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PRELIMINARY DESIGN REVIEW DOCUMENT
APPLICATION OF MULTI-FOIL INSULATION TO
THE BRAYTON ISOTOPE POWER SYSTEM
AND CONCEPTUAL DESIGN OF MULTI-FOIL
INSULATION FOR THE FLIGHT SYSTEM
(Phase I)
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Prepared For
Energy Research and Development Administration
Division of Advanced Nuclear Energy Systems
Germantown, Maryland 20767

Prepared By
Thermo Electron Corporation
85 First Avenue
Waltham, Massachusetts 02154

Under Subcontract To
Advanced Closed Cycle Engines Project
AiResearch Manufacturing Company
Phoenix, Arizona 85034

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Approved by: Fred Huffman
Fred N. Huffman
MULTI-FOIL Project Manager

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ABSTRACT

The status of the effort to apply MULTI-FOIL thermal insulation in an effective manner to the Ground Development System (GDS) is reviewed. Heat loss measurements made on cylindrical and elbow heat sources using "Tape" and "Conventional" MULTI-FOIL indicate that the thermal losses are comparable on a per layer basis. However, use of the tape incurs a weight penalty, per layer, of about 20 percent. The effective thermal emissivity of the nickel layer/zirconia powder MULTI-FOIL is approximately 0.32. Parametric studies of GDS insulation losses (using a computer program developed for this purpose) indicate: 1) that the Heat Source Assembly (HSA) heat losses are a major fraction of the total and 2) that a significant reduction in heat loss is possible by optimizing the distribution of foil layers. A meltdown test of a miniature HSA configuration suggests that additional MULTI-FOIL layers can be safely added to the HSA insulation. Test data indicate that "Electroformed" MULTI-FOIL insulation assemblies (as a consequence of decreased edge loss and lower foil emissivity) are approximately four times as effective as either "Conventional" or "Tape" MULTI-FOIL packages on a weight basis. Preliminary GDS insulation design and planning have been completed.

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I. INTRODUCTION AND SUMMARY

This report summarizes the progress that has been accomplished during the first five months of the effort: 1) to apply MULTI-FOIL thermal insulation in an effective manner to the Ground Demonstration System (GDS) and 2) to formulate the conceptual design of MULTI-FOIL insulation for the Flight System. For those not familiar with MULTI-FOIL, a brief background discussion of this insulation is given in Section II.

The principal Thermo Electron GDS MULTI-FOIL activities from January through May were:

- RELATIVE INSULATION EFFECTIVENESS EXPERIMENTS
 - CONVENTIONAL MULTI-FOIL REFERENCE
 - MULTI-FOIL TAPE MEASUREMENTS
 - CYLINDRICAL HEAT SOURCE
 - 3-INCH WIDTH TAPE
 - 1-INCH WIDTH TAPE
 - ELBOW HEAT SOURCE
 - 1-INCH WIDTH TAPE
- FULL-SCALE MOCKUP OF GDS BUILT
- DEVELOPED COMPUTER PROGRAM FOR GDS MULTI-FOIL THERMAL ANALYSIS
- PARAMETRIC STUDY OF MULTI-FOIL SYSTEM HEAT LOSSES PERFORMED
- PRELIMINARY GDS INSULATION DESIGN AND PLANNING COMPLETED
- MELTDOWN TEST OF MINI-HEAT SOURCE ASSEMBLY (HSA)

The primary conclusions drawn from the foregoing efforts are:

- CONVENTIONAL AND TAPE MULTI-FOIL INSULATION LOSSES ARE COMPARABLE (ON A PER LAYER BASIS)

- ON A PER LAYER BASIS, TAPE MULTI-FOIL IS APPROXIMATELY 20 PERCENT HEAVIER THAN CONVENTIONAL MULTI-FOIL
- TO A GOOD APPROXIMATION, THE MULTI-FOIL (NICKEL LAYER/ZIRCONIA) HEAT FLUX, ϕ , IS GIVEN BY -

$$\phi \frac{\text{watt}}{\text{cm}^2} = \frac{1.06 \times 10^{-12} [T^4 - 81 \times 10^8]}{0.778 N + (1.11 \times 10^{-2}) N^2}$$

WHERE

N = NUMBER OF FOIL LAYERS

T = HEAT SOURCE TEMPERATURE, K

- THE EFFECTIVE THERMAL EMISSIVITY OF THE Ni-ZrO₂ MULTI-FOIL IS ABOUT 0.32
- SIGNIFICANT HEAT LOSS REDUCTION (FOR A GIVEN WEIGHT OF INSULATION) IS POSSIBLE BY OPTIMIZING THE DISTRIBUTION OF FOIL LAYERS ON THE GDS
- SYSTEM THERMAL ANALYSIS INDICATE THAT HSA LOSSES ARE A MAJOR FRACTION OF TOTAL
- MINI-HSA MELTDOWN TEST SUGGESTS THAT ADDITIONAL MULTI-FOIL LAYERS MAY BE SAFELY ADDED TO THE HSA INSULATION
- INITIAL TESTS INDICATE THAT ELECTROFORMED MULTI-FOIL INSULATION IS APPROXIMATELY FOUR TIMES AS EFFECTIVE AS EITHER CONVENTIONAL OR TAPE MULTI-FOIL (ON A PER LAYER OR WEIGHT BASIS)
- POTENTIAL HEAT LOSS REDUCTIONS ARE LARGE ENOUGH AND THE PROBABILITY OF SUCCESS HIGH ENOUGH AS TO MAKE AN INVESTMENT IN ELECTROFORMED MULTI-FORM TECHNOLOGY COST EFFECTIVE FOR THE FLIGHT SYSTEM

The balance of this report will provide the basis for these conclusions.

II. BACKGROUND ON MULTI-FOIL THERMAL INSULATION

MULTI-FOIL denotes a thermal insulation system developed by Thermo Electron Corporation in which thin metal foils are spaced in a vacuum by oxide particles. Examples of cylindrical and planar MULTI-FOIL constructions are illustrated in Figure II-1. The oxide particles are selected on the basis of low thermal conductivity and foil compatibility, depending on the application temperature. The oxide particles are optimized with regard to particle size and coating density to minimize thermal transport. A Scanning Electron Micrograph of zirconia particles on nickel foil are shown in Figure II-2. The multiple foils are effective thermal radiation shields. The vacuum environment eliminates convective heat transport. The oxide particles provide a high thermal impedance to conduction by: (a) selection of oxides with low thermal conductivity, (b) high thermal interface resistance between the foils and particles, and (c) the thermal resistance of the thin foil.

MULTI-FOIL has demonstrated low heat losses perpendicular to the foils. A thermal conductivity comparison of MULTI-FOIL and other insulations is shown in Figure II-3. However, extreme care must be taken in the design and fabrication of MULTI-FOIL assemblies to minimize heat losses at the joints. Typically, joint heat loss is comparable to that directly through the foil.

Three types of MULTI-FOIL are being evaluated for the Brayton Isotope Power System (BIPS) Ground Demonstration System (GDS) and Flight System (FS):

- "Conventional" cylindrical-planar MULTI-FOIL
- "Tape" MULTI-FOIL
- "Electroformed" MULTI-FOIL

Figure II-1. "Conventional" Planar Cylindrical
MULTI-FOIL Insulation

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Figure II-2. Scanning Electron Micrograph of Zirconia Particles Deposited on Nickel Foil (1000X, viewed at 45 degrees)

Figure II-3. Thermal Conductivity Comparison

Thermo Electron has extensive experience in tailoring cylindrical-planar MULTI-FOIL insulation to such diverse applications as thermionic energy converters, vacuum furnaces, nuclear artificial hearts and radioisotope thermoelectric generators. All the foregoing applications require thermal insulation of volumes that are, essentially, right cylinders with a few small penetrations. In contrast, the GDS and FS are highly asymmetric and require many large penetrations. Consequently, cylindrical-planar MULTI-FOIL insulation will be difficult or impractical to apply to much of the GDS and FS.

