Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors

February 22 and 23, 2021
Virtual Meeting

PUBLIC AGENDA
Draft: February 23, 2021

Day 1: Monday, February 22, 2021 (All times are ET.)

PUBLIC SESSION 1

WEBEX connection details for February 22:

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11:00 am – 11:10 am **Call Open PUBLIC SESSION 1 to Order and Welcome**
Janice Dunn Lee, Committee Chair, and Charles Ferguson, Study Director

Theme: Advanced Reactor Companies' Fuel Cycle Needs and Waste Management

11:10 am – 11:35 am	**Framatome**—Mr. Lewis Lommers, HTGR Engineering Manager (*confirmed*)
11:35 am – 12:05 pm	**Q&A for Academies committee and staff**
12:05 pm – 12:35 pm	**Break**
12:35 pm – 1:10 pm	**Terrapower, Natrium and Stepwise Approach**—Dr. Pavel Hejzlar, TerraPower Technical Fellow, and Ms. Tara Neider, SVP Program Development and Lab Facilities (*confirmed*)
1:10 pm – 1:40 pm	**Q&A for Academies committee and staff**
1:40 pm – 1:45 pm	**Brief Break**
1:45 pm – 2:00 pm	**Terrapower, Molten Chloride Fast Reactor**—Jeff Latkowski, SVP Innovation (*confirmed*)
2:00 pm – 2:25 pm	**Q&A for Academies committee and staff**
2:25 pm – 2:30 pm	**Brief Break**
2:30 pm – 2:55 pm	**ARC Clean Energy**—Dr. Ed Arthur, Vice President, Fuel Cycle Management and Safeguards, and Dr. John Sackett, Senior Vice President and Chief Technology Officer (*confirmed*)
2:55 pm – 3:25 pm	**Q&A for Academies committee and staff**
3:25 pm – 3:40 pm	**Public Comment Period**
3:40 pm	**Adjourn PUBLIC SESSION – Day 1**

Day 2: Tuesday, February 23, 2021 (All times are ET.)

PUBLIC SESSION 2

WEBEX connection details for February 23:

Same connection info for BOTH days.

11:00 am – 11:10 am	**Call Open PUBLIC SESSION 2 to Order and Welcome** Janice Dunn Lee, Committee Chair, and Charles Ferguson, Study Director **Theme: Advanced Reactor Companies' Fuel Cycle Needs and Waste Management**
11:10 am – 11:35 am	**LeadCold**—Janne Wallenius, Project Leader, SEALER (*confirmed*)
11:35 am – 12:05 pm	**Q&A for Academies committee and staff**

12:05 pm – 12:35 pm	**Break**
12:35 pm – 1:00 pm	**Moltex**—Mr. Rory O'Sullivan, CEO for North America (*confirmed*)
1:00 pm – 1:30 pm	**Q&A for Academies committee and staff**
1:30 pm – 1:35 pm	**Brief Break**
1:35 pm – 2:00 pm	**Oklo—**Ms. Caroline Cochran, COO and Co-Founder, and Dr. Jacob DeWitte, CEO and Co-Founder *(confirmed)*
2:00 pm – 2:30 pm	**Q&A for Academies committee and staff**
2:30 pm – 2:35 pm	**Brief Break**
2:35 pm – 3:00 pm	**X-Energy's TRISO Fuel Production**—Dr. Pete Pappano. Vice Present, Fuel Production (*confirmed*)
3:00 pm – 3:30 pm	**Q&A for Academies committee and staff**
3:30 pm – 3:45 pm	**Public Comment Period**
3:45 pm	**Adjourn PUBLIC SESSION – Day 2**

