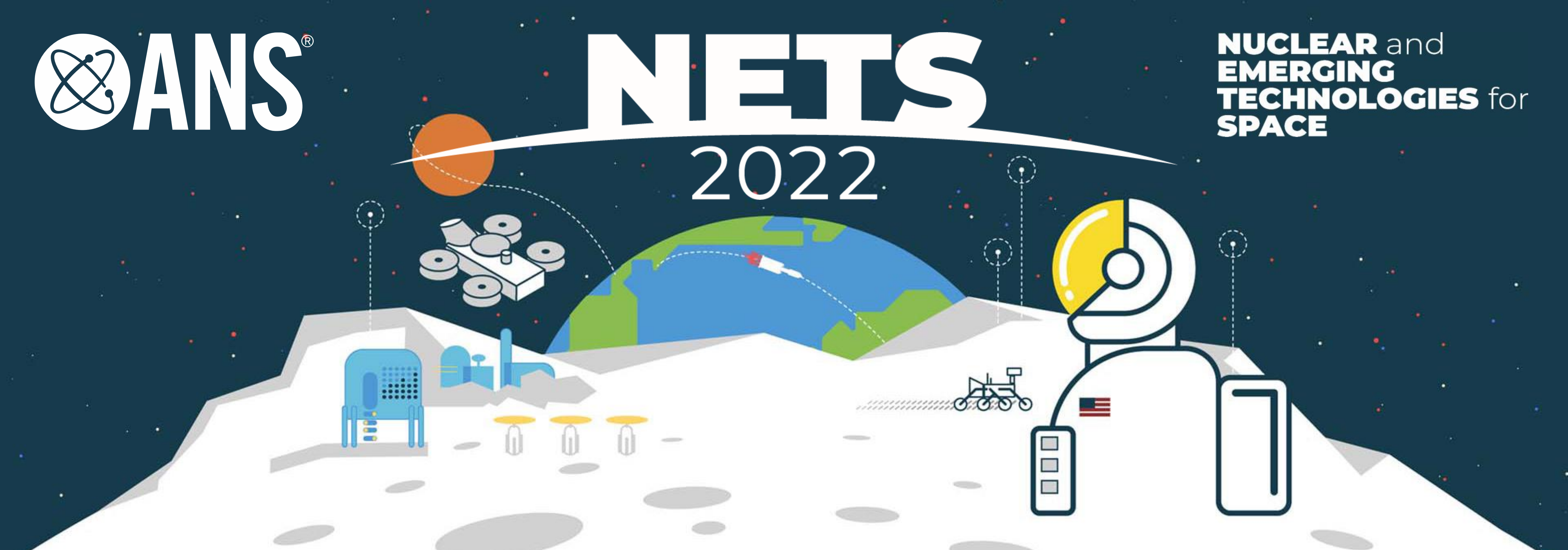

Accessing Icy Worlds using Lattice Confinement Fusion (LCF) Fast Fission

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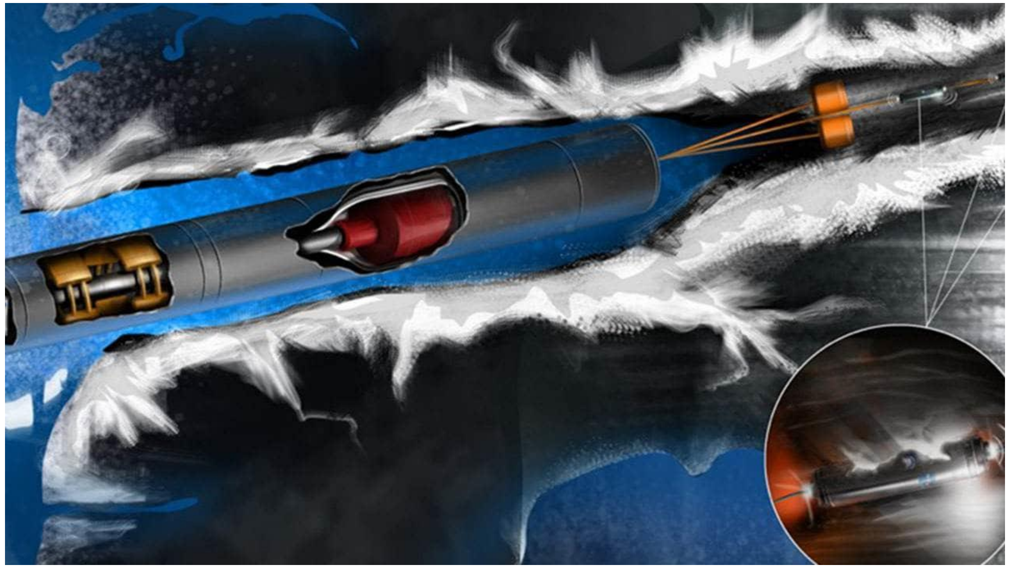
Overview

