NASA GRC Hosts Lattice Confinement Fusion Virtual Workshop

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Executive Summary

Since 2014, the Advanced Energy Conversion (AEC) Project has examined novel nuclear reactions in materials that absorb large quantities of deuterium fuel tightly held in a lattice. These experiments culminated in a bremsstrahlung irradiation campaign that repeatedly induced nuclear reactions in deuterated metals. According to the theory developed during the project, the metal lattice's negative electrons screened positively charged deuterons to overcome the electrostatic barrier to achieve nuclear fusion initiated by photoneutrons. This discovery opens a new path for initiating fusion reactions for the scientific community and possibly deep space power for NASA. The prestigious journal, *Physical Review C* (*PRC*), published the experimental observations and the underpinning theory in their April 2020 issue. A followup virtual Workshop was held on May 21, 2020 using the Webex platform to present the journal papers and have a NASA panel of experts evaluate the research and its application.

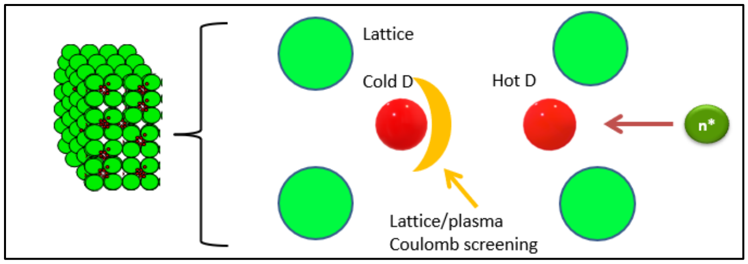


Figure 1: Neutron heating induced fusion in a deuterated lattice

Subsequently, NASA Technical Papers derived from the journal papers and Workshop material appearing on the NASA GRC LCF website garnered 244 visits in the first week of going 'live'. One of the staff writers at IEEE Spectrum took an interest in our work after visiting that website, contacted the NASA GRC News Chief, interviewed 2 of the AEC team members, and ran an article viewed by 45,000 predominately engineers and scientists over its first five days online and within a month had been viewed 50,000 times. Consequently, the IEEE requested a full article for their monthly magazine. The American Nuclear Society also picked up the IEEE Spectrum article and published their own piece. The Asia Times published an article after reviewing the *PRC* journal papers. In addition, Popular Mechanics published an article as a result of visiting the LCF website and shared the LCF animation from the website. The US Army requested and received a briefing on September 14, 2020 that included civilians from the Naval Surface Warfare Center, Indian Head.

The Workshop objectives were to disseminate and discuss the findings published in the *PRC* journal which were both successfully met and are detailed below. This report summarizes the Workshop presentations and includes the Panelists' and Attendee Feedback, Question and Answer Sessions, the table of contents of and links to the NASA Theory and Experimental Technical Reports, and the Panelists' biographies.

Workshop Objectives

Approximately 75 scientists and engineers participated in the 4-hour online workshop where the AEC team presented key results from the two published papers. The presentations emphasized different forms of electron screening in a confined lattice and neutron recoil heating to initiate nuclear fusion. The objectives of the workshop were twofold:

1) Disseminate the key experimental and theoretical findings in the recently published *Physical Review C* journal papers

2) Identify challenges to the findings through invited questions and critiques from all participants, and feedback from invited panelists.

Presenters, Panelists and Attendees

The presenters were: Dr. Bruce Steinetz, (NASA GRC), Dr. Theresa Benyo (NASA GRC), Dr. Arnon Chait (NASA GRC), Mr. Len Dudzinski (NASA HQ), Mr. Lawrence Forsley (GEC and NASA GRC), and Dr. Vlad Pines (Pines Consulting and NASA GRC).

The NASA Panel members were: Dr. Matthew Forsbacka (NASA HQ), Dr. Ron Litchford (NASA HQ), Dr. Mike Houts (NASA MSFC) and Mr. John Scott (NASA JSC). Each of the Panel members came from different NASA Centers. They had also participated in previous NASA HQ requested reviews of the AEC Project. Furthermore, each brought different, and independent, expertise to bear on both the *Physical Review C* papers and the Workshop.

Some of the notable attendees included: Dr. Marla Perez-Davis (GRC Center Director); Dr. John Grunsfeld (former Associate Administrator for the Science Mission Directorate); Dr. Arden Bement (former NIST and NSF director) and Dr. Michael Salamon (former NASA Program Scientist). Several participants provided feedback regarding possible follow-on LCF research.

Background

The NASA Planetary Science Division has successfully used radioisotope thermally powered generators for decades where solar power was impractical. However, future missions require higher power levels and nuclear enabled propulsion. The AEC project demonstrated a new form of driving nuclear reactions without fissioning radioactive material or using large lasers or tokamaks to induce fusion. Their detection of lattice confinement fusion (LCF) takes advantage of non-radioactive, high density deuterium held in non-actinide metal lattices triggered by bremsstrahlung radiation to initiate fusion and other nuclear processes.

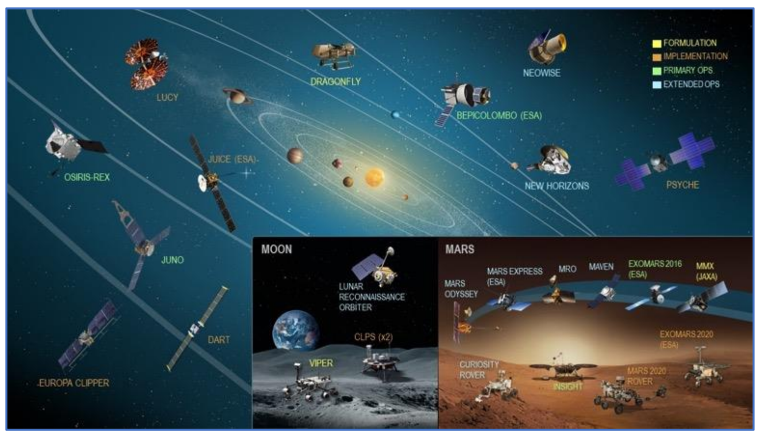


Figure 2: NASA Planetary Probes

Workshop Summary

A new way of both causing and studying long sought-after d-D fusion was presented during the workshop offering the workshop participants a detailed overview of the team's significant scientific work.

