

MAGNETICALLY INFLATED CABLE (MIC) SYSTEM FOR LARGE SCALE SPACE STRUCTURES

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ABSTRACT

A new approach for the construction of large lightweight structures in space is described. In the approach, termed MIC (Magnetically Inflated Cable), the structure is launched as a compact package of coiled superconducting cables and attached tethers on a conventional launch vehicle. After achieving orbit or an outbound trajectory, the superconducting (SC) cables in the MIC package are energized with electrical current. The resulting strong magnetic forces on the MIC SC cables are directed outwards causing them to expand until the tension forces in the attached Kevlar tether network restrains further movement. The final MIC structure of SC cables and tethers is very strong and rigid. The tether network can provide the support structure for a wide range of applications, including solar electric generation, solar thermal propulsion, large space telescopes, lightweight propellant tanks, and so forth. The strong magnetic fields from the SC cables can provide magnetic shielding against cosmic rays for astronauts and store electric energy to meet fluctuating power demands.

The physical size of MIC structures can be very large, e.g., a kilometer or more, even though the SC cable and tethers have very small diameters, e.g., a few centimeters or less. The unenergized SC cables and tethers are flexible and can be compressed into a small volume as payload on a conventional launch vehicle.

The MIC cables employ High Temperature Superconducting (HTS) to carry very large currents, 100's of thousands of amps, with zero electrical resistance. No electric power is needed to maintain current in the MIC cables after they have been energized by an external power source. A small amount of power is required to maintain the HTS conductors at cryogenic temperature. Using existing thermal insulation technology, a 1 kilometer MIC SC cable would need only a few kilowatts of power to maintain cryogenic operating conditions.

A wide variety of MIC applications and systems are examined, including solar electric generation for spacecraft, lunar base power, and beamed power to Earth from space; solar thermal propulsion for orbit raising, a Earth to Moon tug, and Mars cargo spacecraft; energy storage for spacecraft, lunar bases, and robotic rovers; large telescopes for imaging terrestrial type planets around distant stars and studies of the early universe; propellant tankage; propellantless propulsion of spacecraft using the magnetic field of the Earth; and magnetic shielding of astronauts from cosmic rays. Four baseline MIC designs are described: a 1 MW(e) solar electric system for a lunar base; a ~30 ton payload Earth to Moon tug; a 2000 megajoule energy storage system for a lunar base, and a 1 kilometer diameter space telescope.

The three HTS superconductors that are now in commercial production (BSCCO, YBCO, and MgB_2) are evaluated with regard to their suitability and performance in MIC systems. Engineering current densities on the order of 50,000 amps/cm² are presently achieved; with improvements in superconductor film thickness and other factors, even greater engineering current densities, e.g., 100,000 amps/cm² are anticipated. The design of MIC SC cables is described in detail. MIC SC cables can carry up to 1 million amps, and multi-cable arrays can carry much greater currents. The MIC SC cables are designed to prevent single point failure. Each cable has many independent superconductor and coolant circuits. If some of these were to fail, their current would be transferred to neighboring circuits by magnetic induction, so that the total superconducting current carried by the MIC cable would remain essentially constant.

The superconductor and cryogenic technology required for 1st generation MIC systems is already available. SC program to develop MIC capability based on this technology is described. Prototype MIC structures can be fabricated and tested in large vacuum chambers on Earth, to validate the technology. Once validated on Earth, MIC structures can be fabricated for testing and implementation in space.

EXECUTIVE SUMMARY

A new approach for the construction of large structures in space is described. This new approach, termed MIC (Magnetic Inflation of Cables) uses the strong magnetic forces that act on superconducting cables that carry high electrical currents, forming very large, very lightweight structures.

The MIC structure is launched into space as a compact package of superconducting (SC) cables and high tensile strength tethers on a conventional launch vehicle, as illustrated in Figure ES-1. During the launch phase, the SC cables are not electrically energized. After the payload achieves its planned orbit or outwards trajectory, the SC cables are energized to their high current level, causing the structure to automatically deploy into its final form.

As illustrated in Figure ES-1, this could be a large space telescope, with a diameter as great as 1000 meters. A wide range of other MIC applications is possible. Figure ES-2 shows some of these applications. MIC can be used for solar electric power generation for satellites, lunar bases, electric propulsion, and beamed power from GEO orbit to Earth. It also can be used as solar thermal propulsion, producing hot H_2 propellant with a specific impulse of ~ 900 seconds, magnetic storage of electrical energy, expandable tankage for storage of propellants, etc.

MIC structures are part of the class of “tensegrity” structures, which rely on strong forces that act on various structural members to create a strong, rigid, high integrity structure. Conventional existing tensegrity structures use a combination of tension and compression members to create and carry the forces. In contrast, in MIC there are no compression members. Instead, the SC cables in a MIC structure are arranged so they all directly experience outwardly directed magnetic forces from the currents that they carry. In turn, these magnetic forces are restrained and held in place by a network of lightweight, high tensile strength tethers, resulting in a strong, rigid, very light structures.

The MIC tethers would be made of Kevlar or Spectra (oriented polyethylene), with ultimate tensile strengths on the order of 2 to 3 GPa (300 to 400,000 psi) and mass densities on the order of 1 to 1.5 g/cm^3 . The SC cables used for MIC operate with engineering current densities on the order of 100,000 amps per square centimeters in their conductors, with zero I^2R losses. The only operating power required by the SC cables is that used to maintain them at cryogenic temperatures. Using conventional multi-layer thermal insulation, refrigeration power can be very low, on the order of a few kilowatts for kilometer long lengths of cable. The MIC cables can use High Temperature Superconductor (HTS) to minimize the refrigeration power. Three different types of HTS conductors, BSSCO, YBCO, and MgB_2 , have been recently put into commercial production, and are available for use in MIC systems.

Figure ES-3 illustrates how a MIC structure can be used for solar electric generation. In the configuration at the left, the MIC SC cable forms a simple circular loop. The radially outwards magnetic forces on the SC cable are restrained by a 2-dimensional mesh of tensile tethers, made either of Kevlar or Spectra material. Attached to and supported by the 2D tether

network is an array of thin film solar cells. Their electrical output is conveyed through ordinary, ambient temperature conductors in series/parallel connections (not shown) to the load. In practice, the tether network would have a mix of larger primary tethers, to which the smaller secondary tethers that directly supported the thin film solar cells, would be attached.

Alternatively, instead of using a circular SC loop configuration, a square or rectangular loop configuration could be used.

Another MIC solar electric configuration is shown on the right side of Figure ES-3. The MIC structure functions as a concentrator, focusing sunlight onto a relatively small solar cell array. This reduces the cost and weight of the solar cell array, and allows the use of cells that have higher electrical generation efficiency, since the cost of individual cells can be greater, since the total cell area is much smaller.

As with the thin film MIC structure shown on the left side of Figure ES-3, the radial outwards magnetic forces on the MIC cable are restrained by a 2D mesh network of Kevlar or Spectra tethers in the plane of the MIC loop. [The tethers network is not shown in Figure ES-3.] In addition to the large primary SC loop, there is a smaller secondary SC loop located behind the primary loop. The current direction in the secondary SC loop is opposite to that in the primary loop. The axial magnetic forces between the two loops acts to drive them apart. These forces are restrained by tethers attached to the primary and secondary SC loops. The tethers also are attached to the 2D mesh network shown in Figure ES-3, which supports a thin aluminized mirror film that focuses the reflected and concentrated sunlight into the solar “cell” array.

The tether placements and tensile forces are designed so that the aluminized mirror film has the correct shape to concentrate the sunlight on the solar cell may by a factor of 10 or more, as compared to the ambient solar flux in space.

The MIC solar concentrator can also have other structural shapes besides a simple circular loop. For example, it can be a long rectangular loop that concentrates sunlight onto a small central line array of solar cells.

Figure ES-4 illustrates how the MIC solar concentrator can be used for solar thermal propulsion. Instead of concentrating sunlight onto a solar cell array, the MIC concentrator focuses it onto a high temperature thermal receiver. H₂ propellant flowing through the thermal receiver is heated to a high temperature, e.g., 2500 K, and then exhausted to space through a nozzle to generate thrust for a spacecraft. The specific impulse (I_{SP}) of 2500 K is ~850 seconds, almost double the ~450 seconds for H₂/O₂ chemical combustion engines. The higher I_{SP} enables spacecraft to achieve substantially greater OV's while at the same time using less propellant mass. MIC solar thermal propulsion systems can be used for a variety of applications, including orbital transfer of spacecraft, transport of payloads between the Earth to the Moon, and Mars cargo vehicles.

Figure ES-5 illustrates the use of a MIC structure for large space telescopes. The Hubble space telescope has dramatically expanded our knowledge of the Universe, and the James Webb telescope that will soon begin operation will further add to our knowledge.

These space telescopes are relatively small, only a few meters in diameter, which limits their light gathering power and their image resolution capability. The much larger diameter of MIC supported telescopes, hundreds of meters in diameter, other than a few meters would enable astronomers to find and examine in detail terrestrial type planets around distant stars, to study the boundaries of black holes, to go even further back towards the Big Bang, and to make many more major new discoveries. Figure ES-6 shows a partial list of the areas in which MIC telescopes could make important findings.

There are many other potential applications of MIC structures. Figure ES-7 shows some of these other applications. MIC SC loops can store large amounts of electrical energy in the magnetic fields created by the high current superconducting (SC) cables. To store electrical energy, the total current carried by the conductors in the SC cable would be increased. To extract electrical energy, the current flowing in some of the conductors in the SC cable would flow through an external load.

MIC structures can also protect astronauts against cosmic radiation, as illustrated in Figure ES-7. The SC cables create a quadrupolar magnetic fields in the center of the quadrupole, where the crew quarters would be located, and very strong magnetic fields at the surface of the MIC structure. Incoming ionized particles, e.g., protons, etc., which account for the bulk of the radiation dose from cosmic rays, would be reflected back by the strong magnetic fields, and prevented from hitting the crew quarters.

In situations where a planetary magnetic field exists, e.g., around Earth or Jupiter, MIC structures can be used to propel spacecraft. Figure ES-7 illustrates the process. The SC cables on the side of the loop closest to Earth experience a stronger outwards magnetic force than those on the side further from Earth. Depending on the direction of the current in the SC cables, there is a net propulsion force radially outwards from Earth, or radially inwards. The MIC structure can then move a spacecraft to a higher orbit from a lower one, or to a lower orbit from a higher one energized. No propellant is needed. Electrical energy is required to charge the MIC SC cables, which can come from a solar cell array or a nuclear reactor power system.

MIC structures can also be used to form large, lightweight tankage for the storage of propellants and other materials. Figure ES-7 shows a side view of a MIC quadrupole tankage structure. Each of the 4 SC cables that form the quadrupole experiences a net radially outwards magnetic force, which is restrained by a tether network inside the quadrupole. The tether network in turn is attached to the flexible liner of the propellant tank, expanding it into a rigid strong structure. The tankage can be cylindrical in shape, or square, or elliptical, or whatever shape appears optimum. The MIC tank would be launched as a compact package of cables, tethers, and flexible liner. Once in space, the SC cables would be energized to form the large tank, which would then be ready to store propellants, or whatever material it was intended for.

Four MIC applications were chosen for further study:

- Solar electric generation
- Solar thermal propulsion
- Energy storage
- Large telescope

For each MIC application, three different potential systems were evaluated in terms of their utility and ability to be implemented within the next 10 to 20 years. For the MIC solar electric application, for example, MIC systems were evaluated for electric propulsion, power for a manned lunar base, and beamed electric power to Earth from solar satellites in GEO orbit. Of the 3 candidate systems, the MIC power system for a manned lunar base was selected as a baseline for detailed analysis. It was judged to have a high utility in the relatively near term, and to be simpler to implement than the beamed power application. Moreover, its implementation would provide a strong impetus for continued development as a major source of clean renewable power for Earth using beamed power from GEO satellites.

Figure ES-8 summarizes the systems evaluated for the 4 applications, and the results of the evaluation process. For the solar thermal propulsion application, the Earth-Moon solar tug was selected for more detailed study; for the energy storage application, a lunar energy storage system, and for the large space telescope, a deep field version to examine the early universe.

Figure ES-9 Summarizes the principal features of the baseline designs of the systems selected for the 4 MIC applications. All appear feasible based on already available superconductor and cryogenic technology, and all other very attractive performance capabilities. Three of the 4 baseline MIC systems are oriented towards supporting a manned lunar base.

- a. Solar electric generation
- b. Solar thermal propulsion for an Earth-Moon shuttle vehicle
- c. Electric energy storage

Besides providing major new capabilities for the declared NASA goal of returning to the Moon, development of these MIC systems would provide a strong base for extending them to other important applications, such as power beaming to Earth, solar thermal propulsion to Mars and energy storage for robotic and manned rovers.

The baseline designs for the 3 lunar oriented MIC applications assume that the lunar base is located at the South Pole of Moon, in the vicinity of the Shackelton Crater. The MIC systems could be used for any base location on the Moon, however. The systems can also be scaled to deliver smaller or larger outputs, as desired. Multiple MIC systems can also be used to provide redundancy and reliability. For example, the MIC solar electric system for the lunar base assumes an output of 1 MW(e). If higher output is desired, a larger MIC solar collector could be used, or several separate solar electric systems, each of 1 MW(e) could be used. The latter approach has the advantage of providing greater reliability and redundancy.

Figure ES-10 gives an assessment of the various superconductor options for the MIC system. Important criteria for this assessment include:

- Engineering current density, e.g., Amps/cm² of conductor
- Cryogenic temperature and refrigeration requirements
- Conductor stability and magnetic field capability
- Operating experience
- Commercial availability

High engineering current density, J_e , i.e., the amount of amps per unit area that a superconductor can carry, takes into account not only the superconductor itself, but the material on which it is deposited. High J_e is desirable because it minimizes the size and mass of the conductor that forms the MIC structure. J_e values of 100,000 amps/cm² are desired.

Low temperature superconductors (LTS) have been in use for decades in many superconducting systems. The main material used has been multi-filament Nb-Ti (Niobium Titanium) alloy imbedded in a copper or aluminum matrix. Nb-Ti superconductor offers high J_e ; however, it must operate at ~4 K with liquid Helium coolant, requiring substantial amounts of refrigeration power. More recently, practical High Temperature Superconductors (HTS) have become commercially available. The HTS conductors operate at much higher temperatures than Nb-Ti, up to liquid nitrogen temperature (77 K) for certain HTS conductors, and require much less refrigeration power.

LTS conductors have to be stabilized with high electrical conductivity materials such as high purity copper and aluminum to prevent them from transitioning out of the superconducting state into the resistive normal state when I^2R heating would quickly destroy them. HTS conductors, because of their much greater specific heat, are much less affected by small movements of the conductor, or sudden jumps in magnetic field, and are not subject to this problem.

Two practical HTS conductors, YBCO (Yttrium Barium Copper Oxide) and BSCCO (Bismuth Strontium Calcium Copper Oxide) have become commercially available in the last few years, and a third one, MgB₂ (Magnesium Diboride) is now starting to be commercialized.

HTS superconductors are favored for MIC applications because of their simpler thermal insulation and reduced refrigeration power requirements, as compared to LTS superconductors. The refrigeration power can be an order of magnitude smaller, and the cryocooler refrigeration equipment is less complex and more reliable than liquid helium refrigerators. HTS superconductors are presently several times more expensive in dollars per kiloamp meter of superconducting capacity than LTS superconductors. However, the price of HTS superconductors is dropping rapidly, and in any case, the cost of HTS conductors is only a small fraction of the \$10,000 per kilogram cost of launching payloads into Low Earth Orbit, and negligible compared to the much greater costs for payloads to the Moon, Mars, and beyond.

Of the HTS options, the YBCO and MgB₂ conductors appear the most promising. BSCCO conductors use a silver metal matrix for the superconductor, which will eventually limit production output. The YBCO and MgB₂ conductors use materials that are not limited in supply, and have high engineering current densities. For this study, both YBCO and MgB₂ are retained as options, with the principal difference between them being the higher operating temperatures possible with YBCO compared to MgB₂. The practical operating temperature for YBCO conductor appears to be in the range of 20 to 50 K, while for MgB₂ conductor the temperature range would be 15 to 20 K.

Figure ES-11 shows an illustrative view of the MIC superconducting cable. The superconductor region is enclosed inside a blanket of multi-layer thermal insulation (MLI). MLI insulation has been used for many years in superconducting systems on Earth. It consists of multiple layers of thin aluminum foil separated by a low density mat of glass fibers in a vacuum environment. The thermal conductivity of MLI insulation for cryogenic systems is extremely low, on the order of 0.5×10^{-6} w/cm K. Providing the vacuum environment is often difficult on Earth, because small air leaks through the piping that encloses the MLI region will destroy its insulating capability. In space, however, the vacuum environment for the MLI insulation automatically exists.

Using only 2 centimeters thick of MLI insulation, the refrigeration power for a MIC cable with HTS superconductor that carries 100's of thousands of supercurrent, with zero I^2R losses, is only a few kilowatts(e) per kilometer of cable length.

During the launch phase, the MIC superconducting cables are coiled up in a compact package, with the thermal insulation layer compressed to high density. After the MIC structure deployed in space, and energization of the superconductors in the MIC cable is initiated, a very small current, on the order of 1 Amp, is applied to the aluminum wires located on the outer surface of the MLI insulation. The small currents in these wires flow in the opposite direction to the 100's of thousands of amps in the MIC superconducting cable, producing a radial outwards magnetic force that expands the MLI insulation to its design operating thickness.

Figure ES-12 illustrates how the individual MIC superconductors would be supported in a MIC cable to prevent single point failures. The MIC cable consists of multiple independent conductor circuits, each with their own refrigerated coolant flow arranged on a support tube. If one or more of the individual circuits fail, the remaining superconducting circuits take over almost all ($\geq 99\%$) of their currents by magnetic induction, so that the total current carried by the cable is virtually unchanged.

The diameter of the support tube depends on the total current carried by the cable. A 400,000 Amp MIC cable with an OD of 4 centimeters for the superconductor pack on the support tube, would have a maximum magnetic field at the surface of 4 Tesla, an acceptable value. If the MIC cable is designed to carry a higher current, the diameter of the conductor pack would be proportionally greater; with 600,000 Amp current, for example, the OD of the superconductor pack would be 6 centimeters, assuming a surface magnetic field of 4 Tesla.

Each of the multiple individual conductors in the MIC cable has its own independent electrical and refrigeration circuits. For a current of 10,000 Amps in each individual conductor, a MIC cable that carried 400,000 Amps would have 40 separate conductors on its support tube. In turn, each individual conductor consists of a small diameter (0.3 centimeter) aluminum tube that carries its flowing refrigerant. Bonded to the outer surface of the aluminum tube is the HTS superconductor. This arrangement provides excellent thermal contact between the HTS conductor and its refrigeration circuit.

The multiple individual conductors can run in straight lines along the support tube, or be helically wound around it (Figure ES-12). If the conductors run in a straight line, there is a strong azimuthal magnetic field that exerts an inwards magnetic pressure on the conductors. For a surface magnetic field of 4 Tesla, the inwards pressure is ~6.4 MPa (~950 psi). This modest external pressure can be carried by the support tube. Alternatively, the conductors are helically wound at a 45 degree winding angle on the support tube, the inwards radial magnetic pressure from the azimuthal field is counteracted by the outwards radial magnetic pressure from the solenoidal field inside the support tube, resulting in a zero net radial magnetic force on the superconductors and the support tube.

The properties of the HTS superconductors considered for MIC are described in detail in Section 6 of the report; how they would be used in MIC cables is described in Section 7 of the report, together with analyses of the refrigeration requirements, and principal features of MIC cables (Figure ES-13).

A number of important conclusions can be drawn from the MIC study:

1. The MIC approach can be used to quickly erect large, very strong and rigid structures in space for a wide range of applications. The MIC structure can be launched as a compact package of coiled superconducting (SC) cables and Kevlar tethers. When the SC cables are energized with electrical current, the magnetic forces on them cause the compact package to automatically expand into the final large structure. No humans or robotic machines are needed to build the MIC structure
2. Previous studies of how to construct large structures in space without human or robotic operations have focused on mechanically extendable components and inflatable devices. The mechanical system approach tends to limit structure size and substantially increase its mass. Large scale inflatable structures appear possible, but have the disadvantages of being limited in rigidity, with the potential for substantial loss of the gas used to inflate and maintain the structure. The gas can escape through holes created in the large surface area of the inflatable structure by micrometeors and space debris. In contrast, MIC structures are much stronger than inflatable structures, with much greater rigidity. Moreover, the much smaller area of the superconducting cables allow them to be armored against micrometeors and space debris without significantly increasing system mass.

3. MIC structures can be 100's of meters in physical size, with very low specific masses, i.e., 0.1 kg/m^2 or less. MIC structures can be used in space or on bodies like the Moon or Mars. MIC structures can be used to generate large amounts of solar electric power, to heat H_2 propellant to high temperatures for spacecraft propulsion, for the storage of large amounts of electrical energy, for very large space telescopes, for the storage of propellants in space depots, for magnetic shielding of manned spacecraft, for propellantless propulsion using the planetary magnetic fields of Earth and Jupiter, and many other applications.

4. MIC would use the YBCO and MgB_2 High Temperature Superconductors (HTS) that have been recently commercialized. These HTS conductors operate at temperatures well above the 4 K customary with the older NbTi superconductor and require much less.

5. 1 kilometer long MIC superconducting cables carrying 100's of thousands of amps will only required a few kilowatts of electric power input to cryocoolers to maintain the superconductor at operating temperature, for example. [Since the superconductor has zero electrical constant, there are no I^2R losses requiring electric power input.]

6. MIC structures can be developed and demonstrated in vacuum diameters on Earth before being launched into space. The presence of Earth gravity will not cause problems with the deployment and rigidity of the MIC structure. Because of extensive existing cryogenic and superconducting technology base, large MIC structures could be implemented in the next decade.

7. MIC structures will play a major role in space exploration, enabling permanent manned bases on the Moon, high efficiency propulsion, effective magnetic shielding against cosmic radiation, major new astronomical discoveries, including detection and imaging of terrestrial type planets around distant stars, and many more applications. MIC structures can also play a major role in providing Earth with greatly improved communication capability, better environmental monitoring, and large amounts of clean electrical power beamed from space solar power satellites.

Figure ES-1 MIC Launch and Deployment Sequence

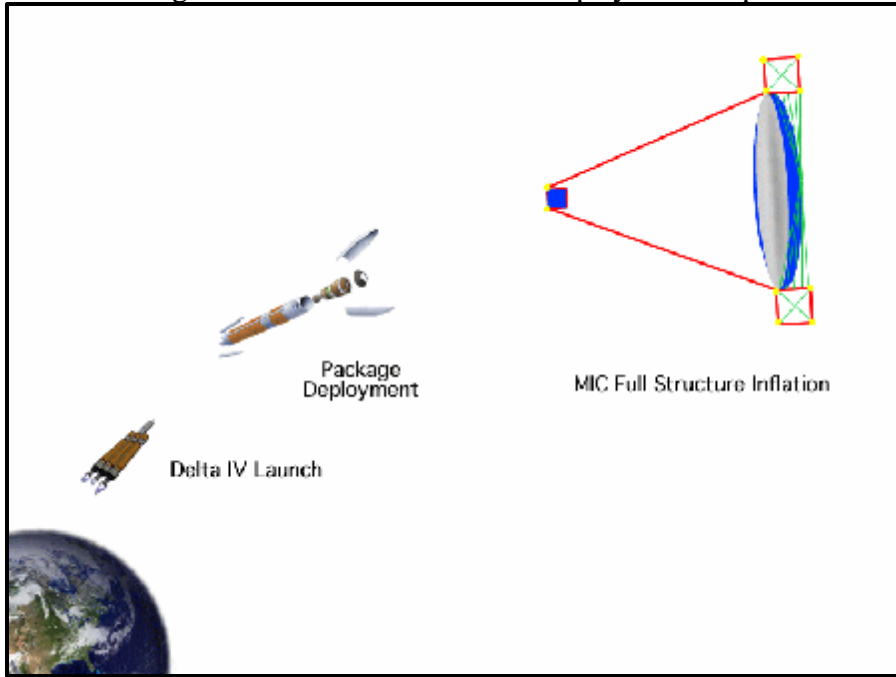


Figure ES-2 Potential Space Applications for MIC Structures

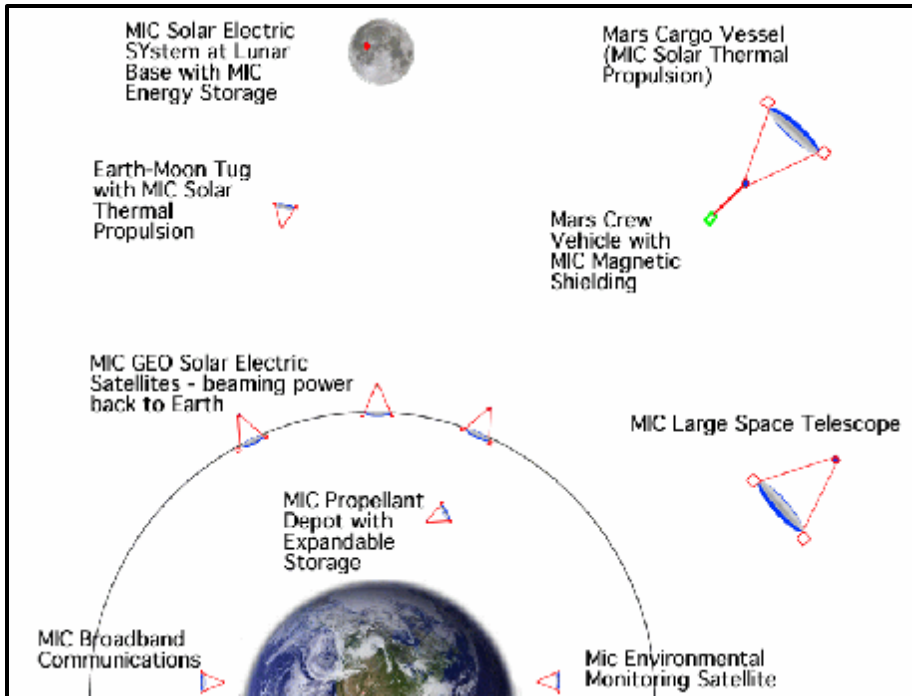


Figure ES-3

SOLAR ELECTRIC GENERATOR USING MIC STRUCTURES

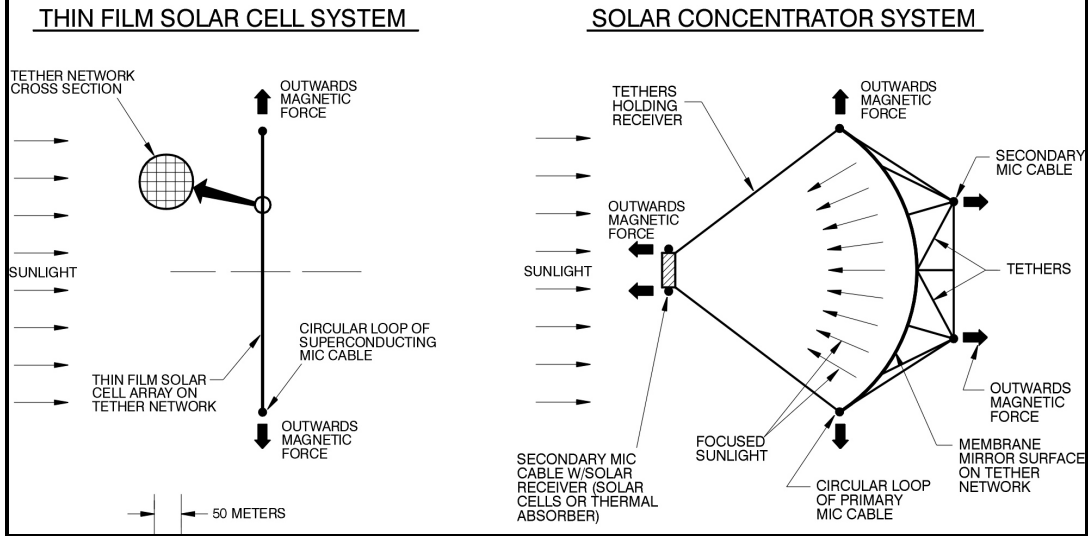
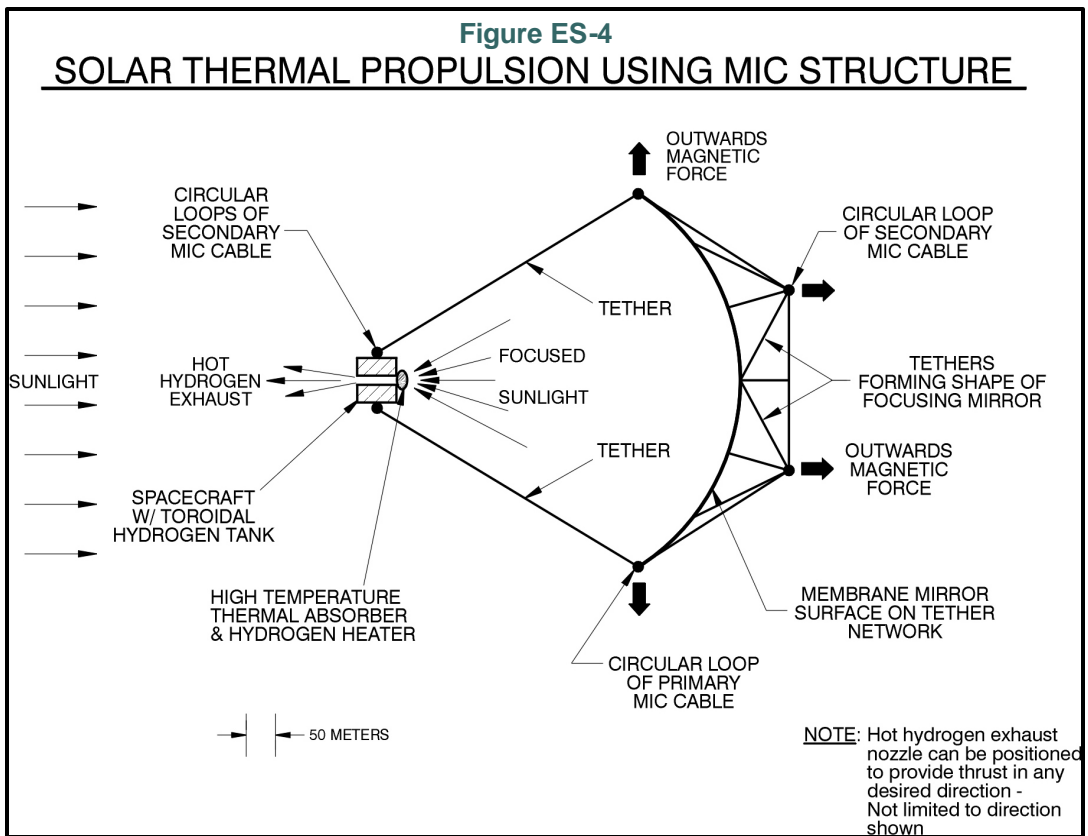


Figure ES-4

SOLAR THERMAL PROPULSION USING MIC STRUCTURE



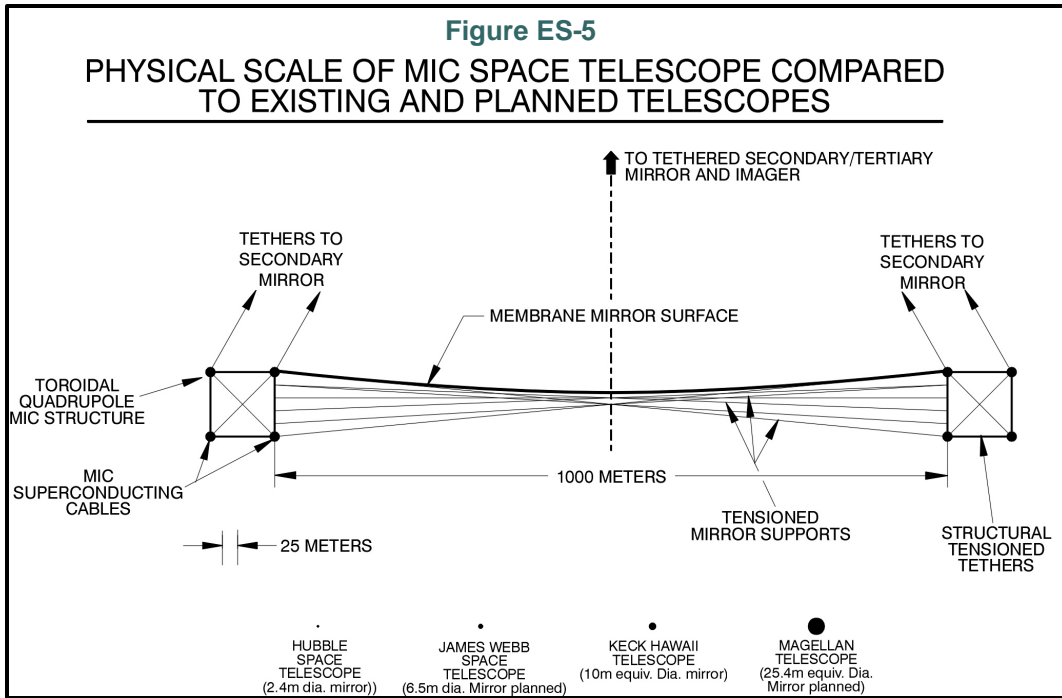


Figure ES-6
New Astronomical Discoveries Enabled by MIC Space Telescope

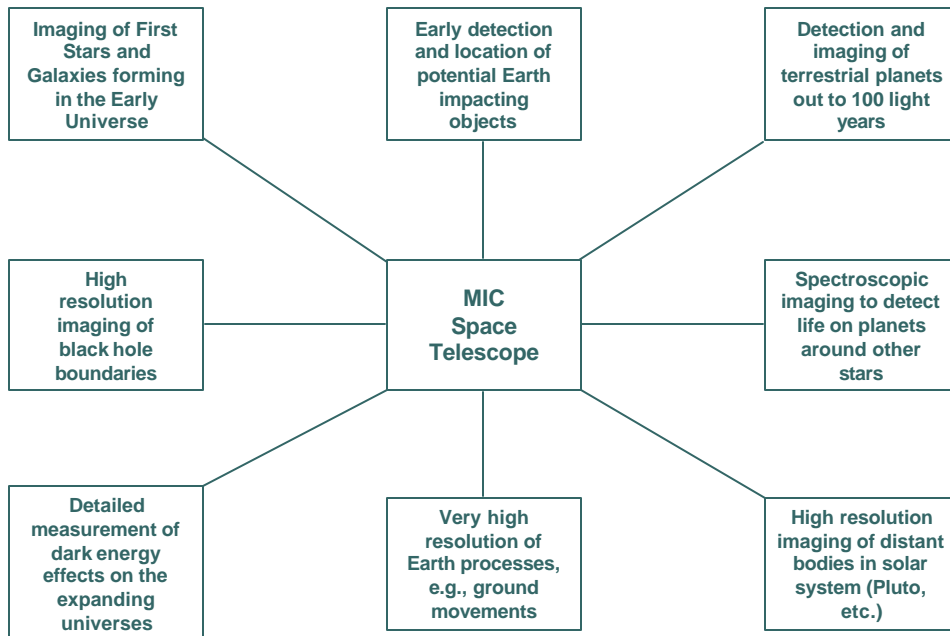
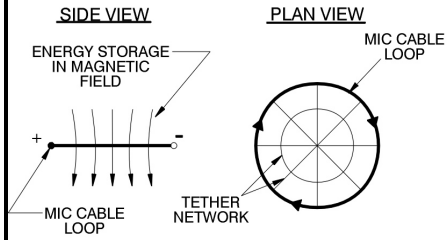


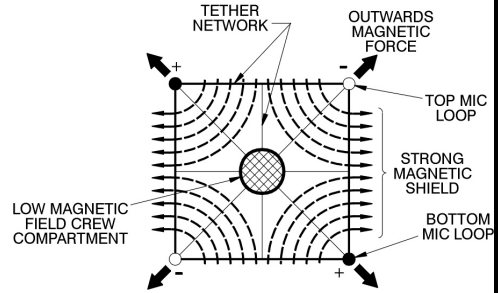
Figure ES-7

ADDITIONAL SPACE APPLICATIONS USING MIC STRUCTURES

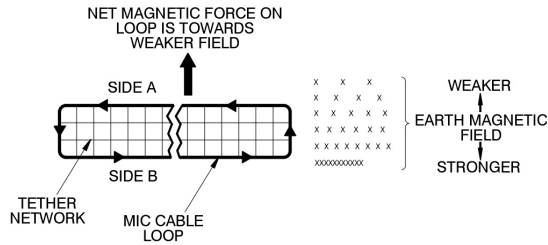
ENERGY STORAGE USING RECTANGULAR OR CIRCULAR MIC LOOP



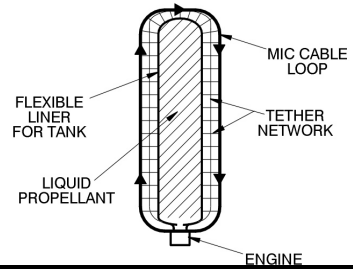
MAGNETIC SHIELDING USING RECTANGULAR QUADRUPOLE MIC STRUCTURE



PROPELLANTLESS PROPULSION USING RECTANGULAR MIC LOOP



SIDE VIEW



**Figure ES-8 Evaluation of Potential Systems for Three MIC Applications –
Solar Electric Generation, Solar Thermal Propulsion, and Energy Storage**

MIC Application	Systems Considered	MIC Parameters	Evaluation
1. Solar Electric Generation	<ul style="list-style-type: none"> • Lunar base power MIC solar concentrator • Solar electric propulsion at 3 AU • Power beaming to Earth from GEO 	<p align="center">1 MW(e) 70 Meter Diameter 100 KW(e) 70 Meter Diameter 200 MW(e) 900 Meter Diameter</p>	<p>Lunar base power application selected for baseline design as having greatest near term potential. Power beaming to Earth has greatest long term potential</p>
2. Solar Thermal Propulsion	<ul style="list-style-type: none"> • Earth-Moon tug for payload to lunar base • Orbital tug, LEO to GEO • Mars cargo vessel 	<p align="center">5 MW(th) 70 Meter Diameter 1 MW(th) 30 Meter Diameter 10 MW(th) 100 Meter Diameter</p>	<p>Earth-Moon tug application selected for baseline design, as having greatest near term potential. Tug can transport ~30 ton payloads to Moon in ~5 days</p>
3. Energy Storage	<ul style="list-style-type: none"> • Lunar base • Spacecraft • Robotic rover 	<p align="center">2000 Megajoules 100 Meter Diameter 100 Megajoules 50 Meter Diameter 5 Megajoules Meter Long Quadrupoles</p>	<p>Lunar base application selected for baseline design, as having most important near term potential. Storage system can deliver power when power during lunar night period.</p>

Figure ES-9 Principal Features of Baseline Design for Four MIC Applications

MIC Application	Principal Features	Design Parameters
1. 1 MW(e) solar electric system for lunar base	<ul style="list-style-type: none"> • MIC mirror is magnetically supported and moves to follow Sun position • Long trough shape of MIC mirror focuses sunlight on central lunar solar cell array 	<ul style="list-style-type: none"> • Vertical quadrupole, 300 meters high, 30 meters wide • 200,000 Amp MIC cable forms quadrupole
2. 5 MW(th) solar thermal propulsion for Earth-Moon tug	<ul style="list-style-type: none"> • MIC mirror focuses sunlight onto high temperature receiver • 70 meter diameter MIC mirror 	<ul style="list-style-type: none"> • 5 day trip to Moon from LEO • 30 metric ton payload
3. 2000 Megajoules energy storage for lunar base	<ul style="list-style-type: none"> • Circular MIC loop is magnetically levitated above lunar surface 	<ul style="list-style-type: none"> • 1 million Amp MIC cable • 700 meter loop diameter
4. Large space telescope	<ul style="list-style-type: none"> • Much greater resolution (400 x) and light gathering power (160,000 x) than Hubble telescope • MIC primary mirror focuses on small secondary mirror that has adaptive optics 	<ul style="list-style-type: none"> • 1 km diameter • 50.1 kg/m² mass • Short focal length option can make wide field survey of early universe • Long focal length option can investigate extra terrestrial planets

Figure ES-10 Assessment of Superconducting Options for MIC Systems

Superconductor Type
[LTS = Low temperature SC; HTS = High temperature SC]

Evaluation Area	NbTi/LTS	YBCO/HTS	BSSCO/HTS	MgB₂/HTS
1. Practical temperature range	4 K	20 to 20 K	20 to 70 K	15 to 20 K
2. Coolant type	Liquid He	He gas or liq. N ₂	He gas or liq. N ₂	He gas
3. Refrigeration factor W(e)/W(th) @ temp for 20% of Carnot efficiency	370 W(e)/W(th) @ 4K	W(e)/W(th) @ 40 K		74 W(e)/W(th) @ 20 K
4. Eng current density*	~2x10 ⁵ A/cm ²	~10 ⁵ A/cm ² **	~10 ⁵ A/cm ² **	~8 x 10 ⁴ A **/cm ²
5. Fabricated form	Multi-filament NbTi in copper or Al wire	Thin film of YBCO on nickel alloy tabe	Multi-filaments in silver wire	Multi-filament in Nb wire. Also thin film option
6. Stability	Very low specific heat – require Cu or Al stabilizer	Good – does not need Cu or Al stabilizer	Good – does not need Cu or Al stabilizer	Good – does not need Cu or Al stabilizer
7. Commercial availability	Excellent – available for more than 30 years	Good – now commercially available	Good – now commercially available	Coming commercial production
8. Overall evaluation	*Not favored – refrigeration is different for space systems	Favored – practical conductor with acceptable refrigeration requirements	Limited – availability of silver matrix may limit production amount	Practical – conductor with acceptable refrigeration requirements

* Nominal external magnetic field of 2 Tesla

** Projected, assuming thicker SC film and improved SC crystal interface provides ~3 fold increase

Figure ES-11

MULTI LAYER THERMAL INSULATION OF MIC CONDUCTOR AFTER EXPANSION

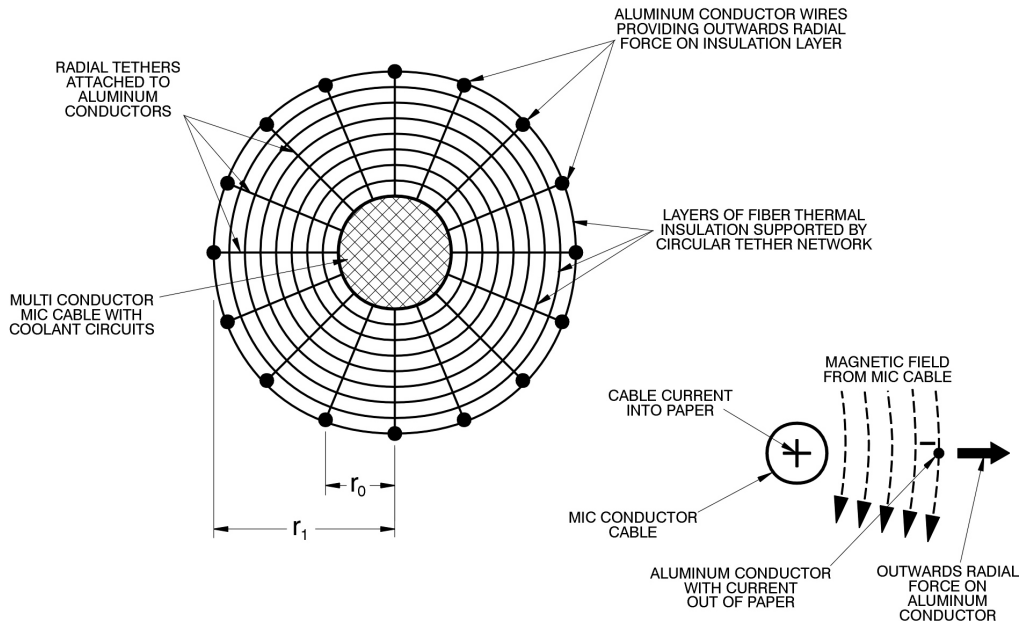


Figure ES-12

Illustrative Views Of Method For Support Of Multiple MIC Conductors On Single MIC Cable Using Central Structural Tube

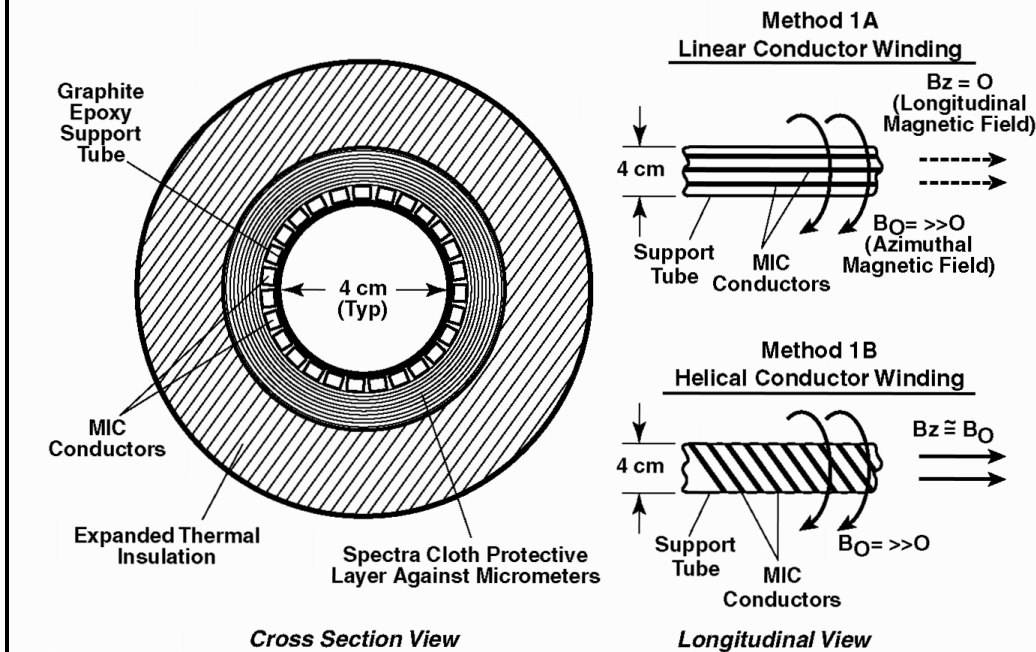


Figure ES-13 Principal Features of MIC Superconducting Cables

Feature	Description
1. Form of MIC Cable	Multiple independent superconductors positioned around circumference of central support tube with several centimeter thick layer of thermal insulation around conductors.
2. Method of Cooling	Each independent superconductor has its own coolant flow circuit carrying pressurized helium gas or liquid N ₂ coolant, depending on operating temperature and type of superconductor. Coolant is refrigerated by conventional cryocoolers using electric power input.
3. Reliability and Redundancy of MIC Cable	Each independent superconductor has its own persistent current connection that carries only the current that flows in the conductor. If an individual circuit superconductor circuit should fail due to mechanical, coolant, or other problems, virtually all of its current will automatically transfer by magnetic induction to the many neighboring superconductor circuits, so that the total current carried by the MIC cable will remain essentially constant.
4. Protection Against Micro Meteors and Space Debris	The multiple superconductors on the MIC cable are protected by a thick outer layer of high strength material that encloses the cable.
5. MIC Cable Current Capacity and Size	A single MIC cable can carry up to one million amps, with a cable diameter of ~10 centimeters for the superconducting region, and an overall outer diameter of ~15 centimeters, including thermal insulation. All applications except, energy storage, propellantless propulsions and magnetic shield can be accomplished using a single MIC cable. For the applications requiring more than 1 million amps, several MIC cables would be used.
6. MIC Cable Mass and Refrigeration Power Requirements	A one kilometer length of 2 centimeter diameter MIC cable designed to carry 200,000 Amps using YBCO superconductor of 40 K would require a refrigeration power of ~2 KW(e) and have a mass of ~2 tons.

