A HIGH-TEMPERATURE FURNACE FOR APPLICATIONS IN MICROGRAVITY

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Technology in the area of material processing and crystal growth has been greatly furthered by research in microgravity environments. The role of efficient, lightweight furnaces with reliable performance is crucial in these experiments. A need exists for the development of a readily duplicated, high-temperature furnace satisfying stringent weight, volume, and power constraints.

A furnace has been designed and is referred to as the UAH SHIELD. Stringent physical and operating characteristics for the system have been specified, including a maximum weight of 20 kg, a maximum power requirement of 60 W, and a volume of the furnace assembly, excluding the batteries, limited to half a Get-Away-Special canister. The UAH SHIELD furnace uses radiation shield and vacuum technology applied in the form of a series of concentric cylinders enclosed on either end with disks. Thermal testing of a furnace prototype has been performed in addition to some thermal and structural analysis. Results indicate the need for spacing of the shields to accommodate the thermal expansion during furnace operation. In addition, a power dissipation of approximately 100 W and system weight of approximately 30 kg has been found for the current design.

INTRODUCTION

The low-gravity environment of space provides researchers with conditions suitable for furthering technology in the areas of materials processing and crystal growth. The effects present during terrestrial materials processing experiments such as sedimentation and buoyancy-driven convection are greatly reduced in microgravity[1]. Thus, the ability to produce high-quality crystals such as zinc selenide and high-temperature refractory materials is a viable objective in space. These improved materials have direct implications for advanced research in metallurgy and applications in optical computers, and electro-optical devices, among other areas.

Although ideal in principal, research in microgravity is very limited for most investigators due to limited access and on-orbit restrictions. Considerable energy losses tolerated on Earth can not be accommodated in space. For flight applications, a system must be robust to withstand the vibrational loads induced on launch and re-entry, while being reliable to provide a standard level of performance over many flights[1]. In addition, volume, weight, and safety considerations, along with experimental requirements, pose a great challenge to designers of hardware for microgravity research.

Several furnaces such as NASA's Crystal Growth Furnace (CGF) and NASA's Advanced Automated Directional Solidification Furnace (AADSF) are being developed to meet the needs of various researchers. The design of these furnaces is driven by the factors mentioned above, as well as their key experimental requirements which are summarized in Table 1. Both the CGF and the AADSF support a maximum hot zone operating temperature ranging from 1500° to 1600°C and utilize conventional solid insulation in conjunction with liquid cooling. In order to satisfy design objectives, the CGF and AADSF are massive furnaces by weight and volume with sizable energy requirements. In particular, the CGF furnace module and auxiliary components measure 60.9 cm in diameter, with a height of 162.5 cm and

TABLE 1. Key experimental requirements for the AADSF and CGF[2,3]

Furnace	Max. Temp. C°	Sample O.D. cm	Sample Length cm	Translation mm/hr	Other
AADSF	1500	2.0	25	0.5 -50.0	Multizone
CGF	1600	2.0	20	0.24-498	Multizone Auto Sample Change

requires 1250 W power[2]. The AADSF furnace container is 43 cm in diameter, 130 cm in height, requires 775 W power, and weighs 213 kg[3].

The role of efficient, lightweight furnaces with reliable performance is crucial for materials processing in microgravity environments. While satisfying a broad range of experimental requirements, the high cost and limited accessibility of the AADSF and the CGF restrict their simultaneous use by several investigators. A need exists for the development of a readily duplicated, high-temperature furnace satisfying stringent weight, volume, and power constraints.

PROBLEM STATEMENT AND DESIGN REQUIREMENTS

The objective of this research was to design an efficient, high-temperature furnace that would satisfy the requirements of two materials processing experiments for the development of zinc selenide crystals and high-temperature refractory materials. The furnace will be candidate for flight on the shuttle or other orbital carrier in a Get-Away-Special (GAS) canister-sized volume. The experiment will be designated to occupy a nonman-rated volume. Weight and power requirements must be compatible with several carriers such as the GAS, the Hitchhiker, and the Complex Autonomous Payload (CAP) programs accommodated in the shuttle and also on the Orbital Free Flyer, the Commercial Experiment Transporter (COMET).

