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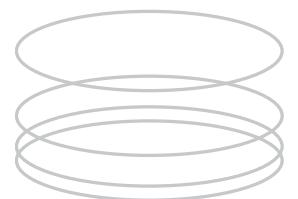
SMART SPACE TECHNOLOGY

High Power Inflatable Raoiator for Thermal Rejection

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HIGH POWER INFLATABLE RAOIATOR FOR THERNAL REJECTION
FROM SPACE POWER SYSTEMS

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by

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ABSTRACT

The present study has investigated a novel concept of an inflatable radiator which **captures** burst heat from space-based defense systems during its short generation period and radiates it to space later over a longer period. During the operation phase, the radiator is extended out of the spacecraft and filled with steam generated by the waste heat. As the spacecraft continues orbiting the earth, the steam is condensed gradually. The radiator is retracted during condensation so as to maintain a constant saturation pressure, and is folded neatly into the spacecraft, ready for the next mission.

A preliminary design of the inflatable radiator has been performed during which various aspects of its operation were studied. The paper discusses the results of these studies including the choice and evaluation of candidate materials, design of the bag with the retraction, folding and drive mechanisms, the thermal, dynamic stability and survivability analyses.

1.0 INTRODUCTION

Space-based defense systems require large amounts of power for short periods of time, on the order of several megawatts in a few minutes. During their operation, the power generation and power consuming systems produce large amounts of waste heat which must be rejected. Earlier studies have shown conventional radiators to be inadequate for this purpose due to the large weight penalty. Numerous studies have been conducted over the past few years in an attempt to deal with the problem.

The present study has been conducted to investigate a novel concept of an inflatable radiator which captures the heat during the short generation period and radiates it to space later over a longer period. The original idea, described in a recent article [1] has resulted in an Air Force patent application by Mahefkey [2]. The main part of this radiator is an inflatable bag made of a strong, lightweight and specially coated fabric. During the operation phase, the radiator is extended out of the spacecraft and filled with steam generated by absorbing the waste heat. Then, as the spacecraft continues orbiting the earth, the steam is condensed gradually as heat is radiated into space. The radiator is retracted during condensation so as to maintain a constant saturation pressure, and is folded neatly into the spacecraft, ready to be extended again during the next mission. The concept is illustrated in Figure 1.

A radiator that can be kept packaged until needed has other distinct advantages in the space defense scenario. The large radiator areas required would otherwise create significant drag in the thin atmosphere at low orbits. The resulting deceleration translates directly into weight of propellant for station keeping.

Also, the satellite would be more vulnerable to tracking and being attacked if a highly-observable, large conventional radiator is attached to it. Furthermore, a
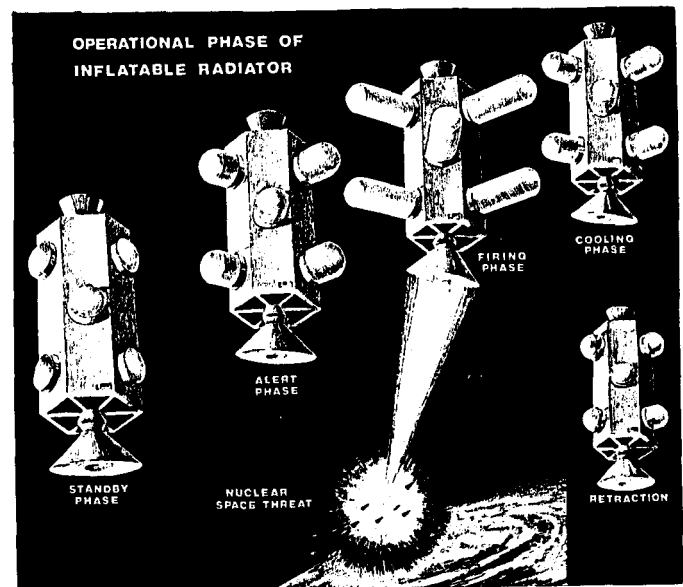

Figure 1. Operational Phase of HIRS

system with a packaged radiator is easier to harden to attack, especially to nuclear bursts in the vicinity. The packaged radiator is protected from meteoroid and space debris punctures. Thus, significant advantages result from using an expandable radiator; these advantages can make the difference between the satellite system being feasible or impractical.