TABLE OF CONTENTS

	Page #
ABSTRACT	ii
EXECUTIVE SUMMARY	iii
LIST OF FIGURES	xxiii
LIST OF TABLES	xxix
1.0 INTRODUCTION.....	1-1
2.0 POTENTIAL APPLICATIONS OF LARGE MIC SPACE STRUCTURES.....	2-1
3.0 EXISTING CONCEPTS FOR THE CONSTRUCTION OF LARGE SPACE STRUCTURES	3-1
4.0 THE MAGNETICALLY INFLATED CABLE (MIC) CONCEPT FOR THE CONSTRUCTION OF LARGE SPACE STRUCTURES	4-1
5.0 EVALUATION AND SELECTION OF PROMISING SPECIFIC APPLICATIONS BASED ON THE MIC CONCEPT	5-1
5.1 MIC Solar Electric Applications.....	5-1
5.2 MIC Solar Thermal Propulsion.....	5-2
5.3 MIC Energy Storage Application	5-4
5.4 MIC Space Telescopes.....	5-7
5.5 MIC Propellantless Propulsion	5-8
5.6 MIC Magnetic Shielding.....	5-10
5.7 MIC Expandable Tankage	5-11
5.8 MIC Earth Communications and Sensing.....	5-13
6.0 EVALUATION AND SELECTION OF SUPERCONDUCTORS FOR MIC APPLICATIONS	6-1
6.1 Goals and Requirements for MIC Superconductors	6-1
6.2 Comparison of LTS and HTS Superconductors for MIC Applications.....	6-2
6.3 Present and Projected Capabilities for High Temperature Superconductors	6-4
6.3.1 BSCCO High Temperature Superconductor.....	6-4
6.3.2 YBCO High Temperature Superconductor.....	6-4
6.3.3 MgB ₂ High Temperature Superconductor	6-5
6.4 Selection of HTS Conductors for Proposed MIC Applications	6-6

TABLE OF CONTENTS
(continued)

	Page #
7.0 CONSTRUCTION, ERECTION, AND OPERATION OF MIC STRUCTURES	7-1
7.1 MIC Thermal Insulation.....	7-1
7.2 MIC Cooling and Refrigeration.....	7-3
7.3 MIC Conductor Support Methods	7-7
7.4 Redundancy and Reliability of MIC Conductor Systems	7-10
8.0 BASELINE DESIGN OF MIC SOLAR ELECTRIC SYSTEM FOR A LUNAR BASE	8-1
9.0 BASELINE DESIGN OF MIC SOLAR THERMAL PROPULSION SYSTEM FOR A EARTH-MOON TUG.....	9-1
10.0 BASELINE DESIGN OF MIC ENERGY STORAGE SYSTEM FOR A LUNAR BASE	10-1
11.0 BASELINE DESIGN OF MIC LARGE SPACE TELESCOPE.....	11-1
12.0 DEVELOPMENT OF MIC TECHNOLOGY	12-1
12.1 High Temperature Superconductor Development and Testing	12-1
12.2 Testing and Validation of MIC Structures	12-2
13.0 SUMMARY AND CONCLUSIONS	13-1

LIST OF FIGURES

	Page #
ES-1 MIC Launch and Deployment Sequence	xi
ES-2 Potential Space Applications for MIC Structures	xi
ES-3 Solar Electric Generator Using MIC Structure	xii
ES-4 Solar Thermal Propulsion Using MIC Structure	xii
ES-5 Physical Scale of MIC Space Telescope Compared to Existing and Planned Telescopes	xiii
ES-6 New Astronomical Discoveries Enabled by MIC Space Telescope	xiii
ES-7 Additional Space Applications Using MIC Structures	xiv
ES-8 Evaluation of Potential Systems for Three MIC Applications: Solar Electric Generation, Solar Thermal Propulsion, and Energy Storage	xv
ES-9 Principal Features of Baseline Designs for Four MIC Applications: Solar Electric, Solar Thermal Propulsion, Energy Storage, and Large Telescope.....	xvi
ES-10 Assessment of Superconductor Options for MIC Systems	xvii
ES-11 Multi-Layer Thermal Insulation of MIC Conductor After Expansion	xviii
ES-12 Illustrative Views of Method for Support of Multiple MIC Conductors on Single MIC Cable Using Central Structural Tube	xviii
ES-13 Principal Features of MIC Superconducting Cables.....	xix
2.1 Solar Electric Generation Using MIC Structures.....	2-6
2.2 Electrical Generation Capability of MIC Solar Electric Systems as a Function of MIC Loop Diameter	2-7
2.3 Solar Thermal Propulsion Using MIC Structure	2-7
2.4 Thrust Capability of MIC Solar Thermal Propulsion System as a Function of MIC Loop Diameter	2-8

LIST OF FIGURES
(continued)

		Page #
2.5	Physical Scale of MIC Space Telescope Compared to Existing and Planned Telescope	2-8
2.6	New Astronomical Discoveries Enabled by MIC Space Telescope	2-9
2.7	Different Types of Structures based on High Temperature Superconducting Cables ..	2-9
2.8	Additional Space Applications Using MIC Structures	2-10
2.9	Earth Communications and Sensing Applications Using MIC Structures: Some Illustrated Examples.....	2-10
4.1	MIC Disc Geometry for Solar Electric, Solar Thermal Propulsion, Space Telescope, and Energy Storage Applications	4-7
4.2	MIC Rectangular Dipole Loop and Quadrupole Geometry.....	4-7
4.3	Launch, Deployment, Energization, and Operation Sequence for MIC Structures	4-8
4.4	MIC Launch and Deployment Sequence	4-8
4.5	Principal Components of MIC Structures	4-9
4.6	Illustrative Views of Method for Support of Single MIC Cable Using Central Structural Tube.....	4-9
4.7	Magnetic Force on a MIC Conductor Cable as a Function of MIC System Size and Conductor Current, for the MIC Dipole Rectangular Loop Geometry.....	4-10
4.8	Stored Electrical Energy in MIC Structure as a Function of Size of MIC System and Conductor Current for Rectangular Dipole Loops.....	4-10
4.9	Mass Budget for MIC Solar Electric and Energy Storage Structures.....	4-11
5.1.1	Potential MIC Solar Electric Applications - Goals and Requirements	5-15
5.1.2	Evaluation of MIC Solar Electric Applications	5-16
5.2.1	Potential MIC Solar Thermal Propulsion Applications - Features and Requirements	5-17

LIST OF FIGURES

(continued)

	Page #
5.2.2 Evaluation of MIC Solar Thermal Propulsion Applications	5-18
5.3.1 Potential MIC Energy Storage Applications - Features and Requirements.....	5-19
5.3.2 Evaluation of MIC Energy Storage Applications	5-20
5.4.1 Strehl Ratio	5-21
5.5.1 MIC Propellantless Propulsion - Features and Requirements	5-22
5.5.2 Evaluation of MIC Propellantless Propulsion.....	5-23
5.6.1 MIC Magnetic Shielding - Features and Requirements.....	5-24
5.7.1 Features and Requirements for MIC Expandable Propellant, Tankage Applications	5-25
6.1.1 Functional Requirements for MIC Superconductor.....	6-8
6.3.1.1 Description of BSCCO HTS Superconductor.....	6-9
6.3.1.2 Fabricated form of BSCCO High Temperature Superconducting Wire Tape	6-10
6.3.1.3 Current Density vs Operating Temperature and Magnetic Field for BSCCO High Temperature Superconductors	6-11
6.3.1.4 Present and Projected Future Capabilities of BSCCO Superconductor	6-12
6.3.2.1 Description of YBCO HTS Superconductor.....	6-13
6.3.2.2 High Temperature Superconductor (HTS) 2G Wire Architecture.....	6-14
6.3.2.3A 77K Performance of YBCO (MOD)/RABITS 2G Wire.....	6-15
6.3.2.3B Nanodot Improvement of I_C in Field at 27 K.....	6-16
6.3.2.4 Present and Projected Future Capabilities of YBCO Superconductor Based on American RABITS Process	6-17

LIST OF FIGURES
(continued)

	Page #
6.3.3.1 Description of MgB ₂ HTS Superconductor	6-18
6.3.3.2A Continuous Manufacturing Process	6-19
6.3.3.2B Multifilament Strands.....	6-20
6.3.3.3 Current Density in MgB ₂ Superconductor by HyperTech - Best Short Sample Results	6-21
6.3.3.4 Present and Projected Future Capabilities of MgB ₂ Superconductor Based on HyperTech Data for MgB ₂ 7 Multi-Filament Wire	6-22
6.4.1 Criteria for Selection of HTS Conductor for the Various MIC Applications	6-23
6.4.2 HTS Conductor Assessment for Various MIC Applications	6-24
7.1.1 Multi-Layer Thermal Insulation of MIC Conductor After Expansion	7-12
7.1.2 Thermal Leakage into MIC Cable as Function of Insulation Thickness and Local Surface Temperature	7-12
7.1.3 Distribution of Surface Temperature and Thermal Heat Leak Around Circumference of MIC Cable Exposed to Non-Uniform Illumination.....	7-13
7.1.4 Erection Process for MIC Thermal Insulation.....	7-13
7.2.1 Flowsheet for MIC Cooling and Refrigeration System	7-14
7.2.2 Refrigeration Factor as a Function of Superconductor Temperature Fractional Carnot Efficiency, and Radiator Temperature	7-14
7.2.3 Refrigeration Power of 1 Km MIC as a Function of Superconductor Temperature, Fractional Carnot Efficiency, and Radiator Temperature	7-15
7.2.4 Radiator Area for Reject Heat from Cryocooler for 1 kilometer MIC Cable as a Function of Superconductor Temperature, Fractional Carnot Efficiency and Radiator Temperature	7-15
7.2.5 Illustrative Cross Section of MIC Conductor with Attached Coolant Tube	7-16
7.3.1 Methods of Supporting Conductor in MIC Cables	7-16

LIST OF FIGURES

(continued)

	Page #
7.3.2 Illustrative Views of Method for Support of Multiple MIC Conductors on Single MIC Cable Using Control Structural Tube	7-17
7.3.3 Illustrative View of Method 2 for Support of Multiple MIC Conductors on Single MIC Cable Using Central Solenoidal Field	7-17
7.3.4 Superconducting Connections for MIC Cable	7-18
7.4.1 Reliability and Redundancy Features of MIC Conductor and Cable Systems	7-18
7.4.2 Persistent Switch and Charging Process for MIC Sub-Conductor	7-19
8.1 MIC Lunar Quadrupole Configuration for Solar Electric Concentrator on the Moon...	8-5
8.2 Support and Rotation of MIC Solar Electric Quadrupole on the Moon.....	8-6
8.3 Principal Features of the Solar Electric System for a Manned Lunar Base	8-7
8.4 Design Parameters for MIC Solar Electric System for a Manned Lunar Base.....	8-8
8.5 Output Power from MIC Solar Electric System for a Manned Lunar Base.....	8-10
9.1 Principal Features of the Solar Thermal Propulsion System for an Earth-Moon Tug..	9-3
9.2 Design Parameters of the Solar Thermal Propulsion System for an Earth-Moon Tug.	9-4
10.1 Potential MIC Energy Storage Configurations for a Manned Lunar Base	10-3
10.2 Assessment of MIC Energy Storage Configurations for a Manned Lunar Base	10-4
10.3 MIC Energy Storage System for a Manned Lunar Base Using an Anchored Circular Loop	10-5
10.4 Design Parameters for MIC Energy Storage System for a Manned Lunar Base	10-6

LIST OF FIGURES
(continued)

	Page #
11.1 Notional Concept of Hugh Filled Aperture MIC Telescope with Pamela Correction Package	11-4
11.2 Three Mirror Large Aperture Telescope for High Orbit.....	11-5
11.3 Mass Scaling of Optical Telescopes	11-6
12.2.1 Deployment Program for MIC Structures.....	12-4

LIST OF TABLES

	Page #
5.1.1 Nominal Design Parameters for Potential MIC Solar Applications	5-26
5.2.1 Nominal Design Parameters for Potential MIC Solar Thermal Propulsion Applications	5-27
5.3.1 Nominal Design Parameters for Potential MIC Energy Storage Applications	5-28
6.2.1 Comparative Performance Capabilities of High Temperature Superconductor (HTS) and Low Temperature Superconductors (LTS) for MIC Applications.....	6-25
6.2.2 Examples of Large Scale Superconducting Applications Using Low Temperature Superconductors.....	6-26
7.1.1 Illustrative Parameters for MIC Thermal Insulation.....	7-20
7.1.2 Thermal Insulation Parameters for Illustrative MIC Applications	7-21
7.2.1 Helium Coolant Flow Rate and Pressure Drop Through MIC Conductor.....	7-22
7.3.1 Illustrative Operating Envelope for MIC Cable Regimes.....	7-23

1.0 INTRODUCTION

Space structures, whether small in scale like communications satellites or large in scale, like the International Space Station (ISS), are essential to the exploration, commercial utilization, and human presence in space. As these activities grow in scope, larger structures will be needed. For example, space power outputs will increase, necessitating larger solar cell or mirror arrays. If nuclear energy sources are used, larger structures will be required to radiate away waste heat. Eventually, space structures with kilometer size dimensions could generate thousands of megawatts of electric power to be beamed back to Earth, for clean, non-polluting energy. Other applications include much larger space telescopes to find and image terrestrial-like planets around distant stars, hotels for space tourists, mining operations on the Moon and asteroids, and so on.

To date, space structures generally have been launched either in finished form if they are small (the structure may involve mechanical unfolding of rigid components like solar panels after reaching orbit) or built up by multiple assembly steps if they are large, like the International Space Station. Such multi-step assembly processes generally require substantial amounts of human operations in space.

The Magnetically Inflated Cable (MIC) concept described in this report is a completely new approach to constructing large space structures. MIC structures consist of a flexible network of superconducting cables, high strength tensile tethers, and depending on the particular MIC structure to be erected in space, various other components. When not energized by electric current, the complete MIC structure can be compressed into a compact package for launch on a conventional launch vehicle, e.g., Atlas, Delta, etc. After it is placed into orbit or on its way to its target destination, the superconducting cables are energized with electric current, causing the MIC structure to automatically expand into its final operational form. Multi-step assembly and human personnel are not necessary.

Besides eliminating the need for a complex, multi-step assembly process, the MIC approach also results in very lightweight, very rigid structures that have precise and controllable dimensions and properties. MIC structures can be used for structures that are multi-kilometer in scale, and have a wide range of applications, including power generation, energy storage, propulsion, habitats, large telescopes, and other uses.

In the rest of this report, the basic MIC concept is described, together with baseline designs for various applications. The status of the superconductors that would be used in MIC structures is also reviewed particularly with regard to high temperature superconductors.

2.0 POTENTIAL APPLICATIONS OF LARGE MIC SPACE STRUCTURES

There are many potential applications for the MIC concept, which are described in detail in the following sections of this report. In this section, these potential applications are briefly shown in order to give an overall view of the range and performance capabilities of MIC structures.

Figure 2.1 illustrates how MIC structures would be used to generate large amounts of electric power, either in space, or on the surface of the Moon or Mars. In the left hand drawing, the MIC superconducting (SC) cable forms a large circular ring after it is electrically energized to produce the radially outwards magnetic force on the cable. The magnetic forces are restrained by a network of high strength tension tethers that are attached to the SC cable. The tether network also acts as a support surface for a large array of thin film solar cells, which convert the sunlight shining onto the MIC disc into electric power.

The right hand drawing in Figure 2.1 illustrates an alternate MIC approach for solar electric generation. The MIC SC cable and restraining tether network form a parabolic shaped surface on which a reflecting material (e.g., aluminized mylar) rests. The incoming sunlight is then reflected and focused onto a considerably smaller receiver, greatly increasing the solar flux intensity. For example, the incoming solar flux of 1.2 kW(th)/m^2 in Earth orbit could be increased by a factor of 50, 100, 200, to whatever flux the receiver was designed for.

The received sunlight on the receiver would then be converted to electric power using either a high temperature solar cell array, or a solar dynamic power cycle (e.g., a gas Brayton cycle or a steam cycle).

Additional MIC SC cables and tensile tethers are required for this approach, in order to form the parabolic mirror shape and hold the receiver at the proper focal point. As illustrated in Figure 2.1, there would be a smaller secondary SC loop behind the primary large MIC SC loop. This would be magnetically pushed away from the primary SC loop, because there would be oppositely directed currents flowing in the two loops. The magnetic repulsion forces between the two loops would be restrained by tensile tethers, with their lengths and attachment points chosen so as to create the proper parabolic shape.

The receiver is attached to another secondary MIC SC loop, which is also magnetically pushed away from the primary SC loop, and restrained by tensile tethers. The lengths and attachment points of the tethers are chosen to position the receiver at the correct focal point.

The MIC solar concentrator geometry is more complex than the disc, but does not pose any significant difficulty in construction, deployment or operation. For the solar cell electric system, the solar concentrator option will be substantially lighter and cheaper, because of the much smaller number of solar cells required.

The solar dynamic system probably will be substantially heavier than the solar cell system, because of the need for a large waste heat radiator. Figure 2.1 does not show the radiator, which would be integrated into the MIC structure, probably on the back side of the solar concentrator.

Figure 2.2 shows the electrical generation output of a MIC solar electric system as a function of the MIC loop diameter. The solar flux intensity is assumed to be 1.2 kW(th)/m^2 (Earth orbit intensity) with a 20% conversion efficiency, thermal to electric. Three potential application areas are shown

- electric propulsion @ outputs of several 100's of kilowatts(e)
- lunar base @ outputs of several megawatts(e)
- power beaming to Earth @ several gigawatts(e)

The corresponding MIC loop diameters are very reasonable. A ~20 meter diameter loop would be sufficient for electric propulsion, a ~100 meter loop for a lunar base, and a ~2 kilometer loop for power beaming.

Figure 2.3 illustrates a second MIC application solar thermal propulsion. The MIC structure would form a large parabolic mirror, similar to that shown in Figure 2.1, that would focus sunlight onto a high temperature receiver. Hydrogen propellant flowing through the receiver would be heated to a high temperature, e.g., 2500 K or more, and then exit through a nozzle, providing propulsive thrust.

The hot hydrogen propellant would have a high specific impulse, 900 seconds or more, depending on exit temperature. The high Isp would be much greater than that from chemical propellants (the highest Isp using chemical propellant is 450 seconds, for H_2/O_2 fuel), and would enable much greater payload fraction and/or much higher OV capability for space missions.

While similar in construction to the MIC solar electric system, the MIC solar thermal propulsion system requires substantially greater solar concentration factors, on the order of a 1000 or more, as compared to a value of 100 or so for the solar electric application. This will require a more precise shape for the concentrating mirror.

Figure 2.4 shows the thrust capability of the MIC solar thermal propulsion systems as a function of the MIC loop diameter. The thrust increases as the square of loop diameter. At 100 meters diameter, for example, the MIC system will generate 1800 Newtons of thrust, which would provide a OV increase of 1.5 kilometers per second for a 100 ton spacecraft after only 1 day of operation. A 200 meter diameter MIC loop would provide 7200 Newtons of thrust, for a OV of 6 kilometers per second after 1 day of thrust. Using longer periods of thrusting, the diameter of the MIC loop could be reduced. For example, for a mission to the outer solar system with a 10 ton spacecraft, a 30 meter diameter MIC loop operating for 10 days would yield a OV of 15 kilometers per second.

Figure 2.5 shows one possible configuration for a large MIC space telescope. Other configurations are also possible, including the parabolic mirror configurations shown in Figures 2.1 and 2.3. The configuration in Figure 2.5 does not use a secondary MIC cable loop in back of the primary MIC loop as illustrated in Figures 2.1 and 2.3. Instead, the MIC ring consists of 4 separate SC cables alternating in direction as one proceeds around the quadrupole. Each SC cable then experiences a net outwards radial magnetic force, which is restrained by the network of tensile tethers inside the square cross section of the quadrupole.

The resultant MIC quadrupole ring is very strong and rigid. A network of tensile tethers stretches across the ring to form a precise, parabolic support surface that holds a large number of individual mirror segments. The attachment points for the tethers are chosen so as to provide a shallow parabolic shape that focuses the collected starlight into a secondary mirror (not shown) and then onto a CCD or other imaging device.

The precise shape and local control of the mirror surface are controlled by the choice of the attachment points and the controlled tension in the tethers.

A MIC telescope structure can be very large, e.g., 1000 meters or more in diameter, and still be capable of being launched using conventional rockets. Moreover, after reaching orbit the large MIC telescope can be quickly deployed into its final form without requiring any intermediate assembly steps.

Figure 2.6 shows some of the important new astronomical discoveries that would be possible with a large MIC telescope. Finding and imaging terrestrial-like planets orbiting distant stars, and being able to determine whether they harbor life, would be extremely exciting and important. Other major achievements would be the capability to image the very first stars and galaxies forming in the early universe, the regions adjacent to the event horizons of black holes, potential impactors heading for Earth, and many other discoveries not now possible.

There is a wide variety of possible MIC structural configuration. Figure 2.7 shows 4 of these forms:

1. Simple circular dipole loop
2. Simple rectangular dipole loop
3. Rectangular quadrupole
4. Circular quadrupole

In general, the simple circular and rectangular loops would be used for applications where just a surface is needed, like solar concentrators, solar cell array, large telescopes, etc. The simple loop configuration would also apply to energy storage applications.

The quadrupole configurations would be used for applications involving a need for interior volume, e.g., a magnetically shielded manned spacecraft or propellant tankage.

In all of the above configurations, the MIC superconducting cables experience outwards magnetic forces, which are restrained by a network of high tensile strength tethers. For the simple circular loop, the magnetic forces on the MIC SC cables are radially outwards; for the simple dipole loop, the magnetic forces are outwards on the parallel straight sides of the loop, and longitudinally outwards on the curved ends of the loop. As a result, the tensile tether network for the rectangular loop is laid out in 2 directions, (i.e., x and y) in the plane of the loop.

For the circular quadrupole, in addition to the tensile tethers that run in the radial direction to carry the outwards magnetic forces on the MIC superconducting cables, there are also tethers that run in the z direction. These hold the 2 loops together and keep them from flying apart (the currents in the upper and lower MIC loops circulate in opposite directions, resulting in magnetic forces that act to push the loops away from each other to form the tension stabilized structure).

For the rectangular quadrupole, the tethers run in a 3-dimensional network of x, y, and z directions. The tethers not only maintain each rectangular loop in its proper (x, y) configuration, but also restrain the z directed magnetic forces that act to push the loops apart.

Figure 2.8 shows some additional MIC applications other than the solar electric, solar thermal propulsion, and large space telescope systems. Large amounts of electrical energy can be stored in the magnetic field created by the superconducting current. Electrical energy is pumped into the loop by using an external power source to increase the current in the loop. When it is desired to extract the stored electrical energy, the superconducting current is directed through an external load, e.g., either resistive or mechanical (i.e., a motor) in nature.

The MIC energy storage loop can store energy, deliver energy, or be in a standby mode. It can switch back and forth between the 3 modes as desired.

The second MIC application shown in Figure 2.8 is to magnetically shield a manned spacecraft from high energy solar and cosmic ray particles. The MIC quadrupole configuration has a very low magnetic field at the center of the quadrupole, where the crew quarters would be located, and very high converging type magnetic fields on the 4 faces of the quadrupole. Incoming charged particles would be stopped and reflected away from the quadrupole by the “magnetic mirror” effect. In a magnetic mirror, the forward directed kinetic energy of an incoming charged particle is converted to orbital kinetic energy as it approaches the quadrupole face and encounters the continually increasing magnetic field. When all of the forward kinetic energy of the particle has been converted to orbital energy in its revolution around the magnetic field lines, it stops and then bounces away from the quadrupole. The strong MIC quadrupole field will reflect almost all of the incoming particles except those having very high energy, and greatly reduce the radiation dose to the crew during the mission.

The third MIC application is propellantless propulsion. For planets having appreciable magnetic fields such as Earth and Jupiter, a MIC superconducting loop can be positioned and energized so as to move inwards to or outwards from the planet, depending on the orientation of the planetary field and the direction of the current in the MIC loop. Figure 2.8 shows a

rectangular MIC loop oriented so that the planetary magnetic field is perpendicular to the plane of the MIC loop. The magnetic forces on the sides of the loop are then unequal if the planetary field is weaker on one side than on the other. This condition is achieved for a MIC loop orbiting a planet that has a magnetic field. Since the planetary field is dipolar in nature, the strength of the magnetic field decreases with radial distance from the planet.

If the current in the superconducting MIC loop flows in the direction that produces a radially outwards magnetic force on the side of the loop that is closest to the planet, then the loop will move outward from the planet. If the current flows in the direction that produces a radially inwards magnetic force on the side of the loop that is closest to the planet, then the loop will move inwards to the planet. No propellant is consumed using the MIC loop; however, electrical energy must be pumped into the loop as it moves outwards or inwards to maintain its current at a constant value.

The MIC propellantless propulsion loop can serve as an orbital tug to transport payloads to higher orbits, or to retrieve payloads from high orbits. It can also impart OV to a spacecraft headed for a destination beyond the Earth – e.g., the Moon, Mars, or beyond.

The fourth MIC application is expandable propellant tankage. The MIC quadrupole forms a very strong, very rigid, very lightweight structure that can support a lightweight large propellant tank. The large deadweight of propellant tankage, on the order of 10% for high performance propellants like H_2/O_2 , severely constrains payload weight and the OV that can be achieved.

The tether network inside a MIC quadrupole supports a lightweight insulated liner that is filled with propellant. MIC propellant tankage can be used for large launch vehicles taking off from Earth, such as the new cargo carrier rocket proposed by NASA for the Moon and Mars exploration program. The MIC based launch vehicle could lift much more payload, and be much cheaper to manufacture.

MIC tankage can also be used for propellant storage in orbit. Launched as a compact, lightweight package, it could be expanded into a large propellant tank after reaching orbit. The shuttle H_2/O_2 main tank, for example weighs 60 tons; an equivalent volume MIC tank would weight less than one-third as much.

MIC tankage could also enable for refueling operations on Mars and other bodies having ice or other in-situ resources that could be used to manufacture propellant. For example, a compact collapsed MIC tank with an attached rocket engine could land on Mars, Europa, or other body having an ice sheet or polar cap. After landing, a solar or nuclear power unit could electrolyze melt water, converting it to H_2/O_2 chemical propellant. The propellant would then be stored in the expanded MIC tankage after refueling, the MIC rocket could hop to another site on the planet for further exploration, or return to Earth with collected material. Making repeated hops, one MIC spacecraft could explore many different sites across a planet, greatly increasing the scientific results from a give the mission.

Finally, MIC space structures could greatly enhance the capability for World-wide communications and environmental monitoring of earth. Figure 2.9 lists some of the potential benefits enabled by large MIC structures orbiting the Earth. The increase in communication capacity possible using the large amounts of solar power, together with the much greater antenna capability of MIC, would permit 24/7 coverage of the Earth for hundreds of millions of cell phones, greatly expanded TV broadcasting, and virtually complete internet connectivity for all of Earth's population.

Similarly, the 24/7 coverage and much greater environmental sensing capability would enable quantitative continuous monitoring of all of the significant pollution sources on Earth, all of its food production, habitat and species changes, weather events, etc. With the increased capability to monitor micro-movements and micro-quakes around the Earth, the ability to provide early warnings of natural disasters, including major earthquakes and tsunamis, would be improved.

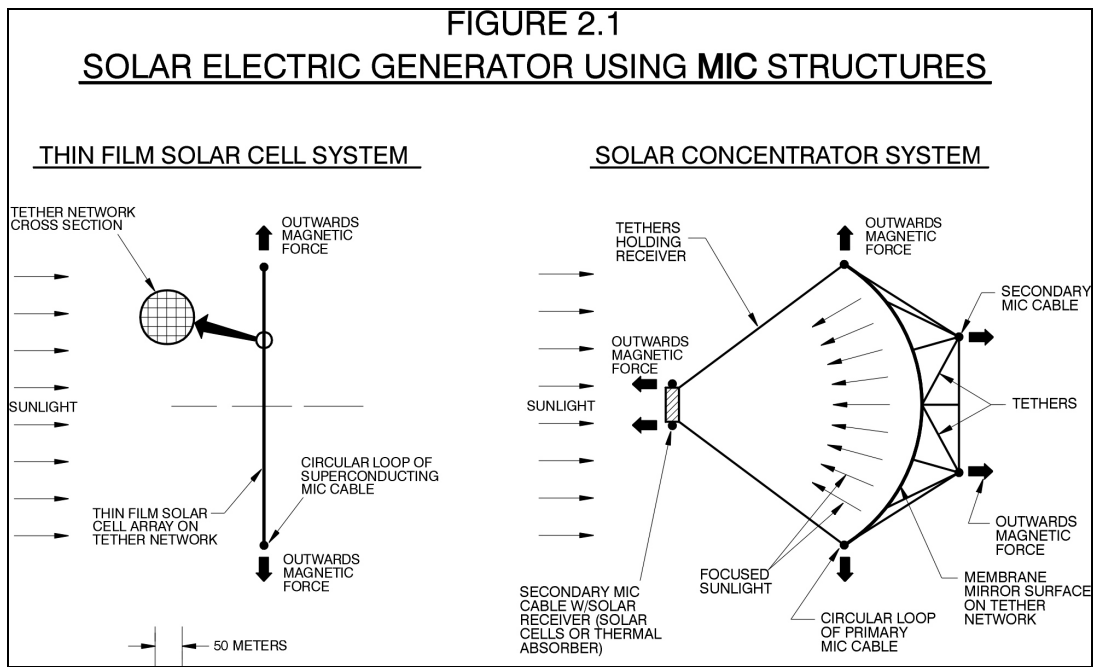


Figure 2.2

Electrical Generation Capability of MIC Solar Electric Systems As A Function of MIC Loop Diameter

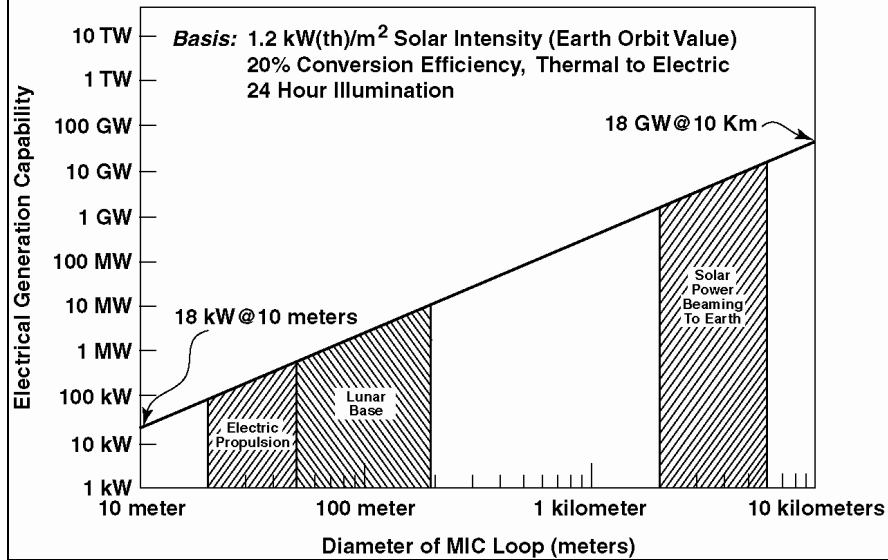


FIGURE 2.3

SOLAR THERMAL PROPULSION USING MIC STRUCTURE

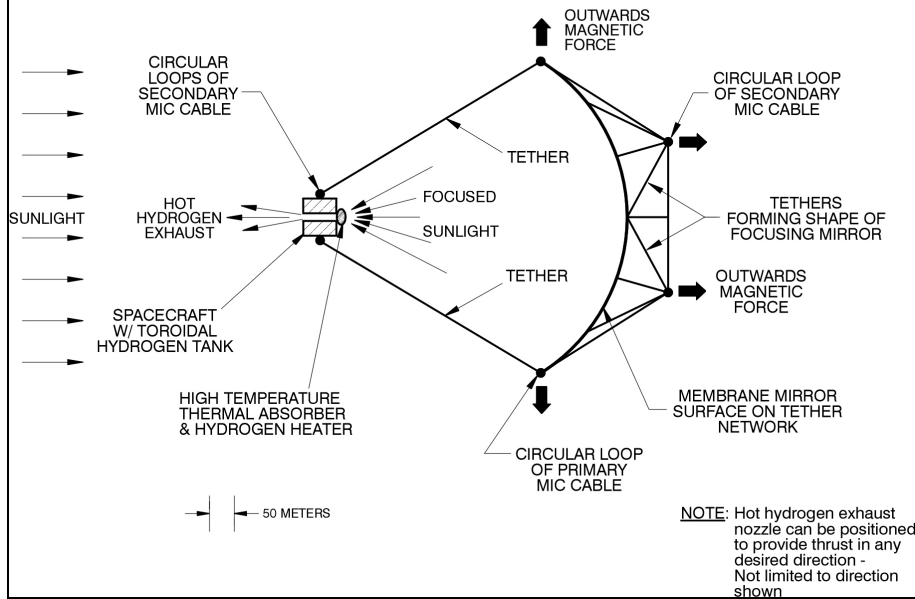


Figure 2.4

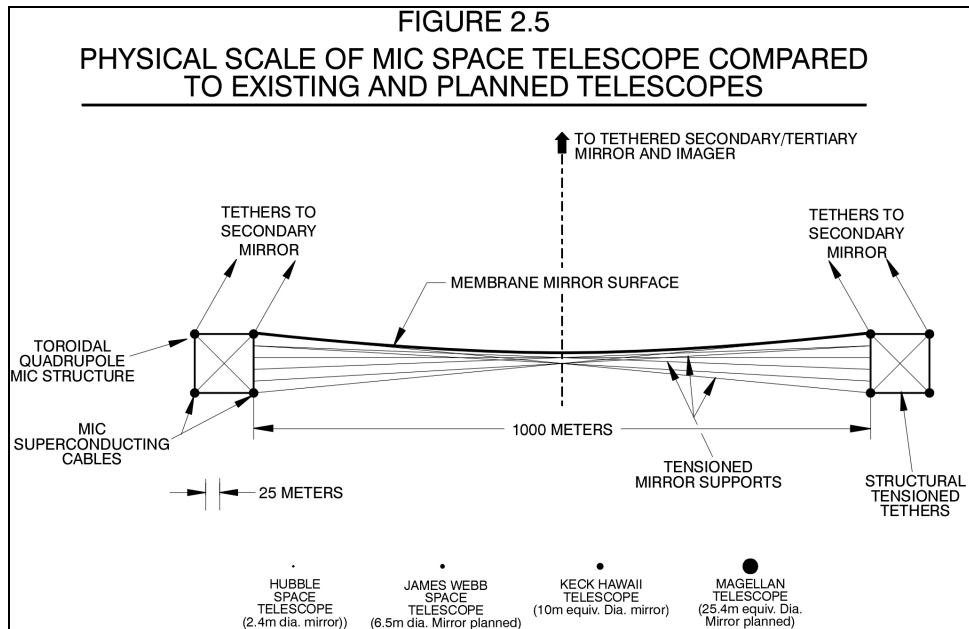
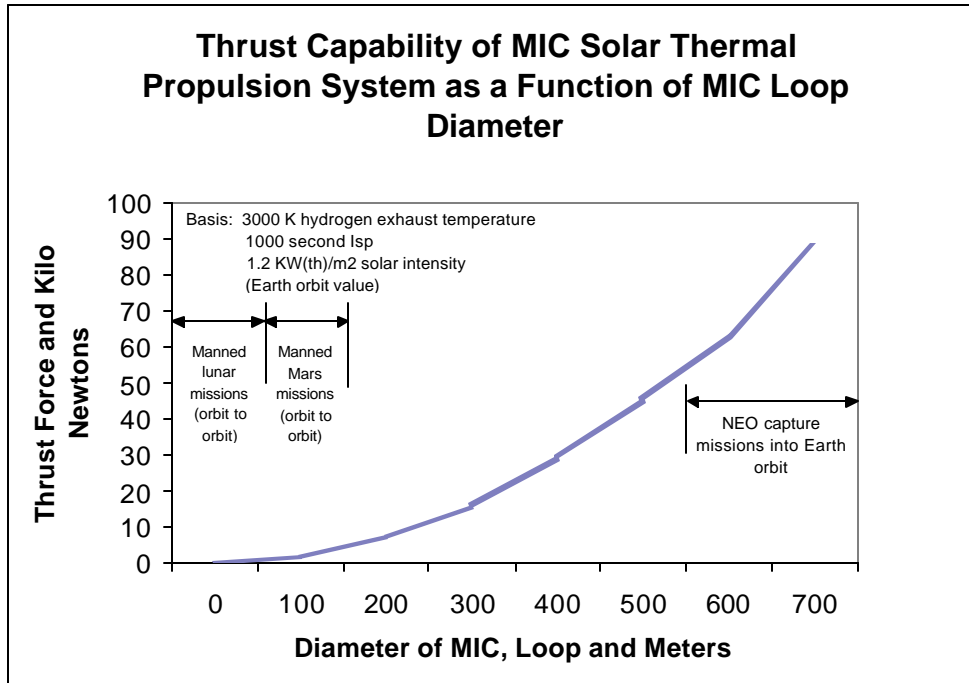
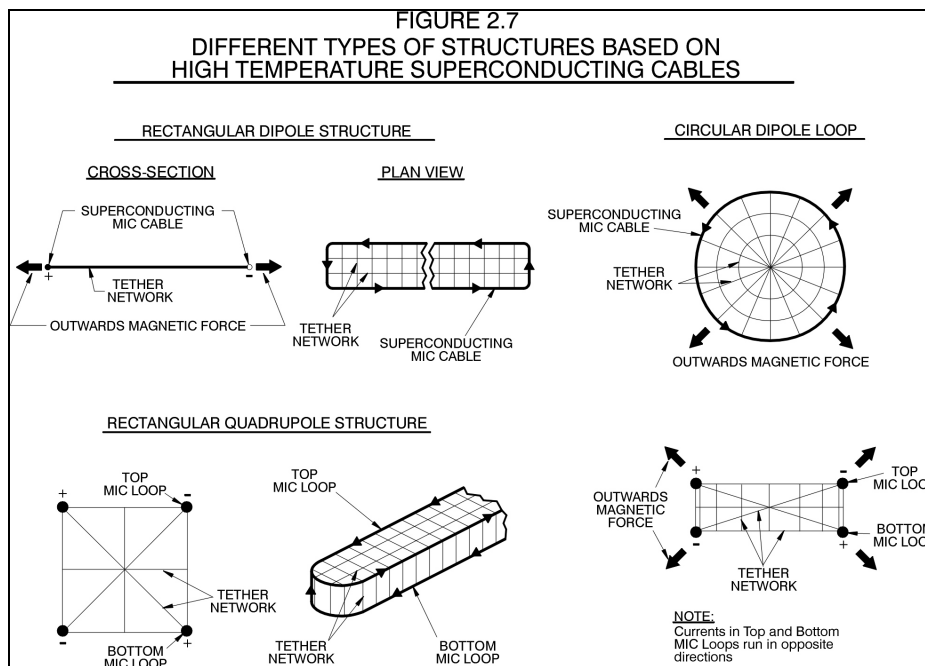
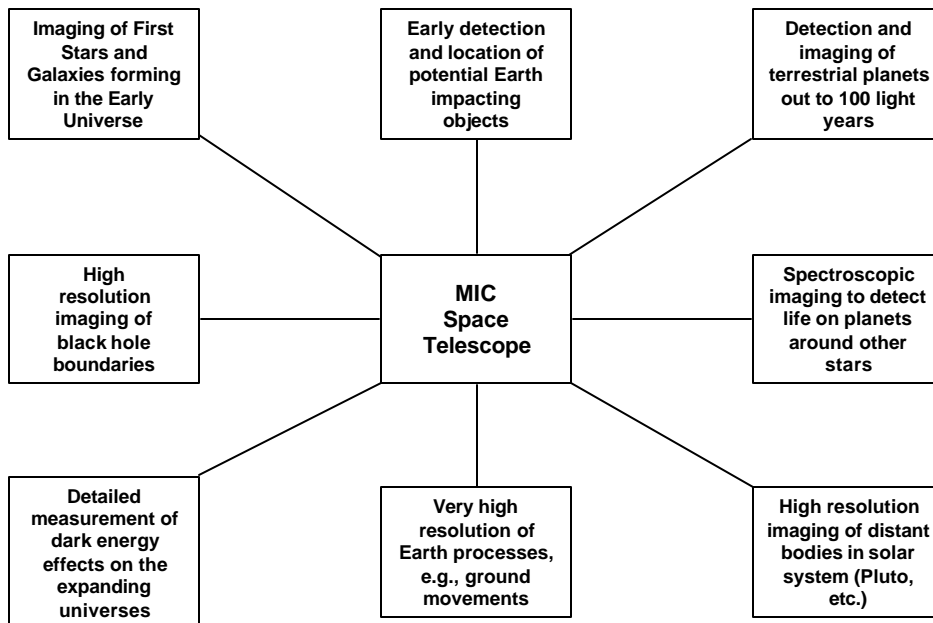


Figure 2.6

New Astronomical Discoveries Enabled by MIC Space Telescope



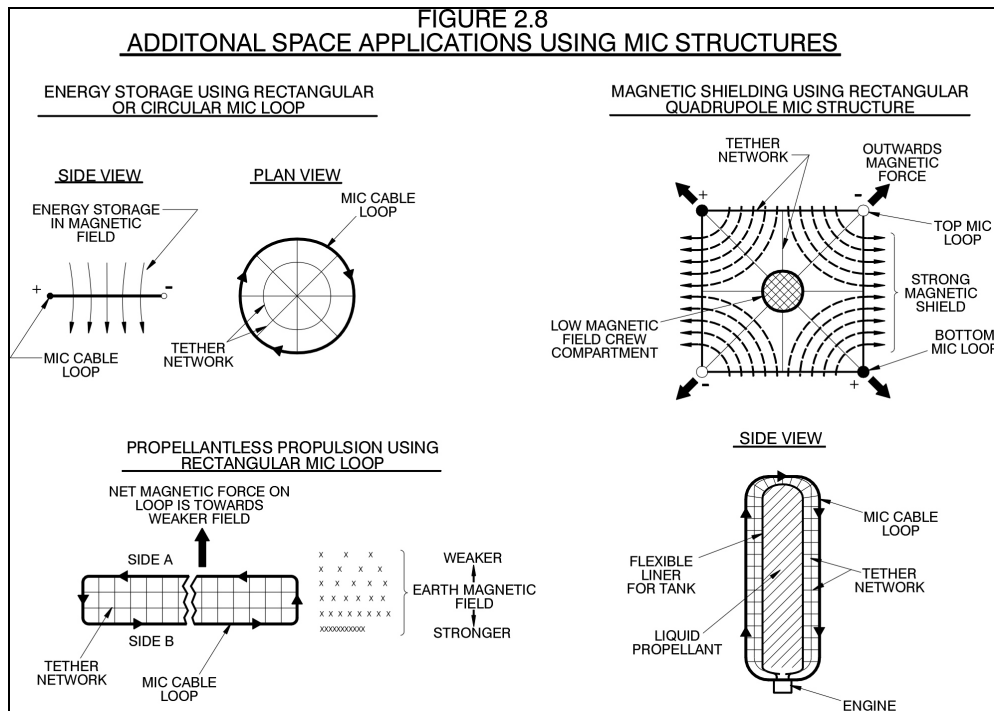


Figure 2.9

**Earth Communications and Sensing Applications Using MIC Structures:
Some Illustrative Examples**

Large Orbiting MIC Structures

World Wide Communications

- Global plane communication
 - 2-way, 24/7 coverage to energy point on Earth
 - Low cost for phones and usage time
- Global broadband TV and internet
 - Capability to receive HDTV everywhere on Earth
 - Interactive TV education classes in remote and poor locations
 - Ability to connect with internet at all points on Earth

Environmental Sensing

- Pollution monitoring
 - Global surveillance of all important pollution sources
 - 24/7 monitoring of each source
 - Quantitative measure amounts of CO₂, NO_x, SO₂, Hg, particulates, etc.
- Enhanced survey of global warming effects
 - Storms, droughts, flooding, etc.
 - Crop production
 - Habitat and species changes
- Natural disaster warning
 - Improved prediction of severe tracks and impacts of severe weather
 - Global monitoring and detection of microquakes as precursors to major earthquakes

3.0 EXISTING CONCEPTS FOR THE CONSTRUCTION OF LARGE SPACE STRUCTURES

The two existing concepts for the construction of large space structures are: 1) mechanical structures and 2) gas filled inflatable structures. The advantages and disadvantages of both are discussed below.

