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Research Article

The History of LENR Research at NASA Glenn Research Center

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Abstract

NASA requires novel power sources to accomplish future planetary science missions. A range of power systems will likely be required for both scientific investigations and future manned missions on the moon and Mars. NASA has successfully used radioisotope power systems for over five decades for missions throughout the solar system. For example, both the Curiosity and Perseverance, *aka* Percy, Mars rovers have "nuclear batteries". The two Voyager spacecraft that launched in 1977 continue to operate after 46 years, a little over half of the half-life of the heat source ^{238}Pu's alpha particle decay and are now in interstellar space! However, radioisotope thermoelectric generators, or RTGs, have been limited to producing less than 1 kilowatt of electrical power and usually only produce a few hundred watts. Consequently, for decades NASA has investigated fission and fusion reactors. The NASA Glenn Research Center (GRC) has had deep space power and propulsion as part of its mission portfolio beginning with Nuclear Thermal Propulsion (NTP) in the 1960s. Later, ion propulsion, (used with deep space probes and geosynchronous satellite station keeping), radioisotope power systems (used in nearly all deep space missions) and most recently the Kilopower space/fission reactor tested in 2018 were added. For the past several years, NASA Glenn researchers have been investigating an unconventional approach to initiate nuclear reactions [1]. This work has been called by various names including Low Energy Nuclear Reactions (LENR), Chemical Assisted Low Energy Nuclear Reactions (CANR-LENR), and more recently Lattice Confinement Fusion (LCF) reactions. Using a high flux of energetic electrons in an environment containing a high atomic density of nuclear fuel, such as deuterium, researchers have seen compelling evidence of condensed matter nuclear reactions, including charged particle and neutron emissions, as well as small levels of excess heat, which cannot be explained by chemical reaction processes. This paper provides a summary of the 30+ year history of LENR research at NASA Glenn Research Center from 1989 to the present and cites several reports published during that period.
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1. INTRODUCTION

GRC has studied LENR or Lattice Confinement Fusion under various names since the 1989 University of Utah announcement by Drs. Fleischmann and Pons. We began with D_2 gas cycling [2] then investigated Mills' potassium-carbonate [3] and energy harvesting from sonoluminescence [4]. Later, we undertook gas cycling Pd/Ni powders, Pd/D co-deposition [5,6], x-ray [7], electron and bremsstrahlung irradiation [8, 9] following Didyk's experiments [10], glow discharge repeating Karabut's experiments [11], and plasma loading calorimetry [12]. Lipson's TiD_2 SEM irradiation [13] was repeated. We modeled [14] or measured [15] various loading and triggering mechanisms. Our later efforts began in 2014 under the Advanced Energy Conversion Project and have continued under the Lattice Confinement Fusion Project. Many of our published papers can be found through our website:

https://www1.grc.nasa.gov/space/science/lattice-confinement-fusion/

NASA GRC conducted LCF research with several organizations ranging from the Naval Surface Warfare Centers Pd/D co-deposition replications and Density Functional Theory modeling to the Department of Energy Los Alamos National Laboratory on nuclear modeling with MCNP.

To verify nuclear reactions, we have used or developed nuclear diagnostics like High Purity Germanium (HPGe) Gamma Ray Spectroscopy, Solid State Nuclear Track Detectors (CR-39), liquid scintillator alpha/beta spectroscopy, neutron scintillator [16] and moderating-type spectrometers [17]. We have used a variety of elemental and isotopic assays to determine LENR effects including optical microscopy, Scanning Electron Microscopy with Energy Dispersive X-Ray Analysis (SEM/EDX), X-Ray Photoelectron Spectroscopy (XPS) and Transmission Electron Microscopy (TEM). All these methods observe the surface of a material. By dissolving or vaporizing samples, Inductively Coupled Plasma Optical Element Spectroscopy (ICP-OES) has been used to determine elemental composition (in parts per billion) or with mass spectroscopy, isotopes (ICP/MS). Focused ion beam (FIB) is used to slice open a sample and observe the "cut" with either SEM/EDX, or Time-of-Flight Secondary Ion Mass Spectroscopy (TOF-SIMS) [18]. Notably, we have learned and documented the limitations associated with each of these methods ranging from handling contamination, background interferences, instrumental limitations including sensitivity and field of view, and sample preparation.

2. Novel Nuclear Fusion Reactions as an Energy Source

Harnessing fusion would provide humanity with nearly limitless energy. Many NASA missions require a compact, controllable power source that is unaffected by environmental concerns such as lunar dust. Novel energy producing materials could lead to a scalable novel power source, extending the state-of-the-art in specific power compared to photovoltaic-based solar cells. NASA could take advantage of a new source of power eliminating the need for high-cost radioisotopes and nuclear fission-based reactors.

For 30 years, multiple labs have observed fusion reactions suggesting Lattice Confinement Fusion (LCF). LCF may be the key to harnessing fusion within a compact, contained system. The advantages of LCF include:

- Eliminates the need for low enriched uranium (LEU), high assay low enriched uranium.(HALEU) and weapons-grade uranium (HEU).
- Reduces safety, security, and supply concerns.
- Nearly zero radioactive waste.
- Offers compact, controllable power.

Figure 1 illustrates the many long-term applications that the LCF team at NASA GRC has in mind that could take advantage of LCF reactions.

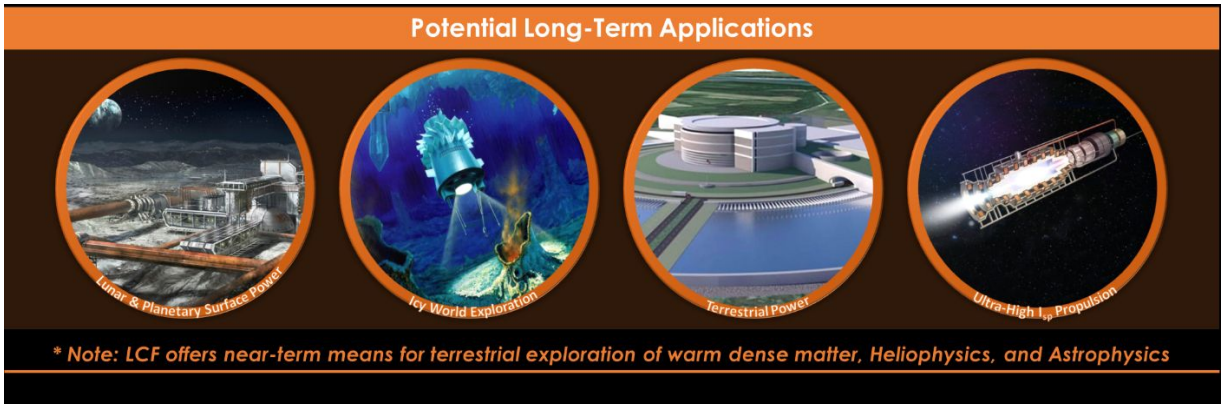


Figure 1. NASA Applications Needing Compact Controllable Power.

3. Timeline of Events

Several groups at NASA; Langley Research Center (LaRC), Marshall Space Flight Center (MSFC) and GRC followed various LENR researchers including Pons/Fleischmann, Focardi, Piantelli, Miley, Widom and Larson, Nagel, and Rossi (1989 to 2011). The NASA teams discussed and reviewed various approaches. Dennis Bushnell (Chief Scientist, NASA LaRC) met with GRC researchers Fralick, Niedra, Wrbanek, and Decker along with several GRC managers to discuss Bushnell's LENR concept. After that meeting, Bushnell invited Robert Hendricks to visit MSFC and learn about the LENR work there. Inspired by the LENR work being done at LaRC and MSFC, Robert Hendricks formed a group and with GRC R&D management approval, Mr. Hendricks (GRC) organized a LENR/Innovations Workshop held on Sept 21, 2011, at NASA GRC in Cleveland, OH. Speakers from GRC, LaRC and MSFC shared their current research. Dr. Bruce Steinetz, Dr. Theresa Benyo, and others attended with great interest. Robert Hendricks briefed GRC Center Director, Dr. Ray Lugo shortly after. Dr. Bruce Steinetz, Dr. Arnon Chait (representing Drs. Vladimir and Marianna Pines), Gus Fralick, and Dr. Lei (GRC R&D Director) attended Mr. Hendricks' briefing. Hendricks proposed a LENR research project at GRC. Dr. Lei authorized a small effort at GRC led by Dr. Steinetz and named Advanced Energy Conversion (AEC). Dr. Lugo orchestrated a briefing at NASA HQ where all NASA efforts were presented.

The AEC Project grew from a few researchers to about 25 over the years from 2011 to 2018. Dr. Steinetz met with Lawrence Forsley and Dr. Pam Mosier-Boss to discuss co-deposition papers at Navy SPAWAR in 2012. Forsley, between GEC and GRC, set up a NASA Space Act Agreement to identify high temperature Solid State Nuclear Track Detectors. A small amount of funding from the Director's Discretionary Fund (~2012–2013) under Dr. Ray Lugo's and Dr. James Free's tenures as NASA GRC Center Director grew to a large NASA Science Mission Directorate, Planetary Science Division funded effort (2014 to 2018) under Dr. James Free's and Dr. Janet Kavandi's tenures as NASA GRC Center Director. Various NASA HQ and other government agency reviews were held of the work over the active years. The AEC Project's work culminated in the *Phys Rev C* journal publication of experiment [9] and theory [14] papers in 2020.

Many individuals contributed to the success of GRC's past LENR research efforts. The diverse and talented team consisted of experimental physicists, nuclear physicists, solid state physicists, electrochemists, material scientists, research technicians, mechanical engineers, electrical engineers, plasma physicists, statisticians, mathematicians, computer scientists, data analysts, and project managers. The following paragraphs list the individuals along with their activities and contributions during our LENR research efforts.

3.1. AEC Research Scientists and Engineers

Mr. Gustave Fralick conducted experiments cycling D_2 gas in palladium (Pd) as a source of nuclear activity (compare with Celani et al). This gas cycling was one of the first non-electrochemical experiments. Mr. Fralick also investigated the possibility of the existence of sub-normal hydrogen energy levels (Niedra et al) and sonoluminescence (Wrbanek et al) sources of energy. The cycling experiments were reported in International Journal of Hydrogen Energy in 2020 (Fralick et al).

Mr. Robert Hendricks recognized the value of conducting LENR experiments at NASA and was instrumental in orchestrating a formal LENR research project at NASA GRC. His investigation in prior LENR research outside of NASA helped guide the direction of the AEC project. He conducted electrolytic wet cell slow co-deposition and x-ray irradiation experiments. As a senior technologist, Mr. Hendricks continually provided his expertise and offered guidance to all members on the team conducting LENR experiments that the NASA GRC team performed during his tenure at NASA.

