FOAM CORE SHIELD (FCS) SYSTEMS
A NEW DUAL-PURPOSE TECHNOLOGY FOR SHIELDING AGAINST METEOROID STRIKE DAMAGE AND FOR THERMAL CONTROL OF SPACECRAFT/SATELLITE COMPONENTS

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ABSTRACT

A new technology is being developed that can protect spacecraft and satellite components against damage from meteoroid strikes and control the thermal environment of the protected components. This technology, called Foam Core Shield (FCS) systems, has the potential to replace the multi-layer insulation blankets (MLI) that have been used on spacecraft for decades. In order to be an attractive candidate for replacing MLI, FCS systems should not only provide superior protection against meteoroid strikes but also provide an equal or superior ability to control the temperature of the protected component. Properly designed FCS systems can provide these principal functions, meteoroid strike protection and thermal control, with lower system mass and a smaller system envelope than MLI.

These interim findings of an on-going development and optimization task demonstrate the superiority of FCS over MLI for meteoroid strike protection. Limited experimental studies and preliminary modeling indicate that the performance of FCS as a thermal control technology should be at least equal to and, properly implemented, superior to MLI and clearly superior in planetary atmospheres. Central to the comparison of meteoroid strike protection provided by FCS vs. MLI is a new formalism for rational and consistent characterization of damage levels in the protected component and consideration of the stochastic nature of this damage. Using this new formalism, hypervelocity impact experiments have shown that the level of strike protection provided by a given MLI system is inconsistent and unpredictable, i.e. highly stochastic. Furthermore, in practice, MLI has very limited capability for being upgraded to shield against the more aggressive meteoroid threat flux encounter in long duration missions, with large area critical components and/or for missions that require a high probability of survival. In contrast, the protection level provided by FCS systems can be easily upgraded to any level required including those requiring the highest levels of meteoroid strike protection.

INTRODUCTION

For decades spacecraft and satellite engineers responsible for assuring the temperature control of critical, sensitive components in the space environment have relied on multi-layer insulation (MLI) "blanket" technology. In the space environment, MLI's multiple layers of reflective surfaces provided a mass efficient solution to significantly reducing heat loss from a protected component. Additionally, the MLI design can be optimized for a particular thermal control requirement by adjusting the number of reflective layers used in the blanket.

In practical application, several problems associated with the use of MLI have never been completely solved:
(1) MLI blankets are fabricated using seams sewn in a manner similar to clothing manufacture. These seams create thermal anomalies that are difficult to model, predict or control.
(2) MLI is either wrapped over the protected component or supported off its outer surface with some type of structure. The amount of contact between the protected component and the MLI is a major variable in the actual performance achieved and in the success of predicting the performance of the design.
(3) Being a blanket composed of many very low mass layers, MLI's insulating properties are significantly affected by the degree of contact between the layers due to spacecraft motion or compression of the blanket in wrapped areas.

Although models have been developed for predicting the performance of MLI in a particular application, the reality is that cut and try methods are used to develop and finalize the installation on a spacecraft. MLI does not always perform on the spacecraft as initially expected. These test-modify design-test again cycles of development require expensive thermal vacuum chamber testing and engineering modification. If MLI must be removed to rework an underlying component or system, replacement of the original MLI after rework often results in different thermal control behavior of the reinstalled MLI. New MLI must be fabricated and installed.

As concern over the possibility of unacceptable damage to critical spacecraft/satellite components from meteoroid strikes has grown, engineers have come to rely on MLI not only for thermal control but also to provide protection against meteoroid strike damage. *Belief* in wondrous protection levels provided by MLI grew, as necessary, with the increasing demands made of the MLI systems to provide shielding against meteoroid damage. Often*, without any supporting test data*, MLI was *assumed* to provide astounding, impossibly high levels of protection.

The actual, quite modest protection levels that MLI can provide against meteoroid strike damage can and has been marginally improved with the addition of a woven inorganic fiber cloth that provides increased areal density of the MLI shield and may meaningfully augment the shock produced in the incident meteoroid, facilitating its break-up. Beta Cloth (a tight weave E-glass fiber material coated with Teflon) is now commonly used by spacecraft engineers for this purpose. Because of installation problems, e.g. bending around curved surfaces, support of the more massive blanket, only a limited amount of this material can be added to an MLI blanket. This limits the maximum protection level that can be attained. In many instances that involve long duration missions, large area critical components and/or requirements for very high probabilities of survival, MLI or augmented MLI simply cannot provide the level of protection needed.

Foam Core Shield (FCS) systems are being developed to provide a solution to all of the problems associated with MLI design, modeling and implementation. FCS systems have no inherent or practical limitations to the level of protection that they can provide. Compared with an MLI system, an FCS system that provides equivalent or better thermal control and superior, more reliable protection against meteoroid strike damage will have a lower mass and will occupy significantly less volume on the spacecraft. Contrasted with the difficulties of engineering MLI to reliably perform a particular thermal control function, the thermal control characteristics of FCS are easily modeled, optimized and controlled and FCS behavior is uniform and consistent. FCS systems are integrated into the spacecraft/satellite architecture just as any other component; they are not "hung on the spacecraft" after it is designed. They can be removed and reinstalled with no effects on their performance characteristics. In an atmosphere, e.g. planetary lander, FCS systems provide much more efficient thermal control technology.

WHAT ARE FCS SYSTEMS?

In general, FCS systems are composed of three major components: a face sheet, a foam core and a back sheet. These components form a robust, self-supporting, foam core sandwich structure that can be attached to a spacecraft/satellite at a limited number of convenient attachment points. This sandwich shell can be used in any appropriate shape to best fit the application: flat plate, singly curved surface (thick walled tube shielding propellant pressure lines) or doubly curved surface (spherical shell shielding propellant tank). The face sheet thickness, foam thickness and foam density can be selected to provide the optimal combination of thermal control characteristics and meteoroid strike protection level with minimum mass and with minimum volume of the FCS system envelope around the protected component. The outer surface of the face sheet and the inner surface of the back sheet are coated with appropriate thin films that provide the optimum thermo-optical properties for each surface.

If the FCS system cannot be supported by attachment of its face sheet or back sheet to the spacecraft but must be supported by the protected component itself, thermal bumps (protrusions on the inner face of the back sheet) are used to accomplish this support. Thermal "shorts", pathways for conductive heat loss, caused by contact between the protected component and the FCS system can degrade the thermal insulation characteristics of FCS. The thermal bumps, arranged in a configuration providing adequately stiff structural support for the FCS system, minimize the FCS contact with the surface of the protected component to less than 1%, eliminating any meaningful level of conductive heat loss.

Depending on the application, FCS systems may be implemented using one component (the foam), two components (the face sheet and the foam) or all three components as described above. If the thermal control requirement is to maximize heat loss rather than to insulate, as discussed below in the Jupiter Icy

Moons Orbiter (JIMO) mission application, the FCS system may consist of only high temperature stable, high conductivity inorganic carbon or metallic foam or metallic glass foam. Such a system would be mounted directly on the hot component to enhance conductive thermal shorting and its cavity filled outer surface would provide a high emittance radiating surface.

The current program, described in this paper, is developing FCS systems that employ fully dense polymer face sheets and back sheets (polycarbonate) and low density (0.5 to 6 lb/ft3) organic foams (polyimides and polyurethanes) for protection of propulsion system components such as tanks and pressure lines operating in an "intermediate temperature range". In these less demanding structural applications that require the reduction of heat loss from the protected component, the goals are to maximize the insulation characteristics and meteoroid protection level with minimum system mass and minimum FCS envelope volume. For larger structural applications, e.g. the large meteoroid shield required for protection of the entry heat shield on the Mars Sample Return spacecraft, high performance fiber/matrix structural composite materials will be used for the face sheet and back sheet.

Since FCS systems are being developed to provide *general* solutions to the problem of providing both thermal control and meteoroid strike shielding in a single system, it is recognized that some applications must operate at high temperatures while providing either maximum or minimum heat loss from the protected component. For such applications, FCS systems can be constructed of high temperature materials: face and back sheets composed of refractory metals, ceramics or carbon-carbon and foam cores constructed from carbon, ceramic or other high temperature foams. In certain high temperature applications, the thermal control requirement is to maximize heat transfer to space from the protected component while providing protection of that component against meteoroid strikes. The primary coolant lines carrying hot sodium or NaK from the nuclear reactor to the large radiator on the JIMO spacecraft is such an application.

