE-4 with $207.5M, which is slightly above the FY16 enacted budget of $203.8M. Advanced fuels was plussed up, as was systems analysis and integration. All R&D funding is taxed at rate of 20%; this goes to the Nuclear Energy University Programs (NEUP). NE-4 is the largest contributor to NEUP at approximately $26M. The FY18 budget numbers were not available for discussion.

III. Office of Nuclear Technology Research & Development (NE-4) Organizational Overview

Highlights and Observations

John Herczeg, The Deputy Assistant Secretary for NE-4, described the new DOE-NE organizational structure and the six offices (NE-3, -4, -5, -6, -7, and -8) that make up the Office of Nuclear Energy. A lot of the work associated with NE-4 and NE-5 (Office of Nuclear Technology Demonstration and Deployment) is interconnected. NE-4 is the steward of long term R&D and the proposed Test Reactor R&D effort. John then described the breakdown of his organization, which includes NE-41 (Office of Advanced Reactor Technologies), NE-42 (Office of Advanced Fuels Technologies), and NE-43 (Office of Materials and Chemical Technologies). John also showed us his "functional management structure," which includes seven national technical directors and two technology area leads.

John also described the "Versatile Reactor-based Fast Neutron Source Research and Development Organization." This Test Reactor program is focused on five areas – Core Concept and Safety Analysis, Fuel Concept Analysis, Experimental Capability Development, Reactor/Secondary, and Instrumentation, Control and Protection. A sixth element focused on Pre-NEPA activities will be separate from the overall program. NE-4 has invested $5M in FY17 to jump start the organization with a request for $10 million specifically included in the FY 2018 budget request. John admitted that this is still a work in progress – "This just kicked off in April." At our next Subcommittee meeting, we will have a program briefing with a chart of milestones and deliverables.

- As we stated in our last report, merging Advanced Reactors with Fuel Cycle Technologies in NE-4 is an excellent organizational option for enabling the conceptualization and planning of full "nuclear energy systems".

- Interfaces between NE-4 and NE-5 will require managed coordination and careful budget planning to achieve desired outcomes. Otherwise, longer-term R&D in NE-4 may always be at risk in budget-constrained scenarios. Also, activities pursued by NE-4 should be informed by industry plans for deployment.

  Careful management of the NE-4/NE-5 interface will need to be maintained in order to realize the benefit of transformational impact resulting from high-fidelity, multi-scale, multi-physics simulations in support of all program elements of NE. The conceptual design of the Test Reactor in NE-4 must be informed by the modeling and simulation program to ensure a facility that is adequately instrumented to promote validation of advanced simulations.

Recommendations

- It is still unclear what scope will be assigned to activities in the Office of Budget and Planning. This office may be the appropriate home for a permanent strategic planning cell that will maintain close coordination between NE strategic planning, program planning, and budgeting.

- The stand-up of a Test Reactor organization is timely and in sync with a recent NEAC recommendation. However, we recommend that the proposed organization be phased in gradually. This large management organization is more appropriate for a major program rather than the conceptual design effort currently planned for FY17 and FY18. We anticipate further discussions on the design authority and interdependencies across the organization.

III. Advanced Reactor Technologies Program

A wave of engineers, entrepreneurs, and investors are working to develop non-light water reactor systems because of their potential benefits related to passive safety, fuel cycle management, reactor siting, and high temperature applications. To support this interest, the Advanced Reactor Technologies (ART) Program has been established with the overarching mission to identify and address technical challenges associated with these systems and to facilitate development of their detailed design, regulatory review, and deployment by the early 2030's. The ART program has defined several objectives:

- Conduct focused research and development to reduce technical barriers to deployment of advanced nuclear energy systems, including space fission systems and other special purpose applications.
- Develop technologies that can enable new concepts and designs to achieve enhanced affordability, safety, sustainability and flexibility of use.
- Collaborate with industry to identify and conduct essential research to reduce technical risk associated with advanced reactor technologies.
- Sustain technical expertise and capabilities within national laboratories and universities to perform needed research.
- Engage with Standards Developing Organizations (SDO's) to address gaps in codes and standards to support advanced reactor designs.

