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

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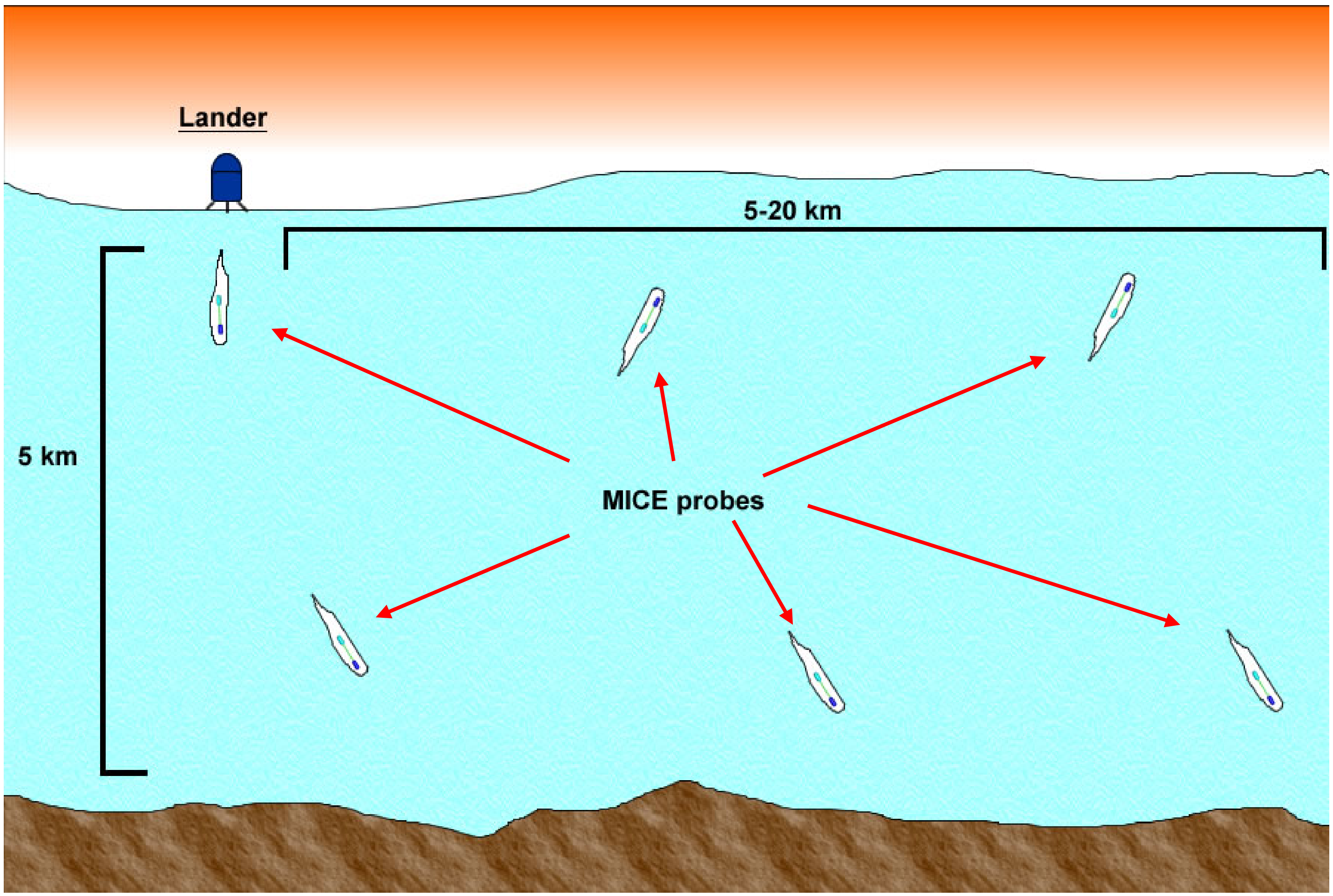
NIAC Phase 1 Fellows Meeting, Atlanta, GA
March 7-8, 2005