The common FCS features in all of these applications are:

(1) The significant mass and volume efficiency realized by using a face sheet/foam/back sheet construction for a shield to defeat meteoroid strikes. For equivalent shield mass, neither single fully dense plates nor a combination of spaced plates is as efficient. Maximum mass/volume efficiencies are achieved through the combination of plates and foam as discuss in this paper.
(2) The thermal insulating characteristics of the three component FCS systems are equivalent to or exceed that of an MLI system.
(3) The range of materials available for use in FCS systems enables the construction of systems that can maximize heat loss, a requirement for which MLI is clearly not even a remote candidate.

CHARACTERIZATION OF THE DAMAGE CREATED BY METEOROID STRIKES

In order to develop superior and reliable meteoroid shield systems, a rational and consistent formalism for damage characterization is required. Some of the work done by the hypervelocity impact damage community suffers from a lack of such formalism. Sometimes this can result in uncertain and confused data interpretation. Without consistent application of a fixed approach to damage categorization and recognition of the stochastic nature of impact damage, any statement of shield performance or comparison between shield performances becomes suspect if not useless. During the development of these FCS systems and in all comparisons with the MLI technology to be replaced, a consistent set of definitions has been combined with a statistically based approach to the analysis and interpretation of the acquired data. The formalism being used is described below.

With regard to the protection of a component, *Critical Damage* is defined by set of *Type(s)* and *Level(s)* of damage any one of which prevents the *Protected Component* from performing its *Critical Function(s)*. Different kinds of components are susceptible to different Types of Critical Damage. Propellant tanks and pressure lines sustain Critical Damage if they are caused to leak. The Type of damage is structural and the Level of damage is loss of structural ability to contain the pressurized contents. This does not imply that the striking meteoroid or the debris cloud produced by meteoroid impact on the shield must *Perforate* the tank. The tank wall may be only *Partially Penetrated* by the meteoroid/debris and sustain Critical Damage, i.e. leak, fail. The impulse from the impact in combination with the pre-existing stress in the tank wall from the pressurized contents can create crack damage through the tank wall or extending to spall created on the internal surface of the tank even though the meteoroid/debris only partially penetrated into the wall.

Often this seemingly simple and pedantic logic becomes badly confused or ignored by spacecraft reliability engineers or shield developers overly enthused about their creations. A *protected component* is a *critical component* because it performs one or more *critical functions*; otherwise it would not need protection. *Critical Damage* in the Protected Component is damage that destroys the ability of the component to perform the critical function(s). From the critical functions and *Failure Modes* of these critical functions we can define the Types and Levels of damage that are critical. There are many kinds of critical components on every spacecraft/satellite with a variety of critical functions, failure modes, types of damage and critical damage levels. Any shield system that does not prevent impact on the protected component, e.g. MLI systems, must consider the complex factors discussed above. FCS systems enable complete protection at low mass and system envelope volume.

An important case of partial meteoroid/debris penetration causing failure (Critical Damage) can occur in ultra-light, metal lined, filament wound tanks. In these tanks, structural integrity arises from the filament wrap; the metal liner is often designed to simply prevent leaking through the wrap, not to support the pressurized contents. Damage to the wrap (destruction of load carrying cross-section) exceeding the loci of a set of critical depth and diameter combinations will cause the tank to fail. In this case, perforation of the tank or complete penetration of the wall is not required for tank failure. The Level of Critical Damage is dependent on fracture mechanics analyses of the composite structure. Damage over a larger area but at less depth may be less or more lethal to the tank than damage over a smaller area but to a greater depth.

Hot plasma in the debris cloud likely cannot damage any propellant tank or stainless steel pressure line. However, if the protected component is electrical cabling or an optical surface, hot plasma may be more likely to cause Critical Damage than small particle solid debris that would fail a propulsion component because metallic materials can be deposited from the plasma causing electrical shorting or optical obscuration. The Types and Levels of Critical Damage are highly dependent on the nature of the Protected Component, its Critical Functions and its Failure Modes. FCS systems suppress all forms of insult that the debris cloud produces in the protected component.

When struck with meteoroids of concern, MLI shielding always produces a debris cloud whose effects on the protected component must be understood before the adequacy of the shielding can be determined. These determinations then become dependent on the particular component being protected and its susceptibility to critical damage and failure from the damage that results from MLI's partial shielding. MLI only provides partial shielding of a component; the protected component is always hit with debris during any strike event of concern. In contrast, FCS systems can be designed, with lower system mass that provides complete protection of the component. FCS is a "real" shield. The component is completely protected from any damage and the complex MLI shielding problem of how much damage can be allowed before the protected component is critically damaged is completely avoided.

The work discussed in this paper employed a standardized target configuration that consisted of the shield system, the protected component (0.030 in thick 304 stainless steel plate representing the protected component, the wall of a pressure line) and a soft aluminum witness plate spaced off the stainless plate a sufficient distance that the dynamic deformation of the steel plate could not slap the witness plate. Five coarse damage levels are defined for this target system:

BLUE: The shield system is not completely penetrated. The extreme, down range portion of the shield system is not damaged or spalled.
GREEN: The shield system is breached (perforated, completely penetrated or the back side of the shield is spalled); however, the protected component sustains NO Damage.
YELLOW: The shield system is breached and the protected component sustains damage but the damage is less than Critical Damage. In the case of the test program being reported here, a leak is not produced in the stainless steel plate.
RED: The shield system is breached and the protected component sustains Critical Damage. For the current test program, the stainless steel plate leaked after the test as determined by a helium leak test on the plate.
BROWN: The shield system is breached, the protected component sustains Critical Damage and damage is produced in the witness plate.

A fine scale of damage in the YELLOW, RED and BROWN regions of behavior were measured using micro x-ray radiography and surface profiling with a precision laser profilometer. The data and analyses reported herein use this damage categorization formalism and nomenclature. Where appropriate, the measurements made on the damage fine scale are given.
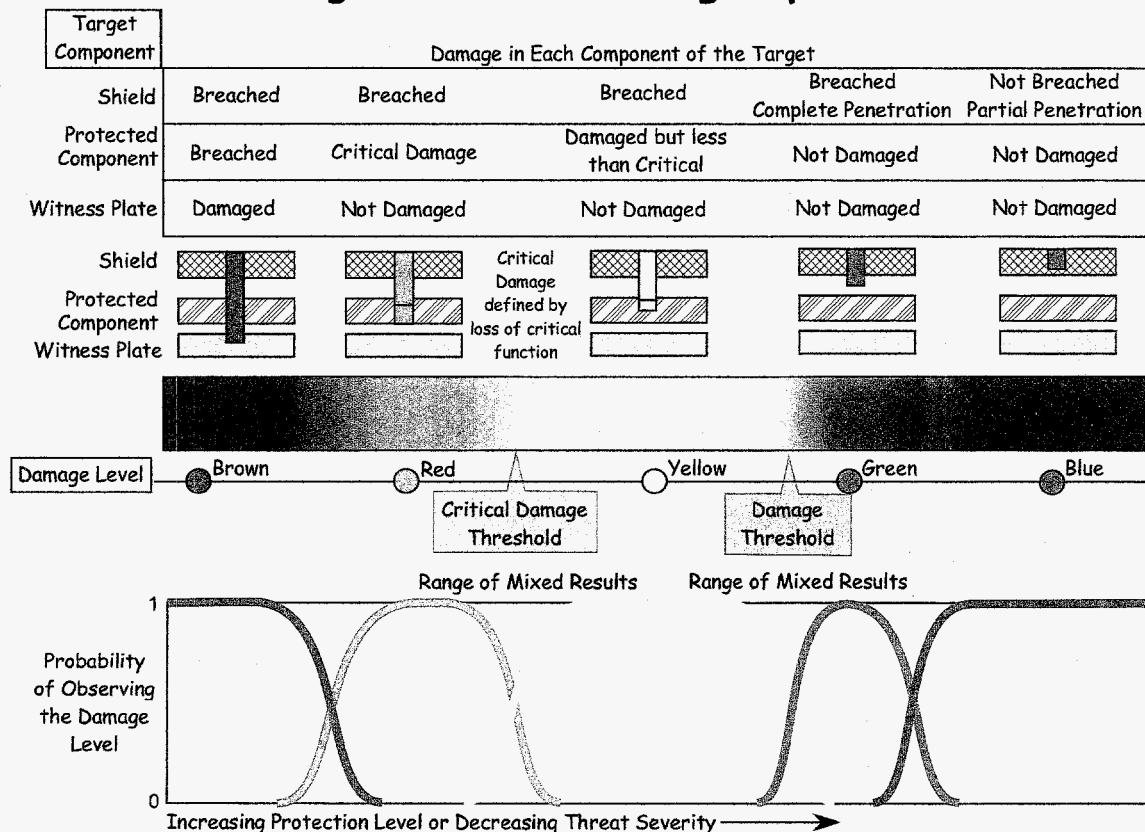
These five regions of damage level are portrayed in Figure 1, The Damage Spectrum. The lower portion of the figure gives a conceptual idea of the underlying statistical nature of the damage behavior. Different types of shield systems may well exhibit significantly different statistical behavior as is evidenced by the MLI and FCS data measured in this study.

