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Development and Operation of a Microgravity Furnace System for Sintering Experiments

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Microgravity experiments have been performed aboard STS-57, STS-60, and STS-63 with an isothermal high-temperature automated furnace. The equipment for controlled liquid phase sintering experiments-SPACEHAB variant facility was used to conduct powder metallurgy experiments on compacts at temperatures exceeding 1100°C. An overview of the evolution of the program from a laboratory mock-up through four sounding rocket flights is presented, including a description of the hardware that successfully operated during three Space Shuttle missions. These accomplishments were traced directly to the decisions made and numerous lessons learned throughout the applied research program. Development of the hardware required an extremely interdisciplinary approach. A continuous path of upgrades was pursued between flights, increasing capabilities while reducing payload mass and volume. This evolutionary experience base resulted in significant cost and schedule savings. The design features of containment and redundancy with the proven flight performance data minimized expensive component testing and analysis. The hardware was designed with inherent growth capabilities to maximize safety, to promote long-term usage/future flight opportunities, and to simplify on-orbit operations. The next-generation design scheduled to fly aboard STS-79 (August 1996) also is described.

Introduction

ONE of the primary goals of the NASA and industry-sponsored Consortium for Materials Development in Space (CMDS) at the University of Alabama in Huntsville (UAH) has been the investigation of materials processing in low gravity, where the potential for commercial applications has been identified. Fundamental phenomena can be clarified based on the knowledge gained by experiments in space and on the ground. Additionally, the development of operational concepts as well as designing, fabricating, and flight-qualifying hardware creates the infrastructure for future missions and discoveries.

Liquid-phase sintering (LPS) is an important powder metallurgy technique with widespread application in fabrication of both metallic and ceramic materials.[1,2] Sintering is defined as a phenomenon that occurs when compacted powders bond together by diffusion at temperatures below the complete liquefaction state of the material system. Sintering to fully dense parts frequently is aided by applying pressure in a special high-temperature press.[3] This process is slow and expensive. An alternative way to speed sintering is to add a portion of powder that melts at a lower temperature (minority phase) and surrounds the powders that remain solid (majority phase).[4] Thus, LPS occurs when a liquid phase coexists with a particle solid during some part of the thermal cycle. LPS materials consist of interconnected crystalline grains in a homogeneous matrix phase that liquefies at elevated temperatures.[5] This liquid lets particles and materials move more easily, allowing the powders to more rapidly form a solid compact. The process saves both time and energy and has been adopted by industry worldwide. Broad uses today include the manufacturing of extremely hard cutting tools, structural materials, irregularly shaped mechanical parts for high-stress environments, radiation shields for transporting radioactive materials, armor-piercing projectiles, automotive transmission gears, magnetic materials, oil-less bearings, and possible new and improved catalysts for chemical production.[2–6]

In spite of the widespread industrial applications of LPS materials, there are problems with compact slumping, distortion, and defect inclusion. Densification during LPS initially is driven by surface free energy, convection, and gravitational effects, which cause rapid rearrangement and dislocation of solid particle centers. The density difference in the presence of a gravitational field leads to solid migration, stratification, nonuniform coarsening, and anisotropic sintered mechanical and material properties. The result often is part rejection or premature component failure, which leads to increased cost and manufacturing complexity.

Conducting LPS experiments in microgravity has promising potential.[4,7–24] Elimination of density effects provides the unique opportunity to isolate transport from sedimentation mechanisms and enables the study of thermodynamic equilibria between the solid, liquid, and gaseous phases. Thus, this research was conducted with two parallel goals in mind. The first objective was to clarify fundamental phenomena based on the knowledge and discoveries attained by experiments in space and on the ground. These results have numerous applications toward screening higher-temperature LPS systems for additional study in low gravity (future flight investigations), improving ground-based processing, and increasing commercial applications of these materials. The second goal was to develop and support infrastructure by designing, fabricating, and testing a versatile furnace facility [equipment for controlled liquid-phase sintering experiments (ECLiPSE)] that could be utilized by our team as well as by future investigators. This text presents an overview of the evolution of the program, from a laboratory mock-up through four sounding rocket flights, and includes a description of the hardware that successfully flew on three Space Shuttle missions. Work continues on a new generation of the experiment, which is scheduled to fly aboard several upcoming Space Shuttle missions. These successes can be traced directly to the numerous lessons learned early in the program.