Team

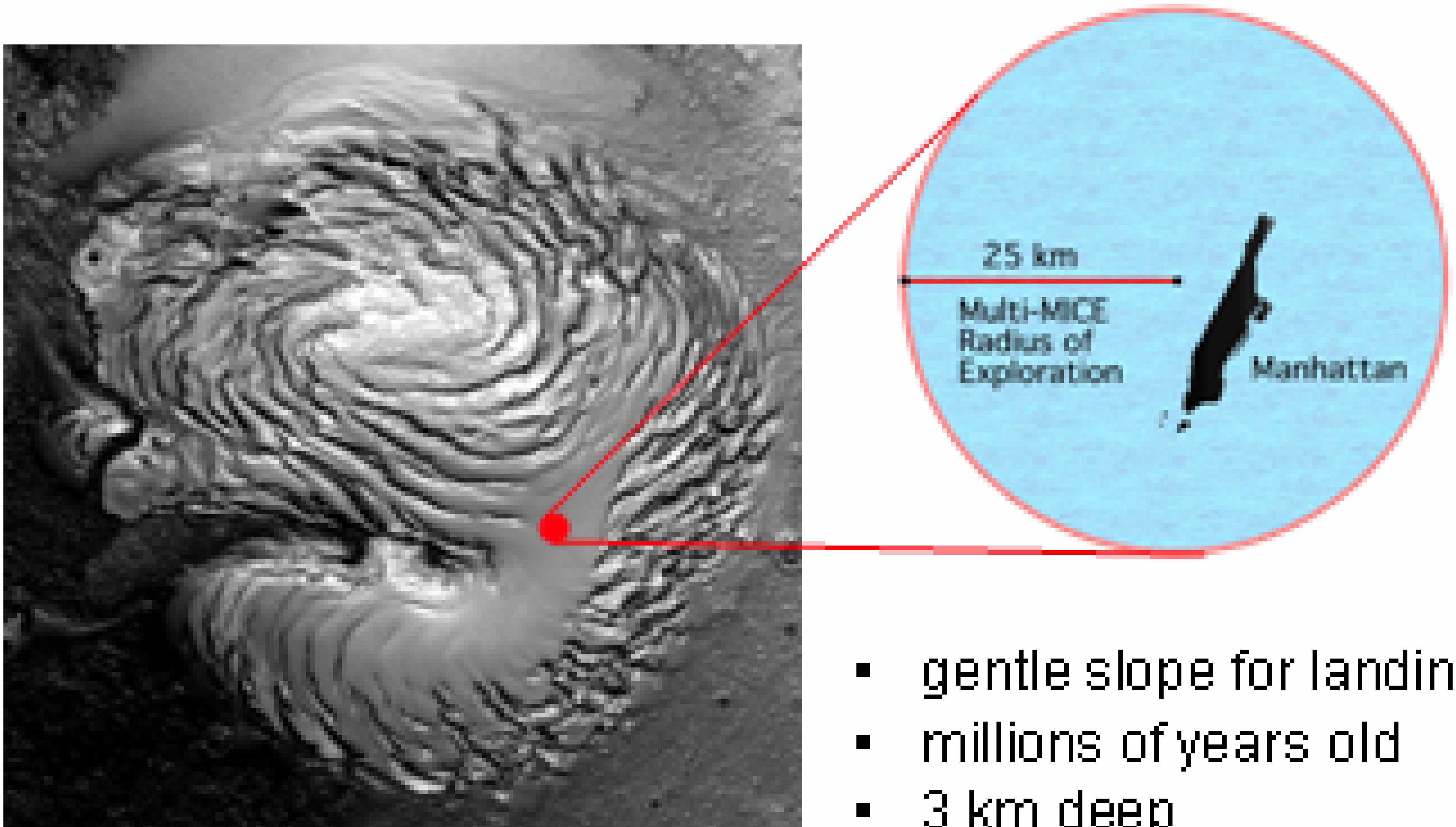
- **James Powell**: Nuclear Reactor Design
- **Hans Ludewig**, Consultant, BNL: Neutronics Calculations
- **Jesse Powell**, Consultant, Scripps Inst. of Oceanography: Instrumentation, Search for Traces of Past Life
- **John Paniagua**: Mission analysis
- **George Maise**: PI and Thermal/Hydraulics

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-climatology 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

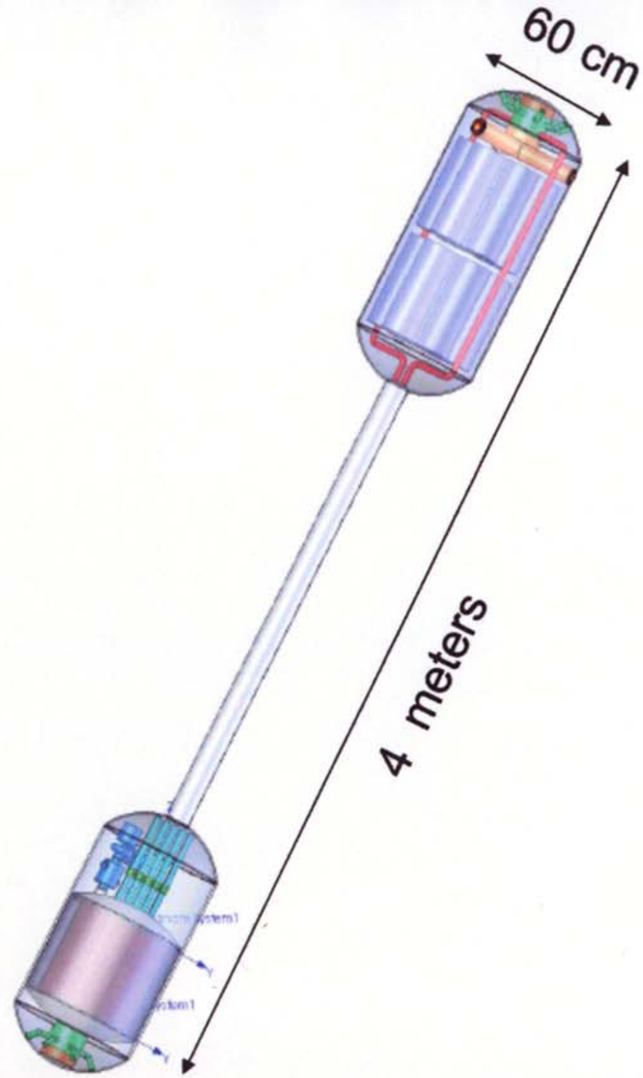
- Power, control and water flow lines
- Pressurized to form rigid structure

Reactor / Generator Package

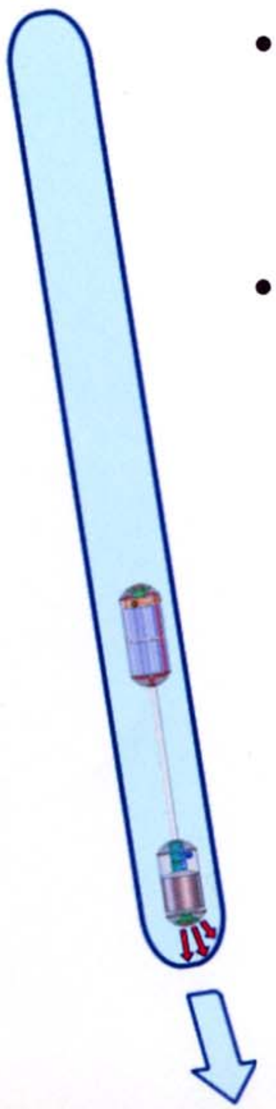
- up to 500 kW of thermal power available
- Steam cycle generator provides 10 kW(e)

