



AN OVERVIEW OF THE THERMAL CHALLENGES OF DESIGNING MICROGRAVITY FURNACES

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ABSTRACT

Marshall Space Flight Center is involved in a wide variety of microgravity projects that require furnaces, with hot zone temperatures ranging from 300 °C to 2300 °C, requirements for gradient processing and rapid quench, and both semi-conductor and metal materials. On these types of projects, the thermal engineer is a key player in the design process.

Microgravity furnaces present unique challenges to the thermal designer. One challenge is designing a sample containment assembly that achieves dual containment, yet allows a high radial heat flux. Another challenge is providing a high axial gradient but a very low radial gradient.

These furnaces also present unique challenges to the thermal analyst. First, there are several orders of magnitude difference in the size of the thermal “conductors” between various parts of the model. A second challenge is providing high fidelity in the sample model, and connecting the sample with the rest of the furnace model, yet maintaining some sanity in the number of total nodes in the model.

The purpose of this paper is to present an overview of the challenges involved in designing and analyzing microgravity furnaces and how some of these challenges have been overcome. The thermal analysis tools presently used to analyze microgravity furnaces and will be listed. Challenges for the future and a description of future analysis tools will be given.

INTRODUCTION

Marshall Space Flight Center (MSFC) is the Lead Center for NASA’s Microgravity Research Program and manages microgravity research projects at Marshall and other NASA Centers. One of the disciplines that Marshall is responsible for managing is materials science. A fundamental goal of microgravity materials science research is to better understand how buoyancy driven convection and sedimentation affect the processing of the materials. By suppressing these gravity driven phenomena in the microgravity environment of low earth orbit (LEO), other phenomena normally obscured by gravity may be investigated. Studying the phenomena normally obscured by gravity allows the gravity driven phenomena to be better understood as well.

Scientists from the academic and research communities apply to NASA to become Principal Investigators in various materials science disciplines. The materials science discipline that is discussed here is directional solidification processing of metals and semi-conductors. This specific discipline requires high temperature furnaces that must meet challenging thermal requirements. These thermal requirements include providing a large thermal gradient in the sample, a rapid quench at the end of processing, and very stringent isothermal specifications within certain sections of the sample, to name a few. While meeting these thermal requirements, containment of (sometimes-hazardous) materials and all other safety requirements must be met. Many times, meeting the safety requirements makes meeting the thermal requirements extremely difficult. Temperature measurement and other types of instrumentation issues are also significant furnace design challenges.

Thermal mathematical modeling is very important in the design of these high temperature furnaces. Thermal mathematical modeling is used in the preliminary design of the furnace, aids in the design process, and is used to diagnose test data from the furnace. The thermal mathematical models must include the numerical representation of the PI's sample as well as the furnace in order to assess the sample's impact on the thermal performance of the furnace. This presents many challenges as well: adequately characterizing the sample without generating a huge amount of nodes, several orders of magnitude difference between thermal conductors in the model, and dealing with furnace control issues.

The main focus of this paper is to discuss the above referenced challenges. As an introduction to microgravity materials science processing of metals and semiconductors, two types of furnaces will be described. Following, some examples of sample systems and their containment will be described. Next, furnace processing and control will be outlined. Then, the challenges associated with furnace design and analysis will be discussed. Solutions that have been implemented and that are being considered will be included. Finally, conclusions will be discussed.

DESCRIPTION OF TWO TYPES OF MICROGRAVITY FURNACES

There are a wide variety of furnaces that are used for materials processing. However, there are two types that have been used for most of the furnaces designed and built by Marshall for metal and semi-conductor processing. These two furnaces are related: 1) Bridgman-Stockbarger and 2) Bridgman furnaces.

Figure 1 shows a cutaway view of a Bridgman-Stockbarger furnace. This particular furnace operates in an inert gas environment; however, Bridgman-Stockbarger furnaces may also be designed to operate in a vacuum environment.

There are three main zones in this furnace: a hot zone, an adiabatic zone, and a cold zone. The hot zone is designed to add heat to the sample radially such that the sample melts. Heat is radially extracted from the sample in the cold zone such that the sample re-solidifies. Ideally, there is no radial heat transfer in the adiabatic zone. The temperature difference between the hot zone and cold zone produces the required axial gradient in the sample. The optimally designed furnace will operate such that the location of the solid-liquid interface is located in the gradient zone. This is normally the gradient specified by the PI. It is desirable that this gradient is in the adiabatic zone for the following reason: since there is (ideally) no radial heat transfer in the adiabatic zone, the shape of the solid-liquid interface is flattest in the adiabatic zone. Since the furnace is designed so that the design gradient is located in the adiabatic zone, this zone is also commonly called the gradient zone.

A Bridgman-Stockbarger furnace has a "heated" cold zone as a distinguishing characteristic. The cold zone is only "cold" relative to the hot zone. That is, the required axial thermal gradient is achieved by operating the hot zone at temperatures on the order of 1200 – 2200 °C, while the cold zone operates on the order of 400 – 1000 °C. Bridgman-Stockbarger furnaces are typically used for semi-conductor directional solidification processing.