Dr. Bruce Steinetz was the original Principal Investigator (PI) of the AEC Project. He advocated for the initial funding for the effort by convincing the then Center Director to provide some discretionary funding to cover initial hardware and staffing needs. Under his leadership the project grew slowly first and then rapidly later as we started to make some very interesting physics findings (anomalous heat generation, apparent nuclear transmutations, evidence of charge particle and neutron emissions). The Team grew with the addition of experts in many fields including: both theoretical and experimental physicists; solid state physicists; materials scientists; a large staff of engineers to design hardware to carry out carefully constructed experiments; and engineering technicians to implement the experimental hardware. The project continued to grow through ~2017 at which time NASA Headquarters gave us direction to verify and publish clear evidence of novel nuclear reactions, namely bremsstrahlung radiation of highly deuterated ErD_3 targets. We completed that assignment in 2018. The culminating papers (experimental and theoretical) were published in the high impact factor Journal *Phys Rev C* in April 2020. Late in 2019, Dr Steinetz was asked by management to support other pressing Agency projects so turned over the reins of the project to Dr. Theresa Benyo and Mr. Lawrence Forsley.

Dr. Arnon Chait helped launch and lead the LENR project and NASA GRC. With training and experience covering physics, engineering, and biosciences, Dr. Chait extensively published in multiple fields and is the co-inventor of LENR patents. Dr. Chait advised the AEC Team and helped develop the electron screening theory.

Dr. Vladimir Pines is a theoretical physicist instrumental in developing the electron screening theory that guided the AEC Team's experiments. Dr. Pines expertise in nuclear physics and attention to fundamental physics theories helped the AEC Team to achieve success with the bremsstrahlung irradiation studies conducted at IBA. Dr. Pines helped guide many AEC experiments with his expert knowledge in experimental nuclear physics.

Dr. Marianna Pines worked closely with Dr. Vladimir Pines and helped develop the AEC project's electron screening theory. Dr. Marianna Pines was instrumental in writing and running Mathematica codes that determined the cross sections of d-d fusion reactions with deuterated metals according to the main theory developed by Dr. Vladimir Pines. She also helped develop a novel nuclear reactor design that the AEC team tested in small scale experiments.

Dr. Theresa Benyo is the Lattice Confinement Fusion Project PI and an analytical physicist. During the AEC Project she was the nuclear diagnostics lead conducting nuclear diagnostics including gamma spectroscopy, alpha/beta detection, and half-life determination. Dr. Benyo carried out nuclear Monte Carlo and Density Functional Theory modeling and oversaw material assays. In addition, Dr. Benyo worked to merge experimental data with electron screening theory by analyzing all the nuclear diagnostic data to help explain how to orchestrate nuclear fusion reactions.

Mr. Lawrence Forsley is the senior lead experimental physicist on the NASA GRC AEC Project and the Lattice Confinement Fusion Project of which he currently serves as co-PI. Mr. Forsley assisted with planning many of the

AEC experiments and guided the team in collecting experimental data and detecting nuclear reaction products. He instituted the use of CR39 chips for charged particle and neutron detection and liquid beta scintillation for beta and tritium detection. Previously he worked on diagnostics, command, and control systems (C4I) for laser and magnetic fusion systems in the US and Germany.

Dr. Bayar Baramsai joined the AEC team in 2017 to perform neutron spectroscopy, working especially with liquid scintillators. He supported nuclear events diagnostics using pulse-shape-discrimination (PSD) and neutron unfolding codes with neutron scintillator spectrometers. He also supported the bremsstrahlung beam characterization and nuclear event rate calculations for the experiments at IBA.

Dr. Philip Ugorowski joined the AEC team in 2017 to perform neutron spectroscopy, working especially with a moderating-type neutron detector. Tests were made at Neil Armstrong Test Facility using a linear accelerator. Tests at ATF also involved scintillator panel Time-of-Flight neutron spectroscopy. Experiments using the IBA Dynamitron used the moderating-type neutron detector to precisely calibrate the gamma-ray beam energy. Dr. Ugorowski also contributed to theory discussions of LCF and experimental planning for wet-cell experiments and analysis of wet-cell data.

Dr. Wayne Jennings prepared many of the samples used in the AEC project, primarily through deuterization of rare earth metals. He also was central to characterization of pre- and post- experiment materials by SEM/EDS and ToF-SIMS.

Dr. Fred Van Keuls initially assisted Mr. Fralick with the deuterium gas cycling experiments with palladium and captured thermal output of the experiments. Dr. Van Keuls also worked at loading metals with deuterium gas for later experiments involving irradiation of deuterated metals.

Mr. Phillip Smith conducted electrolytic wet cell experiments using the slow co-deposition protocol. His no-nonsense and unbiased approach to scientific experiments enabled an unprejudiced set of LENR experiments. The results of which were worthy of publication in the “Journal of Electroanalytical Chemistry”. Mr. Smith’s background in fuel cells and batteries was invaluable to the AEC team.

Mr. Richard E. Martin served as the Deputy PI for the AEC project and was responsible for much of the X-ray based experiment development, testing and data acquisition.

Dr. Timothy Grey is a Plasma Physicist who supported the modeling and design of both AEC plasma rigs.

Dr. James Gilland is a Plasma Physicist who supported the modeling and design of both AEC plasma rigs.

Mr. Anthony Colozza led the design, construction and operation of the plasma test stand and the diaphragm reactor. He also coordinated the test plan for each set of experiments.

3.2. Material Science Experts

Dr. David Ellis performed material analysis of pre- and post-test samples under SEM and ToF-SIMS for the GRC programs, including the Naval Surface Warfare Center, Dahlgren Division and samples provided by Dr. Francesco Celani with INFN in Frascati, Italy. His material science expertise also assisted the AEC Team with deuteration of many metals.

Dr. Ivan Locci is a material scientist who supported the AEC Team through material analysis of many samples from AEC experiments under SEM and prepared Pd ‘straw’ samples with brazing techniques.

Mr. Dereck Johnson performed ICP-OES analysis on pre- and post- exposed materials for trace elements in the ppm-ppb range as well as confirmation of the bulk composition. Mr. Johnson also coordinated with outside commercial labs to arrange for analysis by techniques such as ICP-MS, GDMS, and NMR, where in-house capability did not exist.

Dr. Kathy Chuang characterized materials used during the x-ray irradiation experiments, mainly deuterated polyethylene using FTIR.

3.3. Technical Support Experts

Mr. Nicholas Penney provided invaluable technical support throughout the AEC project. Mr. Penney completed many tasks such as experimental equipment build-up, material vessels development, and LabView connectivity for capturing nuclear product detection under the electron beam and x-ray irradiation experiments.

Ms. Annette Marsolais worked with the AEC Team to help analyze data and integrate it into research efforts. Ms. Marsolais also researched the electron screening theory to help provide a link between theoreticians and other members of the team.

Mr. Michael Becks managed the Chain of Custody of experimental test samples, including documenting pedigree of raw materials, storing pre- and post-test samples, and shipped test samples and other equipment to off-site testing locations as needed. He assisted in assembling test samples, split off materials for pre- and post-test analysis, consolidated and organized test data, and was a member of the IBA test team. He documented test sample details, i.e., test sample name, masses of ingredients, configurations. Mr. Becks also provided data analysis support and software support using MCNP.

Dr. Christopher Daniels provided assistance with experimental data processing to establish proper statistics and determining experimental error.

Ms. Kristen Bury provided project management support during the project formulation phase. Ms. Bury also provided some hands-on support during the gamma irradiation experiments.

Ms. Tracey Kamm served as a research technician and assisted Dr. Benyo with nuclear diagnostics running pre- and post-test samples under various nuclear detection systems such as the alpha/beta detection system at NASA GRC.

Mr. Robbie Malcolm helped develop engineering plans and designs for many of the AEC team's experimental equipment, mainly the calorimeter apparatus.

Mr. Paul Passe is a design engineer who designed much of the Glow Discharge rig and assisted with the design of the Plasma rig.

Mr. Brian Jones operated the AEC project's Linear Accelerator (LINAC) during the gamma irradiation campaign from 2015 to 2017.

Mr. Paul Stout is an electrician who was instrumental in helping make LINAC operate and assisted in much of the electrical work that was needed to support the gamma irradiation experiments. Mr. Stout was also one of the LINAC operators.

Mr. Joseph Assion is a hardware designer who provided many of the detailed drawings for test hardware and fixtures used during the AEC experiments.

Mr. Francis Gaspare is a machinist and mechanic who fabricated several sample holders and other fixtures used during the AEC experiments.

Mr. Frank Bremenour is a technician who supported rig buildup and test sample assembly of test facilities used during the AEC experiments.

Mr. John Zang is an engineer who supported some of the early facilities design for the Igloo and LINAC installation.

Mr. Christian Maloney is an engineer who supported installation of Data Systems and remote operation capabilities for the LINAC. Mr. Maloney also served as one of the LINAC operators.

Mr. Mark Bell is an engineer who provided some initial LabView work with the buildup of the AEC calorimeter.

Ms. Marian Cronin is a systems engineer who coordinated the systems engineering work and created the work instructions for the AEC plasma rigs.

Mr. Csongor Hollohazy performed cleaning and loading of experimental disks for the AEC plasma rig.

Mr. Ian Jakupca is a direct energy conversion researcher who operated the AEC plasma rig.

Mr. Scott Panko is an electrical engineer who provided support in operating the AEC plasma rig.

Mr. Lawrence Edwards provided support in operating the AEC plasma rig.

Mr. Don Johnson served as an Electrical Engineer in support of various experimental needs during the AEC project and operated the AEC plasma rig.

Mr. Stephen J. Guzik served as an Electrician in support of various experimental needs during the AEC project.

Mr. Christopher Garcia developed LabVIEW data acquisition and control programming that assisted the operation of many AEC experiments.

Mr. Joseph Rymut is an electrical engineer who was involved with building up and running the Arc Glow Reactor experiments, the Johnson-Matthey experiments, and the Parr Reactor experiments.

Mr. Arthur Erker was instrumental in procuring the needed diagnostic and other experimental equipment for the AEC Team. Mr. Erker's background in nuclear diagnostic systems helped the AEC team a great deal with procuring the correct equipment for such a research effort.

Lori Bulat provided support with analyzing the many CR-39 chips used in the AEC experiments.

Victoria Leist provided support with analyzing the many CR-39 used in the AEC experiments. Ms. Leist also used liquid scintillator spectroscopy to analyze experimental materials.

Amy Rankin provided support with analyzing the many CR-39 chips used in the AEC experiments.

Ms. Rebecca 'Beckey' Johannsen was one of the health physics technicians that performed nuclear diagnostics on samples from the AEC Team's LINAC experiments. Ms. Johannsen was proficient at HPGe spectroscopy, liquid beta scintillation operation, and CR39 chip etching.

Ms. Karen Novak was one of the health physics technicians that performed nuclear diagnostics on samples from the AEC Team's LINAC experiments. Ms. Novak was proficient at HPGe spectroscopy and liquid beta scintillation operation.