For the ducting bends, flanges, penetrations and other irregularities that do not lend themselves to cylindrical-planar assemblies, a "Tape" MULTI-FOIL insulation may be utilized. In this concept, a tape of suitable metal foil sprayed with the optimized oxide coating will be used to continuously wrap the areas to be thermally insulated. Application of "Tape" MULTI-FOIL to an elbow is illustrated in Figure II-4. Note the reverse bias wraps of the adjacent layers. This approach has the virtues of simplicity, flexibility and low cost. However, since Thermo Electron had no experience with "Tape" MULTI-FOIL prior to the subject program - questions of thermal and weight penalties associated with the tape approach had no experimental answers. These questions are addressed in the next section of this report.

"Electroformed" MULTI-FOIL represents a third option for thermally insulating the FS. Undoubtedly, "Electroformed" MULTI-FOIL insulation will provide significantly lower heat losses than either "Conventional" or "Tape" MULTI-FOIL. Thermo

Electron has limited experience with "Electroformed" MULTI-FOIL in its artificial heart program. Since foils can be electroplated in complex shapes and around penetrations to eliminate joints, "Electroformed" MULTI-FOIL should have quite low thermal losses. An example of one mil thick electroformed foils is shown in Figure II-5. Test data comparing "Electroformed" and "Conventional" MULTI-FOIL insulation packages of the same dimensions are given in Section IV. These results demonstrate that the heat loss from the 20-layer "Electroformed" MULTI-FOIL is somewhat less than that from an 80-layer "Conventional" package. This improvement is due to two factors: 1) elimination of a high temperature joint and 2) the lower thermal emissivity of the vapor deposited electrically conductive layer used for electroplating the nickel foil. The reduced heat and/or weight reduction implications of using "Electroformed" MULTI-FOIL are discussed in Section V. This technology is in its infancy and many fabrication variables remain to be explored.

For FS application, the complex geometries would not permit separation of the electroformed layers by thermal cycling. In this case, the individual foils would be "skinned" from the mandrel, cleaned, sprayed and fired. Care would be taken so that the splits required in the skinning operation would not align to give an unobstructed radiation escape path. Insulation assembly would require the individual fitting of each foil onto the FS. A sketch illustrating the application of "Electroformed" MULTI-FOIL to a "tee" is given in Figure II-6. Although "Electroformed" MULTI-FOIL is clearly the best technical solution to minimizing the heat loss from the FS, it is more expensive than either "Conventional" or "Tape"

Figure II-4. "Tape" MULTI-FOIL Applied to Elbow

Figure II-5. "Electroformed" MULTI-FOIL Insulation
(Note smooth contours and reflective surfaces).

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Figure II-6. "Electroformed" MULTI-FOIL

MULTI-FOIL. This increased insulation expense must be weighed against the Pu-238 fuel cost of approximately \$ 1000 per thermal watt. Thermo Electron expects that a cost/benefit analysis would indicate that the investment to develop "Electroformed" MULTI-FOIL for the FS would be in the long-range interests of the program.

By comparison, a very intensive effort would be required to develop "Electroformed" MULTI-FOIL in time for the GDS. At the present time, such an effort would not appear to be justified.

III. EFFECTIVENESS FACTOR EXPERIMENTS

A. RATIONALE

Since the complex configuration of the GDS precludes the use of "conventional" MULTI-FOIL in many regions, it is necessary that "tape" MULTI-FOIL be used in these areas. Prior to this program, Thermo Electron had no experience with "tape" MULTI-FOIL. Therefore, it was imperative that the weight and heat loss factors associated with tape be evaluated experimentally. No meaningful thermal insulation analyses would be possible without these data.

It is convenient to define an "effectiveness factor, " e:

$$e = \frac{\text{Heat loss of "tape" MULTI-FOIL for a given configuration}}{\text{Heat loss of "conventional" MULTI-FOIL for a right cylinder}}$$

Thus, the heat losses from a "tape" MULTI-FOIL construction can be estimated by applying the effectiveness factor to the heat losses calculated from a "conventional" cylindrical-planar MULTI-FOIL assembly of the same area and temperature.

In order to evaluate the "effectiveness factor," the heat flux from "conventional" and "tape" MULTI-FOIL insulated assemblies on cylindrical and elbow heat sources were measured as a function of heat source temperature and number of foil layers. The configurations that have been investigated are:

Cylindrical Heat Source

"Conventional" MULTI-FOIL

3 inch width "Tape" MULTI-FOIL

1 inch width "Tape" MULTI-FOIL

Elbow Heat Source

1 inch width "Tape" MULTI-FOIL

Based on the data in this section, it is concluded that "Conventional" and "Tape" MULTI-FOIL insulation losses are comparable (on a per layer basis). However, there is a weight penalty of approximately 20 percent (due to overlap) associated with using the 1-inch width tape. The use of 2- and 3-inch width tapes on the elbow proved impractical.

B. HEAT TRANSPORT THROUGH MULTI-FOIL INSULATION

The heat flux, ϕ , through MULTI-FOIL thermal insulation is a function of the following parameters:

$$\phi = \phi = (T, N, T_C, S, \sigma, d, P, k_p, \epsilon, k_{FOIL}, t_{FOIL})$$

1st
Order

2nd Order

3rd Order

where

- T = Heat source temperature
- N = Number of foil layers
- T_C = Heat sink temperature
- S = Spacing between foil layers
- σ = Particle density per unit area
- d = Characteristic dimension of particles
- P = Pressure applied to foils
- k_p = Thermal conductivity of particle spacers
- ε = Emissivity of foils
- k_{FOIL} = Thermal conductivity of foils
- t_{FOIL} = Thickness of foils

For a given choice of particles for spacing, k_p is determined and d , σ and S can be optimized. The choice of the foil establishes k_{FOIL} , t_{FOIL} and ϵ . Therefore, for a lightly loaded foil-particle system -

$$\phi \approx \phi(T, N, T_C)$$

For most applications, T_C is established by radiation to an ambient environment (typically, at about 300 K). Therefore, the heat flux will be measured as a function of T and N for optimized d , σ and S for zirconia particles where the foil assembly radiates to room ambient. That is (for practical purposes),

$$\phi \approx \phi(T, N)$$

C. TEST APPARATUS

The cylindrical heat source geometry is shown in Figure III-1. The heat source is approximately 4 inches in diameter and 24 inches long. The same insulated end plugs are used for both "Tape" and "Conventional" geometries. A tantalum wire (0.020 inch diameter) radiantly heats the cylinder. The heat source temperature is measured by two shielded thermocouples located about 1/3 of the way from each end. Three thermocouples are tack welded to the outside of the insulation. The thermocouple placements are shown in Figure III-1. The heat source configurations are shown in Figure III-2. The dimensions were chosen to minimize experimental error, within vacuum system constraints. The heater and thermocouple arrangements are similar to those for the cylindrical heat source. For all tests, the vacuum pressure was maintained at less than 10^{-5} torr.

