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NASA Innovative Advanced Concepts

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

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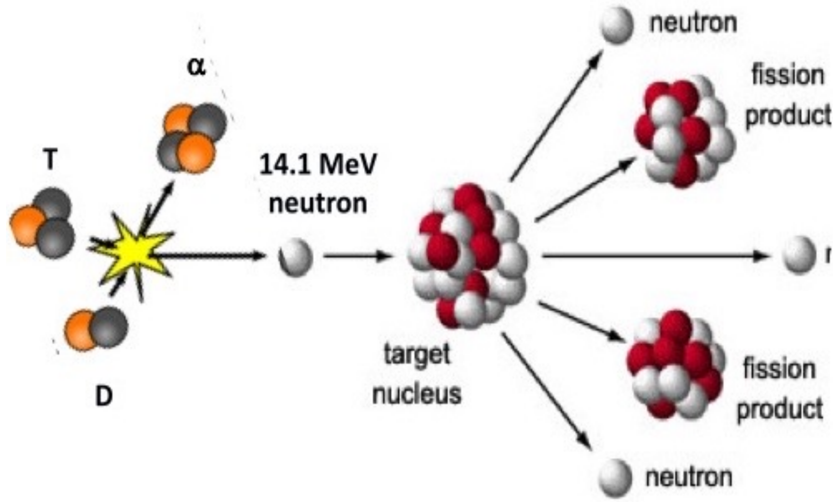
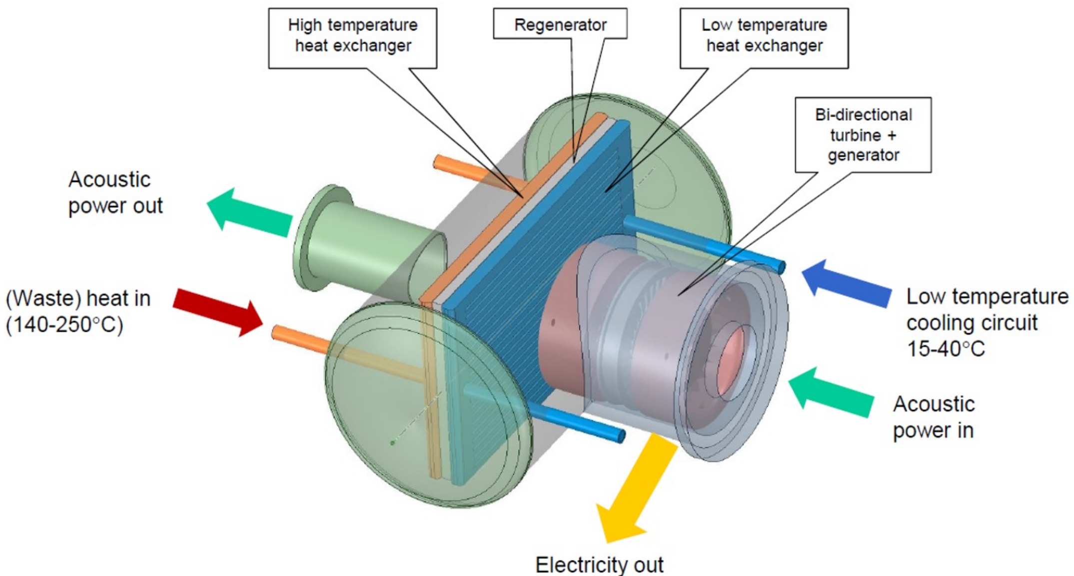
Overview

- Innovation
  - Hybrid Fusion Fast Fission
  - Robotic Probe
- Impact
  - Revolutionize Power Generation
  - Efficient Use of Waste Heat
- Mission
  - Enceladus Ice Plumes
  - Enceladus Orbilander Mission
- Approach

Innovation

- Hybrid Fusion Fission Reactor
  - Non-fissile, compact, scalable nuclear energy source sufficient to power and provide heat for melting and boring through icy shelves.
- 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