Exposing deuterated Er and Ti (which hold deuterium fuel at near stoichiometric levels) with bremsstrahlung radiation, the team reported that they were able to cause reproducible d-D fusion in metal lattices. The starting fuel was tightly confined within the metal lattice. The team also developed a theory that explains not only the d-D reactions but also how the lattice provides screening to allow interaction with the parent metal resulting in Oppenheimer-Phillips (O-P) deuteron stripping reactions.

The environment is characterized as globally cold (ie. the fuel is at ambient temperature) yet locally hot (where the average center of mass deuteron temperature is 3.5×10^8 °C) where photo neutrons "heat" deuterons to levels such that both primary fusion occurs, as do subsequent O-P processes resulting in even higher energy neutrons and the potential for reaction boosting and scale-up.

The team's detection of lattice confinement fusion was compared to the other two common fusion approaches: inertial confinement fusion and magnetic confinement fusion. The team believes the theoretical foundation in the theory paper provides valuable insight into not only lattice confinement fusion but also fusion processes across the spectrum.

The workshop organizers also invited a panel of NASA senior engineers and managers to identify challenges to the theory, and provide critiques to the recently published papers on lattice confinement fusion theory and experimental results.

After each presentation (Experimental Paper, Theory Paper, Panelist Session or Going Forward Session), workshop participants were invited to ask questions of the presenters. There were insightful questions asked and the answers given by the presenters helped give the audience better insight into the material presented.

Comparison of Fusion Reaction Types

Fusion reactions primarily consist of deuteron-deuteron (DD), deuteron-triton (DT) and deuteron-helion (D^3He) reactions where the ^3He, or helium-3, is known as a helion. The primary DD reaction produces either a proton and a triton or a neutron and a helium-3. Subsequent secondary reactions amongst these products result in helium-4 or alpha particles being produced. 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 of time, 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 and 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. 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 discovery accomplishes the same at room 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.

Approach	Core Diameter	Fuel	Density (ions/cm^3)	Confinement Time	Fusion Initiation	Example
Lattice Confinement Fusion (LCF) (New Process)	~Centimeters (scalable)	• Deuterated metals (e.g. ErD_3; TiD_2) • Other	10^{22}-10^{23}	Indefinite	n heats "d" (e.g. n from photoneutron) New Process→	
Magnetic Confinement Fusion (MCF) (Tokamak)	Meters	• D-D • D-T	10^{14}	Seconds	Plasma TFTR →	
Inertial Confinement Fusion (ICF) (LASER Fusion)	<100-micron core	• D-T hohlraum • Other	10^{26}	Nano-seconds	Laser Implosion Omega→	

Figure 3: Comparisons among Lattice Confinement, Inertial Confinement and Magnetic Confinement Fusion

Figure 3 compares three forms of fusion:

- Lattice Confinement Fusion (LCF):
  - high density, long confinement, photo-neutron initated, < 1 – 64 keV *hot*
- Magnetic Confinement Fusion (MCF)[1]:
  - low density, modest confinement, RF heating initiated, 1 - 10 keV *hot*
- Inertial Confinement Fusion (ICF)[2]:
  - high density, brief confinement, laser compression initated, 3 - 10 keV *hot*

Inertial and Magnetic Confinement Fusion

Whereas ICF and MCF maintain the DD or DT fuel as a gaseous plasma, LCF keeps the bulk of it as a low temperature, dense plasma in a lattice. Fusion rates depend upon fuel density, confinement time and plasma temperature. ICF and MCF rely upon alpha particles to inefficiently heat the entire the fuel. Notably, the LCF deuteron fuel is globally at room temperature but locally heated by neutrons and screened particle recoils. Furthermore, both ICF and MCF start with radioactive tritium to improve their fusion probability.

ICF relies upon laser ablation and compression (direct drive) or induced x-ray compression (indirect drive). Consequently, as the fusing target rapidly expands and disassembles the reaction stops as the fuel density and temperature drop. MCF uses various combinations of radio-frequency and ohmic heating to simultaneously produce, compress and heat an underdense plasma. However, the plasma is difficult to maintain as it kinks and escapes, or becomes contaminated by interacting with the vessel, stopping the fusion reactions.

Lattice Confinement Fusion Reactions

LCF relies upon the electric and magnetic forces inherent in a metal lattice to constrain a low temperature plasma while the same electrons screen and either enhance the fusion rate or promote interactions with the metal lattice via Oppenheimer-Phillips stripping reactions. These stripping reactions provide both additional energetic particles and, by capture on the lattice, a means of forming new isotopes useful to medicine with other applications. The pathways are shown in the adjacent figure where:

(A) Highly deuterated host metal materials are irradiated by X-rays (or gamma rays), which at sufficient energy split deuterons into constituent neutrons (n) and protons (p).

(B) Energetic neutrons impinge on and transfer energy to neighboring deuterons (d), accelerating them to keV energies (d^*).

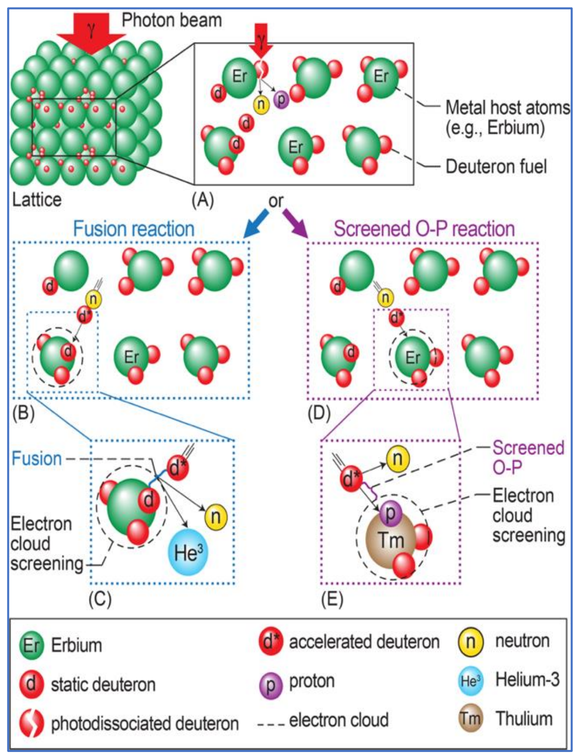


Figure 4: Lattice confinement nuclear reactions

[1] https://commons.wikimedia.org/wiki/Category:Tokamak_Fusion_Test_Reactor#/media/File:U.S._Department_of_Energy_-_Science_-_114_035_002_(14281232230).jpg

