ULTRALIGHT REACTIVE METAL FOAMS PRODUCED AS STRUCTURAL SHAPES IN SPACE: SYSTEM DESIGN

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Introduction. A series of studies both inside and outside of NASA have concluded that the production of foamed metals is an important space-manufacturing possibility (1-6). It is possible to produce foamed metals on earth by a variety of powder metallurgical and other methods (7-10); therefore it is unlikely that it would be economical to produce structural foamed metals in space and then return them to earth for actual use. Produced in space for use in space, however, foamed metals can have very significant structural advantages (11). In the absence of substantially all air and water vapor (although traces of active gases are present in near earth orbits) it is possible to use ultralight reactive metals such as Mg-Li alloys of high lithium content, whose use on earth in structural applications is precluded. The use of such alloys would enable extremely light (0.1 g/cc) foams to be produced. By foaming such materials in orbit into useful shapes such as I-beams, earth based handling is made very much easier. Substantial studies are currently underway to investigate the mechanical fabrication of trusses and triangular beams in orbit from solid, non-foamed materials but there appears to have been little or no effort directed to the *in situ* production of structural members by foaming methods. Certainly there has been no work done involving the use of ultra-light alloys. As large scale space engineering projects are considered, the stiffness, strength, and density of the materials chosen becomes of increasing importance and ultra-light reactive foams produced as structural shapes in space may well offer significant engineering advantages, particularly for satellite armour applications. In the following sections we describe our GAS payload design, which is designed to produce I-beam shapes of Al-Mg-Zn, Mg-Al, and Mg-Al-Li-Ca alloys.

Systems and Subsystems: Experiment Design

The Duke-Omni GAS 286 payload dimensions are 2.5 cubic feet and 60 pounds. Engineering is constrained by NASA safety guidelines and regulations as outlined in NHB 1700-7A (Safety Policy and Requirements for Payloads Using the Space Transportation System) and the GAS Safety Manual. Implementation of the experiment was also heavily constrained by the expected storage lifetime before launch of the sealed experiment (approximately 90 days). This long storage time precludes the use of Ni-Cd batteries whose self discharge rates approach 1-3 % per day.

This autonomous experiment for foaming metals in space involved (a) payload support structure; (b) furnace and foaming apparatus; (c) electronic controls; (d) battery power; and (e) metallurgy. Emphasis was laid on a modular design which was easily modifiable and which offered maximum durability, safety, and failure tolerance.

Payload Support Structure. This design primarily requires a skeleton with a high strength-to-weight ratio capable of withstanding a 10 g acceleration along the axis of the payload and a 6 g acceleration transverse to this axis, as might be experienced in an emergency landing. The ultimate factor of safety should be at least 1.5 if verified by test or 2.0 if verified by analysis. Our payload has a f.s. of greater than 2.0 verified by mechanical tests.

Figure 1 shows an overview of the basic payload support structure. The payload pallet plate is held to the NASA top-plate by sixteen steel bolts extending through individual thermal stand-off washers. Lateral support at the top-plate end is accomplished with eight bumper assemblies.

The design of the bumpers is shown in Figure 2. This design consists of a 6061-T6 aluminum bracket, one side of which is bolted to the Duke "bottom-plate." The bolt which drives the bumper plate has a rotatable foot of the type used in C-clamps, attached using silver-solder to the steel bumper plate. This plate is four square inches in area and has a ten inch radius of curvature to conform to the walls of the cylinder. The surface of the plate is covered with a sheet of Viton, an extended temperature range synthetic rubber.

The primary load-carrying structure consists of two 1/4" end or pallet plates held 8 inches apart by