Figure III-1. Cylindrical Heat Source for Effectiveness Factor Experiment

III-5

Figure III-2. Heat Sources for Effectiveness Factor Experiment

A block diagram of the instrumentation for the effectiveness factor experiments is given in Figure III-3. The current and voltage to the heater are read with digital instrumentation. Voltage taps are placed where the heater exits from the MULTI-FOIL package. The heat power is provided by a voltage regulated dc supply. The thermocouples are read on a digital thermometer. For each heater setting, the conditions are considered to be stabilized when there is no more than 2 C between readings taken an hour apart. Typically, thermal stabilization takes about one day.

Each insulation package was assembled with the maximum number of foils for the test. (Zirconia-coated nickel foil was used for all insulation assemblies.) Subsequently, some of the foils would be unwound for measurements with fewer foils. For example, "conventional" cylindrical data were taken for 90, 60, 36, 20, 10 and 5 layers.

The period required for thermal equilibrium was much longer than anticipated. In order to maintain program schedule, it was necessary to set up a second test stand for the effectiveness factor determinations.

Photographs of the insulated elbow and cylindrical test arrangements are shown in Figures III-4 and III-5, respectively. The insulation thickness would build-up in the elbow region of the insulation package in Figure III-4 after many layers were wrapped.

Bias wrapping of the "Tape" MULTI-FOIL presented three major problems: 1) stabilization of the loosely wrapped layer, 2) securing the ends and 3) wrapping around the bend. Stabilization of the loosely wrapped layers was achieved by occasional tack welds (using a spot welder) in the overlap region of the spiral windings. The most

III-7

Figure III-3 Instrumentation for Effectiveness Factor Experiment

Figure III-4. Photograph of Elbow Heat Loss Set-up

Figure III-5. Photograph of Cylindrical-Planar Heat Loss Set-up

satisfactory means of securing the bias wrap was to tack weld a small cuff at each end of the winding. In order to wrap around the bend, an appropriate tape width must be used. For the duct diameters and bend radii characteristic of the GDS, one inch width tape should prove satisfactory. Attempts to wrap two-inch width tape on the elbow heat source were completely unsatisfactory.

D. HEAT FLUX DATA SUMMARY

The corrected heat flux data from the effectiveness factor experiments are summarized in Figures III-6 through III-9. The method of correcting the raw data will be described later. For reasons that are detailed in a subsequent discussion of errors, these heat flux determinations are not precision measurements. Typically, a relative probable error of about ± 15 percent is expected. Within this uncertainty, it can be concluded that the thermal insulation losses from "tape" and "conventional" MULTI-FOIL are comparable on a per layer basis. That is, the "effectiveness factor" can be considered to be 1.0. Of course, there is a weight penalty of about 20 percent due to the overlap required with the tape. This is a fortunate result since (prior to the measurements) it was feared that the "effectiveness factor" might be as high as 1.5. There is fair agreement between the heat flux data in Figures III-6, III-7 and III-9. However, the 3-inch width "tape" data in Figure III-8 is significantly lower. This is thought to be due to a larger foil spacing and a superior fit between the cylindrical and planar foils which would minimize edge losses.

Figure III-6. "Conventional" MULTI-FOIL (Cylindrical Heater)
Heat Flux as a Function of Source Temperature,
Parametric in Number of Foils

Figure III-7. One-Inch Width "Tape" MULTI-FOIL (Cylindrical Heater) Heat Flux as a Function of Source Temperature, Parametric in Number of Foils

Figure III-8. Three-Inch Width "Tape" MULTI-FOIL (Cylindrical Heater) Heat Flux as a Function of Source Temperature, Parametric in Number of Foils

Figure III-9. One-Inch Width "Tape" MULTI-FOIL (Elbow Heater) Heat Flux as a Function of Source Temperature, Parametric in Number of Foils

From inspection of the data, review of the fabrication procedures and consideration of experimental errors - it is evident that the variability in the spacing between the foil layers is an important factor in the heat flux data scatter. The sensitivity of the heat flux data to layer spacing was not fully appreciated until the effectiveness factor data were analyzed. In the future, additional care will be taken to optimize this parameter.

Theoretically, for a given heat source temperature, the heat flux data would be expected to exhibit a $1/(1 + N)$ dependence where N is the number of layers. Review of the data will show that for lower number of layers (say, less than 36) the heat flux increases more rapidly than expected for decreasing number of foils. This result is probably a consequence of the inner foil layers being wound more tightly than the outer layers since the foils tend to "fluff" as the number of foils increase. Since the data for the reduced number of layers is obtained by removing the outer foils, it is not surprising that the heat flux values for the lower number of foils are higher than expected.

The "weight factors" for two geometries are given in Table III-1. Typically, use of "Tape" instead of "Conventional" MULTI-FOIL carries a 20 percent weight penalty. This "weight factor" will be incorporated into the GDS computer program.

For the effectiveness factor experiments, calculated heat losses due to penetrations of the MULTI-FOIL insulation by thermocouples and heater leads are small compared to the measured heater power. Consequently, no corrections were made to the raw data for these penetrations losses. Since voltage taps were placed on the heater as they exited from the insulation,

TABLE III-1
TAPE WRAP WEIGHT FACTOR
(ONE INCH WIDTH TAPE)

Configuration	Cylinder	Elbow
Calculated for an Average Layer, g	41	45
Observed Mass for an Average Layer, g	50	63
Less Cuffs, g	46	59 [*]
Weight Factor	1.12	1.31

^{*} Cuff weight estimated from cylinder data.

no heater lead loss correction was applied. The only correction factor applied to the raw data was an estimate of the edge loss between the cylindrical and planar foils. Previous Thermo Electron edge loss measurements for 80 layer overlap joints were averaged and extrapolated to give the data in Figure III-10. Experience has indicated that these data are consistent with the edge losses from the mitre joint used in these measurements. The data for all the effectiveness factor experiments were corrected, independent of the number of foil layers, using the curve in Figure II-10.

E. DISCUSSION OF ERRORS

Four major factors are thought to be responsible for the data scatter in Figures III-6 through III-9. In the order of their assumed importance, these factors are:

- Foil spacing variation
- Improper edge loss correction
- Nonuniform zirconia coating density
- Non-negligible heater lead loss at high power inputs

Variations in foil spacing are a major factor in the data scatter. These variations reflect: 1) lack of sensitivity to this problem prior to data reduction, 2) the tendency to wrap the inner layers more tightly in order to obtain an aesthetically more pleasing insulation package, 3) individual differences in technician technique and 4) the fact that spiral wrapping of tapes naturally gives a "fluffier" package (i. e., greater spacing between foil layers).

Improper edge loss correction is more important at low temperatures and low number of foils. At high temperatures, edge losses

766-4

Figure III-10. Heat Loss Per Unit Length of Edge Versus Source Temperature

become a small fraction of the heat input. The lack of data to correct the edge loss for number of foil layers may explain part of the discrepancy from the analytically expected $1/(1 + N)$ dependency at low foil layers. Certainly, the edge loss should increase as the number of foils decrease. However, in terms of system design, this factor should not be particularly serious since the edge loss function incorporated into the GDS Computer Program is identical to that used in correcting the raw data. Although the split between the perpendicular and edge insulation losses may be off significantly, the sum (i. e., the total insulation loss) of the perpendicular and edge losses should not be in great error.

Nonuniform zirconia density is expected to be a small, but significant factor in the data scatter. The heat flux versus zirconia density dependence has a broad optimum so that factors of ± 50 percent in particle density should not constitute a major effect.