[2] https://upload.wikimedia.org/wikipedia/commons/8/86/U.S._Department_of_Energy_-_Science_-_282_022_002_%2816502292185%29.jpg

(C) Energetic deuterons (d^*) impact and fuse with adjacent deuterons (d), resulting in standard products per either of the following reactions:

$d+d^* \rightarrow n(2.45\ MeV) + He\text{-}3$ (shown) or
$d+d^* \rightarrow p(3.02\ MeV)$ + tritium.

(D) Some limited number of accelerated deuterium (d^*) are screened by the neighboring lattice metal atom's shell electrons.

(E) d^* particles react with host metal atoms via Oppenheimer-Phillips processes, either absorbing the proton (shown) or neutron and ejecting the remaining energetic particle.

Key Accomplishments

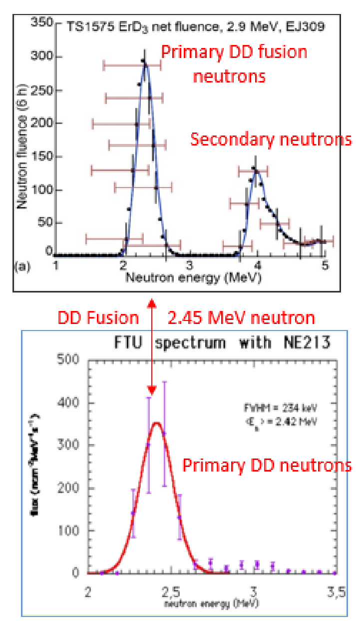
The workshop presented the key accomplishments completed during the experimental campaign that culminated with the publication of the two journal papers.

- Demonstrated d-D fusion in a unique environment by using room temperature fuel with locally hot deuterons heated by photoneutrons or other neutron sources.
- Measured nuclear emissions by state-of-the-art calibrated neutron spectroscopy indicating fusion neutrons and boosted nuclear reactions possibly leading to energy gain.
- Correlated observations with models, external data, and supported by the physics community.
- Gained theoretical insights from astrophysical modeling to address Coulomb Barrier reduction via lattice electron screening and predicted the rate of d-D fusion reactions.
    - d-D interactions enhanced by favorable large/small angle scattering probability.
    - High-Z interactions: O-P processes benefit from increased nuclear tunneling probability and further creates hot reaction products n*, p*.
- Developed critical concentration of expertise in multiple disciplines, experimental and theoretical resources.

Key Experimental Results

In order to carry out this experimental program, the team developed nuclear diagnostics capable of operating in a high radiation background and algorithms to separate gamma rays from neutron signals for spectroscopy. High-intensity primary bremsstrahlung from the Dynamitron beam and secondary fluorescence x-rays were the major challenges for postprocessing the detector signal, even though the detectors were shielded in the lead cave. The strategy was to record all detector signals without any information loss with the fast data acquisition system throughout the beam exposure. A sophisticated model-based pulse shape discrimination (PSD) signal analysis procedure was developed for the postprocessing data analysis.

Other modeling taken into consideration were radiation shielding, neutron scattering and detector responses, which led the team to devise methods of modeling electron screening, neutron heating and fusion reactions. In particular, electron screening was found to exponentially increase nuclear reaction rates and is important to astrophysics with regards to stellar evolution, proto-star formation and



Italian ENEA-Fusion Tokamak[1]

[1] "Neutron spectrum in FTU ohmic discharges" Fig 10, https://www.afs.enea.it/basilio/neutronica/Neutroni.html

Figure 5: LCF vs MCF neutron energies

gas giant planets. Lattice confinement fusion requires Fermi-degenerate matter, where electron densities are sufficiently high to require quantum mechanical treatment. Fermi-degeneracy is present in conductive metals and it prevents white dwarf stars from collapsing. LCF energies are in the range of eV to multi keV with MeV reaction products while overlapping the 1 eV – 100 eV temperature range and ion densities of warm dense matter. The team accomplished the following:

- Demonstrated feasibility of initiating fusion reactions with simple, relatively inexpensive equipment.
- Developed and deployed nuclear spectroscopy in high gamma background.
- Exploited neutrons to effectively heat deuterons in primary and subsequent reactions with the well-screened cold target fuel.
- Demonstrated impact of efficient electron screening on localized fusion rates in a dense fuel environment.
- Performed fusion cycle at high fuel density inside a metal lattice, which enables subsequent reactions with the host metal nuclei and other secondary processes.
- Boosted fusion results indicate scaling path.

Detailed neutron energy spectroscopy indicated both fusion energies (2.45 MeV) and neutrons having greater than fusion energy. The figure to the right compares neutron spectra from the current work (top) to the Italian ENEA Tokamak showing the same peak of fusion neutrons at 2.45 MeV.

Key Theoretical Development

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[3,4]. The nuclear reaction rate includes two primary factors: the projectile nuclei Coulomb scattering on the target nuclei or tunneling through the Coulomb barrier. 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.