The furnace designed is referred to as the UAH SHIELD. This furnace has been developed with the intent to provide a maximally efficient facility for materials processing. Stringent physical and operating characteristics were specified in an attempt to satisfy this objective. These requirements include a maximum weight of 20 kg, excluding batteries, and a maximum power of 60 W. The volume of the furnace assembly and auxiliary components, excluding the batteries, is limited to half a GAS canister. In particular, this is a payload volume of 2.5 cu ft defined by a payload with a diameter of 19.75 in and a height of 14.13 in[4].

Experimental conditions to be accommodated by the UAH SHIELD furnace include a maximum centerline temperature of 1660°C obtainable for a 2-cm-diameter specimen. A second thermal performance capability required is a temperature profile restricted to low gradients. This specification consists of obtaining a centerline temperature of 1050°C to be maintained over an entrance length of 5 cm. This constant temperature is to be followed by a thermal gradient of 10°C/cm over the next 5 cm of a silica quartz ampoule with the dimensions of 2 cm in diameter and 22.0 cm in length. The furnace must be able to translate with respect to the specimen at a minimal rate of 2 mm/day for a distance of 2 cm. In addition, the entire assembly must tolerate a vacuum environment.

Other design requirements for the UAH SHIELD furnace include the preservation of structural and thermal performance in the harsh environment to which it is subjected. The furnace assembly must be able to maintain its structural integrity under an applied launch load of 12 *g* on the launch axis and 6 *g* on each transverse axis[4]. In addition, a 12.9 *g* overall root-mean-squared random vibration level must be withstood. Thermal environmental parameters applied to GAS can payloads are highly dependent on orbital conditions and the internal heat produced by payload items. Steady state orbital bay temperature range from -160° to 100°C. A worse case approximation of half the container's temperature, based on a power dissipation of 60 W, should be assumed to be 25°C. In addition to the key design parameters previously mentioned, considerations were required with respect to furnace reusability, ease of sample changing, safety, materials availability, and compatibility of materials, among others.

DESCRIPTION OF THE UAH SHIELD FURNACE

The stringent power, volume, and weight requirements stipulated have dictated a radical departure in design from the use of solid insulation commonly found in conventional high-temperature furnaces. The UAH SHIELD furnace utilizes radiation shield and vacuum technology to achieve its efficiency. The SHIELD design consists of a series of concentric cylinders, referred to as radial shields, enclosed on either end with disks or end shields as shown in Fig. 1. Two designs currently being considered to maintain the spacing between the shields and minimize losses due to conduction include the use of dimples pressed into the shields and the use of a cone to position the radial and end shields. Variable spacing of the shields is proposed in an attempt to accommodate the thermal expansion.
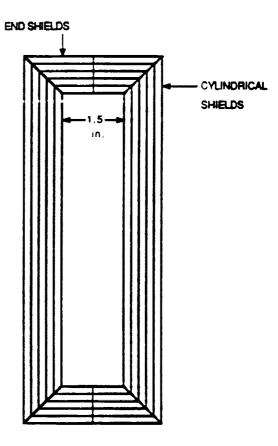

Fig. 1. UAH SHIELD furnace insulation.

The radiation shields are to be constructed from low-emissivity materials to reduce the net radiation transfer between the series of surfaces. In addition, the interior region of the furnace module will be exposed to temperatures of 1660°C and above, requiring materials with high melting and recrystallization temperatures. The shields are proposed to be made of a 0.005-in thick niobium alloy, WC-103, with a melting point of approximately 2400°C[5]. For temperatures below 1063°C, which is below the melting point of gold, gold-plated niobium will be utilized. Emissivity as a function of temperature for niobium, gold and with several other materials, is illustrated in Fig. 2[6]. Niobium was selected based on its high melting and recrystallization temperature, as well as its relatively low emissivity, density, and thermal conductivity values. As seen from the graph, the use of gold at temperatures below its melting point is advantageous because of its highly desirable emissive properties. The radial and end shields are depicted in Fig. 3, showing a longitudinal, cross-sectional view of the furnace module.