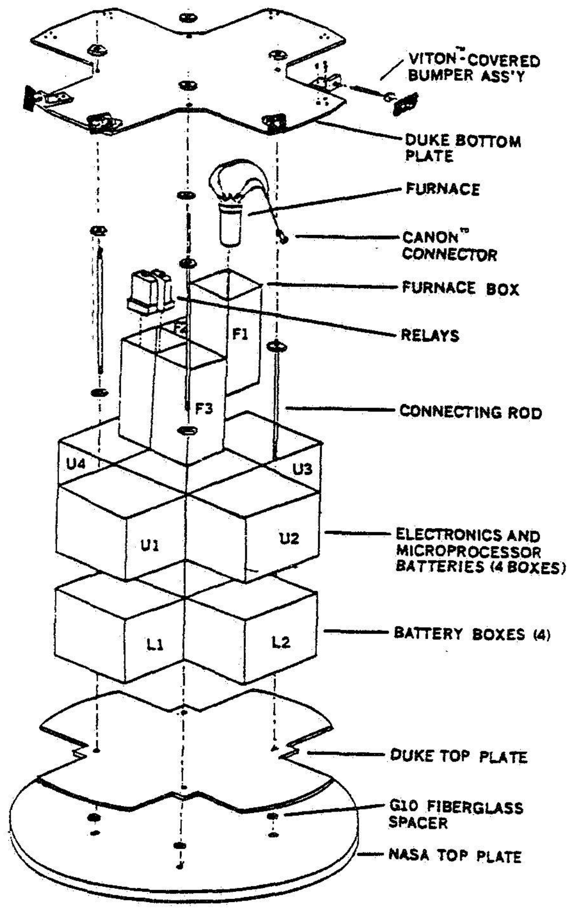

Figure 1. Support structure, exploded view.
U = Microprocessor System.
L = Furnace Power Batteries.
F = Furnace Housings.

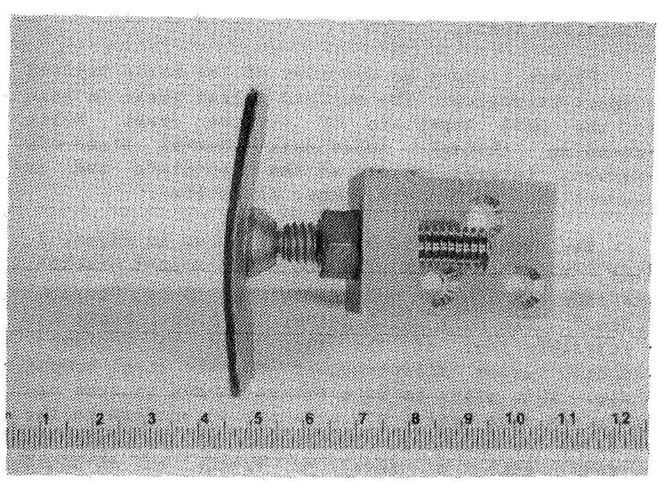

Figure 2. Bumper, top view. Scale in cm.

four 3/8" rods and eight 1/2"x1/2" corner brackets, all machined out of 6061-T4 aluminum. This alloy in this temper is very resistant to stress corrosion cracking. Twelve type 1100 aluminum sheet metal boxes are fastened between the plates, each box containing a separate subsystem. This use of multiple boxes allows for a modular and flexible design. All electrical interconnections between boxes were realized using Canon mil. spec. connectors.

As stated, the Duke top-plate is fastened to the NASA-provided top-plate by sixteen steel bolts. The use of our own top-plate allows us to transfer the entire assembly to the final launch container intact and as a single unit. In order to minimize the response of the payload to temperature changes on the outside of the canister, the Duke top-plate is separated from the NASA-provided top-plate using 3/8" thick thermal stand-offs 1/2" in diameter made of G-10 (a phenolic material impregnated with glass fibers). The final structure is covered with a foil designed to minimize the emissivity of the payload, thereby minimizing the radiation heat transfer from the payload to the cannister. The foil chosen is type #852 aluminum on Mylar (with acrylic adhesive) purchased from the 3M Company. The use of thermal stand-offs and reflective coatings is critically important if excessively low payload temperatures are to be avoided.

Alloy steel fasteners were used in all cases due to their high strength. Lockwashers were used liberally to prevent vibration from loosening connections.

Battery Power. Temperature considerations play a key role in determining the design of the experiment. The primary problem is the fact that a fully charged battery contains progressively less usable energy as the temperature of the cell drops. Thus in the worst case, where the shuttle tail is pointing to the sun, the bay area is radiating into deep space. The equilibrium temperature for the batteries in this flight attitude would be -100 C (see GAS Thermal Design Summary, X-732-83-8). This is unacceptable for any choice of batteries. A well insulated payload requires a relatively long time (several days) to approach such temperatures.

Many different types of batteries were considered for use, including Ni-Cd cells and primary (non-rechargeable) cells. Gates sealed rechargeable lead-acid D-cell (2 volt) sized batteries (Gates Energy Products, Denver, Colorado) were chosen for their ability to supply high (2 amp) current rates at low (-40 C) temperatures, their lack of free electrolyte, and their sealed nature. Even though sealed, they will still release significant hydrogen especially after charging but will not release oxygen. Such D cells have a capacity of 18,000 joules per cell fully charged (room temperature), as well as acceptable operation when cooled down to -40 C. The D-Cells were relatively easy to mount into boxes, and are provided with plus-and-minus tabs on the same side of the cell; the latter feature proved to be a great advantage mechanically over the typical flashlight battery design, because lug terminals could be used to make all electrical connections.