- Introduction
- Innovation
  - Lattice Confinement Fusion Technology
  - Hybrid Fusion Fast fission
  - Addressing Icy World Conditions
- Potential Impact
- Mission Context
- Technical Approach
- Conclusions

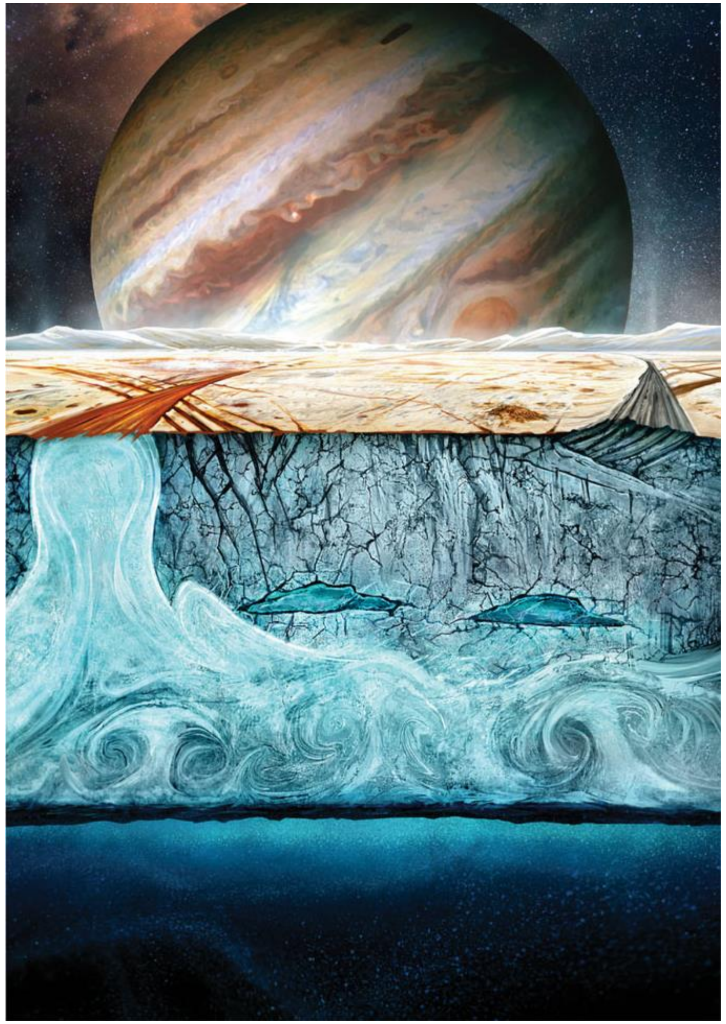
Introduction



- Ocean Worlds Exploration Program
  - Search for Extraterrestrial Life
  - Ceres, Europa, Enceladus, Pluto
  - Challenges:
    - Operate under extreme 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

