

***THERMAL, RADIATION AND IMPACT PROTECTIVE SHIELDS (TRIPS) FOR ROBOTIC AND HUMAN SPACE EXPLORATION MISSIONS**

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ABSTRACT

New concepts for protective shields for NASA's Crew Exploration Vehicles (CEVs) and planetary probes offer improved mission safety and affordability. Hazards include radiation from cosmic rays and solar particle events, hypervelocity impacts from orbital debris/micrometeorites, and the extreme heating environment experienced during entry into planetary atmospheres. The traditional approach for the design of protection systems for these hazards has been to create single-function shields, i.e. ablative and blanket-based heat shields for thermal protection systems (TPS), polymer or other low-molecular-weight materials for radiation shields, and multilayer, Whipple-type shields for protection from hypervelocity impacts. This paper introduces an approach for the development of a single, multifunctional protective shield, employing nanotechnology-based materials, to serve simultaneously as a TPS, an impact shield and as the first line of defense against radiation. The approach is first to choose low molecular weight ablative TPS materials, (existing and planned for development) and add functionalized carbon nanotubes. Together they provide both thermal and radiation (TR) shielding. Next, impact protection (IP) is furnished through a tough skin, consisting of hard, ceramic outer layers (to fracture the impactor) and sublayers of tough, nanostructured fabrics to contain the debris cloud from the impactor before it can penetrate the spacecraft's interior.

1. INTRODUCTION

NASA's new vision for Space Exploration calls for a sustained and affordable robotic and human program for the exploration of space beyond low Earth orbit. The human and robotic vehicles involved in these missions must survive long-duration exposure to radiation from Solar Particle Events (SPE), Galactic Cosmic Rays (GCR) and micrometeorites. In many instances, the vehicles - planetary entry probes, sample return capsules and NASA's new Crew Exploration Vehicle (CEV) - must also survive very harsh aerothermal heating during hypervelocity, atmospheric maneuvers.

High launch costs continue to motivate significant weight reduction for such vehicles, driving a need for multi-functional materials that perform structural roles, while providing shielding against these harsh space environments.

A new generation of strong, lightweight materials, able to fill this need, is emerging from the developing field of nanotechnology. The fabrication approach to these materials is from the bottom up, so materials of the future can be designed for multiple functions when the material properties for one function are suitable for another. For example, materials comprised of elements with low atomic weight, such as hydrogen and carbon, make good radiation shields because less secondary radiation is produced in collisions with high-speed cosmic rays and solar particles. It also happens that carbonaceous materials filled with low-molecular-weight pyrolyzing materials such as carbon phenolic make good ablative heat shields for missions involving high aeroconvective entry heating. In regions of lower heat flux, flexible blankets filled with fibrous insulating materials are used for thermal protection. Similarly, Whipple-type shields, (for protection from hypervelocity impact) have inner layers of tough, fibrous materials to slow down and contain shield penetrants. Clearly, many of these shielding materials have common elemental constituents and similar associated properties, allowing the possibility for one material to perform several functions.

Carbon nanotubes (CNTs) have many properties that make them ideal candidates as the basic building block for multifunctional materials. Their high strength, toughness and low weight make them ideal materials as fibers for impact shields. Their low molecular weight, ability to be functionalized with hydrogen, and ability to form lightweight composites with materials such as polyethylene, make them ideal for use as radiation shields. Their low thermal conductivity in directions normal to the fiber, and high temperature stability when protected from oxidizing environments, make them apt for both ablative and blanket-based heat shields. The high axial thermal conductivity of CNTs allows their use as passive heat pipes to transport heat

from hot spots on thermal shields to cooler areas, resulting in lighter, thinner heat shields.

Here, we discuss our approach to conduct research to integrate, redesign and re-engineer heat shields, radiation shields, and impact shields, using nanotechnology-based multifunctional materials. The goal is to develop a single shield with significant weight savings, increased functionality and improved safety and affordability for NASA's next-generation space exploration vehicles.

2. 0 FUTURE MISSIONS BENEFITING FROM TRIPS

2.1 Robotic Missions

The NRC New Frontiers Decadal Report [1] envisions missions to the outer planets with multiple atmospheric probes. The new Jupiter Icy Moons Orbiter (JIMO) mission plan [2] involves very long (8-10 years) interplanetary transit voyages to these regions of the solar system. The use of this transportation system for the deployment of atmospheric probes is being discussed. These long duration flights will result in large Total Integrated Doses (TID) of radiation, and involve a greater risk of micrometeorite strikes, providing a technology "pull" for TRIPS technology for robotic missions. TRIPS will enhance more conventional missions and shorter duration robotic missions involving atmospheric entry (Mars, Venus and sample return{s}). The outer ceramic micrometeorite shield on TRIPS would help prevent heat shield erosion in the event of a robotic probe having to enter the Mars atmosphere during a dust storm.