Early Development

The furnace and technology were developed over four Consort suborbital rocket flights, which provided the background material necessary to design the advanced system. The ECLiPSE, which first flew in 1991 aboard Consort 4, evolved from the LPS furnace (LPSF), which flew aboard Consort 1 in 1989.[25–28] The LPSF was an isothermal furnace that operated at 1114°C during flight. The module was preheated on the pad to 1040°C and ramped at 16°C/min

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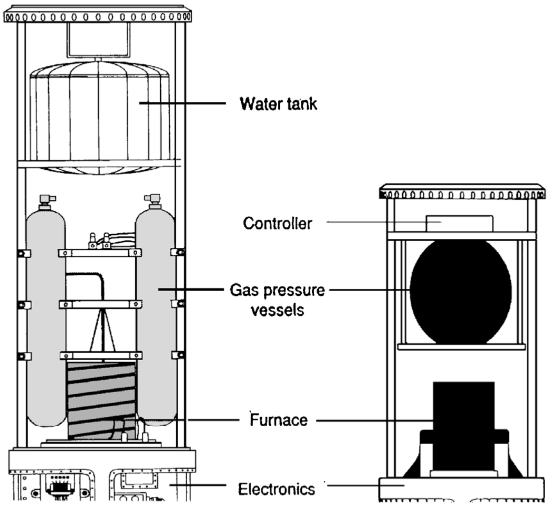

Fig. 1 Consort 1 LPSF (left) and ECLiPSE (right).

during flight. The equipment was designed to handle the extreme launch/ascent loads (10 g) and those of landing, which could reach 25 g. With the centerline furnace module temperatures approaching 2.5 times the melting point of the rocket airframe, considerable engineering was required to protect the system against a worst-case failure scenario. Concerns also were expressed that the exterior of the furnace body itself could reach temperatures that could damage adjacent electrical components and wiring. Thus, a brass water jacket was used to surround the furnace. A 9-liter-capacity pressurized bladder tank (Fig. 1) supplied demineralized water to the cooling jacket. Four 3-liter tanks of helium provided a slow flow rate to protect the samples from oxygen desorbed from the ceramics and gas for a rapid quench of the samples prior to re-entry. Two of these cylindrical tanks are shown surrounding the central furnace body (Fig. 1). Both the water (as superheated steam) and helium would exit overboard through nonpropulsive vents. The furnace heating element was fabricated from molybdenum wound upon an alumina tube and insulated with solid zirconia. This core was surrounded by a layer of silica-based fibrous batt insulation and a stainless steel shell. The components were mounted in a cylindrical aluminum rocket skin. Numerous control electronics, a pressure regulator, and batteries were located in the lower segment of the package. The LPSF section of the rocket payload was approximately 140 cm tall and 44 cm in diameter, with a final loaded mass (including consumables) of approximately 145 kg. The techniques and solutions necessary to successfully accomplish these tasks were the basis for further flight hardware design.

Furnace design and development is a complex art, further complicated by the rigors of space flight. The vibration and g levels, cooling requirements, inert atmosphere, and heating cycles posed great challenges in both design and reliability. The learning curve is best advanced through continued production and improvement of operational hardware with associated trial and error. The LPSF in fact was based on knowledge gained from in-house analytical work performed on other proposed microgravity flight furnace designs. Much also was learned from the design and development of a ground-based multiuse processing furnace (MPF).[29] This facility was a 1600°C multizone Bridgeman-type directional solidification furnace. The module translated over the sample zone to minimize induced accelerations. These techniques have future applications.

