Multi-MICE: A Network of Interactive Nuclear Cryoprobes to Explore Ice Sheets on Mars and Europa

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Team

• James Powell: Nuclear Reactor Design
• Hans Ludewig, Consultant, BNL: Neutronics Calculations
• Jesse Powell, Consultant, Scripps Inst. of Oceanography: Instrumentation, Search for Traces of Past Life
• John Paniagua: Mission analysis
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Multi-MICE Concept – Big Picture

1. Multiple, networked, un-tethered, semi-autonomous, high-powered, high-mobility, long-duration nuclear-powered probes

2. Uses existing technology
1. Multi-MICE Concept - Extreme Mobility

- gentle slope for landing
- millions of years old
- 3 km deep
- 6000 km$^3$ exploration area
The Multi-MICE Concept

- Compact, ultra lightweight nuclear reactors power a network of mobile probes that explore the interior of Mars North Polar Cap
- Probes move along melt channels in the ice sheet; can travel up and down vertically, and at angles to vertical
- Probes travel at 100’s of meters per day inside the ice sheet. Can reach bed-rock at multi-kilometer depths
- Probes obtain detailed data on the internal geologic/geophysical structure of the ice sheet, the paleo-climatoloogy of Mars, cosmic ray, solar and meteoroid history, and search for evidence of past life
- Probes in the network communicate with each other in real time and with surface lander that is in 2-way communication with Earth
- Scientists on earth obtain data in real time (subject to light speed limitations) and direct the activities of the probes
- Probes return samples to lander spacecraft for eventual transport back to Earth
Objectives of Program

• Design Multi-MICE (Mars Ice Cap Explorer) system with the following capabilities:
  – Powered by a small nuclear fission engine.
  – MICE probes can travel rapidly in both descent and ascent modes; also at angles to vertical.
  – MICE probes are fully instrumented to unravel physical and biological histories from information trapped in Martian polar ice caps and Europa’s ice sheets.
  – Multiple MICE probes communicate with each other and with lander and Earth.
  – MICE can return collected samples to surface.

• Develop plan for experimental validation of concept under NIAC Phase 2.

• Layout of development plan (including schedule and cost) for implementation of Multi-MICE system.
MICE Probe Design - Overview

**Instrument Package**
- contains both a standard payload (common to every MICE probe) and specialized payload

**Flexible Tether**
- Power, control and water flow lines
- Pressurized to form rigid structure

**Reactor / Generator Package**
- up to 500 kW of thermal power available
- Steam cycle generator provides 10 kW(e)

**Hot Water Jets**
- directionally controlled water jets
MICE Probe Design - Movement

- Directional water jetting + buoyancy control = Navigation
  - 45 degree ascent/descent possible
  - Debris avoidance
- Lateral traverses and azimuthal control allows full three-dimensional exploration of the ice cap
MICE Fuel Element Forms Using 3 Commercial Nuclear Fuel Options

**Zr/UO$_2$ Cermet Fuel**

**Hollow Tube Element**

- Water Coolant
- Zr/UO$_2$ Cermet Tube (~1 to 2 cm)
- Water Coolant

**Solid Rod Element**

- Water Coolant
- Zr/UO$_2$ Cermet Rod (~1 cm)
- Water Coolant

**Solid Plate Element**

- Water Coolant
- Solid Zr/UO$_2$ Plate (~2 mm)
- Water Coolant (~40 cm)

**TRIGA Fuel**

- Water Coolant
- Stainless Steel Cladding
- UH$_3$/ZrH$_2$ Metal Hydride (~1 to 2 cm)

**TRISO Fuel**

- Outlet Water Coolant
- Outer Porous Stainless Tube
- Annular Packed Bed of TRISO Particles
- Inner Porous Stainless Tube

**Radial Outflow Of Water Coolant**

- Water Inlet Flow Along Central Channel (~40 cm)
- ~2 cm
Summary of MICE Reactor Parameters

• 318 hollow tube Zr/UF2 cermet fuel elements
  – Fuel element OD/ID/length = 2.0/1.9/47 centimeters
  – Fuel element pitch/diameter ratio = 1.1/1

• Reactor core diameter/length = 47 centimeters
  – Water reflector thickness/OD = 5 cm/57 cm
  – Aluminum pressure vessel OD = 60 cm

• Water coolant/moderator (Tcore = 550 K), 500 KW(th)

• 13 control rods; Zr/B2O3 cermet
  – Beginning of life (t = 0); Keff = 1.082 (all rods out); Keff = 0.811 (all rods in)
  – End of life (t = 4 years); Keff = 1.095 (all rods out); Keff = 08.24 (all rods in)
  – 6 kg U-235 loading; 12% burnup after 4 years

• 120 kg total dry mass
  – 90 kg reactor
  – 30 kg heat exchangers, T-G, controls
Neutronic Analyses of MICE Reactor