2.2. Human Lunar Missions

Mature concepts of the CEV to be employed on the planned new Lunar missions are not available. However, it is clear that the transit times to/from the moon are short (3 days) and that the re-entry environment will be similar to Apollo (11 Km/sec entry speed and peak heating rates near 400 W/cm^2), if the geometry and mass are similar to that for the Apollo Earth Return Vehicle (Apollo Command Module). Peak entry heating for Apollo was ten times that on the Space Shuttle wing leading edge, therefore ablative heat shield systems/materials (Apollo used an ablator called AVCOAT 5026, which is no longer available) will be required, and entry heating is a serious hazard. Integrated radiation fluxes for normal sun activity are small during the short transit times, but strong solar flares could occur, and it is desirable that the transit vehicle offer protection from them. Micrometeorite/Orbital Debris (MMOD) impacts are possible for Lunar mis-

sions. The longer the CEV stays in Lunar orbit or on the Moon, the greater the risk of a micrometeorite strike, and TRIPS would therefore reduce risk of loss of vehicle and crew and be mass efficient for human Lunar Missions.

2.3 Human Mars Missions

During the 1990's, the Johnson Space Center led NASA's development of detailed Reference Missions for the Human Exploration of Mars [3,4]. These studies clearly showed that mass lifted into low Earth Orbit (LEO) is the principal metric to be minimized for affordable Human Mars Exploration Missions. Aerocapture, and subsequent out-of-orbit descent to the surface of Mars was identified as a "winner" for mass reduction, regardless of the propulsion system used (chemical, nuclear or solar-electric) for trans Earth to Mars trajectory insertion, and the vehicles that perform these maneuvers require protective shields. These studies pioneered the notion of multifunctional structures as a mass-saving tool. For example, the Earth surface to Low Earth Orbit (LEO) launch shroud, containing the Mars exploration systems, doubled as the Mars aerocapture/descent vehicle aeroshell. Clearly, additional mass reduction in the aerocapture/descent systems could be achieved through a single system providing protection against multiple threats, but these benefits have not yet been quantified by systems analysis. In this case, the outer ceramic micrometeorite shield on TRIPS would help prevent heat shield erosion in the event of a crewed aerocapture/descent vehicle having to maneuver in the Mars atmosphere during a dust storm.

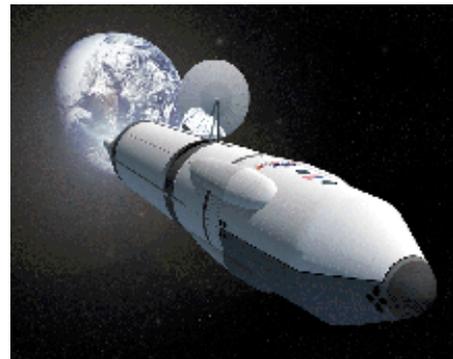


Fig. 1. Nuclear Thermal Rocket/Mars Aerocapture Vehicle leaving Low Earth Orbit. The Apollo shaped cap on the front served as the Earth Return Vehicle in the mission study [3,4].

3.0 THERMAL PROTECTION SYSTEMS HERITAGE AND DEVELOPMENT

NASA Ames has a 40 + year heritage in developing tools to predict aeroconvective heating environments for entry vehicles and Thermal Protection Systems (TPS) to allow safe entry, descent and landing. This heritage stretches back to Apollo, and leaders in the vehicle's heat shield development are still active at Ames. Ames played a central role in the development of the tile and blanket TPS employed on the Space Shuttle and the carbon phenolic ablative heat shield for the Galileo entry probe.

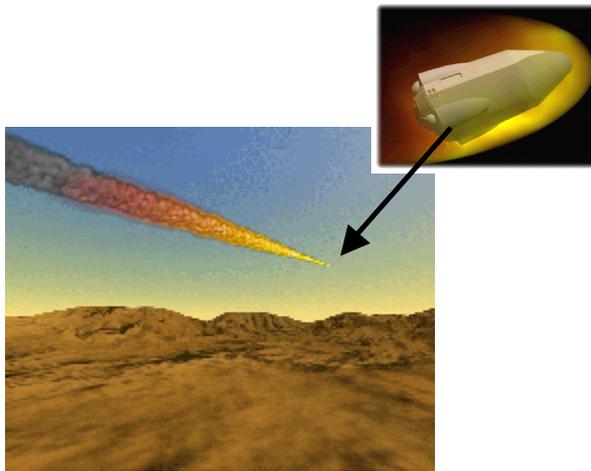


Fig. 2. Aerocapture maneuver where aerodynamic deceleration mass-effectively replaces the need for retro-rockets for insertion into Mars orbit. Aerocapture speeds at Mars range from 7 - 8.5 km/sec and the braking would occur over a ground track covering about 1/3 of the circumference of the Red planet. The aerocapture vehicle was sized to be 28 meters long.