Internal to the shields is the ceramic heating core, which is proposed to be alumina oxide. The core must be supported in a simple but effective manner, allowing easy access to the sample. For the core support, the UAH SHIELD furnace uses caps made from niobium alloy having a cup section that surrounds the core and a thin walled tube section projecting
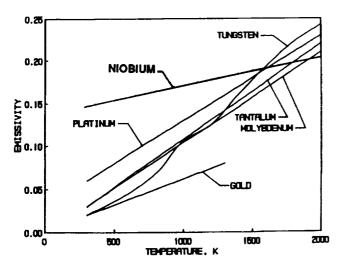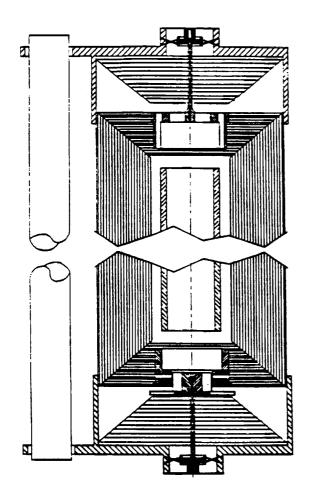
Fig. 2. Emissivity vs. temperature.

through the end shields as shown in Fig. 3. The core caps are attached to niobium alloy hubs. A system of wires or spokes is proposed to provide interfacing between the hubs and the external structure for support, in addition to minimization of heat loss.

The external structure of the furnace module is supported through endcaps made of 6061-T6 aluminum. The endcaps allow the outer radiation cylinder to be supported, in addition to providing an anchoring base for the spoke system that supports the internal core. A longitudinal view of this part is also shown in Fig. 3. The endcaps are designed to have two tangs on their perimeter to allow the insertion of a translation support rod and a threaded translation rod. The bearing rod and threaded rod are supported by pillow blocks mounted in the GAS can. The furnace module and auxiliary components within the GAS can are shown in Fig. 4. The configuration of the endcaps, threaded rod, and bearing rod with respect to their positioning in the GAS can are clearly depicted in this illustration. Translation of the furnace is accomplished by programming the vacuum-compatible controller to the prescribed rate and duration. With a stepper motor geared for the desired translation, rotation of the threaded rod is performed through a belt-sprocket system.

As specified in the requirements, the specimen is to remain stationary with respect to the furnace translation. In addition, the ampoule/specimen must be supported so that vibration is minimized, alignment in the core is maintained, conduction losses through the furnace are minimized, and sample changing is permitted. The ampoule support system is based on the

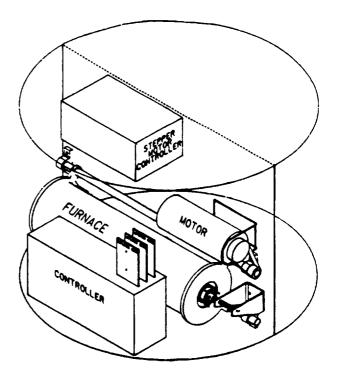Fig. 3. UAH SHIELD furnace cross-sectional view.

Fig. 4. The UAH SHIELD furnace within 1/2 a GAS Can.

suspension of the ampoule between two rigid supports anchored external to the furnace. The suspension of the specimen is performed using a unique system of support wires and accommodates the elongation of the wires during furnace operation.

The control system for the UAH SHIELD furnace includes a power source, temperature controls, heating elements, and a microprocessor-based controller in order to satisfy the experimental conditions of a 1660°C maximum temperature. The power for this system will be supplied by two zinc-silver oxide batteries. Three thermocouples are to be positioned within the core at different locations along its axial length. This will allow temperature measurements to be obtained and relayed back to an amplifier module and the controller. An additional thermocouple is to be placed within the GAS can to monitor its temperatures. A 60% platinum/40% rhodium alloy wire is proposed for use as the heating elements.

METHODOLOGY AND RESULTS

Evaluation of the UAH SHIELD furnace has been performed based on experimental, analytical, and numerical techniques. To investigate the feasibility of the proposed design, thermal testing of a prototype has been conducted. Thermal analysis using numerical techniques has been performed in order to evaluate and ultimately optimize the design of the insulation and the supporting structures. Finally, structural evaluation based on hand calculations and finite element analysis has been performed on various components of the supporting structure of the furnace.