Figure 2 shows a Bridgman furnace design. This furnace operates in an inert gas environment. As with a Bridgman-Stockbarger, a Bridgman furnace may also be designed to operate in a vacuum environment. The Bridgman furnace has the same main components as the Bridgman-Stockbarger furnace: a hot zone, a gradient or adiabatic zone, and a cold zone. However, a Bridgman furnace has an actively cooled cold zone. The cold zone extracts heat from the sample at temperatures slightly warmer than ambient or cooler if necessary. There are other features on the particular furnaces shown: a quench block is on both and a vacuum block is shown on the furnace in Figure 2. On this Bridgman furnace, a water spray is used to quench or rapidly cool the sample. The vacuum block is used to remove the water and steam mixture that results when water is sprayed at a hot surface.

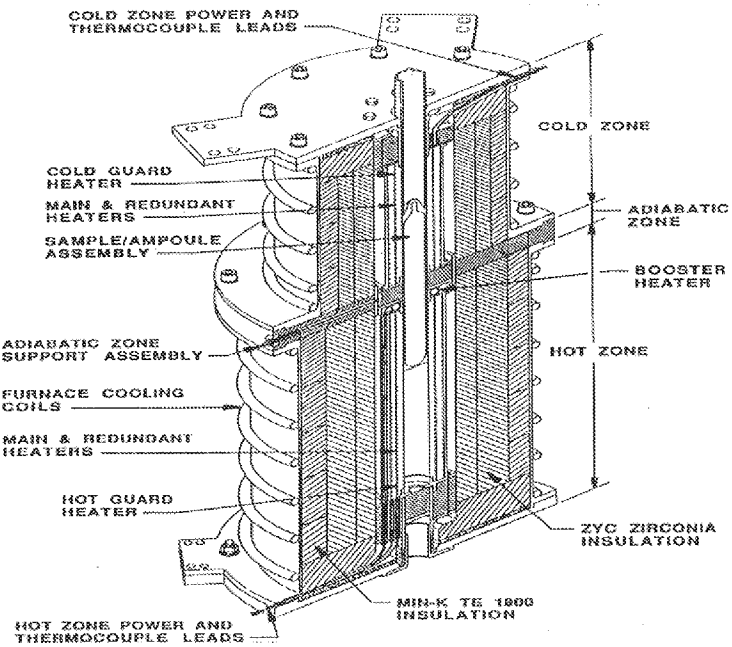


Figure 1: Bridgman-Stockbarger Furnace that operates in an inert gas environment.

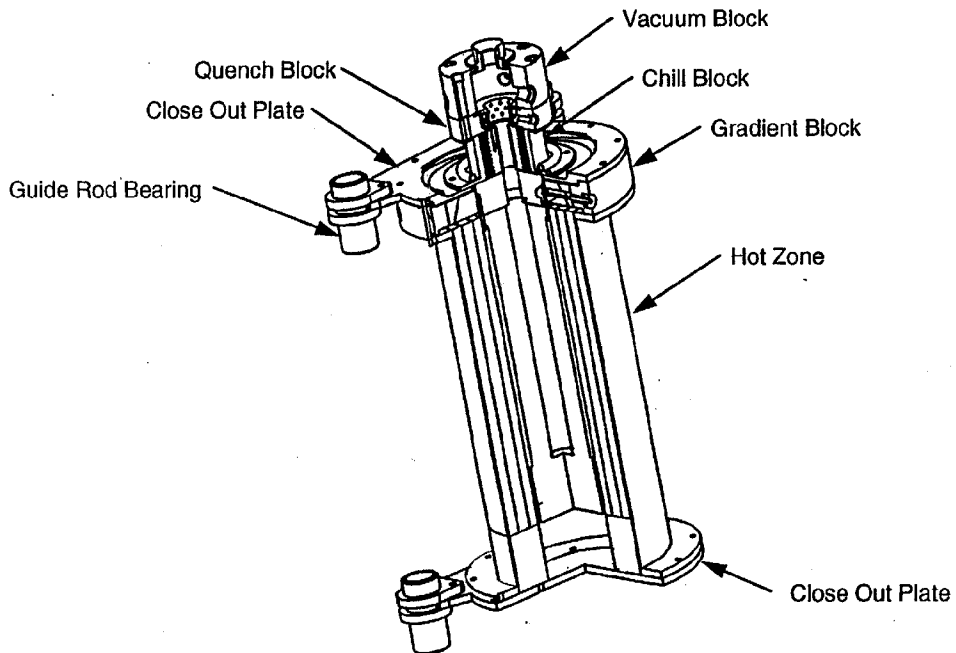


Figure 2: Bridgman Furnace that operates in an inert gas environment.

