Columbus is a design for a mission to Mars that uses solar-electric propulsion that avoids the major problems. The key feature is that the solar array needed for the interplanetary leg is divided into three parts for the Earth spiral. The three parts carry unmanned cargo to the high-Earth-orbit rendezvous point. The three cargo packages are not equal in mass. The package launched first is heaviest and thus requires the longest time to travel to the rendezvous point, and the package launched last requires the shortest time for the spiral. When the three packages arrive at the rendezvous point, the human crew arrives in a small vehicle with chemical propulsion.

Figure 1 shows the assembled Columbus vehicle, with the three large solar array parts joined, looking at the planform from the illuminated side. Each array has a thruster package, shown as a square above the array. A major structural keel is shown running from the point where the arrays join and passing under the thruster to the outer edge of each array. Figure 2 shows the side view of one part, where the crew module is visible. The truss carrying the solar array is the long horizontal linear framework. Both the top and bottom thruster packages are visible on booms above and below the solar array. The crew modules are located near the point where the three solar arrays attach, and tunnels provide access among them during the flight.

The time line for the mission is shown in Fig. 3. The first package (Pinta) is assembled from five launches of a heavy-lift vehicle and then starts to spiral from Earth. The second package (Nina) is assembled from the next three launches. The final package (Santa Maria) requires only two launches. After the crew joins the Columbus at the rendezvous point, the Mars leg starts.

The Columbus design provides for a crew of six to travel to Mars on a 1000-day conjunction-class mission. The total mass that would depart from low-Earth orbit was found to be $536 \times 10^3$ kg. Dividing the solar array into three parts appears to have several advantages. The requirements of the node are minimized. The problems caused by the Earth spiral time are reduced.

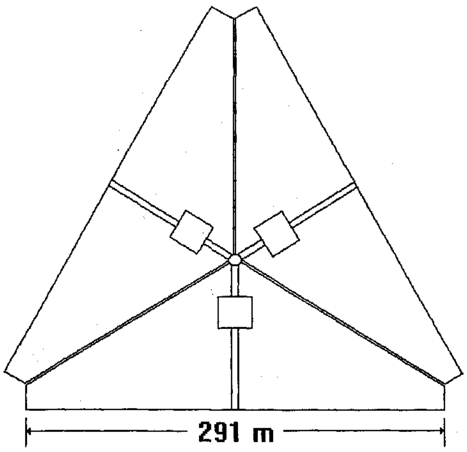


Fig. 1 Top view of Columbus.

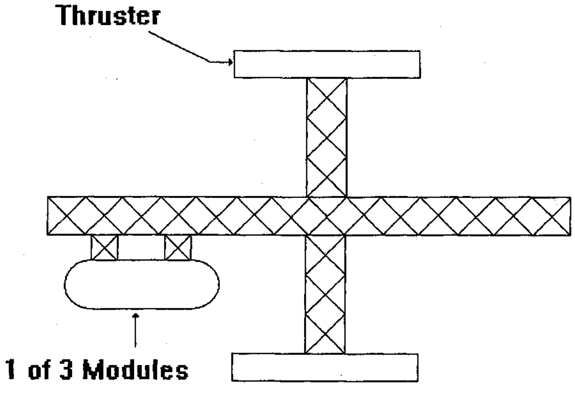


Fig. 2 Side view of one part of Columbus.

| MILESTONE ITEMS | 2019 | 2020 |
|---|---|---|
| PINTA CONSTRUCTION | V____V | |
| LAUNCHES 1 TO 5 | VVVVV | |
| PINTO TO HIGH EARTH ORBIT | V____V | |
| NINA CONSTRUCTION | V__V | |
| LAUNCHES 6 TO 8 | VVV | |
| NINA TO HIGH EARTH ORBIT | V____ | V |
| SANTA MARIA CONSTRUCTION | V__ | V |
| LAUNCHES 9 TO 10 | V V | |
| SANTA MARIA TO HIGH EARTH ORBIT | | V__V |
| CREW AT SPACE STATION | | V_V |
| CREW TO HIGH EARTH ORBIT | | V |
| HELIOCENTRIC LEG TO MARS | | V____ |

Fig. 3 Timeline for the Columbus mission.