Each furnace requires roughly 50,000 joules of energy, including heat lost to the environment, to reach approximately 650 C. Because the payload may sit on the orbiter up to 90 days, the cells are assumed to be only 3/4 charged by the time of lift off. In addition, because the experiment may be run at very low temperature, the remaining available energy within each cell is assumed further cut in half, leaving a state of about 35 % charge or roughly 5000 joules per battery. With this rationale we have allotted 18 batteries for each of three experiments for a total of 54 cells. The furnace requires twelve volts, allowing each set of 18 to be composed of three stacks of six connected in parallel. Each stack of six is diode protected (two 2.5 amp diodes in parallel) to prevent a stronger stack from recharging a lower voltage stack, thus preventing the consequent release of hydrogen gas. Each set of 18 uses a 10 amp fuse in line in case of an electrical short. As a result, roughly 90,000 joules is provided for each 50,000 joule experiment. With this excess capacity, the experiment should still function even with the failure of one stack of six batteries, as might occur with the failure of a single cell.

The battery housing is shown in Figure 3. Twelve batteries per box are allotted to 4"x5"x6" boxes. Thus four and one-half boxes are required for the lead acid batteries. Batteries are held by right-handed and left-handed "S-curves" (upper and lower, respectively), plus a template in the middle. The batteries rest on a fiberglass mat on the box bottom, and are held on top by an aluminum retainer bar.

All aluminum parts within the battery boxes are coated with PT-201 Epoxy Resin coating. This paint is designed to resist highly corrosive environments. PT-201 is NASA-approved, provided a bake out at 360 F for 1 hour is used to remove volatiles (Products/Techniques, Inc., Los Angeles, California). Between the batteries and the box bottom we have placed 2-ply fiberglass cloth for additional thermal insulation (Aircraft Spruce & Specialty Co., Fullerton, CA). The interstices of the batteries are filled with fiberglass-covered acid-absorbing pillows which contain sodium silicate

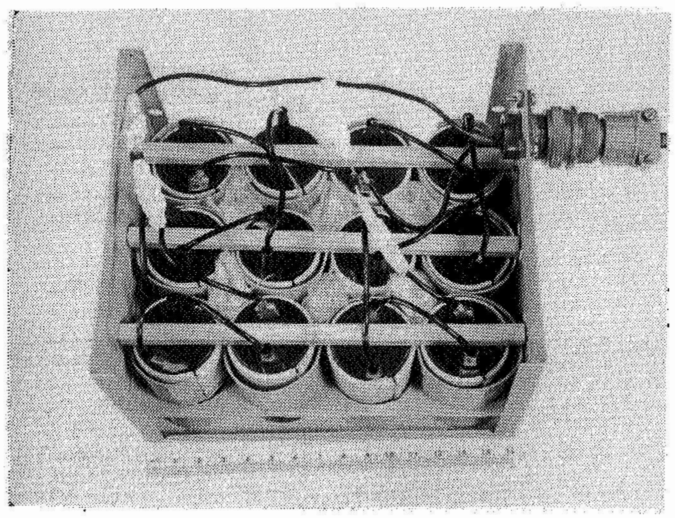

Figure 3. Housing for 12 lead-acid batteries, top view. Diodes in white, placed in line with battery stacks of six. Scale in cm.

to absorb any possible spillage even though those batteries normally do not contain free electrolyte.

Electronics and Controls. This payload utilizes industrial and military (rather than commercial) components wherever possible, together with back-up systems where appropriate. The overall electrical schematic is shown in Figure 4.

Two completely independent systems were employed in order to decrease the severity of a single component failure. A dedicated microprocessor, described below, was used for measurement of temperature change and control of two of the furnaces, utilizing 36 batteries. Such temperature measurements allow for flexible controls in order to get the most out of batteries performing at low temperatures; but this advantage must be weighed against an increased chance for control failure. Therefore a second, relay-controlled system was employed to run the third furnace. This second system is composed of two mechanical relays (R13 and R14) and controls 18 batteries. The basic relay system is considered highly reliable but takes no account of temperature. As a result, furnace 3 runs immediately upon payload activation.