EXAMPLES OF SAMPLE CONTAINMENT ASSEMBLIES (SCA)

Figure 3 shows two sample containment assemblies (SCAs). The one on the left is that of a double-contained system. The sample is contained directly within an ampoule. Common ampoule materials are ceramics such as aluminum oxide (alumina), aluminum nitride, and graphite. The outer container is called the cartridge, normally constructed of metals. There is a gap between the ampoule and the cartridge. The materials or design of this gap will be explained in detail later on in this paper. The cartridge is affixed to the support structure of the SCA.

The right side of Figure 3 shows a single-contained SCA, or simply, a crucible. The crucible is made of the same materials as ampoules: ceramics such as aluminum nitride, etc. The SCA support structure is attached to the crucible material in this case.

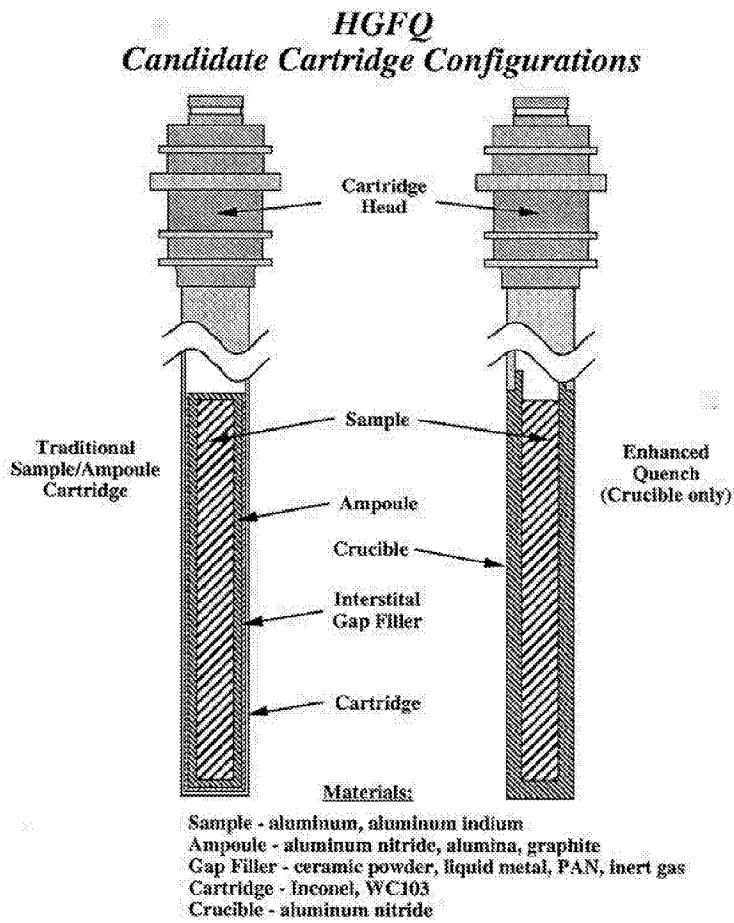


Figure 3: Two different Sample Container Assembly (SCA) Designs.

FURNACE PROCESSING AND CONTROL

Furnace processing normally begins by inserting the sample into the hot zone such that the entire sample is melted. The sample is left to “soak” in the hot zone for several hours so that it is of uniform temperature and composition. This is especially important with alloy materials.

After the soak period, the furnace is translated with respect to the sample so that in effect, the sample is “removed” from the furnace. Note, translating the furnace rather than the SCA is preferred so that the furnace, not the sample, absorbs any disturbances associated with this translation. The translation rate is on the order of millimeters per minute. As the sample is translated into the gradient (adiabatic) zone and then into the cold zone, the molten sample material solidifies. There are transients due to end effects, but the translation rate is often slow enough such that heat transfer can be characterized as a quasi-steady-state process. Some scientists will vary the translation rate during one sample run, which then produces a break in the quasi-steady-state process.

The structure and morphology of the solid-liquid front is very dependent on the material, the magnitude of the gradient, and the translation speed. An entire paper could be written on this subject, but this is beyond the scope of this paper. The phenomenon occurring at the solid-liquid interface and the resulting microstructure are what the PI controls via his science requirements. A point should be made that in alloys, the phase change is not isothermal. That is, the phase change takes place over a finite temperature range. Therefore, there is not a distinct spatial solid-liquid interface. Rather, there is a finite length of sample over which the phase change takes place. The length of the sample that contains both liquid and solid components is known as the mushy zone.

The characteristics of the solid-liquid interface or mushy zone cannot be seen while it is being processed. The nature of the solid-liquid interface or mushy zone may be predicted from the solidified microstructure after processing, but it cannot be known exactly. Therefore, it is desirable to take a snapshot of what is going on at the solid-liquid interface or mushy zone. This can be accomplished via rapid cooling or quench. When a quench occurs, the materials at the solid-liquid interface do not have time to change into their equilibrium morphology. The rapidness of the quench determines the quality of this snapshot. Therefore, it is desirable to make this quench as rapid as physically possible.