The plot shows the probability of observing a particular level of damage as a function of protection level provided by the shield and threat severity, e.g. meteoroid mass and impact speed. The *Damage Threshold* (the GREEN/YELLOW boundary) and the *Critical Damage Threshold* (the YELLOW/RED boundary) are seen to be "fuzzy". At a given combination of threat severity and shield protection level in this range, the probability of observing one level of damage or the other level are both less than unity. If many tests are performed that perfectly replicate the same threat severity/protection level value, a mixture of both results will be obtained. This is called the range or zone of "mixed results". Without sufficient testing, the wrong conclusions may be drawn from a limited data set. Statistical considerations clearly indicate that most data sets are far too limited to draw any but the most general conclusions with any statistical confidence.

Shield designs that perform in the BLUE region are over-designed for protecting against the threat. Shield designs that perform in the RED or BROWN region are under-designed. Depending on the approaches to survivability that a particular spacecraft/satellite project has adopted, an adequate shield will have performance somewhere between the GREEN/YELLOW Damage Threshold (DT) and the YELLOW/RED Critical Damage Threshold (CDT). For this reason, the work being reported herein has concentrated on determination of the Damage and Critical Damage Threshold values for the various shield systems that have been investigated.

As shown by the data discussed below, MLI exhibits particularly large dispersion in its shielding behavior. The range of mixed results for MLI is very large. This fact makes it difficult to design reliable shields with MLI. It causes any reliable design to have greater mass/envelope volume because the design must be placed at the conservative extreme of the mixed result range to assure a high probability of the desired protection level. MLI is a statistically "inefficient" system because of the large variance (uncertainty) in the protection level that a give design may afford.

Figure 1. The Damage Spectrum

| Target Component	Damage in Each Component of the Target				
Shield	Breached	Breached	Breached	Breached Complete Penetration	Not Breached Partial Penetration
Protected Component	Breached	Critical Damage	Damaged but less than Critical	Not Damaged	Not Damaged
Witness Plate	Damaged	Not Damaged	Not Damaged	Not Damaged	Not Damaged

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SURROGATE TEST PROJECTILES USE TO REPRESENT THE METEOROID THREAT

An extensive survey of the community that models the meteoroid environment (unpublished study done for the Cassini spacecraft project in 1995) concluded that the most abundant meteoritic material in the mass range of concern to spacecraft/satellites (micro-grams to one gram) was silicate minerals. Soda-lime glass has been determined to be the best available surrogate for silicate minerals. All testing conducted in this program used spherical, fully dense, soda-lime glass projectiles.

Four projectile masses were chosen for use in evaluation of the FCS and MLI shield systems, 0.8, 6.7, 42 and 289 milligram. These four masses, when impacted at the 5.3 km/s standard velocity chosen for this study, represent the entire range of critical meteoroid kinetic energies for missions with very short exposure time, small critical component area and/or low survival probability to missions with long duration, large critical component area and/or high survival probability. The range of exposure times and areas addressed by the testing conducted in this study is illustrated in Figure 2. The figure presents the critical values of the four test masses for four levels of survival probability each (0.8, 0.9, 0.95 and 0.99) as a function of time of exposure to the meteoroid flux and the exposed area of the critical component. Higher survival probabilities (0.95, 0.99, 0.999 and 0.9999) were applied to the largest particle. These calculations are based on the meteoroid flux distribution at the 1 AU position in the solar system and assumes that a critical value of incident kinetic energy will determine the level of damage produced in the target.

Figure 2. Range of Mission Applications Addressed by Hypervelocity Test Program (Critical Component Area, Period of Exposure to Meteoroid Flux and Probability of Survival for 5.5 km/s Impact Velocity Testing. Meteoroid Threat at 1 AU)
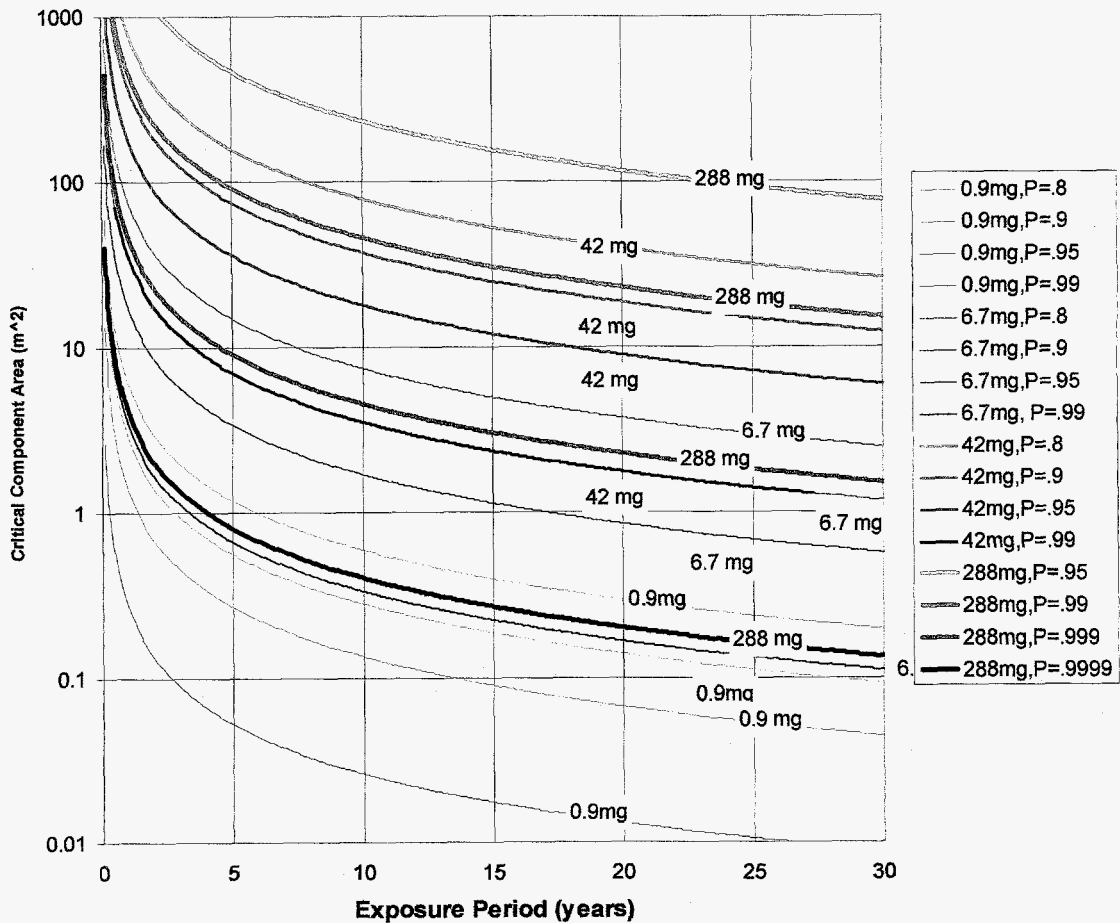
SHIELD SYSTEMS THAT HAVE BEEN INVESTIGATED

MULTI-LAYER INSULATION SYSTEMS

Because a primary goal of the current FCS development work is to demonstrate the superiority of FCS systems over MLI systems for both the thermal control and the protection of critical components against meteoroid strike damage, both FCS and MLI systems have been evaluated. MLI systems can vary in the number of layers included in the blanket as well as the coatings applied to the various layer sheets, e.g. carbon filled Kapton to provide black surfaces that reduce glare or second surface aluminized Kapton to minimize the absorption of sunlight. These applied coatings are so thin that they have little effect in hypervelocity impact of meteoroid particles. The MLI system selected in this program was derived from a survey of spacecraft missions and is representative of most spacecraft applications. Two MLI systems have been experimentally characterized. The two represent common MLI designs used on many spacecraft. The first system, called MLI, has the following construction:

Outboard, space facing surface
1 mil (0.00254 cm) Kapton face sheet, second surface aluminized coating on back side
Alternating 16 layers of Dacron mesh and
15 intermediate layers of 0.25 mil (0.000635 cm) Mylar, aluminized on both sides
1 mil (0.00254 cm) Kapton aluminized on the both surfaces
Inboard, protected component surface

The second system, called Beta MLI , represents a typical Beta Cloth enhanced MLI shielding system flown on Cassini and other spacecraft in areas where enhanced shielding was required. Beta cloth is composed of 4 micron diameter Owens Corning "E-Glass" composition yarn woven into a mat substrate and lightly coated with PTFE. The Beta MLI system has the following construction:

Outboard, space facing surface
1 mil (0.00254 cm) Kapton face sheet, second surface aluminized coating on back side
Alternating 16 layers of Dacron mesh and
15 intermediate layers of 0.25 mil (0.000635 cm) Mylar, aluminized on both sides
2 layers of Beta Cloth
1 mil (0.00254 cm) Kapton aluminized on the both surfaces
Inboard, protected component surface

A matrix of FCS systems have been investigated to determine first order design trade-offs and to provide data to model the relationships of the individual materials and component areal densities to the performance of these systems.

