Accessing Icy World Oceans Using Lattice Confinement Fusion Fast Fission

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Exploring the oceans of icy moons and planets requires a robust robotic probe powered by an energy source that can operate under icy world ocean conditions and be self-contained. We propose a non-fissile, compact, scalable nuclear energy source to electrically power untethered, autonomous probes to melt or bore through icy world crusts. The probe can be used for planetary (i.e. Pluto, lunar (i.e., Europa), or asteroid exploration (i.e. Ceres) where ice caps are encountered. This new approach may yield a variable output fission power source with a higher performance than ^{238}Pu and a non-fissile alternative to a highly enriched uranium (HEU) core. This approach saves uranium enrichment expense, and both HEU and ^{238}Pu security and launch safety costs. The reactor will produce electrical power with thermal waste heat to melt through the ice crust with possible sonic assistance. This paper will introduce the hybrid fusion-fission reactor concept, explore the potential for and benefits of this new type of nuclear reactor, and discuss the technical approach to developing this new technology.

I. INTRODUCTION

NASA proposed the Ocean Worlds Exploration Program[1,2] to search for extraterrestrial life. The challenge is that up to 40 kilometer-thick ice must first be broken through to reach sub-surface oceans. These icy ocean worlds include Ceres, Europa, Enceladus, and Pluto. Each world may have a liquid water ocean beneath their ice crust. These oceans are likely heated by the parent planet's tidal forces, or in the case of Pluto or Ceres, by residual radioactive decay. A robotic probe exploring the oceans beneath must either melt or bore through the ice crust first. Consequently, the proposed probe needs to contend with hydrostatic ice pressure, ice phase and density changes, then water pressure. Such a mission requires a small, but robust and long lived, electrical energy and heat source.

The assumption has been made that one needs to melt through the ice to reach the underlying ocean. Previous autonomous probe studies[3] have considered radioactive decay of plutonium-238 (^{238}Pu) or a highly enriched uranium ^{235}U (HEU) fast fission reactor as long-lived heat sources. The ^{238}Pu energy density requires multiple Radioisotope Thermal Generator (RTG) modules for electrical power conversion with the residual heat available for ice melting. However, it is not a controllable heat source due to the ^{238}Pu 87.7-year half-life. An HEU fission reactor, like Kilopower[4], has a higher energy density, and can be controlled to reduce or increase heat, but it requires significant radioactive shielding that adds mass. Both actinide-based systems have significant fabrication, safety, and launch costs

Fig. 1. Artistic rendering of a robotic probe (i.e., Europa Tunnelbot) capable of melting and/or drilling through icy crusts of planets, moons, or asteroids[3].

I.A. Innovation

Instead, we propose a novel, compact, scalable nuclear energy source using neither highly enriched uranium (HEU) nor ^{238}Pu similar to the hybrid fusion-fission generator described by Forsley and Mosier-Boss[5]. This nuclear energy source uses Lattice Confinement Fusion (LCF) neutrons[6] to fast-fission thorium or depleted uranium where neither ^{232}Th nor ^{238}U isotopes are fissile. An important advantage of using non-fissile materials is that they do not have the fabrication, safety or launch costs of ^{238}Pu or HEU. This new energy source is sufficient to provide power and heat for untethered, autonomous probes to melt or bore through ice crusts to the ocean below, then return with samples if desired. These probes can be used for planetary (i.e., Pluto), lunar (i.e., Europa), or asteroid (i.e., Ceres) exploration where icy crusts are encountered. An example of a proposed robotic probe is shown in Figure 1.

The hybrid fusion-fission reactor design uses previously demonstrated[7,8] 6.4 MeV average neutron energy sufficient to fast fission thorium, and natural and depleted uranium. Figure 2 shows data from the hybrid fusion-fission experiment at US Navy SPAWAR-Pacific with sufficient, sustained, neutron flux (average 10^6 n/sec) indicating the neutron energy by neutron-germanium recoils within the detector. The liquid scintillator measured the alpha and beta energies (by channel) of both natural uranium decay daughters as well as fission products and neutron activation of uranium. An output heat at 500 °C or higher would enable the use of the existing Advanced Stirling Engine Generator[9] or a closed Brayton Cycle[10,11] to generate electrical power using "waste" fission heat to melt ice.