In order to prevent the batteries from being drained to exhaustion in the event of a microprocessor or other failure, all power to the furnaces flows through voltage sensitive relays (R4 and R13) which open the circuit if battery voltage drops below 9.5 volts (5 % of battery power remaining). Additionally, timed relays (R11, R12, and R14) are used in line with each furnace so that total heating time can be controlled to fixed lengths (typically 10 minutes). (Relays R11 and R12 are redundant when the microprocessor is functioning correctly.)

The microprocessor controls the heating sequence for furnaces F1 and F2. Its internal design is described under a separate heading. Furnace F1 is activated by causing output line H1 to go high. This activates the power bus (relay R4) through relay R2; output H1 also causes relays R6 and R9 to close, therefore sending power to the furnace coils. The microprocessor sends output H1 low again after either 10 or 15 minutes, thereby shutting off the furnace. After allowing the lead acid batteries to recover (1/2 hour), furnace F2 is activated in a similar fashion. Power is not put to the coils on voltage sensing relay R4 until power is to be run to furnace F1 or F2, in order to conserve energy.

In order to reduce the severity of a microprocessor failure, a relay-based by-pass system was integrated into the microprocessor controls. Bypass is accomplished by programming the microprocessor to store two binary bits of data upon power-up in special output port positions. If an incorrect value is stored in either of those positions, the back-up system begins its sequence; otherwise the microprocessor is assumed to be working and the relay bypass will be held inactive by holding the FAIL line high. If the "not fail" line in Figure 4 stays low, the bypass system engages. First, power is sent to furnace F2 through relays R10 and R12; R12 opens this circuit after 10 minutes. As the bypass system engages, power is also put to delay relay R8, which closes after 2 hours to put power to furnace F1; relay R11 opens

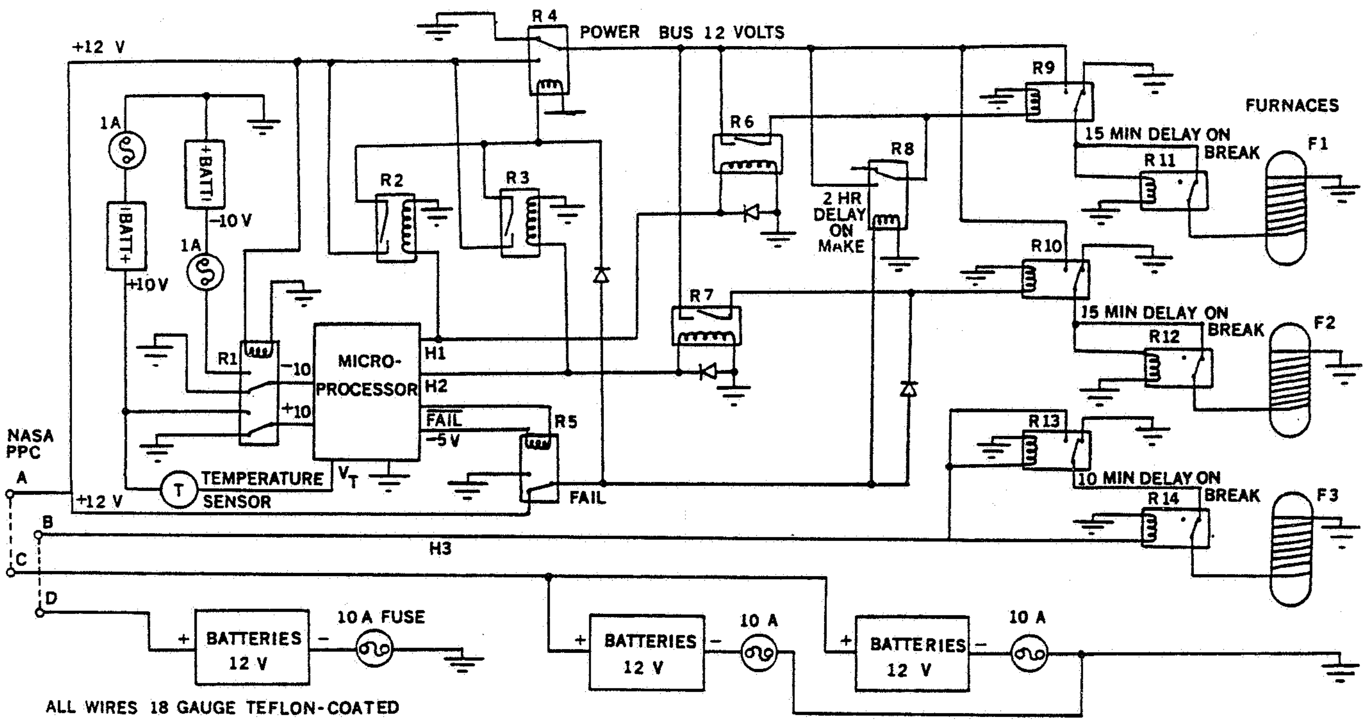

Figure 4. Overall electrical schematic, including furnaces. R3, R4, R6, and R7 are reed relays. R5 is low current bypass activation relay. R1 is low current microprocessor activation relay.

this circuit after 12 minutes. Delay relay R8 allows for battery recovery in the interval between running furnace F1 and furnace F2.