This paper describes a feasibility study of the inflatable radiator concept, including preliminary design of the system and key components, material selection ar! evaluation, analysis of dynamic stability, thermal behavior and survivability. A test plan has been developed for ground testing of a prototype system.

2.0 SYSTEN DESCRIPTION

The High Power Inflatable Radiator System (HIRS) consists primarily of an inflatable bag made of thin, lightweight coated fabric. It employs water as the working fluid and is characterized by a high condensation heat transfer rate inside the radiator, low operating fluid mass due to the large latent heat of vaporization, and high radiator effectiveness due to near isothermal operation. It stores a substantial heat quantity during the peak power portion of the duty cycle, and rejects the stored heat during the cooling

and retraction phase. It offers minimum contamination to space sensors because the heat exchange medium is recycled rather than released into space.

The time phasing of the HIRS is outlined below:

	ALERT PHASE	FIRING PHASE	COOLING & RETRACTION PHASE
TIME, (in min)	0	2 6	100
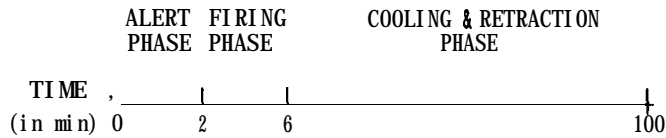
The space application for HIRS requires a polar orbit of 100 minutes. The Alert phase requires a small amount of water vapor to extend the radiator fabric bag and ready it for the weapon firing. This is done to keep the bag from bursting as a result of the high water vapor impulse developed in a relative short time during the Firing phase. Four minutes are allocated for the Firing phase but the radiator operates continuously only a small portion of this period. The remaining 94 minutes are used for cooling and retraction of the bag.

Figure 2 shows the radiator in its inflated condition. The cylindrical bag, 8' diameter x 40' long, is made from a Teflon-coated Kevlar fabric for maximum water impermeability. Selection of the material was based on earlier work [3,4]. A single seam along the cylinder is used. The fabric is formed into pleats to force systematic folding when it is pulled into storage. The position of the fabric bag is controlled by the balance between the internal steam pressure forcing it outward, and the restraining force of the six cables holding it back.
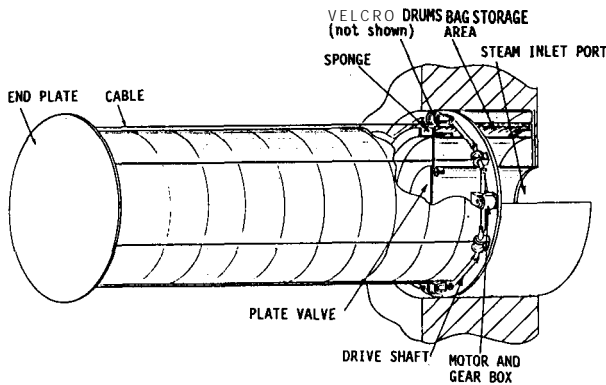

Figure 2. Inflatable Radiator in Fully Extended Position

Extension of the bag begins when a small mass of water vapor is injected into it, and the cable drums are released, so that the force on the end plate pulls it out of storage. As the bag extends, its material remains taut because of the restraining friction of Velcro-covered drums which wind up constant force clock springs as the fabric passes under them. The cable drums are on a one way roller clutch. They rotate free in the extend direction and lock to the gear motor shaft in the retract direction. The extended bag is now ready to accept the full mass of steam, 13.77 Kg (30.3 lbs.) at 75°C (167°F). When the bag is fully pressurized, a plate valve closes by means of return springs to prevent the return of uncondensed steam from the bag into the inlet port.