More recently, new ablative materials developed at Ames have been adopted by Agency missions: Silicon Impregnated Ceramic Reusable Ablator (SIRCA) was flown on the afterbody of the entry vehicles for both the Mars Pathfinder Mission and, most recently, the MER missions. SIRCA was sized for the Human Mars Aerocapture vehicle [3,4] and considered to be a viable candidate, as was the commonly used ablator SLA 561-V, developed by Lockheed-Martin Astronautics. Another ablator developed at Ames, Phenolic Impregnated Carbon Ablator (PICA), is suitable for very high heat fluxes (up to about 1,200 W/cm²). This very lightweight ablator enabled the Stardust Discovery Mission and will protect the Earth Return Capsule during its 12.7 Km/sec re-entry in January, 2006.

New, mid-density ablative heat shield materials, appropriate for use on crewed Moon and Mars missions,

need to be developed, and our work on TRIPS will be associated with such an effort. At present, it appears that a new mid-density material will have its roots in PICA and the fully-dense carbon phenolic heritage.

4.0 TRIPS TECHNOLOGY DEVELOPMENT APPROACH

The concept being proposed here (Fig. 3) is to undertake a steady, evolutionary technology development approach, with the long term goal of developing nano-based materials for use in aerocapture and entry vehicles employed in robotic and human exploration missions. The materials would constitute a *single-shield* system, capable of simultaneous protection against aerodynamic atmospheric heating, solar and cosmic radiation and micrometeorite/orbital debris strikes.

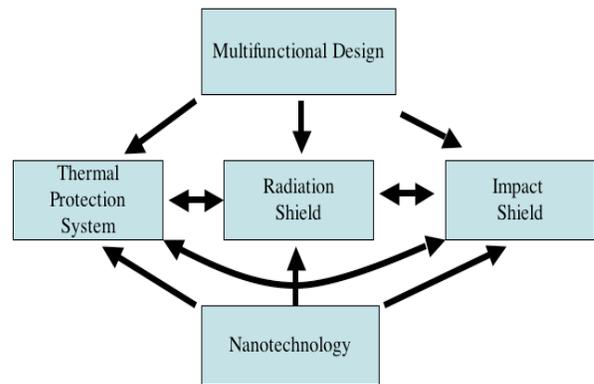


Fig. 3. Key concept of the Thermal, Radiation, Impact Protective Shield (TRIPS) development approach.

In the following sections, we discuss how nano-based materials can be employed independently in shields against the aforementioned hazards, and then discuss the commonality of the materials and concepts for a single shield protecting against multiple hazards.

4.1 Concept: Nanotechnology-Based Shield for Solar Particles and Cosmic Rays

Lightweight materials such as hydrogen, lithium and boron make better radiation shields than those made of high atomic weight systems, since less secondary radiation is produced during the collision process with high-speed cosmic rays and solar particles. This is in contrast to X-rays and gamma rays, which are better shielded by heavy materials.

While not as effective as hydrogen, carbon is also an effective radiation shield. Carbon chain polymers such as polyethylene or polystyrene contain a significant fraction of hydrogen and are often used in radiation

shielding. For baseline NASA radiation shielding comparisons, polyethylene is the standard material.

Polymer-carbon nanotube composites have the potential to improve radiation shielding performance if the nanotubes can be functionalized, or filled with significant amounts of hydrogen, lithium or boron. Given the high strength of carbon nanotubes, these properties may enable a multifunctional material with high strength and high radiation shielding capability to be fabricated.

4.2 Approaches for attaching lightweight atomic species in carbon nanotubes and making fibers

Many approaches have been developed recently to functionalize and or fill carbon nanotubes with a variety of materials. Perhaps the largest interest comes from the fuel cell industry, where there is potential for a huge market for reversible hydrogen storage. These techniques are based either on the use of high pressure, electrochemical methods, or filling by capillary action as the nanotube is formed. The results have been somewhat disappointing, especially in terms of hydrogen storage, where early claims of large storage capability were later refuted.