As an alternative to melting through the ice, sonically assisted ice fracturing may improve melting efficiency. This method borrows from Navy research on super-cavitating torpedoes while noting the Europa Tunnelbot[3] proposed a sonar transceiver for navigation. Although high speed transit isn't expected (mission specifications expect 3 years to transit the ice[3]), the combined melting and fracturing could shorten this time. Super-cavitation involves a sheath of bubbles along a torpedo[12] thereby reducing friction with water. Here, we would propose penetrating the crust via a melted ice sheath vibrating against and fracturing local ice. In addition, like sonar, a sonic transducer can operate in a pump-probe manner, listening to return echoes to measure ice density directly and possibly to communicate to the surface from some depth within the ice.

I.A.1. Lattice Confinement Fusion Technology

Deuterium-Deuterium (DD) fusion has conventionally required either large magnetic fields to hold an underdense plasma at a density of 10^{14} ions/cm^3 or large lasers to briefly compress a dense plasma with a density of 10^{26} ions/cm^3 for about 1 nanosecond[13]. Instead, Lattice Confinement Fusion (LCF) uses deuterated metals at a high density of 10^{23} ions/cm^3 where deuterons are held indefinitely in a metal lattice[14,15]. 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[15]. LCF is then triggered and controlled by bremsstrahlung or phonon-nuclear coupling resulting in an equivalent local deuteron ion temperature of up to 2.1 keV (Ref. 16) kinetic energy (24 million °C) as compared to the sun at 1.5 keV (17 million °C).

A fusion-fast-fission micro-reactor has been demonstrated using natural thorium (^{232}Th), and uranium (both natural abundance ^{238}U and depleted DU)[8]. The 2.5 MeV energy neutrons resulting from DD fusion have been proposed to drive a deep space fission power system[17]. Current estimates of a non-optimized LCF fast fission power density are 1/3 that of the HEU-based Kilopower system[5]. Ongoing work with the Naval Surface Warfare Centers (NSWC) has observed 90-200 watts-thermal/gram[18], without actinides by a patented protocol[19], that exceeds the ^{238}Pu 0.54 watt-thermal/gram in RTGs.

I.A.2. Addressing Icy World Conditions

The Compass Final Report[3] (CFR) suggested several mission requirements when they compared ^{238}Pu RTG and HEU based power systems for a Europa Tunnelbot probe. However, higher LCF power densities without requiring equivalent shielding would change the constraints. The Compass Final Report[3] also noted the mission tradeoffs discussed earlier regarding ice crust traversal time by the probe.