Ms. Catherine Jensen was one of the health physics technicians that performed nuclear diagnostics (HPGe and liquid beta scintillation spectroscopy) on samples from the AEC Team's LINAC experiments. Ms. Jensen was also proficient at the logistics of shipping and receiving sensitive research equipment and samples for the AEC Team.

Mr. Christopher Blasio is NASA GRC's Radiation and Laser Safety Officer and has assisted the AEC Team with obtaining the necessary safety permits for all the experiments performed by the team. He also was responsible for conducting radiation safety training for all the AEC Team members that handled experimental materials from the AEC research activities.

Mr. Roderick Case is a health physicist and has supported the AEC Team with HPGe spectroscopy expertise and the proper handling of radioactive materials.

Ms. Jennifer Baumeister, Bastion Technologies, Principal Risk Management Facilitator. From 2016 to 2018, Ms. Baumeister ensured AEC Project Team compliance with NASA Continuous Risk Management (CRM) Procedures by tailoring the CRM section of the Project Plan, creating a Risk Board Charter, and conducting CRM training and risk identification workshops. She initiated monthly Risk Boards to guide the AEC Project team in identifying and managing technical, schedule, cost, and safety threats that may have created obstacles in meeting requirements and goals.

3.4. LENR Research Partners

Dr. Pamela Mosier-Boss is a retired analytical chemist from SPAWAR San Diego, now NIWC. Along with Stan Szpak, she was involved in the development of Pd/D co-deposition process. Her work was duplicated by the AEC Team, and she currently serves as a consultant to the LCF team. Besides her work in LENR, she had been involved in the development of sensors to map contaminant plumes in the environment as well as materials science research on thionyl chloride batteries, drag reducing polymers, polyacetylene, and hydrogen generation to inflate lighter than air vehicles.

Dr. Timothy Koeth is an assistant professor of Material Science & Engineering at the University of Maryland. He performed gamma irradiation experiments with their 3MV LINAC to replicate the gamma irradiation experiments performed at NASA GRC.

Ms. Amber Johnson is the director of the Radiation Facilities at University of Maryland and oversees the operation of the LINAC that was used to replicate NASA GRC's gamma irradiation experiments. Ms. Johnson was instrumental in orchestrating the gamma irradiation experiments at the University of Maryland with Dr. Timothy Koeth.

Dr. Lou DeChiaro, Naval Surface Warfare Centers: Indian Head and Dahlgren Division, conducted Quantum Espresso Density Functional Theory modeling of various hydrided/deuterided metals supporting co-deposition and bremsstrahlung irradiation campaigns, and parametric pumping. Dr. DeChiaro analyzed co-deposition calorimetry data from Dahlgren and Indian Head and conducted RF signal acquisition from the Indian Head DARPA co-funded HIVER Project.

Dr. Pearl Rayms-Keller, Naval Surface Warfare Center: Dahlgren Division, conducted SEM/EDX analyses of co-deposition cathodes run at Dahlgren.

Ms. Stacy Barker, Naval Surface Warfare Center: Dahlgren Division, conducted co-deposition experiments at Dahlgren using the Fast Protocol including preparing multiple cells and collecting data.

Ms. Karen Long, Naval Surface Warfare Center: Dahlgren Division, assisted and led various aspects in the design, setup, implementation, and data analysis of the NSWC Dahlgren co-deposition LENR experiments including XPS analysis.

3.5. Project Management Support

Mr. Paul Westmeyer provided support for the GRC team overseeing the AEC project and serving as the liaison between the research team and NASA HQ. Mr. Westmeyer routinely visited NASA GRC to provide hands-on support during the x-ray and gamma irradiation experimental campaigns. His interactions with members of the AEC team proved invaluable as progress was made in demonstrating d-d nuclear fusion.

Mr. Leonard Dudzsinki is a Chief Technologist for the PSD at NASA HQ. He has supported the AEC/LCF Team with countless discussions on the nuclear fusion reactions being studied and sharing our successes with the PSD management team at NASA HQ. He oversees the sustainment of NASA's deep space power capabilities and development of new power systems based on Plutonium-238.

General (ret.) David Stringer is the director of NASA's Neil Armstrong Test Facility (ATF) and was instrumental in supporting the AEC Team's build-up of the LINAC facility at ATF.

Mr. Gerald Hill was a facility manager at NASA's Plum Brook Station (now called the Neil Armstrong Test Facility) who oversaw the operation of the AEC project's LINAC housed in one of the 'bunkers' at that test facility. Mr. Hill also managed and supervised the technicians that were supporting the LINAC gamma irradiation experiments conducted by the AEC Team.

Mr. John Heese worked as the NASA Advanced Energy Conversion (AEC) integration manager from 2016 to 2018. Then, from 2019 until the present, he has been providing NASA Contractor management oversight to AEC and Lattice Confinement Fusion (LCF) related work.

Ms. Susan Jansen, Branch Chief, Thermal Systems and Transport Process, was the Task Lead for the AEC contract work from 2012 to 2018. At one time, the AEC contract employed 30 Vantage Partner employees, carried subcontracts with researchers including Larry Forsley, Vladimer Pines, Jim Gilland, Nick Penney, Frank Lynch, Edmund Storms, and support from CWRU (TOF-SIMS analysis), the University of Akron, the Ohio Aerospace Institute and Ohio State University. She managed procurements of materials and equipment, including a Linear Accelerator for Armstrong Test Facility. Ms. Jansen's goal was to supply the research team with essential personnel, materials, and equipment.

Ms. Jennifer Grof is a budget analyst and provided guidance and support for the AEC funding.

Dr. Hakimzadeh Roshanak was the project manager of AEC from 2014-2016.

Mr. John Hamley was the project manager of AEC from 2016-2017.

Mr. Carl Sandifer served as the AEC Review Manager for the project in 2016. At that time, the Science Mission Directorate (SMD) Planetary Sciences Division (PSD) desired a new energy source to enable science priorities identified in both the 2010 Planetary Science Decadal Survey and the 2014 Science Plan. The AEC Project sought to develop a safe and cost-effective heat source for power generation and in a follow-on project, would integrate this with an electric power conversion system. The intent was for the system to offer significant performance, cost, safety, and/or operability improvements compared to current or currently conceived planetary science power systems. Following the successful review, Mr. Sandifer became the AEC Project Manager from 2017-2019. In early 2017, he worked with the team to develop a research plan to address the PSD direction to focus the latest AEC project research on investigating clear evidence of sub-threshold nuclear activation using either an electron beam or photon irradiation of highly deuterated target materials, and to provide suitable experimental evidence to address the physics community scrutiny, questioning if unconventional physics had been revealed. After conducting a successful test campaign, the team evaluated and complied the data to publish two peer-reviewed papers within *Phys Rev C*, sharing our lessons learned and results to enhance the societal body of knowledge regarding the initiation of fusion reactions.

Mr. Mathew DeMinico led strategic planning, communication, and coordination for NASA's LCF as Project Manager, and supported coordination of independent review of LCF research and publications from 2020 to 2022.

Mr. Andy Presby is the current LCF Project Manager. Mr. Presby's background is in nuclear physics and his expertise with nuclear submarines lends itself well to the LCF Project. He leads diverse multi-Agency teams supporting the development of advanced nuclear in-space propulsion systems to enable fast crewed missions to Mars and exciting new robotic science missions to the outer planets.

3.6. Virtual Workshop

The AEC Project held a virtual workshop in May of 2020 [19] to announce the results of the published work which was attended by 70 LENR researchers from industry, government, and academia. During the 4-hour online workshop the AEC team presented key results from the two [9,14] *Phys Rev C* published papers. The objectives of the workshop were twofold:

(1) NASA Glenn Research Center (GRC) disseminated the key findings detailing experiments and theory to select invited external researchers and a NASA panel of reviewers. The presentations emphasized electron screening in a confined lattice which allows enhanced nuclear fusion.
(2) Identified challenges to the theory and the results through invited questions and critiques from all participants, and feedback from invited panelists. The feedback received from several participants was very positive and was used to further direct follow-on LCF research.

The AEC Project transitioned to the LCF Project with the current funded effort (July 2021 to present) where the leadership transitioned from Dr. Steinetz to Dr. Benyo. Additionally, a 2023 NASA Innovative Advanced Concepts grant was awarded to the LCF team to study accessing icy world oceans using LCF fast fission for the power source of an autonomous robotic probe.

The Appendix has figures detailing the AEC and LCF projects timelines.

4. Experiments

Many experiments were conducted by the AEC/LCF team using various methods of triggering the fusion reactions to happen. Figure 2 illustrates the types of experiments that were completed to investigate the best trigger and conditions for nuclear fusion reactions to take place.

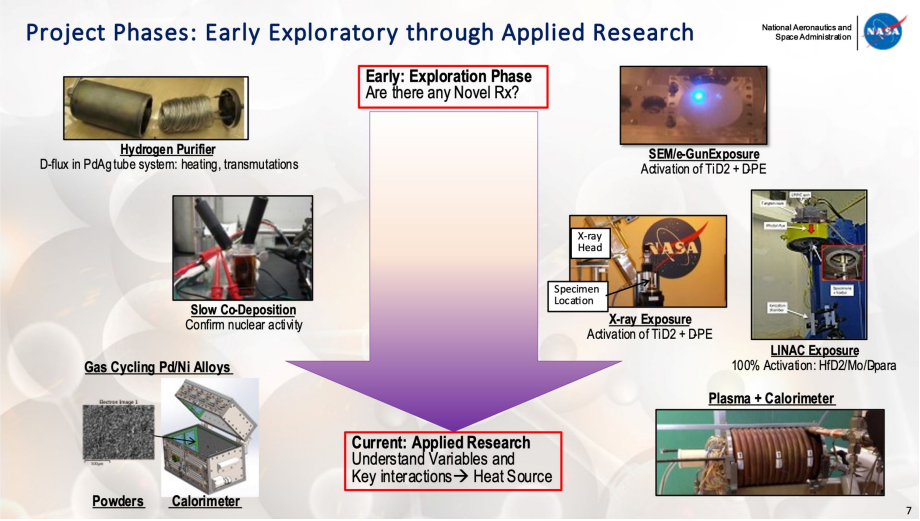


Figure 2. Exploration of LCF Through Experimentation.

5. Hydrogen Purifier

In 1989, Fralick and his NASA colleagues documented anomalous thermal behavior when performing tests with a Johnson-Matthey (JM) hydrogen purifier loaded weeks prior with deuterium gas [2]. The authors detected anomalous heating when D_2 but not when H_2 was dumped from the JM purifier and concluded that neutron activity was insufficient to satisfy the desired 3σ proof of fusion. As the JM purifier is sealed, no metallurgical analysis was pursued at that time. The actual experiment consisted of monitoring temperature and neutron counts. Fralick continued testing with the JM purifier cycling the deuterium gas at various pressures, temperatures, and rate of compression, holding at constant conditions and expansion cycling-rates, noting each cycle produced a particular anomalous behavior. During these early experiments, Fralick et al. [2] found the evidence of anomalous heat and enigmatic neutrons when the purifier was filled with D_2 at a temperature of 383 °C and a pressure of about 1.38 MPa. Several researchers in Italy (Celani), Japan (Iwamura) and China (Zhang) were inspired by this work to undertake their own gas phase explorations as noted during ICCF-23 [1].

