MULTI-MICE: A Network of Interactive Nuclear Cryo Probes to Explore Ice Sheets on Mars and Europa

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EXECUTIVE SUMMARY

The exploration of Mars is an exciting challenge to humanity. Despite decades of research and numerous spacecraft dispatched to it, Mars still retains many mysteries. Does life exist there now? Did it exist in the past? How has its climate changed over the ages? Did it have a thicker, different atmosphere in the past? Was there an ancient ocean? Are there large amounts of sub-surface water on Mars? And so on, with many other questions, all of which we cannot answer without much greater exploration activity, both robotic and manned.

The polar regions of Mars are an extremely important part of the future exploration of Mars. They are a repository that can yield data stretching back for millions of years about the physical, geology, meteorology, climatology, volcanology, and cosmic ray and solar activity, but also may hold evidence of past life on Mars, including microbes and microfossils, both in the ice sheet itself and in sedimentary layers at its base, together with trace amounts of organic chemicals produced by life forms.

Besides the unique and important scientific data that the Polar Caps can yield, they are a vast reservoir of readily accessible water ice. The North Polar Cap, in particular holds many thousands of cubic kilometers of water ice, of which a portion, ~1000 square kilometers in area, is directly exposed at its surface, with a thickness of probably several kilometers. A small, lightweight robotic factory unit that was landed on the North Polar Cap could manufacture many tons of propellants, fuels, air, water, plastics, and foodstuffs using the Polar Cap ice and CO$_2$ from the Martian atmosphere. These supplies could be stockpiled in sub-surface cavities in the ice awaiting the arrival of astronauts. In addition, sub-surface cavities could be created in the ice to serve as habitats for the astronauts. Located 10 meters below the ice surface, the astronauts would be fully shielded from the 50 R/year dose they would receive on the surface, experiencing no more radiation exposure than they would on Earth. Using the stockpiled supplies, the astronauts would construct robotic and manned rovers and flyers, powered by the fuels and propellants produced by the robotic factory unit to explore large areas of Mars in great detail, from their main base on the North Polar Cap.

Adopting this approach would enable a much safer and more capable manned exploration of Mars at greatly reduced cost, since all of the supplies needed on Mars and for the return trip to Earth would already be stockpiled on Mars when the astronauts landed. The North Polar Cap base could be permanently manned by a substantial staff, with new astronauts landing as the previous ones left for Earth.

This report describes a new approach for the exploration of the interior of the Polar Cap on Mars. The MICE (Mars Ice Cap Explorer) system uses a mobile probe to melt a channel through the ice sheet, along which the probe travels. Powered by a compact, very lightweight nuclear reactor, the MICE probe can move through the ice sheet at a rate of 100's of meters per day. It can descend and ascend vertically, or at a substantial angle to the vertical, allowing it to travel laterally as well as vertically. It can be used as a single individual probe, or part of a network of multiple probes, termed the Multi-MICE System.
The Multi-MICE System described here can explore the interior of the Mars Polar Cap for lateral distances of many kilometers, and vertical distances down to the bed rock on which the ice sheet rests. As the MICE probes explore inside the ice sheet, they obtain detailed data on the geology of the ice sheet, its age as a function of depth, the composition and properties of the ancient Martian atmosphere over millions of years from the trapped gas in the ice, the composition and geology of the wind blown dust particles transported from the dry regions of Mars and deposited in the ice, the history of the Martian climate over eons, how cosmic rays and solar activity have varied over millions of years, records of ancient meteor impacts and volcanic eruptions, and many other important scientific data. The probes would also search for evidence of past and present life, looking for microbes and microfossils inside the ice and in the sedimentary bed rocks at its base, and traces of organic chemicals produced by life forms.

The probes would communicate with each other and transmit their findings in real time to their surface lander, which in turn would instantly relay the data to scientists on Earth. The scientists, lander spacecraft, and probe, would be in constant 2-way communication, with the scientists on Earth having the capability to direct the paths of the probes and to instruct them as what data to take, how long to stay at a particular location, where they should go next, and so on. This control would be subject to speed of light limitations, but the delays would be minor – an hour at most for the least favorable planetary positions.

The MICE probes would also be able to collect samples of the ice and the materials it contains, as well as samples of the bed rock at the base of the ice sheet, and return them to the surface lander. At the end of the 18 month stay on Mars, the lander would return to Earth with the collected samples, using H₂/O₂ propellant which would have been manufactured by electrolysis from the water ice of the Polar Cap.

Earlier proposals of exploration of the interior of ice sheets, whether on Mars, Europa, or other bodies have for the most part concentrated using a cryobot. The cryobot probe would be powered by the decay heat from radioactive plutonium-238, the same material that has been used to generate small amounts of electrical power for robotic space missions like Gaileo, Cassini, etc.

However, cryobots would be extremely limited on their capability to explore the interior of ice sheets on Mars and other bodies. Because of their very constrained power level, e.g., a kilowatt or less, their rate of movement would be very slow, on the order of a meter per day. Moreover, they only would descend, not ascend, and could not collect and return samples. The ice sheet volume that could be explored by a cryobot would be orders of magnitude smaller than that possible using a MICE probe, and the amount and types of instrumentation that it could carry would be much less. In addition, the cryobot power technology could not be used as a basis for manufacturing supplies for the manned exploration of Mars.

Figure ES-1 shows a satellite view of the North Polar Cap of Mars. Clearly, its volume is immense, and exploring its interior in detail will require a probe system that is highly mobile and can investigate many points at a variety of depths.
Figure ES-2 summarizes the scientific areas that the MICE probe system would investigate and potentially yield major discoveries in. The discoveries from earlier robotic missions to Mars, such as the Viking landers and the Spirit and Opportunity rovers, have been tremendously exciting and of great scientific importance. The MICE mission is very likely to yield even more important discoveries, because it will investigate a completely unknown region that promises to hold a wealth of otherwise unobtainable information about many areas of inquiry about the past history of Mars.

Figure ES-3 shows an overview of the MICE probe design. The probe has two pods, a lower pod (the R-Pod) that contains the compact MICE reactor and a small steam turbine-generator system, and an upper pod (the I-Pod) that contains the instrumentation and sample collecting system, plus the communications systems linking the network of MICE probes to each other, and to the lander spacecraft, and in turn, to scientists on Earth.

The R-Pod and I-Pod each have an outer diameter of approximately 60 centimeters, and a length of about 1 meter. They are tied together with a tether. During launch and the journey to Mars, the tether is un-pressurized and flexible. After landing and deployment of Mars, the tether is pressurized with water as the probe begins its descent into the Polar Cap, forcing the R and I-Pods apart. The pressurized tether maintains a separation distance of approximately 2 meters between the Pods. The melt water column between the Pods greatly reduces the radiation dose to the I-Pod from the MICE reactor, by a factor of ~10^7, enabling the electric equipment in the I-Pod to operate without degradation or damage.

Figure ES-4 shows the various possible movement patterns of the MICE probe. Melt water from the channel is heated by the MICE reactor. (The melt water does not actually flow through the reactor, but is heated in a small heat exchanger that transfers heat from the reactor coolant system.) The heated melt water is then directed through a set of jets onto the ice surface to advance the melt channel.

If the probe is descending, the hot water jets at the bottom of the R-Pod are used (Figure ES-4); if ascending, the hot water jets at the top of the I-Pod are used. (Hot water can flow from the R-Pod where it is heated, to the upper I-Pod through a small pipe attached to the tether between the Pods.)

The ascent and descent movement can be controlled to be vertical, or at an angle to vertical (Figure ES-4) by controlling the flow rate through the set of angled jets to create an asymmetric flow of the hot water. Depending on which side of the channel receives the greater amount of hot water flow, the probe will have a horizontal component of movement to the left or right. The maximum angle of descent or ascent, measured from vertical, is probably about 45 degrees.

Using a sequence of descent and ascent movements, the MICE probe can travel laterally over long distances. This can be in a straight line or in a curved path, or even in a circle, as illustrated in Figure ES-4.
Figure ES-5 shows how a number of MICE probes would move through the Polar Cap in an interactive network, enabling detailed investigation of a very large volume of the Polar Cap interior. The various individual probes (6 probes are shown in Figure ES-5, a nominal number for the MICE mission - an actual mission could use a smaller or larger number of probes) would communicate with each other in real time and with the lander spacecraft on the surface, using a communications system that would transmit data and instructions through the intervening ice. The probes probably would use both RF and acoustic communication systems to ensure good transmission capability under all conditions when moving through the ice sheet. The 30 locations of the various probes would be accurately known at all times in their travel through the ice sheet.

The lander spacecraft would relay the transmission from the network of probes to Earth in real time via a 2-way communication link, so that scientists on Earth would know within a few minutes subject to delays due to the finite speed of light, what the various probes were finding, what their conditions were, etc. The scientists on Earth could then direct the paths of the probes, and instruct them on which locations to investigate, what kinds of data to take and samples to collect, etc., again subject to the speed of light time delay. The 2-way time delay between probes sending data and then receiving updated instructions from the scientists on Earth would be no more than 1 hour even for the maximum distance between Earth and Mars at the least favorable planetary configuration.

The samples collected by the probes would be brought back to the lander spacecraft to be returned to Earth after its 18 month stay on the surface of the Polar Cap. During its 18 month stay, the lander spacecraft would be refueled with H₂/O₂ propellant manufactured by electrolysis of melt water from the Polar Cap, using electric power generated by an on-board MICE type reactor. After the lander spacecraft departed for Earth with the samples collected by the MICE probes, the probes would continue to operate for many months inside the Polar Cap, obtaining additional data. The data would be transmitted back to Earth in real time, via a 2-way communication link between Earth, using a communications package left on the surface by the lander spacecraft, and the network of MICE probes. The probes would continue to receive instructions from the scientists on Earth.

Figure ES-6 shows the layout of the R-Pod. It contains the compact water cooled and moderated reactor, a compact steam turbine to generate 10 KW(e) of electric power for the controls, instrumentation, and communication equipment on the I-Pod, a small condenser and heat exchanger, water jets, and a sonar transducer for mapping the structure of the ice sheet ahead of, and around the probe.

Figure ES-7 shows the cross section of the MICE reactor. It uses zirconium/UO₂ cermet nuclear fuel elements in the form of hollow tubes, with the water moderator/coolant flowing inside and between the hexagonal array of fuel in tubes. Zr/UO₂ cermet fuel is fully established, extremely reliable and safe. It has been used for decades in hundreds of reactors operating around the World. All fission products are completely contained in the fuel elements, which can operate for many years to high burnup levels of its uranium content.
Detailed 3 dimensional Monte Carlo neutronic analyses of the criticality and burnup behaviour of the MICE reactor have been carried out. Such analyses are extremely detailed and accurate, and can predict the neutronic behaviour of actual reactors very closely. They indicate that the overall size of the MICE reactor is very small and can readily fit inside the 60 centimeter diameter of the R-Pod. The design power of the MICE reactor is 500 kilowatts, which would enable a movement rate of 200 meters per day through the ice sheet when the reactor operates at full power. (Reactor power would be reduced when a slower movement rate was desired.) At full power, the maximum power density of the reactor core is only ~10 kilowatts(th) per liter, or about 1/10th of the core power density in operating commercial light water power reactors.

Burnup analyses of the MICE reactor found that it can operate at full power for at least 4 years – as far as the calculation was carried out – With further study and optimization, it probably operate much longer than 4 years.

Figure ES-8 summarizes the principal features of the MICE reactor. Overall, the technology of the MICE reactor and its steam power cycle is very well developed and has been widely used for many decades. Moreover, the operating parameters of the reactor, e.g., power density, coolant flow velocity, etc. are very conservative when compared to reactor systems now operating on Earth.

An important point to note is that the MICE reactor and power conversion systems in the R-Pod will not have water when the MICE probes are transported to Mars. After landing on the Polar Cap, melt water from the ice sheet is filtered and distilled to a pure state, using an on-board nuclear power source. The purified water is then loaded into the R-Pods of the MICE probes, enabling them to begin operation. This operation significantly reduces the payload to be transported to Mars. For a network of 6 MICE probes, the reduction in payload is approximately 1000 kilograms.

Figure ES-8 summaries the principal features of the MICE reactor and power conversion systems.

Figure ES-9A shows the layout of the MICE I-Pod. It contains modular bays for the various instruments held in the pod, a buoyancy control chamber, a water jet array, acoustic and RF communications equipment, and a standoff/sampling device so that pristine non-melted ice and dust samples can be extracted from the solid ice sheet that surrounds the melt channel.

The buoyancy chamber compensates for variations in the empty space above the I-Pod produced when the probe melts a channel through the ice sheet. Because water is denser than ice, as the ice melts to form the channel, the melt water will not completely fill the channel, but will leave a pocket of empty space above the I-Pod.

Figure ES-9B shows the types of instrumentation carried by the I-Pod. The structure of the ice sheet will be investigated in detail, both at short range in the vicinity of the melt channel, and at long range and using sonar and RF radar mapping. The contents of the ice sheet, both trapped gases and dust particulates will be analyzed as to composition, geology, meteorology, etc. The age of the local ice sheet will be determined by the amounts of residual action produced
by past cosmic rays when the ice was deposited. Debris from meteor impacts, volcanic eruptions, etc. will be collected and analyzed. The structure and composition of the bed rock at the base of the ice sheet will be investigated, along with any of hydrothermal vents – active or inactive – that are discovered. The I-Pod will examine the interior of the ice sheet for evidence of past and present life, including microbes, microfossils, and biological organic chemicals produced by life forms, and will carry out growth chamber experiments.

Figure ES-10 outlines potential exploration scenarios for the MICE mission. Assuming that the mission was approved and a R&D program was funded to develop the technology to the level required for launch, the MICE spacecraft could land on Mars by 2019 (even earlier, if strongly funded). The parameters for the mission are summarized in Figure ES-11.

The lander spacecraft (Figure ES-12) would remain on the surface for 18 months, after deploying the MICE probes (which would have their R-Pods filled with water produced from the ice sheet by the power source on the lander). The spacecraft would serve as the 2-way communications line between the MICE probes and Earth scientists, as the probes explored the interior of the North Polar Cap. During the 18 month period, the lander spacecraft would be refueled with H2/O2 propellant generated by electrolysis of melt water, using power from the nuclear power source on the lander. At the end of the 18 month period, the spacecraft would depart for Earth, taking along the samples that had been collected by the MICE probes and carried back by them to the spacecraft.

The spacecraft would leave behind the power source and communications package on the surface of the Polar Cap, so that the MICE probes could continue to explore the interior of the ice sheet and transmit their findings back to scientists on Earth, who would continue to direct the exploration program. The MICE probes could explore for many years after the departure of the spacecraft without losing power or wearing out.

The development and implementation of the MICE system would be a major stepping stone to the much broader robotic and manned exploration of the Solar System. Besides investigating the Polar Caps on Mars, MICE systems could explore the ice sheets and deposits found on many bodies in the outer Solar System. One of the prime targets for exploration is the Jovian moon, Europa. Europa’s surface is covered by a thick ice sheet. Underneath the ice sheet is an unexplored planet-wide ocean, of which virtually nothing is known, and which may harbor life.

The MICE system can explore the interior of Europa’s ice sheet in detail. Even better, a MICE probe can carry a small submersible (Figure ES-13) that would detach from the probe when it reached the base of the ice sheet, and then swim off to explore the sub-surface ocean. This mission, termed NEMO (Nuclear Europa Mobile Ocean) would enable scientists to obtain a wealth of data on Europa and its hidden ocean, including samples that would be returned to Earth, as with the MICE mission to Mars, and to find out whether or not Europa harbored life.
There are many other bodies in the Solar System that would yield major scientific
discoveries from a MICE exploration program. Included in the list are Callisto, Ganymede, and
the other Jovian moons, Enceladus, Titan, Triton, and the many other moons around Saturn,
Uranus, and Neptune, Pluto and Charon, and many ice objects orbiting in the Solar System. A
MICE exploration of Chiron, a 200 km sized chunk of ice on a chaotic orbit between Saturn and
Uranus, for example, could be very important. Monte Carlo simulation studies appear to indicate
that it could be flung into an Earth crossing orbit within a relatively short time (by life on Earth
standards) of a few tens of thousands of years.

MICE can also serve to enable a much more robust, much safer, much more capable
program for the manned exploration of Mars, at a much lower cost than presently envisaged.
Virtually all of the supplies needed for a major manned exploration of Mars can be manufactured
from the in-situ resources that are easily accessible on the North Polar Cap, including water ice,
CO₂ and N₂ from the Martian atmosphere, and a wide range of elements from the dust deposits in
the ice sheet.

Compact reactor and power conversion systems similar to those on the MICE probes can
supply the electrical and thermal power required for manufacturing the supplies. By adding
several compact process units that utilize well developed commercial industrial technology, an
enormous amount of supplies can be produced. The robotic MICE/ALPH factory unit would use
the MICE reactor and power conversion system, together with the necessary process units.

Landed on the North Polar Cap, the compact lightweight MICE/ALPH unit would
electrolyze melt water to produce H₂ and O₂. Together with CO₂ and N₂ from the Martian
atmosphere, MICE/ALPH could then generate and stockpile many tons of supplies, including
liquid H₂/O₂ propellant, liquid methane and methanol fuels, plastics for construction of rovers
and flyers, and life support supplies, e.g., liquefied N₂/O₂ air for breathing, water, and foodstuffs.
These supplies would be stockpiled in sub-surface cavities hollowed out of the ice by hot melt
water. Additional large cavities could be produced to serve as shielded habits, reducing the 50
R/year dose from cosmic rays at the surface down to the exposure of ~0.3R that they would
receive on Earth.

A single robotic MICE/ALPH factory unit could generate the many tons of supplies in
only 20 months. The supplies would be immediately available to the astronauts when they
stepped off their spacecraft, and they could move right into their thermally insulated, large
habitats under the surface of the ice sheet. The astronauts would use the supplies for life support
and exploration during their time on Mars as well as for their return trip to Earth including
propellants. The supplies would be stockpiled in advance of their departure from Earth to Mars
the amounts of supplies that would have to be transported to Mars from Earth could be greatly
reduced, which would cut the cost of exploration considerably. Moreover, the exploration
program would be much more robust – the astronauts could construct and fuel long distance
robotic and manned rovers and flyers from the stockpiled materials, for example – with a much
greater margin of safety for the expedition, since there would be no need to skimp on supplies to
reduce payload weight.

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With MICE/ALPH making virtually all of the supplies and propellants needed for operations on Mars, plus the transport of astronauts to and from Mars (the returning astronauts could ferry along extra supplies and propellants for the astronauts scheduled for the next journey to Mars), permanent manned bases could be maintained on the planet, at a cost less than for separate individual missions where all the supplies had to be transported from Earth. Not only would the cost be less, but mission risk would be greatly reduced, and much more data would be obtained.

Figure ES-14 summarizes the overall features of the MICE/ALPH approach to establishing permanent manned bases on Mars. The first MICE/ALPH unit could land on Mars as early as 2025 AD, with the first manned mission landing in 2027 AD followed by additional missions. The permanent manned base would be established soon after 2030 AD.

Figure ES-15 summarizes the findings and conclusions developed in this study. Briefly, the MICE system can:

1. Obtain a vast amount of unique, very important scientific data on a wide range of areas about the ancient history of Mars and the Solar System – data that is not obtainable in any other way.

2. Use existing, well developed nuclear and other technologies to carry out robotic exploration missions of the Polar Caps, in a relatively near term time frame, and at acceptable cost.

3. Explore the ice sheet and sub-surface ocean of Europa, and to search for life there. MICE can also be used to explore the ice sheets on many other bodies in the Solar System including the moons of the giant planets, Pluto and Charon, and numerous large ice objects that orbit the Sun.

4. Robotically produce many tons of supplies on Mars using water ice from the Polar Caps and CO₂ and N₂ from the Martian atmosphere. These supplies of propellants, fuels, water, air, plastics and foodstuffs can be stockpiled in advance of the landing of astronauts, awaiting their arrival. The greatly reduced transport requirements for manned missions to Mars will increase exploration capability, reduce mission risk, and reduce mission cost. Using the MICE/ALPH system, large permanent manned bases can be established on Mars.

Because the MICE system is based on well developed commercial technology, it appears to be a very desirable and practical approach to the robotic and manned exploration of Mars.
Figure ES-1
Multi-MICE Concept - Extreme Mobility

- gentle slope for landing
- millions of years old
- 3 km deep
- $6000 \text{ km}^3$ exploration area

Figure ES-2
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 - cryogenically concentrated gases
Figure ES-3 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

Figure ES-4 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
1. Multiple, networked, un-tethered, semi-autonomous, high-powered, high-mobility, long-duration nuclear-powered probes.
2. Uses existing technology.
Figure ES-7 Reactor Pod - Fuel Element Design
continued
Figure ES-8  Principal Features of the MICE Reactor/Power Conversion System

- 500 kilowatts thermal power, 10 kilowatts electrical power using steam turbine power cycle
- Zr/\text{UO}_2\) cermet nuclear fuel, water cooled and moderated
- 2 centimeter OD, 1.9 centimeter ID hollow tubular Zr/\text{UO}_2\) fuel elements
- 47 centimeter diameter, 47 centimeter height reactor core with 5 centimeter thick water reflector
- 60 centimeter outer diameter of reactor vessel
- 6.1 kg U-235 loading with boron-10 burnable poison
- 12 control rods, control rod $\Delta k_{eff}$ margin = 0.20
- Minimum of 4 years operation at full 500 KW power level = analyses, stopped at 4 years point - value of $k_{eff}$ still well above 1.0, indicating reactor could continue to operate for many more years
- Total reactor dry mass = 88 kg; total R-Pod mass, including heat exchangers, steam turbine, etc., is 118 kg
- Water coolant/moderator for MICE reactor and power conversion system is obtained from melt water from North Polar Cap
Figure ES-9A 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

Figure ES-9B
MICE Instrument Pod - 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

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

Other
- Mass Spec
- LIBS
- Seismic source / seismometer
Figure ES-10A

Possible MICE Exploration Scenarios - Moderate Penetration Depth

Polar Cap Surface  MICE Lander Spacecraft

North Polar Ice Sheet

Bed Rock

-1 to 5 km, Depending On Location

Outward Bound Path  Inward Bound Path

Note: Paths are shown as straight lines for clarity. In practice the paths can be curved or wiggly.

Figure ES-10B

Possible MICE Exploration Scenarios - Penetration To Bed Rock

Polar Cap Surface  MICE Lander Spacecraft

North Polar Ice Sheet

Bed Rock

-1 to 5 km, Depending On Location

Outward Bound Path  Inward Bound Path

Note: Paths are shown as straight lines for clarity. In practice the paths can be curved or wiggly.
Control of MICE Movements By Earth Scientists - Illustrative Scenarios

Examination of Nature of Deposited Dust Layers
- Polar Cap Surface
- Thin Dust Layer
- Thicker Dust Layer
- Bed Rock

Examination of Trapped Debris From Meteor/Asteroid Impact
- Polar Cap Surface
- Debris from Meteor/Asteroid Impact
- NICE Probes

Examination of Sediment Layers in Bed Rock To Search For Fossils
- Polar Cap Surface
- Ancient Hydrothermal Vent
- NICE Probes
- Bed Rock

Measurement of Residual Activation In Ice Sheet As A Function of Depth To Determine Amount of Cosmic Ray Activity As A Function of Age
- Polar Cap Surface
- NICE Probes
- Bed Rock
Figure ES-11  MICE Mission Parameters

- Overall mission objectives
  - 6 MICE units explore the North Polar Cap interior
  - MICE units in 2-way real time communication with scientists on Earth
  - Earth scientists direct exploration by probes and receive their data promptly
  - Probes bring back samples to lander spacecraft for return to Earth

- Departure of MICE spacecraft from Earth
  - Launched on May 2018 using Delta 4 launch vehicle
  - IMLEO payload of 13.5 metric tons
  - 260 day trip time to Mars ($\Delta V = 2.25$ km/sec)
  - $\text{H}_2/\text{O}_2$ RL-10 engine

- Landing of MICE spacecraft on the North Polar Cap
  - Aerobraking for capture into elliptical orbit, followed by aerobrake to suborbital and final thrusted landing (total $\Delta V = 2.5$ km/sec)
  - 3300 kg spacecraft dry mass
  - Lands on North Polar cap in February 2019
Figure ES-11
MICE Mission Parameters
(continued)

- MICE Spacecraft stay on Mars
  - Remains on North Polar Cap for 18 months
  - Receives samples collected by MICE probes
  - Refueled with H$_2$/O$_2$ produced by electrolysis of melt water from ice sheet

- MICE spacecraft departure for Earth
  - $\Delta V = 6.50$ km/sec
  - 940 kg dry mass of departure spacecraft
  - 4406 kg H$_2$/O$_2$ propellants loading
  - 260 day trip time to Earth

- MICE sample return to Earth craft
  - Aerobraking and aeroparachute for landing on Earth
  - Lands on March 2021
  - 250 kg dry mass of sample return craft
  - 50 kg of samples
Figure ES-12
Mission Parameters - Lander Schematic

Figure ES-13
NEMO Science Mission - Overview

ICE STUDIES
• Ice Chemistry / Stratigraphy
• Entrained microbes / microfossils
• Ice-Ocean interface

Ocean Studies
• Physical Oceanography
• Inherent Optical Properties
• Particulates
• Marine Chemistry
• Plume Sensing

Search for Life
1. Tidal Cracks
2. Interface
3. Hydrothermal Vents

Ocean Bottom Studies
• SONAR profiling / Bathymetry
• Hydrothermal Vent Chemistry & Life Detection
• Seismology
Figure ES-15
Summary and Conclusions on the MICE System

1. Compact, nuclear reactor powered MICE probes can travel at 200 meters per day along melt channels through the deep interiors of the Polar Caps on Mars, descending and ascending vertically or at an angle to vertical.

2. MICE probes can obtain vast amounts of unique and important scientific data on the ancient climatology, geology and meteorology of Mars over millions of years, and the composition and structure of the Polar Caps.

3. MICE probes can search for evidence of past and present life on Mars including microbes, micro-fossils, and traces of organic chemicals produced by life forms.

4. MICE probes would operate in an interactive multi-probe network that would be in continuous real-time 2-way communication with the lander spacecraft on the Polar Cap surface, which in turn would be in continuous 2-way communication with scientists on Earth.

5. Scientists on Earth would receive all data obtained by the multi-probe network and could quickly direct their paths and activities, subject to the speed of light time delay, which at the least favorable planetary configuration, would be less than 1 hour.
6. The MICE probes would collect samples from the Polar Cap interior and bring them back to the lander spacecraft for return to Earth. The spacecraft would be refueled with H₂/O₂ propellant produced by electrolysis of melt water from the Polar Cap, using electric power from a compact nuclear reactor similar to those that power the MICE probes.

7. A MICE mission based on a network of 6 interactive probes could be launched on a Delta 4 vehicle in 2018 AD. The MICE spacecraft would land on the North Polar Cap of Mars in 2019. After an 18 month exploration period by the probes of hundreds of cubic kilometers of the Polar Cap, the lander spacecraft would take off for Earth with the collected samples. The MICE probe network would continue to operate in 2-way communication with scientists on Earth via a relay left on the surface.

8. The high power nuclear reactor systems used on the MICE probe are small in size, e.g., ~60 centimeters in diameter, and light in weight, ~100 kilograms. The Zr/UO₂ cermet nuclear fuel has been used safely and reliably in hundreds of reactors around the World for decades, and the water coolant/steam power technology is very well established.

