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THERMACORE, INC.
LANCASTER, PENNSYLVANIA

FINAL REPORT

PHASE I

LOW-MASS, INTRINSICALLY-HARD HIGH TEMPERATURE RADIATOR

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PREPARED FOR:

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1.0 EXECUTIVE SUMMARY

Thermacore, Inc. of Lancaster, Pennsylvania has completed a Phase I SBIR program under subcontract no. 9-X29-H0659-2 to investigate the use of layered ceramic/metal composites in the design of low-mass hardened radiators for space heat rejection systems. The program is being monitored by the Los Alamos National Laboratory (LANL) for the Strategic Defense Initiative Organization (SDIO).

This effort evaluated the use of layered composites as a material to form thin-walled, vacuum leaktight heat pipes. The heat pipes would be incorporated into a large heat pipe radiator for waste heat rejection from a space nuclear power source. This approach forms an attractive alternative to metal or silicon-carbon fiber reinforced metal heat pipes by offering a combination of low mass and improved fabricability.

Titanium has been shown to have a yield strength too low at 875°K to be a useful radiator material. A silicon carbide fiber reinforced titanium material produced by Textron, Inc. appears to have sufficient strength at 875°K, but the Textron composite cannot be welded due to the continuous fibers, and the preferred heat pipe working fluid (potassium) has been demonstrated to be incompatible with silicon carbide at 875°K. Moreover, titanium does not appear to be acceptable for radiators subjected to anticipated laser threats.

As part of this effort, Thermacore performed composite material evaluations on combinations of refractory metals and ceramic powders. Layered composite tube samples with wall thicknesses as thin as 0.012" were developed by Thermacore and United Technologies Research Center (UTRC), East Hartford, Connecticut. Fabrication experiments were performed that demonstrated the weldability of layered composites. Two titanium/titanium diboride composite tubes were successfully fabricated into potassium heat pipes and operated at temperatures in excess of 700°C. A hybrid composite tube was also fabricated into a potassium heat pipe. The tube was composed of alternating layers of niobium-1% zirconium foil and layers of a mixture of titanium powder and titanium diboride powder. The hybrid composite wall heat pipe and one of the titanium composite heat

pipes are currently undergoing a 5000 hour compatibility life test. The life testing work is being performed in addition to meeting all of the Phase I contract requirements.

Hypervelocity impact tests were performed on 1" diameter, 0.024" wall thickness tubes. Two layered composite tubing samples and one CP Grade 2 titanium tube was tested by impacting them with 7 km/sec, 1 mm diameter aluminum pellets. A layered titanium/titanium diboride composite tube survived impact with less damage than the CP Grade 2 titanium metal tube, but the niobium/titanium/titanium diboride hybrid composite tube sustained greater damage. A higher fabrication temperature for the hybrid composite tube is anticipated to improve the impact resistance of this design.

Analysis has been completed to estimate the specific mass for an 875°K hardened radiator using this approach. Depending on the threat levels, a specific mass of 3 to 5 kg/m² appears to be feasible.

Niobium or molybdenum composite transverse heat pipes appear to show promise for providing the lowest weight radiator design. UTRC believes that fabrication of 1 cm wide, square cross-section niobium composite heat pipe tubes will be achievable in wall thicknesses of 0.005" to 0.010". The niobium composite tubes will be over 20% lighter than a plain niobium tube, will have improved hypervelocity impact resistance, will have 20 to 30% higher yield strength, and will possess improved fabricability compared to plain niobium tubing.

This Phase I study has verified the feasibility of using layered composites for forming thin-walled, light-weight heat pipe tubes for use in hardened space radiators. Additional development work in Phase II will be required to demonstrate the application of this technology in a full scale SP-100 hardened radiator configuration.

2.0 INTRODUCTION

2.1 BACKGROUND

Hardened space radiator designs are currently being evaluated by SDIO for SP-100 waste heat rejection systems. These systems must be lightweight, survivable against debris and threats, and capable of radiating several megawatts of waste heat at temperatures near 875°K.

Trade studies performed by aerospace design firms have shown that liquid metal heat pipes play a key role in weight minimization and high performance for these radiators. Hardenability against hostile threats is important for radiator survivability.

Heat pipes are sealed, evacuated devices that transfer heat by evaporating and condensing a working fluid. They are passive devices which require no external power for their operation. Figure 1 shows a cut-away view of a typical heat pipe. Heat is input to the evaporator section and evaporates some of the working fluid. This increases the local vapor pressure and causes the vapor flow back to the evaporator section by the capillary pressure which is developed by the wick structure.

Metal-ceramic composites are currently under evaluation for use in high temperature space radiator designs because they show promise for low-weight and increased strength at elevated temperatures. All composite materials developed to date have significant drawbacks that make these materials undesirable for heat pipe envelope materials. Close examination of a leading candidate material illustrates these problems.

A titanium alloy composite material reinforced with a SiC fiber has been developed by Textron Specialty Materials/Subsidiary of Textron, Inc. (Lowell, MA) that is being considered for use as a heat pipe radiator material. Figure 2 shows a photomicrograph of this material. It consists of silicon carbide fibers encased in a titanium alloy matrix. Testing of this material shows it to be strong enough for a heat pipe envelope material at 875°K, unlike pure titanium. It is also a relatively low-weight material that is potentially compatible with alkali metal working fluids.

Figure 1. Cut-away view of a heat pipe

Figure 2. Textron composite material photomicrograph

However, potential loss of vacuum-tight seal due to grain growth makes this titanium alloy composite material undesirable as a heat pipe vessel material. For weight minimization, wall thicknesses on the order of 0.005" to 0.010" are required to reduce radiator mass to a specific mass of 3 to 5 kg/m², which is a design goal for these radiators. Materials such as titanium are susceptible to grain growth at temperatures near operating conditions. For thin-walled vessels, this can result in failure of the heat pipe due to loss of the vacuum-tight seal at a grain boundary after the grain size has bridged from wall-to-wall. Grain growth can occur from wall-to-wall in the region between SiC fibers in much the same way as it does in pure titanium metal. Furthermore, titanium melts at a relatively low temperature, reducing its survivability for SDIO applications. Lastly, fabrication of tube shapes such as square tubes with circumferential fibers is not currently possible.

Thus, the problem is to develop an advanced composite material capable of being formed into thin-walled, vacuum-tight vessels that is also compatible with alkali metal heat pipe working fluids, survivable to refractory metal temperatures, and is easily fabricable into space radiators. This Phase I effort is concerned with a solution to the problem. A new composite material is being developed which shows promise for meeting SDIO requirements for a lightweight radiator wall material.

Thermacore has been coordinating an effort with United Technologies Research Center (UTRC) of East Hartford, Connecticut to develop a niobium composite material for use in hardened radiators. In a meeting between UTRC and Thermacore technical personnel, Thermacore proposed a concept to replace a fiber-reinforced metal matrix with a layered, hot isostatically pressed (HIP) particulate ceramic-reinforced metal matrix. UTRC then proceeded to successfully develop a fabrication approach which provides excellent results. Thermacore has applied for a patent on the structure.

A sketch of this wall structure is shown in Figure 3. The wall consists of alternating layers of refractory metal foil and layers of ceramic powder interspersed in refractory metal powder. The composite is formed by wrapping around a mandrel, followed by hot isostatic pressing. The layered composite has many advantages compared to the Textron titanium composite. First, the layering approach is believed to make possible a thin-walled (0.005") vessel which will remain leaktight at elevated temperatures for extended periods. Leaktightness occurs because the

Figure 3. Layered composite wall structure

ceramic-reinforced layers will form boundaries between the metal layers, which tends to inhibit crystal grain growth. Secondly, the structure was believed to behave similarly to plywood in that the layering would increase damage tolerance potential to micrometeoroids and space debris.

The approach should be favorable for energy absorption of micrometeoroids and debris colliding with the wall. At any interface between two adjacent layers, one component of the impact-induced pressure pulse is reflected, and the remainder is transmitted through the interface. This process proceeds through each layer of the composite. The multiple reflections and transmissions may either amplify or reduce the pressure pulse. Figure 4 shows a typical damage profile to a layered material [Ref: NASA SP-8042]. Although there is no accurate method of predict the degree and type of damage to the composite material, it is possible to predict the effect of the composite design on the reduction of the pressure pulse. A composite wall can be designed with microstructural characteristics such that delamination of layers will occur upon impact, thus absorbing the resulting shock. Hypervelocity particle testing is necessary to confirm the capability of a particular design.

Additionally, this material is believed to be survivable to a melting temperature in excess of 2400°C, if fabricated in molybdenum or niobium composites. This compares with 1600°C for the titanium alloy. A high melting temperature is critical for survivability under directed energy threats. Lastly, the boron-containing ceramics may be useful as a neutron absorber for some types of threats. Boron 10 isotope is widely used for control rods for nuclear reactors and as a shield for nuclear radiation [Ref: CRC Handbook of Chemistry & Physics, 68th ed].

An example of a composite design using boron carbide ceramic, niobium metal powder and foil illustrates the advantages of this approach. Boron carbide reduces the density of the niobium composite to a value 85% greater than the titanium composite. The specific modulus of elasticity of the niobium composite at 875°K is 70% that of the titanium composite in the transverse direction, but the yield strength of the niobium composite is expected to be significantly higher. Niobium itself has two to three times the yield strength of the titanium composite in the transverse direction. Therefore, a similar wall thickness of the new composite will exhibit equal or superior characteristics in every respect compared to the titanium composite.

Figure 4. Impact test results for a layered material

2.2 TASK STATEMENT

The principal objective of this Phase I SBIR program was to demonstrate the feasibility using advanced metal/ceramic composites for hardened radiators. A central issue is to determine if the thin-walled material can be formed into a vacuum-tight vessel. Fabrication of one or more vacuum-tight, tubular heat pipes approximately one inch in diameter and six inches long was completed, using material supplied by United Technologies Research Center (Task 4). A second objective was to integrate this material into a complete hardened radiator design to provide a basis for prototype development in Phase II (Task 2). Hypervelocity particle bumper capability of this composite was measured by experiment (Task 5). Lastly, alternative metal-ceramic composites were evaluated to determine which combinations of refractory metal powders, metal foils, and ceramic powders formed a favorable layered composite design (Task 3).

This report documents the effort on each of the above tasks. The principal conclusions are summarized in the following section.

3.0 CONCLUSIONS AND RECOMMENDATIONS

The purpose of this Phase I effort was to study the feasibility and potential benefits of using layered metal-ceramic composites to form lightweight heat pipes for integration into a hardened radiator for space waste heat rejection at 875°K. The program was fully successful. It has been demonstrated that intrinsically-hard, thin-walled layered composite heat pipes can be fabricated inexpensively using the selected approach, and that an improved low-mass, 875°K hardened radiator can be designed using this approach.

The specific conclusions reached during the Phase I program are listed below.

1. Layered composites show promise for reducing the mass of space-based hardened waste heat rejection equipment. A specific mass of 3 to 5 kg/m² appears to be attainable, depending on the threat level. Improved resistance to micrometeoroid and debris, neutron-absorbing capability, a 700°C higher failure temperature and easier fabrication are also anticipated. Niobium composite heat pipes are predicted to be 20% lighter than plain niobium versions, and should have equal or superior properties in every respect compared to plain niobium.
2. Three 1" diameter layered composite potassium heat pipes were fabricated and tested at temperatures in excess of 700°C. A wall thickness of 0.012" was demonstrated in Phase I; thicknesses between 0.005" to 0.010" are believed to be achievable in Phase II. Life testing has been initiated with one titanium/titanium diboride heat pipe and one niobium foil/titanium powder/titanium diboride powder heat pipe. Life testing is being performed to demonstrate long-term survivability and working fluid compatibility. As of the report date, over 700 hours of operation have been demonstrated with no degradation or failure of the devices.

3. Hypervelocity impact tests were performed on layered composite tubes. A titanium/titanium diboride tube survived impact by a 1 mm dia., 7 km/sec aluminum pellet with less damage than a plain CP Grade 2 titanium tube, but a niobium foil/titanium powder/titanium diboride powder tube sustained greater damage. Incomplete diffusion of the niobium due to a low fabrication temperature is believed to be the cause of this result. Further generations of composite tube developments are required to determine the best fabrication temperature and pressure for particular metal-ceramic composites.
4. Materials evaluation studies were completed on combinations of refractory metals and ceramics. Molybdenum/ceramic and niobium/ceramic composites show potential for providing the lightest weight hardened radiator design. Both alternatives are recommended for fabrication technology development in Phase II, although current fabrication technology does not permit fabrication of composites in molybdenum.
5. Welding has been demonstrated as the method of joining 0.012" thick heat pipe tubes to end caps and fill tubes. This enables simple low-cost fabrication.
6. Detailed design and fabrication of a full-scale 875°K radiator segment is recommended to demonstrate this technology in the size and geometry required for hardened space radiators.

4.0 REQUIREMENTS AND GOALS

This section of the report summarizes the requirements for a full-scale 2.4 MW space-based hardened heat rejection system for an SP-100 application. Table 1 defines these requirements. Threat levels are established by a specification known as SUPER. The SUPER specification is a classified document and has not been included as part of this report. The full-scale radiator design work was based on a range of threat levels so that the design results can also remain unclassified.

TABLE 1. Full Scale Radiator Design Requirements

<u>REQUIREMENT</u>	
Total Power	2.4 MW
Heat Rejection Temperature	875°K
Size Limit	Shuttle bay dimensions
Weight	3 to 5 kg/m ³ , depending on threat level
Micrometeoroid/Debris	NASA statistical model
Threats	SUPER specification
Life	>10 years
Reliability	99%

5.0 DISCUSSION

This section describes the work done to complete the tasks described in Section 2.2. The work performed and the results from each of these tasks are summarized in the following discussion.

5.1 TASK 2 -- PROTOTYPE RADIATOR DESIGN

A design was completed for a full-scale 2.4 MW, 875°K hardened radiator for an SP-100 application, based on the requirements shown in Table 2. Figure 5 shows a conceptual drawing of the SP-100 space nuclear power system, including cylindrical radiator assembly. The goal of Task 2 of the current effort was to develop a hardened version of this radiator using layered composite technology. Space Power, Inc. (SPI) of San Jose, California assisted Thermacore in the design effort. The following discussion summarizes the results of the design work. The detailed report is provided in Appendix A.

TABLE 2. Full Scale Radiator Optimized Specifications

Number of Core Heat Pipes	30
Core Heat Pipe OD	7.5 cm
Graphite Fin Thickness	0.025 cm
Bumper Fin Heat Pipe Center-to-Center Spacing	6 cm
Bumper Fin Heat Pipe Radiating Length	22.5 cm
Areal Specific Mass (Basis, Titanium)	3.36 kg

5.1.1 Radiator Configuration

Previous design studies on an unhardened version of this radiator were completed by SPI under NASA Contract NAS3-25208. As shown in Figure 6, the radiator design is cylindrical, and consists of a parallel series of core heat pipes up to 9 m long.

NASA Advanced Radiator Concepts

2.4 MW, 875 K Heat Rejection Radiator for Space Nuclear Power Systems

Sponsor: **NASA**
National Aeronautics and
Space Administration

Lewis Research Center

By:

Space Power, Incorporated

Figure 5. 2.4 MW advanced radiator for SP-100

Figure 6. Full scale radiator cut-away view

To each core heat pipe, a large number of small wrap around transverse heat pipe fins are attached. Thus, each core heat pipe forms a heat pipe header. Figures 7 and 8 show the configuration of these heat pipes. Each transverse heat pipe contains a sintered wick in the evaporator section and an annular screen wick elsewhere. Each transverse heat pipe has a graphite conducting fin brazed to it, and each assembly is brazed to a core heat pipe. The transverse heat pipe and graphite fin assembly provides protection for core heat pipes from micrometeoroid and debris damage. This design was first optimized under the current program in order to minimize mass, in the absence of threats.

Table 2 shows the results of the design trade study. Many variables were optimized simultaneously in order to determine the minimum mass design. Specifications that were varied included spacing of transverse heat pipes on core heat pipes, number of core heat pipes, diameter of core heat pipes, and graphite fin thickness. It was determined that, in the absence of threats, a specific mass of 3.36 kg/m^2 is achievable using titanium as a heat pipe wall material.

Threats were then considered. An unclassified discussion of the effects of threat on radiator design is summarized below.

5.1.2 Effects of Threats on Radiator Design

Three types of threats were considered in this discussion: laser, x-ray and pellet threats.

Laser attack on a radiator will result in large-scale heating of illuminated surfaces of the radiator. With currently available coatings, the heat flux absorbed by the transverse heat pipes will be large enough to dry out the wick in the illuminated region. The heat pipes will then rise in temperature until melting occurs or until radiation equals incident absorbed heating. Calculations show that molybdenum or niobium composite transverse heat pipes form the lightest weight designs that can survive a laser threat without melting of the heat pipe wall.

X-rays have the effect of inducing destructive shock waves in the graphite radiation fins and then into the underlying heat pipes. SPI believes that the graphite fin design itself will prevent x-ray damage to the radiator. However, coatings for the graphite fins may be required to protect against exceptionally high threat levels.

Figure 7. Fin heat pipe configuration with thermal diode option

Total Mass of VHC Fins = 52.8 kg.

Figure 8. Transverse heat pipe/graphite fin configuration

Pellet threats appear to be circumvented best by means of building redundancy into the radiator design. Space Power calculations show that it is not feasible to protect an unsegmented radiator of the type shown in Figure 6 against the anticipated pellet threats. A segmented design of the radiator will be done in Phase II. This design will reduce the projected area of the core heat pipes by using a greater number of highly segmented components to carry heat to the transverse heat pipes.

A way to reduce the projected area of critical components is to reduce the overall size of the radiator. There is a great deal of interest in a survivable 40 kW system such as that required for SSTs or radar satellites. SPI has completed calculations which show that pellet threats can be reasonably managed in this application. Since the 40 kWe power level is more likely to have near-term military application than the 100 kWe (2.4 MW_{th}) hardened radiator system, it is recommended that the Phase II segmented design be based on the 40 kW initiative being advocated by AFWL at Kirtland Air Force Base, New Mexico.

Radiator mass calculations were performed based on use of niobium and molybdenum bumper fin heat pipes. Calculations showed that a specific mass of nearly 5 kg/m² will be achievable with niobium or molybdenum, assuming a 0.025 cm transverse heat pipe wall thickness. It appears to be feasible to fabricate composite tubes with a wall thickness of 0.013 cm to 0.025 cm (0.005" to 0.010"). Tubing fabrication development work and trade studies in Phase II will be necessary to identify the minimum mass bumper fin specifications for a full-scale radiator.

5.2 TASK 3 - MATERIALS EVALUATION

Work has been completed to evaluate candidate materials for use in layered composite 875°K space radiator components. Materials properties were collected for refractory metals listed in the Aerospace Structural Metals Handbook with a similar or higher melting point than titanium. Materials were being evaluated for maximum service temperature, survivability, strength, density, thermal properties, fabricability, and cost. A critical property for buckling stability of thin-walled vessels is Young's Modulus. The composite material Modulus was estimated using the Halpin-Tsai equations. Derivation of the composite modulus is shown

in Appendix B. Buckling can become a limiting factor in the design of thin-walled vessels under internal vacuum.

A figure of merit for buckling of thin-walled tubes is the one-third power of the elastic modulus divided by the composite material density. Maximizing this ratio will provide for the lightest weight heat pipe tube wall. Appendix C shows a derivation of this figure of merit. Calculations were performed to estimate composite materials properties to provide a basis for materials selection in Phase II.

The figure of merit was determined for 4500 combinations of refractory metal foils, refractory metal powders, and ceramic powders having a melting point greater than that of titanium. A computer program was written to perform the calculations and rank the highest combinations in tabular form. Table 3 shows the refractory metals that were considered, and Table 4 shows the ceramics that were included.

The lowest weight composite design proved to be one which used titanium foil, titanium powder, and boron carbide powder. Carbide-containing ceramics are strong and lightweight, but they are not compatible with potassium in a heat pipe operating at 600°C. [Personal communication, Mr. Jack Devan, ORNL, 1989.] If the metal foil liner on the inside of the heat pipe envelope is not continuous, a compatibility problem would then result. Of the foil/powder combinations using a ceramic without carbides, a design using titanium foil, titanium powder, and titanium diboride powder appears to be the lowest weight composite design. This design would be 7.6% heavier than one with boron carbide.

Combinations of dissimilar metals for the foil and powder must be considered cautiously because of the possibility of creating low melting point eutectics. Table 5 shows leading candidates for thin-walled composite for heat pipe walls. Combinations of metals which form low-melting eutectics have been excluded from this list. Since the melting point of the metals generally increases as the figure of merit decreases, the heavier choices are potentially capable of handling higher threat levels. The particular composite chosen for a given application is dependent on the threat level.

TABLE 3. Candidate Refractory Metals and Properties

Material	Elements	Density (g/cc)	E @ RT (KSI)	E @ 600°C (KSI)
----- METAL POWDERS / FOILS -----				
1. COLUMBIUM/ NIOBIUM	Cb/Nb	8.66	15.0	14.0
2. FS - 85	Cb-28Ta-10W-1Zr	10.6	15.0	14.0
3. FS - 80	Cb-1Zr	8.57	15.0	14.0
4. B - 66	Cb-5Mo-5V-1Zr	8.43	15.0	14.0
5. Cb - 752	Cb-10W-2.5Zr	9.01	15.0	12.0
6. Cb - 132	Cb-20Ta-15W-5Mo-ZR-C	10.7	15.0	14.0
7. Cb - 129Y	Cb-10W-10Hf-0.1Y	9.50	16.0	16.0
8. TITANIUM	Ti	4.54	16.0	10.0
9. MOLYBDENUM	Mo	10.2	45.0	45.0
10.	Mo-0.5Ti	10.6	17.0	15.0
11. TZM	Mo-0.5Ti-0.08Zr	10.2	46.0	38.0
12.	Mo-30W	11.9	50.0	50.0
13.	Mo-50Re	13.8	53.0	53.0
14. TANTALUM	Ta	16.6	28.0	26.0
15. HAYNES ALLOY/ Ta - 782	Ta -10W	16.8	21.0	21.0
16. T - 111	Ta-8W-2.4Hf	16.7	26.0	24.0
17. T - 222	Ta-9.6W-2.4Hf-0.01C	16.7	26.0	24.0
18. TUNGSTEN	W	19.3	59.0	52.0
19. TUNGSTEN-HfC	W-0.35Hf-0.025C	19.1	59.0	52.0
20. TUNGSTEN- 4Re-HfC	W-4Re-0.35HfC-0.025C	19.1	59.0	52.0
21.	W-25Re	19.8	60.0	60.0
22. HAFNIUM	Hf	13.3	20.0	20.0
23. VANADIUM	V	6.37	20.0	20.0
24. RHENIUM	Re	20.5	68.0	59.0
25. Zr 702	Zr (CHEMICAL GRADE)	6.48	14.0	14.0
26.	Zr-0.010Hf	6.51	14.0	14.0
27. IRIDIUM	Ir	22.5	79.0	79.0
28. OSMIUM	Os	22.7	80.0	80.0
29. RHODIUM	Rh	12.4	46.0	46.0
30. RUTHENIUM	Ru	12.3	60.0	60.0

TABLE 4. Candidate Ceramics and Properties

<u>Ceramic Powder</u>	<u>Elements</u>	<u>Density (g/cc)</u>	<u>E @ RT (KSI)</u>	<u>E @ 600°C (KSI)</u>
1. Boron Nitride	BN	2.25	9.0	9.0
2. Boron Carbide	B ₄ C	2.52	54.0	54.0
3. Silicon Carbide	SiC	3.23	54.0	54.0
4. Titanium Diboride	TiB ₂	4.50	72.0	72.0
5. Zirconium Diboride	ZrB ₂	6.09	72.0	72.0

Based on the SUPER threat level, a niobium or a molybdenum composite tube will be required. Of these choices, molybdenum offers the advantages of 13% lower weight, 142°C higher melting point, several times the yield strength at operating temperature, and a better thermal expansion coefficient match to the graphite fins. However, UTRC reports that the etching acids used in fabrication of the tubes will dissolve molybdenum. Thus, a modified fabrication approach would be required to fabricate the heat pipes from molybdenum composites. Since relative ease of fabrication of each composite will affect the selection of niobium versus molybdenum, fabrication technology development of both alternatives is recommended in Phase II.