Non-negligible heater loss at high power inputs would be most pronounced with small numbers of foils. With few foils, a higher heater power is required to reach a given heat source temperature than with a large number of foils. Under these conditions, radiation heat losses associated with the heater might be of some consequence.

F. FUNCTION FIT TO MULTI-FOIL MEASUREMENTS

Assuming an ambient temperature of 300K, analysis of sample heat flux curves (for a given number of foils) gave the theoretically expected fourth power dependence on source temperature. However, for a given source temperature, a $1/(N + 1)$ dependence was not satisfactory - especially for $N < 20$ foils. For the "conventional"

MULTI-FOIL data, the following function was found to give reasonable agreement to the measurements:

$$\phi \frac{\text{watt}}{\text{cm}^2} = \frac{1.06 \times 10^{-12} [T^4 - 81 \times 10^8]}{0.778 N + (1.11 \times 10^{-2}) N^2}$$

where

ϕ = Heat flux perpendicular to the foils

T = Heat source temperature, K

N = Number of foils

A comparison of values calculated from this expression with experiment is given in Figure III-11. Except for an anomaly for N = 10 foils, this function fits the measured data well within experimental error.

The effective thermal emissivity corresponding to the function fit is 0.32. This value is in agreement with published data for sandblasted nickel foil. Presumably, the zirconia particles "roughen" the foil surface - but do not constitute an important heat transport mechanism (i. e., conduction through the particles) relative to radiation above 400 C.

Figure III-11. MULTI-FOIL Heat Flux Calculated from Function Fit Expression

IV. ELECTROFORMED MULTI-FOIL EXPERIMENT

A. BACKGROUND

As described in Section II, "Electroformed" MULTI-FOIL has the advantages of:

- (1) Conforming to complex geometries,
- (2) Eliminating heat losses associated with joints, and
- (3) Providing a lower thermal emissivity.

This section describes recent comparison tests between "Electroformed" and "Conventional" MULTI-FOIL insulation packages of identical system configuration. The twenty layers of "Electroformed" MULTI-FOIL outperformed by a significant margin the 80 layers of "Conventional" MULTI-FOIL. In view of the magnitude of the GDS heat losses estimated in Section V for "Tape" and "Conventional" MULTI-FOIL, the potential significance of this result to the BIPS program is of major proportions.

The comparison experiments described in this section were performed by Thermo Electron's nuclear powered artificial heart group (sponsored by the National Heart and Lung Institute). Since the miniature vapor cycle engine ("Tidal Regenerator Engine") operates at 900 F, high-performance thermal insulation is indispensable in minimizing the heat load to the body. For this application, the ability of "Electroformed" MULTI-FOIL to be contoured to minimize system volume and not damage adjacent organs is an important consideration.

In these experiments, the electrical power required to reach 900 F in the engine compartment was measured for three different MULTI-FOIL insulation assemblies. First, two presumably identical 80-layer "Conventional" MULTI-FOIL thermal insulation assemblies were tested. Later, one 20-layer "Electroformed" MULTI-FOIL assembly was tested. The identical configuration was tested in each instance - that configuration conforming to the current nuclear-powered mechanical heart design.

B. TEST DESIGN

The test configuration is shown in Figure IV-1. Each MULTI-FOIL thermal insulation assembly was contained within a static vacuum (10^{-5} torr or better) maintained by a double-walled structure completely surrounding the insulation. The shape of the insulation assemblies was a right circular cylinder closed at one end and open at the other. The open end fits snugly over the nuclear-powered engine. An electric heater simulated the 33-watt Pu-238 heat source.

Note that a fraction of the electric power dissipated by the resistance heating element passes through the MULTI-FOIL insulation, a fraction is conducted down the thin inner cylinder of the double-walled vacuum container towards the open end, and still another fraction passes through the material used to block the open end of the static vacuum cannister. The material chosen to block that open end simulates the temperature distribution achieved with an operating engine.

The goal is to isolate the performance of the different types of MULTI-FOIL thermal insulation. This requires that the gross

Figure IV-1. Insulation Package Test Stand

data (i. e., the amount of power dissipated by the electric heater to reach a common operating temperature of 900 F) be reduced by subtracting the losses attributable to inner cylinder conduction and through the open end plug. These corrections are applied in Section IV.

C. TEST DATA

- System 1 Thermo Electron Serial Number 376.
 Eighty layers of "Conventional"0.0005"
 Ti-ZrO₂ MULTI-FOIL thermal insulation.
- System 2 Thermo Electron Serial Number 390.
 Eighty layers of "Conventional"0.0005"
 Ti-ZrO₂ MULTI-FOIL thermal insulation.
- System 3 Twenty layers of "Electroformed"0.0007"
 Ni-ZrO₂ MULTI-FOIL thermal insulation.

NOTE: All relevant details of the static vacuum enclosure remained constant for Systems 1-3. In addition, the same plug (heater, leads, thermocouples, fibrous insulation, etc.) was used to test each of the three systems.

	T ₁	T ₂	Power
System 1	900° F	670° F	5.67 watts
System 2	900° F	645° F	5.00 watts
System 3	900° F	655° F	4.40 watts

D. DATA REDUCTION

	System 1	System 2	System 3
Power In, watts	5.67	5.00	4.40
Losses			
Min-K, watts	0.40	0.40	0.40
Wires, watts	0.28	0.28	0.28
Inner Cylinder, watts	1.81	1.81	1.81
MULTI-FOIL, watts	3.18	2.51	1.91

E. DISCUSSION

The "Electroformed" MULTI-FOIL in System 3 permitted 76% of the thermal losses of System 2, and only 60% of the losses in System 1. Thus, on a per-layer basis, each of the twenty layers of the "Electroformed" MULTI-FOIL was a factor of 5 to 7 times as effective as each of the eighty layers of "Conventional" MULTI-FOIL.

The two most obvious reasons why the "Electroformed" MULTI-FOIL was more effective than "Conventional" MULTI-FOIL are:

- (1) Elimination of the major thermal leak at the cylindrical-planar interface at the closed end of the cylinder and
- (2) A much lower emissivity of the bare portions of the foil.

The electroformed nickel foil had a mirror finish which made the as-rolled titanium look dull by comparison.

Little significance is attached to the titanium foil-nickel foil difference between Systems 1 and 2 and System 3. Thermo Electron's experience indicates that the performance of "Conventional" MULTI-FOIL fabricated from rolled metal foils is remarkably insensitive to the foil material. Approximately the same results would have been expected had the "Conventional" MULTI-FOIL been fabricated using nickel rather than titanium foil.

V. ANALYSIS OF GDS MULTI-FOIL INSULATION

Initial hand calculations of GDS insulation losses proved to be tedious and time-consuming. In view of the number of parameter and optimization analyses that are required to characterize the GDS insulation losses, it became imperative that the calculations be computerized. Such a computer program has been written in BASIC and debugged. This tool is operational on Thermo Electron's PDP-11/05 computer. The GDS MULTI-FOIL Computer Program is described in detail and listed in Appendix A. Printouts of sample cases are given in Appendix B.