At the fully extended position, the bag's internal pressure is a maximum. As the vapor condenses on the bag's interior surface, the pressure drops and is sensed by a pressure transducer located inside. The transducer signals the gear motor to operate, winding in the cables and pulling the end plate until the internal pressure is restored. As the end plate moves in, the slack in the bag is taken out by the Velcro drums which exert a constant force on the bag at all times. This controls the gathering of the bag for storage in the area in back of the Velcro drums. A water recovery sponge is in front of the Velcro drums, and the bag is always taut as it passes over the sponge, allowing the latter to wipe the entire bag area. This winding and wiping continues until the end plate returns to the stowed position.

At this stage all the water collected from the bag has been absorbed in the sponge. As the end plate approaches the sponge, the sealing tube on the end plate covers the sponge retainer and seals the top surface. The sponge area is now completely sealed off. The end plate then continues to move in, squeezing the sponge. The only opening in the sponge area-is the water return line. The water is forced through a check valve in the water return line to the water-reservoir. When the sponge is completely squeezed the end plate hits a limit switch shutting off the gear motor. The water return check valve closes and the end plate returns to the stowed position by means of return springs on the seal ring. The sponge retainer returns to the stowed position by its return spring.

Breakdown of total radiator weight is as follows:

STRUCTURE	WT. LB.
Aluminum support structure	
Plate valve support	9
Sponge/retainer support	24
Drum Support	15
Plate valve	2
End plate	22
RADIATOR BAG (L'GARDE FABRIC #201)	90
MECHANISM	
Kevlar cables	8
Cable drums	
Brackets/small components	I
Bearings/U-joints	3
Drive shaft	18
Motor and gear box	35
Total	235 lb.

3.0 ANALYSIS

Several analyses were carried out under the present study, in support of the design. The most critical were the dynamic stability and thermal analyses. The results of these are summarized here. In addition, survivability issues were considered. Details have been described in Reference [5].

3.1 DYNAMIC STABILITY

The objective of the dynamic stability analysis has been to evaluate the effect of extending, pressurizing, and retracting of the inflatable radiator on the stability of the spacecraft. As the radiator is

extended out and pressurized there is a shift of mass from the inside of the spacecraft outward at a certain velocity, resulting in momentum transfer which in turn produces an impulse acting on the spacecraft. A similar effect occurs during the retraction process, although at a much slower rate, and hence the resulting forces are considerably smaller. To minimize this effect, identical bags are placed on opposite sides of the spacecraft, to operate in unison as shown in Figure l. Thus, equal and opposite impulses are generated during the extension and pressurization phases, which counter-balance each other. The balance may be somewhat off during the retraction phase, if the condensation rate differs from one bag to its opposite counterpart, as would be the case if one bag faced the sun and the opposite • away from the sun. However, the forces during the retraction phase would be small to begin with compared to those during the extension and pressurization phases.

In the analysis, a "worst case" situation was considered, when one bag fails and the one on the opposite side works. The forces calculated provide an upper limit. A real situation is highly unlikely to be quite so extreme. If a failure is detected in a bag prior to its deployment, the control strategy may call for not deploying its opposite counterpart.

In the Extension (Alert Phase) a small mass of steam is injected into the folded bag at time $t = 0$ which fills the available volume V_0 at pressure P_0. The steam begins to expand, pushing the bag outward. The pressure decreases with time and the velocity increases. At the end of the expansion, the cables have to brake the motion of the bag during which time the maximum force is transmitted to the spacecraft. Our preliminary desian relies on the flexibilitv of the cables to dissipate the kinetic energy. The-calculations show the maximum force transmitted to the spacecraft to be 3095 Newtons per bag. This considerable force is due to the abrupt stop of the bag as it becomes fully extended. Three options have been considered for reducing this force: 1) Reducing the mass of the the bag, which would be desirable all around; 2) Adding *more* "spring" action to the cables so as to brake the motion of the bag more gradually; 3) Designing a cable drive mechanism with the ability to recover the energy expanded during extension which would not only reduce the forces during extension but also the power required to retract the bag.

Forces during the Pressurization (Firing Phase) and Cooling/Retraction Phase were found to be 4.5 x 10⁻ and 2.8 x 10⁻ Newton, respectively, and therefore pose no serious problem.