5.3 TASK 4 - PROOF-OF-CONCEPT HEAT PIPE

Thermacore has worked closely with United Technologies Research Center (UTRC) technical personnel to develop thin-walled composite tubes using the selected approach. Seven tubes were delivered to Thermacore (Table 6) during the Phase I effort. A discussion is presented of the results of experiments conducted with each sample.

The first tube sample delivered to Thermacore was a one-inch diameter, six-inch long, 0.012" wall, titanium/boron carbide composite tube. Thermacore determined that the tube sample was vacuum leaktight, and then subjected the tube to five thermal cycles between room temperature and 600°C. The sample remained leaktight. A CP-2 titanium endcap was then welded into one end of the tube; the weld was found to be vacuum leaktight. Although the weld area appeared less shiny than a pure

TABLE 5. Leading Candidate Composite Designs

<u>Foil Type</u>	<u>Metal Powder Type</u>	<u>Ceramic Powder Type</u>	<u>Composite Density (kg/m³)</u>	<u>Composite Modulus at 25°C (N/m²)</u>	<u>Figure of Merit ($E^{1/3}/\rho$)</u>	<u>Melting Point Range (°C)</u>
Ti	Ti	TiB ₂	4532	1.62 x 10 ¹¹	1.19	1668
TZM or Mo	Ti	TiB ₂	6230	2.24 x 10 ¹¹	0.97	1668 to 2610
V	V	TiB ₂	5977	1.91 x 10 ¹¹	0.95	1900
Zr	Zr	TiB ₂	6064	1.47 x 10 ¹¹	0.86	1852
TZM or Mo	V	TiB ₂	7126	2.44 x 10 ¹¹	0.87	1900 to 2610
Nb-1% Zr	Ti	TiB ₂	5740	1.61 x 10 ¹¹	0.94	1668 to 2468
Nb-1% Zr	Nb-1% Zr	TiB ₂	7805	1.52 x 10 ¹¹	0.68	2468
TZM or Mo	TZM or Mo	TiB ₂	9003	3.51 x 10 ¹¹	0.78	2610

TABLE 6. Composite Tube Specifications and Test Results

<u>Tube No.</u>	<u>Wall Thickness (Inches)</u>	<u>Foil</u>	<u>Ceramic Powder</u>	<u>Metal Powder</u>	<u>Leaktight</u>
1	0.012	CP-2 Ti	B ₄ C	CP-2 Ti	Yes
2	0.012	Nb-1% Zr	TiB ₂	CP-2 Ti	Yes
3	0.012	CP-2 Ti	TiB ₂	CP-2 Ti	Yes
4	0.024	CP-2 Ti	TiB ₂	CP-2 Ti	N/A (Hypervelocity Particle Test Article)
5	0.024	Nb-1% Zr	TiB ₂	CP-2 Ti	N/A (Hypervelocity Particle Test Article)
6	0.012	CP-2 Ti	TiB ₂	CP-2 Ti	Yes
7	0.014	Nb-1% Zr	TiB ₂	CP-2 Ti	Yes

metal weld, the presence of compressed layers of boron carbide did not result in a porous weld. The result is significant because welding is a generally simpler, less costly, and more reliable method of closure as compared to brazing or other methods.

The welded tube was then thermally cycled to 700°C, and remained vacuum leaktight.

The second tube sample contained Nb-1%Zr foil, with TiB₂/CP-2 Ti powder layers. It was tested for vacuum leaktightness on the helium mass spectrometer leaked detector and found to be vacuum leaktight. The sample was then returned to UTRC at their request.

The third tube sample was identical to the first, except that TiB₂ replaced the B₄C as the ceramic powder. The sample was produced with short pure titanium metal foil ends to facilitate welding. This feature was retained in subsequent tubing generations. This sample was also found to be vacuum leaktight.

Tubes 4 and 5 were subjected to hypervelocity particle impact tests. Results of these tests are presented in Section 5.4.

Composite tube Nos. 3, 6 and 7 were successfully fabricated into potassium heat pipes. A description of the procedure and results for each tube is described below.

Titanium endcaps and a titanium fill tube were welded into the ends of the third tube sample, after two wraps of 120 x 120 mesh molybdenum screen were placed inside to form the wick structure. After welding, a pinhole leak was discovered near the center of the tube which is believed to have developed during welding and handling.

A decision was made to try to seal the leak by brazing. A thin coating of Microbraz 10 mixed with Microbraz cement was painted on a 0.1 inch diameter region surrounding the leak location. The heat pipe was then heat treated at 1050°C for five minutes in a vacuum furnace. The heat pipe was then found to be vacuum leaktight using a helium mass spectrometer leak detector. Microscopic examination of the brazed area showed that the braze seemed to cover the outer surface of the tube, without a significant penetration into the tube wall. The ceramic/metal powder layer beneath two 0.001" layers of titanium foil may have assisted in preventing braze from penetrating the thin tube wall. This result is encouraging because brazing or similar approaches will probably be required to join full-scale radiator heat pipes to each other as well as to fins and other radiator components. The layered composite wall structure thus appears to be potentially easy to fabricate into a radiator as compared to a purely metallic structure. Tube 3 was then filled with potassium and the fill tube was sealed. The heat pipe was then operated in a vacuum at temperatures in excess of 700°C with no signs of dryout.

Sixth and seventh heat pipe tubes were also fabricated into heat pipes. Each of these tubes were found to be vacuum leaktight. At Thermacore's suggestion, UTRC made a successful effort to maintain a continuous foil liner on the inside of each of these tubes. This was done in order to separate the ceramic from the potassium working fluid. The tubes were lined with 120 x 120 mesh molybdenum screen and assembled into heat pipes, as was done for the third tube. A 0.5 gram piece of titanium was placed in the niobium heat pipe to act as a getter for oxygen and

nitrogen. Each heat pipe was then filled with about 5 grams of potassium working fluid, and the fill tubes were sealed. Each heat pipe operated isothermally in a vacuum system at temperatures in excess of 700°C. Figure 9 shows the niobium composite heat pipe in operation.

The heat pipes made from tubes no. 6 and 7 were then mounted in a vacuum system for life testing. As of the report date, the heat pipes have been operating for over 700 hours with no signs of degradation, dryout, or noncondensable gas generation. The life testing work is being done as work in addition to the successful completion of all Phase I tasks. The demonstrated compatibility of refractory metal/ceramic composite heat pipes with potassium at 875°K establishes a firm basis for use of this approach in Phase II to develop a lightweight, intrinsically-hard radiator prototype.

TABLE 7. Hypervelocity Impact Test Results

<u>TUBE TYPE</u>	<u>TUBE WALL MATERIAL</u>	<u>WALL THICKNESS (in)</u>	<u>PELLET DIA. (in)</u>	<u>PELLET VELOCITY (km/sec)</u>	<u>REAR WALL LEAKTIGHT</u>
Composite Tube 4	Ti/Ti/TiB ₂	0.024	0.04	6.95	Yes
Composite Tube 5	Nb/Ti/TiB ₂	0.024	0.04	6.94	No
CP Grade 2 Ti Tube	TI	0.024	0.04	6.62	Yes

5.4 TASK 5 - HYPERVELOCITY PARTICLE RESISTANCE TESTING

The fourth and fifth tube samples were subjected to hypervelocity impact tests. The wall thickness on these tubes was 0.024 inches. One tube contained Nb-1%Zr foil, and the other contained commercially pure Grade 2 (CP-2) titanium foil. Both tubes were reinforced with layers of a mixture of titanium diboride powder and CP-2 titanium powder. The tube samples were inspected, and were delivered to the University of Dayton Research Institute for impact testing. Each tube was impacted with a

THIS SIDE UP

Figure 9. Niobium layered composite heat pipe in operation

nominally 7 km/sec aluminum sphere 1 mm in diameter, representative of the kinetic energy of metallic space debris in earth orbit. A plain CP Grade 2 titanium tube was also tested. A summary of test conditions and results is shown in Table 7. A detailed test report is shown in Appendix D.

The impact test results were favorable. In each case, the pellet penetrated the front tube wall, but did not penetrate the rear tube wall. A helium mass spectrometer leak detector was used to check the rear wall of each tube for vacuum leaktightness. The rear wall of the titanium composite tube (No. 4) was vacuum leaktight, but the niobium/titanium composite tube (No. 5) contained a pinhole leak in the rear wall. The niobium/titanium composite tube was as well bonded, since UTRC reported that similar temperatures were used in hot isostatic pressing for all tubes. A higher HIP temperature should produce more favorable results. Figures 10 and 11 show a photograph of the tube rear wall for tubes No. 4 and 5, respectively. Delamination of powder layers is evident in each case and is probably responsible for absorbing the impact without an actual penetration of the rear wall.

The plain titanium tube rear wall also remained leaktight after impact, but had greater and larger impact craters than the composite tube. Figure 12 shows a cross section of the rear wall of the plain titanium tube after impact. This impact velocity of the aluminum pellet was 5% lower than for the composite tubes, due to a seal failure in the launching tube during the test.

The front wall of each tube formed a circular hole in the impact region. Figures 13 and 14 show cross-sectional photographs of the edge region for the fourth and fifth composite tubes, respectively. Impact occurred from the top surface, in each case. The titanium composite tube (No. 4) formed a hole of minimal curling of foil at the edges. The Nb-1% Zr/Ti/TiB₂ tube (No. 5) produced a hole with a region curled, delaminated foil on both the outside and inside of the tube. On this tube, delaminated foil extends back as much as 0.6 cm from the centerline of the impact. The larger size and quantity of rear wall impact dimples and lack of vacuum leaktightness of the rear wall for the fifth tube would suggest that curling and microscopic delamination of the tube wall correspond with less favorable bumping protection. This information will be used in development of successive generations of composite tubes.

Figure 10. 80 x photograph of Ti/Ti/TiB₂ tube rear wall impact area

Figure 11. 80 x photograph of Nb-1%Zr/Ti/TiB₂ tube rear wall impact area

Figure 12. 80 x photograph of CP Grade 2 titanium tube
rear wall impact area

Figure 13. 40 x photograph of Nb-1% Zr/Ti/TiB₂ tube front wall impact region

Figure 14. 40 x photograph of front wall impact region of Ti/Ti/TiB₂ tube

APPENDIX A

PROTOTYPE RADIATOR DESIGN REPORT

SPI-48-1

CONTRACT # 1063

FINAL REPORT

SURVIVABLE RADIATOR

JUNE 16, 1990

PREPARED FOR:

THERMACORE, INC
LANCASTER, PENNSYLVANIA

PREPARED BY:

LESTER L. BEGG & ERIK H. ENGDAHL

SURVIVABLE RADIATOR
FINAL REPORT

1.0 INTRODUCTION

The NASA-Lewis Advanced Radiator Concepts Program emphasized the development of low-mass, reliable radiator systems that could operate for ten years. SPI won the down selection into Phase III of the program using an 875 K heat pipe radiator system that achieved a specific mass of 4.1 kg/m². The design emphasized the use of very high conductivity graphite fiber composite fins which were used as radiant fins. Because of their excellent conductivity, large spacings between heat pipes were bridged with these relatively light fins. Since the radiator was designed for a civilian, NASA mission, it was not hardened to withstand hostile threats.

It was found that with relatively minor changes, the existing radiator design could be modified to make it survivable against high levels of x-ray, pellet and laser threats. An optimization run was made to determine the most mass-effective combination of heat pipe header diameters, heat pipe header spacing, transverse heat pipe spacing and graphite fin thickness.

2.0 OPTIMIZATION STUDY

An optimization study was made of the radiator system to determine the best combination of component spacings and thicknesses. The figure of merit to be used as a basis of comparison was taken to be kW of energy radiated per kg of radiator mass (kW/kg). Table 2.1 shows the results of varying the number and diameter of the heat pipe headers. Since the thermal throughput per pipe decreased when using an increased number of heat pipes, smaller diameter heat pipes were used as the number of pipes increased. The temperature drop through pipes was determined and factored into the radiant capacity of the radiator. The smaller temperature drop of the systems with more pipes, however, was not able to overcome the mass of additional pipes.

HEAT PIPE DELTA T'S
(2m condenser)

REV. 0, 2/13/90 pip-16

#PIPES	Q/PIPE	DIA	EVAP L*	TOTAL DT	AVE T	MASS #		CORR L	CORR M	RAD PWR, MASS
						9m Cond L				
	(KW)	(CM)	(CM)	(C)	(K)	(kg)		(m)	(kg)	(KW/kg)
30.0	80.0	5.5	132.4	Sonic Limited						
30.0	80.0	6.5	112.0	35.87	839.1	4.62	7.50	3.93	20.44	
30.0	80.0	7.5	97.1	23.50	851.5	5.23	7.07	4.22	18.96	
30.0	80.0	8.5	85.6	13.00	856.0	5.85	6.92	4.61	17.34	
30.0	80.0	9.5	76.6	16.30	858.2	6.46	6.85	5.04	15.87	
35.0	68.6	5.5	113.4	66.30	808.1	3.91	8.73	3.81	40.00	
35.0	68.6	6.5	96.0	28.60	846.4	4.53	7.24	3.73	18.39	
35.0	68.6	7.5	83.2	20.70	854.3	5.14	6.98	4.09	16.78	
40.0	60.0	5.5	99.3	44.40	830.6	3.85	7.81	3.39	47.70	
40.0	60.0	6.5	84.0	24.60	850.4	4.46	7.11	3.60	16.65	
40.0	60.0	7.5	72.8	18.90	856.1	5.08	6.92	3.99	15.03	
40.0	60.0	8.5	64.2	16.54	858.5	5.69	6.84	4.42	13.58	
45.0	53.3	5.5	88.2	35.48	839.5	3.80	7.48	3.21	46.59	
45.0	53.3	6.5	74.7	22.09	852.9	4.41	7.02	3.52	15.17	
45.0	53.3	7.5	64.7	17.75	857.3	5.03	6.88	3.92	13.60	
45.0	53.3	8.5	57.1	15.86	859.1	5.64	6.82	4.36	12.24	
50.0	48.0	5.5	79.4	30.40	844.6	3.76	7.30	3.10	45.46	
50.0	48.0	6.5	67.2	20.40	854.6	4.37	6.97	3.45	13.31	
50.0	48.0	7.5	58.2	16.93	858.1	4.99	6.85	3.87	12.41	
50.0	48.0	8.5	51.4	15.39	859.6	5.60	6.80	4.31	11.14	

*Heat Flux = 35 W/cm²

Table 2.1

In general, the kW/kg value decreased as the number of heat pipe headers increased. The best figures of merit for each pipe grouping is summarized below:

# Pipes	Min Pipe Dia (cm)	kW/kg
30	7.5	18.96
35	6.5	18.39
40	6.5	16.65
45	6.5	15.17
50	6.5	13.91

While Table 2.1 does show some smaller pipe diameters than the minima presented above, the vapor velocity in these smaller pipes was too high for them to be considered as credible heat pipe candidates. As seen above, minimizing the number of heat pipe headers seems to maximize the mass efficiency of the radiator system. In order to economize calculational effort, the results of the 30, 40 and 50 heat pipe header runs were taken forward into the next level of calculations.

Table 2.2 shows the detailed analysis of the case of 30 heat pipe headers. Three heat pipe header diameters were evaluated: 7.5 cm; 8.5 cm; and 9.5 cm. The temperature drop through the transverse heat pipe fins was also calculated as a function of the spacing between them. Fewer heat pipe fins meant that each fin had to carry more thermal load, hence a larger temperature drop through it. For each heat pipe header diameter and transverse heat pipe fin spacing, the thickness of the attached graphite conduction fin was varied to; 0.020 cm (0.008"); 0.025 cm (0.010"); 0.050 cm (0.020"); and 0.075 cm (0.030"). While thicker graphite conducting fins led to increased radiator mass, the thicker fins minimized the conduction temperature loss.

Table 2.2, 1/7

HEAT PIPE FIN DELTA T's (heat pipe hdr L=3m)

# Heat Pipe Headers = 30.0									
Wall Material: Tiedens = 4.5									
Heat Pipe Header Dia (cm) = 7.5									
Wall Thermal Conductivity = 0.19									
T = 851.5									
Wick Therm Cond = 0.30									
CONDENSER									
EVAPORATOR									
WALL									
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NOTE: (1) BASE FOR PIPE HEAD, PIPE HEADERS
(2) GRAPHITE CONDUCTING FIN

