ARTICLE NO. 79-0521R

A80-048

Swedish Materials Science Experiment in the Texus 1 and 2 Rockets

30020

40012

Sven Grahn* and Lars Stenmark†

Swedish Space Corp., Solna, Sweden

Texus is a sounding rocket project for materials science experiments in low gravity. A 40-kg experiment module is included in the reusable payload. The experiments on the first and second Texus flights in 1977 and 1978 were 12 metal solidification experiments, two involving directional solidification in a gradient furnace and ten "thermal analyses" of small samples in so-called mirror furnaces. The gradient furnace is designed for studies of samples with melting points ≤1000°C. The furnace consists of a tubular resistive heating element inside which the sample is placed and a phase-change heat sink which extracts heat from one end of the sample to get a unidirectional solidification. The mirror furnace is designed for thermal analysis experiments below 1000°C. The radiation from two halogen lamps focused by ellipsoidal mirrors on the sample provides the heating.

Experiment Concept and Design Philosophy

Scientific Program Aspects

WHEN the Texus[1] program was started in mid-1976, materials science in weightlessness was a field of space activity in its infancy. Early experiments on Apollo and Skylab showed great promise.[2]

At that time, Spacelab was five years away, and very few scientific groups showed any enthusiasm at the prospect of making a few space experiments five years into the future. The only way to provide flight opportunities at an earlier date was found to be the use of sounding rockets.

In late 1975, a feasibility study of an alloy solidification experiment on sounding rockets proposed by *Hasse Fredriksson* was started.[3] In the course of this study, contact was established with the Texus rocket program.

The original experiment concept was to make basic metal alloy solidification experiments of two types:

1)"Thermal analysis" of small samples. These samples are rapidly melted and immediately thereafter cooled. The size and thermal environment of the samples are such that they can be regarded as isothermal. Thus, solidification starts anywhere in the sample.

2)Directional solidification experiments with samples ~10 cm long and ~0.5 cm in diameter.

Also, it was decided to use only alloys with rather low melting points (≤1000°C) in order to simplify the technical problems involved in designing the furnaces.

Furnace Design Concepts

The time constraints of a sounding rocket flight made it natural to base the furnace design on three principles: 1) low thermal mass to achieve rapid heating and cooling times consistent with the flight duration of the rocket; 2) passive cooling by conduction and radiation only; and 3) no moving parts in order to increase reliability and avoid disturbance of the micro-*g* level.

Presented as Paper 79-0521 at the AIAA 5th Sounding Rocket Technology Conference, Houston, Tex., March 5-7, 1979; submitted April 25, 1979; revision received Oct. 18, 1979.

Index categories: Space Processing; Sounding Rocket Systems.

*Staff Engineer, Space Applications Div.

†Staff Engineer, Space Science Div.

Use of existing, commercially available components to the greatest possible extent was another principle adopted because of the rather short time available for developing the furnaces.

For the small samples, the requirement of small thermal mass for the furnace prompted the consideration of an "optical" furnace where heat radiation is focused on the sample by mirrors. The first breadboard model of such a furnace was based on a commercially available elliptical reflector lamp. The configuration of the breadboard furnace is shown in Fig. 1.

Experiments with this breadboard model showed that the furnace concept was sound, but that two reflector lamps focused on the sample were required to achieve symmetrical heating and permit melting samples of a reasonable size. This configuration eventually became the final design concept which evolved into the flight-model furnace described later.

The basic design principle of the gradient furnace for the directional solidification experiments is shown in Fig. 2. The strong and well-defined temperature gradient along the axis of the cylindrical sample is achieved by the heat sink at one end of the sample and the multilayer insulation to minimize transverse heat flow.

The design concept was tested in a breadboard setup. The heater used in these tests, and also in the flight-model furnace, was a silicon-carbide ceramic resistance heater. The heat sink at the breadboard stage was a container filled with standard paraffin. The paraffin works as a phase-change heat sink well-known from satellite thermal control systems. The breadboard results were very promising and the flight-model design evolved directly from the breadboard model. In the final design, extra care was taken to minimize transverse heat flow to reduce heating of sensitive temperature measurement electronics mounted near the furnace.

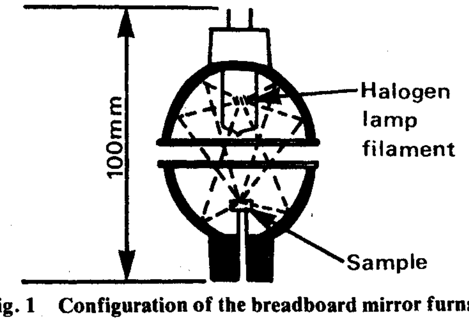

Fig. 1 Configuration of the breadboard mirror furnace.