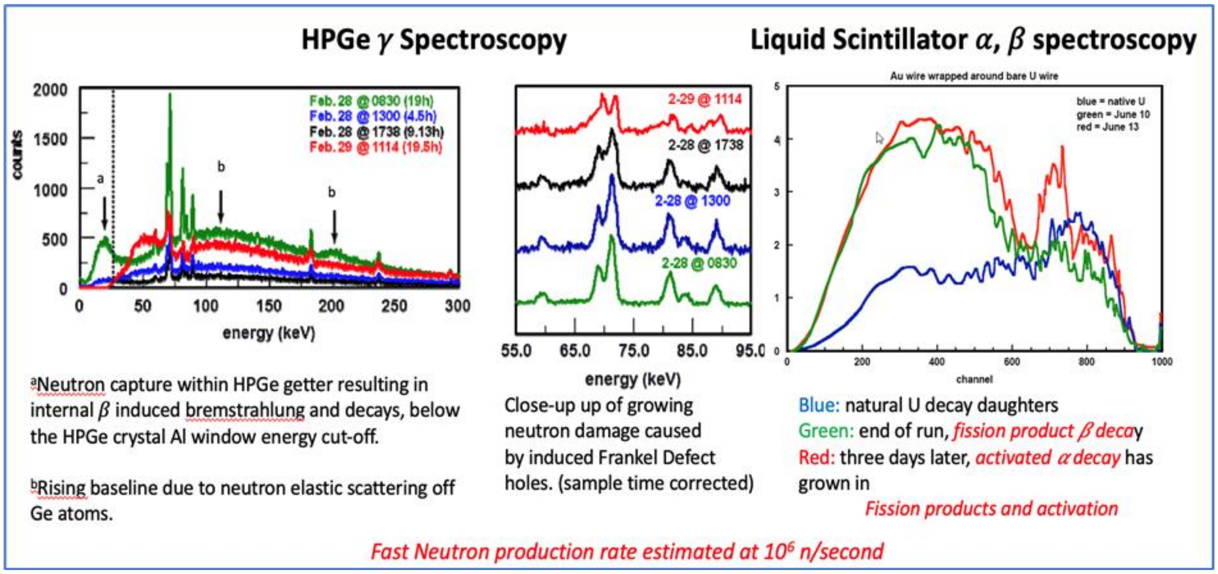

Fig 2. LCF Fast-Fission of Deuterated Uranium at US Navy SPAWAR (Ref. 7) showing fast neutron production (left and middle) and fission and neutron activation products (right).

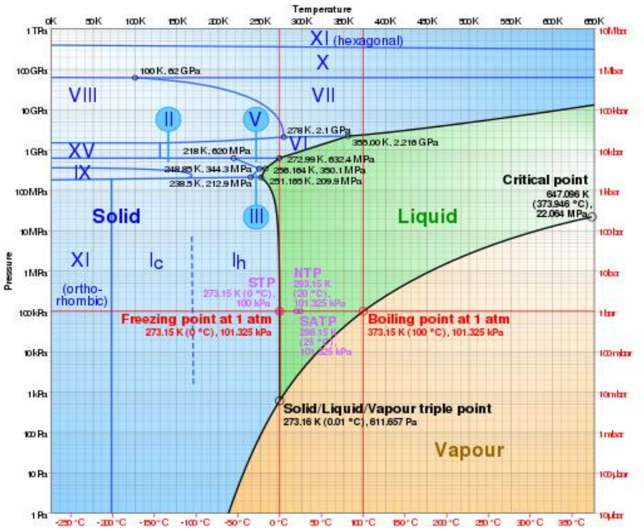

Fig. 3. Ice Phases by pressure and temperature[20].

Laboratory observations of high-pressure ice phases (Figure 3) introduce additional complexities requiring a variable power source. As Figure 3 indicates, an icy crust will likely exist over a pressure range from vacuum to possibly exceeding 10 kbar with temperatures from cryogenic temperatures to 270°K. Consequently temperature/pressure ice structure changes will likely begin with orthorhombic ice XI at the surface with transitions among ice phases IX, II, III and XV before encountering pressurized liquid water. Each of these phase changes will have an impact on probe travel rate and pressure necessitating a variable power output. Sub-surface brine lakes may exist that that would require rapid changes in power output, ice melting rates, and probe orientation, especially if samples need to be taken and analyzed. The proposed study will address this variable output requirement in its preliminary power and heat source design.

I.B. Potential Impact

A "hybrid" Lattice Confinement Fusion fast fission reactor provides power for both melting and vibrating through the ice and has the potential to reduce mass, volume, and power requirements for the probe and its mission. These reductions are a potential game-changer for space exploration. Studies[3] have indicated the tradeoffs among probe mass, volume, aspect ratio, and available heat to melt ice. Changes amongst these variables, in particular probe aspect ratio, volume, and ability to move through initially cryogenic ice more quickly, have a major impact on the mission profile. A faster transit through the ice by the probe will reduce probe stress and Jovian radiation damage to the lander on Europa's surface, or any other probe's surface support in a high radiation environment.