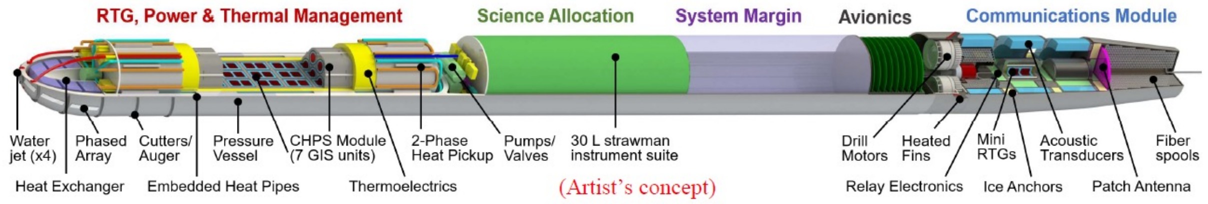




Impact

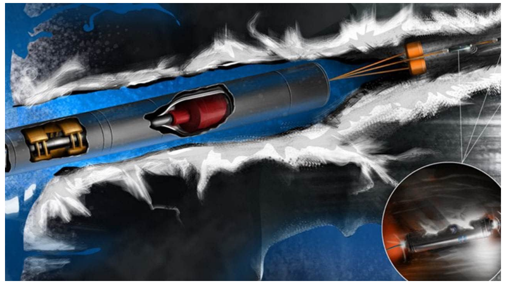
- Probes for icy moons require unacceptable amounts of ^{238}Pu isotope.
- A small, low-mass, variable power source is needed.
- New hybrid approach yields a variable output power source smaller than existing fissile reactors.
- Non-fissile alternative to high-enriched uranium (HEU), low-enriched uranium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

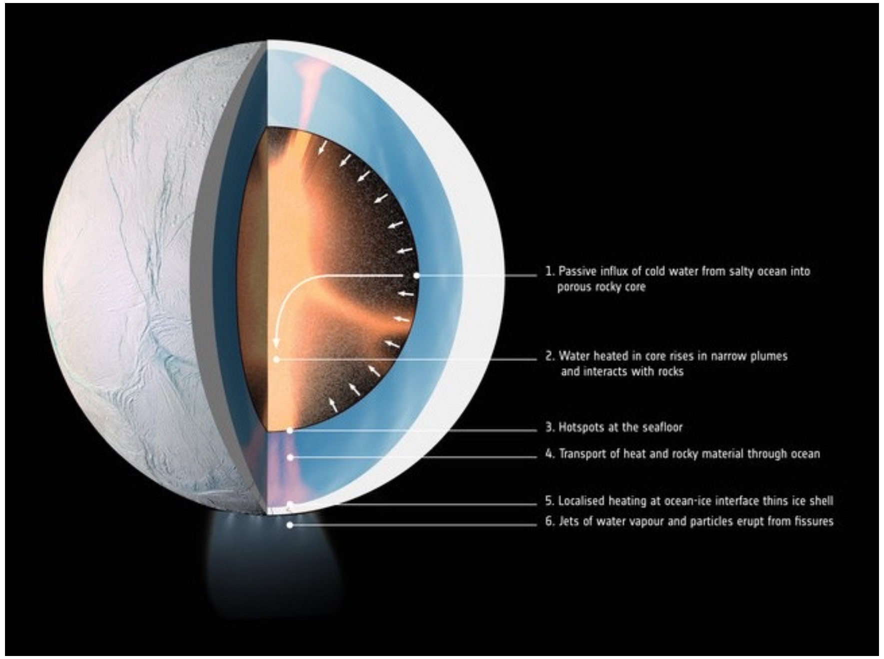


JPL Cryobot

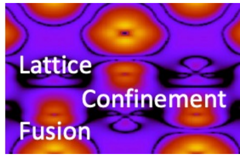
- Ocean Worlds Exploration Program
  - Search for Extraterrestrial Life
  - Enceladus: icy world candidate
  - Challenges
    - Operate under extreme environmental conditions
    - Break through up to 40 km thick ice
  - Lattice Confinement Fusion (LCF) Fast Fission can provide power and heat transfer