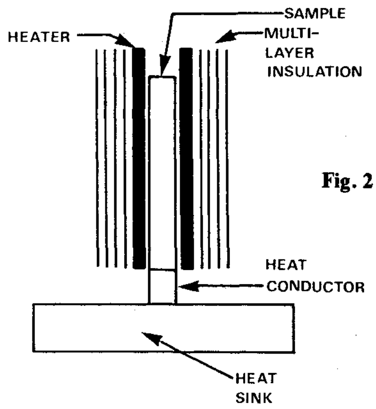

Fig. 2 Gradient furnace principle.

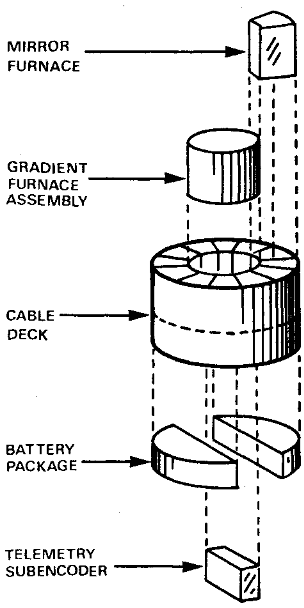

Fig. 3 Modular concept of the experiment module.

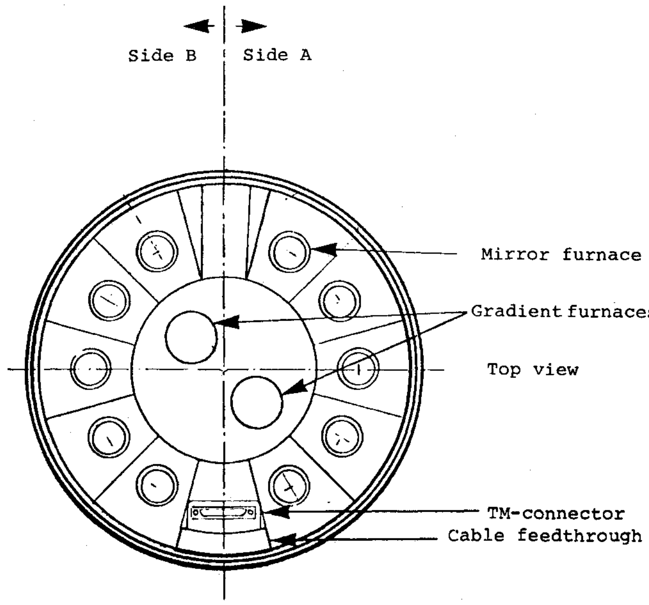

Fig. 4 The division of the experiment module into redundant halves.

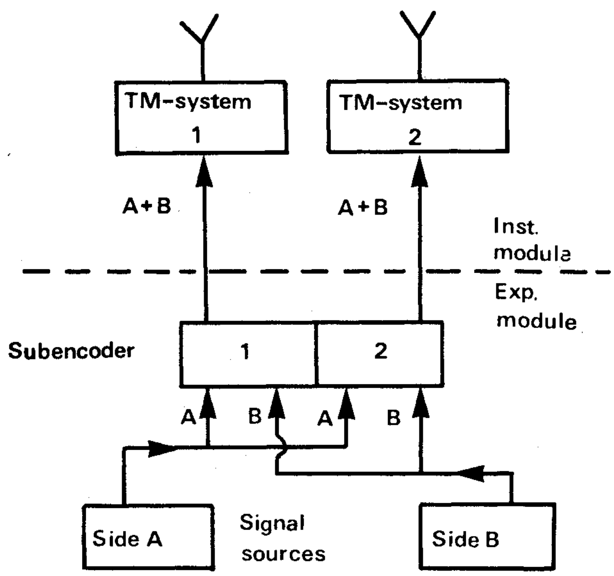

Fig. 5 Telemetry system layout.

Experiment Module Design Philosophy

Design Constraints

Design constraints for incorporating the furnaces in the Texus payload were decided upon early in the project. In agreement with the modular design concept for the overall payload, it was decided that the experiments should be contained in a 0.35-m-long × 0.44-m-diam module. The interfaces with the rest of the payload were kept very simple and included only 1) the mechanical joints, 2) telemetry transmission from the module through the Texus TM system, and 3) liftoff signal transmitted from the Texus instrumentation module to the module for starting the furnace programmers.