Hot Water Jets

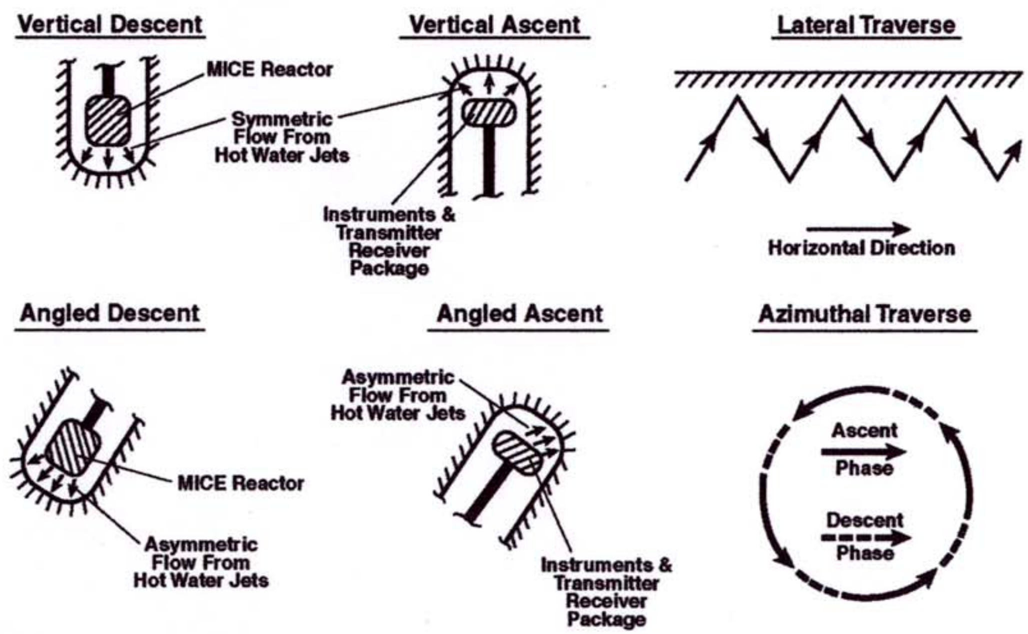
- directionally controlled water jets



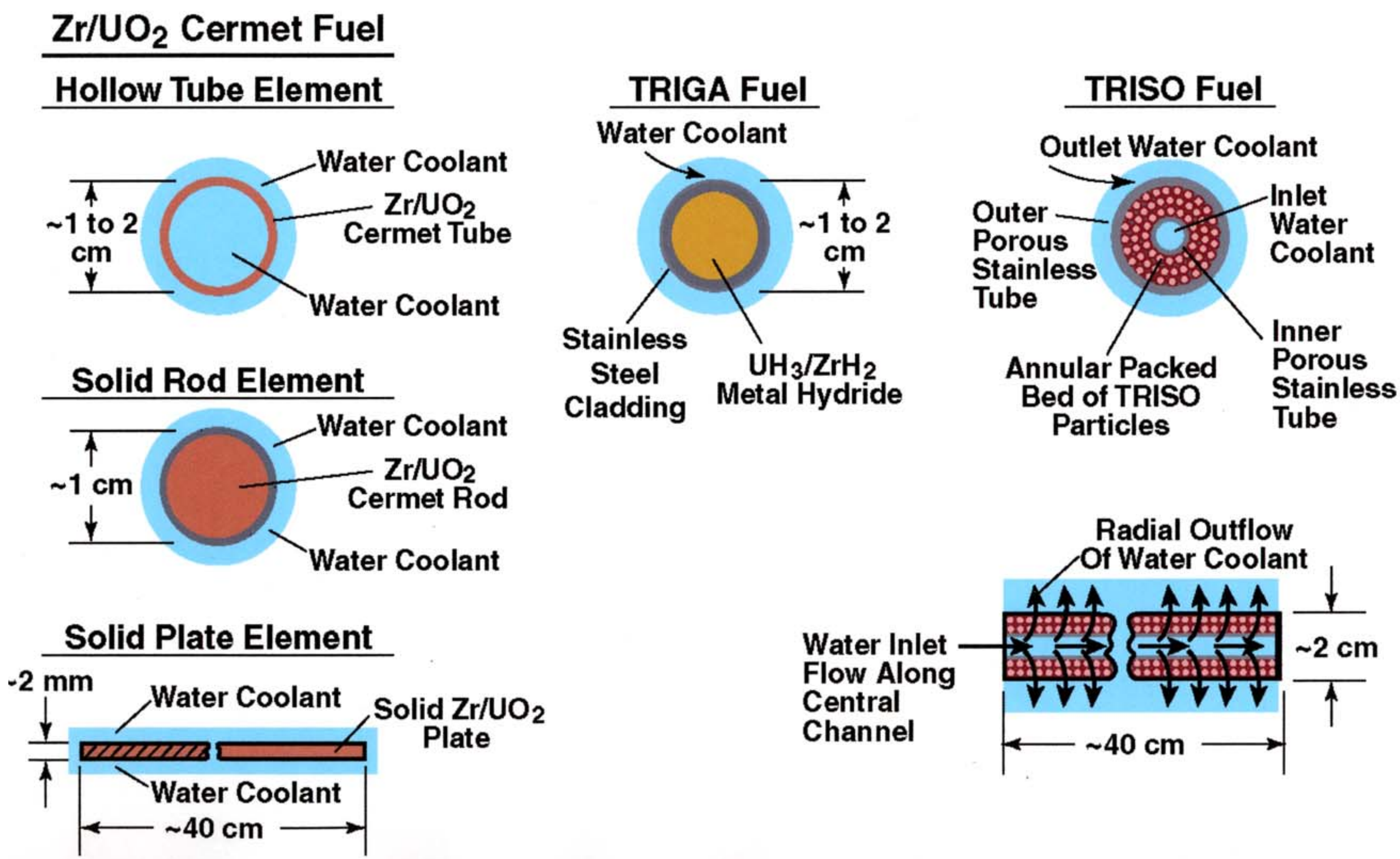
MICE Probe Design - Movement



- 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



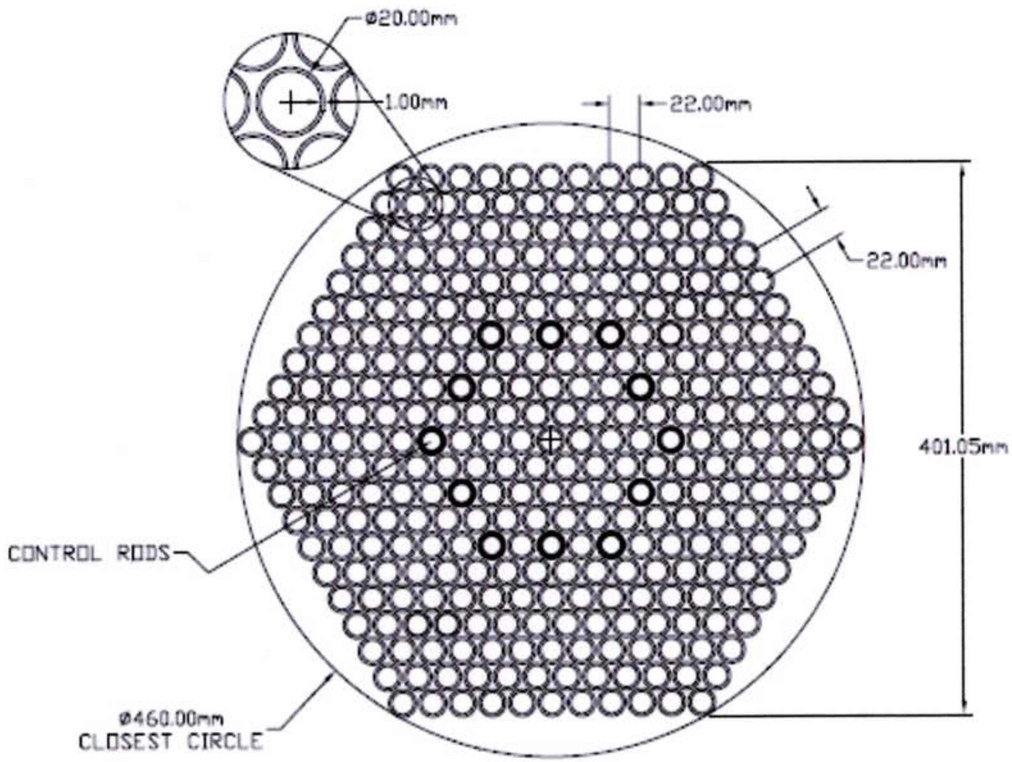
Summary of MICE Reactor Parameters

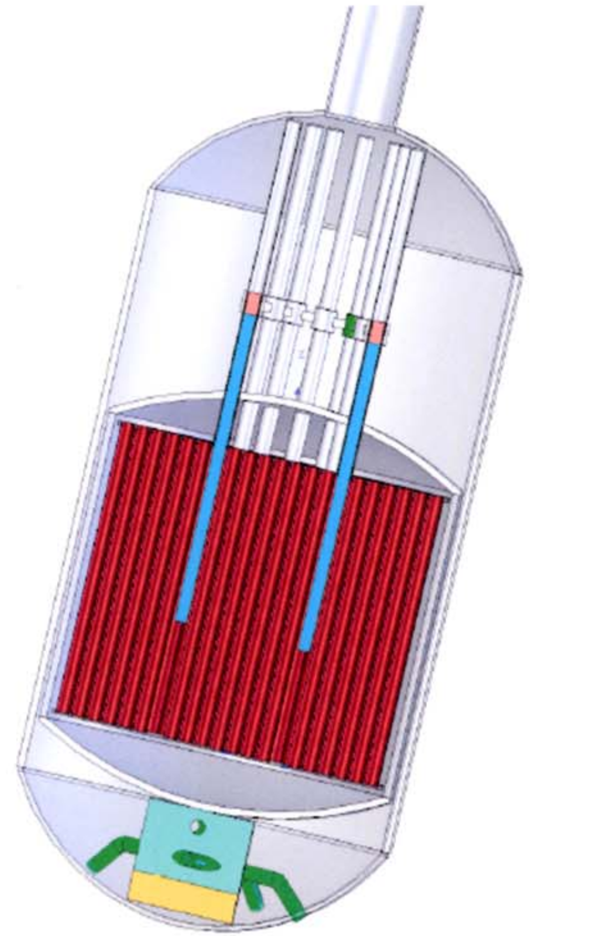
- 318 hollow tube Zr/UO_2 cermet fuel elements
  - Fuel element OD/ID/length = 2.0/1.9/47 centimeters
  - Fuel element pitch/diameter ratio = 1.1/1
- Reactor core diameter/length = 47 centimeters
  - Water reflector thickness/OD = 5 cm/57 cm
  - Aluminum pressure vessel OD = 60 cm
- Water coolant/moderator (Tcore = 550 K), 500 KW(th)
- 13 control rods; Zr/B_2O_3 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