To date, almost all space structures have been built using mechanical construction methods. This is perfectly understandable, since these construction methods have served us very well on Earth in the familiar 1-g environment. Also, to date, the space structures have ranged from small to only medium-sized. As we contemplate larger structures, say 10's of meters, we have to rethink our construction methods and look at structures which may be more advantageous in a zero-g, near-vacuum space environment. This brings us to inflatable structures, both gas-filled and MIC-based. The gas-filled structures have been researched for many years, including an on-orbit experiment in 1996. The MIC concept, of course, is revolutionary and is the subject of the study at hand. The estimated advantages for gas-inflated structures are 50% reduction in launch mass and 75% reduction in stowed volume compared to the best mechanical system [3-1]. JPL has estimated that the cost of a large (gas) inflatable antenna is an order of magnitude lower than a mechanical antenna of comparable performance [3-1]. The MIC system, although not investigated to the same degree as the gas-inflated systems, is expected to yield nearly the same weight, volume, and cost advantages.

The gas-filled inflatable structures are practical only if the inflation pressure is very low, i.e., ~0.0001 atmospheres. The reason for this is that the structure will inevitably be damaged by micrometeorites and the inflating gas will escape through the puncture holes. If the inflation pressure is low and the hole size is small, the leakage will be manageable. Current estimates are that if the inflation pressure is sufficiently low, it is practical to replenish the escaping gas from an on-board supply for a period of 5-10 years [3-2]. The low gas pressure may be acceptable for some large structures. For example, an inflation pressure of 3×10^{-4} psi (2.1 Pa) in a 14 meter diameter lens-shaped antenna will produce a wall stress of 1200 psi (8.3 MPa) in a 6.35 micron aluminized mylar film. This tensile stress is sufficient to produce a good reflective surface of correct curvature.

The on-orbit experiment (Inflatable Antenna Experiment, IAE) mentioned above was designed to test the proof-of-principle of large gas-inflated structures [3-3]. It was carried into orbit by Space Shuttle Endeavor, STS 77, on May 20, 1996. The test article, manufactured by L'Garde, Inc., consisted of a 14 meter diameter antenna, a toroidal support structure for the antenna, and three 28 meter long struts. All were to be inflated by nitrogen gas once in orbit. The duration of the experiment was one orbit. The experiment was a partial success. The struts and the torus inflated properly, however, the antenna part did not fully inflate.

The antenna of IAE was formed as one half of an inflatable lenticular pillow. One half of it is transparent mylar and the other half, i.e., the antenna part, is an aluminized mylar film. The lenticular pillow is anchored to an inflatable torus along its edge. The cross section diameter of the torus is 61 cm. The torus has to be sufficiently rigid since a tension force is needed along the edge of the pillow to give the antenna the correct parabolic shape. As a measure of rigidity, we calculated the hoop tension force in the torus as a result of pressurization to 3×10^{-4} psi (2.1 Pa), the same as the design pressure in the lenticular structure. The resultant tension was only 0.28 newtons. Obviously, this level of rigidity is insufficient to support the lens structure. However, if the inflation pressure were increased substantially to increase the rigidity of the torus, the leakage rate would become excessive and the structure would deflate. We note that if we replaced the inflatable torus by a superconducting cable 1 cm in diameter, which carried a current of 100,000 amperes, the tension force in the cable would be approximately 4000 newtons. This tension force is **15,000** times greater than a structure inflated to a pressure that could be maintained for long periods with make-up gas. Thus, gas inflated space structures are only practical for large structures which are very lightly loaded.

To overcome the problem of deflation from micrometeorite puncture holes, the emphasis in research has shifted from inflatable structures to inflatable **and** rigidizable structures. In this case, gas inflation is used to expand the structure to its desired shape but after deployment, the film becomes rigid and does not depend on inflation to maintain its shape. Several methods of rigidization are mentioned by Freeman, et al [3-2]. These include: "a) fabric impregnated with resin that is cured by exposure to ultraviolet light, b) fabric impregnated with water soluble resin that rigidizes as the water evaporates, c) fabric impregnated with resin that rigidizes when it is cooled below

glass transition temperature, d) thermal set plastic resin that cures upon application of heat, d) a laminate of aluminum foil and thin Kapton film that is rigidized when the aluminum is strained beyond its yield point.” All show good resistance to space environment. One drawback is that all have finite coefficients of thermal expansion which can lead to structural warping because of uneven heating. It remains to be seen whether it is practical to achieve sufficient structural rigidity with these methods for very large structures. Flight in orbit, in spite of zero-g and near vacuum conditions, is not free of forces and torques [3-1]. The major on-board disturbance stems from attitude control rockets. Among environmental disturbances in orbit are: gravity gradient torques, solar radiation pressure, magnetic torques, thermally induced torques, and aerodynamic drag (for altitudes below ~700 km). Almost all of these forces increase with increasing size. (The magnetic torque depends on the currents in the structure and not necessarily the size.) The space structure must be designed to withstand these forces. Whether inflated and rigidized structures can be built on a kilometers scale remains to be seen. Our own calculations show that kilometer scale structures are practical using MIC technology.

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4.0 THE MAGNETICALLY INFLATED CABLE (MIC) CONCEPT FOR THE CONSTRUCTION OF LARGE SPACE STRUCTURES

The magnetically inflated cable (MIC) structure system is extremely simple in principle. It has four fundamental components:

- a. High current superconducting (SC) cables
- b. High tensile strength tethers
- c. Cryogenic coolant and refrigeration equipment
- d. Electrical power supply

The MIC assembly is formed into a compact, high density package of SC cables, tethers, refrigeration equipment and power supply that can be launched into space using a conventional launch vehicle, e.g., Atlas, Delta, shuttle, Soyuz, etc. After reaching its planned orbit or outbound trajectory, the superconducting cables would be energized with electric current, causing the MIC structure to expand into its final operational configuration.

The MIC package could either be launched with the superconducting (SC) cables already pre-cooled to superconducting temperatures, but not energized with electrical current, or the cables could be at ambient temperature when launched and then cooled down after achieving orbit or the desired outbound trajectory. Both approaches appear practical; the choice probably will depend on the particular application and operation involved.

As discussed in Section 2, a variety of MIC configurations and applications is possible. This section describes the possible applications and configurations in more detail. The following Section 5 then evaluates the various application and selects several of the most promising ones for detailed analyses and descriptions of baseline designs.

Figure 4.1 illustrates MIC disc type structures that can be used for solar electric, solar thermal propulsion, energy storage, and large space telescope applications. The primary structural component is a large circular ring formed by the MIC cable. The superconducting current flows continuously around the ring, with zero resistance and zero I^2R losses. The MIC SC cable, which is described in more detail in Section 7, actually consists of an array of multiple parallel superconducting circuits that carry current and operate independently of each other. If some of these independent superconducting circuits were to fail, almost all (~99%) of their current would automatically transfer by magnetic induction to their neighboring conductors.

The MIC SC cable experiences a strong radial outward magnetic force from the magnetic field inside the loop generated by the MIC loop current. The magnetic field is normal to the plane of the loop. The azimuthal SC current interacts with the vertical magnetic field to produce the outwards radial magnetic force.

The outwards radial magnetic forces are restrained by a network of radial tethers. Using radial tethers to restrain the magnetic forces substantially reduces the mass of structural material, as compared to azimuthally directed tensile cables attached to the SC cable that restrain the forces by hoop stress. In addition, the radial tether network serves as structural support for a

mirror surface for the solar electric, solar thermal propulsion, and large space telescope applications.

The individual radial tethers are connected together by azimuthal tethers at appropriate radial distances (only one azimuthal tether is shown in Figure 4.1. In general, there would be multiple azimuthal tethers at different radii.)

The MIC disc can provide a flat planar support surface as shown by the left hand drawing in Figure 4.1, or a curved disk shaped surface, as in the right hand drawing. The curved surface is achieved by having a second, smaller superconducting cable ring behind the primary ring. The current in the secondary ring circulates in the opposite direction to that in the primary ring, producing a repulsive magnetic force between the two rings. This repulsive force is restrained by a network of tethers between the 2 rings. The shape of the curved surface is then determined by the length and placement of the tethers that connect the primary and secondary discs. The surface can have a parabolic shape that concentrates sunlight onto a smaller separate absorber or imager, or any other desired shape.

As indicated in Figure 4.1, the MIC cables consist of a small diameter tube that has a number of separate parallel superconducting circuits attached to it. Each superconducting circuit has its own coolant circuit, so that a failure of an individual superconductor or coolant line will not affect its neighbors surrounding the support tube and the superconductor/coolant circuits is a layer of thermal insulation, which keeps the heat leakage into the superconductor region at a very low level. The thermal insulation consists of multiple layers of thin aluminum foil separated by low density fiberglass layers. In the high vacuum of space, the effective thermal conductivity of the insulation is 0.5×10^{-4} watts/mK. This insulation is routinely used in cryogenic systems on Earth. A more detailed description of the MIC cable and its insulation is given in Section 7.

The tethers are attached directly to the MIC support tube to restrain the magnetic forces on it. The tethers would be made of a high strength, lightweight, low thermal conductivity material such as Kevlar or Spectra (oriented polyethylene). The tether materials have very high tensile strengths, on the order of 300,000 psi, and would operate at a low fraction of their tensile strength, e.g., 10 to 20% (30,000 to 60,000 psi). The heat leak through the attached tethers is very small. For a 1 kilometer long MIC cable, the heat leak through thermal insulation is on the order of 100 watts, (Section 7 describes the insulation system in detail). The heat leak through the tethers is only about 5 watts, for a representative magnetic force of 1000 Newtons per meter of cable.

Figure 4.2 shows how the MIC concept would be used for rectangular loop structures. Simple planar dipole loop and quadrupole loop structures are both shown. The quadrupole loop structure consists of two parallel rectangular loops separated by a distance equal to their width. The superconducting currents in the upper and lower loops circulate in opposite directions, producing magnetic forces that act to push the 2 loops apart. The magnetic forces are restrained by the tethers that hold the loops together.

In the MIC disc geometry shown in Figure 4.1, the primary tethers that restrain the outwards magnetic forces run in the radial direction. The azimuthal tethers that connect the radial tethers from a 2 dimensional support network on which a surface reflector or other structure can be placed, but the azimuthal tethers do not carry the magnetic forces.

For the MIC rectangular loop structures shown in Figure 4.2, however, there is a 2 dimensional network of tethers in the planes of the rectangular loops, with both dimensions acting to restrain the outwards magnetic forces. The outwards forces on the parallel sides of the rectangular loop are restrained by the tethers that tie the sides together, while the outwards forces on the ends of the rectangular loop are restrained by longitudinal tethers.

The MIC rectangular loop length/width ratio can be any desired value. For the simple rectangular dipole loop, the energy storage and propellantless propulsion applications appear to be the most appropriate, since the rectangular surface does not focus sunlight at a point.

For the quadrupole rectangular loop geometry, the main applications appear to be magnetic shielding against high energy particles, which cause substantial radiation dose to astronauts during long space missions, and for various 3 dimensional structures. Of the 3D applications, propellant tankage appears very attractive. A MIC propellant tank could be launched as a compact package into space, and then expanded to full size once in orbit, to serve as a fuel depot. It also could be landed on a planet or moon, e.g., the Mars polar cap or the ice sheet on Europa, to be filled with H_2/O_2 propellant manufactured from in-situ ice.

Another potential application of MIC propellant tankage is for very large launch vehicles that would lift off Earth. The shuttle main tank, for example, weighs 60 tons. Besides being very expensive to manufacture, its very large weight substantially reduces the weight of payload that can be launched into orbit. Using MIC tanks, the weight and cost of the propellant tank could be considerably reduced, with a consequent increase in payload weight, and reduction in the cost per kg of payload launched. MIC propellant tanks could be used for any large launch system, whether of the expendable or reusable type.

Figure 4.3 shows the operational sequence for placing a MIC structure into space. The first step is to prepare the MIC payload for launch. The goal is to package the SC cables, tethers into a compact package that will fit into a conventional launch vehicle, but can expand into its final large configuration without hindrance when it is energized with current.

The way it is packaged will depend on its final configuration and operating parameters, including dimensions, type of superconducting cable, associated material (e.g., solar cells or reflecting mirror membrane, etc.). for example, a MIC rectangular dipole loops structure probably would be folded like a blanket into a compact layered package. Once in space the package would be unfolded into a single layer by energizing either the main superconducting cables or a secondary SC cable whose function was to carry out the unfolding operation.

The energization of the superconducting cable would actually be done in two steps. The first step would be an energization at less than full current, e.g., on the order of 20%, to test the

cable and expand the thermal insulation layer around it. After the thermal insulation layer is established and the cable is at design temperature, it would be energized to full current, and the persistent superconducting switches connected enabling the expanded structure to operate at steady state.

Figure 4.4 shows an artists view of the launch, deployment and energization sequence for the MIC solar electric system.

Figure 4.5 shows the principal components of MIC structures. These components are described in detail in Sections 6 and 7. All of the components use existing commercial technology – no new materials and equipment are required. In certain areas, such as the engineering current density in the commercial version of high temperature superconductors, some improvement on present capability is projected, based on the known properties of short samples of the material.

A key feature of the MIC cable is that it has very high reliability and redundancy, so that even if individual parts of it were to fail - a low probability event, but possible - the cable would continue to function and the MIC structure could still operate. Figure 4.6 shows the cross section of a typical MIC cable. It has many separate individual conductors, each of which is cooled by its own coolant circuit. If a conductor, or several conductors were to fail, the current that had been carried in the failed conductor(s) would automatically transfer by magnetic induction to the neighboring conductors, with only a minor decrease (<1%) of the total current carried by the cable.

An individual conductor on the MIC cable might fail because of a leak in its coolant circuit, or a mechanical break, or penetration by a micrometeorite or small bit of space debris. The chance of such events is made very small by armoring the cable against micrometeorites and space debris and having each of the multiple conductors in the MIC cable incorporate in turn a substantial number of parallel smaller conductors. These are electrically bonded together, so that if one mechanically failed at some location, its current would temporarily transfer to its parallel neighbors in the vicinity of the break, and then return to it after the break. Using such construction, it is virtually impossible for a local break from mechanical effects or space debris/meteorite impact to cause more than a local transfer of current in any of the multiple conductors in the MIC cable.

The magnetic forces on the MIC cables are determined by the particular configuration used, the amount of current carried by the cable, and the distance between the cables. Figure 4.7 illustrate how the outwards magnetic forces on the sides of a MIC simple rectangular loop vary with current in the MIC cable and the width of the loop.

The magnetic forces are considerable, even for relatively modest currents and wide loops. For a 200 meter wide rectangular loop, for example, the magnetic force on each side of the loop is 250 Newtons per meter (25 kilograms force per meter) at a MIC cable current of 500 kiloamps. At an operating current density of 200,000 amps per cm^2 , and a critical engineering current density of 300,000 Amps per cm^2 , which would provide a 50 percent safety margin, only

2.5 cm² of superconductor would be required using MgB₂ superconductor, the superconductor in the cable would weigh only about 2 kg per meter, 1 kg for each side. Operating as a solar electric system in Earth orbit, with 20% solar to electric efficiency, the 2 kg of superconductor would generate ~50 kilowatt of electrical power. A 2 kilometer panel would generate 100 megawatts(e), and 10 panels on an array would beam 1000 megawatt(e) to Earth from geosynchronous orbit, requiring a total of about 40 tons of superconductor. The tethers, thermal insulation, and cryogenic system would add a comparable amount of mass, bringing the total MIC structure weight for a 1000 MW(e) power system to approximately 100 tons, or only about 0.1 Kg/KW(e), a very small unit weight.

Accordingly, the unit weight per KW(e) of the MIC structure for large, solar electric systems will be very low. As a result, the total unit weight per KW(e) of a MIC solar electric system will probably be set by the weight of the solar cell and power conversion/transmission equipment, and not the weight of the structure.

Figure 4.8 illustrates the energy storage capability of a MIC rectangular loop structure as a function of the MIC current and the loop width. The stored energy is substantially independent of loop width, since the inductance of the loop depends on the logarithm of the quantity, loop width divided by cable radius, which varies only slightly with loop width. The stored energy is strongly dependent on cable current, however, varying as the square of current. At 5 megamps current, for example, 1 kilometer of loop would store ~10,000 kilowatt hours. The total superconductor weight in the 1 kilometer loop would be 20 tons, or 2 kg per KWH(e), using the same operating current density as for the previous example of the MIC solar electric system. The magnetic forces on the sides of the 200 meter wide loop would be much larger, e.g., 2500 kg per meter, requiring greater tether volume and mass. At 60,000 psi, using Spectra tethers, the tether mass per kilometer of loop would be 10 tons, or half of the superconductor weight. For a given current, increasing the loop width will not significantly change the mass of the superconductor, the stored energy, or the tether weight. For different current levels, the mass of the superconductor will scale linearly with current, while the stored energy and mass of the tethers will scale as the square of the current.

Figure 4.9 shows the mass breakdown for a 1 kilometer section of the MIC rectangular loop structures for the solar electric and energy storage applications discussed above.

As discussed above for the MIC solar electric system, the specific mass of the structure is projected at ~0.1 kg per KW(e). [For the more complex configuration, lower solar cell efficiency, current density used in the baseline design described in Section 8, the specific mass of the MIC structure is significantly greater.] The dominant contributors to the unit mass are the superconductors, support tube and insulation. The tether mass, based on an operating tensile stress of 50,000 psi in Spectra fibers, is only 15% of the total unit mass. This operating stress is only 10% of the tensile strength. The refrigeration equipment (cryocoolers, pumps, heat exchangers) unit mass is projected at 25 kg per KW(e) of power input (1250 kg per KW(th) of cooling capacity). At this conservative value, the refrigeration equipment is still only 5% of total unit mass. Even if the unit mass, kg/KW(e), of the refrigeration equipment is considerably larger, which appears unlikely, it would not substantially impact specific mass.

In minimizing the unit mass of the MIC solar electric structure, the principal gains will be made by increasing the current density in the superconductor and by reducing support tube mass. The thermal insulation mass is ~20% of the total, and some reductions in its mass may be possible.

The mass of the MIC structure for energy storage is much greater than that for solar electric generation due to the very large support capability required to store large amounts of electrical energy. The superconductor mass increases by a factor of 10 and the tether mass by a factor of 100, compared to the solar electric system. This is a result of the magnetic forces scaling as (current)², while the superconductor mass only scales as (current)¹. The tether unit mass can be substantially reduced by operating at higher tensile strengths. At 90,000 psi, for example, the tether weight would be cut by a factor of 3, making it only 10% of the total unit mass, with the total structure mass reduced from 72,000 kg down to 58,000 kg. The total unit mass would then be 6 kg/KWH(e), or about 0.6 MJ/kg. With optimization and improvements in superconductor current capability, it should be possible to increase energy storage capability to ~1 MJ/kg.

More detailed descriptions of the MIC superconductors, thermal insulation, support tube construction, and refrigeration systems are given in Section 6 and 7.

FIGURE 4.1
MIC DISC GEOMETRY FOR SOLAR ELECTRIC, SOLAR THERMAL PROPULSION
SPACE TELESCOPE AND ENERGY STORAGE APPLICATIONS

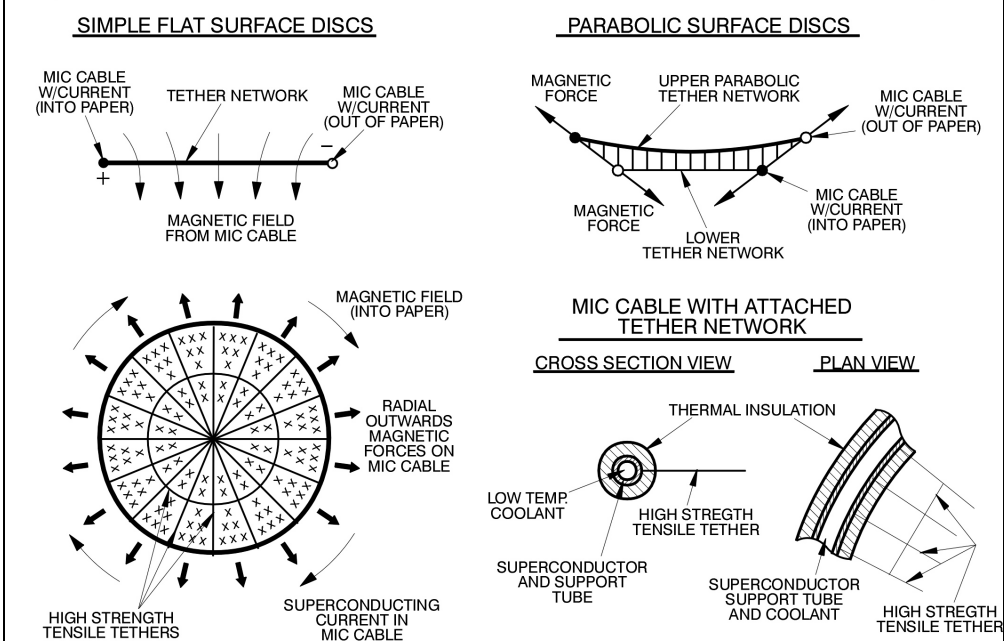


FIGURE 4.2
MIC RECTANGULAR DIPOLE LOOP AND QUADRUPOLE GEOMETRY

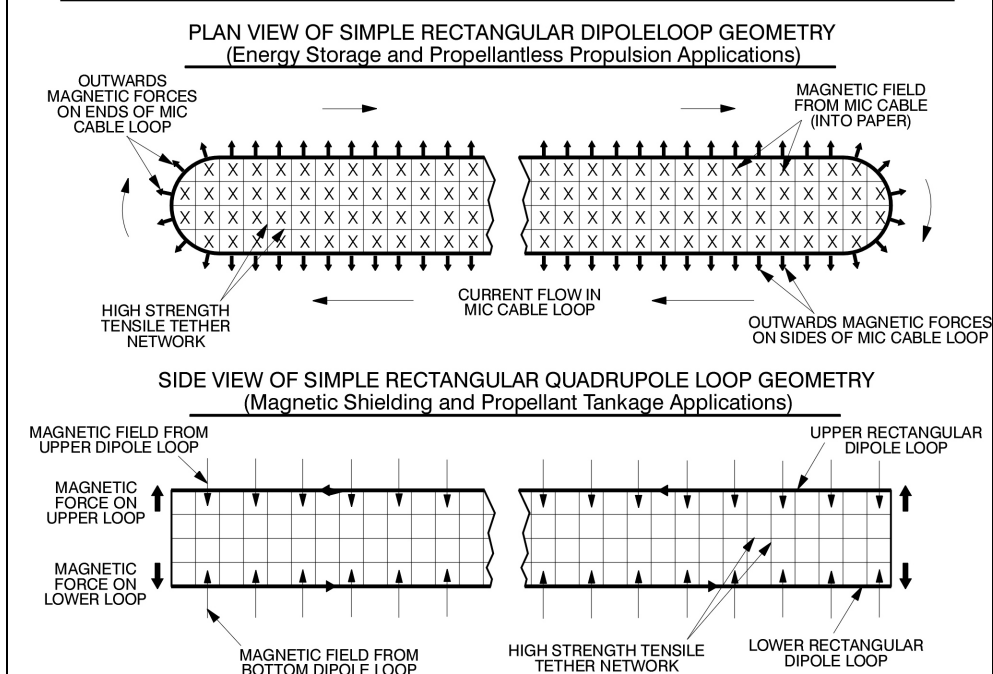


Figure 4.3

Launch, Deployment, Energization, and Operation Sequence for MIC Structures

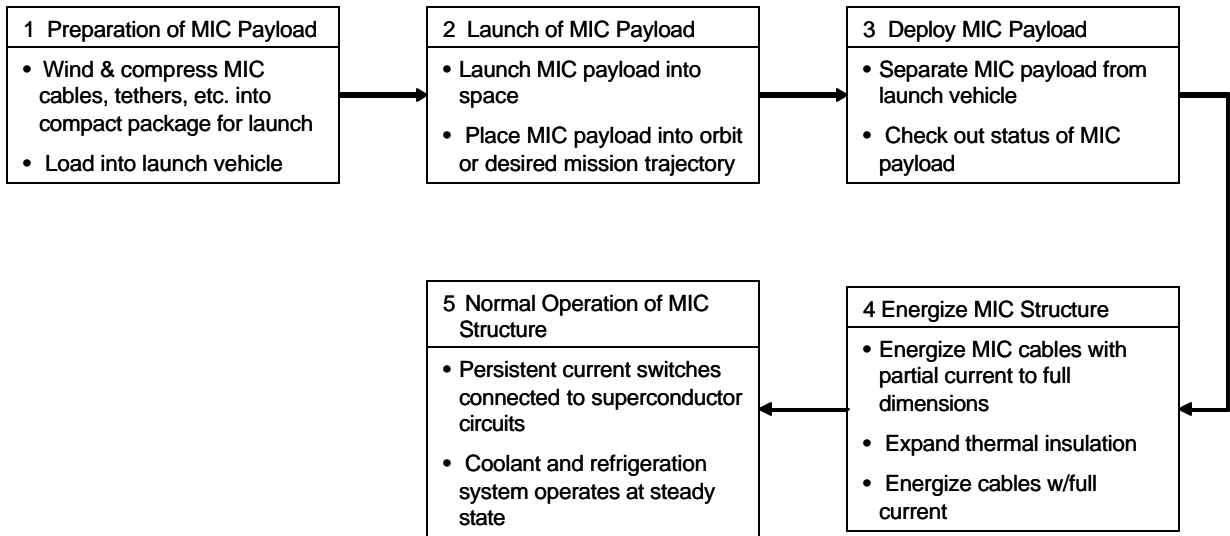


Figure 4.4 MIC Launch and Deployment Sequence

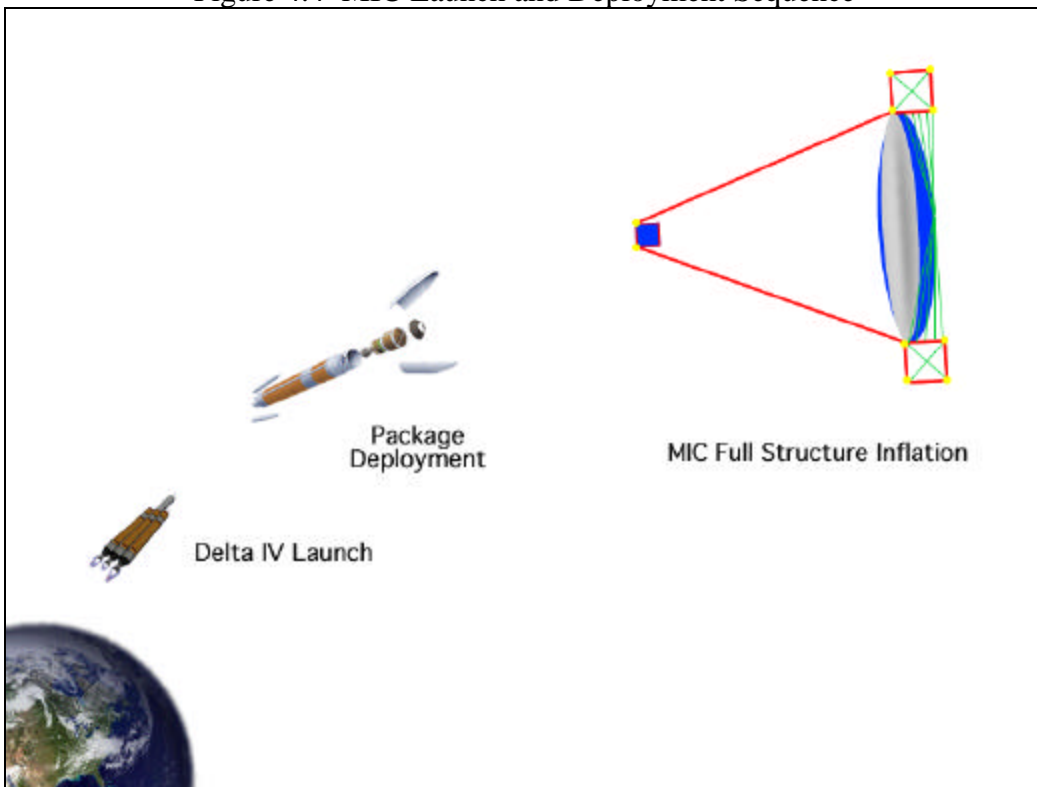


Figure 4.5

Principal Components of MIC Structures

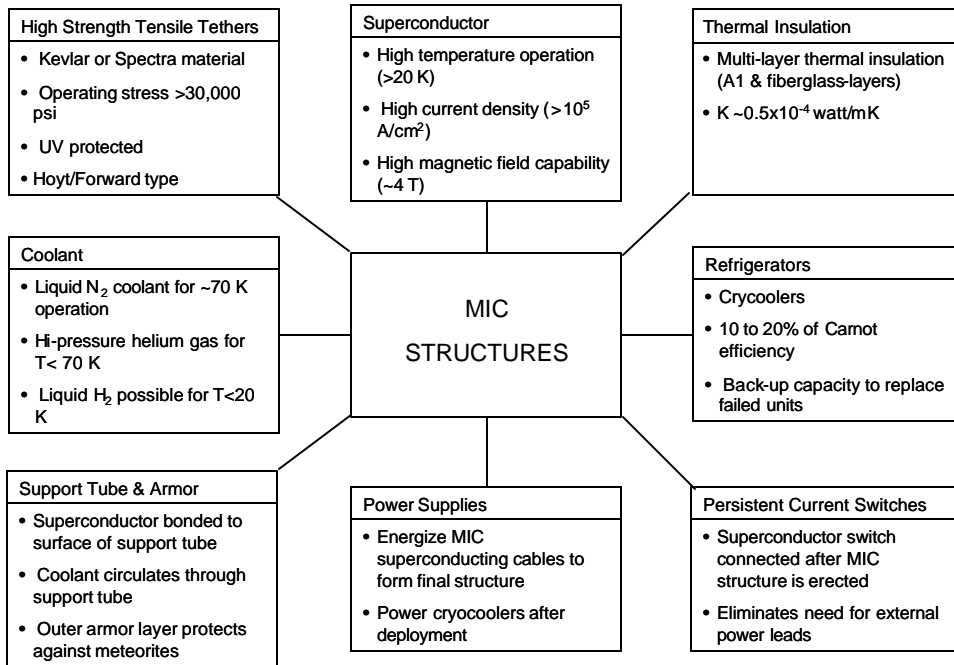


Figure 4.6

Illustrative Views Of Method For Support Of Multiple MIC Conductors On Single MIC Cable Using Central Structural Tube

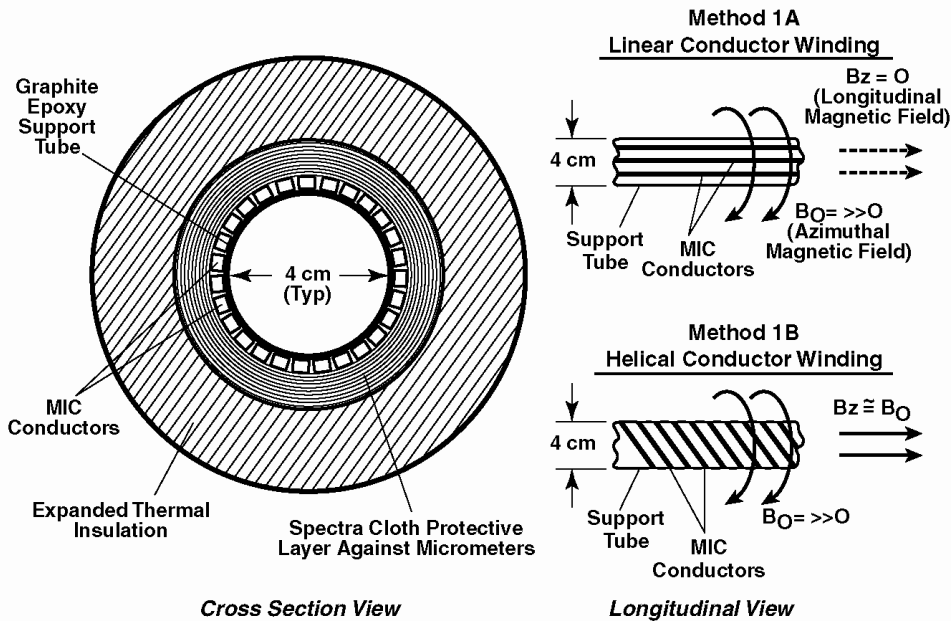


Figure 4.7

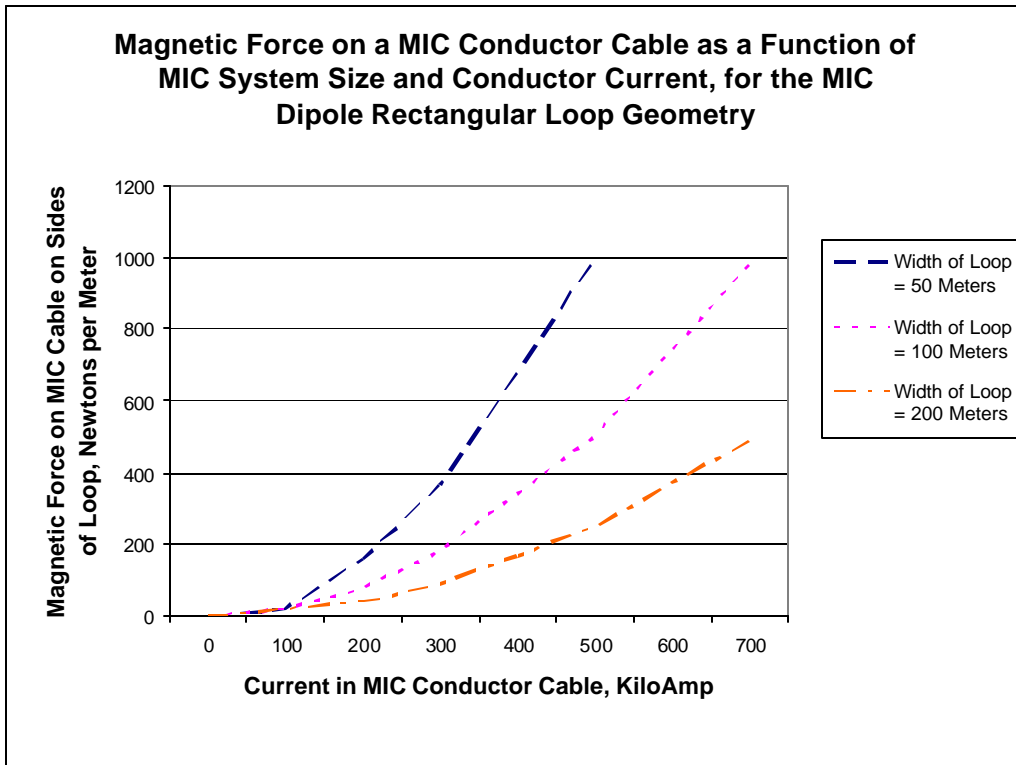


Figure 4.8

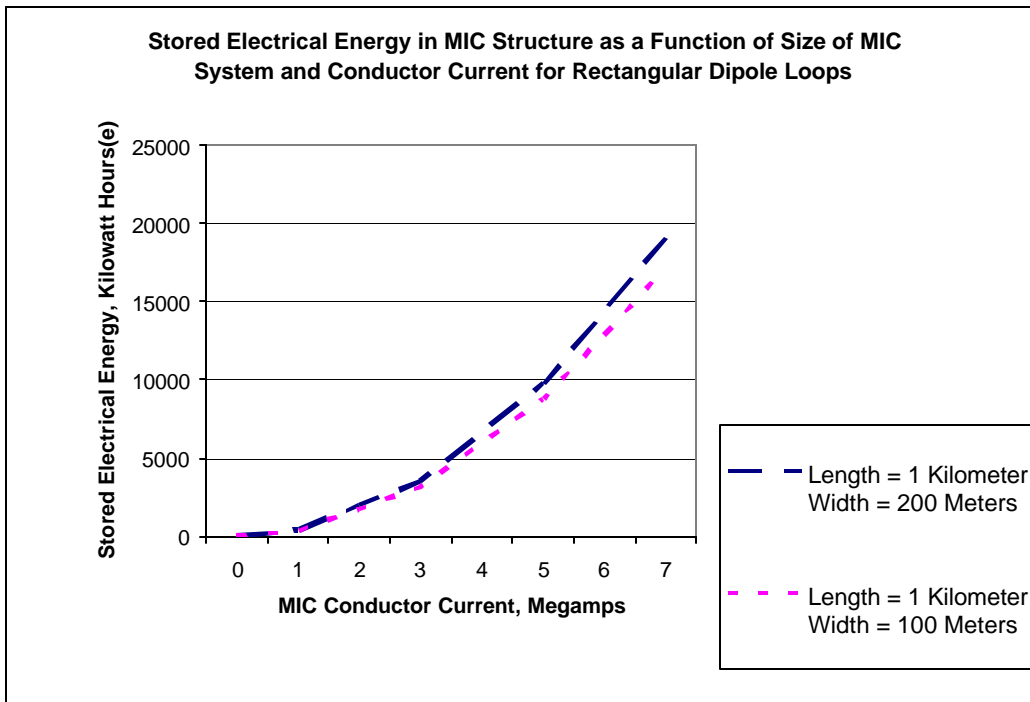


Figure 4.9 Mass Budget for MIC Solar Electric and Energy Storage Structures

Feature/Parameter	MIC Solar Electric System	MIC Energy Storage System
MIC Geometry	Rectangular loop	Rectangular loop
Width of loop, meters	200	2000
Length of loop section, meters	1000	1000
Cable current, Amps	500,000 (0.5 MA)	5,000,000 (5 MA)
Superconductor operating current density (A/cm ²)	200,000	200,000
Output, electric power or stored electric energy	50 MW(e)	10,000 KWH
Superconductor mass, kg	2000	20,000
Insulation mass, kg	1000	10,000
Support tube mass, kg	2000	20,000
Tether mass, kg	200	20,000
Refrigeration system mass, kg	200	2000
Total MIC structure mass, kg	5400	72,000

5.0 EVALUATION AND SELECTION OF PROMISING SPECIFIC APPLICATIONS BASED ON THE MIC CONCEPT

5.1 MIC Solar Electric Applications

Figure 5.1.1 shows the overall features and requirements for MIC solar electric applications. The MIC solar concentrator option has been chosen over the MIC flat disc configuration, as illustrated in Section 2, because it substantially reduces the number of solar cells required and the area of the solar cell array.

The solar concentration factor used will depend on the particular application and the temperature capability of the solar cells employed. MIC solar concentration factors of up to ~100 appear readily achievable. The optimum concentration factor will probably be less than 100, and determined by the cost and weight of the solar cells used. In this section, a preliminary assessment of MIC solar electric performance is made, to select the system for the more detailed baseline in Section 8 of the report. The parameters chosen for this assessment are generic and are not specific to those used for the baseline design.

The goal of a specific mass of 1 kg/KW(e) or less for the MIC concentrator at 1 AU distance from the Sun appears reasonable, and low enough to be very attractive for practical applications. The specific mass is low enough that MIC concentrators could be used beyond 1 AU. The specific mass would increase with the square of the distance from the Sun. The goal of being useful out to the orbit of Jupiter appears possible.

For most applications, MIC solar concentrators will have to adjust their viewing angle to compensate for the apparent motion of the Sun relative to the concentrator. This requires some method of adjusting the concentrator's position over time. In space, this could be accomplished by re-orienting the mirror and solar cell array using small thrusters. On the surface of the Moon or other bodies, the support mechanism holding the concentrator could move it in response to its apparent motion relative to the Sun.

Table 5.1.1 lists the principal parameters of a MIC solar concentrator for 3 important applications:

- ? Electric propulsion
- ? Electric power generation for a lunar base
- ? Power beaming from Earth orbit to surface

For maximum usefulness, MIC solar electric propulsion should be mass effective at distances well beyond 1 AU. Table 5.1.1 shows the concentrator parameters at 3 AU, where the solar flux is ~10% of that at 1AU. The 3 AU distance is about halfway between the orbits of Jupiter and the Earth, and provides a rough guide as to the performance of a MIC solar electric propulsion system used for missions to Jupiter and its Moons. Table 5.1.1 only examines the MIC solar concentrator parameters and does not evaluate the performance of other components for the various applications. The same solar cell efficiency of 20%, solar to electric, is assumed for all

applications. The specific mass of the solar cell array is not considered, nor are the specific masses of other components, such as power conditioning equipment, electric thrusters, batteries, antennas and microwave generators for power beaming, etc.

The power levels shown in Table 5.1.1 assume that multiple MIC concentrators are used for the application, in order to provide redundancy and reliability. For example, for the electric propulsion application, 3 MIC units could be used, provide a total electric power of 300 KW(e) for electric propulsion. Similarly, the lunar base could have 3 units for a total of 3 MW(e). Then if one unit were to fail, the remaining units could still maintain system function. For power beaming to Earth 10 units at 200 MW(e) per unit would beam 2000 MW(e) to Earth's surface. If one unit failed, the reduction would be only 10%, and could be handled by other back-up means.

The dominant contributors to the mass of the MIC concentrator are the mirror surface and the superconductor. The mirror surface is assumed to be an aluminized Mylar film of 0.05 millimeter thickness (2 mils) supported on a network of fine Kevlar or Spectra tethers. The superconductor is assumed to be MgB₂ with an engineering current density of 100,000 amps per square centimeter. The other contributors to concentrator mass, i.e., tethers, thermal insulation, conductor support tube, coolant, and refrigeration equipment are a relatively small fraction of total mass.