During the experiments conducted by Fralick, the supply lines to the purifier were pumped down and the purifier was evacuated prior to running another background count. As the valve on the hydrogen purifier was cracked open to allow the gas to evacuate the pressure vessel, the temperature began to rise. He continued to open the valve slowly. By the time the valve was fully open (10 or 15 s), the temperature had increased to 400 °C before it began to decrease. During this time, the temperature control setting remained at 382 °C, and the temperature rise was much more rapid than was possible using the electric heater. The expansion should have cooled, not heated, the gas, further adding to the anomalous heating observed.

Twenty years later in 2009, the NASA Innovative Partnership Program sponsored additional gas cycling experiments to investigate the anomalous heat observed in the 1989 experiments. More experiments performed in 2014 and 2018 repeated the anomalous heat results and in addition, surface transmutations were discovered on the surfaces of the PdAg alloy tubing used in the gas cycling experiments [18].

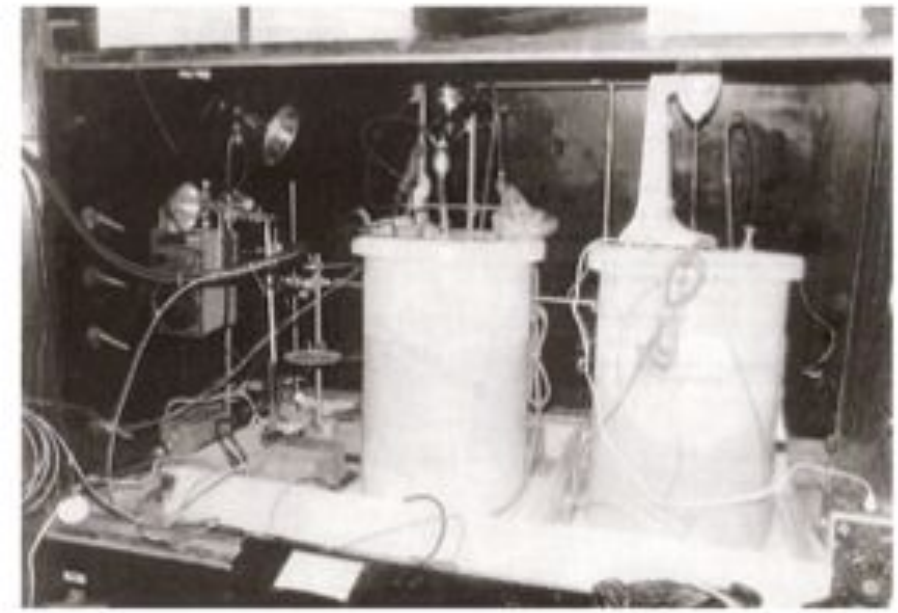


Figure 3. Two 28-liter electrolytic cells.

6. Early Electrolytic Wet Cell Experiments

In 1996, Niedra et al [3] intended to replicate experiments performed by Mills and Kneizys [20]. They used an electrolytic solution of H_2O-Ni-K_2CO_3. They discovered an apparent current-dependent excess heat consistent as heat from hydrogen-oxygen recombination. The experiment consisted of two 28-liter electrolytic cells; one active cell for electrolytic tests and one inactive cell for reference thermal measurements. Figure 3 shows the setup of the experiment. The experiments were conducted at several DC currents and a pulse mode current. Although there was excess heat production with a possible anomalous power gain of ~1.7 at the lowest current (5 A) in the NASA 1996 experiments, it was not as large as other experiments reported in literature (gain > 10). This gain was achieved without a recombiner, but Faradaic efficiency calculations and water loss measurements attempted to take recombination into account.

7. Multi-Bubble Sonoluminescence Investigation

These sonoluminescence experiments [4] were inspired by Stringham's work [21] and sponsored by NASA's Low Emissions Alternative Power (LEAP) Project and Breakthrough Propulsion Physics (BPP) Project. The experiments investigated energy of ultrasonic-generated multi-bubble sonoluminescence (MBSL). The sonoluminescence was achieved with palladium chromium (PdCr) alloy thin films over platinum (Pt) traces on alumina. When light water (H_2O) was used, no crater was seen on the PdCr thin films. However, when heavy water (D_2O) was used, crater formation was observed. Figure 4 shows the results of the MBSL experiments. In addition, large grain features are usually seen in thin films due to mismatches in coefficients of thermal expansion at high temperature (~1000 °C). The question remains: Did this result indicate point heating in the PdCr films?

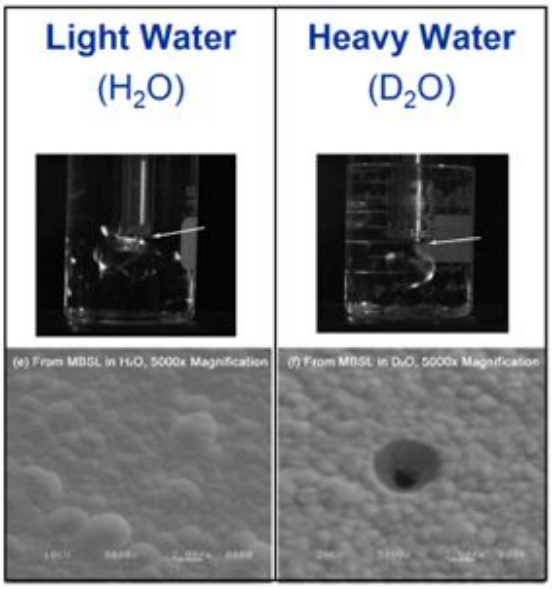


Figure 4. Surface morphology of films exposed to sonoluminescence in light water (left) and heavy water (right).

8. Scanning Electron Microscope (SEM) Energetic Electrons into Deuterated Targets

In unpublished SEM work, the objective was to investigate direct enhanced electron screening of deuterated targets via 10's of kV energetic electrons delivered by the SEM. These experiments were replications of claims by Lipson [13] of nuclear reactions under these conditions. The AEC Team exposed titanium deuteride disks to electron beams with energies of 4 to 30 kV from late 2013 into 2014. The exposure of TiD_2 targets resulted in novel nuclear effects when exposed to electron beam energies under 30keV. In approximately 20% of the cases with freshly polished TiD_2 disks, the team measured beta activation of the disks after the beam exposure. In contrast, undeuterated titanium disks did not show any evidence of nuclear reactions. Figure 5 shows the SEM and closeup photo of a TiD_2 sample surrounded by CR-39 SSND track detectors, and neutron detection foils.

9. Volumetric Electron Screening with X-ray Photons

In the goal of scaling up the reactions observed with the SEM experiments, the team investigated volumetric electron screening of deuterated targets exposed to x-ray photons. Figure 6 shows the x-ray with one of the many samples irradiated during the experiments. Titanium deuteride (TiD2) plus deuterated polyethylene (DPE), DPE alone, and for control, hydrogen-based polyethylene (HPE) samples and non-deuterated titanium samples were exposed to x-ray irradiation. These samples were exposed to various energy levels from 65 to 280 kV with prescribed electron flux impinging on the tungsten braking target from 500 to 9000 μA, with total exposure times ranging from 55 to 280 min. Alpha and beta activities were measured using a gas proportional counter and for select samples, beta activity was measured with a liquid scintillator spectrometer. Most of the deuterated materials subjected to the microfocus x-ray irradiation exhibited post-exposure beta activity above background and several showed short-lived alpha activities. The HPE and non-deuterated titanium control samples exposed to the x-ray showed no post-exposure alpha or beta

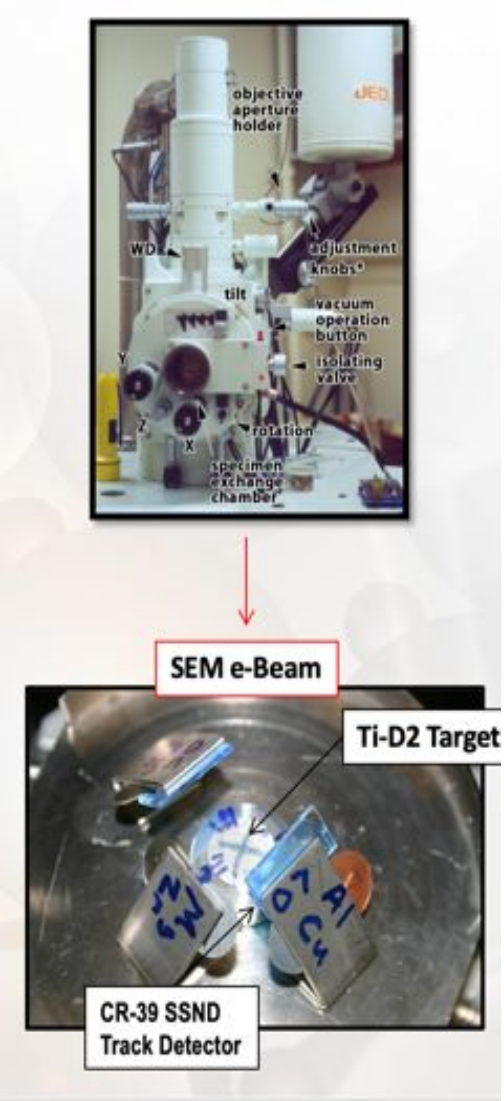


Figure 5. SEM apparatus and photo of deuterated titanium target surrounded by nuclear diagnostics materials.

activities above background. Several of the samples (SL10A, SL16, SL17A) showed beta activity above background with a greater than 4 sigma confidence level, months after exposure. Portions of SL10A, SL16, and SL17A samples were also scanned using a beta scintillator and found to have beta counts in the tritium energy band, continuing without noticeable decay for over 12 months. Beta scintillation investigation of as-received materials (before x-ray exposure) showed no beta counts in the tritium energy band, indicating the beta emitters were not in the starting materials. Full details of the x-ray irradiation experiments are documented in Benyo's NASA Technical Memorandum [7].