FCS SYSTEMS

Due to limited resources and an objective to demonstrate a Technology Readiness Level of 6 for the technology, the current program is restricted to investigating two families of foams, the polyurethanes and the polyimides. As discussed below, work to date has shown that the most promising family is the polyimides and these will be pursued exclusively to the end of the program. Polycarbonate material has been chosen for the face and back sheet components. As discussed above, many other materials may be excellent candidates for these components depending on the particular application. However, polycarbonates are an inexpensive, "space qualified" material that is easily fabricated into the required shapes and possesses attractive impact properties for intermediate temperature applications.

Table I summarizes some information about the FCS systems that have been characterized in impact tests with the 6.7 mg projectile to date.

Table I. FCS Systems Evaluated with the 6.7 (mg) Projectile

Foam Density		Polycarbonate Face Sheet Thickness (mil)		
(lb/ft3)	(g/cm3)	0	15	30
0.44	0.007	Polyimide (5) G-Y-Br	Polyimide (5) BI-G-Y-Br CBS Line (DT & CDT) CBS Tank (DT & CDT)	Polyimide (3) G-Y-Br
3.0	0.048	Flexible Polyurethane (6) BI-Y-Br CBS Line (DT & CDT)	Flexible Polyurethane (2) G-Br	Flexible Polyurethane (1) R
3.0	0.048	Rigid Polyurethane* (7) BI-G-Y-R-Br	Rigid Polyurethane* (1) G	
3.5	0.056	Rigid Polyurethane (3)Y-Br	Rigid Polyurethane (2) Y-Br	Rigid Polyurethane (1) Br
6.0	0.096	Rigid Polyurethane (1) Br		Rigid Polyurethane (1) R

* Foam discontinued by manufacturer

Foam Chemistry
(Number of valid tests) Damage levels observed
Current Best System (CBS) for application (DT/CDT)

SHIELD GEOMETRIES

This task focused on demonstrating FCS systems for two propulsion system components: 1) a 0.375" (0.95 cm) diameter stainless steel pressure line and 2) a spherical 36" (91.4 cm) diameter filament wound propellant tank with metal liner. The levels and types of damage necessary to fail such "ultra light weight" tanks are not known in general. Depending on pre-stress in the tank wall from the contents and the diameter and depth of the fiber volume destroyed by meteoroid impact, the tank can be caused to fail, typically through liner bulging and rupture. Tank designers do not understand these complex and dynamic failure mechanics; hence, only the Damage Threshold (no damage to the tank) is addressed for this component.

Targets were tested in a flat configuration and ballistic performance was mapped to the two shield geometries. The following equations were used in this mapping to convert flat shield geometry masses to the corresponding cylindrical shield and the doubly curved spherical shield geometry masses:

Mass of Shield = Mass of Foam + Mass of Face Sheet = (Foam Density x Foam Volume) + (Face Sheet Density x Face Sheet Volume)

Cylindrical Mass of Shield/unit length = $\rho_f \pi (2 r t_f + t_f^2) + \rho_{fs} \pi (t_{fs}^2 + 2 t_{fs} (r + t_f))$

Spherical Mass of Shield/unit area = $(\rho_f 4/3 \pi ((r_t + t_f)^3 - r_t^3) + \rho_{fs} 4/3 \pi ((r_t + t_f + t_{fs})^3 - (r_t + t_f)^3))/(4 \pi r_t^2)$

where: ρ_f = foam density, ρ_{fs} = face sheet density, r = pressure line radius, t_f = foam thickness, t_{fs} = face sheet thickness, r_t = the tank protected component radius.

TARGET CONFIGURATION

All testing in this program was accomplished using normal impacts to a flat shield configuration. A typical target set up is pictured in Figure 3. The target configuration is as follows:

The 6" x 6" x 1" aluminum witness plate (labeled 163FCS in the figure) is rigidly supported on a steel target fixture base plate. The surrogate for the spacecraft pressure line protected component is a 4" x 4" x 0.032" (10 cm x 10 cm x 0.08 cm) 304 SS plate. This plate was positioned 0.237" (0.60 cm) above the witness plate. This spacing was selected to allow the protected component to deform dynamically during the impact event without contacting the aluminum witness plate. The FCS system rested directly on the protected component. The FCS system included the foam and a polycarbonate face sheet if one was required in the test configuration. These target components were snugly sandwiched between an upper aluminum fixture plate and the steel bottom fixture plate as illustrated. The upper aluminum plate had a circular hole, illustrated in the top view of the figure, to enable the incoming meteoroid particle to impact only the FCS system during the hypervelocity test.

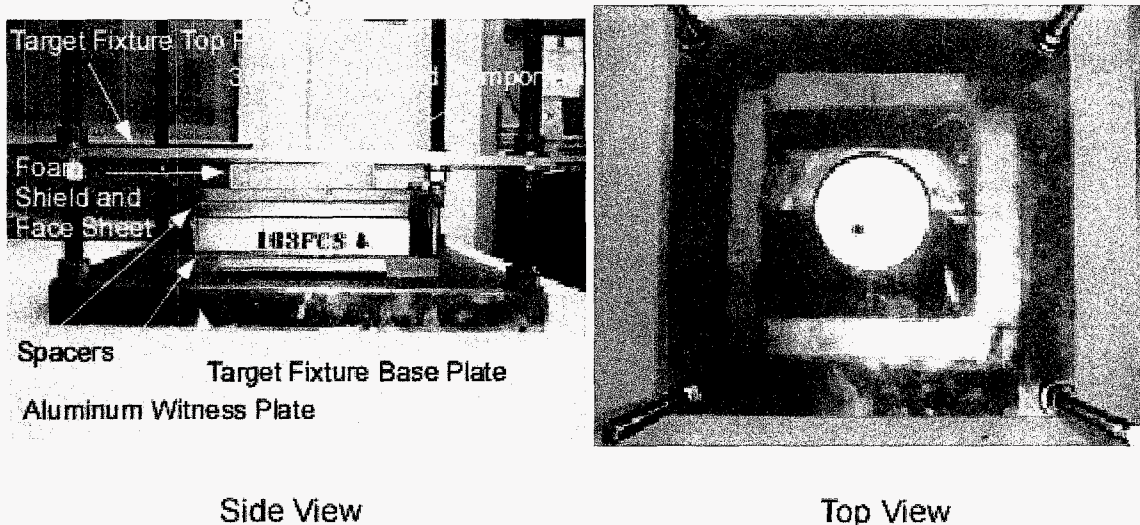Side View   Top View

Figure 3. The Target Configuration.

MLI and Beta MLI targets were tested in the same fixture. The 4" x 4" (10 cm x 10 cm) test blankets were attached to the upper aluminum fixture plate and spaced the required distance above the 304 SS protected component and aluminum witness plate.

Note that a target is composed of three components. These components include the shield, which is either an FCS system or an MLI system, the protected component and the witness plate. Damage levels found in the target can run from Blue through Brown. The target should be distinguished from the Protected Component where damage levels can only result in Green, Yellow or Red.

HYPERVELOCITY IMPACT TEST RESULTS

A sample of the results of the hypervelocity impact tests performed on various FCS and MLI shield systems are discussed below. First, the flat plate data is presented without consideration of the "shaped" shields that represent the optimal designs for different kinds of protected component geometries. Then the flat plate data is used to develop the characteristics of selected shaped shield systems for the two target applications of this program, a 3/8" diameter pressure line and a 36" diameter propellant tank.