Innovation

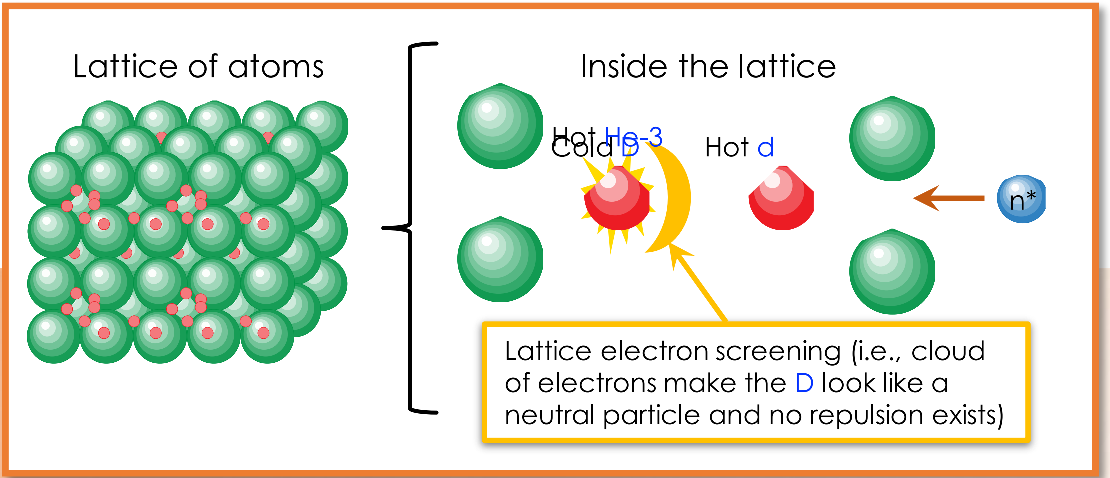
- Lattice Confinement Fusion (LCF) Technology
  - Develop a non-fissile, compact, nuclear energy source sufficient to power and provide heat for melting and boring through icy shelves with untethered, autonomous probes.
  - Future development could go beyond the icy-moon mission to a lightweight power 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
  - A trigger (e.g. electron beam) starts & controls reactions

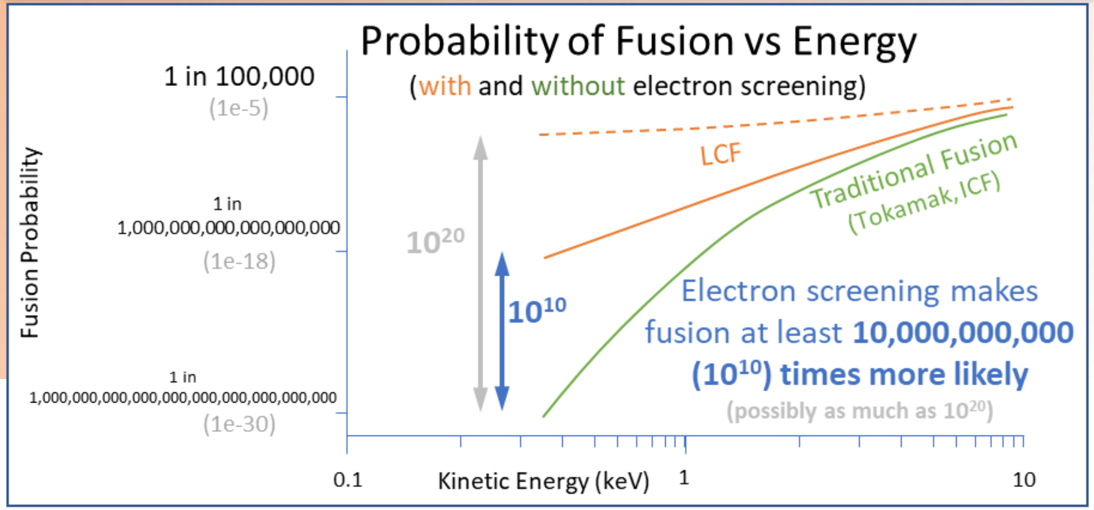


Technical Details Simplified

Part A: **Electron Screening**
(increases fusion probability)