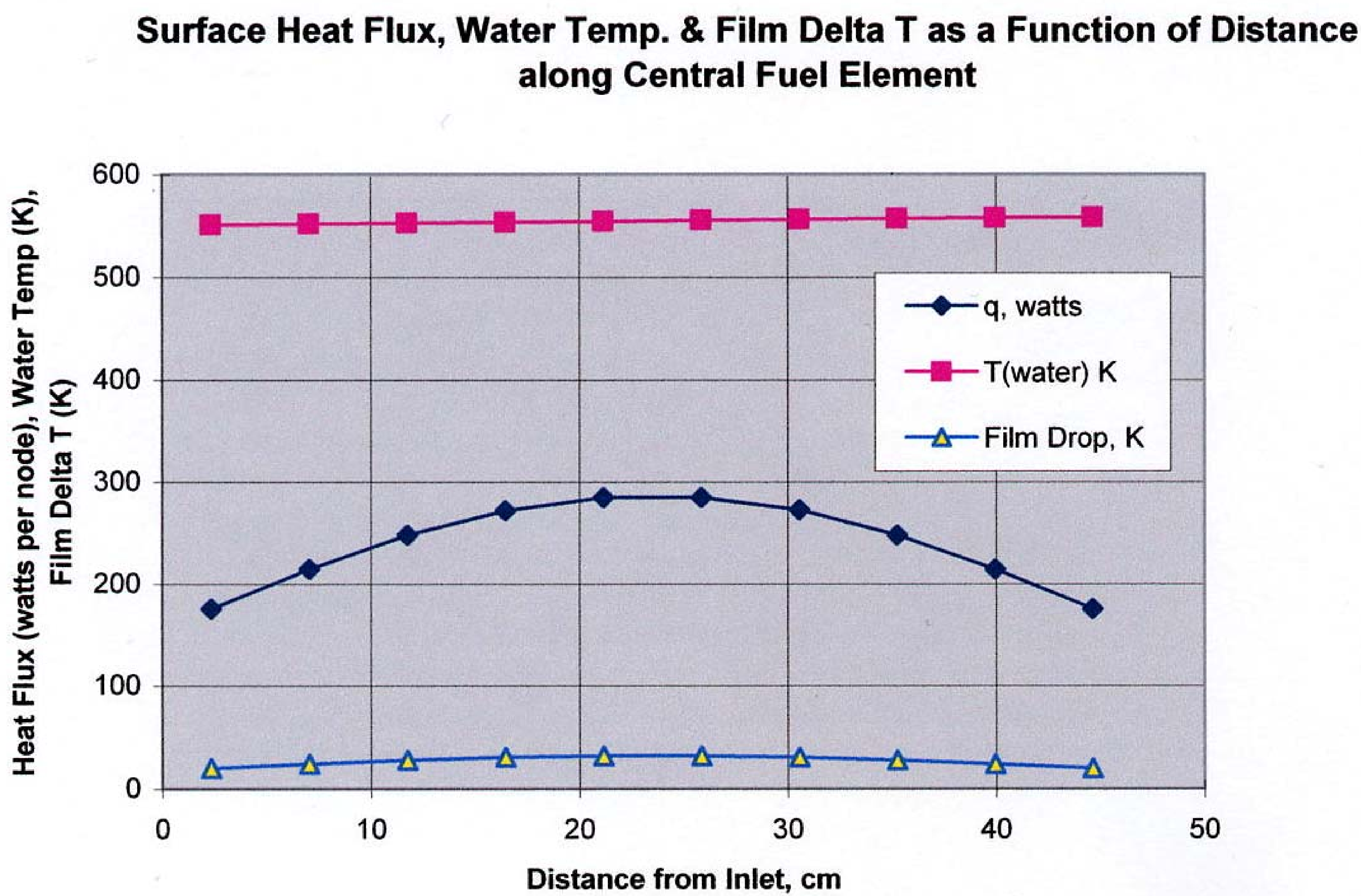
Neutronic Analyses of MICE Reactor

- 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 Keff for criticality in similar actual particle bed reactor assemblies to within ½ 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 [Keff = 1.082 (all rods out); Keff = 08.11 (all rods in)]
  - Criticality (Keff) 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