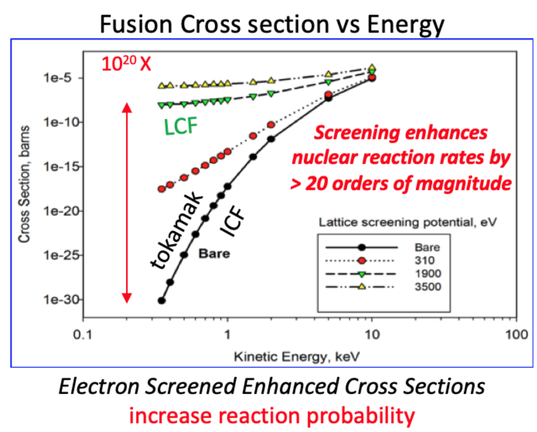


Figure 6: Fusion cross-section vs deuteron energy

- Neutron large angle scattering is the most efficient means to heat cold deuterons, e.g. bremsstrahlung photoneutrons and fusion neutrons most efficiently heat d to initiate d-D fusion
  - Globally "cold", locally "hot"
  - Other neutron source may be substituted for photo-neutrons
- Screening: Shell, conduction, or plasma electrons

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[3] Strieder, F., et al.: Electron-Screening Effects on Fusion Reactions. *Naturwissenschaften*, **88**, (2001), pp. 461–467. https://link.springer.com/article/10.1007/s001140100267

[4] Bonomo C., et al.: Enhanced Electron Screening in *d*(*d*, *p*)*t* for Deuterated Metals: A Possible Classical Explanation. *Nucl. Phys. A*, **719**, (2003). https://www.sciencedirect.com/science/article/abs/pii/S0375947403009552?via%3Dihub

- Unique environment for fusion
- Localized fusion rates enhanced by efficient electron screening in a dense fuel environment (~10^{23} fuel atoms/cm^3)
- Window into novel path of initiating d-D fusion
- Essential role of electron screening in nuclear fusion: Seemingly negligible – but <u>critical</u>
- Unified formulation of all screening types: shell, conduction, plasma channels created by gamma and Compton electrons
- Increase in astrophysical factor *S(E)* due to screening independent of tunneling

- Large angle scattering with screened charged particles and neutrons

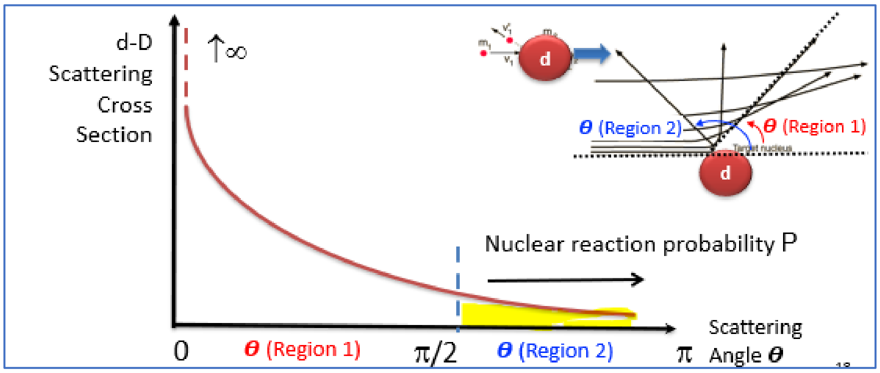

Figure 7: Electron screening and large angle scattering

Figure 7: Electron screening (lattice) → Large angle scattering (***θ*** (Region 2)) resulting in smaller distances between the deuterons → quantum tunneling becomes possible, increasing transparency of Coulomb barrier → increased fusion probability.

- Kinematic equations for calculations of all reaction product energies including subsequent events.

Panelist Feedback

The invited panel of NASA senior engineers and managers identified challenges to the theory and provided critiques to the recently published papers on lattice confinement fusion theory and experimental results. The panel was comprised of the following individuals:

- Dr. Michael Houts, Ph.D., NASA Marshall Space Flight Center, Principal Investigator for Nuclear Thermal Propulsion
- Mr. John Scott, NASA Johnson Space Center, Chief Technologist, Propulsion and Power Division
- Dr. Ron Litchford, Ph.D., NASA Headquarters, Space Technology Mission Directorate, Principal Technologist for Propulsion
- Dr. Matt Forsbacka, Ph.D., NASA Headquarters, Office and Safety and Mission Assurance, Director, Mission Assurance Standards and Capabilities Division

The panelists addressed general themes regarding how lattice confinement fusion is gaining acceptance in the technical community, technical comments and questions, and next steps towards practical application.

Dr. Michael Houts

Dr. Houts led a discussion about how feedback from the recently published papers could help guide work going forward. Dr. Steinetz indicated that several dozen inquiries had been received in the few weeks since publication of the papers. He then discussed the key topics the *Physical Review C* brought up by the peer reviewers during the publication process. Dr. Chait provided background on the delay of the papers due to both papers being reviewed in tandem and delays in getting comments from one of the peer reviews. Dr. Steinetz noted all of the reviewers agreed that the papers merited publications. An area of technical feedback was discussed regarding the topic of signal filtering related to neutron spectroscopy and discriminating signals attributed to gamma radiation and neutron interactions. Additionally, the papers' authors addressed questions regarding plasma conditions in solid-state material.

Dr. Houts commented that a very limited number of people understood the concept of nuclear fission at the time of its discovery in 1939 and approximately three years later the first human-made self-sustaining fission chain reaction was demonstrated in the Chicago Pile-1. He asked the team to comment on any parallels to lattice confinement fusion with regard to gaining general acceptance. Dr. Chait commented that the near-term goals for lattice confinement fusion are driven by more modest power output goals; however, the technology could have scaling potential when integrated with more conventional nuclear fission systems. He went on to discuss that modeling and small scale experiments could be done by other groups at relatively low cost that would further demonstrate the utility of lattice confinement fusion and lead to broader acceptance of the theoretical concept and its implementation in power systems. Dr. Chait also highlighted that special nuclear material is not required and that the experiments are essentially "walk away" safe, so the barriers to entry to this field are relatively low. Dr. Houts concluded his portion of the panel discussion by commenting that the potential for other groups to replicate the experimental methods given its scalability and inherent safety characteristics is very encouraging.

Mr. John Scott

Mr. Scott noted the substantial progress in expressing the theory underlying lattice confinement fusion since he was first exposed to the subject in 2017. It can be now be understood by a non-specialist audience, and the theory is coherent. He commented that with respect to energy balance there remain unknown intermediate charged particle reactions that could be controlling factors regarding the photon going into the deuterated material and the resulting neutrons and additional photons that emanate from the lattice confinement fusion process. This comment led to a discussion of how the process is controlled and whether lattice confinement fusion is subject to the concept of criticality in context of a self-sustaining reaction. Mr. Forsley answered that the scale of the system in terms of neutron mean free paths is a determining factor in managing the neutron economy in a lattice confinement fusion-enabled energy production system. He went on to state that while the two papers that have been published don't go into the detail on how to harness lattice confinement fusion, the research group has been developing the conceptual basis for relatively near term realization of a practical power system. Dr. Benyo indicated that the incremental steps in the experimental program have created the building blocks for extending the research towards realizing engineering solutions. Mr. Scott also offered praise that the team doesn't overpromise such as "ending the carbon economy" but is instead continuing to focus on exploring the fundamental physics.