- 3D Monte Carlo codes were used to model MICE reactor
  - MCNP code for reactor criticality
  - Monte Burns code for burnup behavior
- Full 3D geometric representation of all components in reactor including all fuel elements, control rods, reflector, grid plates, and pressure vessel
  - Required to accurately model neutron leakage and absorption in highly heterogeneous, 3D reactor systems
  - 3D Monte Carlo codes predicted $K_{\text{eff}}$ for criticality in similar actual particle bed reactor assemblies to within $\frac{1}{2}$ percent
- MICE reactor easily controlled and can operate at full power of 500 KW(th) for many years
  - Large safety margin – reactor strongly subcritical when all control rods are in [$K_{\text{eff}} = 1.082$ (all rods out); $K_{\text{eff}} = 08.11$ (all rods in)]
  - Criticality ($K_{\text{eff}}$) essentially constant during 2000 KW(th) year operating period when Boron-10 is used as burnable poison [12% of U-235 loading burns out]
  - Reactor has strong negative temperature and void coefficient
Reactor Pod - Fuel Element Design

- Control Rods
- Closest Circle
- Dimensions:
  - Diameter: 460.00 mm
  - Height: 401.05 mm
  - 22.00 mm
  - 20.00 mm
  - 1.00 mm
Surface Heat Flux, Water Temp. & Film Delta T as a Function of Distance along Central Fuel Element

- Heat Flux (watts per node), Water Temp (K)
- Film Delta T (K)

- q, watts
- T(water) K
- Film Drop, K

Distance from Inlet, cm
MICE Melt Channel

$q_c$, $q_{\text{cond}}$

$\sim 5 \text{ cm}$

Ice Meltwater

MICE

$Q = 500 \text{ kW}$ $\rightarrow$ $V \approx 300 \text{ m/day}$

$1.2 \text{ m}$

$60 \text{ cm}$
Temperature Propagation into Surrounding Ice

- Ice Temperature, K
- Radius (R - Ro), cm

- 900 sec
- 1800 sec
- 3600 sec
Mars North Polar Cap – Why go?

- **Life Detection**
  - Biosignatures
  - Microfossils
  - Growth chamber experiments

- **Glaciology and Paleo-climate**
  - Stratigraphy
  - Ice chemistry / Mass Spec of ancient gases
  - Optical imagery / Dust layers
  - Solar / cosmic ray / micrometeoroid history

- **Geology and Geophysics**
  - Examination of trapped particulates
  - Possible Ocean basin sediment profiling
  - Seismology

- **Scout for Permanent Human Bases**
  - Pole has abundant water
  - Pole provides shelter - large melt chambers
  - *In situ* resources - cyrogenically concentrated gases
MICE Instrumentation and Sampling System – Goals and Requirements

• Measure Age of Ice as a Function of Depth and Location (years since deposition as ice)
• Determine Composition and Temperature of Ancient Martian Atmosphere as a Function of Time over Millions of Years
  – Also determine dust loading in atmosphere over the same time frame
• Sample Both Melt Water and Solid Ice around Melt Channel
  – Determine temperature, atmospheric composition, dust, etc. in ice that is unaffected by melt channel
• Sample Both Surface and Interior of Sedimentary Layers at Base of Ice Sheet
• Determine Types and Amounts of Different Organic Chemicals in Melt Water, and Whether They Are Life Specific
• Continuously Image Solid Particulates From Ice Sheet to Determine Whether Microfossils Are Present, and What Geology and Material They Represent
MICE Instrumentation and Sampling System – Biological Science Capability

• Microfossils
  – flow microscope continuously samples meltwater and images particles at high resolution (~1 micron per pixel).

• Life Detection – “Earthlike” Life

• Life Detection – Minimal Assumptions
  – Growth chamber experiments track minute changes in ion balances between meltwater inoculated growth chamber versus sterilized meltwater control chamber.
### MICE Instrumentation and Sampling System – Desired Instruments

<table>
<thead>
<tr>
<th>Aqueous Sampling</th>
<th>Acoustic Instrumentation</th>
<th>Imagery &amp; Free-space optics</th>
<th>RF</th>
<th>Other</th>
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</table>
| • Conductivity, Temperature, Depth (CTD)  
• O2, CO2 sensors  
• Ion-Sensitive Electrodes (ISEs) (MICA)  
• Flow Fluorometers / spectrophotometers  
• Flow microscope / particle counter  
• Lab-on-Chip Life Detector  
• Growth Chamber Experiment | • Obstacle Sonar  
• Ice / Sub-bottom Profiler | • High Res Macro Imager  
• Video  
• Laser Nephelometer | • Ice-Penetrating Radar  
• Source/receive studies  
• Comm & Navigation | • Mass Spec  
• LIBS  
• Seismic source / seismometer |
MICE Instrument Pod - Design

- **Sonar transducer**
- **Water Jet Controller**
- **Expandable Standoffs / Ice Sampling Device**
- **Modular Instrument Bays / Buoyancy Control**
- **Water Conduits to/from Reactor Pod**
MICE Instrument Pod - Sampling

- Extensible Standoffs provide support during hot water jetting
- Ultrasonic drill permits sampling from pristine ice
Communications - Mesh Network