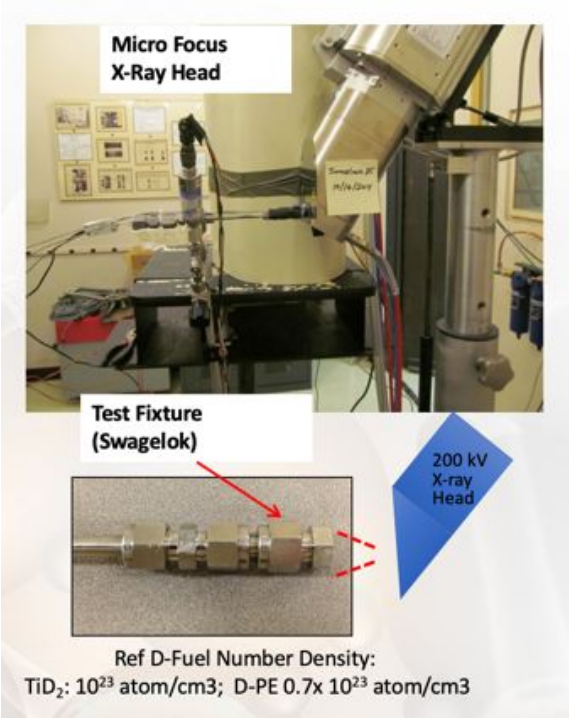


Figure 6. Photo of x-ray head (top) and test fixture containing the sample to be irradiated.

10. Linear Accelerator (LINAC) Volumetric Electron Screening Via Gamma Photons

Linear Accelerator (LINAC) bremsstrahlung irradiation of deuterated material was inspired by the work of Didyk [10]. The objective of this set of irradiation experiments was to investigate volumetric electron screening of deuterated targets exposed to gamma-ray photons at sub-threshold energies less than 2.226 MeV which is the energy at which deuterium photo-dissociates. A LINAC Model LS200 manufactured by Varian was used to expose the samples to photon energies of < 2.2 MeV (Figure 7). This industrial LINAC allowed specimens to be positioned very close to the braking target. For this study, the specimens were positioned within approximately 7.4 mm (0.29 in.) from the exit plane of the tungsten-braking target. No flattening filter was used in these tests. At 7.4 mm it is estimated that the samples saw a radiation dosage of 2.4 x 10^6 rad/min at the nominal 2-MV beam energy. An ion gage (RadCal PN 10X6-0.6) radiation detector was set-up below the test samples at the iso-center (~100 cm from the braking target). The radiation level as well as reflected power, gun current (voltage), and target current (voltage) were used to monitor beam operation to ensure that the beam flux was not changing with time.

Exposure of highly deuterated materials to a low-energy (<2.225-MV) photon beam resulted in activation of both the parent metals of hafnium and erbium and witness materials (e.g., molybdenum) mixed with the reactants. Gamma spectral analysis of all six of the deuterated materials $ErD_{2.8}$+D-Para+Mo and all six of the HfD_2+D-Para+Mo showed that nuclear processes had occurred as shown by unique gamma signatures. For the deuterated erbium specimens, post-test gamma spectra showed evidence of unstable isotopes of erbium (e.g., ^{163}Er, ^{165}Er, ^{171}Er)

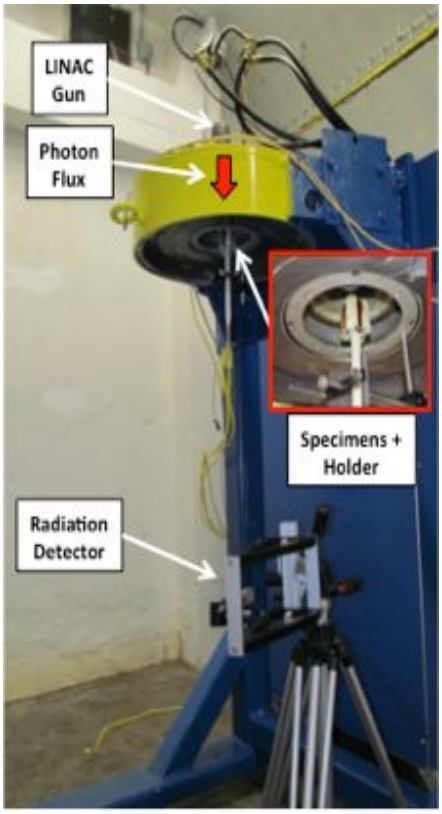


Figure 7. Varian 2-MV LINAC system with specimens positioned just below braking target and ion chamber radiation detector positioned 100 cm below target.

and of molybdenum (^{99}Mo) and by beta decay technetium (^{99m}Tc). For the deuterated hafnium specimens, post-test gamma spectra showed evidence of unstable isotopes of hafnium (e.g., ^{180m}Hf, ^{181}Hf) and molybdenum (^{99}Mo), and by beta decay, technetium (^{99m}Tc). In contrast, when either the hydrided or non-gas loaded erbium or hafnium materials were exposed to the gamma flux, the gamma spectra revealed no new isotopes. In those hydrided or non-loaded specimens, the gamma spectra peaks showed only background decay lines. Although the deuterated materials showed gamma activation lines like those resulting from activation by neutron capture, no sources of conventional neutrons have been identified that can account for this activation. Details of the LINAC experiments at NASA GRC are documented in Steinetz's NASA Technical Memorandum [8].

11. IBA Dynamitron Photoneutron Initiated Fusion with Gamma-Induced Electron Screening

The initial set of experiments performed by the AEC team did not include neutron spectroscopy and therefore, did not offer conclusive evidence of d-d nuclear fusion reactions. The most promising method triggering d-d fusion reactions at the time was the LINAC-based experiments. However, using organic scintillators for neutron spectroscopy under the high gamma and/or EMI background from the Varian LINAC proved to be almost impossible. Another type of LINAC

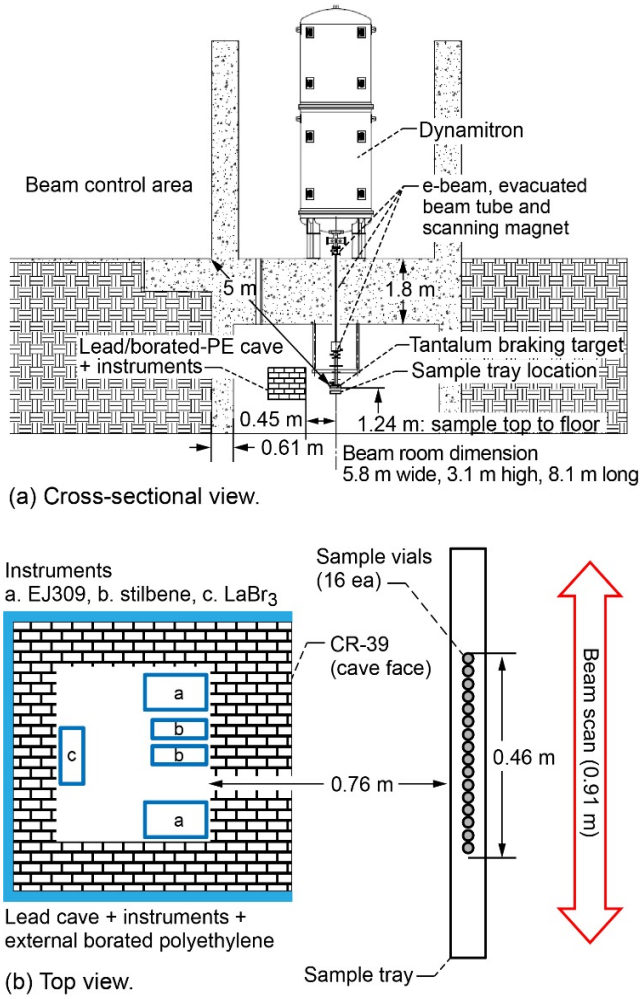


Figure 8. Schematic of beam, samples, cave, and instruments. (a) Overall cross-sectional view of setup; (b) Top view of test samples, cave (top removed), instruments, and beam scan.

needed to be used for the next generation of experiments. A Dynamitron LINAC was located and leased for additional bremsstrahlung irradiation of deuterated metals where the high gamma and EMI background was much less.

As a result, d-d nuclear fusion events were observed in an electron-screened, deuterated metal lattice by reacting cold deuterons with hot deuterons (d*) produced by elastically scattered neutrons or electron screened fast protons originating from bremsstrahlung photodissociation.

Tests were performed using a Dynamitron electron accelerator having independent control of beam energy (450 keV to 3.0 MeV) and beam current (10 μA to 30 mA), as shown in Figure 8(a). The direct-current accelerated electron beam enters the beam room via an evacuated tube and is scanned over the braking target, utilizing the scanning magnet ~1 m above the target. The beam was operated in photon mode for the current tests, utilizing a 1.2-mm-thick tantalum

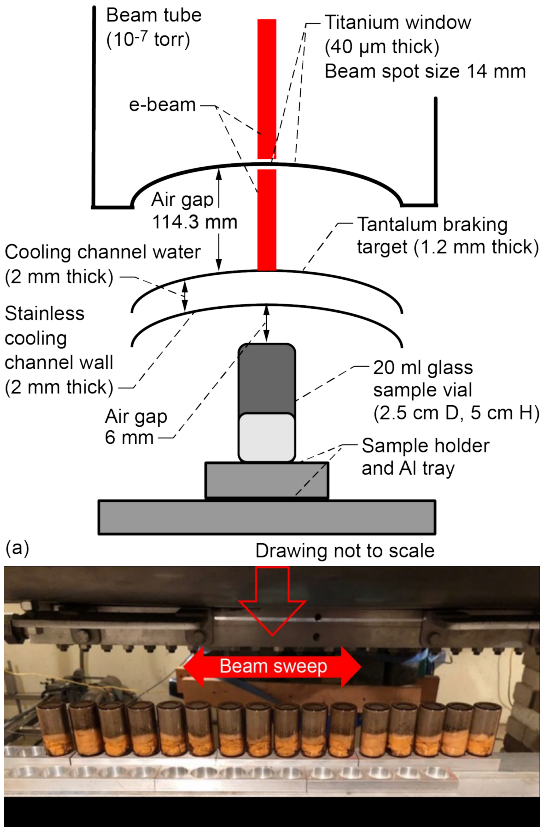


Figure 9. (a) Cross section of electron beam, titanium vacuum window, tantalum braking target, stainless steel cooling channel, and sample; (b) Photograph of specimens in glass vials.

braking target. Samples in glass vials were placed on an aluminum exposure tray close to the tantalum braking target and were exposed while the electron beam scanned at a frequency of 100 Hz over the length of 0.91 m. Figures 8(a) and (b) show the relative position of the 16 samples (total length 0.46 m) and the lead cave, which housed the neutron detectors and will be described below. Figure 9(a) illustrates the proximity (11.2 mm distance) of the 20-ml sample vials relative to the braking target, which was cooled with ambient-temperature water flowing spanwise in a stainless-steel cooling channel. Figure 9(b) illustrates how the beam scanned back and forth over the 16 glass vials.