Dr. Ron Litchford

Dr. Litchford provided further observations on the experiment and theory. He noted that publishing the papers in tandem made the full story much more powerful. He observed that the experiment paper clearly indicated meticulous execution and attention to detail. He highlighted that the work done in signal discrimination and the attention to potential spoofing events lends a high degree of credibility to the overall effort. With regard to interpretation of the experimental results, he noted that the team:

- Showed well-characterized neutron production rates and energy spectra
- Demonstrated reproducibility with multiple ErD_3 and bare Er experiments
- Provided a theoretically framed analysis and interpretation of results
- Showed compelling evidence for electron screening in advancing the lattice confined fusion hypothesis

With regard to the theory paper, Dr. Litchford noted that the novel physical mechanisms are rooted in well-established foundational physics. The approach to parameterizing the theory in terms of electron screening parameters and the Coulomb barrier tunneling probability enhancement factor was helpful in clarifying and quantifying the lattice confinement fusion process. He also noted that the team had performed an exhaustive evaluation of contributing mechanisms and non-ideal effects such as:

- Enhanced Coulomb barrier screening mechanisms
- Enhanced probability of large-angle Coulomb scattering
- Enhanced secondary nuclear reactions

Dr. Litchford noted the theory paper enables *a priori* predictions on known or estimable parameters which enhances testability and verifiability of lattice confinement fusion.

Next Steps

In the concluding portion of Dr. Litchford's comments, he noted areas for future work that echoed comments by Mr. Scott and set the stage for Dr. Forsbacka's comments. In particular, he noted that:

- Fine grain quantification of primary/secondary contributing mechanisms will most likely help resolve masking effects from competing lattice confinement fusion processes
- Further work in resolving lattice structure effects could accelerate practical engineering solutions by considering:
    - Fuel loading optimization
    - Screening dependencies in terms of lattice scales, void fraction, defects, dislocations, and grain structure
    - Engineered lattice assemblies enabled by atomic layer deposition and epitaxial growth methods
- Resolving fusion reaction energetics and overall fusion power yield

Addressing these topics will benefit understanding of gain and power scaling, engineering assembly configurations and process optimization, evaluating technical application scenarios, and reduce LCF to engineering practice.

Dr. Matt Forsbacka

Dr. Forsbacka focused his comments on practical applications for power systems by integrating lattice confinement fusion with traditional nuclear engineering. The neutron yield of the lattice confinement fusion process favors nuclear engineering solutions that operate on a fast neutron economy. Dr. Forsbacka provided the energy dependent fission cross sections for ^{235}U and ^{238}U which show that the two isotopes are roughly equivalent when the fission inducing neutron is above 1 MeV. This obviates the need for using special nuclear material and further confirmed Dr. Chait's earlier comment that the barrier to entry to conducting research in this area is much lower in comparison to systems requiring uranium enriched in the ^{235}U isotope. Whereas boosted thermonuclear devices operate on a fission-fusion-fission principle, an energy producing system capitalizing on lattice confinement fusion would operate on a fusion-fission-fusion principle with depleted uranium that is incapable of sustaining a fission chain reactor on its own. Dr. Forsbacka also suggested that a lattice confinement fusion matrix containing tritium in lieu of deuterium may provide a greater yield of high energy neutrons that will further enhance a practical fusion-fission-fusion power solution.

Panelist Session Conclusion

The panel discussion concluded with a question from the audience on what the next steps should be. Dr. Forsbacka offered that the goals of the team will shape the future. One path could be to focus on continually refining the science of lattice confinement fusion and attempt to make the science applicable to a broad spectrum of potential users. Another path could be to set a pragmatic engineering goal for a realizable power system using lattice confinement fusion in a hybrid capacity with conventional nuclear engineering methods. Dr. Forsbacka opined that the latter path is the quickest way to get lattice confinement fusion off the lab bench and speed integration into power solutions of relevance to NASA missions and eventually to other users.

Attendee Comments

Positive comments from various attendees listed below noted the AEC team used recognized scientific methods and should pursue LCF further:

> "I wish to thank you and all of the panelists yesterday for the superb and compelling presentations. As a former advisor to the director of NASA Glenn (Larry Ross) and the NASA Administrator (Dan Goldin), I feel some of the pride that must permeate the Glenn experimental the theory teams. The work is outstanding."
>
> *Arden Bement, Ph.D. (former Director of NSF and NIST)*
>
> "Fun event, very nice presentations and discussions. I'd be happy to be part of follow ups if there is interest (e. g. ideas for next experiments, cross checks, etc). Also an interesting example of a targeted workshop in the "new normal" of no or hardly any travel, which we might be stuck in for a while."
>
> *Thomas Schenkel, Ph.D. (Lawrence Berkeley National Lab)*
>
> "Thank you for inviting me to attend yesterday's briefing. The team has made remarkable progress during these last few years in the conduct and findings of the experimental work along with its theoretical underpinnings. Congratulations to you all for your impressive advances!"
>
> *Michael Salamon, Ph.D. (former Program Scientist, NASA HQ)*
>
> "…that was a really terrific session, thank you! I congratulate you and your team and look forward to your further successes!!"
>
> *Curt Brown (PointSource Energy)*
>
> "Thanks for including me in the virtual workshop today. I was glad to hear that other labs are working in the area of LCF. Verification by independent sources was mentioned by a nuclear scientist friend as an important step in gaining acceptance of LCF."
>
> *Frank Lynch (Hydrogen Components, Inc.)*

Going Forward Session

- The *PRC* papers demonstrate repeatable Lattice Confinement Fusion initiated by bremsstrahlung γ irradiation of deuterated lattices.
- The goal is to further understand and scale LCF through modeling, experiments and analyses.
  - Modeling allows us to predict the best lattice materials, mass, geometry and reaction rates.
- This understanding will lead to useful gain and scaling necessary for engineering and application.
- There is a "sweet spot" between neutron heating in a confined lattice and locally warm dense matter driven under electron screening.
  - Subsequent work will explore neutron heating, screened charged particle scattering, and scaling while searching for the sweet spot.
- Besides energy research, LCF provides means to explore electron screened, warm dense matter, laboratory astrophysics.