Reading Materials

From Framatome

- Lew Lommers, Finis Southworth, Bernard Riou, Michel Lecomte; "Risk Minimization for Near-Term Deployment of the Next Generation Nuclear Plant"; Proceedings of ICAPP '08; Anaheim, CA USA, June 8-12, 2008
- L. Lommers, F. Shahrokhi, J. Mayer III, and F. Southworth;"AREVA Modular Steam Cycle – High Temperature Gas-Cooled Reactor Development Progress"; Proceedings of the HTR 2014; Weihai, China, October 27-31, 2014
- Lewis Lommers, "Advanced Fuel Cycles and Actinide Burning in HTRs and the NGNP"; MIT Symposium on NGNP Goals and Challenges, February 23-24, 2005
- M. Miller, L. Lommers, F. Shahrokhi; "Main Features of the Reactor Cavity Cooling System for the Framatome SC-HTGR"; Proceedings of HTR 2018; Warsaw, Poland, October 8-10, 2018
- Werner von Lensa, Gerd Brinkmann, John Lillington, Farshid Shahrokhi; "The Status Quo on HTGR Decommissioning"; Proceedings of HTR 2018; Warsaw, Poland, October 8-10, 2018
- J. Delrue, F. Shahrokhi, L. Lommers; "The Framatome SC- HTGR Heat Transport System"; Proceedings of HTR 2018; Warsaw, Poland, October 8-10, 2018
- L.J. Lommers, B.E. Mays, F. Shahrokhi; "Passive heat removal impact on AREVA HTR design"; Nuclear Engineering and Design 271 (2014) 569–577
- L.J. Lommers, F. Shahrokhi, J.A. Mayer III, F.H. Southworth; "AREVA HTR concept for near-term deployment"; Nuclear Engineering and Design 251 (2012) 292–296.

Presenter Biographies

Dr. Ed Arthur, Vice President, Fuel Cycle Management and Safeguards
ARC Clean Energy

Dr. Arthur is presently the Vice President for Fuel Cycle Management and Safeguards at ARC Clean Energy. He retired from Los Alamos National Laboratory in 2003 after a 30 year technical and management career. There he was involved in a wide range of nuclear technologies and applications, including accelerator applications for the destruction of nuclear waste, and management of nuclear materials to reduce proliferation risk. He served as the national project leader of a Department of Energy (DOE) advanced fuel cycle initiative that proceeded current Office of Nuclear Energy research programs in fuel cycle technology. After retiring from Los Alamos he consulted for a number of national laboratories - Sandia, Argonne, and Idaho. He was also a research professor in the Nuclear Energy Department at the University of New Mexico where he helped establish the UNM Center for Nonproliferation and a graduate level track in nuclear safeguards. Dr. Arthur has a PhD in Nuclear Physics from the University of Virginia.

Ms. Caroline Cochran, COO and Co-Founder
Oklo

Caroline Cochran is the COO and co-founder of Oklo, a Sunnyvale, California based company working on advanced fission clean power technology. She has worked with energy technologies that span natural gas, oil, nuclear, and solar. Prior to graduate school, she was a program manager at the University of Oklahoma where she was part of establishing a technology commercialization program. She received her SM in NSE from MIT, a BA in Economics, and a BS in Mechanical Engineering from the University of Oklahoma.

Dr. Jacob DeWitte, CEO and Co-Founder
Oklo

Jacob DeWitte is the co-founder and CEO of Oklo Inc., a Sunnyvale, CA based company developing and building very small nuclear reactors. Jacob has experience working on a variety of advanced reactor designs including sodium fast reactors, molten salt reactors, and next-generation PWRs, as well as nuclear fuel cycle technology development and analysis. He also has experience working with experimental irradiation testing facilities during his time at a national lab. Jacob is originally from Albuquerque, NM. He earned his BS in nuclear engineering from the University of Florida and his SM and PhD in nuclear engineering at MIT.

Dr. Pavel Hejzlar, Technical Fellow
TerraPower, LLC

Pavel Hejzlar is a Technical Fellow at TerraPower, LLC. Pavel is responsible for delivering advanced science and engineering solutions for macro scale design and development of various products or technologies. Prior to this position he was the Manager of Core Design, responsible for the core design development of sodium-cooled traveling wave reactor concept capable of operating in a once-through cycle on natural or depleted uranium. He came to

TerraPower with 20 years of experience in the development of innovative reactor concepts to advance nuclear power. As Program Director for Advanced Reactors at the MIT Center of Advanced Nuclear Energy Systems he led numerous projects involving the development of various fast reactor designs, such as sodium-cooled fast reactor with improved economics and safety and proliferation constraints, lead and lead-bismuth cooled reactors for actinide burning, fast reactors with flexible conversion ratios for gas, liquid salt, sodium, and lead coolants. He has extensive experience with LWR design through the development and analyses of advanced LWR concepts, such as high-performance annular fuel for PWRs and Cross Shaped Twisted fuel for BWRs. He was one of the key authors behind the development of supercritical CO2 power cycle for Generation IV reactors. The high-performance annular fuel for PWRs and supercritical CO2 power cycle received worldwide attention and are now under development by industry and laboratories for practical application. Pavel Hejzlar is an author or co-author of more than 150 publications in technical journals and conference proceedings, including one book and 5 patents, and is reviewer for professional journals Nuclear Technology, Nuclear Science and Engineering, Nuclear Engineering and Design. He holds Master of Science degree from the Czech Technical University and Sc.D. degree in Nuclear Engineering from MIT.