Specifically, exposure of deuterated materials including ErD_3 and TiD_2 to bremsstrahlung photon energies (~2.9 MeV) resulted in both photodissociation-energy neutrons and neutrons with energies consistent with $D(d,n)^3He$ fusion reactions, and demonstrated process reproducibility. This study [9] and its analyses [14] identified several key ingredients required for fusion reactions. Deuterated metals present a unique environment with high fuel density (10^{22} to 10^{23} D-atoms/cm^3), which further increases the fusion reaction probability through shell and lattice electron screening, reducing the d-d fusion barrier. Exposing deuterated fuels to a high photon flux enhanced screening conditions near the cold D-fuel. This additional screening further increases the Coulomb barrier transparency and further enhances fusion reaction rates. In these tests, deuterons were initially heated by photoneutrons with an average

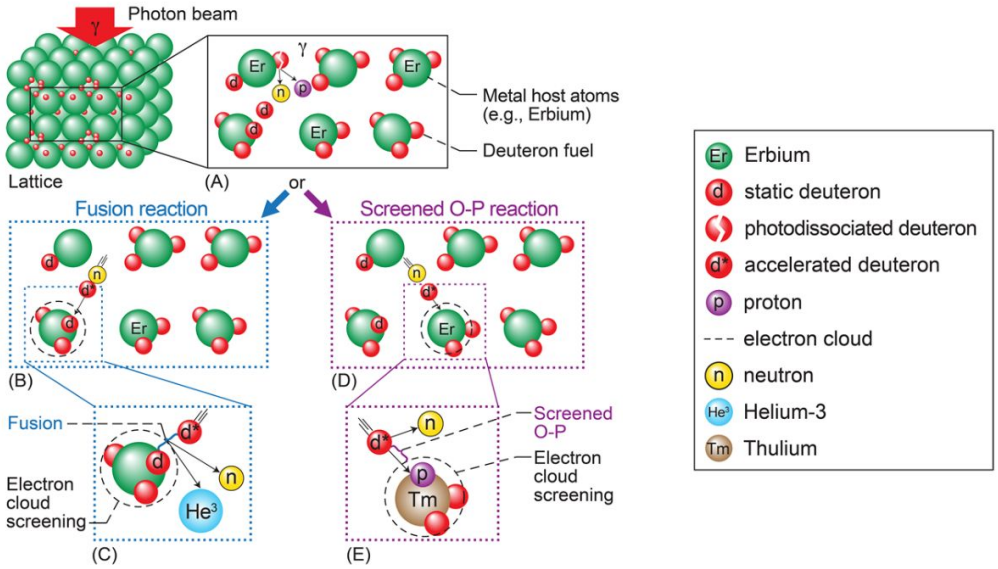


Figure 10. Illustration of reactions detected in the Gamma-Induced Electron Screening experiments. (A) lattice of erbium is loaded with deuterium atoms. Upon irradiation with a photon beam, a deuteron dissociates, and the neutron and proton are ejected. The ejected neutron collides with another deuteron, accelerating it as an energetic "d*" as seen in (B) and (D). The "d*" induces either screened fusion (C) or screened Oppenheimer-Phillips (O-P) stripping reactions (E). The fusion reaction depicted in (C) releases either a neutron and helium-3 (shown) or a proton and tritium. These fusion products may also react in subsequent nuclear reactions, releasing more energy. In (E), a proton is stripped from an energetic "d*" and is captured by an erbium (Er) atom, which is then converted to a different element, thulium (Tm). If the neutron instead is captured by Er, a new isotope of Er is formed (not shown).

energy of 145 keV from the 2.9-MeV beam energy to initiate fusion. However, other neutron sources would also provide the necessary deuteron kinetic energy.

Neutron spectroscopy revealed that both d-d 2.45-MeV fusion neutrons and other processes occurred. Figure 11 shows a comparison GRC-observed d-d fusion neutrons during these experiments with the Italian Tokamak neutron spectra. The data indicates that the significant screening enabled charged reaction products hot d* or ^{3}He* to interact with the host metal. These interactions may produce the ~4- and ~5-MeV neutrons where Oppenheimer-Phillips stripping processes occurred in the strongly screened environment, capturing the proton, and ejecting the neutron (Figure 10). The current work demonstrates the ability to create enhanced nuclear reactions in highly deuterated metals with the deuteron fuel in a stationary center-of-mass frame. This process eliminates the need to accelerate the deuteron fuel into the target with implications for several practical applications.

12. Plasma Reactor: Delivery of Ions/Energetic Electrons into Deuterated Targets

The objective of the plasma reactor experiments was to investigate dynamic loading of D+ with screening electrons into deuterated targets with a customized microstructure.

A reactor [12] was designed and constructed to generate a plasma and expose various materials to this plasma. The reactor could heat the plasma chamber and supply a gas to the chamber at pressures from vacuum levels to 200 psi. A calorimeter was constructed around the plasma chamber to accurately monitor the thermal power exiting

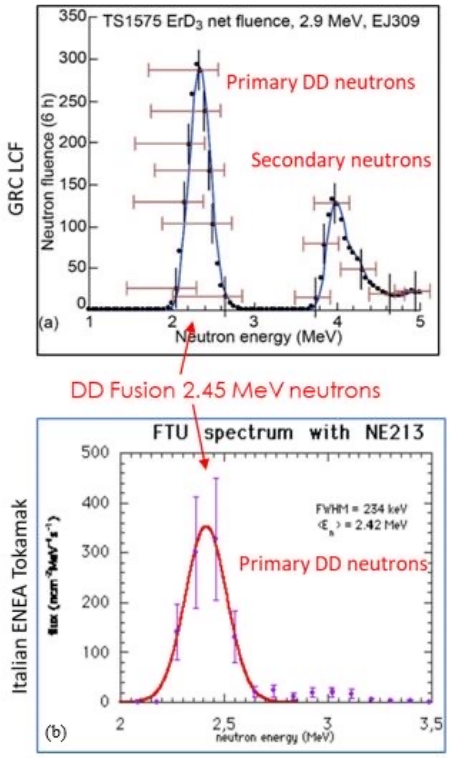


Figure 11. Comparison of neutron spectra from (a) bremsstrahlung radiation of deuterated erbium samples (TS1575 6 h exposure) and (b) fusion neutrons from the Italian ENEA Fusion Tokamak.

the plasma chamber. A steady state or pulsed plasma could be generated. The input and output electrical power for creating the plasma was monitored, and the current and voltage waveforms were observed and recorded using a series of oscilloscopes. The results of initial experiments showed the accuracy of measuring the plasma input power and of the calorimeter in measuring the total heat output of the system. It was determined that the system had a total power measurement accuracy of ± 1.36 percent. A schematic of the plasma reactor is shown in Figure 12.

The plasma reactor test rig was designed with standard anode and cathode electrode pair contained inside of a stainless-steel reaction chamber. The entire system was designed to operate with pulsed direct current (DC) plasma at pressures from integer torr to several atmosphere gas pressures. The system was designed to handle most gas types but was mainly used with hydrogen, deuterium, or inert gases. The stainless-steel reactor is wrapped in a water-cooled calorimeter capable of dissipating upwards of 2,500 W of power. The calorimeter removes the total power input into the chamber as either heat or electrical power and any heat generated within the chamber. Any heat generated within the chamber is measured by calculating the difference in the total output heat (determined by the measured temperature rise for the metered water flow) less the total input power (strap on heaters plus plasma electrical power). For materials testing, a range of powders and metal foam combinations were used. Tests that utilized hydrogen or deuterium gas also introduced the possibility of gas loading into the materials. Some disks contained powders made of materials that had no hydrogen or deuterium loading and others contained hydrogen or deuterium at high atomic number density (e.g., 10^{21} atoms/cm^3).

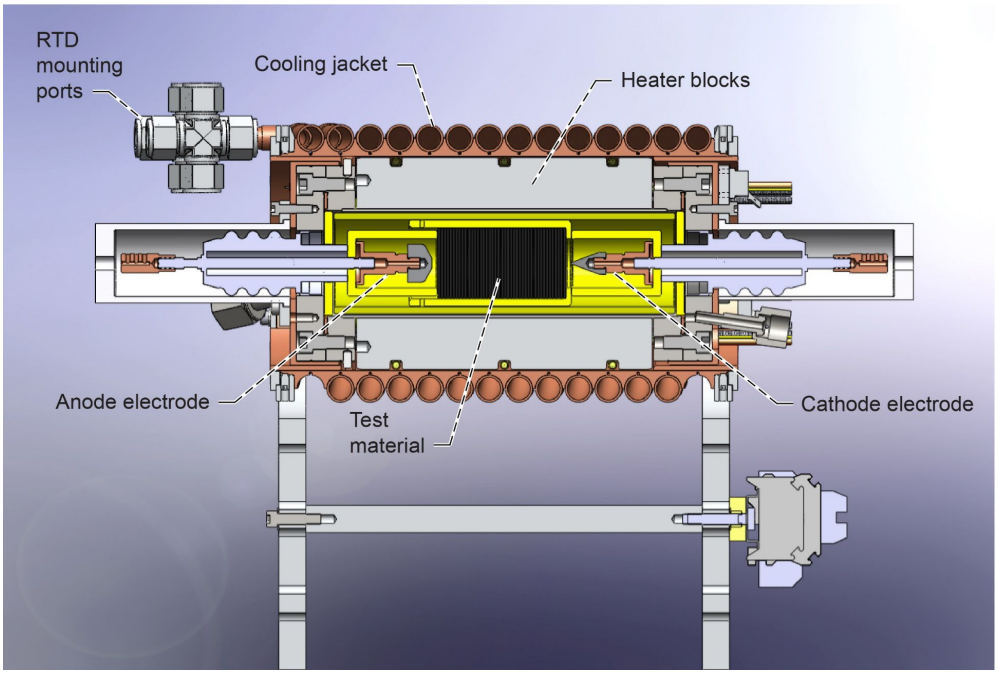


Figure 12. Plasma reactor internal layout.

The results of these plasma reactor experiments showed that tests with TiD_2 powder and PdAg indicated excess power. However, it was difficult to accurately know the input power, hence the excess thermal power was questionable despite an accurate calorimeter measuring the output power.

There were also RF emission losses during these experiments. The production of possible excess thermal power repeated with, on average, ~20–30% of the experimental runs. The team also observed anomalous gas changes which were measured during the test; growth of AMU-2, 3, 5, 6 and a decline in AMU-4 (presumed to be D_2) as shown in Figure 13.

Unbeknownst to our group, the Lawrence Berkeley National Laboratory under Dr. Thomas Schenkel's group with Google Research Funding also conducted plasma loading experiments and detected fusion neutrons [22].

13. Electrochemistry: Dynamic In-Situ Creation of High-Density Deuterated Microstructure

The objective of conducting electrolytic wet cell experiments is to investigate high current (900mA) D+ along with Pd and Li co-deposited on a metal wire. The approach for these types of experiments is either a slow [5] or fast [23] Pd/D/Li co-deposition protocol consisting of using heavy water (D_2O) or light water (H_2O) in the electrolytic solution during multi-hour runs. Calorimetry is used to measure the amount of heat produced during the experiment. The NASA Advanced Energy Conversion Project supported excess heat producing electrolytic co-deposition experiments at the Naval Surface Warfare Center (NSWC), Dahlgren Division and Density Functional Theory (DFT) modeling of hydrided materials by Dr. Louis DeChiaro. This work led to the DARPA funded HIVER effort at NSWC, Indian Head replicating these results. The NASA Lattice Confinement Fusion Project funded additional DFT results at Indian Head also by DeChiaro.