The deepest ice drilling accomplished to date in the Antarctic was 2.1 km using 90°C water pumped from the surface. This technique is not possible on an extraterrestrial icy world. As noted, researchers have proposed using a nuclear powered, heated probe. However, rather than using either a ^{238}Pu radioisotope heat source or a shielded enriched ^{235}U fission reactor with significant security and launch safety costs, we propose making use of the demonstrated[6] lattice confinement fusion (LCF) neutron source.

LCF can drive and control a sub-critical fission reactor with less mass than traditional fission reactors with reduced shielding by producing fewer radiation by-products. The CFR (Ref. 3) suggested 100 Gy radiation exposure as the maximum, although this is arbitrary and less would be preferred. Probe radiation is harmful to onboard electronics and possible indigenous life-forms in subsurface lakes or oceans. Another advantage is that the LCF Fast-Fission design does not modify bio-signatures by radioactively denaturing biomolecules encountered during invasive extraterrestrial searches.

Above all, LCF Fast-Fission may provide a variable output power source smaller than existing reactors which greatly advances the ability for probes to meet space mission requirements. In addition, sonically assisted augmented melting may allow the probe to bore through an ice crust faster than a solely heated probe.

I.C. Mission Context

There are many icy worlds in our solar system. The potential for extraterrestrial life beneath these surfaces is high enough that NASA designed missions to explore these icy worlds[21]. Specifically, the Europa Clipper[22] mission is scheduled to launch in 2024 to Jupiter's icy moon, Europa. The mission's goal is to orbit Europa, investigate its ice plumes for biochemicals, and measure the icy crust's stability and depth to aid in selecting a landing site for the Europa Lander mission[23] which may launch in 2027. Previously, the 1999 Galileo Jovian Mission swung by each of the Gallilean moons and collected preliminary data on Europa as will JUNO in a close Europa flyby in 2022. Figure 4 shows the anticipated Europa structure from that mission's data and analyses. In addition, from that mission, Table 1 lists the characteristics of Europa in terms of size, surface temperature, and depths of both the ice layer and ocean underneath. Data from the Europa Clipper and Lander missions will allow an autonomous probe, such as Europa Tunnelbot, to be designed, engineered and built for a future Europa mission such as Vision 2050 (Ref. 24) as depicted in Figure 5. There is sufficient time in the intervening years to flight test both a novel power supply and the autonomous probe at a place that resembles an icy world such as Antarctica or Greenland.

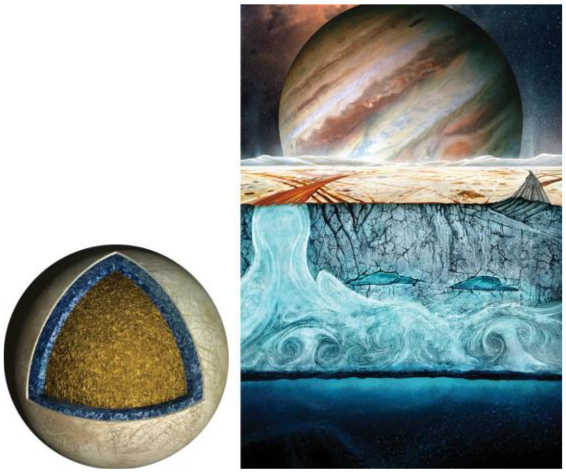

Fig. 4. An artist's rendition of the structure of Europa's terrestrial layers (left) and a depiction of the ocean underneath Europa's icy layer (right). Image from Howell and Pappalardo[22].

TABLE I. Characteristics of Europa.