The program has identified three major system categories: fast metal-cooled reactor technologies (including sodium and lead cooled fast reactors), gas reactors (including high temperature thermal, very high temperature thermal, and fast gas reactors), and molten salt systems (including a collection of thermal and fast reactors with various fuel forms and salt coolants). In addition, the program includes cross-cutting activities related to advanced materials qualification, energy conversion, and special advanced reactor applications such as space or defense use.

Since we last reviewed this topic, the program is implementing an organizational structure that includes Focus Areas for the three major reactor system categories. National Technical Directors (NTDs) have been identified to coordinate activities within each Focus Area and Technology Area Leads coordinate cross-cutting research areas that span multiple Focus Areas. In addition to their role of interfacing with international and domestic organizations, NTDs obtain input from industry Technology Working Groups (TWGs) to develop a prioritized list of consensus research needs. Priorities from the TWGs are not specific to particular concepts, but are common within a category of advanced reactors. The NTDs are developing Technology Roadmaps to identify high impact research needs and research gaps for proposed reactor concepts. NTDs can also commission studies to inform a design team about the feasibility of their concept.

The amount of detail in proposed advanced reactor designs and data to characterize candidate fuels and materials for use in these designs varies significantly. Likewise, organizations participating in Focus Area TWGs have a range of experience. However, all proposed designers recognize the need for irradiation testing for evaluating the performance of fuels and materials under prototypic conditions. TWGs within the Fast Reactor Systems and Molten Salt Systems Focus Areas have prioritized the need for an advanced irradiation facility that can provide fast-spectrum neutrons. The GCR Focus Area is targeting research to support thermal design concepts, so that associated irradiation needs can be addressed with existing U.S. materials and test reactors.

The DOE-NE reorganized at the beginning of FY 2017. During FY17, ART NTDs coordinate activities that receive funding allocated from several sources, including prior DOE-NE programs, direct grants to industry, and university research. Currently, it appears that the Gas Reactor Systems Focus Area and the Fast Reactor Focus Area, which both include development and qualification efforts initiated under earlier substantial DOE-NE programs, receive significantly more funding than the molten salt system efforts, which are presently funded principally through the university program. In contrast, the Molten Salt Systems Focus Area is developing plans to initiate an integrated research campaign that will address the fundamental technology challenges associated with design, construction and operation of molten salt reactors.

Although managed by a different organization, NE is sponsoring efforts to develop a regulatory framework for advanced reactors. Results from this effort include the draft regulatory guide DG-1330, “Guidance for Developing Principal Design Criteria for Non-Light Water Reactors,” a white paper on licensing basis events, and pilot studies on the applicability of consensus codes and standards to non-light-water reactor designs. NE and NRC have also co-sponsored three joint workshops on topics related to licensing advanced reactors.

Technology System Progress

NTDs for each technology system highlighted recent progress. The selected research pursued in each Focus Area reflects interests expressed by their TWGs, as well as the range of maturity of concepts proposed by organizations within these TWGs.

- **Fast Reactor Systems**

The Fast Reactor Systems Focus Area emphasizes research that will reduce system cost, development and qualification of new materials, and facilitate licensing. Although limited by the resource availability, on-going research is consistent with the prioritized list of activities provided by the Fast Reactor System TWG. Activities primarily focus on sodium-cooled systems, but it is planned to initiate lead-cooled system activities as additional resources become available.