The ECLiPSE package was flown aboard Consort 4, 5, and 6.[30–33] The in-house knowledge base of the LPSF and the MPF was built upon and were incorporated to concepts from the Wyle Laboratories metals and alloys solidification apparatus, continually refine and upgrade the ECLiPSE. Operationally, the facility was preheated and launched similiar to the LPSF. Numerous improvements and capabilities were added, mindful of future requirements and growth potential. A new transient heating furnace design was utilized. This body provided greater thermal isolation and increased sample size. Water cooling was not required (Fig. 1), and argon gas was used to maintain the inert processing environment. The shared experiment computer used with the LPSF was replaced with a dedicated controller. This unit was specially designed and offered increased operational capabilities and data storage. The wirewrap prototype was flown aboard Consort 4 and subsequently was converted to a single printed circuit card, allowing quick replacement in the event of an anomaly. The ECLiPSE payload section was approximately 110 cm tall and 44 cm in diameter with a final loaded mass (including consumables) of about 77 kg. Nearly a 50% mass reduction was achieved compared to the LPSF, along with a significant reduction in volume while enhancing performance capabilities of the facility. This achievement was a critical evolution to enable transition of the project to a Space Shuttle experiment. For Space Shuttle payloads, launch costs were conservatively estimated at $5000/kg and available volume and allocated payload weights were very limited.

Strategic planning toward the development of a Space Shuttle payload was important. These missions would permit additional investigation opportunities and longer processing times. Thus, the Consort flights served as a test bed for developing and validating both concepts and hardware. On Consort 4, the furnace configuration was in fact the prototype for the Space Shuttle hardware. This mission was followed by flight qualification of the actual design aboard Consort 5 and 6. The successful experiences of the ECLiPSE work enabled rapid conversion of the experiment to a crewed space mission with strict safety requirements. When the opportunity arose for the payload to be manifested aboard the SPACEHAB module, ECLiPSE-HAB was designed, fabricated, tested, and delivered in less than 11 months!

ECLiPSE-HAB Flight Hardware

SPACEHAB is a commercially built and managed pressurized module carried in the Space Shuttle cargo bay to augment the middeck microgravity capabilities. For flights on SPACEHAB, the NASA Office of Advanced Concepts and Technology has arranged for experiment space and integration services to support several centers for commercial development of space. The CMDS at UAH is one of the NASA-sponsored centers that has utilized this flight opportunity. Engineers and technicians from the CMDS and Wyle Laboratories designed and fabricated a SPACEHAB variant of the ECLiPSE facility for flight on Endeavor STS-57 (June 21–July 1, 1993), Discovery STS-60 (Feb. 3–11, 1994), and Discovery STS-63 (Feb. 3–11, 1995).[34–36] The integration of the experiment into the SPACEHAB module was a function of McDonnell Douglas Aerospace (MDA) on behalf of SPACEHAB Incorporated.

For these missions, the ECLiPSE-HAB was configured to initially purge the furnace module for 15 min, followed by heating at 6°C/min past 1090°C. Control algorithms then brought the module to 1110°C for the required processing time. Sample centerline temperatures and gradients were empirically verified, and at peak power the module utilized less than 700 W. The samples (11 compacts of Fe-Cu, Co-Cu, and W-Ni-Cu) were controlled above the copper melting point for about 5 min aboard STS-57, 17 min aboard STS-60, and 66 min on STS-63. The unit also followed a programmed cooling cycle. The system was optimized to process these materials and was capable of even higher temperatures. The sample cartridge was held in the center of the furnace module (Fig. 2). The molybdenum heater elements were covered in cast alumina (Al_2O_3) and surrounded by an alumina muffle tube. The core was encompassed by zirconia (ZrO_2), which provided primary thermal isolation, and was further surrounded with kaolin wool. End closures provided feedthroughs for heater power and for thermocouple probes. Provision also was made for 82.7-kPa pressurized argon gas flow through the furnace during heating and to aid quenching at the end of the processing period. Figure 2 shows fittings for this at either end of the assembly. The efficient, compact, and rugged design of the furnace reflected the earlier flight experience gained from suborbital rocket missions. The module also was customized for easy maintenance and refurbishment based on ergonomic lessons from rocket operations.

The furnace was mounted with a circumferential flange at the middle. This flange was bolted to a water-cooled furnace mounting plate as shown in Fig. 3. The argon supply/metering system was located below the furnace and controlled gas flow during operation.

The furnace assembly was mounted inside a universal space experiment container (USEC). This container was designed by Wyle Laboratories to provide pressure-vessel class containment for experiments on flights such as SPACEHAB. Such containment was essential for safety requirements in a crewed environment. The USEC design provided for electrical, water, vacuum, and gas feedthroughs that maintained the containment quality. For thermal and flammability considerations, USEC was evacuated during operations through a connection to a vacuum vent system supplied as an in-flight service by SPACEHAB. The ECLiPSE-HAB was connected to a SPACEHAB experiment vacuum vent shared with other users. The vacuum vent systems provided both a vacuum source and overboard venting. In front of the furnace within USEC (Fig. 3, left-hand side) was a reflector plate that protected the electronics assembly. Power modules distributed 28 Vdc to the controller and electronics and variable dc to the heater element.