Refer back to the Bridgman-Stockbarger furnace, Figure 1. Notice that within the hot zone, there are four heaters shown: the hot guard heater, the main and redundant heaters, and the booster heater. The main and redundant heaters occupy most of the axial length of the hot zone, with the main heater radially inside the redundant heater. The redundant heater, as its name implies, is available in case the main heater fails. However, to lengthen the life of the main heater, both main and redundant are often operated simultaneously. With the redundant heater on, the main heater can operate at a lower power level, thus increasing its expected operating life.

The guard heater, located on the bottom or cold end of the hot zone, is designed to operate at a higher power density than the main/redundant heater. This helps to “guard” the sample from cooling due to heat losses out the end of the furnace. The higher power density that the guard heater provides helps keep the temperature profile at the end of the sample equal with the rest of the sample.

The booster heater, located adjacent to the gradient (adiabatic) zone, is also designed for a high power density. By “boosting” the heat going into the sample, the axial gradient in the sample may be increased exactly where it’s needed.

The cold zone in the Bridgman-Stockbarger furnace shown has main and redundant heaters and a guard heater, for the same reason as in the hot zone. A booster heater is not necessary in the cold zone. The main/redundant heater setpoint can be adjusted for optimum thermal gradient.

Although this level of detail is not shown in Figure 2, the hot zone of most Bridgman furnaces is designed with a guard heater, a main and redundant heater set, and a booster heater. The actively cooled cold zone on Bridgman heaters obviously contains no heaters. There is presently a Bridgman furnace being designed with two separately controlled booster heaters to allow for even better control and optimization of the thermal gradient in the sample.

FURNACE AND SCA DESIGN CHALLENGES

The design and operation of the furnace and SCA are very interdependent. Therefore, this section includes challenges associated with SCA design as well as furnace design.

FURNACE DESIGN CHALLENGES

There are several furnace design challenges that are critical to meeting the science requirements outlined by the PI. The challenges listed here are hot zone design, gradient (adiabatic) zone design, cold zone design, quench system design, control of multiple heaters in the hot zone, and temperature measurement.

Hot Zone Design

The purpose of the hot zone is to add heat to the sample radially to effect melting of the sample. There are two major challenges to this. The first is to control the hot zone inner diameter temperature so that the sample is driven to the temperature profile required by the PI. This issue is addressed below. The second challenge is to achieve the required temperature profile with as little power as possible. Therefore, sophisticated insulation design is required. Gas furnaces are insulated with high performance ceramic insulation such as Zirconium Oxide. The best performing insulation will often not withstand the extreme temperatures at the center of the hot zone. Therefore, a lower performing high temperature insulation is used in the center, with the higher performing (lower maximum temperature) towards the outside of the furnace. Refer back to Figure 1 to see the different insulation layers in the hot zone of an inert gas furnace.

Vacuum furnaces require high performance radiation shields, and many layers of them. Multiple shields with a low emissivity are used to restrict radiation heat transfer. Structural mechanisms for the heater substrate and for the radiation shields must be designed to minimize the thermal conduction path as well as to minimize radiation heat transfer.

Gradient (Adiabatic Zone) Design

The gradient zone should be designed to optimize the location and shape of the solid-liquid interface. Obviously, the gradient zone also serves as an insulation barrier between the hot zone and cold zone. Design features beside thermal insulation have been added to some furnaces at Marshall. For instance, in the Crystal Growth Furnace (CGF), a thermal shunt was used. The gradient zone had load-bearing structure within it; therefore, it could not be made entirely of low conductivity insulation. The thermal shunt conducted heat out radially, decreasing the cooling load of the cold zone. This shunt gave the furnace flexibility to accommodate multiple PIs with varying thermal requirements.

Cold Zone Design

The cold zone has the role of removing heat from the sample so that solidification occurs and so that the gradient requirement may be met.

The cold zone setpoint temperature in a Bridgman-Stockbarger furnace is usually high enough that radiation heat transfer is effective. The required gradient may be achieved by lowering or raising the cold zone setpoint temperature.

A Bridgman furnace cold zone usually operates at much cooler temperatures than a Bridgman-Stockbarger furnace. Water is an effective and common coolant for the cold zone. Radiation heat transfer at these lower temperatures is ineffective; therefore, it cannot be relied upon for meeting gradient requirements. Conduction heat transfer is the most effective means of transferring heat from the SCA to the cold zone at these relatively low temperatures.

One means of effecting conduction heat transfer from the SCA to the cold zone is to design the furnace such that a very small gap exists between the outside diameter of the SCA and the inside diameter of the cold zone. The entire furnace is then operated in an inert gas such as helium. The helium serves as the conduction path in the small annular gap between the SCA and cold zone. Helium gas is an attractive choice because among inert gases, it has one of the highest thermal conductivities (other than hydrogen, which is not used for obvious reasons). However, a helium gas environment has the disadvantage of severely degrading the thermal properties of hot zone insulation. Therefore, another solution has been implemented in a number of Bridgman furnaces at Marshall. This solution is to use either an argon gas environment or a vacuum environment with vel-therm in the cold zone. Vel-therm provides a sliding thermal contact interface. It is compliant and reliable. Argon gas with the vel-therm thermal interface provides a slightly better thermal conductance than helium gas by itself. Using argon rather than helium resulted in 50% savings in power applied to the hot zone of a particular Bridgman furnace at Marshall.