The design target for mass of the module was initially set at 32 kg. In the course of the design and construction work, the mass exceeded this value. Flight weight for the module was approximately 38 kg.

Design Requirements

Because of the pioneering and developmental nature of the project, it was natural to require that the design of the module should provide for the maximum number of furnaces geometrically possible. Also, reliability should be enhanced by complete independence between the programmer and temperature measurement circuits of the different furnaces. However, this independence does not include the power supply because separate batteries for each furnace are impractical. To prevent a single point failure in the power supply from causing a total failure of the module, it was decided to split the module into two parts, each part having its own battery pack.

Modular Plug-in Concept

With these design requirements in mind, it was natural to choose a modular concept also for the internal configuration of the experiment module. Figure 3 shows how the main parts of the module are arranged in submodules and fitted into the payload body section. The furnaces are plugged in from the top of the body section, and the batteries and telemetry (TM) encoder from the bottom. All modules plug electrically into connectors mounted on a deck approximately in the middle of the module (see Fig. 3). This deck is designed as a cast and extruded aluminum structure with cabling running in "channels." Therefore, all cabling is fixed and no cable harnesses are used. With this modular concept, ten mirror furnaces and two gradient furnaces can be fitted into the experiment module.

Redundancy Concept

As mentioned previously, each furnace is independent with respect to programmer function, power control, and sample temperature measurement. Also, the module is split into two parts, each comprising five mirror furnaces, one gradient furnace, and one battery pack (see Fig. 4).

Because of the inclusion of two redundant TM systems in the Texus instrumentation module, it was possible to carry the division of the module into two redundant halves even further.

The subencoder in the module also consists of two *completely* independent parts corresponding to the two TM systems. Temperature measurement and housekeeping signals from both sides of the module are fed to both parts of the subencoder; i.e., both TM systems transmit signals from data points in both halves of the module (see Fig. 5).

As a standard safety measure, the external commands, "internal power," and "liftoff" are backed up by internal baroswitches.

The independent programming of each furnace also allows a great flexibility which is valuable for possible last-minute changes in sample heat treatment and for reprogramming in connection with a reflight of the module.

Design Details

Mirror Furnace

The mirror furnaces have been designed to perform thermal analysis experiments using small metal samples with melting point temperatures below 1000°C. The furnace is shown in Fig. 6, and its specifications are summarized in Table 1.

Heating

The radiation from two 150-W halogen lamps is focused by ellipsoidal mirrors at the sample which absorbs the radiation and is heated. The furnace cavity is also ellipsoidal, gold-plated, and polished so that as much as possible of the light from the lamps is absorbed by the sample, and so the furnace structure is heated as little as possible. The temperature of the outer surface of the furnace normally does not exceed 100°C. The time between switch-on of the furnace and complete melting of such a sample is 45-90 sec. The melting time will vary from sample to sample depending on composition and size, but 60 s is a typical value.

Cooling

The cooling of the sample takes place by conduction through the sample holder to the furnace main body and by radiation into the furnace cavity. The cooling rate can be adjusted either by using different sample holders or by supplying heat from the lamps during the cooling period.

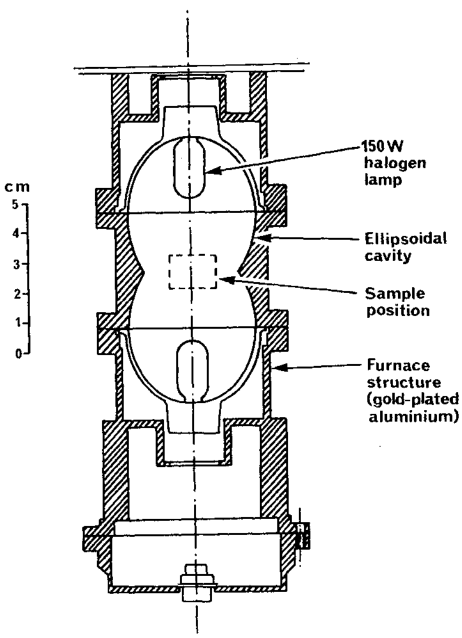

Fig. 6 Mirror furnace flight model principle.