While the superconductor mass can probably be reduced by developing conductors with engineering current densities significantly greater than 100,000 A/cm², it appears unlikely that the mass of the mirror film, which accounts for 30% of total weight for the electric propulsion and lunar base applications, and 60% of the mass for the power beaming application, can be substantially reduced. The assumed thickness of 2 mils might be reduced to ~1 mil, but tests would be needed to confirm this. The unit mass of the MIC concentrator decreases with increasing size of the concentrator, being about 1 kg/KW(e) for the 70 meter diameter concentrator for the lunar base application (the corresponding unit mass for the electric propulsion application is ~10 kg/KW(e), because the solar flux at 3 AU is only about 10% of that at 1 AU) and about 0.5 kg /KW(e) for the ~900 meter diameter concentrator for the power beaming application.

Figure 5.1.2 summarizes the assessment of the 3 MIC solar electric applications. Based on the assessment, and the importance of the lunar base mission, the lunar base application has been selected as the baseline design described in Section 8 of this report. A MIC solar electric system for a future lunar base is an attractive alternative to developing a compact nuclear electric power system. It has a low specific mass [kg/KW(e)] and eliminates concerns about nuclear waste and safety. Development of the MIC solar electric system for a lunar base would also provide a technology base for implementing of larger MIC solar electric systems for power beaming to Earth.

5.2 MIC Solar Thermal Propulsion

Figure 5.2.1 shows the overall features and requirements for the MIC solar thermal propulsion application. MIC solar thermal propulsion systems are similar to MIC solar electric

systems in their structural configuration, size, and requirements. The main difference between them is that the solar thermal propulsion system requires a much higher solar concentration factor, on the order of 1000 to 2000 Suns focused on the final high temperature portion of the receiver that heats the propellant, compared to 50 to 100 Suns for the solar electric systems, and that the sunlight is focused on a high temperature receiver that heats hydrogen propellant to ~2500 K, instead of a solar cell array.

The higher solar concentrator requires a more precise shape of the MIC mirror surface, and more precise positioning of the receiver at the focal point.

The MIC solar thermal propulsion system will operate at significantly lower power and thrust levels than conventional chemical rockets and NTP (Nuclear Thermal Propulsion) engines, because it has a greater specific mass (kg of engine mass per kg of thrust output). However, by operating for longer periods, it can deliver comparable large OV's. The MIC system can operate continuously or intermittently, depending on whether it is continuously or intermittently illuminated by sunlight. (A MIC solar thermal propulsion system operating in low Earth orbit would receive sunlight only half of the time, for example.)

Table 5.2.1 shows 3 potential applications of the MIC solar thermal propulsion system:

- Orbital tug between LEO and GEO
- Earth to Moon tug
- Mars cargo vessel

The Mars cargo vessel would probably be used for cargo transport applications, with a faster transport spacecraft for human crews. The orbital and Earth to Moon MIC tugs could be used for both cargo and human transport, depending on whether or not exposure time in the Van Allen Belts would be a problem. In this connection, the MIC structure could also serve as a magnetic shield to protect astronauts from charged particles as the spacecraft traversed the Van Allen Belts. MIC magnetic shielding systems are described in a later section.

The 3 applications are normalized to the same OV addition of 5 kilometers per second. [The OV addition may vary for actual missions.] The payload mass for the orbital tug mission is 10 metric tons; for the Earth to Moon mission, 30 metric tons; and for the Mars cargo vessel, 100 metric tons. The MIC thermal heating rate increases with payload mass, being 1 megawatt for the orbital tug, 5 megawatts for the Earth to Moon tug and 10 megawatts for the Mars cargo vessel. The same hydrogen propellant exit temperature of 2500 K is assumed for the 3 applications. The 10 megawatt heating rate corresponds to 0.25 kg per second of hydrogen flow. At a specific impulse of 900 seconds this would provide a thrust of 2200 newtons.

It takes the Mars cargo vessel and orbital tug about 3 ½ days to achieve a OV of 5 km/sec assuming constant illumination. The Earth-Moon tug only takes 2 days because the solar collector is larger relative to the payload mass. The thrusting times appear reasonable. The actual operational time will be somewhat greater, because of Earth shadowing during part of the spacecraft's orbit. More detailed analysis taking into account shadowing by the Earth is required

to determine the actual time. As a rough example, the 2 days for the Earth to Moon tug would probably increase by 20 to 30%, but would still be less than 3 days.

The dry mass of the MIC solar thermal propulsion system is a small fraction of the payload mass, about 3 to 5% depending on application. This appears acceptable for further reduction, the MIC solar concentrator can be smaller; however, the thrusting time will increase correspondingly.

Figure 5.2.2 summarizes the assessment of the three MIC solar thermal propulsion systems. Based on the assessment, the Earth to Moon tug application is selected for baseline design, because it has the greatest near term potential. It would significantly reduce the mass of launch payloads required for a permanent lunar base, as compared to chemical rockets. Moreover, it provides an attractive alternative to NTP (Nuclear Thermal Propulsion) systems, and could be quickly developed and tested for Earth to Moon missions. Finally, the same system, with a modest scale-up, would provide high performance transport of large cargoes to Mars for human expeditions to the planet.

5.3 MIC Energy Storage Application

Figure 5.3.1 shows the overall features and requirements for the MIC energy storage application. MIC energy storage systems can be used for applications ranging from power for individual spacecraft to power for manned bases to power for robotic rovers.

In general, MIC energy storage systems will be considerably heavier than other MIC applications like solar electric and solar thermal propulsion, because their main function is not to provide a lightweight structure, but rather to store large amounts of electrical energy. As such, the MIC energy storage system requires a much greater superconducting current than other applications. This substantially increases the weight of the superconductor and the tethers that restrain the MIC cables.

Compared to other options for storing and delivery electric energy, such as batteries, fly wheels, and electrolyzer/fuel cells (which store energy by generating chemical fuels, such as hydrogen and oxygen from water, and then recombining them to generate electricity), MIC has unique capabilities. The instantaneous MIC electrical output can be extremely high, if desired, without requiring massive banks of batteries, flywheels or electrolyzer/fuel cells. The weight of the MIC storage system does not depend on the rate at which energy is delivered, but only on its total stored energy. This enables MIC energy storage system the ability to meet virtually any demand profile, whether at a given steady low level power or short pulsed output at a very high power level.

Second, the electrical efficiency, i.e., the ratio of the output electrical energy from the nine divided by the input energy will be $\geq 99\%$, much higher than with batteries, flywheels, or electrolyzer/fuel cell units.

The goal for the specific mass, kilograms of MIC system mass per megajoule stored, is ≤ 10 kg per megajoule. At this value, the specific mass of MIC storage would be comparable to that of other energy storage options, such as, batteries, etc.

Table 5.3.1 lists the principal parameters of a MIC energy storage system for 3 important applications:

- ? Spacecraft
- ? Lunar base
- ? Robotic rovers

The electrical power demand for a spacecraft can vary considerably during its operation, with relatively long periods at low power, punctuated by short periods of high power output. For example, a spacecraft operating far from Earth, e.g., on a mission to the Outer Solar System, may collect data over a relatively long time, and then transmit it at high power for a brief period back to Earth. High power capability enables strong transmission at high data rates, and minimizes the possibility of errors in transmission due to low signal to noise ratio.

A further example of the desirability of pulsed high power capability is the need to operate instrumentation at its maximum data acquisition capability when passing close to a target object, e.g., on a mission involving high speed flybys of planets and/or moons. It would be very desirable to operate at high power and high data acquisition rates during close encounter(s), with the ability to then recharge the energy system over the long period until the next encounter.

The second application is for lunar base power. The MIC energy system can be used both to supply pulsed high power on demand, whether during the lunar day or night, or as a backup source of steady power during the lunar night. In principle, the MIC energy storage structure can be designed to also provide solar electric generation during the lunar day, by locating solar cells on the MIC energy storage structure.

The amount of stored energy required for a lunar base will very much depend on the location of the base. If it is located at the lunar poles, the solar illumination can be almost constant during the lunar orbital cycle around the Earth (the orientation of the solar electric system would change during the lunar cycle, however, to remain illuminated). If located at lower latitudes, however, solar electric generation will be essentially zero for 2 weeks during the lunar night. Supplying all of the electric power needed by a manned lunar base for a 2 week period would require a very massive MIC structure. In such applications, one would probably use some other form of storage, e.g., electrolyzer/fuel cell units for steady power, with the MIC storage system used to deliver shorter high power outputs when necessary.

A third application for MIC energy storage is for robotic rovers on the Moon or Mars. The MIC system would deliver high power output during the periods when the rover was moving and needed high power. For most of the rovers operating cycle, however, the rover would remain at the site where it was collecting data and analyzing samples. Power usage during these periods would be relatively low, allowing the MIC energy storage system to be recharged.

The energy storage amounts shown in Table 5.3.1 appear representative for the 3 applications. With 100 megajoules energy storage, a spacecraft could broadcast data at 10 kilowatts of power for over 2 hours, carry out orbital or trajectory adjustments using electric thrusters, or operate high power radar scanners and other instruments as it passed by a location of interest.

With 2000 megajoules of energy storage, a lunar base could generate 100 kilowatts of additional power on demand when needed for 6 hours, or a megawatt of pulse power for over 30 minutes, in addition to a chemical energy storage system.

With 5 megajoules of storage, a robotic rover would be able to travel with a 1 kilowatt of drive power input for an hour and a half, going several miles from an old exploration site to a new one.

A number of conclusions can be drawn from the examples shown in Table 5.3.1. First, the weight of the MIC structure for energy storage is much greater than that for the solar electric and solar thermal propulsion applications. This results from the need for very high superconducting currents to store large amounts of electrical energy in the magnetic field of the MIC structure – in fact, much greater than the currents required to form the structure. This greatly increases the weight of the superconductor and the tether network needed to restrain the magnetic forces.

Second, the weight of the MIC energy storage structure could be greatly reduced by increasing the engineering current density of the superconductor, and by operating at higher stress in the tensile tethers. Increasing the engineering current density of the superconductor to 200,000 amps per cm^2 for example, combined with further optimization of the MIC system would cut the overall weight of the three applications shown in Table 5.3.1 almost in half. Such an increase in engineering current density appears likely, given the extremely high current densities in the HTS superconducting material itself, which are on the order of 10 million amps per cm^2 . Thicker superconducting films and improved processing to reduce local imperfections in the HTS material will achieve these higher engineering current densities.

Third, the amount of solar electric power that could be generated by having solar electric cells located on, and supported by, the MIC energy system structure is very large, i.e., 500 KW(e) for the spacecraft application, 2000 KW(e) for the lunar base, and 5 KW(e) for the robotic rover. Clearly, the solar electric generation using the MIC structure would be more than sufficient to rapidly store the requisite electric energy, and very ample for the 3 applications.

Figure 5.3.2 summarizes the assessment of the three MIC energy storage applications. Based on the assessment, and the importance of the lunar base mission, both in terms of itself, and as a prelude to a manned mission to Mars, the energy storage application for a lunar base has been selected for a baseline design, as described in Section 10 of this report.

5.4 MIC Space Telescope

It is a little known fact that in the 1990's NASA and the Department of Defense invested some \$10 Million in development of radical new optics technologies for very large, extremely low weight space telescopes. Known by the acronym PAMELA (Phased Array Mirror, Extendible Large Aperture), these technologies demonstrated the feasibility of using silicon micro-electro-mechanical systems (MEMS) to correct gross errors in optical telescope structures. Development of these technologies was originally funded by the Defense Advanced Research Projects Agency (DARPA) and the Ballistic Missile Defense Organization (BMDO). After the end of the Cold War, the R&D effort was adopted by NASA and pursued vigorously at Marshall Space Flight Center in Huntsville, Alabama. The resulting hardware, software, and analytical expertise still remain as a very valuable untapped resource for breakthrough space telescopes far surpassing the capabilities of the present James Webb Telescope effort. When combined with the presently proposed MIC structural deployment system, the synergistic value of the PAMELA technologies could save decades of time and billions of dollars of development and launch costs. The moderate risk associated with this approach can be the key to a true revolution in space optics within a decade.

To explain the superiority of the MIC / PAMELA approach, we must first qualify the technological constraints. The most fundamental requirement of any telescope is nearly diffraction-limited performance. This is conveniently characterized by the so-called Strehl ratio, which compares the cumulative wavefront errors of light rays traversing a real telescope with the performance of a theoretically perfect one. It is easy to see from Figure 5.4.1 that, if the root-mean-square error distribution of the optics exceeds one-tenth of the wavelength of the observed light, the optical efficiency of the system rapidly plunges toward zero. In the whimsical parlance of optical engineers, a telescope rapidly degenerates into a useless "light bucket" if the Strehl ratio falls below 80%. In other words, the ability to focus on discrete tiny objects becomes impossible because the desired light is scattered into the broad error pattern while stray radiation from off-axis sources swamps the desired image information. Hence, building huge space telescopes at affordable cost depends upon use of extremely clever correction schemes for fine tuning both the physical structure and the implicit wave fronts of light to correct errors in wave propagation. The MIC / PAMELA approach can make this possible to the required precision of 50 nanometers r.m.s. for visible light.

The key to success is to build a structure that deploys near enough to optical perfection to permit wave-front control by adaptive optics technologies to correct residual errors and approach diffraction-limited performance. In Chapter 11 of this report, we shall describe a system concept that may be capable of such performance for primary aperture diameters as large as 1 kilometer or greater. A 1 kilometer diameter telescope would have resolving power 400 times better than the Hubble Telescope and light gathering power 160,000 times greater.

Two generic concepts and their key technologies will be discussed in Chapter 11. The first is a wide field-of-view, short focal length optical system designed for deep survey applications ranging from total protection against Earth-threatening comets and asteroids to statistical cosmological studies extending to the boundaries of the observable universe. The second is a long

focal-length, high magnification telescope optimized for detailed spectrographic observation of objects ranging from Earth-like planets around other stars to galaxies forming in the primeval universe. It is important to note that such telescopes can also look down at the Earth from geostationary range for continuous high-resolution imaging without the absentee problem associated with existing intelligence satellites in low orbits: Three or four high-orbit telescopes can accomplish full-time surveillance of the whole Earth that would require hundreds of low orbit telescopes, provided that equally high ground resolution can be achieved.

Refer to Chapter 11 for more details regarding the feasibility of huge MIC / PAMELA telescopes.

5.5 MIC Propellantless Propulsion

Spacecraft orbiting bodies that possess significant planetary magnetic fields, such as Earth and Jupiter, can use a high current MIC structure to generate forces that raise or lower the orbit of the spacecraft, without requiring propellant to do so. Figure 5.5.1 illustrates the MIC propellantless process.

In the presence of a background magnetic field, a high current MIC cable will experience a substantial JXB magnetic force. Assuming a cable current of 1 million amps flowing at a right angle to an ambient background field of 10^{-4} Tesla [1 Gauss, comparable to the magnetic field strength dose to the surface of the Earth], the MIC cable would experience a transverse magnetic force of 100 Newtons per meter of cable length.

A MIC cable with an engineering current density of 300,000 amps/cm² would weigh approximately 3 kilograms per meter, including superconductor support tube, and thermal insulation. The corresponding acceleration would then be ~ 30 m/sec² of 3 g. If free to move, the MIC cable would then reach a velocity of 1 km/sec in ~ 33 seconds, and 3 km/sec in 100 seconds.

However, the MIC cable is actually a part of an electric circuit, so that the magnetic force on one side of the circuit is in the opposite direction from the force on the other side of the circuit, because the superconducting current in the first side flows in the opposite direction from that on the other side (Figure 5.5.1).

If the background magnetic field is uniform then the net magnetic force on the MIC loop is zero. If however, the magnetic field strength is less on one side of the loop than on the other, then the net magnetic force will be non-zero, as illustrated in Figure 5.1.1.

Such a situation of a non-uniform magnetic field occurs with planetary dipole magnetic fields. For example, Earth's magnetic field strength decreases as the cube of distance from the center of the Earth, being roughly 1/8th as strong at 4000 mile altitude above the surface, as it is at the surface. Accordingly, to achieve a significant net magnetic force on a MIC propellantless propulsion loop, the width of the loop should be large, as measured in the radial direction from the center of the Earth.

For the case of a long rectangular MIC loop orbiting the Earth in the equatorial plane, oriented so that the sides of the loop are perpendicular to the Earth's magnetic field vector, and the long sides are perpendicular to the radius vector from the center of the Earth, so that one of them is closer to the Earth than the other (Figure 5.1.1) the difference $|\Delta B|$, in magnetic field strength between the two sides is given by

$$|\Delta B| = 3B_D \left(\frac{R_E}{R} \right)^3 \left(\frac{\Delta R}{R} \right) \quad (5.1.1)$$

where OR is the distance between the two long sides of the MIC rectangular loop, R_E is the radius of the Earth, and R is the distance of the spacecraft from the center of the Earth.

The corresponding net magnetic force on the MIC cable in Newtons per meter of cable length is then:

$$F_{net} = I_D \Delta B \text{ Newtons / meter} \quad (5.1.2)$$

where I_0 is in amps and OB in Tesla.

For a MIC cable loop orbiting at an altitude of several hundred kilometers above Earth's surface with a cable current of 1 million amps and a OR of 10 kilometers, the net radial magnetic force would be 0.5 Newtons/m corresponding in an equivalent OV of 1 km/sec after 6000 seconds (100 minutes) and 3 km/sec after 18,000 seconds (5 hours).

Depending on the direction of the current in the MIC loop, the radial acceleration could be away from the Earth (i.e., raising the orbit) or towards the Earth (i.e., lowering the orbit), while not using propellant, the MIC system would require electrical input energy to create the current in the loop, and to compensate for the changes in magnetic and gravitational energy as the orbit was raised or lowered. This energy input would probably be supplied by solar cells attached to the tether network that restrained the magnetic forces on the MIC cables.

Under the action of the net radial force acting on it, the MIC loop, together with its attached payload would slowly spiral outwards, or inwards depending on the direction of the current in the loop. The strength of the magnetic force would decrease as the cube of the radial distance from the center of the Earth; however, the gravitational force would decrease as the square of the radial distance, which would significantly offset the reduction in magnetic force.

The time to travel between low and high Earth orbit using the MIC system would be several days, comparable to the time required with solar thermal propulsion. The MIC propellantless propulsion system would have a high mass. For a 1 million amp cable system of

30 km length and 10 km width, and a unit mass of 5 kg/meter (SC cable, insulation tethers, refrigeration, and solar cells, the total payload mass would be about 400 metric tons, about ½ of what would be required for one manned Mars mission.

However, the MIC propellantless system would provide an enormous payload capacity transferring heavy payloads to high Earth orbit from low Earth orbit, without the need for massive amounts of propellants. It would have the capacity to raise 1000's of tons of payload per year to high orbit, from which spacecraft could take off for the Moon, Mars, and the other planets with much less propellant required, and with much greater payloads than if conventional rockets had been used from Low Earth Orbit.

5.6 MIC Magnetic Shielding

MIC structures can be used to magnetically shield astronauts from high energy ionized particles, i.e., protons and higher nuclei (e.g., helium, etc.) which form a large fraction of the ~50 Rem per year radiation dosage that individuals receive if they are not protected by some form of shielding.

Shielding of astronauts using thick layers of mass around their crew quarters has a number of major drawbacks:

- 1.The amount of mass required is very large.
- 2.The size and volume of the crew quarters is small and constricted.
- 3.Nuclear interactions of the cosmic particles with the shielding can produce penetrating secondary particles that are difficult to shield.

Magnetic quadrupole can deflect and reflect ionized particles, preventing them from reaching crew quarters, without having to use large amounts of massive shielding. Figure 5.6.1 illustrates the process for a linear quadrupole. Most of the ionized particles that would otherwise strike the crew quarters located on the axis of the linear quadrupole are deflected or reflected from their original paths by the increasing magnetic fields as they approach the MIC quadrupole. The path labeled particle A in Figure 5.6.1 is typical of the particles that would be prevented from striking the crew quarters.

Some particles would still strike the crew quarters, either because their energy is too great to be deflected or because their original paths are primarily directed along the magnetic field lines, rather than across them. The path labeled Particle B in Figure 5.6.1 illustrates how such particles can still strike the crew quarters. As a result, magnetic shielding cannot completely stop all high energy particles, but it can dramatically reduce the particle flux striking the crew quarters and the corresponding radiation dose.

The crew quarters would be centered on the axis of the quadrupole. The magnetic field strength on the axis is zero, and increases linearly with the outwards distance from it. For a crew cabin with non-zero dimensions, the astronauts would live and work in a low level background magnetic field. The background magnetic field strength would depend on location relative to the

axis of the quadrupole, being zero on-axis, and on the order of 100 Gauss at the outer boundary of a typical size crew cabin with a diameter of ~4 meters. The maximum field strength of ~100 Gauss is 100 times stronger than Earth's magnetic field, but 100 times weaker than experienced in MRI (Magnetic Resonance Imaging) scans. Studies of the effects of long term exposure to low level magnetic fields on animals have not shown any harmful effects. Given a choice, it would seem preferable to experience ~100 Gauss during an 18 month round trip to Mars, rather than ~100 R of cosmic radiation dose, particularly doses that included heavy ion radiation to brain cells.

The MIC structure for magnetic shielding could be a linear quadrupole, enabling the length of the cabin to be several times its diameter, or a circular quadrupole in which the length and diameter of the cabin would be comparable. The required MIC cable current would be on the order of several million amps, with the precise value dependent on the degree of protection desired, and the size of the crew cabin.

5.7 MIC Expandable Tankage

MIC can be used for expandable tankage, to provide a lightweight, strong and very rigid structure that can support a thin flexible liner that holds propellant. Various propellants can be stored in MIC tanks, including kerosene, liquid hydrogen, and liquid oxygen.

The MIC superconducting cables and the tethers that restrain the magnetic forces between them in turn support a network of tethers to which is attached the flexible liner. Examples of the MIC configurations that can be used for propellant tanks include the linear quadrupole, a circular quadrupole, and the coaxial structure.

Using the linear quadrupole structure, for example, the cylindrical propellant tank would be located inside the square cross section of the quadrupole. The flexible liner of the cylindrical tank would be attached to and supported by a woven net of high tensile strength ropes. In turn, the cylindrical woven net would be attached to and support by the network of high tensile strength tethers that restrained the outwards magnetic forces on the 4 superconducting cables used to form the MIC quadrupole. (Figure 2.8 shows an expandable tank using a linear quadrupole configuration.)

The linear quadrupole geometry enables a long, slender expandable tank geometry for take off from and landing on Earth or other bodies with an appreciable atmosphere, with the need to minimize aerodynamic drag forces. A coaxial MIC geometry, in which the superconducting cable currents run in one direction on an outer cylindrical surface, and return in the opposite direction on the inner cylindrical surface, can also be used for long slender expandable tanks. In this geometry, the magnetic field lines are in azimuthal direction in the annular space between the inner and outer cylinders. The magnetic forces on the outer superconducting cables are radially outwards, and radially inwards on the inner superconducting cables. The magnetic forces on the superconducting cables are restrained by high tensile strength tethers attached to the inner and outer cables. In this geometry, the cylindrical surface of the expandable tank would be coincident with the surface defined by the inner set of superconducting cables tank.

For expandable applications where the tank is always stationed in space, or where it lands onto and takes off from bodies with little or no atmosphere, a circular cusp geometry could be used. The circular cusp uses 2 coaxial superconducting loops of equal diameter with the loops spaced apart at a distance equal to their diameters. The superconducting current in loop 1 is oppositely directed from the current in loop 2, so that the loops experience an axially directed magnetic force that acts to push them apart. The magnetic forces are restrained by high tensile strength tethers attached to the two loops.

Three expandable propellant tank applications using MIC structures were considered:

- ? Propellant storage depots in space
- ? Tankage for propellants manufactured from in-situ resources on Mars, Europa, and other bodies
- ? Tankage for launch vehicles taking off from Earth

The space depot application would enable the accumulation and storage of large amounts of propellant in Low Earth Orbit (LEO). The propellants could be ferried up to the storage depots using relatively low cost unmanned reusable launch vehicles. The stored propellants would then be used for manned missions to the Moon and Mars. The astronauts would rendezvous with the propellant storage tank. After attaching their crew vehicle to the tank, they would continue to the Moon or Mars, depending on the mission.

The large amounts of stored propellant enabled by the MIC depots would allow the astronauts to have short travel times to Mars, reducing their radiation dosage from cosmic rays, and minimizing the physiological and psychological stresses of long stay times in space. For trips to the Moon, MIC storage would enable the astronauts to carry more equipment and supplies. This would reduce mission risk, and enhance mission capabilities.

The second MIC expandable tank application is the storage of propellants manufactured from in-situ resources. After a spacecraft landed on the Mars polar cap or ice covered Europa, for example, it could manufacture liquid H₂ and O₂ propellant by electrolyzing melt water from the surrounding ice, using a nuclear power source. The spacecraft would also have a compact MIC expandable tank, which would then be expanded and filled with the manufactured H₂ and O₂ propellants. After completing its exploration mission on the planet or moon, the spacecraft could then return to Earth with collected samples, using the manufactured propellants.

The third MIC expandable tank application is, low cost, large volume tankage for conventional Earth to orbit launch vehicle using either kerosene/liquid O₂ propellants. The MIC cables would provide a strong structure for the tank, with tethers from the cable attached to and supporting relatively thin walled vessels that actually held the propellants. The MIC tank could then either be discarded after launch, or used as a storage depot.

Figure 5.7.1 summarizes the features and requirements for the MIC expandable tankage system for the above 3 applications. The long term propellant depot in space appears to be the

most straight forward and easiest to implement. Since it operates in zero g, the forces on the structure are relatively low, and the required MIC cable current is only about 100,000 Amps, even for a large ~2000 m³, tank. Space debris and micrometeorites are an important technical issue, since armoring the whole tank could require substantial mass. A multi-chamber design may be the best approach.

The MIC tank application for storage of propellants produced from in-situ resources is very attractive since it would greatly enhance the ability to explore other bodies in the Solar System and return samples from them. The tankage volume and g forces during launch are relatively small and do not appear to pose a significant problem. The most difficult application is the large MIC tank used for launch from Earth to orbit. Because of the necessarily huge volume and the high g forces, the MIC cable current is very large, no the order of 10 million Amps. The structural forces will be very large. The concept is very attractive, but requires detailed study of its feasibility.

5.8 MIC Earth Communications and Sensing

The large scale and low mass of MIC structures have the potential to dramatically expand the capabilities of space based communications and Earth sensing systems. Figure 2.9 lists some of the communication and Earth sensing applications.

The ability to generate large amounts of solar electric power using MIC structure, combined with large MIC broadcast and receiver units at GEO will enable continuous 2-way coverage to every point on Earth for cell phones, HDTV, and internet access. Low cost interactive TV education classes will be available to the poorest, most remote populations on Earth, helping people to form more efficient ways to have cleaner water, reduce disease and obtain aid that will make their lives better.

For Earth environmental monitoring and surveillance, a combination of large MIC structures at GEO plus smaller MIC units at lower altitudes would probably be used. A wide variety of surveillance and monitoring methods could use MIC structures including:

- ? MIC telescopes operating in the usual and infrared spectrum
- ? MIC radar transmitters and receivers
- ? MIC laser transmitters and receivers

To list just a few of the capabilities that large MIC environmental monitors could do.

- ? The position and condition of every ship operating in the oceans could be monitored in real time to determine whether it was following its trip plan, whether it was surreptitiously loading or unloading cargo, whether it was in trouble, whether it was discharging pollutants (e.g., dumping oil containing wastes), if fishing boats were violating fishing regulations, etc. The monitoring could be done using a combination or visual and radar observations, plus laser spectrography to investigate discharges of pollutants.

- ? The amounts and types of pollutant emissions from large power plants, chemical process plants everywhere on Earth. These observations would be carried out continuously so that offending emitters could be quickly shut down if they did not comply with emission standards. The measurements would use visual and spectrographic means.
- ? Global monitoring of CO₂ sources and sinks would provide a much more detailed continuous understanding of what processes were most important on how they affected Earth's CO₂ balance and its impact on global warming. For example, determines local and integral amounts of CO₂ released from organic materials in warming permafrost regions and cleared forest areas, CO₂ uptake in re-forested regions, the effect of oxygen deficient zones in the ocean, etc. would be of great value in analyzing where the Earth's climate is headed.

MIC monitoring units can also potentially be used to detect and warn against potential disasters such as tsunamis, earthquakes, and volcanic eruptions. Monitoring surface earth movements in very fine detail with great accuracy over wide areas around fault lines, and active volcanic regions would provide information in real time, what was happening underground and whether or not a disaster was about to happen.

For example, if sub-surface magma was flowing upwards, continuous measurements of the surface above the upwelling liquid would indicate the volume of magma involved, the measurement rate of filling, and where it was located. Measurement of the transient surface movements accompanying frequent microquakes would provide additional information of the underground rigidity, strength and structure by observing the speed of the underground shock waves, and their diffractive behaviour as they move through different liquid and solid zones.

Similarly, continuous monitoring of the surface movements around fault lines from continuous slow slippage and creep of rock along the sides of the fault, plus the seismological observations accompanying frequent microquakes may be able to detect and warn against a major earthquake.

MIC units can also provide real time monitoring of the strength and direction of tsunami waves at all points along its front, giving the maximum possible warning time and degree of hazard involved to all persons at risk from it. In addition by continuously monitoring small ocean surface movements from micro-quakes in the sea bed, it may be possible to provide advance warning of a tsunami.

Figure 5.1.1 Potential MIC Solar Electric Applications – Features and Requirements

- MIC solar concentrator focuses sunlight onto array of solar cells
 - Solar concentration capability up to ~100 Suns
- Specific mass of MIC concentrator is very low
- Goal of 1 kg/KW(e) or less at 1 AU for MIC concentrator, including all components, i.e., superconductors, insulation, tethers, mirror film, and refrigeration and coolant equipment
- Can provide useful solar electric outputs at distances from Sun up to the orbit of Jupiter
- Pointing of MIC concentrator is adjustable to compensate for a moving orientation of Sun

Figure 5.1.2 Evaluation of MIC Solar Electric Applications

- Lightweight MIC concentrator can focus sunlight onto small solar cell array, reducing cost and mass of solar cells
- Specific mass of MIC concentrator at ~1 AU distance from Sun is ~1 kg/KW(e), based on 20% solar cell efficiency
 - Specific mass relatively constant over wide range of power output [e.g., 1 to 200 MW(e)]
 - Specific mass dominated by 2 components
 - Aluminized Mylar mirror film on tether network
 - Superconductor
 - Other components (tethers, refrigeration, etc.) much smaller
- Lunar base MIC solar systems is favored for initial application
 - Early use
 - Can lead to large power beaming application

Figure 5.2.1 Potential MIC Solar Thermal Propulsion Applications – Features and Requirements

- MIC solar concentrator focuses sunlight on a high temperature receiver that heats hydrogen propellant to high temperature
 - Hydrogen propellant heated to ≥ 2500 K
 - MIC concentrator focuses sunlight to ≥ 1000 Suns on last section of propellant heater
[lower temperature portion of propellant heater does not require as high a concentration factor]
 - MIC thermal propulsion power ≥ 1 megawatt(th)
- MIC thermal propulsion units can operate in a shady state or intermittent mode

Figure 5.2.2 Evaluation of MIC Solar Thermal Propulsion Application

- MIC solar thermal propulsion systems have potential to heat hydrogen propellant to high temperature
 - ~900 seconds specific impulse (twice H₂/O₂ Isp of 450 sec)
 - ~2500 K temperatures need ~1000 Suns concentration factor at 1 AU
- Practical applications constrained to ~1 AU distance from Sun
 - Sun distances >>1 AU would require impractically high solar concentration factors to achieve ~2500 K
- Potential applications include
 - LEO/GEO orbital tug
 - Earth/Moon tug
 - Outbound Mars cargo vessel
- Heavy payloads can be handled with relatively short thrust times, e.g.,
 - 100 metric tons to Mars with OV = 5 km/sec and 3 ½ day thrust
 - MIC propulsion system dry mass ~3 % of payload mass
- Earth to Moon MIC tug appears to have priority for near term application

Figure 5.3.1 Potential MIC Energy Storage Applications – Features and Requirements

- MIC system stores and delivers electric power on demand
 - Electric storage and delivery rates vary according to power availability and demand
- Output/input energy efficiency $\geq 99\%$
- Can operate in space or on surface
- Specific mass ≤ 10 kg/Megajoule stored
- Can provide wide range of storage capability – Megajoules to Gigajoules

Figure 5.3.2 Evaluation of MIC Energy Storage Applications

- Storage of electric energy considerably increases the mass of MIC structures as compared to other applications
 - Much higher superconductor currents are required, because stored energy scales as (current)² for given size structure
 - Superconductor mass increases as (current)¹ while tether and support tube mass increases as (current)²
- Specific mass of MIC storage is on the order of 10 kg per megajoule (100 kilojoule/kg), comparable with high performance batteries
 - Can deliver electrical power at much faster rates than batteries or fuel cells
- Practical range of MIC electrical storage system depends on application
 - ~10 to 100 Megajoules for spacecraft
 - ~10,000 Megajoules for lunar base (multiple MIC loops)
 - ~5 to 10 Megajoules for robotic rover
- Lunar base application appears to be the most useful. It provides emergency power during lunar night and also serves to generate solar electric power during lunar day

Strehl ratio

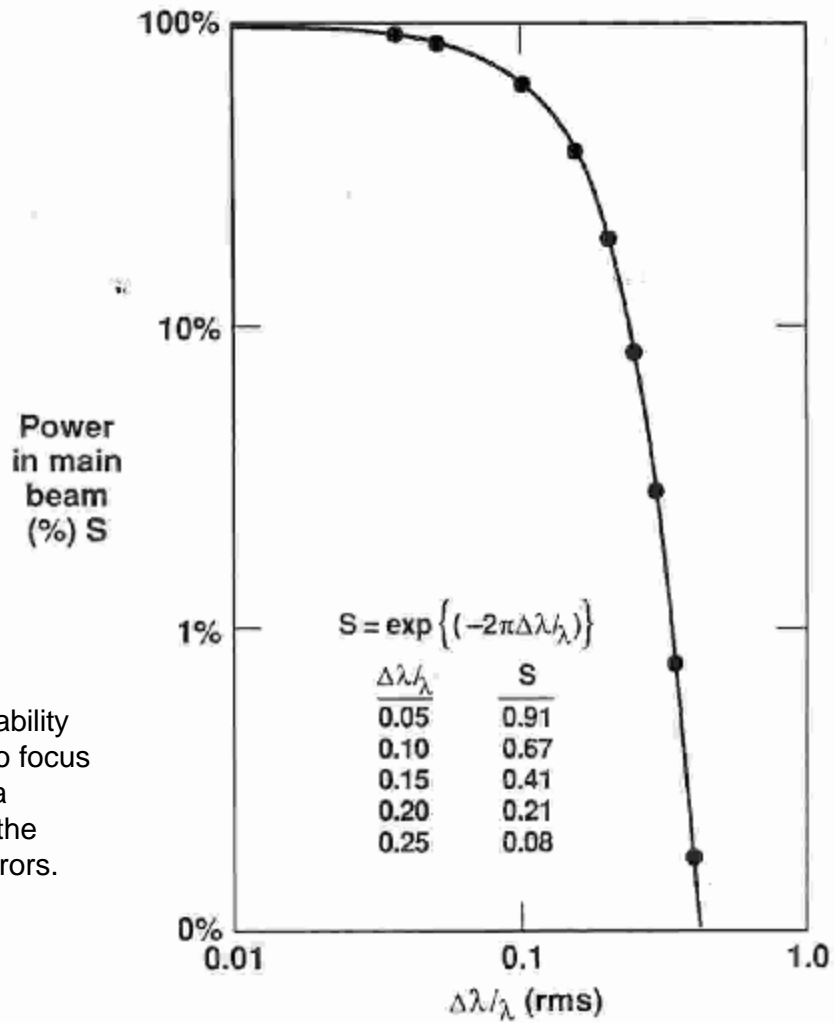


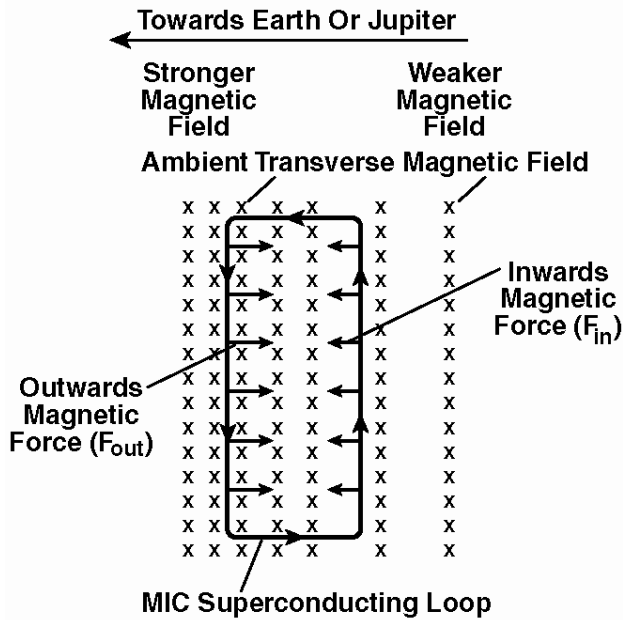
Figure 5.4.1 The ability of any telescope to focus a useful image is a strong function of the r.m.s wavefront errors.

Figure 5.5.1

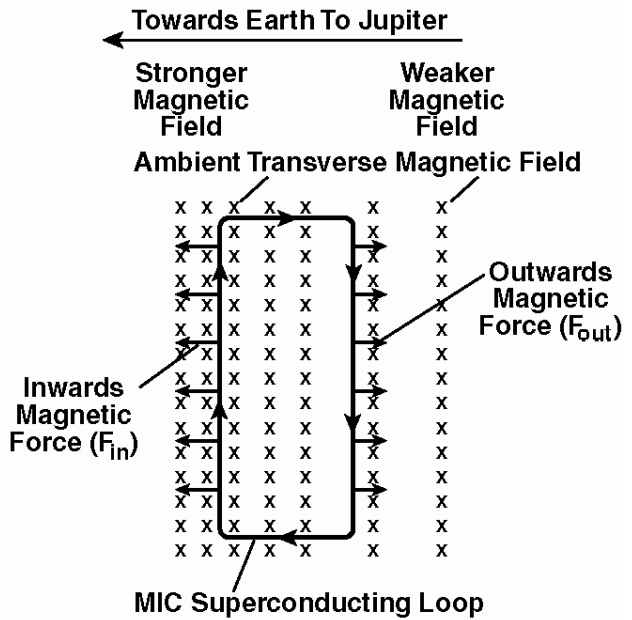
MIC Propellantless Propulsion Process

Moving Outwards From Earth Or Jupiter

Moving Towards Earth To Jupiter



$$F_{out} > F_{in}$$



$$F_{out} < F_{in}$$

Figure 5.5.2 MIC Propellantless Propulsion

MIC superconducting loops can be configured to interact with a planetary magnetic field to provide propellantless propulsive forces

Depending on direction of applied current in the MIC loop, it can move away from, or towards the planet – i.e., raise or lower orbital altitude

Magnetic energy exchanged for gravitational energy

MIC loop can serve as an orbital tug, moving between low Earth orbit and higher orbits

Potential applications limited to Earth and Jupiter – only bodies with appreciable planetary magnetic fields

For Earth applications, can provide ΔV additions on the order of 1 km/sec per day of operation

Nominal parameters are ~1 megamp SC current and ~1 KM loop width

Figure 5.6.1 MIC Magnetic Shielding

MIC magnetic shield structure can protect astronauts against radiation doses from Van Allen Belts and Solar Flares

MIC magnetic configuration can operate as a field free region for astronauts with outer magnetic fields that bounce back high energy particles and prevent them from reaching the astronauts
MIC magnetic shield structure can enable astronauts to traverse Van Allen Belts more slowly, and to survive Jupiter's Radiation Belts

MIC magnetic quadrupole configuration to very promising
Can create large cylindrical low field zone that is fully shielded against high energy electrons

Figure 5.6.1

Magnetic Shielding Of Astronauts From High Energy Charged Particles Using MIC Quadrupole Structure

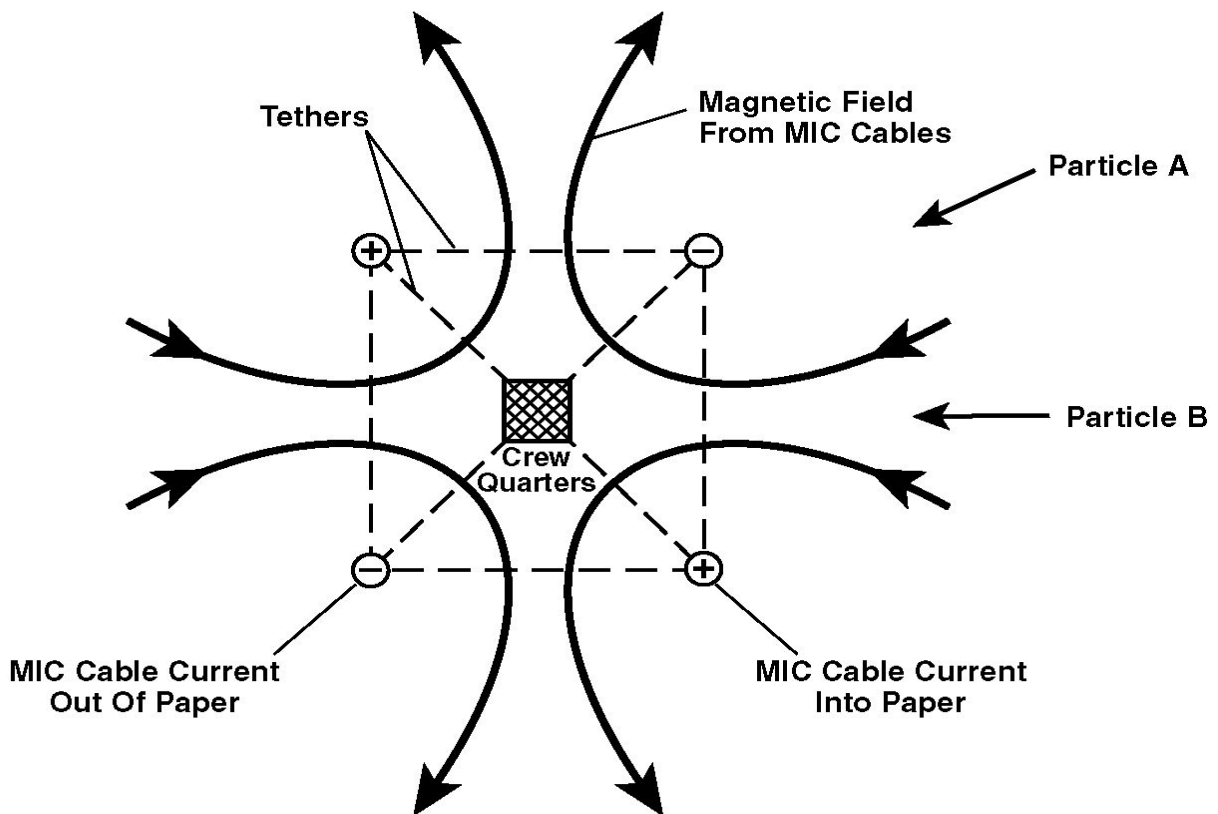


Figure 5.7.1 Features and Requirements for MIC Expandable Propellant Tank Application

Features/Requirements	Application		
	Propellant Storage in Space	Tankage for Propellants from In-Situ Resources	Tankage for Launch from Earth
1. Type(s) of Propellants	Liquid H ₂ & O ₂	Liquid H ₂ & O ₂	Kerosene, liquid H ₂ & O ₂
2. Tankage Size/Volume (illustrative)	10 meter diameter 30 meter long 2000 m ³	3 meter diameter 10 meter long 70 m ³	10 meter diameter 60 meter long 4000 m ³
3. Operating Environment	Zero g Sunlight @ 1 AU High vacuum	~0.5 g takeoff High vacuum on moons ~10 ⁻³ Atm on Mars	~4 g takeoff 1 Atm on Earth
4. MIC Cable Current (illustrative)	100,000 Amp	500,000 Amp	10,000,000 Amp
5. Refrigeration Power (including tankage)	? Multi-layer vacuum thermal insulation ? ~10 kW(e) for refregiration	? Multi-layer thermal insulation ? Refrigeration by boil off	? Shuttle type foam with H ₂ & O ₂ boil off
6. Technical Issues	? Long-term refregiration and power source ? Space debris and micrometeorites (multiple chambers)	? Support of propellant mass against g forces during launch	? Support of propellant mass against g forces during launch ? Very large SC current requirements

Table 5.1.1 Nominal Design Parameters for Potential MIC Solar Electric Applications

Basis: 100,000 A/cm² engineering current density in MgB₂ superconductor
 2 cm thick multi-layer thermal insulation
 15,000 psi tensile stress in tethers

Parameter	MIC Solar Electric Application		
	Electric Propulsion	Lunar Base	Power Beaming to Earth
Unit output power (1)	100 KW(e)	1 MW(e)	200 MW(e)
Solar cell efficiency	20%	20%	20%
Distance from Sun (2)	3 AU	1 AU	1 AU
Concentrator Area, m ²	3750	4170	8.34 x 10 ⁵
Concentrator diameter, m	69	73	913
Length of primary MIC cable, m	217	229	2870
MIC primary cable current, kiloamp (3)	250	250	950
Diameter of primary MIC cable, centimeters (4)	2.5	2.5	9.5
Mass of MIC primary cable, kg	430	430	22,600
Mass of tether and mirror surface, kg (5)	370	370	65,000
Other mass (secondary cable, coolant and refrigeration equipment), kg	100	100	5,000
Total MIC concentrator mass, kg	900	900	92,600
Specific mass of MIC concentrator, kg/KW(e)	9	0.9	0.46

- 1) Multiple MIC solar electric units would be used for reliability and redundancy, for example, electric propulsion and lunar base applications could have 3 multiple units; power beaming could have 10 or more.
 - 2) Electric propulsion distance of 3 AU is taken as the average between Earth and Jupiter.
 - 3) Produces outwards radial force of 200 Newtons per meter of cable.
 - 4) Diameter of superconductor, not including insulation.
- Mirror surface is aluminized Mylar of 5 x 10⁻³ centimeters (2 mils).

