INL/EXT-21-65505

Nuclear Fuel Cycle and Supply Chain (NFCSC) Technical Monthly October FY-22

October 2021

Changing the World's Energy Future

Idaho National Laboratory

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Idaho National Laboratory
Idaho Falls, Idaho 83415

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CONTENTS

FIGURES

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1. ADVANCED FUELS CAMPAIGN (AFC)

1.1 ATF Lab Activities

1.1.1 ATF Core Materials

[LANL] Work is underway to prepare the bulge test samples through drilling down to the Cr/Zircaloy interface to lead to the L2 milestone. Preliminary characterization shows satisfactory preparation.

1.1.2 ATF Irradiation Testing

[INL] ATF-2C design, fabrication, and pin inspection activities continued to support experiment insertion in the Advanced Test Reactor 2A Loop during Cycle 171A ~ May 2022. ATF-2C will consist of four tiers. The bottom tier (Tier 1) will include SiC clad pins with surrogate Mo/W fuel pellets, Tier 2 will include Framatome fueled pins, Tier 3 will include SiC clad pins with surrogate Mo/W fuel pellets, and the top tier (Tier 4/5/6) will be Mitsubishi developed alloy clad UO_2 pins, with temperature and pressure sensors.

[ORNL] A report titled "Accident Tolerant Fuel SiC/SiC Composite Technology Development: Phase II-b Summary" (ORNL/LTR-2021/2310) was submitted to Westinghouse Electric Company and General Atomics.

This report summarizes accomplishments on the development and evaluation of SiC-based accident tolerant fuel cladding technologies for the LWR applications. The highlights include demonstration of the exceptional high-temperature burst resistance and grid-to-rod fretting performance of the SiC/SiC composite tubes and the completion of neutron irradiation of the SiC/SiC composite cladding for investigating a bowing behavior under a fast neutron flux gradient. The research confirmed that a loss of leak tightness due to irradiation under a high heat flux still is a critical concern for the uncoated ceramic cladding. This report also summarizes recommendations for the future development.

1.1.3 ATF Safety Testing

[INL] Preliminary models for select ATF-2 irradiations were developed.

1.1.4 ATF PIE

[INL] Modeling of the ring hoop tension tests is being coupled to the experimental campaign currently in progress on ATF claddings. Finite element analysis and modeling helps in determining the influence of experimental parameters and test geometry on the resulting tensile property of the ATF material. Figure 1 is an example of the plastic strain distribution in the samples using two different test geometries. The configuration with two hemispherical mandrels is shown on the right, while the configuration with the insert between the mandrels is shown on the left.

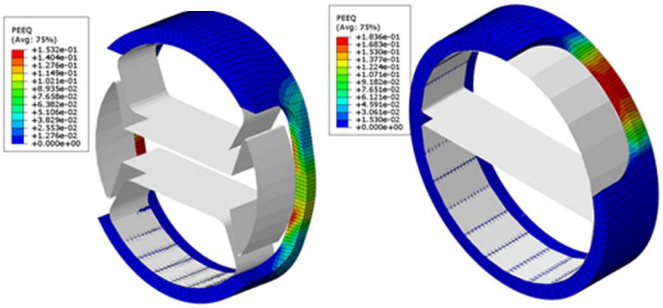

Figure 1. Example of the plastic strain distribution in the samples using two different test

1.2 Advanced Reactor Fuels

1.2.1 AR Irradiation Testing

[INL] The FAST-1 assembly recovery work for the outboard-A group of capsules continues with weld development and facility preparations in EFF. Circumferential welding parameters are finalized. One final test weld in the glove box is required prior to start of bottom end-cap welding. The seal weld parameters using the Weld Under Pressure System are still in development with finalized parameters expected next month.

All but two FAST-1 capsules remain in ATR canal storage during the ATR CIC outage. Irradiation preparations will begin at the end of the outage. Preparations work for cycle analyses have started as the project has experienced some turnover of individual contributors.

PIE work in HFEF remains on-going with radiography in NRAD performed on AFC-4C and AFC-3F specimens. AFC-4C and AFC-3F capsules are now in storage. JFCS AFC-IRT-1 C3 & C4 will undergo NRAD and PGS early in the year. Closeout reports will be finalized and the JFCS support will be concluded. After FAST-1 capsules were disassembled in late September, NRAD and gamma scanning of FAST-1 rodlet specimens were started and these are expected to continue through early next calendar year.