Parameter	Value
Mean radius	1560.8 km
Volume	1.593×10^{10} km^3
Mass	4.799844×10^{22} kg
Mean density	3.013 g/cm^3
Mean surface temperature	-171 °C
Depth of ice layer	10-30 km
Depth of ocean	~100 km

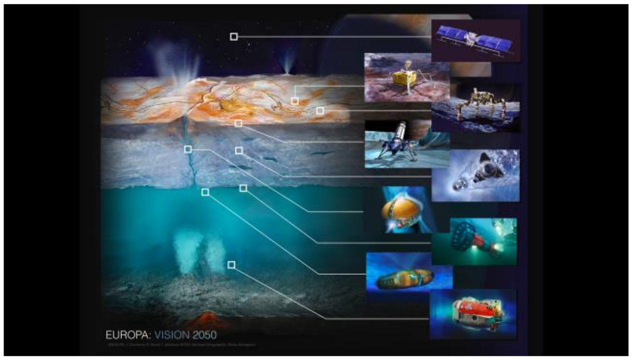

Fig. 5. Conceptualization of the Europa: Vision 2050 autonomous probes. Image from "Europa/Ocean Worlds Lander Mission Concept"[24] (Pre-Decisional Information)

The proposed probe will enable the exploration of the oceans beneath the icy crust of Europa with an architecture capable of powering the probe and a drilling mechanism with enough Watt-electric and Watt-thermal to accomplish its mission. A heated and/or (ultra) sonic drilling mechanism will enable the probe to travel through Europa's icy crust. Augmenting melting with sonic ice fracturing may significantly reduce probe transit time through the ice. This enhancement would reduce both probe lifetime stress and radiation damage to the Europa surface lander communicating with the probe.

I.D. Technical Approach

The project consists of three tasks. First, we plan to establish the likely heat flux, ancillary power requirements, allowable mass, volume, and any shielding requirements, as well as the power plant lifetime to meet the Ocean Worlds Exploration Program's objectives for an Europa Mission. Power requirements include those for internal probe operations, science package, possible sampling, ice melting and/or sonic ice fracturing and communications.

Second, we plan to model the LCF fast fission process using the Los Alamos National Laboratory Monte-Carlo N-Particle® code (MCNP®)[25] from first principals and previous experimental results. For example, during the NASA LCF experimental campaign[6], a neutron detection system characterized neutron energies produced from the irradiation of deuterated metals. Figure 6 shows one of the many neutron signatures acquired during the experiments consisting of a deuteron-deuteron fusion and boosted fusion peaks. This neutron signature will be used as input to MCNP® simulations allowing an understanding of shielding requirements and potentially nuclear reaction scaling.

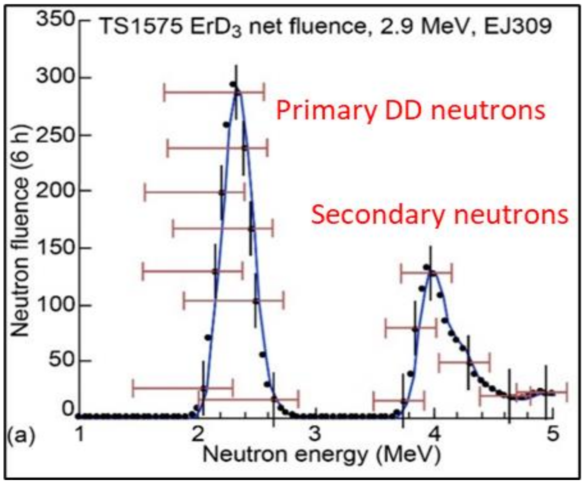

Fig. 6. Neutron spectroscopy data from bremsstrahlung irradiated experiments indicating 2.45 MeV d-d fusion neutrons and boosted neutrons at 4 MeV and higher[6].

