NON-ELECTRIC APPLICATIONS OF NUCLEAR HEAT FULL DAY WORKSHOP

OCTOBER 3, 2022

TORONTO, CANADA

WORKSHOP SYNOPSIS AND FINDINGS

Non-Electric Application of Nuclear Heat (NEANH) Task Force

Background

The Generation IV International Forum (GIF) is a co-operative international endeavour, which was set up to carry out the research and development (R&D) needed to establish the feasibility and performance of the next generation (Gen-IV) nuclear energy systems.

Beginning in November 2020, GIF facilitated an open exchange of expert views on the position of Gen-IV systems regarding applications of nuclear fission-generated heat beyond the electric grid. These activities suggested a path forward for GIF to leverage work being conducted internationally and identify the benefits that Gen-IV reactor systems could bring to the non-electric energy sector in the context of future energy markets. At the 51st GIF Policy Group (PG) meeting held on 20-21 May 2021, the GIF Policy Group members decided to establish a new Task Force (TF) on Non-Electric Applications of Nuclear Heat (NEANH TF), which was officially launched in October 2021 for a period of 24 months.

Under this NEANH TF, a virtual workshop was held in July 2022 to exchange knowledge and perspectives among TF and GIF members, and to align the members in advance of engaging the end-use community. This virtual workshop identified commonalities, key differences, and gaps among work being performed by participating organizations. The workshop also highlighted topic areas for future meetings, including progress toward the demonstration and deployment of non-electric applications of nuclear heat, and analysis tools to inform the opportunities.

A full day open workshop was also held in Toronto, Ontario, Canada on October 3, 2022, in conjunction with the GIF Industry Forum and co-organised by the International Framework for Nuclear Energy Cooperation. This workshop was well-attended, with participation by approximately 150 participants from academia, research laboratories, the energy end-use community (e.g., industry), nuclear technology developers, and others. This document includes a summary and highlights from this event.

NEANH Task Force Objectives

GIF-type reactor technologies can be employed for cogeneration and integration in energy markets with high fractions of renewables, providing ancillary services to support grid stability, enhanced flexibility and high-quality heat. The NEANH TF will identify and review these systems, and develop key performance indicators, such as Technology Readiness Levels, timeliness, adaptability to geographical conditions, CO_2 emission reduction potential, cost, and boundary conditions for economic viability.

The objectives of GIF NEANH TF are as follows:

- Prepare a position paper to illustrate the GIF position regarding the coupling of non-electric applications to nuclear energy systems, focusing on GIF systems and associated technologies, in both the short and long term.
- Improve the general level of knowledge of the GIF members regarding recent and ongoing research activities on NEANH coupled with Gen IV systems, and ongoing research for non-electric applications using water-cooled systems that may be leveraged for Gen IV applications.
- Enhance the general level of knowledge of GIF members on non-grid applications of nuclear systems.
- Highlight relevant system configurations, including system feasibility, emissions impacts, etc.
- Develop a network to connect GIF to the high temperature community outside the nuclear field.
- Conduct systems analysis with regard to key performance indicators. Systems analysis may include nuclear energy integration within a system of other clean energy options, and analysis related to time-of-use of production, transmission, end-of-life costs, and the interactions between electricity and heat markets.
- Provide input to decision makers, industry, licensing authorities, investors, etc. on configurations that will support achieving policy goals, and R&D efforts to be undertaken.

Workshop Synopsis and Findings

Synopsis

Organized by the Generation IV International Forum Task Force on Non-Electric Applications of Nuclear Heat in collaboration with the International Framework for Nuclear Energy Cooperation, this workshop aimed to establish connections between the research community and industry, engaging both nuclear technology developers and energy end users.

Through panel discussions and interactive dialogue, deployment opportunities were discussed in which nuclear energy systems could be used to support heat and electricity demands outside the power sector.

- The research community spoke about computational tools and facilities that could support systems analysis and demonstrations to accelerate the path to commercial advanced reactor deployment.
- Members of the energy end-use community, including chemical processing, oil and gas, and ammonia production, among others, shared details of their energy needs and requirements, and raised potential issues regarding the integration of nuclear energy to drive these processes.
- Nuclear technology developers shared their performance capabilities, system considerations, and deployment timelines for their systems.

Attendees included Gen IV reactor developers, energy system modellers, industrial energy users, researchers, and other stakeholders.