9. The MICE probe system, including its instrumentation can be developed in a relatively short time and tested in Earth ice sheets before launching the MICE mission to Mars.

10. The MICE system can also explore the ice sheets and sub-surface oceans on other bodies in the Solar System, including Europa and the other moons orbiting Jupiter, the Moons of Saturn, Uranus, and Neptune, Pluto and Charon, and a variety of ice objects in the Outer Solar System. If extra terrestrial life forms exist now, or have existed in the past, in the Solar System, MICE will find them.

11. The MICE nuclear power system can be used with a set of compact lightweight process units that would robotically manufacture using tons of H₂/O₂ propellant. H₂/O₂ air, water, methane and methanol fuels, plastics, metals, and footstuffs using as raw materials the ice and dust from the North Polar Cap and CO₂ and N₂ from the Martian atmosphere. The combined unit, termed the MICE/ALPH factory would robotically produce and stockpile the many tons of supplies inside the interior of the Polar Cap, plus produce large shielded habitats for astronauts. All of these materials and habitats would be in place before the astronauts landed at the Polar Cap base. MICE/ALPH would greatly reduce the amounts of supplies to be transported to Mars for manned missions, reduce mission risk, enhance mission exploration capability, greatly reduce the cost of manned exploration of Mars, and enable permanent manned bases on Mars.
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1.0 INTRODUCTION

In depth exploration of the Martian polar caps, and in particular the Northern Polar Cap, would appear to provide a unique opportunity to examine the composition and meteorology of the ancient atmosphere of Mars, the internal structure, age, deposition rate, temperature, and heat flux history of its ice caps, the variation of solar wind activity over long periods of time, the geology of Martian dust, records of ancient asteroid impacts and volcanic events, and possibly, evidence of past Martian biological activity, including microfossils, bacteria, and biochemical residues.

Using a practical compact, lightweight, powerful thermal source, small robotic devices could melt their way through the ice cap, gathering data like that described above, and transmitting it in real time (subject to the speed of light delay, which at the least favorable planetary configuration would be less than 1 hour) back to Earth. Scientists monitoring the results on Earth could then control the path of the robotic units directing them to explore particularly promising regions inside the ice sheet.

Such a heat source appears possible, based on well established and readily available nuclear reactor technology. This paper describes a compact, lightweight robotic unit, termed MICE (Mars Ice Cap Explorer), based on a small lightweight nuclear reactor capable of generating several hundred kilowatts of thermal power, which would traverse a series of ascending and descending melt channels through the Martian ice sheet, at rates of hundreds of meters per day.

After the spacecraft landed on the North Polar Cap, it would deploy several MICE units. The MICE units would then melt their way into and through the ice, transmitting data to a transmitter on the lander from which it would be relayed back to Earth in near real-time. Each MICE unit would communicate in real time with the lander and the other MICE units by a 2-way transmitter/receiver link, using high frequency RF and/or acoustic signals. In turn, the lander would relay data in real time to scientists on Earth and transmit their instruction to the MICE probes.

Using several mobile MICE probes in a multi-probe network, a lander could explore an ice sheet in detail over a wide area, e.g., on the order of 20 km in diameter, to a depth of 10 km or more. Deploying multiple MICE probes also offers a built-in mission redundancy. Each MICE probe would have a standard instrument package which would include a microfluidic ("lab-on-a-chip") biosignature detection instrument, a suite of electrochemical sensors, an optical imager (including microscopic imagery), a seismometer, and an integrated RF communications/ice penetrating radar instrument. Non-standard instruments could include among others: life detection growth chambers, mass-spectrometers, Laser Induced Breakdown Spectrometers (LIBS), and high power acoustic or seismic sources for ice sheet and crustal mapping.

MICE type missions can also be carried out on Europa, Callisto, and other moons with extensive ice sheets. Europa is of particular interest because it has a sub-surface water ocean, in
which existing or fossil life forms could be discovered. The MICE units would melt their way down to the sub-surface ocean, collecting samples and analyzing the composition and properties of the ice sheet. The Europa ice sheet shows evidence of cracking, with upwelling of water from the sub-surface ocean that subsequently freezes into long ridges. Exploration of these upwelling locations could find actual or fossil forms of life frozen into the ice.

Once at the bottom of the Europa ice sheet, the MICE unit could sample the sub-surface ocean itself and collect samples to be returned to the surface lander when the MICE unit melted a channel back to the lander. With some design modifications, one or more of the MICE units could travel through the sub-surface ocean taking data and collecting samples at a variety of locations and depths before returning to the lander. Of particular interest would be a search for hydrothermal vents on the sub-surface ocean floor. Many scientists believe that life on Earth began at such hydrothermal vents, by microscopic bacteria utilizing the energy available from chemicals emitted from the vents.

The in-depth detailed data gained by MICE type missions to Mars, Europa, and other bodies in the Solar System would be of great scientific importance, even if evidence of extra-terrestrial life forms was not discovered. If, in addition, evidence of such life forms that originated beyond Earth were discovered, it would not only be of great scientific importance, but immensely important to the understanding of how life originated, and how prevalent it is likely to be in the Universe.

Moveover, the compact MICE reactor and power system can power a set of small process units to form a robotic factory unit, termed MICE/ALPH that would produce many tons of H₂/O₂ propellant, breathable N₂/O₂ for water, food, methane and methanol fuels, and plastics for constructing rovers and flyers, using melt water from the Polar Cap and CO₂ and N₂ from the Martian atmosphere. These supplies can be stockpiled at a future landing site for manned Mars missions. When the astronauts land, they can use the stockpiled supplies for a robust extensive exploration of Mars.
2.0 EXPLORATION OF THE INTERIOR OF THE MARTIAN POLAR CAPS

2.1 Description of the Martian Polar Caps

Figure 2.1.1 shows a satellite view of the North Polar Cap on Mars. It covers a large area, on the order of a thousand of km in extent. Its central portion, approximately 1000 km² in area, consists of exposed surface water ice. The maximum depth of the North Polar Cap is not known, but it could be more than 1 kilometer. Its structure, origin, and history are virtually unknown; some believe it to be the remnant of a vast ocean that once covered much of the Northern Hemisphere of Mars.

Deep canyons have been carved in the Polar Cap by winds. The sides of the canyons show a complex structure of alternating layers of dusty ice separated by bands of virtually clean ice. Exploration of the Polar Cap interior would provide a window into the ancient history of the planets climatology, meteorology, and geology.

Figure 2.1.2 shows an illustration of the possible internal structure of the North Polar Cap and the scientific discoveries that could result from its exploration. Finding evidence of past or present life forms on Mars would of immense scientific importance. Reading of the variations over millions of years of Martian climatology, meteorology, and geology would also be immensity important in understanding its planetary history.

The North Polar Cap on Mars is considerably larger than the South Polar Cap, and probably would be the first to be explored by MICE probes. It appears to vary more over the Martian year, and to have more readily accessible surface ice. Figure 2.1.3 compares the principal features of the 2 Polar Caps.

Finally, what is the ultimate fate of Chiron? Chiron is a 200 km size ice object in a chaotic orbit between Saturn and Uranus. Monte Carlo simulations of its motion suggest that it may be thrown into an Earth crossing orbit in a relatively short time, on the order of 100,000 years. If it were to fragment into many pieces, it would be very hazardous to Earth. Exploring the interior of Chiron by MICE probes could help to determine whether or not it was a significant hazard to life on Earth.

2.2 Potential Discoveries from Exploration of the Interior of the Martian Polar Caps

Figure 2.2.1 outlines the reasons why exploration of the North Polar Cap will be a very important part of the future exploration of Mars. Not only is it a unique repository of the physical and chemical history of Mars over millions of years, but it is also the most likely place where evidence of past and present life on Mars can be discovered, assuming that it exists or did exist on Mars in the past.

Moreover, because of its readily accessible and vast amount of water ice, it can provide virtually all of the supplies needed for permanent large manned bases on Mars. These supplies
can be produced in great amounts by small, lightweight robotic factory units, using the available water ice, the Martian atmosphere, and dust material contained in the Polar Cap.

Figure 2.2.2 outlines the potential discoveries in the physical sciences that can be made by MICE probes, while Figure 2.2.3 outlines the potential discoveries in the biological sciences.

2.3 Requirements for Extensive Exploration of the Interiors of the Martian Polar Caps

Figure 2.3.1 outlines the mobility and communication requirements for probes that would extensively explore the Polar Caps on Mars. Key to the exploration is the ability for a high rate of travel, e.g., a 100 meters a day or more. Traveling at a few meters per day would explore only a very tiny fraction of the Polar Cap, greatly limiting the discoveries that could be made. A second key feature is the ability to ascend as well as descend. A descent only probe could not travel laterally any appreciable distance, could not explore in detail regions of high interest, and could not return samples to the lander spacecraft. Section 5 of the report describes the movement systems for the MICE probes.

A third key is to be in constant communication with Earth scientists, and to have the capability for the path and operations of the probe to be efficiently and rapidly directed by them, so that the most interesting regions, whether near the surface or deep inside the Polar Cap can be explored in detail. Section 7 of this report describes the communication systems for the MICE probes.

Figure 2.3.2 outlines the instrumentation requirements for the exploration probes. A key objective will be to determine when the ice was deposited. For recent depositions years, the tritium content (produced by cosmic radiation) appears to be a good marker; for moderately old depositions, e.g., thousands of years ago, carbon-14 activation could be used. For very old ice, e.g., many thousands of millions of years, residual activation of selected isotopes in the dust particles should provide good data. The measurement of dust amount and composition in the surrounding ice could be done by analyses of the short life gammas emitted from isotopes activated by neutron leakage from the MICE reactor.

2.4 Exploration of the Ice Sheets on Other Bodies, Including Europa

Figure 2.4.1 lists some of the other exploration missions that could be carried out by the MICE system. Deep ice sheets and deposits are present on many bodies in the Solar System, and could be explored by MICE probes. Of these, the most interesting and important one, at least as currently viewed, is probably Europa. It appears to have an extensive, deep ocean under its thick ice sheet, with the possibility of life forms in the ocean and the tidal cracks in the ice sheet. MICE probes could explore Europa’s ice sheet, and by carrying a detachable small submersible powered by a separate MICE type reactor, also explore the ocean itself, searching for evidence of life. The MICE-Europa mission is described in detail in Section 9 of the report.
Similar MICE missions could be carried out on the many other moons of Jupiter, Saturn, Uranus and Neptune. Of particular interest would be Enceladus, a moon of Saturn, which has been recently discovered to have sub-surface liquid water regions that feed water geysers. Callisto and Ganymede, two other moons of Jupiter, would also be of great interest.

Also of great interest would be Pluto and Charon. The New Horizons mission will obtain the first detailed photos of them as it flies past it high speed, but to really determine their properties and origins, it probably will be necessary to land and explore them in detail. For example, are they part of the original formation of the Solar System, or bodies that were captured at a later time? Answering questions such as this will require extensive exploration.

Another key will be the instrumentation that looks for evidence of past and present life forms in the ice sheet, including actual microbes, microfossils, and biological chemicals. Microbes and microfossils could be transported by winds from distant parts of Mars and deposited in the ice sheet, along with traces of biological chemicals. Microfossils may be found in sedimentary bedrock and/or ancient hydrothermal vents.

The instrumentation for the physical and biological examinatory of the Polar Cap interior is discussed in more detail in Section 6 of the report.
Figure 2.1.1
Multi-MICE Concept - Extreme Mobility

- gentle slope for landing
- millions of years old
- 3 km deep
- 6000 km³ exploration area

Figure 2.1.2
Visualization Of The Possible Interior Structure Of The Martian North Polar Cap

Table: Surface Of North Polar Cap

- Thick Dust Layers From Major Storms During Periods Of Unusual Meteorological Activity
- Dust Particles Scattered Throughout Ice Sheet - Residual Activation Measures Age Of Ice and Cosmic Ray Strength As Function Of Depth
- Dust Layer From Volcanic Eruption
- Configuration Of Dust Provides Data On Mars Geology
- Debris From Ancient Meteor Impact
- Sedimentary Layers
- Extinct Hydrothermal Vent
- Biological Chemicals From Ancient Life
- Analysis Of Trapped Atmospheric Gases Provides Data On Ancient Climate and Meteorology

Microbes Transported By Wind
Figure 2.1.3
Principal Features of the Martian North and South Polar Caps

<table>
<thead>
<tr>
<th></th>
<th>North</th>
<th>South</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter season length</td>
<td>156 sols</td>
<td>179 sols</td>
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<tr>
<td>Typical summer daytime temperature</td>
<td>220 K</td>
<td>270 K</td>
</tr>
<tr>
<td>Typical winter daytime temperature</td>
<td>140 K</td>
<td>140 K</td>
</tr>
<tr>
<td>Summer Ice Cap Edge</td>
<td>80° N</td>
<td>85° S</td>
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<tr>
<td>Winter Ice Cap Edge (CO₂ frost covering)</td>
<td>50° N</td>
<td>55° S</td>
</tr>
<tr>
<td>Water ice volume</td>
<td>1.2-1.7 X 10⁶ km³</td>
<td>&gt;1 X 10⁶ km³</td>
</tr>
<tr>
<td>Winter CO₂ ice mass in Winter</td>
<td>4.2×10¹⁵ kg</td>
<td>6.3×10¹⁵ kg</td>
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<tr>
<td>Estimated maximum thickness (m)</td>
<td>4km</td>
<td>3km</td>
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<tr>
<td>Dust Composition Estimates (%)</td>
<td>20%-50%</td>
<td>n/a</td>
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<tr>
<td>Age Estimate from Surface Cratering</td>
<td>100 X 10³ years</td>
<td>7-15 X 10⁶ years</td>
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<tr>
<td>Maximum Age Estimate from Geological features</td>
<td>&gt;10⁹ years</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Figure 2.2.1
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

Figure 2.2.2
Potential Discoveries from MICE – Physical Sciences

- 3D Composition and Structure of Mars North Polar Cap Interior
  - Amounts and stratigraphic distribution of dust loadings
  - Temperature and pressure distribution in ice interior
  - Topography of ice sheet/bedrock interface
- Physical and Chemical Properties of Dust Grain Loadings
  - Types of compositions
  - Particle size distributions
- Composition and Structure of Sedimentary Layers at Base of Ice Sheet
- Seismological Structure of Bed Rock below Ice Sheet
- Martian Paleoclimatology
  - Composition and temperature of (oxygen isotope measurements) history of Mars atmosphere trapped in ice sheet
  - Wind/storm activity history (dust loading)
- Meteoroid History
  - Composition, amounts, and size distribution of meteoroids
- Cosmic Ray and Solar History
  - He-3 distributions
  - Cosmic ray activation levels
Figure 2.2.3
Potential Discoveries from MIC – Biological Sciences

- Detection and analysis of organic materials (e.g., amino acids) to look for evidence of life
  - Measure degree of homochirality
  - Determine molecular composition and complexity
- Test samples in growth mediums
  - Detect changes in chambers that have been inoculated with sample
- Image melt water for wind-blown microfossils
  - Flow-imaging microscope
- Investigate sedimentary layers at base of ice sheet for evidence of fossils
  - Examine both surface and drill core samples
Figure 2.3.1
MICE Probe Mobility and Communication Requirements

- Direction of probe movement - able to
  - Descend and ascend inside polar cap, both vertically and at a selected angle to vertical
  - Travel in horizontal direction using series of descending and ascending movements at an angle to vertical
  - Return to lander spacecraft

- Depth of operation - when desired, can
  - Travel close to surface
  - Reach bed rock at depths of several kilometers

- Rate of movement - able to
  - Travel at maximum rate of ~200 meters per day
  - Travel at any rate between zero and maximum

- Communication - able to
  - Communicate 2-way in real time with lander and other probes over distances of several kilometers
  - Able to transmit data at high rates
  - Receive instructions for movement and data taking from scientists on Earth in real time
Figure 2.3.2
MICE Probe Instrumentation Requirements

• Analyses of ice - determine
  • Age of deposition
  • Amount of composition of trapped gas
  • Oxygen isotope ratio in ice and trapped gas

• Analyses of dust in ice - determine
  • Composition
  • Deposition amounts and rate of deposition
  • Source (i.e., volcanic, soil, erosion, meteor debris, etc.)

• Analyses for evidence of life - detect presence of
  • Biological chemicals in ice sheet
  • Microbes and microfossils

• Sonar and radar mapping of ice sheet structure - determine
  • Thickness of ice sheet at various locations
  • Topography of bed rock and presence of volcanoes and hydrothermal vents
  • Dust layer structure - thickness, location and extent, concentration of dust, etc.
### Figure 2.4.1

**Other Possible Ice Sheet Exploration Missions in the Solar System**

<table>
<thead>
<tr>
<th>Potential MICE Mission</th>
<th>Exploration Objectives</th>
</tr>
</thead>
</table>
| Europa                 | • Explore ice sheet and sub-surface ocean  
                        |   • Search for evidence of life in ocean and tidal cracks |
| Callisto and Ganymede  | • Explore ice sheets and determine if sub-surface oceans exist  
                        |   • Search for evidence of life |
| Enceladus              | • Explore liquid water regions inside Enceladus and search for evidence of life |
| Pluto and Charon       | • Determine origins of Pluto and Charon - found in early solar system or later captures |
| Chiron                 | • Internal structure and whether it is a future impact hazard to Earth |
3.0 DESCRIPTION OF THE MICE CONCEPT

3.1 The MICE Mobile Probe – Construction and Capabilities

Figure 3.1.1 shows an overview of the MICE probe. It consists of 2 pods, separated by a pressurized tether. The reactor/power generator package, termed the R-Pod, contains a compact nuclear reactor, together with a small steam turbine to generate electric power for the instruments on the probe, plus power for its controls and 2-way communication with the other probes in the MICE network, and the lander spacecraft on the surface of the Polar Cap.

The R-Pod also contains the heat exchangers, steam condenser, control rod mechanisms, and the array of water jets that create a melt channel when the MICE probe descends through the ice sheet. The flow meter through the water jets can be controlled so that the probe can descend vertically, or at an angle to vertical, with the angle determined by the jet flow pattern. The water flow in through the jets is melt water from the channel that has been pumped through the heat exchanger in the R-Pod, where it is heated by the reactor water coolant stream from the reactor. This method of heat transfer ensures that the purified does not mix with the melt water in the channel, and is not contaminated by it.

The MICE reactor power level is designed to be 500 kilowatts (thermal). It could be considerably higher if desired, since its power density is relatively low compared to existing commercial power reactors. However, at this point, a power level of 500 KW appears very adequate for exploration of the Polar Cap, since a faster travel capability does not seem that useful, given that detailed study of the ice contents will require frequently slowing down or stopping.

Similarly, the choice of 10 kilowatts for the electrical generation appears quite adequate. If higher power levels are desired, e.g., 20 to 30 kilowatt(e), the probe could be readily designed to deliver a greater electrical output.

The I-Pod (Instrument-Pod) carried the scientific instrumentation, sampling, and communications equipment. It is separated from the R-Pod by 2 meters of water to shield its electronic equipment from the neutron and gamma radiation emitted by the MICE reactor. The 2 meters of water will reduce the gamma dose to the I-Pod by a factor of $10^7$, which appears quite adequate. Increasing the separation distance to 3 meters would provide an even greater reduction, e.g., by a factor of $\sim 10^{10}$. The reduction in the radiation dose from neutrons would be even greater than that for gamma radiation.

The I-Pod and R-Pod are transported to Mars as a compact package, and can be placed in close proximity, since the MICE reactor is cold and non-radioactive. After starting operation in the Polar Cap on Mars, the tether connecting them would be pressurized with melt water, ensuring that they remain separated by the desired distance as they move along the melt channel in the ice sheet.

In addition to its instrumentation, control, and communication equipment, the I-Pod also contains a buoyancy chamber that provides a net upwards buoyancy, ensuring that the I-Pod
always is kept above the R-Pod as the probe moves along the melt channel. The buoyancy chamber also compensates for the empty space present in the above the water in the melt-channel, which is created by the fact that the melt water is denser than the surrounding ice sheet from which it came.

Figure 3.1.2 illustrates the patterns of movement possible with the MICE probe. It can descend vertically, either in pure downwards vertical movement or at an angle to vertical, using the hot water jets in the base of the R-Pod. It can also ascend vertically, either in pure upwards vertical motion, or at an angle to vertical using the hot water jets in the top of the I-Pod [the hot water for the I-Pod jets flow from the R-Pod through a small flexible pipe attached to the connecting tether].

The MICE probe can travel laterally using a series of descending and ascending movements. The lateral movement can be along a straight line, or a curved path, or even in a circle (Figure 3.1.2).

Figure 3.1.3 shows a more detailed layout of the R-Pod, illustrating the placements of the reactor, control rod housings, steam turbine and heat exchanger, and the water jets. The reactor and power conversion system are described in detail in Section 4 of this report, while the water jet system is described in detail in Section 5.

Figure 3.1.4 shows a more detailed layout of the I-Pod, illustrating the modular bays for the various instruments carried by the I-Pod, a sonar transmitter/receiver unit, and standoffs for holding the I-Pod at a central location in the melt channel. The standoffs would be combined with an ice penetration device that could extract ice samples for analysis from within the ice, away from the surface of the melt channel. This would enable localization of small samples, rather than having everything mix together in the melt water of the channel.

The instrumentation equipment for the I-Pod is described in detail in Section 6 of the report, while the communications equipment is described in Section 7. Section 5 describes the water jet system and the standoff/ice sampling system.

### 3.2 Exploration of the Martian Polar Cap Using an Interactive Network of Multiple Mobile MICE Probes

Figure 3.2.1 illustrates the basic multi-MICE network. The probes are shown in a dispersed mode to explore a large volume of the Polar Cap. Assuming a network of 6 probes, with a Polar Cap thickness of 5 kilometers and an average lateral distance of 3 kilometers between probe, at any one time the network would occupy a total volume of ~200 cubic kilometers inside the Polar Cap.

Over a period of 18 months – the time that the lander spacecraft would remain on Mars, to collect samples from the MICE probes, the probes could explore thousands of cubic kilometers of the Polar Cap. The paths of the probes, together with the particular locations they
explored, the time spent at each location, and the data and samples obtained, would be controlled by scientists on Earth, who would be in continuous real time 2-way communication with the probes, subject to ~1/2 hour time delay due to the finite speed of light.

The MICE probes could be directed to explore locations as individual units or in groups of 2 or more depending on the nature of the region they were exploring. The pattern of exploration would be very flexible, and could quickly be altered from groups to individual units and vice versa, depending on the results obtained and the judgments of the scientists on Earth.

The probes could explore close to the surface of the Polar Cap or deep inside it, all the way down to bed rock. They could follow dust layers, or move vertically through them. They could move back and forth through a debris field left by an impacting meteor collecting samples. The range of possible exploration movements by the probes is extremely broad.

Figure 3.2.2 illustrates the movement capabilities of the MICE probe as a function of the reactor power level and the diameter of the melt channel it would create. The diameters of the R-Pod and I-Pod are 60 centimeters, so that the diameter of the melt channel would have to be somewhat larger than 60 centimeters. If it were as large as 100 centimeters, which appears unnecessarily large, the probes still could still move at over 100 meters per day at a reactor power of 500 kilowatts. For diameters of ~60 centimeters, the probe could travel at about 200 meters per day, which appears very ample. This would have a travel distance of 100 kilometers for an 18 month period at the maximum rate of travel.

The various possible exploration patterns and scenarios, and the rate of travel for MICE probes is described in greater detail in Section 9 of the report.

Figures 3.2.3 and 3.2.4 illustrate the communication capabilities of the multi-MICE network. Each probe acts as a node in the communications network with interactive 2-way real time communication between each probe and every other probe in the network, plus 2-way real time communication lander between every probe and the lander spacecraft. The lander can communicate directly to each probe, and also indirectly through any other probe in the network.

In addition to communication data to Earth scientists, the probe would collect samples that would be periodically returned to the lander spacecraft. The lander would be refueled with H₂/O₂ propellant during its 18 month stay on the Polar Cap, using electricity from its compact MICE reactor to electrolyze melt water from the ice. The H₂ and O₂ products would be liquefied using electric power and a compact refrigerator/liquefier unit and stored in the propellant tanks of the lander spacecraft.

The samples returned to the lander (Figure 3.2.5) would include trapped gases in the ice, the ice itself, dust particles, microbes, micro-fossils and biological chemicals (if life forms exist or did exist on Mars), bed rock pieces, debris from volcanic eruptions and meteor impacts, etc. These samples would usually be relatively small, e.g., on the order of a gram, and would be collected from hundreds of locations inside the Polar Cap. A total of 50 kg of samples would be
transported back to Earth when the lander left Mars. The parameters for the departure are described in more detail in Section 9 of the report.

Following the departure of the lander spacecraft, the MICE probes would continue their exploration of the Polar cap for many years, since their reactors could continue to produce power for a very long time. The probes would continue to have 2-way real time communication with scientists on Earth, who would direct their exploration activities through a communications package and reactor power source left on the surface by the departing lander spacecraft.

This indirect communication capability enables probes to travel beyond the distance that would be the limit for direct communication between it and the lander, by having the communication relayed through the probes between them.

The network is failsafe. All probes keep track of their 3D positions by trilateration of signals and the pressure level in the surrounding ice sheet. If a probe loses communication, it autonomously travels back towards the lander, using an internal gyro system until it re-establishes communication with the network.

The communication inside the ice sheet would use both high frequency RF and lower frequency acoustic signals. The RF mode enables high data transmission rates, but may be alternated more strongly by ice including, dust layers, etc. than the acoustic mode, which would have a lower data transmission rate.

The lander would be in continuous 2-way real time communication with Earth using RF transmission, relaying data from the probes to scientists on Earth and operating instructions back from Earth to the probes, as illustrated in Figure 3.2.4.

The communication methods and capabilities for the MICE network are described in more detail in Section 7 of the report.

### 3.3 MICE Probes and Cryobots – A Comparison

Cryobots have been proposed for the exploration of ice sheets on Mars and moons such as Europa using the decay heat form the radioactive isotope Plutonium-238. However, the power output available from Pu-238 source, which has been used for a range of exploration missions, including the Viking landers, Gaileo and Cassini is very limited. The thermal power from Pu-238 sources is on the order of 1 kilowatt at most, because of the limited availability of Pu-238, which is very difficult to produce its nuclear reactors and its weight. The specific thermal power of Pu-238 is only about 60 watts per kilogram.

As a result of the limited thermal power, a Pu-238 heated cryobot can travel just a few meters a day. It can only travel downwards, not upwards, and cannot collect samples and return them to a spacecraft on the surface. Moreover, it must be small in diameter to generate enough heat flux from its surface to melt the surrounding ice and produce the layer of water through
which it moves. In turn, the small diameter of the cryobot and the very small amount of electric power it can generate greatly contains its instrumentation capability.

Figure 3.3.1 illustrates the comparative sizes of the cryobot and the MICE probe, while Figure 3.3.2 compares their operational capabilities. The MICE probe system can explore a much greater volume of the Polar Cap interior than the cryobot, with a much wider range of instrumentation, and can return samples to Earth. Moreover, the exploration paths and operation of the MICE probes can be directed in real time by scientists on Earth. Using the cryobot, exploration capability is essentially fixed and non-directable.