Briefly, the MULTI-FOIL Computer Program (MFCP) organizes, for purposes of insulation considerations, the GDS design including the two HSAs into 42 regions and 32 edges. The dimensions and temperatures of each region and edge are stored in the MFCP. The expression for MULTI-FOIL heat flux as a function of heat source temperature and number of foils (formulated in Section III from the analysis of the effectiveness factor experimental data) is used to calculate the heat loss from each region, subject to the minimum and maximum number of foils specified in the case input. Similarly, a fit to the edge loss data, given in Figure III-10, is utilized to estimate the heat loss from each edge. The program then sums and prints the planar and edge heat losses for each major component. Of course, a total system heat loss is calculated. The total system insulation mass is also calculated (using the "weight factors" developed from the effectiveness factor experiments) as appropriate. The basic program has been modified to optimize the

distribution of foils for a given insulation mass. Essentially, the program scans the heat loss from each region and adds or subtracts foils so that the MULTI-FOIL mass is used most effectively.

The total GDS system heat loss including two HSAs is given as a function of MULTI-FOIL mass in Figure V-1. The case constraints are indicated on the figure. These calculations imply that significant reductions in heat loss are possible by:

- (1) Optimizing the foil distribution on the GDS,
- (2) Increasing the number of foils insulating the HSA, and
- (3) Utilizing "Electroformed" MULTI-FOIL.

Detailed comparisons of the 24 kilogram cases may be made by referring to the sample printouts given in Appendix B. A sample case is summarized in Table V-1. The heat losses and insulation masses from the individual regions and edges are tabulated in these computer outputs.

The potential reduction in system heat loss is most dramatic for "Electroformed" MULTI-FOIL. These estimated heat losses are based on the assumptions (consistent with the test data presented in Section IV) that:

- (1) The heat flux of "Electroformed" MULTI-FOIL is half that for "Conventional" or "Tape" for a given heat source temperature and number of foils, and
- (2) The edge losses will be reduced by half due to the elimination of many joints.

Figure V-1 MULTI-FOIL Heat Loss as a Function of Insulation Mass

TABLE V-1
SAMPLE GDS CASE

Foil Constraints

HSA 60 Layers
Maximum 110 Layers
Minimum 10 Layers

Component	Planar Loss (watts)	Edge Loss (watts)	Total Component Loss (watts)
Plumbing	74.4	38.8	113.2
BRU	4.9	24.3	29.2
Recuperator	29.5	18.6	48.1
HSA (Two)	254.1	77.1	331.3
TOTAL SYSTEM HEAT LOSS			521.8 watts
TOTAL MASS			23.8 kg

The potential for heat loss reduction in the two HSAs is 116 watts. Clearly, additional experimental data and design effort are required to put the "electroformed" projection on as firm a basis as the "tape" calculations. However, the potential heat loss reductions are large enough and the probability of success is so high as to make an investment in "Electroformed" MULTI-FOIL technology cost effective for the Flight System.

Another design option concerning the HSA insulation has been investigated.

VI. MINI-HSA MELTDOWN TEST

A. RATIONALE

In radioisotope power systems, radiological safety considerations are quite properly thought of as the "tail that wagged the dog." The radiological safety of the FS hinges on the meltdown characteristics of the Heat Source Assembly (HSA) MULTI-FOIL insulation. Although meltdown of the HSA MULTI-FOIL seems quite reasonable, there existed no test data bearing directly on this problem, and the full-scale HSA meltdown at General Electric was not scheduled until August 1976. Therefore, Thermo Electron felt that it was imperative to immediately provide relevant data on a program safety element as critical as the HSA meltdown characteristics.

The relatively high HSA heat losses (see Section V) provided an additional incentive for a miniature meltdown test. If the meltdown characteristics are satisfactory, the possibility of adding additional MULTI-FOIL layers to the HSA should be evaluated. Figure V-1 indicates that for an insulation mass of 23.8 KG, 110 foils on the HSA would save 48 watts, compared to the present 60-foil design.

B. DESIGN OF MINI-HSA MELTDOWN TEST

The objective of this minimum cost test was to obtain a qualitative "feel" for the meltdown characteristics of a miniature MULTI-FOIL package having the following characteristics in common with the current HSA MULTI-FOIL insulation:

- Half-mil nickel foil thickness
- Five-mil inner columbium foil thickness
- 60-layer nickel foils
- Zirconia spray parameters
- Approximate ratio of length to diameter.

The test arrangement to be used in future Mini-HSA meltdowns, if any, is illustrated in Figure VI-1. The test performed differs in two considerations:

- (1) The ceramic heater supports were omitted and
- (2) Only four thermocouples were used.

The first consideration is far more important than the second, since the heavy tungsten heater tightly compressed the bottom planar foils and opened the overlap joint so that the insulating properties of the MULTI-FOIL were severely degraded. Consequently, extremely high power inputs were required to take the heater to operating temperatures. It should be emphasized that this experiment was exploratory and was performed with limited time and funding.

The heater body configuration was dictated by the dimensions of an available piece of scrap tungsten. The radiant heater wire was 0.040-inch diameter tungsten. The heater input power was increased in steps until meltdown. No attempt was made to simulate the temperature profile associated with a working fluid loss or turbine failure.

Figure VI-1 Mini-Meltdown Test Arrangement

C. TEST RESULTS

As expected, meltdown began at approximately 1170 C (~ 2150 F) which corresponds to the Cb-Ni eutectic temperature. Even with greatly increased power, the temperature of the tungsten heater body never exceeded 1200 C. In fact, this temperature decreased in the latter stages of the meltdown even though the heater input was increased. The meltdown period was approximately 20 minutes. The heater wire failed near the end of the meltdown period. Visually, many bright spots (uniformly distributed) were noted. Observation became difficult as the evaporated nickel deposited on the bell jar.

After cooling, the MULTI-FOIL package was disassembled. Photographs of the post-meltdown configuration are shown in Figures VI-2 and VI-3. Only the outer four layers of foil were intact. The balance of the nickel foils were fused into a single structure. As the assembly melted, it moved away from the heater. There was no sign of the 5-mil thick columbium foil which was wrapped around the heater.

D. DISCUSSION

Although this test was quite crude, it provides some experimental evidence that the MULTI-FOIL will melt down as anticipated. In retrospect, it was probably fortunate that the heater filament failed before the entire MULTI-FOIL melted into a puddle. It is remarkable that the meltdown was so uniform (as evidenced by the color uniformity and near-constant wall thickness of the melted cylinder) when there existed such a large heat leak through the bottom planar foils.

766-7

Figure VI-2. Photograph of Post-Melt down Mini-HSA
with Top Cut Away

766-6

Figure VI-3. Photograph of Post-Meltdown Mini-HSA
after Removal of First Foil

The uniform meltdown implies that additional foil layers can be safely added to the HSA MULTI-FOIL insulation to reduce the major source of system heat loss. Although many program considerations factor into such a design perturbation, it should be evaluated.

The meltdown temperature of 1170 (~ 2150 F) is well defined and is uncomfortably close to the highest HSA operating temperatures. A relatively minor system perturbation during operation or testing could trigger the MULTI-FOIL meltdown. It is recommended that materials other than columbium be evaluated for lining the inside of the MULTI-FOIL insulation. For example, molybdenum might be more suitable, since the eutectic temperature for Mo-Ni is 1315 C (~ 2400 F).

From this experiment, one has the impression of a high nickel vaporization rate near the operating temperature. If this impression could be verified quantitatively, it would imply severe long-term degradation of the MULTI-FOIL. It is recommended that consideration be given to using refractory metals (i. e., molybdenum or columbium) for the first few inner foil layers.