Bauschlicher [5] has used rigorous methods of computational nanotechnology to understand the bonding of hydrogen to carbon nanotubes and Fig. 4 was provided by him. Jaffe [6] has estimated the maximum atomic hydrogenation of carbon nanotubes and storage of H_2 within them would lead to a maximum mass fraction of hydrogen at about 10 percent. We would seek to reach this limit for radiation shielding, provided that other properties of interest for the nanostructured TRIPS material such tensile strength or thermal conductivity were not inappropriately compromised by carbon-carbon bond stretching by the hydrogenation.

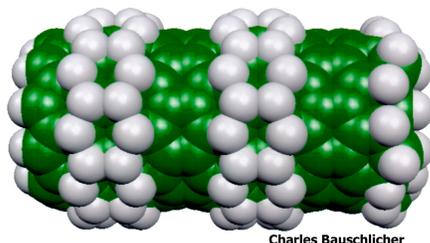


Fig.4. Hydrogenated carbon nanotube

A proposal [7] by our colleagues at NASA Goddard to fill carbon nanotubes with $LiBH_4$ shows significant promise.

Another method of functionalization is ion implantation. This is a technique common in the electronics

industry, but has not received as much attention as the other methods for filling nanotubes, since the technique is not reversible. For NASA applications in radiation shielding, reversibility is not an issue, since the desire is to have the hydrogen a permanent part of the material. Furthermore, the method is compatible with either pre- or post-processing of carbon nanotube polymer composites. This may be advantageous, because many groups (such as the U.S. Army Research Labs) are working on the development of high strength carbon nanotube polymer composites for other applications such as bulletproof vests. Post-processing the best composites developed within or outside of NASA using hydrogen ion implantation may be an efficient use of resources.

In the ion implantation technique, ions are implanted directly into the composite with the energy selected for penetration through the film thickness. For a given energy, the distribution of the ions in the material is roughly Gaussian. Varying the energy can provide a more uniform distribution. Minimal damage to the composite during implantation will result if the film or fiber is relatively thin, enabling the use of low ion energy beams which will not break the carbon-carbon bonds and still penetrate through the proper depth. Once implanted, the hydrogen may functionalize or form covalent bonds with the interior or exterior of the nanotube, as well as form molecular hydrogen, inside the tubes or in the interstices, as shown in Fig. 5.

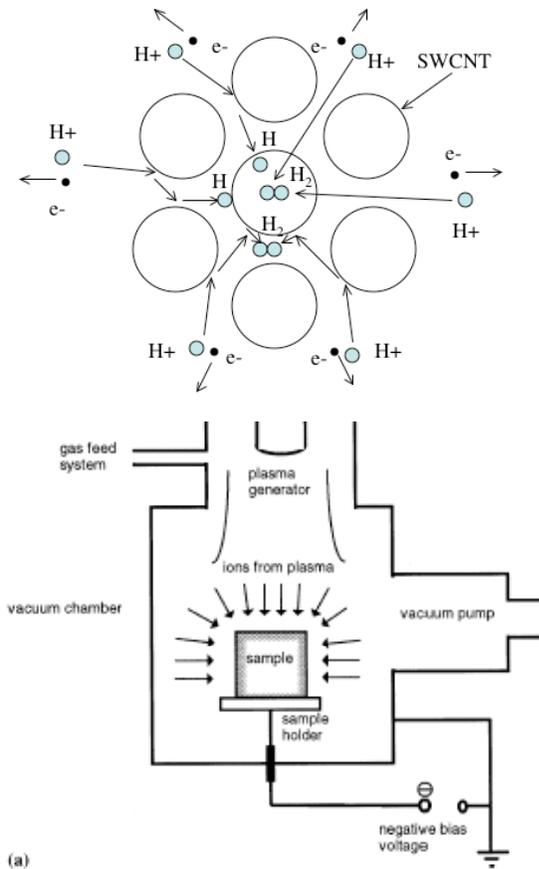


Fig. 5. Schematic of apparatus and process for plasma immersion ion implantation.

We have identified two methods of ion implantation that may be useful in this application. The first uses a commercially available ion gun, which simply accelerates and implants directly into the sample. The second method is plasma immersion or plasma source ion implantation [8,9]. In this technique, the sample is immersed in a low temperature plasma chamber filled with hydrogen or other species. When the sample is biased to a negative voltage, electrons are driven away and ions are accelerated towards the sample and become implanted. It can be shown that if the energy of the ions is kept below 70 eV, the ions will penetrate and dope thin samples but not dislocate carbon atoms from the nanotube lattice, thus retaining the high strength characteristics of the fibers. The method has many advantages over beam-line ion implantation, including high dose rate and uniform coverage.

