PLANCK Sorption Cooler Initial Compressor Element Performance Tests

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Abstract

PLANCK is an ESA-led mission to map the cosmic microwave background using bolometric and hetrodyne instruments; both instruments require cooling, one to ~20K, the other to 0.1K. JPL is developing a sorption-based hydrogen cooler to provide 18—20 K cooling to the two instruments. The system mass and power limitations require tradeoffs in thermal design.

To demonstrate achievement of an acceptable design, three compressor elements of a flight-like configuration have been built and are undergoing characterization and life tests. The compressor elements utilize a $La_{1.01}Ni_{4.78}Sn_{0.22}$ alloy for reversible hydrogen storage, resistive heaters, and an aluminum foam matrix for thermal uniformity, all contained within a high-pressure vessel. A gas-gap switch provides adjustable thermal isolation. Initial results indicate that hydriding alloy bulk and surface contamination levels are insignificant, and that reversible storage capability is near theoretical limits. We report on static and dynamic thermal characteristics of the compressor elements, and gas supply characteristics related to operational modes of a cooler. We then indicate what further characterization will be performed.

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I. Introduction

The Jet Propulsion Laboratory (JPL) is developing continuous-duty hydrogen sorption coolers for ESA's PLANCK satellite mission, which will launch in 2007 to continue investigations of the cosmic microwave background. PLANCK's Low Frequency Instrument employs HEMT amplifiers cooled to ~20 K; the sorption cooler will supply this environment directly, extracting about 1 watt of heat at this temperature. The High Frequency Instrument utilizes bolometers operating at 0.1 K; the sorption cooler provides ~150 mW at 18 K as precooling for a mechanical helium J-T refrigerator and an open-cycle dilution refrigerator cooling chain. Information regarding the thermal architecture and many other aspects of the PLANCK mission is available at the ESA website[1] and in a recent publication[2].

Continuous-duty sorption cryocoolers employing hydrogen as the working fluid and metal hydrides as the sorbent have been discussed by Freeman[3]. The PLANCK mission requires

approximately 24 months cumulative operation, including ground testing. These requirements necessitate pushing the state of the art in hydride compressor lifetime[4] by factor of ~100, within the constraints of mass and power appropriate to a space mission. Both efficiency of operation of the J-T expander and degradation rate of the metal hydride sorbent increase with increased working pressure of the hydrogen fluid; optimal performance is thus a tradeoff between efficiency of operation and degradation rate of components.

The various components of the PLANCK cooler have been described at length[5]. In this report we focus only on the active component of the compressor system, the compressor element, which stores the hydrogen working fluid, releases it at high pressure to generate cooling via Joule-Thomson expansion, and absorbs the hydrogen at low pressure to maintain the cold temperature at the liquid hydrogen reservoir. Compressor elements have been fabricated, utilizing materials and construction techniques expected to optimize the cooler performance for the mission and to minimize degradation in the hydride sorbent during cycling. The purpose of the work described herein is the operation of these compressor elements under conditions similar to those of a functioning cooler, to validate the design and construction techniques, gain information about the operational characteristics, and quantify the degradation rate to be expected in long-term operation. This information will be used to iterate to an optimal design for the flight cooler system.

We begin with an explanation of the operation of a single compressor element, followed by a description of the apparatus that has been constructed to test the various characteristics of the compressor element. Results of the characterizations are given, with discussion of the ramifications of those characteristics for development of a flight cooler. Finally we indicate the direction of future characterization and modifications planned for the test apparatus.

II. Compressor element description and operation

Figure 1 is a cutaway view of a single compressor element. The central portion of the outer shell is aluminum, alloy 6061T6. The outer 75 mm on each end are 316L stainless steel, joined to the central portion via inertial welding prior to final machining. The inner vessel has a 316L wall 1.22 mm thick, containing the hydriding $La_{1.01}Ni_{4.78}Sn_{0.22}$ alloy distributed in an aluminum foam matrix [ERC Corp, Oakland CA] to enhance thermal uniformity. Three penetrations of the inner vessel allow egress and return of the hydrogen gas, access to the single thermocouple inside the inner vessel, and power to the resistive heater elements, also located inside the vessel. The inner vessel is supported by the outer shell only at the ends, via axial pins. All assembly joints are performed in an argon atmosphere using automatic orbital tube welding equipment [Weld Logic Corp].