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

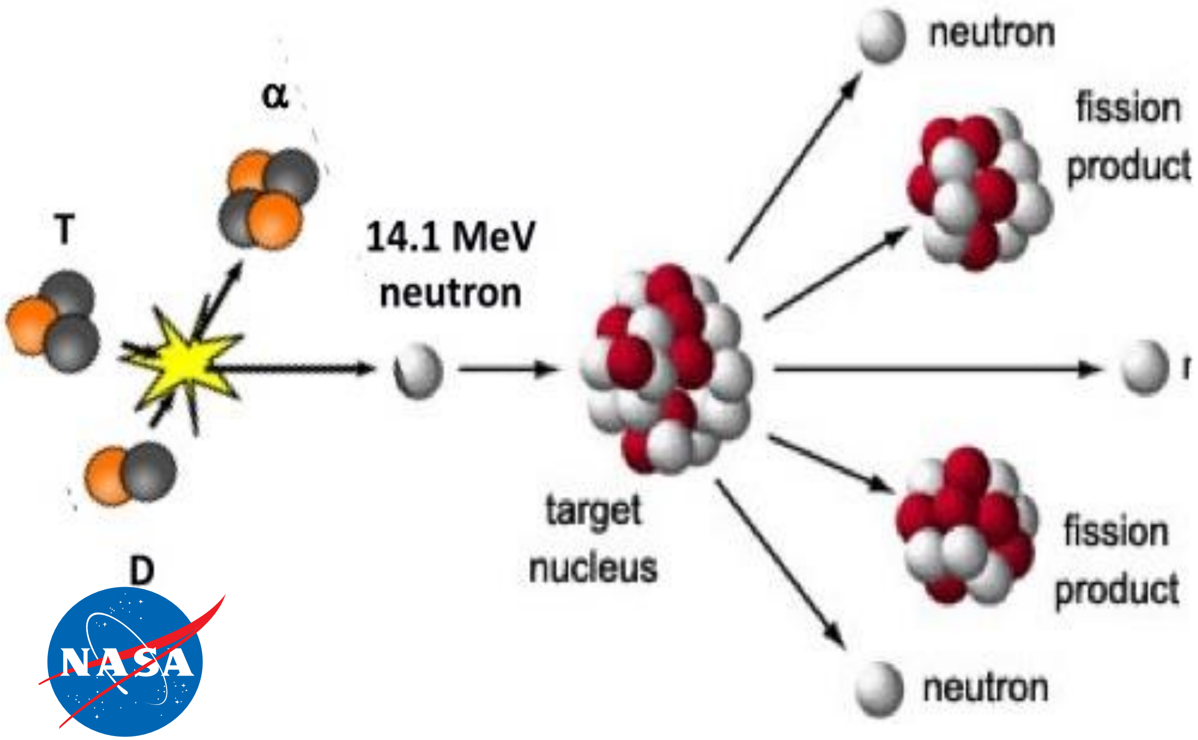
A + B + Trigger = Viable Fusion



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

Hybrid Fusion-Fast Fission

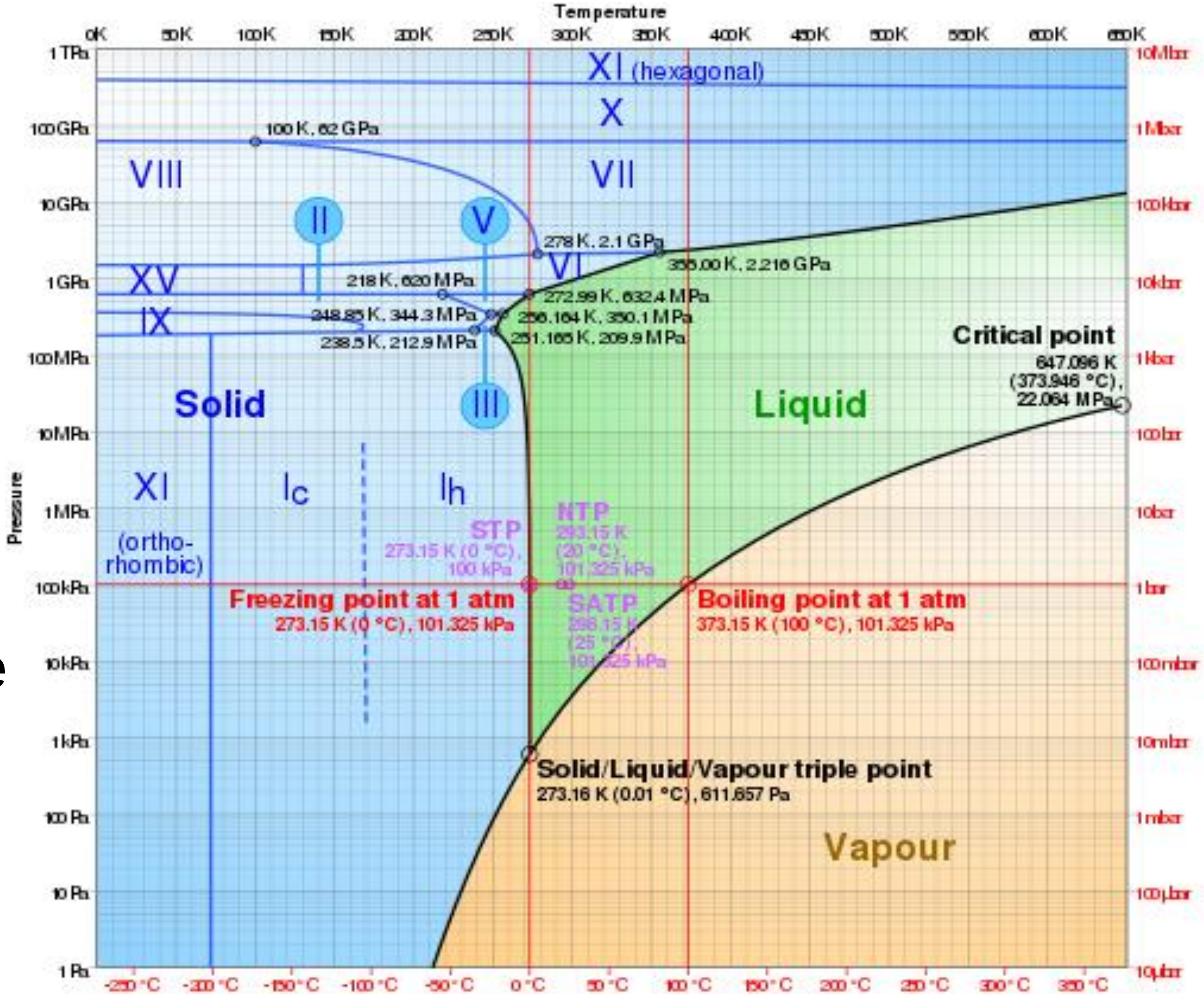
- Takes advantage of both processes
  - Fusion reactions provide the neutrons to fission non-fissile material
  - Require ~2MeV neutrons to fission natural thorium and uranium
  - Fusion reactions can provide up to 14.1 MeV neutrons