Thermal Testing

Early research on the UAH SHIELD furnace assumed a radial shield configuration consisting of a helix surrounding the furnace core. An initial experiment was performed to investigate the feasibility of this design concept. The objective of this test was to determine if the thermal expansion would be accommodated using radiation shields fabricated in the form of a helix with dimples separating successive layers.

The prototype developed was made of AISA 300 series stainless steel measuring 19 ft long, 15 in high, and 0.005 in thick. Dimples of approximately 0.02 in high and having a 0.02-in radius were pressed in the stainless steel sheet using a template and applying a rolling procedure. The sheet was then wound into 70 layers containing approximately 1600 dimples. The final prototype is 15 in high, with an inner diameter of 2.75 in and an outer diameter of 7.0 in. Using an alumina core wrapped with nichrome wire, an internal heat source was developed to be inserted within the prototype. Two thermocouples were used for measurements of temperature within the furnace core and on the outer shield. To support the shields, the core, and the internal thermocouple, as well as minimizing axial heat losses, the ends of the shields were insulated using endcaps. The endcaps were fabricated from 310 ceramic foam[7]. The table-top configuration of the test set-up is shown in Fig. 5.

The prototype furnace was heated to a temperature of 700°C and temperature readings from both thermocouples were recorded for a total of 102.5 min. The steady-state temperature of the outer shield was found to be 152.7°C. Fluctuations of
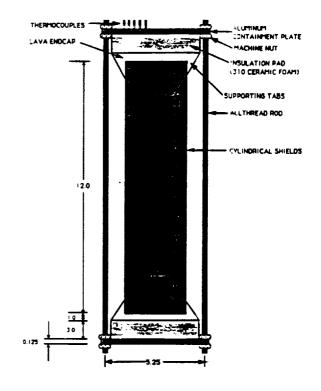

Fig. 5. Experimental set-up for Test 1.

5°C for the outer shield temperature were observed and attributed in part to convection from room air currents. After the test was completed and the furnace thoroughly cooled, the heat shields were unwound and inspected. The innermost shields, those experiencing the greatest temperatures, exhibited severe wrinkling and crimps. This result indicated that the inner shields were being deformed when expansion was restricted by the outer shields, which were expanding a different amount. In addition, a large amount of oxidation was evident on the innermost shields indicating the need for an inert atmosphere during testing. The results from this initial test revealed that the helix configuration of radial shields was inadequate during furnace operation and did not accommodate the thermal expansion.

An iteration in the design of the radial insulation was performed, resulting in the current design of the UAH SHIELD furnace consisting of concentric cylinders with more spacing. This radial insulation was described in an earlier section in this paper. Theoretically, the current radial insulation design addresses many of the problems encountered in the initial design. A second experiment has been proposed and a prototype developed in an attempt to verify the design with respect to thermal expansion qualitatively.

The prototype developed to model the current UAH SHIELD design consists of 9 concentric cylinders with wider spacing. The cylinders were fabricated by spot welding 0.005-in thick sheets of inconel 600. All cylinders were 12 in long while the inner cylinder had an inner diameter of 1 in and the outer cylinder had an inner diameter of 1.555 in. Interior to the

cylindrical shields, a 1.0-in alumina core wrapped with nichrome wire was positioned. Thermocouples of 0.055 in were located between each shield to monitor the temperature distribution throughout the furnace prototype. As in the previous test, endcaps were used to support the shields and the core, and to minimizie axial heat losses.

The testing protocol to be followed involves performing the experiment in a bell jar to simulate the actual environment of the furnace. Using a bell jar and a turbopump system, a pressure on the order of 10⁻⁵ atm will be produced. The core of the prototype will be heated to 700°C and thermocouple readings will be made every 30 sec until the outer shield has reached a steady-state temperature. Following this general approach, it is hoped that qualitative evaluation of the furnace design may be made.