Impact velocities of concern to interplanetary spacecraft include a range which greatly exceeds the particle speeds that can be produced with Earth-based accelerator systems delivering intact, solid particle masses. Little, if any, numerical modeling exists that can be trusted to predict shield performance and the damage produced by particle velocities of 20 to 60 km/s which are contained in the interplanetary meteoroid

flux distribution. This is a glaring deficiency in the engineering of shields to protect against meteoroid impact damage. Rather than attempting to "map" the variations in impact speed obtain in the hypervelocity tests to a single speed to facilitate comparisons between shields, the speed obtained in each test is reported and the shields are compared with impact speed as a confounding parameter. No acceptable impact speed/damage model was found to accomplish such mapping. Furthermore, it is believed that such a model would depend on the particular shield configuration and the materials employed in the shield, making such a model exceedingly complex and expensive to verify.

From a statistical standpoint (See discussion of the Damage Spectrum.), an unacceptably small number of tests were performed on any shield configuration to have high statistical confidence in the results. Although the data presented here give "an indication" of the relative performance of the various shield designs, the variability in the behavior of the systems, especially the MLI systems, indicates that additional data, e.g. replicated tests, are certainly required to make statistically meaningful statements regarding any detail of the behavior of individual systems such as the precise location of their damage thresholds or critical damage thresholds. In spite of this lack of statistical confidence, the large difference between the performance of the MLI and the FCS systems does lend credibility to the conclusion that FCS systems provide significantly better shielding. Additionally, the large variability in the shielding level provided by any MLI system that makes efficient design with such systems very difficult strongly argues for the replacement of MLI with FCS systems wherever possible.

FLAT SHIELD PERFORMANCE

As described above, each shield system was experimentally characterized in a "flat plate" configuration. The figures presented below describe the behavior of each system as a flat plate. In the next section, this data is applied to the shielding applications of a pressure line and a propellant tank. In addition to the shielding level achieved (the damage level produced in the test), two other quantities are important: the areal density of the shield and the system envelope, the amount of space or volume that the shield occupies on the spacecraft or satellite. The required system envelope is related in these studies to the spacing of the MLI or the thickness of the FCS system. Shield systems with smaller spacing or thickness are more easily integrated to a spacecraft and, in general, will have lower shield system mass because the mass is closer to the protected component and less support structure is required for the shield.

MLI AND BETA MLI PERFORMANCE AS FLAT SHIELDS

Figure 4 presents the results of five impact tests performed with the 7.6 mg particle on the 0.47 kg/m^2 MLI system in which the spacing of the MLI off the protected component was varied. Given a fixed MLI design based on thermal control requirements, increasing the spacing of the MLI is the only method of improving its shielding level. On most spacecraft spacings greater than a few inches are extremely difficult to implement for various reasons.

Figure 4. Target Damage Data for MLI System with 7.6 mg Particle
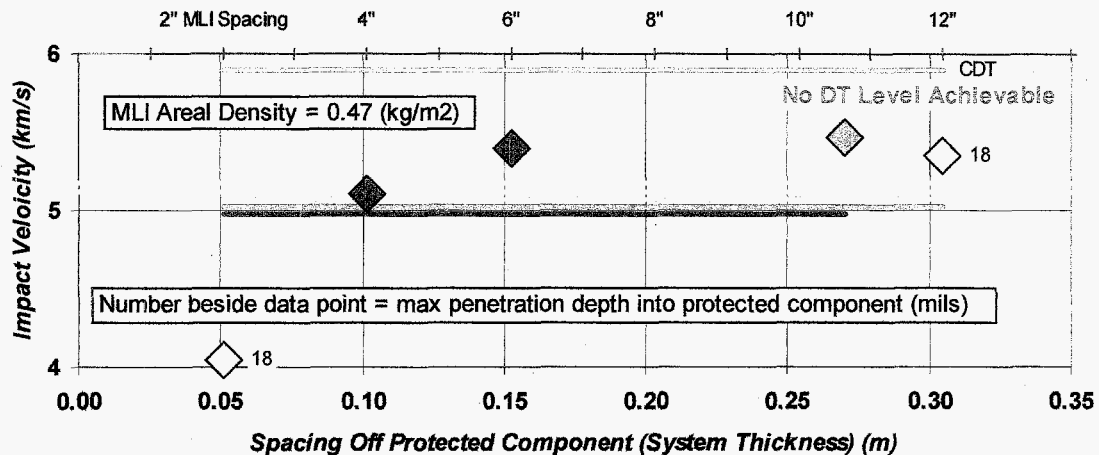
The color of each data point represents the damage level produced in the target (See Damage Spectrum discussion.). The test results are plotted as a function of shield spacing off the protected component and the particle impact velocity. The number beside the Yellow data points is the maximum depth of penetration (in mils) into the 0.030 (in) thick stainless steel plate representing the protected component. The orange bar at the top labeled CDT represents the region of shield spacing over which the Critical Damage Threshold **may** exist with some probability **based on the data that has been taken**. No Damage Threshold could be produced with the MLI system. At the 12 (in) maximum spacing tested (a spacing larger than is practical to use on most spacecraft), significant damage still occurred in the protected component, an 0.018 (in) penetration into the 0.030 (in) thick stainless steel plate. In practical shielding applications against any reasonable threat, this MLI cannot provide complete protection against damage to the critical component.

The horizontal colored bars running between the data points are located at the mean impact velocity. Each bar indicates the spacing over which that particular level of damage **may** occur with some probability **based on the data that has been taken**. As more data are taken, the range of each damage level bar will become, in general, more localized. For well behaved shield systems with little variability in performance, more data will cause the bars to separate into individual regions of occurrence (ranges of spacing in this case) with small overlap between the bars. For poor shield systems with high variability in their performance, additional data will not cause the bars to separate into discrete regions. In such systems, as perhaps the MLI system shown here, the underlying system behavior (which would be observed in a large number of tests) is expected to be highly variable with significant probabilities of occurrence of Brown through Yellow damage levels over a wide range of spacing.

An alternate explanation of the "mixed" behavior of the damage (an unexpected Yellow result at smaller spacing than Brown and Red results) is that the damage level is highly dependent on the impact velocity and the Yellow data point measured at 0.05 m spacing was due to the low speed impact. If this were the case, upwardly sloping iso-damage lines could be constructed connecting the two Yellow points since they sustained identical damage levels. With appropriate damage measurements, a line could be constructed with approximately the same slope connecting the Brown points. The Red point would fall on a line between the Yellow and Brown lines. Such additional analyses are possible given our ability to measure the level of damage in the Yellow targets and in the Brown targets (witness plate damage). However, the data set is insufficient at the present time to extend our analysis to these levels of detail.

The large variability in damage behavior observed in the Beta MLI system discussed below argues against the velocity dependency conclusion. Additional testing is required to resolve this question.

Figure 5 presents the results of eight impact tests performed with the 7.6 mg particle on the 0.97 kg/m^2 Beta MLI system in which the spacing of the MLI off the protected component was varied. JPL spacecraft engineers have informed us that they now "always put Beta cloth in the MLI they fly"; hence, this

is the more important system for comparison with FCS.

**Figure 5. Target Damage Data for Beta MLI System with 7.6 mg Particle**
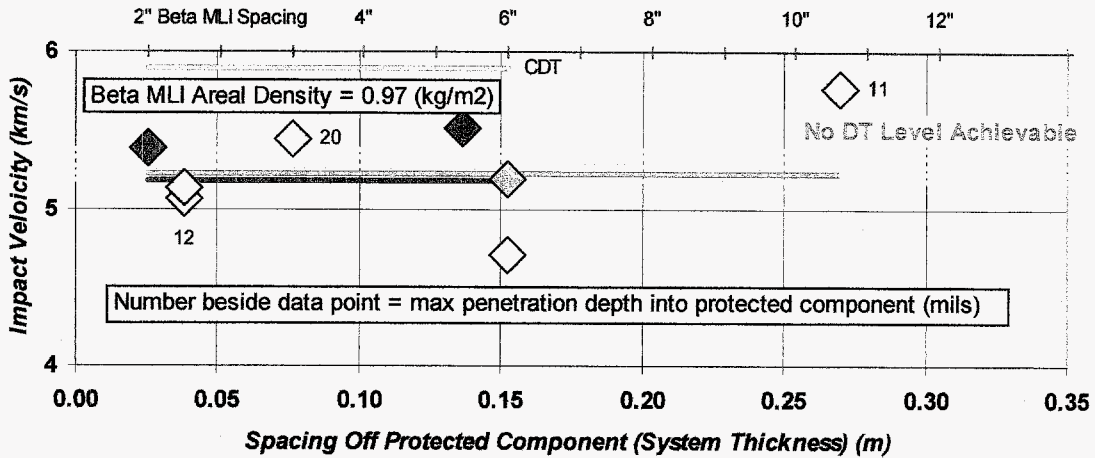
It appears from this limited data set that the performance boost achieved by adding Beta cloth to the MLI (compare this Figure with Figure 4) is marginal at best. Of great concern is the significant variability in the performance of this Beta MLI system. There is no clear pattern of damage dependency on impact velocity. Neither impact velocity nor spacing off the protected component correlate with the levels of damage observed. Further evidence of the variability in protection level provided by this Beta MLI is seen in the comparison of the maximum depths of penetration for the Yellow data points at 0.04 (m) and 0.08 (m) spacing. The shield with the smaller 0.04 (m) spacing resulted in a maximum penetration depth of 12 mils while the shield with the larger 0.08 (m) spacing (believed by some to provide a high level of protection) resulted in a 20 mil penetration depth. As with the MLI system, a Damage Threshold protection level could not be achieved with practicable spacings; Beta MLI will always allow the protected component to be damaged for any meteoroid threat of concern. Beta MLI is a poor shield system with unreliable performance.