Fusion Reaction	MeV	Occurrence	useful particle energy (MeV)
$D(d,n)^3He$	4.00	primary ≈ 50%	n=2.45
$D(d,p)T$	3.25	primary ≈ 50%	p=3.00
$D(^3He,p)\alpha$	18.30	secondary	p=15.00
$D(t,n)\alpha$	17.60	secondary	n=14.10
$T(t,\alpha)2n$	11.30	low probability	n=1 to 9
$^3He(^3He,\alpha)2p$	12.86	low probability	p=1 to 10
Fission Reaction	**MeV**	**Occurrence**	**useful particle/energy (MeV)**
$^{232}Th(n,\gamma)f$	200	high probability	n=1 to 9
$^{232}Th(p,\gamma)f$	200	some probability	p=1 to 10
$^{238}U(n,\gamma)f$	200	high probability	n=1 to 9
$^{238}U(p,\gamma)f$	200	some probability	p=1 to 10

Innovation

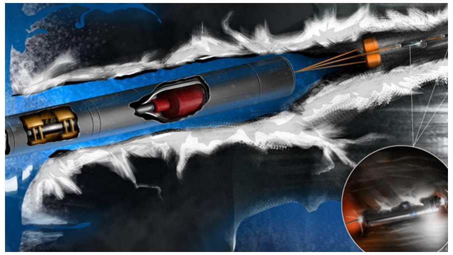
- Addressing Icy World Conditions
  - Icy crust likely exist over a pressure range from vacuum to possibly over 10 kbar
  - Temperature range from cryogenic to > 270 ºK
  - Various ice phases impact probe travel rate and pressure
  - Sub-surface lakes likely[1]
  - *With these conditions, variable power output is required*



https://commons.wikimedia.org/wiki/File:Phase_diagram_of_water.svg

[1] R. Culbert, *et al.*, "Double ridge formation over shallow water sills on Jupiter's moon Europa", *Nature Communications*, **13:**2007 (2022)