Thermal Analysis

Thermal analysis using numerical techniques has been performed in an attempt to evaluate the dissipation of heat and ultimately optimize the design of the insulation and the supporting structures in the UAH SHIELD furnace. In the analysis of the furnace insulation, it was assumed that the heat loss was governed by radiation alone, thus conduction was neglected. A program was developed to determine the number of radial shields required to satisfy the given boundary conditions assuming various heat rates. The radial shields were modeled assuming infinite concentric cylinders as described by the following equation[8].

$$q_{rad} = \frac{SBC \cdot A \cdot (T_i^4 - T_j^4)}{\frac{1}{E_i} + \frac{1 - E_j}{E_j} \cdot \frac{r_i}{r_j}} \tag{1}$$

In this equation, q_{rad} is the heat loss due to radiation; SBC is the Stefan-Boltzman constant having a value of 5.67×10^{-8} W/(m²K⁴); A is the surface area; T_i is the temperature of shield i; T_j is the temperature of shield j; r_i is the radius of shield i; r_j is the radius of shield j; E_i is the emissivity of shield i; and E_j is the emissivity of shield j.

The boundary conditions applied in this analysis assumed the largest possible temperature extremes exist. Thus, the given temperatures of the inner and outer shields were 1700°C and 20°C respectively. The shields were assumed to be 0.005 in thick, separated by a constant vacuum space of 0.01 in, with the innermost shield having an inner radius of 0.775 in. The inner shields were assumed to be composed of the niobium alloy WC-103 until a calculated shield temperature below 1063°C was found. Below 1063°C, the melting point of gold, the shields were assumed to be gold plated. The material properties used in this analysis are given in Table 2 where the emissivities are shown to be a function of temperature (K). In the Fortran program developed, iterations were performed to evaluate the number of shields required to satisfy the given boundary conditions assuming various heat rates. Equation (1) was solved for the temperature of the jth shield allowing the temperature distribution throughout the radial insulation to be

TABLE 2. Selected material properties of the UAH SHIELD insulation.[5,9]

Material	Density kg/m³	Emissivity	Melting Point °C
WC-103	8850	$3.75 \times 10^{-5}T + 0.1325$	2400
Gold	19300	$5.29 \times 10^{-5}T + 0.00914$	1063

TABLE 3. Results of radial shield analysis.

Shield #	Power W	Weight kg
101	55	8.24
118	50	10.44
141	45	13.63
175	40	19.45

determined. In order to simplify the program a conservative assumption was made that the values of emissivity for adjacent shields were the same.

The resulting number of shields and the corresponding weights for values of heat loss ranging from 40 W to 55 W are shown in Table 3. The values of power dissipation assumed in the analysis were chosen since they fell below the 60 W allowed for the entire furnace. For a 15-W reduction in heat from 55 W to 40 W, it is seen that the number of shields required increases almost 75% and the weight more than doubles. The change in weight and size or diameter of the radial insulation as a function of power is clearly depicted in Fig. 6. From this graph, a sharp increase in weight is seen as the power loss is reduced beyond approximately 45 W. This value of power dissipation, 45 W, was chosen to determine the number of shields used in the UAH SHIELD furnace. For this heat loss, 124 niobium alloy shields and 26 gold-plated shields are required, resulting in a weight of 13.77 kg and an outer diameter of 5.8 in. This value of power dissipation through the radial shields allows flexibility in other areas of the furnace design such that power losses of up to 15 W may be accommodated and still allow satisfaction of the maximum heat loss requirement. The outer

Fig. 6. Power vs. weight and diameter.

diameter of the shielding, 5.8 in, may clearly be accommodated in the volume allotted for the furnace. However, the weight of the shielding is almost 70% of the total weight allowed. The temperature distribution as a function of shield number is given in Fig. 7 for a power loss of 45 W. In this graph, the advantage of using gold plating with its low emissivity at temperatures below 1063°C is seen by the sharp temperature gradient over the outer gold-plated shields. This result translates to savings in the number of total shields over that required if niobium alone had been used.

A simple comparison was made to illustrate the effectiveness of the UAH SHIELD furnace in reducing power dissipation over that permitted with conventional solid insulation. For a heat loss of 45 W through the radial shields, it was found that 141 shields were required, resulting in an inner insulation radius of 0.775 in and an outer radius of 2.9 in. A determination was made of the heat transfer through a solid cylinder with the same dimensions as that of the radial insulation. The radial heat transfer rate for a solid cylinder with a logarithmic temperature distribution is given by the following expression[8].

$$q_{cnd} = \frac{2 \cdot \pi \cdot L \cdot k \cdot (T_{s,1} - T_{s,2})}{\ln(r_2/r_1)} \qquad (2)$$

In this equation, q_{cnd} is the heat loss due to conduction; π is a constant having a value of 3.14159; L is the length of the cylinder; $T_{s,i}$ is the inner surface temperature; $T_{s,j}$ is the outer surface temperature; r_1 is the inner radius of the cylinder; r_2 is the outer radius of the cylinder; and k (W/mK) is the value of thermal conductivity.