FCS SYSTEM PERFORMANCE AS FLAT SHIELDS

Figure 6 presents the results of five impact tests performed with the 7.6 mg particle on an FCS system containing only 0.44 lb/ft^3 (0.007 gm/cm^3) flexible polyimide foam. The shield areal densities were change in this test series by changing the thickness of the foam.

Figure 6. Target Damage Data for 0.44 (lb/ft3) (0.007 gm/cm3) Flexible Polyimide FCS System with 7.6 mg Particle
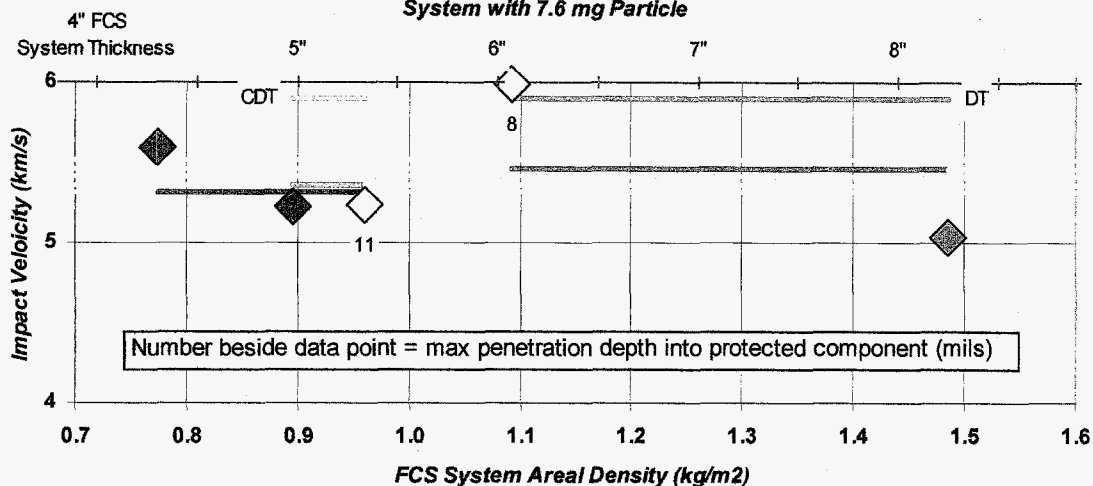
The test results for this system indicate an orderly behavior, transitioning smoothly from Brown damage levels to Yellow and Green as the thickness (areal density) of the foam is increased. Maximum penetration depth behavior of the two Yellow targets is orderly, going from 11 mils to 8 mils as the areal density is increased from 0.96 to 1.09 kg/m^2. This FCS system, like all FCS systems, exhibits not only a Critical Damage Threshold (somewhere in the range of 0.9 to 0.96 kg/m^2) but also a Damage Threshold (somewhere in the range of 1.1 to 0.1.5 kg/m^2). Additional testing will likely narrow the range of the CDT and the DT allowing mass efficient, optimized designs to be determined for specific applications. Our Yellow damage mapping techniques will be used to minimize the number of expensive hypervelocity tests required to identify these optimal designs.

Figure 7 presents the results of five impact tests performed with the 7.6 mg particle on an FCS system containing 0.44 lb/ft^3 (0.007 gm/cm^3) flexible polyimide foam and a 0.015 (in) thick polycarbonate face sheet. The shield areal densities were changed in this test series by changing the thickness of the foam.

Figure 7. Target Damage Data for 0.44 lb/ft3) (0.007 gm/cm3) Flexible Polyimide / 15 mil Face Sheet with 7.6 mg Particle
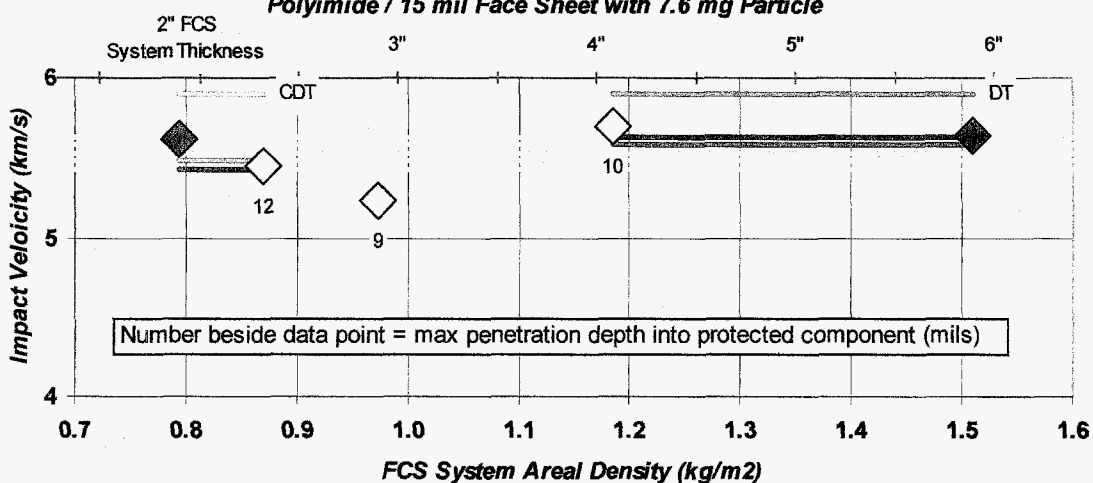

The test results for this system indicate an orderly behavior, transitioning smoothly from Brown damage levels to Yellow and Blue as the thickness (areal density) of the foam is increased. Again, the maximum penetration depth behavior of the three Yellow targets is orderly, going from 12 mils to 9 mils to 10 mils as the areal density is increased from 0.87 to 1.19 kg/m^2. This FCS system, like all FCS systems,

exhibits not only a Critical Damage Threshold (somewhere in the range of 0.79 to 0.87 kg/m^2) but also a Damage Threshold (somewhere in the range of 1.2 to 0.1.5 kg/m^2). Additional testing will likely reduce the range of the CDT and the DT. The top end of the CDT has a maximum penetration depth of only 12 mils into the 30 mil stainless steel plate. The bottom end of the DT is at a Yellow with 10 mils of penetration indicating the requirement for a significant increase in areal density to achieve the DT threshold. The top end of the DT range is bounded by a target with Blue level damage; the shield system itself was not breached by the particle. This end of the DT range will likely become lower with more test data.

Figure 8 presents the results of three impact tests performed with the 7.6 mg particle on an FCS system containing 0.44 lb/ft^3 (0.007 gm/cm^3) flexible polyimide foam and a 0.030 (in) thick polycarbonate face sheet. The shield areal densities were changed in this test series by changing the thickness of the foam.