Conclusion

The AEC Project demonstrated a new and unforeseen means of initiating fusion and other nuclear reactions. Further study will examine means to scale the identified process providing the scientific foundation to engineer a new deep space power system. If the process can be scaled to significant levels, it may fulfill NASA's more demanding power needs for manned and robotic missions. Non-NASA spinoffs include manufacturing medical radioisotopes without either highly enriched (HEU) or low-enriched (LEU) uranium. LCF technology developed for deep space power could be adapted to small scale terrestrial power. However, additional research and development is necessary to reach sufficient power levels for space operation, let alone terrestrial power production.

Appendix I: Questions/Answers (Q/A)

Experimental Session Q/A

1) What are the prior experiments that showed novel reactions I mean what experiments got you interested? Referencing slide 15

Brief Background/Timeline of Current Work

Date	Activity
2012-2016	AEC Project early years: investigated novel reactions observed in highly deuterated materials using various initiation schemes
Feb. 2017	HQ Science Panel Review of AEC: Commissioned Bremsstrahlung Radiation Test Campaign
Sept 2018	Briefed Findings to HQ Sponsor (Science Mission Directorate)
Oct 2018	Submitted two Articles to Phys Rev C Journal for consideration
2019 (various)	Interactions with Journal Reviewers, Editors, Manuscripts
Dec 2019	Journal Papers Accepted for Publication
April 2020	Journal Papers Published On-line; April Issue of *Phys Rev C*
May 2020	Lattice Confinement Fusion Workshop

Figure 8: AEC Project Timeline

We used an x-ray CT scan device with a microfocus beam in one of the earlier experiments where we exposed deuterated metals and deuterated polyethylene and discovered tritium was produced. We also used a 6 MV LINAC at Plum Brook with a braking target and exposed deuterated metals. We observed the production of Mo-99 which decays to Tc-99, for instance. However at that time, we did not have the appropriate instrumentation to do neutron spectroscopy. We were doing all the research via pre- and post- gamma spectroscopy and treating targets as witness materials to see what kind of reactions had occurred. The HQ Science Panel liked that but really wanted us to dig deeper into the nature of those reactions so we developed real-time neutron spectroscopy and we were directed to do this at an external site.

2) Why are the error bars larger on the low-energy side of the neutron spectra?

The error bars are shown in slide 39 (below). The detectors were calibrated with a standard gamma source which is in electron equivalent units. To convert the electron equivalent unit to neutron energy, we used a conversion method which is an inverse problem like the neutron unfolding algorithm. The conversion factor is non-linear, depending on the energy, so the error range is larger at the low end than the high end.

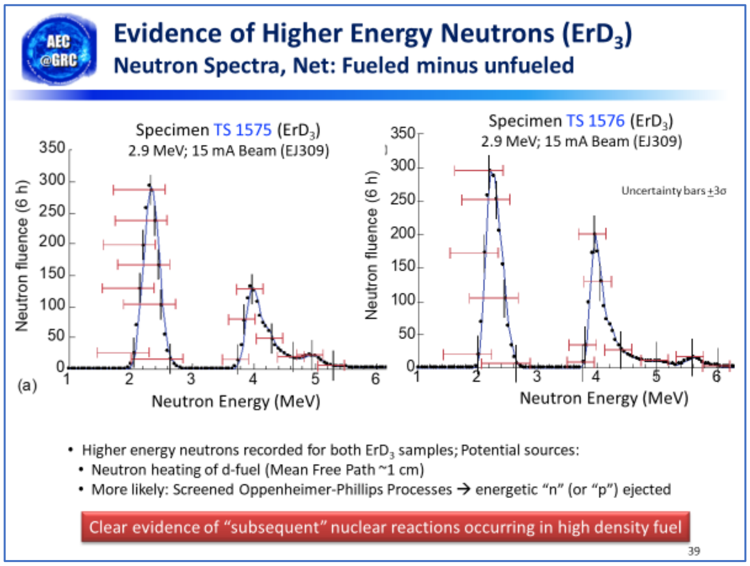

Figure 9: Lattice Confinement Fusion Repeatability, slide 39

3) What is the overall value for neutrons input energy?

The average neutron energy from deuteron photo-dissociation is 145 keV and the maximum is 337 keV. The bremsstrahlung end-point was 2.9 MeV and the deuteron binding energy of 2.22 MeV with a maximum difference of 674 keV. Since the proton and neutron have similar masses any excess kinetic energy is equally shared between them so the excess energy is divided in half.

4) I am not clear on what and how you measured transmutted elements from the O-P reactions.