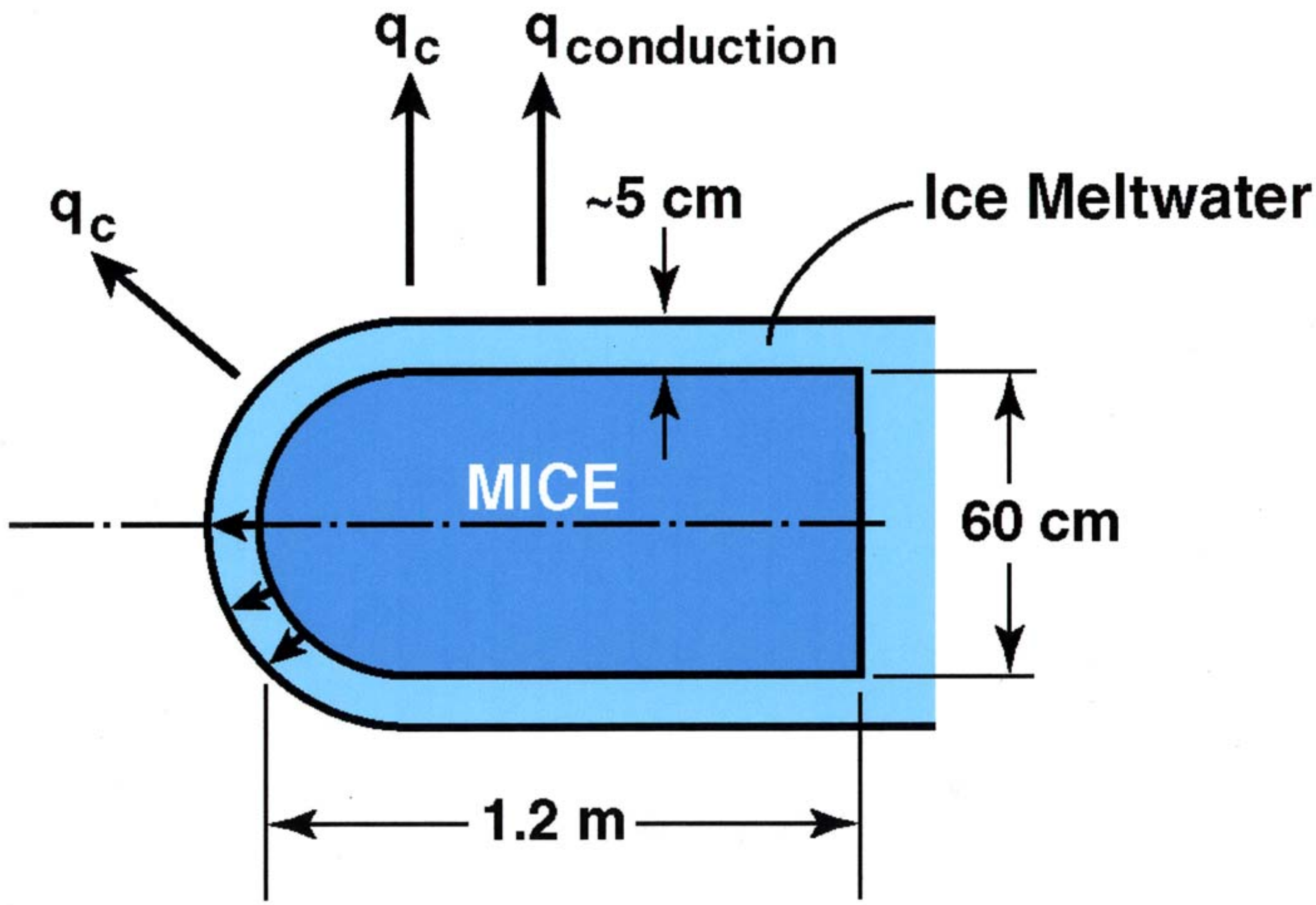
Reactor Pod - Fuel Element Design



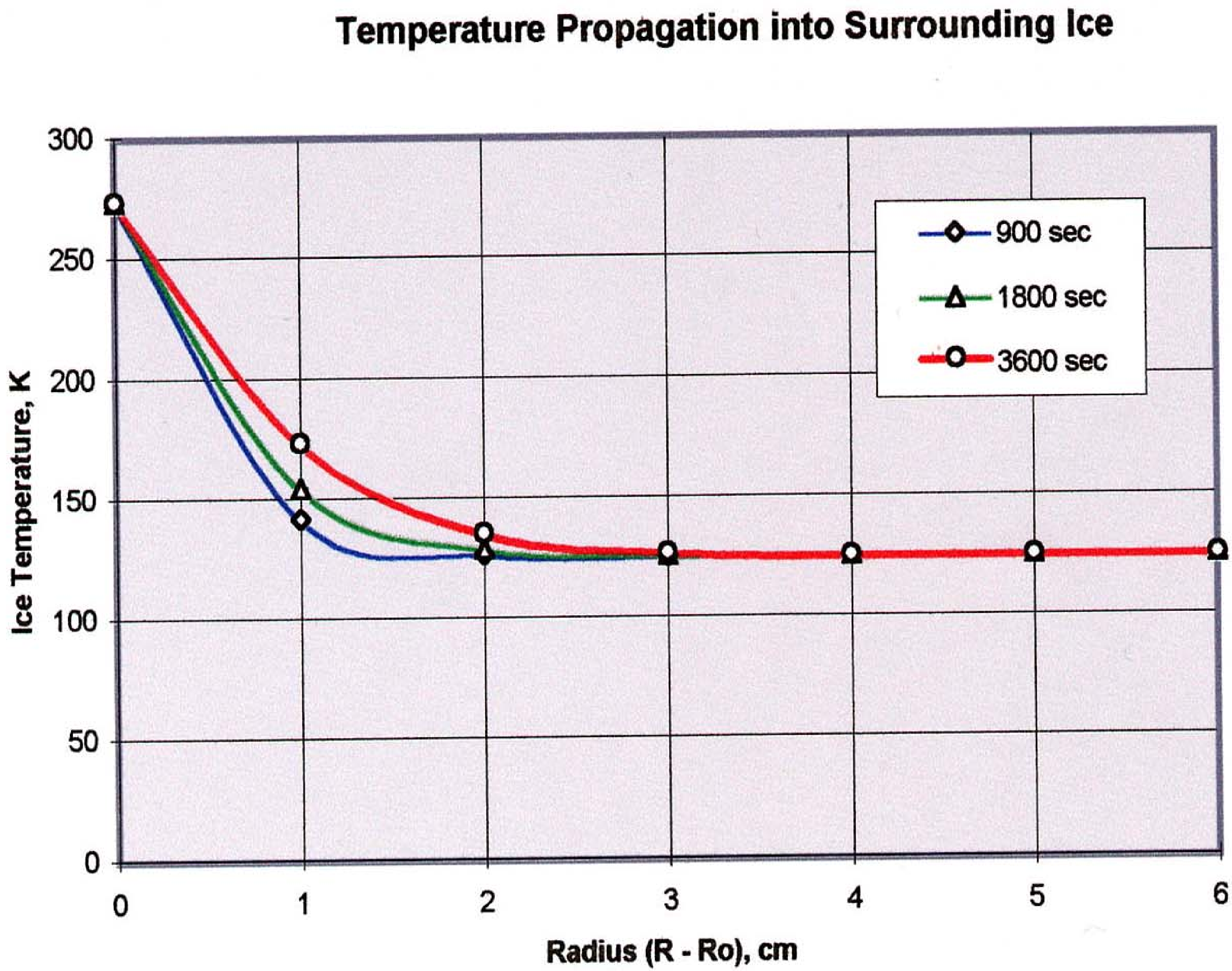



Surface Heat Flux, Water Temp. & Film Delta T as a Function of Distance along Central Fuel Element
Heat Flux (watts per node), Water Temp (K), Film Delta T (K)
Distance from Inlet, cm
q, watts
T(water) K
Film Drop, K
0
100
200
300
400
500
600
10
20
30
40
50

MICE Melt Channel



$Q = 500$ kW ⟶ $V \approx 300$ m/day



Temperature Propagation into Surrounding Ice
Ice Temperature, K
Radius (R - Ro), cm
900 sec
1800 sec
3600 sec
300
250
200
150
100
50
0
0
1
2
3
4
5
6

Mars North Polar Cap – Why go?