Furnaces and Foaming Apparatus. In order to melt the alloys, vacuum furnace assemblies had to be built which could reach at least 650 C. Nickel-chromium resistance heating wire (ribbon) having 1.3 ohms/ft was used. A schematic showing the vacuum furnace assembly is shown in Figure 5. Furnaces were sized to draw about 7 amps and to reach 650 C in approximately 8 minutes.

The actual alloy samples are pellets of approximately 1cc volume placed inside glass I-beam shaped channels; quartz glass was used for its high-temperature durability. Around the quartz was wrapped the heating wire, which was itself encased in a 3/8" layer of furnace cement (#33 from Sauereisen Cements Co., Pittsburgh) in order to protect the coils and to increase the thermal efficiency of the furnace. This unit was then wrapped in Kaowool, an asbestos-free high-temperature fibrous material to act as a mechanical support as well as thermal insulation. At this point it was necessary to place the assembly inside a Pyrex ampoule which could be evacuated in order to insure non-oxidizing conditions during melting. Ampoules are hermetically sealed with Vac-Seal (Perkin-Elmer Vacuum Products, Eden Prarie, Minn.), a very low vapor pressure epoxy. The ampoule is then enclosed in its own 3"x3"x8" aluminum box, and

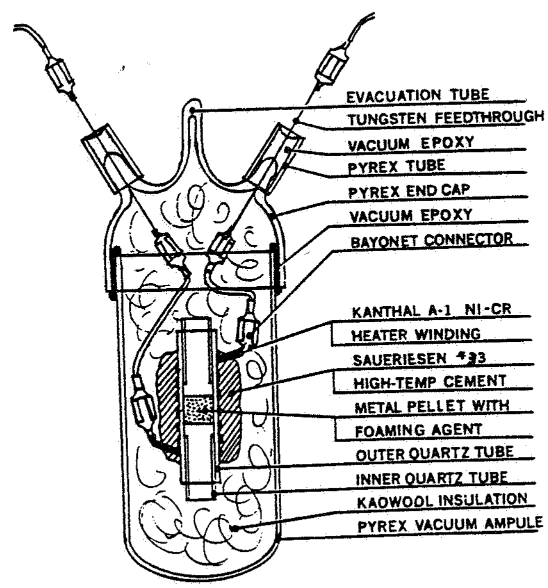

Figure 5. Furnace design, cross-section.