Table 1 Mirror furnace specifications

Characteristic	Specification
Heater type	OSRAM 64635 halogen reflector lamps 150 W (10 A, 15 V)
Maximum heater power	2×150 W
Maximum sample size	20-mm-long $\times$ 12-mm-diam cylinder
Typical melting time	≤ 100 s (for Al-Cu samples ≈ 1 cm^3)
Solidification time	Depends on sample composition, sample holder, and heat treatment. In general, however, less than 3 min.
Furnace size	$\approx 170 \times 100 \times 100$ mm
Furnace mass	1.0 kg (including sample and control electronics, but excluding power supply)

A typical heating and cooling curve is shown in Fig. 7, which represents the temperature of a Sn-Zn eutectic sample during the Texus 1 flight. The solidification was about 50 s. Because of the low melting point of this particular sample, the temperature differential between sample and the heat sink, represented by the furnace structure, was low. Therefore, also the solidification rate was low.

Power Programmer

The power output from the lamps is controlled by a separate programmer for each furnace. This programmer uses an erasable, programmable digital memory, and can therefore be changed to suit the purpose of different samples. The light level in the furnace cavity is used as input signal to a comparator, where the control force is determined by comparing this signal with a predetermined light-level signal from the programmer. The lamp power is regulated by means of a digital pulse-width modulator. The reason for using a light-level control system for the furnace is that the optical output power/electrical input power ratio may differ by tens of percent between 1-*g* and micro-*g* conditions. Because of reduced convective heat losses, the halogen lamp will get hotter and brighter in micro-*g*. How much hotter is not accurately known. To prevent destruction of the lamps at "full" power, it is therefore necessary to measure and control the optical output instead of the electrical input. A block diagram of the light-level control loop and associated programmers is shown in Fig. 8.

For the second flight of the module, a new requirement for sample heat treatment was introduced. Three of the ten mirror furnace samples were kept at a relatively constant temperature in the liquid state for about 1 min, and thereafter cooled to solidification. The purpose of this heat treatment was to study coalescence phenomena in immiscibility gap systems.

This constant temperature heat treatment necessitated modifications in the power control system shown in Fig. 8. The modifications involve removing the temperature hysterisis in the power interrupt circuit so that power is ap-

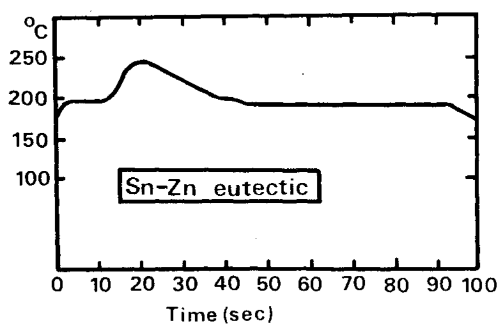

Fig. 7 In-flight temperature profile of a Sn-Zn sample flown in Texus 1.