Quench System Design

This is one of the most challenging design issues. The goal of a quench system is to radially remove as much heat as possible from the outside surface of the SCA. There are a number of quench systems that have been used. Others are being considered. Table 1 lists these systems, along with their advantages/disadvantages and their nominal heat transfer rate.

Water spray has a high surface heat transfer rate, however, this high heat transfer rate occurs when the surface temperature is between the boiling point and the leidenfrost temperature of the coolant. The leidenfrost temperature is the temperature at which the cooling mechanism transforms to nucleate boiling: a very effective means of phase change cooling. The initial surface temperature of the quenched section will be centered at the phase change temperature of the sample material, well above the leidenfrost temperature for most PI materials (approximately 200 °C for water). At temperatures well above leidenfrost, a vapor barrier will form around the SCA surface, which is the reason for the severe degradation in heat transfer rate. Marshall has funded a Small Business Innovation Research (SBIR) Contract to optimize water spray characteristics and overcome some of the degradation that occurs at high temperatures. The SBIR contractor has made significant progress by optimizing water spray pattern, water droplet size, and water droplet velocity, such that the water droplets penetrate the steam barrier. Through these efforts, the heat transfer coefficient can be increased at temperatures well above 200 °C by raising the leidenfrost temperature. Despite these efforts, water spray still has some inherent problems: the water/steam must be recovered, there are concerns about water coming in contact with the furnace heater core, and issues with material contamination.

With a high-pressure gas quench, gas is stored at high pressure in a container outside the furnace enclosure. The gas is released into the annulus between the SCA and its enclosure. The high pressure and small cross-sectional area cause the gas to achieve sonic velocity in the annulus. This heat transfer rate achieved is up to 10,000 W/m²-K. Gas quench is very attractive, not only because it has less operating problems than water, but also because it has the potential of operating in-situ. That is, rather than translating the SCA

	<i>Advantages</i>	<i>Disadvantages</i>	<i>Surface Heat Transfer Rate</i>
<i>Water Spray</i>	<ol style="list-style-type: none"> 1. High Quench Rate. 2. Well-Developed Technology. 	<ol style="list-style-type: none"> 1. Vibration on sample. 2. Water / Steam must be Exhausted. 3. Low Quench Rate at High Temperature. 4. Contamination Hazard. 	2000 – 25000 W/m ² -K (very temperature dependent)
<i>High Pressure Gas</i>	<ol style="list-style-type: none"> 1. Steady and Moderate Quench Rate 2. Gas can be easily exhausted. 3. Well-suited to in-situ quench 	<ol style="list-style-type: none"> 1. High Vibration on Sample 2. High Pressure Gas has Safety Issues 	2000 – 10000 W/m ² -K
<i>Clamp-on Device (No phase Change)</i>	<ol style="list-style-type: none"> 1. No gas/liquid to recover. 2. Easy operation 	<ol style="list-style-type: none"> 1. High Vibration on Sample 2. Low Cooling Rate 	200 – 500 W/m ² -K
<i>Clamp-on Device (With phase Change)</i>	<ol style="list-style-type: none"> 1. No gas/liquid to recover. 2. High Quench Rate. 	<ol style="list-style-type: none"> 1. Vibration on Sample 2. Containment of Liquid Metals 3. Seals at high temperatures. 	2000 – 10000 W/m ² -K

(or furnace relative to the SCA) so that the solid-liquid front/mushy zone is in the cold zone or a separate quench zone, the sample is quenched in place. The solid-liquid/mushy zone is located in the gradient zone and the quenching mechanism is brought to it, in the gradient zone. Doing away with the pre-quench translation avoids a time delay and the vibration that may compromise the integrity of the morphology to be preserved with the quench.

Clamp-on devices have also been investigated. The basic concept is to press down on the quenched surface with a device that has a high heat capacity. One example is a collet mechanism made of copper. Thus far, clamp-on devices without a phase change material have not resulted in high enough surface heat transfer rates. The challenge is to effect an adequate heat transfer path between the clamp-on device and the quenched surface (the SCA outer diameter) without damaging the quenched surface or introducing excessive vibration. Plans are under way to improve the design of these devices using compliant materials that also allow adequate heat transfer from the clamp-on device to the quenched surface.

MSFC is also testing clamp-on devices that use a phase change material to serve as the thermal interface mechanism between the clamp-on device and the quenched surface. The phase change material becomes compliant to offer low thermal resistance as it changes phase from solid to liquid. In addition, the phase change material absorbs much of the heat, right at the quenched surface. At high initial quench surface temperatures such as in metal solidification processing, liquid metals are the only materials that can withstand the temperatures. On-going tests show that these devices hold a lot of promise.