Figure 8. Target Damage Data for 0.44 lb/ft3) (0.007 gm/cm3) Flexible Polyimide / 30 mil Face Sheet FCS System with 7.6 mg Particle
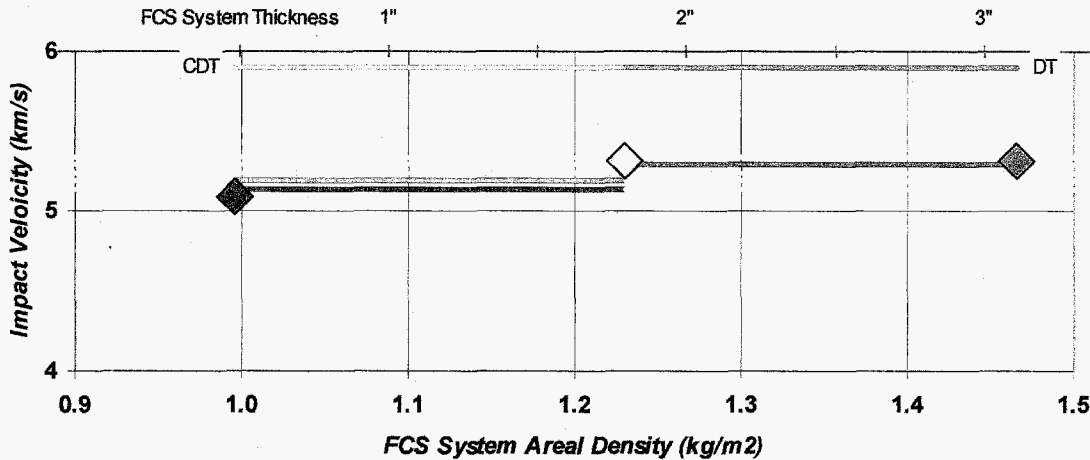
More test data is needed on this system to adequately describe its characteristics. However, comparison of the limited data on this system with the two FCS systems above indicates that the behavior is quite similar. Importantly, comparison of the shielding levels provided by the three FCS systems using 0.44 lb/ft3 polyimide foam with no face sheet, a 15 mil face sheet and a 30 mil face sheet shows that the three systems have very similar performance. Use of a face sheet allows significant reduction in the thickness (system envelope) of the FCS system. The system thickness required for the DT protection level decreases from approximately 7 to 8 (in) for the foam only system to 5 to 6 (in) for the system containing a 15 mil face sheet to <3 (in) for the system containing the 30 mil face sheet. At the CDT protection level the FCS system thicknesses decrease from ~ 5.25 (in) with no face sheet to < 2.5 (in) for the 15 mil face sheet to < 1.5" for the 30 mil face sheet.

Figure 9 presents the data taken on an FCS system consisting of 3 lb/ft3 flexible polyurethane foam only. The shield areal densities were change in this test series by changing the thickness of the foam.

Figure 9. Target Damage Data for 3 (lb/ft3) (0.05 gm/cm3) Flexible Polyurethane FCS System with 7.6 mg Particle
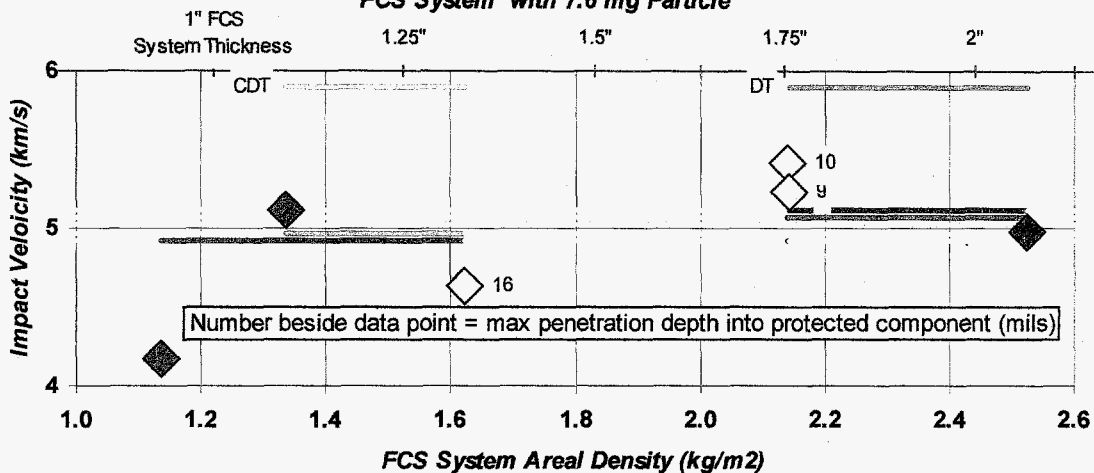
The test results for this system indicate an orderly behavior, transitioning smoothly from Brown damage levels to Yellow and Blue as the thickness (areal density) of the foam is increased. Again, the maximum penetration depth behavior of the three Yellow targets is orderly, going from 16 mils at an areal density 1.62 kg/m^2 to 9 and 10 mils at an areal density of 2.15 kg/m^2. The two higher areal density Yellow targets were equal in areal density (identical targets) and were impacted at the same velocity. This is a replication of the same test which gives an indication of the consistent performance of the FCS system. FCS passes the test. Not only are the two maximum penetration depths into the protected component very similar but also the larger penetration depth occurred in the slightly higher velocity impact test. One should be careful not to put too fine a point on things but FCS certainly appears to possess very consistent shielding performance!

This FCS system, has a Critical Damage Threshold somewhere in the range of 1.3 to 1.6 kg/m^2 and a Damage Threshold somewhere in the range of 2.1 to 2.5 kg/m^2. These values are significantly higher areal densities than the FCS systems based on the 0.44 lb/ft3 foam.

COMPARISON OF FCS & MLI SYSTEMS FOR PROTECTION OF CYLINDRICAL AND SPHERICAL COMPONENTS

As discussed above, when shield systems are configured to protect a component on a spacecraft or satellite, the comparisons of mass and system envelope efficiencies change. The requirement for greater shield system thickness or for greater spacing off a curved component that possesses a small radius of curvature places more of the shielding material at a greater distance from the component and, hence, creates a larger required area of the shield. Shield systems that require equal areal densities to achieve the same protection level in a flat configuration become very sensitive to their thickness when utilized to protect curved components or to protect against "side attack" of flat components. The current program has chosen two propulsion components, a pressure line and a propellant tank, as the two components for demonstration of the superiority of FCS systems over MLI.

Figures 10 and 11 present comparisons between the two MLI systems, the three 0.44 lb/ft3 foam/face sheet FCS systems and the 3 lb/ft3 foam only FCS system for a 3/8" O.D. pressure line application and a 36" diameter propellant tank application, respectively. These plots present the data of the flat shield studies discussed above geometrically mapped onto coordinates of shield mass per unit length of pressure line vs. foam thickness or MLI spacing off the pressure line and shield mass per unit area of the protected tank surface as a function of foam thickness or thermal blanket spacing. These plots present the mass and system envelope efficiencies for all six systems when used in the two applications. The Green and Orange lines representing the Damage and Critical Damage Thresholds are plotted on the black lines that give the shield mass as a function of foam thickness or thermal blanket spacing for each of the shield systems.

Figure 10 compares the six systems as they would be used in the pressure line application. The lowest mass and smallest envelope system for shielding this component at the Damage Threshold level is the 3 lb/ft3 foam FCS system without face sheet. The next best system, which may be marginally

comparable, is the 0.44 lb/ft3 foam FCS system with 30 mil face sheet. These systems will likely require a mass of ~0.4 kg/m2/meter of tube length and have a thickness of 4 to 5 cm . The other two FCS systems require considerably greater mass (>0.6 kg/m2/meter of tube length) and spacing (>10 cm) to provide the DT protection level. Neither MLI nor Beta MLI is capable of providing the DT protection level, even with spacings beyond those that are practical (>30 cm) and masses (>0.8 kg/m2/meter of tube length) well above those of the FCS systems.

For shielding at the Critical Damage Threshold level the above two best FCS system and, perhaps the 0.44 lb/ft3 foam FCS system with 15 mil face sheet are competitive with masses in the range of 0.2 to 0.3 kg/m2/meter of tube length and thicknesses of 3 to 5 cm. MLI and Beta MLI have such variability in their behavior that it becomes difficult to make any statements regarding their ability to protect at the CDT level. The data show that MLI will require a spacing greater than 27 cm and will have a shield mass greater than 0.8 kg/m2/meter of tube length. It is not known how much greater. Beta MLI will require a spacing greater than 14 cm and a mass greater than 0.8 kg/m2/meter of tube length.

Figure 11 compares the six systems as they would be used in the propellant tank application. The lowest mass and smallest envelope system for shielding the tank at the Damage Threshold level is any of the 0.44 lb/ft^3 foam FCS systems without face sheet or with 15 mil or 30 mil face sheet. As the face sheet is added to these systems, they become thinner progressing from near 20 cm for the foam only system to ~ 14 cm for the 15 mil face sheet system to < 8cm for the 30 mil face sheet system. Shield masses for these three FCS systems are approximately 1.5 kg/m^2 of protected tank surface. MLI and Beta MLI cannot provide DT level of protection for this threat level.

For shielding the tank at the Critical Damage Threshold level, the 0.44 lb/ft3 foam FCS system appears to be best with a shield mass of ~1 kg/m^2 of protected tank surface and a thickness of ~6 cm. An MLI shield would have to have a mass greater than 1.2 kg/m^2 of protected tank surface and have a spacing of greater than 27 cm. A Beta MLI shield would have to have a mass greater than 1.6 kg/m^2 of protected tank surface and have a spacing of greater than 14cm.