An alternative option for exploring ice sheets on Mars and Europa, termed the Palmer Quest, has been previously proposed (6). Like MICE, it would use a compact nuclear reactor to generate a melt channel through the ice sheet, along which the Palmer Quest probe would move. It would use a different type of reactor, i.e., a fast spectrum reactor cooled by liquid sodium heat pipes, termed Homer. The Homer reactor would operate at much lower power than the MICE reactor, e.g., 15 kilowatts (th) compared to 500 KW (th) for MICE, with a corresponding reduction in its rate of travel through the ice sheet. Also, its reactor technology would require significantly more development and testing than the existing technology used in the MICE reactor.

### 3.4 MICE Probe Components: Functions and Interfaces

Each MICE probe has two pods connected by a tether. The lower Reactor-Pod (R-Pod) contains the various components illustrated in Figure 3.4.1. The thermal energy released by fission reactors in the fuel elements of the MICE reactor is transferred to its water coolant. The hot water outlet stream from the reactor then flows through a heat exchanger, transferring thermal energy to melt water that has been taken in from the melt channel. The heated melt water stream then flows to an array of directed water jets that melt additional ice to lengthen the channel.

If the MICE probe is traveling downwards, the heated melt water flows out through the hot water jets at the bottom of the R-Pod. If the MICE probe is traveling upwards, the heated melt water stream is piped up to the upper I-Pod, where it is directed through the hot water jets at the top of the I-Pod against the ice surface.

A portion of the outlet hot water from the MICE reactor flows through a second heat exchanger to generate steam for a small steam turbine, which drives an electrical generator, producing electrical power for the controls, pumps, instrumentation, communications and other systems on the probe. The electric power used by the I-Pod is transmitted to it by a small cable attached to the tether that connects the 2 pods.

The upper I-Pod contains the various components illustrated in Figure 3.4.2. The electric power for the instrumentation, controls, communications, and other systems is transmitted to the I-Pod by a small cable from the R-Pod. The hot melt water for the array of hot water jets at the
top of the I-Pod is transmitted from the lower R-Pod. It also contains the instrumentation and communication systems, which are protected from the neutron and gamma radiation emitted by the MICE reactor by the intervening water column between the 2 pods. The I-Pod also contains a buoyancy chamber, which compensates for density differences in the melt channel and keeps the I-Pod floating above the lower R-Pod. Melt water from the channel can be pumped into or out of the buoyancy chamber to maintain the appropriate buoyancy conditions. There will be some empty space in the channel above the surface of the melt water, since the water is denser than the ice from which it was melted. The I-Pod, in addition to its buoyancy chamber can adjust its buoyancy by a set of stand-off struts on its upper surface that contact the ice sheet above it.
**Figure 3.1.1 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

---

**Figure 3.1.2 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
Figure 3.2.1 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

Figure 3.2.2 MICE Probe Design - Capabilities

<table>
<thead>
<tr>
<th>Reactor Power (KW)</th>
<th>Melt Channel Diameter (cm)</th>
<th>MICE Ascent/Descent Rates (m/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>60</td>
<td>122, 44</td>
</tr>
<tr>
<td>500</td>
<td>100</td>
<td>305, 110</td>
</tr>
<tr>
<td>1000</td>
<td>150</td>
<td>610, 220</td>
</tr>
</tbody>
</table>

- Powerful water jets prevent layered dust from accumulating in front of probe
- Leave sediment behind using lateral traverse maneuver
- Reactor power variable to control ascent/descent rates
- 5 year reactor lifetime at 500 KW

<table>
<thead>
<tr>
<th>Reactor Power (KW)</th>
<th>Melt Channel Diameter (cm)</th>
<th>MICE Exploration Distances (km/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>60</td>
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<tr>
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<tr>
<td>1000</td>
<td>150</td>
<td>222, 80</td>
</tr>
</tbody>
</table>
Figure 3.2.3 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

Figure 3.2.4

MICE 2 Way Real Time (Subject To Light Speed Delays)
Link To Scientists On Earth

Earth Scientists

MICE Lander Spacecraft

Mars Polar Cap

Bed Rock

2 Way Communication Between Lander and Earth

Time Delay Due To Finite Speed of Light

2 Way Real Time Communication Lines Between Individual MICE Probes and Between Probes and Lander
Figure 3.3.1

Return Of Polar Cap Samples To Earth

18 Month Exploration Program Before Lander Spacecraft Returns To Earth

- Mars Polar Cap
- MICE Probes Returning Samples To Lander
- MICE Probes Searching Locations For Good Samples
- 6 MICE Probes Move Through Ice Sheet, Collecting Samples and Bringing Them Back To The Lander

5 To 10 Year Exploration Program After Lander Spacecraft Returns To Earth

- Mars Polar Cap
- MICE Probes Going Out To Look For New Samples
- Communications Package and Power Source Left Behind By Departed Spacecraft

Communications Package and Earth Scientists can Communicate With Lander Spacecraft

Bed Rock

6 MICE Probes Continue To Move Through Ice Sheet and Send Data Back To Earth via Communications Package
### Figure 3.3.2
Cryobots and MICE: Comparative Features

<table>
<thead>
<tr>
<th>Feature</th>
<th>JPL Cryobot</th>
<th>MICE</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Heat Source</td>
<td>RTG (Pu-238)</td>
<td>Nucl. Reactor</td>
</tr>
<tr>
<td>• Travel Capabilities</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Move downwards?</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>- Move upwards?</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>- Return samples to lander?</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>- Max rate of travel, meters/day</td>
<td>24</td>
<td>200</td>
</tr>
<tr>
<td>- Days to penetrate 2 km ice sheet</td>
<td>83</td>
<td>10</td>
</tr>
<tr>
<td>- Go thru dust/ice layer?</td>
<td>Unlikely</td>
<td>Yes</td>
</tr>
<tr>
<td>• Power Level, Kilowatts (Thermal)</td>
<td>1</td>
<td>500</td>
</tr>
<tr>
<td>• Probe Dimensions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Outer diameter, cm</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>- Length, meters</td>
<td>1.25</td>
<td>1 + 1</td>
</tr>
<tr>
<td>Total Probe Mass, Kilograms</td>
<td>25</td>
<td>53 (+ instrum.)</td>
</tr>
</tbody>
</table>

### Figure 3.4.1
MICE Reactor Pod: Reactor, Power Conversion, and Melt/Movement Systems

- Heat Exchangers
- Hot Water Jets
- Electric Power Conditioning System
- Steam Generator
- Steam Turbine and Generator
- Steam Condenser
- Pump
- Channel Melt Water
- Melt/Movement System as R-Pod
- Hot Water to I-Pod Jets
- Electric Power to I-Pod (Instruments, Communications, etc)
Figure 3.4.2
MICE Instrumentation Pod: Instrumentation, Sample Collection and Communication Systems

- Electric Power from R-Pod
- Data Collection System
- Communication System to Lander and Other Probes
- Melt/Movement System
- Buoyancy Control System
- Sample Collection Equipment
- Instrumentation for Data on Ice Structure, Gases, Dust, Biology, etc.
- Hot Water Jets
- Adjustable Volume of Water in Buoyancy Chamber
- Transmitted/Received Communications
- Melt Surrounding Ice
- Inflow/Outflow of Melt Water

Hot Water from R-Pod
4.0 MICE REACTOR AND POWER CONVERSION SYSTEM DESIGN

4.1 Compact High Power Reactor Options and Selection of Best Approach

A wide variety of reactor options for space nuclear power systems have been proposed. The various designs include liquid metal cooled fast reactors, such as the proposed SP-100 system, gas cooled fast reactors, and water cooled and moderated thermal spectrum reactors, like the SUSEE system. As part of the total power system, a power conversion sub-systems is used in combination with the reactor. Various power conversion options for space nuclear reactor systems have been proposed, including thermoelectrics, thermionics, the potassium vapor Rankine cycle, the conventional steam Rankine cycle, and the gas Brayton cycle. The Rankine and Brayton cycles operate using a mechanical turbine. The Brayton cycle also requires a mechanical gas compressor, while the Rankine cycles generate high pressure working vapor by boiling a liquid. The thermoelectric and thermionic direct conversion systems have no mechanical parts other than the coolant pump. [If an MHD pump is used, the mechanical pump is not needed; however, a liquid metal coolant is necessary.]

Actual thermionics and thermionic fast reactor power systems have been operated in orbit by the Soviet Union. However, the systems have been low power, with high specific mass [kg/KW(e)].

The criteria for selection of the best approach for MICE type reactors are quite different from those for a nuclear power system operating in space. The differences are in the following areas:

1. Rejection of waste heat
2. Type of power output
3. Operating environment
4. Availability of in-situ resources
5. Reactor size

In the first area, rejection of waste heat, reactors that operate in space must thermally radiate away waste heat from the power cycle using a large, heavy radiator structure. This requirement tends to dominate the design of the reactor and power system leading to high reactor and radiator operating temperatures. The designs generally use liquid metal or gas coolants and exotic high temperature nuclear fuels to minimize radiator size and weight. [However, this need not be the case, as studies of the water cooled and moderated SUSEE space reactor system have shown. Water cooled space reactor systems can have much lower specific masses, kg/KW(e), than high temperature gas or liquid metal cooled space reactor systems.]

For the MICE reactor, rejecting waste heat is simple and easy. The waste heat from a MICE reactor is dumped into the melt water and ice sheet through which the MICE probe moves. In fact, this is necessary since the reactor heat generates the melt channel for the moving MICE probe.
In the second area, type of power output, space power systems generally deliver electrical output, converted from the thermal energy generated in the reactor. Like the first area, high temperature outputs are favored, for good conversion efficiency and to minimize radiator area and weight.

For the MICE reactor, however, most of its power output goes towards melting a channel in the ice sheet through which the probe travels. High temperatures are not needed – mostly just warm water output. Only a small portion of the MICE thermal output is used to generate electrical power, so the electrical conversion efficiency can be quite low. The electrical power from a MICE reactor is easily produced using a steam cycle at a moderate temperature and pressure. High temperature reactors are not needed or desirable.

In the third area, operating environment, space reactor systems operate in high vacuum, completely isolated from any contact with any external environment, except for occasional impacts by micrometeorites and space debris, from which they have to be protected. The reactor, piping system, and radiator must be completely leak-tight; otherwise, any leak of the pressurized coolant into the vacuum of space will inevitably shut down the reactor and power systems.

For MICE reactors, however, the reactor will operate in a water environment. The surrounding melt water will be at low temperature and poses no corrosion or debris problems. The MICE reactor coolant system will be pressurized so that any leakage of its water coolant will be outwards into the surrounding melt water. The loss from the leakage can be readily made up by intake and pressurization of the surrounding melt water.

In the fourth area, availability of in-situ resources, nuclear power systems operating in space have no access to in-situ resources unless they land on a NEO (Near Earth Object), main belt asteroid, moon, or other body. Designing in such capability would be difficult, unless the system was intended to land and remain there in place.

The MICE power system has easy access to melt water, which can be used as a coolant and moderator for the reactor, and as a working fluid for the power conversion system. The melt water can also be electrolyzed to make H₂ and O₂ gas, which can provide buoyancy control, and as an explosive sound source for some imaging of the surrounding ice sheet structure. The H₂ and O₂ can also be used as chemical reactants to test the dusty material collected from the ice sheet.

In the fifth area, reactor size, the diameter of the reactor is not significant for nuclear space power systems; the main goals are good power cycle efficiency and low specific mass, kg/kW(e). For the MICE reactor system, minimizing reactor diameter is important, because it also minimizes the diameter of the melt channel, and maximizes the rate at which the MICE system can move through the ice sheet, for a given power output, because the smaller the diameter of the melt channel, the less thermal energy is needed to create it.

Figure 4.1.1 examines the various types of reactors that have been studied for space reactor systems and assesses them in terms of their performance in the five areas, outlined above.
In addition to the five areas, their performance in a sixth area, status of technology, is also assessed. The development of new nuclear fuels and reactor systems is a very long and expensive process. For space missions, it is very desirable to minimize the R&D efforts, and to use existing nuclear technology wherever possible.

Some down–selection has already been made in the choice of the 3 reactor types considered. For example, a liquid metal cooled reactor using a potassium vapor Rankine cycle is not included because the technology is at a very early stage relative to thermoelectrics, and a high conversion efficiency, thermal to electric, is not needed. Similarly, thermionic power conversion is not included, since it tends to limit the total output power from a given size reactor. The 3 remaining options are then:

• Liquid metal cooled fast reactor with thermoelectric power conversion [e.g., similar to the old SP-100 system].
• Gas cooled fast reactor with a Brayton cycle turbine power conversion system.
• Water cooled and moderated thermal spectrum reactor with a steam cycle turbine power conversion system [similar to the proposed SUSEE system].

The water cooled and moderated thermal reactor system appears to be the best choice for MICE missions for the following reasons (see also Figure 4.1.1).

1. Its technology is much more developed than the other options. The nuclear fuel for a MICE reactor would be the same as that already commercially available and used in many reactors around the World for decades, with excellent safety and reliability. The water coolant and steam turbine technology is also commercially available and has been used in many reactors around the World for decades. The R&D required for a MICE system application would be much less than for the other 2 options, take much less time, and cost much less.

2. The water coolant and moderator used in the MICE reactor and power conversion system can be obtained directly from the Mars ice sheet, making the payload weight to be transported to Mars much less than for the other reactor options. Moreover, any loss of water coolant and/or moderator from a MICE unit can be easily replenished with melt water from the ice sheet.

3. Only a small section of a water cooled MICE reactor need operate at elevated temperature to generate electricity using a small steam turbine. The bulk of the coolant and fuel could then be at temperatures well below 100°C. [This potentially has operational advantages, but makes the design of the reactor more complex.]

Figure 4.1.2 shows the flowsheet for the reactor and power conversion system for a MICE probe using the water cooled and moderated option. The reactor core has a common primary coolant flow geometry with all of the coolant at maximum operating temperature. A small portion of the primary coolant flow is used to generate steam for a power cycle.
In an alternate (Version 2), two different flow circuits would operate inside the reactor core, circuit A and circuit B. Circuit A operates at elevated temperature using fuel elements in the center region of the core; where the power density is highest. Circuit B operates at relatively low temperature, using fuel elements in the outer portion of the core, where power density is lower. Both circuits would operate at the same temperature; however, their flows do not commingle, but are separated by a cylindrical shell located between the inner and outer core regions. The shell would provide thermal isolation between the hotter inner region and the outer cooler region of the reactor core.

The baseline version (Figure 4.1.2, Version 1) results in a simpler and more versatile reactor/power system design. There is a single primary coolant circuit through the reactor, with no need for separate flow regions. Moreover, it allows the MICE system to easily change the ratio of electric power output/thermal melt output as desired, by controlling the relative flow rates to the steam generator and the melt heat exchanger, as desired.

For example, the MICE probe may want to travel relatively slowly through the ice sheet, while keeping electric power output at a given level, and then start to travel at a fast rate while still maintaining essentially constant electric power. Such a situation could occur if the probe were first exploring a scientifically interesting region, where extensive data taking was desired, and then moved into a scientifically dull region where it wasn’t worth spending a lot of time there.

In the slow motion mode, reactor output power would be cut back, with most of the coolant flow going to the steam generator. When in the fast travel mode, the reactor output power would be increased with most of the coolant flow going to the melt water heat exchanger. The flow rate to the steam generator could be essentially constant for the 2 modes. Alternatively, for situations where high electric output was desired, the coolant flow to the steam generator could be increased.

The flow control could be provided using two simple adjustable flow control valves, either electrically or hydraulically controlled to give the proper flow rates to the steam generator and the melt water heat exchanger.

In the alternate version, not only is the reactor construction more complex, but the ratio of electric output to thermal melt water output would have to remain constant, since the ratio of power output of the hotter region to the power output of the cooler region is automatically fixed by the number of fuel elements in each region, and their relative power density. If greater melt water output is desired, the total reactor power would have to be increased, which would automatically also increase electric output. Conversely, if a slower rate of travel was desired, the reactor power would be cut back, reducing the electric output.

The inflexibility of output for the alternate version, together with its more complex reactor design, argues strongly for the baseline version. The requirement that all of the fuel elements then must operate at the same maximum design temperature does not appear to be a significant drawback to the baseline.
There are 3 well developed commercial nuclear fuel options that can be used in the MICE water cooled reactor. All have been used in many reactors around the World for many decades with excellent safety and reliability records. All have zero release rates of fission products, which are completely contained inside the nuclear fuel, and all achieve high burnings of their fissile U-235 loadings.

Figure 4.1.3 illustrates those 3 nuclear fuel options. The Zr/UO₂ cermet nuclear fuel consists of small (~10 micron) uranium dioxide spheres imbedded in a zirconium metal matrix. The uranium is enriched in U-235, enabling high burn up and operating lifetimes of many years. Rare Earth oxide particles can also be embedded in the Zr metal matrix, to minimize swings in the value of the criticality constant, Keff of the reactor as the U-235 fuel is fissioned. These “burnable poison” particles have high neutron absorption cross sections and compete with U-235 for neutrons in the reactor. As the U-235 content in the Zr/UO₂ cermet fuel is depleted, so also is the burnable poison, which tends to maintain Keff at a constant value. The remaining inevitable small changes in Keff over the operating life of the reactor can be readily compensated for by control rods or other methods, so as to maintain the reactor in the Keff = 1 critical state.

The Zr/UO₂ cermet fuel can be manufactured in the form of plates, rods, or hollow tubes depending on the particular reactor designs being considered. Zirconium metal cermet and Zircaloy clad UO₂ fuel is very compatible with hot water coolant and is used widely in many hundreds of reactors around the World.

The second nuclear fuel option, TRIGA fuel, consists of a mixture of UH₃/ZrH₂ (uranium hydride and zirconium hydride), formed into rods and clad with stainless steel. The hydride fuel is a solid metallic like material and stable to high temperatures. TRIGA fueled reactors have the unique capability to automatically and instantly shut down safely if a large reactivity insertion (i.e., Keff >> 1) were to occur. This capability is deliberately used to provide very short, very intense pulse of neutrons for research purposes. The TRIGA reactor is suddenly driven into the high supercritical state by withdrawing a control rod, with a consequent exponential rise time of a few milliseconds for the reactor power level. [In reactor neutronic terms, the ΔKeff insertion can be several “dollars” worth, with one “dollar” being the ΔKeff that drives the reactor into the prompt critical state.] The resultant heat release from uranium fission is instantly transferred to the hydrogen in the UH₃/ZrH₂ fuel, causing Keff to decrease as the temperature of the fuel increase. The temperature continues to rise until the reactor goes sub-critical and shuts down.

The TRIGA fuel is very stable, and not affected or degraded by the many thousands of very large power excursions carried out over its operating life. There are many TRIGA reactors operating around the World, with excellent safety and reliability records.

For the MICE application, TRIGA fuel has the advantage of providing additional control margin for the power level, essentially assuring that excessive power and temperature could not occur during operation of the MICE reactor. It has the disadvantage that the TRIGA fuel is relatively heavy, since metal hydrides are much denser than water, and furthermore, it would have to be transported to Mars, while the water coolant/moderator in MICE reactors could be...
obtained on Mars from the ice sheet where the probes landed. The mass of the ZrH₂/UH₃ TRIGA fuel rods for a nominal MICE reactor would be on the order of 300 to 400 kilograms, much more than the ~50 kilograms for other fuel forms, which would have their water coolant/moderator obtained on Mars.

The third nuclear fuel option is TRISO fuel particles. The TRISO particle was developed for the High Temperature Graphite Reactor (HTGR), but also appears suitable for water cooled/moderated MICE reactors. In HTGR reactors, the TRISO particles are imbedded in graphite blocks or balls, which are cooled by high pressure helium gas. In the MICE reactor, the TRISO particles would be held in an annular bed of packed particles, through which coolant water would flow, directly cooling the particles.

The TRISO particle consists of a central kernel of uranium carbide which is coated with an inner layer of pyrographite, followed by an outer coating of silicon carbide. The SiC layer acts like a miniature pressure vessel, completely containing all of the fission products generated in the uranium carbide kernel. TRISO particles have zero release of fission products, even to very high burn up levels. The nominal diameter of the TRISO particle is approximately 700 microns.

Figure 4.1.4 illustrates the 3 nuclear fuel options would be used in MICE fuel elements. The Zr/UO₂ fuel could be used as plates, rods or hollow tubes. The hollow tube approach appears the best, because it enables a smaller, lighter reactor than the solid rod approach, with twice the heat transfer area available with solid rods. The hollow tube element allows more water coolant per unit cross sectional area of the core than the solid rod approach, resulting in a smaller diameter core and reactor. It also reduces the amount of heavy Zr metal in the core, since the center of the rod is replaced with water.

The TRIGA fuel element is a simple rod of the UH₃/ZrH₂ solid metal hydride, with an outer stainless cladding layer. The diameter of the TRIGA fuel rod will be in the range of 1 to 2 centimeters, depending on design. The TRIGA fuel elements probably will be somewhat greater in diameter than the Zr/UO₂ fuel rod elements, because the hydrogen in the hydride acts as the moderator for the reactor, while the Zr metal matrix for the Zr/UO₂ cermet fuel elements does not act as a moderator. As a result, the Zr/UO₂ fuel rod elements will tend to be substantially smaller in diameter than the TRIGA fuel elements and also the hollow tube Zr/UO₂ elements, which contain water moderator inside the tube.

The third type of fuel element illustrated in Figure 4.1.4 is the annular packed bed element, where the packed bed consists of small diameter TRISO particles. The annular packed bed is contained between two porous stainless steel cylinders, termed “frits”. The water coolant flows along the central channel formed by the inner frit, with a portion of the coolant flowing
outwards at each location. The magnitude of the local outwards flow is controlled by the effective local porosity of the frit at each position, which in turn controls the flow resistance. Where the local power density is high, e.g., at the middle of the fuel element, the frit is more porous, permitting a greater flow rate. Where the power density is lower, e.g., at the ends of the element, the frit is less porous, reducing the local flow rate. With ideal control of porosity and flow rate, the water coolant would emerge through the outer frit at the same temperature everywhere on the element, regardless of the variations in power density along the element and where it is located in the core. In practice, there will be some small differences in the local outlet coolant temperature, but these differences will be small compared to the overall temperature increase acquired by the coolant as it enters and leaves the reactor.

This type of fuel element was studied very extensively, both analytically and experimentally, as part of the extensive SDI/DOD/SNTP program on the Particle Bed Reactor (PBR) program. The very large heat transfer area in the packed particle bed, which is on the order of 100 cm$^2$ per cubic centimeter of bed, enables extremely high power densities. In tests of the PBR elements using hydrogen gas flow through packed bed elements, power densities of 30,000 kilowatts per liter of fuel element were measured. For the 50 liter MICE reactor, such power densities would correspond to a power output of ~1000 megawatts, far more than would ever be desired. The power densities possible with water coolant will be considerably smaller than those for the hydrogen propellant in the PBR nuclear propulsion engine, but it would be possible to obtain approximately 100 megawatts from a MICE reactor, using water coolant. This still is far greater than would ever be needed. Delivery of 1 megawatt for a MICE reactor using the TRISO packed bed element would be easily achievable.

As part of the PBR program, frits with the required (R, θ, z) variation in local porosity were manufactured by Babcock and Wilcox. Similar fabrication techniques would be used for the frits for a MICE reactor. As with the hollow tube Zr/UO$_2$ fuel, the water coolant/moderator probably would be obtained from the Mars ice sheet, making the weight to be transported to Mars small – just the reactor structural mass, plus ~10 kilograms of TRISO fuel particles.

Figure 4.1.5 shows a cross sectional view of the MICE reactor using the 3 types of fuel elements:

1. Hollow tube Zr/UO$_2$ cermet
2. Solid rod TRIGA element
3. Annular packed bed of TRISO particles

The fuel elements are arranged with an appropriate clearance between them that allows for the desired amount of water moderator and coolant. The amount of clearance is determined by the pitch to diameter ratio (P/D), where the pitch P is the distance between the centers of the fuel elements in the array, and the diameter D is their diameter. As illustrated in Figure 4.1.5, the fuel elements are arranged in a hexagonal lattice. A large P/D ratio corresponds to the fuel elements being spaced relatively far apart while a small P/D ratio corresponds to a relatively close spacing between elements.
The 3 types of fuel elements listed above will have relatively low values of P/D because they all incorporate some moderator in the element – water in the case of the hollow tube Zr/UO₂ element and the annular packed bed TRISO element, and solid hydride in the case of the TRIGA element.

The inlet water coolant flow rate can be individually controlled for the hollow tube and TRISO annular bed elements by orifices in the openings that lead to the central channels for each element. This enables each element to have a flow rate that corresponds to its position in the core assembly. The elements near the center of the core tend to experience higher neutron fluxes than elements further out. Thus, for the same uranium loading, they would have higher power density and require a higher water coolant low rate in order that the outlet water temperature from the different elements be essentially equal.

For solid rod type elements such as the TRIGA elements, it is harder to individually control the water flow rate to the various elements in the core, because the space between elements acts as a common plenum. The orificing can control the inlet water flow rate to each (R, θ) point at the base of the core, but after that, the local water flow can shift to other regions in the core. Some degree of flow/temperature control still remains, however, by adjusting the relative spacing between elements (lower power elements can be closer together, for example, to reduce the local water flow rate) and by adjusting the uranium loading in different elements (elements in a lower flux region in a uniformly loaded core, for example, could be modified to have higher uranium loadings so that they would have the same thermal power output as the other elements in the core).

Figure 4.1.6 assesses the 3 candidate types of fuel elements for the MICE system in terms of:

1. Technology status
2. Power capability
3. MICE reactor size and weight
4. Design complexity for MICE
5. Operational reliability for MICE
6. Development requirements and cost for MICE

All 3 types are technically outstanding with tremendous operating experience. The only technical issue is the capability of TRISO particles to operate directly in hot water coolant. It appears very likely that this is not a problem, based on the known material behaviour of silicon carbide and graphite. Testing of actual TRISO fuel particles in flowing hot water should quickly settle this issue. Most of the testing could be out-of-pile, with some confirmatory in-pile tests.

All 3 types are easily capable of delivering 500 kilowatts thermal power for a MICE probe, and could deliver much higher powers, in the multi megawatt range. There does not appear to be a need for such higher powers for a MICE probe, however. For most of its mission, MICE operating power will probably be much less than 500 kilowatts.
Since the rate of movement for a MICE probe will tend to be governed by lengthy scientific investigations at a given location, rather than a need to travel rapidly through the ice sheet high power levels will not be required most of the time.

The size of the MICE reactor is determined by criticality requirements, not power output. As discussed above, all 3 fuel element candidates can easily deliver the nominal design power of 500 kilowatts. Since all 3 elements use water as the coolant and moderator, the overall size of the MICE reactor is essentially the same regardless of which type of element is used. Small differences in reactor size are possible, depending on which fuel element is used, but the overall outer diameter of the MICE reactor, including reflector and pressure vessel will be in the range of 40 to 50 centimeters. The minor differences in reactor OD are not significant in choosing the type of fuel element to be used in the MICE reactor.

Reactor weight, however, is much more significant. Water coolant is used for all 3 nuclear fuel elements, but for reactors employing TRIGA type elements, most of the moderating power for neutrons is supplied by the heavy hydride moderator (e.g., UH$_3$/ZrH$_2$) rather than water. The effective mass density of the hydride moderator is roughly 6 times that of water, for similar moderating capability.