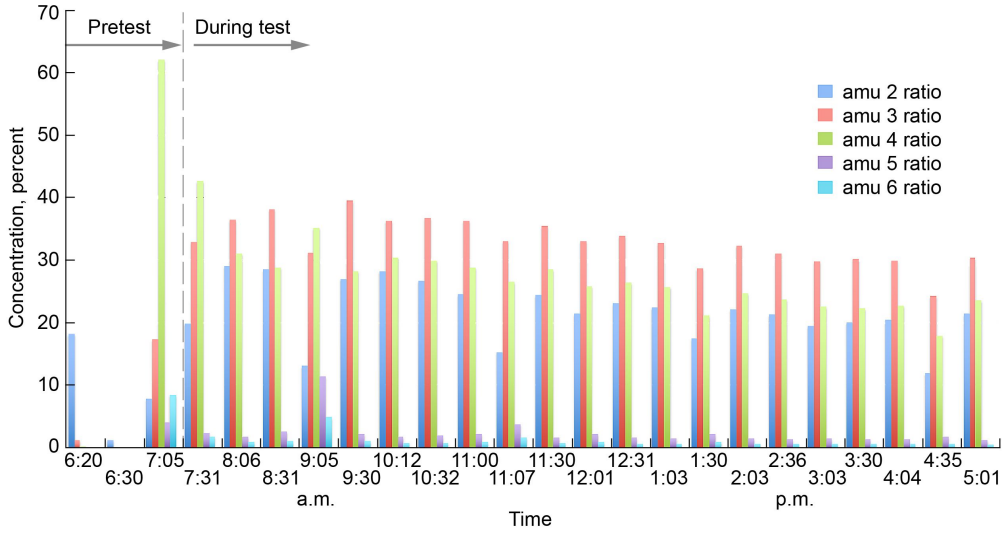


Figure 13. Residual gas analyzer (RGA) scan results taken periodically during a test.

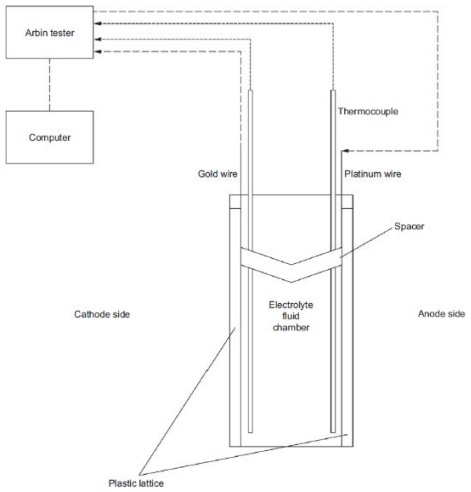


Figure 14. Test system diagram for a single electrolysis cell. A single bubble detector was placed outside the cell behind the electrolyte chamber as shown in this view.

Co-deposition [6] electrochemical cells are a simple means to examine novel nuclear reactions. In the 2016 study by our team, electrolytic cells were built as illustrated in Figure 14. During the experiments, palladium and deuterium atoms were co-deposited on a cathode at stoichiometric densities, forming dendritic morphologies. Bubble detector neutron dosimeters were used to measure equivalent dose levels during electrolytic deposition. Cells expected to

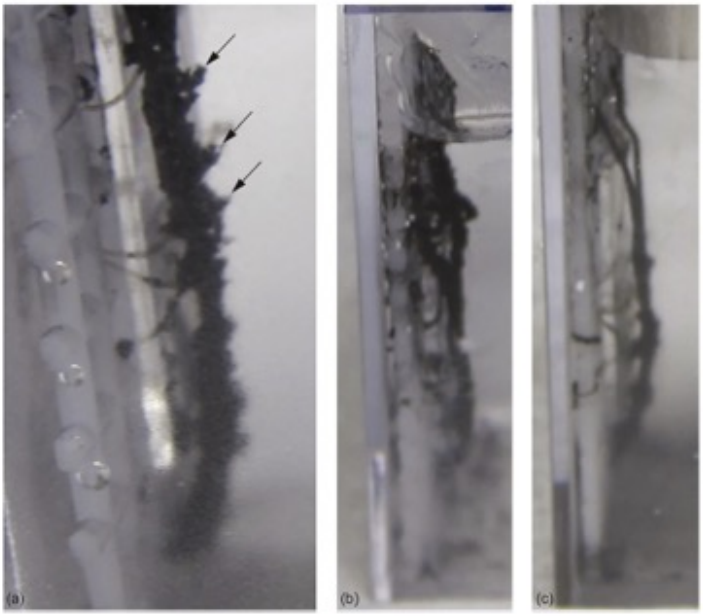


Figure 15. Close-up images of (a) T-III-E1 (above-average neutron emissions), (b) T-IV-E1 (average neutron emissions), and (c) T-III-E5 (below-average neutron emissions). The height of the plastic lattice mesh that the wire is attached to shown in (b) and (c) is approximately 2.5cm.

produce excess neutrons were denoted as experimental cells and contained an electrolyte consisting of palladium(II) chloride, lithium chloride, and heavy water. The control cells used copper(II) chloride, lithium chloride, and heavy water electrolyte. Thirteen experimental and nine control cells were supplied current, increasing from 0.1 to 100.0 mA over a period of 20 days. Neutron radiation levels detected near experimental cells were, on average, greater than those measured near control cells for the entire test profile. For test days 9 through 20, the experimental cells exhibited significantly higher average neutron radiation than the controls at a 99% confidence level.

In the experiments described in the current work, there appears to be a correlation between dendritic deposits on cathodes and observed neutron activity. For comparison, post-test images of several experimental cathode cells are presented in Figure 15 that show the final palladium deposition dendritic macrostructure on the cathode prior to disassembly. Dendrites are clearly visible on the cathode surface of the T-III-E1 cell, which produced the greatest total neutron dose over 20 days of 0.069 μSv—the greatest of all observed cells. This cell is also notable for the electrolyte clarity and lack of deposits at the bottom of the cell at the end of the test run. Cell T-IV-E1 represents an average neutron-producing experimental cell at 0.043 μSv over 20 days. Although 0.031 μSv over 20 days made T-III-E5 a below average neutron-producing experimental cell, it was still above the control cell average. It may be that the higher performing cells exhibit more Pd adhering to the cathode surface and a more distinct dendritic structure.

The findings herein were compared to those of other researchers [24] who found neutron activity using similar cell and operational protocols, but who measured neutron activity with a BF_3 neutron detector. The 2016 work corroborates other research that determined the highest nuclear activity occurred when the PdD deposits resulted in stable dendritic formations on the cathode. In cells where the PdD layer exhibited poor adherence to the electrode, neutron activities were less than the highest neutron-producing cells but remained above control-cell levels. Even though there is clear

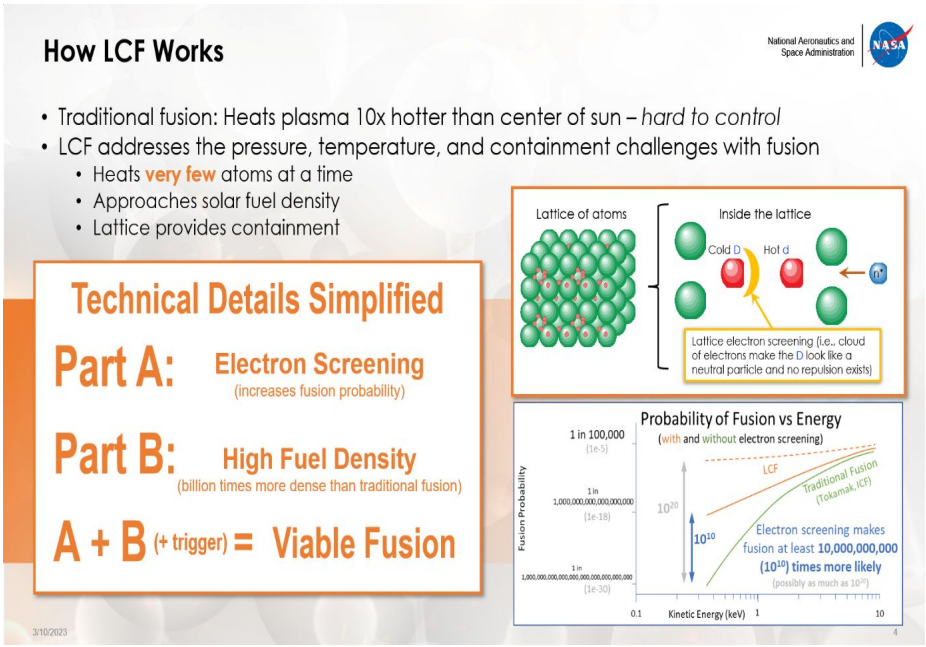


Figure 16. Lattice confinement fusion accomplished with a deuterated lattice of metal atoms, energized neutrons, and lattice electron screening.

evidence of neutron production favoring the experimental cells, the radiation produced by all individual cells was low, and the dose was the equivalent of <0.1 μSv per month adjacent to the cell wall [5].

Highlights of these experiments include:

- Bubble detector neutron dosimeters measured electrochemical cell neutron activity.
- Case control: $PdCl_2/LiCl/D_2O$ cells were compared with $CuCl_2/LiCl/D_2O$ control cells.
- Experimental cells exhibited neutron activity greater than controls: 99% confidence.
- Highest neutron-generating experimental cells produced dendritic cathode deposits.
- Neutron activity cannot be explained by chemical reactions, only nuclear processes.

14. Lattice Confinement Fusion (LCF)

Called Lattice Confinement Fusion, the method NASA revealed accomplishes fusion reactions with the fuel (deuterium, a widely available non-radioactive hydrogen isotope composed of a proton, neutron, and electron, and denoted “D”) confined in the space between the atoms of a metal solid (Figure 16). In previous fusion research such as inertial confinement fusion, fuel (such as deuterium/tritium) is compressed to extremely high levels but for only a short, nano-second period, when fusion can occur. In magnetic confinement fusion, the fuel is heated in a plasma to temperatures much higher than those at the center of the Sun. In the new method, conditions sufficient for fusion are created in the confines of the metal lattice that is held at ambient temperature. While the metal lattice, loaded with deuterium fuel, may initially appear to be at room temperature, the new method creates an energetic environment inside the lattice where individual atoms achieve equivalent fusion-level kinetic energies.

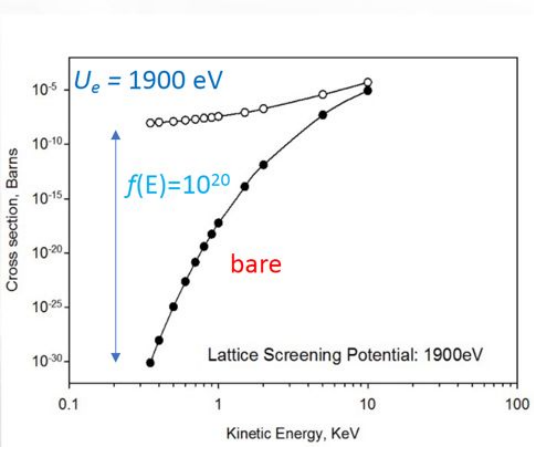


Figure 17. Screening Enhancement.