[INL] The MFF3 MNT-44Z sample was polished and marked to begin collecting data for thermal conductivity using the thermal conductivity microscope. This sample is an irradiated cross-section from the lower end of the experimental pin, therefore, having a lower temperature during irradiation.

1.2.2 AR Safety Testing

[INL] The THOR-C-2 capsule is fabricated and awaiting assembly. THOR-C-2 LVDT calibration has commenced will finish in the coming weeks. Preparations are underway in HFEF to handle the THOR

capsule and is ahead of schedule concerning design. This is in large part due to preliminary work we have done with the current THOR capsule design and including HFEF early in the design process.

1.3 Capability Development

1.3.1 TREAT LOCA Testing Infrastructure

[INL] The preliminary design analysis was completed, and the preliminary design review was held for the Transient Water Irradiation System for TREAT (TWIST) capsule.

1.3.2 Refabrication and Instrumentation Capability

[INL] A kickoff meeting was held to discuss scope, objectives, and expectations for the year.

For more information on Fuels contact Steven Hayes (208) 526-7255.

2. MATERIAL RECOVERY AND WASTE FORMS DEVELOPMENT

2.1 Accelerated EBR-II Processing

[INL] No processing updates for October due to a routine facility maintenance outage.

2.2 Zircex

[INL] The Material Recovery Pilot Plant continued final preparations to bring fuel to CPP-653 and initiate unirradiated fuel runs. These final preparations include revisions to the laboratory instructions, securing the facility by issuance of the security plan, mock-ups, installing vessel lids that were designed for rad work, and finalizing the radiological work permit. With completion of these actions, fuel transfers can begin in November followed by the first instantaneous reaction rate test.

The alternate chlorination studies project has begun establishing work controls for safe handling of the chemicals to be irradiated. Once these controls are established testing can commence.

[INL] Initiated EWR with Walsh Engineering to complete a conceptual design of an enclosure for the system. Working on sending online instrumentation to PNNL to help with setup.

[INL] Started conceptual design for the system to load an ATR element into the Hydrochlorinator.

[ORNL] The milestone M3FT-21OR030106025, "Oak Ridge National Laboratory Fission Product Hydrochlorination," is complete. Three tests were performed investigating the volatility and transport of fission product simulants in a hydrochlorination reactor. The simulants were chosen to represent the major classes of semi and non-volatile fission products in abundances typical of high burnup fuel. The fission product volatilities were tested in flows of HCl(g) at 200 and 350°C, in the presence of aluminum and zirconium, respectively. The results indicate that for some of the fission products studied, tin molybdenum, and tellurium, enhanced volatility was observed in the presence of the cladding materials. Further experiments are recommended to assess the underlying phenomena and to assess the relevance to processing of spent fuel. The report is undergoing internal sensitivity review before it can be released and uploaded into PICS. The status was updated Oct. 29, 2021.

The activity to provide nuclear chemistry and chemical engineering technical consultation and support to INL in the design of a modified direct denitration (MDD) process is complete. The status of the project was updated on Oct. 15, 2021.

2.3 Waste Forms & Off-Gas Capture

[ANL] Separate activities will (1) develop a new test method that combines electrochemical and waste form immersion techniques to characterize degradation behaviors of silica aerogel and mordenite-based iodide waste forms behavior to parameterize the conceptual degradation model, (2) use several test methods to parameterize the degradation model for a reference iron phosphate waste form, and (3) produce salt used to generate iron phosphate waste forms for testing.

[ORNL] The milestone M3FT-21OR0301031, "Produce and Characterize Metallic Waste Form for Molten Salts," is complete. Several metallic waste forms containing different loadings of fluoride salts were produced via cold pressing and sintering, after which they were analyzed to determine their chemical and physical properties. Pellets were pressed between 30,000 and 40,000 psi, sintered at 800-900ºC for 5-6 hours, and contained 10-40% UF_4. Overall, pellet analysis showed favorable qualities for a stable waste form, however, some uranium migration was observed. Further experiments are recommended to determine method of uranium migration, and whether hot isostatic pressing can alleviate

this problem. The report is undergoing internal sensitivity review before it can be released and uploaded into PICS. The status was updated Oct. 29, 2021.

M3FT-21OR03010402. Effects of voloxidation process conditions on the properties of organic-soluble uranium species. Due 11/30/2021. M3FT-21OR03010402 is on track. We sent samples off for SEM, pXRD, and ICP-MS analysis this week and are working on the report. The status was updated Oct. 29, 2021.