The length of the solid cylinder was assumed to be 13 in, an average value of the length of the radiation shields. Zirconia was used in the analysis due to its relatively low thermal conductivity value of approximately 0.23 W/mK at 1650°C[10]. In both the analysis of the radial shields and the solid insulation, the boundary conditions applied included an inner temperature of 1700°C and an outer temperature of 20°C. Approximately 600 W of power dissipation was found for the solid cylinder
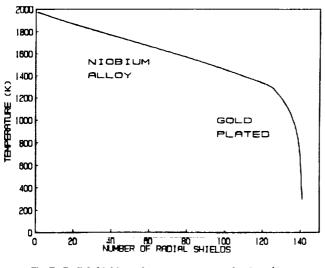

Fig. 7. Radial shield number vs. temperature for Q = 45 W.

described. This analysis does not account for the change in conductivity with temperature; however, it is highly significant that 13 times the heat loss is obtained for solid insulation with approximately the same dimensions as that of radiation shielding.

Thermal analysis of the end shields was performed to determine the heat loss based upon a given number of shields and the applied boundary conditions. For a first approximation, the end shields were modeled as large parallel plates governed by the following equation[8]

$$q_{rad} = \frac{SBC \cdot A \cdot (T_i^4 - T_j^4)}{\dfrac{1}{E_i} + \dfrac{1}{E_j} \cdot - 1} \qquad (3)$$

where the constants shown are the same as those given in equation (1). A-1 in end shield insulation height was assumed per end, resulting in 66 individual shields available. The shields were assumed to be 0.005 in thick and separated by a vacuum space of 0.01 in. An iterative procedure was performed to calculate the heat loss with an inner shield temperature of 1700°C and an outer shield temperature of 20°C. The inner shield diameter was assumed to be 1.55 in while the outer shield diameter was assumed to be 5.8 in. Equation (3) was manipulated to find the end shield temperature distribution, where the emissivity values of adjacent shields were approximated to be equivalent. As before, the innermost shields were assumed to be composed of the niobium alloy WC-103 until a calculated shield temperature below 1063°C was found. Below this temperature, the emissive properties of gold were used in the calculations. The results obtained through this analysis yielded a heat loss of approximately 3 W per end. The 1-in end shield insulation was found to be comprised of 59 niobium shields and 7 gold-plated shields. The weight of the end shields was found to be approximately 1.5 kg total.

The core support was identified as the primary heat sink within the furnace structure. Thus, thermal analysis using the finite element method (FEM) was performed in an attempt to evaluate and optimize the design of this component with respect to heat loss. As described earlier, the core support is composed of a cap having a cup section that surrounds the core, and a thin walled tube section projecting through the end shields to the hubs and ultimately to the endcap rim through a system of wires or spokes. A two dimensional axisymmetric model of the core cap, tube, hub, and spoke section designs were created using ANSYS (Swanson Analysis System, Inc.) finite element software. The core support tube section was defined using quadrilateral elements. Heat loss in this region was assumed to be governed by Fourier's law of conduction. Radiation exchange between the hub and the rim was modeled using one-dimensional, axisymmetric elements. The cross-sectional area for the discrete spokes was found and an equivalent cross-sectional area, axisymmetric, thin disc was used to model the area for conduction transfer in this component. At nodes on the inner surface, a temperature of 1700°C was applied. Those nodes representing the rim were assumed to be at a temperature of 20°C. The axisymmetric model is shown in Fig. 8 and contains 878 elements and 939 degrees of freedom.
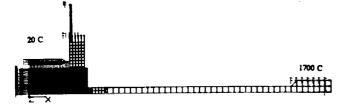
Fig. 8. Axisymmetric model of the core support structure.