TEMP (K)	LENGTH (cm)	WIDTH (cm)	THICK (cm)	HEAT REJ/ FIN (W)	FIN END TEMP (K)	FIN AVE TEMP (K)	HEAT REJ/ HP PER (MW)	MASS/ HP PER (kg)
17.2	0.00	2.50	0.00	27.38	841.04	845.63	38.57	1.41
17.2	0.00	2.50	0.00	27.44	841.00	845.56	38.77	1.41
17.2	0.00	2.50	0.00	27.55	840.95	845.50	38.98	1.41
17.2	0.00	2.50	0.00	27.66	840.90	845.44	39.18	1.41
17.2	0.00	2.50	0.00	27.76	840.85	845.38	39.38	1.41
17.2	0.00	2.50	0.00	27.87	840.80	845.32	39.58	1.41
17.2	0.00	2.50	0.00	27.97	840.75	845.26	39.78	1.41
17.2	0.00	2.50	0.00	28.08	840.70	845.20	39.98	1.41
17.2	0.00	2.50	0.00	28.18	840.65	845.14	40.18	1.41
17.2	0.00	2.50	0.00	28.29	840.60	845.08	40.38	1.41
17.2	0.00	2.50	0.00	28.39	840.55	845.02	40.58	1.41
17.2	0.00	2.50	0.00	28.50	840.50	844.96	40.78	1.41
17.2	0.00	2.50	0.00	28.60	840.45	844.90	40.98	1.41
17.2	0.00	2.50	0.00	28.71	840.40	844.84	41.18	1.41
17.2	0.00	2.50	0.00	28.81	840.35	844.78	41.38	1.41
17.2	0.00	2.50	0.00	28.92	840.30	844.72	41.58	1.41
17.2	0.00	2.50	0.00	29.02	840.25	844.66	41.78	1.41
17.2	0.00	2.50	0.00	29.13	840.20	844.60	41.98	1.41
17.2	0.00	2.50	0.00	29.23	840.15	844.54	42.18	1.41
17.2	0.00	2.50	0.00	29.34	840.10	844.48	42.38	1.41
17.2	0.00	2.50	0.00	29.44	840.05	844.42	42.58	1.41
17.2	0.00	2.50	0.00	29.55	840.00	844.36	42.78	1.41
17.2	0.00	2.50	0.00	29.65	839.95	844.30	42.98	1.41
17.2	0.00	2.50	0.00	29.76	839.90	844.24	43.18	1.41
17.2	0.00	2.50	0.00	29.86	839.85	844.18	43.38	1.41
17.2	0.00	2.50	0.00	29.97	839.80	844.12	43.58	1.41
17.2	0.00	2.50	0.00	30.07	839.75	844.06	43.78	1.41
17.2	0.00	2.50	0.00	30.18	839.70	844.00	43.98	1.41
17.2	0.00	2.50	0.00	30.28	839.65	843.94	44.18	1.41
17.2	0.00	2.50	0.00	30.39	839.60	843.88	44.38	1.41
17.2	0.00	2.50	0.00	30.49	839.55	843.82	44.58	1.41
17.2	0.00	2.50	0.00	30.60	839.50	843.76	44.78	1.41
17.2	0.00	2.50	0.00	30.70	839.45	843.70	44.98	1.41
17.2	0.00	2.50	0.00	30.81	839.40	843.64	45.18	1.41
17.2	0.00	2.50	0.00	30.91	839.35	843.58	45.38	1.41
17.2	0.00	2.50	0.00	31.02	839.30	843.52	45.58	1.41
17.2	0.00	2.50	0.00	31.12	839.25	843.46	45.78	1.41
17.2	0.00	2.50	0.00	31.23	839.20	843.40	45.98	1.41
17.2	0.00	2.50	0.00	31.33	839.15	843.34	46.18	1.41
17.2	0.00	2.50	0.00	31.44	839.10	843.28	46.38	1.41
17.2	0.00	2.50	0.00	31.54	839.05	843.22	46.58	1.41
17.2	0.00	2.50	0.00	31.65	839.00	843.16	46.78	1.41
17.2	0.00	2.50	0.00	31.75	838.95	843.10	46.98	1.41
17.2	0.00	2.50	0.00	31.86	838.90	843.04	47.18	1.41
17.2	0.00	2.50	0.00	31.96	838.85	842.98	47.38	1.41
17.2	0.00	2.50	0.00	32.07	838.80	842.92	47.58	1.41
17.2	0.00	2.50	0.00	32.17	838.75	842.86	47.78	1.41
17.2	0.00	2.50	0.00	32.28	838.70	842.80	47.98	1.41
17.2	0.00	2.50	0.00	32.38	838.65	842.74	48.18	1.41
17.2	0.00	2.50	0.00	32.49	838.60	842.68	48.38	1.41
17.2	0.00	2.50	0.00	32.59	838.55	842.62	48.58	1.41
17.2	0.00	2.50	0.00	32.70	838.50	842.56	48.78	1.41
17.2	0.00	2.50	0.00	32.80	838.45	842.50	48.98	1.41
17.2	0.00	2.50	0.00	32.91	838.40	842.44	49.18	1.41
17.2	0.00	2.50	0.00	33.01	838.35	842.38	49.38	1.41
17.2	0.00	2.50	0.00	33.12	838.30	842.32	49.58	1.41
17.2	0.00	2.50	0.00	33.22	838.25	842.26	49.78	1.41
17.2	0.00	2.50	0.00	33.33	838.20	842.20	49.98	1.41
17.2	0.00	2.50	0.00	33.43	838.15	842.14	50.18	1.41
17.2	0.00	2.50	0.00	33.54	838.10	842.08	50.38	1.41
17.2	0.00	2.50	0.00	33.64	838.05	842.02	50.58	1.41
17.2	0.00	2.50	0.00	33.75	838.00	841.96	50.78	1.41
17.2	0.00	2.50	0.00	33.85	837.95	841.90	50.98	1.41
17.2	0.00	2.50	0.00	33.96	837.90	841.84	51.18	1.41
17.2	0.00	2.50	0.00	34.06	837.85	841.78	51.38	1.41
17.2	0.00	2.50	0.00	34.17	837.80	841.72	51.58	1.41
17.2	0.00	2.50	0.00	34.27	837.75	841.66	51.78	1.41
17.2	0.00	2.50	0.00	34.38	837.70	841.60	51.98	1.41
17.2	0.00	2.50	0.00	34.48	837.65	841.54	52.18	1.41
17.2	0.00	2.50	0.00	34.59	837.60	841.48	52.38	1.41
17.2	0.00	2.50	0.00	34.69	837.55	841.42	52.58	1.41
17.2	0.00	2.50	0.00	34.80	837.50	841.36	52.78	1.41
17.2	0.00	2.50	0.00	34.90	837.45	841.30	52.98	1.41
17.2	0.00	2.50	0.00	35.01	837.40	841.24	53.18	1.41
17.2	0.00	2.50	0.00	35.11	837.35	841.18	53.38	1.41
17.2	0.00	2.50	0.00	35.22	837.30	841.12	53.58	1.41
17.2	0.00	2.50	0.00	35.32	837.25	841.06	53.78	1.41
17.2	0.00	2.50	0.00	35.43	837.20	841.00	53.98	1.41
17.2	0.00	2.50	0.00	35.53	837.15	840.94	54.18	1.41
17.2	0.00	2.50	0.00	35.64	837.10	840.88	54.38	1.41
17.2	0.00	2.50	0.00	35.74	837.05	840.82	54.58	1.41
17.2	0.00	2.50	0.00	35.85	837.00	840.76	54.78	1.41
17.2	0.00	2.50	0.00	35.95	836.95	840.70	54.98	1.41
17.2	0.00	2.50	0.00	36.06	836.90	840.64	55.18	1.41
17.2	0.00	2.50	0.00	36.16	836.85	840.58	55.38	1.41
17.2	0.00	2.50	0.00	36.27	836.80	840.52	55.58	1.41
17.2	0.00	2.50	0.00	36.37	836.75	840.46	55.78	1.41
17.2	0.00	2.50	0.00	36.48	836.70	840.40	55.98	1.41
17.2	0.00	2.50	0.00	36.58	836.65	840.34	56.18	1.41
17.2	0.00	2.50	0.00	36.69	836.60	840.28	56.38	1.41
17.2	0.00	2.50	0.00	36.79	836.55	840.22	56.58	1.41
17.2	0.00	2.50	0.00	36.90	836.50	840.16	56.78	1.41
17.2	0.00	2.50	0.00	37.00	836.45	840.10	56.98	1.41
17.2	0.00	2.50	0.00	37.11	836.40	840.04	57.18	1.41
17.2	0.00	2.50	0.00	37.21	836.35	840.00	57.38	1.41
17.2	0.00	2.50	0.00	37.32	836.30	839.94	57.58	1.41
17.2	0.00	2.50	0.00	37.42	836.25	839.88	57.78	1.41
17.2	0.00	2.50	0.00	37.53	836.20	839.82	57.98	1.41
17.2	0.00	2.50	0.00	37.63	836.15	839.76	58.18	1.41
17.2	0.00	2.50	0.00	37.74	836.10	839.70	58.38	1.41
17.2	0.00	2.50	0.00	37.84	836.05	839.64	58.58	1.41
17.2	0.00	2.50	0.00	37.95	836.00	839.58	58.78	1.41
17.2	0.00	2.50	0.00	38.05	835.95	839.52	58.98	1.41
17.2	0.00	2.50	0.00	38.16	835.90	839.46	59.18	1.41
17.2	0.00	2.50	0.00	38.26	835.85	839.40	59.38	1.41
17.2	0.00	2.50	0.00	38.37	835.80	839.34	59.58	1.41
17.2	0.00	2.50	0.00	38.47	835.75	839.28	59.78	1.41
17.2	0.00	2.50	0.00	38.58	835.70	839.22	59.98	1.41
17.2	0.00	2.50	0.00	38.68	835.65	839.16	60.18	1.41
17.2	0.00	2.50	0.00	38.79	835.60	839.10	60.38	1.41
17.2	0.00	2.50	0.00	38.89	835.55	839.04	60.58	1.41
17.2	0.00	2.50	0.00	39.00	835.50	838.98	60.78	1.41
17.2	0.00	2.50	0.00	39.10	835.45	838.92	60.98	1.41
17.2	0.00	2.50	0.00	39.21	835.40	838.86	61.18	1.41
17.2	0.00	2.50	0.00	39.31	835.35	838.80	61.38	1.41
17.2	0.00	2.50	0.00	39.42	835.30	838.74	61.58	1.41
17.2	0.00	2.50	0.00	39.52	835.25	838.68	61.78	1.41
17.2	0.00	2.50	0.00	39.63	835.20	838.62	61.98	1.41
17.2	0.00	2.50	0.00	39.73	835.15	838.56	62.18	1.41
17.2	0.00	2.50	0.00	39.84	835.10	838.50	62.38	1.41
17.2	0.00	2.50	0.00	39.94	835.05	838.44	62.58	1.41
17.2	0.00	2.50	0.00	40.05	835.00	838.38	62.78	1.41
17.2	0.00	2.50	0.00	40.15	834.95	838.32	62.98	1.41
17.2	0.00	2.50	0.00	40.26	834.90	838.26	63.18	1.41
17.2	0.00	2.50	0.00	40.36	834.85	838.20	63.38	1.41
17.2	0.00	2.50	0.00	40.47	834.80	838.14	63.58	1.41
17.2	0.00	2.50	0.00	40.57	834.75	838.08	63.78	1.41
17.2	0.00	2.50	0.00	40.68	834.70	838.02	63.98	1.41
17.2	0.00	2.50	0.00	40.78	834.65	837.96	64.18	1.41
17.2	0.00	2.50	0.00	40.89	834.60	837.90	64.38	1.41
17.2	0.00	2.50	0.00	40.99	834.55	837.84	64.58	1.41
17.2	0.00	2.50	0.00	41.10	834.50	837.78	64.78	1.41
17.2	0.00							

8.5 cm HEAT PIPE HEADER
NOTE: this table for 300 cm heat pipe headers

TEMP (K)	LENGTH (cm)	WIDTH (cm)	THICK (cm)	HEAT REJ/ FIN (W)	FIN END TEMP (K)	AVE TEMP (K)	HEAT REJ/ HP HDR (kW)	MASS/ HP HDR (kg)
52.1	0.5	2.50	0.05	26.00	88.27	850.40	100.81	1.41
52.1	0.5	2.50	0.05	28.06	88.27	850.73	101.92	1.76
52.1	0.5	2.50	0.05	30.13	88.27	851.13	101.45	1.52
52.1	0.5	2.50	0.05	32.19	88.27	851.56	101.59	1.52
52.1	0.5	2.50	0.05	34.24	88.27	851.94	96.70	1.31
52.1	0.5	2.50	0.05	36.29	88.27	852.32	96.70	1.31
52.1	0.5	2.50	0.05	38.34	88.27	852.69	96.70	1.31
52.1	0.5	2.50	0.05	40.39	88.27	853.07	96.70	1.31
52.1	0.5	2.50	0.05	42.44	88.27	853.44	96.70	1.31
52.1	0.5	2.50	0.05	44.49	88.27	853.82	96.70	1.31
52.1	0.5	2.50	0.05	46.54	88.27	854.19	96.70	1.31
52.1	0.5	2.50	0.05	48.59	88.27	854.57	96.70	1.31
52.1	0.5	2.50	0.05	50.64	88.27	854.94	96.70	1.31
52.1	0.5	2.50	0.05	52.69	88.27	855.32	96.70	1.31
52.1	0.5	2.50	0.05	54.74	88.27	855.69	96.70	1.31
52.1	0.5	2.50	0.05	56.79	88.27	856.07	96.70	1.31
52.1	0.5	2.50	0.05	58.84	88.27	856.44	96.70	1.31
52.1	0.5	2.50	0.05	60.89	88.27	856.82	96.70	1.31
52.1	0.5	2.50	0.05	62.94	88.27	857.19	96.70	1.31
52.1	0.5	2.50	0.05	64.99	88.27	857.57	96.70	1.31
52.1	0.5	2.50	0.05	67.04	88.27	857.94	96.70	1.31
52.1	0.5	2.50	0.05	69.09	88.27	858.32	96.70	1.31
52.1	0.5	2.50	0.05	71.14	88.27	858.69	96.70	1.31
52.1	0.5	2.50	0.05	73.19	88.27	859.07	96.70	1.31
52.1	0.5	2.50	0.05	75.24	88.27	859.44	96.70	1.31
52.1	0.5	2.50	0.05	77.29	88.27	859.82	96.70	1.31
52.1	0.5	2.50	0.05	79.34	88.27	860.19	96.70	1.31
52.1	0.5	2.50	0.05	81.39	88.27	860.57	96.70	1.31
52.1	0.5	2.50	0.05	83.44	88.27	860.94	96.70	1.31
52.1	0.5	2.50	0.05	85.49	88.27	861.32	96.70	1.31
52.1	0.5	2.50	0.05	87.54	88.27	861.69	96.70	1.31
52.1	0.5	2.50	0.05	89.59	88.27	862.07	96.70	1.31
52.1	0.5	2.50	0.05	91.64	88.27	862.44	96.70	1.31
52.1	0.5	2.50	0.05	93.69	88.27	862.82	96.70	1.31
52.1	0.5	2.50	0.05	95.74	88.27	863.19	96.70	1.31
52.1	0.5	2.50	0.05	97.79	88.27	863.57	96.70	1.31
52.1	0.5	2.50	0.05	99.84	88.27	863.94	96.70	1.31
52.1	0.5	2.50	0.05	101.89	88.27	864.32	96.70	1.31
52.1	0.5	2.50	0.05	103.94	88.27	864.69	96.70	1.31
52.1	0.5	2.50	0.05	105.99	88.27	865.07	96.70	1.31
52.1	0.5	2.50	0.05	108.04	88.27	865.44	96.70	1.31
52.1	0.5	2.50	0.05	110.09	88.27	865.82	96.70	1.31
52.1	0.5	2.50	0.05	112.14	88.27	866.19	96.70	1.31
52.1	0.5	2.50	0.05	114.19	88.27	866.57	96.70	1.31
52.1	0.5	2.50	0.05	116.24	88.27	866.94	96.70	1.31
52.1	0.5	2.50	0.05	118.29	88.27	867.32	96.70	1.31
52.1	0.5	2.50	0.05	120.34	88.27	867.69	96.70	1.31
52.1	0.5	2.50	0.05	122.39	88.27	868.07	96.70	1.31
52.1	0.5	2.50	0.05	124.44	88.27	868.44	96.70	1.31
52.1	0.5	2.50	0.05	126.49	88.27	868.82	96.70	1.31
52.1	0.5	2.50	0.05	128.54	88.27	869.19	96.70	1.31
52.1	0.5	2.50	0.05	130.59	88.27	869.57	96.70	1.31
52.1	0.5	2.50	0.05	132.64	88.27	869.94	96.70	1.31
52.1	0.5	2.50	0.05	134.69	88.27	870.32	96.70	1.31
52.1	0.5	2.50	0.05	136.74	88.27	870.69	96.70	1.31
52.1	0.5	2.50	0.05	138.79	88.27	871.07	96.70	1.31
52.1	0.5	2.50	0.05	140.84	88.27	871.44	96.70	1.31
52.1	0.5	2.50	0.05	142.89	88.27	871.82	96.70	1.31
52.1	0.5	2.50	0.05	144.94	88.27	872.19	96.70	1.31
52.1	0.5	2.50	0.05	146.99	88.27	872.57	96.70	1.31
52.1	0.5	2.50	0.05	149.04	88.27	872.94	96.70	1.31
52.1	0.5	2.50	0.05	151.09	88.27	873.32	96.70	1.31
52.1	0.5	2.50	0.05	153.14	88.27	873.69	96.70	1.31
52.1	0.5	2.50	0.05	155.19	88.27	874.07	96.70	1.31
52.1	0.5	2.50	0.05	157.24	88.27	874.44	96.70	1.31
52.1	0.5	2.50	0.05	159.29	88.27	874.82	96.70	1.31
52.1	0.5	2.50	0.05	161.34	88.27	875.19	96.70	1.31
52.1	0.5	2.50	0.05	163.39	88.27	875.57	96.70	1.31
52.1	0.5	2.50	0.05	165.44	88.27	875.94	96.70	1.31
52.1	0.5	2.50	0.05	167.49	88.27	876.32	96.70	1.31
52.1	0.5	2.50	0.05	169.54	88.27	876.69	96.70	1.31
52.1	0.5	2.50	0.05	171.59	88.27	877.07	96.70	1.31
52.1	0.5	2.50	0.05	173.64	88.27	877.44	96.70	1.31
52.1	0.5	2.50	0.05	175.69	88.27	877.82	96.70	1.31
52.1	0.5	2.50	0.05	177.74	88.27	878.19	96.70	1.31
52.1	0.5	2.50	0.05	179.79	88.27	878.57	96.70	1.31
52.1	0.5	2.50	0.05	181.84	88.27	878.94	96.70	1.31
52.1	0.5	2.50	0.05	183.89	88.27	879.32	96.70	1.31
52.1	0.5	2.50	0.05	185.94	88.27	879.69	96.70	1.31
52.1	0.5	2.50	0.05	187.99	88.27	880.07	96.70	1.31
52.1	0.5	2.50	0.05	190.04	88.27	880.44	96.70	1.31
52.1	0.5	2.50	0.05	192.09	88.27	880.82	96.70	1.31
52.1	0.5	2.50	0.05	194.14	88.27	881.19	96.70	1.31
52.1	0.5	2.50	0.05	196.19	88.27	881.57	96.70	1.31
52.1	0.5	2.50	0.05	198.24	88.27	881.94	96.70	1.31
52.1	0.5	2.50	0.05	200.29	88.27	882.32	96.70	1.31
52.1	0.5	2.50	0.05	202.34	88.27	882.69	96.70	1.31
52.1	0.5	2.50	0.05	204.39	88.27	883.07	96.70	1.31
52.1	0.5	2.50	0.05	206.44	88.27	883.44	96.70	1.31
52.1	0.5	2.50	0.05	208.49	88.27	883.82	96.70	1.31
52.1	0.5	2.50	0.05	210.54	88.27	884.19	96.70	1.31
52.1	0.5	2.50	0.05	212.59	88.27	884.57	96.70	1.31
52.1	0.5	2.50	0.05	214.64	88.27	884.94	96.70	1.31
52.1	0.5	2.50	0.05	216.69	88.27	885.32	96.70	1.31
52.1	0.5	2.50	0.05	218.74	88.27	885.69	96.70	1.31
52.1	0.5	2.50	0.05	220.79	88.27	886.07	96.70	1.31
52.1	0.5	2.50	0.05	222.84	88.27	886.44	96.70	1.31
52.1	0.5	2.50	0.05	224.89	88.27	886.82	96.70	1.31
52.1	0.5	2.50	0.05	226.94	88.27	887.19	96.70	1.31
52.1	0.5	2.50	0.05	228.99	88.27	887.57	96.70	1.31
52.1	0.5	2.50	0.05	231.04	88.27	887.94	96.70	1.31
52.1	0.5	2.50	0.05	233.09	88.27	888.32	96.70	1.31
52.1	0.5	2.50	0.05	235.14	88.27	888.69	96.70	1.31
52.1	0.5	2.50	0.05	237.19	88.27	889.07	96.70	1.31
52.1	0.5	2.50	0.05	239.24	88.27	889.44	96.70	1.31
52.1	0.5	2.50	0.05	241.29	88.27	889.82	96.70	1.31
52.1	0.5	2.50	0.05	243.34	88.27	890.19	96.70	1.31
52.1	0.5	2.50	0.05	245.39	88.27	890.57	96.70	1.31
52.1	0.5	2.50	0.05	247.44	88.27	890.94	96.70	1.31
52.1	0.5	2.50	0.05	249.49	88.27	891.32	96.70	1.31
52.1	0.5	2.50	0.05	251.54	88.27	891.69	96.70	1.31
52.1	0.5	2.50	0.05	253.59	88.27	892.07	96.70	1.31
52.1	0.5	2.50	0.05	255.64	88.27	892.44	96.70	1.31
52.1	0.5	2.50	0.05	257.69	88.27	892.82	96.70	1.31
52.1	0.5	2.50	0.05	259.74	88.27	893.19	96.70	1.31
52.1	0.5	2.50	0.05	261.79	88.27	893.57	96.70	1.31
52.1	0.5	2.50	0.05	263.84	88.27	893.94	96.70	1.31
52.1	0.5	2.50	0.05	265.89	88.27	894.32	96.70	1.31
52.1	0.5	2.50	0.05	267.94	88.27	894.69	96.70	1.31
52.1	0.5	2.50	0.05	269.99	88.27	895.07	96.70	1.31
52.1	0.5	2.50	0.05	272.04	88.27	895.44	96.70	1.31
52.1	0.5	2.50	0.05	274.09	88.27	895.82	96.70	1.31
52.1	0.5	2.50	0.05	276.14	88.27	896.19	96.70	1.31
52.1	0.5	2.50	0.05	278.19	88.27	896.57	96.70	1.31
52.1	0.5	2.50	0.05	280.24	88.27	896.94	96.70	1.31
52.1	0.5	2.50	0.05	282.29	88.27	897.32	96.70	1.31
52.1	0.5	2.50	0.05	284.34	88.27	897.69	96.70	1.31
52.1	0.5	2.50	0.05	286.39	88.27	898.07	96.70	1.31
52.1	0.5	2.50	0.05	288.44	88.27	898.44	96.70	1.31
52.1	0.5	2.50	0.05	290.49	88.27	898.82	96.70	1.31
52.1	0.5	2.50	0.05	292.54	88.27	899.19	96.70	1.31
52.1	0.5	2.50	0.05	294.59	88.27	899.57	96.70	1.31
52.1	0.5	2.50	0.05	296.64	88.27	899.94	96.70	1.31
52.1	0.5	2.50	0.05	298.69	88.27	900.32	96.70	1.31
52.1	0.5	2.50	0.05					

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TEMP (°F)	LENGTH (cm)	MIDTH (cm)	THICK (cm)	HEAT REC/ FIN (N)	FIN END TEMP (°F)	HEAT REC/ HP HOR (kW)	HEAT REC/ HP HOR (kW)	MASS/ (kg)
33.4	0.5	50	0.030	26.34	881.21	83.07	12.33	1.41
33.4	0.5	50	0.035	29.40	881.51	83.31	12.33	1.26
33.4	0.5	50	0.050	33.50	881.50	83.40	12.33	1.26
33.4	0.5	50	0.075	38.50	881.50	83.40	12.33	1.26
33.4	1.0	50	0.035	34.97	881.51	83.41	12.33	1.41
33.4	1.0	50	0.050	38.43	881.50	83.40	12.33	1.26
33.4	1.0	50	0.075	43.40	881.50	83.40	12.33	1.26
33.4	1.0	50	0.100	48.40	881.50	83.40	12.33	1.26
33.4	1.5	50	0.035	56.71	881.50	83.40	12.33	1.56
33.4	1.5	50	0.050	60.02	881.50	83.40	12.33	1.41
33.4	1.5	50	0.075	77.31	881.50	83.40	12.33	1.41
33.4	1.5	50	0.100	80.05	881.50	83.40	12.33	1.26
33.4	2.0	50	0.075	81.02	881.50	83.40	12.33	1.56
33.4	2.0	50	0.100	93.45	881.50	83.40	12.33	1.26
33.4	2.0	50	0.125	96.40	881.50	83.40	12.33	1.41
33.4	2.0	50	0.150	102.40	881.50	83.40	12.33	1.26
33.4	2.0	50	0.175	104.31	881.50	83.40	12.33	1.26
33.4	2.5	50	0.125	107.31	881.50	83.40	12.33	1.56
33.4	2.5	50	0.150	111.50	881.50	83.40	12.33	1.26
33.4	2.5	50	0.175	115.50	881.50	83.40	12.33	1.26
33.4	3.0	50	0.125	117.50	881.50	83.40	12.33	1.56
33.4	3.0	50	0.150	123.61	881.50	83.40	12.33	1.26
33.4	3.0	50	0.175	128.04	881.50	83.40	12.33	1.26
33.4	3.0	50	0.200	134.05	881.50	83.40	12.33	1.26
33.4	3.5	50	0.150	137.35	881.50	83.40	12.33	1.56
33.4	3.5	50	0.175	151.37	881.50	83.40	12.33	1.26
33.4	3.5	50	0.200	156.06	881.50	83.40	12.33	1.26