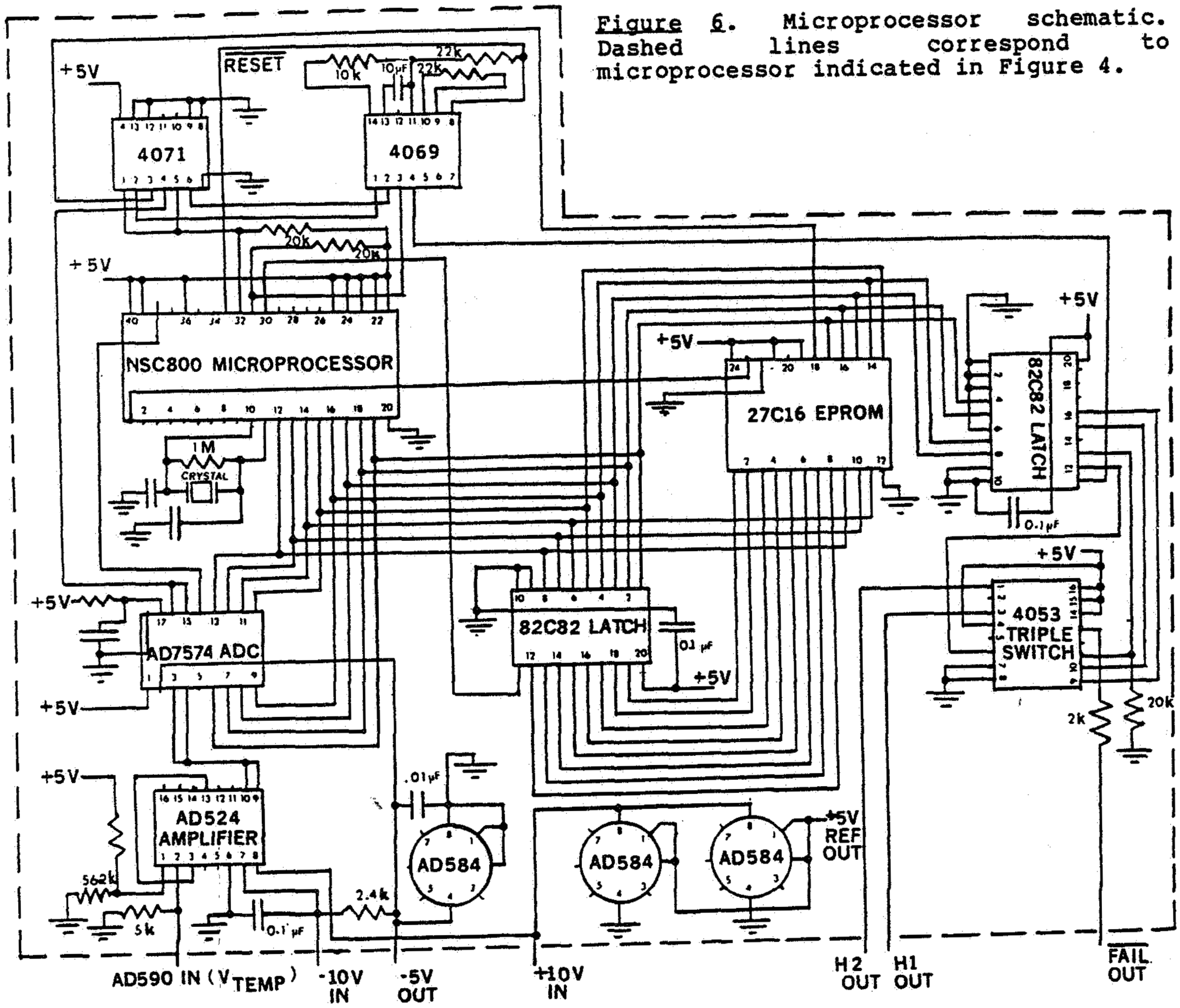

Figure 6. Microprocessor schematic. Dashed lines correspond to microprocessor indicated in Figure 4.

packed with additional Kaowool. Because the battery voltage drops as a function of operating time, the furnaces consistently peak in temperature after 7-8 minutes at approximately *650* C, so that even if power is never shut off these maximum temperatures are not exceeded.

Metallurgy. To cause foaming, magnesium carbonate or manganese carbonate was mixed into the alloys while they were held near their eutectic temperatures (about 433 C). This mixture of alloy and carbonate was then cast by asperation into a borosilicate glass tube to form the desired pellet. Foaming does not occur until the pellet is remelted and heated to over *500* C. Decomposable hydrides were not used due to the possible difficulties associated with the resulting hydrogen gas. Pellets and furnace ampoules were sized so that one atmosphere pressures inside the ampoules were not produced.

The Microcomputer

Having allocated approximately half the weight of the GAS canister to the batteries needed for the experiment, it is not feasible to consider additional batteries for use in warming the entire payload. Instead, a microcomputer system controls furnaces F1 and F2 based on the measured battery temperatures. Power-up on the microcomputer occurs when the PPC switch is closed, thereby closing relay R1 (figure 1).

The control system schematic is shown in Figure 4. This microcomputer could be viewed as a general purpose, compact, low cost, low power, dedicated, programmable controller for space applications. Sufficient detail is provided so that the reconstruction of this microcomputer by other GAS groups should be straight forward. It is flexible and general enough to recieve a multitude of electrical inputs (e.g. accelerations, pressures, displacements), as well as generate several types of electro-mechanical outputs (such as control of servo-motors, valves, and tape recorders) through expanded use of the I/O ports available.

Hardware. Figure 6 details the hardware layout of the microcomputer. A temperature sensor sends an analog signal to the Temperature Sensor Interfacing components. These components amplify and bias the temperature signal and convert it into an eight bit digital signal. This digital signal is sent to the microprocessor via an eight bit data bus. The data bus also receives data from one EPROM memory chip. This data is accessed by a nine bit address bus. Four bits of the data bus are used to send signals to the Relay Interfacing components. These components control the activation of the power relays that switch power to the furnaces. Control signals, generated by simple logic gates, control the activation of the input port, the output port and the EPROM.