Moreover, the hydride moderator in MICE must be transported from Earth and landed on Mars while water coolant/moderator can be obtained from melt water from the ice sheet on which the MICE probes land.

The weight of the hydride moderator for a MICE reactor would be in the range of 300 to 400 kilograms, compared to zero kilograms weight if water moderator were obtained from the Mars ice sheet. For an array of 6 MICE probes networked together to explore the ice sheet, using TRIGA type fuel elements would require transporting roughly an additional 2000 kg from Earth to Mars, compared to a total of only 300 to 600 kilograms for the 6 reactors if the Zr/UO$_2$ or TRISO fuel elements were used and the water coolant/moderator were obtained from the ice sheet.

This additional weight penalty for the TRIGA type fuel appears to rule out its use for MICE, even through it offers advantages in its automatic ability to safely shut down the reactor if an unexpected reactivity insertion were to occur.

In the fourth area, reactor design complexity, the hollow tube Zr/UO$_2$ cermet fuel element appears favored over the other 2 candidates. It can be easily orificed to provide precise local control of water coolant flow rate that corresponds to the local power output. Orificing of this fuel element is simpler than that for the other elements. Moreover, it has twice the surface area for heat transfer as the TRIGA element, which simplifies the thermal hydraulic design of the reactor. Finally, it has the highest U-235 loading per unit volume of the fuel element matrix, which maximizes water volume fraction and minimizes reactor size.

In the fifth area, all 3 fuels are very reliable. The TRIGA fuel has the advantage of a very strong prompt negative temperature coefficient, due to the virtually instantaneous transfer of the
heat released by the fissile uranium to the hydride moderator. While a significant advantage, this feature is not sufficient to offset the disadvantage of its much greater weight.

In the sixth area, development requirements, the Zr/UO₂ and TRIGA fuel elements can be considered as fully proven for MICE application. The TRISO element would require additional testing of the packed particle bed configuration in hot water coolant. While not a major development issue, this would add some additional development time and cost to the MICE development program. Since the very high power output capability of the packed particle bed is not needed for the MICE system, the TRISO type fuel element probably is not favored.

Overall, the hollow tube Zr/UO₂ cermet fuel element appears to be the best choice for MICE. The fuel is completely developed, commercially available, has many thousands of megawatt years of operating experience over decades of use, is extremely reliable, has zero release of fission products with high fissile burn up capability, leads to a simple reactor design with precise control of local water coolant flow, has large surface area for heat transfer from the fuel elements to the water coolant, and has a very low total reactor weight if the water coolant/moderator inventory is obtained from the Mars ice sheet.

Figure 4.1.7 summarizes the assessment and selection of the favored power generation option. Water is used as the coolant for the MICE reactor, with an outlet temperature of ~550K. There are 4 main power generation options:

1. Small steam turbine (micro-turbine)
2. Screw expander
3. Stirling engine
4. Thermoelectrics

The 4th option, thermoelectrics, appears impractical for power outputs significantly above ~1 KW(e). For the relatively low outlet temperature of ~550 K, the thermal to electric efficiency of a thermoelectric power system will be low, substantially less than 5%. For a nominal power level of 10 KW(e) for the instrumentation and communications system almost all of the 500 KW thermal output from the reactor would have to go to the thermoelectric system.

Substantial development work on Stirling engines has been carried out by NASA. The thermal to electric cycle efficiency for Stirling engines is approximately 30% for source temperatures on the order of 550 to 600 K. Specific mass is moderate, on the order of 10 kg per kilowatt(e). A single unit can generate up to about 20 KW(e). While possible, the Stirling engine option appears relatively large and heavy for a MICE probe.

The best approach appear to be to generate high pressure stream at ~1000 psi using a small lightweight heat exchanger, as illustrated in Figure 4.1.2. The high pressure steam would then be expanded in a small micro-turbine, or a screw expander. By using a high exhaust pressure, e.g., 30 psi, the expander could be kept small and lightweight, without still achieving reasonable thermal to electric efficiency. For example, using a steam microturbine with saturated steam inlet at 1000 psi inlet pressure, 30 psi outlet pressure, and 80% mechanical to
electrical efficiency, an overall thermal to electric efficiency of about 20 percent can be achieved. A screw expander using a somewhat higher outlet pressure could achieve about 10 percent thermal to electric efficiency.

The micro turbine option appears favored over the screw expander option for the following reasons:

1. **Smaller size and weight.** The steam throughput velocity through the rotating turbine wheel will be much greater than that through a screw expander, resulting in a much smaller diameter and length, and a much lighter unit.

2. **Higher conversion efficiency.** The micro-turbine option will have a substantially greater thermal to electric conversion efficiency than the screw expander, because it has a lower exhaust pressure and greater mechanical efficiency.

3. **Greater reliability.** The micro-turbine units are sufficiently small and lightweight that several parallel units can be used for a probe without substantially increasing the size and weight of the probe. Three parallel micro-turbine units would provide a high degree of redundancy and reliability. Even if 2 of the 3 micro-turbines were to fail, the probe could still operate. Its rate of data acquisition and transmission might be somewhat reduced, but the unit could still function and provide valuable data. Using a single Stirling engine or screw expander power unit, such reliability and redundancy would not be possible.

4. **Greater operating experience.** There is an immense body of experience using steam turbines, accumulated over many decades of operation. Most of this experience is related to large multi-megawatt systems. There has also been recent extensive experience on kilowatt size micro-turbines using combustion gases. Based on this background, it appears possible to design and operate a practical steam micro-turbine system for a MICE probe relatively quickly with minimal technology development.

### 4.2 Baseline Design of the MICE Reactor and Power Conversion System

Table 4.2.1 summarizes the principal features of the baseline design of the MICE reactor and power conversion system, as determined from the assessment process described in Section 4.

Figure 4.2.1 shows a three dimensional cutaway view of the baseline MICE reactor and its attached control rods, heat exchangers, pumps, and steam turbo generator. It is important to note that the design shown is a first cut at a baseline system, and that further study will probably significantly improve the design by making it smaller and lighter, with a more compact layout.

For example, the baseline design shown is based on a 47 centimeter diameter core, which results in an overall reactor diameter of 59 centimeters. With further optimization, the core
diameter can probably be made smaller, resulting in a corresponding reduction of the overall diameter of the reactor.

The ring of 12 control rod housings at the upper end of the reactor’s aluminum vessel form a cylindrical structure that encloses the primary coolant to melt water heat exchanger, plus the turbine and generator for electrical power generation. The smaller steam generator and condenser are attached to the outer surface of the control rod attached to the outer surface of the control rod ring. Not shown is the melt water jet system and the instrument, control, and communication pods. These are described in other sections of the report. The initial portion of the tether that links the MICE reactor with the instrument, control, and communication pods is also indicated in Figure 4.2.1. The distance between the reactor and the pods is on the order of 2 meters, which enables the melt water in the melt channel to a adequately shield them from the neutron and gamma radiation emitted by the reactor.

Figure 4.2.2A shows the MICE reactor parameters that were used for the 30 Monte Carlo analyses. While they result in a reactor with excellent neutronic and thermal hydraulic performance, and which is compact and lightweight, the reactor design has not been optimized. It is likely that developing an optimized reactor design, which would require additional funding resources, and analyses, will lead to an even more attractive system, which would be even smaller and lighter in weight. For example, a smaller and lighter reactor can probably be achieved using higher uranium loadings in the cermet fuel.

Figure 4.2.2B shows the criticality constant, Keff, as a function of uranium -235 loading for the condition where the control rods are fully out and when they are fully inserted. The criticality analyses when carried out using the 3D MCNP Monte Carlo code (1) with full representation of the detailed geometry of the reactor. In previous work on the Particle Bed Reactor/Space Nuclear Propulsion program, it was found that 3D MCNP analyses using full representation of the detailed reactor geometry gave very accurate results. Comparisons of the predicted Keff using the 3D Monte Carlo code agreed with ½% of the Keff measured on actual PBR critical reactors. Because reactors like MICE and the PBR have very complex heterogeneous geometry and high neutron leakage, accurate prediction of criticality behaviour requires such detailed analysis.

As shown in Figure 4.2.2B the MICE reactor achieves criticality (Keff ≥ 1) over a broad portion of the U-235 loading range studied, from about 3 kg of U-235 to 9 kg. The control margin is sufficiently large that control of reactor power should be straightforward. The ΔKeff between control rods fully out and control rods fully in is 0.27, more than enough to compensate for any changes in Keff that occur over the operating life of the reactor.

The change in Keff over the projected operating life of the MIC reactor was analyzed using the Monte Burns 3D Monte Carlo code. The Monte Burns code employs the same detailed 3D Monte Carlo analyses of the full representational geometry as the MCNP analyses, plus the ability to determine the local depletion of the uranium loading and buildup of fission products, with their consequent effect on Keff for the full reactor.
The Monte Burns analyses were carried out for the MICE reactor operating at full power, i.e., 500 KW(th) for a period of 4 years. This is a very conservative case, since for much of its operational life, the MICE probe will be near stationary at lower power, while it collects detailed data at sites along its path. The average power of the MICE reactor will thus be substantially less than 500 KW(th) during the 18 month period the lander spacecraft will be collecting samples from the MICE probes. Since scientists will be eager to examine the samples collected by the MICE probes, and will want them returned to Earth as soon as possible, rather than wait many years for their return. Accordingly, 500 KW(th) for 4 years was assumed as an upper limit for total burnup analysis – in a real mission, the burnup will probably be substantially less. The MICE probes can keep on operating long after the lander spacecraft departs for Earth.

Figures 4.2.3A, B, and C show Keff as a function of operating time for 3 different U-235 loadings, corresponding to 20, 15, and 10 volume percent of U-235 in the fuel. The maximum volume percent loading of UO₂ in the Zr/UO₂ cermet is on the order of 50 percent, so that the range of 10 to 20 % is well within present manufacturing capability. The corresponding U-235 loadings are 8.2 kg for 20 volume %, 6.1 kg for 15 volume %, and 4.1 kg for 10 volume %.

For each of the uranium loadings, Monte Burns analyses were made first assuming that no burnable poison was added to the Zr/UO₂ fuel, and then assuming that Boron-10 was added as a burnable poison. In each case, the same total amount of ¹⁰B was added, i.e., 7.8 grams. The 7.8 grams was assumed to be uniformly distributed in the Zr/UO₂ material that make up the fuel elements.

For all 3 loadings, the addition of ¹⁰B substantially reduces Keff by about a ΔKeff of 0.10 at the beginning of the operating cycle. [The analyses are made for control rods fully withdrawn.] As the reactor operates, Keff steadily decreases if there is no ¹⁰B in the fuel. With the addition of ¹⁰B, however, Keff is almost constant over the operating cycle of 2000 KW(th) years [i.e., 4 years at 500 KW(th)], and actually rises slightly with time. This occurs because the ¹⁰B depletes faster than the U-235, since its neutron absorption cross section is greater.

Figure 4.2.4 shows the total worth in ΔKeff of the 12 control rods in the MICE reactor as a function of uranium loading, as well as the worth of one control rod, which is taken as 1/12th of the total worth.

The control rod worth is essentially constant with uranium loading, with the worth of one control rod being ~0.02 in ΔKeff, and of all 12 control rods, about 0.27 in ΔKeff.

Figure 4.2.5A shows the corresponding number of control rods that have to be inserted into the MICE reactor to maintain it at a steady power level (i.e., Keff = 1) as a function of uranium loading and operating time. The number given assumes that the control rods are fully inserted; in practice, instead of fully inserting 4 of the 12 control rods, for example, as with the 6.1 kg U-235 loading, probably all 12 would be partially inserted to a depth that resulted in Keff = 1, so as to avoid azimuthal distortion of the power distribution in the core.
For the 8.2 kg U-235 loading (20 volume % UO₂ in the Zr/UO₂ fuel), the equivalent of ~5 to 6 control rods would have to be inserted over the 2000 KW(th) year operating period. For the 6.1 kg U-235 loading (15 volume % loading) the number of inserted control rods would be reduced to the range of 4 to 4 ½. For the 4.1 kg U-235 loading (10 volume % loading) the number of inserted control rods would be further reduced, to ~1 to 1 ½ rods over the operating life.

Figure 4.2.5B shows the corresponding shutdown margins when all of the control rods are fully inserted. The shutdown margin is the ΔKeff difference between a criticality constant of Keff = 1 and the Keff when all control rods are fully inserted. From the standpoint of insuring that the MICE reactor can always be shutdown when necessary. The shutdown margin, ΔKeff, should be 0.10 or greater.

For the 8.2 kg of U-235 loading, the ΔKeff shutdown margin is ~0.15, for the 6.1 kg loading, ΔKeff shutdown is ~0.20; and for 4.1 kg, ~0.25. All of the 3 loadings result in acceptable ΔKeff shutdown margins.

The optimum uranium loading for the 3 cases analyzed appears to 15 volume percent UO₂ with ¹⁰B poison added. Its Keff is sufficiently high, averaging about 1.09 and the variation in Keff is sufficiently small, about 0.01 over the 2000 KW(th) year operating period. That it will be simple to control with all control rods inserted, Keff would decrease from a value of ~1.09 with no control rods inserted down to a value of ~0.82. This is sufficiently enough below Keff = 1 to ensure safe operation and the ability to shutdown whenever required.

The local power density in the fuel element will vary with radial and axial position in the MICE core. Figure 4.2.6 shows the average power density in the MICE fuel elements as a function of their radial position in the core. Radial position is expressed in terms of which ring the fuel element is located. Ring number 1, for example, is the first ring outwards from the center of the core, while ring number 10 is the last ring out from the center. Each ring contains 6 more fuel elements than the previous ring, because of the increased circumference.

The average power density shown for an element is calculated by axially averaging the power over the length of the element. This average value then determines the appropriate coolant flow rate for the element. Fuel elements near the center of the core have a higher average power than those in the outer region of the reactor core. Accordingly, the elements near the core center will have a greater water flow rate than those in the outer region.

The power density in the elements in the outer ring is slightly greater than that in the neighbor ring inside it, due to neutrons coming in from the reactor’s reflector. The overall radial peak to average for all of the elements is low, i.e., 1.6/1. The low value makes the control of the local water flow rate in the core relatively simple.

Figure 4.2.7 shows the heat transfer behaviour for the control fuel element in the MICE core, which has the highest power density of the 331 elements, as a function of axial power of 500 KW(th).
The temperature increases core inlet to core outlet of the water cooling the control fuel element is very modest, only 8 K. The corresponding water flow velocity is also very modest, only 0.25 meters per second, and the pressure drops across the core is only 20 N/m². The $\Delta T$ across the core could be made even smaller by increasing flow velocity; however, there does not appear to be any need to do so.

Also shown is the corresponding film drop temperature difference, $\Delta T$, between the surface of the fuel element and the bulk water temperature. $\Delta T$ is maximum at the midway point along the element (i.e., at the center of the core, both axially and radially). However, even at this location which represents the maximum heat flux and $\Delta t_f$ in the core, the film drop is small, only about 32 K. This is readily accommodated by the fuel element. The film drop could also be reduced by increasing water flow velocity; however, as with the temperature rise across the core there does not appear to be a need to do so.

Table 4.2.2 summarizes the dimensions and masses of the various components for the baseline MICE reactor. The total dry mass of the reactor is estimated to be 88 kg, including fuel elements, grid plates, control rods, and their housings, the core/reflector separator, and an aluminum pressure vessel. The water coolant/moderator weight is put at zero, since it will be provided by melt water from the Polar Cap. The aluminum pressure vessel and fuel elements comprise the dominant portion of the reactor mass accounting for approximately 3/4 of the total mass.

Table 4.2.4 summarizes the principal neutronic parameters for the baseline MICE reactor. The design appears practical and attractive, with a large shutdown margin for the criticality constant, $K_{eff}$, and only a small change in $K_{eff}$ when operating for 4 years at full power. The small change in $K_{eff}$ can be easily controlled by the 12 control rods. The uranium loading in the Zr/UO₂ cermet fuel is only 15 volume %, well below the loadings already in use for the fuel.

Table 4.2.5 summarizes the thermal hydraulic parameters. The radial peak to average power density in the fuel elements is relatively low, ~1.6/1, and is easily handled by orificing the elements to control the local water flow rate. The temperature rise across the core is very small at the full power of 500 K, only a few degrees K. Local variations in the water exit temperature are readily accommodated. The reactivity temperature coefficient of the reactor is strongly negative, which helps to provide safe and effective control.

### 4.3 Interfaces Between MICE Reactor/Power Conversion System and Other Systems

Figure 4.3.1 describes the interface between the MICE reactor/power conversion system and the channel melt system. In path 1, thermal energy from the reactor is transferred from the reactor coolant circuit through the main heat exchanger to water taken in from the melt channel in the ice sheet.
The inlet channel melt water is at a much lower temperature than the primary reactor coolant, e.g., ~300 K compared to 550 K. The large ΔT between the two water streams enables the heat exchanger to be very compact and lightweight.

The outlet temperature of the melt water from the heat exchanger can be controlled over a wide range, depending on the flow rate through the exchanger, from a few degrees above its inlet temperature to near reactor type temperatures. The heated outlet melt water can be directly sprayed onto the ice around the MICE probe to melt it, or it can be mixed with additional melt water from the channel to reduce its temperature before it is directed into the ice surface.

In addition to providing a very flexible operating protocol, which allows the melt channel process to be continuously adjusted for optimum results, the system also permits the melt power output to be independent of the electrical power output level. For example, it may be desirable to have the MICE probe stop moving and remain at a fixed location while data is collected. Electrical power would continue to be generated, but the thermal melt power output would be very low, just enough to prevent the melt channel from re-freezing. The reactor power would then be reduced with most of the primary coolant flow going to path 2, generates steam for the turbine that drives the electrical generator.

After collecting data at the location of interest, and it was desired to move into another location, the reactor power would be increased, with greater flow through the melt water heat exchanger. At the maximum power of 500 KW(th), the MICE probe could move through the ice sheet at 200 meters per day.

The coolant flow rates to the path 1 and path 2 heat exchanger would be controlled by independent valves allowing the ratio of melt power to electric power to vary over a very wide range.

The interfaces between the MICE reactor/power conversion system and the communications and control systems are described in Figure 4.3.2.

The MICE probes will be in continuous real time 2 way communications with the spacecraft lander, so that their current position and operational status is always recorded by the lander. The lander is in continuous 2 way communication with scientists on Earth, subject to the time delay (maximum of ~1 hour) due to the finite speed of light.

Scientists on Earth will be able to direct the paths of the MICE probes, how fast they travel, where they stop to collect data and samples, how long they stay at a given location, reactor power level, melt water and electric output power levels, when they return to the spacecraft lander, etc.

Because of the time delay, some degree of autonomous control of operating parameters is also required, like reactor power, channel movement rate, etc. For example, the scientists on Earth can set reactor power at 200 KW(th) and direct the probe to travel in a certain direction, with a certain melt water temperature and flow rate.
The autonomous control system on the MICE probe would then maintain these operating conditions until directed otherwise from Earth. Because of the inherent time delay, corrections will probably be necessary from time to time. For example, a MICE probe could move past a very interesting and important site inside the ice sheet, without scientists on Earth realizing it until it had traveled several meters beyond the site. Once the information reached Earth, the scientists could then direct the probe to return to the site, stop, and begin to collect data. An hour or so of time would be lost in the process, but this appears acceptable.

The types of autonomous control capability required for the MICE probes already exist in the nuclear and chemical industries, and can be readily adapted for MICE missions.

Figure 4.1.1 Assessment and Selection of the Favored Reactor Type for MICE Missions

<table>
<thead>
<tr>
<th>Evaluation Area</th>
<th>Type of Reactor and Power Conversion System</th>
<th>Water Cooled and Moderated Thermal Reactor with Steam Cycle *</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Rejection of Waste Heat</td>
<td>Designed to radiate to space - can be designed for rejection to ice sheet</td>
<td>Intended for rejection to ice sheet</td>
</tr>
<tr>
<td>2. Type of Power Output</td>
<td>Reactor operates at high temperature to generate electric power - waste heat can be used for melting ice</td>
<td>Reactor operates at high temperature to generate electric power - waste heat can be used for melting ice</td>
</tr>
<tr>
<td>3. Operating Environment</td>
<td>Vacuum of space - compatibility issues of liquid metal coolant with liquid melt water</td>
<td>Vacuum of space - pressure vessel must be designed to be compatible with melt water</td>
</tr>
<tr>
<td>4. Availability of In-Situ Resources</td>
<td>Liquid metal coolant not available in Mars ice sheet</td>
<td>He gas coolant not available in Mars ice sheet</td>
</tr>
<tr>
<td>5. Reactor Size</td>
<td>~40 cm OD suitable for MICE mission</td>
<td>~40 cm OD suitable for MICE mission</td>
</tr>
<tr>
<td>6. Technology Status</td>
<td>High temperature nuclear fuel and reactor still experimental - moderate temperature thermoelectric - liquid lithium coolant still experimental</td>
<td>Nuclear fuel and reactor still experimental - moderate temperature Brayton turbines have been tested</td>
</tr>
</tbody>
</table>
Figure 4.1.2
Coolant Flowsheet for Reactor and Power Conversion Cycle for MICE Probe
Using Water Cooled and Moderated Reactor

Version 1: Common water flow configuration for reactor core
Version 2: Separate water flow configuration for power and melt water systems

Note: Circuits A & B are at same pressure, but Circuit A operates at elevated temperature, while Circuit B operates at low temperature

Figure 4.1.3
Three Commercial Nuclear Fuel Options Considered For The MICE Reactor

<table>
<thead>
<tr>
<th>Zr/UO₂ Cermet Fuel</th>
<th>TRIGA Fuel</th>
<th>TRISO Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zirconium Cladding</td>
<td>Silicon Carbide Coating</td>
<td></td>
</tr>
<tr>
<td>~2 mm</td>
<td>Pyrographite Layer</td>
<td></td>
</tr>
<tr>
<td>Zirconium Metal Matrix</td>
<td>Uranium Carbide Kernel</td>
<td></td>
</tr>
<tr>
<td>UO₂ Particles (~10 micron Diameter)</td>
<td>Stainless Steel Cladding</td>
<td></td>
</tr>
<tr>
<td>~1 cm</td>
<td>UH₃/ZrH₂ Metal Hydride</td>
<td></td>
</tr>
<tr>
<td>~400 microns</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.1.4 Reactor Pod - Commercial Fuels

Zr/\text{UO}_2\text{ Cermet Fuel}

**Hollow Tube Element**

- Water Coolant
- Zr/\text{UO}_2\text{ Cermet Tube}
- ~1 to 2 cm

**Solid Rod Element**

- Water Coolant
- Zr/\text{UO}_2\text{ Cermet Rod}
- ~1 cm

**Solid Plate Element**

- Water Coolant
- Solid Zr/\text{UO}_2\text{ Plate}
- ~2 mm

TRIGA Fuel

- Water Coolant
- Stainless Steel Cladding
- ~1 to 2 cm

TRISO Fuel

- Outlet Water Coolant
- Inner Porous Stainless Tube
- ~2 cm

Figure 4.1.5 Reactor Pod - Fuel Element Design

**Zr/\text{UO}_2\text{ Hollow Tube Fuel Element Array}**

- [7 Element Section]

**TRIGA \text{UH}_2/\text{ZrH}_2\text{ Fuel Element Array}**

- TRIGA Fuel Element
- Water Coolant Between Element

**TRISO Annular Packed Bed Element Array**

- TRISO Packed Bed Element
- Water Coolant Inlet To Elements
- Water Coolant Out From Elements

---

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### Figure 4.1.6 Assessment of Candidate Nuclear Fuel Elements for the MICE System

<table>
<thead>
<tr>
<th>Assessment Area</th>
<th>Type of Fuel Element</th>
<th>Hollow Tube Zr/UO₂ Cermet</th>
<th>TRIGA UH₃/ZrH₂ Hydride Rod</th>
<th>TRISO Annular Particle Bed Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Technology Status</td>
<td>• Zr/UO₂ cermet fuel in commercial production</td>
<td>• TRIGA hydride fuel in commercial production</td>
<td>• TRISO particles in commercial production</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Many thousands of MW - years of operating experience</td>
<td>• Many hundreds of MW years of operating experience</td>
<td>• Many hundreds of MW years of operating experience</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Extremely reliable - zero release of fission products</td>
<td>• Extremely reliable - zero release of fission products</td>
<td>• Extremely reliable - zero release of fission products</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Operates w/high temperature water coolant</td>
<td>• Operates w/high temperature water coolant</td>
<td>• Operates with very high temperature helium coolant</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Usually fabricated as plates - can also be tubular</td>
<td>• Fabricated as rod elements</td>
<td>• Should be able to operate in high temperature water - requires testing</td>
<td></td>
</tr>
<tr>
<td>2. Power Capability</td>
<td>• Operates in multi megawatt reactors</td>
<td>• Operates in multi-megawatt reactors</td>
<td>• Operates in multi-megawatt reactors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Achieves &gt;100 kilowatts per liter core power densities</td>
<td>• Achieves &gt;100 kilowatt per liter core power densities</td>
<td>• Achieves &gt; 1 megawatt per liter core power density</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Can achieve &gt;1 megawatt in MICE reactor</td>
<td>• Not damaged by repeated rapid power transients to hundreds of megawatts</td>
<td>• Can achieve &gt;&gt; 1 megawatt in MICE reactor</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Can achieve &gt; megawatt in MICE reactor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assessment Area</td>
<td>Type of Fuel Element</td>
<td>TRIGA UH$_3$/ZrH$_2$ Hydride Rod</td>
<td>TRISO Annular Particle Bed Element</td>
<td></td>
</tr>
<tr>
<td>---------------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hollow Tube Zr/UO$_2$ Cermet</td>
<td>Reactor OD in range of 40 to 50 cm</td>
<td>Reactor OD in range of 40 to 50 cm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reactor dry weight in range of 50 to 100 kg</td>
<td>Reactor dry weight in range of 50 to 100 kg</td>
<td></td>
</tr>
<tr>
<td>3. MICE Reactor Size and Weight</td>
<td>• Simple design precise control of water flow to each element</td>
<td>• Simple design</td>
<td>• Simple design</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• 2x heat transfer area of TRIGA rod</td>
<td>• Limited control of water flow to each element</td>
<td>• Precise control of water flow to each element</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Very large heat transfer area in each element</td>
<td></td>
</tr>
<tr>
<td>4. Design Complexity for MICE</td>
<td>• Very reliable fuel</td>
<td>• Very reliable fuel</td>
<td>• Very reliable fuel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Low power density relative to present reactors</td>
<td>• Low power density relative to present reactors</td>
<td>• Very low power density relative to capability</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Automatically shuts down from large $\Delta$K$_{eff}$ insertion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Operational Reliability for MICE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Can be quickly developed and tested</td>
<td>• Can be quickly developed and tested</td>
<td>• Can be readily developed &amp; tested</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Full scale, non-nuclear electrically heated MICE system can be tested in Earth ice sheet</td>
<td>• Full scale, non-nuclear electrically heated MICE system can be tested in Earth ice sheet</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assessment Area</td>
<td>Steam Turbine</td>
<td>Screw Expander</td>
<td>Stirling Engine</td>
<td>Thermoelectric</td>
</tr>
<tr>
<td>--------------------------</td>
<td>---------------</td>
<td>----------------</td>
<td>-----------------</td>
<td>----------------</td>
</tr>
<tr>
<td>Thermal to electric</td>
<td>High (~ 20%)</td>
<td>Moderate (~ 10%)</td>
<td>High (~ 20%)</td>
<td>Low (~ &lt; 5%)</td>
</tr>
<tr>
<td>Efficiency</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>Low (~ 1kg/KW(e))</td>
<td>Low to Moderate (~ 5 kg/KW(e))</td>
<td>Moderate (~10 kg/KW(e))</td>
<td>High (~ &gt; 10 kg/KW(e))</td>
</tr>
<tr>
<td>Complexity</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
Figure 4.2.2A Reactor Parameters for 3D Monte Carlo Neutronic Analyses of Criticality
Keff as a Function of U-235 Loading and Position of Control Rods in MICE Reactor