Table 2.2, 4/7

MASS SUMMARY														
7.5 cm dia Heat Pipe Headers (9 m length)														
# PIPES	PIPE DIA	PIPE THK	AVE PIPE TEMP	PIPE WT	HP FIN WIDTH	HP FIN HEIGHT	HP FIN SPAC'G	AVE HPFIN TEMP	HP FIN MASS	COND FIN THICK	COND FIN MASS/HDR	Q/HDR	MASS SUM	Q/MASS
	(cm)	(cm)	(K)	(kg)	(cm)	(cm)	(cm)	(K)	(kg)	(cm)	(kg)	(kW)	(kg)	(kW/kg)
30.0	7.5	0.025	851.5	5.23	1.0	1.0	1.0	847.3	39.76	0.020	1.41	98.57	46.40	2.12
30.0	7.5	0.025		5.23	1.0	1.0	1.0		39.76	0.025	1.76	98.77	46.75	2.11
30.0	7.5	0.025		5.23	1.0	1.0	1.0		39.76	0.050	3.52	99.13	48.52	2.04
30.0	7.5	0.025		5.23	1.0	1.0	1.0		39.76	0.075	5.29	99.22	50.28	1.98
30.0	7.5	0.025		5.23	1.0	1.0	2.0	843.0	19.88	0.020	1.41	93.73	26.52	3.54
30.0	7.5	0.025		5.23	1.0	1.0	2.0		19.88	0.025	1.76	94.52	26.87	3.52
30.0	7.5	0.025		5.23	1.0	1.0	2.0		19.88	0.050	3.52	96.03	28.64	3.35
30.0	7.5	0.025		5.23	1.0	1.0	2.0		19.88	0.075	5.29	96.55	30.40	3.18
30.0	7.5	0.025		5.23	1.0	1.0	3.0	838.6	13.25	0.020	1.41	87.72	19.83	4.41
30.0	7.5	0.025		5.23	1.0	1.0	3.0		13.25	0.025	1.76	89.17	20.25	4.40
30.0	7.5	0.025		5.23	1.0	1.0	3.0		13.25	0.050	3.52	92.24	22.01	4.19
30.0	7.5	0.025		5.23	1.0	1.0	3.0		13.25	0.075	5.29	93.32	23.77	3.93
30.0	7.5	0.025		5.23	1.0	1.0	4.0	834.3	9.94	0.020	1.41	81.10	16.58	4.89
30.0	7.5	0.025		5.23	1.0	1.0	4.0		9.94	0.025	1.76	83.27	16.93	4.92
30.0	7.5	0.025		5.23	1.0	1.0	4.0		9.94	0.050	3.52	88.09	18.63	4.71
30.0	7.5	0.025		5.23	1.0	1.0	4.0		9.94	0.075	5.29	89.85	20.46	4.39
30.0	7.5	0.025		5.23	1.0	1.0	5.0	829.9	7.95	0.020	1.41	74.20	14.59	5.09
30.0	7.5	0.025		5.23	1.0	1.0	5.0		7.95	0.025	1.76	77.10	15.04	5.16
30.0	7.5	0.025		5.23	1.0	1.0	5.0		7.95	0.050	3.52	80.62	16.71	5.01
30.0	7.5	0.025		5.23	1.0	1.0	6.0	825.3	6.63	0.020	1.41	66.11	13.47	4.86
30.0	7.5	0.025		5.23	1.0	1.0	6.0		6.63	0.025	1.76	67.63	13.87	5.10
30.0	7.5	0.025		5.23	1.0	1.0	6.0		6.63	0.050	3.52	70.94	15.62	5.21
30.0	7.5	0.025		5.23	1.0	1.0	6.0		6.63	0.075	5.29	72.96	16.33	5.13
30.0	7.5	0.025		5.23	1.0	1.0	7.0	820.7	5.68	0.020	1.41	61.43	12.32	4.99
30.0	7.5	0.025		5.23	1.0	1.0	7.0		5.68	0.025	1.76	65.07	12.67	5.14
30.0	7.5	0.025		5.23	1.0	1.0	7.0		5.68	0.050	3.52	74.32	14.43	5.15
30.0	7.5	0.025		5.23	1.0	1.0	7.0		5.68	0.075	5.29	78.19	16.20	4.93

Table 2.2, 5/7

Table 2.2, 6/77

MASS SUMMARY													
9.5 cm dia Heat Exch Headers (9 in length)													
# PIPES	PIPE DIA	PIPE THK	AVE PIPE TEMP	PIPE WT	PIPE WIDTH	PIPE HEIGHT	HP FIN DIMENSION	HP FIN SPAC G	AVE HP FIN TEMP	HP FIN MASS	COND FIN THICK	COND FIN MASS/HDR	Q/HDR
(cm)	(cm)	(cm)	(K)	(kg)	(cm)	(cm)	(cm)	(cm)	(K)	(kg)	(cm)	(kg)	(kW)
30.0	3.0	0.035	858.2	6.46	1.0	1.0	1.0	1.0	858.7	42.93	0.020	1.41	102.03
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		42.93	0.025	1.76	102.26
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		42.93	0.075	5.29	102.68
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0	851.1	21.46	0.020	1.41	97.82
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		21.46	0.025	1.76	98.13
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0	847.4	21.46	0.050	3.52	99.73
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		21.46	0.025	1.41	100.27
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		11.31	0.020	1.41	92.27
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0	843.3	11.31	0.050	3.52	96.05
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		11.31	0.025	1.76	97.27
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		10.73	0.020	1.41	85.47
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		10.73	0.025	1.76	85.89
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0	840.1	10.73	0.050	3.52	91.63
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		10.73	0.025	1.76	92.72
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		8.59	0.020	1.41	73.43
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		8.59	0.025	1.76	74.43
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0	836.2	8.59	0.050	3.52	77.51
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		8.59	0.025	1.76	78.41
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		7.15	0.020	1.41	64.30
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0	832.2	7.15	0.025	1.76	65.12
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		7.15	0.050	3.52	68.12
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		6.13	0.020	1.41	57.88
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		6.13	0.025	1.76	58.32
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		5.13	0.020	1.41	47.95
30.0	3.0	0.035		6.46	1.0	1.0	1.0	1.0		5.13	0.025	1.76	48.60

Table 2.2, 7/7

Table 2.3 compiles the results for the case of 40 heat pipe headers and Table 2.4 shows the results for the 50 heat pipe header case. These results are condensed and presented graphically in Figures 2.1 through 2.3. Fig. 2.1 shows that a maximum value of 5.21 kW/kg was achieved with 30 heat pipe headers with a diameter of 7.5 cm and a spacing between transverse heat pipes of 6 diameters. There were no cases of 40 or 50 heat pipe header pipes which had a higher kW/kg value. The transverse heat pipe pitch spacing optimized out at 6 diameters. Increasing spacing out beyond this caused the radiant power to decrease, because of additional temperature drop, faster than incremental mass savings were accumulated. At this value of specific power, the radiator specific mass calculates to be 3.36 kg/m^2 .

3.0 HOSTILE THREAT SURVIVABILITY

3.1 Pellet Attack

Pellet attacks are overcome in that the radiator system is made with enough redundancy such that sufficient numbers of components will survive an attack so as to carry out the intended mission.

3.2 X-Ray Attack

X-Ray attacks are mitigated through the use of low-Z, high melting temperature components. The entire surface area of the radiator system is covered with graphite/carbon composite fin material. Low-Z materials tend to accept the incoming thermal flux and distribute it over a relatively large thickness. This spreading of the thermal flux and the high melting temperature of carbon make it intrinsically survivable against x-ray inputs.

3.3 Laser Attacks

The radiator system is designed to encounter a laser flux, raise in temperature and reradiate. To prevent heat from being transported back into the power system, the transverse heat pipes are made into heat pipe diodes. This modification prevents the heat which is deposited by the laser threat from traveling backward. Because of reradiation temperatures, a higher

Table 2.3, 2/7

7.5 cm HEAT PIPE HEADER
(NOTE: this table for 900 cm heat pipe headers)
GRAPHITE CONDUCTING FIN

TEMP (K)	LENGTH (cm)	WIDTH (cm)	THICK (cm)	HEAT REJ/ FIN (W)	FIN END TEMP (K)	FIN AVE TEMP (K)	HEAT REJ/ HP HDR (1W)	MASS/ HP HDR (kg)
852.7	0.5	16.88	0.020	21.06	849.26	850.99	75.02	1.06
852.7	0.5	16.88	0.025	21.10	849.94	851.33	75.98	1.32
852.7	0.5	16.88	0.050	21.19	851.32	852.02	76.30	2.64
852.7	0.5	16.88	0.075	21.27	851.78	852.25	76.41	3.96
849.2	1.0	16.88	0.020	40.50	836.13	842.74	75.35	1.06
849.2	1.0	16.88	0.025	40.52	839.63	842.97	75.33	1.32
849.2	1.0	16.88	0.050	41.13	843.81	846.52	74.13	2.64
849.2	1.0	16.88	0.075	41.41	845.58	847.40	72.64	3.96
845.8	1.5	16.88	0.020	56.67	818.58	832.55	67.94	1.06
845.8	1.5	16.88	0.025	57.67	823.55	834.92	69.09	1.32
845.8	1.5	16.88	0.050	59.61	824.19	840.07	71.59	2.64
845.8	1.5	16.88	0.075	60.32	827.95	841.92	72.39	3.96
842.4	2.0	16.88	0.020	69.95	798.31	821.22	62.96	1.06
842.4	2.0	16.88	0.025	71.88	805.84	824.71	64.69	1.32
842.4	2.0	16.88	0.050	76.14	812.67	832.70	66.83	2.64
842.4	2.0	16.88	0.075	77.71	828.89	835.71	69.84	3.96
838.8	2.5	16.88	0.020	89.67	777.04	809.88	57.76	1.06
838.8	2.5	16.88	0.025	91.59	788.30	814.05	59.04	1.32
838.8	2.5	16.88	0.050	96.84	809.72	824.67	62.06	2.64
838.8	2.5	16.88	0.075	97.42	816.67	830.92	63.76	3.96
835.2	3.0	16.88	0.020	97.34	756.13	796.61	52.77	1.06
835.2	3.0	16.88	0.025	97.36	767.60	803.55	55.41	1.32
835.2	3.0	16.88	0.050	103.11	796.06	816.27	61.06	2.64
835.2	3.0	16.88	0.075	107.42	807.67	821.89	64.45	3.96
831.7	3.5	16.88	0.020	94.44	736.41	758.34	48.95	1.06
831.7	3.5	16.88	0.025	98.11	748.93	793.55	50.97	1.32
831.7	3.5	16.88	0.050	113.02	781.95	807.96	60.43	2.64
831.7	3.5	16.88	0.075	119.74	796.14	814.48	61.58	3.96

Table 2.3, 3/7

Table 2.3, 4/7

MASS SUMMARY													
6.8 cm dia Heat Pipe Headers (3 m length)													
PIPE DIA	PIPE THK	AVE PIPE TEMP	AVE PIPE DIMENSION	HP FIN	AVE HP FIN TEMP	HP FIN SPAC	HP FIN MASS	COND THICK	COND FIN MASS	Q/HDR	MASS SUM	Q/MASS	
(cm)	(cm)	(K)	(cm)	(cm)	(K)	(cm)	(kg)	(cm)	(kg)	(kW)	(kg)	(kW/kg)	
40.0	0.026	850.4	1.0	1.0	846.7	1.0	31.21	0.020	1.06	73.71	36.72	2.01	
40.0	0.026		1.0	1.0		1.0	31.21	0.025	1.32	73.86	36.99	2.00	
40.0	0.026		1.0	1.0		1.0	31.21	0.050	2.64	74.17	38.23	1.94	
40.0	0.026		1.0	1.0	842.9	1.0	31.21	0.050	2.64	74.27	38.33	1.93	
40.0	0.026		1.0	1.0		1.0	15.60	0.020	1.06	70.83	21.40	3.26	
40.0	0.026		1.0	1.0		1.0	15.60	0.025	1.32	71.37	21.91	3.21	
40.0	0.026		1.0	1.0		1.0	15.60	0.050	2.64	71.37	21.91	3.21	
40.0	0.026		1.0	1.0	839.2	1.0	15.60	0.020	1.06	71.37	21.91	3.21	
40.0	0.026		1.0	1.0		1.0	10.40	0.025	1.32	67.04	16.18	4.14	
40.0	0.026		1.0	1.0		1.0	10.40	0.050	2.64	67.17	16.23	4.13	
40.0	0.026		1.0	1.0	835.4	1.0	10.40	0.025	1.32	67.17	16.23	4.13	
40.0	0.026		1.0	1.0		1.0	7.80	0.020	1.06	63.37	14.44	4.39	
40.0	0.026		1.0	1.0		1.0	7.80	0.025	1.32	63.37	14.44	4.39	
40.0	0.026		1.0	1.0	831.6	1.0	7.80	0.025	1.32	63.37	14.44	4.39	
40.0	0.026		1.0	1.0		1.0	6.24	0.020	1.06	59.11	13.44	4.44	
40.0	0.026		1.0	1.0		1.0	6.24	0.025	1.32	59.11	13.44	4.44	
40.0	0.026		1.0	1.0	827.7	1.0	6.24	0.025	1.32	59.11	13.44	4.44	
40.0	0.026		1.0	1.0		1.0	5.00	0.020	1.06	55.23	10.73	4.73	
40.0	0.026		1.0	1.0		1.0	5.00	0.025	1.32	55.23	10.73	4.73	
40.0	0.026		1.0	1.0	823.7	1.0	5.00	0.025	1.32	55.23	10.73	4.73	
40.0	0.026		1.0	1.0		1.0	4.46	0.020	1.06	46.40	10.34	4.58	
40.0	0.026		1.0	1.0		1.0	4.46	0.025	1.32	46.40	10.34	4.58	
40.0	0.026		1.0	1.0		1.0	4.46	0.050	2.64	46.40	10.34	4.58	
40.0	0.026		1.0	1.0		1.0	4.46	0.050	2.64	46.40	10.34	4.58	

Table 2.3, 5/7

Table 2.3, 6/7

MASS SUMMARY														
0.5 cm dia Heat Pipe Headers (9 m length)														
# PIPES	PIPE DIA	PIPE THK	AVE PIPE TEMP	PIPE WT	HP FIN DIMENSION	HP FIN SPAC'G	AVE HPFIN TEMP	HP FIN MASS	COND FIN THICK	COND FIN MASS/HDR	Q/HDR	MASS SUM	Q/MASS	
	(cm)	(cm)	(K)	(kg)	(cm)	(cm)	(K)	(kg)	(cm)	(kg)	(kW)	(kg)	(kW/kg)	
40.0	8.5	0.025	858.5	5.69	1.0	1.0	855.4	34.37	0.020	1.06	76.78	41.12	1.87	
40.0	8.5	0.025		5.69	1.0	1.0		34.37	0.025	1.32	76.95	41.39	1.86	
40.0	8.5	0.025		5.69	1.0	1.0		34.37	0.050	2.64	77.28	42.71	1.81	
40.0	8.5	0.025		5.69	1.0	1.0		34.37	0.075	3.96	77.33	44.03	1.76	
40.0	8.5	0.025	852.3	5.69	1.0	1.0	852.3	17.19	0.020	1.06	73.38	23.93	3.07	
40.0	8.5	0.025		5.69	1.0	1.0		17.19	0.025	1.32	73.33	24.20	3.06	
40.0	8.5	0.025		5.69	1.0	1.0		17.19	0.050	2.64	75.20	25.52	2.92	
40.0	8.5	0.025		5.69	1.0	1.0		17.19	0.075	3.96	75.62	26.84	2.82	
40.0	8.5	0.025	849.3	5.69	1.0	1.0	849.3	11.46	0.020	1.06	69.00	18.21	3.79	
40.0	8.5	0.025		5.69	1.0	1.0		11.46	0.025	1.32	70.17	18.47	3.80	
40.0	8.5	0.025		5.69	1.0	1.0		11.46	0.050	2.64	72.69	19.79	3.67	
40.0	8.5	0.025		5.69	1.0	1.0		11.46	0.075	3.96	73.56	21.11	3.48	
40.0	8.5	0.025	846.3	5.69	1.0	1.0	846.3	8.59	0.020	1.06	64.01	15.34	4.17	
40.0	8.5	0.025		5.69	1.0	1.0		8.59	0.025	1.32	65.80	15.61	4.22	
40.0	8.5	0.025		5.69	1.0	1.0		8.59	0.050	2.64	69.75	16.93	4.12	
40.0	8.5	0.025		5.69	1.0	1.0		8.59	0.075	3.96	71.20	18.25	3.90	
40.0	8.5	0.025	843.3	5.69	1.0	1.0	843.3	6.87	0.020	1.06	58.56	12.62	4.52	
40.0	8.5	0.025		5.69	1.0	1.0		6.87	0.025	1.32	61.16	13.39	4.41	
40.0	8.5	0.025		5.69	1.0	1.0		6.87	0.050	2.64	66.57	15.21	4.38	
40.0	8.5	0.025		5.69	1.0	1.0		6.87	0.075	3.96	68.64	16.53	4.15	
40.0	8.5	0.025	840.0	5.69	1.0	1.0	840.0	5.73	0.020	1.06	53.77	12.40	4.31	
40.0	8.5	0.025		5.69	1.0	1.0		5.73	0.025	1.32	56.50	12.74	4.43	
40.0	8.5	0.025		5.69	1.0	1.0		5.73	0.050	2.64	63.17	14.06	4.40	
40.0	8.5	0.025		5.69	1.0	1.0		5.73	0.075	3.96	65.96	15.38	4.28	
40.0	8.5	0.025	836.9	5.69	1.0	1.0	836.9	4.91	0.020	1.06	49.01	11.56	4.20	
40.0	8.5	0.025		5.69	1.0	1.0		4.91	0.025	1.32	52.02	11.92	4.36	
40.0	8.5	0.025		5.69	1.0	1.0		4.91	0.050	2.64	59.75	13.54	4.31	
40.0	8.5	0.025		5.69	1.0	1.0		4.91	0.075	3.96	63.02	14.57	4.13	

Table 2.3, 7/7

Rev. 0. 10. 80

HEAT PIPE FIN CELLS T's (heat pipe hole 0.2m)

Heat Pipe Headers =		Heat Pipe Header Dia (cm) =		Heat Thermal Conductivity =		T = 854.6		Wick Therm Cond =		0.30	
Wall Material: Titanium =		4.5		4.5		0.19					
FIN DIMENSIONS		HYD DIA		FIN HT REJ'D		WALL		EVAPORATOR		CONDENSER	
WIDTH (cm)	HEIGHT (cm)	SPACING (cm)	WICK	HT REJ'D (W)	WALL (C)	EVAP'N (C)	COND'N (C)	WICK (C)	COND'N (C)	WICK (C)	COND'N (C)
1.0	1.0	1.0	1.0	34.5	0.3	0.1	0.0	0.0	0.0	0.4	0.3
1.0	1.0	2.0	1.0	28.9	1.0	0.1	0.0	0.0	0.0	0.3	0.3
1.0	1.0	3.0	1.0	103.4	2.7	0.3	0.0	0.0	0.0	1.0	0.3
1.0	1.0	4.0	1.0	137.8	3.6	0.4	0.0	0.0	0.0	1.6	0.3
1.0	1.0	5.0	1.0	172.3	4.4	0.5	0.0	0.0	0.0	1.7	0.3
1.0	1.0	6.0	1.0	206.7	5.3	0.5	0.0	0.0	0.0	2.4	0.3
1.0	1.0	7.0	1.0	241.2	6.2	0.6	0.0	0.0	0.0	2.4	0.3

7.5 cm HEAT PIPE HEADER
(NOTE: this table for 900 cm heat pipe headers)
GRAPHITE CONDUCTING FIN

TEMP (°F)	LENGTH (cm)	WIDTH (cm)	THICK (cm)	HEAT REJ/ FIN (W)	FIN END TEMP (K)	FIN AVE TEMP (K)	HEAT REJ/ HP HDR (kW)	MASS/ HP HDR (kg)
200.0	0.5	13.50	0.020	17.03	951.70	952.45	61.00	0.05
200.0	0.5	13.50	0.025	17.02	952.39	953.80	61.45	1.00
200.0	0.5	13.50	0.050	17.15	952.73	954.43	61.75	2.11
200.0	0.5	13.50	0.075	17.16	953.25	954.72	61.84	2.17
200.0	1.0	13.50	0.020	32.53	833.31	846.60	50.07	0.05
200.0	1.0	13.50	0.025	32.66	841.35	846.86	50.14	1.00
200.0	1.0	13.50	0.050	32.40	846.70	847.45	50.12	2.11
200.0	1.0	13.50	0.075	32.53	848.49	850.34	50.45	2.17
200.0	1.5	13.50	0.020	45.93	821.62	836.73	50.15	0.05
200.0	1.5	13.50	0.025	46.77	820.65	836.20	50.13	1.00
200.0	1.5	13.50	0.050	49.44	837.44	842.42	50.13	2.11
200.0	1.5	13.50	0.075	49.03	841.26	845.30	50.37	2.17
200.0	2.0	13.50	0.020	57.91	801.57	824.81	51.21	0.05
200.0	2.0	13.50	0.025	62.43	808.15	823.34	51.24	1.00
200.0	2.0	13.50	0.050	62.00	826.24	829.08	51.29	2.11
200.0	2.0	13.50	0.075	62.25	827.50	833.51	51.29	2.17
200.0	2.5	13.50	0.020	75.32	780.20	813.01	47.00	0.05
200.0	2.5	13.50	0.025	75.35	780.23	818.00	47.00	1.00
200.0	2.5	13.50	0.050	75.04	812.51	822.00	47.00	2.11
200.0	2.5	13.50	0.075	75.24	822.67	827.13	47.35	2.17
200.0	3.0	13.50	0.020	71.72	782.60	802.82	45.0	0.05
200.0	3.0	13.50	0.025	75.35	781.33	806.36	45.21	1.00
200.0	3.0	13.50	0.050	84.28	800.12	826.85	46.48	2.11
200.0	3.0	13.50	0.075	87.33	811.55	820.39	46.70	2.17
200.0	3.5	13.50	0.020	76.23	740.02	792.86	39.25	0.05
200.0	3.5	13.50	0.025	80.07	752.75	799.22	41.63	1.00
200.0	3.5	13.50	0.050	92.33	738.21	812.81	42.00	2.11
200.0	3.5	13.50	0.075	92.68	790.67	819.45	50.44	2.17