Workshop Agenda

- Concept Overview
- Session 1 – Researchers panel
- Session 2 – Industry: Energy end users
- Session 3 – Industry: Advanced reactor developers
- Moderated Discussion

Key Findings

- There is a real opportunity for nuclear heat to support the decarbonisation of non-electric applications, driven by climate change policies internationally.
- It is technically possible to couple these processes with nuclear energy, and there are historic precedents.
- There is a significant need for the development and sharing of detailed data by relevant parties, including by building demonstration projects.
- There is significant demand for heat applications below 550ºC. Advanced reactors create opportunities for these applications, but they can also support higher temperature processes.
- In addition to primary heat transfer standard in nuclear reactor designs, there is a desire for a secondary heat transfer loop and thermal energy storage to isolate the nuclear reactor from the heat customer. This may enable greater flexibility and safety related to utilizing heat directly from the nuclear reactor system.
- Nuclear energy is a “drop-in” solution expected to be capable of directly replacing fossil fuel-powered steam supply operations, but not direct fossil-fuel fired operations.
- Hydrogen has promising applications, but its role should be considered on case-by-case basis that considers the benefits it offers with respect to certain sectors and processes, and its potential for decarbonisation.
- There are a range of options for owner-operator models. Energy end-users do not desire to own and operate a reactor themselves, but are customers for nuclear-generated heat, steam, and electricity.
- Cost is a significant driver for adoption, along with energy security, reliability, time to deployment, and social acceptance. Regulatory processes are viewed as a significant barrier for adoption; clarity is needed regarding interaction across the regulatory bodies for nuclear systems and industrial processes.

Workshop Summary

Concept Overview

Opening Remarks - Shannon Bragg-Sitton, NEANH TF Chair

Dr. Bragg-Sitton highlighted the importance of pursuing non-electric applications of clean nuclear energy, including the pressing need for climate change mitigation. She notes that nuclear energy provides an opportunity to support decarbonisation of the grid and industrial applications without sacrificing resilience and reliability. Participation and active dialogue with the audience was encouraged to increase the value of the workshop to all stakeholders.

In conclusion, the day's agenda was introduced, and there was a commitment to capture what was discussed, the opportunity, and what is next for the Task Force.

Ramesh Sadhankar, Natural Resources Canada

Dr. Sadhankar provided a history of GIF, including the 2002 technology roadmap which includes non-electric applications in its scope.

The historic precedent to use nuclear technologies for non-electric applications was discussed. Historically, these applications have included:

- 43 reactors that have been used for district heating (~500 reactor years)
- 17 reactors that have been used for desalination (~250 reactor years)
- 7 reactors that have been used for industrial process heat

Past experience using nuclear energy for non-electric applications mostly utilised water-cooled reactors. Examples of specific applications include:

- Heavy water production – Canada, Bruce A, CANDU reactors
- Salt refinery – Germany, Stade, Pressurized Water Reactor (PWR)
- Cardboard factory – Switzerland, Gösgen, PWR
- Fuel Plant – UK, Calder Hall, MAGNOX gas-cooled reactor

Previous initiatives exploring the opportunity for non-electric application of nuclear heat were highlighted, identifying where there are similarities to the NEANH Task Force and where end-users were engaged:

- NGNP Industrial Alliance (2010) – Formed to develop high-temperature gas reactors (HTGR) and expand its industrial applications. Membership included end-users.
- EUROPAIRS (2009) – Evaluated coupling of HTGRs with industrial processes. This group concluded that 50% of industrial heat demand is below 550ºC and recommended strong partnerships with nuclear technology developers and end users.

The scope of this GIF NEANH TG was proposed to be constrained to a 6x3x6 matrix of options. Specifically:

- 6 reactor systems corresponding to the technologies selected by GIF (the gas-cooled fast reactor [GFR], the lead-cooled fast reactor [LFR], the molten salt reactor [MSR], the sodium-cooled fast reactor [SFR], the supercritical-water-cooled reactor [SCWR] and the very high-temperature reactor [VHTR]),
- 3 reactor sizes (GW-scale power reactor, small modular reactor [SMR], micro reactor), and
- 6 applications (cogeneration, hydrogen production, desalination, process heat, synthetic fuel [synfuel] production, and cooling)

