NIAC 23 Project: Accessing Icy Worlds using Lattice Confinement Fusion (LCF) Fast Fission

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Overview

• Introduction

• Mission Context

• Robotic Probe Specifications/Options

• Innovation
  - How Lattice Confinement Fusion (LCF) Works
  - Hybrid Fusion Fast Fission

• Potential Impact

• Takeaways
Introduction

• Ocean Worlds Exploration Program
  - Search for Extraterrestrial Life
  - Ceres, Europa, Enceladus, Pluto
  - Challenges:
    ▪ Extreme operating environmental conditions
    ▪ Break through up to 40 km thick ice

• Robotic Probe
  - Small, robust, long-lived electrical energy and heat source
  - Traditional nuclear power systems require significant radioactive shielding
  - Enriched actinide-based systems: significant fabrication, safety, launch costs

• Cryobot reference
  - Power Density > 1 W/cc
  - Total (thermal) power: 8 – 12 kW
  - Lifetime: 2-6 years, operating at full power
  - Maturity: TRL 6, flight ready in ~10 years

Mission Context

- **Icy World Exploration**
  - Proposed probe capable of powering the probe and a drilling mechanism with enough Watt-electric and Watt-thermal to accomplish its mission
  - Heated and/or (ultra) sonic drilling mechanism will enable the probe to travel through icy crusts
  - LCF-driven Fast Fission can provide Nuclear Electric Propulsion for shorter journey
  - Ceres, Europa, Enceladus and Pluto are icy world candidates
Addressing Icy World Conditions

- Icy crust likely exist over a pressure range from vacuum to possibly over 10 kbar
- Temperature range from cryogenic to > 270 °K
- Various ice phases impact probe travel rate and pressure\(^1\)
- Sub-surface lakes likely\(^2\)
- With these conditions, variable power output is required

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Robotic Probe Specifications/Options

• Europa Tunnelbot

• Cryobot

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Innovation

• Lattice Confinement Fusion (LCF) Technology
  - Develop a non-fissile, compact, scalable nuclear energy source sufficient to power and provide heat for melting and boring through icy shelves with untethered, autonomous probes.
  - Possible high $I_{sp}$ (specific impulse) Nuclear Electric Propulsion (NEP)
  - Future development could go beyond the icy-moon mission to a lightweight power source for human & robotic missions.

Depiction of the ocean underneath Europa's icy layer
How LCF Works

• Traditional fusion: Heats plasma 10x hotter than center of sun – hard to control
• LCF addresses the pressure, temperature, and containment challenges with fusion
  • Heats very few atoms at a time
  • Approaches solar fuel density
  • Lattice provides containment

Technical Details Simplified

Part A: Electron Screening
(increases fusion probability)

Part B: High Fuel Density
(billion times more dense than traditional fusion)

A + B + Trigger = Viable Fusion

https://www1.grc.nasa.gov/space/science/lattice-confinement-fusion/
Hybrid Fusion-Fast Fission

- Takes advantage of both processes
  - Fusion reactions provide the neutrons to fission non-fissile material
  - Require ~2MeV neutrons to fission Th and natural U
  - Fusion reactions can provide up to 14.1 MeV neutrons

<table>
<thead>
<tr>
<th>Fusion Reaction</th>
<th>MeV</th>
<th>Occurrence</th>
<th>Useful particle energy (MeV)</th>
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<tbody>
<tr>
<td>$^2$H$(^3$He,n$)$</td>
<td>4.00</td>
<td>primary ≈ 50%</td>
<td>n=2.45</td>
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<td>p=3.00</td>
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<tr>
<td>$^3$He$(^3$He,α$)$</td>
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<td>secondary</td>
<td>p=15.00</td>
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<td>secondary</td>
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<td>low probability</td>
<td>p=1 to 9</td>
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<table>
<thead>
<tr>
<th>Fission Reaction</th>
<th>MeV</th>
<th>Occurrence</th>
<th>Useful particle energy (MeV)</th>
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<tbody>
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<td>$^{232}$Th(n,γ)f</td>
<td>200</td>
<td>high probability</td>
<td>n=1 to 9</td>
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<tr>
<td>$^{232}$Th(p,γ)f</td>
<td>200</td>
<td>some probability</td>
<td>p=1 to 10</td>
</tr>
<tr>
<td>$^{238}$U(n,γ)f</td>
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<td>high probability</td>
<td>n=1 to 9</td>
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Potential Impact

• Probes for icy moons require unacceptable amounts of $^{238}\text{Pu}$ isotope.

• A small, low-mass, variable power source is needed.

• New hybrid approach yields a variable output power source smaller than existing fissile reactors.

• Non-fissile alternative to high-enriched uranium (HEU) or high-assay, low-enriched uranium (HALEU) core saves uranium enrichment, security and launch safety costs.

• Efficient operation with reactor thermal waste heat allows probe to melt and/or vibrate through ice shelf.
Takeaways

• Hybrid Fusion-Fast Fission Power system
  - No HEU or HALEU necessary
  - Built on NASA GRC\textsuperscript{1} and US Navy research\textsuperscript{2} published in Phys Rev C and elsewhere
  - With scaling, suitable for ice crust penetration and power
  - Variable output power possible so probe is throttleable
  - Compact system supports small size of the probe

• Recognition of Icy World ice-phase temperature and pressure changes
  - Requires power/penetration flexibility
  - Possible near-surface ice pools\textsuperscript{3}

• Combined ice melting/ultrasonic penetration
  - Takes advantage of skin layer adjacent to probe

\textsuperscript{3} R. Culbert, et al., “Double ridge formation over shallow water sills on Jupiter’s moon Europa”, \textit{Nature Communications}, \textbf{13}:2007 (2022)
Acknowledgments

• Thanks to the Cryobot Workshop Organizers for inviting us!
• We’re looking forward to learning more from you as to the changing requirements
• While looking forward to increasing the TRL of LCF Fast-Fission