GRC Tunnelbot

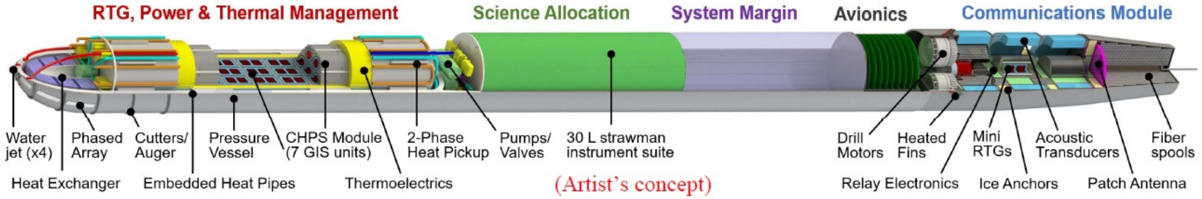


Enceladus Cutaway

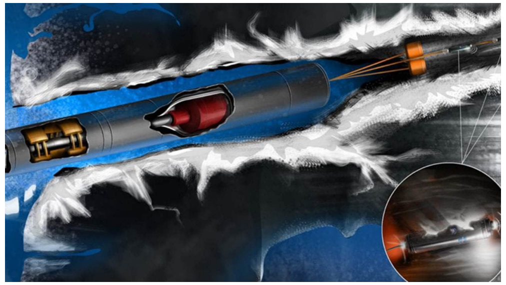


Mission

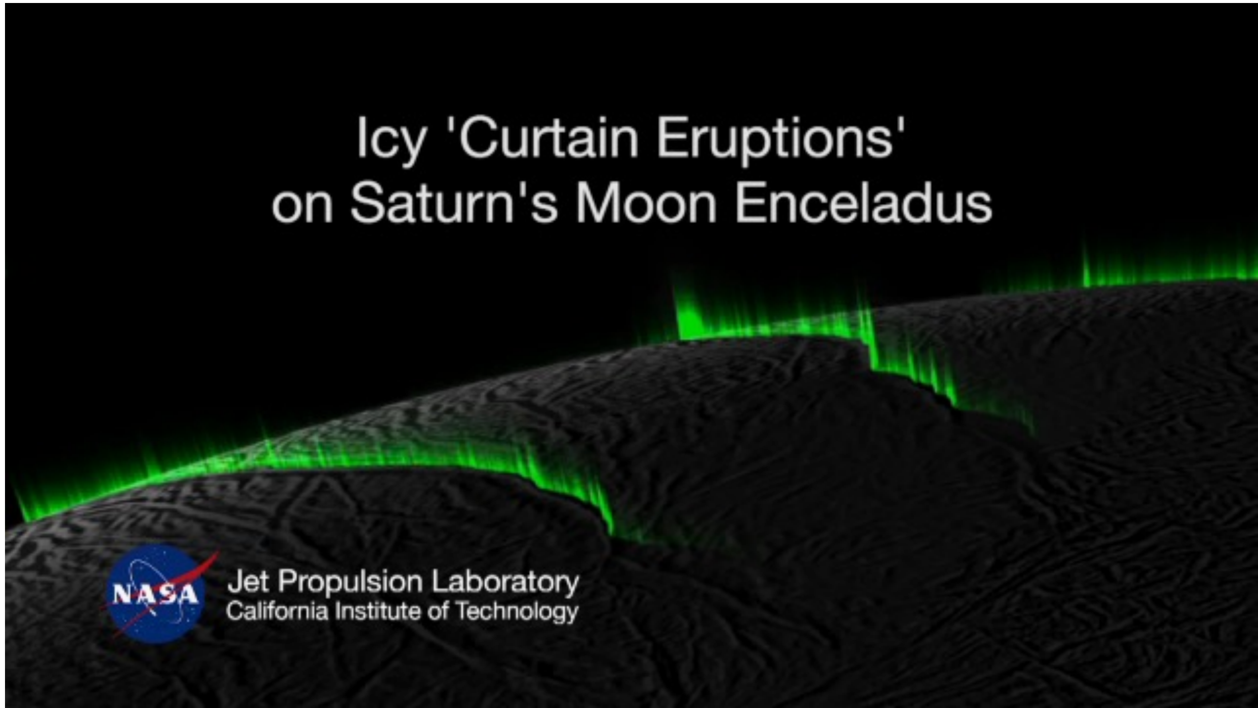
- Ocean Worlds Exploration Program
  - Proposed probe capable of powering the probe and heating/drilling mechanism with sufficient Watt-electric and Watt-thermal
  - Heated and/or (ultra) sonic drilling mechanism enables probe to cut through ice
  - Take advantage of the ice plumes evident on the south pole of Enceladus