Session 1 – Research Panel

Panelists

- (Moderator) Gilles Rodriguez, Commissariat à l'énergie atomique et aux énergies alternatives (CEA)
- Aaron Epiney, US, Idaho National Laboratory (INL): Modeling and Simulation and Experimental Systems Development
- Ali Siddiqui, Canada, Canadian Nuclear Laboratories (CNL): Canadian Overview
- Rob Arnold, UK, Department for Business, Energy and Industrial Strategy (BEIS): UK Research and Development Overview
- Hiroyuki Sato, Japan, Japan Atomic Energy Agency (JAEA): JAEA R&D Overview
- Michael Futterer, EU, European Commission (EC) Joint Research Center: GEMINI 4.0 Project

Key Findings from Session

- There are multiple historical examples of non-grid applications of nuclear energy to draw upon.
- Researchers are developing tools to evaluate these non-traditional energy systems, building upon existing energy system planning tools and extending application to multi-output systems.
- Researchers need more accurate design and cost data to support analysis of technical and economic viability.
- Existing analyses do not point to major technology gaps, but there is a need to implement demonstration projects, initial deployments, and to work through licensing across multiple regulatory agencies for nuclear and industrial facilities.

Summary

Gilles Rodriguez introduced the panelists in turn. He also provided an overview of the concept of utilizing nuclear heat to support chemical processes, which requires R&D to be closely connected with industry.

Aaron Epiney, INL

- The timing of the opportunity and the motivation related to tackling climate change was noted, especially as electricity is a small component of the decarbonisation challenge.
- The importance of system modelling was highlighted, including modelling necessary to support technical and economic performance evaluation and to understand ownership models.
- INL has a set of analysis tools that comprise the Framework for Optimization of ResourCes and Economics (FORCE), all of which are available as open source (available here: https://ies.inl.gov). A recorded training session from 2022 for these tools is available as well (https://ies.inl.gov/SitePages/System_Simulation.aspx), with additional training sessions planned for 2023.
- There is a misconception that water-cooled reactors cannot produce sufficient heat for industrial processes. There are existing technologies that can augment heat to achieve the temperatures required for many candidate industrial processes.
- Modelling has been performed for nuclear-integrated hydrogen production and multiple end use scenarios. Multiple studies are available from reports available at https://ies.inl.gov, and additional analysis results will be published as they are completed. Additional case studies are being advanced for applications including nuclear-integrated synfuels production, carbon conversion, and energy storage.

- INL is advancing a physical integrated system setup to validate these models and to increase the scale of the demonstrated systems. This includes facility design for demonstration with micro reactor systems (e.g., the DOE-designed MARVEL microreactor and other industry-developed concepts) and implementation of these capabilities in the mid-2020s.
- Audience questions related to the benefits of coupling to thermal energy storage. Studies have explored this concept and found that there is a benefit to thermal storage to separate the nuclear island from the customer, and to address safety concerns for licensing.
- It was noted that there will be conflicting priorities for heat, between industry's needs and electricity demand. This will need to be managed as a system design and operation are optimized.

Ali Siddiqui, CNL

- Previous examples of nuclear heat use in Canada were highlighted, including building heat (1980s), heavy water production (1973-1998), and bulk steam (1972-2006).
- Relevant policy initiatives in Canada, including the *Hydrogen Strategy for Canada* and the *SMR Action Plan*, highlight the role of nuclear energy for non-electric applications.
- Previous and ongoing R&D initiatives have supported nuclear energy, the development of hydrogen rail fuel, maritime fuel from hydrogen, synthetic jet fuel for aviation, biofuels, and battery energy storage.
- Energy analysis and optimization tools are under development, including the Hybrid Energy System Optimization (HESO) model which includes electricity, heat, and hydrogen produced from a variety of energy sources under carbon emission constraints.
- Feasibility studies that can inform this work include work performed on:
    - Remote mining applications in the Canadian North,
    - Thermal energy storage in a nuclear-renewable hybrid energy system, and
    - The use of a SMR at Chalk River to reduce emissions from a Department of National Defense garrison by up to 50%.
- A demonstration platform is proposed for industry to test processes coupled to nuclear energy through the Clean Energy Demonstration Innovation and Research (CEDIR) Initiative.
- Audience questions raised the consideration that although there are no major technological gaps to coupling nuclear energy to industrial processes, initial deployments are required to demonstrate the licensing requirements. These demonstrations may be high risk.