15. How LCF Works

In the current research, nuclear reactions are triggered in titanium or erbium metal lattices loaded with the hydrogen isotope deuterium—at densities approaching 10^{23} ions/cm^3. Such high fuel densities are greater than those available in current magnetic confinement (tokomak) fusion reactors, which have densities of only 10^{14} ions/cm^3 (Greenwald Limit). Also, previous deuterium (and tritium, another isotope of hydrogen) fusion research with tokamaks has relied upon temperatures 10 times the center of the Sun, yet the NASA method accomplishes the same in the loaded metal lattice. While the deuterium-loaded metal lattice may initially be at room temperature, the new method creates an environment where individual atoms achieve equivalent fusion-level kinetic energies first through electron screening and then through momentum transfer.

16. LCF Demonstrated Nuclear Fusion

Lattice Confinement Fusion uses deuterated metals at a high-density of 10^{23} ions/cm^3 where deuterons are held indefinitely in a metal lattice. The negative charge of lattice electrons screen and partially neutralize the positive deuteron charges. This neutralization effect reduces the Coulomb barrier allowing the deuterons to fuse. LCF is then triggered and controlled by bremsstrahlung [9], phonon-nuclear coupling, [25] or other means resulting in an equivalent local deuteron ion temperature of > 2.1 keV kinetic energy (24 million °C) as compared to the sun at 1.5 keV (17 million °C).

17. Electron Screening

Electron screening, noted as U_e, is where electrons 'screen' positively charged particles to approach more closely and "slip" under the Coulomb barrier. This method was applied to astrophysics by Salpeter in 1954 [26] and Hagino in 2002 [27]. Later, laboratory astrophysics experiments in 1986 [28] and later [29] using accelerated deuteron beams demonstrated electron screening effects below 10 keV that exponentially increased at lower energies as compared to the fusion of bare deuteron nuclei. As Figure 17 shows, the enhancement factor *f(E)*, can exceed 20 orders of magnitude at low kinetic energies!

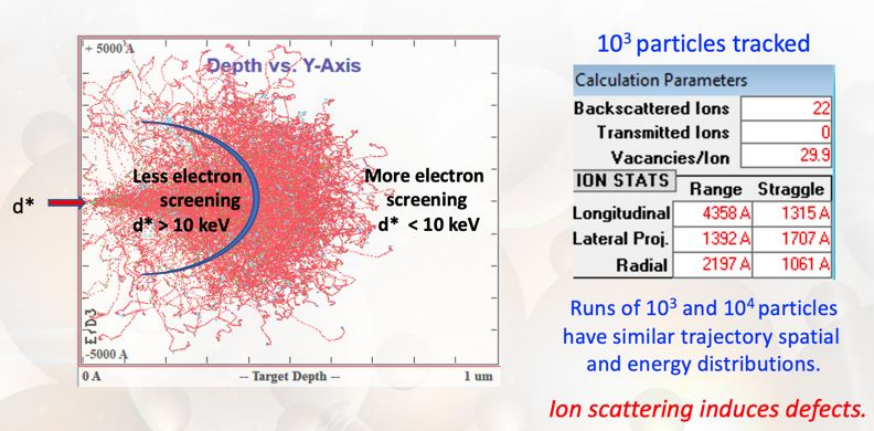


Figure 18. Ion Transport.

Remarkably, 1 keV of screening is the equivalent of 11 million degrees C where *the deuterons are locally hot but globally cold*.

Electron screening is essential for efficient nuclear fusion reactions to occur. Screening effects on fusion reaction rates as measured in deuterated materials have been demonstrated to be important.

The nuclear reaction rate includes two primary factors: the Coulomb scattering of the projectile nuclei on the target nuclei as well as nuclei tunneling through the Coulomb barrier [14]. During elastic scattering of charged projectiles on a target nucleus, such as a deuteron, some of the energy of the projectile particle is transferred to the target nucleus, hence heating it. Depending on the projectile particle energy and the efficiency of kinetic energy transfer during the scattering event, the target deuteron may become energetic enough to enable subsequent nuclear fusion reactions via tunneling through the Coulomb barrier. Electron screening plays a significant role in this process because of hot fuel interacting with lattice nuclei in the highly screened environment, as has been demonstrated in the companion experimental work reported in Steinetz et al. [8], [9].

Figure 18 shows a fast deuteron slowing in ErD_3 using the SRIM/TRIM Ion transport code [30]. Even a 64 keV deuteron will eventually slow to below 10 keV where electron screening predominates. Similar results have been shown using co-deposition with the observation of > 10^5 energetic protons and alpha particles with CR-39 detectors [31].

18. Summary

We have demonstrated multiple nuclear reactions initiated by various experimental techniques where detected nuclear emissions were neutrons, alphas, protons, betas, and ^{3}He. However, not all methods produce expected d-d reaction products. Transmutations, including tritium and heat release were also observed and detected. The co-deposition and LINAC photon stimulation experiments were highly reproducible by our team.

LCF electron screening theory along with astrophysics [27] and accelerator [28] experiments have provided insights in addressing the Coulomb barrier.

During our research efforts, we have developed critical concentration of expertise in multiple disciplines plus experimental and theoretical resources and are following evidence-based approach to enable timely progress. We have enlisted LANL MCNP [32], PoliMi [33] and CERN GEANT-4 [34] nuclear modeling codes, Quantum Espresso Density Functional Theory code and SRIM/TRIM [30] for modeling ions in condensed matter. It was problematic to realize that neither MCNP nor GEANT-4 can model light ions, like protons, deuterons, or alphas at energies below

1 MeV [35]. Conventional fusion occurs at energies below 100 keV whereas electron screened reactions predominate below 10 keV.

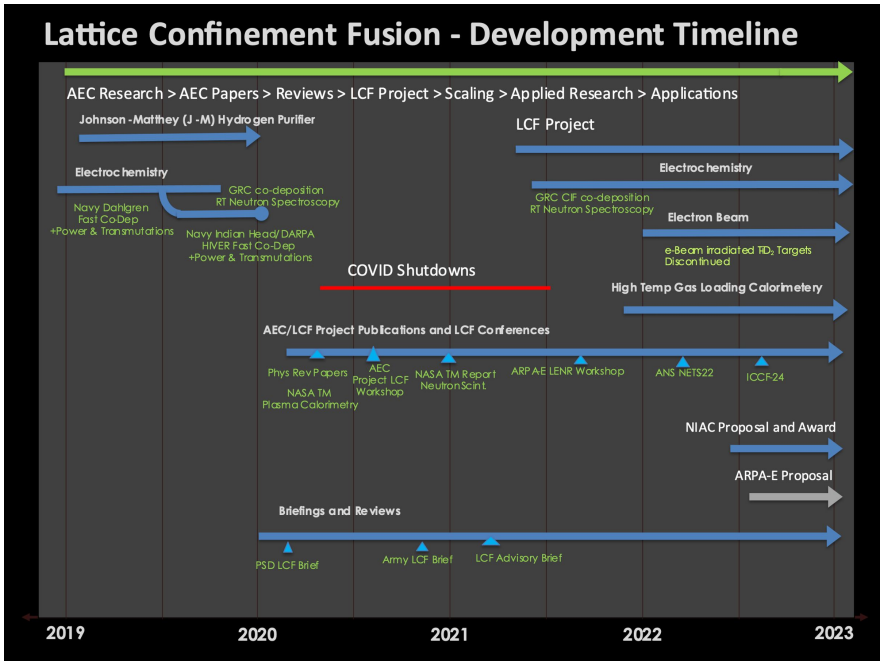
Just as important, we have learned the limitations of various hydrogen isotope loading, material triggering and diagnostic confluences. Depending upon the triggering used, these limitations can range from a high gamma ray background to electromagnetic interference. Material assays are complicated by handling and various means of contamination transportation. Nuclear diagnostics can be compromised by background gamma and alpha sources and cosmogenic neutron flux. The latter is especially problematic in identifying low level 2.45 MeV D$(d,n)^3$He fusion neutrons as the cosmogenic neutron flux also has a neutron evaporation peak at 2.5 MeV! [36].

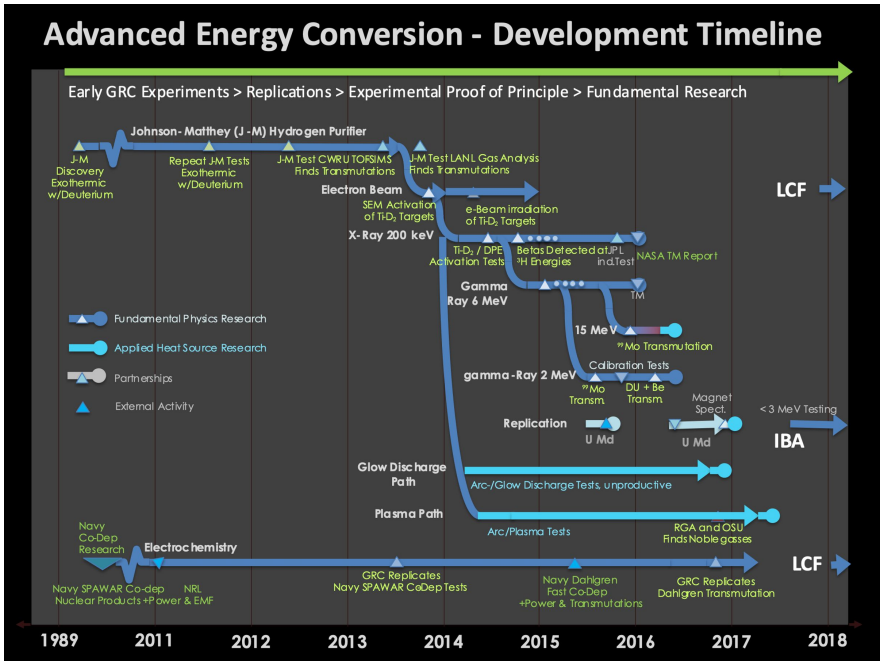
The further development and scaling of Lattice Confinement Fusion reactions could have significant space and terrestrial applications. A NASA Innovative Advanced Concepts (NIAC) Proposal, "Accessing Icy World Oceans Using Lattice Confinement Fusion Fast Fission" was accepted and began on February 1, 2023, with a presentation to the NASA JPL Cryobot Workshop in March 2023 [37].

Appendix

NASA AEC and LCF Development Timelines

This paper is based upon an ICCF-24 Invited Session updated for submission to JCMNS at: https://www.youtube.com/watch?v=axH4kmYediQ





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