The controller and relays assembly monitored and commanded operation of the ECLiPSE-HAB after main power activation. The controller itself was an upgraded version of the ECLiPSE printed circuit card unit used during the Consort program. Improvements included engineering the thermocouple amplifiers and ice-point circuitry from schematics onto the card itself. The electrically erasable programmable read-only memory (EEPROM) microchips were replaced with erasable programmable read-only memory (EPROM) integrated circuits. The use of EPROMs increased the reliability of data storage, because EEPROMs could have been erased by an overvoltage anomaly. The controller also was equipped with additional digital and analog input/output channels that allowed continual monitoring of several equipment parameters. Safety requirements dictated monitoring of values such as internal temperatures and pressures to provide out-of-limit indications and to activate automatic experiment shut-down routines.

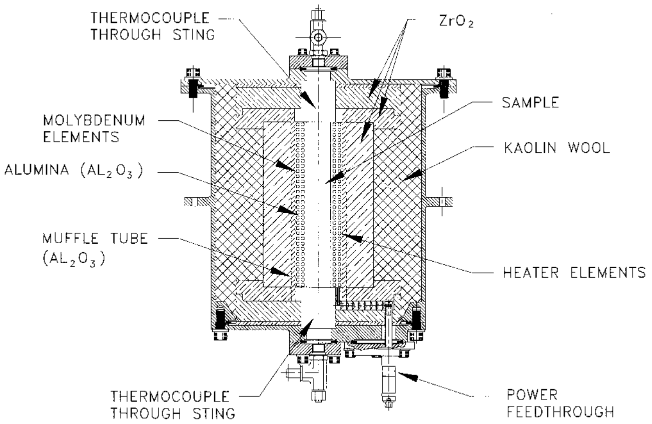

Fig. 2 Interior of the ECLiPSE furnace module.

Placement of the electronics within an evacuated pressure container substantially eased outgassing and flammability requirements on components. This design simplified the flight certification requirements and reduced program timeline and costs. However, some additional engineering challenges were encountered such as in designing the controller. The printed circuit board had to operate in vacuum, which required a multilayer configuration with a copper core for heat dissipation. Not shown in Fig. 3 are water lines within USEC that were routed to the electronics for cooling. Above the USEC body was the switch and indicator panel. Behind the USEC was an extension assembly, which provided mounting interfaces to a SPACEHAB single rack. A sound muffler and check valve assembly provided overpressurization protection of the USEC. Two argon cylinders supplied gas through pressure regulators. The vacuum filter prevented particle flow from USEC into the vacuum vent valve and into the SPACEHAB common vacuum vent line.

The ECLiPSE-HAB was fitted into a SPACEHAB single rack as shown in Fig. 4. The rack was designed by MDA for SPACEHAB. Behind USEC, a special support structure designed by Wyle Laboratories was attached to the rear structural members of the rack. Also shown in Fig. 4 is a rectangular container attached to the top of the rear support structure. This casing contained a remote