Dr. Jeff Latkowski, Senior Vice President (Innovation) and Program Director of Molten Chloride Fast Reactor Program
TerraPower, LLC

Jeff Latkowski is the senior vice president of innovation at TerraPower, LLC where he is responsible for the origination, evaluation, and development of high-risk, high-potential energy solutions within TerraPower. He also leads the Molten Chloride Fast Reactor program. Jeff has 30 years of experience in the generation, analysis and evaluation of new ideas and designs for nuclear systems. He was previously employed by Lawrence Livermore National Laboratory (LLNL), where he most recently served as the chief scientist for the Laser Inertial Fusion Energy (LIFE) program. Jeff received a Bachelor of Science in nuclear engineering from the University of Illinois at Champaign-Urbana and a doctorate in nuclear engineering from the University of California at Berkeley. He is named on approximately 30 patent applications and is an author on nearly 100 journal articles and conference papers.

Mr. Lewis Lommers, HTGR Engineering Manager
Framatome, Inc.

Mr. Lommers provides technical design oversight of Framatome's Steam Cycle-HTGR concept. He leads design and analysis activities for the Framatome concept, and he also provides expert support on other high temperature reactor concepts. Lew Lommers has over 30 years of experience in the design, analysis, and development of High Temperature Gas-cooled Reactors, first at General Atomics and then at Framatome. Lew has worked on numerous HTGR concepts including the MHTGR, the GT-MHR, VHTR concepts under the US DOE Next Generation Nuclear Plant program, pebble bed reactor evaluations, Framatome's previous ANTARES HTGR concept, and the current SC-HTGR concept. Along the way, he has been involved in a broad spectrum of HTGR development activities including transient analysis, safety analysis, fission product transport, performance optimization, reactor design, heat transport system design, overall plant design, and technology development. Mr. Lommers has extensive experience in Systems Engineering and thermal system design and analysis. Beyond HTGR development, he has also worked on thermal design and analysis for aerospace systems. He also supports safety analysis methods for Light Water Reactors.

Ms. Tara Neider, Senior Vice President (Program Development) and Program Director of Natrium Reactor Program
TerraPower, LLC

Tara Neider is Senior Vice President of Program Development and Director of the Natrium program. She has overall responsibility for the development of sodium fast reactors at TerraPower and leads the Natrium Advanced Reactor Demonstration. Neider comes to TerraPower with more than 30 years of experience in nuclear engineering, project management and licensing. Previously, she worked as senior vice president of Back End Business Development and Sales at AREVA, Inc. Neider had responsibility for directing back end customer relations for AREVA in North America, developing an overall fuel and decommissioning strategy for the company, and pushing sales revenues for AREVA and AREVA subsidiary Transnuclear, Inc. to double their sales targets. For four years prior, Neider served as President and CEO of AREVA Federal Services. She established the overall strategy for AREVA Federal Services. In this role, she held board positions on major Department of Energy project teams, including the MOX Fuel Fabrication Facility, Hanford Tank Operations, Yucca Mountain, Savannah River Remediation and Waste Isolation Pilot Plant. Neider spent much of her early career with Transnuclear, Inc. She began as a project manager and design engineer and rose to serve as President and CEO of the company. Neider holds a Bachelor of Science and a Master of Science degree in Mechanical Engineering, both from the Massachusetts Institute of Technology (MIT). She also earned an MBA in Finance and International Business from New York University.

Mr. Rory O'Sullivan, CEO for North America
Moltex

Rory O'Sullivan is the Chief Executive Officer, North America at Moltex. He joined the company as Chief Operating Officer in the UK, before moving to Canada to set up the North American business. Rory began his career as an award-winning project manager at the Bouygues group, running £50m+ projects. With a passion for delivering clean, low-cost energy to the world, he co-founded Energy Process Developments Ltd to pursue advanced nuclear and led a government-funded feasibility study on the development of a prototype molten salt reactor. Rory sat on the IAEA MSR advisory committee and was a Forbes 30 Under 30 Standout. He obtained a first class honours degree in Mechanical and Manufacturing Engineering from Trinity College Dublin and a degree in Mechanical Design Engineering from INSA Lyon in France.