4.3 Expertise for manufacture of fibers

Several groups have made remarkable progress recently in producing high strength carbon nanotube fibers. We highlight two here to demonstrate the pro-

gress which can be leveraged for NASA's purposes and TRIPS developments:

(1) Researchers have developed [10] a procedure for spinning composite carbon nanotube fibers that are tougher than spider silk and any other natural or synthetic organic fiber reported so far. The new fibers are being used to make supercapacitors and to weave textiles. To prepare the fibers, Ray H. Baughman, Alan B. Dalton and their coworkers at UTD and at Trinity College Dublin use single-walled nanotubes synthesized from CO and a surfactant (lithium dodecyl sulfate) in a coagulation-based spinning process. The process produces nanotube-polyvinyl alcohol gel fibers that the group converts to 100-meter-long nanotube composite fibers roughly 50 μm in diameter. On the basis of strength tests, the Texas researchers report that their nanotube product can be drawn into fibers that exhibit twice the stiffness and strength and 20 times the toughness (ability to absorb mechanical energy without breaking) of steel wire of the same weight and length. The fiber toughness is more than four times that of spider silk and 17 times greater than Kevlar fibers used in bullet-proof vests.

(2) Pasquali and Smalley have reported [11] that a sulfuric acid-based superacid makes an excellent medium for dispersing single-walled carbon nanotubes (SWNTs) at concentrations that are useful for industrial processes. They also found that the acids coat SWNTs with a layer of protons. This discovery enabled them to process the dispersion into the first continuous fibers of aligned, pristine SWNTs. Fibers like these might be used to make ultralight, ultrastrong materials with remarkable electronic, thermal, and mechanical properties. This phenomenon allows the team to overcome the tubes tendency to clump together, and they can make solutions composed of up to 10 percent SWNTs by weight – ten times more concentrated than any previously prepared dispersions. At these high concentrations, the SWNTs self-align in a liquid-crystalline phase, similar to the polymer used for making Kevlar. More dilute dispersions employ hard-to-remove detergents and polymer additives and are considered impractical for industrial purposes.

4.4 Modeling

Modeling will be used to predict radiation shielding effectiveness in order to better guide the development and experimental efforts. Based on our collaborations with NASA Goddard, we have decided to use the GEANT4/MULASSIS suite of codes for applications in this area.

GEANT4 is a toolkit for the simulation of the passage of particles through matter. Its application areas in-

clude high-energy physics and nuclear experiments, medical, accelerator and space physics studies. GEANT4 exploits advanced software engineering techniques and object oriented technology, to achieve the transparency of the physics implementation and hence provide the possibility of validating the physics results. The GEANT4 software was developed by RD44, a world-wide collaboration of about 100 scientists participating in more than ten experiments in Europe, Russia, Japan, Canada and the United States. A description of the code, which can run on a Windows-based laptop, can be found in [12].

The Multi-Layered Shielding Simulation Software (MULASSIS) is a Monte Carlo simulation-based tool for dose and particle fluence analysis associated with the use of radiation shields. Users can define the shielding and detector geometry as planar or spherical layers, with the material in each layer defined by its density and elemental/isotopic composition. Incident particles can be any GEANT4 particles, including protons, neutrons, electrons, gammas, alphas and light ions. There is a wide choice for their initial energy and angular distribution. A description of the code can be found in [13].

4.5 Facilities for testing of radiation-shielding capabilities of materials

Ground testing of shielding materials for space radiation is routinely done at proton and heavy ion accelerator facilities, two of which are found in California. A good review of this topic can be found in the article by Miller [14].

The Crocker Nuclear Laboratory at UC Davis houses a medium-energy particle accelerator, the Davis 76-inch isochronous cyclotron, with associated facilities, and scientific and technical personnel. NASA, The Naval Research Laboratory, JPL and Lawrence Livermore National Laboratory have all used the CNL Cyclotron to support their research in various areas of radiation effects produced by solar and cosmic radiation. The facility can be used to produce protons from 1 to 70 MeV

Loma Linda University Medical Center's Proton Therapy Center has the world's smallest variable-energy proton synchrotron. The accelerator has a range of energies between 40 and 250 MeV. It is designed to deliver a sufficient beam of particle energy to reach the deep localized solid tumors in patients. When not in use for patient treatment, the facility is available for biophysics and radiobiology experiments. In 1994 NASA and LLUMC officials signed a Memorandum of Agreement to study ways to protect astronauts from radiation in space. LLU and NASA scientists are using

the University's proton laboratory to simulate cosmic and solar radiation encountered by astronauts, plants, animals, and supportive hardware.