Significant accomplishments in this area include startup of a new facility, the Mechanisms Engineering Test Loop (METL) Facility, for testing fast reactor systems and components. Activities are also underway to demonstrate the performance of several new intermediate heat exchanger designs, to evaluate new instrumentation for use in sodium systems, and to develop (or extend) ASME code cases for alloys (e.g., Alloy 709 and Alloy 91) proposed for fast reactor systems. The NTD emphasized efforts to retrieve existing fast reactor information and to archive new information. In this and other fast reactor efforts, the program is leveraging international experience. Efforts are also underway to retrieve and update analysis codes used in prior sodium reactor development and to leverage the Simulation-based High-fidelity Advanced Reactor Prototyping (SHARP) toolkit that is being developed by DOE's Nuclear Energy Advanced Modeling and Simulation (NEAMS) program. Although fuel designs are vendor-specific, this Focus Area supports development of enabling technologies that will advance fuel fabrication methods and obtain data for validating fuel modeling methods. To support vendors wishing to use historical fast reactor fuel irradiation data, efforts are underway to develop a quality assurance plan that can be used to determine if the acquisition, development, or processing of such data was performed in accordance with requirements and guidance of NQA-1.

The Subcommittee observes that several important nuclear countries, including Russia, China, and India, have recently built and now operate modern sodium-cooled fast reactors. Other countries, such as France and Belgium, have important on-going projects to design and build demonstration reactors. However, information presented to the Subcommittee suggests that efforts to leverage international experience is not as effective and concrete as it could be in terms of sharing advanced technologies, advanced core-fuel designs or even the feasibility of building such reactors. Furthermore, the Subcommittee observes that the design of the fuel and the advanced core should be integrated - as well as the design of the systems for reprocessing the fuel, if closing the fuel cycle is an objective of this effort. We recommend that core and fuel designers and fuel vendors work together in this effort -- and as early as possible in the process.

- **Gas Reactor Systems**

The Gas Reactor System Focus Area emphasizes research that raises technology readiness of fuels, materials, and components to levels required for deployment by the 2030s. In addition to TWG input, research in this Focus Area is guided by input received from members of their Industrial Alliance, a consortium of vendors and end-users of GCR industrial energy (electrical power, steam, etc.).

Accomplishments from research completed in this area will enable concepts employing either pebble or prismatic fuel containing coated U-C-O particles. A multi-year irradiation program is underway to characterize the performance of prototypic particles fabricated by a commercial fuel vendor. Several new national laboratory facilities are operational with the capabilities required to obtain material characterization data required to develop ASME code cases for alloys, steels and weldments, and graphite in higher temperature helium environments. In addition, new national laboratory and university facilities have been established for development and testing of systems and components, development and validation of methods for reactor design and safety analysis. These new facilities were developed such that data would be obtained in accordance with NQA-1 requirements. Finally, this Focus Area supports licensing framework interactions. New information and insights gained from GCR research is of interest to U.S. designers as well as the international community that participates in relevant research activities.

- **Molten Salt Systems**

Although some members have experience in plant operations and some experience in molten salt technology, the Molten Salt System TWG is unique because the underlying design concepts and technologies are less mature. The Focus Area includes activities to support concepts with significant design differences (liquid and solid fuel forms, thermal and fast spectrums) and a range of potential benefits, including high-temperature process heat applications and enhanced fuel utilization. The Molten Salt Reactor community shares the goals of all advanced reactor system communities to reduce costs with respect to light water reactor systems, and to deploy designs with inherent safety. Despite this diversity, organizations within this TWG have agreed to focus on research activities that will enable deployment. Research activities will assist TWG members to develop detailed designs, a licensing strategy, and a market case for their concepts and to identify gaps in their deployment strategy.

During FY17, the ART program will complete efforts to stand up this Focus Area and coordinate molten salt research activities, including industry and university awards and relevant cross-cutting efforts. TWG input emphasized near-term activities that enable deployment. For example, an activity to collect and archive historical data related to material handling and to component (pump, heat exchanger) design and performance will enable designers to develop more-detailed concepts. In addition, the NTD is encouraging designers to select candidate materials for their concepts. The use of materials for which ASME code cases already exist is encouraged. The TWG is working to identify what types of facilities and instrumentation will be required to characterize and monitor chemical interactions between materials and structures and to evaluate components within molten salt systems.