Table 2.4, 4/7

Table 2.4, 5/7

Table 2.4, 6/7

MASS SUMMARY														
8.5 cm dia Heat Pipe Headers (9 m length)														
PIPE DIA	PIPE THN	AVE PIPE TEMP	PIPE WT	HP FIN WIDTH	HP FIN HEIGHT	HP FIN SPAC G	AVE HPFIN TEMP	HP FIN MASS	COND FIN THICK	COND FIN MASS/HR	Q/HR	MASS SUM	Q/MASS	
(cm)	(cm)	(K)	(kg)	(cm)	(cm)	(cm)	(K)	(kg)	(cm)	(kg)	(kW)	(kg)	(kW/kg)	
50.0	8.5	0.025	859.6	5.60	1.0	1.0	856.9	30.19	0.020	0.85	61.65	36.64	1.69	
50.0	8.5	0.025		5.60	1.0	1.0		30.19	0.025	1.06	61.93	36.85	1.66	
50.0	8.5	0.025		5.60	1.0	1.0		30.19	0.050	2.11	62.22	37.31	1.64	
50.0	8.5	0.025		5.60	1.0	1.0		30.19	0.075	3.17	62.54	38.36	1.60	
50.0	8.5	0.025		5.60	1.0	2.0	854.2	15.10	0.020	0.85	59.21	31.54	1.75	
50.0	8.5	0.025		5.60	1.0	2.0		15.10	0.025	1.06	59.63	31.75	1.72	
50.0	8.5	0.025		5.60	1.0	2.0		15.10	0.050	2.11	60.69	33.61	1.66	
50.0	8.5	0.025		5.60	1.0	2.0		15.10	0.075	3.17	61.92	35.87	1.56	
50.0	8.5	0.025		5.60	1.0	3.0	851.6	10.06	0.020	0.85	55.75	26.51	2.13	
50.0	8.5	0.025		5.60	1.0	3.0		10.06	0.025	1.06	56.71	26.72	2.13	
50.0	8.5	0.025		5.60	1.0	3.0		10.06	0.050	2.11	57.75	27.78	2.10	
50.0	8.5	0.025		5.60	1.0	3.0		10.06	0.075	3.17	59.47	29.84	2.16	
50.0	8.5	0.025		5.60	1.0	4.0	848.9	7.55	0.020	0.85	51.75	23.99	2.20	
50.0	8.5	0.025		5.60	1.0	4.0		7.55	0.025	1.06	52.74	24.20	2.20	
50.0	8.5	0.025		5.60	1.0	4.0		7.55	0.050	2.11	53.97	25.26	2.16	
50.0	8.5	0.025		5.60	1.0	4.0		7.55	0.075	3.17	56.32	27.33	2.06	
50.0	8.5	0.025		5.60	1.0	6.0	846.0	6.04	0.020	0.85	47.67	22.48	2.12	
50.0	8.5	0.025		5.60	1.0	6.0		6.04	0.025	1.06	48.67	22.70	2.14	
50.0	8.5	0.025		5.60	1.0	6.0		6.04	0.050	2.11	49.92	23.76	2.10	
50.0	8.5	0.025		5.60	1.0	6.0		6.04	0.075	3.17	52.33	25.81	2.03	
50.0	8.5	0.025		5.60	1.0	8.0	842.5	5.03	0.020	0.85	40.75	19.43	2.08	
50.0	8.5	0.025		5.60	1.0	8.0		5.03	0.025	1.06	41.75	19.64	2.08	
50.0	8.5	0.025		5.60	1.0	8.0		5.03	0.050	2.11	43.15	20.79	2.03	
50.0	8.5	0.025		5.60	1.0	8.0		5.03	0.075	3.17	45.75	22.80	1.96	
50.0	8.5	0.025		5.60	1.0	7.0	840.7	4.31	0.020	0.85	37.77	16.76	2.26	
50.0	8.5	0.025		5.60	1.0	7.0		4.31	0.025	1.06	38.74	16.97	2.26	
50.0	8.5	0.025		5.60	1.0	7.0		4.31	0.050	2.11	40.17	18.03	2.22	
50.0	8.5	0.025		5.60	1.0	7.0		4.31	0.075	3.17	42.76	19.98	2.12	

Table 2.4, 7/7

RADIATOR SPECIFIC POWER

30 Heat Pipe Headers

\\tcore\30tl.cht

Fig. 2.1

RADIATOR SPECIFIC POWER

40 Heat Pipe Headers

\\tcore\40tl.cht

Fig. 2.2

RADIATOR SPECIFIC POWER

50 Heat Pipe Headers

\\tcore\50tl.cht

Fig. 2.3

temperature braze joint becomes necessary at the interface of the transverse heat pipe to graphite conducting fin.

4.0 CONCLUSIONS

With the inherent strengths of the basic NASA radiator design, and the modifications described above, the system can become a low-mass radiator capable of encountering and surviving SUPER-level hostile threats.

APPENDIX B

DERIVATION OF THE ELASTIC MODULUS FOR THE LAYERED COMPOSITE STRUCTURE

Title: _____

Page 1 of 2Calculated by: Q. H. R. / J. L. / Date 1-30-90

Approved by: _____ Date _____

PURPOSE: SHOW THE METHOD OF ESTIMATION OF THE MODULUS OF ELASTICITY OF THE LAYERED COMPOSITE TUBING.

USE THE EXAMPLE OF NIOBIUM FOIL WITH TITANIUM DIOXIDE

AND CP-2 TITANIUM POWDER LAYER REINFORCEMENT. [REF: HALPIN, PRIMERMAN

ANALYSIS:

COMPOSITE MATERIALS]

MATH MODEL / ALGORITHMDATA: $X_F = 0.3$ SUBSCRIPTS $X_m = 0.7$ $F \equiv \text{FOIL}$ $(a/b)_F = 4$ $m \equiv \text{MATRIX}$ $\nu_{cp} = 0.3$ $MP \equiv \text{METAL POWDER}$ $E_F = 15 \times 10^6 \text{ psi}$ $CP \equiv \text{CERAMIC}$ $E_{cp} = 65 \times 10^6 \text{ psi}$

POWDER

 $E_{mp} = 15 \times 10^6 \text{ psi}$ $(a/b)_{cp} = 1$

$$\textcircled{1} \quad \zeta_{11} = 2(a/b)_{11} + 40\nu_{cp}^{10}$$

$$\textcircled{2} \quad \eta_{11} = \frac{\left(\frac{E_{cp}}{E_{mp}} - 1\right)}{\left(\frac{E_{cp}}{E_{mp}} + \zeta_{11}\right)}$$

$$\textcircled{3} \quad E_{m11} = E_{mp} \frac{(1 + \zeta_{11} \eta_{11} \nu_{cp})}{(1 - \eta_{11} \nu_{cp})}$$

$$\textcircled{4} \quad \zeta_{22} = 2(a/b)_{22} + 40\nu_{cp}^{10}$$

$$\textcircled{5} \quad \eta_{22} = \frac{\left(\frac{E_{cp}}{E_{mp}} - 1\right)}{\left(\frac{E_{cp}}{E_{mp}} + \zeta_{22}\right)}$$

$$\textcircled{6} \quad E_{m22} = E_{mp} \frac{(1 + \zeta_{22} \eta_{22} \nu_{cp})}{(1 - \eta_{22} \nu_{cp})}$$

$$\textcircled{7} \quad E_m = 3/8 E_{m11} + 5/8 E_{m22}$$

$$\textcircled{8} \quad E_c = E_F X_F + E_m X_m$$

SOLVING THESE EQUATIONS FOR E_c YIELDS $E_c = 21.8 \times 10^6 \text{ psi}$.

Title: _____

Page 2 of 2

Calculated by: J. H. H. H. Date 5-15-90

Approved by: _____ Date _____

NOTATION:

a/b	ASPECT
η	MEASURE OF REINFORCEMENT
E	MODULUS OF ELASTICITY, N/m^2
ξ	MEASURE OF REINFORCEMENT
v	VOLUME FRACTION OF POWDER COMPONENT IN POWDER LAYER
x	VOLUME FRACTION OF FOIL OR POWDER MIX LAYER IN COMPOSITE

SUBSCRIPTS:

11	ORIENTATION DIRECTION, LONGITUDINAL + CIRCUMFERENTIAL
22	ORIENTATION DIRECTION, RADIAL
F	FOIL
M	MATRIX OF METAL AND CERAMIC POWDER
MP	METAL POWDER
CP	CERAMIC POWDER

COMPOSITE WALL CROSS SECTION

R E V I S E D

Primer on Composite Materials: ANALYSIS

J. C. HALPIN
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Materials Research Laboratory
Washington University
St. Louis, Missouri

6.4 THE HALPIN-TSAI EQUATIONS

The product of the above cited efforts is contained in a series of curves (Figures 6-1,2) computed as a function of material parameters. While these curves are of great value they are limited in that only a few cases are available in graphical form. For design purposes it is often desirable to have simple and rapid computational procedures for estimating the ply properties. A desirable situation is one in which simple but approximately precise formula would be available to interpolate the existing exact machine calculations available in the current literature.

Such interpolation procedures have been developed by Halpin and Tsai [6-56] who were able to show that Hermans' solution [6-5] generalizing Hill's self consistent model [6-2] can be reduced to the approximate form:

$$E_{11} \cong E_f v_f + E_m v_m \quad (6-7)$$

and

$$\nu_{12} \cong \nu_f v_f + \nu_m v_m \quad (6-8)$$

and

$$\frac{\bar{p}}{p_m} = \frac{(1 + \xi \eta \nu_f)}{(1 - \eta \nu_f)} \quad (6-9)$$

where

$$\eta = (p_f/p_m - 1)/(p_f/p_m + \xi) \quad (6-10)$$

Figure 6-1. Comparison of Halpin-Tsai calculation, solid circles, with square array calculations for transverse stiffness.

Figure 6-2. Comparison of Halpin-Tsai calculation, solid circles, with Adams and Doner's square array calculations for longitudinal shear stiffness.

In this formulation the quantities $\bar{p}$, p_f , p_m and ζ are identified as:

- $\bar{p}$ = composite moduli, E_{22} , G_{12} , or G_{23} ;
- p_f = corresponding fiber modulus, E_f , G_f , v_f respectively;
- p_m = corresponding matrix modulus, E_m , G_m , v_m ;
- ζ = a measure of reinforcement which depends on the boundary conditions.

Once the ζ factors are known for the geometry of inclusions, packing geometry and loading conditions, the composite elastic moduli for fiber, tape, and particulate composites are approximated from the Halpin-Tsai formulas. Reliable estimates for the ζ factor can be obtained by comparison of equations (6-9) and (6-10) with the numerical micromechanics solutions employing formal elasticity theory. For example, Figures 6-1 and 6-2 show the predictions of equations (6-9) and (6-10) for various reinforcements/matrix stiffnesses and is compared with the results of Adams, and Doner [6-37,38]. The approximate formula does duplicate their results for all ratios of p_f/p_m . In Figures 6-3 and 6-4 we have a comparison of the dependence of composite moduli, based upon Foye's calculations [6-45,46], as a function of volume fraction for square fibers in a diamond array. For the predictions of shear G_{12} , $\zeta=1$ and for stiffness E_{22} , $\zeta=2$ for the calculations shown in Figures 6-1-6-4. In Figures 6-5 and 6-6 we show the results of our generalized formula compared against the results of different micromechanics calculations. Note that our approximate formula provides a good correlation with Foye's computations for hexagonal array of circular fibers up to $v_f = 65$ percent. At higher volume fractions Hewitt and deMalherbe [6-57] have shown that the following modification adjusts for this effect:

Figure 6-3. Comparison of Halpin-Tsai calculation, solid circle, with Foye's calculations for the transverse stiffness of a composite containing rectangularly-shaped fibers.

Figure 6-4. Comparison of Halpin-Tsai calculation, solid circle, with Foye's calculation for longitudinal shear stiffness of composite containing rectangularly-shaped fibers.

Figure 6-5. Comparison of various calculations for the transverse stiffness of a glass-epoxy composite.

Figure 6-6. Comparison of various calculations for the transverse stiffness of a boron-epoxy composite.

$$G_{12} = 1 + 40 v_f^{10} \quad (6-11)$$

$$E_{22} = 2 + 40 v_f^{10} \quad (6-12)$$

Further confidence can be gained in this interpolation procedure by returning to Figures 6-3 and 6-4 and examine the dependence of the transverse stiffness moduli and the longitudinal-transverse shear moduli upon increasing aspect ratio for square filaments. The factors ζ_E and ζ_G are functions of the width to thickness ratios and were found [6-58] to be of the form:

$$\zeta_E = 2(a/b) \quad (6-13)$$

and

$$\log \zeta_G = \sqrt{3} \log (a/b)$$

These ζ factors were determined by fitting Foye's results. Results in Figures 6-3 and 6-4 indicate good agreement between our approximate formulas and elasticity calculations for different aspect ratios and volume fractions. These results allow the extension of the limited elasticity calculations to the prediction of, for example, the dependence of the moduli, E_{22} and G_{12} , on the aspect ratio, reinforcement stiffness/matrix stiffness and volume fraction loading as illustrated in Figures 6-7 and 6-8.

The ζ term is a parameter which reflects reinforcement geometry and modulus influences on the elastic coefficients. These ζ and η terms are summarized below for some typical material geometrics:

Figure 6-7. Composite transverse stiffness versus aspect ratio for ribbon-shaped reinforcements.

Figure 6-8. Composite longitudinal shear stiffness versus aspect ratio for ribbon-shaped reinforcements.

(a) Particulate Composites:

$$\zeta_G \cong \zeta_{G,,} \quad \text{equation (6-11)}$$

$$\zeta_E \cong \zeta_{E,,} \quad \text{equation (6-12)}$$

$$G/G_m \text{ and } E/E_m \quad \text{equation (6-9)}$$

(b) Voids, a foam, a porous solid:

$$p_f/p_m \rightarrow 0$$

therefore

$$\eta_G = 1/\zeta_G; \eta_E = 1/\zeta_E$$

$$G/G_m \text{ and } E/E_m \quad \text{equation (6-9)}$$

(c) Oriented continuous fibers:

$$\zeta_{G,,} \text{ and } \zeta_{E,,} \quad \text{equations (6-11) and (6-12)}$$

$$\zeta_{G,,} \cong \frac{1}{4-3\nu_m} \quad (6-14)$$

It can be shown that any balanced, symmetric laminate constructed of $2N$ plies oriented at $\theta = \pi/N$ radians, where $N \geq 3$, yields an in-plane stiffness matrix which is isotropic. The term quasi-isotropic is utilized because the bending stiffness matrix, D_{ij} , will not, in general, be isotropic. Both the strength and fracture toughness, Table 4-1, will reach a stable value independent of an increased number of lamina orientations, π/N when $N \geq 3$, and laminate orientation θ . In Table 4-1 $[0/\pm 60]$, is a $\pi/3$ laminate, $[0/\pm 45/90]$, is a $\pi/4$ laminate, etc.

An examination of equation (2-43) for the expansional strains will indicate that the expansional strains are independent of θ whenever $e_x = e_y$. The expansional strain field is isotropic in the lamination plane any time a balanced and symmetric laminate has equal properties $\bar{A}_{11} = \bar{A}_{22}$. This statement is valid even for a laminate which may not be quasi-isotropic with respect to the in-plane stiffness: for example $[0/90]$, or $[\pm 45]$, laminates. The term quasi-isotropic expansion is used in recognition that the out of plane strain e_z will generally be different, greater than, the in-plane strain; $e = e_x = e_y$. The quasi-isotropic expansional strain is developed in [6-65] and Section 6.6 as

$$e^0 = W_1 + \frac{2(E_{11} - E_{22})W_2}{E_{11} + (1 + 2\nu_{12})E_{22}} \quad (6-18)$$

where the terms W_1 and W_2 are defined in equation (3-72).

Problem 6-1

What is the moduli of a composite material fabricated from a matrix of $E_m = 0.3 \times 10^6$ psi and 40 volume percent of Silicon Carbide platelets, $E_R = 70 \times 10^6$ psi, possessing a ratio of length to thickness of 16/1?

For a crude estimate of the modulus of a flake or platelet reinforced material we may employ equations (6-9)–(6-13). For a material of this type $E_{11} = E_{22}$ and is equal to E_{22} of the equivalent ribbon reinforced composite possessing the equivalent aspect ratio (a/b):

From equation (6-13)

$$\xi_E = 2(a/b) + 40\nu_f^{10} = 2(16) + 40(0.4)^{10} = 32$$

using equation (6-10),

$$\eta = \frac{(70/13) - 1}{(70/13) + 32} = .0877$$

Therefore equation (6-9) yields,

$$\stackrel{(6-9)}{\bar{E}} = \frac{1 + (32)(.877)(.40)}{1 - (.877)(.40)} E_m$$

$$= 18.8$$

$$E = 5.65 \times 10^6 \text{ psi}$$

This result compares favorably with experiment as indicated in Figure 6-9. A similar procedure is followed if one desires to compute the shear modulus G_{12} or the moduli of continuous fiber reinforcement.

Problem 6-2

There is much discussion today regarding the use of two or more different reinforcements in a composite structure. How would we estimate expected moduli of such a material?

For a general hybrid composite one would generally fabricate the composite as a laminated material possessing different material properties in different material layers. Accordingly one may employ lamination theory as developed in Chapters 3 and 4; which allows one to sum through the thickness in proportion to the fraction of the thickness of materials a , b , c , . . . etc., to obtain $[A_{ij}]_H$ for the hybrid composite [6-57]:

$$[A_{ij}]_H = \frac{a}{h} [A_{ij}]_a + \frac{b}{h} [A_{ij}]_b +$$

If, however, two or more reinforcements are uniformly mixed in a common matrix one would compute $(p/p_m)_a$ for reinforcement a , then incorporate reinforcement b into the composite employing $\bar{p}_a$ as the "effective matrix moduli."

Figure 6-9. Composite Young's modulus for platelet reinforcements.

Problem 6-3

How would you compute the modulus of a random short fiber composite? The analysis would proceed in the following fashion:

1. A random fiber orientation means that the moduli will be isotropic in the plane of a sheet. This situation is described in laminated plate theory as "quasi-isotropic."

$$E \equiv \frac{4U_3(U_1 - U_3)}{U_1}$$

$$\nu \equiv \frac{U_1 - 2U_3}{U_1}$$

$$G \equiv U_3$$

The engineering constants E_{11} , E_{22} , etc. are those representative of the *unidirectionally oriented material*.

2. For a short fiber composite one must now compute the engineering constants. For example, consider a short boron fiber of length, 0.125 in. and a diameter, .004 in., used as reinforcement, 40 percent in an epoxy matrix:
 - a) Compute E_{11}

$$a/b = l/D = \frac{0.125}{.004} = 31$$

$$\zeta = 2(32) + 40(0.4)^{10} = 62 \quad E_f/E_m = \frac{60 \times 10^6}{.5 \times 10^6} = 120$$

$$\eta = \frac{120 - 1}{120 + 62} = 0.655$$

$$\frac{E_{11}}{E_m} = \frac{1 + 62(.655)(.40)}{1 - (.655)(.40)} = 23.3$$

$$E_{11} = 11.7 \times 10^6 \text{ psi}$$

- b) Compute E_{22}

$$\zeta = 2(1) + 40(0.4)^{10} = 2$$

Transverse response to short fiber is assumed to be similar to transverse response of continuous fiber.

Following above procedure, we obtain

$$E_{22} = 1.3 \times 10^6 \text{ psi}$$

- c) Compute E

$$\begin{aligned}\bar{E} &= [3/8(11.7) + 5/8(1.3)] \times 10^6 \\ &= 5.2 \times 10^6 \text{ psi}\end{aligned}$$

This crude stiffness estimate can be compared against experiment in Figure 6-10. Mixtures of two chopped fibers can be evaluated by combining problems 6-2 and 6-3. The same procedure would also be applied if one wished to compute the bending stiffness of a beam containing chopped fiber in the mid section and continuous oriented fiber layers on the surface faces.

6.5 TRANSPORT PROPERTIES

Composite materials are frequently employed in engineering applications in which one is concerned with the transport of electrical and/or magnetic fields, electrical conduction, heat conduction, or the permeation of a material by a contained fluid or vapor. Accordingly, we are concerned with the relationship between composite structure and such physical constants as dielectric constants, heat conduction, magnetic permeability, electrical conduction, and the diffusion coefficients. As indicated in section 6.2 these material parameters are second order tensors described by equation in the form of (6-1) and (6-2).

For a fiber reinforced material, the axial coefficient, k_1 is simply expressed as [6-66]

$$k_1 = v_f k_f + v_m k_m \quad (6-19)$$

The transverse coefficient, k_2 can be computed by invoking an analogy from [6-54] classical physics between the in-plane shear field equations and boundary conditions to the transverse transport coefficient, k_2 , as indicated in

Figure 6-10. Prediction of a random short boron fiber mat reinforced composite.

APPENDIX C

DERIVATION OF COMPOSITE WALL TUBING FIGURE OF MERIT

Purpose: The purpose is to identify a figure of merit which denotes low mass for a thin-walled cylinder. The cylinder wall will consist of foil and powder (70% metal and 30% ceramic powder) layers.

Approach: 1) Identify suitable figure of merit.

2) Use "1111066ME.BAS" BASIC PROGRAM OR "1111066ME.EXE" PROGRAM TO CALCULATE FIGURES OF MERIT FOR ALL FOIL, METAL POWDER, AND CERAMIC POWDER COMBINATIONS FOR WHICH THE FILES "METALS.DAT", "CERAMICS.DAT", AND "ELEMENTS.DAT" CONTAIN DATA. THE METALS CHOSEN REPRESENT THOSE WHICH MELT AT OR ABOVE THE MELTING POINT OF TITANIUM.

ANALYSIS: 1) IDENTIFY A FIGURE OF MERIT.

THE GOAL IS TO MINIMIZE THE MASS OF A THIN-WALLED CYLINDER WHILE MAINTAINING STRENGTH. THE MASS OF A THIN-WALLED CYLINDER IS

$$m = L \cdot 2\pi r t$$

WHERE m = MASS OF CYLINDER, L = LENGTH OF CYLINDER, r = INNER RADIUS OF CYLINDER, t = WALL THICKNESS AND ρ = DENSITY OF WALL MATERIAL.

MATERIAL.

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IT MUST FIRST BE DETERMINED IF THE CYLINDER WILL BUCKLE OR YIELD. THE STRESS ON AN EVACUATED CYLINDER IS GIVEN BY (EQ. 9-2, POPOV, MECHANICS OF MATERIALS)

$$\sigma = \frac{Pr}{t} \quad (2)$$

WHERE $\sigma \equiv$ STRESS ON THE CYLINDER,
 $P \equiv$ PRESSURE ON THE CYLINDER,
 $r \equiv$ INNER RADIUS OF CYLINDER,
 AND $t \equiv$ WALL THICKNESS.

THE ACTUAL STRESS ON AN EVACUATED CYLINDER AT ATMOSPHERIC PRESSURE IS

$$\begin{aligned} r &= 0.50 \text{ INCHES} \\ t &= 0.007 \text{ INCHES} \end{aligned}$$

$$\sigma = \frac{Pr}{t} = \frac{(14.7 \text{ psi})(0.50 \text{ IN})}{(0.007 \text{ IN})}$$

$$\sigma = 1050 \text{ psi.}$$

USE THE EXAMPLE OF NIOBIUM FOIL, TITANIUM POWDER, AND TITANIUM DIBORIDE POWDER. NIOBIUM HAS A YIELD STRESS, $\sigma_{yNb} = 30,000 \text{ psi}$ AT 600°C . ACCORDING TO UNITED TECHNOLOGIES, A CONSERVATIVE ESTIMATE OF YIELD STRENGTH INCREASE, USING DISCONTINUOUS REINFORCEMENT, IS 20%.