The main components of the microcomputer are a National Semiconductor NSC800 CMOS microprocessor and 27C16 CMOS EPROM memory chip. These IC's consume very little power, a great advantage since the microcomputer will need to operate for up to 27 hours. The microcomputer control system requires only 15 mA at +7.5 to + 20 volts and 4.0 mA at -7.5 to -20 volts. The power is implemented through the use of one and one half pounds of alkaline batteries that are rated at ten times the required capacity (so that continuous power for 27 hours is insured even at -40 C). Initially, the microcomputer batteries will supply the control system with +12 V and -15 V. However, during the course of the 27 hours in which the payload is activated, the supply voltages may drop to values as low as +8.5 V and -8.5 V (depending on the cargo bay temperatures and on the initial charge state of the batteries). For convenience, the microcomputer power supply voltages are labeled in all figures in this report as +10 V and -10 V.

Since all digital logic is based on mil. spec. voltage references (Analog Devices AD584's) which have a minimum supply voltage of 7.5 V, functional operation is insured for the entire expected range of the power supply voltages. In addition, these microprocessor components offer the following advantages:

(1) They have ample memory and I/O addressing capabilities.

(2) They have more than adequate speed. (the maximum expected rate of temperature change of the contents of the GAS canister is about 1.5 C per hour.)

(3) There is ample literature, software, and hardware support for these and similar components available.

(4) Industrial specification versions (operating at temperatures down to -40 C) of these chips are available at reasonable costs with short delivery times. Although military versions of these and other components are avilable with operating temperature ranges extending to -55 C, the high cost and long delivery times of these components made them infeasible.

The NCS800 microprocessor is operated with a 102 kHz crystal. This small frequency is employed in order to conserve power. One Harris Corporation 82C82 CMOS latch serves as a demultiplexer for the microprocessor's multiplexed address/data bus. The 4071 and 4069 chips are CMOS logic gates used for debouncing the RESET IN signal and generating simple control signals.

Temperature Sensing. The main component of the temperature sensing apparatus is an Analog Devices AD590 temperature transducer that is located in the power battery stack. This device produces a current that is directly proportional to the temperature of the power battery stack in degrees Kelvin. Since each degree K corresponds to 1 micro-amp, passing this current through a 5 K resistor causes the voltage across this resistor to vary 5 mV per K. This voltage is input to an instrumentation amplifier that is biased by 1.050 V on its inverted input. The output of this amplifier is input to an Analog Devices AD7574 analog to digital converter with a -5V reference. The resulting eight bit digital output covers a range from -63 C to +37 C, thereby extending well outside the expected temperature extremes. The accuracy, both theoretical and experimental, is within 1 degree C.

Analog to digital conversion is initiated by any I/O read. This will cause the AD7574's BUSY pin to go low, forcing the microprocessor's WAIT pin low and generating a NCS800 wait state. Since the AD7574 has a tri-state microprocessor compatable output, the digital output of the ADC is connected directly to the NSC800's data bus. The use of a high impedence device such as an instrumentation amplifier is essential because the analog to digital converter has a relatively low input impedence that is sensitive to temperature.

Relay Control Interfacing. All of the relay control signals are latched from the NSC800 data bus by an 82C82 eight bit latch. Since this is the only output port and since no RAMs are used, the microcomputer will write to this port exclusively. The output signals of this latch are buffered by a 4053 CMOS triple switch that drives four Magnecraft W107DIP-2 reed d.i.p. relays. These reed relays switch the 150 mA necessary to drive the coils of the power latching relays that supply 6 A to the furnaces.

Software. The microprocessor control system has two primary functions:

1. To activate furnaces F1 and F2 for a temperature dependent amount of time in a sequential manner with a 1/2 hour pause in between to allow for battery recovery.

2. To begin this heating sequence at an optimum time.

The first primary function presents no problem; the second one depends upon relative changes in payload temperatures and therefore requires temperature sensing as well as calculations of temperature gradient.

The rated capacity of the batteries is attained at approximately 25 C, and the available energy drops off markedly at temperatures below 0 C. Tests indicate that at temperatures below -19 C, the batteries may not have enough capacity to heat the furnaces to over 600 C.