Modeling and Simulation

Several members of the Subcommittee voiced concern over the potential vulnerability of the ART program to the currently envisioned management of the NE Advanced Modeling and Simulation effort (NEAMS). Arguably, all fields of scientific and technical endeavor in the 21st century have witnessed the transformational impact that advanced modeling and simulation has brought to their respective enterprises. So also should be the case in the Office of Nuclear Energy. Science-based prediction must be directed toward enabling quick deployment and sustainability of advanced reactor technologies in the 2030 timeframe. This is especially critical in the process of qualifying fuels (informing a more effective plan for fuel irradiations), as well as addressing the safety margins in a scientific, probabilistic methodology, paving the way to regulatory relief and shortening licensing timelines. Science-based prediction is critically dependent on verification and validation of multi-scale, multi-physics simulations from atomistic scales to engineering system scales, employing a suite of codes across the enterprise. The science must be incorporated at the smallest scale, and very careful attention must be paid to maintaining simulation fidelity and quantifying uncertainties from scale-to-scale, across multiple codes. The emphasis of seamless management and accountability of this program between NE-4 and NE-5 must not be understated. This is especially true at a time of constrained budgets and resource redistributions to accommodate ART within the evolving NE program.

It is still unclear to the Subcommittee why NEAMS is positioned in NE-5, which presumably is geared toward >TRL-6 technical efforts, rather than NE-4 which is more focused on science and design (<TRL-6). This is not in any way an indictment of the management in NE-5, just an observation directed at identifying vulnerability to understandable bureaucratic inertia across organizational boundaries. Alternatively (or in conjunction), empowering the National Technical Directors (NTDs) with significant input to the NEAMS budget, as well as ensuring accountability to the ART program requirements will be imperative. One suggestion might be to ensure that the Methods, Modeling and Validation Manager within each ART Focus Area, publicize and manage a set of integrated simulation and experimental milestones that reflect the reactor technology roadmaps and ensure that resources are applied to support these milestones. This will demand vigilance across separate budget lines (simulation and experiment), and tight management/accountability for efforts across multiple laboratories and facilities. The coherence of this effort is so important to the success of ART as to be tightly monitored from headquarters. As it is now, there appears to be too little demonstrated sense of urgency that is needed to support the design, regulatory review, and deployment of the advanced technology reactors by the early 2030s.

Materials R&D for Advanced Reactor Concepts

All the advanced reactor concepts being pursued among the three Focus Areas share a need for structural materials R&D since the designs apply materials with coolants and temperatures beyond the range currently codified for nuclear applications. Furthermore, some of the proposed technologies need more fundamental data about corrosion or other material interaction phenomena, particularly irradiation-enhanced phenomena.

Development of consensus standards (ASME, ASTM, etc.) for materials is a long-term process, so it is vital that advanced reactor designers understand existing constraints and include any reasonable estimates for time and funding required to address new or modified standards in the Focus Area Technology Roadmaps.

To assure prioritization of materials R&D within finite resources and to effectively address common needs among the Focus Areas, a cross-cutting Technology Area Lead (TAL) for Advanced Materials has been appointed within the new ART National Laboratory Management Structure. DOE-NE's Advanced Reactor Materials initiatives have existing across a variety of coordinated management vehicles, including program directed work; university integrated research projects; NE University Projects (NEUP); Small Business Innovation Research (SBIR) and Small business Technology Transfer (STTR); the Gen-IV International Forum; International Nuclear Energy Research Initiatives (INERI); participation in IAEA activities; and the US-Japan Bilateral Agreement. While the breadth of prior endeavors was driven to address industry concerns via multiple forms of reviews and solicitations, the TAL approach with close-cooperation of the three Focus Area NTDs should help to integrate the materials R&D with the other Focus Area R&D.