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COM $\equiv$ COMPOSITE

THEREFORE,

$$\text{INCREASED YIELD STRESS, } \sigma_{y, \text{COM}} = 1.2 (\sigma_{y, \text{Nb}}) \quad (3)$$

$$= 1.2 (30,000 \text{ psi})$$

$$\sigma_{y, \text{COM}} = 36,000 \text{ psi.}$$

THE BUCKLING PRESSURE FOR CYLINDER IS GIVEN BY (TABLE 35, EXAMPLE 19a, P. 556, ROARK AND YOUNG, FORMULAS FOR STRESS AND STRAIN)

$$P_B = \frac{Et^3}{4(1-\nu^2)r^3} \quad (4)$$

WHERE $P_B \equiv$ BUCKLING PRESSURE,

$E \equiv$ YOUNG'S MODULUS,

$\nu \equiv$ POISSON'S RATIO,

$r \equiv$ INNER RADIUS OF CYLINDER,

AND $t \equiv$ WALL THICKNESS.

FOR NIOBIUM FOIL, TITANIUM POWDER, AND TITANIUM DIBORIDE POWDER,

$$P_B = \frac{(17.8 \times 10^6 \text{ psi})(0.007 \text{ in})^3}{4(1-0.4^2)(0.50 \text{ in})^3}$$

$$P_B = 14.5 \text{ psi.}$$

$r = 0.50$ INCHES
 $t = 0.007$ INCHES
 $E_{\text{COM}} = 17.8 \times 10^6 \text{ psi}^*$
 AT 600°C
 $\nu_{\text{Nb}} = 0.4$
 * SEE PAGE A5

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THEREFORE,

$$\begin{aligned} \text{BUCKLING STRESS, } \sigma_{B,COM} &= \frac{P_B r}{t} \quad (2) \\ &= \frac{(114.5 \text{ psi})(0.50 \text{ in})}{(0.007 \text{ in})} \end{aligned}$$

$$\sigma_{B,COM} = 1036 \text{ psi.}$$

SINCE $\sigma_{B,COM} \ll \sigma_{Y,COM}$, THE TUBE WILL BUCKLE BEFORE YIELDING OCCURS. IT IS THEN NECESSARY TO BASE A FIGURE OF MERIT FOR THIN-WALLED CYLINDERS ON A BUCKLING CRITERION.

THE GOAL IS TO MINIMIZE THE MASS OF A LONG, THIN-WALLED CYLINDER, WHERE

$$m = 2\pi r t \rho L. \quad (1)$$

FOR A LONG, THIN-WALLED CYLINDER, THE BUCKLING PRESSURE IS GIVEN BY

$$P_B = \frac{Et^3}{4(1-\nu^2)r^3}. \quad (4)$$

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SOLVING EQUATION (4) FOR t GIVES

$$t = \left[\frac{4 p_B (1 - \nu^2) r^3}{E} \right]^{1/3} \quad (5)$$

COMBINING EQUATIONS (1) AND (5) GIVE

$$m = 2\pi r^2 \rho L \left[4 p_B \frac{(1 - \nu^2)}{E} \right]^{1/3} \quad (6)$$

FOR CONSTANT r , p_B , AND L , THE FIGURE OF MERIT TO MINIMIZE, IN TERMS OF PHYSICAL PROPERTIES, BECOMES

$$M = \rho \left(\frac{1 - \nu^2}{E} \right)^{1/3} \quad (7)$$

ALTERNATELY, MAXIMIZATION OF

$$\frac{1}{\rho} \left[\frac{E}{(1 - \nu^2)} \right]^{1/3} \quad (8)$$

WILL PROVIDE A SUITABLE FIGURE OF MERIT.

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SINCE THE VALUE OF $\left(\frac{1}{1-\nu^2}\right)^{1/3}$ IS NEARLY CONSTANT FOR MOST REFRACTORY METALS, THE FIGURE OF MERIT CAN BE SIMPLIFIED TO

$$\eta = \frac{E^{1/3}}{\rho} \quad (9)$$

CONCLUSION:

THE CONCLUSION IS THAT MAXIMAZATION OF EQUATION (9)

$$\eta_{COM} = \frac{[E_{COM}]^{1/3}}{\rho_{COM}}$$

WILL PROVIDE A SUITABLE FIGURE OF MERIT BY WHICH TO EVALUATE ALL COMBINATIONS OF FOILS, METAL POWDERS, AND CERAMIC POWDERS BEING CONSIDERED.

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2) CALCULATION OF FIGURE OF MERIT,

THE PROGRAM "111066.EXE" OR "111066.ME.BAS"
(RUNNING UNDER BASIC) WILL CALCULATE A
FIGURE OF MERIT

$$\eta_{COM} = \frac{[E_{COM}]^{1/3}}{\rho_{COM}} \quad (9)$$

FOR ALL COMBINATIONS OF FOILS, METAL
POWDERS, AND CERAMIC POWDERS FOR WHICH
THE FILES "METALS.DAT", "CERAMICS.DAT", AND
"ELEMENTS.DAT" CONTAIN DATA,

THE FIGURE OF MERIT WILL BE CALCULATED
FOR ROOM TEMPERATURE AND 600 °C DATA.
THE FIGURE WILL BE DISPLAYED IN SI UNITS.

THE VALUE E_{COM} WILL BE CALCULATED AS
SHOWN ON PAGES A1 - A5. FOR THE EXAMPLE
OF NIOBIUM FOIL, TITANIUM POWDER, AND
TITANIUM DICORIDE POWDER,

$$E_{COM} = 23.3 \times 10^6 \text{ psi} \quad \text{AT ROOM TEMPERATURE}$$

AND

$$E_{COM} = 17.8 \times 10^6 \text{ psi} \quad \text{AT } 600^\circ \text{C.}$$

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IN SI UNITS,

$$E_{COM} = \left(23.3 \times 10^6 \text{ psi} \right) \left(\frac{1 \text{ N/m}^2}{1.4504 \times 10^{-4} \text{ psi}} \right)$$

$$E_{COM} = 16.1 \times 10^{10} \text{ N/m}^2 \quad \text{AT ROOM TEMPERATURE}$$

AND

$$E_{COM} = 12.3 \times 10^{10} \text{ N/m}^2 \quad \text{AT } 600^\circ\text{C.}$$

THE VALUE

$$\begin{aligned} \rho_{COM} = & \left(\text{VOLUME FRACTION OF FOIL} \right) \rho_{FOIL} + \left(\text{VOLUME FRACTION OF METAL POWDER} \right) \rho_{MP} \\ & + \left(\text{VOLUME FRACTION OF CERAMIC POWDER} \right) \rho_{CP} \end{aligned}$$

FOR THE EXAMPLE OF NIOBIUM FOIL, TITANIUM POWDER, AND TITANIUM DIBORIDE POWDER,

$$\begin{aligned} \rho_{COM} = & (0.3)(8.66 \text{ g/cc}) + \dots \\ & + (0.7)[(0.3)(4.54 \text{ g/cc}) + (0.7)(4.50 \text{ g/cc})] \\ = & 5.76 \text{ g/cc.} \end{aligned}$$

IN SI UNITS,

$$\rho_{COM} = 5760 \text{ kg/m}^3.$$

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CONCLUSION:

THE FIGURE OF MERIT FOR NIOBIUM FOIL,
TITANIUM POWDER, AND TITANIUM DIBORIDE POWDER,
IN SI UNITS, IS

$$\eta_{\text{COM}} = \frac{[16.1 \times 10^{10} \text{ N/m}^2]^{1/3}}{(5760 \text{ kg/m}^3)}$$

$$\eta_{\text{COM}} = 0.94 \text{ (N/m}^2\text{)}^{1/3} / (\text{kg/m}^3)$$

AT ROOM TEMPERATURE.

AND AT 600°C IS

$$\eta_{\text{COM}} = \frac{[12.3 \times 10^{10} \text{ N/m}^2]^{1/3}}{(5760 \text{ kg/m}^3)}$$

$$\eta_{\text{COM}} = 0.86 \text{ (N/m}^2\text{)}^{1/3} / (\text{kg/m}^3) .$$

Title: LOW MASS INTRINSICALLY HARDPage A1 of 5HIGH TEMPERATURE RADIATOR, Calculated by: JHR/JEL Date 3-6-90TASK 3 - MATERIAL EVALUATION, Approved by: _____ Date _____

PURPOSE: CALCULATE COMPOSITE MODULUS OF ELASTICITY FOR THIN-WALLED, LAYERED CYLINDER. USE THE EXAMPE OF NIOBIUM FOIL, TITANIUM POWDER, AND TITANIUM DIBORIDE POWDER.

DATA: X_F = VOLUME FRACTION OF FOIL
 $= 0.3$,
 X_M = VOLUME FRACTION OF POWDER
 $= 0.7$,
 $(a/b)_{11} = \frac{\text{CERAMIC FIBER LENGTH}}{\text{CERAMIC FIBER DIAMETER}}$
 $= 4.0$,
 V_{CP} = VOLUME FRACTION OF CERAMIC POWDER IN POWDER LAYER
 $= 0.3$,
 E_F = FOIL MODULUS
 $= 15.0 \times 10^6 \text{ psi AT ROOM TEMPERATURE}$
 $= 14.0 \times 10^6 \text{ psi AT } 600^\circ\text{C}$,
 E_{CP} = CERAMIC POWDER MODULUS
 $= 72.0 \times 10^6 \text{ psi AT ROOM TEMPERATURE}$
 $= 72.0 \times 10^6 \text{ psi AT } 600^\circ\text{C}$,
 E_{MP} = METAL POWDER MODULUS
 $= 16.0 \times 10^6 \text{ psi AT ROOM TEMPERATURE}$
 $= 10.0 \times 10^6 \text{ psi AT } 600^\circ\text{C}$,
 AND $(a/b)_{22} = \frac{\text{METAL 'FIBER' LENGTH}}{\text{METAL 'FIBER' DIAMETER}}$
 $= 1.0$.

SUBSCRIPTS: F = FOIL,
 M = (POWDER) MATRIX,
 MP = METAL POWDER,
 CP = CERAMIC POWDER,
 COM = COMPOSITE.

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HIGH TEMPERATURE RADIATOR, Calculated by: JHR/JEL Date 3-6-90
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ANALYSIS:

MATH MODEL / ALGORITHM

1) AT ROOM TEMPERATURE,

FOR COMPOSITE MODULUS OF ELASTICITY OF
 NIOBIUM FOIL, TITANIUM POWDER, AND TITANIUM
 DICHLORIDE POWDER (CHAPTER 6, PP. 130-142, HALPIN, J.C.,
PRIMER ON COMPOSITE MATERIALS: ANALYSIS).

$$\sum_{ii} = 2 \left(\frac{a}{b} \right)_{ii} + 40 (\chi_{cp})^{10} \quad (A1)$$

$$= 2(4.0) + 40(0.3)^{10}$$

$$\sum_{ii} = 8.00.$$

$$\eta_{ii} = \frac{\left(\frac{E_{cp}}{E_{mp}} - 1 \right)}{\left(\frac{E_{cp}}{E_{mp}} + \sum_{ii} \right)} \quad (A2)$$

$$= \frac{\left(\frac{72.0 \times 10^6 \text{ psi}}{16.0 \times 10^6 \text{ psi}} - 1 \right)}{\left(\frac{72.0 \times 10^6 \text{ psi}}{16.0 \times 10^6 \text{ psi}} + 8.00 \right)} = \frac{3.5}{12.5}$$

$$\eta_{ii} = 0.28.$$

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$$E_{M_{11}} = \frac{E_{MP} (1 + \sum_{11} \eta_{11} \nu_{CP})}{(1 - \eta_{11} \nu_{CP})} \quad (A3)$$

$$= \frac{(16.0 \times 10^6 \text{ psi}) [1 + (8.00)(0.28)(0.3)]}{[1 - (0.28)(0.3)]}$$

$$E_{M_{11}} = 29.2 \times 10^6 \text{ psi.}$$

$$\sum_{22} = 2 \left(\frac{a}{b} \right)_{22} + 40 (\nu_{CP})^{10} \quad (A4)$$

$$= 2(1.0) + 40(0.3)^{10}$$

$$\sum_{22} = 2.00.$$

$$\eta_{22} = \frac{\left(\frac{E_{CP}}{E_{MP}} - 1 \right)}{\left(\frac{E_{CP}}{E_{MP}} + \sum_{22} \right)} \quad (A5)$$

$$= \frac{\left(\frac{72.0 \times 10^6 \text{ psi}}{16.0 \times 10^6 \text{ psi}} - 1 \right)}{\left(\frac{72.0 \times 10^6 \text{ psi}}{16.0 \times 10^6 \text{ psi}} + \sum_{22} \right)} = \frac{3.5}{6.5}$$

$$\eta_{22} = 0.54.$$

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$$E_{m_{22}} = \frac{E_{mp} (1 + \sum_{j_{22}} \eta_{22} \nu_{cp})}{(1 - \eta_{22} \nu_{cp})} \quad (A6)$$

$$= \frac{(16.0 \times 10^6 \text{ psi}) [1 + (2.00)(0.54)(0.3)]}{[1 - (0.54)(0.3)]}$$

$$E_{m_{22}} = 25.3 \times 10^6 \text{ psi.}$$

$$E_M = \frac{3}{8} E_{m_{11}} + \frac{5}{8} E_{m_{22}} \quad (A7)$$

$$= \frac{3}{8} (29.2 \times 10^6 \text{ psi}) + \frac{5}{8} (25.3 \times 10^6 \text{ psi})$$

$$E_M = 26.8 \times 10^6 \text{ psi.}$$

$$E_{com} = X_F E_F + X_M E_M \quad (A8)$$

$$= (0.3)(15.0 \times 10^6 \text{ psi}) + (0.7)(26.8 \times 10^6 \text{ psi})$$

CONCLUSION:

$$E_{com} = 23.3 \times 10^6 \text{ psi}$$

AT ROOM TEMPERATURE.

Title: LOW MASS INTRINSICALLY HARD

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2) AT 600 °C,

$$\sum_{11} = 2(4.0) + 40(0.3)^{10} = 8.00. \quad (A1)$$

$$\eta_{11} = \frac{\left(\frac{72 \times 10^6 \text{ psi}}{10 \times 10^6 \text{ psi}} - 1\right)}{\left(\frac{72 \times 10^6 \text{ psi}}{10 \times 10^6 \text{ psi}} + 8\right)} = 0.41. \quad (A2)$$

$$E_{M_{11}} = \frac{(10.0 \times 10^6 \text{ psi})[1 + (8.00)(0.41)(0.3)]}{[1 - (0.41)(0.3)]} \quad (A3)$$

$$E_{M_{11}} = 22.6 \times 10^6 \text{ psi.}$$

$$\sum_{22} = 2(1.0) + 40(0.3)^{10} = 2.00. \quad (A4)$$

$$\eta_{22} = \frac{\left(\frac{72 \times 10^6 \text{ psi}}{10 \times 10^6 \text{ psi}} - 1\right)}{\left(\frac{72 \times 10^6 \text{ psi}}{10 \times 10^6 \text{ psi}} + 2\right)} = 0.67. \quad (A5)$$

$$E_{M_{22}} = \frac{(10.0 \times 10^6 \text{ psi})[1 + (2.00)(0.67)(0.3)]}{[1 - (0.67)(0.3)]} \quad (A6)$$

$$E_{M_{22}} = 17.5 \times 10^6 \text{ psi.}$$

$$E_M = \frac{3}{8}(22.6 \times 10^6 \text{ psi}) + \frac{5}{8}(17.5 \times 10^6 \text{ psi}) \quad (A7)$$

$$= 19.4 \times 10^6 \text{ psi.}$$

$$E_{COM} = (0.3)(14.0 \times 10^6 \text{ psi}) + (0.7)(19.4 \times 10^6 \text{ psi}) \quad (A8)$$

CONCLUSION: $E_{COM} = 17.8 \times 10^6 \text{ psi AT } 600^\circ \text{C.}$

```
'$DYNAMIC
```

```
' *****
' PROJECT 11-1066 LOW MASS INTRINSICALLY *****
' HARD HIGH TEMPERATURE RADIATOR *****
' TASK 3 - MATERIAL EVALUATION *****
' *****
' THIS PROGRAM WILL CALCULATE A FIGURE OF MERIT, *****
' *****
' 
$$\frac{1}{3} \left( \frac{E}{COM} \right) / \rho_{COM}$$
 *****
' *****
' WHERE *****
' 
$$\frac{1}{3} \left( \frac{E}{COM} \right) = \text{COMPOSITE YOUNG'S MODULUS FOR A}$$
 *****
' ***** FOIL/METAL POWDER/CERAMIC POWDER, *****
' ***** THIN-WALLED CYLINDER *****
' *****
' AND *****
' 
$$\rho_{COM} = \text{COMPOSITE DENSITY FOR A FOIL/}$$
 *****
' ***** METAL POWDER/CERAMIC POWDER, *****
' ***** THIN-WALLED CYLINDER. *****
' *****
' THE FIGURE OF MERIT WILL BE CALCULATED FOR ALL *****
' ***** COMBINATIONS OF FOILS/METAL POWDERS/CERAMIC *****
' ***** POWDERS. *****
' ***** THE FORTY FOIL/METAL POWDER/CERAMIC POWDER *****
' ***** COMBINATIONS WITH THE HIGHEST FIGURE OF MERIT *****
' ***** VALUES WILL BE DISPLAYED FOR BOTH ROOM TEMPERATURE *****
' ***** AND 600 DEGREES CENTIGRADE DATA. *****
' *****
' JAMES E. LINDEMUTH THERMACORE, INC. *****
' MARCH 7, 1990 *****
' *****
```

```
' *****
CLS '***** PROGRAM INTRODUCTION *****
PRINT
PRINT " PROJECT 11-1066 LOW MASS INTRINSICALLY"
PRINT " HARD HIGH TEMPERATURE RADIATOR"
PRINT " TASK 3 - MATERIAL EVALUATION"
PRINT
PRINT " THIS PROGRAM REQUIRES THREE FILES:"
PRINT " 1) METALS.DAT,"
PRINT " 2) CERAMICS.DAT,"
PRINT " AND 3) ELEMENTS.DAT."
PRINT
PRINT
```

```
PRINT
INPUT " PRESS RETURN TO CONTINUE...", A$
```

```
CLS
```

```
PRINT
PRINT " THE FORMAT OF THE FILE METALS.DAT IS"
```

```
PRINT
PRINT
PRINT "          1,          8.66,          15,          14"
PRINT "          2,          10.6,          15,          14"
PRINT "          3,          8.57,          15,          14"
PRINT "          ...          ...          ...          ..."
PRINT "          ...          ...          ...          ..."
PRINT "          ...          ...          ...          ..."
PRINT "          n,          x,          y,          z"
```

```
PRINT
PRINT
PRINT " THE NUMBER IN THE FIRST COLUMN REFERS TO THE FILE 'ELEMENTS.DAT'"
PRINT " WHICH LISTS ALL FOILS, METAL POWDERS, AND CERAMIC POWDERS BEING"
PRINT " CONSIDERED. THE SECOND COLUMN LISTS THE MATERIAL DENSITY IN g/cc."
PRINT " THE THIRD COLUMN LISTS THE VALUE FOR YOUNG'S MODULUS AT ROOM "
PRINT " TEMPERATURE. THE FINAL COLUMN LISTS YOUNG'S MODULUS AT 600 DEGREES"
PRINT " CENTIGRADE. YOUNG'S MODULUS MUST BE ENTERED IN KSI."
PRINT
PRINT " (NOTE: THE COMMAS THAT APPEAR IN THE EXAMPLE ABOVE MUST BE "
PRINT " INCLUDED IN THE DATA FILE, 'METALS.DAT'.)"
PRINT
INPUT "PRESS RETURN TO CONTINUE...", A$
```

```
CLS
```

```
PRINT
PRINT " THE FORMAT OF THE FILE CERAMICS.DAT IS"
```

```
PRINT
PRINT
PRINT "          1,          2.25,          11,          11"
PRINT "          2,          2.52,          11,          9"
PRINT "          3,          4.09,          54,          54"
PRINT "          ...          ...          ...          ..."
PRINT "          ...          ...          ...          ..."
PRINT "          ...          ...          ...          ..."
PRINT "          m,          u,          v,          w"
```

```
PRINT
PRINT
PRINT " THE NUMBER IN THE FIRST COLUMN REFERS TO THE FILE 'ELEMENTS.DAT'"
PRINT " WHICH LISTS ALL FOILS, METAL POWDERS, AND CERAMIC POWDERS BEING"
PRINT " CONSIDERED. THE SECOND COLUMN LISTS THE MATERIAL DENSITY IN g/cc."
PRINT " THE THIRD COLUMN LISTS THE VALUE FOR YOUNG'S MODULUS AT ROOM "
PRINT " TEMPERATURE. THE FINAL COLUMN LISTS YOUNG'S MODULUS AT 600 DEGREES"
PRINT " CENTIGRADE. YOUNG'S MODULUS MUST BE ENTERED IN KSI."
PRINT
PRINT " (NOTE: THE COMMAS THAT APPEAR IN THE EXAMPLE ABOVE MUST BE "
```

PRINT " INCLUDED IN THE DATA FILE, 'CERAMICS.DAT'."