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# Deployed High-Temperature Superconducting Coil Magnetic Shield

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## Introduction

IN any manned space mission that lasts for an extended period of time and involves travel beyond the magnetosphere, the danger posed by radiation becomes of tantamount importance.[1,2] Radiation shielding must be considered for a permanently manned lunar base or a manned expedition to Mars. The radiation hazard that will be encountered during

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missions is in three distinct forms: 1) Van Allen belt radiation, 2) galactic cosmic rays, and 3) solar flare radiation.[1-5] Van Allen belt radiation consists of charged particles, especially He nuclei, protons, and electrons that have been ejected by the sun and entrapped within the Earth's magnetic field.[5] Shielding from this type of radiation is currently not needed since suitable trajectory shaping reduces the level of radiation received from passing through the Van Allen belt to the level of 5 rems per two trips.[2] This is approximately the level of radiation received from many medical x-ray procedures. Galactic cosmic rays are the most difficult type of radiation to shield against due to their extremely high energies, typically $1.0 \times 10^9$ eV or higher. Fortunately, the overall level of the radiation is moderate, approximately 12 rems per year.[2] The extreme energy of cosmic rays, which consists primarily of charged particles such as Fe nuclei,[6] produces significant amounts of spallation radiation in the shielding material, unless enormous mass shields are used.[7] The third and final form of hazardous radiation is that produced from solar flares and prominences. This kind of radiation consists of mostly He nuclei and protons.[4] The sun emits large amounts of these types of particles every few weeks in the form of flares, whose resulting radiation can exceed 100 rems in major events. Some form of radiation shielding must be provided in any mission that extends beyond the magnetosphere inasmuch as a dose of 500 rems produces 50% mortality.[6]

## Shielding Strategies

The types of radiation shielding that have been proposed fall into two broad areas: passive and active. Passive shields refer to using mass alone to absorb radiation. The simplest approach is to use storm shelters on the mission platform.[6,7] Personnel would be required to safe all active systems and then retire to a storm shelter to ride out the flare "storm." The second option is to provide shielding surrounding the entire crew habitat. Calculations by Townsend et al.[8] determined that to achieve a safe level of solar flare protection a thickness of aluminum shielding of 9–11 cm to stop the most penetrating of solar flare events is required. Based on the density of the aluminum (2.699 g/cm$^3$) and the surface area of the proposed habitats on a Mars mission vehicle,[6,9,10] the weight of shielding required for complete habitat protection is on the order of $1.0 \times 10^5$ kg (Ref. 11). This mass approach to whole habitat radiation shielding is thus an extremely heavy one to implement.

Active shields are of two types: electrostatic and magnetostatic. The electrostatic shield involves the generation of an electric field of sufficient strength to repel incident charged particles. This approach, studied by Vogler[12] and Kash,[4] suffers from system complexity as well as heavy masses stemming from the required supporting structures, to say nothing of the extremely high voltages involved. The magnetostatic shielding strategy operates by deflecting charged particles using a magnetic field in the same way as does the Earth's magnetosphere.[1,2,4] Superconducting coils are required to generate the magnetic field because of the very high currents involved. Before the advent of the high transition temperature superconductors, these superconducting coils needed to be housed within the hull of the spacecraft since helium refrigeration units were required to cool the coils. Because superconductor transition temperatures have risen above 77 K, the cooling requirements are not as stringent and allow the superconducting coils to be deployed beyond the spacecraft hull. Outboard deployment of the superconducting coils permits much larger coils that result in huge power and mass savings compared to earlier inboard designs.[3]

Störmer[13] determined that a measure of the radially shielded area around a magnetic flux line is given by

$$C_{st} = \sqrt{\frac{q\mu_0 M}{4\pi P}} \quad (1)$$

where $q$ is the particle's electrical charge, $\mu_0$ the permeability of free space, $M$ the magnetic moment required to shield the Störmer radius $C_{st}$, and $P$ the particle momentum. Other calculations have shown that, in general, only 40% of $C_{st}$ is completely protected.[14] Selecting $C_{st}$ to be 25 m, which gives a completely shielded radius of 10 m, and a proton momentum based on an energy of 500 MeV,[2,3] Eq. (1) can be solved for $M$, which yields a required magnetic moment of $2.78 \times 10^{10}$ A-turns · m$^2$ (Ref. 3). The magnetic moment can then be used to determine the current needed to raise the magnetic shield based on the relation[3]