3.2 THERMAL ANALYSIS

The objective of the thermal analysis has been to evaluate the abilitv of the radiator to condense the steam during the Retraction/Cooling Phase in the allotted time of 94 minutes or less. The rate of condensation will also determine the extent of projection of the bag out of the spacecraft at any given time, which reflects on its vulnerability to meteoroids and enemy attack.

The system under consideration is described schematically in Figure 3, showing a typical temperature distribution through the baa fabric wall and condensate film. Heat **flows** from **the** condensing steam at

temperature $T_s = 75^0C$ down the temperature gradient, and is radiated out to space from the outer surface of the bag.
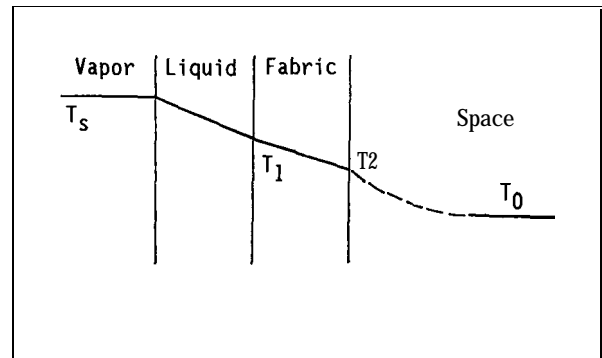

Figure 3. Temperature Profile in Condensation

Under quasi-steady conditions, the heat flux q is the same through the condensate film and the fabric, and is also equal to the radiant heat flux out. The following equations, therefore, apply:

Through the condensate:

$$q = h_c\left(T_s - T_1\right) \tag{1}$$

Through the fabric:

$$q = \frac{k_f}{D_f}\left(T_1 - T_2\right) \tag{2}$$

Out to space:

$$q = \sigma\epsilon\left(T_2{}^4 - T_o{}^4\right)$$

$$= \sigma\epsilon\left(T_2{}^2 + T_o{}^2\right)\left(T_2 + T_o\right)\left(T_2 - T_o\right)$$

$$= h_r\left(T_2 - T_o\right) \tag{3}$$

where:

σ = Stefan-Boltzmann constant, 5.672 x 10⁻⁸ W/m²K⁴

ϵ = fabric outer surface emissivity

h_r = radiant heat transfer coefficient,

k_f = thermal conductivity of the fabric

D_f = thickness of the fabric

h_c = condensation heat transfer coefficient

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By calculating the driving temperature differences from equations (1) through (3) and adding them up, it is possible to express the heat flux in terms of the overall temperature difference $(T_s - T_o)$ and the overall resistance to heat transfer:

$$q = \frac{T_s - T_o}{\frac{1}{h_r} + \frac{D_f}{k_f} + \frac{1}{h_c}} \quad (4)$$

The three terms in the denominator of equation (4) describe the resistances to heat transfer in radiation to space, in conduction through the fabric and in condensation through the water film, respectively. Each may be calculated to evaluate their relative magnitudes.

Using the expression of equation (3) we obtain for the radiative resistance, R_r:

$$R_r = \frac{1}{h_r} = \frac{1}{\sigma\epsilon\left(T_2^2 + T_o^2\right)\left(T_2 + T_o\right)} \quad (5)$$

Let us assume an outer surface emissivity $\epsilon = 0.9$ and an ambient temperature $T_0 = 240^0K$ for a 400 Km orbit. The outer surface temperature, T_2, will have to be guessed, and the guess verified later. A good initial guess would be $T2 = T_s - 1^0K = 347^0K$. Then:

$$R_r = 0.1875 \ \frac{m^2K}{W} \quad (6)$$

Assuming the fabric thickness $D = 0.011$ inch and its thermal conductivity kf = 0.35 W/m-K we obtain from (4) for the resistance to conduction:

$$R_f = \frac{D_f}{k_f} = 0.008 \ \frac{m^2K}{W} \quad (7)$$

To evaluate the resistance to heat transfer through the condensate film, we have to estimate its thickness. The thickness varies with the condensate build-up; the largest resistance would occur when all the vapor has condensed. Let us assume that the entire 13.77Kg of water is spread uniformly over the radiator inner surface. Since on the average *only* half the radiator is extended, we will assume an 8' diameter x 20' long cylindrical surface. The film thickness would then be:

$$D_c = \frac{13.77 \times 10^{-3}(m^3)}{\pi \times 8 \times 20 \ (ft^2) \times (0.3048 \ m/ft)^2} = 0.295 \ mm \quad (8)$$