PRINT

INPUT "PRESS RETURN TO CONTINUE...", A\$

CLS

PRINT " THE FORMAT OF THE REFERENCE FILE ELEMENTS.DAT IS"

PRINT

MATERIAL	ELEMENTS	DENSITY	E @ RT	E @ 600
----------	----------	---------	--------	---------

C"		(g/cc)	(KSI)	(KSI)
----	--	--------	-------	-------

PRINT " -----

--"

PRINT " METAL POWDERS/FOILS"

PRINT " -----"

1. COLUMBIUM	Cb	8.66	15.0	14.0
--------------	----	------	------	------

PRINT

2. FS - 85	Cb-28Ta-10W-1Zr	10.6	15.0	14.0
------------	-----------------	------	------	------

PRINT

...	...	...	...	...
-----	-----	-----	-----	-----

PRINT

n. XXXXXX	Xx-Zz	a	b	c"
-----------	-------	---	---	----

PRINT

PRINT " CERAMIC POWDERS"

PRINT " -----"

1. BORON NITRIDE	BN	2.25	9.0	9.
------------------	----	------	-----	----

O"

PRINT

...	...	...	...	..
-----	-----	-----	-----	----

PRINT

m. YYYYYY	Yy-X	d	e	f
-----------	------	---	---	---

PRINT

INPUT "PRESS RETURN TO CONTINUE...", A\$

CLS

PRINT

PRINT " ENTER THE NUMBER OF METALS (FOILS / METAL POWDERS)"

INPUT " FOR WHICH THERE IS DATA IN FILE 'METALS.DAT' :"; METLS

PRINT

PRINT " ENTER THE NUMBER OF CERAMIC POWDERS "

INPUT " FOR WHICH THERE IS DATA IN FILE 'CERAMICS.DAT' :"; CERAMCS

PRINT

***** READ THE METAL AND CERAMIC DATA FILES FROM THE DISK *****

***** FOILS(x,1) = DENSITY OF FOIL X. *****

```

' ***** FOILS(x,2) = E @ RT FOR FOIL x. *****
' ***** FOILS(x,3) = E @ 600C FOR FOIL x. *****
' ***** METPWDRS(y,1) = DENSITY OF METAL POWDER y. *****
' ***** METPWDRS(y,2) = E @ RT FOR METAL POWDER y. *****
' ***** METPWDRS(y,3) = E @ 600C FOR METAL POWDER y. *****
' ***** CERPWDRS(z,1) = DENSITY OF CERAMIC POWDER z. *****
' ***** CERPWDRS(z,2) = E @ RT FOR CERAMIC POWDER z. *****
' ***** CERPWDRS(z,3) = E @ 600C FOR CERAMIC POWDER z. *****

```

CLS

PRINT "READING DATA..."

DIM FOILS(METLS, 3), METPWDRS(METLS, 3), CERPWDRS(CERAMCS, 3)

OPEN "A:METALS.DAT" FOR INPUT AS #1

'READ THE METALS FILE

FOR I = 1 TO METLS

FOR J = 0 TO 3

SELECT CASE J

CASE 0

'CASE 0 = METAL NUMBE

R

INPUT #1, DATUM

' (UNUSED)

CASE 1

'CASE 1 = DENSITY

INPUT #1, DATUM

'g/cc

FOILS(I, J) = DATUM * 1000

'kg/m3 = 1000 * g/cc

METPWDRS(I, J) = FOILS(I, J)

CASE 2, 3

'CASE 2 = E @ RT

INPUT #1, DATUM

'CASE 3 = E @ 600C

FOILS(I, J) = DATUM * 1000000 / 1.4504E-04

'KSI TO N/M

2

METPWDRS(I, J) = FOILS(I, J)

END SELECT

NEXT J

NEXT I

CLOSE #1

OPEN "A:CERAMICS.DAT" FOR INPUT AS #2

'READ THE CERAMICS FI

LE

FOR K = 1 TO CERAMCS

FOR L = 0 TO 3

SELECT CASE L

CASE 0

'CASE 0 = CERAMIC NUM

BER

INPUT #2, DATUM

' (UNUSED)

CASE 1

'CASE 1 = DENSITY

INPUT #2, DATUM

'g/cc

CERPWDRS(K, L) = DATUM * 1000

'kg/m3 = 1000 * g/cc

CASE 2, 3

'CASE 2 = E @ RT

INPUT #2, DATUM

'CASE 3 = E @ 600C

CERPWDRS(K, L) = DATUM * 1000000 / 1.4504E-04

'KSI TO N/M

2

END SELECT

NEXT L

NEXT K

CLOSE #2

```

' *****
' ***** CALCULATE THE COMPOSITE DENSITY OF THE CYLINDER WALL *****
' *****
' ***** DENSITY(x,y,z) = THE COMPOSITE DENSITY CALCULATED *****
' ***** FOR THE FOIL x, METAL POWDER y, *****
' ***** AND CERAMIC POWDER z. *****
' ***** = COMMASS / COMVOL. *****
' *****

```

PRINT "CALCULATING DENSITIES..."

DIM DENSITY(METLS, METLS, CERAMCS)

FOR I = 1 TO METLS

FOR J = 1 TO METLS

FOR K = 1 TO CERAMCS

'STEP THROUGH THE FOILS

'STEP THROUGH THE METAL PWDRS

'STEP THROUGH THE CERAMIC PWD

RS

FDENSITY = .3 * FOILS(I, 1)

'DENSITY OF FOIL

MPDENSITY = .7 * .7 * METPWDRS(J, 1)

'DENSITY OF METAL POWDER

CPDENSITY = .3 * .7 * CERPWDRS(K, 1)

'DENSITY OF CERAMIC POWD

ER

'DENSITY OF COMPOSITE

DENSITY(I, J, K) = FDENSITY + MPDENSITY + CPDENSITY

NEXT K

NEXT J

NEXT I

```

' *****
' ***** CALCULATE THE COMPOSITE YOUNG'S MODULUS OF THE CYLINDER *****
' ***** WALL AT ROOM TEMPERATURE AND AT 600 DEGREES CENTIGRADE *****
' *****
' ***** RTMODULS(x,y,z) = THE COMPOSITE YOUNG'S MODULUS AT *****
' ***** ROOM TEMPERATURE CALCULATED FOR *****
' ***** FOIL x, METAL POWDER y, AND CERAMIC *****
' ***** POWDER z. *****
' *****
' ***** MODLS600(x,y,z) = THE COMPOSITE YOUNG'S MODULUS AT *****
' ***** 600 DEGREES C CALCULATED FOR *****
' ***** FOIL x, METAL POWDER y, AND CERAMIC *****
' ***** POWDER z. *****
' *****
' ***** FOILFRAC = THE RATIO OF FOIL VOLUME TO COMPOSITE *****
' ***** VOLUME. *****

```



```

' *****          = 0.3.          *****
' *****          *****
' ***** PWDRFRAC = THE RATIO OF POWDER VOLUME TO COMPOSITE *****
' ***** VOLUME. *****
' *****          = 0.7.          *****
' *****          *****
' ***** CERPFrac = THE RATIO OF CERAMIC POWDER VOLUME TO *****
' ***** METAL AND CERAMIC POWDER VOLUME. *****
' *****          = 0.3.          *****
' *****          *****
' ***** AB11 = THE RATIO OF THE CERAMIC FIBER LENGTH TO ITS *****
' ***** FIBER DIAMETER. (AB11 = 4.0 FOR THIS PROGRAM.) *****
' *****          *****
' ***** AB22 = THE RATIO OF THE METAL POWDER 'FIBER' LENGTH TO *****
' ***** ITS 'FIBER' DIAMETER. (AB22 = 1.0 FOR THIS *****
' ***** PROGRAM.) *****
' *****          *****

```

PRINT "CALCULATING MODULI..."

DIM RTMODULS(METLS, METLS, CERAMCS), MODLS600(METLS, METLS, CERAMCS)

AB11 = 4

AB22 = 1

FOILFRAC = .3

'VOLUME FRACTION OF FOIL

PWDRFRAC = .7

'VOLUME FRACTION OF METAL AND CERAMIC POW

DER

CERPFRAC = .3

'VOLUME FRACTION OF CERAMIC POWDER

ZETA11 = 2 * AB11 + 40 * CERPFRAC ^ 10

'EQ.1

ZETA22 = 2 * AB22 + 40 * CERPFRAC ^ 10

'EQ.4

FOR I = 1 TO METLS

'STEP THROUGH FOILS

FOR J = 1 TO METLS

'STEP THROUGH METAL PWDRS

FOR K = 1 TO CERAMCS

'STEP THROUGH CERAMIC PWDRS

ETATOP = (CERPWDRS(K, 2) / METPWDRS(J, 2) - 1)

'@ RT

ETABOT = (CERPWDRS(K, 2) / METPWDRS(J, 2) + ZETA11)

ETA11 = ETATOP / ETABOT

'EQ.2

ETABOT = (CERPWDRS(K, 2) / METPWDRS(J, 2) + ZETA22)

ETA22 = ETATOP / ETABOT

'EQ.5

EM11 = METPWDRS(J, 2) * ((1 + ZETA11 * ETA11 * CERPFRAC) / (1 - ETA11 * CERPFRAC))

'EQ.3

EM22 = METPWDRS(J, 2) * ((1 + ZETA22 * ETA22 * CERPFRAC) / (1 - ETA22 * CERPFRAC))

'EQ.6

MATRXMOD = 3 / 8 * EM11 + 5 / 8 * EM22

'EQ.7

RTMODULS(I, J, K) = FOILS(I, 2) * FOILFRAC + MATRXMOD * PWDRFRAC

'EQ.8

```

ETATOP = (CERPWDRS(K, 3) / METPWDRS(J, 3) - 1)      '@ 600C
ETABOT = (CERPWDRS(K, 3) / METPWDRS(J, 3) + ZETA11)
ETA11 = ETATOP / ETABOT                             'EQ.2

```

```

ETABOT = (CERPWDRS(K, 3) / METPWDRS(J, 3) + ZETA22)
ETA22 = ETATOP / ETABOT                             'EQ.5

```

```

EM11 = METPWDRS(J, 3) * ((1 + ZETA11 * ETA11 * CERPFRAC) / (1 - ETA11 *
CERPFRAC))      'EQ.3

```

```

EM22 = METPWDRS(J, 3) * ((1 + ZETA22 * ETA22 * CERPFRAC) / (1 - ETA22 *
CERPFRAC))      'EQ.6

```

```

MATRXMOD = 3 / 8 * EM11 + 5 / 8 * EM22              'EQ.7

```

```

MODLS600(I, J, K) = FOILS(I, 3) * FOILFRAC + MATRXMOD * PWDRFRAC      'EQ.
8

```

```

NEXT K
NEXT J
NEXT I

```

```

' *****

```

```

' ***** CALCULATE THE FIGURES OF MERIT FOR ALL FOILS, METAL POWDERS, ***
' ***** AND CERAMIC POWDERS AT ROOM TEMPERATURE AND 600 C *****

```

```

' ***** FOMRT(i,j,k) = FIGURE OF MERIT FOR FOIL i, METAL *****
' ***** POWDER j, AND CERAMIC POWDER k AT *****
' ***** ROOM TEMPERATURE. *****

```

```

' ***** 1/3 *****
' ***** = ( E ) / p *****
' ***** COM RT COM *****
' ***** *****

```

```

' ***** FOM600(i,j,k) = FIGURE OF MERIT FOR FOIL i, METAL *****
' ***** POWDER j, AND CERAMIC POWDER k AT *****
' ***** 600 DEGREES C. *****

```

```

' ***** 1/3 *****
' ***** = ( E ) / p *****
' ***** COM 600C COM *****
' ***** *****

```

```

PRINT "CALCULATING FIGURES OF MERIT..."

```

```

DIM FOMRT(METLS, METLS, CERAMCS), FOM600(METLS, METLS, CERAMCS)

```

```

FOR I = 1 TO METLS
  FOR J = 1 TO METLS
    FOR K = 1 TO CERAMCS

```

```

      FOMRT(I, J, K) = RTMODULS(I, J, K) ^ .333 / DENSITY(I, J, K)      '@R

```

```

T
FOM600(I, J, K) = MODLS600(I, J, K) ^ .333 / DENSITY(I, J, K) ' @6
OOC

```

```

                NEXT K
            NEXT J
        NEXT I
    
```

```

***** SEARCH THE FIGURE OF MERIT ARRAYS TO FIND THE FORTY *****
***** COMBINATIONS OF FOIL, METAL POWDER, AND CERAMIC POWDER *****
***** THAT HAVE THE HIGHEST FIGURES OF MERIT. THERE WILL BE *****
***** FORTY COMBINATIONS FOR ROOM TEMPERATURE AND FORTY *****
***** COMBINATIONS FOR 600 C. *****

```

```

, ***** TOPRT(40, 4) = THE FORTY HIGHEST FIGURES OF MERIT *****
, ***** FOR ROOM TEMPERATURE FOIL, METAL POWDER, *****
, ***** AND CERAMIC POWDER COMBINATIONS. *****

```

```

***** TOP600(40, 4) = THE FORTY HIGHEST FIGURES OF MERIT FOR *****
***** 600 DEGREE C FOIL, METAL POWDER, AND *****
***** CERAMIC POWDER COMBINATIONS. *****

```

***** THE FORMAT FOR BOTH ARRAYS IS

RANKING	FOIL NUMBER	METAL POWDER#	CERAMIC POWDER#	FIGURE OF MERIT
1	x1	y1	z1	i
2	x2	y2	z2	j
3	x3	y3	z3	k
...	...	...	...	...
40	x40	y40	z40	m

```
PRINT "SORTING FIGURES OF MERIT..."
```

```

DIM TOPRT(40, 4), TOP600(40, 4) -

```

```
FOR I = 1 TO 40
  FOR J = 1 TO 4
    TOPRT(I, J) = 0
    TOP600(I, J) = 0
  NEXT J
NEXT I
```

```
FOR I = 1 TO METLS
  FOR J = 1 TO METLS
    FOR K = 1 TO CERAMCS
```

5

'STEP THROUGH FOILS
'STEP THROUGH METAL PWDRS
'STEP THROUGH CERAMIC PWDR

SELECT CASE FOMRT(I, J, K)

'ROOM TEMPERATURE SORTING

```
CASE IS > TOPRT(1, 4)      'FIGURE OF MERIT
  RANK = 1                  'RANKING 1
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(2, 4)      'FIGURE OF MERIT
  RANK = 2                  'RANKING 2
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(3, 4)      'FIGURE OF MERIT
  RANK = 3                  'RANKING 3
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(4, 4)      'FIGURE OF MERIT
  RANK = 4                  'RANKING 4
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(5, 4)      'FIGURE OF MERIT
  RANK = 5                  'RANKING 5
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(6, 4)      'FIGURE OF MERIT
  RANK = 6                  'RANKING 6
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(7, 4)      'FIGURE OF MERIT
  RANK = 7                  'RANKING 7
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(8, 4)      'FIGURE OF MERIT
  RANK = 8                  'RANKING 8
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(9, 4)      'FIGURE OF MERIT
  RANK = 9                  'RANKING 9
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(10, 4)     'FIGURE OF MERIT
  RANK = 10                 'RANKING 10
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(11, 4)     'FIGURE OF MERIT
  RANK = 11                 'RANKING 11
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(12, 4)     'FIGURE OF MERIT
  RANK = 12                 'RANKING 12
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(13, 4)     'FIGURE OF MERIT
  RANK = 13                 'RANKING 13
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(14, 4)     'FIGURE OF MERIT
  RANK = 14                 'RANKING 14
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(15, 4)     'FIGURE OF MERIT
  RANK = 15                 'RANKING 15
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(16, 4)     'FIGURE OF MERIT
  RANK = 16                 'RANKING 16
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(17, 4)     'FIGURE OF MERIT
  RANK = 17                 'RANKING 17
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(18, 4)     'FIGURE OF MERIT
  RANK = 18                 'RANKING 18
  GOSUB RESHUFFLERT         'RESHUFFLE ARRAY
CASE IS > TOPRT(19, 4)     'FIGURE OF MERIT
```

RANK = 19	'RANKING 19
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(20, 4)	'FIGURE OF MERIT
RANK = 20	'RANKING 20
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(21, 4)	'FIGURE OF MERIT
RANK = 21	'RANKING 21
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(22, 4)	'FIGURE OF MERIT
RANK = 22	'RANKING 22
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(23, 4)	'FIGURE OF MERIT
RANK = 23	'RANKING 23
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(24, 4)	'FIGURE OF MERIT
RANK = 24	'RANKING 24
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(25, 4)	'FIGURE OF MERIT
RANK = 25	'RANKING 25
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(26, 4)	'FIGURE OF MERIT
RANK = 26	'RANKING 26
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(27, 4)	'FIGURE OF MERIT
RANK = 27	'RANKING 27
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(28, 4)	'FIGURE OF MERIT
RANK = 28	'RANKING 28
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(29, 4)	'FIGURE OF MERIT
RANK = 29	'RANKING 29
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(30, 4)	'FIGURE OF MERIT
RANK = 30	'RANKING 30
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(31, 4)	'FIGURE OF MERIT
RANK = 31	'RANKING 31
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(32, 4)	'FIGURE OF MERIT
RANK = 32	'RANKING 32
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(33, 4)	'FIGURE OF MERIT
RANK = 33	'RANKING 33
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(34, 4)	'FIGURE OF MERIT
RANK = 34	'RANKING 34
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(35, 4)	'FIGURE OF MERIT
RANK = 35	'RANKING 35
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(36, 4)	'FIGURE OF MERIT
RANK = 36	'RANKING 36
GOSUB RESHUFFLERT	'RESHUFFLE ARRAY
CASE IS > TOPRT(37, 4)	'FIGURE OF MERIT
RANK = 37	'RANKING 37

40

```
      GOSUB RESHUFFLERT
CASE IS > TOPRT(38, 4)
      RANK = 38
      GOSUB RESHUFFLERT
CASE IS > TOPRT(39, 4)
      RANK = 39
      GOSUB RESHUFFLERT
CASE IS > TOPRT(40, 4)

      TOPRT(40, 1) = I
      TOPRT(40, 2) = J
      TOPRT(40, 3) = K
      TOPRT(40, 4) = FOMRT(I, J, K)
END SELECT

SELECT CASE FOM600(I, J, K)
CASE IS > TOP600(1, 4)
      RANK = 1
      GOSUB RESHUFFLE600
CASE IS > TOP600(2, 4)
      RANK = 2
      GOSUB RESHUFFLE600
CASE IS > TOP600(3, 4)
      RANK = 3
      GOSUB RESHUFFLE600
CASE IS > TOP600(4, 4)
      RANK = 4
      GOSUB RESHUFFLE600
CASE IS > TOP600(5, 4)
      RANK = 5
      GOSUB RESHUFFLE600
CASE IS > TOP600(6, 4)
      RANK = 6
      GOSUB RESHUFFLE600
CASE IS > TOP600(7, 4)
      RANK = 7
      GOSUB RESHUFFLE600
CASE IS > TOP600(8, 4)
      RANK = 8
      GOSUB RESHUFFLE600
CASE IS > TOP600(9, 4)
      RANK = 9
      GOSUB RESHUFFLE600
CASE IS > TOP600(10, 4)
      RANK = 10
      GOSUB RESHUFFLE600
CASE IS > TOP600(11, 4)
      RANK = 11
      GOSUB RESHUFFLE600
CASE IS > TOP600(12, 4)
      RANK = 12
      GOSUB RESHUFFLE600
CASE IS > TOP600(13, 4)
      RANK = 13
```

'RESHUFFLE ARRAY
'FIGURE OF MERIT
'RANKING 38
'RESHUFFLE ARRAY
'FIGURE OF MERIT
'RANKING 39
'RESHUFFLE ARRAY
'FIGURE OF MERIT-RANKING

'FOIL NUMBER
'METAL PWDR NUMBER
'CERAMIC PWDR NUMBER
'FIGURE OF MERIT

'600 DEGREE C SORTING
'FIGURE OF MERIT
'RANKING 1
'RESHUFFLE ARRAY
'FIGURE OF MERIT
'RANKING 2
'RESHUFFLE ARRAY
'FIGURE OF MERIT
'RANKING 3
'RESHUFFLE ARRAY
'FIGURE OF MERIT
'RANKING 4
'RESHUFFLE ARRAY
'FIGURE OF MERIT
'RANKING 5
'RESHUFFLE ARRAY
'FIGURE OF MERIT
'RANKING 6
'RESHUFFLE ARRAY
'FIGURE OF MERIT
'RANKING 7
'RESHUFFLE ARRAY
'FIGURE OF MERIT
'RANKING 8
'RESHUFFLE ARRAY
'FIGURE OF MERIT
'RANKING 9
'RESHUFFLE ARRAY
'FIGURE OF MERIT
'RANKING 10
'RESHUFFLE ARRAY
'FIGURE OF MERIT
'RANKING 11
'RESHUFFLE ARRAY
'FIGURE OF MERIT
'RANKING 12
'RESHUFFLE ARRAY
'FIGURE OF MERIT
'RANKING 13

GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(14, 4)	'FIGURE OF MERIT
RANK = 14	'RANKING 14
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(15, 4)	'FIGURE OF MERIT
RANK = 15	'RANKING 15
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(16, 4)	'FIGURE OF MERIT
RANK = 16	'RANKING 16
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(17, 4)	'FIGURE OF MERIT
RANK = 17	'RANKING 17
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(18, 4)	'FIGURE OF MERIT
RANK = 18	'RANKING 18
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(19, 4)	'FIGURE OF MERIT
RANK = 19	'RANKING 19
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(20, 4)	'FIGURE OF MERIT
RANK = 20	'RANKING 20
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(21, 4)	'FIGURE OF MERIT
RANK = 21	'RANKING 21
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(22, 4)	'FIGURE OF MERIT
RANK = 22	'RANKING 22
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(23, 4)	'FIGURE OF MERIT
RANK = 23	'RANKING 23
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(24, 4)	'FIGURE OF MERIT
RANK = 24	'RANKING 24
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(25, 4)	'FIGURE OF MERIT
RANK = 25	'RANKING 25
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(26, 4)	'FIGURE OF MERIT
RANK = 26	'RANKING 26
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(27, 4)	'FIGURE OF MERIT
RANK = 27	'RANKING 27
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(28, 4)	'FIGURE OF MERIT
RANK = 28	'RANKING 28
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(29, 4)	'FIGURE OF MERIT
RANK = 29	'RANKING 29
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(30, 4)	'FIGURE OF MERIT
RANK = 30	'RANKING 30
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY
CASE IS > TOP600(31, 4)	'FIGURE OF MERIT
RANK = 31	'RANKING 31
GOSUB RESHUFFLE600	'RESHUFFLE ARRAY

```

CASE IS > TOP600(32, 4)      'FIGURE OF MERIT
RANK = 32                   'RANKING 32
GOSUB RESHUFFLE600          'RESHUFFLE ARRAY
CASE IS > TOP600(33, 4)      'FIGURE OF MERIT
RANK = 33                   'RANKING 33
GOSUB RESHUFFLE600          'RESHUFFLE ARRAY
CASE IS > TOP600(34, 4)      'FIGURE OF MERIT
RANK = 34                   'RANKING 34
GOSUB RESHUFFLE600          'RESHUFFLE ARRAY
CASE IS > TOP600(35, 4)      'FIGURE OF MERIT
RANK = 35                   'RANKING 35
GOSUB RESHUFFLE600          'RESHUFFLE ARRAY
CASE IS > TOP600(36, 4)      'FIGURE OF MERIT
RANK = 36                   'RANKING 36
GOSUB RESHUFFLE600          'RESHUFFLE ARRAY
CASE IS > TOP600(37, 4)      'FIGURE OF MERIT
RANK = 37                   'RANKING 37
GOSUB RESHUFFLE600          'RESHUFFLE ARRAY
CASE IS > TOP600(38, 4)      'FIGURE OF MERIT
RANK = 38                   'RANKING 38
GOSUB RESHUFFLE600          'RESHUFFLE ARRAY
CASE IS > TOP600(39, 4)      'FIGURE OF MERIT
RANK = 39                   'RANKING 39
GOSUB RESHUFFLE600          'RESHUFFLE ARRAY
CASE IS > TOP600(40, 4)      'FIGURE OF MERIT-RANKING

40
TOP600(40, 1) = I           'FOIL NUMBER
TOP600(40, 2) = J           'METAL PWDR NUMBER
TOP600(40, 3) = K           'CERAMIC PWDR NUMB

ER
TOP600(40, 4) = FOM600(I, J, K) 'FIGURE OF MERIT
END SELECT

NEXT K
NEXT J
NEXT I
'*****

' ***** DISPLAY TOP EIGHT COMBINATIONS FOR FOIL, METAL POWDER, *****
' ***** AND CERAMIC POWDER COMBINATIONS AND FIGURE OF MERIT VALUE *****
' ***** ON THE SCREEN. *****

*****

CLS

PRINT "    ROOM TEMPERATURE FIGURES OF MERIT          600 DEGREES C FIGURES
OF MERIT"
PRINT "-----"
PRINT "
FIGURE
OF MERIT"
PRINT "    METAL    CERAMIC    OF MERIT          METAL    CERAMIC
OF MERIT"
PRINT "    FOIL    POWDER    POWDER    1/3          FOIL    POWDER    POWDER