The inner vessel and outer shell are separated by a radial space of 0.75 mm which forms the conductive link of a gas-gap switch; the two sections are thermally decoupled when the annular region separating them is evacuated. The facing surfaces are gold plated [Epner Technology Inc, Brooklyn, NY] to reduce radiative thermal transport and to chemically passivate the surfaces.

Hydrogen is reversibly stored in the LaNiSn alloy, with equilibrium pressure and temperature as shown in Figure 2. The cycle of operation of a single compressor element in a cooler can be described briefly as follows: The vessel containing the hydrogen storage media is heated to drive off hydrogen at high pressure, typically ~50 bar, which is then cooled to below the inversion temperature, and passes through a Joule-Thomson expansion orifice to collect as liquid hydrogen. When the source vessel is depleted of hydrogen it is cooled; it is then able to reabsorb hydrogen gas boiling off from the liquid reservoir, typically at a pressure ~0.3 bar. An arrangement of checkvalves permits a CE to desorb into a manifold at high pressure, then absorb hydrogen supplied by another identical CE. Four or more such CEs are required, operating sequentially, for continouus-duty cooling.

At 283 K, with a H:M ratio of 5.3, the equilibrium pressure of H_2 over the hydriding alloy is ~300 torr. The hydriding alloy could absorb more hydrogen, but only at a higher equilibrium pressure. Since it is the reabsorption pressure of H_2 that determines the minimum temperature of the liquid H_2 reservoir, the maximum allowable H:M ratio is determine by the required cold tip

temperature. Typically the H:M ratio is varied over the relatively flat plateau region, as indicated in Figure 2 by the trapezoidal box.

To begin desorbing H_2 from the CE, the gas-gap region is evacuated and the inner vessel heated. Flow of H_2 gas from the vessel will begin when the internal pressure exceeds the external system pressure, and will continue so long as energy is added to desorb the gas and maintain vessel temperature, until the alloy is depleted of hydrogen. As small H:M the equilibrium temperature at fixed pressure rises steeply, thus in practice the desorption is terminated prior to complete depletion, at a temperature set by practical considerations. In this application the maximum temperature is derived from considerations of alloy stability[6].

With the desorption phase of the cycle complete, the gas-gap region is filled to ~30 torr of H_2 gas, thermally coupling the inner vessel to the outer shell and thence to a heat sink. When the H_2 equilibrium pressure over the depleted alloy decreases below the external system pressure, which is approximately the vapor pressure over the liquid H_2 reservoir, hydrogen begins to resorb into the alloy, and continues so long as the heat of absorption is removed via the gas-gap conductance. Eventually the alloy returns to the initial state of temperature, pressure, and H:M ratio.

III. LifeCycle Tests: Apparatus Design, Test Regimen, Results

As described in References 5 and 6, high temperature and pressure of H_2 is the condition most deleterious to the hydriding alloy, for the effect on both intrinsic and extrinsic degradation. To simulate the conditions a CE would experience in the operation of a cooler, we have constructed an apparatus to cycle CEs through the four phases described above. The apparatus faithfully reproduces the heatup, desorption, and cooldown phases in all respects, allowing variation of all relevant parameters and conditions.

Three CEs were fabricated for this effort, known as the LifeCycling testing. All materials, handling, and construction techniques were identical to those intended for the flight devices. Each of the 3 CEs was bolted to an aluminum heat sink, which was maintained at constant temperature via a circulating water bath and chiller [Neslab Instruments Inc. RT-6221]. A Type K thermocouple inside each CE, and another Type K and a Si diode [Lakeshore Cryotronics DT470] in close proximity to the CE on each heat sink provided thermometry. Readout wiring for the thermometers and electrical power for the resistive heaters passed through the wall of a vacuum chamber via hermetic connectors. To simulate the operational conditions, the chamber was evacuated during testing. Figure 3 shows the CEs within the lower portion of the vacuum chamber.

The gas-handling portion of the LifeCycle apparatus is fabricated entirely of 316L stainless steel tubing electropolished to the standards of the semiconductor industry. All valves and components were cleaned to similar specifications. Prior to exposing the hydriding alloy to the system, all tubing and valves were vacuum baked with an oil-free pumping system [Leybold TOPS turbomolecular pump] to remove contaminants, primarily water with some hydrocarbons and argon. The contaminant level was monitored with an RGA system [Stanford Research RGA200], which verifies elimination of impurities before exposing the alloys to hydrogen.