• Zr/UO₂ hollow tube cermet elements
  • 2 centimeters OD, 1.9 centimeters ID
  • 47 centimeter length
  • 10, 15, and 20 volume % UO₂ loadings analyzed
  • Boron-10 oxide burnable poison

• Core assembly
  • 10 rings of fuel elements, 318 total number of elements
  • 47 cm equivalent core diameter, 47 centimeter core height
  • 1.1/1 fuel element pitch to diameter ratio

• Zr hollow tubes with ⁴⁰B₂O₃ poison loading
  • 2 centimeters OD, 1.8 centimeters ID
  • 47 centimeters length
  • 12 control rods in 4th ring from center
  • (12 fuel elements also in ring, for total of 24 units, control rods plus fuel elements)
Figure 4.2.2B  Criticality Constant (Ke) of MICE Reactor as a Function of Uranium-235 Loading for Control Rods(Out) and Control Rods(In) Conditions

Figure 4.2.3A  Criticality Constant (Ke) of MICE Reactor as a Function of Operating (In Days) at 500 Kilowatts(thermal) for 20 Volume (percent) UO₂ Loading in Zr/UO₂ Fuel, With and Without Boron-10 Burnable Poison in Fuel and Control Rods Out
Figure 4.2.3B  Criticality Constant (Ke) of MICE Reactor as a Function of Operating Time in Days at 500 Kilowatts (Thermal), for 15 Volume Percent UO$_2$ Loading in Zr/UO$_2$ Fuel, With and Without Boron-10 Burnable Poison in Fuel, and Control Rods Fully Out

Figure 4.2.3C

Criticality Constant (Ke) of MICE Reactor as a Function of Operating Time in Days at 500 Kilowatts (Thermal) for 10 Volume Percent UO$_2$ Loading in Zr/UO$_2$ Fuel, With and Without Boron-10 Burnable Poison in Fuel, and Control Rods Fully Out
Figure 4.2.4  Control Rod Worth in MICE Reactor as a Function of U-235 Loading at Beginning of MICE Reactor Operational Life Without B-10 Burnable Poison

Figure 4.2.5A  Number of Control Rods Inserted into MICE Reactor to Maintain Criticality Constant $K_{eff} = 1.0$, as a Function of U-235 Loading and Operational Time at 500 Thermal Kilowatts, with B-10 Burnable Poison
Figure 4.2.5B  Shutdown Margin, $K_{eff}$, to Make MICE Reactor Subcritical as a Function of U-235 Loading and Operational Time at 500 Thermal Kilowatts, Using B-10 Burnable Poison

![Graph showing the shutdown margin, $K_{eff}$, as a function of operational time and U-235 loading.](image)

Figure 4.2.6 Fuel Element Power Output as a Function of Radial Position in the MICE Reactor Core

![Graph showing the power output of fuel elements as a function of radial position.](image)
1. Thermal energy in transferred to the channel melt system from the primary reactor coolant by 2 paths
2. Path 1 is a compact heat exchanger that directly transfers thermal energy from the primary coolant to circulating melt water from the melt channel
3. Path 2 is a smaller, compact heat exchanger that acts as a condenser for the exhaust steam from the steam power turbine. The thermal energy of condensation is transferred to a separate melt water flow system.
4. The thermal energy transferred by 2 paths can independently vary over a wide range, depending on operational conditions (melt channel travel rate, electric power requirements, etc. Total reactor power and flow rate can be adjusted to melt the time varying needs.
5. Path 1 thermal transfer rate can vary from ~20 kilowatts to a maximum of 450 kilowatts
6. Path 2 thermal transfer rate can vary from ~10 KW(th) [2 KW(e)] to a maximum of 50 KW(th) [10 KW (e)]
7. Independent flow control valves adjust flows to the path 1 and path 2 heat exchangers
8. Control of operating temperature and water quality
9. Reactor primary coolant and steam operate at high temperature (~550 K) in closed circuits with zero impurities
10. Melt water flow operate at low temperatures (~300 K) in open circuits with the impurities that are present in the Mars ice sheet [the dust particulates down to few microns in diameters are filtered out].
Figure 4.3.2 Description of the Interfaces Between the MICE Reactor/Power Conversion System and the Communication and Control System

1. MICE reactor and power conversion systems operate in semi-autonomous mode
2. MICE communications and control systems operate using power generated by MICE reactor/power conversion system
3. Back-up power system (e.g., H₂/O₂ fuel cell) provides power to recover operation if reactor scram or other off-normal event occurs
4. Reactor thermal and turbine electric outputs operate at constant level as directed from Earth, until new instructions are received
5. Control rods, flow valves, turbine speed, etc. autonomously operate so as to maintain output at directed levels
6. MICE probe continuously transmits data to the surface lander on its operating state and local conditions inside the ice sheet
7. Surface lander continuously relays data from the probe to control center on Earth
8. Earth control center can transmit new operating instructions to the lander when appropriate. Lander then relays new directions to the MICE probe
9. Speed of light constraints result in time delay between the signal from the MICE probe, to when it can receive new instructions. Maximum delay time from Mars to Earth and back to Mars is approximately 45 minutes
Table 4.2.1 Principal Design Features of the Baseline MICE Reactor and Power Conversion System

• Zr/UO₂ cermet fuel

• Hollow tube fuel element

• 500 kilowatts maximum thermal power

• 10 kilowatts maximum electric power

• Water coolant/moderator/reflectors

• 3 years operational capability

• 2 primary circuit heat exchangers
  • One to generate steam for power cycle
  • One to heat water for melt channel

• Steam cycle conditions
  • Turbine inlet, 1000 psi saturated steam
  • Turbine outlet, 30 psi wet steam

• Steam micro-turbine w/hi field permanent magnet generator

• Core control rods
Table 4.2.2 Component Masses and Dimensions of the Baseline MICE Reactor

**Nuclear Fuel Elements**
- Zr/UO$_2$ cermet hollow tube fuel elements
- 15 volume % UO$_2$ in Zr matrix
- Tube OD/ID = 2.0/1.9 centimeter; tube length = 47 centimeter
- 318 elements in core
- Pitch/diameter ratio = 1.1/1
- 6.1 kg of U-235
- 26 kg of Zr

**Control Rods**
- Zr/B$_2$O$_3$ cermet hollow tube control rods
- 20 volume % B$_2$O$_3$ in Zr matrix
- Tube OD/ID = 2.0/1.6 centimeter; tube length = 4 centimeter
- 12 control rods in core
- 0.2 kg of B$_2$O$_3$
- 3.0 kg of Zr

**End Grid Plates Between Core and Reflector**
- Zircaloy plates at inlet and outlet ends of core
- Plate thickness = 0.5 centimeter
- Plate diameter = 50 centimeter
- 84% openings in grid plates
- 2.0 kg of Zr

**Core/Reflector Separator**
- Zircaloy cylinder between core and reflector regions
- 47 centimeter diameter; 47 centimeter height
- 2 millimeter thick
- 5.0 kg of Zr

**Reactor Pressure Vessel and Control Drives**
- Core OD = 47 centimeter; core height = 47 centimeter
- Reflector OD = 57.4 centimeter; reflector height = 57.4 centimeter
- Aluminum pressure vessel; 1 centimeter wall thickness
- 12 control rod housings and drives
- Pressure vessel mass = 33 kg
- Control rod housing and drive mass = 13 kg

**Water Coolant/Moderator**
- 0 mass (obtained from Mars ice sheet)

**Total Reactor Mass**
- 88 kg total mass
Table 4.2.3 Component Masses and Dimensions for the Baseline MICE Power Conversion System

**Steam Generator**
- Thermal power = 50 KW [10 KW(e)]
- Titanium shell and tube heat exchanger (HX)
- HX OD/length = 9/9 centimeter
- Tube diameter/wall thickness = 0.5/0.05 centimeter
- Number of tubes = 140
- Tube mass = 0.5 kg
- Shell thickness = 0.5 centimeter
- Shell mass = 1.0 kg

**Melt Water Heat Exchanger**
- Maximum thermal power = 450 KW
- Titanium shell and tube heat exchanger (HX)
- HX OD/length = 18/18 centimeters
- Tube diameter/wall thickness = 0.5/0.05 centimeters
- Number of tubes = 625
- Tube mass = 4 kg
- Shell thickness = 0.5 centimeter
- Shell mass = 3.5 kg

**Exhaust Steam Condenser**
- Thermal power = 40 KW
- Titanium shell and tube heat exchanger (HX)
- HX OD/length = 8/8 centimeters
- Tube diameter/wall thickness = 0.5/0.05 centimeters
- Number of tubes = 120
- Tube mass = 0.5 kg
- Shell thickness = 0.5 centimeters
- Shell mass = 1.0 kg

**Turbo Generator System**
- 10 KW(e) output
- T-G Mass = 10 kg [1 kg/KW(e)]

**Piping, Pumps and Controls**
- 10 kg total mass

**Total Power Conversion System Mass**
- 30 kg for HX's, T-G, pumps, piping, and controls
Table 4.2.4 Neutronic Parameters for Baseline MICE Reactor

- Zr/UO₂ hollow tube cermet fuel elements
- Fuel element OD/ID/length = 2.0/1.9/47 centimeters
- Zr/B₂O₃ hollow tube cermet control rods
- 318 fuel elements; 12 control rods
- Element/control rod pitch/diameter ratio = 1.1/1
- Radius of control rod ring = 10 centimeters
- Water moderator/coolant/reflectors (T = 550 K)
- Core OD/height = 47/47 centimeter
- Reflector OD/height = 57/57 centimeter
- 6 kg U-235 loading, 30 grams ^1⁰B₂O₃ burnable poison
- Start of operation, Keff = 1.082 all control rods out
  Keff = 0.811 all control rods in
- End of life Keff = 1.095 all control rods out
  (2000 KW years) Keff = 0.824 all control rods in
- Temperature coefficient, ΔKeff = -5.65x10^-4 per degree K
- Peak/average power density = 1.6/1
- 12% burnup of U-235 @ 2000 KW years
Table 4.2.5  Thermal Hydraulic Parameters for Baseline MICE Reactor and Power Conversion System

**MICE Reactor**
- 500 KW maximum thermal output
- Inlet/outlet coolant temperature = 550/558 K
- Peak/average heat flux from fuel element = 8.0/5.6 w/cm²
- Coolant velocity inside/outside fuel element = 0.25/0 m/sec
- $\Delta P$ across core = 20 N/m²

**MICE Melt Water Heat Exchanger**
- 450 KW thermal transfer
- Inlet/outlet primary coolant temperature = 556/550 K
- Inlet/outlet melt water coolant temperature = 273/323K
- Average heat flux across tube wall = 25 w/cm²
- Flow velocity inside/outside tubes = 2.8/0.11 m/sec
- $\Delta P$ of primary coolant across HX = 1630 N/m²

**Steam Generator**
- 50 KW thermal transfer
- Steam outlet temperature = 500 K
- Steam outlet pressure = 6.8 x 10⁵ N/m²
- Steam flow velocity inside tubes = 1.7 m/sec
- Primary water flow velocity outside tubes = 0.05 m/sec
- $\Delta P$ primary coolant across team generator = 5 N/m²

**Steam Turbine**
- Steam inlet/outlet pressure = 6.8 x 10⁶/2 x 10⁵ N/m²
- Steam inlet/outlet temperature = 550/403 K
- Steam inlet/outlet quality = 100%/80%
- Turbine generator efficiency = 85%
- Overall thermal to electric conversion efficiency = 20%
5.0 MICE CHANNEL MELT AND MOVEMENT SYSTEM DESIGN

5.1 Projected Conditions Inside Mars Polar Ice Caps

It is known that the Mars ice caps contain huge quantities of water ice. The diameter of the south polar cap is approximately 250 km in the summer; the north polar cap is much larger - approximately 1000 km in diameter during summer in the northern hemisphere [5-1]. The thickness of the caps is not known accurately, but is on the order of several kilometers. Other than the size, what distinguishes the north and south polar caps is that the south polar cap is covered by a layer of solid CO₂ all year long, whereas the northern polar gap loses its CO₂ layer in the summer. For this reason, the north pole is a better candidate for the initial Multi-MICE exploration. The probe is designed to penetrate water ice but not necessarily CO₂ which goes directly into the vapor phase upon heating.

The conditions existing inside the Mars polar caps are expected to vary with depth measured from the surface. Unfortunately, since the interiors of the Mars polar caps have not been explored, there is considerable uncertainty as to the characteristics of the polar ice. In fact, acquiring such information is one of the goals of the Multi-MICE program. The information we do have comes primarily from photographs and other remote monitoring instruments [5-1]. With regard to Mars polar cap temperature, measurements from orbit indicate that the summer surface temperature of the north polar ice is ~200 K. On the south pole the summer surface temperature is 150 K, i.e., the sublimation temperature of CO₂. There is no actual data on the temperatures inside the polar ice caps. Since Mars has a molten core, as does the Earth, the temperature at the base of the ice cap may be somewhat elevated. (Note: Lake Vostok, containing liquid water, is located under the Antarctic polar Cap). For the purposes of our melt channel analysis, we will assume, conservatively, that the water ice is at -100°C (173 K). The pressure inside the Mars polar ice caps is, of course, lower than at comparable depths on Earth, due to the lower Martian gravity (0.38 g). At -100°C the density of ice is approximately 929 kg/m³. Based on this value, the pressure at 1 km depth is 3.45 MPa (38 atm). Since the compressibility of ice is low, the density does not vary appreciably with pressure. Thus, for our purposes the local pressure can be assumed proportional to the depth below the surface.

One characteristic of the Mars ice caps that could complicate the melt channel formation is the presence of horizontal dust/sand layers entrapped in the polar ice. These layers extend laterally for many kilometers. Not much is known about the composition of these layers, but they are clearly visible in many photographs taken from orbit [5-2]. The reasonable explanation for the presence of these layers is that they are composed of dust/sand deposited by Martian wind storms over many years. If this explanation is correct, the size of the individual particles is small. We calculated that the maximum diameter of an airborne particle carried in the Martian winds to be approximately 50 microns. In several locations in the northern ice cap deep canyons have formed in the ice cap exposing to view the alternating dust and ice layers. From the visual evidence it appears that the alternating ice plus dust/sand layers are from 10 to 50 meters thick [5-2]. The resolution of the photographs has been insufficient to determine the thicknesses of the dust layers. This determination is further obscured by the fact that the exposed edges of the dust...
layers have been eroded by the elements and may not be representative of the dust layers inside the ice caps.

Since the dust/sand layers would be encountered very frequently by a descending or ascending MICE probe, penetrating these layers will be a routine event. Fortunately, the MICE nuclear fission powered probe is up to this task. With a power level of 500 kW(th), the probe can produce large quantities of hot water and also have ample pumping power to produce high-velocity jets that can penetrate the dust/sand deposits. If even higher power should be necessary, the reactor could be operated at 1 MW(th), or even higher, with no design changes except for increasing the coolant flow rate in proportion to the power.

5.2 Assessment of MICE Probe Channel Melt and Movement Options and Selection of Best Approach

In order to create the melt channel, the heat generated in the fission reactor must be transferred into the ice located in front of the probe. The simplest way to do this would be to construct the hemispherical probe tip of a highly conductive metal (e.g., copper) and heat the tip with hot water from the reactor. This is a closed system. The hot tip of the probe would melt the ice in its path by conduction. A much more effective way to melt the ice is to use high temperature water jets to create the flow channel. This open system requires a heat exchanger, since the reactor pressure differs from the pressure in the melt channel. An even more compelling reason to choose the flowing jets is that conduction alone would not penetrate the dust layers, unless they were very thin. For these reasons we have chosen the open system for the MICE design.

5.3 Description of Baseline MICE Channel Melt and Movement System

The baseline MICE probe is illustrated in Figure 3.1.1. More detailed illustrations of the two pods that comprise the probe, i.e., the power pod and the instrument pod, are shown in Figures 3.1.3 and 3.1.4, respectively. The melt channel is created by the hot jets which emanate from the tips of the two pods - the I-Pod for upward motion and the R-Pod for downward motion. For axially symmetric flow of the water jets, the up or down travel will be in the vertical direction, assuming the ice is uniform. For probe travel at an angle to the vertical, the water flow from the jets is non-uniform, with more water flowing from the nozzles on the side of the probe in which the probe is angled. These maneuvers have been described earlier in this report. A more complex maneuver, one that definitely requires further study, pertains to the horizontal travel in a zigzag mode. This is beyond the scope of the Phase I effort since it requires detailed modeling of the melt channel, including determination of the thickness of the water layer on the sides of the probe. As the probe approaches the tip of the zigzag it must come to a vertical position. This is limited by the turning radius of the probe in ice. The latter, in turn, is dependant on the width of the channel that was created and the refreezing rate behind the probe. To model these phenomena requires application of the CFD, which we propose to do under Phase II effort.
5.4 Analysis and Description of MICE Movement Capabilities for Various Operating Scenarios and Conditions Inside Polar Cap

Our estimate of probe velocity is based on the simplifying assumption that all the heat produced in the reactor goes into melting the ice. This is, of course, overly optimistic, since some of the reactor heat inevitably ends up heating the surrounding ice. The latter is lost heat and is not useful for creating the melt channel through which the probe travels. A detailed thermal/hydraulic analysis of the melting process is needed to provide accurate travel times and other parameters (melt channel diameter, length of water trail, etc.). CFD methods are commercially available which can readily solve this problem. For example, we have been in contact with Fluent, Inc. and they have a code (FLUENT) which is fully capable of providing accurate solutions to this problem. Unfortunately, application of this code, and others with comparable capabilities, is outside the scope of the Phase 1 program primarily because of its cost. We may be able to use these sophisticated tools if the program continues to Phase II. For now, we are developing and using rational approximate analytical methods to characterize the thermal/hydraulics of the melt channel.

Consequently, we have analyzed the melt channel formation process using approximate analytical methods. A schematic illustration of the channel formation is shown in Figure 5.4.1. The outside diameter of the probe is 60 cm. We assumed that a melt water layer of 5 cm surrounds the probe. Thus, the melt channel that needs to be formed is 70 cm in diameter. All of the energy produced by the nuclear reactor (500 kW) is ultimately transferred as heat into the surrounding ice. The major portion of this heat is, of course, contained in the hot water jets which emanate from the tip of the probe. Since the ice temperature is typically well below the melting point (e.g., -100°C on Mars), the ice must first absorb enough sensible heat to bring it up to the melting temperature. At that point melting will commence. The results of our calculations are shown in Figure 5.4.2. We see that in the Mars ice cap, the probe will travel 255 meters per second. On Europa, where the ice is colder, the travel speed is 215 m/sec. In ice near its melting point, the travel speed is 360 m/sec.

The calculations described above were based on the assumption that all the heat produced by the nuclear reactor goes into melting the ice. Of course, this is overly optimistic, since some of the heat goes into increasing the temperature of the surrounding ice. To quantify this heat loss, we solved the transient conduction problem of heat flow into the surrounding ice. The results of these calculations are presented in Figure 5.4.3 as temperature profiles in the surrounding ice at various times. We note that after 1 hour the temperature pulse has propagated 3 cm into the surrounding ice. To judge the significance of this conduction loss, we can compare the time scales of heat propagation to the probe motion. The probe travels at a speed of approximately 200 meters per day, which translates to 833 cm per second. Comparing this to 3 cm per second, we conclude that lateral heat loss into the surrounding ice should not have a major impact on the probe velocity. In other words, the probe travels too fast to lose significant heat laterally into the ice.
REFERENCES


Figure 5.4.1 MICE Melt Channel

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

Ice Meltwater

$\sim 5$ cm

MICE

1.2 m

60 cm

$Q = 500$ kW $\quad V \approx 300$ m/day

Figure 5.4.2 Velocity of MICE Probe vs. Temperature of Ice

Temp. Ice, K

Probe Velocity, m/day
Figure 5.4.3  Temperature Propagation into Surrounding Ice

- 900 sec
- 1800 sec
- 3600 sec

Ice Temperature, K

Radius (R - Ro), cm
6.0 MICE INSTRUMENTATION AND SAMPLING SYSTEM

6.1 Desired Physical Data and Samples to be Collected by MICE Probes

As on Earth, the polar caps of Mars present an unparalleled opportunity to peer back in time at the planet’s geologic, volcanic, and climatic history. Previous studies of imagery from the Mars Orbital Camera of the North Polar Layered Deposits (Milkovich and Head 2005), indicate that the climate cycles due to changes in insolation and obliquity have significantly altered the north polar ice cap through time. It is possible that during times of extreme obliquity (>40 degrees), the north polar cap may disappear completely or migrate to the south. The true age of the north polar ice cap is not known, with estimates ranging from less than 100,000 years to billions of years. The record of the north polar ice cap’s evolution (as well as the changes in Mars’ climate) is likely captured in the stratigraphy of the ice.

Ideally, a primary goal of any subsurface mission to the polar cap would be to generate a chronology of the ice cap. Because of the constant waxing and waning of the ice cap due to seasonal and orbital cycles, it may not be possible to develop a high-resolution chronology of the ice cap. On Earth, highly precise methods for absolute dating of ice layers rely on the radiometric dating of cosmogenic radioisotopes (\(^{10}\text{Be}\) and \(^{36}\text{Cl}\)). These methods require the use of Accelerator Mass Spectrometry, and thus are not applicable for \textit{in situ} studies on Mars. However, the Multi-MICE mission could reveal an approximate chronology of the ice cap, and achieve a relative dating of sections within the ice cap. For example, seasonal and climatic signals can be tracked by stable isotope ratios (such as O\(^{16}\)/O\(^{18}\), H/D and C\(^{12}\)/C\(^{13}\)). Stable isotope ratio data would also increase our understanding about Mars’ ancient atmosphere composition and the paleoclimate temperature record. In addition to \textit{in situ} measurement by the MICE probes, small samples of the melt water will be stored for by the probes for return to surface lander and eventual return to Earth.

The layering structure of dust in the ice cap is a good proxy for seasonal and orbital cycles. Thus, if strata within the ice cap have not been too extensively reworked, then the local stratigraphy should provide further insight into the age of the ice cap, as well as the conditions under which it formed. As the MICE probe travels through the ice, it will continually record the layering of dust trapped in the walls of the melt-chamber. Simple macro video imaging, as was done in the Antarctic Borehole Camera Program (Carsey, Behar et al. 2002) is sufficient for differentiating dust layers in the ice. Also, a laser nephelometer will provide more detailed data on dust particle size spectra. Detailed particle size spectra will allow estimation of the strength of dust storm events during the evolution of the ice cap.

Additionally, ice and dust layering structure could be measured remotely using either Ice Penetrating Radar (IPR) or acoustic profiling. Whereas close-up macro imaging and laser scanning of the dust layers provides excellent data on the characteristics of individual layers, long range remote profiling (on the order of 100 meters), will allow the MICE probes to see the big picture (i.e. to measure the regularity of the layering structure, and also detect anomalies such
as impact craters from a distance). Because multiple MICE probes are deployed, detailed source/receiver experiments can be performed using RF and acoustic signals. RF and acoustic attenuation through different parts of the ice sheet can be measured simultaneously, allowing for identification of areas that warrant further study. Thus, a detailed 3-dimensional map of the ice cap can be built up over time.

Dust layers also provide an opportunity to study the mineralogy of the dust grains. Dust suspended in the melt-water will be sampled for use by a flow-through microscope. Layers consisting of different particle types would give some indication of the relative contribution of different areas of the planet to the global storm dust budget. It is also possible that volcanic events may have deposited ash layers in the deeper layers of the ice cap. Understanding past Mars volcanic activity is a key area of study. Finally, the MICE probes will sample the dust layers to look for micro-meteorites that may be identified using the flow-through microscope. Samples containing dust with interesting mineralogical characteristics, or containing suspected micro-meteorites will be saved for return to the lander.

Another prime area of inquiry will be the ice chemistry of the ice cap. Changes in Mars’ past atmospheric CO₂ concentrations, or the concentrations of other gases, such as sulfur or nitrogen, will be reflected in the chemistry of the ice. Therefore, the melt-water will be continually monitored for changes in pH and ion concentrations. Pristine samples will be periodically extracted from the walls of the melt chamber by means of an integrated ultra sonic drill/thermal melting system. The pristine samples will then be passed into a suite of electrochemical sensors that contains an array of ion-selective electrodes (ISE), similar to those to be used by the Phoenix mission (Kounaves 2003). The integrated sensor modules will measure an panel of specific ion concentrations including Ag⁺, Br⁻, Ca²⁺, CD²⁺, Cl⁻, ClO₄⁻, Cu²⁺, HCO₃⁻, Hg²⁺, I⁻, Li⁺,K⁺,Mg²⁺,Na⁺,NH₄⁺,NO₃⁻,SO₄²⁻,Pb²⁺, as well as pH, oxidants, reductants, redox potential, conductivity, dissolved O₂ and CO₂.

Such a detailed analysis of ice chemistry will address several questions. First, the ice chemistry will reveal any past volcanism on Mars, as indicated by changes in sulfur chemistry. Second, the chemistry data will illuminate the role that the deposition of saline dust layers plays in the evolution of the ice cap. The fate of salts during the continual waxing and waning of the ice cap is an open question. On Earth, salts are expelled from ice sheets over time by means of brine and brine channels in the ice. On Mars, wind-blown dust picked up from evaporite basins and is likely continually deposited on the ice cap. Under the right conditions, this could potentially lead to the presence of acidic brines in the ice caps. Do these brines, if present, play a role in restructuring the ice cap? Detailed salinity and pH measurements are required to address this question.

Furthermore, the north polar ice cap overlays an area of Mars that was likely the site of a large ocean basin during Mars’ earlier periods. MICE probes will directly examine the sedimentary layering of this ancient ocean basin. The probes’ powerful water jets can stir up sediment at the basal layer of the ice sheet. The sediment will then be examined using the same methods used for examining dust layers (flow microscopy and chemical analysis). Also, if there is likely to be liquid water anywhere in the ice cap, it is most likely to be at the basal layer. Thus,
a close examination of the physical conditions at this boundary is warranted. Layering of sediments beneath the ice cap and also be examined remotely with acoustic profiling. Ocean type sediment layers would confirm the theory of an ancient ocean, and give scientists insight into the geochemical cycling that produced the layering.

Finally, the MICE probe will listen with its geophones to the sounds of the ice sheet. The Mars north polar cap is probably not very active compared to ice sheets on Earth, but it is possible that ice sounds still might be detected. Listening to the sounds of the ice sheet, and localizing the sounds by means of trilateration among the different probes, could provide valuable insight into ice mechanics and ice-tectonics on Mars. Additionally, because the MICE probes are well coupled to the ground, the presence of any Mars quakes may also be detectable by the MICE geophones.