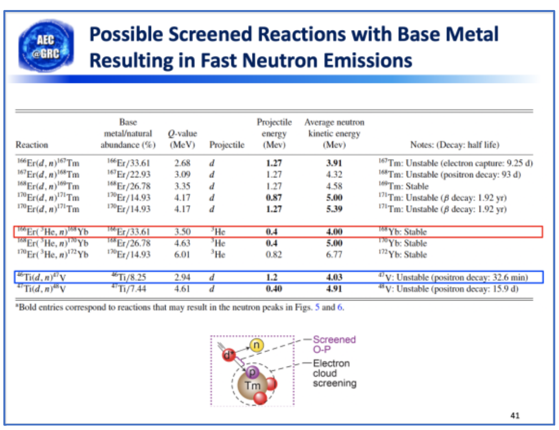

Figure 11: Slide 41 from LCF Workshop

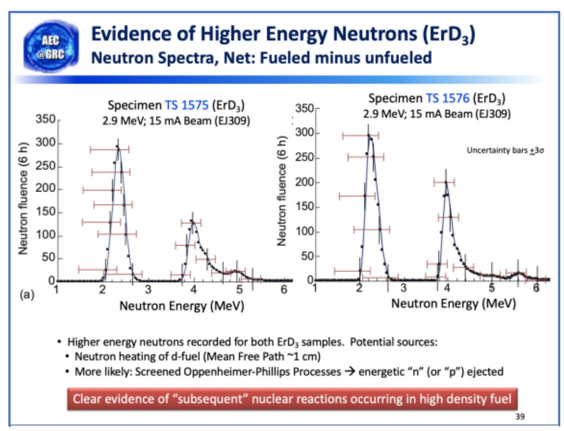

Figure 10: Slide 39 from LCF Workshop

Fast neutrons > 3 MeV could be a function of both boosted fusion and stripping reactions. We measured both the neutron energy above the DD fusion energy shown in slide 39 and the possible activation of the erbium and titanium lattices as seen on slide 41 for given neutron energy. Slide 41 also tabulates the deuteron and helion energies for various stripping reactions and the new stable or radioactive isotopes.

5) Comment/suggestion: Another commercial neutron source for neutron activation analysis (NAA) uses inertial electrostatic confinement (IEC) fusion for DD neutrons. Regarding medical isotopes, a comparison of your approach to that would be interesting.

   NAA is best performed with thermal neutrons as there is a 1/E relationship for most neutron capture save for narrow resonances at higher energies. Photo-neutron energy, as we've used to induce fusion and stripping reactions, is a function of the bremsstrahlung energy and the photo-dissociation thereshold. By choosing an appropriate end-point, the majority of deuteron photo-neutrons can be tuned to be primarily thermal, with few fusion reactions, without requiring moderation as with IEC fusion neutrons.

6) How does the long term funding picture look for LCF within NASA?

   Right now, the long-term funding for this work is undecided. We are very interested in hearing feedback from all of you on the value of this work. And certainly hearing thoughts on what are the appropriate next steps for NASA to consider to do with this work. We'd be very interested in the potential here and so I think that with the publication of these papers gives us confidence that under peer review the results stands up to scrutiny. So there is some credible work that is being done here. That is a very important consideration. But, the team is right now formulating the next steps and part of that formulation process is all of your feedback and that will be given consideration in terms of what NASA decides what to do next.

7) How is it a fair comparison to "confinement" time, as locked in the solid this is just a fuel tank and fusion occurs during the bombardment time? Tokamaks can hold their fuel indefinitely as can the deuterated/tritiated laser confinement fusion too. Thanks!

   The MCF deuterons remains in a near vacuum ionized plasma. Adding tritium brings additional radioactive material handling and safety issues. However, by simply adding deuterium gas to the metal we have a nuclear active fuel pellets that can literally sit on the shelf for months, years before you want to work with them.

   With regards to ICF, it's true you can keep the fuel frozen for an indefinite period of time as long as you can maintain cryogenic temperatures. But once you begin the fusion process, the target disassembles on the order of a few nanoseconds. Similarly with MCF, you can keep the gas at very low density inside the tokamak but once you begin to compress it, you get a whole series of instabilities and as soon as that happens the plasma stops. In our case, as long as we continue irradiating it with the bremsstrahlung, we continue to fuse. And in fact, our experiments ran as long as 6 hours.

Theory Session Q/A

1) Karabut and Lipson used plasma ion bombardment of deuterated targets to produce collimated photons. The process seems to have some relation to your work - have you considered that?

   Yes, we are familiar with Karabut and Lipson, and even better is an experiment done at Dubna [Russian Joint Institute for Nuclear Research]. They used liquid [density, gaseous] deuterium in a few cm length, tiny capsule and they used a copper LINAC accelerator which consumed 25 kW of power from the wall but they delivered kW output power continuously for 6 hours. It had a COP (coefficient of performance) of 4%. If you substitute a copper LINAC accelerator with a superconducting LINAC you cut wall power consumption by 200 times, so it will use only 100 W_e.

Right away you get 10 times more power production than consumption. We're working on this right now.

But Karabut's and Lipson's work provide some initial interest. They had a series of papers and we tried to connect with them but unfortunately they had both passed away. We tried to reproduce a lot of their work. We did experiments with the scanning electron microscope and glow and plasma discharge following up on Karabut's work. These were very good experiments. However, plasma screening is very poor so we decided to stay away from the plasma experiment at the time, but maybe in the future we could do some.

The research was successful and we developed diagnostics for those systems. These other LCF drives are advantageous if we can scale reactions at lower energy inputs than we do with the bremsstrahlung. The theory paper shows both what you could do with electron screening and where it falls off.

2) Does the probability of fusion go up significantly if a deuteron is accelerated from within a dense cluster of D, e.g. C15 Laves Phase hydrides?

   We acknowledge one of our colleagues Frank Lynch (Hydrogen Components, Inc.) did a lot of the deuterating and hydriding of various materials. [Dr. Lou DeChiaro, at NSWC Dahlgren Division, had suggested these and modeled them with DFT under AEC contract.] Frank also brought to our attention the Laves Phase materials that can achieve even higher densities than what we published here. We did shoot at some of them but haven't fully vetted the post-processed data. However, on a cursory look, we saw a proportionate nuclear response using Laves Phase deuteron storage.

3) In steady-state operation, how long would it take to use up the deuterium that is loaded in the lattice?

   That goes back to a calculation that was done awhile ago. If a Watt is 10^{12} to 10^{15} reactions, depending on how you calculate efficiencies, and a mole is 10^{23}, then you can divide and determine how many seconds you can run. [With 3 x 10^{7} s/year, and 10^{8} to 10^{11} reactions/watt/mole] it's many dozens of years. We did that calculation in the past but we think it's going to be in the lifetime of a NASA mission.

4) Very nice work and new angle on electron screening in a fuel of low disorder. Seems hard to scale if high energy neutrons are needed.

   Liquid D is a material which posseses internal multiplication because if you have high energy neutrons, the neutron delivers about half of its kinetic energy on average to a deuteron and if it's a pretty good energetic neutron it has enough kinetic energy left over that can join another deuteron so this is obvious for multiplication. Dubna demonstrated there was enough neutrons that were capable to fission palladium. But in Dubna they have fairly energetic gammas (9.8 MeV), so when they break deuterons with that gamma you get energetic protons and neutrons capable of also breaking a deuteron, so there was a lot of multiplication. So quality of fuel and quality of neutron source is paramount.