Multi-Heater Control

As mentioned earlier, a hot zone has up to five separately controlled heaters: one or two boosters, a set of main and redundant heaters, and a guard heater. A cold zone may have up to three heaters. These heaters are coupled to each other. For example, if more heat is applied to the booster heater, the control measurement of the main heater will be affected as well as the booster heater. Therefore, very sophisticated heater control is necessary. In addition, tight isothermal requirements in the hot zone ($\pm 1^\circ\text{C}$) can make heater control even more difficult.

Temperature Measurement

Temperature measurement is very critical in microgravity furnaces. Two examples are heater control temperature measurement and furnace / sample performance characterization to assure that science requirements are met. Problems and solutions are discussed here.

Thermocouples are the most common measurement device for heater control. Control thermocouples can be stressed due to thermal expansion and exposure to high temperature over long periods of time. Thermocouples can lose calibration over time, especially at high temperatures. Therefore, heater control temperature measurement should have at least one level of redundancy; this allows continued operation if one of the control thermocouples fails. An alternative to using thermocouples is optical fiber thermometers, which transport and analyze the blackbody radiation being absorbed by a probe placed at the desired temperature measurement location. This method of temperature measurement also has its challenges, including having to be very careful about placement of the optical fiber.

Sample measurement can be extremely difficult. Depending on the sample, a thermocouple can be destroyed when it reacts with the sample. Liquid aluminum, for example, is extremely corrosive and can destroy a thermocouple after a relatively short exposure time. On double-contained SCA configurations, thermocouples can be placed in the annular gap between the ampoule and the cartridge, with the thermocouple bead bonded to the ampoule. This type of measurement provides good steady state or quasi-steady-state temperature measurement but is very limited for transient temperature measurement of the sample. Thermal analysis is often used to correlate the temperatures measured on the outside of the ampoule to the desired temperature measurement within the sample.

SCA DESIGN CHALLENGES

The design of the SCA is probably one of the most important and challenging design considerations for furnace design. Its design will affect the quality and magnitude of the gradient and even more so, the success of the quench.

Effect of SCA Gap on Gradient

Figure 4 shows a detailed cross-section of a two containment level SCA design. The thermal heat path down the SCA in the axial direction affects the thermal gradient in the sample. If the axial conductance of the SCA is on the order of or higher than that of the sample, more heat will flow from the hot zone to the cold zone through this path, and the magnitude of the axial thermal gradient will be reduced significantly.

The quality of the thermal axial gradient can also be affected by the thermal properties of the SCA. If the thermal conductance through the SCA is much greater than that of the sample, the solidification front will be closer to the cold zone near the wall than in the sample center. The opposite effect will occur if the

thermal conductance of the SCA is much less than that of the sample. The thermal conductance of the SCA cannot be matched exactly to that of the sample, but measures should be taken to minimize this effect.

Effect of SCA Gap on Quench Rate

The SCA thermal conductance affects quench rate significantly. Here, the conduction path in the radial direction is very important. Referring back to Figure 4, there are three major resistances between the quench medium on the outside of the cartridge to the sample: the cartridge wall, the filler gap, and the ampoule wall. The major challenge is the gap between the inside of the cartridge and the outside of the ampoule. Figure 5 shows the overall thermal conductance versus the gap heat transfer coefficient for three different ampoule materials. The figure shows that up to a gap heat transfer coefficient of $1000 \text{ W/m}^2\text{-K}$, the ampoule material is irrelevant. That is, for a gap thermal conductance of $1000 \text{ W/m}^2\text{-K}$ or below, the thermal resistance of the cartridge wall and of the ampoule wall are insignificant compared to that of the gap between them.

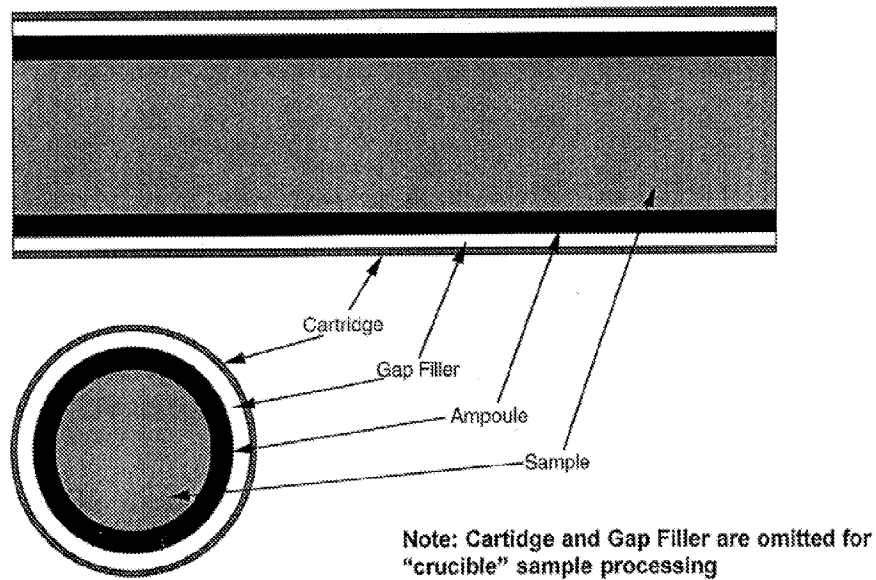


Figure 4: Sample Container Assembly (SCA) Cross-section.