JPL Cryobot



GRC Tunnelbot

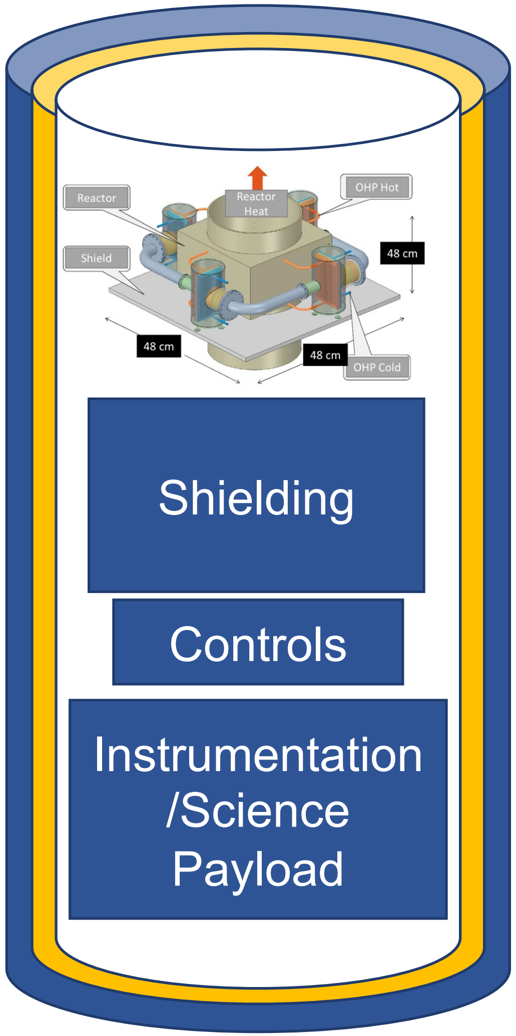


Approach: Requirements

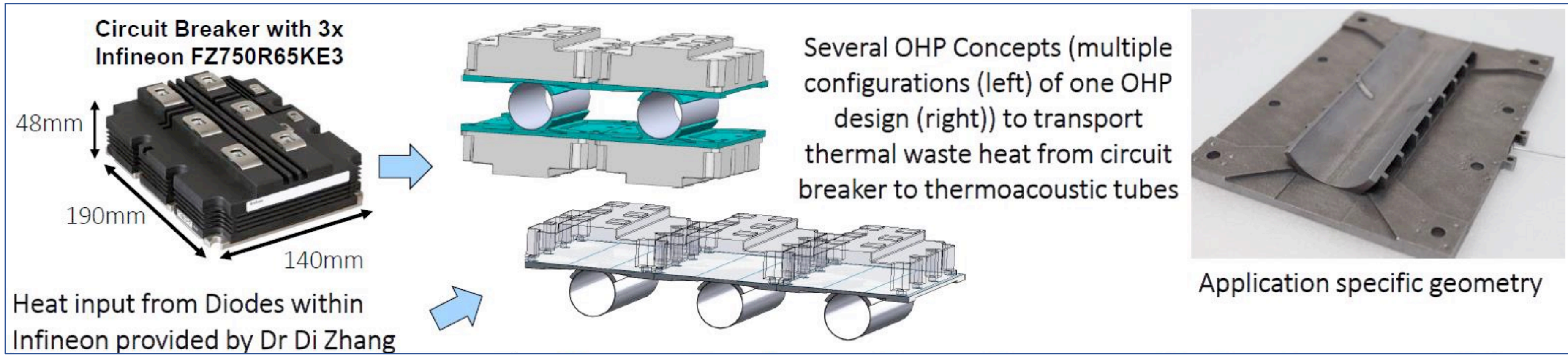
- Evaluate Robotic Probe and Power Requirements
  - Studied GRC's Europa Tunnelbot and JPL's Cryobot
  - Develop list of requirements
    - Heat source density: > 1W/cc
    - Total thermal power: 8-12 kW
    - Lifetime: 2-6 years; time to reach ocean under ice crust
    - Maturity: needed in 10 years
    - Probe Design; Water jet, drill/auger & heated fins
    - Communication: Fiber optic
    - Ability to return
    - Method to avoid ice reformation after traversing through solid ice