The condensation resistance is therefore:

$$R_c = \frac{1}{h_c} = \frac{D_c}{k_c} = \frac{0.295 \times 10^{-3}m}{0.65 \ (W/mk)} = 0.00045 \ \frac{m^2k}{W} \quad (9)$$

In comparing the three resistances of equations (7), (8), and (9) it is clear that the dominant one is the radiative resistance, and the others are negligible. From equation (4) we find the heat flux:

$$q = \frac{348 - 240}{0.187 + 0.0008 + 0.00045} = 574 \ W/m^2 \quad (10)$$

From (1) we obtain:

$$\left(T_s - T1\right) = \frac{q}{h_c} = 574 \times 0.00045 = 0.26^{\circ}K \quad (11)$$

and from (2):

$$\left(T_1 - T2\right) = \frac{qD_f}{k_f} = 574 \times 0.008 = 0.46^{\circ}K \quad (12)$$

hence: $T2 = T_s - 0.46 - 0.26 = 347.3^0K$ and our original assumption about T2 was quite close.

The total amount of heat which must be rejected to condense the 13.77 Kg of steam is:

$$Q = 13.77 (Kg) \times 2221.4 \ KJ/Kg = 30590 \ KJ \quad (13)$$

The total heat flux through the radiator surface, assuming only half the area is exposed, on the average:

$$qA = 574 \ W/m^2 \times \pi \times 8 \ ft \times 20 \ ft \times (0.3048 \ m/ft)^2 = 26,800 \ W \quad (14)$$

The time required to condense all the steam is therefore 30,590/26.8 = 1141 sec or 19 minutes which is quite compatible with the available time.

In the foregoing analysis we have considered the quasi-steady condensation with heat rejection by radiation into space, which was assumed to have an average effective temperature of 240^0K. This temperature was arrived at by considering the shape factor of the radiator with respect to the sun, the earth and deep space at a typical position while in a 400 km orbit. We should, however, be concerned with two extreme cases. One is the possibility of freezing on a portion of the bag exposed to and radiating into deep space; the other is the possibility of overheating of a portion of the bag exposed to direct radiation from the sun.

The above analysis was repeated with T_0 set equal to zero, and showed the inner surface temperature, T_1, to be 347.7^0K. Thus there is no danger of freezing even under this extreme condition. It is shown that in all cases, the wall temperature remains within 1^0K of the saturation temperature, while the condensation heat flux is maintained.

A portion of the bag exposed to solar radiation normal to its surface will have the following heat balance:

$$q \ \text{net out} = \epsilon\sigma T_2^4 - \alpha Q_s \quad (15)$$

where $Q_s = 1353 \ W/m^2$ is the insolation in space and α is the solar absorptivity of the bag outer surface. Based on the earlier results $T_2 \approx T_s$ and the long wave radiative flux is 748.7 W/m^2. Equation (15) indicates that in order to have a net heat-flux out one must have:

$$748.7 - 1353 \ \alpha > 0$$

or

$$\alpha < 0.55 \quad (16)$$

Thus, to support any heat loss in direct solar radiation, the bag outer surface must reflect more than 45% of the incident solar radiation. This should be easy to achieve with an appropriate reflective coating. As the angle between the solar radiation and the radiator surface becomes more acute, the solar heat input decreases and more condensation heat can be rejected.

4.0 SURVIVABILITY ISSUES

Survivability is defined as the degree to which a system is able to avoid or withstand a hostile environment, natural or man-made, without suffering an abortive impairment of its ability to accomplish its designated mission. Survivability for the High Power Inflatable Radiator is enhanced by minimum exposure time to the space environment, its physical and thermal protective enclosure while not in use, and the material used in the inflatable bag. A single inflatable bag rather than segmented or -disposable- bags was adopted because of its simpler design, minimum space contamination near the satellite sensors, lack of complexities in using this design, and the belief that the single bag is as survivable as the others for many hazards.