2.4 Simplified Single Cycle

[ANL] Two new functional enhancements were made to AMUSE. (1) AMUSE can now read and populate the front-end input page using the XML flowsheet specification file directly, avoiding the need to convert XML flowsheet files to XLS format prior to import. This capability permits users to modify existing flowsheet parameters directly. (2) A software utility to compare AMUSE reports when doing parametric studies was modified to enable comparison of multiple reports. The improved utility recursively prompts the user for the report files. Individual graphs containing aqueous and organic concentrations for each component are created, and the graph reports need not contain identical sets of components or stages.

[INL] No significant highlights for October. α/β-Discrimination liquid scintillation counting (LSC) was evaluated as a method for determination of liquid-liquid distribution of Tc-99 in samples containing large quantities of depleted uranium. The Tc distribution values obtained using a calibrated LSC discrimination protocol statistically match those obtained using γ spectroscopy with Tc-99m radioisotope. The Tc-99 activity in β window must be corrected for the activity contribution from depleted uranium as obtained in the preliminary distribution studies. The results suggest LSC is an appropriate analytical tool for screening of Tc distribution in liquid-liquid systems containing large quantities of uranium.

[ORNL] Extensive literature search on three topics: (a) use of monoamides for U and Pu extraction, b) use of ureas for U and Pu extraction, and c) selective recognition of pertechnetate in aqueous solutions) has been carried out to design and identify optimal ligand systems for further investigation. The ORNL and INL team members recently had a meeting during which they selected the list of ligands (neutral extractants and masking agents/aqueous holdback agents) for the initial investigation, agreed on the controls and set of experimental conditions that will be used, and identified the specific areas where computational input would be extraordinarily informative and helpful. Both ORNL and INL teams are set to meet on a regular basis. Synthesis of two neutral extractants on >20 g scale has been initiated.

2.5 Pyro/Molten Salt Processing

[ANL] Two separate activities will (1) demonstrate efficient drawdown of lanthanides for disposal and purification by applying recent advances in electrolysis using solid cathodes and (2) develop a robust reference electrode for use in process salts to improve the monitoring and control of pyrochemical operations supporting electrorefining and deposition efficiencies and product quality.

[INL] Design activities for a U/TRU co-deposition assembly for the kg-scale electrorefiner at INL were initiated. Existing cathode assembly geometry will be used where applicable to facilitate quick development of the design. A progress report summarizing the work to-date and future plans for filtered salt sampling technology development was prepared and a memo documenting its completion was submitted to PICS to satisfy milestone M3FT-22IN030102029. Initiation of several other activities associated with actinide oxide and oxychloride molten salt chemistry also took place, including quantitative analysis technique method development and re-chlorination studies.

[INL] No significant experimental progress was made in October. Plans are being formulated for the replacement of the electrorefiner heater elements in HFEF. Progress towards finalizing the JFCS Annual CRADA report was made in October.

2.6 Innovative Aqueous Separations

[INL] A manuscript entitled, "Influence of uranyl complexation on the reaction kinetics of the dodecane radical cation with used nuclear fuel extraction ligands (TBP, DEHBA, and DEHiBA)" was published in the Royal Society of Chemistry (RSC) journal *Physical Chemistry Chemical Physics* (PCCP, impact factor = 3.676 in 2020 Journal Citation Reports, Clarivate Analytics, 2021): https://doi.org/10.1039/D1CP03797H.

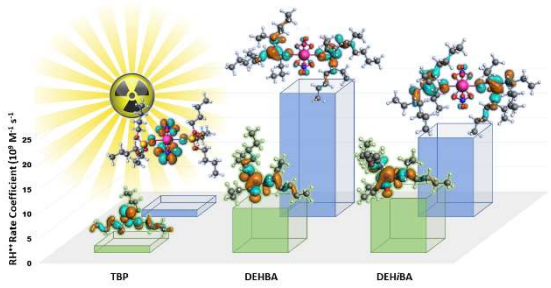

Figure 2**.** Changes in radiation-induced dodecane radical cation reaction kinetics of tributyl phosphate (TBP), N,N-di-(2-ethylhexyl)butyramide (DEHBA), and N,N-di-2-ethylhexylisobutryamide (DEHiBA) in the presence and absence of uranyl complexes as measured by pulsed electron radiolysis and evaluated electronic structure calculations.