Robotic Probe Specifications/Options

- No pumps, no vibration -> reliable heating and power

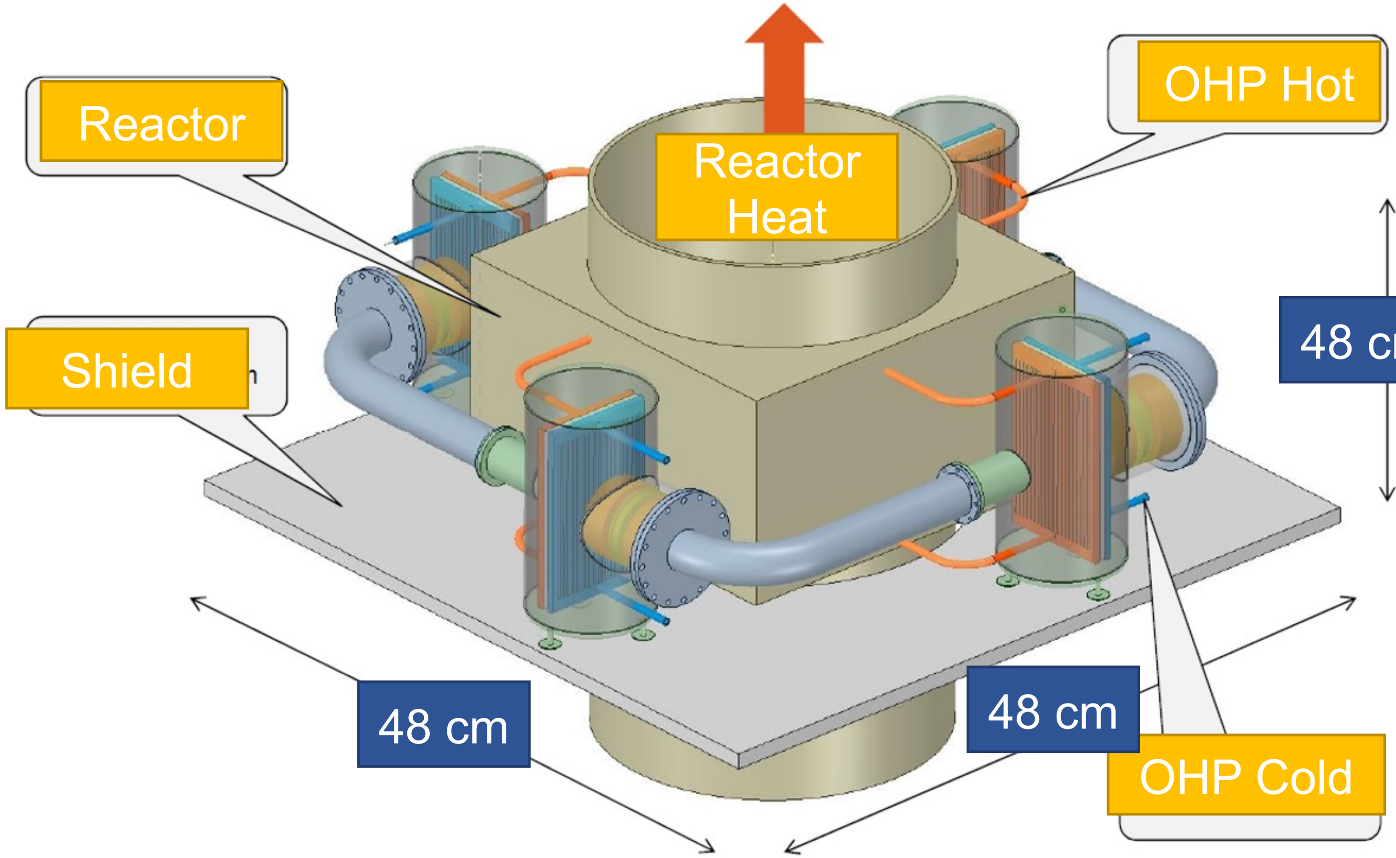


3D printed Oscillating Heat Pipe (OHP) Heating Cylinder



Robotic Probe Specifications/Options

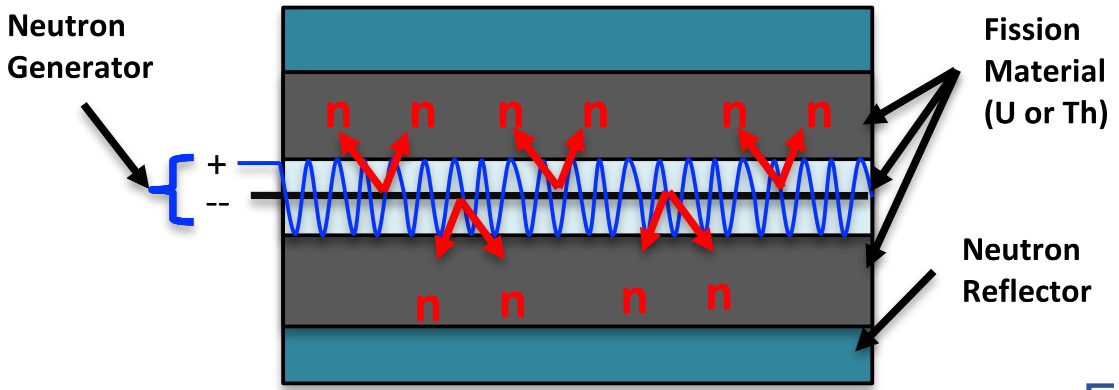
- No pumps required for power and heat transfer
  - Use Oscillating Heat Pipe (OHP) instead

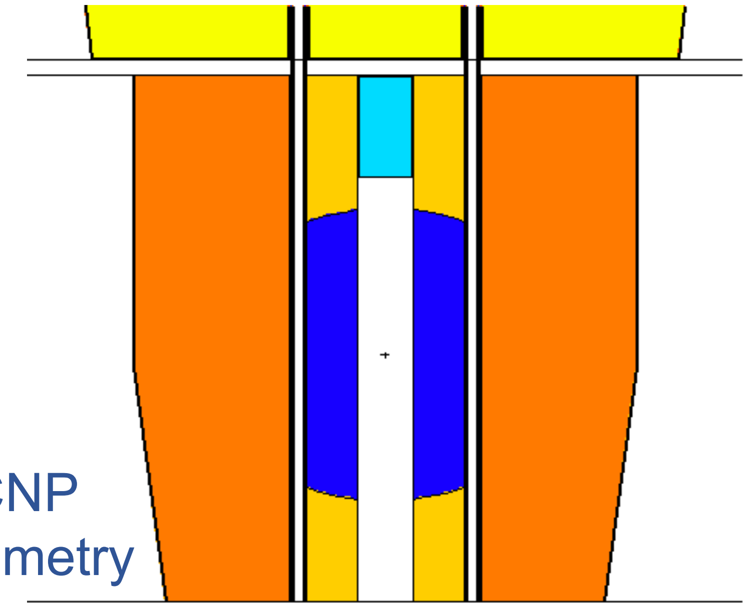


Approach: MCNP Modeling

- Model Fusion Fast Fission
  - Use Monte-Carlo N-Particle (MCNP) to model nuclear fission reactions from fusion neutrons
- Model Hybrid Fusion Fast Fission Reactor
  - Compare/contrast different molten salt based fusion fission reactors