Figure 4 shows schematically the layout of all plumbing, expansion tanks, valves and pressure sensors, for the testing of the three CEs. There are three identical channels, one for each CE; the only common connection is the gas source for the gas-gap switches. Characterization proceeded as follows; static thermal characteristics of the CE structure prior to introduction of hydrogen: storage capacity of the hydriding alloy: dynamic thermal characteristics of the CE with hydrogen as per operational conditions: and behavior of the CE during desorption, with particular emphasis on the reversible storage capacity and kinetics of gas desorption. These four sets of tests, and the interpretation of the results, are detailed below.

A. Static thermal tests: Parasitics and Gas-Gap Conductance

Thermal coupling, conductive and radiative, between the inner vessel and the outer shell was measured as a function of ΔT and of gas-gap pressure. Conductance was determined by applying constant power to the inner vessel, which was either evacuated or filled with argon at about 1 bar, and observing the equilibrium temperature of the inner vessel as the outer shell was held at constant temperature. Research-grade hydrogen was supplied to the gas-gap switch volume via a mechanical regulator and a Brooks 5866 pressure controller, with the pressure set via computer interface. The control and data acquisition system will be detailed in the section on dynamic thermal characterization.

With gas-gap pressure less than 10^{-3} torr, the parasitics are a amall component of the total system power, <2%. The parasitic losses are comfortably smaller than required for CEs in the flight cooler. Conductance of the gas-gap during the resorption phase, when the $\Delta T \sim 10$ K, is important for the effective operation of the cooler cold end. Results from these tests are shown in Figure 5. The gas-gap conductance exhibits the expected saturation as the mean free path in the gas approaches the wall separation; the measured conductance at gas-gap pressure of 30 torr is 1.4 times that required to extract the heat of reabsorption at the required pressure of hydrogen over the alloy.

B. Hydride alloy storage capacity

The quantity of hydriding alloy included in each CE is known to within 0.1%, as is the theoretical capacity for reversible reaction with hydrogen. The amount of hydrogen that the hydride is capable of storing is then an indicator of the quality of the hydride and of the assembly and handling techniques. Prior to introducing hydrogen, the ullage volume of the inner vessels and of all other components of the has handling system were determined to <1%. Each of the CEs was initially reacted three times with high purity hydrogen prior to the start of the thermal tests. These hydrogen capacities are summarized in **Table 1** and demonstrate excellent uniformity and complete activation.

C. Dynamic thermal tests: heatup and cooldown characteristics

Of the energy dissipated by the resistive heaters to achieve and maintain desorption temperature of the hydride vessel, the only portion that contributes to heat lift at cryogenic temperature is the heat of desorption of hydrogen from the alloy. Of the energy remaining, the enthalpy added to the hydride vessel and its contents is the most significant by a large margin. It is thus beneficial that the inner vessel be designed with minimal thermal mass, consistent with mechanical strength requirements. As the heatup phase must be completed within a time determined by the operational requirements of the cooler, the thermal mass is the most significant factor in determining the electrical input power required. The specific heat of the hydriding alloy at high H:M and high temperature, where the pressure is significantly larger than 1 bar, has not previously been measured accurately. Here we report only the measurements indicating the power necessary to heat the inner vessel to desorption pressure in the required time; more detailed results related to the hydride properties will be reported elsewhere.

In an operating cooler of the PLANCK design, a CE will start the heatup phase from close to the sink temperature of ~280 K, with H:M of ~5.3. The heatup test began with this condition, with the gas-gap pressure below 10^{-3} torr. Constant voltage was applied at the resistive heater via a power supply [Hewlett Packard 6032A]; voltage and current were monitored each second, and Joule power calculated. In the constant-voltage mode, the power varied by less than 1% during the heatup cycle. The operational requirement, derived from the cooling requirements for this cooler design, is that the heatup phase take no more than 667 seconds. The voltage required to bring the inner vessel to a temperature at which the pressure of hydrogen is 50 bar, the pressure at which hydrogen will begin to flow out of the CE and into the remainder of the system, is determined by iteration to meet this requirement. Figure 6 shows the heatup phase time-

temperature and time-pressure profiles. The electrical power required is in all cases within the system requirement of 240 watts for a CE in heatup phase.