A final conclusion to be drawn from this initial experiment is that much relevant information can be obtained from such relatively low cost tests. Other parameters that could be explored include:

- (1) Additional nickel foils
- (2) Molybdenum inner liner (instead of columbium)
- (3) First few foil layers of molybdenum or columbium
- (4) Thickness of inner liner
- (5) Temperature-time profiles and
- (6) MULTI-FOIL vaporization rates.

VII. PRELIMINARY GDS MULTI-FOIL DESIGN

The first step in formulating the GDS MULTI-FOIL design was to build a full-scale GDS mockup. A photograph of this mockup is shown in Figure VII-1. Although unfinished and inexpensive, this mockup has been quite valuable in visualizing design approaches to the MULTI-FOIL insulation. As spare or reject component housings become available, the mockup will be upgraded. Eventually, the GDS mockup will be used to practice applying the MULTI-FOIL insulation.

Design concepts have been formulated for all major components. The design philosophy is to use "Conventional" cylindrical-planar MULTI-FOIL wherever feasible. "Tape" MULTI-FOIL will be used on elbows and flanges. The recuperator will utilize a "package" wrap. The primary design problem that has not been addressed concerns the interface between the various types of insulation. Experiments will be performed to help resolve these problems.

The preliminary GDS MULTI-FOIL design is illustrated in Figures VII-2 through VII-5. The design approach for each component is independent of the number of foil layers. The number distribution of foils will be determined by analyses such as described in Section V.

The design concept for the elbows is shown in Figure VII-2. The techniques and problems associated with "Tape" MULTI-FOIL have been discussed in Section III.

Figure VII-1. Photograph of Full-Scale GDS Mock-up

Figure VII-2. "Tape" MULTI-FOIL Applied to Elbow

Figure VII-3 "Tee" Insulation Design Concept

Figure VII-4 Recuperator "Christmas Wrap" Insulation Design Concept

Figure VII-5 BRU Insulation Design Concept

The insulation design concept for "tees" is illustrated in Figure VII-3. It uses a combination of planar and tape foils. The method of assembly is evident from the figure.

The recuperator is quasi-rectangular. For purposes of insulation, it will be idealized into a box. The recuperator design concept is shown in Figure VII-4. Planar foils will be precut to size so that no direct radiation paths will result at the joints. The foils will be assembled by wrapping the recuperator in a manner analogous to wrapping a Christmas package.

The BRU insulation design concept is given in Figure VII-5. The BRU is a complex geometry that is quite difficult to insulate. The insulation in the turbine plenum will be the first MULTI-FOIL package to be delivered. Detailed design of the turbine plenum insulation has been started.

APPENDIX A

GDS MULTI-FOIL COMPUTER PROGRAM

APPENDIX A

GDS MULTI-FOIL COMPUTER PROGRAM

A computer program has been written to aid in the design of the MULTI-FOIL insulation system for the GDS. It is written to provide the minimum heat loss for a given weight.

The entire GDS was divided into cylindrical and planar envelopes covering all components of the GDS. At the joint of each region an edge was established. Figures A-1 through A-5 identify each region and edge. Table A-1 identifies the number, temperature and area of each region. Table A-2 gives the number, temperature and length of each edge. The HSA temperature distribution shown in Figure A-5 was provided by Dr. Peter Allen of General Electric on February 18, 1976.

The planar heat losses for the MULTI-FOIL were calculated from a correlation described in Section III. The edge losses were calculated from a polynomial fitted to the data given in Figure III-10. The flow chart for the computer program is shown in Figure A-6. The heat losses and weight for all regions are calculated for an initial number of foils. Then the gradient of heat loss/weight is calculated for each region. Next, the region of maximum gradient is selected and a number of foils in that region is incremented. This case is printed out so that the progress of the calculation can be monitored. In this program the number of foils for regions around the HSA may be specified. Constraints may be placed on both the maximum and minimum number of foils for the regions.

Figure A-1 Region and Edge Identification

Figure A-2 Region and Edge Identification

Figure A-3 Region and Edge Identification

Figure A-4 Region and Edge Identification

Figure A-5 Region and Edge Identification

Figure A-6. Flowchart for Computer Program

TABLE A-1
REGION PARAMETERS

Region No.	Temp., R	Area, Inch ²	Effectiveness
1	1757	264	1
2	1757	242	1.25
3	1757	138	1
4	1757	99	1
5	2060	106	1
6	2060	106	1
7	628	131	1.25
8	628	156	1.25
9	628	142	1.25
10	1778	297	1.25
11	1778	231	1
12	1900	31	1
13	2060	11	1
14	2060	34	1
15	680	17	1
16	680	98	1
17	650	14	1
18	650	75	1
19	650	44	1
20	535	18	1
21	1768	187	1
22	1644	110	1
23	1520	110	1
24	1395	110	1
25	1271	110	1
26	1147	110	1
27	1023	110	1
28	899	110	1
29	774	110	1
30	650	187	1
31	1993	140	1
32	2190	140	1
33	1927	182	1
34	1900	182	1
35	1936	182	1
36	1986	182	1
37	2034	182	1
38	2077	182	1
39	2115	182	1
40	2147	182	1
41	2121	90	1
42	2280	90	1

TABLE A-2
EDGE PARAMETERS

Edge No.	Temp., R	Length, Inch
1	1757	11
2	1757	11
3	1757	11
4	1757	11
5	1757	11
6	2060	12
7	2060	12
8	628	6
9	628	6
10	628	8
11	1778	11
12	1778	11
13	1900	9
14	2060	9
15	2060	19
16	680	15
17	680	21
18	650	21
19	650	25
20	650	25
21	535	8
22	535	8
23	680	6
24	680	6
25	1768	11
26	650	8
27	650	36
28	1768	36
29	1993	38
30	2190	38
31	1993	38
32	2190	38

After each ten iterations, the heat losses for all regions are printed, as well as a complete summary for all components. The incrementing proceeds until the operator stops the computer run. By this means the locus of least heat loss as a function of MULTI-FOIL mass is obtained as shown in Figure V-1.

A listing of the GDS MULTI-FOIL program follows Figure A-6. The program is written in BASIC and is currently running on a DEC PDP-11/05.

PROGRAM LISTING GDS OPTIMIZATION

```

2 PRINT#1, "18-MAY-76  0 GDSGM5 BAS"
10 REM GDS , V1 GM
15 REM GDS, V4 CR
20 REM T(R), A(INSQ), EFTVNF
30 DEF FNA(X)=INT(X*1000+ 5)/1000
100 DIM A(50), P(50), T(50), E(50)
102 DIM Q(50)
104 DIM S(50), R(50)
105 DIM N(50)
106 DIM B(50)
110 LET J9=32
115 LET D=10
116 LET J8=0
120 LET I9=42
121 GOTO 3050
130 PRINT#1, "NUMBER OF ZONES=", I9
132 PRINT#1, "ZONE", "FOILS", "RATIO", "WEIGHT G", "LOSS W"
140 LET W=8 9* 0005*2 54
790 REM COEFFICIENTS FOR POLFITS
800 DATA - 1912997E-1, 120331E-3, - 235483E-6, 1613705E-9
810 DATA - 1223141E-1, 7978615E-4, - 1540625E-6, 1041667E-9
820 DATA - 1205224E-1, 7574939E-4, - 1323596E-6, 8190008E-10
830 DATA - 1669917, 816205E-3, - 9840117E-6, 474863E-9
840 READ B0, B1, B2, B3
850 READ C0, C1, C2, C3
860 READ D0, D1, D2, D3
870 READ E0, E1, E2, E3
1000 DATA 1757, 264, 1
1010 DATA 1757, 242, 1 25
1020 DATA 1757, 138, 1
1030 DATA 1757, 99, 1
1040 DATA 2060, 106, 1
1050 DATA 2060, 106, 1
1060 DATA 628, 131, 1 25
1070 DATA 628, 156, 1 25
1080 DATA 628, 142, 1 25
1090 DATA 1778, 297, 1 25
1100 DATA 1778, 231, 1
1110 DATA 1900, 31, 1
1120 DATA 2060, 11, 1
1130 DATA 2060, 34, 1
1140 DATA 680, 17, 1
1150 DATA 680, 98, 1
1160 DATA 650, 14, 1
1170 DATA 650, 75, 1
1180 DATA 650, 44, 1
1190 DATA 535, 18, 1
1200 DATA 1768, 187, 1
1210 DATA 1644, 110, 1
1220 DATA 1520, 110, 1
1230 DATA 1395, 110, 1
1240 DATA 1271, 110, 1
1250 DATA 1147, 110, 1
1260 DATA 1023, 110, 1
1270 DATA 899, 110, 1
1280 DATA 774, 110, 1
1290 DATA 650, 187, 1
1300 DATA 1993, 140, 1
1310 DATA 2190, 140, 1
1320 DATA 1927, 182, 1
1330 DATA 1900, 182, 1
1340 DATA 1936, 182, 1
1350 DATA 1986, 182, 1
1360 DATA 2034, 182, 1