Fusion-Fission Concept





Example MCNP Reactor Geometry

Lattice Confinement Fusion

Takeaways

- Hybrid Fusion-Fast Fission Power system
  - *No LEU, 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 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[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)

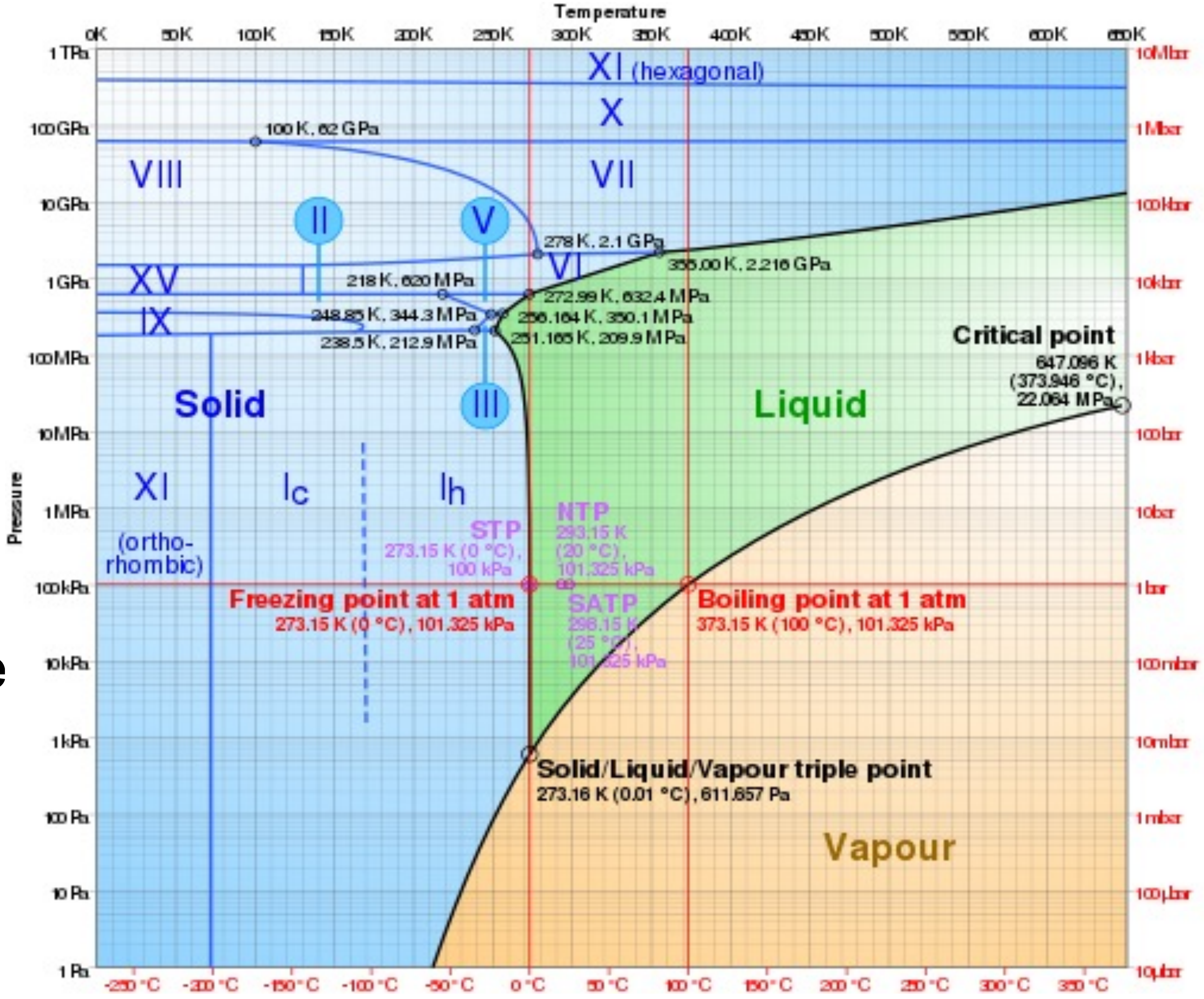
NASA Innovative Advanced Concepts

Lattice Confinement Fusion

Backup Slides

Mission

- 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*



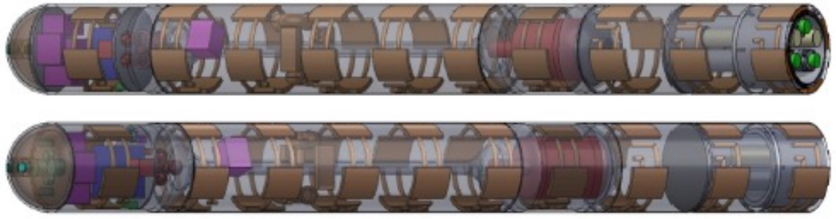
https://commons.wikimedia.org/wiki/File:Phase_diagram_of_water.svg