Extraction of enthalpy from the inner vessel, as it cools following desorption phase, is likewise an important parameter in the operation of the cooler. The hydride vessel must cool sufficiently to begin reabsorbing hydrogen, else the cooler will cease to function. Although prior analyses[7] have found this requirement to be a non-critical contributor to the gas-gap design, it is significant in that the heat transferred to the sink will influence the thermal environment experienced by other components of the cooler. We have thus measured the time required for the depleted CE to cool to the absorption temperature following removal of Joule power from the heater. The measurement begins with a CE with H:M = 2.0 and T = ~450 K, as would be the case at the completion of the desorption phase. The gas-gap pressure is quickly raised to 30 torr, and the resulting temperature of the inner vessel and heat sink monitored. The time-temperature profile is also shown in Figure 6. The thermal power conducted to the sink is initially large, ~1000 W, and decreases rapidly as the enthalpy is extracted. It is clear that the cooling time requirement of 667 seconds is easily satisfied by the existing design at this gas-gap pressure, and is expected to be adequate for gas-gap pressures as low as 20 torr.

D. Hydride desorption—absorption cycling: hydride capacity and desorption kinetics

The greatest portion of the LifeCycling Apparatus is dedicated to an examination of the behavior of the CEs during the desorption cycle, wherein the CE supplies hydrogen to the high-pressure portion of the cooler system. The intent is to examine in detail the dynamic behavior of the hydriding alloy, the containing vessel, and the entire compressor element; and, once the dynamic behavior is well-understood, to operate the CE for an extended period to determine usable lifetime. The apparatus constructed for this purpose runs each CE through the heatup phase at constant voltage or power, desorbs the hydrogen gas at constant pressure, cools the CE without allowing absorption, then transfers the hydrogen back into the CE. This simulates the cooler operation in all except the final, absorption, phase, in that the absorption does not occur at constant pressure as would be the case in a functioning cooler. At the inception of this program, the degradation rate attainable for the hydride alloy in a temperature cycling CE was the least well known, and thus highest risk, component of the design space. Separate tests are underway to evaluate the intrinsic degradation rate[8]; the purpose of the tests reported here is evaluation of the implementation, which includes the alloy, the materials and handling techniques used in the fabrication of the CE, and the effects of cycling the hydride through many desorption—absorption cycles. Operation of the flight cooler over the totality of ground testing and flight mission will require approximately 18,000 cycles of each CE. We plan to operate the individual CEs for at least this many cycles.

Figure 3 shows schematically the three independent channels of the LifeCycle apparatus. The CEs connect through the wall of the vacuum chamber via a valve pair. As the temperature of the CE inner vessel rises during heatup phase, the hydrogen gas flows to the pressure control valve [Brooks 5866RT], which contains a PID servo loop and a mass flow sensor. A capacitive pressure transducer [MKS 850B] upstream of the valve monitors gas pressure and supplies this information to the control valve; when the upstream pressure exceeds the setpoint of the control valve, the valve opens to allow hydrogen to escape into the expansion volume. Pressure in the expansion volume is monitored by an identical transducer. The PID loop maintains constant desorption pressure in the CE until the end of desorption phase, when power to the CE heater is removed and the gas-gap switched to conductive mode. At the end of the cooldown phase, an electropneumatic bypass valve [Nupro HBVCR4] is opened, allowing hydrogen to flow from the expansion volume back into the CE, returning the system to the initial condition, whereupon the cycle is repeated.

Hydrogen for the gas-gap switch volume is supplied from a bottle of research grade H_2. The pressure in the gas-gap is set by another 5866RT operating in downstream control mode. The gas-gap is evacuated via a molecular drag pump [Hovac DRI-2].

The cycling of the apparatus is controlled via a PC running LabVIEW 5.1 under MS Windows NT 4.0. The power supplies are controlled via GPIB, data is collected via two A—D converter cards [National Instruments PC-MIO-16XE-50], and the setpoints for the desorption and gas-gap pressure control valves is set from the computer via a D—A card [National Instruments AT-AO-10]. Timing of the electropneumatic valves is controlled by the software, and the valves actuated via a relay card driven from the RS232 bus [National Instruments CB-50LP and SC-2062]. The software collects data from all of the pressure and mass flow sensors and all the thermometers, to allow monitoring of all aspects of the cycle.