According to the GAS Thermal Design Summary, internal temperatures are estimated at between -20 C and 0 C for most of the mission (assuming the payload is properly insulated). Two criteria are used for establishing the optimum time to activate the heating sequence: First the temperature must be above -19 C and second it must be falling. In this way if the experiment is activated when the top of the shuttle is facing the sun, the microcomputer will wait until the maximum temperature is reached (and the batteries will attain maximum capacity) before it activates the furnaces. If after 12 hours the temperature remains below -19 C, a low temperature heating sequence is activated unconditionally. This low temperature sequence applies power to the first furnace (F1) for a longer time than in the normal sequence in the hope that at least one alloy will receive enough energy to properly melt.

Upon astronaut activation of the experiment, the control system will first set all the relay outputs to a logic level zero. At the same time it will set the "not fail" line high, disengaging the bypass system. Next the microprocessor system will begin sampling the temperature. The microprocessor receives temperature information in the form of an eight bit binary number, TNEW. If TNEW is less than 0 F, then the microprocessor will continue to monitor the temperature until either TNEW rises above 0 F or until 12 hours elapse, causing activation of the low temperature heating sequence. This sequence consists of battery power being supplied to the first furnace for 9.5 minutes, a 30 minute pause and then battery power diverted to the second furnace for 13 minutes.

If, however, the temperature does rise above 0 F during the first 12 hours of activation, the control system will seek the maximum temperature. The microprocessor looks for a significant temperature drop as its indication that temperature has peaked. While the temperature is rising, the current temperature (TNEW) is continually stored in a register and referred to as TOLD. While the temperature is falling, TNEW is compared with TOLD (the maximum temperature thus far). If TNEW drops below TOLD by more than 3 degrees F, or if at any time TNEW rises above 19 C, or if the temperature continues to rise or remain steady for a period of 12.5 hours, the high temperature heating sequence is carried out. This sequence consists of power being supplied to the first furnace for 8.5 minutes, a 30 minute pause and then power is switched to the second furnace for 10 minutes.

The program was written in Intel 8080 assembler pneumonics and hand assembled into machine language. It occupies 218 bytes of ROM and requires no RAM.

Conclusion

The intent of this project is to demonstrate that ultralight, reactive metal foams can be produced directly as structural, I-beam shapes in a zero gravity environment. The design of the payload needed to accomplish this goal is given in detail. A lightweight computer that may be useful in other GAS payloads is also described in sufficient detail that its duplication by other interested groups should be straightforward.

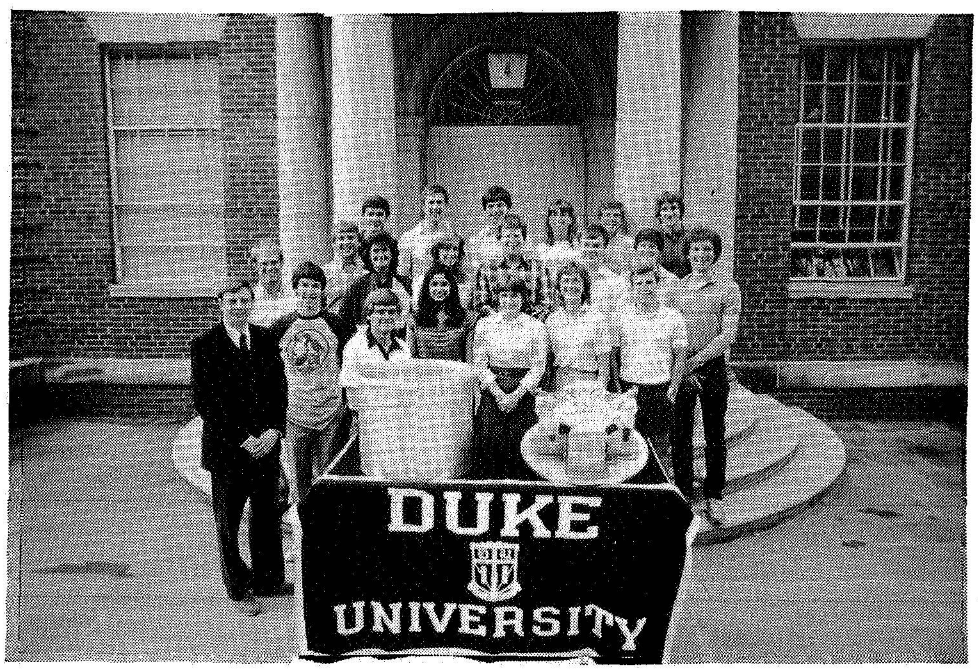

Figure 7. GAS 286 design team. Payload is displayed on table.

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