The \$34-million NASA Space Radiation Laboratory (NSRL) at Brookhaven is one of the few places in the world that can simulate the harsh cosmic and solar radiation environment found in space. The facility, opened in 2003, employs beams of heavy ions extracted from Brookhaven's Booster accelerator, the best in the United States for radiobiology studies. The NASA Space Radiation Laboratory features its own beam line dedicated to radiobiology research, as well as state-of-the-art specimen-preparation areas. These beams simulate the high-energy, high-charge (HZE) components of galactic cosmic rays that constitute the biologically most significant component of space radiation.

5.0 IMPACT SHIELD CONCEPT AND INTEGRATION WITH THERMAL/ RADIATION SHIELD

5.1 Impact Shield Concept for TRIPS

Christiansen has developed [15] a strategy for incorporation of MMOD shielding into a flexible, deployable concept for the Transhab, which we would adopt and propose to modify for TRIPS; it is said [15] to be the most capable MMOD shield yet developed. Christiansen's approach is depicted in Fig. 6 [15, p.54]. Christiansen reports that his 8 cm thick MMOD shield can prevent back-wall penetration of a 3.6 mm diameter aluminum sphere that strikes the front Nextel layer at an incidence angle of 45° and a velocity of 5.8 km/sec. The test article had no material filling the voids between each layer of the shield.

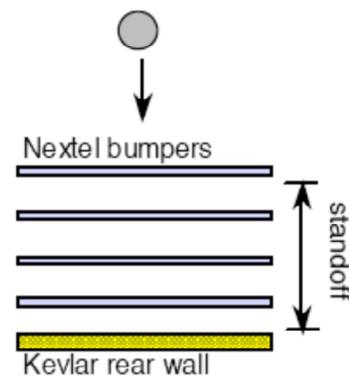


Fig. 6. Adopted from [15 p.54], depicting a MMOD shield developed for the Transhab.

Each Nextel layer in Christiansen's MMOD Transhab shield provides a shock to the penetrating threat, breaking it into smaller debris particles the deeper it goes. The Kevlar layers use the stopping power of this

material (used for bullet-proof vests) to arrest the debris and prevent it from penetrating the Transhab interior.

As previously discussed, CNT nanostructured composite fibers have been developed [10] that are 17 times tougher than those from which Kevlar fabric is woven. We would adopt a fabric for TRIPS woven from the CNT nanostructured fibers, with weave spacing to be determined by ballistic range tests. We would also

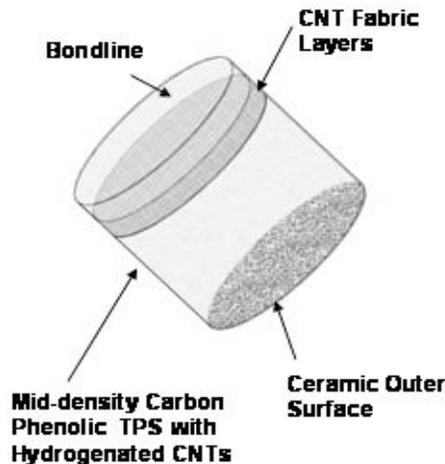


Fig. 7. Conceptual TRIPS Lay-Up. The number of ceramic layers and CNT fabric layers below the outer mold line and their spacing is determined from ballistic range tests.

consider Nextel or other suitable materials, perhaps more capable as a heat shield, to provide the multiple shocking layers, whose function is to progressively break penetrating debris into smaller pieces

Finally, we note that Christiansen, [15, p. 74] first suggested the value of carbon nanotube fibers in MMOD shields, holding particular promise for the intermediate and rear wall materials.

5.2 Impact Shield Modeling

Christiansen's work [15] provides an approach to develop Ballistic Limit Equations (BLE's) that are conservative in their prediction of the amount of shielding necessary for design purposes to protect against debris penetration for a given MMOD threat. These equations use appropriate materials constants and are derived from hypervelocity impact testing conducted in a ballistic range. Further, the approach includes a rationale for the use of BLE's for impact velocities beyond those

tested in the ballistic range. Our plans also take account of recommendations of the Columbia Accident Investigation Board [16], that improved physics-based codes should be developed to predict damage to spacecraft by debris.

5.3 End-to-End impact and arc jet testing

Following the work reported in [17], simulated MMOD particles, traveling at hypervelocities, would be fired into test articles in the ballistic range, to develop understanding of impact shield performance and to validate ballistic limit equations (BLEs). Our work will mimic mission profiles in which a presumed MMOD strike would occur prior to the vehicle executing atmospheric maneuvers, when thermal protection is required. Subsequent to the ballistic range testing, the MMOD-damaged test article will be exposed to aerocconvective heating in an arc jet, simulating the aerocapture/entry heating. From these results, databases to define safety limits for MMOD-damaged TRIPS can be derived, as for the Space Shuttle [17].