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

Lattice Confinement Fusion

Robotic Probe Specifications/Options

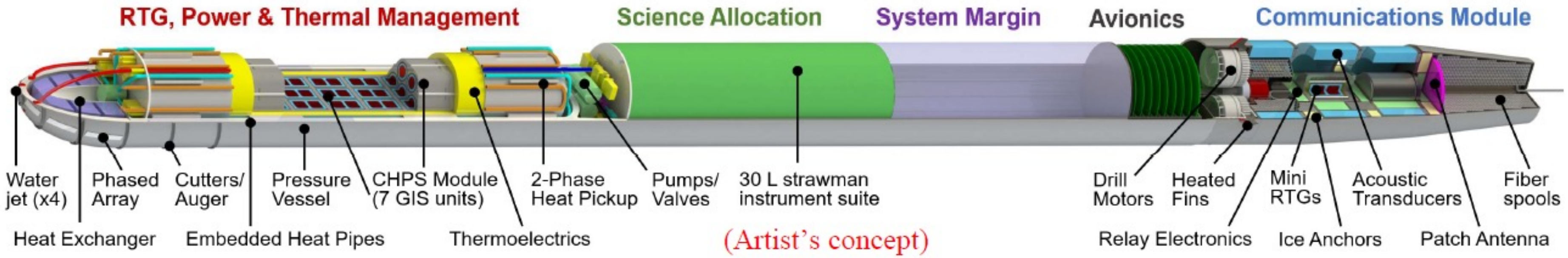
- Europa Tunnelbot



Subsystems:
Science
Thermal
Attitude Determination and Control
Communications
Power
Command and Data Handling
Structures

Figure 16.—Additional transparent views of Europa Tunnelbot reactor case.

- Cryobot



(Margined)

System	
Mass	**350 kg**
Volume	150 L
Length	3.1 m (cylinder) 3.9 m (total)
Diameter	23 cm

Mobility System	
Speed (cold layer)	4.4 km/yr
Speed (warm layer)	17.2 km/yr
Detectable hazard	1 cm (estimated)
Steering radius	10 m (estimated)
Debris Removal	Waterjet / drill

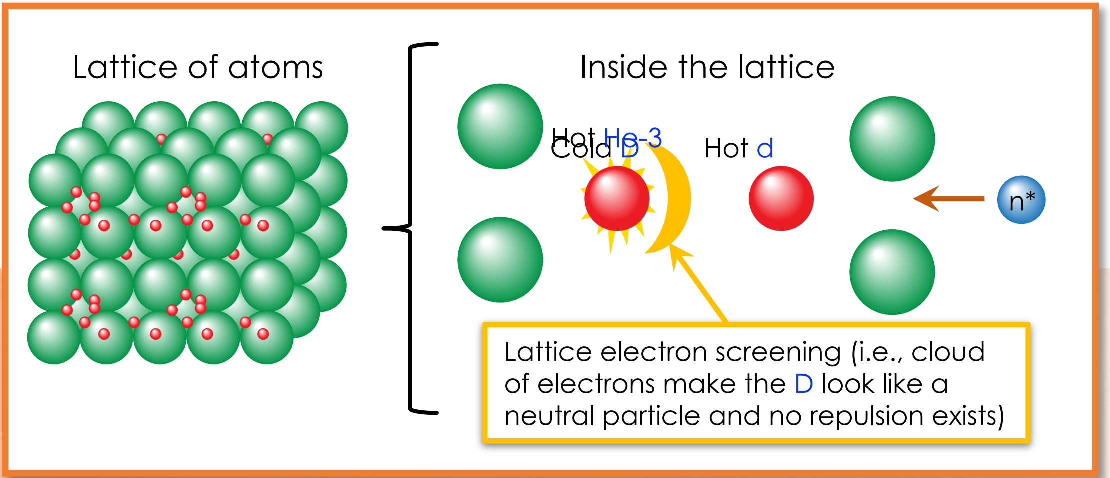
Power/Thermal System	
Total Heat	10.5 kWt
Peak Power	1 kWe
Skin temperature	25 C
WJ flow rate	3 L/min
Survival pressure	53 MPa

Communication System	
Data (primary)	1 kbps
Data (secondary)	100 bps
# Relays	3
Relay power	10 W
Fiber Length	70 km

Figure 1.—Tunnelbot reaching ocean after deploying communication repeaters and anchor (artist impression).