Marshall has investigated the use of liquid metals such as certain indium alloys or crushed powders like alumina or boron nitride as heat transfer "filler" in the SCA gap. However, implementation of these design solutions has been impractical. Problems with thermal expansion of the liquid metals and too low of an effective thermal conductivity with the ceramic powders have been problems thus far.

Applying a metal coating to a ceramic ampoule material via Vacuum Plasma Spray (VPS) is an option being investigated. The metal coating has the purpose of holding the SCA together in case of ceramic failure during quench or other stress causing events. Whether this type of system meets safety requirements for hazardous materials is still being assessed.

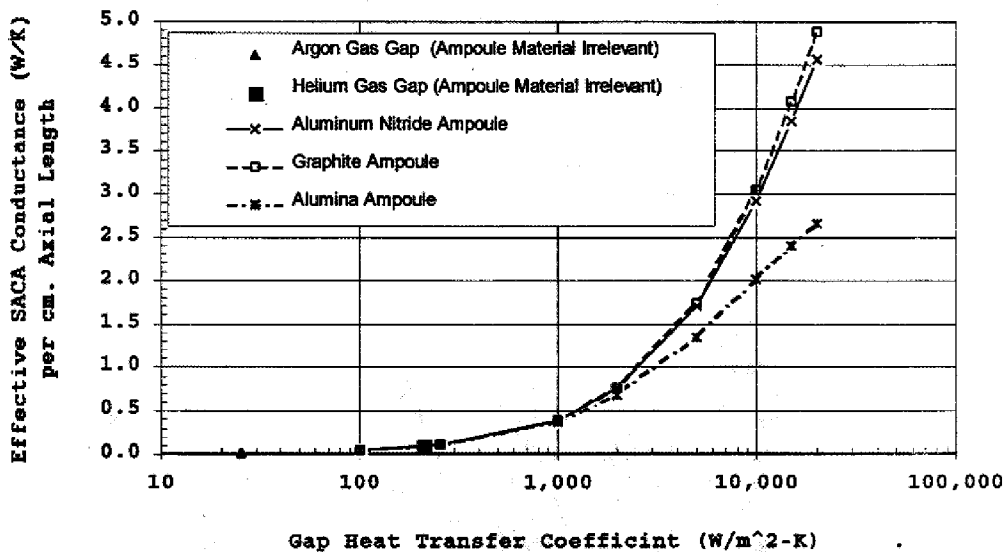


Figure 5: SCA Conductance vs. Gap Heat Transfer Coefficient for a 1.0 mm Gap.

FURNACE THERMAL ANALYSIS DESIGN CHALLENGES

Bridgman and Bridgman-Stockbarger furnaces have a cylindrical geometry, which lends itself to two-dimensional (2-D) axisymmetric thermal models. Figure 6 shows an example of a 2-D axisymmetric model of a Bridgman furnace.

A 2-D axisymmetric model has the advantage of requiring much fewer nodes than a 3-D model. Obviously, this type of model assumes isothermality in the theta (θ) direction. Even though most furnace and sample components are cylindrical and therefore axisymmetric, even the best-designed furnace will have some non-axisymmetric features (i.e., heater wire connections, thermocouples, water lines, structural components, insulation split down the middle for ease of construction, etc.). Assumptions and simplifications must be made to account for these deviations from axisymmetry. A 3-D model of some or the entire furnace may be necessary to assess the effect of these deviations on isothermality in the theta direction.

MULTI-HEATER CONTROL

Thermal analysis plays a key role in heater control. The cross coupling of heaters with each other can be modeled. The design setpoints can be programmed into the thermal model and the power required by each heater may be predicted. Accurate representations of the heater winding locations and heater winding density are critical for accurately predicting the power drawn by each heater. Thermal contact resistance between heater winding substrates and thermal properties are very important for accurate thermal modeling.