Figure 10.

Comparison of the Damage Protection Provided by the Two MLI's with Three FCS Systems using 0.44 (lb/ft3) Flexible Polyimide Foam and an FCS System Using 3 (lb/ft3) Flexible Polyurethane Without a Face Sheet for Shielding a 0.375" OD Pressure Line
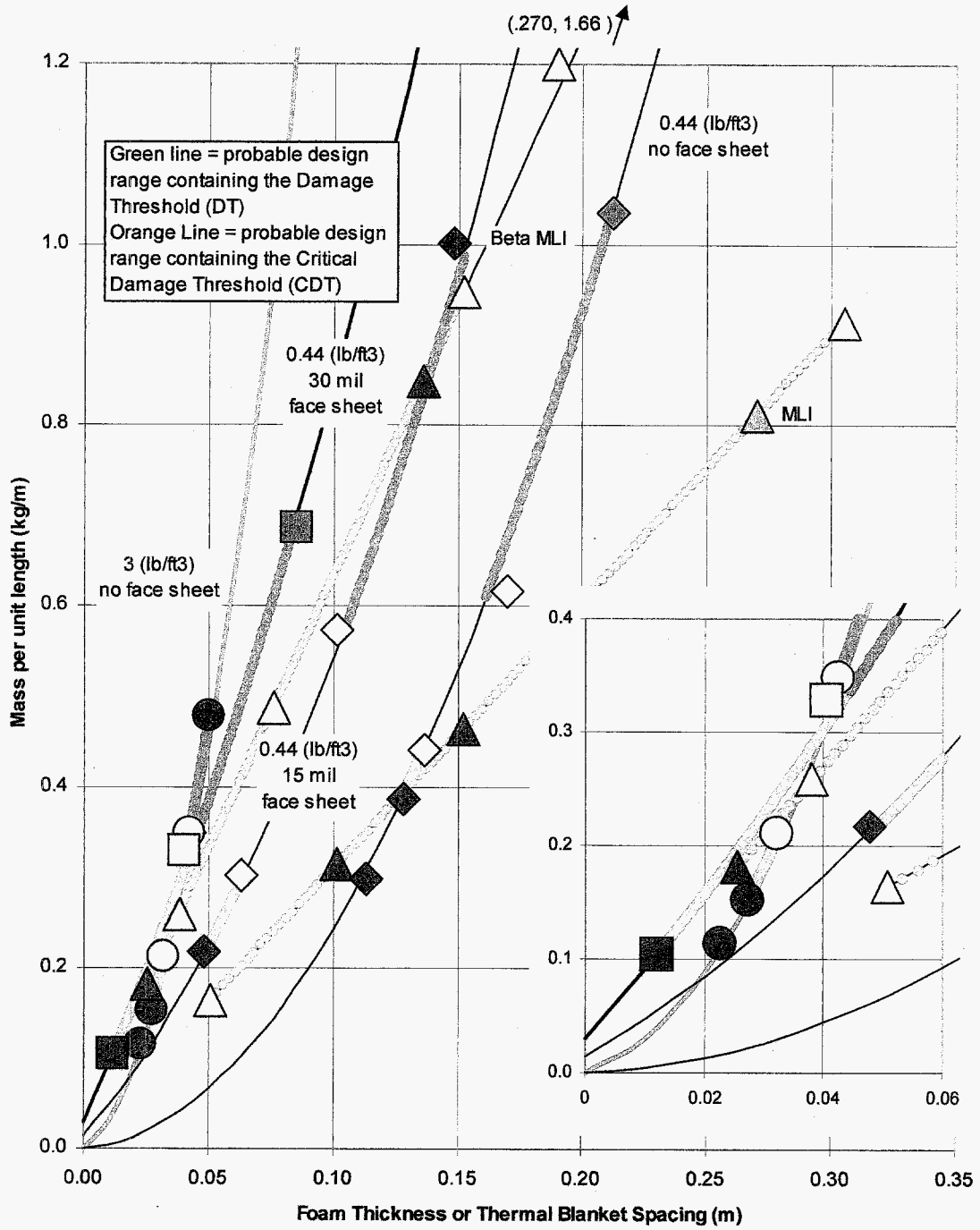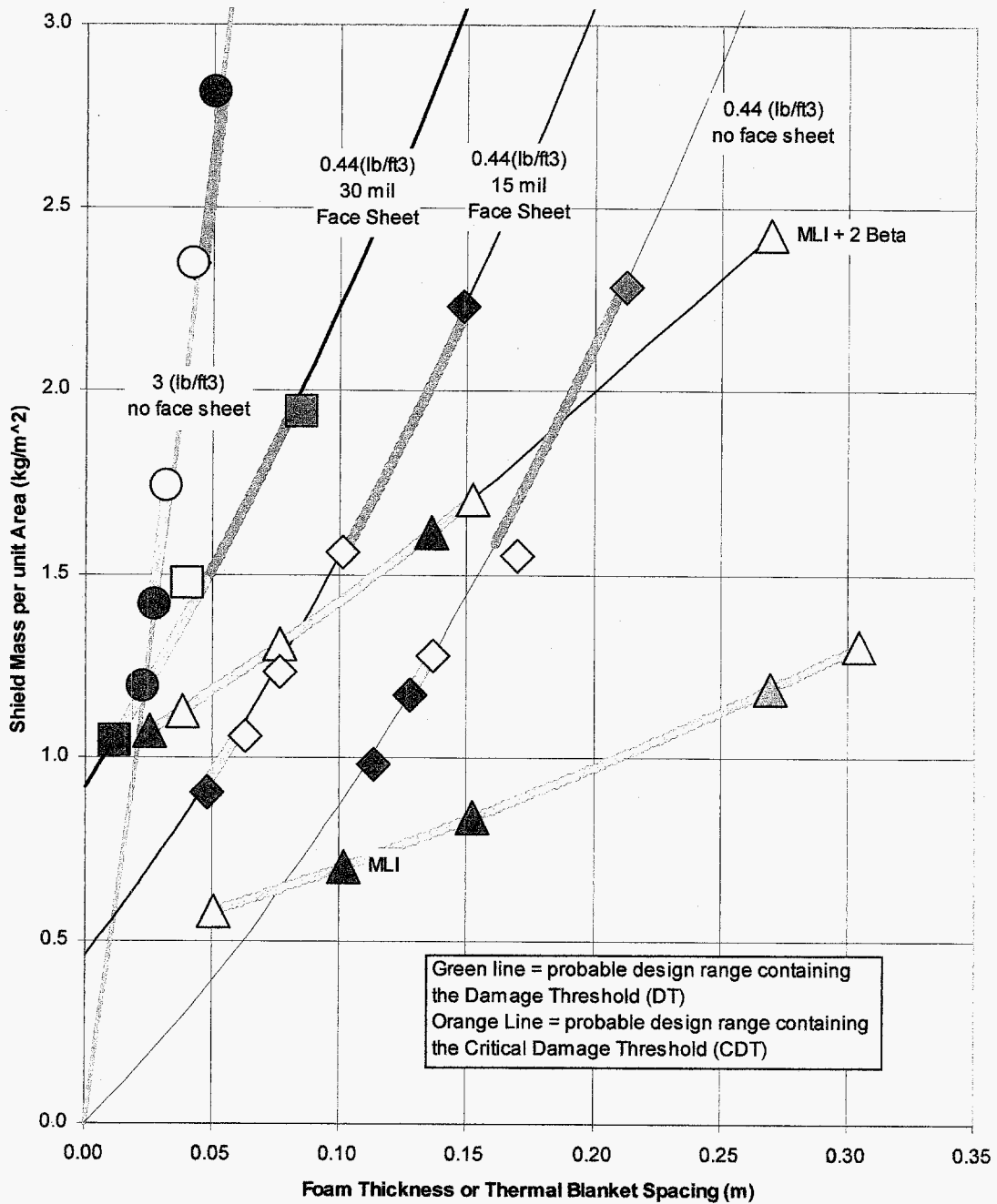
Figure 11.

Comparison of the Damage Protection Provided by the Two MLI's with Three FCS Systems using 0.44 (lb/ft3) Flexible Polyimide Foam and an FCS System Using 3 (lb/ft3) Flexible Polyurethane Without a Face Sheet for Shielding a 36" Diameter Propellant Tank

THE SUPERIORITY OF FCS SYSTEMS OVER MLI SYSTEMS

THERMAL CONTROL PERFORMANCE OF FCS COMPARED WITH MLI

CONCLUSIONS