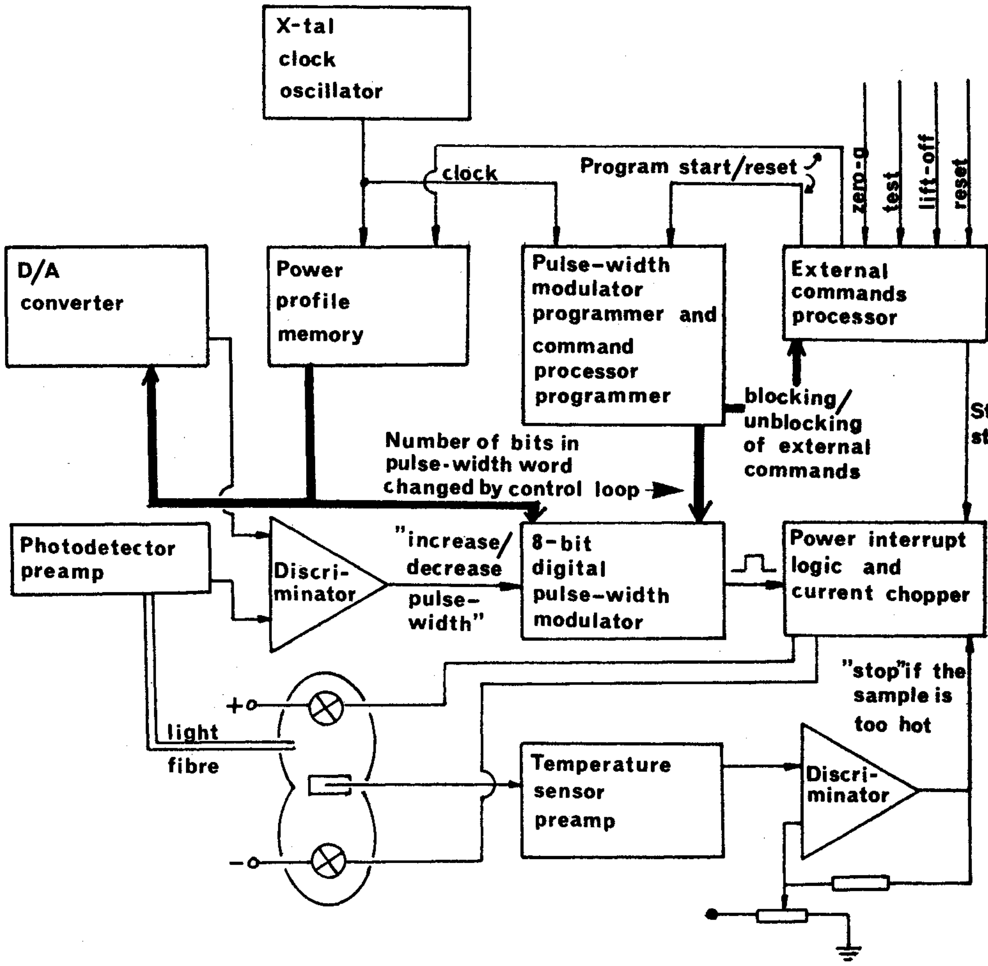

Fig. 8 Mirror furnace power control system.

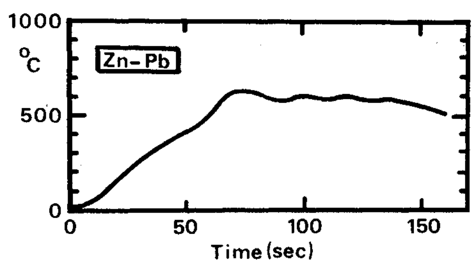

Fig. 9 In-flight temperature profile of a Zn-Pb sample flown in Texus 2.

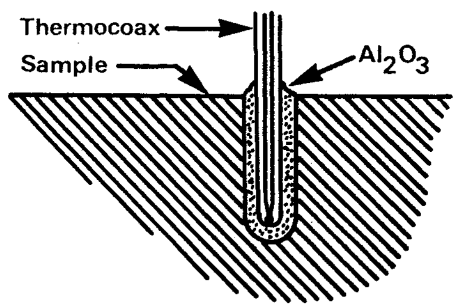

Fig. 10 Thermocouple arrangement in the sample.

plied to the lamps whenever the sample temperature drops below the desired value. To make the response of the system less sluggish, the lamp power levels applied to keep the sample above the desired temperature are considerably lower than the full power applied at the initial melting of the sample.

In this way, the unavoidable temperature oscillations can be reduced. However, the thermal inertia of the sample introduces a time constant in the control loop which tends to reduce the damping in the system. This can be avoided if the temperature at the surface of the sample, instead of the internal temperature, is used to steer the control loop. This modification will be introduced in future models of the mirror furnace. Figure 9 shows an example from the Texus 2 flight of a constant-temperature heat treatment. As can be seen from the graph, the sample temperature was kept within $\pm 12°C$ for ~ 60 s.

Sample Size

The maximum sample size is determined by the size of the furnace cavity and the thermal characteristics of the sample. For samples with melting points $\leq 900°C$, a practical upper limit for the sample size is 2 cm^3 shaped like a 20-mm-long × 12-mm-diam cylinder.

Pressure

The furnace cavity is normally evacuated in space, and the samples have to be designed with this in mind, but if necessary, the furnace can be made airtight and with a pressure at or above ground level pressure. In the present design, there are no provisions for filling the furnace cavity with an inert gas, but this is a possible future design improvement and could be incorporated if a serious need for it arises.

Temperature Measurement

The temperature of each sample is measured by means of a Thermocoax Chromel-Alumel thermocouple. Each mirror furnace is equipped with a low-drift chopper-stabilized