Rob Arnold, BEIS

- The UK Government's approach to advanced modular reactor (AMR) R&D, feasibility studies, and development was introduced. The UK's Energy Innovation Programme (2016-2021), and the £12B revised 10-Point Plan UK Energy Strategy were both noted, which identify a role for nuclear energy and for AMRs to be used in decarbonisation.
- An energy white paper on "powering our net zero future" proposes how to:
    - Deliver on current commitments to build large nuclear power plants;
    - Deploy LWR SMRs by the early 2030s;
    - Demonstrate non-LWR AMRs in the early 2030s; and
    - Support commercial viability of fusion by 2040.
- The UK has also introduced an industrial decarbonisation strategy, where a Generic Design Assessment opened to SMRs and AMRs in 2021. In April 2022, the Rolls Royce SMR development team commenced first steps toward this assessment.
- Public discourse on modular nuclear technologies is advancing in the UK, where ~30% of the public are currently aware of SMRs, and common feedback includes a need for sufficient necessity, safety, and waste management processes.
- AMR feasibility and development is advancing in two phases:

    - Phase 1 (2016-2020) included feasibility studies of 8 AMR designs
    - Phase 2 (2022) aims to develop AMR designs, namely HTGR, LFR, and compact fusion.
- AMR R&D work is also advancing, with Phase A representing pre-feed studies to inform future work. There is an advanced fuel cycle programme that is progressing as well.
- During audience Q&A, Mr. Arnold confirmed that suitable sites have been identified for deployment of nuclear technologies by early 2030, leveraging existing sites.
- Modelling tools were also noted, including the TIMES techno-economic optimization model coupled with systems-based tools.

Hiroyuki Sato, JAEA

- JAEA has focused R&D efforts on HTGRs, including safety evaluations and coupling nuclear heat to high temperature applications, hydrogen production (utilizing the sulfur-iodine [S-I] process), and with chemical plants.
- Studies have explored thermal storage paired with a HTGR-renewable hybrid energy system.
- A study evaluating steel production using nuclear heat suggests that the steel plant could potentially reduce emissions by 100%.
- The High Temperature Test Reactor (HTTR) in Japan is the only prismatic HTGR in operation. Temperatures up to 950ºC are possible, and safety demonstrations are currently being pursued.
- Hydrogen production through the S-I process is also advancing, and the capacity and duration of operation has progressed over time.
- A HTTR heat application test began in 2022, with the goal to establish safety designs.
- Audience questions pointed to the fact that while energy end-users do not officially provide specific requirements to nuclear technology developers, a reference facility and desired temperatures are provided for assessment purposes.

Michael Futterer, EC

- The European Commission maintains an ambitious approach to reach net zero in Europe by 2050.
- Europairs, a study funded by the European Commission, concluded that 550ºC steam was very common, and a “low hanging fruit” for industrial decarbonisation.
- NC2I – a nuclear cogeneration European industrial initiative – aims to structure the R&D capabilities for delivering a demonstrator to meet market needs.
- Gemini is an international initiative. Gemini+ ended in 2021 confirming the feasibility of a demonstration facility. In the Gemini+ concept, the customer receives tertiary (waste) heat/steam, which corresponds well to existing demand for heat-dependent applications.
- Gemini 4.0 started in 2020, which includes both industrial and hydrogen end-users within scope. In Gemini 4.0, a series of technical work conducted with partners in Europe, Japan, and South Korea will advise and guide a technological approach.
- Inclusion of a secondary heat transfer loop to separate the nuclear island from the heat customer is likely ideal to improve safety and feasibility of coupled nuclear cogeneration.
- A HTGR demonstration in Poland was noted as important, and a persisting top national priority project since 2016.

Session 2 – Industry Panel

Panelists

- (Moderator) Diane Cameron, Nuclear Energy Agency
- Antonio Vaya Soler, Nuclear Energy Agency
- Jeremy Shook, Electric Power Research Institute (EPRI), (district heating)
- Bronwyn Hyland, The Pathways Alliance (Canada’s oil sands)
- Gautam Phanse, Chevron Technology Ventures (oil and gas sector)
- John Kutsch, Ammonia Energy Association (ammonia production)
- Gretchen Baier, Dow Chemical (chemical industry)

Key Findings from Session

- Several end-user companies (or consortia of companies) have initiated studies on the utilization of nuclear energy to support decarbonisation efforts.
- Industry is currently working to plan their means to achieve decarbonisation. If nuclear energy technologies have the potential to play a role, it is important for their capabilities to be highlighted now.
- Public announcements are coming forth, including:
    - An announced partnership between Dow Chemical and X-Energy
    - A request for information will be issued by Pathways Alliance in the near-term.
- Companies require reliable data (e.g., cost, performance, timeline to deployment) to support technology assessments.