Dr. Peter Pappano, Director of Fuel Manufacturing
X-Energy

As vice president for fuel production, Pete leads the development of X-energy's pebble fuel production strategy, establishing a high assay low enriched uranium (HALEU) supply chain, and the design and licensing of the TRISO-X Fuel Fabrication Facility. Pete manages two X-energy US Department of Energy (DOE) Cooperative Agreements. The first, a $53 million Advanced Reactor Concept project, allows X-energy to further its reactor design, develop a pebble/compact fuel production capability, and initiate interactions with the US Nuclear Regulatory Commission. The second, a $38 million Industry Funding Opportunity Announcement project, focuses on the design and license application development for the TRISO-X Fuel Fabrication Facility. Prior to joining X-energy, Pete worked at Oak Ridge National Laboratory (ORNL) on their research staff where he managed TRISO-based nuclear fuel compact manufacturing process development for the DOE Next Generation Nuclear Plant and Advanced Gas Reactor Fuel Qualification Programs. While at ORNL Pete also oversaw activities associated with irradiated nuclear-grade graphite recycling for DOE's Nuclear Energy

Deep Burn Program. Prior to ORNL, he worked as a process engineer for SGL Carbon. Pete also served in two capacities at the US DOE: as a detailee to the Office of Nuclear Energy where he managed the Advanced Graphite Creep graphite program, and then as a materials science program manager for the Office of Fusion Energy Sciences. Pete also Chairs the Nuclear Energy Institute HALEU Task Force. Pete received a B.S. in General Science, and an M.S. and Ph.D. in Fuel Science, all from the Pennsylvania State University.

Dr. John Sackett, Senior Vice President and Chief Technology Officer
ARC Clean Energy

Dr. Sackett has a PhD in Nuclear Engineering from the University of Arizona. He retired from Argonne National Laboratory in 2004 as the Associate Laboratory Director for Engineering Research, which included nuclear technology research and development at the Laboratory. He joined Advanced Reactor Concepts (ARC) in 2006. His entire career has been related to research in sodium-cooled fast reactors, having worked at Argonne National Laboratory for 34 years. Ten years of his career was as the Division Director for the Experimental Breeder Reactor – II (EBR-II) and subsequently as the site manager for ANL-W in Idaho. At EBR-II he was instrumental in developing the Operational Safety Testing program, culminating in the demonstration of self-protecting response to the full range of Anticipated Transients Without Scram (ATWS) events, including station blackout without scram. Following the shutdown of EBR-II in 1994, he oversaw the first phase of decommissioning the facility and treatment of EBR-II spent fuel. He currently resides in Bozeman MT.

Dr. Janne Wallenius, Project Leader, SEALER
Blykalla/LeadCold

Professor Wallenius has conducted research on lead-cooled reactors at KTH Royal Institute of Technology since 1997. His areas of competence include reactor design and safety analysis, nuclear fuel development and radiation damage physics. In 2013 he co-founded LeadCold Reactors, with the intent to commercials small lead-cooled reactors for power production. In 2018, the UK government selected LeadCold's SEALER design as one of eight advanced reactors that were funded for feasibility studies. In 2020, KTH obtained a 6 MUSD grant from the Swedish research foundation for design of a lead-cooled research reactor to be operational in Oskarshamn in 2030. In 2021, LeadCold and nuclear power utility Uniper announced a cooperation intending to design, fund and construct an electrically heated prototype of SEALER, with the intent to commercialise lead-cooled SMRs in Sweden in the 2030's.

Advance Questions from the Committee

ADVANCED REACTOR DESIGN

Briefly, describe the baseline reactor design: (shown in parentheses are the types of information being requested)

- Reactor core (thermal power, refueling cycle, thermal or fast neutrons, nominal fuel inventory (kg), time to burnup, burnup at discharge)
- Fuel and cladding (material, chemical composition, physical form, level of enrichment, expected fuel enrichment at discharge)
- Moderator, if required (material, chemical composition, physical form, nominal inventory)

- Coolant (material, chemical composition, physical form, nominal inventory, operating pressure, inlet/outlet temperature)
- Heat transport and steam/electrical generation systems
- Approach to criticality, reactivity control, decay heat removal, shutdown, and inherent safety support systems

RESOURCE UTILIZATION

- What will be the impact on the mining and use of uranium and thorium resources?
- Describe fuel characteristics and in-reactor parameters that impact the overall efficiency of the consumption of fissile material.
- In what sense is the proposed advanced reactor technology and fuel cycle sustainable?