This publication was produced as part of the work supported by Milestone M3FT-21IN030101026, "Effect of Metal Ion Complexation on the Radiolysis of TBP and Monoamide Extractants."

2.7 Innovative Salt Systems

[ANL] Separate activities will, (1) develop advanced electrochemical techniques to chlorinate actinide-bearing metals and oxides, including oxide management in closely coupled systems, and (2) develop advanced on-line monitoring capabilities that improve electrorefining efficiencies and control the composition of deposited metals and alloys.

[INL] In October, the literature review on continuous uranium removal options was initiated. Guoping Cao generated slides to lead a technical survey meeting in November to evaluate options with a team of experts. Additionally, Kevin Tolman prepared the salt crystallization hardware in a non-radiological facility glovebox in preparation for initial tests on LiCl-KCl molten salt. (S. Warmann)

[ORNL] In the reported period, the experimental study of lanthanide oxide solubility in molten alkali chloride salts was started. Particularly, electronic absorption spectra of a KCl-MgCl2 melt containing Nd2O3 were collected. The measurements were caried out at 800C. It was shown that Nd2O3 has no solubility in pure KCl melt. However, the addition of even small amounts of MgCl2 to the KCl-Nd2O3

mixture leads to the appearance of absorption peaks of Nd3+ species. Increasing the amount of MgCl2 results in an increasing concentration of Nd3+ in the melt. (S. Mahurin)

For more information on Material Recovery and Waste Forms Development contact Ken Marsden (208) 533-7864.

3. MPACT CAMPAIGN

3.1 Campaign Management

3.1.1 NTD & Management Support

[LANL] NTD and CAM worked to align actual carryover numbers to the respective work packages. Efforts continue to coordinate the stakeholders' meetings, which will be used to inform near-term and future MPACT R&D efforts. These meetings will take place in early December.

3.2 Front-End Domestic Safeguards

3.2.1 NMAC Training

[LANL] A kickoff meeting was held with LANL, SNL, and BNL to discuss the overall goals of the project and create a path forward for the assessment of training gaps and areas of improvement. The team outlined the need to identify training requirements as specified in regulations, best industry practice, and actual tasks performed by facility personal. The team will work to create a list of NRC and industry professionals to interview.

3.3 Back-End Domestic Safeguards

3.3.1 Electrochemical & Aqueous Spike-based Reprocessing NMAC

[INL] The last radioactive tracer dilution experiment was completed. All of the salt samples taken during the experiments are in the containers and ready to be transferred to analytical laboratory. However, the HFEF hot cell has maintenance issues. So, the salt samples are expected to be transferred in January 2022. Paperwork for the sample transfer is being prepared. A draft manuscript on the analysis of gamma spectroscopy for salt mass determination has been completed. It will be submitted to Journal of Radioanalytical and Nuclear Chemistry after the INL review is completed.

3.3.2 Electrochemical & Aqueous Reprocessing Acoustic Interrogation

[LANL] Work focused on prototype development. Testing on a second generation prototype unit has begun, with focus on using a standardized sample geometry to enable physical property measurements of solutions.

3.3.3 Molten salt PM/NMA

[ANL] Coordination with INL regarding FY22 testing has taken place. An alternate approach to remote operations has been identified due to the deprecation of the previously-used remote desktop program. Plans for transfer of data from the final FY21 measurement campaign have been initiated.

[INL] Worked on calibrating the Ta bubbler tubes built at the end of FY21.

3.3.4 Reprocessing Sampler

[ANL] Uranium bearing salt sample pellets were generated from Argonne's co-deposition electrorefiner for distribution to LANL to support their microcalorimeter development work.

3.3.5 Reprocessing Modeling

[SNL] Continuing development of the Zircex model.

3.3.6 Microcalorimetry

[LANL] Upgraded intermediate-frequency multiplexing electronics were installed on the INL spectrometer to replace the setup used for initial testing with the first detector module. The upgraded electronics provide the increased bandwidth needed to operate all four detector modules simultaneously. A source of low-frequency noise in the detector signal that is associated with the pulse tube cryocooler has been identified. The next steps will be to conduct additional testing to understand this problem, and redesign the detector mounting bracket to provide additional vibration isolation if needed.

[INL] Preparation work to ensure there is lab space and infrastructure to receive the instrument from LANL.

For more information on MPACT contact Mike Browne at (505) 665-5056.