In the preliminary design of the UAH SHIELD furnace, the core support components were assumed to be made of tantalum. The current design uses a niobium alloy, however, in this analysis the material properties for tantalum were used. ANSYS's capability to enter up to a fourth degree polynomial for thermal conductivity as a function of temperature was uses in this analysis. The polynomial used is of the form[8]

$$k = 57.598 + 2.518 \times 10^{-3} T + 1.846 \times 10^{-6}$$
$$T^2 - 6.537 \times 10^{-10} T^3$$

(4)

where the unit of temperature is degrees C. A value of 0.11, which is fairly constant over the range of 300 K to 1100 K, was used for the emissivity of tantalum[9]. The results yielded a 19.3 W heat loss for the core support per end of the furnace[11]. With a power dissipation of 45 W through the radial insulation and 6 W through the end shields, this value of heat rate through the core support causes the total heat loss of the furnace to exceed the required 60 W.

In an attempt to assist in the redesign of this component to optimize the heat loss, further analysis was performed. A simplified version of the model described above was used in this second investigation. Only the core support tube section was used resulting in the hub, spoke, and radiation assumptions being neglected. This simplified model consisted of 59 elements and 109 degrees of freedom. The model was analyzed using various values of conductivity given as a function of temperature. The heat flow was determined and divided by the cross-sectional area of the thin-walled tube to obtain the heat flux. The resulting conductivity vs. heat flux is given in Fig. 9. This graph may
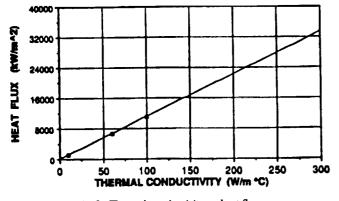

Fig. 9. Thermal conductivity vs. heat flux.

be used to allow a first approximation of the required cross-sectional area for an optimized design of this component given a thermal conductivity value and a desired heat loss.

Structural Analysis and Safety Considerations

Structural evaluation based on hand calculations and finite element analysis has been performed on various components of the supporting structure of the UAH SHIELD furnace. Some of the key analyses performed are briefly reviewed here. The total weight of the structural and translation components was found to be approximately 7.5 kg. The forces in the 0.025-in tungsten ampoule support wires were calculated to verify their integrity under a launch condition of 12 g on the launch axis. A factor of safety greater than 1.5 was found for the ampoule suspension system.

An iteration in the design of the aluminum endcaps has been performed based on a preliminary finite element analysis of this component. The 6061-T6 aluminum endcaps and tangs were modeled separately using three-dimensional isoparametric elements. The forces due to acceleration were assumed to be transferred through the flanges to the endcap body. ANSYS structural analysis software was used in this investigation. The results indicated that severe stress concentrations were present at the junction of the tangs or flanges and the endcap body. The maximum principal stresses in these locations were found to exceed the yield strength of the material. Subsequently, a redesign of this part was performed where corners were filleted and material redistributed in an attempt to reduce stress concentrations. In order to evaluate the current endcap design, a three-dimensional model of this component has been created for future analysis on a Cray X/MP supercomputer. The model has been refined and consists of 2768 elements having 13,000 degrees of freedom.

The area of safety is a critical aspect in any design project. Applicable safety procedures and requirements have been reviewed at each step in the design of the UAH SHIELD furnace. A preliminary hazard analysis of the payload was performed and a safety data package for Get Away Special payloads was compiled in accordance with NASA's "Get Away Special Payloads Safety Manual" and "NASA's Safety Policy and Requirements Manual."[12,13] Materials used within the UAH SHIELD furnace assembly have been selected based upon safety ratings prescribed by Marshall Space Flight Center's "Materials Selection List for Space Hardware Systems."[14] In addition, a preliminary materials listing has been developed for the system designed.

CONCLUSIONS

The objective of this research was to design an efficient, high-temperature furnace that would satisfy the requirements of two materials processing experiments for the development of zinc selenide crystals and high-temperature refractory materials. The UAH SHIELD furnace has been designed in an attempt to address many of the needs specified by these experiments. In addition, the UAH SHIELD furnace was developed to provide researchers with a readily reproducible, high-temperature furnace satisfying stringent weight, volume, and power constraints. The criteria imposed upon the system have dictated a radical departure in

design from the use of solid insulation commonly found in conventional high-temperature furnaces. The UAH SHIELD furnace insulation using radiation shields has been shown to be significantly effective in reducing the power dissipation when compared to solid insulation under similar conditions.