6.0 INITIAL EVALUATION OF TRIPS MASS SAVINGS

6.1 Approach and limitations

The analysis in this section is limited to the TPS and radiation shielding aspects of TRIPS and is intended only as an initial evaluation of the benefits of our concept. We chose to evaluate an Apollo shape and mass, since it can be considered as a first approximation to a CEV that might be used for out-of-Earth Orbit, Lunar return and Mars return missions. We envision a CEV with an upgradable, replaceable heat shield that could be developed in a "spiral" approach to meet the increasingly higher entry severity (Earth orbit, Earth return, Mars return) and in a fashion that allows for TRIPS research and development. We selected Carbon Phenolic for the TPS material for three reasons: its heritage (military, Pioneer-Venus [18] and Galileo [19]); the low atomic weights of its constituents - carbon + Phenolic (C_6H_6O); and the rule-of-thumb that low atomic weight materials are superior for radiation shields.

6.2. Thermal – conceptual TPS sizing

Our colleague, Dr. Gary Allen, provided the analysis herein with a code that can perform trajectory, engineering aerothermodynamics, TPS sizing and mass estimation for a uniform thickness heat shield. His calculations were validated against Apollo Command Module test flight data.

Fig. 8 shows three trajectories, plotting altitude versus range in km. AS 202 is a rather high speed, out-of Earth orbit, Apollo test flight. AS 501 for Apollo 4 was a rather long flight, and is the closest we have come to demonstrating aerocapture through the use of roll modulation to execute a lifting maneuver with a blunt body. The dotted curve represents a Mars return mission, using the Apollo Command Module to perform aerocapture at 12.5 km/sec to a 700 km altitude.

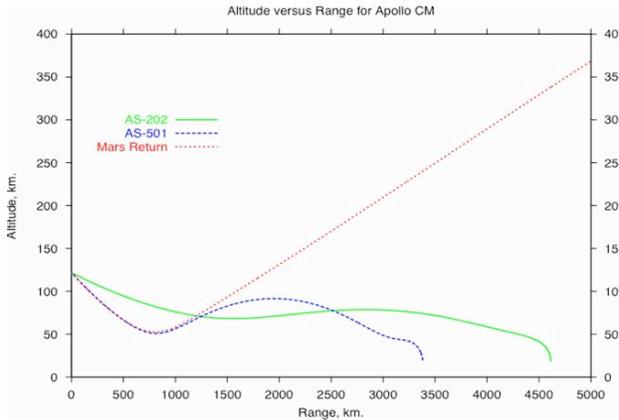


Fig. 8. Trajectories for the Apollo Command Module for the current study

Fig. 9 is the companion chart, showing total heat fluxes (convective plus hot gas radiation). Table 1 summarizes the results of Allen's calculations. Note the very low recession rates predicted in the last two columns of the Table: thickness (sized for the stagnation point) and heat shield recession from ablation. The bondline temperature is the sizing constraint and in each case was chosen to be 250 °C, with no margin beyond this level (zero bondline temperature margin).

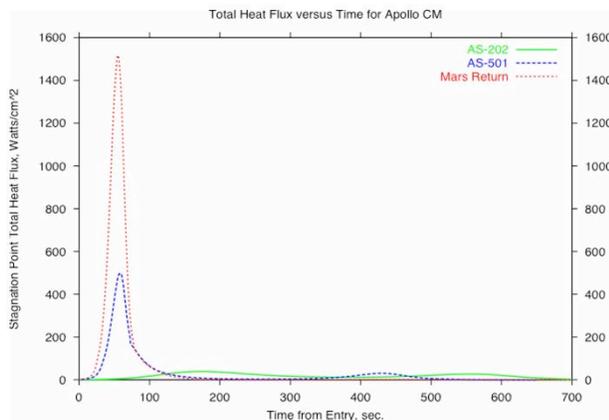


Fig. 9. The peak heat fluxes for the three trajectories in Fig.8 are 39, 521 and 1500 W/cm², respectively. The heat fluxes include both convective q_c and hot gas

shock layer radiation q_r . The subscript max means maximum values.

Vehicle Design	Vel km/s	q_{c-max} W/cm ²	q_{r-max} W/cm ²	Heat Load J/cm ²	Carbon-Phenolic	
					Thick. cm	Recess. cm
AS-202	8.7	39	0.00	12678	3.86	0.05
AS-501	11.2	185	336	21590	4.05	0.05
Mars R	12.5	241	1283	42480	4.46	0.12

Table 1. Summary of Apollo Command Module TPS Sizing Calculations.