JPL / NASA

- 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

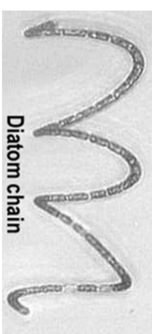
MICE Instrumentation and Sampling System – Biological Science Capability

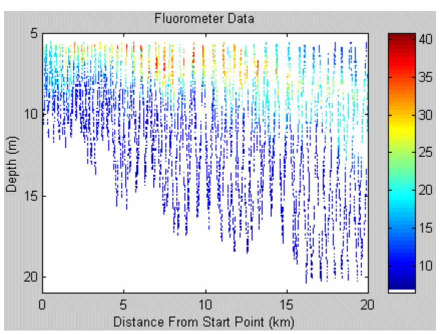
- Microfossils
  - flow microscope continuously samples meltwater and images particles at high resolution (~1 micron per pixel).
- Life Detection – “Earthlike” Life
  - Lab-on-Chip design for micro-Capillary Electrophoresis of general classes of known biomolecules (amino acids, nucleic acids, lipids, sugars). Detection of homochirality. Antibody assays and DNA microarrays.
- 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

Aqueous Sampling

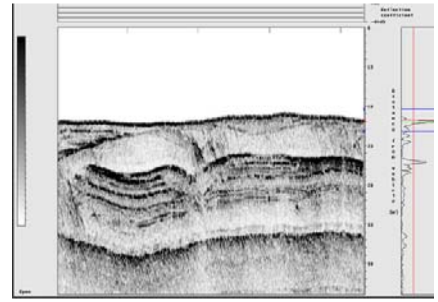
- Conductivity, Temperature, Depth (CTD)
- O2, CO2 sensors
- Ion-Sensitive Electrodes (ISEs) (MICA)
- Flow Fluorometers / spectrophotometers
- Flow microscope / particle counter
- Lab-on-Chip Life Detector
- Growth Chamber Experiment





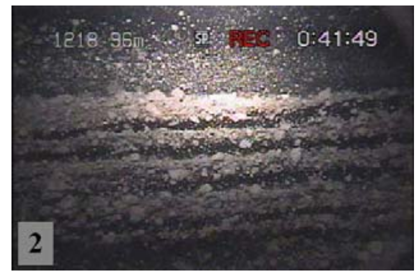
Acoustic Instrumentation

- Obstacle Sonar
- Ice / Sub-bottom Profiler



Imagery & Free-space optics

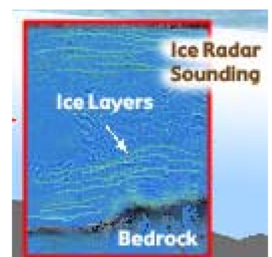
- High Res Macro Imager
- Video
- Laser Nephelometer

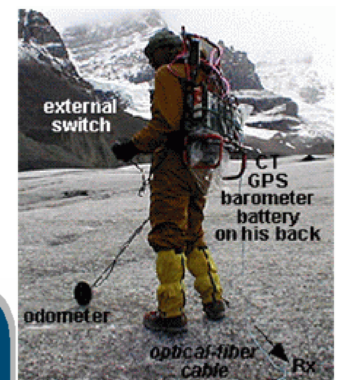


JPL / NASA

RF

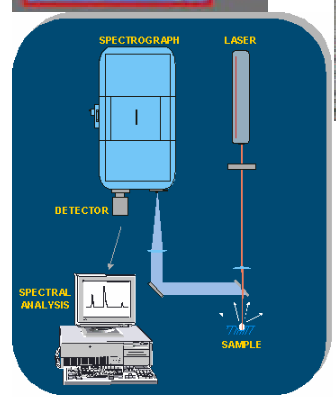
- Ice-Penetrating Radar
- Source/receive studies
- Comm & Navigation