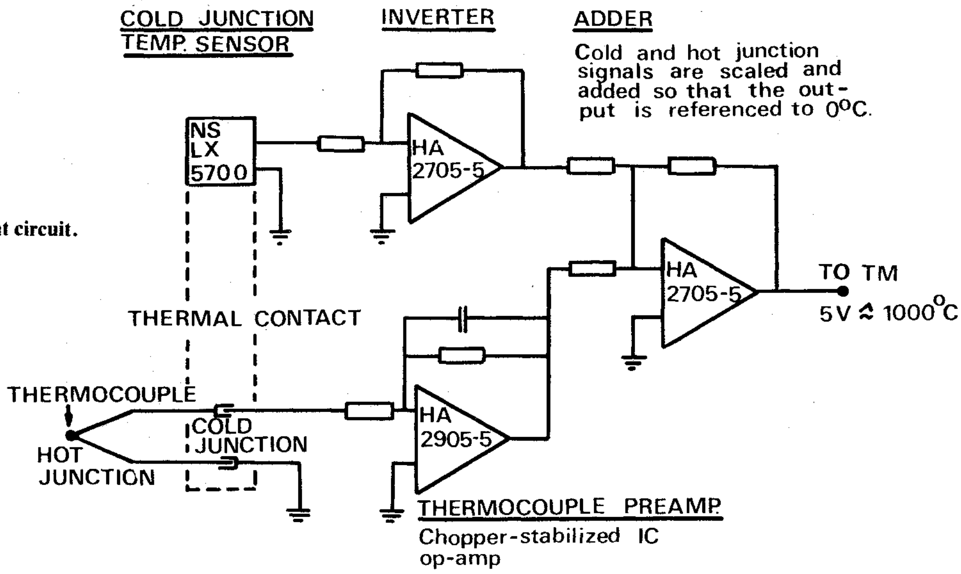

Fig. 11 Sample temperature measurement circuit.

preamplifier for amplifying the thermocouple signal. Before transmission to the ground by telemetry, the thermocouple signal is processed in an analog circuit so that the cold junction temperature is compensated for. This is done by adding to the hot junction signal a properly scaled signal corresponding to the cold junction temperature. The cold junction temperature signal is generated by a IC semiconductor thermometer.

Figure 11 shows a simplified diagram of the temperature measurement circuit. Preflight temperature calibrations of this circuit showed that an absolute accuracy of $\sim 2°C$ was achieved.

The thermocouple, which is of a "coaxial" type, is surrounded in the sample by a thin layer of aluminum oxide cement. This arrangement provides good thermal contact in vacuum between the sample and the thermocouple, and safety from contamination of the sample by the thermocouple stainless-steel cover. Figure 10 shows a magnified view of this arrangement.

Operating Sequence

All mirror furnace programmers are started at liftoff, but power is not applied to the lamps until micro-*g* conditions are attained. The furnaces are then operated in succession, one after the other. To save time, two furnaces can be melting their samples simultaneously. If more than two furnaces are melting their samples at the same time, the battery voltage will drop too much.

Table 2 Gradient furnace specifications

Characteristics	Specification
Heater type	Crusilite silicon-carbide ceramic helix (resistance $\approx 1.5\ \Omega$), or Kanthal wire wound directly on the boron nitride crucible, (resistance $\approx 1.2\ \Omega$).
Heater power	600-800 W
Heater and sample in sulation	Multilayer insulation, gold deposited on the inside and outside of four concentric quartz tubes.
Heat sink	Latent heat storage, $\approx 500\ cm^3$ of Merck paraffin, 69-73°C melting point.
Typical melting time	≈ 100 s (100-mm-long × 8-mm-diam Al-Cu sample)
Typical solidification rate	25 mm/min (100-mm-long × 8-mm-diam Al-Cu sample)
Two-furnace assembly	Size $\approx 180 \times 180$-mm cylinder
Two-furnace assembly	Mass 5 kg

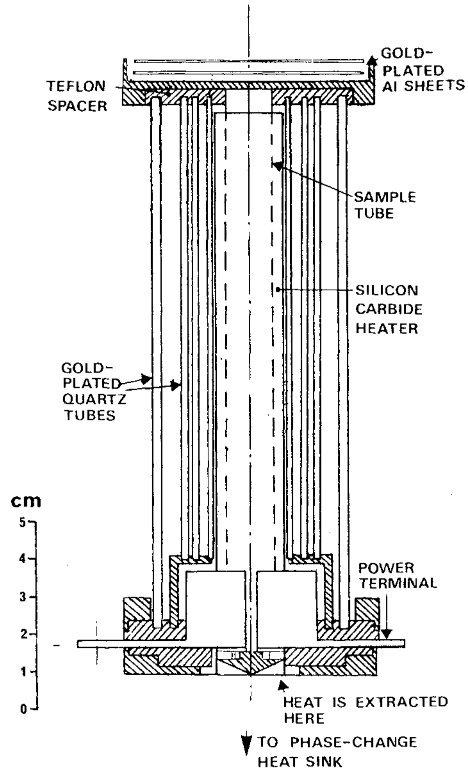

Fig. 12 Gradient furnace.

Gradient Furnace

This device is designed for studies of directional solidification of metal samples with melting points $\leq 1000°C$ and consists of: 1) a tubular, ceramic (Crusilite), resistive heating element inside which the cylindrical sample in its boron nitride crucible is placed; and 2) a phase-change heat sink which extracts heat from one end of the sample in order to get a nearly unidirectional solidification.