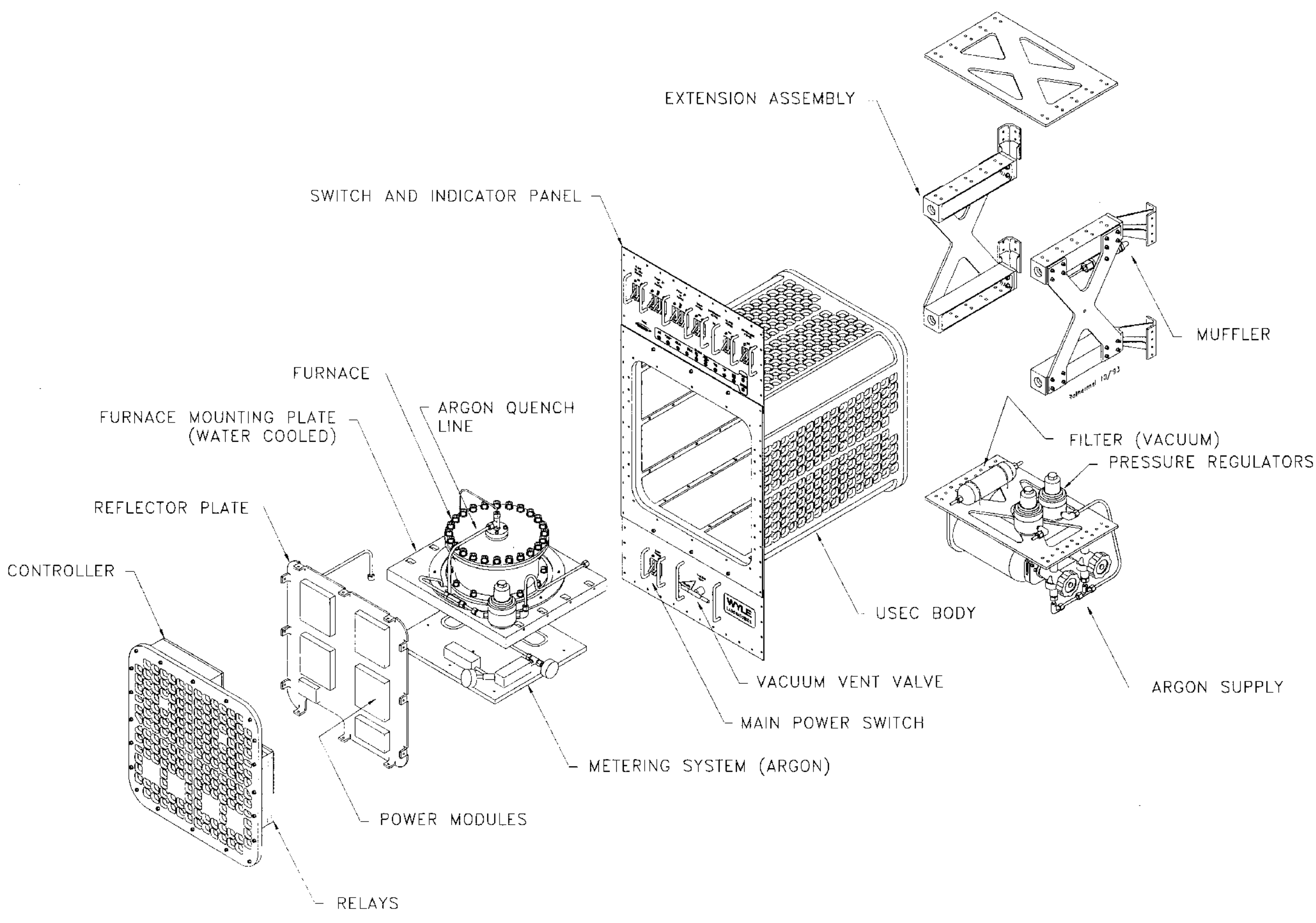

Fig. 3 ECLiPSE-HAB system modules.