4. SYSTEMS ANALYSIS AND INTEGRATION (SA&I) CAMPAIGN

4.1 CAMPAIGN MANAGEMENT

[ANL, INL] Completed the modifications to the Campaign work packages to incorporate the carry-over funds and establish activities for the funds. All the work packages have been submitted and approved.

[ANL, INL] Provide review comments to the nuclear supply chain document being coordinated by GAIN/NRIC for DOE NE.

[PNNL] Contributed to INL-led report on estimation of HALEU requirements for decarbonization of US power sector.

4.2 NUCLEAR ENERGY SYSTEM PERFORMANCE (NESP)

4.2.1 Scenario Analysis and Technology Roadmap Studies of Fuel Cycle Facilities for Demonstration Reactors

[PNNL] In the process of planning analyses for US and Global nuclear energy response to evolving climate change policies. Expanding PNNL GCAM modeling capability to address flexible nuclear power operations and production of nuclear hydrogen and heat for greater nuclear energy utilization.

[ANL, BNL, INL, ORNL] The national team for the transition scenario study developed work plans to identify nuclear fuel cycle facilities needed for large-scale deployment of ARDP reactors based on decarbonization goals, including the potential evolutionary fuel cycles from the reactor systems and technology roadmap.

[BNL] Supported ANL Lead on “Scenario Analysis”.

[ORNL] Attended initial meetings and had discussions with colleagues from ANL, INL and BNL regarding our deliverables for this fiscal year.

4.2.2 Investigate Benefits and Challenges of Converting Retiring Coal Plants into Nuclear Plants

[INL, ANL, ORNL] Assigned staff at INL met with counterparts at partner labs (ANL, ORNL). Discussed work scope content, applicable literature, and path forward. Met with researchers at INL working in this area. With staff from partner labs, discussed expertise and how best to use it execute scope.

[ORNL] Prepared a geographic information system (GIS) review of the 4 coal plant sites of interest to TerraPower in Wyoming using OR-SAGE. A draft letter report was prepared to document the OR-SAGE analysis of the 4 sites. Initial discussions were held with INL on investigating the benefits and challenges of converting retiring coal plants into nuclear plants in the US. This initial discussion with INL also included a presentation on OR-SAGE.

4.2.3 Nuclear Roles for Electricity Market Reliability in Deep Decarbonization Scenarios

[**ANL, BNL, INL]** The national team for this activity developed work plans to examine the reliability and resilience benefits of nuclear power in deeply decarbonized electric grids. The work plans will focus on the reduction of energy distribution disruption risk in severe weather events (such as the cold event in Texas in February 2021) and the role of nuclear power to reduce system-cost. The grid model will be developed based on historic severe weather events and the roles of nuclear power will be analyzed for a deep decarbonization scenario.

4.2.4 Develop Fuel Cycle Data Packages and Update/Maintain of Nuclear Fuel Cycle Options Catalog

[SNL] We continued to investigate temporary options for moving the Nuclear Fuel Cycle Options Catalog to the cloud. We also worked on getting the "Evaluate My Option" webpage, which requires some programming and logic, to work using the tools we think will be available in the cloud environment. The issue with accessing the database from the development (non-public) side was resolved and data entry and checking has resumed.

4.2.5 Quick Turn-Around Studies

[INL, ANL] Developed a laboratory report on "Advanced Nuclear Reactors and HALEU Requirements to Support Decarbonization of the U.S. Energy Sector," INL/EXT-21-64913. A whitepaper on the HALEU requirement to support advanced reactor deployment, issued in April 2021, was revised and transformed into the INL regular report to enable citation in the future.

4.2.6 Support DOE NE in International Engagements

[**ANL]** Participated in the 4th Scientific Advisory Committee meeting (virtual) of the 16th Information Meeting on Actinide and Fission Product Partitioning and Transmutation (16IEMPT), on October 22, 2021. The 16-IEMPT will be held on 26-30 June 2022 in Saint Petersburg, Russia, hosted by Rosatom. Discussed potential panelists in the opening session and track leaders.

[BNL] Provided input to the author of the "ADS Transmutation Systems" chapter of the NEA High-Level Report on the status of work on ADS in the US.

[BNL] Participated in the 6th Meeting of the "NEA Task Force on the Demonstration of the Fuel Cycle Closure Including Partitioning & Transmutation for Industrial Readiness by 2050" on October 7, 2021.