The natural environment which could affect the survivability of the inflatable radiator includes meteoroid and space debris, atomic oxygen, and ultraviolet radiation. It was assumed for many years that the aspect of the Low Earth Orbital (LEO) environment most degrading to materials were ultraviolet radiation and meteoroids. With the advent of frequent space flights and opportunity to examine returned surfaces, it now appears that effect of atomic oxygen may be more serious than previously thought. LEO here is considered from 200 to 500 KM and is well within the proposed orbit for the inflatable radiator.

4.1 METEOROIDS AND SPACE DEBRIS

One of the biggest arguments against using an inflatable radiator was its survivability in a meteoroid and space debris environment. Each of these represent a threat to any satellite system, particularly at LEO. In a tradeoff between survivability, payload weight, reliability, payload packaging efficiency and cost factors the inflatable radiator has many advantages over a conventional radiator. In the HIRS, the inflatable bag is made of Kevlar - one of the strongest man-made fabrics available today. In addition, the bag is only exposed for a very short time - the design exposure was for 100 minutes but the thermal analysis shows that it may be as short as 20 minutes. During most of that time, the bag is partially retracted.

Calculations of the probability of meteoroid hits have been conducted for the HIRS. Number of hits, holes and total leak area were calculated for two radiators, each 8' diameter x 40' long, exposed to meteoroids under two scenarios: 1) ten years with one test firing per year; 2) one battle phase with five firings per day for three days. The details of the calculation are given in Ref. [5]. The results are summarized as follows:

10 Annual Test Firings:

Hits	418
Holes	85
Leak Area (cm^2)	0.107

Battle Phase (5 firings per day x 3 days):

Hits	627
Holes	127
Leak Area (cm^2)	0.161

In both cases, the total leak area is very small, less than a quarter of a square centimeter. This analysis is overly conservative for two reasons. First, these calculations were based on assumptions that the material has properties close to those of lead; actually the coated fabric is made of Kevlar fibers. which show much greater strength. Secondly, man-made debris is two to five times as prevalent as natural meteoroids; the upper limit of five was chosen for this analysis. Therefore, it is estimated that the values listed are an upper limit for the leak area created by meteoroids.

4.2 Atomic Oxygen

Atomic oxygen is an area of current interest but not fully understood. It appears as though the degradation of materials caused by it results from a complex chemical oxidation process and from a kinetic impact of the material with atomic oxygen causing ablation. Controlled testing in space has been minimal in terms of time, but there has been sufficient empirical data to make NASA and other scientists very concerned about the survivability of satellite materials in space. The observed phenomena of atomic oxygen degradation of materials (organic, inorganic, and metallic) have included effects such as surface erosion, weight loss, oxidation, changes in absorptivity and emissivity and in some cases even changes in bulk properties.

Data obtained from various NASA sources (principally Marshall Space Flight Center and Lewis Research Center) indicated that Kevlar coated with PTFE, which is L'Garde's 201 fabric composition, showed little or minimal degradation to atomic oxygen. With a minimal exposure of the inflatable bag to space, and the empirical data available on the material, it appears that the fabric is ideally suited to survive in the atomic oxygen environment.

4.3 Ultraviolet Radiation

The design life of the inflatable radiator material is 20 years on earth. Since the bag has limited exposure in space during its 10 year life cycle (between 9 and 43 hours) it is expected to exceed a 10 year life. Similar materials are being used in sport stadiums and regularly undergo the extremes of winter and summers with varying loads due to wind, rain and snow. The L'Garde 201 fabric exceeds the specifications for these fabric coverings for large sport stadiums.

The L'Garde 201 fabric has undergone 600 hours of UV radiation in a QUV chamber and its tensile strength was not affected. The Kevlar was covered on both sides with Polytetrafluoroethylene (PTFE) and on one side with UV blockers to reduce material degradation. UV blockers have their limitations and Kevlar is sensitive between 300 and 450 nm. The most effective screen is a coating opaque to UV radiation.