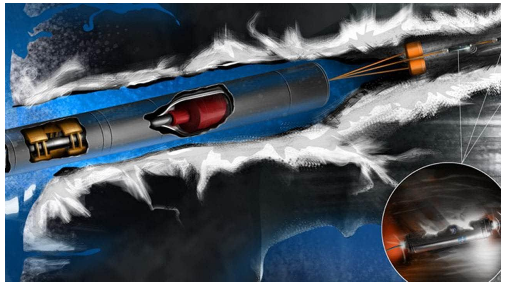
Potential Impact



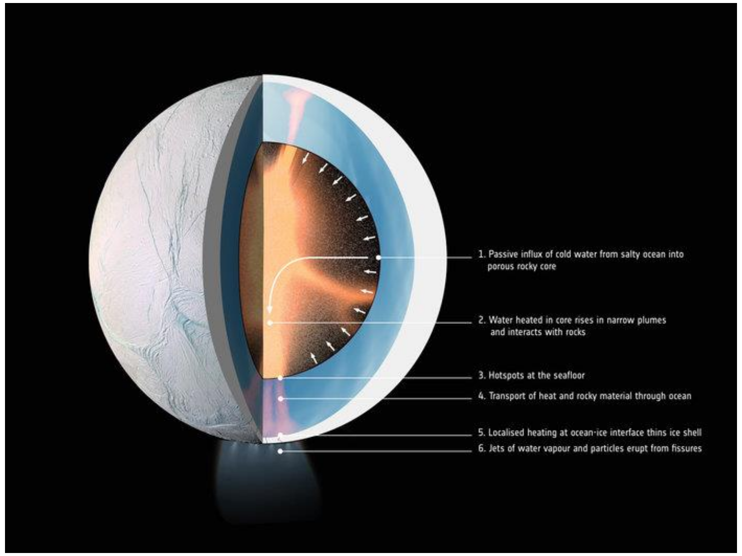
- Probes for icy moons require unacceptable amounts of ^{238}Pu isotope.
- A small, low-mass, variable power source is needed.
- New hybrid approach yields a variable output power source smaller than existing fissile reactors.
- Non-fissile alternative to high-enriched uranium (HEU) or high-assay, low-enriched 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.

Mission Context

- Icy World Exploration
  - Proposed probe will have architecture 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
  - Europa and Enceladus are icy world candidates