4.2.7 Fuel Cycle Analysis to Support Technology Campaigns

[**ANL, INL, ORNL]** Exchanged emails with the Integrated Waste Management (IWM) campaign leadership for the collaboration tasks between SA&I and IWM campaigns, which include exchanging information on high-level fuel cycle strategies discussed by industry/DOE, sharing user experience on OR-SAGE and other tools, and coordinating relevant activities during regular meetings between SA&I and IWM staff.

[SNL] We searched for and collected information regarding disposal costs associated with repositories and the variables that have the most influence on disposal cost.

4.3 ECONOMIC AND MARKET ANALYSIS FOR NUCLEAR ENERGY SYSTEMS (EMANES)

4.3.1 Pros and Cons Analysis of HALEU Utilization in Alternative Fuel Cycles

[ANL, BNL, INL, ORNL] The national team developed work plans to evaluate the pros and cons of HALEU utilization in once-through versus continuous recycle fuel cycles. Both front and back end fuel cycle supply chains and costs will be evaluated, including potential technical issues on the reuse of HALEU UNF.

[ORNL] Performed economic evaluation of extended burnup and HALEU fuel to study the economic driver as well as other implications using G4Econs. The discharge burnups for the HBU/HALEU fuel is based on models set up with Polaris developed as part of the MegaSCALE project at ORNL.

4.3.2 Costing and Techno-economic Assessment Automation

[**ANL]** Hired one post-doc to support campaign activities and to initially convert the ACCERT algorithms for cost assessment into a computation software.

4.3.3 Cost Basis Report Improvement/Update

[INL] Team from INL and partner labs met to discuss work scope activities for FY22. Team discussed each of the 5 tasks in this activity and made assignments based on team members' expertise. Continued work of technical updates to modules, coordinating reviews and publishing to website.

4.3.4 Risks of Market-Driven Nuclear Power Plant Closures

[**ANL, INL**] The national team developed work plans to update the potential government incentives to support struggling nuclear plants in highly competitive energy markets. The revenue and expense data of nuclear plants will be updated, and the opportunity cost of supporting existing nuclear plants to accelerate decarbonization will be analyzed.

For more information on Systems Analysis and Integration contact Temitope Taiwo (630) 252-1387.

5. AFCI-HQ PROGRAM SUPPORT

Site: University Research Alliance at West Texas A&M University in Canyon TX, and the following universities: Purdue University, Massachusetts Institute of Technology, Georgia Institute of Technology, Pennsylvania State University, North Carolina State University, University of Tennessee at Knoxville, Washington State University, Colorado School of Mines, University of California at Santa Barbara, University of South Carolina, University of Central Florida, Clemson University, Virginia Commonwealth University, Air Force Institute of Technology, University of Michigan, University of Texas at Austin, Coastal Carolina University, Missouri University of Science and Technology, University of Illinois at Urbana-Champaign, and other universities.

Universities engaged in Nuclear Technology research via URA programs since 2001:

Boise State University
Boston College
Clemson University
Colorado School of Mines
Columbia University
Georgia Institute of Technology
Georgetown University
Idaho State University
Florida International University
Florida State University
Kansas State University
Massachusetts Institute of Technology
Missouri University of Science and Technology
North Carolina State University
Northern Illinois University
Northwestern University
Ohio State University
Oregon State University
Pennsylvania State University
Purdue University
Rensselaer Polytechnic Institute
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University of New Mexico
University of North Texas
University of Notre Dame
University of Ohio
University of South Carolina
University of Tennessee at Knoxville
University of Texas at Austin
University of Toledo
University of Utah
University of Virginia
University of Wisconsin
Vanderbilt University
Virginia Commonwealth University
Washington State University

5.1 Innovations in Nuclear Technology R&D Awards

5.1.1 University Programs

5.1.1.1 Summary Report

University Research Alliance provided information to the 2021 First Place winners of the Innovations Awards, and worked with the award winners and the American Nuclear Society on the Innovations in Nuclear Technology R&D Awards special session, to be held during the ANS Winter Meeting in Washington DC November 30-December 3. ANS has announced that the Winter Meeting shall be in-person and also virtual, and they have promised more information soon. The winners may elect to attend the session or present virtually.

University Research Alliance received award trophies for the 2021 Innovations Awards winners. Letters of congratulations from the DOE, signed by Andrew Griffith, Deputy Assistant Secretary for Nuclear Fuel Cycle and Supply Chain, will be included with the trophies.

University Research Alliance continued to update the Innovations Awards announcement distribution list, in anticipation of the 2022 Innovations Awards.

For more information on the University Research Alliance contact Cathy Dixon (806) 651-3401.