Summary

Diane Cameron, NEA, delivered introductory remarks and introduced speakers to deliver opening statements.

Antonio Vaya Soler, NEA

- The importance of decarbonising non-electric applications in the context of international energy requirements was highlighted, suggesting that nuclear capacity should triple by 2050.

- While heat applications show compatibility with nuclear technologies, implementation is not straight forward. Dialogue with end users is essential to ensure the nuclear industry is sufficiently informed to capture market share for non-emitting heat.
- NEA techno-economic studies on applications of nuclear heat provide recommendations to:
    - Demonstrate the concept by supporting pilot projects where industrial players are involved,
    - Explore the competitiveness of nuclear-based options for non-electric applications,
    - Adopt a holistic approach with input from end-users throughout the design process, and
    - Enable policy frameworks, in part to build capacity and economic incentives.
- Relevant NEA reports to inform this analysis include:
    - *Role of Nuclear Power in the Hydrogen Economy* (www.oecd-nea.org/nuclear-hydrogen)
    - *Beyond Electricity: The Economics of Nuclear Cogeneration* (www.oecd-nea.org/cogen22)
    - *HTGRs and Industrial Heat Application* (https://www.oecd-nea.org/jcms/htr2022)

Jeremy Shook, EPRI (District Energy)

- District energy refers to district heating (steam or hot water), but also district cooling (chilled water) and district power (including emergency power). It is used when large buildings are close together, such as airports, universities, industrial complexes, etc.
- For these processes, reliability and resilience is critical, and markets are requiring decarbonisation.
- There is significant opportunity, and work by EPRI suggests that a large market already exists. There are also many challenges, including regulatory review and insurance.
- The NuIDEA (nuclear energy in district energy applications) project aims to develop a roadmap to enable nuclear energy as a viable option for district energy markets by 2026.

Bronwyn Hyland, The Pathways Alliance (Oil Sands)

- The Oil Sands Pathways to Net Zero Alliance represents six oil companies who are collectively assessing the viability of SMRs, and other clean energy technologies, to reduce emissions associated with in-situ oil extraction.
- In-situ mining requires pumping steam underground to recover oil. A reference facility requires 500 MWth at 330ºC and 10-14 Pa, and an additional 30 MWe. Total demand across the industry is 26 GWth for brownfield sites, and 47 GWth longer term potential in-situ projects.
- It is not obvious that SMRs are the answer to deliver this heat. Challenges include:
    - Social acceptance (e.g., the jurisdiction of Alberta currently does not have nuclear energy)
    - Economics with cost and schedule certainty; additional costs are expected in remote areas
    - Regulatory (challenges or uncertainties)
    - Technical feasibility (i.e., integration)
    - Nuclear waste management and storage.
- The Pathways Alliance requires good, detailed data to support their assessment. A Request for Information will be issued shortly, where the reference facility will be shared in hope that the Alliance can understand how to license and operate a SMR and how to integrate an SMR with their facilities.

Gautam Phanse, Chevron Technology Ventures (Oil and Gas)

- Chevron produces 3.1 M barrels of oil per day, and processes 1.8 M barrels of crude. They are involved in upstream, midstream, and downstream processes. Operations include deep water facilities.
- As Chevron operates around the world, they are interested in standardized energy solutions that can be licensed and deployed at various locations and environments.

- Chevron New Energies is growing low carbon businesses related to hydrogen; carbon capture, utilisation, and storage (CCUS); offsets; and other emerging energies.
- Chevron is intrigued in nuclear energy for decarbonisation opportunities, with particular interest in the potential for nuclear technologies to produce 550-600ºC process heat for steam-reliant operations.