6.2 Desired Biological Data and Samples to be Collected by MICE Probes

There are three main biological questions that the Multi-MICE mission seeks to answer: first, is life present in the north polar ice cap? Second, if there is no evidence of present life, is there evidence of past life? Third, if there is no evidence of life (either present or or past), what is pre-biotic potential of the ice cap environment?

Finding life on Mars would be profound event in the history of science. The most unequivocal evidence of life, barring a Martian wooly mammoth trapped in the ice, would probably be imagery of living or fossilized multi-cellular organisms with complex structures. The MICE probe might capture these images using its macroscopic imager or its flow microscope. However, the possibility of stumbling across this type of proof of life is very remote. If microbial life ever evolved on Mars, then it is likely, due to low energy availability, that total biomass in the Mars polar caps would be small (compared to Earth) and metabolism rates very low. Therefore, if life on Mars ever did evolve past the unicellular stage, then any multi-cellular organisms (which fed on the unicellular “primary producers”) would rare and most likely be very small. Such organisms would be likely be millimeter scale or less. Nonetheless, unambiguous imagery of tiny creatures either living or fossilized, captured with the flow microscope, would be a momentous event.

If life does exist or ever did exist on Mars, however, it is most likely to be restricted to microbial and unicellular forms. Detecting life at small scales is challenging -- even on Earth. Visual evidence of microbial life, either extant or fossilized, is often ambiguous at best. The disputed evidence of microfossils in the Alan Hills meteorite is a case in point. Thus, cleaner, more sensitive methods are required. Such methods generally rely on finding evidence of complex bio-molecules, or at least, evidence of metabolism.

The MICE probe will continually sample the melt-water as it travels through the ice. Pristine ice from areas of particular interest will occasionally be sampled with the extendable ultra-sonic drill/thermal melt-probe. The melt-water from the ice sample will then be assayed for likely biomolecules, including amino acids, polysaccharides, lipids and nucleic acids using a
microfluidic, “lab on a chip” type instrument similar to the Mars Organic Analyzer (MOA) (Skelley, Scherer et al. 2005). Currently, MOA is in advanced development and slated for use on the ESA ExoMars mission in 2011. MOA has been extensively field tested in the Atacama Desert. The primary evidence of life from a MOA type instrument would be the detection of non-racemic mixtures of amino acids. On Earth, all biologically derived amino acids have a left-handed or “L” structure. They exhibit homochirality. Amino acids generated by non-biological processes are racemic: they exhibit equal amounts of left-handed and right-handed amino acids. It is generally believed by astrobiologists that if life arose elsewhere in the solar system, or the universe, it would exhibit homochiral biomolecules as well -- either all left-handed or all right-handed. The MOA instrument can detect amino acids at parts-per-trillion sensitivity and can distinguish left-handed from right-handed amino acids.

Besides looking for amino acid homochirality, the MICE probe will search for additional biomolecular evidence of life using two other methods. First, it will search for microbial life that is similar to life on Earth. Aqueous samples will be assayed for nucleic acids (DNA and RNA). If nucleic acids are detected, the samples will be further subjected to both hybridization and PCR assays. Secondly, the aqueous samples will also be assayed for other biogenic molecules, including proteins and complex lipids and carbohydrates. Current commercial biotechnology allows detection of known biomolecules at picogram and femtogram levels. Of course, such methods are targeted at life as we would expect to find it on Earth. Finding similar life on Mars (i.e. life that could be detected with such specific assays) is not likely, but could be possible according to the Panspermia Hypothesis (Wickramasinghe 2004). However, since the technology is easily miniaturizable, can be integrated into lab-on-chip designs, is robust, and commercially available, it should be included as part of the multi-MICE mission.

Besides searching for direct evidence of biomolecules, the MICE probe will also employ a “minimal assumptions” search for life (Kounaves, Noll et al. 2002). In this approach, two growth chambers are inoculated with melt water samples. One of the melt water samples is heat-sterilized before inoculation, and acts as a control for the experiment. The two growth chambers each contain a growth media which comprises several potential nutrients and sources of energy. The theory is that the microbial life, if present, will metabolize the nutrients. After inoculation, Ion Selective Electrodes (ISEs) monitor any minute changes that take place within the growth chambers. Differential chemical change in the “living” chamber versus the control chamber, would be evidence of active metabolism, and thus life.

Finally, if evidence of life is not discovered, the Lab-on-Chip will still generate useful data, by studying the pre-biotic potential of Mars. The study of presence and abundance of pre-biotic organic molecules on a planet other than Earth is important knowledge for assessing the likelihood of life arising elsewhere in the universe.

Samples that have been analyzed with the life detection instrumentation can be shunted to collection vials that will preserve the samples for return to Earth.

6.3 Description of Baseline MICE Sampling System
Compared to Mars surface exploration missions, sample collection in the Multi-MICE mission is relatively straightforward. As the MICE probe travels through the ice, it sits in a melt-chamber filled with water and particulates continually mixed by the action of the probe’s hot water jets. The probe merely collects melt-water by pumping water through a sample inlet and filtering system, and then into the various instrumentation modules for analysis. The probe can track changes in ice chemistry and particulate composition as it moves through the ice.

Of course, sampling water only from the melt-water chamber has the serious disadvantage of low spatial resolution. Because the MICE probe is continually mixing the melt-water, newly melted ice water is diluted by the water that has been entrained in the probe’s movement. Thus, a strong, brief signal (e.g. a thin layer of the ice enriched in amino acids) might be missed due to the continuous spatial averaging present in the melt-water.

For this reason, the MICE probe is equipped with an extendable sampling device which collects pristine water by specifically drilling and melting a small portion of the ice from the walls of the larger melt-chamber (Figure 6.3.1). In this design, an ultrasonic drill corer is integrated into one of the supports of the extensible stand-offs that are used by the MICE probe during its movement through the ice. Ultrasonic coring drills have previously been examined by NASA as a way to quickly and efficiently extract rock cores from surface rocks (Bao, Bar-Cohen et al. 2003). In the MICE design, the ultrasonic drill corer will be extended into the ice face, isolating a pristine sample of ice. Then, an internal heating element will melt the ice, and the resulting water/particulate mixture will then be pumped into the appropriate instrumentation module.

In this manner, layers in the ice that are of particular interest will be sampled and analyzed with a higher effective sensitivity than could be achieved by sampling the bulk water in the melt-chamber alone. Water and particulate mixtures collected by the ultrasonic drill corer can be shunted into storage vials for sample return to the lander, and eventual return to Earth, if desired by mission scientists.

6.4 Description of Baseline Design of MICE Instrumentation Pod

Compared to surface missions, a cryoprobe faces one major design challenge that surface robots do not: pressure. At the deepest point in the ice sheet, a MICE probe might experience close to 200 bars of pressure (equivalent to 2 kilometers ocean depth on Earth). Modern oceanographic robots routinely face these conditions, but no Mars exploration mission thus far has faced this type of challenge.

The MICE probe’s instrumentation pod (Figure 6.4.1) is designed to be highly modular, with individual instrument packages occupying smaller pressure vessels mounted inside the outer shell of the I-pod. Upon entry into the melt-channel, the outer shell of the I-pod is flooded, and functions only to house the smaller pressure vessels and protect them from being dragged along the wall of the melt-channel. This design was chosen for several reasons. First, it significantly
decreases the overall mass of the I-pod. Second, it increases overall robustness. If a single pressure vessel fails, then the probe may still salvage its mission. Third, and perhaps most importantly, because of the consequences of having a large air volume enclosed by the I-pod’s shell. The probe would require significant ballast for descent.

In the current design, several of the individual pressure vessels can be dedicated to buoyancy control to accommodate a range of salinity and density conditions that might be encountered with in the melt-chamber. Because the composition of the melt-water is unknown, the anticipated density of the melt water could possible vary from that of nearly fresh water (1 g/cm3) to that of concentrated brine (~1.2 g/cm3). With a single pressure vessel design that housed all instruments, it would be nearly impossible to imagine a mechanism that changes overall probe density by 20%. In the current design, however the flooded outer shell can be filled with gas (produced by an electrolyzing unit) to compensate for low density melt-water. Additionally, some of the individual pressure vessels can be dedicated to the role of fine buoyancy control. Each individual pressure vessel is capable of displacing about 4kg of water with air generated by electrolyzer.

Instrumentation on the MICE probe can be divided into three main categories: Aqueous sampling instruments that analyze melt water; Optical imaging and spectrometer instruments that examine the walls of the melt chamber; and finally “remote sensing” instruments that use radar or acoustics to study the ice sheet structure and basal sediment layers at distances of 10 to 100s of meters from the probe. Many of these instruments have already been integrated into small Autonomous Underwater Vehicles on Earth, and thus have already reached a level of miniaturization and robustness so that they could be incorporated into a Multi-MICE mission without much added development. Table 6.4.1 lists the various instruments that fall into these categories.

The multi-vessel approach allows for 14 separate pressure vessels, each 15 cm in diameter and 30 cm long. This design provides abundant volume not only for scientific instrumentation, as well as buoyancy control units and command and control electronics.
Figure 6.3.1: MICE Instrument Pod - Sampling

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

Figure 6.4.1: 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
### Table 6.4.1 Candidate Instruments for Inclusion in the MICE Probe Baseline Design

<table>
<thead>
<tr>
<th>Instrument / Instrument Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lab-on-Chip Life Detector</strong></td>
<td>Microfluid device samples meltwater for various biomolecules. Looks specifically for non-racemic amino acids, as well as nucleic acids</td>
</tr>
<tr>
<td><strong>Ion-Sensitive Electrodes (ISEs)</strong></td>
<td>A micro chemical array of 10-20 electrodes each of which are designed to sample only one specific ion species</td>
</tr>
<tr>
<td><strong>Growth Chamber Experiment</strong></td>
<td>Uses ISEs to determine minute differential chemical changes in a melt-water inoculated chamber compared to a sterilized control chamber</td>
</tr>
<tr>
<td><strong>Flow microscope / particle counter</strong></td>
<td>Microfossils and dust grain structure</td>
</tr>
<tr>
<td><strong>Flow Fluorometers / spectrophotometers</strong></td>
<td>Analysis of dissolved chemical species</td>
</tr>
<tr>
<td><strong>Conductivity, Temperature, Depth (CTD)</strong></td>
<td>Tracks bulk changes in ice cap during descent/ascent</td>
</tr>
<tr>
<td><strong>Dissolved O2, CO2 sensors</strong></td>
<td>Tracks bulk changes in ice cap during descent/ascent</td>
</tr>
<tr>
<td><strong>Flow sampling Mass Spec</strong></td>
<td>Analysis of dissolved chemical species</td>
</tr>
<tr>
<td><strong>Flow Raman Spectrometer</strong></td>
<td>Analysis of dissolved chemical species</td>
</tr>
<tr>
<td><strong>High Res Macro Imager</strong></td>
<td>Tracks and measures dust layers is melt-chamber ice wall as probe descends/ascends</td>
</tr>
<tr>
<td><strong>Laser Nephelometer</strong></td>
<td>Quantifies dust loadings and dust grain size spectra</td>
</tr>
<tr>
<td><strong>Stand-off LIBS</strong></td>
<td>Chemical analysis of ice wall</td>
</tr>
<tr>
<td><strong>Stand-off Raman spectrometer</strong></td>
<td>Chemical analysis of ice wall</td>
</tr>
<tr>
<td><strong>Side-scan sonar</strong></td>
<td>Images structure of surrounding ice (50-100m)</td>
</tr>
<tr>
<td><strong>Ice / Sub-bottom Profiler</strong></td>
<td>Can image layer structure of ice above or below probe (100m), and layering of sediments at basal layer</td>
</tr>
<tr>
<td><strong>Ice-Penetrating Radar</strong></td>
<td>Images structure of surrounding ice (100-1000m)</td>
</tr>
<tr>
<td><strong>Acoustic and RF Source/receiver studies</strong></td>
<td>Long range (5000m) attenuation data between probes</td>
</tr>
<tr>
<td><strong>Seismometer /geophone</strong></td>
<td>Listens to ambient noises in ice cap</td>
</tr>
</tbody>
</table>
REFERENCES


7.0 MICE COMMAND, CONTROL, AND COMMUNICATIONS SYSTEM

7.1 Assessment of Options for the Communications Network Between MICE Probes, the Lander, Spacecraft and Earth, and Selection of Baseline Option.

One of the primary engineering challenges facing the Multi-MICE mission is the communications challenge. How will probes communicate through ice with the surface lander that is potentially up to 25 kilometers away? Other cryoprobe mission proposals (e.g. Cryobot and Palmer Quest) face a significantly easier communications environment: a single cryoprobe descending more or less straight down, trailing an optical fiber. However, because the individual MICE probes in the Multi-MICE mission must travel much further total distances, traveling both up and down and along lateral traverses, the choice of optical fiber is inadequate. Over the 5-year lifespan of a MICE probe, it must travel more than 100 kilometers in total distance. This is too much fiber for a probe to carry on-board. There is also a large risk of communications failure using optical fiber, since even minor ice strain over time may break the fiber link between probe and surface during the lifespan of the probes.

Therefore, some “wireless” alternative is needed for the present Multi-MICE mission. Two options present themselves: 1) RF communications, and 2) acoustic communications. Initially, it was hoped that RF communications might meet the needs of the mission. RF communications have a great advantage in terms of data communications bandwidth, on the order of megabits per second compared to kilobits per second for acoustic communications. Additionally, cold, clean ice is relatively transparent to radio frequencies in the 0.1 and 1.0 GHz range. Several studies of RF attenuation in Antarctic ice have demonstrated the feasibility of through-ice communications (Barwick, Besson et al. 2005). Radio frequency absorption lengths in pure ice of 6 km have been measured. Thus, with powerful enough transmitters, one could confidently assume that RF would allow effective communication over several kilometers.

However, the Mars north polar ice cap contains significant dust loadings, possibly with layers that are many meters thick containing very high dust content (80% dust). Because the dust layers are likely to be both saline, and high in iron oxide content, it is probable that RF attenuation in the Mars ice will be very much higher than in Antarctica. Thus, it is highly unlikely that a data communications strategy based solely on RF would succeed. Probes might travel only a few hundred meters from the lander before losing communications completely.

The remaining option, acoustic communications, has several advantages. First, as is the case with radio waves, cold ice is relatively transparent to acoustic communications, even at frequencies above 100kHz (Price 2006). Absorption lengths are roughly on the order of 10 km. Second, compared to RF communications, acoustic communications are relatively robust to higher salinities and dust layers. Third, an analogous terrestrial technology is already available – underwater acoustic communications. Acoustic modems for oceanographic applications are a mature technology and commercially available. For example, a typical marine modem can be
expected to communicate at 10-15kbs over a range of 5 km in the 10-20kHz frequency band. In the Mars polar cap, we would expect communication to be substantially improved since: 1) absorptivity is much lower in ice than water 2) communications at 100+ kHz are possible, and 3) there is much lower ambient noise present. It is reasonably expected that MICE probes will be able to communicate over a range of 10 km at a data rate of 50-60 kbs.

One potential problem with using acoustic communications in a Mars ice cap setting is the likely problem of multi-path interference. Because the ice cap is heterogeneous and consists of many layers, acoustic communications are subject to reflection and refraction. Thus a data transmission from one MICE probe can potentially be received MICE probe as a series of echoing and interfering messages. Some dust layers may also act as acoustic waveguides, further complicating efforts at range finding, localization and communication.

Thus, the Multi-MICE mission will rely on communication protocols that are specifically designed to be robust to multi-path effects. Several such protocols have been developed for RF data communications by the telecom industry, especially for use in high multi-path environments like urban centers with many tall buildings. The most robust of these protocols seems to be Orthogonal Frequency Division Multiplexing (OFDM), and already is being actively developed for underwater communications (Akyildiz, Pompili et al. 2005).

Another potential problem with using only acoustic communications in the Multi-MICE mission is that acoustic energy will not travel well through low density layers (e.g. snow, firn, or CO2 frost) that might be present near the surface of the ice sheet. If the MICE probes cannot communicate with the lander, then it doesn’t matter how well they can communicate between themselves. The proposed Multi-MICE solution is reserve one of the MICE probes for tethered operation. The tethered probe will be tasked with the dual duty of providing a non-acoustic communications relay to the lander, and also providing power to the lander. The tethered probe will be deployed approximately 100 meters below the lander. The tether includes an optical fiber line for data communications, as well as an electrical conductor line that the powers the lander. Additionally, the tether will have a gas transfer line that will be used to transfer hydrogen gas to the lander for propellant replenishment to enable the sample return part of the mission.

Additionally, both the lander and probes will carry backup RF transmitters in case there are unforeseen problems with acoustic communications. The inclusion of RF transmitters will allow short-range, high bandwidth communications, if needed.

7.2 Description of the Capabilities of Baseline MICE/Lander/Earth Communications Network

The baseline communications network is shown in figure 7.2.1. The Multi-MICE probes communicate with one another using an ad-hoc mesh network (Melodia, Pompili et al. 2005), in which the single tethered probe acts as a relay to the surface lander. The advantage of mesh networking is that only one of the untethered probes needs to maintain communications with the tethered relay probe at any one time. Other untethered probes, which are beyond
communications range of the tethered relay probe, can use node-hopping to relay their message to the tethered probe for data communication with the surface lander, and transmission to Earth. Mesh networks are flexible because, as the MICE probes move through the ice cap, the network continually updates the network node map in order to optimize the ideal path for relaying data back to the surface. If one probe moves beyond communications range, it can backtrack to towards the position of last network contact, re-establish its network connection and resume sampling.

The proposed baseline network configuration has several additional advantages. First, the dedication of one probe to the tasks of probe/lander relay, lander power generation, and lander propellant generation simplifies the lander design by eliminating the need for an extra nuclear reactor on the lander. Second, the tethered probe is the most reliable of the MICE probes, and will enter the ice first to scout the way for the subsequent probes during the initial deployment. Third, because the position of the tethered probe is known, the tethered probe can act as central acoustic navigational beacon for the other probes. The central acoustic beacon will allow localization and timing synchronization services to the other MICE probes.

Since the probes gather data continuously and simultaneously relay it to the surface lander at 50+ kbs (total communications bandwidth), the mission can easily relay over 500MB of data to the surface lander per day. If the total communications bandwidth is closer to 100kbs, then 1GB of data per day can be generated. This data might include everything from small data files (e.g. pH and salinity measurements) to large data files (borescope camera and microscope imagery). The surface lander is supplied by abundant electrical power by the tethered MICE probe, so direct transmission to earth is not constrained by power, but rather by antenna size, weight and complexity constraints. Also, direct transmission from Mars to Earth is limited to times when Earth is in view. Alternatively, depending on relay satellites in place (e.g. MRO), data could be relayed by orbiting satellite.

7.3 Description of MICE Command and Control System

Because the untethered MICE probes are relatively slow moving, and are in no danger of tipping over or falling off a cliff (as is the case with surface rovers), little or no human guidance is needed when they travel through the ice. Mission controllers can simply set a waypoint (e.g. 100 meters down at a specified angle on a specified heading), and then wait for the scientific data to return to earth. Any obstacles in the direction of travel will spotted hours in advance by the forward looking sonar, and appropriate action can be taken at the controller’s leisure. Thus, Multi-MICE probes can be described as semi-autonomous. The only time a probe would need to be fully autonomous would be in the event of a complete communications failure with the other probes. In this case, the probe would need enough autonomy to navigate back towards the central tethered probe location, and then attempt to re-establish communications.

Mission controllers are likely to actively select ice sampling locations, however. For example, if the macro imager spots an interesting layer in the wall of the melt-chamber that merits sampling with ultrasonic/thermal corer, then the controller would need to instruct the
probe to sample at that location. This involves a communications delay of 10 to 40 minutes. By the time that the probe receives the instruction to sample the layer, the probe may have already passed the layer by several meters. This is not a problem since the probe would merely adjust its buoyancy and water jet pressure to retrace its path, and then sample at the desired location.

In general, sampling in the Multi-MICE mission is much simpler than sampling in surface exploration missions. Much of the MICE sampling is done with continuous, flow-through instruments, and thus requires no human intervention. When the ultrasonic/thermal sampling system is required, it will usually be much easier to deploy than the typical surface system (e.g. the Rock Abrasion Tool) which often requires more detailed planning and multiple roundtrip communication delays.

Thus, the Multi-MICE computing requirements for probe movement and sampling decisions are lower than those of a typical surface rover mission. However, one aspect of the Multi-MICE mission does have higher computing requirements: managing the mesh communications network. Because all probes will share the same bandwidth, the probes must cooperatively manage such tasks as adaptive channel optimization, signal coding, packet routing, network load management, synchronization and localization. In other words, the probes must manage and continually optimize the network so that the maximum data volume eventually reaches the surface lander for transmission to Earth. Because acoustic communications are relatively slow speed and high latency (compared to RF or wired communications), the probes must have the inherent ability to manage and optimize their network on a minute by minute basis without waiting for instructions from Earth.

REFERENCES

Figure 7.2.1: Multi-MICE Network Configuration

Tethered MICE probe:
1) Power and propellant supply to lander
2) Comm relay to lander
3) Navigation beacon for untethered probes

Untethered MICE probes:
1) Acoustic communications
2) Mesh networking
3) Autonomous capability


8.0 DESCRIPTION OF BASELINE MICE MISSION

8.1 Definition of MICE Vehicle Requirements and Mission Timelines

Issues that drive the MICE spacecraft design include the requirement to return the science data and samples as soon as possible, and the high ΔV requirements for orbital insertion and landing at the Polar Caps on Mars. Accommodating these requirements while keeping the related mission operations, spacecraft and launch system issues in mind is not a simple task and requires a very iterative design process.

The quickest way to get to Mars efficiently would be to launch from Earth direct to Mars and perform the required midcourse trajectory changes that would allow a Martian orbit insertion at the Polar Caps. To allow for optimum propulsion requirements, insertion into the Martian Polar orbit would entail an aerocapture maneuver and subsequent aerobrake re-entry landing with an engine burn to facilitate the final leg of the Martian surface landing. With chemical propulsion, the requirements for Martian orbital insertion would result in spacecraft size that fits into the payload fairing volume of the Delta IV Medium at a minimum.

The proposed baseline schedule has the MICE spacecraft launching in May 2018 on a direct trajectory to Mars. Mid-course trajectory adjustments would place the spacecraft on arrival at Mars at the Polar Cap and results in a flight time of 260 days using an upper stage Pratt & Whitney RL10 liquid propellant rocket engine. Isp is conservatively estimated at 400 sec. As the spacecraft approaches Mars, an aerocapture maneuver utilizing an advanced aeroshield through the Martian upper atmosphere is used to lower the arrival velocity and place the spacecraft into a highly elliptic orbit around Mars. Similar aerocapture maneuvers are used to place the spacecraft in less elliptic orbits and then subsequently the velocity is reduced enough to begin re-entry through the Martian atmosphere at the Polar Cap. The spacecraft then proceeds ignite its RL10 engine and perform a burn and execute the landing maneuvers for touchdown on the Martian surface.

The MICE Sample Return Mission falls into the category of lander missions, which require additional propellant, as compared to fly-by or orbital capture missions, for landing on the target planet (1). The MULIMP (2) trajectory code was used to calculate IMLEO for a 2018 Earth departure opportunity. No gravitational assists were employed in this analysis. The mission has a 260-day outbound direct trajectory with an approximate eighteen-month stay on the Polar Cap surface and culminates with another 260-day return after departure from Mars in 2020 with the samples onboard and after indigenous refueling. Earth arrival occurs in March, 2021.

The deterministic ΔV is the total amount of velocity change required for the design mission trajectory. The statistical ΔV is the ΔV required to correct for any errors in navigation of the trajectory, spacecraft state, or execution of burning maneuvers to ensure the MICE spacecraft follows the deterministic trajectory as close as possible. A summary of the current estimate for the MICE Illustrative Mission deterministic ΔV is provided in Table 8.1.1 below.
Table 8.1.1 MICE Mission $\Delta V$s (km/sec)

<table>
<thead>
<tr>
<th>Mission Event</th>
<th>$\Delta V$ (km/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth Departure</td>
<td>2.25</td>
</tr>
<tr>
<td>Mars Capture/Landing</td>
<td>2.50</td>
</tr>
<tr>
<td>Mars Departure</td>
<td>6.50</td>
</tr>
<tr>
<td>Earth Re-entry</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**Description of Lander Spacecraft**

The main design factor for the MICE Illustrative Mission is to minimize the spacecraft Initial Mass in Low Earth Orbit (IMLEO) by minimizing the $\Delta V$ or propellant requirement by using as much natural or potential energy in the form of aerobraking assists as possible. As the spacecraft orbit is pumped down to elliptic orbits through aerocapture, the MICE spacecraft design requires a high temperature aeroshield to withstand this extreme environment and address this design concern. The MICE Lander is illustrated in Figure 8.1.1. The propulsion system is the Pratt & Whitney RL10 liquid propellant rocket engine capable of multiple restarts and has an approximate 5:1 fuel/oxidizer mixture ratio.

The height of the Lander is 3m with the landing gear fully extended. The main propellant tank is 3.3 m in diameter and 2 m in height. The main propellant tank is subdivided into liquid hydrogen and liquid oxygen tanks that are indigenously refueled by the H$_2$/O$_2$ Production Power System located underneath the main propellant tank on the Lander. On top of the main propellant tank is the Sample Return Spacecraft consisting of the Sample Return Tank, an aeroshield and parachute system for Earth re-entry, navigation thrusters for the journey to Earth, telecommunications system, and the 100 kg sample return from the Martian Polar Cap. The sample return tank with aeroshield is highlighted in Figure 8.1.2.

Because lander missions must perform multiple burns, they require long-term storage of propellant (3). Since solar propellant heating would act to boil-off this stored propellant, mitigation strategies include tank insulation and active refrigeration. The system weight of the RL10 engine is conservatively estimated at 250 kg. IMLEO optimization studies resulted in a single-stage vehicle configuration with two propellant tanks. The MICE Sample Return Spacecraft configuration with IMLEO of 13,505 kg is shown in Figure 8.1.2. The first propellant tank, used for Earth departure, is a disposable lightweight tank of 5% tankage fraction that is jettisoned after the burn is completed. The single stage is powered by the 400 sec Isp RL10 engine with restart capability. The second propellant tank also has a 5% tankage fraction and is jettisoned during the landing burn at Mars.

**Landing on Polar Cap and Deployment of MICE Probes From Lander**

The first aerocapture maneuver upon arrival at Mars places the MICE spacecraft into a highly elliptical orbit where the MICE spacecraft subsequently performs repeated aerobrakes
through the upper Martian atmosphere with each pass reducing the elliptic orbits. The final aerobrake pass is designed to reduce the velocity to suborbital by at least 1 km/sec and initiate the landing burn for landing at Mars Polar Cap. The MICE Lander spacecraft on Mars Polar Cap ice sheet is shown in Figure 8.1.1. Also located underneath the main propellant tank is the MICE deployment. The MICE Lander’s propellant tank has a more conservative tankage fraction of 10%.