$$M = NIA \quad (2)$$

where $N$ is the number of coil turns, $I$ the operating current, and $A$ the area enclosed by the coil. Assuming one coil turn and an enclosed coil area of 314.16 m$^2$, based on a coil radius of 10 m, which is 40% of the 25-m Störmer radius, the operating current for a shipboard coil is $8.8 \times 10^7$ A. By deploying the superconducting coils beyond the hull of the craft in a $1.0 \times 10^6$ m$^2$ area coil, the operating current is reduced to $2.78 \times 10^4$ A (Ref. 3). Since the stored energy in the coil varies with the square of the current, it is apparent that huge energy savings can be realized. Impressive mass savings are also obtained, and by using a superconducting material having a critical current of $1.0 \times 10^5$ A/cm$^2$, even allowing for a coil containment structure to provide the supplementary cooling, the overall system weight can be as low as approximately 4000 kg to protect a cross-sectional area of 314.16 m$^2$ (Ref. 3). This offers two orders of magnitude improvement over passive shielding systems.

One of the primary subsystems of this design is the superconducting circuits that must carry the electrical current to generate the shielding magnetic field. Such circuits must possess the highest critical current density possible to reduce the shielding mass, have a transition temperature above 80 K, and be flexible enough to allow the deployment and stowage of the coil without damage. Such superconducting circuits would also find use in the design of a magnetic sail propulsion system that is currently being considered for interplanetary travel and interstellar travel.[15-17]

## Results

Flexible thin superconducting films may be produced by deposition of the superconducting material onto a flexible substrate. The substrate can then be affixed to the containment structure that could be produced from metallized Mylar, as was the case with the Echo I satellite.[18] The substrate used in this study was gold foil that had an area density of $6.8 \times 10^{-3}$ g/cm$^2$. Gold, studied by Cieplak et al.[19] and Chien et al.,[20] is one of the few elements that, when incorporated into the superconducting lattice, does not substantially degrade superconductivity. In fact, gold may substitute up to 10 at.% into the lattice. Further substitution results in gold being precipitated within the lattice, which improves the mechanical properties of the film.

Because of this fact, it appears possible to produce flexible superconducting thin films possessing some ability to bend by depositing these films onto gold foil, carrying out the appropriate sinter and oxygenation heat treatments with the film in situ on this foil, and then bonding the gold foil to a Mylar backing for strength. In the present case, the superconducting medium consisted of an alcohol-based vehicle, a polymer binder, and $YBa_2Cu_3O_{7-x}$ superconducting powder. This paint was tape cast[21,22] onto gold foil, dried, and sintered in a furnace for 8 h at 1223 K followed by an anneal at 773 K for 10 h in an atmosphere of flowing oxygen. The anneal schedule was based on that used by Johnson and Grader.[21] These films exhibited a transition temperature of 100 K with a zero resistance temperature of 90 K. The best critical current density achieved, however, was only 61 A/cm$^2$, which is about three orders of magnitude lower than the original design current density. The flexibility of the film, however, was such that it could be bent into a radius of curvature of 2 cm before spallation occurred. The spallation/bending stress of the film was found to be 52.5 MPa from the equation[23]

$$\sigma_m = Eh/2r \tag{3}$$

where the modulus of elasticity $E$ is 150 MPa, the film thickness $h$ is 14 $\mu$m, and the radius of curvature $r$ is 2 cm. The result agrees well with the value reported by Crabtree et al.[24] for the material $La_{1.85}Sr_{0.15}CuO_4$. In a similar investigation, Singh et al.[22] were able to produce tape-cast superconducting films on flexible silver substrates with a current density of 300 A/cm$^2$. A much higher critical current density, $2.8 \times 10^5$ A/cm$^2$, was measured in this study using a film produced by off-axis rf sputtering of $YBa_2Cu_3O_{7-x}$ onto a rigid substrate of yttria stabilized zirconia (YSZ). Here, the substrate resulted in epitaxial growth of the deposited film and reduces the Josephson effect that was encountered in the tape-cast film on the gold substrate. The advantage of using a metallic substrate is the increased flexibility of the film along with a current path to carry momentarily the current in the event of failure in superconductivity, whereas the disadvantage is the lack of significant epitaxy to increase the critical current density.

## Concluding Remarks

The overall deployed high-temperature superconducting coil design concept allows for two orders of magnitude savings in mass over the whole-habitat mass shielding protection strategy. It is apparent, however, that to produce actual, practical shields, thin superconducting films having good flexibility and high critical current densities still remain to be developed. Such films could possibly be produced using ultrathin YSZ substrates together with mechanically bonded metal foils on the surface of the epitaxial superconducting film to supply alternate conduction paths.

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