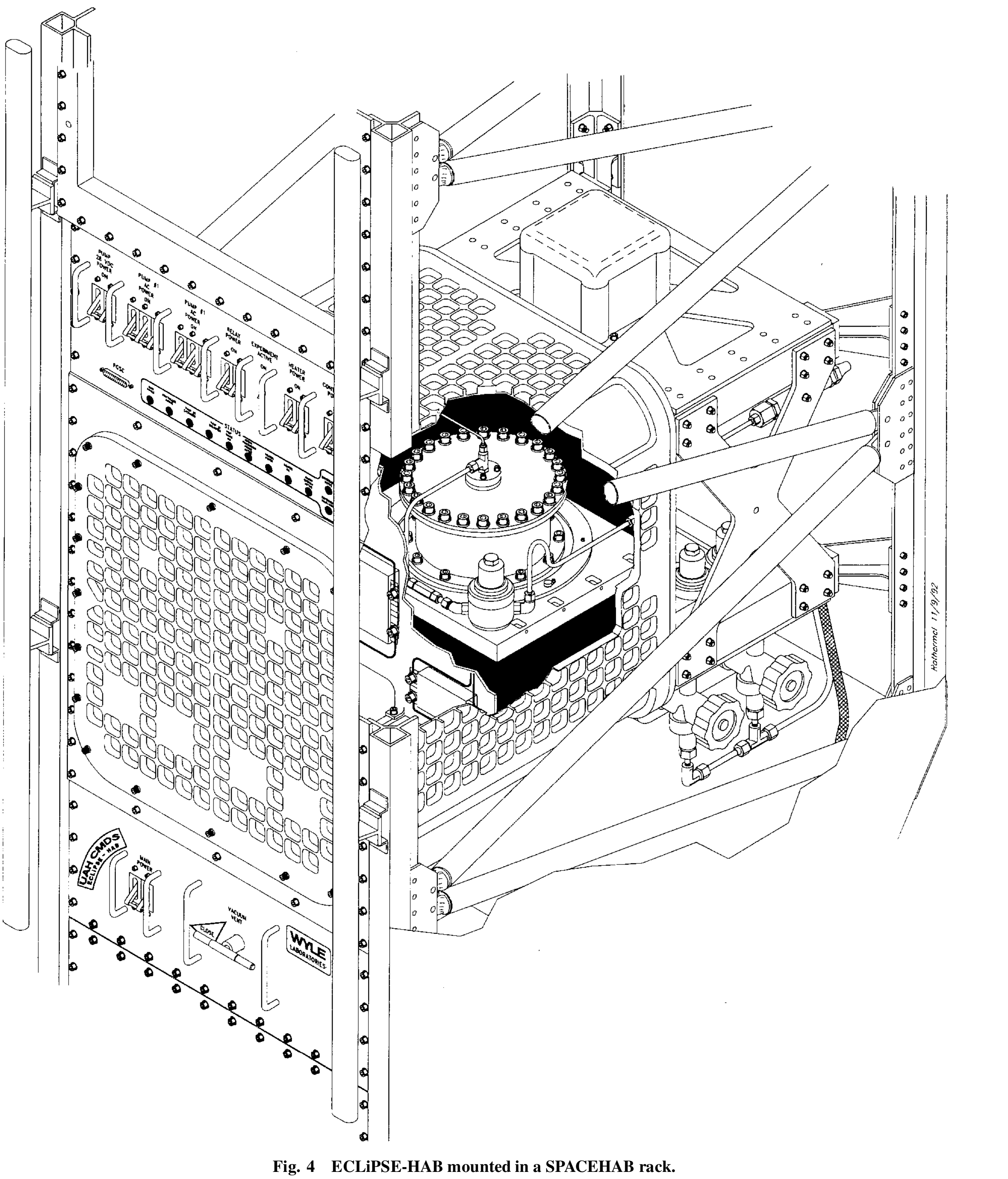

Fig. 4 ECLiPSE-HAB mounted in a SPACEHAB rack.

accelerometer that was capable of quantifying vibrations of various origins transmitted through the structure as well as continuous or very long period accelerations. This three-dimensional microgravity accelerometer had a long history of space flight and also was fabricated and operated by the UAH CMDS. Water for cooling was supplied from a pump in the bottom of the rack and was routed through a heat exchanger in the SPACEHAB subfloor. This pump and heat exchanger were supplied by MDA for SPACEHAB as an optional service. The experiment water pump package (EWPP) encompassed two alternating-current-powered pumps and four direct-current-powered sensors (inlet pressure, outlet pressure, pump temperature, and pump accumulator quantity). The ECLiPSE-HAB powered and controlled the pump operation. The operating pressure of the EWPP was monitored by the controller to switch to the backup pump in the event of primary failure. The heat exchanger was capable of rejecting in excess of 1 kW of waste heat.

Crew interface with the payload was accomplished via the front-mounted controls (Fig. 5). The upper panel contained a series of circuit breakers that provided power to individual systems. A crew member followed an activation sequence recorded in the ECLiPSE-HAB flight data file. The main power breaker (lower panel) was the first circuit enabled and the last step was to toggle the experiment active switch. The control software and hardwired safety interlocks were designed so that status lights provided a code to verify experiment health and progress. These indicators allowed the principal investigator and crew, with the aid of the flight data file, to diagnose failure conditions and provide on-orbit monitoring and troubleshooting. The flight data file included a visual key that correlated the light sequence to known states for the experiment. During STS-57, the experiment was performed during a crew wake period and required crew monitoring during processing. During STS-60, a video image of the status lights was downlinked to the