Panelist Session Q/A

1) What is the timeline for taking the next step? And can you clarify what this next step is?

   We would like to hear from the panelists what they think the next steps should be.

   From Matt Forsbacka: First, having the big goal established helps define what the next steps really need to be and what areas of engineering do you have to start dialing into. Are we going to have a pure fusion power source or a hybrid style approach of a fusion/fission power source for example? It depends on how what you need. My advice is to queue up what is the prize and what are the critical path steps to get to it. And to me, it's basically turning the behavior of the d-d system into either a useful neutron source that drives the reaction or a self-critical system that you are able to somehow maintain.

   From Len Dudzinski: From the NASA HQ sponsor stand point, we are in the phase now where we are disseminating the information from the papers that were published and we're looking for feed-back and we're looking to the team to help formulate the plan and proposal to go forward with and it will take some time to do that. There will be additional activities that the team will be considering in the next few months to help them prepare a plan. And we'll probably carry that into a decision sometime later this year. But we are looking forward to making a decision on the next steps.

Going Forward Session Q/A

1) Do you know if electron screening effects have been observed in ICF?

   Larry Forsley: I think to a degree they have been acknowledged but not much attention has been paid to it. Those codes are primarily used in modeling hydrodynamics and grow out of a whole different application area. The 2nd problem is electron screening is so short-lived that there may not be as much of an opportunity to back [its effect] out. The plasma temperature and density are in the electron screening region, but it has not received a lot of attention. I should add there is a desire to keep electrons out of an ICF target. These targets are constructed (this is in direct drive which I'm more familiar with) so the outer shell is ablated away keeping the low Z constituents, low atomic number, from heating up. The electrons get trapped in the field of the laser itself and they escape after they've accelerated to many MeV and heat up the core. It's harder to squeeze something hot than something cold. In a lot of ways I think the ICF community has steered away from discussions about electrons in general and that may be part of the reason.

2) What is the most important prior experiment in your reference list?

   Larry Forsley: Probably Dubna. The Dubna experiments that Vlad mentioned where they had high pressure D gas and Pd irradiated by a bremsstrahlung photon beam as ours was. One of the authors of the Dubna work, Alex Didyk, and I had met in South Korea and discussed this over a number of years. Unfortunately, he passed away in 2016 and it's only been recently that I appreciated the fact that the boosting that we saw is likely a combination of Oppenheimer-Phillips, stripping reactions [and hot deuterons fusing] . Heated deuterons would have had a much larger effect in their system because they had a lot more deuterons than we had [in] a larger sample.

3) The electron screening can be time dependent, changing on the femtosecond scale, especially when parametric pumping is used to "heat" the deuterons.

Larry Forsley: When we initially did these experiments, we used a LINAC with rise and fall time micropulses of about 10 picoseconds, getting close to femtosecond scales. The Dynamatron we used is a CW device and so we did not benefit from the screening occurring on close to femtosecond time scales. Still, even at 10 picoseconds we are way off from that but still we're getting down to that region so this might very well be good way to heat them.

4) Could supercapacitor technology be used to create enhanced screening effects? You mentioned lattice defects - is there time for d filling them?

Larry Forsley: What an interesting question. I don't know, but I suppose it's worth considering because one of the ways of making the supercapacitor is you have a screening film, if you will on the surface, so you can imagine something like layers of graphene so I could imagine this could create enhanced screening effects.

Theresa Benyo: Or kind of related to that, what about superconductivity? You could really pump a lot of electrons through a superconductor.

Larry Forsley: This is true and you could even in fact use a quenched superconductor to suddenly provide a lot of instantaneous electrons.

Appendix II: Physical Review Papers as NASA Technical Papers with Table of Contents

Theory Paper (NASA-TP-20205001617)

Experimental Paper (NASA-TP- NASA-TP-20205001616)

Appendix III: LCF Workshop NASA Panelist's Biographies

Dr. Matt Forsbacka (NASA HQ)

Director, Safety Assurance and Requirements Division (SARD)

Leads the SARD team of subject matter experts

Past assignments

Nuclear Flight Safety Assurance Manager within SARD

Senior Executive at the Defense Nuclear Facilities Safety Board

Program Director for human portable radiation detection systems at Dept of Homeland Security

Education

B.S., M.S. in Nuclear Engineering from Univ of Florida

Ph.D. in Nuclear Engineering from Univ of Virginia

Dr. Michael Houts (NASA MSFC)

Principal Investigator for Nuclear Thermal Propulsion

Nuclear Research Manager: provides guidance and technical advice on research and development related to the design, development, and utilization of space nuclear power and propulsion systems

Past assignments

Team Leader for Criticality, Reactor, and Radiation Physics

Deputy Group Leader at Los Alamos National Laboratory

Education

BSME & BS Nuclear Engineering from Univ of Florida

PhD in Nuclear Engineering from MIT

Dr. Ron Litchford (NASA STMD | HQ)

Principal Technologist, NASA STMD

Expertise: Aerospace Propulsion & Power and Advanced Energy Systems

Professional Experience:

NASA Graduate Student Research Fellow (1987-1989)

Research Engineer, UT-CALSPAN Center for Space Transportation & Applied Research, a NASA Sponsored Center for the Commercial Development of Space (1989-1994)

Project Manager, Advanced Product Development Division, ERC Inc. (1994-1999)

Aerospace Technologist, NASA (1999-Current)

Education:

BSME, Tennessee Technological University, 1987

MSAE, University of Tennessee Space Institute, 1989

PhD AE, University of Tennessee Space Institute, 1992

PE Licensure, 1994

Mr. John H. Scott (NASA JSC)

Chief Technologist for the Propulsion and Power Division

Responsible for advancing the technology needed by Human Spaceflight

Past assignments

Project manager/supervisor supporting Space Shuttle, ISS, & Human Exploration study programs

Aerospace Engineer at TRW

Published articles on spacecraft fuel cell and nuclear power technologies.

Education:

BSME from Rice University

MSME and MBA from UCLA