```

PROGRAM LISTING (CONTINUED)

```

1370 DATA 2077,182,1
1380 DATA 2115,182,1
1390 DATA 2147,182,1
1400 DATA 2121,90,1
1410 DATA 2280,90,1
1500 REM EDGE LOSS DATA S.P
1510 DATA 1757,11
1520 DATA 1757,11
1530 DATA 1757,11
1540 DATA 1757,11
1550 DATA 1757,11
1560 DATA 2060,12
1570 DATA 2060,12
1580 DATA 628,6
1590 DATA 628,6
1600 DATA 628,8
1610 DATA 1778,11
1620 DATA 1778,11
1630 DATA 1900,9
1640 DATA 2060,9
1650 DATA 2060,19
1660 DATA 680,15
1670 DATA 680,21
1680 DATA 650,21
1690 DATA 650,25
1700 DATA 650,25
1710 DATA 535,8
1720 DATA 535,8
1730 DATA 680,6
1740 DATA 680,6
1750 DATA 1768,11
1760 DATA 650,8
1770 DATA 650,36
1780 DATA 1768,36
1790 DATA 1993,38
1800 DATA 2190,38
1810 DATA 1993,38
1820 DATA 2190,38
2000 FOR I=1 TO I9
2010 READ T(I),A(I),E(I)
2015 NEXT I
2018 FOR J=1 TO J9
2020 READ S(J),P(J)
2022 NEXT J
2025 FOR I=1 TO I9
2035 NEXT I
2037 FOR I=1 TO I9
2040 LET A(I)=2.54*A(I)*2.54
2060 LET T(I)=T(I)/1.8
2070 LET B(I)=1.06E-12*(T(I)-4-81E8)*E(I)*A(I)
2075 LET N(I)=10
2080 NEXT I
2090 FOR J=1 TO J9
2092 LET S(J)=S(J)/1.8
2094 LET P(J)=P(J)*2.54
2096 NEXT J
2100 LET L=0
3000 REM CALC LOSSES
3010 LET Q0=0
3020 LET Q=0
3040 GOTO 3112
3050 PRINT#1
3060 PRINT#1, "PLUMBING I=1 TO 11"
3070 PRINT#1, "BRU I=12 TO 20"
3080 PRINT#1, "REFUR I=21 TO 30"
3090 PRINT#1, "TWO H-A I=31 TO 42"

```

PROGRAM LISTING (CONTINUED)

```

3100 PRINT#1
3101 GOTO 132
3112 LET Q0=0
3113 LET Q8=0
3114 LET W2=0
3115 LET W9=0
3116 FOR I=1 TO I9
3130 GOSUB 3210
3140 NEXT I
3150 GOSUB 5000
3155 GOTO 3112
3210 REM
3240 LET W9=W9+N(I)*A(I)
3242 REM TOTAL FOIL AREA
3250 LET Q9=B(I)/( 778*N(I)+1 11E-2*N(I)*N(I))
3252 LET Z1=Q9/(A(I)*N(I)*D)
3255 LET Q(I)=Q9
3260 LET Q0=Q0+Q9
3261 IF I<31 GOTO 3270
3262 IF N(I)>50 GOTO 3310
3270 IF N(I)>100 GOTO 3310
3280 IF Z1>08 GOTO 3310
3290 LET Q8=Z1
3295 LET IO=I
3310 RETURN
3430 REM
3436 PRINT#1,"ZONE FOILS TEMP F"," LOSS W","WEIGHT FG"
3440 FOR I= 1 TO I9
3442 PRINT#1,I,N(I),INT(T(I)-272.5),INT(Q(I)*10+ .5)/10,INT(N(I)*A(I)*W)
3443 NEXT I
3444 IF J8<0 GOTO 3460
3445 PRINT#1,"EDGE LOSS REGIONS"
3446 PRINT#1,"REGION","TEMP F","LOSS W"
3450 LET J8=J8+1
3460 REM
3470 NEXT I
3540 LET R=0
3550 FOR J=1 TO J9
3560 LET H=E0+S(J)*(E1+S(J)*(E2+S(J)*E3))
3570 LET R(J)=H*P(J)
3572 IF J8=1 GOTO 3575
3573 GOTO 3590
3575 PRINT#1,J,INT(S(J)),INT(R(J))
3590 LET R=R+R(J)
3600 NEXT J
3602 LET J8=J8+1
3620 PRINT#1,"TOTAL WEIGHT,FG=",W9*W/1000
3700 LET Q1=0
3710 FOR I=1 TO 11
3720 LET Q1=Q1+Q(I)
3725 NEXT I
3730 LET R1=0
3740 FOR J=1 TO 12
3750 LET R1=R1+R(J)
3760 NEXT J
3780 LET Q2=0
3790 FOR I=12 TO 20
3800 LET Q2=Q2+Q(I)
3810 NEXT I
3820 LET R2=0
3830 FOR J=13 TO 24
3840 LET R2=R2+R(J)
3850 NEXT J
3870 LET Q3=0
3880 FOR I=21 TO 30
3890 LET Q3=Q3+Q(I)

```

PROGRAM LISTING (CONTINUED)

```

3900 NEXT I
3910 LET R3=0
3920 FOR J=25 TO 28
3930 LET R3=R3+R(J)
3940 NEXT J
3960 LET O4=0
3970 FOR I=31 TO 42
3980 LET O4=O4+O(I)
3990 NEXT I
4010 LET R4=0
4020 FOR J=29 TO 32
4030 LET R4=R4+R(J)
4040 NEXT J
4100 PRINT#1, "DEVICE", "PLANAR LOSS", "EDGE LOSS", "TOTAL"
4110 PRINT#1, "PLUMBING", O1, R1, O1+R1
4120 PRINT#1, "BRU", O2, R2, O2+R2
4130 PRINT#1, "RECUP", O3, R3, O3+R3
4140 PRINT#1, "HSA", O4, R4, O4+R4
4141 PRINT#1, "GRAND TOTAL", O1+O2+O3+O4, R1+R2+R3+R4, O1+O2+O3+O4+R1+R2+R3+R4
4143 PRINT#1, CHR$(12)
4144 PRINT#1, "INCREMENT NEXT ZONE"
4145 RETURN
4150 END
5000 REM INCREMENTS N(I)
5005 PRINT#1, IO, N(IO), FNA(OS), INT(W9*W+ 5), INT(OO+ 5)
5010 LET N(IO)=N(IO)+10
5015 LET L=L+1
5020 IFL 19 GOTO 5060
5021 PRINT#1, , , , , "DETAILED PRINTOUT OF LAST CASE"
5023 PRINT#1, "PLANAR LOSS REGIONS"
5024 PRINT#1, "ZONE FOILS TEMP I LOSS W WEIGHT G"
5025 PRINT#1
5030 GOSUB 3440
5040 LET L=0
5060 RETURN