Table 5.2.1 Nominal Design Parameters for Potential MIC Solar Thermal Propulsion Applications

Basis: 100,000 Amps/cm² engineering current density in MgB₂ superconductor
 2 cm thick multi-layer thermal insulation
 15,000 psi in tensile tethers

Parameter	MIC Solar Thermal Propulsion Application		
	Orbital LEO to GEO	Earth to Moon Tug	Mars Cargo Vessel
Thermal power, megawatt	1	5	10
H ₂ propellant temperature, K	2500	2500	2500
H ₂ flow rate, kg/sec	0.025	0.13	0.25
Thrust Newtons (Isp = 900 sec)	220	1100	2200
Distance from Sun, AU	1	1	1
Concentrator area, m ²	830	4170	8340
Diameter of MIC concentrator, meter	32	73	103
Length of primary MIC cable, meter	100	229	460
MIC primary cable current, Kilo Amp	180	250	320
Diameter of MIC primary cable, cm	1.8	2.5	3.2
Mass of MIC primary cable, kg	150	430	1120
Mass of tether and mirror surface, kg	80	370	740
Other mass (secondary cable & refrig eq.) kg	50	100	200
Total MIC concentrator mass, kg	280	900	2060
High temperature receiver plus misc mass, kg	200	1000	1500
Total solar thermal propulsion system mass	560	1900	3560
Nominal OV(kg/sec)/thrust time, days	5/3.7	5/2	5/3.6
Payload mass, metric tons	10	30	100
Total weight of H ₂ propellant, metric tons	8.1	24	79
Total weight in LEO, metric tons	19	56	183

Table 5.3.1 Nominal Design Parameters for Potential MIC Energy Storage Applications

Basis: 100,000 A/cm² engineering current density in MgB₂ superconductor
 2 cm thick multi-layer thermal insulation (4 cm for rover)
 30,000 psi tensile strength in tethers and support tube

Parameter	MIC Energy Storage Application		
	Spacecraft	Lunar Base (1)	Robotic Rover
Energy storage, Megajoules	100	2000	5
Form of storage	Circular loop	Circular loop	Linear quadrupole
Dimensions of storage unit	50 meters diameter	100 meters diameter	10 meters length, 2 meters width
Diameter of support tube, centimeters	11	33	5.5
Current in MIC cable, Amps	1.1 x 10 ⁶	3.3 x 10 ⁶	500,000
Length of MIC cable, meters	160	320	50
Mass of MIC superconductor, kg	1000	6000	150
Mass of thermal insulation, kg	360	1920	70
Mass of support tube, kg	125	2400	25
Mass of tether network, kg	190	300	40
Mass of refrigeration equipment, kg	50	300	10
Total mass of MIC storage unit, kg	1725	10,920	295
Refrigeration load, watts(th)	7	42	2
Solar power generated at 1 AU using integrated solar cell array , KW(e)	500	2000	5
Specific mass, kg/MJ(e) stored	17	5.5	59
Specific mass, kg/KW(e) generated at 1 AU	3.4	5.5	59
1) several independent storage loops, each of 2000 MJ capacity, would be used for the lunar base			

6.0 EVALUATION AND SELECTION OF SUPERCONDUCTORS FOR MIC APPLICATIONS

6.1 Goals and Requirements for MIC Superconductors

Figure 6.1.1 summarizes the principal goals and requirements for potential superconductors for MIC applications. The first principal requirement is that the superconductor should be able to operate at temperatures substantially above the liquid helium temperature of 4K. Not only does this reduce refrigeration power considerably, it also simplifies the thermal insulation and coolant systems.

At a minimum, the MIC superconductor should be able to operate at 15 to 20K, with the goal of even higher temperatures. To achieve this temperature capability, low temperature superconductors such as Niobium-Titanium (NbTi) and Niobium Tin (Nb_3Sn) can be ruled out. The only practical high temperature superconductor options that meet this requirement are Magnesium Diboride (MgB_2), Yttrium Barium Copper Oxide (YBCO) and Bismuth Strontium Calcium Copper Oxide (BSCCO).

The second principal requirement is that the MIC superconductor must operate at a high engineering current density in strong external magnetic fields. Superconductor performance is often expressed in terms of the critical current density in just the superconducting material. While important, high current density in a superconductor, by itself, does not tell the whole story. The superconducting material is present as a film on a tape substrate, or as filaments in a surrounding matrix. The amount and weight of this support material is also an important determinant in choosing a MIC superconductor.

The engineering current density (J_e) accounts for the support material, and is defined as the actual current carried by the conductor, divided by the full cross sectional area of the conductor. The full area includes the superconductor itself, support material, stabilizer (if used), electrical insulation, etc. The engineering current density is typically substantially smaller than the actual superconductor current density (J_c). Typically, J_c is about 0.2 to 0.3 of J_e .

The third principal requirement is operational stability. The MIC superconductor must remain in the superconducting state for all anticipated operating conditions, including the inevitable flux jumps that occur in the superconductor, as well as micro-movements of the conductor. Such events generate minute amounts of local thermal energy which is absorbed by the superconductor. This is of considerable concern for the low temperature superconductors (LTS) that operate at liquid helium temperatures, of ~4 Kelvin, because of the extremely low specific heat of material at such temperatures. LTS conductors are made stable in two ways. First, by intimate contact with liquid helium coolant, which does have a high specific heat at low temperatures, and second, by intimate bonding with a metal stabilizer like high purity copper or aluminum that has very high thermal and electrical conductivity. If a local thermal pulse occurs, the stabilizer rapidly spreads it over a large area, preventing the temperature of the superconductor from rising enough to go into its normal non-superconducting state. The stabilizer also functions to momentarily carry the conductor current even if the superconductor were to transition to the normal state, allowing it to cool back down to the superconducting state. The I^2R thermal power

in the stabilizer is low enough that the attached superconductor can recover.

The flux jump and micro-movement issue is virtually eliminated for high temperature superconductors (HTS). The specific heats of the superconductor and its associated structure are much larger than for LTS, greatly reducing the temperature rise in the conductor if a flux jump or micro-movement occurs. Moreover, the allowable temperature rise itself can be much greater for HTS than acceptable for LTS, giving an even greater safety margin.

The fourth principal requirement is mechanical integrity of the superconductor. The HTS superconductors of interest retain their superconductivity with tensile strains of 0.3 to 0.4%, sufficiently high for practical MIC systems. Also, the candidate HTS conductors can be wound into compact packages for launch, without cracking or loss of mechanical integrity.

6.2 Comparison of LTS and HTS Superconductors for MIC Applications

Table 6.2.1 compares the performance capabilities of HTS and LTS conductors for the various MIC applications. The most important difference is the much greater refrigeration power required for LTS conductors. Also important is the simpler plumbing system for HTS conductors, and the increased OT's allowed for heat transfer and thermal transport.

HTS and LTS superconductors can have comparable engineering current densities, on the order of 100,000 amps/cm², when the necessary associated structure and stabilizers are taken into account. They also have comparable maximum magnetic field capability, on the order of 6 to 7 Tesla.

LTS conductors have been used for large scale applications for many years. Table 6.2.2 shows examples of some of these applications. In high energy physics, high field (e.g., 6 Teslas) magnets accelerate and guide intense beams of high energy particles. These particle accelerators require thousands of high field magnets, with total lengths of many kilometers of magnets in the accelerator. All of the magnets must work perfectly, otherwise the particle beam would not be produced. The large Hadron Collider (LHC), for example, will have 42 kilometers of magnets. The superconducting supercollider would have had 76 kilometers of superconducting magnets, if it had been completed. The LTS magnets for particle accelerators, besides having to operate at high field and work perfectly, are much more complex and require much greater precision of construction than the MIC superconductor systems.

LTS superconductors are also used in many thousands of superconducting magnets in MRI (Magnetic Resonance Imaging) units for medical diagnostics. These MRI superconducting magnets operate routinely and reliably, with very little maintenance and control required. LTS conductors are also used in the Japan Railways Maglev System now operating in Yamanashi, Japan. The Maglev magnets operate routinely and reliably in vehicles traveling at speeds up to 360 mph, and have carried over 50,000 passengers in perfect safety.

HTS superconductors, because they have only been developed in the last few years, do not yet have the widespread application achieved by LTS superconductors. However, important

demonstration projects have been carried out using HTS conductors, as shown in Table 6.2.3. These demonstrations include HTS motors and generators and power transmission lines. The US Navy is funding the development of a 36 megawatt HTS electrical motor, with the goal of using all-electric propulsion for ships with HTS motors and generators. Ships would have distributed propulsion capability, with substantial savings in ship size, weight, and cost.

The principal LTS superconductor uses a multitude of very fine (micron size) filaments of Nb-Ti (niobium-titanium) metal in a high purity copper matrix, which is drawn into small diameter wire starting from a large Cu/Nb-Ti billet. The small diameter of the filaments enables thermal energy generated in them by flux jumps to be quickly transferred to the copper matrix without having the superconductor transition to its normal state. The drawing process is simple and conventional, and produces high quality, very long lengths of uniform wire.

Multi filament HTS wire is produced using MgB_2 (Magnesium Diboride) and BSCCO (Bismuth Strontium Calcium Copper Oxide) superconductor materials. The manufacturing process is not as simple as that for the NbTi LTS superconductor, but high quality wire product can be produced. Because HTS conductor manufacturing methods are still in development, further improvements are likely.

YBCO (Yttrium Barium Copper Oxide) HTS superconductor is not manufactured as a multi-filament conductor, but rather as a thin film (~1 micron thickness) deposited on a thin metal tape substrate. Various deposition methods can be used, including ion beams, sputtering, chemical vapor deposition, etc. The present YBCO conductor is manufactured using metal organic deposition, on tapes 4 centimeters in width. The tape can then be slit into multiple narrower tapes for use in superconducting systems.

Illustrative present and projected engineering current densities for MgB_2 , BSCCO, and YBCO HTS superconductors as a function of temperature, in an external magnetic field of 2 Tesla are shown in more detail in the following sections. Clearly, the performance of the 3 HTS superconductors is good enough that they could be used for a variety of attractive MIC applications.

6.3 Present and Projected Capabilities for High Temperature Superconductors

6.3.1 BSCCO High Temperature Superconductor

Figure 6.3.1.1 gives a description of the principal features of BSCCO (Bismuth Strontium Calcium Copper Oxide) superconductor. Of the 3 candidate HTS conductors, BSCCO is the most developed and commercially available.

BSCCO has the highest critical temperature, 110 K, of the 3 HTS conductors. It can operate in liquid nitrogen coolant at 77 K, and at lower temperatures. The current production capacity is 1 million meters of wire per year, with an anticipated increase to 2 million meters per year by 2006.

Figure 6.3.1.2 shows a drawing of the BSCCO conductor, which has multiple small diameter filaments in a silver metal matrix. The conductor is strong and flexible, with a bend diameter of 5 centimeters.

Figure 6.3.1.3 shows data from American Superconductor brochures on the relative current density in BSCCO conductors as a function of temperature and external magnetic field relative to the current density is given at 77 K, with self field. A ratio of 4 for example, corresponds to an operating current density that is 4 times greater than that at 77 K in self field. The engineering current density (superconductor plus structure) for BSCCO conductors operating at 77 K in self field is 13,000 Amp/cm². At a normalized current density of 4, the actual current density in the conductor would be 4 x 13,900 or 55,000 Amp/cm².

Current density increases as the operating temperature decreases, and decreases as the external magnetic field increases. A perpendicular external magnetic field (i.e., normal to the surface of the BSCCO conductor) causes a greater decrease in current density than an external magnetic that is parallel to the surface of the conductor. For MIC applications, the parallel magnetic field case applies, not the perpendicular one.

Figure 6.3.1.4 gives numerical values for the current density in the BSSCO conductor as a function of temperature and parallel magnetic field. For the external field conditions in MIC applications, i.e., 2 Tesla and above, present BSSCO conductors operating at 20 Kelvin could achieve on the order of 50,000 Amp/cm². With future improvements in the alignment of the copper oxide based planar superconducting layers in adjacent crystallites, BSCCO conductors could probably operate at ~100,000 Amp/cm². Operation at 50 K at such current densities appears unlikely, however.

6.3.2 YBCO High Temperature Superconductor

Figure 6.3.2.1 gives a description of the principal features of YBCO (Yttrium Barium Copper Oxide) superconductor. Unlike the multifilament NbTi, BSCCO, and MgB₂ superconductors, the YBCO conductor is manufactured by depositing a very thin film, (~ 1 micron thick) on a metal tape, typically a nickel based alloy. The key to a practical YBCO

conductor is to deposit the YBCO film on a suitable thin substrate that has been previously deposited on the metal tape. This thin substrate enables the YBCO film to form a high integrity continuous film in which the superconducting current travels without hindrance in the planar copper oxide based superconducting layers.

Various substrates have been used for the YBCO conductor. A material that appears to work well is YSZ (Yttria Stabilized Zirconium Oxide). After the YBCO film has been deposited, a thin copper metal layer is deposited on top as a stabilizer and protective cover. The YBCO tape is now being manufactured in 4 centimeter widths, which can then be slit into multiple narrower tapes of whatever width is desired. Tape lengths of up to 1 kilometer are being manufactured.

For MIC applications, present engineering current densities of 20,000 to 100,000 Amp/cm² are achievable, depending on the operating temperature and external magnetic field. With thicker YBCO films, and the use of multiple films on the substrate, considerably greater current densities can probably be achieved.

Figure 6.3.2.2 shows a drawing of the present YBCO superconductor now being manufactured by American Superconductor. Figures 6.3.2.3A and B show data on the current carrying capability of the YBCO superconductor, as supplied by American Superconductor. The current density in the actual YBCO film is >1 megamp/cm² at fields of 2 Tesla, for the case where the external field is parallel to the tape surface (i.e., H_{11c}, or equivalently, at a 90 degree angle). The current carrying capability in Figure 6.3.2.3A is expressed both as current density J_c in the superconductor film (i.e., MA/cm²) and as current capability per centimeter of tape width, for 0.8 micron and 1.4 micron thick films.

Figure 6.3.2.3B shows the increase in YBCO current capability achieved by operating at lower temperature. At 1 Tesla and 26 K, the critical current at 90° angle is ~1000 Amp/cm of width, as compared to ~120 Amp/cm of width at 1 Tesla and 77 K, a factor of ~8 increase. At 3 Tesla and 26 K, the critical current is slightly reduced, to ~900 Amp/cm of width. Using nanodot YBCO material, critical current can be substantially increased for magnetic fields that are perpendicular to the surface. For fields parallel to the surface (i.e., 90 degrees), the increase is only a few percent.

Figure 6.3.2.4 summarizes the present and projected current carrying capabilities of YBCO conductor. Engineering current densities of ~50,000 to 60,000 Amp/cm² at 26 K are presently achievable. With thicker YBCO films and potentially having 2 or 3 films on the substrate, engineering current densities of 100,000 to 200,000 Amp/cm² are possible.

6.3.3 MgB₂ High Temperature Superconductor

Figure 6.3.3.1 gives a description of the principal features of MgB₂ (Magnesium Diboride) superconductor (1, 2, 3). While a multifilament conductor, MgB₂ is not manufactured by extending and drawing down a large billet into small diameter wire, as is done with NbTi. Instead MgB₂ is made using the powder in tube (PIT) process, as illustrated in Figure 6.3.3.2A. MgB₂ powder is injected into an open tube, which after being filled is closed around the powder and

drawn down to the desired diameter. A number of these tubes are then stacked together to form the multiple filament conductors, which depending on the desired form, can have 7 filaments, 18, 36, etc. (Figure 6.3.3.2B). The primary enclosing tubes can be copper, iron, niobium, or other suitable material.

MgB₂ has a much lower critical temperature (39 K) than either BSCCO (110 K) or YBCO (93 K). This restricts its practical operating temperature range to 15 to 20 K. MgB₂ wire is presently being manufactured by HyperTech in 1 kilometer lengths with engineering current densities in the range of 20,000 to 100,000 Amp/cm², depending on operating temperature and the external magnetic field.

Figure 6.3.3.3 shows HyperTech data on the superconductor current density in the MgB₂ conductor as a function of operating temperature and external magnetic field. For magnetic fields up to ~3 Tesla, MgB₂ conductor has a J_c of ~400,000 Amp/cm² at 20 K. At 15 K, it can achieve the same current densities at fields up to about 5 Tesla.

Present engineering current densities in MgB₂ conductor are substantially lower than the current density in the superconductor, because the superconductor fill fraction in the conductor is low, only about 15%. Figure 6.3.3.4 shows the engineering current density for 15% fill fraction. At 8K temperature of 15K and an external field of 2 Tesla, ~50,000 Amp/cm² can be achieved. Increasing the superconducting fill fraction to 30%, the goal of HyperTech, would raise the engineering current density to ~90,000 Amp/cm². In addition to the limitation on engineering current density due the presently low to superconductor fill fraction, only about 10% of the current capability in the individual MgB₂ crystallites is actually used due to imperfect alignment and contact between neighboring crystallites. It appears possible that with improved manufacturing techniques that reduce this resistance to supercurrent transfer, substantial increases in J_c can be achieved. A factor of 2 increase to 20% transfer capability instead of the present 10%, would increase J_c to ~200,000 Amp/cm² at 15K and 2 Tesla external field.

6.4 Selection of HTS Conductors for Proposed MIC Applications

Figure 6.4.1 lists the major criteria for selection of the best HTS conductor for various MIC applications. In general, all of the HTS conductors appear suitable for MIC, in that they have high engineering current densities at temperatures of 15 K and above, in external magnetic fields of 2 to 3 Tesla, that they have all been fabricated and tested, and that they can all be produced in the quantities required for large MIC systems.

The principal issue for use of the BSCCO conductor for MIC appears to be the cost and availability of the silver used as the matrix for the superconductor filaments. However, at the present cost of \$30 per kiloamp meter (kA·m) only about 10% of that is for silver. The finished cost of the BSCCO conductor at \$30 per kA·m corresponds to ~\$3000 per kilogram, which is 30% of the present launch cost of ~\$10,000 per kg. Accordingly, while MgB₂ and YBCO conductors will be cheaper to make for MIC applications, and probably would be preferable, BSCCO would be acceptable if the other conductors were not suitable for some reason.

Figure 6.4.2 addresses the three HTS conductors for the various MIC applications. For

most applications, including solar electric, solar thermal propulsion, and the large space telescope, either MgB_2 or YBCO appear to be the favored choices. More detailed data on their performance and the expected improvements in J_c , conductor weight, and refrigeration power requirements is needed before making a final selection. Since it probably will be at least 10 years before a decision on the MIC conductor would be required, and since very rapid improvements on the HTS conductors are being made, it appears best to wait for a few years before making the selection.

However, with regard to some MIC applications, a preliminary selection appears possible at the present time. For example, for magnetic shielding applications, YBCO conductor appears favored, since it has the highest magnetic field capability, a very desirable feature for deflecting high energy particles away from manned vehicles. Similarly, for the energy storage application for a lunar base, MgB_2 conductor appears favored, because extremely large currents will be required to store the very large amounts of energy needed during the lunar night. MgB_2 appears to have the highest superconductor current capability per unit mass of superconductor, as compared to BSCCO and YBCO. This parameter is an important factor for a large scale energy storage system.

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Figure 6.1.1

Functional Requirements for MIC Superconductor

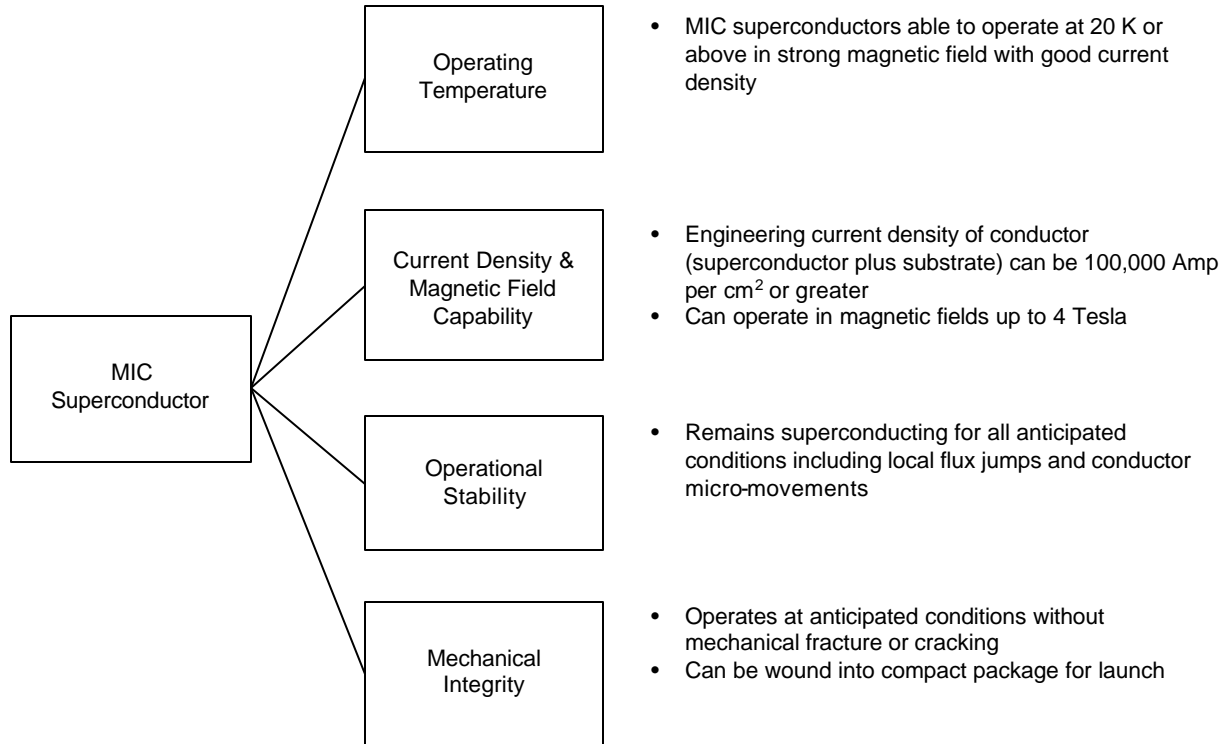


Figure 6.3.1.1 Description of BSCCO HTS Superconductor

Material and Form:

Small diameter (~10 Micron) multi-filaments of Barium Strontium Calcium Copper Oxide (BSCCO) in silver matrix

Fabrication Process:

Silver billet containing BSCCO rods is drawn and rolled down into small diameter wire tape

Critical & Practical Temperature Range:

110 Kelvin critical temperature; 20 K to 77 K practical operating temperature range

Parameters of Present Commercial Wire:

4 millimeter width, 0.24 millimeter thick, 1 kilometer lengths, maximum rated tensile stress of 45,000 psi (w/stainless steel laminate); 5 centimeter bend diameter

Present Engineering Current Density:

10,000 to 80,000 A/cm², depending on operating temperature and external magnetic field

Coolant Compatibility:

Can operate with liquid nitrogen or helium gas coolant

Present Production Capability for Wire:

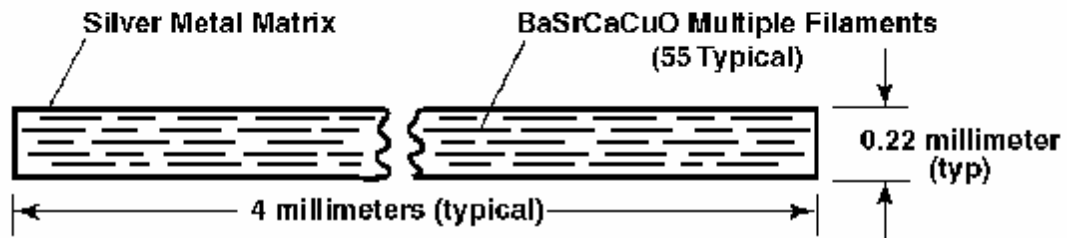
1 million meters per year will expand to 2 million meters per year in 2006. Production rate determined by market

Limitations:

Cost and availability of silver matrix

Figure 6.1.2

Fabricated Form Of BSCCO High Temperature Superconducting Wire Tape



External Magnetic Field Orientations

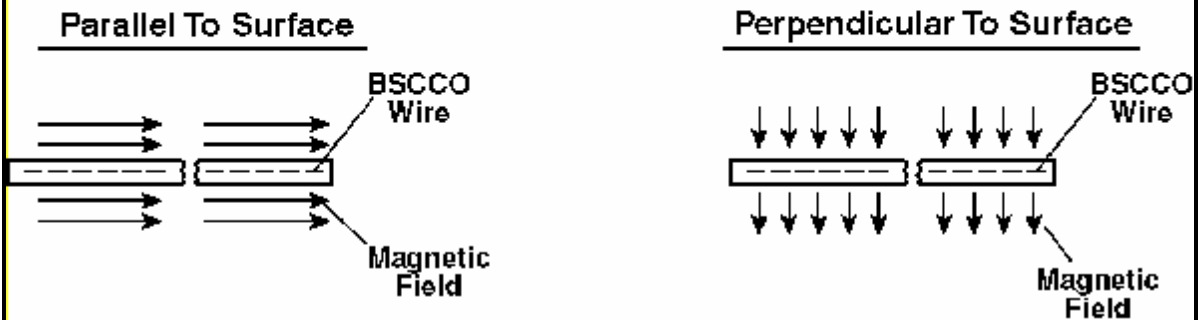
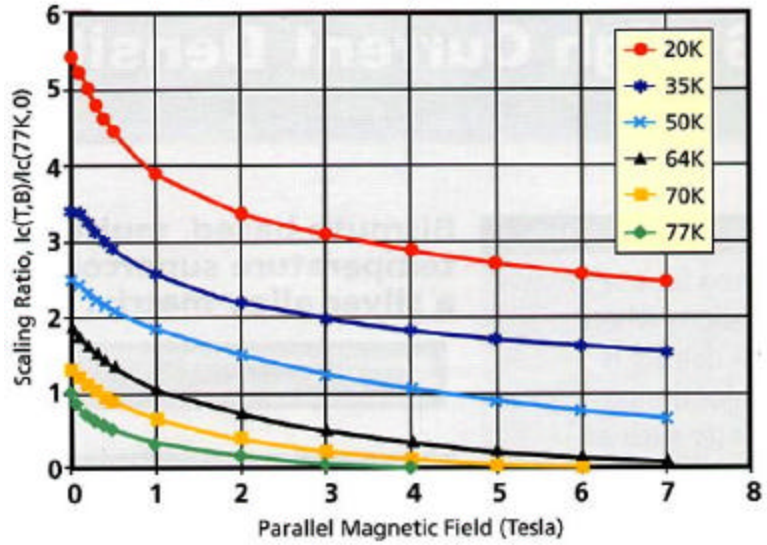


Figure 6.3.1.3

Wire performance with magnetic field parallel to tape surface



Wire performance with magnetic field perpendicular to tape surface

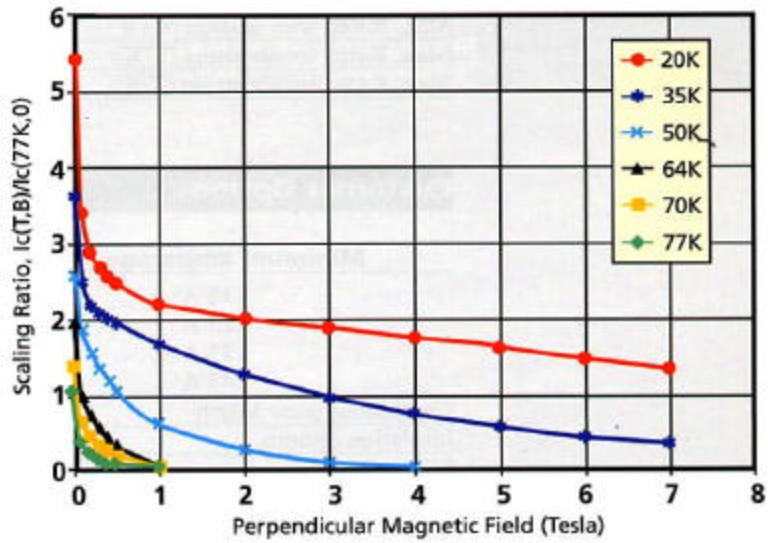


Figure 6.3.1.4 Present and Projected Future Capabilities of BSCCO Superconductor

Present Engineering Current Densities (High Current Density American Wire Tape Superconductor) Engineering Current Density, A/cm²

T(K)	External Magnetic Field (Tesla)	0	1	2	3	4
77		15,000	3,800	1,500	750	~0
70		18,000	10,500	6,000	4,500	1,500
64		27,000	15,000	11,000	7,500	4,500
50		37,500	29,000	22,500	18,000	16,000
35	Note: External magnetic field is parallel to surface of wire tape	51,000	39,000	32,000	30,000	29,000
20		81,000	58,000	50,000	46,000	44,000

Potential Future Improvements in Engineering Current Density

•High temperature cuprate superconductors like BSCCO carry supercurrent in copper oxide based planar layers, with current densities >1 Megamp/cm² when crystallite layers are optimally aligned. Improving crystallite interface in fabricated BSCCO wire could increase engineering current densities to >>100,000 A/cm²

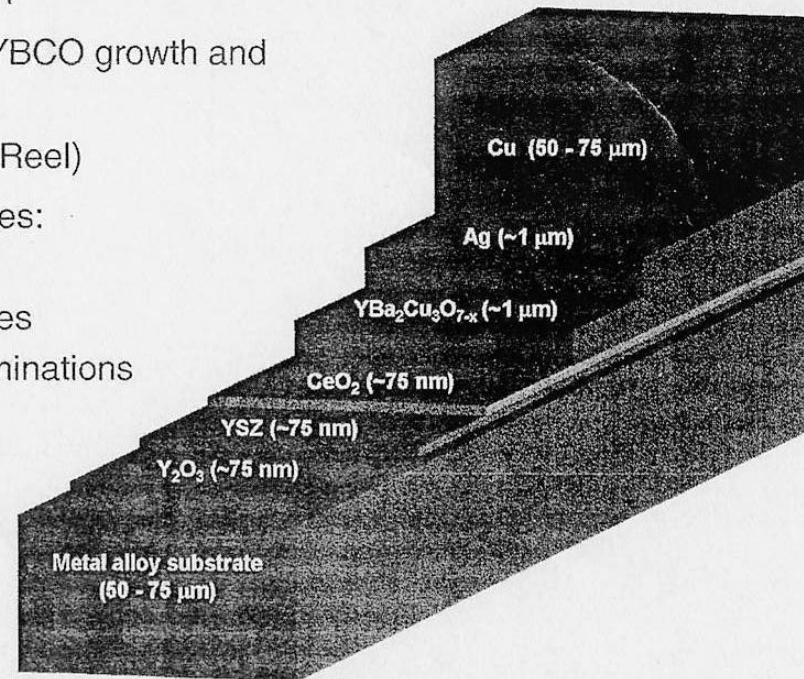
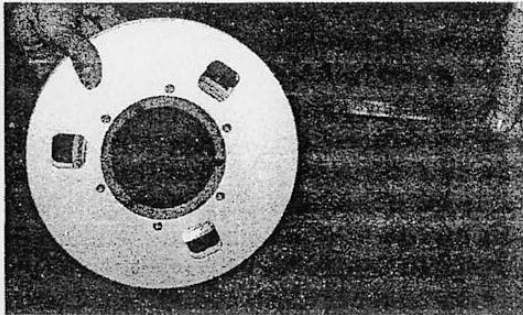
Figure 6.3.2.1 Description of YBCO HTS Superconductor

<u>Material and Form:</u>	Thin film (~1 micron) of Yttrium Barium Copper Oxide (YBCO) on metal tape substrate
<u>Fabrication Process:</u>	The YBCO film is deposited by the Metal Organic Deposition process (MOD) on a thin Yttrium stabilized zirconia (YSZ) Epitaxial layer that is on top of a textured Nickel Alloy metal tape. After the YBCO film has been deposited, a silver metal upper layer is deposited on top as a stabilizer and protective cover
<u>Critical and Practical Temperature Range:</u>	93 Kelvin critical temperature; 20 to 5 K practical operating temperature range
<u>Parameters of Present Commercial Wire:</u>	Producing 4 cm wide tape in 1 kilometer lengths (tape can be slit into multiple tapes of smaller widths (e.g., 4 tapes each 1 cm wide, or 10 tapes; each 0.4 cm wide) maximum allowable strain of 0.45%
<u>Present Engineering Current Density:</u>	20,000 to 100,000 Amp/cm ² , depending on operating temperature and magnetic field
<u>Coolant Compatibility:</u>	Liquid Nitrogen, pressurized Helium, liquid Hydrogen
<u>Present Production Capability:</u>	Conductor tape for demonstration projects - anticipate large scale production in next few years
<u>Limitations:</u>	No apparent limitations

Figure 6.3.2.2

High Temperature Superconductor (HTS) 2 G Wire Architecture

- RABiTs™/ MOD low cost approach
- Buffer layers proved template for YBCO growth and barrier to diffusion.
- Fully continuous process (Reel-to-Reel)
- Lamination of copper stabilizer gives:
 - Enhanced electrical stability
 - Superior mechanical properties
 - Easy electrical joints and terminations

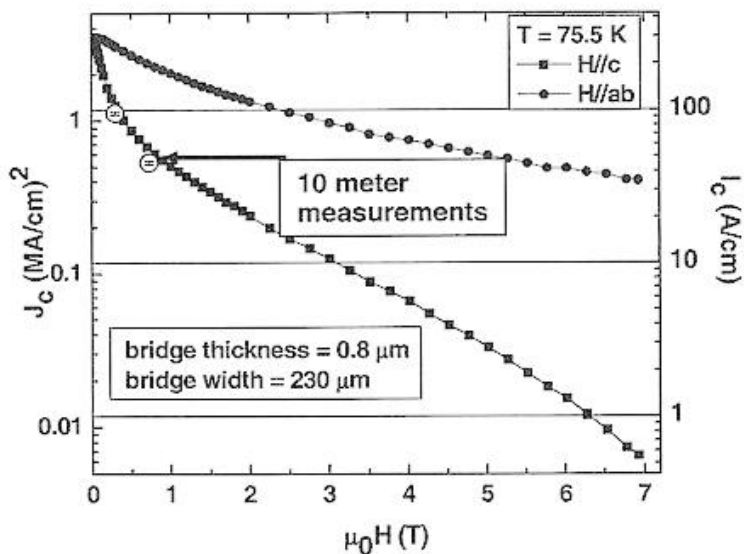


Second generation wire goal: Form-Fit-Function replacement at 2-5X lower cost

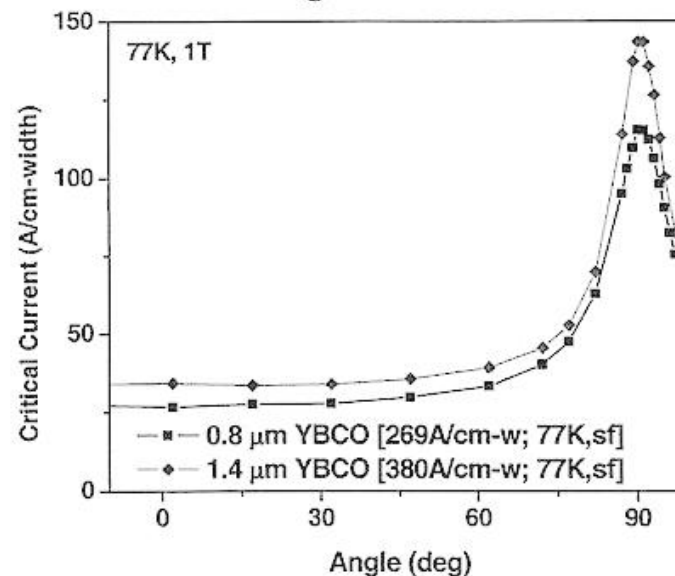
Figure 6.3.2.3A

77K Performance of YBCO(MOD)/RABiTS 2G Wire

$I_c = 270\text{A/cm-w}$ at 77K, self field, YBCO thickness = $0.8\ \mu\text{m}$
 Samples cut from 10 meter length



$J_c > 3\text{MA/cm}^2$ is close to films on single crystal substrates

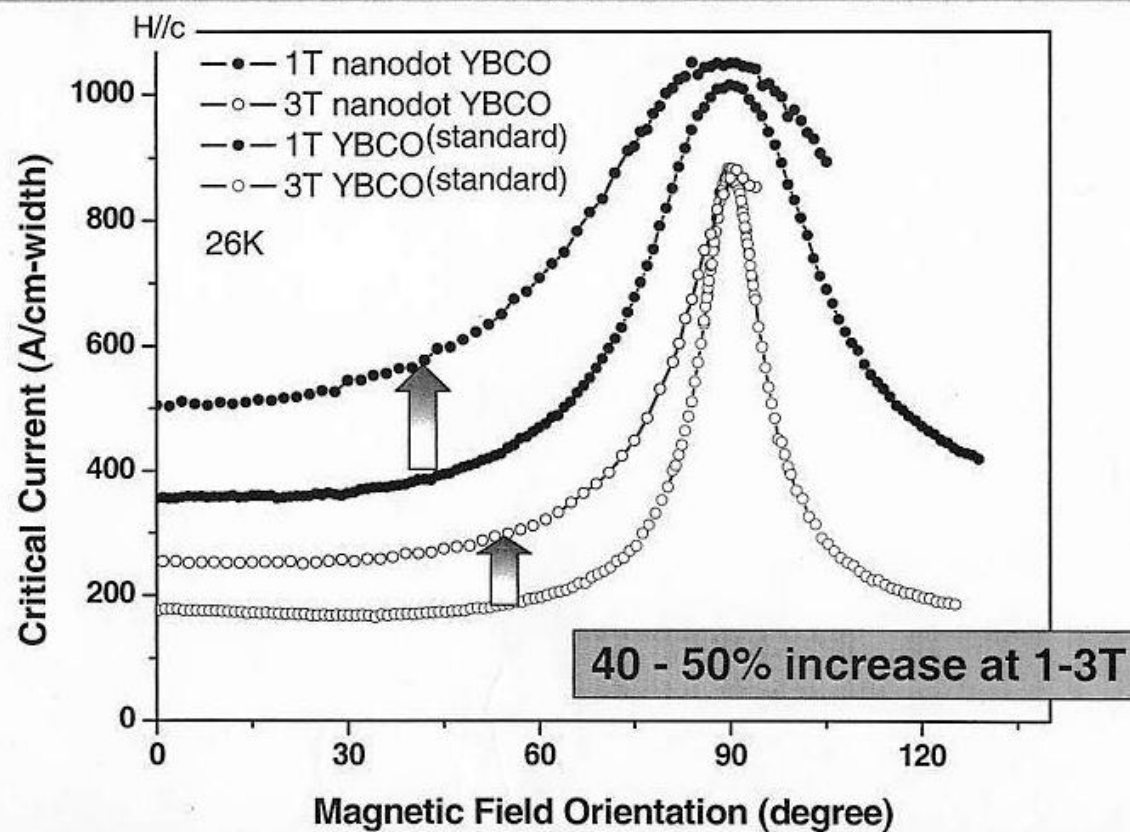


I_c increased to 380A/cm-w in two step $1.4\ \mu\text{m}$ films

Pinning studies to optimize field, temperature and angular dependence.