Other

- Mass Spec
- LIBS
- Seismic source / seismometer



MICE Instrument Pod - Design

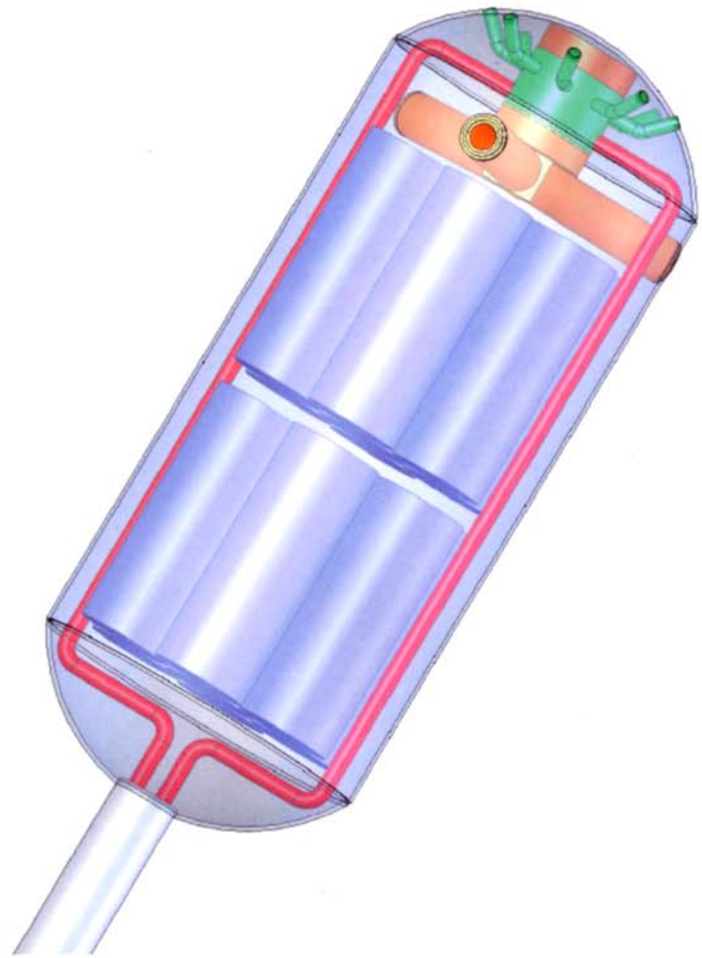
Sonar transducer

Water Jet Controller

Expandable Standoffs / Ice Sampling Device

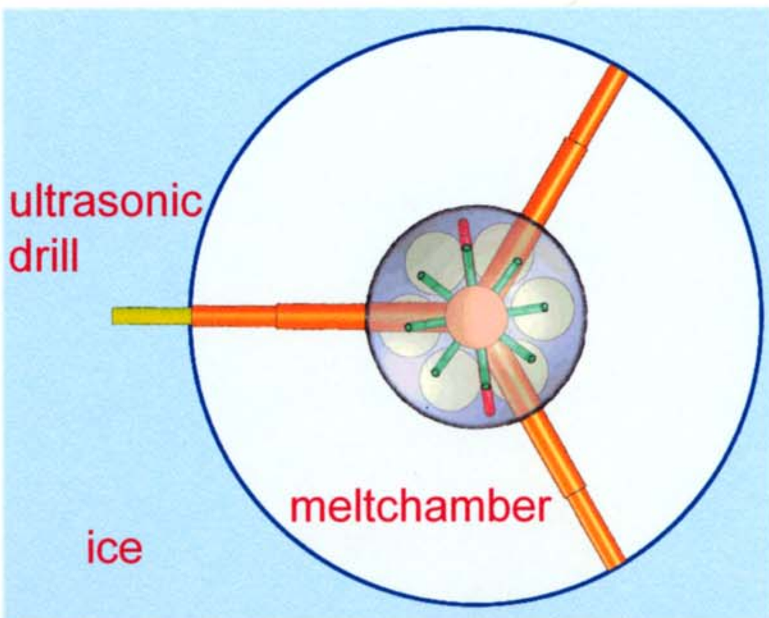
Modular Instrument Bays / Buoyancy Control

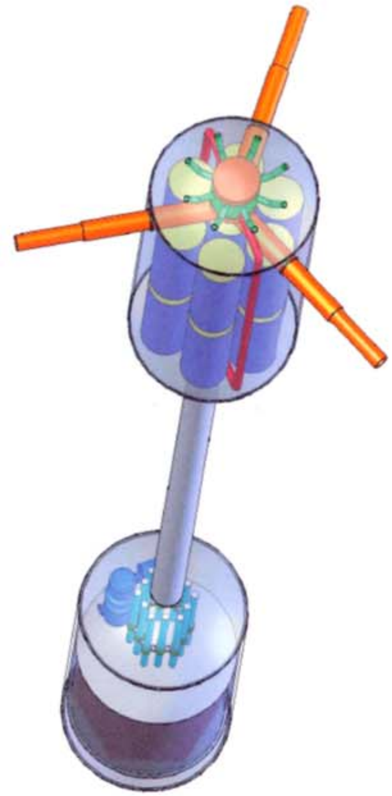
Water Conduits to/from Reactor Pod



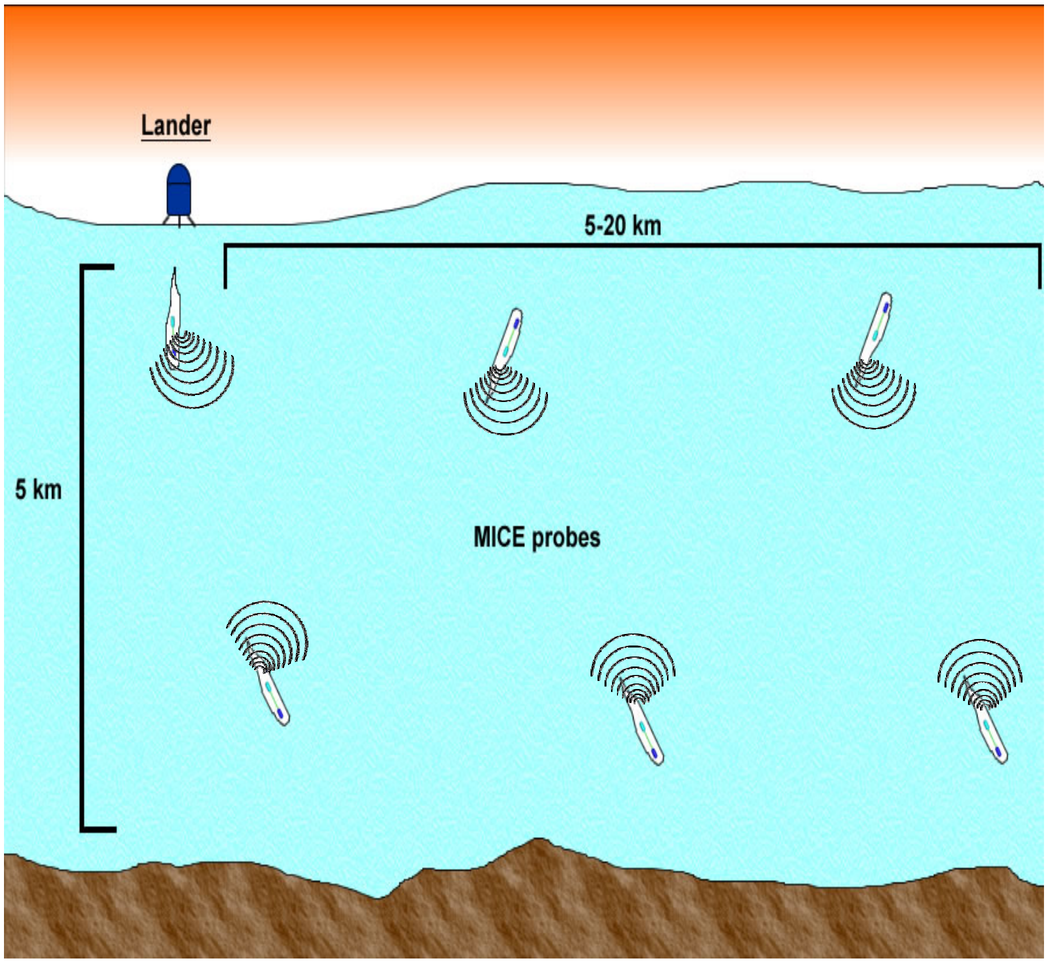
MICE Instrument Pod - Sampling

- 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_2/O_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_2/O_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 CO_2 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 H_2 and 1680 tons of liquid O_2
  - 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