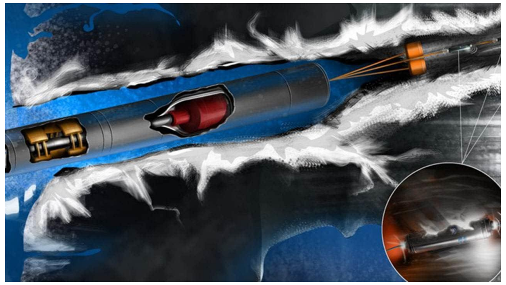


Europa Cutaway



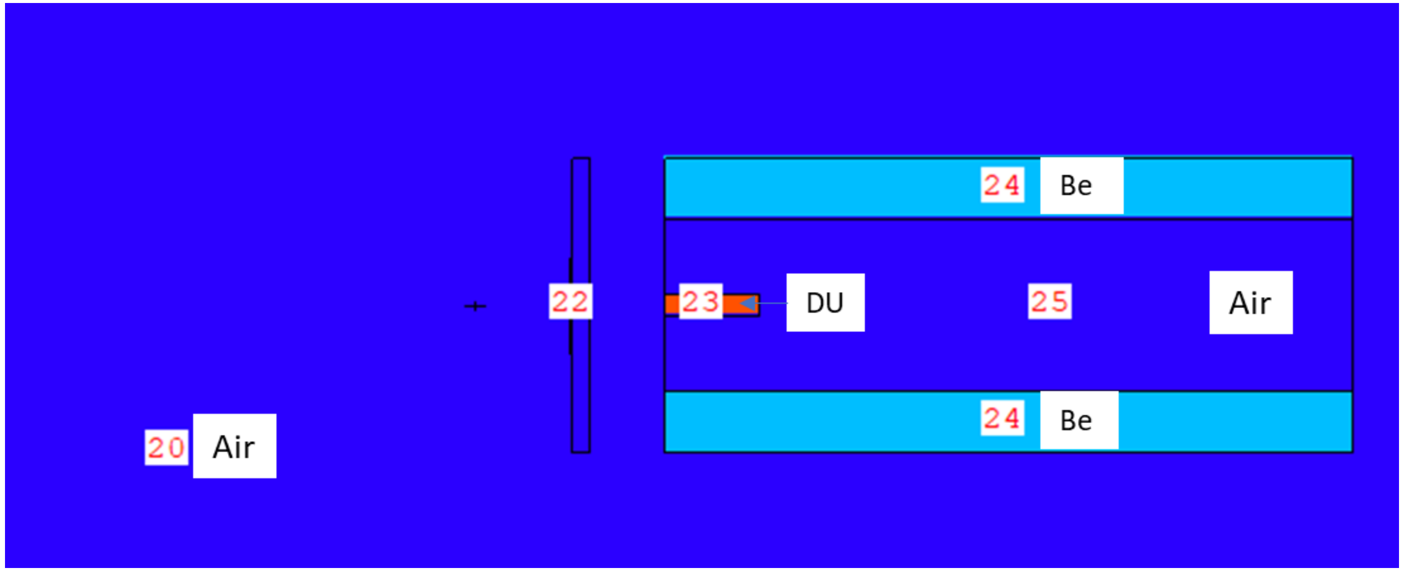
Enceladus Cutaway

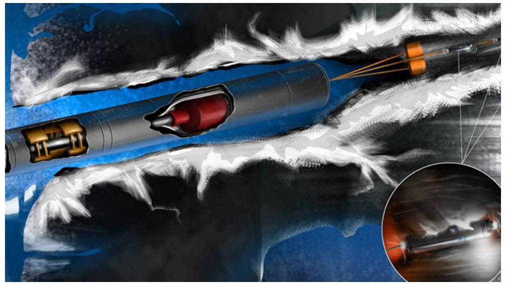
Technical Approach



- Evaluate the requirements for operating a robotic probe to melt or bore through an ice shelf.
- Model the LCF fast fission process based on first principals (using non-fissile materials such as depleted uranium or thorium in a molten lithium salt) and previous experimental results to provide guidance for building a hybrid fusion fast fission reactor providing power and heat to operate the probe.

Example of geometry layout of MCNP model of depleted uranium enclosed within a tube and surrounded by a neutron reflecting beryllium cylindrical sleeve.

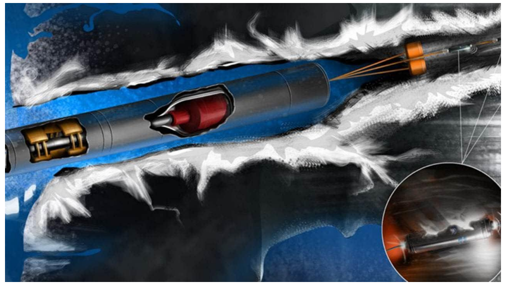




Conclusions

- 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.
  - Require a skinny probe so reactor needs to be compact
  - Breaking through the various ice phases requires a probe to be throttleable and not overheat
- Although traditional fission-based power sources could meet most of the requirements of such a mission, the cost and required handling of fissile materials such as HEU and ^{238}Pu are unattractive.
  - Traditional fission not as controllable and subject to overheating
- A hybrid fusion-fission reactor could be the answer to making accessing icy world oceans safer and less costly than using fission-based reactors
  - LCF as the source of energetic neutrons and molten salts as the fissionable material
  - Provides both heat and power for the robotic probe

Takeaways



- Hybrid Fusion-Fast Fission Power system
  - *No HEU or HALEU necessary*
  - *Built on NASA GRC[1] and US Navy research[2] published in Phys Rev C and elsewhere*
  - *With scaling, suitable for ice crust penetration, power and deep space propulsion*
  - *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[3]*

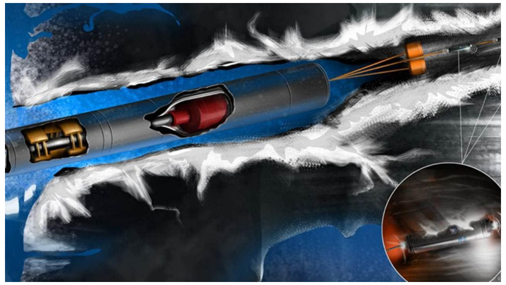
- Combined ice melting/ultrasonic penetration
  - *Takes advantage of skin layer adjacent to probe*

1. Pines, *et. al*., “Nuclear Fusion Reactions in Deuterated Metals”, *Phys Rev C*., **101**, 044609 (2020)
2. Mosier-Boss, *et al*., “Investigation of Nano-Nuclear Reactions in Condensed Matter”, *Defense Threat Reduction Agency*, (2016).
3. R. Culbert, *et al.,* “Double ridge formation over shallow water sills on Jupiter’s moon Europa”, *Nature Communications*, **13**:2007 (2022)

Backup Slides

A Mission Context

- Europa Clipper Mission
  - Europa Tunnelbot proposed as part of Europa/Ocean Worlds Lander Mission Concept
  - Proposed probe will have architecture 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 Europa's icy crust



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