Figure 6.3.2.3B

Nanodot Improvement of I_c in Field at 27K



Nanodots improve I_c in both perpendicular and intermediate angle fields

**Figure 6.3.2.4 Present and Projected Future Capabilities of YBCO Superconductor
Based on American Superconductor RABITS™ Process**

Present Capabilities: Jc (77 K, self field) = 270 A/cm width (10 meter lengths)
Jc (77 K, self field) = 15,900 A/cm² (10 meter lengths)
Minimum bend diameter = 2.5 centimeters (1 cm wide tape)
Je (26 K, 3 Tesla) = 50,000 A/cm² (parallel field)
Je (26 K, 1 Tesla) = 60,000 A/cm² (parallel field)

Potential Approaches to Increase Je:

Multiple YBCO films on substrate - e.g., use 3 films instead of 1 film (factor of 3 higher Je)
Increase YBCO film thickness from present ~1 Micron thickness (factor of 2 to 3 higher Je)
Improve processing parameters to make long length conductors approach short sample results more closely
Thinner substrate and buffer layers

Potential YBCO Je Goal for MIC Applications: 100,000 to 200,000 Amp/cm²

Figure 6.3.3.1 Description of MgB₂ HTS Superconductor

Material and Form:

Small diameter (~10 Micron) multi-filaments of magnesium diboride (MgB₂) in niobium metal matrix

Fabrication Process:

In the powder in tube (PIT) process MgB₂ powder is projected into a half cylindrical metal strip which is then mechanically closed around the powder. The tube is drawn into a mechanically strong monofilament wire form, which is then bundled with other monofilament wires into a multi-filament wire (typically 7 or 19 filaments) in a surrounding secondary metal matrix. The primary tube can be copper, iron, or niobium. The secondary matrix can be a wide variety of metals

Critical and Practical Temperature Range:

39 Kelvin critical temperature; 15 to 20 K practical operating temperature range

Parameters of Present Commercial Wire:

0.8 millimeter diameter; 1 kilometer lengths; 0.3% maximum allowable strain

Present Engineering Current Density:

20,000 to 100,000 Amp/cm², depending on operating temperature and external magnetic field

Coolant Compatibility:

Pressurized Helium, liquid Hydrogen and Neon (liquid Nitrogen temperature is above MgB₂ critical temperature)

Present Production Capability:

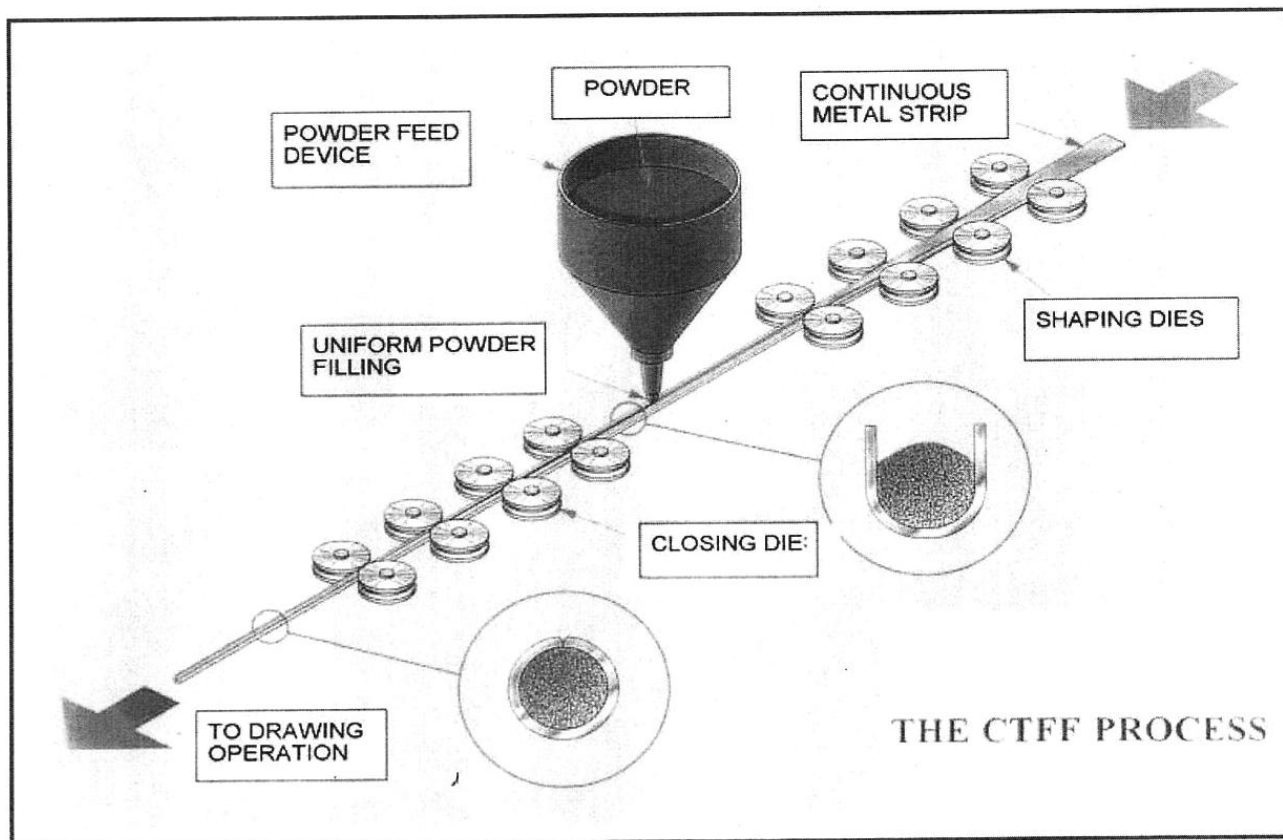
Wire for demonstration projects - anticipate large scale production in next few years

Limitations:

No apparent limitations

Figure 6.3.3.2A

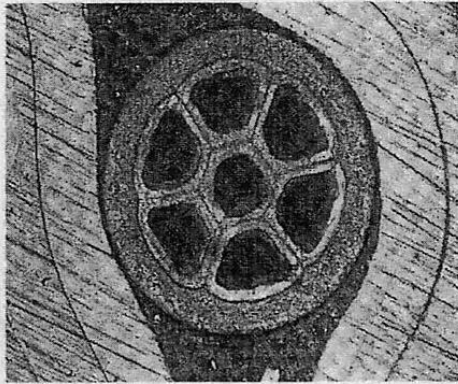
Continuous Manufacturing Process



Hyper Tech Research

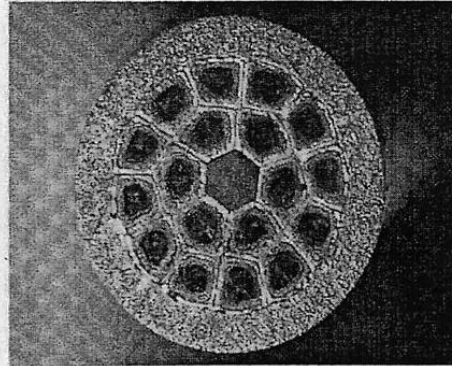
Figure 6.3.3.2B Multifilament Strands

7 filaments



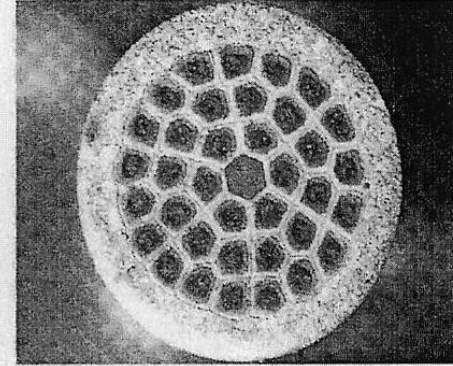
Fe-CTFF in Cu tube
Restacked in CuNi

18 filaments with Cu center



Nb-CTFF in Cu tube
Restacked in CuNi

36 filaments with Cu center

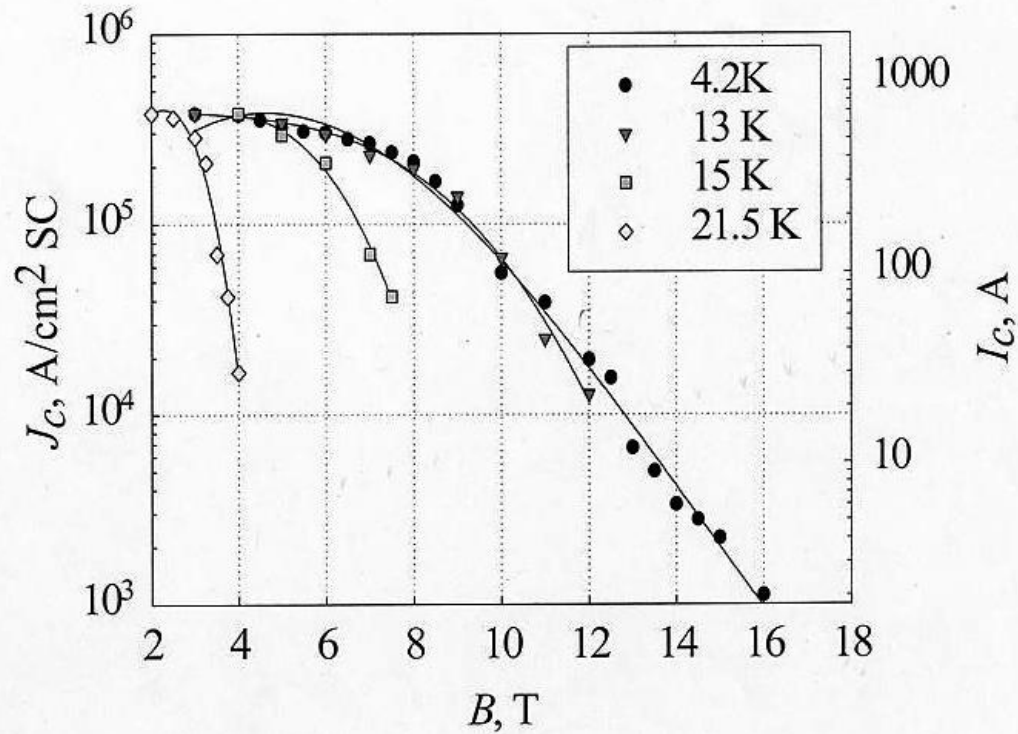


Nb-CTFF in Cu tube
Restacked in CuNi

Hyper Tech Research

Figure 6.3.3.3

BEST SHORT SAMPLE RESULTS



J_c and amperage vs Field, Double Fe CTFF in Cu-Ni sheath with nano-SiC, wire diameter 0.8 mm
 Short sample 4-5 cm. The power supply limit was 680 amps, a pulsed power supply was used

NHMFL

Hyper Tech Research

Figure 6.3.3.4 Present and Projected Future Capabilities of MgB₂ Superconductor Based on HyperTech Data for MgB₂ 7 Multi-Filament Wire

Wire parameters: 0.83 millimeter diameter
 7 filaments
 15% superconductor fill factor
 310 meter conductor length

T(K)	B(T)	J_c, Current Density in SC, A/cm²	J_e, Current Density in Wire, A/cm²	J_e, 30% SC Fraction, A/cm²	J_e, 30% SC Plus 2 Fold Increase in J_c*
15	0	6 x 10 ⁵	9 x 10 ⁴	2 x 10 ⁵	4 x 10 ⁵
15	2	3 x 10 ⁵	4.5 x 10 ⁴	9 x 10 ⁴	2 x 10 ⁵
15	4	8 x 10 ⁴	1.2 x 10 ⁴	2.5 x 10 ⁴	5 x 10 ⁴
20	0	5 x 10 ⁵	7.5 x 10 ⁴	1.5 x 10 ⁵	3 x 10 ⁵
20	2	1.1 x 10 ⁵	2 x 10 ⁴	4 x 10 ⁴	8 x 10 ⁴
20	4	2 x 10 ⁴	3 x 10 ³	6 x 10 ³	1.2 x 10 ⁴

* At present, J_c is limited by transfer of superconducting current across the interfaces between MgB₂ crystallite grains, and is only

- 10% of J_c inside the grains. A factor of at least 2 increase in J_c Appears quite possible and eventually could be much greater

Figure 6.4.1 Criteria for Selection of HTS Conductor for the Various MIC Applications

Criteria	HTS Conductor		
	MgB ₂	YBCO	BSCCO
1. Conductor can carry $\geq 50,000$ A/cm ² at 2 to 3 Tesla	OK with present conductor @ 15 K Future conductor should be OK @ 20 K	OK with present conductor @ 25 K Future conductor should be OK @ 50 K	OK with present conductor @ 20 K possibly could go to 35K
2. Production capability potential	Unlimited	Unlimited	Limited by availability of silver
3. Tensile strain capability $\geq 0.3\%$	OK; 0.3% achieved	OK; 0.45% achieved	OK; 0.3% achieved
4. Ability to be wound into compact package for launch	OK, can be wound into 2 meter packages	OK, 2.5 centimeter bend radius	OK; 5.0 centimeter radius
5. Projected large scale cost	~\$1 to \$2 per kiloamp meter [~\$50 to \$100 per kg]	~\$5 to \$10 per kiloamp meter [\$250 to \$1000 per kg]	~\$30 per kiloamp meter [\$3000 per kg]

Figure 6.4.2 HTS Conductor Assessment for Various MIC Applications

MIC Application	HTS Conductor		
	MgB ₂	YBCO	BSCCO
Solar electric Solar thermal propulsion	Both MgB ₂ and YBCO appear attractive - choice will depend on system weight [superconducting cable plus refrigeration system] which in turn will depend on future developments in Jc as a function of operating temperature and external magnetic field		Less favorable because of silver availability for large scale production, plus cost of silver
Large scale space telescope			
Energy storage	Potentially MgB ₂ - requires very large currents and MgB ₂ has best potential		Same as above
Magnetic shielding	3d best - relatively low Jc in fields; >3 Tesla at ~15 K	Appears best - can operate with high Jc in very high magnetic fields at 15 to 20 K	2 nd best - high Jc capability in high magnetic field, but less capable than YBCO

Table 6.2.1 Comparative Performance Capabilities and Feature of High Temperature Superconductors (HTS) and Low Temperature Superconductors (LTS) for MIC Applications

Capabilities/Features	LTS Conductors	HTS Conductors
Practical Operating Temperature	4 Kelvin	20 K to 50 K, Depending on type of HTS
Coolant	Liquid Helium	Pressurized Helium Gas
Refrigeration Factor Watts(e) per Watt(th) @ 20% of Carnot	300	25 to 70 Depending on type of HTS
Refrigerator Power for 1 Kilometer Long MIC Cable @ 20% of Carnot	30 Kilowatts(e)	2.5 to 7 Depending on type of HTS
Material & Form of Conductor	Multi NbTi Filaments in Copper Metal Matrix	Multi Filaments in Metal Matrix (BSCCO & MgB ₂). Thin film on metal substrate (YBCO)
Present Engineering Current Densities in Conductor	100,000 A/cm ²	30,000 to 100,000 A/cm ² Depending HTS Type and Operating Temperature
Maximum Practical Operating Magnetic Field Capability	6 Tesla	7 Tesla

Table 6.2.2 Examples of Large Scale Superconducting Applications Using Low Temperature Superconductors

Features, Facilities, Scale & Requirements	Applications		
	High Energy Physics Research	Magnetic Resonance Imaging (MRI)	Maglev
1. Superconductor (SC) function	High field SC magnets accelerate and guide high energy particle beams	High field SC magnets image Tissue inside human body	High field SC magnets levitate and propel high speed trains
2. Facilities	a) Fermi Doubler 6 kilometers SC magnets (operating for >10 years) 2. Large Haldron Collider (LHC) 42 kilometers SC magnets (almost complete)	Thousands of medical diagnostic centers around the World, operating for >10 years	Superconducting Maglev line in Yamanashi, Japan 42 kilometers in length, speeds of 350 mph
3. Scale	~10,000 separate superconducting magnets - total length ~100 kilometers (2 rings)	1000's of individual SC magnets, each several meters in diameter	~100 SC magnets on Maglev vehicles that have carried >50,000 passengers since 1987
4. Requirements	~6 Tesla, extremely precise field quality, zero failure rate	~3 Tesla, extremely precise field quality, very low failure rate	~4 Tesla maximum field, zero failure rate

7.0 CONSTRUCTION, ERECTION, AND OPERATION OF MIC STRUCTURES

7.1 MIC Thermal Insulation

MIC superconductors usually will require a layer of thermal insulation to minimize the thermal input to them, so that the electric power input to the refrigerator that keeps them at superconducting temperature is also minimized.

In deep space, very far from the Sun, the natural thermal radiation from a MIC superconducting cable would be sufficient for it to achieve superconductivity without any thermal insulation or refrigeration. However, for most applications, whether in Earth orbit, on the Moon or Mars, or anywhere inside the orbit of the giant planets, insulation and refrigeration will be necessary.

Insulating MIC superconductors is generally much simpler than on Earth, because except for missions to locations where there is some appreciable atmosphere (e.g., the surface of Mars) the MIC conductors will operate in a vacuum that is much better than ever achieved on Earth. Cryogenic engineers on Earth go to great lengths to provide a high vacuum for the thermal insulation around superconductors. Keeping the outside atmosphere out of the insulation is difficult, expensive, and often compromised by minute leaks in the vacuum jacket that surrounds the thermal insulation.

Superconductor systems on Earth generally use multi-layer insulation (MLI) which consists of multiple layers of thin aluminum foil separated by a layer of fiberglass fibers. The aluminum foils act as multiple radiation shields to reduce radiation transport of thermal energy into the superconductor region, while the fiberglass fibers reduce thermal transport by conduction.

Present MLI insulation achieves an effective thermal conductivity of 0.5×10^{-4} watt/mK in vacuum. The corresponding thermal input to a superconductor is then extremely low. For example, for a 5 centimeter thick insulation layer and a 300 K outer temperature only 0.3 watts per square meter of surface area will leak into the superconductor region.

Figure 7.1.1 shows a representative view of a MLI layer around the MIC conductor. There is no vacuum jacket surrounding the insulation, since the MIC conductor is assumed to operate in the vacuum of space. The insulation is attached to and supported by a network of high strength Kevlar or Spectra (oriented polyethylene) fibers. This network in turn is supported by the magnetic forces between aluminum wires attached to its outer surface and the central MIC superconductor. Small currents in the aluminum wires magnetically interact with the high current in the MIC conductor to produce radially outwards magnetic forces.

This arrangement enables the superconducting cables for the MIC structure to be coiled up into a small package for launch, and then, when orbit is reached, to be energized into its final shape, with the thermal insulating layer fully expanded into its effective form. The MLI insulation, which has a density of only about 5% of solid density, would be compressed when launched as a package, and then expanded into its final low density form.

Figure 7.1.2 shows the thermal leakage into a MIC conductor of nominal size (e.g., 4 centimeters in diameter, with a current carrying capability of 400,000 amps) as a function of insulation thickness for outer surface temperatures of 100, 200 and 300 K. At a surface temperature of 200 K and an insulation thickness of only 2 centimeters, for example, only 82 watts would leak into the MIC superconductor per kilometer of conductor length. This already very low level of thermal leakage could be cut by a factor of 2, down to just 42 watts per kilometer, by increasing the 2 centimeter thick insulation layer to 4 centimeters.

In most MIC applications, the surface temperature of the thermal insulation layer will not be uniform, but will vary substantially around its circumference, due to variations in thermal input to the surface. Figure 7.1.3 illustrates the effect of having one side of the MIC insulation layer exposed to sunlight. The exposed side will tend to be at a higher temperature than the non-exposed side. In Earth orbit, for example, the sunlit side will roughly be at ~300 K, while the dark side can be much lower in temperature, e.g., at ~100 K. Thermal energy will transport azimuthally through the thermal insulation layer from the bright side to the dark side under the influence of the temperature difference between them. Thermal energy will flow from the dark side insulation into the MIC superconductor, but the amount of energy transported will be substantially less than if the entire surface of the thermal insulation layer were at 300 K.

Numerical solutions to the 2 dimensional heat transport situations are possible, and are discussed in later sections on specific MIC applications. Here, the general nature of the 2 D heat flow process is highlighted. For the case where the MIC conductors experience sunlight at Earth-like intensities, e.g., ~1 KW(th)/m², with one side of the conductor exposed to sunlight, an average surface temperature of ~200 K for the thermal insulation appears reasonable for scoping analysis.

Figure 7.1.4 shows a flowsheet of the erection process for the MIC thermal insulation. After reaching its desired position in space, the MIC structure begins its deployment by a partial energization of the MIC superconductor current. The MIC structure then expands to form its desired configuration, and the aluminum wires attached to the surface of the insulating layer are energized, expanding it and reducing the thermal leakage to the design value. The MIC conductor would then be energized to its full current. This 2 step process enables the MIC conductor to safely operate at higher temperature during the increased thermal leak period, because it is not yet carrying its full current.

Table 7.1.1 summarizes the thermal leakage per kilometer of MIC cable as a function of insulation thickness and its average surface temperature. As discussed above, the thermal leakage is quite low. Table 7.1.1 also gives the outwards magnetic force on the aluminum wires and the I²R power they require to maintain the expanded state of the insulation layer. The

diameter of the aluminum wires is only 1 millimeter, yet the outwards magnetic force is quite strong, about 1 Newton per meter on each wire - more than enough to maintain the expanded state in zero 'g' conditions. The total I^2R power for the A1 wire assembly is low, only 280 watts per kilometer. This can be readily supplied by the power generation system associated with the MIC structure.

The total volume of insulation in the packaged state is small, ~1 cubic meter per kilometer of MIC conductor for an expanded insulation thickness of 2 centimeters. This volume can be readily accommodated on standard launch vehicles, including the Atlas, Delta, and other systems. Thickness of the insulation package is also modest, being about 500 kilograms per kilometer of MIC conductor for the 2 centimeter insulation thickness, including both the insulation, aluminum wires, and Kevlar fiber network.

Table 7.1.2 illustrates the thermal leakage and insulation mass for several MIC applications using nominal design parameters. For the solar electric generation, solar thermal propulsion, and space telescope applications, the leakages and insulation masses are very modest. For the energy storage application, the values are substantially higher, because of the very large amount of stored energy needed for a lunar base.

The overall conclusions for MIC thermal insulation are:

- 1.Heat leakage into the MIC superconducting region is quite low, only a few tens of watts per kilometer of conductor.
- 2.Existing multi-layer thermal insulation is very satisfactory for MIC systems.
- 3.The MIC insulation can be compressed into a small volume during launch, and then expanded into its final low density state once in space using the magnetic forces between small diameter attached aluminum wires and the main MIC conductor.
- 4.The mass of the MIC insulation for MIC systems is acceptably small.

7.2 MIC Cooling and Refrigeration

Figure 7.2.1 shows the overall flowsheet for cooling and refrigeration of MIC conductors. As discussed below, a MIC conductor cable is actually made up of a large number of separate conductors, each with their own individual coolant circuit. If one of the coolant circuits were to leak its coolant out into space, it would not compromise the cooling of the other conductors.

To help ensure this multi-conductor reliable operational capability, each conductor circuit is cooled by a primary heat exchanger (Figure 7.2.1). If the kilometer long conductor coolant circuit were to leak, the only coolant lost would be from the leaking circuit - the other circuits, because they transfer their thermal loads to the refrigeration circuits through a primary heat exchanger, would not be affected.

Refrigeration would be supported by a set of small cryocoolers coupled to the primary

heat exchangers. Thermal energy leaking into the MIC conductors would then be transferred from the conductor coolant circuits to the cryocooler circuits, as illustrated in Figure 7.1.1. If a cryocooler were to fail, it would be shutdown and a backup cryocooler inserted into the set (or equivalently, the refrigeration load on the remaining cryocoolers would increase somewhat). In this way, single point failures, whether in a conductor or a coolant circuit or a cryocooler, would not stop operation of the MIC cables.

The cryocoolers, in turn, use electric power input to refrigerate their coolant circuits (Section 7.5 describes current and projected cryocooler technology and the types of systems that would be used for MIC refrigeration). The input thermal leakage is “pumped up” to a higher temperature and be radiated to space using a conventional type thermal radiator. However, not only is the input thermal leakage energy disposed of by the radiator, but also the electric input energy used to pump the thermal leakage energy up to the radiator temperature.

For a perfect Carnot engine operating between T_2 and T_1 , where T_2 is the temperature of the thermal radiator that disposes of the waste heat input and the electric power consumed by the cryocooler and T_1 is the temperature of the refrigerant supplied by the cryocooler, the Carnot refrigeration factor, P_c , in watts of electric power per watt of thermal input is

$$P_c = \frac{\eta}{1 - \eta} \text{ watts}(e) / \text{watts}(th) \quad (7.2.1)$$

where η is the Carnot efficiency

$$\eta = \frac{T_2 - T_1}{T_2} \quad (7.2.2)$$

In practice, refrigeration equipment only achieves a modest percentage of Carnot efficiency, so that the electric power input (and thermal radiator power) is considerably greater than would be the case for a refrigerator operating at Carnot efficiency.

The actual refrigeration factor for the cryocooler is then

$$P_{ref} = P_c / f_c \text{ watts}(e) / \text{watts}(th) \quad (7.2.3)$$

where

f_c = fraction of Carnot efficiency actually achieved by the refrigeration systems. Large refrigeration systems, e.g., 10's of KW(th), achieve about 25% of Carnot efficiency ($f_c = 0.25$). Smaller systems generally achieve in the range of 10 to 20% efficiency ($0.10 \leq f_c \leq 0.20$).

Figure 7.2.2 shows the estimated refrigeration factor for the MIC cryocooler as a function of the superconductor operating temperature, ranging from 15 to 50 Kelvin, a radiator temperature of 300 and 400 K, and a fractional Carnot efficiency of 10 and 20%.

Clearly there is a significant refrigeration advantage for operation at higher superconductor temperatures, with almost a factor of 3 lower power input for operation at 50 K (a nominal value for BSCCO and YBCO superconductors) compared to 20 K (a nominal value for MgB₂ superconductor). However, other factors such as engineering current density in the superconductor, magnetic field capability, mechanical properties, etc. can outweigh the advantage of a lower refrigeration factor.

Figure 7.2.3 shows the electric power input to the MIC refrigeration system for a 1 kilometer long MIC conductor cable as a function of superconductor temperature, radiator temperature, and fractional Carnot efficiency. The power inputs appear reasonable, on the order of 10 KW(e), even for the lower superconductor temperature of 20 K, taking into account the capability of the corresponding MIC structure to generate multi-megawatts of power.

The required electric power input increases as radiator temperature increases. However, the radiator area and correspondingly, its mass, decreases by almost a factor of 2 when its temperature is increased from 300 to 400 K (Figure 7.2.4). Depending on radiator mass, it may be advantageous to use a higher temperature radiator, even though a larger power input is needed. For a superconductor temperature of 20 K, a 1 kilometer long MIC conductor cable operating with a 400 K radiator and 20% fractional Carnot efficiency of the cryocooler requires only 3 square meters of radiator area (2 sides radiation) and 8 kilowatts of electric power. Again, this is very modest considering the corresponding multi-megawatt capability of the MIC system.

Figure 7.2.5 shows 2 cross sectional views of 2 different options for an individual MIC conductor. One option uses a circular tube geometry and the other a flat strip geometry. A number of these conductors would be bundled together to form the cable. For purposes of illustration, the individual conductors each carry 10,000 amps (the current could be smaller or larger, depending on design). A MIC cable carrying 400,000 amp turns would then have 40 of the separate 10,000 amp conductors.

In the illustrations, the MIC conductor would have 8 individual sub-conductor wires, each 1 millimeters wide by 0.6 millimeter thick, which would be bonded to the coolant tube. This arrangement provides further redundancy and reliability. If one of the sub-conductors had a local defect or mechanical failure that prevented it from carrying normal current at that point, its current would locally transfer to the other 7 sub-conductors upstream of the defect, and then return downstream of the defect. Each of the sub-conductors would normally carry 1/8th of the total current in the conductor, or 1250 Amps. There would be some very small, very local I²R heating in the aluminum tube in the vicinity of the defect, as the current flowed from one sub-conductor to the other, but the effect on the total refrigeration load would be tiny.

The coolant tube dimensions are chosen so that the peak self magnetic field experienced

by the superconducting strips is less than 2 Tesla, well within the capability of the high temperature superconductors being considered.

The circular tube geometry appears preferable to the flat strip geometry in that it is more compact, simpler to fabricate, and has a somewhat lower pressure drop for the helium coolant. Table 7.2.1 shows the helium pressure drop for a 1 kilometer long MIC cable as a function of the temperature rise ΔT of 2 and 4 degrees Kelvin, inlet to outlet. The cable consists of a bundle of 40 MIC conductors of the dimensions and current capacity shown above in Figure 7.2.4. The thermal insulation thickness is 2 centimeters, resulting in a total thermal leakage into the cable of 82 watts per kilometer with an average surface temperature of 200 K for the insulation. The helium coolant pressure is taken as 1000 psi, which results in a coolant density of 0.10 g per cm^3 (70% of liquid density).

The corresponding helium flow rate per 10,000 amp conductor is very small, 0.2 grams/sec ($2 \text{ cm}^3/\text{sec}$) for a ΔT of 2 K and 0.1 grams/sec ($1 \text{ cm}^3/\text{sec}$) for a ΔT of 4 K. The corresponding helium velocities inside a circular 0.3 conductor tube are 30 and 15 cm/sec., respectively. The associated pressure drops are 45,000 N/m^2 (0.45 atm) and, 10,125 (0.10 atm), which are quite reasonable.

The helium flow velocities and pressure drops are even smaller for larger coolant tubes. Increasing tube inner diameter from 0.3 to 0.4 centimeters, for example, decreases pressure drop by a factor of 5. Clearly, the MIC cable coolant system can easily handle the thermal load on it, even for long cable flow lengths. For example, assuming the smallest conductor diameter of 0.3 centimeters and the smallest ΔT of 2 K, the total hydraulic power per channel is $45,000 \times 2 \times 10^{-6}$ or 0.09 watts. The total hydraulic power for the 40 conductors would be only 3.6 watts. The total hydraulic power for the 40 conductors would be less than 1 watt with a 0.4 centimeter diameter conductor.

The overall conclusions for the MIC cooling and refrigeration are:

1. The superconductors in the MIC cable can be easily cooled using pressurized helium, even in long lengths, e.g., a kilometer or more. Pressure drop is low, well below one atm, and the corresponding hydraulic power is also very low, on the order of a few watts for a cable length of 1 kilometer that carries 400,000 amps. The hydraulic power thermal load is a small fraction of the thermal leakage load handled by the refrigeration system.
2. The electric power input to the MIC refrigeration system is modest, on the order of a few kilowatts (e) for cable lengths of a kilometer or so. This power requirement is very small compared to the power output that the MIC structure would generate using solar photovoltaic or a dynamic power cycle. This electric input requirement is based on presently achievable actual cryocooler efficiencies, e.g., an efficiency that is 10% of a Carnot refrigerator that operates between the superconductor and reject temperature values. (That is, the actual refrigeration cycle would use 1/0.1 or 10 times the electric input required for a refrigerator operating on a reversible Carnot cycle.)

3. The electric power requirements for the actual refrigeration system are acceptable for the types of superconductor that would operate in the contemplated range of 20 to 50 K.
4. The optimum radiator reject temperature is probably in the range of 300 to 400 K. Refrigeration power input increases as radiator temperature increases, but radiator area and mass decrease. The optimum value will probably depend on the specific application.
5. The MIC conductors and cable are designed to be highly redundant and fail safe. Multiple failures of the superconductor, coolant circuits, and refrigeration equipment could occur, but the MIC cable would still continue to operate.

7.3 MIC Conductor Support Methods

The MIC cable bundles together a number of individual MIC conductors of the type described in Section 7.2 to achieve the desired total current. Depending on the total current level, one of 2 methods of support would be used. Figure 7.3.1 shows the overall features of the 2 methods.

For a total cable current of 1 million amps or less, the conductors would be bundled together, as illustrated in Figure 7.3.2, on a single support tube. The diameter of the support tube would be sufficiently large that the surface magnetic field of the bundled conductors would be low enough, e.g., 4 Tesla maximum, that the current density capability of the individual conductors would not be seriously degraded. For a 400,000 amp cable, for example, a 4 centimeter diameter support tube results in a surface field of 4 Tesla.

If the conductors in the cable bundle run longitudinally along the support tube, the corresponding magnetic field is in the azimuthal direction, and the resultant magnetic force is directed radially inwards. For a surface magnetic field of 4 Tesla, the inwards magnetic pressure is 70 bars, or about 1000 psi. This inwards magnetic force can be structurally carried by the graphite epoxy support tube (method 1A in Figures 7.3.1 and 7.3.2). Alternatively, the conductors can be helically wound on the support tube to produce a solenoidal field inside the tube. The solenoidal field generates a radially outwards magnetic force on the conductors. At a helical winding pitch of 45 degrees, the inwards and outwards magnetic forces balance, so the net magnetic force on the support tube is zero (method 1B).

Either method is acceptable. The stress in the graphite epoxy support tube in method 1A is relatively small. For a 4 centimeter diameter tube with a 2 millimeter wall thickness (10% of the tube radius), the stress in the graphite epoxy tube is only about 10,000 psi, well below its mechanical limit. Method 1B reduces the stress to essentially zero, but requires an additional amount of superconductor.

For cable currents greater than 1 million amps, method 1 would require a support tube larger than 10 centimeters in diameter, which would be too large to wind into a compact package for launch into space. For MIC cables with currents greater than about 1 million amps, method 2 appears the best approach, as illustrated in Figures 7.3.2.

The multi-megamp MIC cable would be made up of a number of sub-megamp MIC cables that would use the method 1 type of construction, but would be helically wound on a support network of tethers such that they produced a solenoidal magnetic field inside the tether network. The winding pitch of the MIC sub-megamp cables is chosen so that the outwards radial magnetic force from the interior solenoidal field is greater than the inwards radial magnetic force from the azimuthal magnetic field. The net magnetic force on each sub-megamp MIC cable would then be radially outwards, producing tensile forces on the tether network, causing it to expand into the desired cylindrical shape. The length of the tethers would be chosen so as to yield an acceptable maximum magnetic field on the MIC conductors.

Table 7.3.1 shows the number of MIC sub-megamp cables and corresponding diameter of the tether network as a function of the total current carried by the MIC cables in method 2. For a total current of 10 million amps, for example, with each MIC cable carrying 400,000 amps, a total of 25 cables would be required for the tether network, with an overall diameter of the network being 1 meter. This would result in a maximum magnetic field on each conductor of ~4 Tesla.

To minimize thermal leakage into a MIC cable system, as well as minimizing system weight, persistent superconducting switches are used. Such switches are often used in existing superconducting magnet systems. The superconducting circuit would be critically energized by an external power supply, using leads that carry the current from an external power source. This source operates at ambient non-superconducting temperatures, e.g., 300 K. A superconductor “switch” is then closed to connect the two ends of the superconducting circuit. The current in the circuit then continues to flow when the current leads from the external power supply are disconnected and withdrawn. Because the “switch” is superconducting, the circuit continues to flow without decreasing with time, because the voltage drop in the circuit is zero.

Figure 7.3.4 illustrates how each of the conductors in a MIC cable would have its own superconducting switch. For a cable carrying 400,000 amps total current, for example, with 40 separate conductors that each carry 10,000 amps, there would be 40 persistent current switches. These switches would already be in place across the 2 ends of the long conductor (which would be 100's of meters to kilometers in length, depending on the particular MIC application), but would not be at superconducting temperature during the period when the external power supply energized the conductor. During this period, energizing current would be fed to the 2 ends of the conductor through external leads that were temporarily connected to it. As the charging process contained, the current in the conductor would steadily increase, at a rate determined by the applied voltage and the inductance of the conductor circuit.

After reaching the desired current on the conductor circuit, the persistent current switch would be cooled until it reached the superconducting state. The leads from the external power supply would then be detached, leaving a complete circuit - the long conductor plus its persistent current switch - in the fully superconducting state. The current in the circuit would then continue to flow indefinitely, until the circuit was warmed up so that it no longer was superconducting.

This approach has 2 important benefits. First, heat leakage through external current leads

is eliminated, since after the MIC cable is energized, persistent currents flow in the conductors with no need for an external power supply. Second, if current were supplied to each conductor from an external power supply, a large number of power supplies - 40 in the example of the 400,000 Amp MIC cable discussed above - would be necessary. The weight and power requirements of the large number of power supplies would be excessive. Instead, by successively energizing individual conductors in the MIC cable only a small number of power supplies would be required. After energizing the Nth conductor, for example, the detached power supply would be attached to the (N+1) st conductor to energize it. In this manner, only one power supply would be necessary; however, in practice, to provide redundancy and backup capability, several power supplies would actually be used.

The overall conclusions for the MIC conductor support methods are:

1. MIC cables carrying up to approximately 1 million amp turns could use multiple conductors attached to a small diameter support tube. The conductors would be of the type described in Section 7.2. The diameter of the support tube would be a few centimeters.
2. The conductors on the MIC support tube could run longitudinally along the tube, or be helically wound on it. If a straight longitudinal run were used, there would be a radially inwards magnetic force on the tube wall. At the design maximum magnetic force of 4 Tesla, the radially inwards magnetic force would be approximately 1000 psi. This force could be readily sustained by the support tube.
3. If the MIC conductors were helically wound onto the support tube, a solenoidal magnetic field would be created inside the tube. The radial outwards magnetic force from this solenoidal field would oppose the radial inwards magnetic force from the azimuthal magnetic field produced by the longitudinal current along the tube. At a helical winding pitch of 45 degrees, the net magnetic force on the tube would be zero, so there would be no mechanical stress on the tube. However, additional superconductor would be required, compared to the straight longitudinal run case.
4. For MIC cable currents above approximately 1 million amps, the diameter support tube would be too large to allow the cable to be wound into a compact package for launch. Instead, a set of sub-megamp smaller MIC cables would be attached to a tether network using as helical winding pattern for the MIC cables. The pitch of the helical winding would be somewhat greater than 45 degrees, so that when the MIC cables were energized, the radially outwards magnetic force from the solenoidal field would be somewhat greater than the radially inwards magnetic force from the longitudinal current. The net magnetic force is then radially outwards, causing the tether network to expand into its quasi-cylindrical shape, with a diameter determined by the tether dimensions, and designed to have the maximum magnetic field experienced by the MIC conductors not exceed the allowed limit, e.g., 4 Tesla. The tension stabilized tether network provides a strong rigid structure for the individual MIC cables.
5. Persistent superconducting current switches are used for each MIC conductor

circuit to carry the circuit current after it has been energized by an external power supply. When energization is complete, the leads from the external power supply are withdrawn, after the persistent current switch has been cooled into its superconducting state.

7.4 Redundancy and Reliability of MIC Conductor Systems

Figure 7.4.1 illustrates how MIC conductor systems can be designed to maintain normal operation in the event of possible damage to some of its components. MIC systems are not susceptible to “single point failure”, and can maintain reliability and redundancy at all times.

Figure 7.4.1 shows for 4 possible events how the MIC system would respond and what would be the effect on its operational capability. The first potential event is the leak of the coolant tube in a MIC conductor. As a consequence, the coolant in the conductor circuit would leak into space. Since each conductor has its own coolant circuit, the leak and its effects would be confined to the particular conductor that leaked. The remaining conductors would retain all of their coolant. Since the coolant circuit for a conductor transfers its thermal load through a protected primary heat exchanger to a cryocooler circuit, it is not necessary to valve off the leaking circuit. The coolant in the leaking coolant tube will drain off into space, and the coolant flow will automatically shut off.

If no further action is taken, virtually all of the current that had been carried by the conductor will be automatically inductively transferred to the other conductors in the cable. Because of the large dimensions of the MIC structure, which are much greater than the distance between the individual conductors on the MIC cable, the magnetic coupling coefficient between the leaking conductor and the other conductors will be very close to 1, resulting in almost complete inductive transfer of its current, e.g., 99% or more.

The other conductors in the MIC cable are designed to normally operate well below their current carrying limit, so they will be able to carry the small increase in current without any problems. For example, assuming a MIC cable with 40 individual conductors, having one inductively transfer its current to the others because its coolant leaked away, would increase the current in the remaining 39 conductors by only 2.5% of their normal value. In general, MIC conductors will probably normally operate at 50 to 60% of their maximum capacity.

If it is desired to make up for the small decrease in total cable current capacity, some of the individual conductors can be temporarily reconnected to an external power supply and their current increased so that the total MIC cable current is restored to its full design value. Figures 7.4.2 and 7.4.3 illustrate this process.

For the second potential event, local failure of the MIC conductor due to a manufacturing defect, mechanical stress, or other cause, the same process would occur. Almost all of the current originally carried by the failed conductor would automatically inductively transfer to the remaining conductors in the cable. If it was desirable to completely restore all of the original

current in the cable, some of its individual conductors could be temporarily reconnected to an external power supply.

The third potential event is a small micrometeorite or piece of space debris hitting the MIC cable. The conductor bundle on the cable is enclosed in a layer of protective armor, so that in most cases, the conductors would continue to operate normally after the impact. If the impacting object were large enough to penetrate the armor layer, a very unlikely event, one or more of the conductors could fail. The failure could result from either a penetration of the coolant tube with subsequent leakage, or damage to the superconductor. In either case, the current would inductively transfer to the remaining conductors in the cable.

The fourth potential event is failure of a cryocooler. MIC systems will employ multiple cryocoolers, with the capability to disconnect a failed unit and plug in a backup unit (or alternatively increase the refrigeration capacity of already connected cryocoolers) so that the required refrigeration level would be maintained. In practice, MIC systems would operate several cryocoolers in parallel, with several more in a standby, backup mode.

The overall conclusions for the MIC redundancy and reliability design are:

1. MIC cables are designed to have multiple (e.g., 40 or more) individual conductor circuits that can fail without compromising the continued operation of the MIC system.
2. An individual conductor potentially could fail due to a coolant leak, mechanical stress, micrometeorite impact, etc. Its failure would not propagate to the remaining conductors in the cable.
3. Virtually all ($\geq 99\%$) of the current in the failed conductor will automatically transfer by induction to the remaining conductors in the MIC cable. Their maximum current capability is substantially greater than the small additional current transferred to them by induction, so that they easily carry the current from the previous failed conductor. Total cable current will be $>99\%$ of its value.
4. If it is desired to completely restore all of the original current in the MIC cable, some of the MIC conductors can be temporarily re-connected to an external power supply to bring back the total current to 100% of its original value.
5. MIC systems will use multiple operating cryocoolers with redundant, stand-by cryocoolers. Any failure of one or more cryocoolers can be rapidly handled by insertion of a standby unit and/or increase in refrigeration output from already on-line units, without affecting MIC system operation.