Thermal testing of a furnace prototype has demonstrated the importance in the design of the radial shields coupled with the thermal expansion of the system. The results from the initial test revealed that the helix configuration of radial shields was inadequate during furnace operation and did not accommodate the thermal expansion. This finding motivated a redesign of the radial insulation from a helix configuration to concentric cylinders with wider spacing. A second test using the current radial insulation design, as outlined earlier, should aid in a qualitative evaluation of the furnace design. Future quantitative experimentation needs to ultimately be performed by testing the actual furnace design with its specified materials under true operating conditions.

Through thermal analysis of the insulation and core support structure, a power dissipation of approximately 100 W was found for the UAH SHIELD furnace design. This value exceeds the specified 60 W, but is still well below that required for the CGF furnace or the AADSF. Further analysis and eventual testing is necessary to better approximate the heat loss through the insulation, taking into consideration conduction paths. Redesign and analysis of the core support must be performed in order to optimize this design with respect to the power dissipated. To insure a low gradient thermal profile can be accommodated with this system, further research in this area is essential.

Evaluation of the furnace component dimensions indicate the system may be assembled in half the volume of a Get Away Special canister, excluding the batteries. However, the weight of the furnace has been found to be approximately 30 kg, excluding the batteries. Once again, this value is still below the weight specified for the AADSF. Eventual structural analysis and testing is suggested for all components within the furnace assembly to verify their integrity under simulated launch conditions.

While the UAH SHIELD furnace has many areas requiring further analysis and testing, efforts to date have resulted in the development of a high-temperature furnace that is fundamentally different from most conventional systems. Theoretical results indicate that considerable reductions in power dissipation, volume, and weight are potentially feasible with this unique furnace when compared to solid insulation furnaces. The ultimate goal for future research in the design of the UAH SHIELD furnace is to provide a maximally efficient facility for materials processing in microgravity environments.

ACKNOWLEDGMENTS

REFERENCES

1. Rosenthal B. N., Krolikowski C. R. (1990) Programmable Multi-Zone Furnace for Microgravity Research. *J. Amer. Inst. of Aeronaut. and Astronaut., 91,* 0781, 1—6.
2. NASA Publication, *Crystal Growth Furnace (CGF),* Marshall Space Flight Center, Experiment Payloads Projects/JA51, January 1989.
3. NASA Publication, *Advanced Automated Directional Solidification Furnace (AADSF),* Marshall Space Flight Center, Experiment Payloads Projects/JA51, January 1989.
4. NASA Publication, *Get Away Special (GAS) Small Self- Contained Payloads Experimenter Handbook,* Goddard Space Flight Center, Special Payloads Division, 1989.
5. Teledyne Wah Chang Albany, (1990) *Niobium,* pp. 15—16.
6. Touloukian Y. S.and Ho R. W. (1970) *Thermophysical Properties of Matter: Thermal Radiative Properties-Metallic Element and Alloys,* Vol. 7, Plenum, Washington
7. Cotronics Corporation, *Ceramics and High Temperature Materials Handbook,* p. 13. Brooklyn, NY.
8. Incropera F. P. and Dewitt D. P. (1990) *Fundamentals of Heat and Mass Transfer.* Wiley, New York.
9. Dewitt D. P. and Touloukian Y. S. (1970) *Thermophysical Properties of Matter VII,* IFI/Plenum, New York, p. 474.
10. Touloukian Y. S. and Ho R. W. (1970) *Thermophysical Properties of Matter: Thermal Radiative Properties-Non Metallic Solids,* Vol. 8, Plenum, Washington.
11. McGuire M., personal communication, May 1991.
12. NASA Publication, *Get Away Special Payloads Safety Manual,* NASA, 1986.
13. NASA Publication, *Safety Policy and Requirements,* NSTS 1700.7B, Lyndon B. Johnson Space Center, 1989.
14. NASA Publication, *Materials Selection List for Space Hardware,* Marshall Space Flight Center, HDBK-527.