Versatile Reactor-based Fast Neutron Source Development

In addition to providing an overview of the implementation of reorganization within NE-4 (and in particular NE-41), information was provided on NE's planned approach for development of a reactor-based fast neutron source. As described above, a common need that seems to be emerging from many industry Technology Working Groups is access to a domestic fast neutron source for evaluation of technologies, fuels, and materials.

In recognition of this input, NE-4 has established a task led by Idaho National Laboratory to examine potential technologies and design concepts for such a source and identify and plan the R&D needed. There is a multi-lab working group, funded initially at a modest level in FY17 to begin the process of formulating core and fuel concepts, as well as to examine approaches to instrumentation and controls, as well as possible experimental capabilities. In addition to laboratory participation, NE is seeking input from industry and engagement with academic partners. The identified team appears to have strong technical participation, as well as engagement from senior laboratory leaders and external experts in an advisory group to provide advice to INL.

The Subcommittee looks forward to hearing more about the progress of this initiative. We also look forward to hearing more about the technology roadmaps; these roadmaps should inform the priority of the fast reactor-based neutron source capability within NE's overall investment strategy.

Findings and Recommendations:

As noted above, the ART program objective is focused on deployment by the early 2030's. In their document, "Vision and Strategy for the Development and Deployment of Advanced Reactors" (DOE/NE-0147), DOE-NE states that their goal is to have at least two non-light water advanced reactors reach technical maternity, demonstrated safety and economic benefits, and completed licensing reviews by the early 2030s. Government funding is too limited to support deployment of all of the advanced concepts being proposed by reactor designers. If the U.S. is to have a leadership role in advanced technologies, it is important that ART programmatic research be prioritized. We recommend that this strategy consider technology readiness as well as industry interest in deployment. Synergies in needs for advanced materials and advanced simulation R&D exist across the distinct Focus Areas, and should be carefully coordinated for efficiency and effectiveness. We encourage the program to use Technology Roadmaps in their prioritization strategy and in developing a credible schedule for deployment.

We observe that each Focus Area emphasizes the need to compete with the cost of other power production options. Although we agree that economic power production is an important objective of the ATR program, it should not be the sole objective. Other attributes of advanced nuclear systems make it worthwhile for the U.S. to develop and deploy advanced reactor systems, including enhanced safety and security features; potential for high-temperature process heat applications; more flexible siting due to reduced reliance of water resources and smaller emergency planning zones; and fuel cycle advantages.

In addition, we observe that many non-weapons states are considering deployment of advanced reactor concepts. It is important that advanced systems benefitting from this federally-funded research program be consistent with and advance US policies related to non-proliferation.

IV. Energy Conversion R&D

The Subcommittee heard an in-depth report on the status of Sandia National Labs' effort to enable the commercial deployment of Supercritical CO_2 (sCO_2) Brayton cycle energy conversion systems. The Brayton Power Cycle, conceptualized as far back as 1872, is the basis of gas turbine engines, but has not yet seen broad commercial application in electrical power generation. The Brayton Cycle, as distinct from the more familiar Rankine Cycle, involves isentropic (adiabatic) compression, followed by heat addition at constant pressure, isentropic expansion in a turbine, and finally cooling (heat rejection) at constant pressure. For the cycle under consideration in this effort, there is no change in phase of the CO_2, which enters the turbine as close to the thermodynamic critical point as possible. The promise of such power cycles stems from higher theoretical thermodynamic efficiencies than those characterizing the more standard Rankine power cycles. Brayton cycle efficiencies can range from 40%-60%, depending on the pressure ratio across the compression cycle. Typical nuclear power plants running on the Rankine cycle, which involves phase change of the working fluid, are characterized by efficiencies in the mid-to-high 30% range.