6.3 Radiation shielding

Fig. 10, taken from [20], plots the 5 cm depth dose equivalent (rem/yr) versus the absorber aerial weight (g/cm²). The plotted doses are the sum of the (nearly constant) galactic cosmic ray flux and the solar flux, held constant at the solar minimum. The plot does not account for the event of Coronal Mass Ejections (CMEs). The plot does illustrate that the best of the selected shield materials, in order of efficiency, are liquid hydrogen, liquid methane, polyethylene and graphite, depicting the rule-of-thumb that lower atomic weight materials are better for radiation shielding. The horizontal line at 50 rem/yr locates the 1999 recommended maximum allowable annual depth-dose [20] for astronauts working in low Earth orbit.

As noted in [20], crews on interplanetary missions must have safe haven from CMEs and suggestions for shielding range from 5 – 20 g/cm² aluminum equivalent. From Fig. 10, it can be seen that 10 gm/cm² of graphite and polyethylene are respectively, equivalent to and slightly better shielding materials than 20 cm of

GALACTIC COSMIC RAYS - SOLAR MINIMUM (Depth vs. Dose Functions for Selected Materials)

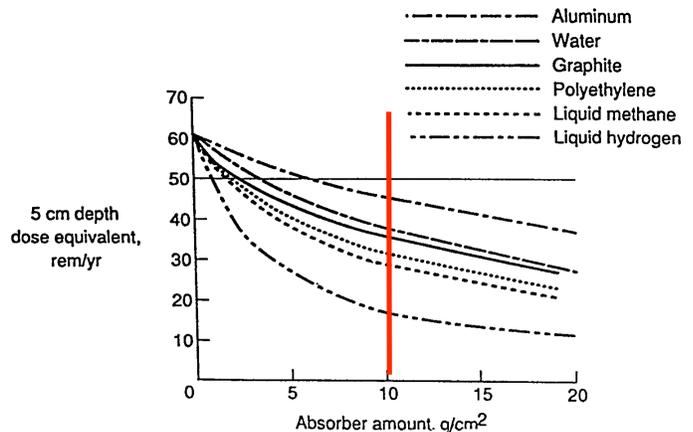


Fig. 10. Five cm depth (in tissue) dose equivalent in rem/yr vs absorber amount, g/cm²

aluminum. As located by the vertical bar at 10 gm/cm², the materials trade space for TRIPS, using a composite of Carbon Phenolic and hydrogenated CNT's lies between polyethylene and graphite, correlating to the 20 gm/cm² upper bound aluminum equivalent [20].

6.4 Impact shielding

This initial analysis of our concept does not include evaluation of impact shielding.

6.5 CONCLUSIONS FROM INITIAL EVALUATION OF TRIPS

The Carbon Phenolic thickness of the TPS for the Mars return case shown in Table 1 is 4.46 cm. The aerial weight of the heat shield is the product of the heat shield thickness and its density: (4.46 cm)x(1.5gm/cm³) = 6.7 g/cm². From the discussion in section 6.3, the aerial weight of the radiation shield is 10 g/cm². Assuming that Carbon Phenolic would be approximately as effective as graphite/polyethylene as a radiation shield for this first-cut analysis, we see that the dual-use TPS/radiation shield approach provides TPS and about 70 per cent of the upper range of the suggested radiation shielding, encouraging us to develop TRIPS technology. For a mid-density Carbon Phenolic TPS, the fraction of radiation shielding would be less, perhaps 20-40 percent.

As NASA improves its understanding of the biological effects of radiation on deep space missions, it is hoped that less radiation shielding will be required. In this event, the concept of TRIPS will become even more important.

6.4 Self-healing TRIPS

Polyethylene was tested as a potential heat shield material in the early days of thermal protection materials development. To the best of our knowledge, it has not been flown as a TPS material, because it liquifies in the ablation process. It is possible that a layer of polyethylene, placed between the bond line of the vehicle structure and the TRIPS, would melt and fill a hole caused by MMOD, perhaps preventing enlargement of the hole by cavity heating. The resulting system would amount to a self-healing TRIPS.

7.0 SUMMARY

We have presented an approach to develop a single protective shield that can protect robotic and human space transportation vehicles from the triple threat as-

sociated with deep space missions: thermal (aerothermodynamic entry heating), radiation and MMOD strikes.

A simple study has shown that using a fully dense Carbon Phenolic TPS for a Mars return capsule also provides about 70 percent of the needed radiation shielding for astronaut health. Use of mid-density Carbon Phenolic TPS would reduce this fraction to 20-40 percent.

We believe that emerging nanotechnologies will enable the development of TRIPS, leading to safer, more affordable space exploration.

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