```

APPENDIX B
SAMPLE GDS MULTI-FOIL CASES

TABLE E-1
SAMPLE PRINTOUT FOR GDS OPTIMIZATION
ALL REGIONS 110 FOILS MAXIMUM

DETAILED PRINTOUT OF LAST CASE

PLANAR LOSS REGIONS

ZONE FOILS TEMP C LOSS W WEIGHT G

1	60	703	18.7	1155	
2	60	703	21.5	1058	
3	60	703	9.8	603	
4	60	703	7	433	
5	60	871	14.3	463	
6	60	871	14.3	463	
7	10	76	.8	95	
8	10	76	1	113	
9	10	76	.9	103	
10	60	715	27.7	1299	
11	60	715	17.2	1010	
12	60	783	3	135	
13	60	871	1.5	48	
14	60	871	4.6	148	
15	20	105	.1	24	
16	20	105	.4	142	
17	10	88	.1	10	
18	10	88	.5	54	
19	10	88	.3	32	
20	10	24	0	13	
21	60	709	13.6	818	
22	60	640	6	481	
23	60	571	4.3	481	
24	50	502	4	401	
25	50	433	2.7	401	
26	40	364	2.4	320	
27	30	295	2.2	240	
28	30	226	1.2	240	
29	20	157	1	160	
30	10	88	1.3	136	
31	60	834	16.5	612	
32	110	944		11.1	1123
33	90	798	10.2	1194	
34	90	783	9.6	1194	
35	90	803	10.4	1194	
36	90	830	11.5	1194	
37	90	857	12.6	1194	
38	100	881	11.6	1327	
39	100	902	12.5	1327	
40	100	920	13.3	1327	
41	100	905	6.3	656	
42	110	994	7.2	721	

TOTAL WEIGHT, KG= 24.0593

DEVICE	PLANAR LOSS	EDGE LOSS	TOTAL
PLUMBING	133.2729	38.8455	172.1184
BRU	10.47163	24.31037	34.782
RECUP	38.69802	18.59397	57.29199
HSA	132.6722	77.14645	209.8187
GRAND TOTAL	315.1148	158.8963	474.011

TABLE B-2
SAMPLE PRINTOUT FOR GDS OPTIMIZATION
60 FOILS MAXIMUM HSA REGION
110 FOILS ALL OTHER REGIONS

DETAILED PRINTOUT OF LAST CASE

PLANAR LOSS REGIONS

ZONE FOILS TEMP C LOSS W WEIGHT G

1	80	703	12 2	1540
2	90	703	11 6	1588
3	80	703	6 4	805
4	80	703	4 6	577
5	110	871	6 6	850
6	110	871	5 6	850
7	20	76	4	191
8	20	76	4	227
9	20	76	4	207
10	90	715	15	1949
11	80	715	11 2	1347
12	90	783	1 6	203
13	110	871	6	88
14	110	871	1 8	272
15	20	105	1	24
16	20	105	4	142
17	20	88	0	20
18	20	88	2	109
19	20	88	1	64
20	10	24	0	13
21	80	709	8 9	1090
22	70	640	4 8	561
23	70	571	3 5	561
24	60	502	3 1	481
25	50	433	2 7	401
26	40	364	2 4	320
27	40	295	1 5	320
28	30	226	1 2	240
29	20	157	1	160
30	20	88	6	272
31	60	834	16 5	612
32	60	944	24 1	612
33	60	798	18 8	796
34	60	783	17 7	796
35	60	803	19 1	796
36	60	830	21 2	796
37	60	857	23 3	796
38	60	881	25 4	796
39	60	902	27 3	796
40	60	920	29	796
41	60	905	13 6	393
42	60	994	18 2	393

TOTAL WEIGHT, FG= 23 79094

DEVICE	PLANAR LOSS	EDGE LOSS	TOTAL
PLUMBING	74 35421	38 8455	113 1997
BRU	4 907623	24 31037	29 21799
RECUP	29 50649	19 59377	48 10045
HSA	254 1479	77 14645	331 2943
GRAND TOTAL	362 9162	158 8963	521 8125

TABLE B-3

SAMPLE PRINTOUT FOR GDS OPTIMIZATION
REFERENCE CASE ALL REGIONS 60 FOILS

DETAILED PRINTOUT OF LAST CASE
PLANAR LOSS REGIONS

ZONE	FOILS	TEMP C	LOSS W	WEIGHT G
1	60	703	18.7	1155
2	60	703	21.5	1058
3	60	703	9.8	603
4	60	703	7	433
5	60	871	14.3	463
6	60	871	14.3	463
7	60	76	.1	573
8	60	76	.1	682
9	60	76	.1	621
10	60	715	27.7	1299
11	60	715	17.2	1010
12	60	783	3	135
13	60	871	1.5	48
14	60	871	4.6	148
15	60	105	0	74
16	60	105	.1	428
17	60	88	0	61
18	60	88	.1	328
19	60	88	0	192
20	60	24	0	78
21	60	709	13.6	818
22	60	640	6	481
23	60	571	4.3	481
24	60	502	3.1	481
25	60	433	2.1	481
26	60	364	1.4	481
27	60	295	.8	481
28	60	226	.5	481
29	60	157	.2	481
30	60	88	.1	818
31	60	834	16.5	612
32	60	944	24.1	612
33	60	798	18.8	796
34	60	783	17.7	796
35	60	803	19.1	796
36	60	830	21.2	796
37	60	857	23.3	796
38	60	881	25.4	796
39	60	902	27.3	796
40	60	920	29	796
41	60	905	13.6	393
42	60	994	18.2	393

TABLE B-3
(Continued)

EDGE LOSS REGIONS			
REGION	TEMP K	LOSS W	
1	976	3	
2	976	3	
3	976	3	
4	976	3	
5	976	3	
6	1144	5	
7	1144	5	
8	348	0	
9	348	0	
10	348	0	
11	987	3	
12	987	3	
13	1055	3	
14	1144	4	
15	1144	9	
16	377	1	
17	377	1	
18	361	1	
19	361	1	
20	361	1	
21	297	0	
22	297	0	
23	377	0	
24	377	0	
25	982	3	
26	361	0	
27	361	1	
28	982	12	
29	1107	16	
30	1216	21	
31	1107	16	
32	1216	21	
TOTAL WEIGHT, KG= 23. 73188			
DEVICE	PLANAR LOSS	EDGE LOSS	TOTAL
PLUMBING	130. 7865	38. 8455	169. 632
BRU	9. 28671	24. 31037	33. 59708
RECUP	32. 1096	18. 59397	50. 70357
HSA	254. 1479	77. 14645	331. 2943
GRAND TOTAL	426. 3307	158. 8963	585. 227