Figure 12 shows the main features of the furnace without heat sink and its specifications are given in Table 2.

Heating

Up to 600 W of electrical power is applied to the Crusilite heater to melt the sample rapidly. The dimensions of the sample, which is inclosed in for example boron nitride, are approximately 6-mm in diam and 8-cm long. The period between application of heater power and complete melting of an Al-Cu sample with these dimensions is less than about 100 s. The heater and sample is insulated by a multilayer reflective insulation system which uses gold films deposited on quartz tube substrates.

For Texus 2, one of the two furnaces was equipped with a different heater. The Crusilite heater was found to require too long a time to melt a Cu-Pb sample, and was replaced by a more compact Kanthal wire wound directly on the outside of the crucible.

Cooling

When the heater power is turned off, the heat balance of the sample is determined mainly by the extraction of heat through one of the samples into the phase-change heat sink. This heat sink consists of a container filled with solid paraffin. (A paraffin with a melting point at 69-73°C has been chosen.) Heat from the sample enters the heat sink via copper heat conductors and is converted into latent heat as the paraffin starts to melt around the conductors. The unidirectional extraction of heat from the sample will result in a solidification of the sample starting from one end. The solidification time of the previously mentioned Al-Cu sample is approximately 3 min.

Power Programmer

The power programmer for the gradient furnace simply applies and removes voltage to the Crusilite heater at predetermined instances. If the sample has melted before the programmed "off" command is given, power is interrupted. Melting of the complete sample is monitored by the temperature sensor nearest the heat sink. The signal from this sensor is compared in a discriminator with a present value, and an "off" command is given if the temperature exceeds this value.

A short "test" heating program can be run while the payload is being tested before launch. This test program is a short 10-s heating period which raises the sample temperature by only ~200°C. Figure 13 shows a block diagram of the power programmer.

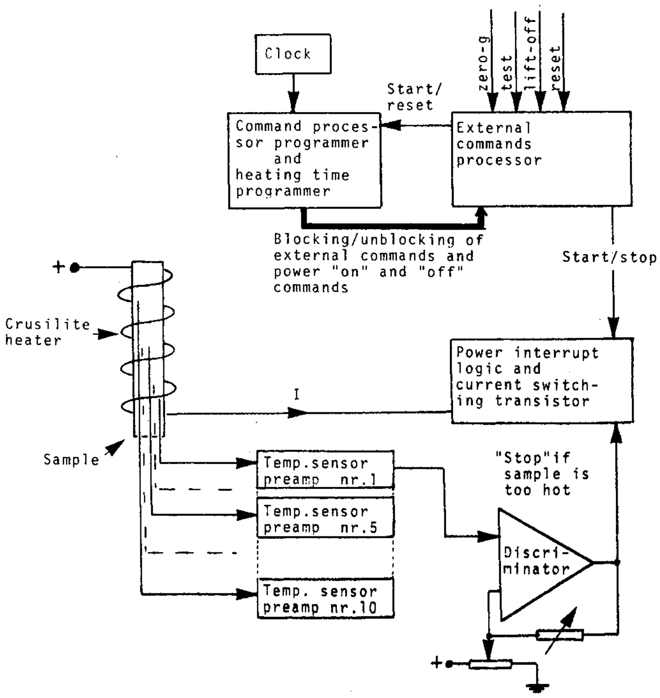

Fig. 13 Gradient furnace programmer.

Temperature Measurements

Thermocouple amplifiers for up to 10 measuring points are available for each gradient furnace. The design of these amplifiers is identical to the mirror furnace thermocouple amplifiers. In the first flight temperatures at five points in the middle of the sample and five points at the outside of the sample were measured in order to monitor the position of the solidification front.

Operating Sequence

Because of the rather long melting time for the samples in the gradient furnace, the heating of the samples starts at liftoff. As the rocket rapidly ascends, the air is evacuated from the furnace by venting, and heat losses from the furnace are eliminated by convection. The samples melt approximately 90 s after liftoff well into the micro-*g* period of the flight which nominally starts at T + 77 s. Power is cut from the gradient furnaces either when an indication of complete melting is received by the control circuit or when the programmer issues the "off" command. When the gradient furnaces are "off," the use of the battery power supply is taken over by the mirror furnaces.

Data Management

Sixty-four telemetry channels are available to the experiment module and are used to monitor 1) 30 sample temperatures (1 in each mirror furnace and 10 in each gradient furnace), 2) 12 cold junction temperatures (1 in each mirror furnace and 2 in each gradient furnace), and 3) 22 housekeeping data points.