Considerable care was exercised in the design of the cycling apparatus and in particular in the operational modes of the control system, to guarantee that no dangerous condition could exist as a result of single-point component failure or computer problems. In addition to software checks on parameter ranges, a keep-alive system was implemented such that if the software were to cease operation, the CE heater power would be interrupted within seconds. This was accomplished with a Watchdog relay [Macromatic TR-51822-08TV05], which requires a periodic reset signal, generated in this case from the computer software. Tests, intentional and otherwise, have demonstrated this system to be reliable.

Figure 7 shows the temperature, pressure, and mass flow as a function of time, for a single compressor element over three cycles. Prior to testing, it was expected that the desorption phase would proceed with constant power supplied to the resistive heaters, with nearly constant mass flow proceeding from desorption of hydrogen at constant pressure as most of the heater power goes into heat of desorption. However, it was found that under these conditions we experience larger mass flows during the initial portion of the desorption phase, where the H:M is larger and the heat of desorption smaller, and reduced mass flow at the end of desorption where the heat of desorption is larger. Profiling the desorption phase power has reduced the output mass flow variation to <1%, which has important ramifications for the operation of the cooler system but is beyond the scope of this report. Also shown in Figure 7 is a detail of the power profile during desorption, and the mass flow attained.

E. Future work

Not reported here is the rate at which the alloy reabsorbs hydrogen, as the apparatus is not instrumented for that measurement. In an operational cooler, the reabsorption takes place at essentially fixed mass flow, with the absorption pressure determining the cold head temperature. As discussed above, the reabsorption phase is not believed to be critical for hydride degradation. At the time of design, it was not expected that this apparatus would be required to provide detailed examination of the reabsorption phase; changes in the program have made it advisable to examine this portion of the cycle in greater detail, and modifications to one channel of the apparatus are under way to permit detailed examination of the reabsorption phase. These results will be reported at a later time.

Upon completion of these modifictions, the remaining two CE channels will be dedicated to long-term cycling to determine the usable lifetime of compressor elements under operational conditions; this is a critical parameter for the cooler design, as it determines by what factor BOL performance must be above the EOL requirements, with ramifications on launch mass, power requirements, and thermal radiator sizing. These tests are expected to begin in the summer of 2000.

IV. Summary

We have constructed an apparatus to test three compressor elements of a design to be used in the PLANCK sorption cooler. Initial results for the thermal behavior of the compressor elements as regards power and mass requirements indicate significant margin in the design. The $La_{1.01}Ni_{4.78}Sn_{0.22}$ hydriding alloy shows storage capacity essentially at the theoretical limit, no evidence of intrinsic or extrinsic contamination, and excellent reversible storage capacity. The hydride results are thus a strong indication that the starting material and handling and construction techniques are adequate to provide for good hydride life. The pressure-temperature

function relating the rate of gas released from the CEs has proven to be more complex than anticipated, but the reasons for this are understood and operational methods to take advantage of the behavior are under development. In all, we have gained significantly more information from this effort than was expected at inception, and anticipate considerably more as the apparatus capabilities are extended.

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Table 1. Storage capacity (x) for $LaNi_{4.78}Sn_{0.22}H_x$ hydride in the LCE beds

	LCE#1	CE#2	LCE#3
1st Reaction	6.00	6.00	5.99
2nd Reaction	6.00	6.01	6.00
3rd Reaction	6.00	6.00	6.00

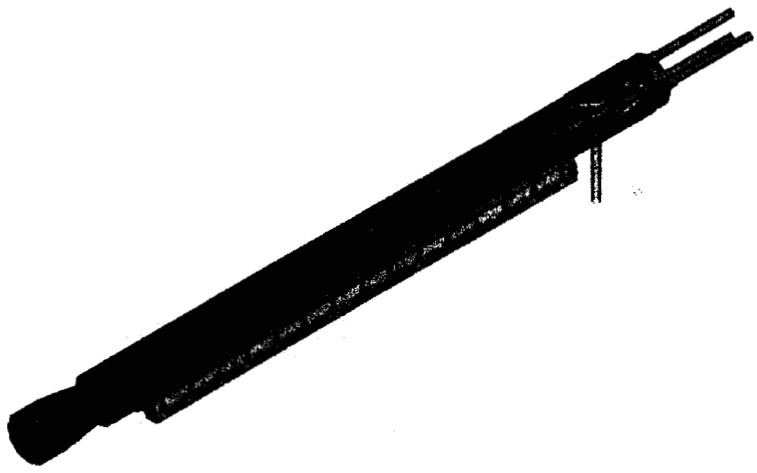

Figure 1. Cutaway view of single compressor element,showing outer shell, inner vessel, gas-gap switch port, and three access penetrations.