**FIGURE 7.1.1
MULTI LAYER THERMAL INSULATION OF MIC CONDUCTOR
AFTER EXPANSION**

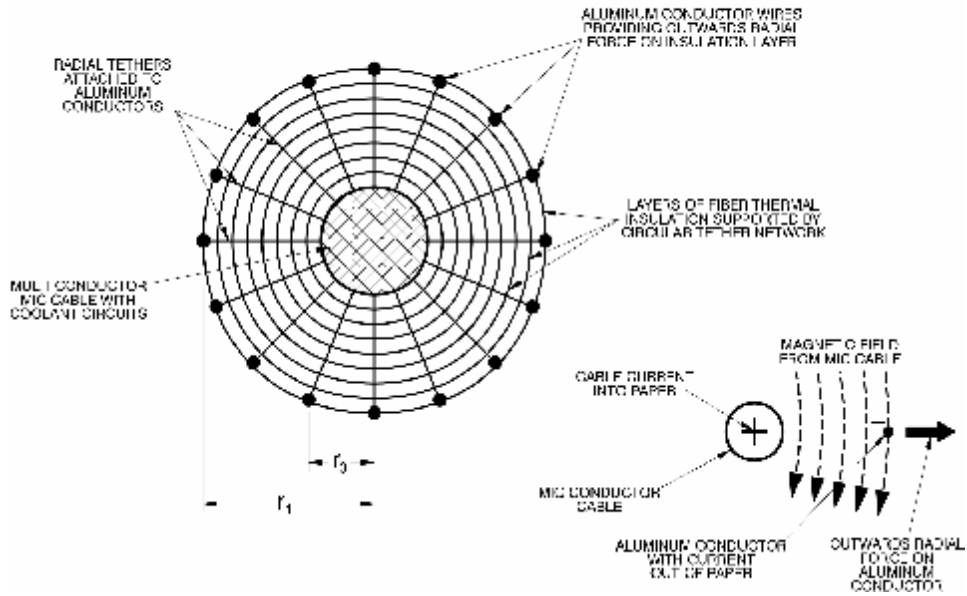


Figure 7.1.2

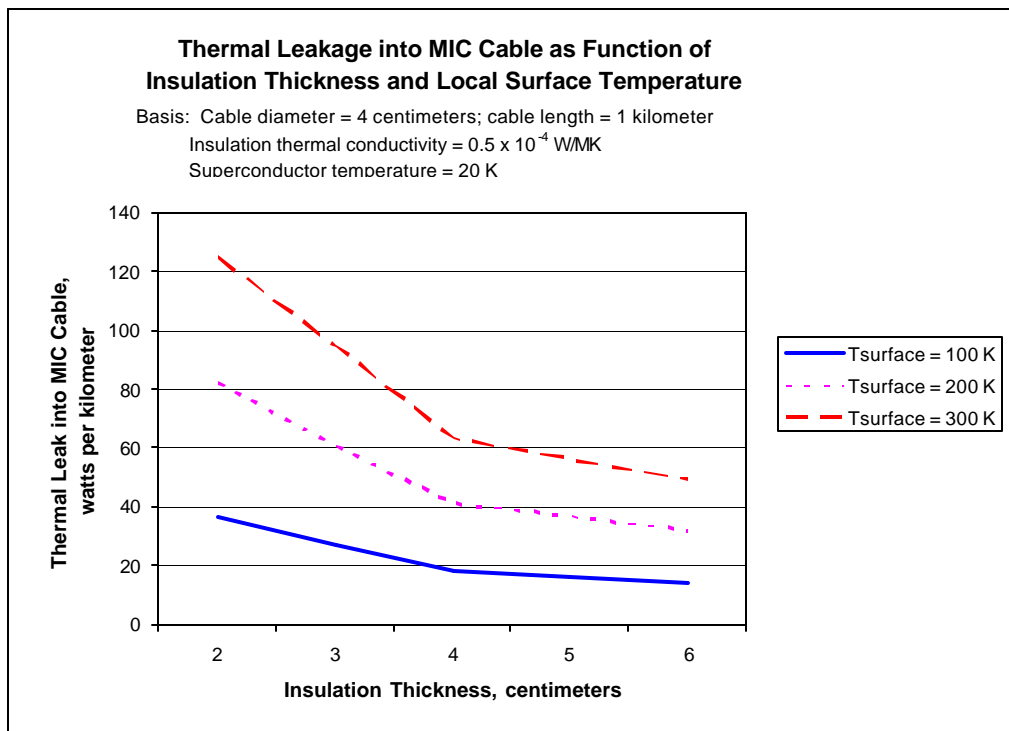


FIGURE 7.1.3
DISTRIBUTION OF SURFACE TEMPERATURE AND THERMAL HEAT LEAK
AROUND CIRCUMFERENCE OF MIC CABLE EXPOSED TO
NON-UNIFORM ILLUMINATION

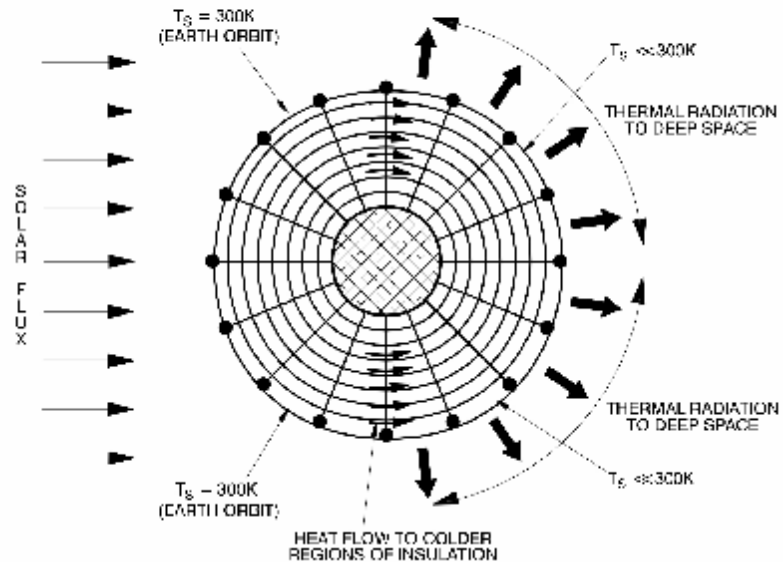


Figure 7.1.4 Erection Process for MIC Thermal Insulation

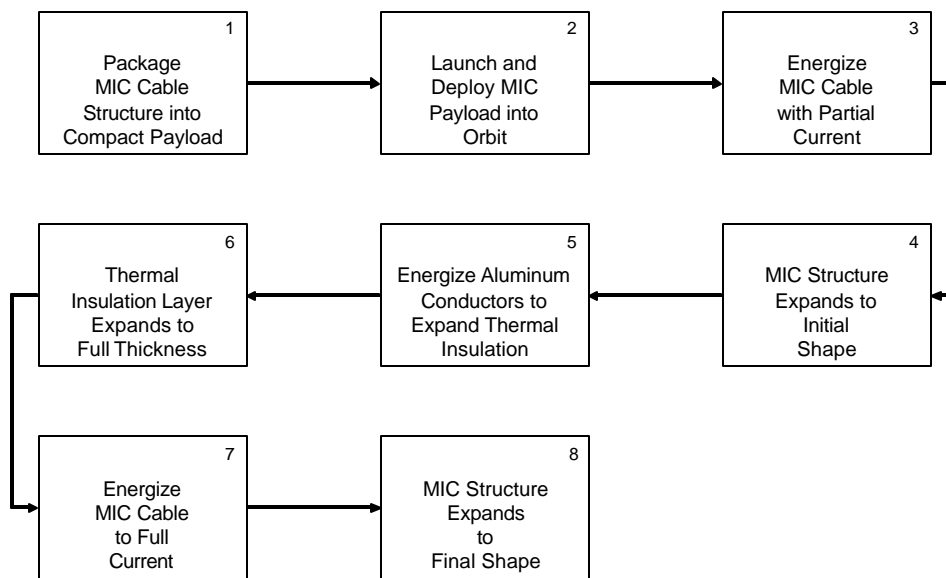
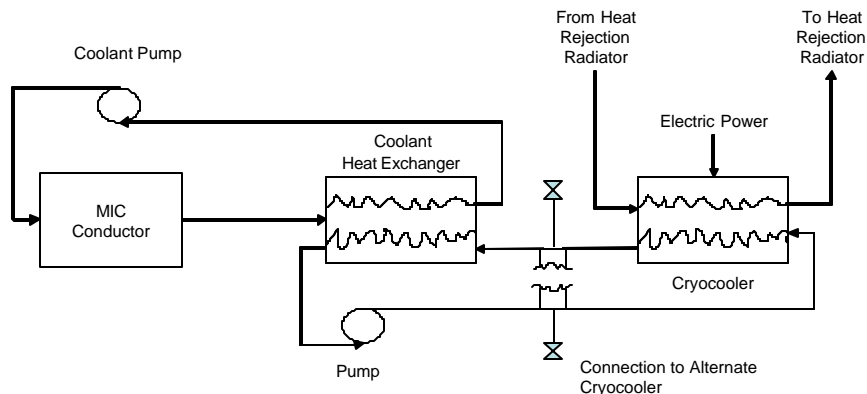


Figure 7.2.1 Flowsheet for MIC Cooling and Refrigeration System



Features of MIC Coolant/Refrigeration System

- Leak in MIC conductor coolant circuit is confined to that circuit – Does not compromise other conductor circuits
- Refrigeration function of failed cryocooler can be taken over by other cryocoolers – MIC conductor circuit continues to operate
- Reject heat from cryocooler can be handled by fail-safe multi-heat pipe radiator

Figure 7.2.2

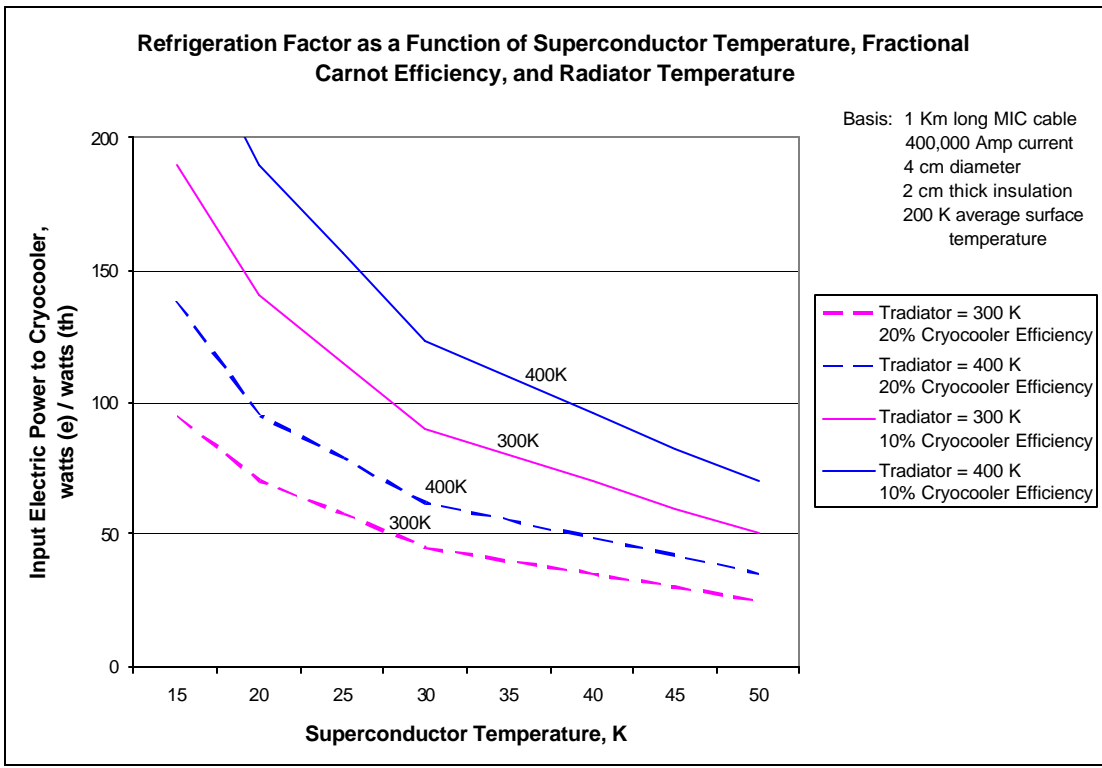


Figure 7.2.3

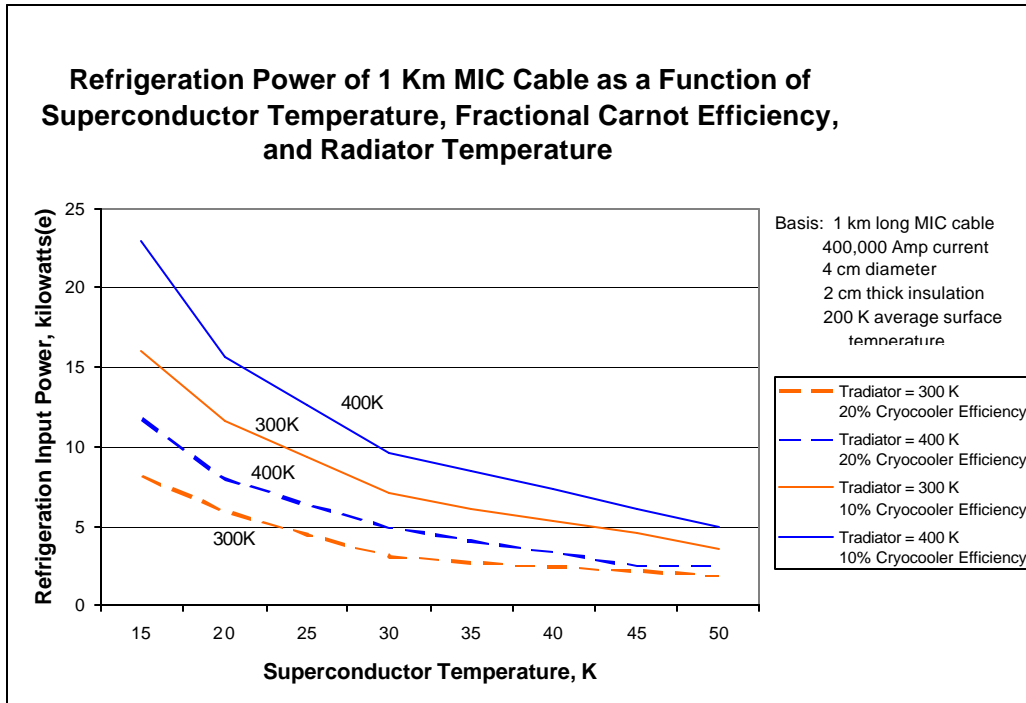


Figure 7.2.4

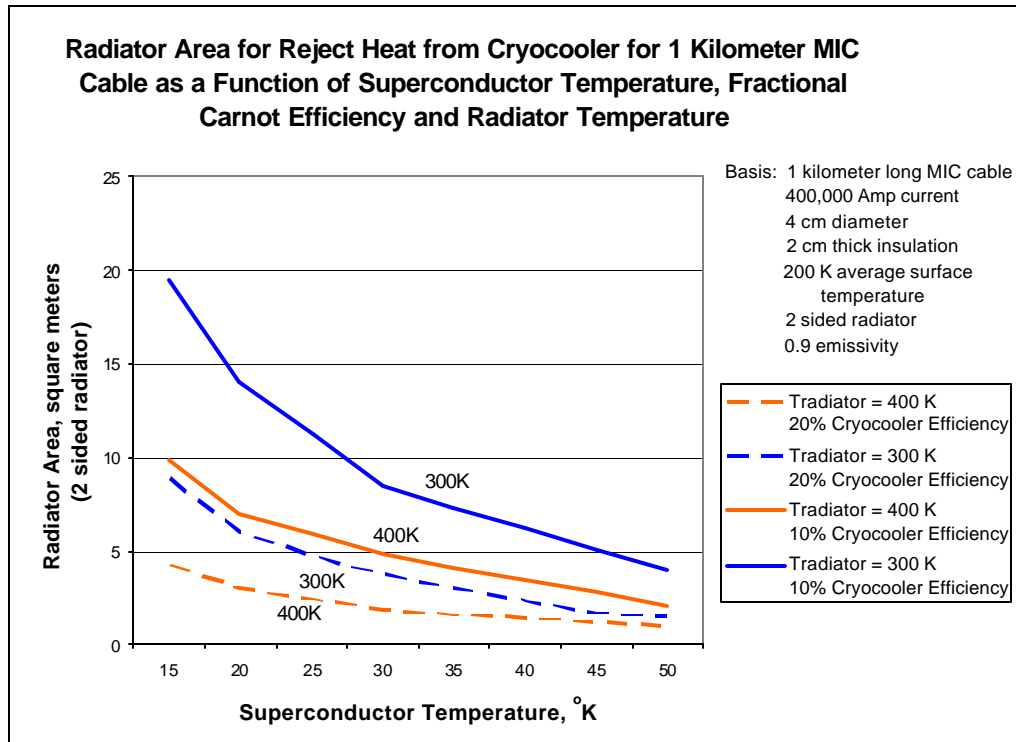


FIGURE 7.2.5
ILLUSTRATIVE CROSS SECTION OF MIC CONDUCTOR WITH
ATTACHED COOLANT TUBE
 Basis: 10,000 Amp Total Current Per Conductor

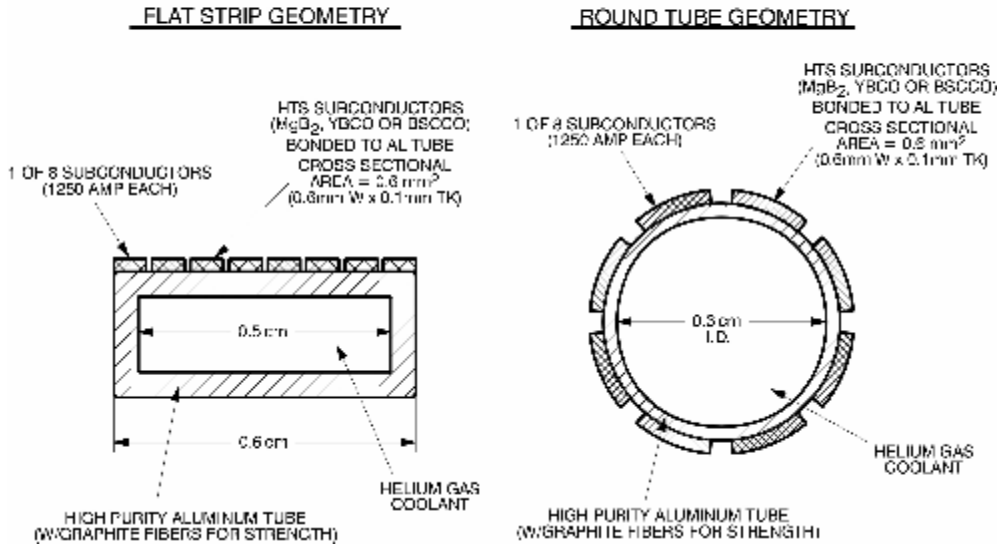


Figure 7.3.1 Methods of Supporting Conductors in MIC Cables

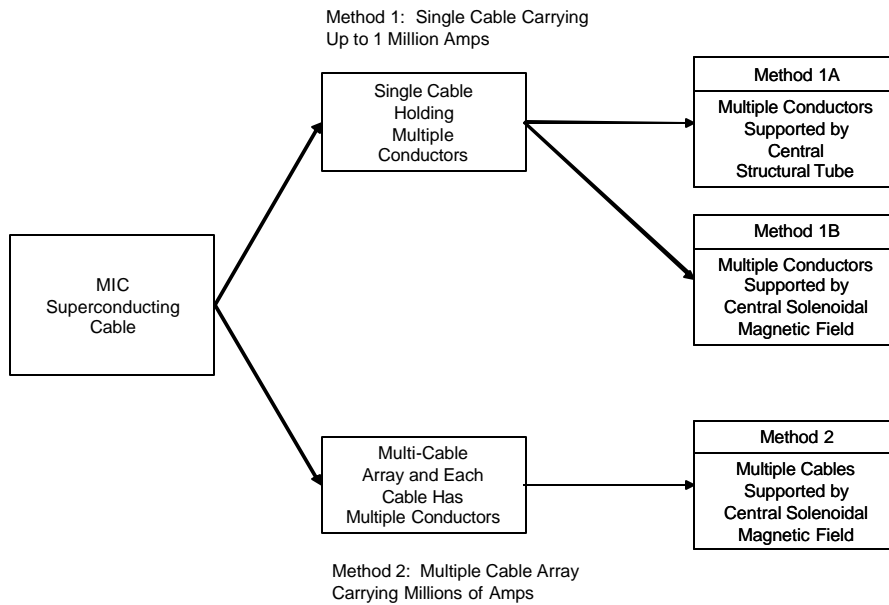


FIGURE 7.3.2
ILLUSTRATIVE VIEWS OF METHOD 1 FOR SUPPORT OF MULTIPLE MIC CONDUCTORS ON SINGLE MIC CABLE USING CENTRAL STRUCTURAL TUBE

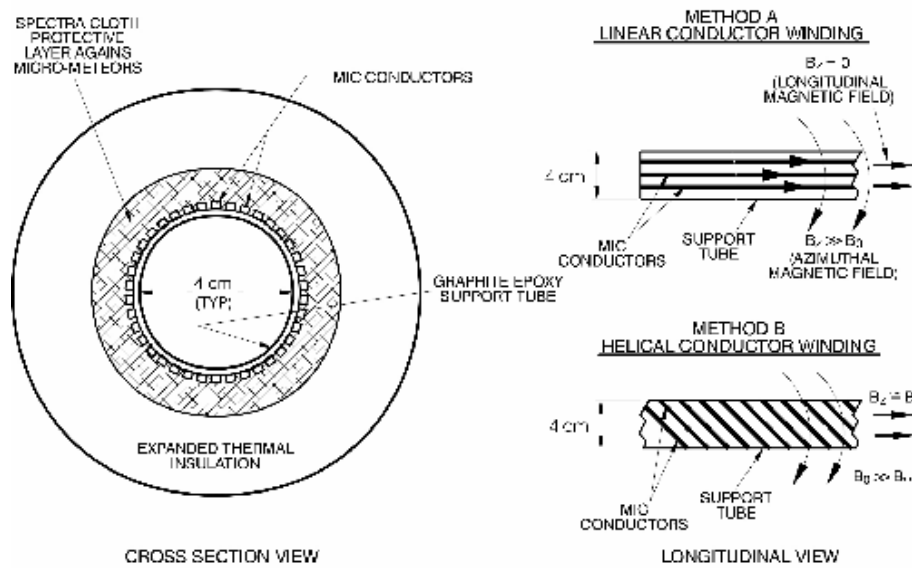


FIGURE 7.3.3
ILLUSTRATIVE VIEWS OF METHOD 2 FOR SUPPORT OF MULTIPLE MIC CONDUCTORS ON SINGLE MIC CABLE USING CENTRAL SOLENOIDAL FIELD

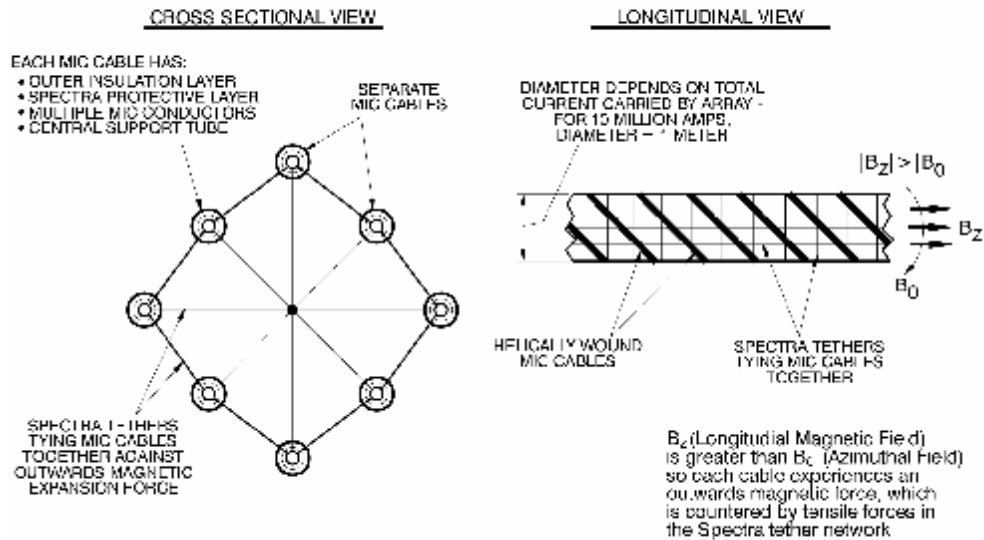


Figure 7.3.4 Superconductor Connections for MIC Cable

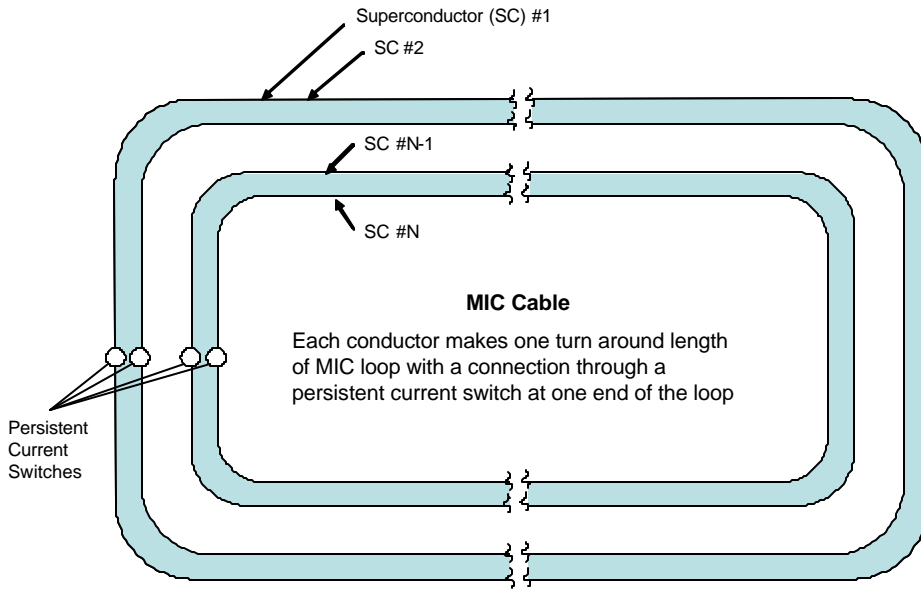


Figure 7.4.1 Reliability and Redundancy Features of MIC Conductor and Cable Systems

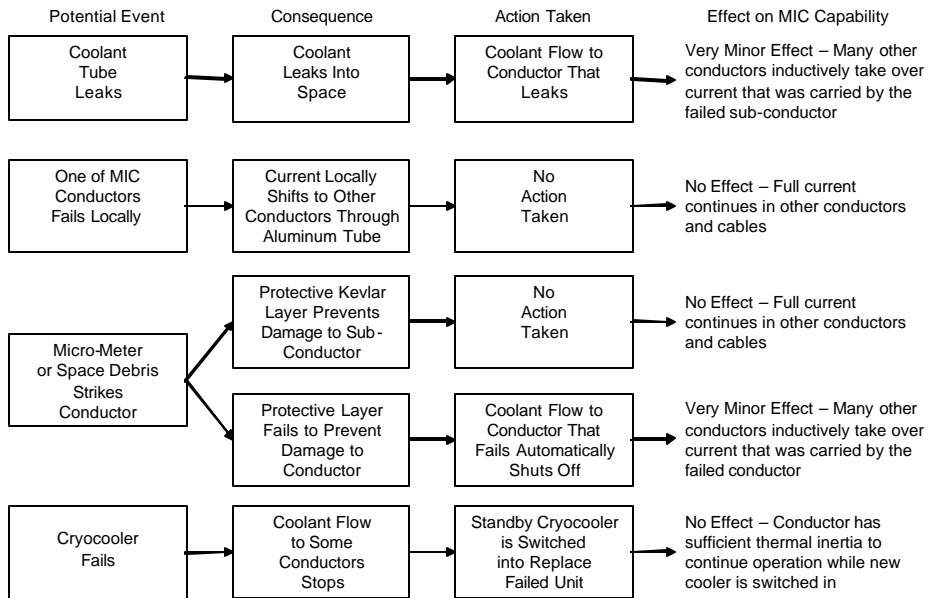


FIGURE 7.4.2
PERSISTENT SWITCH AND CHARGING PROCESS FOR MIC SUB-CONDUCTOR

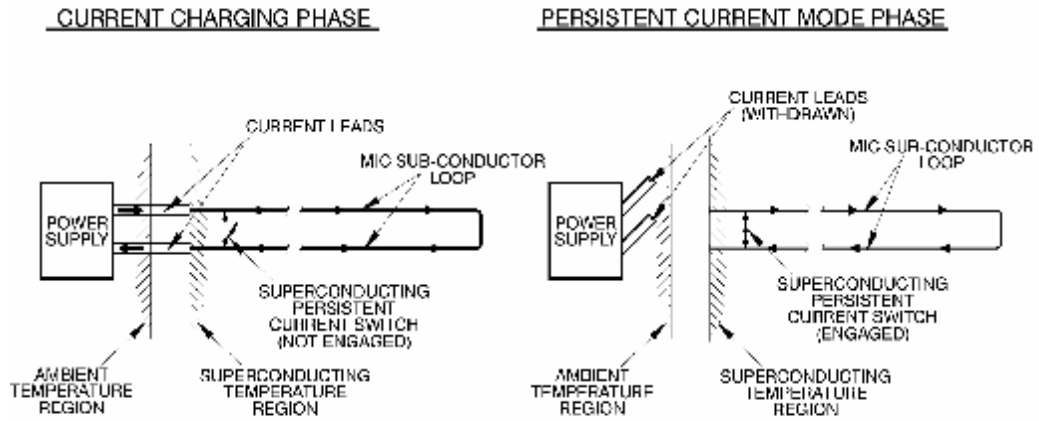


Table 7.1.1 Illustrative Parameters for MIC Thermal Insulation

Basis: MIC Cable Diameter = 4 cm; Cable Length = 1 kilometer
 Insulation Thermal Conductivity = 0.5×10^{-4} W/mK
 Superconductor Temperature, Current = 400,000 Amps
 16 Aluminum Wires, 1 millimeter diameter, 0.7 Amp current in each wire
 Insulation Density = 120 kg per cubic meters
 Tether Network = 10 kg per cubic meters

	Radial Thickness of Insulation		
	2 cm	4 cm	6 cm
<u>Heat leak into 20 K superconductor with effective surface temperature</u>			
300 K (solar flux on full circumference)	127	63	49
200 K (solar flux on 1/2 of circumference)	82	42	32
100 K (no solar flux on surface)	36	18	14
<u>Aluminum wire expansion system</u>			
I ² R power in surface aluminum wires, watts/kilometer (total for 16 wires)	280	280	280
Radial outwards force on each wire, Newtons per meter of length	1.4	0.97	0.7
<u>Insulation Volume</u>			
Expanded, cubic meters per meter of cable	3.7×10^{-3}	1.0×10^{-2}	1.9×10^{-2}
Compressed, cubic meters per kilometer of cable	0.20	0.55	1.05
Total volume, compressed insulation plus cable, m ³ /Km	1.46	1.81	2.31
<u>Mass budget, kilograms per kilometers of cable</u>			
Insulation	440	1540	2880
Aluminum wires	35	35	35
Tether network	37	100	190
	512	1675	3105

Table 7.1.2 Thermal Insulation Parameters for Illustrative MIC Applications

Applications

<u>Parameter</u>	<u>Solar Electric</u>	<u>Solar Thermal Propulsion</u>	<u>Energy Storage</u>	<u>Space Telescope</u>
Location	Lunar Base	Space	Lunar Base	Space
Performance	5 MW(e) @ 20% solar cell efficiency	50 MW(th) H ₂ propulsion I _{sp} = 950 sec [10,000 Newton thrust]	30 MWH [100 KW for 2 weeks]	300 meter [200 times Hubble diameter]
# of MIC cables on loop @ 400,000 Amps per cable	1	1	16 ^(c) [inside 0.5 m insulated tube]	1
MIE loop diameter, meters	160	230	1000	300
Total MIC cable length, km	0.51	0.73	3.1	0.94
Total mass of insulation ^(a) package, kilograms	260	370	2500 ^(d)	480
Mass of insulation, kg per square meter of loop	1.2 x 10 ⁻²	8.8 x 10 ⁻³	3.5 x 10 ⁻³	6.8 x 10 ⁻³
Heat leak, watts ^(b)	42	60	500 ^(e)	77

Notes:

1. Insulation thickness on MIC cable is 2 centimeters
Density = 120 kg/m³
2. Heat leak based on 200 K average surface temperature
3. Multiple MIC cables (16 total) required to achieve total current of 7 x 10⁶ Amps in energy storage coop. The 16 cables are contained inside a 0.5 meter diameter thermally insulated tube, with 4 centimeters of insulation
4. Mass of insulation based on 4 centimeters thickness, with density of 120 kg/m³
5. Refrigeration during 2 week night period is supplied from cold sink refrigerated by power generated during 2 week day period

Table 7.2.1 Helium Coolant Flow Rate and Pressure Drop Through MIC Conductor

Basis: 1 kilometer cable length
 40 conductors @ 10,000 Amps per conductor
 2 cm thick radial insulation
 82 watts per kilometer thermal load; 2 watts per conductor
 0.10 g/cm³ Helium gas density (70% of liquid)
 Circular channel; friction factor = 0.03

Parameter	OT =	Flow Channel Diameter, cm					
		0.3		0.4		0.5	
		2K	4K	2K	4K	2K	4K
Helium total mass flow rate, g/sec		8	4	8	4	8	4
Helium mass flow rate per conductor, g/sec		0.2	0.1	0.2	0.1	0.2	0.1
Helium volumetric flow rate per conductor, cm ³ /sec		2	1	2	1	2	1
Helium velocity in channel, cm/sec		31	15	15	7.5	10	5
Helium pressure drop, N/m ²		45,000	10,125	8,400	2,100	3,000	750

Table 7.3.1 Illustrative Operating Envelopes for MIC Cable Regimes

	Single Cable	Multi Cable Array
Maximum Current Capability	1 million Amp	>> 1 million Amps
Diameter of conductor bundle @ 4 Tesla max field and # of conductor in cable at 10,000 Amps per conductor for current capacity of:		
200,000 Amp	2 cm; 20 conductors	—
400,000 Amp	4 cm; 40 conductors	—
1,000,000 Amp	10 cm; 100 conductors	—
Diameter of cable array @ 4 Tesla maximum field and # of cables in array @ 400,000 Amp per cable for capacity of:		
4,000,000 Amp	—	40 cm; 10 cables
6,000,000 Amp	—	60 cm; 15 cables
10,000,000 Amp	—	100 cm; 25 cables

8.0 BASELINE DESIGN OF MIC SOLAR ELECTRIC SYSTEM FOR A LUNAR BASE

Following the evaluation process described in Section 5.1, the baseline selected for a MIC solar electric application was a 1 MW(e) system for a manned lunar base. The evaluation process was generic and did not specify the location of the lunar base and the MIC solar electric system, nor did it select the shape and size of the MIC structure (a generic circular MIC solar concentrator configuration was used in the evaluation).

There appears to be substantial interest in having a manned base at the Moons South Pole, near the Skackelton Crater. Such a base would have a number of attractive features:

- Near constant solar, during the 28 day lunar cycle for locations on elevated ridges.
- Potential sources of water ice in the shadowed floors of the Skackelton Crater.
- Continuous wide angle view of the Southern Celestial Hemisphere.

Accordingly, the Southern Pole of the Moon has been selected as the site of the baseline MIC solar electric system. The same design could also be used at the North Pole of the Moon. For mid latitude bases, some modifications would be required, but not radical ones.

Instead of the circular solar concentrator configuration shown in Sections 2 and 3 of the report, a linear solar configuration was chosen, using a linear MIC quadrupole structure to support the mirror surface and the solar cell array. Figure 8.1 shows the linear quadrupole solar electric system in 2 possible configurations:

1. Flat surface solar cell array.
2. Linear through mirror surface focusing on smaller central solar cell array.

Configuration #1 is a simpler structure, but requires more solar cells. Configuration #2 uses substantially fewer solar cells, e.g., $\sim 1/10$ th as many, with a lower total mass. However, the MIC structure is somewhat more complex (but still quite reasonable) and the solar cells have to operate at a somewhat higher temperature. (Though with heat pipe cooling their temperature could be kept at a level not much above that of a flat array.)

The linear quadrupole configuration has a number of important advantages:

1. The vertical height of ~ 1 kilometer minimizes concerns about shadowing of solar illumination by surrounding linear terrain.
2. The vertically oriented quadrupole is relatively simple to magnetically support above the rough lunar surface, and can be easily rotated to follow the changing direction of solar illumination during the 28 day lunar cycle.
3. The lunar trough reflecting surface is relatively easy to shape and focus onto a linear solar cell array.

Figure 8.2 illustrates how the vertical linear quadrupole would be supported and rotated to follow the changing direction of solar illumination. The ends of the MIC superconducting cables are curved to form a circle with 4 quadrants, in which the directions of the superconducting current alternate. [Each of the four vertical MIC SC cables actually consists of a bundle of 2 parallel independent cables. The 2 cables go off in opposite directions at the ends of the quadrupole to form a horizontal circle of 4 quadrants, with the direction of the currents alternating in the quadrants.]

The effective currents in the end horizontal circles are then $\frac{1}{2}$ of the current carried in each of the 4 vertical cables that run the length of the MIC quadrupole. This arrangement of end currents is made so that the linear quadrupole can be levitated above the surface of the Moon and slowly rotated 360 degrees during the 28 day lunar cycle (Figure 8.2). The quadrupole is levitated by the repulsion magnetic forces between the currents in the circular horizontal loop at its base, and the oppositely directed currents in a matching circular loop located on the surface of the Moon beneath.

The current in the loop on the surface is much smaller than the current in the MIC cables. With a surface current of 20,000 amps, for example, the MIC quadrupole can be levitated several meters above the Moon's surface. The direction of the currents in the surface loop would be slowly rotated in synch with the Moon's 28 day cycle to continue to be in opposite direction from the end loop currents of the quadrupole above. A very small steady magnetic propulsion force would be applied to make the quadrupole rotate once every 28 days.

Figure 8.3 lists the principal features of the MIC solar electric system for the two options considered, i.e., the flat solar cell array, and the solar concentrator version. An overall solar cell efficiency of 10%, solar thermal energy to electrical output, is assumed. This is conservative. Solar cells can achieve significantly higher efficiency. The 10% value is chosen to reflect a number of factors that can reduce net efficiency, such as the degradation of solar cell efficiency with time, power conditioning requirements, etc.

With a 10% efficiency and 1.2 KW(th)/m^2 solar flux, an output of 1 MW(e) would require $\sim 9000 \text{ m}^2$ of solar collector area. A 10/1 length/width ratio was chosen for the linear quadrupole, which results in a height of 300 meters and a width of 30 meters. These dimensions are quite reasonable, but not necessarily optimized. More detailed study is needed to determine an optimum design, taking into account total system mass, desired height, refrigeration power, etc. The optimum length/width ratio may turn out to be larger or smaller.

The main difference between the two MIC options is their solar cell arrangements. The flat solar cell array will have more mass, but will be simpler in construction. The 1 sun flat cell array is assumed to have a specific mass of 5 kg/KW(e). The 10 Sun solar cell array is assumed to have a specific mass of 2 kg/KW(e). Although a concentration factor of 10 Suns is assumed, which reduces the solar cell area by a factor of 10, the solar cells are assumed to be thicker and have heat pipe removal, which raises their mass per unit area by a factor of 2.

Figure 8.4 summarizes the design parameters for the MIC solar electric system. Conservative values are taken for the mass density of the multi-layer thermal insulation, engineering current density of the superconductor, tether tensile stress, etc.

A number of important conclusions can be drawn about the MIC solar electric system for a manned lunar base. They include:

1. The refrigeration power input to maintain cryogenic conditions in the MIC structure is very small compared to the electric power output, e.g., ~5 KW(e) is 1000 KW(e) output.
2. The maximum magnetic field (2 Tesla) and engineering current density (100,000 A/cm²) parameters for the YBCO superconductor are reasonable in terms of present capabilities.
3. The tether tensile stresses and masses are quite small. Spectra is assumed as the tether material with a working stress of 15,000 psi, about 1/30th of its ultimate strength. Kevlar could also be used. Tether mass would increase somewhat, but it still would be a very small fraction of total system mass. Tether stress could also be substantially reduced without penalizing system mass, although there does not appear to be any need to reduce working stress, which is already quite low.
4. MIC structure mass is substantially less than the mass of the solar cells for the flat solar array option, and comparable to the mass of the solar cells and aluminized film concentrator for the MIC concentrator option.
5. The specific mass of ~6 kg/KW(e) for the total MIC system appears attractive. It probably can be significantly reduced by further optimization of the system, using lighter solar cells, higher current densities, etc.
6. The effective weight of the MIC system on the Moon will be much less than on Earth, because of the Moon's lower gravity, which is ~1/6th that of Earth. An important parameter for the MIC structure is the ratio of the longitudinal stretching force on the linear quadrupole to its effective weight on the Moon, since that is a measure of the rigidity and stiffness of the structure. For the two options considered, the ratio of longitudinal stretching force to the effective total weight of the MIC structure is in the range of 4 to 5. This appears acceptable, since there are no wind or other forces on the Moon that would affect the MIC structure.
7. With a 20,000 amp ground current loop, the MIC structure could be magnetically levitated 3 to 4 meters above the surface of the Moon depending on the option selected. This seems sufficiently high to encompass any variations in the lunar terrain below the MIC structure. The MIC ground loop would also be superconducting. However, the amount of additional superconductor required would be relatively small, about 1% of the superconductor that would be used for the linear MIC quadrupole. The additional system mass and refrigeration power would not significantly impact the overall MIC solar electric system.

The 1 MW(e) choice of output power appears reasonable for a small permanent manned lunar base. For larger manned bases, the MIC solar electric structure can be readily scaled to considerably greater power levels using the same technology. Figure 8.5 illustrates the output power level as a function of quadrupole height, assuming the same 10/1 length to width ratio used for the 1 MW(e) system.

The output electrical power will scale as (quadrupole weight)², since for a constant length/width ratio, the total area illuminated by the solar flux will scale as (height x width) or equivalently, as (height)². The MIC cable current is assumed to scale linearly with height. As a result the mass of superconductor and its insulation will increase as (height)², since the area of the superconductor in the cable increases as height, and the length of cable also increases as height, making the superconductor mass equal to (height) x (height) or equivalently (height)². The masses of one other system components also scale as (height)², with the result that the system specific mass, i.e., kg/KW(e) is constant and independent of the quadrupole height, and equal to 6.0 kg/KW(e) [Figure 8.5].

The longitudinal magnetic force scales at a rate slightly greater than (height)² making the ratio of longitudinal force to effective weight essentially also constant.

To reduce system specific mass below 6 kg/KW(e), the most promising approaches are to increase the engineering current density of the superconductor, and to decrease the specific mass of the solar cells, probably with a greater solar concentrator efficiency.

Figure 8.1

MIC Linear Quadrupole Configurations For Solar Electric Generation On The Moon

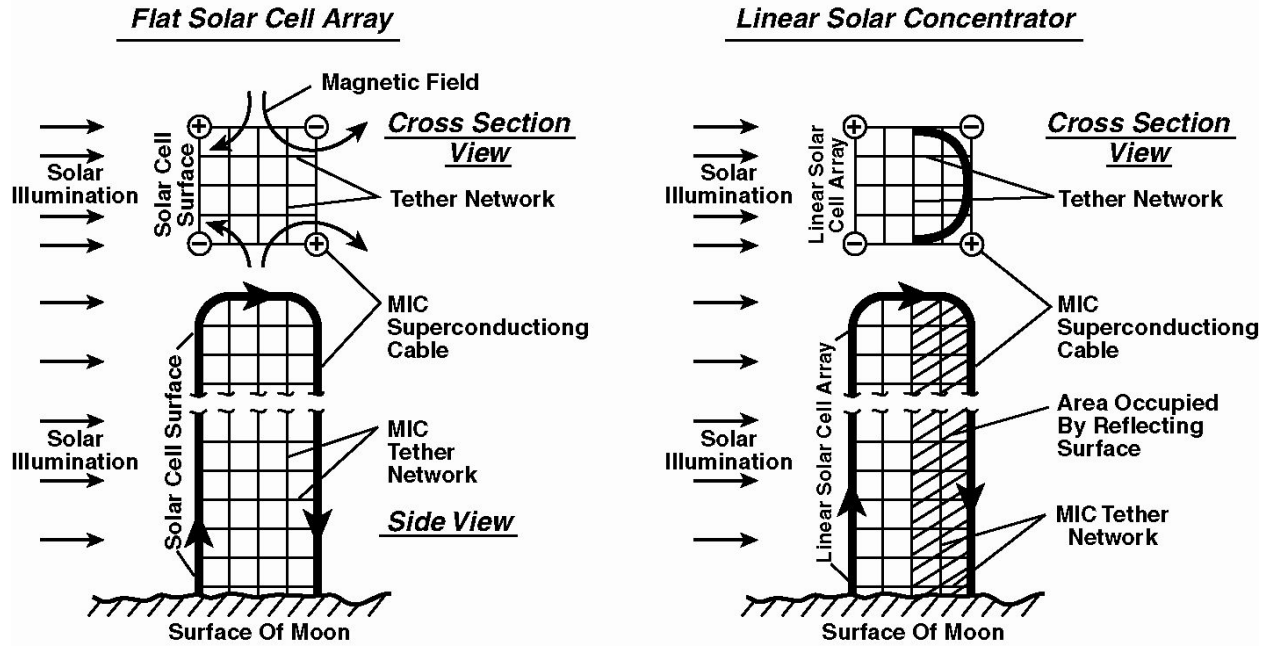


Figure 8.2

Support and Rotation Of MIC Solar Electric Quadrupole On The Moon

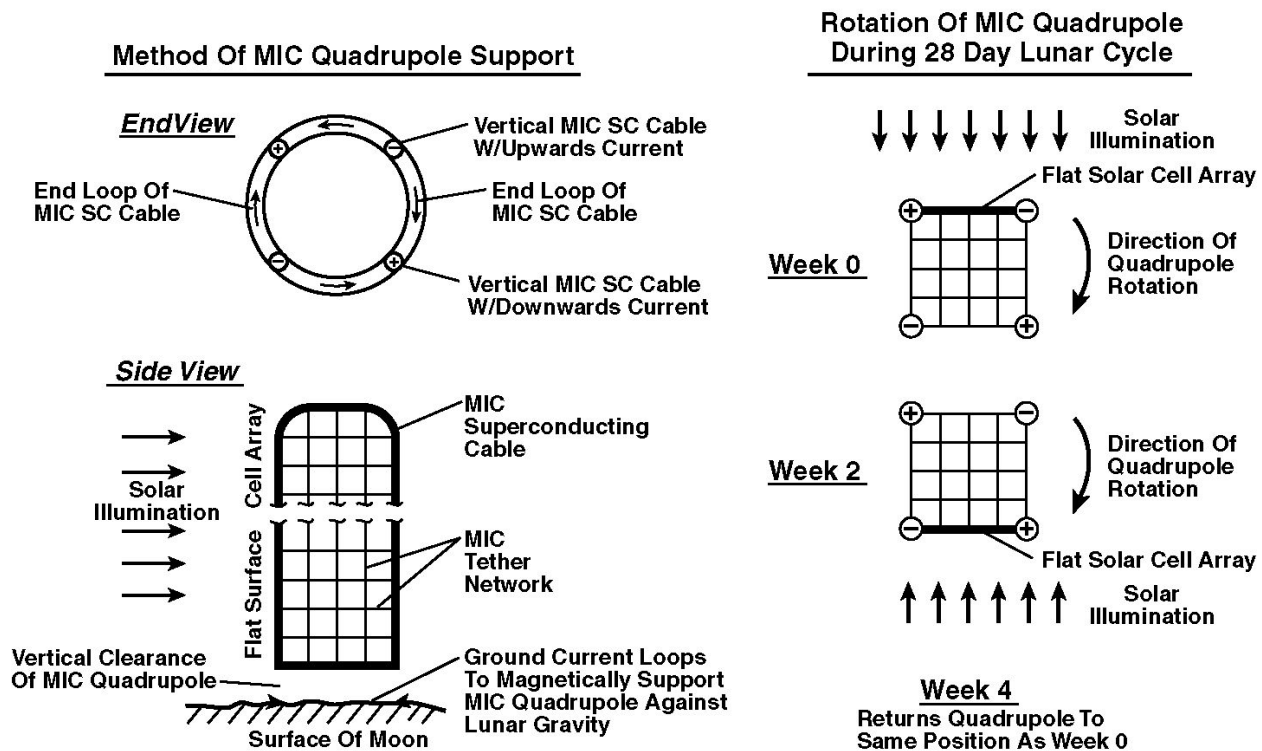


Figure 8.3 Principal Features of the MIC Solar Electric System for a Manned Lunar Base

System Feature	MIC Option	
	Flat Solar Cell Array	Linear Trough Solar Concentrator and Cell Array
MIC system location	Lunar South Pole near Skackleton Crater	
Type of MIC structure	Vertical linear quadrupole	
Electric power output	1 Megawatt(e)	
Solar flux	1.2 KW(th)/m ²	
Solar cell net efficiency (including conditioning, etc.)	10% (thermal to electric)	
Quadrupole height/width	300 meters/30 meters	
Solar collector area	9000 m ²	9000 m ²
Solar concentration factor	1 Sun	10 Suns
Solar cell area	9000 m ²	900 m ²

Figure 8.4 Design Parameters for MIC Solar Electric Systems for a Manned Lunar Base

Design Parameter	MIC Option	
	Flat Solar Cell Array	Linear Trough Concentrator on Solar Cell Array
Output electric power	1 Megawatt(3)	1 Megawatt(e)
Current in one MIC cable	100,000 Amp	100,000 Amp
# of MIC cable loops in quadrupole	4	4
Length of cable in one MIC loop	700 meters	700 meters
Total length of cable in all MIC loops	2.8 km	2.8 km
Diameter of superconductor in MIC cable	2 cm	2 cm
Maximum magnetic field on superconductor	2 Tesla	2 Tesla
Type of superconductor	YBCO	YBCO
Operating temperature	30 K	30 K
Engineering current density in superconductor	100,000 A/cm ²	100,000 A/cm ²
Avg. insulation thickness around 2 cable bundle	2 cm	2 cm
Total length of 2 cable bundles	1.4 km	1.4 km
Thermal leak into superconductor	120 watts(th)	120 watts(th)
Refrigeration power (20% of Carnot)	5.2 KW(e)	5.2 KW(e)
Mass of MIC cable and insulation	3100 kg	3100 kg
Radial outwards magnetic force on 2 cable bundle	190 N/m	190 N/m
Longitudinal magnetic force on end loops	50,000 N	50,000 N

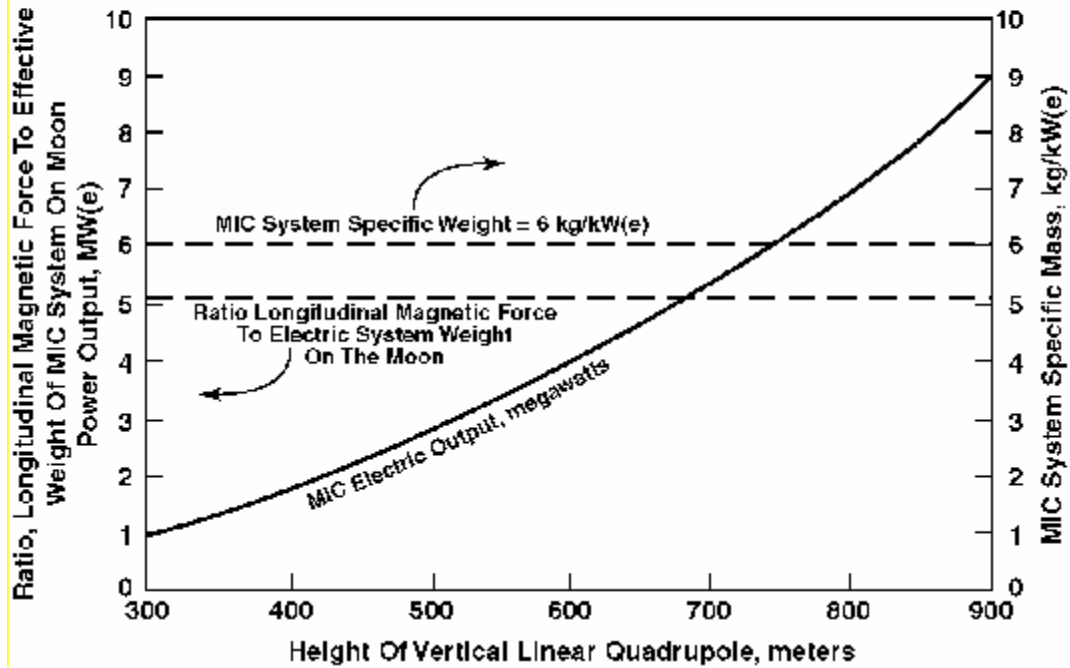
Design Parameter	MIC Option	
	Flat Solar Cell Array	Linear Trough Concentrator on Solar Cell Array
Mass of radial tethers (tensile stress = 15,000 psi)	50 kg	50 kg
Mass of longitudinal tethers (tensile stress = 15,000 psi)	150 kg	150 kg
Mass of MIC structure	3300 kg	3300 kg
Mass of solar cell array	5000 kg	2000 kg
Mass of solar concentrator *	—	700
Total system mass (weight on Moon)	8300 (1328) kg	6000 (960) kg
Longitudinal tether force/system weight ratio	3.8	5.2
Specific mass of MIC structure	3.30 kg/KW(e)	3.30 kg/KW(e)
Specific mass of complete MIC solar electric system	8.30 kg/KW(e)	6.00 kg/KW(e)
Levitation current in surface loops	20,000 Amps	20,000 Amps
Levitation height of quadrupole above Moons surface	2.7 meters	3.9 meters

* Assumed to be 4 mil thick aluminized Kapton film supported by tether network.