Return of Samples Collected By MICE Probes to Lander and Take-off to Earth

For return to Earth, to minimize the ΔV requirements on the propulsion system, aerobraking at Earth for ballistic re-entry would save considerable propellant for the 100 kg sample return thereby eliminating another complex Earth orbital insertion burn. Therefore, the only major burn required for return to Earth is performed lifting-off from Mars and entering into a direct trajectory to Earth. For the mission design, this necessitates the use of an aeroshield and an aerobraking parachute unit (in the sample return stage), for operation when the aeroshield is discarded after main Earth re-entry. The estimated total ΔV necessary (including contingencies) for Earth return is 6.5 km/sec. This direct return trajectory results in an approximate 260-day time of flight. The MULIMP trajectory code was used to ΔVs for a range of various mission durations centered about the June 2021 Earth departure opportunity.

Operational Parameters for the MICE Mission

A detailed parametric analysis of the entire mission design was completed for the MICE Mission Illustrative Sample Return spacecraft. The mission operation parameters are summarized in Table 8.1.2. The mission design analysis was focused on framing the envelope for the many parameters and factors that influence the overall spacecraft and mission designs. One goal of the mission design is to use a medium-size booster such as the Delta IV Medium to reduce the launch costs. The launch vehicle selection parameter is dictated by its payload-lifting capability and payload fairing volume of the booster.

Initial Mass in Low Earth Orbit (IMLEO) has been calculated to be approximately 13,505 kg and the spacecraft stack illustrated in Figure 8.1.3 is volumetrically small enough to be housed inside the fairing of a Delta IV Medium+ launcher. The Delta IV Medium+ booster is the newest and a powerful version of the Delta family of medium-to-heavy capacity expendable launch vehicles. The Delta IV Medium+ will provide a payload lift capability of 13,700 kg to Low-Earth Orbit (LEO) and 6,800 kg to Geosynchronous Transfer Orbit (GTO). Launch costs are estimated to be in the $95 - $110 million range.

The MICE mission considered in this analysis is restricted to starting from LEO only after being placed in a stable orbit by a launch vehicle. The relatively high propulsive efficiency of the upper stage RL10 liquid propellant rocket engine yields the benefits of reduced transit time and a smaller launch vehicle.

References
8.2 Deployment and Operation of the MICE Network in the North Polar Cap

After it lands on the North Polar Cap, the small on-board nuclear power unit would be deployed onto the ice surface. It then would melt a channel and move downwards to a depth of ~3 meters below the surface, using either reactor thermal power, or a chemical fuel source. After reaching the ~3 meter depth, the reactor would remain in place, to generate electrical power for the MICE spacecraft during the mission. The electrical power would be used for the various spacecraft functions, including real time communications with the MICE probes and scientists on Earth, and to produce liquid H₂ and O₂ propellants for the spacecraft’s return trip to Earth with the samples collected by the MICE probes.

The on-board nuclear power unit, termed MICE-2, would be a smaller version of the reactor on the MICE probe, and operate at a lower power level. The MICE reactors have a maximum thermal power of 500 kilowatts, while the MICE-2 reactor power is 100 kilowatts. Most of the MICE reactor’s output is used to create a melt channel in the ice sheet along which it moves. Each of the MICE reactors also generates 10 kilowatts of electrical power for operation of its controls, instrumentation, and communication systems. Once in place in the ice sheet, the MICE-2 reactor remains stationary, generating 20 kilowatts of electric power. The waste heat from the power cycle, ~80 kilowatts, is rejected to the surrounding ice sheet.

The ~3 meters of ice between the MICE-2 reactor and the MICE spacecraft provides a large shielding factor, on the order of 10¹⁰ reduction in radiation dose from the reactor. The use of water shielding is standard for Earth based swimming pool reactors. On Mars, an ice layer will provide a similar large shielding factor, and reduce the radiation dose to the spacecraft to negligible levels.

If reactor thermal energy is used to create the ~3 meter long melt channel during the deployment of the MICE-2 reactor, there will be a small radiation dose to the electronics on the spacecraft. This can be reduced to an acceptable, e.g., ~10² Rad by a thin, lightweight shadow shield on the reactor. Alternatively, a small amount of chemical fuel, e.g., ~10 kg of H₂/O₂ would provide the energy required to create the initial melt channel and shield the spacecraft when the MICE-2 reactor started up.

Once in place and operating, waste heat from the MICE-2 reactor would be used to melt ice to provide water moderator/coolant needed for the 6 MICE probes. Each probe would
require an inventory of ~200 kg of water for its reactor, piping, heat exchangers, and steam power cycle. By supplying this water from the ice sheet, the payload required to be brought from Earth would be cut by over 1000 kilograms, as compared to transporting the water from Earth.

To ensure purity and properly controlled water chemistry, the melt water from the ice sheet would first be filtered, and then distilled, using electric power from the MICE-2 reactor. The filter/purification units would be located on the spacecraft, with the electric power feed coming from the sub-surface MICE-2 reactor. After purification, the water would then be loaded into the MICE probes.

Figure 8.2.1 shows the flowsheet for operation of the MICE network after the probes have been loaded with water moderator/coolant and are ready to begin their exploration of the North Polar Cap.

Real time 2-way communication between the probes and Earth scientists is essential for an effective exploration program. An autonomous pre-planned exploration program not only could miss out on exploring the really important portions of the ice sheet - which would only become known after the exploration started-, but also would run the risk of encountering difficult and dangerous portions, e.g., very thick dust layers that could damage or destroy the probes. With real time communications and scanning ahead, the scientists on Earth could control the probe paths so as to avoid such regions. There would be time delays due to speed of light constraints, but at the worst planetary configuration, the 2-way delay would be less than 1 hour, allowing sufficient time to avoid dangerous regions.

Equally important would be the ability of the scientists on Earth to direct the probes to concentrate on, and spend time at, particularly interesting locations. This could be an extinct hydrothermal vent in the bed rock at the base of the ice sheet, for example, or a dust layer with an unusual composition, or the debris field from an ancient meteor impact.

After an exploration period of 18 months, the MICE probes would return their collected samples to the MICE spacecraft, which would then transport them back to Earth. The spacecraft would leave behind the communication package connecting the MICE probes with the scientists on Earth. The MICE probe exploration program could then continue for many years, allowing further discoveries. The operating life of the MICE and MICE-2 reactors is expected to be at least 10 years.

Figures 8.2.2A, 8.2.2B, and 8.2.2C show illustrative possible exploration scenarios for the MICE probe network. The actual exploration program would be decided by the MICE scientific team, and is likely to be a mixture of the various possible scenarios.

Figure 8.2.2A shows a scenario in which the MICE probes travel at a moderate depth, e.g., with a maximum depth of a few hundred meters. This scenario would apply if the major discoveries were to be found in the fluctuating surface zone. Each MICE probe would perform a sequence of ascent and descent movements as it traveled outwards from the MICE spacecraft.
The angles, rates of movement, and depths of these movements would not be fixed, but would vary depending on the degree of scientific interest at the various locations. When the MICE probe headed back to the MICE spacecraft (dotted line) it could revisit the general area explored on the outwards journey, though at different specific locations, or it could take a different return path that did not overlap the original outwards trip.

Figure 8.2.2B shows a scenario in which the MICE probes go down to bedrock, which could be several kilometers below the surface of the North Polar Cap. Exploration of the bedrock under could yield major scientific discoveries, including fossils of past life on Mars, studies of extinct hydrothermal vents, and evidence of sedimentary layers beneath an ancient ocean in the Northern Hemisphere of Mars. As with the moderate depth exploration scenario shown in Figure 8.2.2A, the angle of descent/ascent and the rate of probe movement could vary with location and would be controlled by scientists on Earth. Also, as before, the probe on its return trip to the MICE spacecraft could revisit the general region it went through on the outward trip, or could explore a completely new region.

Figure 8.2.2C shows possible scenarios for return of collected samples to the MICE spacecraft. The MICE probe could collect samples along its outwards and return paths during the 18 month exploration period, and then return all of the samples to the spacecraft at the end of 18 months. Alternatively, it could periodically bring back samples to the lander at various times during the 18 month period, where they could be examined in greater detail by additional instrumentation on the spacecraft. This second option would provide Earth scientists the opportunity to more precisely evaluate the significance of the samples, and to more effectively guide the exploration paths of the probes.

Bringing back samples at intervals during the 18 month exploration period would reduce the outward distance capability of the exploration program. Bringing back samples at intervals of 1 month, for example, would reduce the maximum outwards possible distance by a factor of 9, since one could only travel outwards for 1 month instead of 9 months. The relative benefits of greater exploration distance, vs frequent more detailed examination of samples would have to be evaluated by the scientists directing the exploration program.

Figure 8.2.3 shows the maximum outwards distance capability of a MICE probe as a function of its average rate of movement and the average ascent/descent angle assuming an outwards trip of 9 months in duration. The maximum angle of 45 degrees (measured from the vertical) appears possible. [Greater angles are probably not possible, however.] The various ascent/descent angles also reflect the degree of interest in the region through which the probe moves. For interesting regions, the ascent/descent angle would be less (i.e., more vertical) and the average rate of movement smaller, reflecting the desire to spend more time in the region.

For a 500 KW MICE probe power and 200 meters per day, with an average ascent/descent angle of 45 degrees, the MICE probe could move 25 kilometers outwards from the MICE spacecraft during a 9 month period. The actual outwards distance will depend on what is found in the ice sheet and the judgements of the Earth scientists directing the exploration program.
Figure 8.2.4 shows some possible illustrative exploration scenarios that could affect the decisions of Earth scientists of which regions inside the ice sheet to explore in detail, and that would require concentration of probes. The concentration and thickness of dust layers may vary greatly inside the ice sheet, reflecting variations in Martian meteorology and climatology, ancient volcanic eruptions, meteor impacts, etc. It may be very desirable to examine unusual dust layers to determine the origin, and effect on Mars, and to date their age. Similarly, one would want to examine the debris from large ancient meteor impacts.

Exploring the bedrock for fossils and extinct hydrothermal vents will clearly be a high priority. If fossils and evidence of past life on Mars is found, these would be a very exhaustive exploration of the site(s) where such evidence was found. Another example is the exploration of how ancient cosmic ray and solar storm activity varied over the ages. Data relating to this area would be obtained by having the MICE probes operating over the full depth of the ice sheet.

Figure 8.2.5 shows possible exploration patterns that Earth scientists might employ for the MICE network. One could have the probes follow the same single line but at different depths, providing a very detailed look at a thin long slice of the ice sheet. Alternatively, one could have the probes travel along parallel lines, providing a less detailed look at a thick long slice of the ice sheet.

Rather than follow parallel paths, the MICE probes could go off as individual units. If one probe encountered a particularly interesting region, then other probes could converge on the region to explore it in more detail. Or, groups of 2 probes could head off in separate directions, providing greater assurance that a particularly important region could be discovered, though reducing the total volume that could be explored.

At this point, it is not possible to predict which exploration approach will be followed – most likely, the actual exploration program will employ a combination of approaches, which will be modified as results come in from Mars. However, it is clear that the MICE network is very flexible in its exploration capabilities and can readily adapt to whatever conditions are found in the North Polar Cap.
Figure 8.1.1
Mission Parameters - Lander Schematic

Figure 8.1.2
MICE Sample Return Tank With Aeroshield
Figure 8.1.3

MICE Spacecraft With Earth Departure & Mars Landing Propellant Tanks, Designed To Fit Delta IV Fairing

- 3.3 m
- 2.5 m
- 1.5 m
- 6 m
- 10 m

Earth Departure Propellant Tank
Mars Capture/Landing Propellant Tank
Propellant Tanks
Aeroshield
Sample Return Tank
Telecom Envelope
RL10

MICE Spacecraft
Figure 8.2.1 Flowsheet for Deployment and Operation of the MICE Network

1. MICE spacecraft lands on North Polar Cap and deploys MICE probes on surface

2. 1st MICE probe operates to melt ice for water coolant/moderator for other probes

3. MICE probes begin pre-planned exploration program inside North Polar Cap

4. MICE probes communicate scientific data to Earth scientists

5. Earth scientists adjust exploration paths and activities of MICE probes including taking samples

6. MICE probes continue to explore for 18 months

7. MICE probes return samples to lander spacecraft which takes off for Earth

8. MICE probes continue to explore North Polar Cap and send data to Earth, under direction

9. • Samples returned to Earth in 8 months
   • MICE probes continue exploration for years

Exploration program Directed by Earth scientists

2 way real time communications

Figure 8.2.2A

Possible MICE Exploration Scenarios - Moderate Penetration Depth

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Figure 8.2.2 B

Possible MICE Exploration Scenarios - Penetration To Bed Rock

-1 to 5 km, Depending On Location

Note: Paths are shown as straight lines for clarity. In practice the paths can be curved or wiggly.

Figure 8.2.2 C

Possible Scenarios For Return of Samples Collected By MICE To Lander Spacecraft

End of Mission Scenario

Quick Return Scenario

Points Denoted By C Are Sample Collection Points
Figure 8.23
Radial Outwards Distance Exploration Capability Of MICE Probes As A Function Of Average Rate Of Movement And Average Ascent/Descent Angle

Basis: 18 Month Exploration Period
9 Months Outwards From Lander
9 Months Return To Lander

Average Ascent/Descent Angle
- 45° 125@200 meters/Day
- 30° 180@200 meters/Day
- 20° 12@200 meters/Day

500 kW MICE Probe
750 kW MICE Probe

Average Rate Of Probe Movement (meters per day)
0 50 100 150 200 250 300

Outwards Distance From Lander After 6 Months (kilometers)

Figure 8.24
Control of MICE Movements By Earth Scientists - Illustrative Scenarios

Examination of Nature of Deposited Dust Layers
- Polar Cap Surface
- Thin Dust Layer
- Thick Dust Layer
- Thin Dust Layer
- Bed Rock

Examination of Trapped Debris From Meteor/Asteroid Impact
- Polar Cap Surface
- Debris From Meteor/Asteroid Impact
- MICE Probes

Examination of Sediment Layers In Bed Rock To Search For Fossils
- Polar Cap Surface
- Ancient Hydrothermal Vent
- MICE Probes

Measurement of Residual Activation In Ice Sheet As A Function Of Depth To Determine Amount of Cosmic Ray Activity As A Function Of Age
- Polar Cap Surface
- •
- •
- •
- Bed Rock
MICE Network Exploration Pattern Options

Exploration Along A Single Line of Polar Cap

Top View
- Exploration Line of MICE Probe
- Out
- Lander Spacecraft
- Return

Cross Sectional View
- Polar Cap Surface
- Bed Rock
- MICE Probe Paths

Exploration Along Parallel Lines Of Polar Cap

Top View
- Parallel Lines of MICE Probe
- Path of One MICE Probe
- To Lander

Cross Sectional View
- Polar Cap Surface
- Bed Rock

Exploration By Several Groups of MICE Probes

Note: MICE Probes Travel At Different Depths

Exploration By Separated Single MICE Probes

Paths of Separate MICE Probes

Lander Spacecraft
### Table 8.1.2 MICE Mission Parameters

#### MICE Spacecraft Earth Departure Operational Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Earth Departure $\Delta V$ (km/sec)</td>
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<tr>
<td>Mars Aerocapture &amp; Landing $\Delta V$ (km/sec)</td>
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<tr>
<td>Time of Flight to Mars</td>
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#### MICE Spacecraft Lander Baseline Design

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass</th>
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<tbody>
<tr>
<td>MICE Spacecraft Tank Structure/Insulation</td>
<td>440 kg</td>
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<tr>
<td>Reactor Power Unit (H2O2 Generation)</td>
<td>350 kg</td>
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<tr>
<td>6 MICE Units</td>
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<tr>
<td>MICE Deployment Mechanism</td>
<td>150 kg</td>
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<tr>
<td>Communication System with MICE Probes</td>
<td>200 kg</td>
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<tr>
<td>Landing Gear</td>
<td>300 kg</td>
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<tr>
<td>Miscellaneous &amp; Contingency</td>
<td>360 kg</td>
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#### MICE Sample Return Craft

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass</th>
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</thead>
<tbody>
<tr>
<td>Telecommunications</td>
<td>25 kg</td>
</tr>
<tr>
<td>Ion Thrusters (Navigation)</td>
<td>25 kg</td>
</tr>
<tr>
<td>Sample Return Tank &amp; Aeroshield System</td>
<td>150 kg</td>
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<tr>
<td>Miscellaneous &amp; Contingency</td>
<td>50 kg</td>
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<tr>
<td><strong>MICE Sample Return Craft Mass</strong></td>
<td>250 kg</td>
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#### Pratt & Whitney RL10 Engine System

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<th>Component</th>
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<td><strong>Pratt &amp; Whitney RL10 Engine System</strong></td>
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</table>

#### MICE Lander Total Dry Mass

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<th>Component</th>
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<td>Earth Departure $\Delta V$ Propellant Loading</td>
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<td>Earth Departure Propellant Tank Mass</td>
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<td>Mars Insertion &amp; Landing Aeroshield System</td>
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<td>Mars Insertion &amp; Landing $\Delta V$ Propellant Loading</td>
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<td>Mars Insertion &amp; Landing Propellant Tank Mass</td>
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<td><strong>REE Total Mass (IMLEO)</strong></td>
<td>13505 kg</td>
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Figure 8.1.2 MICE Mission Parameters

**MICE Spacecraft Mars Departure Operational Parameters**
- Mars Departure from Surface ΔV (km/sec): 6.50
- Earth Capture & Re-entry ΔV (km/sec): 0.00 (Ballistic Re-entry)
- Time of Flight to Earth: 260 Days

**MICE Spacecraft Lander Baseline Design**
- MICE Spacecraft Tank Structure/Insulation: 440 kg

**MICE Sample Return Craft**
- Telecommunications: 25 kg
- Ion Thrusters (Navigation): 25 kg
- Sample Return Tank & Aeroshield System: 150 kg
- Miscellaneous & Contingency: 50 kg
- **MICE Sample Return System Mass:** 250 kg

**Pratt & Whitney RL10 Engine System:** 250 kg

**MICE Return Spacecraft Total Dry Mass:** 940 kg

- Mars Departure from Surface ΔV Propellant Loading: 4406 k
9.0 MICE TECHNOLOGY – A MAJOR STEPPING STONE TOWARDS LARGE SCALE EXPLORATION OF THE SOLAR SYSTEM

9.1 Robotic Exploration of Other Ice Sheet Interiors in the Solar System, Including Europa and Its Sub-Surface Ocean

Thick ice deposits are found on many bodies in the outer solar system. Exploration of their interiors would yield unique and important scientific information about their origin and structure, how conditions in the Solar System have varied over billions of years, and for some bodies, whether life exists on them, or has existed in the past. Going beyond Mars, the MICE system would provide the capability for extensive exploration of many of these bodies.

Figure 9.1.1 shows some of the potential MICE exploration missions in the outer solar system. Europa is a prime objective for exploration. It appears to have a planetary water based ocean beneath its thick outer ice sheet cover based on measurements of varying magnetic fields probably caused by induced electrical current in a liquid sub-surface ocean, and by cracks in the ice sheet apparently caused by tidal motions. If life exists, or has existed in the past, on Europa, evidence of it would be found in the ocean, in the re-frozen zones associated with the tidal cracks, and on the floor of the sub-surface ocean.

Figure 9.1.2 shows an artists view of the NEMO (Nuclear Europa Mobile Ocean) mission that could be carried out by the MICE system. NEMO would use a combination of the MICE probe, plus a small attached submersible which would use a separate MICE reactor for power and propulsion. The MICE probe would melt a channel down through Europa’s ice sheet to the sub-surface ocean. After reaching the ocean, the submersible would detach from the MICE probe, and travel through the ocean, obtaining data and collecting samples.

The submersible would be in continuous real time communication with the MICE melt probe, as illustrated in Figure 9.1.3. The MICE probe would be in continuous 2-way communication with the lander spacecraft on the surface of Europa, which in turn would be in continuous 2-way communication with scientists on Earth. The scientists would receive data from the submersible almost instantly (subject to the ~1 hour delay due to speed of light constraints), and then respond with updated instructions on what locations to explore, and what data and samples to obtain (again, subject to speed of light time delays).

Long distance communication between the submersible and the MICE probe would be by acoustic transmission, which could function reliably over distances of many kilometers, even if the Europa ocean had high salinity and/or large amounts of suspended particulates, which would prevent long distance RF or optical communication. Data transmission rates using acoustic communication would be relatively slow. The submersible could periodically rendezvous with the melt probe to transmit large amounts of detailed data using close range RF or optical communication equipment.
The MICE probe would serve as a homing beacon for the submersible by acting as a continuous acoustic source. The submersible could then always find its way back to the MICE probe. It would also use the time delay between when a time marker signal was sent from the MICE probe to when it was detected by the submersible to determine its radial distance from the probe. (The submersible and MICE probe would have synchronized, highly stable and accurate clock systems). The 3D position of the submersible relative to the MICE probe could be determined by combination of range measurement and triangulations at several locations, using gyroscopes to measure the distances between the measurement locations.

The MICE probe could communicate with the surface spacecraft using a variety of methods, including acoustic, RF, or a trailing small diameter optical fiber between the probe and the spacecraft.

After completing its exploration program, the submersible would rendezvous with, and reattach to, the MICE probe. The probe and submersible would then ascend back to the surface spacecraft (Figure 9.1.4), in a new melt channel, using the same technique as on the Mars North Polar Cap, as with the Mars MICE mission, the lander spacecraft would have been refueled with liquid H₂ and O₂ produced by electrolysis of melt water from the Europa ice sheet. After transferring samples collected by the submersible, the spacecraft would take off for its return to Earth.

Alternatively, the spacecraft could hop to a different location on Europa, together with the MICE probe and submersible, to perform another exploration of the ocean at a different spot. After completing a sequence of explorations, the spacecraft would then return to Earth.

As shown in Figure 9.1.1, in its descent and ascent travel through Europa’s ice sheet, the MICE probe would carry out a wide variety of data measurements and sample collections with the objective of determining the Ice Sheets Origin, Composition, Age, and Geology (ISOCAG). The Europa ice sheet appears to periodically recycled, and probably does not go back for more than a few hundred millions of years. The portions around the long crack regions that presumably are a result of tidal motions, are probably much younger, so that depending on the exploration location, data could be limited to relatively recent periods, but also at other locations, go back in the Moon’s history to a much older period.

As with the North Polar Cap on Mars, the Europa ice sheet should provide a wealth of unique and important information on the origin of the ice sheet, its age, how rapidly it is recycled, what its composition is and what it contains, including material from the sub-surface ocean, a record of ancient meteor, cosmic ray, and solar activity, etc. Discovery of past or present life on Europa would be of immense scientific importance. Evidence may be found in the sub-surface ocean in tidal crack zones, or in and on the sea floor, or at all three. The composition and geology, properties and topography of the sub-surface ocean and the sea floor would also be of great scientific importance. Because of the strong tidal forces and associated heating in Europa’s core, one may discover undersea volcanoes and hydrothermal vents, where life could originate, evolve, and flourish.
MICE could also carry out exploration of the ice sheets on Callisto, Ganymede, and other Jovian moons. Sub-surface oceans probably would not be found on all of Jupiter’s moons, because tidal forces and heating decrease with distance from Jupiter, but liquid pockets may be found on some of the closer-in moons - such pockets may be havens for sub-surface life. Comparison of the exploration results from the different Jovian moons would help to understand the history of the solar system, including Jupiter and its moons. On these moons without sub-surface oceans and recycling of the ice sheets, data obtained by MICE probes could read back to the formation of the solar system billions of years ago.

MICE missions to the moons of the other giant planets – Saturn, Uranus, and Neptune – would provide additional important data about their origin, composition, etc., and help to understand solar system history. Of particular interest would be MICE missions to two of Saturn’s moons, Enceladus and Titan. The Cassini mission recently obtained the first detailed photos of the Titan’s surface and has observed water geysers on Enceladus. Exploration of the interior of the ice sheets on these moons and the liquid regions inside them could find evidence of life forms there. It would also provide important information on their history, structure, composition, etc.

MICE exploration of possible ice deposits on Pluto and Charon would also be of great scientific importance. So far, we have no detailed data on their surface features. Hopefully, some limited data will be obtained in the next decade when the New Horizons spacecraft flies past Pluto and Charon at high speed. A MICE mission could yield answers to such questions as: Do Pluto and Charon have the same origin and properties, or do they have different origins and properties? Are they part of the original formation of the Solar System along with the other planets and moons, or were they captured later? What can we learn about the history of meteor, solar, and cosmic ray activity at the outer edge of the Solar System? These among many other questions could be answered by a MICE mission to Pluto and Charon.

MICE can also be used to explore the interiors of the larger ice bodies that exist in the Solar System. Of particular interest is Chiron, a 200 kilometer diameter ice object that is on a chaotic orbit between Uranus and Neptune. At some future time in a few hundred thousand years, it probably would be either fling into an Earth crossing orbit or completely out of the Solar System. Information about its composition and properties would be very important in determining whether or not it could be dangerous to life on Earth.

9.2 Robotic Production of Propellants and Life Support Supplies for Manned Bases on Mars Using MICE

Present scenarios for the manned exploration of Mars envision bringing from Earth most of the supplies needed for the astronauts to operate on Mars and for their return to Earth. These supplies include food, water, air, fuels habitats, and propellants. There is virtually no use of the in-situ resources on Mars. Zubrin (1) has proposed bringing liquid H2 from Earth and converting it to methane propellant for the return journey by reaction with CO2 from the Martian atmosphere. The benefits from this are relatively marginal however.
Having to bring all of the supplies needed for the mission from Earth imposes very serious limitations and perils for manned exploration of Mars. The very large IMLEO requirements, 500 tons or more for each mission, makes a manned Mars exploration program involving a series of missions extremely expensive, on the order of hundreds of billions of dollars. Moreover, there is an inevitable dynamic to minimize the mass of materials to be carried to Mars, so as to keep cost down. In turn, this results in reduced safety margins for the astronauts, and constrained capability for exploration.

If water were widely and readily available on Mars, manned exploration would be much easier, safer, and less costly. With water and CO\textsubscript{2} from the atmosphere, initially all of the supplies needed for a stay on Mars, as well as the return to Earth could be manufactured by the astronauts.

This realization has sparked the search for water on Mars. Scientists look for evidence that there may be ice deposits beneath the surface, and speculate how it could be mined. This is ironic, since thousands of cubic kilometers of ice exist in the North Polar Cap, in thick sheets that are readily accessible and easily mined.

What is even more ironic is that investigating the interior of the ice sheet would be much simpler and easier than drilling into solid rock, and could yield results from a much greater exploration volume. Moreover, the results would provide a much more detailed picture of the geological, meteorological, biological, etc. history of Mars than local drilling into a rock at a few sites.

MICE and the North Polar Cap offer a much better way to carry out the manned exploration of Mars than the present plan to land a few astronauts at site in the dry part of Mars, who would have to bring all of their supplies from Earth, and conduct a limited local exploration around the landing site for a relatively short period, and then return to Earth.

Instead of the present plan, the MICE system can be the basis for a robotic lightweight factory unit called MICE/ALPH that would land on the North Polar Cap in advance of the manned mission to Mars. After landing, the MICE/ALPH unit would manufacture and stockpile many tons of propellants, fuels, water, air, plastics, and foodstuffs in cavities under the ice surface. In addition, the MICE/ALPH factory unit would create a number of sub-surface habitat rooms inside the ice sheet, where the astronauts would live when not engaged in exploration on the surface, with 10 meters of ice shielding above them, the astronauts would not be subject to high radiation dosages (more than 50 R/year) from cosmic rays. Instead, they would receive about the same radiation dose as they would by living on Earth.