```



```

      1/3"
PRINT "  NUMBER  NUMBER  NUMBER  E  /  p  NUMBER  NUMBER  NUMBER
      E  /  p  "
PRINT "  -----  -----  -----  -----  -----  -----  -----
      -----"
PRINT "                                     (SI UNITS)
      (SI UNITS)"
PRINT ""

```

```

K = 9                                     'DISPLAY EIGHT HIGHEST VALU
ED                                         '
FOR I = 1 TO 8                           'FIGURES OF MERIT AND THE
  L = 4                                  'FOIL, METAL POWDER, AND
  FOR J = 1 TO 4                         'CERAMIC POWDER COMBINATION
S                                         '
    SELECT CASE J                        'FOR ROOM TEMPERATURE.
      CASE 1, 2, 3
        LOCATE K, L
        PRINT USING "##"; TOPRT(I, J)
        L = L + 9
      CASE 4
        LOCATE K, L
        PRINT USING "##.##"; TOPRT(I, J)
        K = K + 2
    END SELECT
  NEXT J
NEXT I

```

```

K = 9                                     'DISPLAY EIGHT HIGHEST VALU
ED                                         '
FOR I = 1 TO 8                           'FIGURES OF MERIT AND THE
  L = 46                                  'FOIL, METAL POWDER, AND
  FOR J = 1 TO 4                         'CERAMIC POWDER COMBINATION
S                                         '
    SELECT CASE J                        'FOR 600 DEGREES C.
      CASE 1, 2, 3
        LOCATE K, L
        PRINT USING "##"; TOP600(I, J)
        L = L + 9
      CASE 4
        LOCATE K, L
        PRINT USING "##.##"; TOP600(I, J)
        K = K + 2
    END SELECT
  NEXT J
NEXT I

```

```

' *****
' ***** PRINT TOP FIFTEEN COMBINATIONS FOR FOIL, METAL POWDER, AND *****
' ***** CERAMIC POWDER COMBINATIONS AND FIGURE OF MERIT VALUE ON *****
' ***** THE PRINTER. *****

```

```

OPEN "LPT1:" FOR OUTPUT AS #1

```

```
PRINT #1, CHR$(12)
```

```
PRINT #1, " ROOM TEMPERATURE FIGURES OF MERIT "
```

```
PRINT #1, " -----
```

```
PRINT #1, " FIGURE
```

```
PRINT #1, " METAL CERAMIC COMPOSITE COMPOSITE OF MERIT
```

```
PRINT #1, " FOIL POWDER POWDER DENSITY MODULUS 1/3
```

```
PRINT #1, " NUMBER NUMBER NUMBER (kg/m3) (N/m2) E / p
```

```
PRINT #1, " -----
```

```
PRINT #1, " (SI UNITS)"
```

```
PRINT #1,
```

```
'PRINT FORTY HIGHEST VALUED
'FIGURES OF MERIT AND THE
'FOIL, METAL POWDER, AND
'CERAMIC POWDER COMBINATION
```

```
S
```

```
FOR I = 1 TO 40
```

```
'FOR ROOM TEMPERATURE.
```

```
PRINT #1, SPC(4); USING "##"; TOPRT(I, 1);
```

```
PRINT #1, SPC(6); USING "##"; TOPRT(I, 2);
```

```
PRINT #1, SPC(6); USING "##"; TOPRT(I, 3);
```

```
PRINT #1, SPC(7); USING "####.#"; DENSITY(TOPRT(I, 1), TOP
RT(I, 2), TOPRT(I, 3));
```

```
PRINT #1, SPC(6); USING "###.##^"; RTMODULS(TOPRT(I, 1),
TOPRT(I, 2), TOPRT(I, 3));
```

```
PRINT #1, SPC(5); USING "###.##"; TOPRT(I, 4)
```

```
NEXT I
```

```
PRINT #1, CHR$(12)
```

```
PRINT #1, " 600 DEGREE C FIGURES OF MERIT "
```

```
PRINT #1, " -----
```

```
_"
```

```
PRINT #1, " FIGURE
```

```
PRINT #1, " METAL CERAMIC COMPOSITE COMPOSITE OF MERIT
```

```
PRINT #1, " FOIL POWDER POWDER DENSITY MODULUS 1/3
```

```
PRINT #1, " NUMBER NUMBER NUMBER (kg/m3) (N/m2) E / p
```

```
PRINT #1, " -----
```

```
PRINT #1, " (SI UNITS)"
```

```
PRINT #1,
```

```
'PRINT FORTY HIGHEST VALUED
'FIGURES OF MERIT AND THE
'FOIL, METAL POWDER, AND
'CERAMIC POWDER COMBINATION
```

```
S
```

```
FOR I = 1 TO 40
```

```
'FOR 600 DEGREES C.
```

```
PRINT #1, SPC(4); USING "##"; TOP600(I, 1);
```

```
PRINT #1, SPC(6); USING "##"; TOP600(I, 2);
```

```
PRINT #1, SPC(6); USING "##"; TOP600(I, 3);
```

```
PRINT #1, SPC(7); USING "####.#"; DENSITY(TOP600(I, 1), TOP
```

```
600(I, 2), TOP600(I, 3));  
    PRINT #1, SPC(6); USING "##.##^"; MODLS600(TOP600(I, 1),  
    TOP600(I, 2), TOP600(I, 3));  
    PRINT #1, SPC(5); USING "##.##"; TOP600(I, 4)
```

```
NEXT I
```

```
PRINT #1, CHR$(12)
```

```
CLOSE #1
```

```
'*****
```

```
END
```

```
' ***** SUBROUTINES THAT RESHUFFLE THE FIGURES OF MERIT IN THE *****  
' ***** ARRAYS THAT CONTAIN THE FIFTEEN HIGHEST VALUES FOR ROOM *****  
' ***** TEMPERATURE AND 600 DEGREES CENTIGRADE. *****
```

```
RESHUFFLERT:
```

```
'ROOM TEMPERATURE  
'RESHUFFLING
```

```
    FOR T = 40 TO (RANK + 1) STEP -1  
        FOR L = 1 TO 4  
            TOPRT(T, L) = TOPRT(T - 1, L)  
        NEXT L  
    NEXT T  
    TOPRT(RANK, 1) = I  
    TOPRT(RANK, 2) = J  
    TOPRT(RANK, 3) = K  
    TOPRT(RANK, 4) = FOMRT(I, J, K)  
    RETURN
```

```
RESHUFFLE600:
```

```
'600 DEGREES C  
'RESHUFFLING
```

```
    FOR T = 40 TO (RANK + 1) STEP -1  
        FOR L = 1 TO 4  
            TOP600(T, L) = TOP600(T - 1, L)  
        NEXT L  
    NEXT T  
    TOP600(RANK, 1) = I  
    TOP600(RANK, 2) = J  
    TOP600(RANK, 3) = K  
    TOP600(RANK, 4) = FOM600(I, J, K)  
    RETURN
```

```
' *****
```

```
END
```

Material C	Elements	Density (g/cc)	E @ RT (KSI)	E @ 600 (KSI)

METAL POWDERS / FOILS				

1. COLUMBIUM/ NIOBIUM	Cb/Nb	8.66	15.0	14.0
2. FS - 85	Cb-28Ta-10W-1Zr	10.6	15.0	14.0
3. FS - 80	Cb-1Zr	8.57	15.0	14.0
4. B - 66	Cb-5Mo-5V-1Zr	8.43	15.0	14.0
5. Cb - 752	Cb-10W-2.5Zr	9.01	15.0	12.0
6. Cb - 132	Cb-20Ta-15W-5Mo-ZR-C	10.7	15.0	14.0
7. Cb - 129Y	Cb-10W-10Hf-0.1Y	9.50	16.0	16.0
8. TITANIUM	Ti	4.54	16.0	10.0
9. MOLYBDENUM	Mo	10.2	45.0	45.0
10.	Mo-0.5Ti	10.6	17.0	15.0
11. TZM	Mo-0.5Ti-0.08Zr	10.2	46.0	38.0
12.	Mo-30W	11.9	50.0	50.0
13.	Mo-50Re	13.8	53.0	53.0
14. TANTALUM	Ta	16.6	28.0	26.0
15. HAYNES ALLOY/ Ta - 782	Ta -10W	16.8	21.0	21.0
16. T - 111	Ta-8W-2.4Hf	16.7	26.0	24.0
17. T - 222	Ta-9.6W-2.4Hf-0.01C	16.7	26.0	24.0
18. TUNGSTEN	W	19.3	59.0	52.0
19. TUNGSTEN-HfC	W-0.35Hf-0.025C	19.1	59.0	52.0
20. TUNGSTEN- 4Re-HfC	W-4Re-0.35HfC-0.025C	19.1	59.0	52.0
21.	W-25Re	19.8	60.0	60.0
22. HAFNIUM	Hf	13.3	20.0	20.0

23. VANADIUM	V	6.37	20.0	20.0
24. RHENIUM	Re	20.5	68.0	59.0
25. Zr 702	Zr (CHEMICAL GRADE)	6.48	14.0	14.0
26.	Zr-0.010Hf	6.51	14.0	14.0
27. IRIDIUM	Ir	22.5	79.0	79.0
28. OSMIUM	Os	22.7	80.0	80.0
29. RHODIUM	Rh	12.4	46.0	46.0
30. RUTHENIUM	Ru	12.3	60.0	60.0

CERAMIC POWDERS

1. BORON NITRIDE	BN	2.25	9.0	9.0
2. TITANIUM DIBORIDE	TiB2	4.50	72.0	72.0
3. ZIRCONIUM DIBORIDE	ZrB2	6.09	72.0	72.0

APPENDIX D

HYPERVELOCITY IMPACT TEST REPORTS

The University of Dayton

5 March 1990

Thermacore, Inc.
ATTN: Mr. John Rosenfeld
780 Eden Rd.
Lancaster, PA 17601

SUBJECT: Purchase Order No. 9470-11-1066

Dear John,

Enclosed please find two copies of a test summary detailing the tests performed under the subject purchase order. A total of five shots were fired. The first three shots, 4-1087 through 4-1089 were test shots fired at a 1/2 x 3 x 3-inch block of silicon powder reinforced aluminum furnished by Thermacore for use in test firings. The projectile failed to reach the target material for the first two shots. In Shot 4-1089, the projectile and two 7075-T6 aluminum sabot elements struck the target at a velocity of 6.99 km/s. The 1-mm-diameter aluminum ball weighed 1.5 mg; each of the aluminum sabot elements weighed 22.9 mg. Shots 4-1090 and 4-1091 were at the tube samples supplied by Thermacore. Impact site and velocity for each of these shots was well within the limits specified by Thermacore. A more detailed description of each of these two tests is given in the enclosed test summary. All tests were performed with 8 mm Hg air pressure in the range.

Also enclosed please find two copies of the list of test articles, photographs, and negatives being sent to you with this letter. Finally, I have also enclosed an annotated copy of a description of the two stage, light-gas gun range used for performance of your tests. Submission of the test summary and return of the tested articles completes our effort under the subject purchase order.

Please accept my apologies for our delay in returning the test articles to you. We have been a little bit more than busy during the past two months. If you have any questions regarding the test results or if we can be of service to you in the future, please feel free to call me.

Sincerely,

Andrew J. Piekutowski
Andrew J. Piekutowski
Research Engineer

(513) 229-3812

AP/gh

cc: UDRI
93619-41

RESEARCH INSTITUTE
Experimental and Applied Mechanics Division
300 College Park Dayton, Ohio 45469-0001

TEST SUMMARY

The test firings at the two tubular targets identified as 4-11-1066 TiB₂/Ti-LAM-16 (UDRI SHOT 4-1090) and as 5-11-1066 HYBRID-2 (UDRI Shot 4-1091) were made using the University of Dayton Research Institute 50/20 mm, two stage, light-gas gun facility. A description of the range has been enclosed as a separate document.

The tubes were mounted in C-clamp type test fixture (see photo 3-584-4-1 and -3, for example). Approximately 1/8 inch of each end of the tubes fit in a cavity machined in the aluminum pads shown in the referenced photographs. A 1/8-inch-thick rubber disc was placed in each cavity to cushion the ends of the tubes when a slight clamping pressure was applied using the socket head screw at the top of the clamp.

Prior to installation of the tube in the fixture, the fixture was carefully aligned so that the centerline of the aluminum pads was coincident with the range centerline. After the tube was installed in the fixture, the tube was rotated to bring the desired impact point in alignment with the range centerline. All alignment procedures were completed with a bore scope mounted beyond the breech end of the pump tube. Accuracy of alignment and post shot measurements is to within ± 0.01 inch (0.25 mm).

In each of the tests, a 7 x 7 x 0.080-inch thick piece of aluminum was placed behind the tube to serve as a witness plate in the event both sides of the tube were perforated. The witness plate was placed 3 inches behind the center of the tube. The witness plates have been returned to Thermacore with the tested tube samples.

The 1-mm-diameter aluminum spheres used for projectiles were made of 2017-T4 and had a mass of 1.5 mg.. They were loaded into two-piece plastic sabots that were aerodynamically separated from the ball using a reduced air atmosphere of 8 mm Hg in the range. The sabot is stripped away from the ball by having the separated sabot halves crash into a thick steel stripper plate after travelling about 18-1/2 feet from the muzzle of the gun. The ball passes through a small hole in the stripper plate and carries an additional 2-1/2 ft downrange before striking the target. Two debris plates located between the sabot stripper plate and the target serve to restrict the unwanted

impact of debris generated by the sabot stripping process. Occasionally, some of this debris, travelling along the line of sight which must be left open for the projectile, strikes the target.

Four laser-photodetector stations are used to detect passage of the sabot and/or projectile during its flight downrange. Velocity of the projectile is determined by dividing the distance between any two stations by the time of flight between the two stations. The velocities reported for the two tests were computed using the distance and time of flight between the first and the fourth station and are accurate to within ± 0.5 percent or better.

Following is a summary of test conditions and results.

Shot Number	Tube Identification	Impact Velocity		Impact Sight	
		ft/s	km/s	Rt/Lt	Up/Down
4-1090	4-11-1066 TiB ₂ /Ti-LAM-16	22,794	6.95	0.03" Rt	0.38" Dn
4-1091	5-11-1066 Hybrid-2	22,774	6.94	0.09" Rt	0.16" Dn*

* Tube also struck by small piece of debris from sabot stripper plate.

In both tests, only the front side of the tube was perforated. A number of small bulges were noted on the rear side of the tube for Shot No. 4-1091. A considerable amount of petalling of tube material surrounding the hole was also observed for this shot. The hole produced by Shot No. 4-1090 was rather clean, with little lip formation.

Pretest and post test photographs were made of each test article. The 35 mm negatives of these photographs and two prints of selected photographs have been included with the test articles. Debris collected from inside the tube has also been included with the test articles.

LIST OF ITEMS SUBMITTED TO THERMACORE

2 each	Copies of Test Summary
2 each	Copies of This List
1 each	Annotated Copy of Description of 50/20 mm, Two Stage, Light-Gas Gun
1 each	Target Block, Shots 4-1087 through 4-1089 Inclusive
1 each	Target Tube, Witness Plate, and Bag of Debris, Shot 4-1090
1 each	Target Tube, Witness Plate, and Bag of Debris, Shot 4-1091
2 each	1 mm diameter, 2017-T4 Aluminum Balls
1 each	35 mm Negatives and Contact Prints of Negatives Film Strip No. 3584-4-1 to 7 Film Strip No. 3585-4-1 to 24 Film Strip No. 3586-4-1 to 4
2 each	5 x 7 Black and White Prints of Film Strip Nos.: 3584-4-1, -3, -4, and -6 3585-4-1, -3, -5, -7, -9, -11, -13, -15, -19, -22, and -24 3586-4-1 and -3

LIST OF ITEMS SUBMITTED TO THERMACORE

2 each	Copies of Test Summary
2 each	Copies of This List
1 each	Annotated Copy of Description of 50/20 mm, Two Stage, Light-Gas Gun
1 each	Target Block, Shots 4-1087 through 4-1089 Inclusive
1 each	Target Tube, Witness Plate, and Bag of Debris, Shot 4-1090
1 each	Target Tube, Witness Plate, and Bag of Debris, Shot 4-1091
2 each	1 mm diameter, 2017-T4 Aluminum Balls
1 each	35 mm Negatives and Contact Prints of Negatives Film Strip No. 3584-4-1 to 7 Film Strip No. 3585-4-1 to 24 Film Strip No. 3586-4-1 to 4
2 each	5 x 7 Black and White Prints of Film Strip Nos.: 3584-4-1, -3, -4, and -6 3585-4-1, -3, -5, -7, -9, -11, -13, -15, -19, -22, and -24 3586-4-1 and -3

The University of Dayton

20 April 1990

Thermacore, Inc.
ATTN: Mr. John Rosenfeld
780 Eden Road
Lancaster, PA 17601

SUBJECT: Purchase Order No. 9867-11-1066

Dear John,

Enclosed please find the target and witness plate from Shot 4-1131, pretest and post test photographs of the target, and the negatives of those photographs. Range conditions and projectile specifications were the same as those outlined in the test summary of the previous Shots 4-1090 and 4-1091. The target was a 1 inch diameter x 5-7/8 inches long titanium tube supplied by Thermacore.

A hydrogen leak in the Burst Diaphragm Seal during the shot caused a drop in pressure behind the sabot which dropped the velocity down from the nominal 7.00 km/sec. The actual test velocity was 21,730 ft/s (6.62 km/s). The impact sight was within 0.25 inch guideline and was 0.10 inch right and 0.04 inch down from the point marked on the tube. The projectile only perforated the front of the tube and left small bulges on the back.

Submission of this test summary and return of the tested materials concludes our effort under the subject purchase order.

If you have any questions about this test or if we can be of service to you in the future, please feel free to call us.

Sincerely,

Kevin L. Poormon

Kevin L. Poormon
Assistant Research Engineer

KP/gh

Enclosure

cc: UDRI
93619-41

THE UNIVERSITY OF DAYTON RESEARCH INSTITUTE
50/20 mm, TWO STAGE, LIGHT-GAS GUN

Andrew J. Piekutowski

University of Dayton Research Institute
Dayton, Ohio 45469

The University of Dayton Research Institute's 50/20 mm, two stage, light-gas gun has been in operation since mid-1984. It is currently being used for a variety of impact experiments and in the range's present configuration, the projectile has a free-flight distance of about 6.1 meters. A view of the range from the breech end of the first stage is given in Figure 1; a view of the range from the target end is shown in Figure 2. A layout of range components and instrumentation is presented in Figure 3.

RANGE DESCRIPTION

The 50-mm diameter first stage or pump tube is 6.2 m long from the mouth of the powder chamber to the base of the cone in the high-pressure section. Ignition of the main powder charge is accomplished with use of a small black powder charge contained in a primer tube that is centrally located in the 1550 cm³ powder chamber. Pistons assembled from three components--(1) a deformable front section, (2) a weighted center section, and (3) an obturating rear section--are used to compress the light gas charge. Piston weight, controlled by varying the weight of the center section, is one of several loading parameters that are varied when determining the particular loading conditions for a shot.

The high-pressure section is attached to the muzzle of the pump tube using a locking collar employing a differential thread system. The second stage or launch tube (20 mm diameter by 4.88 m long) is joined to the high-pressure section using six bolts that pass through a heavy collar threaded on the end of the launch tube. A tapered transition section (7-degree half-angle) in the high-pressure section controls the reduction of the deformable front section of the piston to produce an acceleration of the piston front face and extend the duration of the high-pressure phase of gas compression. Release of the gas charge is accomplished with use of a burst diaphragm located in an insert installed between the high-pressure section and the launch tube.

During the first 4.6 m of flight, the launch package passes through a three-section blast tank that allows expansion of the high-pressure gasses. A series of baffles in these tanks also deflects the expanding gasses from the trajectory of the

Figure 1. View of UDRI 50/20 mm, two stage, light-gas gun from powder chamber.

Figure 2. View of UDRI 50/20 mm, two stage, light-gas gun from target chamber.

UDRI 50/20 mm LIGHT GAS GUN

Figure 3. Layout of range components and instrumentation.

launch package. After passing through the blast tankage, the launch package enters a 1.22-m-long instrumentation section where the projectile and sabot are photographed while in flight. Stripper plates, installed in the end of the instrumentation tank, separate the sabot, obturator, etc., from the projectile that is allowed to enter the 0.6-m-square by 1.2-m-long target tank and impact the target.

Peripheral range components include: (1) a vacuum system for evacuation of the pump tube prior to charging with light-gas, (2) light-gas handling system, (3) a vacuum pump for evacuation of range tankage, and (4) venting systems for exhausting powder gasses and blast/target tank residual gasses. Firing of the gun is done from a main control room using a computer controlled firing sequence to insure proper timing of events and safe operation of the range.

RANGE INSTRUMENTATION

^{Nine}
Five piezoelectric pressure transducers installed in the gun are used to monitor gun performance. Two transducers in the pump tube, approximately 5 and 5.5 m from the powder chamber monitor light-gas pressures during early stages of compression. Characteristic signatures in the transducer output signals are also used to determine piston velocity. Representative pump tube pressure-time histories are shown in Figure 4. A second pair of pressure transducers, located 0.3 m from either

Six

at various distances along the

Figure 4. Pressure-time histories from pressure transducers in pump tube.

Figure 5. Pressure-time histories from pressure transducers in launch tube.