- Each probe acts as node in a mesh network

- Mesh networking allows MICE probes to travel further from lander by relaying commands

- Redundant: if one node fails, probes that lose contact with lander migrate back towards lander to re-establish network

- Trilateration and depth (pressure) information allows highly accurate positioning of the probes for scientific inquiry
Communications - Control System

- MICE probes are in continuous 2-way real time communication with other probes and with surface spacecraft lander
- Lander is in continuous communication with scientists on Earth, subject to speed of light delays
- Scientists receive data from probes in $\leq$1 hour and can control where probes go and what data they take
- Communications inside ice sheet are dual mode
  - RF for medium range and high data rates (1 Mbs) can transmit multi kilometers but may be affected by ice inclusions and dust layers
  - Acoustic for long range and moderate data rates (10-20 kbs) can transmit for many kilometers. Not sensitive to inclusions and dust layers
  - Range can be extended by node hopping
- Semi-autonomous control functions on probes
  - Probes keep track of 3D movements and location
  - Probes maintain power level, movement rate, direction and sampling operation activities at value directed from Earth, and change to different values when so directed
Mission Parameters - Time Line

• Delta 4 launch vehicle departs Earth in May 2018
  – 260 day flight time to Mars polar cap
  – Upper stage RL10 H\textsubscript{2}/O\textsubscript{2} engine; Iso = 400 seconds
• MICE spacecraft lands on North Polar Cap in February 2019 using thrusted burn after aerocapture maneuver
  – On-board reactor power system melts ice to generate water coolant, moderator for MICE probes
  – 6 MICE probes deploy and begin exploration of North Polar Cap
• MICE probes explore Polar Cap for 18 months
  – On-board reactor replenishes H\textsubscript{2}/O\textsubscript{2} propellant for MICE spacecraft
  – MICE probes return collected sampled to spacecraft
  – MICE spacecraft departs from Earth in July 2020
• MICE spacecraft arrives Earth in March 2021
  – Aeroshield and aerobraking parachute land sample container on Earth
Future Work - Development

- MICE reactor uses existing, well proven technology
  - Nuclear fuel and water coolant/steam turbine components can be directly applied to MICE
  - MICE reactor & power system can be built and tested within ~3 years
- Much of the instrumentation for MICE is already in use on AUV’s (Autonomous Underwater Vehicles) and other applications
  - MICE is not power and duration limited, unlike AUV’s and other systems – not subject to input power limitations, compared to present systems
  - Development of additional new instruments, particularly in relation to search for biologic traces, is highly desirable
  - Instrumentation can be tested and validated in Earth ice sheets
- MICE technology development is required in 3 areas
  - Channel melt and movement system
  - Long range communications through ice
  - Operational control – combined autonomous and external control systems
- Integrated MICE probe can be tested and validated in Earth ice sheets before being sent to Mars – can use non-nuclear energy input
MICE – A Stepping Stone to Permanent Manned Bases on Mars and Large Scale Exploration of the Solar System

• The MICE reactor system can robotically operate at sites on Mars North Polar Cap using water and atmospheric CO₂ and dust minerals to produce virtually all of the supplies needed for permanent manned base – operating at 5 MW, a compact MICE factory could produce and stockpile in just 20 months:
  – 160 tons of liquid H₂ and 1680 tons of liquid O₂
  – 60 tons of liquid methane and 30 tons of methanol
  – 30 tons of plastic and 10 tons of food
  – 8 sub-surface large habitat insulated caves, completely shielded from cosmic rays
  – All supplies and habitats would be stockpiled before astronauts left Earth

• When astronauts landed on Mars, they would have very ample supplies and safe habitats awaiting them
  – Astronauts would use supplies to construct and operate rovers to explore large regions on Mars

• Robotic MICE factories can produce many tons of propellants, water, and other supplies to be robotically transported to Earth orbit
  – Supplies from Mars would enable large lunar bases, space tourism, and extensive exploration of the solar system
Summary & Conclusions

The Multi-MICE concept can provide a unique and important window into the geologic, meteorological, and biologic history of Mars, together with data on cosmic irradiation and solar system processes over many millions of years.

• Compact, lightweight mobile MICE probes would travel inside the Icy North Polar Cap of Mars, each powered by a small (50 cm diameter) nuclear reactor that melts a channel through ice.
  – 200 meter per day travel capability
  – Can descend or ascend, vertically or at an angle
  – Can reach base of multi-kilometer thick ice sheet
  – Take data on composition and geologic history of ice sheet, Martian atmosphere, and wind-blown dust; cosmic irradiation and Solar system history, and search for biologic and fossil evidence of life on Mars.
  – Can return samples to spacecraft lander.

• Multi-MICE probes are in continuous real time communications with each other, with the spacecraft lander, and with scientists on Earth (subject to speed of light delay)

• Mice reactor uses well proven commercial technology – much of MICE instrumentation already exists.

• MICE probes can be tested and fully validated in Earth ice sheets prior to a Mars mission