ADVANCED FUEL CYCLE

- What is the specific fuel cycle that is envisioned to support the baseline advanced reactor design? Please describe the progression of fissile nuclear fuel from source material, through enrichment, fuel fabrication, reprocessing/recycling (if applicable), storage, and disposal and note any technology gaps that will need to be resolved.
- Specifically, identify and estimate the inventories of fissile radionuclides at each step in the fuel cycle.
- For different types of reactors, the transition to equilibrium can take many cycles and would have different fuel cycle characteristics than the equilibrium cycle. What is the expected time of equilibrium and how does this affect resource needs and waste generation during transition cycles?
- Is the supporting infrastructure currently available or do components have to be developed and/or adapted to support the proposed nuclear energy system?
- Describe any special requirements for fuel fabrication.
- What reprocessing/recycle technologies, if any, are planned?
- If reprocessing/recycle is part of the strategy, describe the process envisioned, its level of technical readiness, and requirements to upgrade the technology to an industrial scale.
- Are there any unique or special issues that need to be addressed related to the transportation of materials or wastes between steps in the fuel cycle that supports your advanced reactor design?

NUCLEAR WASTE MANAGEMENT and DISPOSAL

- Identify the types of nuclear waste streams generated at the back-end of the proposed fuel cycle. Describe their chemical, isotopic and physical form. If possible, specify the masses of the individual radionuclides in the waste streams at discharge from the reactor (kg/MWd/tHM).
- For the back-end of the advanced fuel cycle, identify and estimate the volumes and/or masses that will be generated in the different waste classifications (i.e., low level waste (LLW), Greater-than-Class-C waste, high-level waste (HLW), and spent nuclear fuel (SNF)).
- Describe for the following groups: (1) long-lived uranium/thorium and transuranium isotopes (TRU), (2) short-lived fission products, and (3) long-lived fission products, the expected radionuclide inventories in the final waste streams. Describe the strategy for handling each of these groups.

- For the high-level waste, describe the waste forms that will be used for their disposal. Will the final waste forms require special processing, handling, or a particular disposal environment?
- Does your nuclear energy system introduce new wastes streams that could be considered problematic (e.g., chemically unstable in air or water)?
- Will the reactor design pose special challenges for decommissioning, such as activated structural components?
- Please provide to the Committee any additional information you might have regarding wastes streams (e.g., masses, chemical, isotopic and physical form, etc.,) for other (non-reactor) steps in the fuel cycle.

NUCLEAR SECURITY and PROLIFERATION RESISTANCE

- How is nuclear security[1] and proliferation resistance[2] of your design/nuclear energy system ensured?

NUCLEAR SAFETY

- How is nuclear safety[3] addressed in the design of your advanced nuclear energy system? That is, does your design utilize passive or active safety concepts?

ADVANTAGES or ATTRIBUTES of your ADVANCED REACTOR DESIGN

- What are the advantages or most important attributes of your baseline nuclear energy system compared to current nuclear energy generation systems? Provide the bases for these assertions (design, experimental, operational data, etc.).

CHALLENGING TECHNICAL ISSUES for COMMERCIALIZATION

- What are the most challenging technical issues that must be overcome for commercialization of the baseline nuclear energy system?
- At this time, what is the overall technology readiness level of your baseline nuclear energy system?

CHALLENGING LICENSING ISSUES for COMMERCIALIZATION

- What are the regulatory challenges for your advanced nuclear energy system associated with waste management and facility decommissioning?
- What is your reference implementation plan for commercializing your nuclear energy system (development / prototype / first-of-a-kind / deployment)? That is, do you intend to do a prototype/demo?
- What is your timeline for licensing, construction, and operation for the nuclear fuel cycle capabilities that support your advanced nuclear reactor?
- What are the key milestones?

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[1] Efforts that promote the prevention and detection of and response to, theft, sabotage, unauthorized access, illegal transfer or other malicious acts involving nuclear material

[2] Mechanisms that impede the diversion or undeclared production of nuclear material, or misuse of technology with the purpose of acquiring nuclear weapons or other nuclear explosive devices

[3] Nuclear safety is defined by the International Atomic Energy Agency (IAEA) as "The achievement of proper operating conditions, prevention of accidents or mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation hazards."

CONSTRUCTION and OPERATING COSTS

- If possible, provide an estimate of the costs associated with the fuel cycle capabilities to support your advanced reactor.
- Discuss the methodology and assumptions used as well as the potential uncertainties associated with your cost estimates.