John Kutsch, Ammonia Energy Association (Ammonia Production)

- The Ammonia Energy Association (AEA) is a global industry association that promotes responsible use of ammonia in a sustainable energy economy.
- Notably, AEA avoids the use of colour descriptors (i.e., green ammonia) and focuses instead on carbon intensity. They are moving towards a graded ammonia certification.
- AEA is a nuclear-positive organization, with a mission to decarbonize the ammonia cycle and improve the adoption of ammonia in energy markets. In spite of this, it was noted that it is difficult for the AEA to realistically consider nuclear energy given a range of uncertainties.
- Fertilizer production currently accounts for approximately 90% of the demand for ammonia, with the remainder associated with various industrial processes. Hydrogen is used to produce ammonia, and its production currently relies on steam methane reformation.
- Nuclear energy will need to become an economically competitive option (subsidy free) capable to support the development speed and scale of ammonia production.

Gretchen Baier, Dow Chemical (Chemical Industry)

- Dow Chemical is the largest US chemical producer, with global operations.
- Dow's operations are varied, and manufacturing sites have unique needs. For example, the needs for ethane cracking are distinct from ethylene production.
- Dow Chemical has targets to achieve carbon neutrality by 2050, while driving growth. They have publicly identified nuclear energy as an option to support this goal.
- Dow Chemical currently supplies hydrogen to industry through two mechanisms:
    - Ethane cracker ($C_2H_6 \rightarrow C_2H_4 + H_2$), producing C_2H_4 and hydrogen (H_2) at a massive scale
    - Electrolysis to produce chlorine and bromine, where hydrogen is a by-product.
- Reliability of energy supply is critical to Dow, as their operations would likely not tolerate even seconds of down time.
- Cogeneration at 850ºC currently relies on natural gas, and it is not clear that nuclear energy can address this and other high temperature heat needs. It was noted that nuclear energy is not always a suitable replacement for direct fire needs.

Audience Questions and Discussion

- Steam reformation of methane with CCUS is the leading competitor to implementing nuclear energy, and specifically SMRs, in these industrial applications. Uncertainties related to integration and the associated costs are current barriers.
    - Notably, there are geographic considerations related to the use of CCUS for sequestration.
- The most significant items to help end-users implement nuclear energy include:
    - Sharing of high-quality data, with costing information, which they need to assess the viability of these technologies. Likely required to build physical systems to generate the required data.
    - An improved understanding of regulatory and waste management processes.
- Panelists agreed that the use of hydrogen for industrial decarbonisation might be over emphasized at present, and that it is important to focus on the larger opportunity.

- An audience question raised the point that it is much less costly to make heat than electricity with a nuclear system. Participants were encouraged to revisit industrial processes that would utilise lower steam temperatures.
- Industrial end users are very interested in piloting technologies to explore the integration of nuclear energy in their operations, but simultaneously are not ready to support a demonstration directly. Adoption would be facilitated by requiring ready-to-deliver solutions from nuclear technology vendors or third party operators.

Session 3 – Advanced Reactor Panel

Panelists

- (moderator) Aiden Peakman, UK National Nuclear Laboratory
- Katherine Moshonas Cole, X-Energy Canada
- David LeBlanc, Terrestrial Energy
- Tim Abram, U-Battery
- Dominick Claudio, NuScale Power
- Cristian Rabiti, Ultra Safe Nuclear Corporation
- Patrick Alexander, TerraPower

Key Findings from Session

- Most nuclear technology vendors include hydrogen production capabilities in their specifications.
- Energy storage (e.g., by molten salt) for flexible response to heat demand fluctuations and for separation of nuclear and conventional plants is included in many designs, which could facilitate integration with industrial processes.
- Uncertainties exist related to cost, licensing status, and other performance data.

Summary

Cristian Rabiti, Ultra Safe Nuclear Corporation (HTGR)

- The HTGR technology is very well known, and there are significant benefits to the TRISO fuel concept, including providing enhanced safety.
- Characteristics of Ultra Safe Nuclear Corporation's Micro Modular Reactor (MMR) technology include:
    - HTGR system
    - A 20-year fuel cycle, depending on the capacity factor
    - Includes a molten salt thermal storage reservoir. Commercial salt stores heat at 550ºC where the MMR core output is in the range of 600-650ºC.
- Two upcoming MMR deployments:
    - Chalk River, Canada, aiming for operation by 2026
    - Illinois, United States, aiming for operation by 2027.

Katherine Moshonas Cole, X-Energy (HTGR)

- X-Energy is advancing multiple HTGR technologies:
    - The Xe-100 design would provide 80 MWe, and is expected to be used in a 4-pack
    - Xe-Mobile development was initially driven by defense applications, which the company aims to repurpose for civilian use.
- These technologies feature a design life of 60 years, with refurbishment scheduled at 30 years, required mostly because of the graphite material.
- Questions remain on how the technologies should be most efficiently integrated into industrial applications.