4.4 Threat Environment

The threat environment here is man-made to include DEW, KEW weapons and nuclear blasts. Since the SDI technology is still under development and much of DEW & KEW weapons effects are classified and in most cases

unproven in space, survivability under enemy attack was not considered in depth in this study.

4.5 Conclusion

The inflatable radiator bag is protected thermally and physically over 99.99% of the time in the spacecraft interior. The bag is exposed to space a minimum of 9 hours and a maximum of 43 hours during a 10 year life span. Meteoroids are not a severe issue. The low probability of meteoroid hits and the strength of the inflatable bag virtually ensures its survivability. The atomic oxygen problem is greatly minimized by the proven combination of Kevlar and PTFE coatings. The material uses ultraviolet blockers to reduce the UV radiation degradation of the fabric. The 20 year design life of the bag and its proven utility in extremes of heat and cold-under varying load conditions gives confidence for its use in space. The man-made threats are mainly unproven in space and are classified which makes a survivability analysis quite difficult at this time.

5.0 TEST PLAN

A comprehensive test plan has been formulated under the present study of the HIRS to generate design parameters, validate design concepts, verify design criteria, determine design margins, identify failure modes, and to verify manufacturing processes. The tests were divided into three main categories: Basic Material Tests, Component Tests and System Tests, to be conducted in that order [5].

First, tests of the basic coated fabric are conducted to validate its suitability for the radiator bag. These tests include the thickness of the bare fabric and coating, tensile stress and elongation, tearing resistance and water permeability • to minimize weight while maintaining water tightness and strength. They also include accelerated life tests under folding and unfolding, temperature and solar radiation exposure. A test of surface radiative properties is also included in this category.

Under component testing, the performance of different parts of the radiator is evaluated. A test has been included for the mechanical properties of seams in the bag made of the coated fabric. The Velcro strips used to keep the bag taut during retraction and the sponges are also evaluated.

Last, system tests are conducted on a model bag made of the candidate material. They include folding and unfolding under simulated pressure and temperature conditions and simulated wiping; steam injection with a liquid nitrogen cooled shroud to simulate space conditions; and water recovery efficiency. These system tests come close in many respects to testing of a flight unit and should provide sufficient information for the design of such a unit.

6.0 CONCLUSION

After a thorough review of nine inflatable radiator concepts previously developed by L'Garde [4], a retractable, cylindrical configuration with a stationary sponge was chosen as the best candidate. It encompassed many of the best qualities of the other candidates. Concepts previously considered involving rotation of the bag were found impractical due to the added complexity. A preliminary design of the Inflatable Radiator based on the above concept was carried out.

The material chosen to fabricate the inflatable bag was the L'Garde 201 fabric based on PTFE coated Kevlar. This fabric was chosen from among several others because of its high strength, light-weight, water impermeability and environmental resistance which makes it the best candidate to survive the effects of atomic oxygen, UV radiation and meteoroids. For terrestial applications, it has a proven 20 year design life.

Several design options were examined for the extension, retraction and water recovery mechanisms with the object of making them simple, lightweight and versatile. The retraction mechanism in our design involves six lightweight Kevlar cables for compressing the bag under pressure, and Velcro drums for keeping the unfolded portion of it taut. The stationary sponge wipes the taut portion of the bag as it goes by while being retracted. The same cables are used to apply force on the end plate of the bag to squeeze the sponge, and to restrain the plate when the bag is extended.

Analyses were conducted to evaluate the radiator dynamic stability, thermal behavior and survivability. The forces produced during pressurization and retraction were found to be quite manageable in terms of the spacecraft dynamic stability, and the force during extension can be taken care of by a properly designed drive mechanism. The thermal analysis shows the time allocated for condensation to be more than adequate, and examination of extreme situations rules out the possibility of freezing or overheating of the bag. A third analysis indicates a high probability of survival under both natural and man-made threat environment.

A system ground test was devised. The test approach is to first test basic materials which leads into component testing to prove the parts of the system will work. The components are then integrated into system test.

Overall, the study has shown the Inflatable Radiator to be a viable concept for capturing and rejecting waste heat from space-based defense systems.

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