The Sandia program for enabling this cross-cutting energy conversion technology is supported by ART (Reactor-to-sCO_2 Power Block), as well as the broader DOE Supercritical Transformational Electric Power (STEP) program that funds the Power Block R&D. Of great interest to NE is the development of the sodium-sCO_2 heat exchanger that addresses the Sodium-Cooled Fast Reactor goals of the ART program. By taking this technical route, the issues and challenges of dealing with the possibility of sodium-water reactions are avoided, thus reducing long-term program risk and enhancing sustainability. The program collaborates with the Argonne National Laboratory's PCHE heat transfer testing facility (Printed Circuit

Heat Exchanger, in which coolant passages are very small and compact and allow for the studies of plugging and fouling). These and other experiments have studied chemical reactions between sodium and sCO_2, showing that solid reaction products can stop the flow of sCO_2 even at 200 atm. Work is continuing to develop acoustic leak detection technology. A major effort is directed at heat exchanger development: investigating sodium draining, refilling, freezing, re-melting, and plugging.

Whereas SNL is focusing on the scientific development and cycle testing of the Brayton cycle with a focus on the Sodium Fast Reactor applications, industry is engaged in advancing the TRL of various components to 550˚C and higher temperatures. The vision for ART/SFR research is to develop, with industrial collaboration, an operational sCO_2 Brayton Power Conversion development platform (550˚C, 1MW) to support R&D by the end of FY2019. In addition, ART and SNL are supporting STEP, an up to 700˚C, 10 MW(e) pilot-scale test facility to be located at the Southwest Research Institute in San Antonio, TX. As industry uses the test facility and SNL R&D to systematically identify and retire technical risks, studies and research supporting the sodium-to-sCO_2 heat exchanger will continue to be funded by ART to support SFR deployment with RCBC in the 2030 timeframe.

V. Office of Science Basic Research Needs for Future Nuclear Energy

Linda Horton provided the Subcommittee with an overview of an upcoming Basic Research Needs (BRN) Workshop addressing research needs for nuclear energy. This was described as an update of a BRN workshop held in 2006. This workshop reflects an emphasis on future advanced nuclear energy systems, and focuses on the need for significantly improved understanding of the stability and performance of materials and fuels in extreme environments. The workshop is structured around planned breakout sessions in the design and discovery of coolants and liquid fuels, physics and chemistry of interfaces, understanding behavior under coupled extremes, and design and discovery of structural materials and solid fuels. A strategic planning session was held (including industry representation) in March 2017; the workshop is planned for later in 2017, and will bring together ~80 experts in diverse technical areas (representing government, labs, academia, and industry), as well as notable plenary speakers. Past BRN workshop reports have translated into special funding calls, or into priorities identified in annual calls or calls for Energy Frontier Research Centers.

The intent is for the workshop to identify longer-term needs. It is anticipated that the ongoing NE technology roadmap exercise will (in addition to developing specific strategies for realizing the goal of advanced reactor deployment) help inform long-term research needs in developing novel nuclear energy systems, as well as improving the reliability and efficiency of currently envisioned advanced reactors. There appears to be a robust level of coordination between NE and BES in the planning for this workshop; we applaud both Offices for their engagement and cooperation.

VI. Spent Fuel and Waste Disposition

A brief update on ongoing activities in this area was given that indicated waste disposition initiatives started in the previous Administration were still ongoing, while the Department seemingly is pivoting back to restart Nuclear Waste Policy Act (NWPA) activities associated with the defense of the Yucca

Mountain Repository license application, that is currently before the Nuclear Regulatory Commission (NRC).

The Subcommittee recognizes the policy gyrations that have plagued this area over the past eight years. However, as the Department moved with alacrity to terminate NWPA activities, it must now show similar energy and enthusiasm to restart those activities that will lead to an NRC decision on the Yucca Mountain repository license. As such, those activities initiated without clear authorizing legislation (other than vague annual appropriations language) should be of lesser priority in terms of management attention and resource allocation. The lesser priority activities include consent-based siting, deep borehole development and separate defense-repository development activities. Given the importance of completing the licensing defense on the Yucca Mountain repository site, the Subcommittee recommends that available NE resources should be martialed and focused on assisting the Yucca Mountain licensing effort.