David LeBlanc, Terrestrial Energy (MSR)

- Terrestrial's Integral MSR (IMSR) is based on demonstrations dating back to the 1960s.
- The IMSR features:
    - 822 MWt (390 MWe when operating at 100% electric) twin facility requiring <7 hectares of land
    - Primary salt coolant, with secondary and tertiary salt loops (585ºC, solar salt), which enables separation of the nuclear island from the heat facility, and steam can be transported multiple kilometers
    - A 7-10 year lifetime limited by graphite material
    - Potential to use <5% enriched fuel, avoiding potential supply constraints of High-Assay Low-Enriched Uranium (HALEU).
- The IMSR team is pursing discussions directly with other industrial end-users, instead of engaging utilities.
- Terrestrial Energy sees a role for hydrogen and ammonia production from nuclear energy with multiple potential production pathways:
    - From water: High-Temperature Steam Electrolysis or a Cu-Cl cycle, which could produce 235-265 tonnes/day compared to 179 tonnes/day for conventional electrolysis
    - From gas: Nuclear-assisted steam methane reforming with CCUS (1800 tons/day H_2)
    - From methane: Methane pyrolysis (1500-2500 tonnes/day H_2).

Tim Abram, U-Battery (HTGR)

- UK industrial energy usage is on the order of 300-400 TWh/year of process heat.
- Characteristics of the U-Battery concept include:
    - 10 MWt prismatic core HTGR with 750ºC outlet temperatures
    - Helium-cooled, graphite moderated, with a 30-year design life.
- U-Battery is focused on taking required steps to integrate technology with industrial end users.
- Targeting heat applications, U-Battery is focused on delivering a first-of-a-kind (FOAK) unit by the late 2020s, potentially at Urenco UK Limited's nuclear licensed site at Capenhurst in Cheshire.

Dominick Claudio, NuScale Power (LWR)

- NuScale's reactor technology features:
    - 250 MWth/module, translating to 77 MWe with 100% steam bypass when electricity is not needed
    - Can be deployed in multi-unit plants (e.g., 4, 6, or 12 pack of modules)
    - 60-year design life
    - LWR fuel and reactor concepts, which are currently well understood by regulators.
- NuScale extensively reviewed constructability during the design phase.
- NuScale is advancing cogeneration studies, including with a focus on coupling with an oil refinery, desalination plant, and high temperature steam electrolysis for the production of hydrogen.
- Notably, by using a 2% electrical feedback, NuScale's outlet steam temperature can be increased from 300ºC to 850ºC.

Patrick Alexander, TerraPower (SFR)

- The 345 MWe Natrium reactor features:
    - Sodium cooling

  - 14-acre footprint
  - Nuclear Island separation via intermediate loops and thermal storage, with steam bypass to further isolate energy users
  - Walk away safety and below-grade siting of the reactor core.
- Variable size storage tanks are being considered based on application needs.
- TerraPower is targeting construction by 2026.

Audience Questions and Discussion

- SMR vendors acknowledge that industrial end users do not want to operate the nuclear assets and are considering this in their business operations.
- With regard to costs, SMR vendors are working towards moving components outside of the nuclear island where possible to reduce costs and enhance cost certainty. Robust costing will also be informed by advancing the respective demonstration projects.
- Multiple vendors asserted that public acceptance, and ongoing engagement with communities, is critical for adoption.
- Engagement with regulators is also viewed as critical. Ensuring regulators have high quality data is expected to reduce timelines associated with the adoption of heat applications for nuclear energy.
- SMR vendors believe advanced reactors will be competitive with alternatives, but there is a need to translate the benefits from nuclear energy into monetary terms in order to support competitiveness.
- Potential fuel supply constraints were noted, as many SMR systems based on generation IV technology will rely on high assay low enriched uranium (HALEU).

Moderated Discussion

Moderator

- Shannon Bragg-Sitton, NEANH TF Chair

Key Findings from Session

- Thermal energy storage increases both flexibility and process compatibility.
- Vendors are adopting design approaches to make the secondary circuit and balance of plant non-safety significant; this also facilitates integration and reduces interference, improving the safety cases.
- End-users do not want to operate nuclear reactors; partnership with utilities is required.
- Key stakeholders that should be a part of the conversation were not in attendance at the workshop (e.g., licensees and regulators, both nuclear and for industrial processes).
- Timeliness of nuclear energy solution is critical to their adoption, recognizing the necessity to align investment cycles and expectations.