With the MICE/ALPH approach to manned exploration of Mars, the astronauts would not depart from Earth until it was confirmed that all of the planned supplies and habitats were in place at the landing site. Then, after the astronauts landed on Mars they would simply use the stockpiled supplies for their operations on the planet and their return trip to Earth.

The sub-surface habitats for the astronauts would be large in size, thermally insulated
from the surrounding ice sheet, and pressurized to 1 atmosphere with ordinary air (80 volume % N₂/20 volume % O₂). Life in the habitats would be very comfortable, with ample water and food. The MICE/ALPH unit would produce and stockpile 10 or more tons of basic foodstuffs, i.e., algae and yeasts, containing a proper balance of protein, fats, and carbohydrates. With texturing, sauces, and spices, a variety of appetizing meals could be prepared, much as is done today with tofu, veggie burgers, and other forms. In addition, the basic algae and yeast foodstuffs could be used as feed for fish ponds and animals, which could then be used as food for the astronauts.

Using plastics and other materials manufactured by the MICE/ALPH robotic factory unit, the astronauts could construct robotic and manned rovers and flyers to carry out explorations of locations beyond the North Polar Cap. Exploration of the Polar Cap itself could be carried out by continued operation of MICE probes, plus trips using manned surface rovers. With such rovers, the astronauts could explore thousands of square kilometers of the Polar Cap.

With the MICE/ALPH approach, a very rigorous and extensive program for the exploration of Mars would be possible, with greatly reduced risk and at much lower cost than with the presently planned approach. Permanently staffed bases on the Mars Polar Cap could be set up, with a new group of astronauts landing at the base as the previous group took off for the return to Earth. MICE/ALPH would enable a much larger staff of astronauts to live at the base, resulting in greater and more diverse exploration capabilities, and reduced psychological and physical stress. Medical care and treatment capabilities would be greatly improved, and the astronauts would feel much less isolated and alone. Short term bases could be set up at interesting locations beyond the Polar Cap, where astronauts would explore for a few days or weeks and then return to their main base on the Polar Cap. Supplies and transport for these distant temporary bases would be produced at the main base(s) on the Polar Cap.

Figure 9.2.1 shows a flowsheet for the MICE/ALPH exploration approach. As the program continued, the MICE/ALPH factory units would begin to manufacture large amounts of propellants and supplies (water, air, plastics, foodstuffs, etc.) that would be transported back to high Earth orbit in unmanned cargo vessels. The materials could then be stockpiled in orbit, to be used as resources for the outward bound trips to Mars, for lunar bases, for space industries and tourism, and exploration missions to the Outer Solar System. The ΔV requirement to bring supplies to high Earth Orbit from the surface of Mars is substantially smaller than that from the surface of Earth. Moreover, the environmental issues involved with the use of nuclear thermal propulsion, a very efficient method for space transport will be much less for Mars than for Earth.

Figure 9.2.2 shows an overall flowsheet for the production of supplies on Mars using robotic MICE/ALPH factory units and the in-situ Martian resources, i.e., water, CO₂ and N₂ from the atmosphere, and the various metals and other elements that make up the dust material contained in the ice sheet. H₂ and O₂ are obtained by electrolysis of melt water from the ice sheet. Electrolysis is a standard industrial process and can be readily applied for production on Mars. Similarly, the H₂ and O₂ can be readily liquified using conventional industrial processes, and stored in subsurface cavities created by melt water in the ice sheet. [The H₂ and O₂ would be stored in expandable plastic bladders that were inflated inside the storage cavities].
CO₂ could be extended from the atmosphere (which is predominantly CO₂) by a variety of conventional industrial processes including pressurization and material, membranes, etc. Selection of the best method will require further study. CO₂ and H₂ can then be reacted using standard industrial processes to make a wide variety of products, including methane, methanol, plastics (polyethylene, polypropylene, etc.), carbon fibers for reinforcement of composite materials, etc. Algae and yeast foodstuffs can be produced from methanol using conventional industrial bioreactors. All of these materials can be stockpiled in sub-surface cavities awaiting the astronauts when they land.

Dust material collected from the melt water stream can be processed to recover various metals and other elements, including iron, aluminum, silicon, etc., that would prove useful for a manned Mars base. Nitrogen, which is present to ~2% in the Martian atmosphere, can be easily recovered to be blended with O₂ to produce breathable air, which can be liquefied and stored in sub-surface cavities. It can also be used to produce certain desired plastics.

Figure 9.2.3 shows a more detailed flowsheet for the various processes. The ALPH factory concept has been described in a previous Phase 1 NIAC study(2), which provides detailed analyses of the various processes and equipment that would be used. Figure 9.2.4 gives examples of the very large tonnages of supplies that would be produced by a compact lightweight ALPH unit in just 20 months of operation.

The MICE/ALPH approach to manned exploration of Mars is very attractive, and a logical follow on to the MICE exploration of the North Polar Cap. The MICE exploration program would pinpoint desirable landing sites for a manned mission. MICE/ALPH factory units would then follow on to manufacture the supplies for the astronauts. The basic MICE nuclear power reactor would stay the same but operate at higher power output. Process modules using conventional industrial technology would be added. MICE/ALPH factory unit operation would be monitored and controlled from Earth, in a similar fashion to the monitoring/control of the MICE exploration probes.

The R&D efforts needed for MICE/ALPH appear relatively straight forward, since most of the work would have already been done in developing the MICE probes. MICE probe units could be operating on the North Polar Cap by 2019, given a program to develop them, and MICE/ALPH factory units would be operating by 2025 AD, enabling a robust manned exploration program to start a couple of years later. The MICE/ALPH approach appears to have very major benefits in terms of greatly reduced risk to the astronauts, much lower cost for the manned exploration program, and much greater exploration capabilities.
# Potential Other Ice Sheet Exploration Missions in the Solar System Using MICE Probes

[ISOCAG = Ice Sheet Origin Composition Age and Geology]

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<thead>
<tr>
<th>Potential Exploration Mission</th>
<th>Exploration Conditions</th>
<th>Exploration Activities</th>
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<tbody>
<tr>
<td>1. Europa</td>
<td>Fully covered by thick ice sheet</td>
<td>Determine Ice Sheet Origin Composition Age and Geology (ISOCAG)</td>
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<tr>
<td></td>
<td>Sub-surface ocean is likely</td>
<td>Explore sub-surface ocean</td>
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<tr>
<td></td>
<td></td>
<td>Search for evidence of life</td>
</tr>
<tr>
<td>2. Ganymede and Callisto</td>
<td>Fully covered by thick ice sheet</td>
<td>Determine ISOCAG</td>
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<tr>
<td></td>
<td>Possible sub-surface oceans</td>
<td>Explore sub-surface oceans if present and search for life</td>
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<tr>
<td>3. Outer Jovian Moons</td>
<td>Ice deposits</td>
<td>Determine ISOCAG</td>
</tr>
<tr>
<td></td>
<td>Sub-surface oceans unlikely</td>
<td></td>
</tr>
<tr>
<td>4. Enceladus</td>
<td>Covered by ice sheet</td>
<td>Determine ISOCAG</td>
</tr>
<tr>
<td></td>
<td>Water geysers observed</td>
<td>Search for life</td>
</tr>
<tr>
<td>5. Titan</td>
<td>Ice deposits and liquid regions</td>
<td>Determine ISOCAG</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Search for life</td>
</tr>
<tr>
<td>6. Other Moons around Saturn, Uranus, and Neptune</td>
<td>Ice deposits</td>
<td>Determine ISOCAG</td>
</tr>
<tr>
<td>7. Pluto - Charon</td>
<td>Ice deposits</td>
<td>Determine ISOCAG</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Determine origins of Pluto and Charon</td>
</tr>
</tbody>
</table>
Figure 9.1.2  
NEMO Science Mission - Overview

Ocean Studies:
- Physical Oceanography
- Inherent Optical Properties
- Particulates
- Marine Chemistry
- Plume Sensing

Ocean Bottom Studies:
- SONAR profiling / Bathymetry
- Hydrothermal Vent Chemistry & Life Detection
- Seismology

Search for Life:
1. Tidal Cracks
2. Interface
3. Hydrothermal Vents

Figure 9.1.3  NEMO AUV - Operation

- Most instruments on AUV portion for mobile sampling
- Meltprobe remains at interface to act as beacon, data relay and acoustic source

- acoustic modem (64 kbaud)
- close range RF or optical communication
Figure 9.1.4 NEMO Melt Probe - Design

- Directional water jetting + buoyancy control = Navigation
  - 45 degree ascent/descent possible
  - Debris avoidance

1. Melt Probe Reactor
2. Pressurized Tether
3. Instrument Package
4. AUV Reactor Unit

Figure 9.2.1 Robotic Development of a Permanent Manned Mars Base on the North Polar Cap, Using the MICE/ALPH System

1. MICE mission explores North Polar Cap for suitable site for manned Mars probe
2. MICE/ALPH robotic factory lands at selected site on North Polar Cap
3. Robotic MICE/ALPH factory operates for 20 months, stockpiling 100's of tons of supplies, food, & creates shielded habitats
4. Astronauts land at base – use stockpiled supplies and live in shielded habitats – construct rovers and flyers
5. Astronauts explore Mars using constructed rovers and flyers, both robotic and manned
6. New group of astronauts land at base – old group departs for Earth using supplies produced by MICE/ALPH
7. Exploration of Mars continues using permanent manned base
8. Propellants and supplies produced by MICE/ALPH units on Mars are transported back to Earth orbit for space communication and exploration activities
Figure 9.2.2 Production of Supplies and Habitats Using the MICE/ALPH System to Process In-Situ Resources from the North Polar Cap and the Mars Atmosphere

MICE/ALPH Robotic Factory Unit

Multi cavities in ice sheet

Habitats for astronauts

Cavities for stockpiled supplies

H₂ & O₂ propellants

H₂ & O₂ for life support

Methane & methanol fuels

Plastics for construction of rovers, flyers, etc.

Foodstuffs (algae, yeasts, proteins, etc.)

Construction materials

Thermal Power

Melt water for processes

Electrolysis to H₂ & O₂

Liquid H₂ & O₂

H₂

Extract CO₂ from atmosphere

Synthesize hydrocarbons

Methane & methanol fuels

Plastics

Bio reactors to make foods

Electrical Power

Extract materials from dust layers

Gases for processes

Metals, Silicon, etc.

Figure 9.2.3

ALPH PRODUCTION FLOWSHEET
Figure 3.24

Stockpiled Supplies Inside The North Polar Cap

- Rover Hanger
- Access Shafts
- Air Supply
- Food
- Plastic
- Insulated Sub-Surface Chambers For Astronaut Habitats
- 10 metres
- Melt Water Pool
- Ice Cover
- Water Supply Line
- Lander Spacecraft
- With ALPH Process Units
- Liquid O₂
- Liquid H₂
- MICE Reactor
- Breathable Air Storage
- Propellant Storage
- Propellant Storage
- Power Cables & Warm Water Lines Between MICE Reactor & Lander Spacecraft

20 Month Operation
- Lining: 5 MW(thermal) (5 MW(electric))
- MICE Reactor Produces:
  - 160 Tons Of Liquid H₂
  - 1600 Tons Of Liquid O₂
  - 80 Tons Of Liquid Methane
  - 30 Tons Of Methanol
  - 30 Tons Of Plastics
  - 10 Tons Of Food
- 6 Habitats (9 m wide, 15 m long, 15 m high)
10.0 MICE R&D PROGRAM

10.1 MICE Reactor and Power Conversion System

There is a very strong technology base for the MICE reactor and power conversion system. The Zr/UO₂ cermet nuclear fuel has been used in hundreds of water cooled and moderated power reactors for decades with exceptional safety and reliability. In many of these reactors the same fuel elements have operated in the reactor for a decade or more without being replaced. Zr/UO₂ fuel completely contains all fission products, and using a burnable poison incorporated in the cermet matrix can burnup a large fraction of its initial uranium loading.

Zr/UO₂ fuel is normally fabricated as thin plates, but can be manufactured in a variety of forms. The present MICE reactor design would use hollow tubes of Zr/UO₂ cermet fuel. If this were the fuel form chosen for the final design, fabrication and testing of the Zr/UO₂ tubes would be required. The R&D effort in this area would be very modest, because of the extensive existing technology base.

Fuel fabrication and testing would be carried out in Phase 1 of the MICE reactor and development program as part of the general component development and testing activities. Also carried out in Phase 1 (Figure 10.1.1) would be thermal hydraulic testing of the fuel element heat transfer performance, using electrical heating of the metal matrix. Fuel elements would be tested under conditions that fully duplicated all of the dimensions, heating rates, material, coolant temperatures, heating and pressures, etc. that would be present in the actual MICE reactor. The data obtained would provide a very accurate representation of the operating performance of the actual MICE reactor. The testing program probably would include tests of a full size simulated reactor at full power of 500 KW.

The third part of the Phase 1 reactor and power conversion system would include the fabrication and testing of the 10 KW(e) steam turbine/generator system. At the proposed operating conditions of the actual MICE power system a long term running test would be carried out as part of the program.

The results from the Phase 1 efforts would provide the information for proceeding to Phase 2 of the reactor/power conversion R&D program. In Phase 2, an actual MICE reactor would be constructed and undergo initial testing. Criticality, thermal hydraulic, power distribution in the core, etc. performance would be determined.

Also in Phase 2, the full-up integrated MICE reactor/power conversion system could be tested using electrical heating of the fuel elements to simulate nuclear heating. Thermal hydraulic and power generation performance would be determined at various power levels including full power of 500 KW.

Following the Phase 2 testing, the Phase 3 efforts would have 2 main efforts. Part 1 would carry out long term testing of the actual MICE nuclear reactor at varying power levels and operating conditions that duplicated the anticipated environment inside the North Polar Cap of Mars. These tests would establish the ability of the MICE reactor to operate under all conditions
anticipated for the actual mission. Part 2 would integrate the electrically heated simulated reactor/power conversion system that was tested in Phase 2 with the MICE instrumentation pod to form a full size electrically heated, full capability simulated MICE probe. This simulated probe would then be tested inside an Earth ice sheet e.g., Greenland or Antarctica, where it would travel in patterns similar to those that it would follow on the North Polar Cap.

Following the tests in Phase 3, actual MICE probes would be fabricated for the first mission to Mars.

10.2 MICE Melt/Movement System

The development of the MICE melt/movement system is also divided into 3 phases, which would run concurrently with the 3 phases of the MICE reactor/power conversion R&D program.

Phase 1 of the melt/movement R&D program focuses on component development and testing, and involves 3 parts: Part 1 would carry out detailed 3D computer analyses of the melt/movement process. The analyses would determine the optimum number and placement of the water jets and what flow rates would be required as a function of the jet temperature, desired rate and angle of movement, etc., melt channel diameter, etc., for the descent and ascent movements. The analyses would also determine the reactor power requirements associated for the various movement conditions, together with the rate of re-freezing of the channel behind the moving probe.

The 3D finite element analyses are expected to provide an accurate picture of the probe travel process for a wide variety of conditions. To validate the analyses, a number of benchmark experiments would be carried out using known jet flow rates, jet placement arrangements, jet temperatures, etc. (Figure 10.2.1). The experimental results would be compared with the results predicted by the 3D computer analyses, to ensure their ability to accurately model the melt/movement process.

The experiments would be carried out in preformed ice blocks under controlled laboratory conditions, using full scale water jet configurations.

The third part of the Phase 1 effort would involve tests of the ability to filter out dust loadings inside the ice sheet so that dust did not interfere with the operation of the water jets. These experiments would be done in conjunction with the benchmark experiments described above, using preformed blocks of ice with dust layers incorporated into the blocks. The experimental water jet system would move through the simulated dust layers, demonstrating the ability to travel through dusty ice without hindrance, and without clogging of the hot water jets.

The results from the Phase 1 laboratory experiments and computer analyses would be used to design full scale hot water jet systems for simulated MICE reactor pods (R-Pod) and instrumentation (I-Pods). These simulated pods and their hot water jet melt/movement systems would then be tested in actual Earth ice sheet in Phase 2 of the melt/movement R&D program.
These tests would demonstrate the ability of the full scale jet system to move the MICE probe through the North Polar Cap at the desired rate under all anticipated operating conditions.

In Phase 3, the optimized melt/movement system would be incorporated into a full scale MICE probe that would be tested inside an Earth ice sheet, using electrical heating to simulated the nuclear heating from the actual MICE reactor. The MICE probe would be the same one referred to in Section 10.1, in which all systems, including reactor power conversion, melt movement, and instrumentation would be tested as an integrated unit under the anticipated conditions in the Mars North Polar Cap.

Following the Phase 3 tests, the results would then be used for the fabrication of the actual MICE probes that would be used in the Mars mission.

10.3 MICE Instrumentation and Communications System

The MICE instrumentation and communications R&D program, shown in Figure 10.3.1, follows the same pattern as that for the reactor/power conversion and melt/movement systems. Phase 1 would carry out component development and testing Part 1 of the Phase 1 effort would focus on testing the RF and acoustic communication options at a number of locations in various ice sheets on Earth. The effective range, data transmission rate, and fidelity of transmission would be determined for a variety of conditions, i.e., amount of fracturing and heterogeneity, presence of inclusions, including dust and earth layers, degree of ice consolidation, etc.

Since conditions on the North Polar Cap are poorly known, it probably will be advisable to have both RF and acoustic communication systems on the MICE probes. The tests in Earth ice sheets can help to define the frequencies, directionality, that are likely to perform satisfactorily in the North Polar Cap.

Phase 1 would also test the MICE instrumentation and sampling systems in melt channels created inside Earth ice sheets. The ability to measure the composition and amounts of trapped gas, to detect and analyze microbes, microfossils and life-based chemicals, collect and analyze trapped dust particles, determine the age of the deposited ice, etc. would all be tested as the instrumentation was moved along a melt channel.

Following the Phase 1 tests, the Phase 2 effort would test the integrated instrumentation assembly, i.e., I-Pod, in Earth ice sheets to demonstrate the capability of the fully integrated system to carry out all of the instrumentation functions. In conjunction with the tests of the I-Pod instrumentation, the 2-way communications system between the sub-surface probe and a relay station on the surface of the ice sheet would also be tested. Data transmission rates, transmission fidelity, etc. would be determined as a function of I-Pod depth and distance the nature of the intervening ice sheet, etc.

In Phase 3, the I-Pod would be integrated with the reactor pod to form a full scale simulated MICE probe. The probe would travel through an Earth ice sheet to depths and distances anticipated for the actual MICE probe on the North Polar Cap, collecting data and
transmitting it in real time to the surface relay station through the intervening ice. The simulated MICE probe would use electrical heating of the simulated fuel elements in the reactor instead of nuclear heating, with the electrical power fed to the probe through a trailing electrical cable.

Following Phase 3, the data obtained from the Phase 1, 2, and 3 programs would be used to construct the probes for the first MICE mission to Mars.

### 10.4 MICE Tests in Earth Ice Sheets

Figure 10.4.1 summarizes the main features of the MICE testing program in Earth ice sheets, and the anticipated results that would be obtained with regard to the probes capabilities in the areas of melt/movement rates, scientific data on the ice sheet properties, evidence of life, the meteorological and geologic history of Mars, etc., and the communication capabilities between the individual probes and between the probes and the surface lander.

A DC cable operating at ~10,000 volts 50 amps of current would supply 500 KW of electrical power to the simulated probe, enabling it match the anticipated full power performance of the nuclear reactor on the actual MICE probe. A 1 kilometer long power cable with an OD of 0.5 cm would have an $I^2R$ power loss of only 20 KW (counting the losses in the 2 conductors in the cable) and a volume of only 20 liters (about 2/3 of the cubic foot). The simulated MICE probe could easily carry the power cable, which would unroll from the probe as it moved through the ice sheet. The power cable behind the moving probe would freeze back into the ice sheet after a day or so, but there would be sufficient cable available on board that could be unrolled to demonstrate long distance travel, including ascent and descent movements, even though the unrolled cable would have frozen into the ice sheet.

Further study is needed to layout in greater detail the various tasks and experiments that would be involved in the MICE R&D program and to determine the costs and schedules for them. Based on preliminary estimates, the MICE Phase 1 program would take approximately 3 years, Phase 2 approximately 2 years, and Phase 3 about 2 years, for a total of 7 years. If funded in 2007, the results from the 3 phase program would be available in 2014, which would leave 4 years to construct the actual probes for the first MICE mission to Mars in 2018. This schedule appears achievable assuming that the MICE probes operated successfully, then a MICE/ALPH factory unit could be developed to land on the North Polar Cap by 2025 AD, with a manned mission a couple of years later.
Figure 10.1.1 Development and Testing of MICE Reactor and Power Conversion System

**Phase 1: Component Development & Testing**
- Fabrication and testing of actual nuclear fuel elements
- Thermal hydraulic testing of electrically heated simulated reactor
- Fabrication and testing of steam turbine power conversion system

**Phase 2: Integrated Reactor/Power System Testing**
- Construction and initial testing of MICE reactor
- Testing of integrated electrically heated simulated reactor and power conversion system

**Phase 3: Integrated MICE Probe Testing**
- Long term testing of MICE reactor under varying operating conditions
- Integration with MICE instrumentation pod
- Testing of integrated electrically heated MICE probe in Earth ice sheet
- Construction of actual MICE probe for MICE mission

Figure 10.2.1 Development and Testing of MICE Melt/Movement System

**Phase 1: Component Development & Testing**
- Detailed 3D computational modeling of melt/movement process
- Tests of ice melt & refreeze process as function of hot water jet design & placement
- Tests of ability to filter out dust loading & move through ice that contains dust

**Phase 2: Integrated Melt/Movement System Testing**
- Testing of hot water jet system for reactor pod inside ice sheet
- Testing of hot water jet system for instrumentation pod inside ice sheet

**Phase 3: Integrated MICE Probe Testing**
- Testing of integrated electrically heated MICE probe in Earth ice sheet
- Integration with electrically heated simulated reactor & power conversion system
- Construction of actual MICE probe for MICE mission
**Figure 10.3.1 Development and Testing of MICE Instrumentation and Communication System**

**Phase 1: Component Development & Testing**
- Testing of MICE RF & acoustic communication options in Earth ice sheet
- Tests of MICE instrumentation in melt channels in Earth iced sheets
- Tests of MICE sampling systems on melt channels on Earth ice sheets

**Phase 2: Integrated Instrumentation Pod System Testing**
- Testing of 2-way communication between probes and between probe and surface in Earth ice sheet
- Testing of integrated instrumentation/sampling system in MICE i-Pod

**Phase 3: Integrated MICE Probe Testing**
- Testing of integrated electrically heated MICE probe in Earth ice sheet
- Integration with electrically heated simulated reactor & power conversion system
- Construction of actual MICE probe for MICE mission
### Figure 10.4.1
Testing of MICE Probes in Earth Ice Sheets

<table>
<thead>
<tr>
<th>Features of Test MICE Probe</th>
<th>Testing of MICE Melt/Movement System</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Heated by trailing electric power cable, not nuclear reactor</td>
<td>• Determine travel rate as function of power input</td>
</tr>
<tr>
<td>• MICE test probe duplicates all other features of nuclear MICE probe, including melt/movement and inst./comm. systems</td>
<td>• Demonstrate capability to ascend/descend inside ice sheet vertically and at an angle</td>
</tr>
<tr>
<td>• Can ascend/descend in Earth ice sheet at up to 200 meters/day [@500 KW input]</td>
<td>• Descend to depth of ~1 kilometer (equivalent in pressure to ~3 km on Mars)</td>
</tr>
<tr>
<td>• Trailing power cable unrolls from moving MICE probe - remains behind in refrozen channel</td>
<td>• Demonstrate capability to move through dusty ice layer (natural or artificial)</td>
</tr>
<tr>
<td>• Probe can travel 2 km with small volume of cable</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Testing of MICE Instrumentation/Sampling System</th>
<th>Testing of MICE Communication/Control System</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Measure composition and amount of trapped bases in ice</td>
<td>• Determine communication capability inside ice sheet for RF and acoustic systems as a function of distance to probe</td>
</tr>
<tr>
<td>• Determine age of ice as a function of depth</td>
<td>• Demonstrate capability of scientists to control movement and operation of the MICE probe, including time delays that would occur for operation on Mars</td>
</tr>
<tr>
<td>• Determine ability to detect and collect microbes and organic chemicals present inside ice sheet</td>
<td>• Determine effect of dust layers and occlusions on communication capability</td>
</tr>
<tr>
<td>• Determine ability to measure composition and amounts of various dusts inside ice sheet</td>
<td></td>
</tr>
</tbody>
</table>
11.0 SUMMARY AND CONCLUSIONS

A study of the MICE (Mars Ice Cap Explorer) concept has been carried out to investigate its feasibility and the potential scientific results that it would yield. Based on the study, a number of important conclusions can be drawn:

1. The MICE system would yield an enormous wealth of new and important scientific information about the structure and contents of the deep interiors of the North and South Polar Caps on Mars. The data would provide a unique window into the ancient geology, climate, atmospheric meteorology, volcanology, meteor impacts, cosmic ray activity, etc. over millions of years. The MICE system could also discover evidence of present or past Martian life in the form of microbes, microfossils, and/or traces of biological chemicals.

2. Data from the MICE probes could be transmitted continuously in real time via a 2-way communication link to scientists on Earth, who would direct the paths and activities of the probes in near real time, subject only to the ~1 hour delay due to finite speed of light constraints. In addition, the MICE probes would collect and bring back samples to the lander spacecraft, which would return them to Earth for analysis after an 18 month stay on Mars. After departure of the lander spacecraft, the MICE probes would continue to explore the deep interior of the Polar Cap for many more years, with continuous 2-way communication with scientists on Earth.

3. The MICE probes can move through the interior of the Polar Cap at a rate of up to 200 meters per day, with the capability to stop at important locations for detailed investigation. The probes can ascend and descend vertically or at an angle of up to 45 degrees from vertical. They can travel to the bottom of the Polar Cap to investigate bed rock, and many kilometers horizontally through a series of ascending and descending traverses.

4. The MICE nuclear reactor and power system would use well established existing technology that has been used in hundreds of reactors for many decades with excellent safety and reliability. The MICE probe can be developed and tested in Earth ice sheets prior to a MICE mission to Mars. The MICE mission could be launched in 2018 using a Delta IV launch vehicle. After landing on the North Polar Cap, 6 MICE probes would be deployed in an interactive network to move through the Polar Cap. Samples collected by the probes would return to Earth in 2021.

5. The MICE system can be used to explore the deep interiors of the ice sheets on many other bodies in the Solar System, including Europa, Ganymede, Callisto, Titan, Enceladus, Triton, Pluto, Charon, etc., obtaining scientific data and searching for evidence of present or past life. On bodies with sub-surface oceans, such as Europa, the MICE probe can dispatch a small nuclear powered submersible to explore the ocean.
6. The MICE reactor/power conversion system can also be used to robotically produce hundreds of tons of supplies of propellants, foods, air, water, fuels, and plastics using the in-situ ice resources in the Polar Cap and the Martian atmosphere. These supplies can be stockpiled in advance of astronauts landing on Mars, and can support large permanent manned bases for the detailed exploration of Mars.

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