FINE MESH IN SAMPLE

Oftentimes, Principal Investigators depend on accurate and detailed predictions of their samples' operating temperatures. Therefore, a high level of fidelity is required in the sample. The modeled representation of the furnace may not require as much fidelity. Therefore, to avoid an enormous model, methods must be

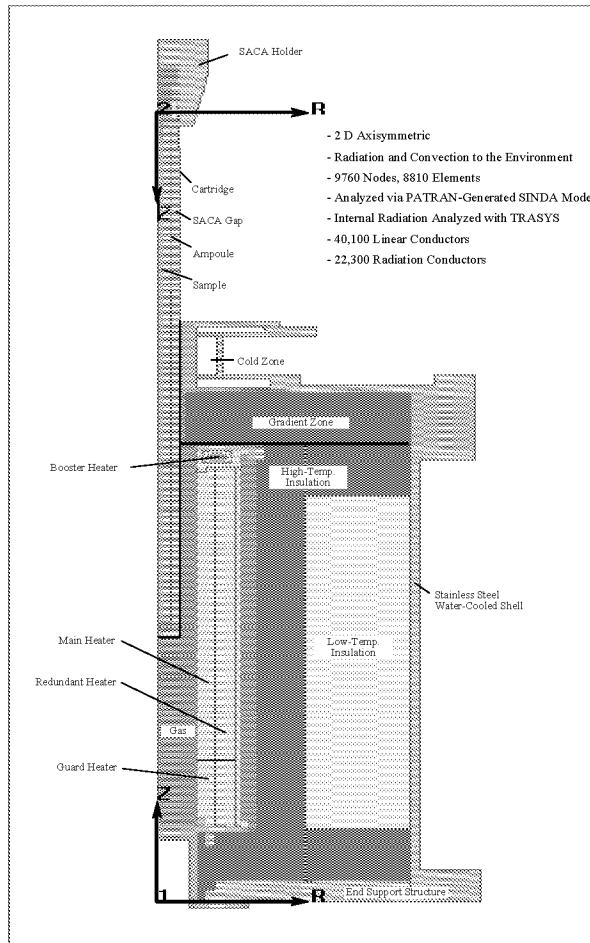


Figure 6: A Thermal 2-D Axisymmetric Model of a Bridgman Furnace.

employed to reduce the node spacing from sample to furnace level in the thermal model. Most modern mathematical modeling tools have mesh generators that allow either a gradual change in model fidelity or discontinuities in the mesh, with internal interpolation schemes communicating across the discontinuous interface.

An alternative to modeling the sample in detail in the furnace model is to model the sample at the lower fidelity of the furnace, and also in a separate more detailed model. Boundary conditions from the furnace/sample model are used as input for the more detailed sample model. This modeling scenario does allow one to run smaller furnace/sample models but has the disadvantage of requiring a lot of data manipulation. Iterations may be required so that the two models converge to one solution.

LARGE ORDER OF MAGNITUDE DIFFERENCE IN THERMAL “CONDUCTORS”

The nature of an axisymmetric thermal model contributes to large geometric variations between thermal conductors in the center of the model versus those near the outer diameter. The variation of thermal properties between the sample and the furnace insulation and the general practice of high fidelity modeling

of the sample (in the center of the model) and lower fidelity modeling of the furnace insulation (near the outer diameter of the model), adds to the problem.

THERMAL PROPERTIES

Thermal properties for samples, particularly alloys, are notoriously hard to come by. In fact, the purpose of some investigations is to determine thermal properties. In addition, there is often a large change in properties between liquid and solid with the mushy zone properties very hard to come by.

The thermal properties of ceramic insulation are often hard to find, or are defined only at one or two temperatures. In vacuum furnaces, the surface thermal properties are often very temperature dependent but known only at one or two temperatures. Manufacturing processes of ceramics (pyrolytic graphite vs. "normal" graphite) can also make for huge differences in thermal properties.

THERMAL TOOLS FOR MICROGRAVITY FURNACE: PAST, PRESENT, AND FUTURE

The most common thermal modeling tool used for microgravity furnaces is the Systems Improved Numerical Differencing Analyzer (SINDA), both SINDA '85 and GASKI SINDA. Graphical interfaces to SINDA, such as Thermal Desktop have improved its use and flexibility. Thermal Radiation Analysis System (TRASYS) is still used, but is giving way to better, more modern tools. RADCAD is an example.

PATRAN has become popular as a furnace design tool in the last few years. It has the advantage of being very quick for modeling simple furnaces or individual furnace components, yet allows a high degree of sophistication and detail when necessary. PATRAN has its own thermal (including radiation) modeler, but also has SINDA and TRASYS interfaces.

FIDAP has some of the advantages of PATRAN, but also has fluid analysis capabilities, allowing the user to model sample liquid convective flows. FIDAP also has excellent pre-processing and post-processing capabilities.

A tool that is going to be implemented for furnace design soon is ProCAST. ProCAST has been developed by the metal casting industry, and will allow transient modeling of a sample/furnace system as the sample is translated out of the furnace. ProCAST was developed for the metal casting industry and includes much of the detailed calculations that metallurgists are interested in.

CONCLUSIONS

Microgravity furnace design and analysis present unique challenges to the thermal designers. Particularly, the high temperatures, steep science requirements, and stringent safety requirements make the job of the thermal designer very difficult. This paper explains some of these challenges and presents some solutions. However, there is much to be done and much to be learned.

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