Summary

- Thermal energy storage can provide significant benefit by isolating the customer from the nuclear island. Heat loss in transporting thermal energy can be effectively managed through engineering design; 1-2 miles is feasible, and greater distances are currently being investigated.
- Related to sharing data, stakeholders were encouraged to find a way to overcome issues with proprietary data, as detailed costing and technical information is required both for research and eventual adoption of these advanced technologies.
- There is a need to demonstrate to regulators that the customer can be isolated from the nuclear island, and the safety of the nuclear reactor operations can be decoupled from the industrial application.
- There may be a role for micro reactors to demonstration and test integration of nuclear energy with industrial end users.
- It was noted that key stakeholders were missing in the discussion, specifically:
    - More regulators should be engaged, including both nuclear and industrial regulators (e.g., for a chemical facility)
    - Licensees who are responsible for proving the safety case to the regulator, and to build and operate the plants and supply heat to the end users.
    - Representatives from the mining sector, where there is an opportunity for remote mining operations to benefit from SMRs.
- The audience noted that it would be useful to inventory the risks and uncertainties that exist for this opportunity, including the need to discuss nuclear waste management strategies early.
- High quality data is key. There is a critical need to demonstrate the advanced nuclear technologies, as implementation will aid in overcoming current uncertainties.
- Control room management needs to be considered, including who owns the heat and who dictates how it gets used.
- The opportunity for nuclear energy was reiterated, including the importance of reliability to industrial end-users. The potential for adoption of nuclear energy will depend on the application.

Next Steps for the NEANH Task Force

Actions for the NEANH Task Force

For Discussion

- Facilitate early interaction between nuclear and conventional regulators; ensure regulators are engaged as early as possible.
- Evaluate drivers outside North America (e.g., energy security, more stringent emission caps).
- Aim to include the mining industry in future engagements.
- Facilitate familiarizing end-users with nuclear energy such that end-users feel as comfortable with nuclear as they do with CCUS, or other competitors.
- Engage a variety of regulatory bodies, including industrial end-users which may not have familiarity interacting with the nuclear industry.

APPENDIX

APPENDIX A – Presentation Slides

Concept Overview – Moderator and Chair: Shannon Bragg-Sitton (Idaho National Laboratory, United States of America)

- Overview of "Non-Electric Applications of Nuclear": History, current status and paths forward, Ramesh Sadhankar (Department of Natural Resources, Canada)

Research Panel - Moderator: Gilles Rodriguez (CEA, France)

- Modeling and Simulation and Experimental Systems Development under the DOE Office of Nuclear Energy Integrated Energy Systems Program, Aaron Epiney (INL, United States of America)
- Canadian Overview, Ali Siddiqui (CNL, Canada)
- UK Research and Development Overview, Rob Arnold (BEIS, United Kingdom)
- JAEA R&D Overview, Hiroyuki Sato (JAEA, Japan)
- GEMINI 4.0 Project, Michael Fuetterer (JRC, European Commission, Netherlands)

Industry Panel - Moderator: Diane Cameron (OECD Nuclear Energy Agency, Canada)

- Scene-setting: techno-economics of non-electric applications, Antonio Vaya Soler (OECD/NEA, France)
- Chemical Industry, Gretchen Baier (Dow Chemical, United States of America)
- Oil sands industry, Bronwyn Hyland (The Pathways Alliance, Canada)
- Oil and gas refineries, Gautam Phanse (Chevron Technology Ventures, United States of America)
- District energy, Jeremy Shook (EPRI, United States of America)
- Ammonia productions, John Kutsch (Ammonia Energy Association, United States of America)

Advanced Reactor Panel - Moderator: Aiden Peakman (UK National Nuclear Laboratory)

- Ultra Safe Nuclear Corporation presentation, Cristian Rabiti (HTGR)
- X-Energy Canada presentation, Katherine Moshonas Cole (HTGR)
- Terrestrial Energy presentation, David LeBlanc (MSR)
- U-Battery presentation, Tim Abram (HTGR)
- NuScale Power presentation, Dominick Claudio (LWR)
- TerraPower presentation, Patrick Alexander (SFR)