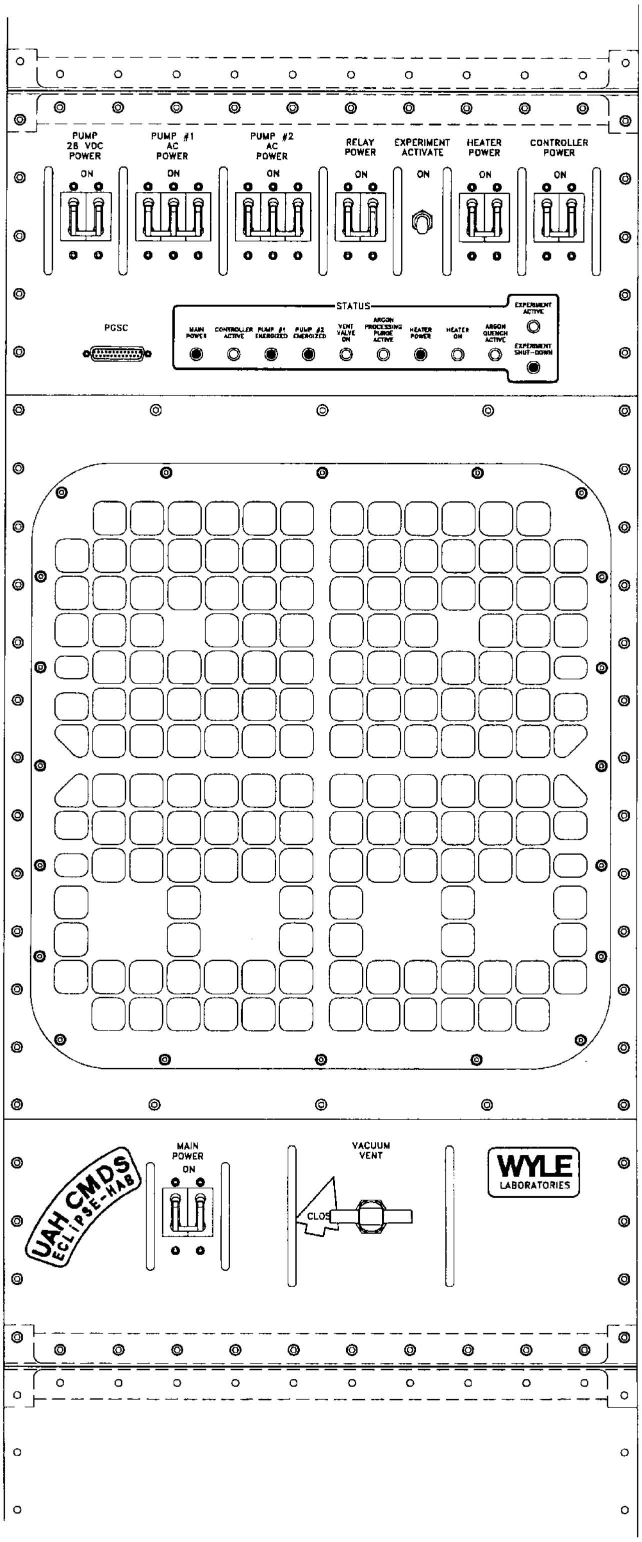

Fig. 5 Front view of the ECLiPSE-HAB.

principal investigator at the payload operations control center. When the ECLiPSE-HAB was activated, the onboard controller shut down the experiment immediately. Upon investigation of the anomaly, the status light code provided the crew and principal investigator indication that the USEC had not reached the required pressure level during experiment startup. The experiment was recycled and proceeded flawlessly. Continued remote monitoring by the principal investigator allowed the crew to enter a sleep period and the experiment was performed overnight. This video downlink was very significant in that crew workload was reduced and timeline flexibility was now available. The ECLiPSE-HAB operation could be scheduled during a crew sleep period when the microgravity conditions were superior.