All TM channels are sampled at a rate of 4.3 Hz and represented by ten bit words. The signals from all data points are fed in analog (0-5 V) form to a redundant pulse code modulation (PCM) subencoder in the experiment module. This subencoder transfers data to the instrumentation module under control from the main encoder.

Power Supply System

Power for heating the samples and for powering all electronics is delivered by the same source, a silver-zinc battery for each of the redundant halves of the module. In each instrumentation subsystem where battery power is used, ripple caused by the furnace current chopping is removed by series regulators. Dc-dc converters for providing balanced voltages are not used because each battery pack delivers a balanced voltage.

Each battery pack consists of 28 silver-zinc cells and delivers approximately ±17-18 V when the greatest load, a gradient furnace heater, is applied. The silver-zinc cell type chosen for the battery pack is SAFT SOGEA 5AGD, a 5-A-h cell selected primarily because of its rugged mechanical construction and high tolerance to heavy overloads.

To save weight and space in the module, it was decided not to use a sealed box for the battery pack, but rather an open frame-type structure. A venting system, using a thin polyethylene tube connecting each cell to two redundant safety valves, was installed to release the pressure built up by the unavoidable outgassing in this type of cell. The valves were designed to close at a differential pressure of 0.6 bar, which is sufficient to avoid boiling in the electrolyte even after applying a 25-A load for 15 min.

Flight Test Results

The experiment module has been flown twice: on Dec. 13, 1977 and Nov. 16, 1978. Both flights were launched by Skylark 7 rockets from Esrange, Sweden, and reached about 260-km altitude. During the exoatmospheric portion of the flights, the rate control system achieved micro-*g* levels below $10^{-4}g$ for periods up to about 360 s.

After both flights, the payload was recovered in such an excellent condition that the module can be reflown after minor repair work.

Both the gradient and mirror furnaces have worked well during the flights. A total of nine technically perfect mirror furnace samples and at least three gradient furnace samples have been obtained. During the first flight, some anomalies were experienced which were successfully corrected for in the second flight. Thus, there was a leak in the crucible of one gradient furnace during the first flight.

Through this leak, liquid metal was drawn by capillary forces. This caused a temporary short across the silicon-carbide heater which in its turn caused a deep voltage drop in the side A battery. This voltage drop had the effect that the samples in the side A mirror furnace did not reach their target temperatures. However, some samples melted partially and are therefore still interesting. On the B side of the module, four of five mirror furnaces operated during flight. Two samples did melt, one only partially. The other two came very close to melting, but the time margins for the melting time programmed into the furnace programmers were obviously too narrow. This was corrected in the second flight by allowing a longer time for each sample to melt.

Eight fully successful mirror furnace sample heat treatments were therefore achieved during the second flight, including a unique series of four Zn-Bi immiscibility gap alloy samples. In these samples, a fine dispersion of Bi particles in the Zn matrix was achieved. Such a structure cannot be made in 1-*g* conditions with similar heat treatment.

Scientific results from the Texus 1 and 2 missions can be found in Refs. 4-6.

References

[1] Franke, B. and Geisel, I., "Design and Performance of the Texus 1 Materials Science Payload," *Zeitschrift für Flugwissehschaft and Weltraum forschung,* Vol. 2, No. 5, 1978, pp. 329-337.

[2] Bredt, J. and Montgomery, B., "Materials Processing in Space-A Challenge to Industry," *Astronautics & Aeronautics,* May 1975, pp. 22-41.

[3] Fredriksson, H., "Possible Dendrite Growth and Segregation Phenomena during Solidification of Alloys in Space," *Proceedings of the Second European Symposium on Materials Sciences in Space,* European Space Agency, SP-114, Sept. 1976, pp. 291-299.

[4] Carlberg, T., Fredriksson, H., Sunnerkranz, P., Grahn, S., and Stenmark, L., "The Swedish Texus Experiment - A Technical Description and Some Preliminary Results," *Proceedings of the Symposium on European Sounding Rocket Research,* European Space Agency, SP-135, June 1978, pp. 325-338.

[5] Carlberg, T., "Solidification of Some Eutectic Alloys under Microgravity Conditions and at 1-g," *Proceedings of the Third European Symposium on Materials Science in Space,* European Space Agency, SP-142, June 1979, pp. 221-231.

[6] Carlberg, T. and Fredriksson, H., "The Influence of Microgravity on the Structure of Bi-Zn Immiscible Alloys," *Proceedings of the Third European Symposium on Materials Science in Space,* European Space Agency, SP-142, June 1979, pp. 233-243.