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

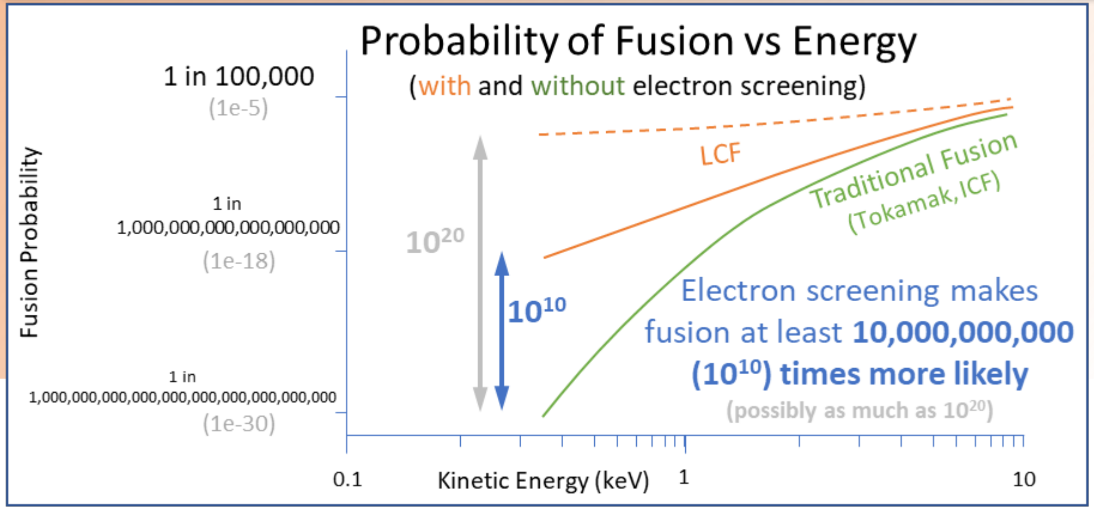


Technical Details Simplified

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

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

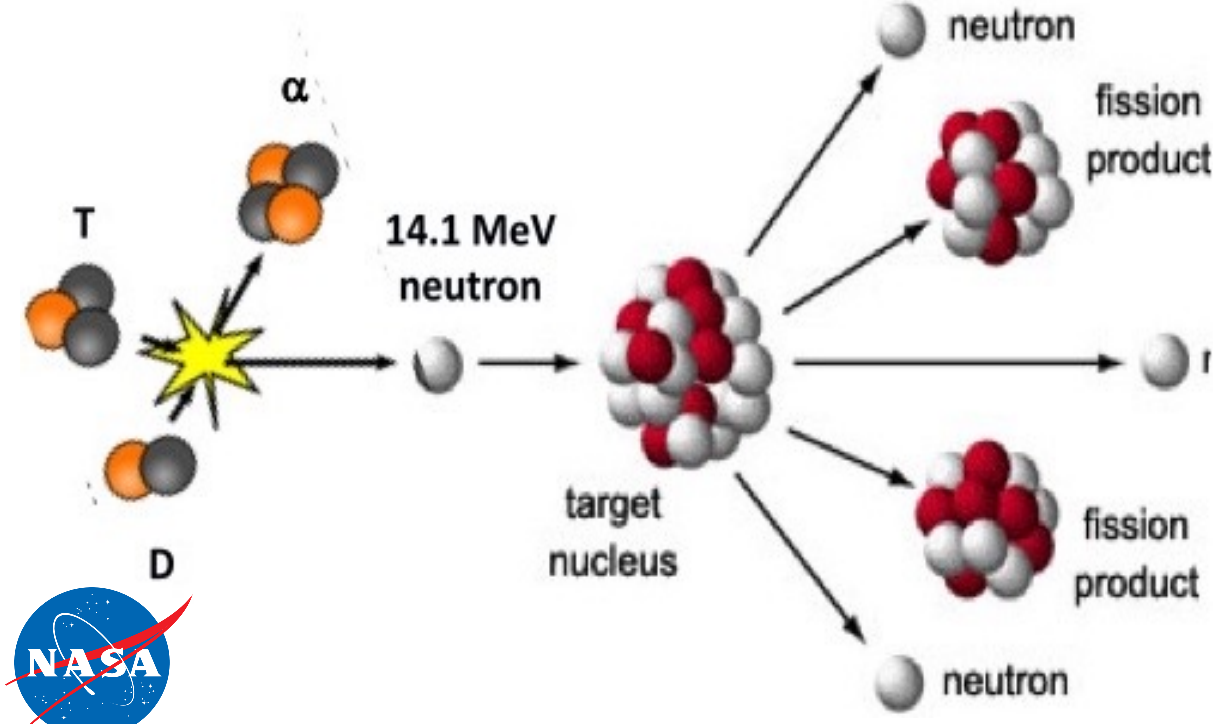
A + B + Trigger = Viable Fusion



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



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