The upper panel also contained the payload general support computer (PGSC) connector for data communications. On STS-57 and STS-60, this computer was used only for postexperiment data backup. A crew member connected the PGSC and downloaded the EPROMs for redundancy and to prevent subsequent data loss. During the STS-63 mission, real-time monitoring was accomplished by attaching the PGSC and transmitting a video image of the computer screen. This video provided the capability for ground monitoring, giving the principal investigator additional insight into the health and status of the experiment that was not available through the use of status lights alone. During operation, the front panel touch temperature was higher than expected. It was determined that the cabin temperature, although within SPACEHAB operational specifications, was much higher than previously encountered in ground-based testing. This information was relayed and the cabin temperature was lowered, thus avoiding a premature shutdown of the unit. Future expansion could incorporate further on-orbit crew monitoring options and ground commanded telescience with downlink operations.

Future Work

The ECLiPSE-HAB operated successfully on SPACEHAB 1, 2, and 3. The samples produced are being analyzed utilizing several different paths with different parameters leading to modification of future investigation plans. The specimens were processed with different time intervals, allowing for, among other things, a comparison of microstructural rearrangement, densification, and pore evolution vs time. Although to date the facility has been used only for liquid metal sintering, the ECLiPSE-HAB furnace easily could be adapted for other investigations. In the current configuration, the module provides isothermal heating to approximately 1100°C, but it could be modified to produce a thermal gradient. The basic design with modest changes also could achieve substantially higher temperature. An evolution to higher-temperature processing is under way with a new facility with planned investigation of additional commercially attractive materials. This payload is the extreme temperature translation furnace (ETTF) and is manifested for flight on STS-79 (August 1996). The ETTF (Fig. 6) is being jointly developed by the CMDS and MDA. The upper segment includes a gas/vacuum distribution system, a powerful computer controller, active color matrix display, and a crew interface keypad and mouse to aid on-orbit operations. Telemetry uplink and downlink will be possible for ground-based telescience. The central module contains a 1600°C Bridgeman-type directional solidification furnace with on-orbit manual sample exchange capability. The lower segment

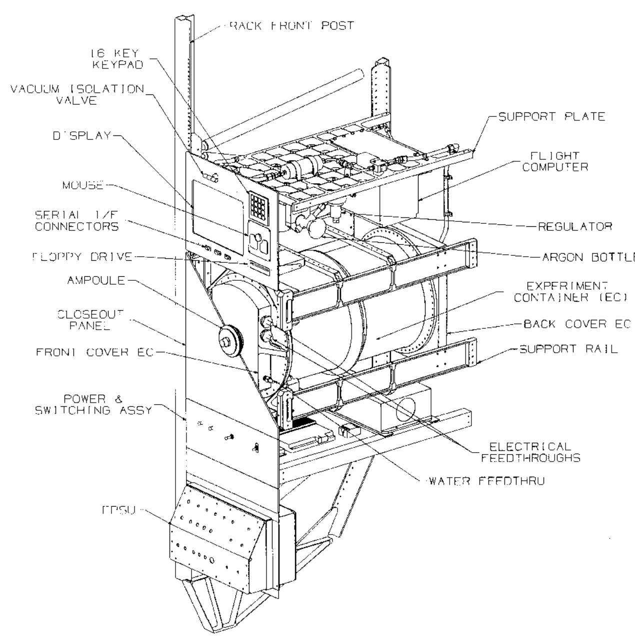

Fig. 6 ETTF single rack assembly.

encompasses the electrical power switching unit and the water pump package used for ECLiPSE-HAB.

Conclusions

The successes of ECLiPSE-HAB can be traced to decisions made and lessons learned early in the program. The development of the hardware required an extremely interdisciplinary approach involving elements of aerospace, mechanical, electrical, and software engineering. This methodology is indicative of the nature of future space flight projects in the era of increasing goals and decreasing budgets. Containing the equipment in a pressure-vessel class carrier solved several difficult safety and verification issues and permitted the use of commercial parts. This design resulted in significant cost and schedule savings. The involvement of industrial partners provided specialized support and analysis. The design features of containment and redundancy as well as the proven flight performance data from the Consort test bed minimized expensive component testing and analysis. This evolutionary program approach provided important lessons on experiment flight hardware fabrication and integration in a very cost-effective manner. The hardware was designed with inherent growth capabilities to maximize safety, to promote long-term usage/future flight opportunities, and to simplify on-orbit operations. Indeed, the lessons learned offer even further rewards in their application toward future facilities. Continued development of this type of evolutionary "faster, better, cheaper" hardware must be pursued.

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