Figure 8.5

Output Power From The MIC Solar Electric System For A Manned Lunar Base

Basis: Vertical Linear Quadrupole With 10/1 Height/Width Ratio
Solar Concentrator Option With 10 Suns Concentration



9.0 BASELINE DESIGN OF MIC SOLAR THERMAL PROPULSION SYSTEM FOR EARTH-MOON TUG

The design of the MIC solar thermal propulsion system for an Earth-Moon tug depends strongly on the operational parameters assumed for the tug (payload, trip time, H_2 temperature) as well as the operational plan, e.g., does the tug make multiple round trips or not, does it bring back payloads from the Moon, does it obtain H_2 propellant from in-situ resources on the Moon (for example, from ice deposits in permanently shadowed craters such as the Shackleton Crater at the Moon's South Pole) or is the H_2 propellant lifted into LEO from the Earth, and so on.

For a permanently manned lunar base on the Moon, an Earth-Moon tug that could make multiple round trips to deliver and return heavy payloads from the Moon, in addition to taking out and returning astronauts, would be very attractive. The MIC solar thermal propulsion system can do this very efficiently because of its high Isp.

Figure 9.1 gives the principal features of the MIC Earth-Moon tug. Unlike conventional rocket engines or nuclear thermal propulsion engines, which deliver a high thrust for a short period, producing an "impulse" type OV addition, the MIC tug delivers a low level continuous thrust during the journey. Although not as efficient as an impulse type burn the MIC tug, because of its high Isp, can still achieve a relatively short trip time, e.g., 5 days from the Earth to the Moon trip, with a similar period of time for the return trip, and a high payload fraction, i.e., about 40%.

The design parameters for the Earth-Moon tug system are summarized in Figure 9.2. The trip time and propellant requirements were calculated using an available computer modal that was based on a constant acceleration of the spacecraft, not a constant thrust. As a result, the thrust level is a maximum of 1100 Newtons when the tug starts from LEO, and their steadily decreases until it achieves orbit around the Moon. The MIC system is thus underutilized for most of the trip, with greater thrust capability than is needed. More detailed mission analyses using a variable thrust model would probably optimize the system to a somewhat smaller dry mass.

For the initial Earth to Moon trips, the H_2 propellant would be brought from Earth by a heavy lift launch vehicle, such as the Delta IV Heavy, which can deliver a payload of 24,500 kilograms to LEO. The H_2 propellant would be stored in a lightweight MIC expandable propellant depot, to be loaded into the tug whenever it made a trip. For the initial return trips from the Moon, the tug would take along enough extra H_2 propellant for the return journey. Since the payloads carried back from the Moon would be much lighter than those going to the Moon, the tug would require much less H_2 propellant for the return trip.

As the Moon base becomes permanent and expands in size, H_2 propellant produced on the Moon from ice deposits in the shadowed craters would fuel the return trips of the tug, plus being brought back to LEO and stored in the MIC expandable propellant depots, to be used for the outbound trips to the Moon with heavy payloads. This would be considerably cheaper and easier than launching the H_2 propellant from Earth.

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2. Hill, P., Peterson, C., "Mechanics and Thermodynamics of Propulsion," 2nd Ed., Addison-Wesley, Massachusetts, 1992.
3. Wiesel, W., "Spacecraft Dynamics," 2nd Ed., McGraw Hill, New York, 1997.

Figure 9.1 Principal Features of the MIC Solar Thermal Propulsion System for an Earth-Moon Tug

- MIC solar concentrator focuses sunlight on high temperature receiver to heat H₂ propellant to 2500 K
- MIC solar concentrator is zoned so that the lower temperature portion of the H₂ heating process does not require a high solar concentration factor – only the last portion requires a high concentration factor
- Earth-Moon tug shuttles between low Earth orbit (LEO) and low Moon orbit
 - Flight time for Earth to Moon trip is 5 days – similar time for return trip
 - Maximum payload capability per trip is ~30 metric tons
 - DeltaIV lifts payloads to LEO to rendezvous with Earth-Moon tug
- H₂ propellant for MIC Earth-Moon tug assumed to come from ice deposits at Moon's polar regions

Figure 9.2 Design Parameters of the MIC Solar Thermal Propulsion System for an Earth-Moon Tug

Design Parameter	Design Value
Low thrust Earth-Moon orbital transfer OV	6.80 km/sec
Flight time, LEO to Moon orbit	5.25 days
Constant acceleration	0.015 m/sec ²
Orbital tug mass	
• Dry mass (MIC system, controls, tankage, etc.)	5,000 kg
• Payload	26,000 kg
• H ₂ propellant in LEO	42,000 kg
• Total mass in LEO	73,000 kg
Thrust levels from MIC propulsion system	
• LEO departure	1100 Newtons
• Arrival at Moon	470 Newtons
MIC solar concentrator	
• Thermal power	5 megawatts
• H ₂ propellant temperature	2500 K
• Isp	850 seconds
• Maximum thrust	1100 Newtons
• Diameter of MIC concentrator	73 meter
• Length of MIC primary	229 meters
• Current in MIC primary cable	250,000 Amps
• Mass of MIC concentrator (MIC cables, mirror surface, tethers, and refrigeration system)	900 kg
Mass of high temperature receiver and piping	500 kg
Miscellaneous and contingency	500 kg
TOTAL MIC propulsion system mass	1900 kg

10.0 MIC ENERGY STORAGE

Figure 10.1 illustrates 4 potential configurations for a MIC energy storage system at a manned lunar base. Each involves the use of high current superconducting MIC cables to store the electric energy in the magnetic fields of the MIC cables. When storing the electric energy, the current in the MIC cables is increased using electric power from an external source. The stored energy resides in the increased magnetic fields of the MIC cables. When withdrawing electric energy the current in the MIC cables goes through an external loads reducing the magnetic field energy of the cables.

This method of electrical energy storage is not new. SMES (Superconducting Magnetic Energy Storage) systems have undergone substantial development during the last 30 years and a number of SMES devices have been operated widespread application of SMES system on Earth has not taken place, because their cost has been too high. However, the rapid development of High Temperature Superconductors (HTS) will reduce cost, and could result in their widespread use on Earth. For space applications, the costs of the superconductor in the system will be small compared to launch and other costs.

The 4 MIC cable configurations illustrated are:

1. Simple circular horizontal loop
2. Simple horizontal dipole loop
3. Horizontal quadrupole loop
4. Vertical quadrupole loop

In each case, the MIC cable configuration is levitated above the irregular lunar terrain by a much smaller current system that is located on the surface. The levitation height is several meters, enough to accommodate local bumps and depressions in the lunar surface.

Figure 10.2 shows an assessment of the 4 configurations for the lunar energy storage application. All of the four are assumed to use a 1 megamp (10^6 Amp) MIC cable. In practice, the 1 megamp would be the total current carried by the cable; however, the cable would actually have many individual conductor circuits, each of which would carry a considerably smaller current, with the total current from all the conductors adding up to 1 megamp.

Figure 10.2 shows the length of 1 megamp MIC cable required for each of the 4 configurations, based on a maximum energy storage of 2000 megajoules (10 KW(e) for 200,000 seconds equals 2000 megajoules). This amount of energy storage would enable a manned lunar base to have emergency power if needed, and to meet pulsed high power demands that could not be provided by its steady power source. Figure 10.2 also shows the dimensions of the loop, as calculated from the inductance and the assumed 2000 MJ energy storage at 1 megamp of total current.

The total length of MIC cable is almost the same for all 4 configurations, varying from

the smallest value of 2.2 kilometers for the circular loop up to the longest value of 3.3 kilometers for the quadrupole configuration. Accordingly, the choice of the optimum configuration will not be strongly dependent on the length of the MIC cable for the various configurations, but it will be a factor.

The mass of the tethers to restrain the outwards magnetic forces for the simple loop configuration is very small on the order of 1 percent or less, of the MIC cable mass when the tethers are attached to the lunar surface. Even when the tethers are attached to the MIC cables for the quadrupole configurations, their mass is still only a modest fraction, in the order of 10% of the cable mass.

The main factors affecting the choice of configuration are:

1. Simplicity of construction
2. Potential ability to also be used for solar electric generation

As described in Section 8 of the report, the vertical quadrupole configuration can be used for solar electric generation, so that both electric energy generation and storage can be incorporated into the same MIC structure. Because of the difficulty of rotating the horizontal dipole loop and the quadrupole, they do not appear switch for solar electric generation.

The MIC circular loop configuration, because of its ability to rotate and follow the sun, can also be used for solar electric generation. However, it cannot elevate the solar cell array hundreds of meters above the local terrain to minimize shadowing effects and obtain the best view of the Sun. The solar cells for the circular loop configuration will be close to the lunar surface, e.g., a few tens of meters above it. Moreover, it would be difficult to use a solar concentrator with the circular loop. Flat solar cell panels with a 1 Sun illumination seem to be necessary. Finally, the electric output level will be considerably less using the circular loop configuration than the quadrupole, because of the smaller available area.

Figure 10.3 shows the MIC circular loop configuration levitated above the lunar surface using a small current in loops located on the ground. To generate a limited amount of solar power, e.g., up to about a MW(e), flat solar panels could be attached to the MIC cables, and the circular loop rotated so as to follow the movement of the Sun during the 28 day lunar cycle.

Figure 10.4 gives the design parameters for the energy storage only application using the MIC circular loop configuration. The mass of the MIC system is dominated by the mass of the superconductor, which at 100,000 Amps/cm² engineering current density accounts for 16.5 metric tons, about 92% of the total. Increasing HTS current density to 200,000 Amps/cm², which appears achievable would reduce system mass by over 8 tons, increasing it to 300,000 Amps/cm², which should be possible, would reduce it by 11 tons, to a total system mass of only 7 tons.

Figure 10.1

Potential MIC Energy Storage Configurations For A Manned Lunar Base

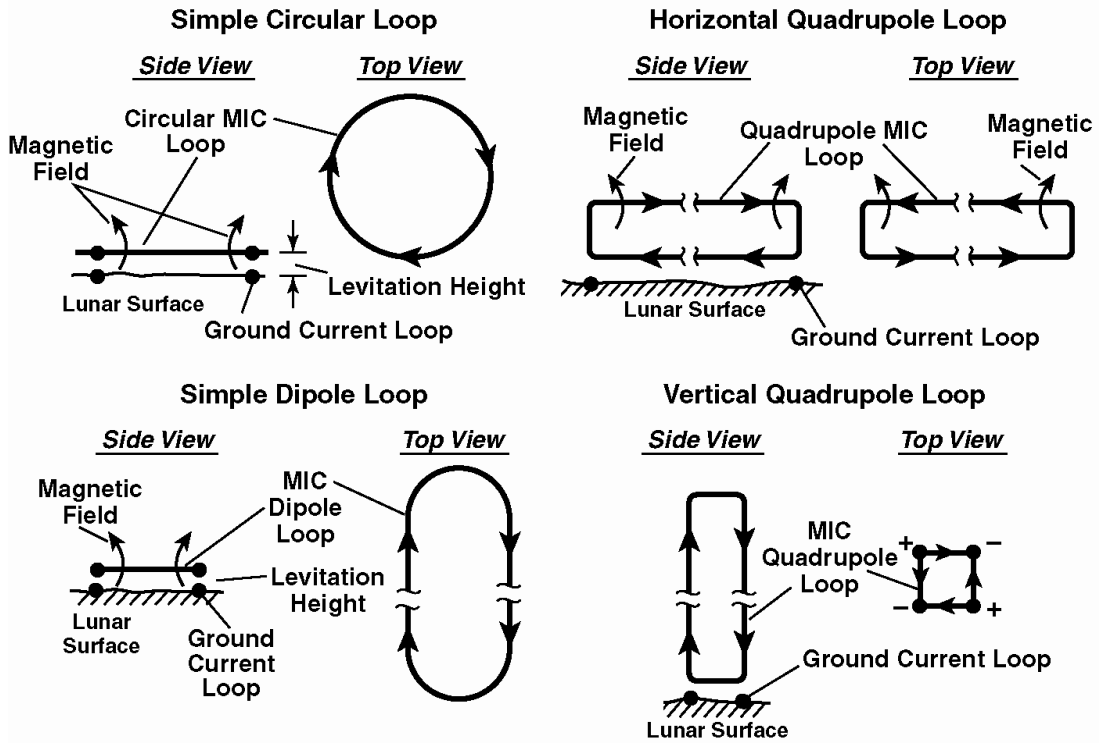


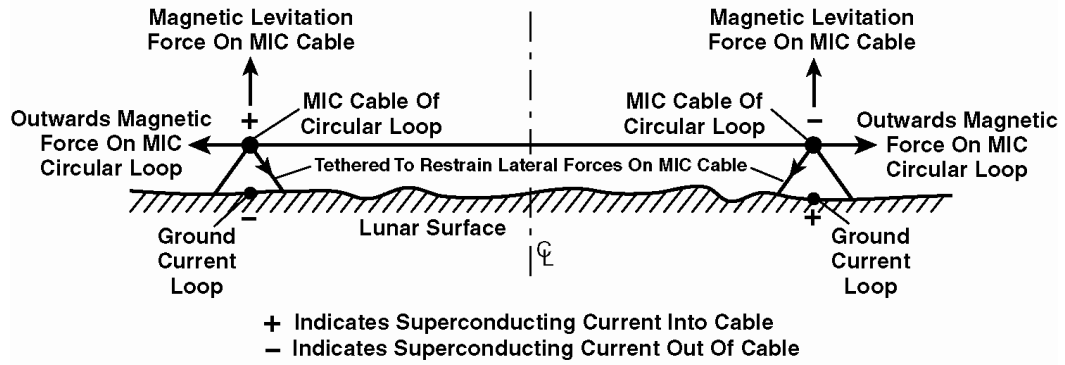
Figure 10.2 Assessment of MIC Energy Storage Configurations for a Manned Lunar Base

Basis: 2000 Megajoules stored energy, 1 million Amp MIC cable

Area of Assessment	Configuration Type			
	Simple Circular Loop	Simple Dipole Loop	Horizontal Quadrupole	Vertical Quadrupole
Length of MIC cable	2.2 km	3.2 km	3.3	3.3
Loop dimensions	700 meter diameter	1400 meter long 140 meter wide	720 meters long 2 meters wide	
Tether method	Short tethers anchored to lunar surface	Short tethers anchored to lunar surface	Long tethers between MIC cables	
Tether mass @ 15,000 psi compared to cable mass	Very small compared to cable mass (<1%)	Small compared to cable mass (~1%)	Modest compared to cable mass (~10%)	
Ability to rotate to follow Sun during	Readily able to rotate	Difficult to rotate	Difficult to rotate	Readily able to rotate
Ability to integrate solar electric power system	Relatively simple	Difficult to follow Sun	Difficult to follow Sun	Relatively simple

Figure 10.3

MIC Energy Storage System For A Manned Lunar Base Using An Anchored Circular Loop



Angled Tethers Are Attached To The 1 Megamp MIC Cable That Forms The Circular Loop To Store Electric Energy. The Tethers Are Anchored To The Lunar Surface and Restrain The Magnetic Forces On The MIC Cable, Holding It In Place. The MIC Cable Experiences Both Outwards Horizontal and Upwards Vertical Magnetic Forces.

Figure 10.4 Design Parameters for MIC Energy Storage System for a Manned Lunar Base

Parameter	Design Value
Stored electric energy	2000 megajoules
MIC structure configuration	Circular loop levitated above surface
MIC cable current	1 million Amps
Diameter of circular loop	700 meters
Length of MIC cable	2.2 kilometers
Type of HTS conductor	YBCO
Operating temperature of HTS conductor	30 K
Thermal leakage into cryogenic region	180 watts
Power input to refrigerator (20 ₁₀ of Carnot)	8.1 KW(e)
Engineering current density	100,000 Amp/cm ²
Mass of superconductor	16.5 metric tons
Mass of superconductor plus insulation	17.6 metric tons
Levitation height above lunar surface	5 meters
Levitation current in ground loops	20,000 Amp
Tether mass (15,000 psi stress)	0.25 metric tons
Total mass of MIC structure	18 metric tons
Specific mass (100,000 A/cm ²)	9 kg/megajoule
Specific mass (300,000 A/cm ²)	3.3 kg/megajoule

11.0 HUGE TELESCOPES FOR ASTRONOMY AND SURVEILLANCE

Many of the important MIC applications discussed in this report do not require structural precision necessary for astronomical or surveillance telescopes. For example, solar concentrators for power or propulsion applications can tolerate relatively large errors in the gross geometry without suffering impairment of function. Telescopes for imaging or spectrographic applications, however, must approach optical perfection.

In Section 5.4, the fundamentals of revolutionary telescopes having filled apertures as large as one kilometer were discussed. The reader may wish to review Section 5.4 before proceeding. Here the principal engineering features of candidate telescope designs using MIC structures synergistically combined with PAMELA (i.e., Phase Array Mirror, Extendible Large Aperture) adaptive optics will be described.

To achieve near-diffraction-limited performance, the cumulative wavefront errors in the optical train must not exceed 0.1 wavelength at the shortest wavelength to be observed. For example, visible wavelengths around 500 nanometers require stable ray traces having net errors not exceeding 50 nanometers r.m.s. Clearly, such mechanical perfection is not likely to be realized in gigantic telescope macro structures. Although some interesting basic research is now being pursued at Sandia National Laboratory seeking to correct local errors in large membrane mirrors by using a combination of electron beams and piezoelectric membranes, it is highly likely that very sophisticated adaptive wavefront control at a secondary or tertiary point in the optical train will still be essential because of large scale errors in any reasonable structure. This is why the highly synergistic combination of MIC structural deployment and PAMELA adaptive optics has such high promise for quickly advancing the state-of-the-art of huge space telescopes: Unlike conventional adaptive optics methods which typically have a corrective range of plus or minus 10 micrometers, PAMELA can correct for structural distortions of thousands of micrometers. As shown in numerous other sections of this report, the MIC structure itself can be fine-tuned by delicate control of magnetic forces and low weight tethers to form a surface of adequately accurate optical figure to enable final wavefront correction with PAMELA adaptive optics.

Figure 11.1 shows a notional representation of the key system components. The MIC deployed primary mirror can be either a continuous membrane or a plethora of plates such as thin silicon wafers. Depending upon the intended applications of the telescope, the focal ratio will be short or long. The short focal length configuration would have a deeply concave primary mirror requiring a large secondary corrector mirror (also deployed by a MIC ring) attached by tethers and compression struts to the primary mirror. The adaptive optics package would be an integral component of the telescope constrained to its position by tethers made rigid by magnetic force.

Long focal length configurations, on the other hand, would have a shallow concave primary with a relatively small secondary mirror feeding into the adaptive optics subsystem

directly. For a one kilometer diameter, f:20 system, the secondary package would be 20 kilometers away from the primary. Hence, the secondary/adaptive optics package would have to be a free-flying, station-keeping unit in any other system than a MIC. The MIC magnetic fields, however, are strong enough that they can directly control the position of the secondary package without the need for station-keeping fuel and thrusters. The latter capability is extremely important for practical telescope designs because the telescope must have the ability to slew rapidly to any point in space. In other words, the secondary package would follow the slewing motion of the primary by using modulated magnetic fields to cause it to stay at the focal point while slewing: The rotating and translating magnetic field would carry the secondary package in a dynamically stable potential well.

In either the short or long focal length configurations, the adaptive system and imaging/spectrographic subsystems would be packaged in an autonomous unit having its own power and communications capabilities. For a one-kilometer diameter primary, the focal package would be similar in size and complexity to the Hubble telescope, although it could be less expensive and lighter-weight than the Hubble because of the technical and hardware economies of the PAMELA approach.

Short focal length designs are suitable for wide-field-of-view applications where large light-gathering power at relatively low magnification is desired. Detailed engineering studies of wide-field-of-view space telescopes show the maximum fields of about 5 degrees can be achieved with a combination of ring-shaped primary and secondary mirrors. Surprisingly, these primary and secondary elements can have a nearly spherical surface figure, which is easier to achieve than parabolic and hyperbolic aspherical elements: In spherical optical surfaces, all of the sub-elements can be identical and the surface stress is uniform.

In 1994, one of the authors of the present report (John Rather) was Manager, Advanced Concepts Systems Integration at NASA Headquarters. He undertook a scaling study of ultra-large space telescopes that incorporated the most accurate engineering calculations possible. Dietrich Korsch, the late great master of reflective optics who saved the Hubble telescope from its design flaw, headed the theoretical design team. Glenn Zeiders, noted optical engineering physicist, led the effort to develop extremely low weight deployable structures and optics. These studies led to considerable follow-on experimental work and design studies at NASA Marshall Space Flight Center. Figure 11.2 summarizes a point design for a 20 meter diameter wide-field telescope capable of being launched by the Space Shuttle or by Titan IV class rockets. The blue line in Figure 11.3 shows how the additional advantages of MIC combined with PAMELA can engender a second generation of space telescopes beyond the presently struggling James Webb telescope effort.

The key points that make the MIC / PAMELA telescope uniquely advantageous are as follows: (1) Superconducting MIC structures can have both very low specific mass and extremely high rigidity, thus enabling precise large-scale structures; fine adjustments to the structural geometry can be accomplished magnetically. (2) The primary and secondary optics

can be easily deployed to very large aperture diameters; the superconducting elements slowly and gracefully drag the optical elements to their proper places as the current increases. (3) The resulting large-scale optical surfaces do not have to be “perfect” because errors of thousands of wavelengths in the gross optical figure can be corrected with PAMELA adaptive optics at a tertiary point in the optical train; local small-scale zones resolved by the adaptive optics; however, must be of high optical quality. (4) Very light-weight reflective materials such as aluminized kapton or thin silicon wafers can be used for the primary and secondary apertures because they can have adequately precise local optical figure as explained above; though the optical efficiency of the overall system may be as low as 50%, lost photons will be scattered completely out of the optical train while usable photons (i.e., photons scattered through small angles) retain their coherence. Such systems yield a near-diffraction-limited point-spread function at the focus when adaptive wavefront correction is accomplished.

Figure 11.1 Notional concept of huge filled aperture MIC telescope with PAMELA wavefront correction package.

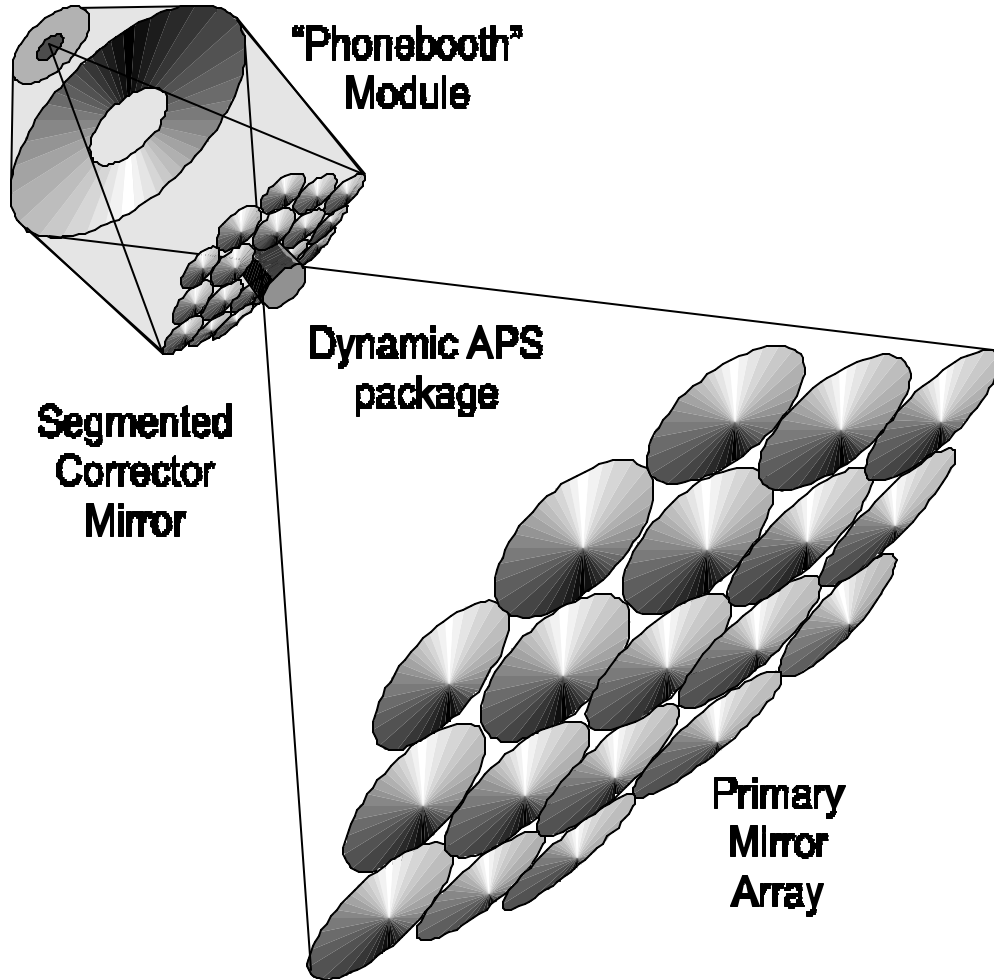


Figure 11.2 This 15 meter wide-field design by Dietrich Korsch is directly scalable to much larger size. The economies of scale resulting from MIC/PAMELA make this design ideal for astronomy and surveillance

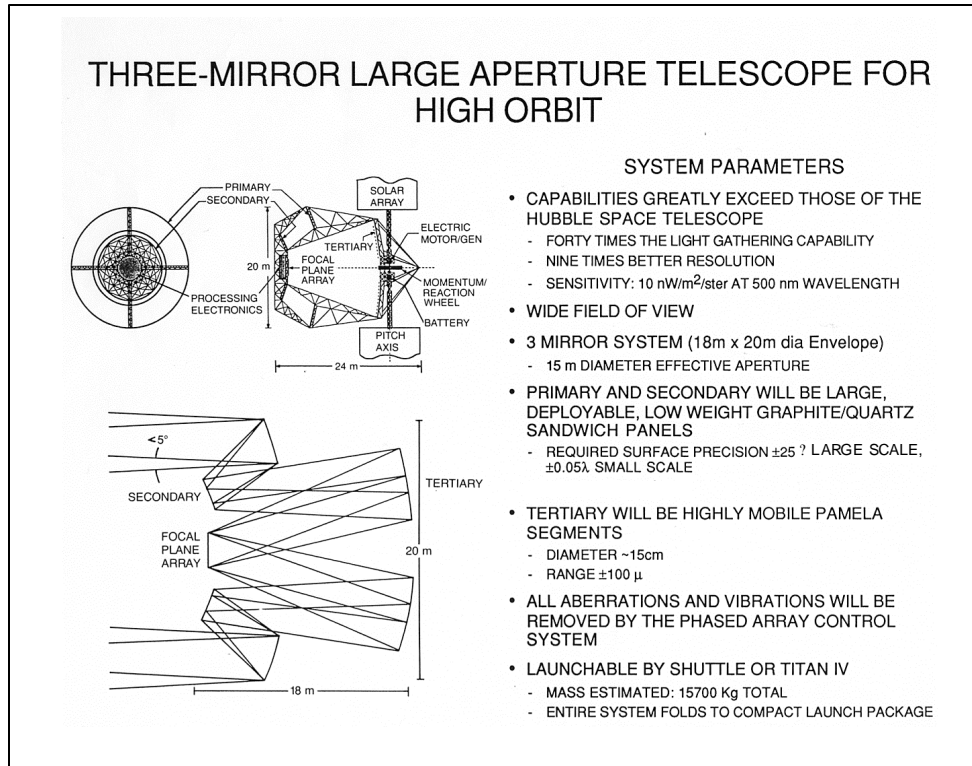
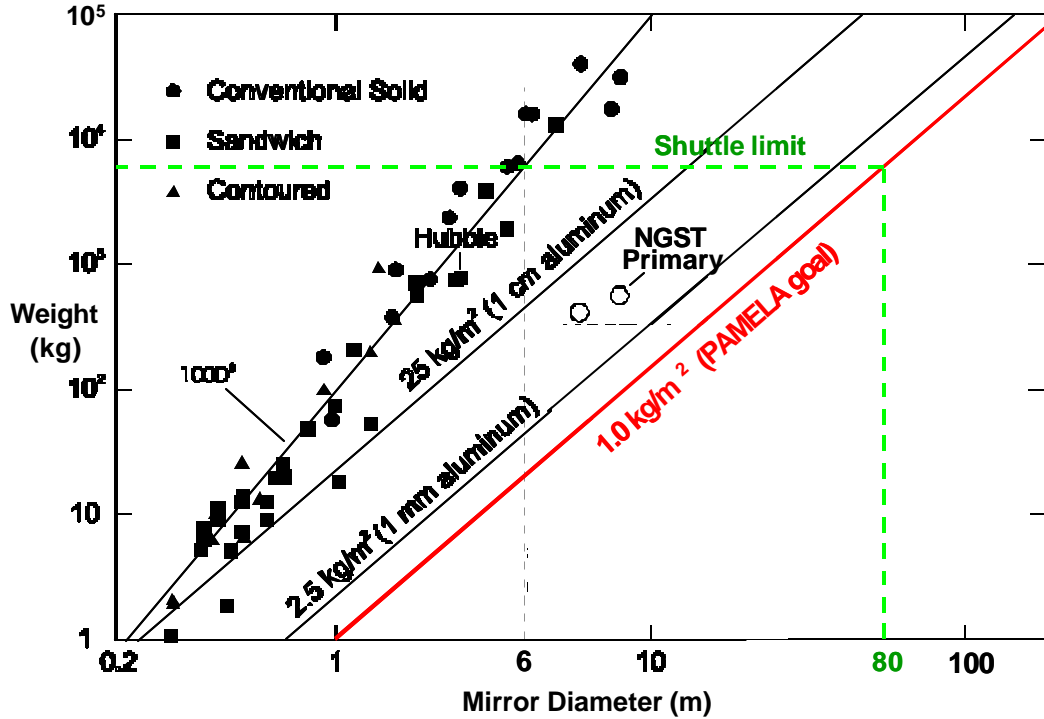


Figure 11.3 Mass scaling of all optical telescopes to date limits space optics to diameters less than 10 meters. The PAMELA principle combined with MIC structural deployment enable 100x increase in size.



Mass scaling of all optical telescopes to date limits space optics to diameters less than 10 meters. The PAMELA principle can achieve apertures ten times larger.

12.0 DEVELOPMENT OF MIC TECHNOLOGY

12.1 High Temperature Superconductor Development and Testing

High Temperature Superconductors (HTS) are now undergoing dramatic improvements in performance and major reductions in cost, a result of incorporating interest in them for applications on Earth. For example, the US Navy is funding the development of large electric motors and generators based on HTS conductors to be used for ship propulsion. Power transmission lines utilizing HTS conductors are being developed. Japan Railways is purchasing large amounts of HTS conductor for use on its high speed Maglev vehicles. These and other applications are spurring the development of conductors with higher engineering current densities.

Present HTS current densities are only a very small fraction of the actual current density of millions of amps per cm^2 of cross section in the superconductor. Imperfections in the interfaces between the individual crystallites of superconductor limit the current that can be transferred across the interface, which in turn limits the overall current capability of the conductor. In addition, the amount of superconductor that can be incorporated into a matrix or deposited as a thin film on a substrate is relatively small, using present manufacturing techniques.

As a result of these factors, the engineering current density, which is the actual current carried by a superconductor divided by its actual cross section, which includes in addition to the superconductor, the material in which it is incorporated or deposited on, is typically a few percent of the true current density in the perfect superconductor. The engineering current density is continually being raised, through improvements in the manufacturing process. The fraction of superconductor in the overall conductor is being increased through the use of thicker and multiple films in film deposited type conductors, and larger amounts in matrix type conductors. In addition, better deposition and texturing methods are reducing imperfections in the crystallite interfaces. Within the next few years, it appears likely that the engineering current densities of YBCO and MgB_2 HTS conductors will be well over 100,000 amps per cm^2 . The MgB_2 conductor is particularly promising, because MgB_2 has a 3 dimensional superconductor structure, compared to the 2 dimensional layer structure of YBCO making the transfer of current across interfaces easier.

These on-going improvements in HTS conductor performance will take place without funding or input from a MIC program. Assuming that a MIC development program is funded, it will only need to keep abreast of the on-going developments in HTS conductors.

The principal tasks of a MIC development program will be to develop and demonstrate a practical MIC cable, and to develop and demonstrate the deployment and erection of practical MIC structures based on the MIC cable. These tasks are interdependent to a considerable degree, since the design of the MIC cable will depend on the structural application, and the design of the MIC structure will depend on the performance capabilities of the MIC cable.

These 2 tasks are described in the following section.

12.2 Testing and Validation of MIC Structures

Figure 12.1 illustrates a possible route for the development and implementation of MIC structures, using a phased approach. In Phase 1, phototype MIC structures would be fabricated and tested on Earth, using available large vacuum chambers. The prototype MIC structures would be smaller than those that would be deployed in space, but the tests would demonstrate that the MIC concept was practical.

As an example, a 1/10th scale MIC solar concentrator could be erected in the vacuum chamber, using an ~7 meter diameter MIC dish. The MIC concentrator could demonstrate the ability to focus light onto a solar cell array or a simulated propellant, heater, at the desired concentration factor.

The test would confirm the ability of a compacted package of MIC cables and tethers when electrically energized to automatically deploy into the final MIC structure and to operate for long periods in the deployed state using a refrigeration system to maintain cryogenic conditions in the MIC cables. The ability to maintain operation even when one or more of the multiple individual conductors in the MIC cable were made to fail could also be demonstrated.

The ability to deploy and operate even in the 1 g gravity field of the Earth would also be important, since it would demonstrate that the MIC structure was able to operate under gravitational conditions that far exceed the microgravity conditions that would be experienced in space, or the reduced gravity conditions that exist on the Moon.

The MIC cable current needed to test MIC prototype structures be substantially smaller than the current required for a full scale structure. The magnetic forces per meter of length on the MIC cables scale as I^2/D where I is the cable current and D is the appropriate dimension of the structure. For a 1/10th scale demonstration, the MIC cable current could be reduced by a factor of 3, and still have approximately equal magnetic forces per meter of cable length.

Accordingly, the prototype demonstration will only require about 50 to 100,000 amps of current in the cables with the precise amount depending on the particular application to be demonstrated.

However, in addition, demonstrating the deployment and operation of a sub-scale MIC prototype, Phase 1 should also develop and demonstrate the performance of MIC cables that would be suitable for a full scale MIC system in space. Depending results from the detailed studies of MIC applications that would also be carried out in Phase 1, the current in the full size MIC cable would probably be in the range of 250 to 500,000 amps. The tests of this full size cable would include measurements of the thermal leakage into the cable under various simulated illumination conditions (e.g., full sunlight on one side of the cable, in space with no sunlight, thermal radiation from the surface of the Moon, etc.); the amounts and effects of flux pumps in

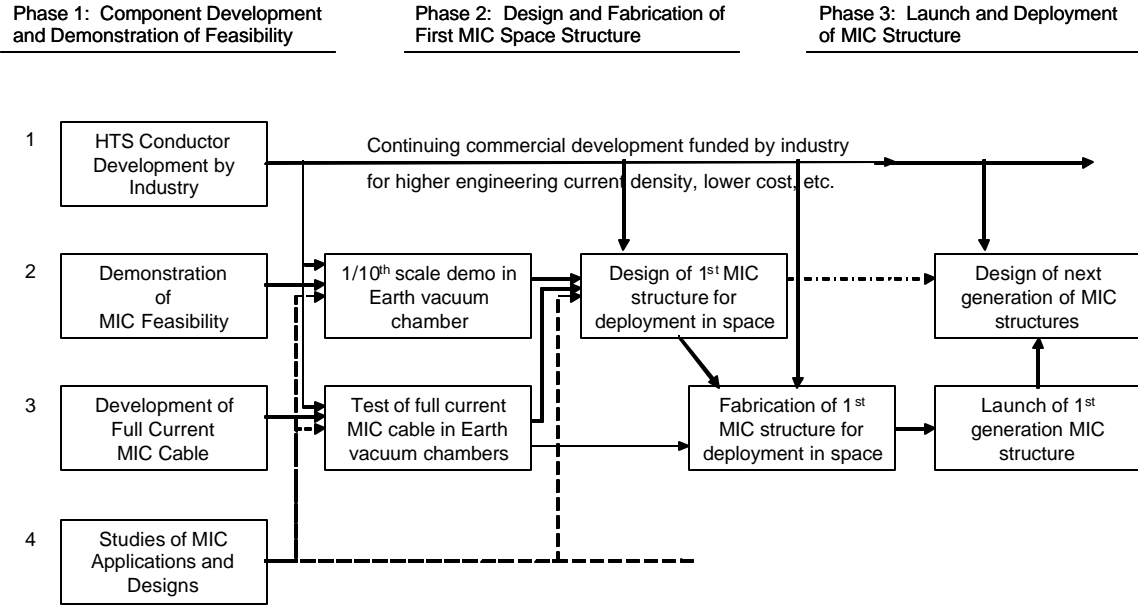
the superconductor; the effectiveness of persistent current switches; the ability to transfer current by magnetic induction of one of the individual conductors were to fail; the effects of simulated micrometeor impact on the protective armor around the superconductor, and so on.

To simulate conditions in space, the full scale MIC cable could be tested in a large vacuum chamber on Earth with its thermal insulating layer exposed to vacuum conditions. This method of testing would eliminate the need to enclose the MIC cable inside a pipe to keep out the ambient atmosphere, and would be a truer test of cable performance. Coiling several turns of the MIC cable inside the vacuum chamber would enable long lengths, e.g., on the order of 100 meters, to be tested.

The Phase 1 prototype demonstrations of MIC structures, plus the development and testing of full scale MIC cables, plus the detailed studies of potential applications that would also be carried out would enable the MIC program to proceed to Phase 2 (Figure 12.1), in which a large MIC structure would be fabricated and launched into space. This first structure would probably be either a solar electric system for space power, or a large space telescope. Following its successful operation, additional MIC applications and structures could be implemented in Phase 3.

Phase 1 would take approximately 4 years to complete. The beginning of Phase 2 would overlap the final year of Phase 1, and take about 4 more years beyond the end of Phase 1 to implement a MIC structure in space. Assuming the MIC development program started in 2007, Phase 3 could then begin about 2015 AD, with MIC solar electric, solar thermal propulsion, and energy storage systems to be used for a manned lunar base.

Figure 12.2.1 Development Program for MIC Structures



13.0 SUMMARY AND CONCLUSIONS

A number of important conclusions can be drawn from this study.

1. The Magnetically Inflated Cable concept (MIC) offers an attractive new approach for the construction of large, lightweight very strong and rigid structures in space.

2. Previous approaches for the construction of large structures in space have been based on mechanical systems that either require human or robotic assembly operations, or that depend on inflatable structures. Structures using the latter approach have limited rigidity and strength, and potentially could lose pressurization through leaks.

3. The very strong outwards magnetic forces in the MIC superconducting cables are restrained by a network of high strength, lightweight tension tethers made of Kevlar, Spectra, or similar material, producing a very strong and rigid structure that can support a mirror surface, propellant tank, or other secondary structure.

4. MIC structures can be launched as compact packaged payloads on conventional launch vehicles. Once in space, they are energized with electrical current, causing them to automatically deploy into the final large MIC structure.

5. MIC can be used for a wide range of applications including multi-megawatt solar electric power, solar thermal propulsion using high temperature H_2 propellant to achieve I_{sp} of 900 seconds, large space telescopes for detecting and investigating extra terrestrial planets around distant stars, storage of large amounts of electrical energy, magnetic shielding of astronauts from cosmic rays, and many other applications. The size of MIC structures can range from 10's of meters to a kilometer or more, depending on applications.

6. The diameters of the superconducting MIC cable are very small, on the order of a few centimeters. MIC cables can carry 100's of thousands of amps of current with zero I^2R losses. The MIC cable can be designed with multiple independent individual conductors, so that if some fail their current will transfer by magnetic induction to neighboring conductors, allowing total cable current to remain essentially constant. The MIC superconducting cable can be armored to protect it from the micrometeors and space debris.

7. MIC cables would use one of the three High Temperature Superconductors (HTS) now in production. Of the 3 options, YBCO and MgB_2 conductors appear the most promising. Optimum operating temperatures are in the range of 15 to 40 K, depending on the type of superconductor and magnetic field strength. Present engineering current densities for the conductors (superconductor plus support material) are on the order of 50,000 amps/cm². Improvements in manufacturing methods are expected to increase engineering current densities to 100,000 amps/cm² or more.

8. The refrigeration requirements for MIC cables are low using HTS conductors and the existing, well developed multi-layer thermal insulation technology. A MIC cable that was 1 kilometer in length and carried several hundred thousand amps would require only a few kilowatts of electric power input to its cryocooler refrigeration system to maintain cryogenic conditions.

9. MIC systems appear very attractive for a manned lunar base. The MIC solar electric system could generate megawatts of electric power for the base. The MIC solar thermal propulsion system could provide high Isp propulsion to deliver heavy payloads to the Moon, along with personnel, and could bring back material from the Moon, along with returning personnel. A MIC energy storage system could provide gigajoules of stored electric energy that could meet peak power needs, and a large MIC space telescope could survey large portions of the sky from the manned base.

10. The deployment of 1/10th scale prototype MIC structures could be operationally demonstrated in large vacuum chambers on Earth during Phase 1 of the MIC development program. Full scale, long MIC cables that could carry 100's of thousands of amps could also be tested in Earth vacuum chambers,. Once demonstrated, in Phase 2 of the program, a full scale MIC structure could be fabricated and launched into space for testing and use. Phase 1 would take approximately 4 years, with Phase 2 continuing for an additional 4 years after the completion of Phase 1.

11. There appears to be no technology breakthroughs required for development of MIC systems. The necessary HTS superconductors, cryogenic insulation, and refrigeration systems are already in commercial use. Engineering development of the MIC cables and tethers network is required, but the development efforts appear to be straightforward with no “show-stopper” issues.

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