Third, we plan to model different reactor materials and shielding to determine whether or not the estimated mission requirements of mass, volume and power can be met. For example, we will model two or more types of fission reactor cores including a molten lithium salt thorium core and a molten lithium salt depleted uranium core. Figure 7 shows an example geometry of a depleted uranium (DU) sample surrounded by a neutron reflector for MCNP® modeling. Geometry creation within MCNP®

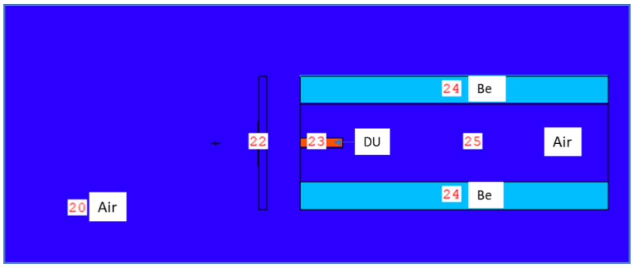

Fig. 7. MCNP® model geometry of depleted uranium enclosed within a tube and surrounded by a cylindrical beryllium neutron reflector sleeve.

allows a 3D depiction of the desired model with an extensive material database. Figure 8 is an example of MCNP® output from modeling a 6 MeV bremsstrahlung photon beam triggering photo-fission in a DU sample.

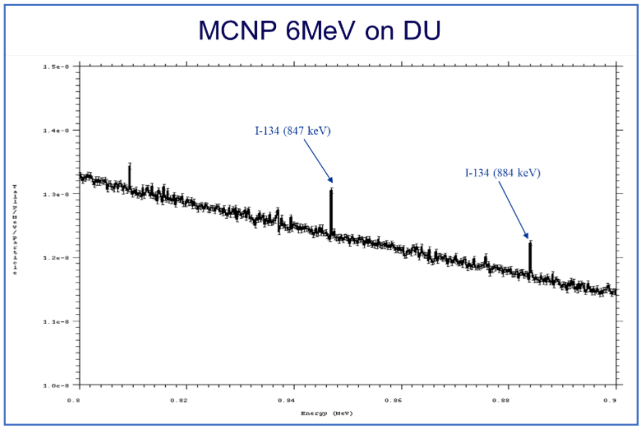

Fig. 8. MCNP® simulated HPGe detector gamma spectra of a depleted uranium (DU) 6 MeV modeled photo-fission product, I-134, with 847 keV and 884 keV lines.

The simulated gamma ray peaks indicate an iodine fission product. Other types of MCNP® output include but are not limited to particle flux, particle energy, and particle collisions. The simulation results will indicate the amount of fusion and fission energy generated in the reactor core providing heat for power conversion and ice melting.

Although LCF can efficiently fast-fission depleted uranium and thorium[7,8], this type of fission hasn't been done in a high-temperature, lithium-based molten salt. MCNP® modeling can reveal reactor material options allowing an appropriate hybrid fusion fast-fission nuclear reactor design. In addition to materials, the modeling can indicate alternative means of triggering LCF, effective high temperature operation and appropriate power conversion systems[10,11]. For example, conducting LCF in a molten eutectic, lithium-deuterided, thorium or uranium salt at 500°C may provide sufficient thermal energy to melt cryogenic ice while efficiently converting thermal to electric energy to power systems. There may be power tradeoffs between melting and/or sonically fracturing ice.

II. CONCLUSIONS

Future space missions that explore the icy worlds of our galaxy will need robust autonomous robotic melting and/or boring probes to enable breaking through the icy surface. Although traditional fission-based power sources could meet the requirements of such a mission, the cost and required handling of fissile materials such as HEU and ^{238}Pu are unattractive. A hybrid fusion-fission reactor could be the answer to making accessing icy world oceans safer and less costly than using fission-based reactors.

One possible hybrid system uses Lattice Confinement Fusion which provides energetic neutrons which can fission thorium or uranium molten salts. Through comprehensive study of Europa's characteristics and the requirements for the planned Europa Lander mission, a hybrid fusion-fission reactor will be designed with LCF as the source of neutrons and molten salts as the fissionable material providing heat and power for the robotic probe. First principal modeling of LCF fast fission and previous LCF experimental results will provide guidance for building a hybrid fusion fast fission reactor that will power autonomous and compact robotic probes.

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