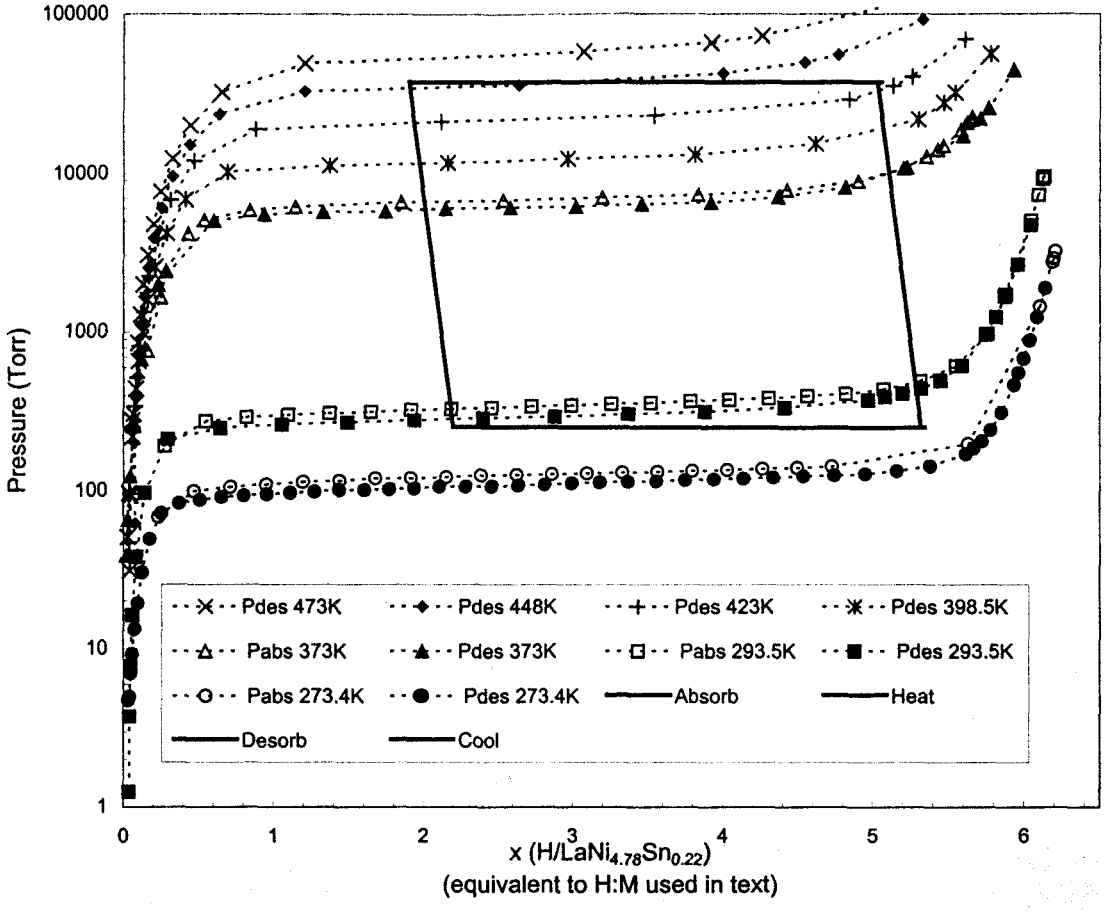

Figure 2. Van t'Hoff plot of equilibrium isotherms for the alloy chosen. The boundry of the trapezoidal region shows the path in P:x space followed by the compressor element: Heatup begins in the lower right, with large H:M and low pressure, moves to high temperature with small change in H:M as high-pressure hydrogen gas fills the ullage volume, remains at constant pressure with decreasing H:M as hydrogen is desorbed at constant pressure, returns tolow pressure with small change, and returns to initial condition as hydrogen is reabsorbed at constant pressure.

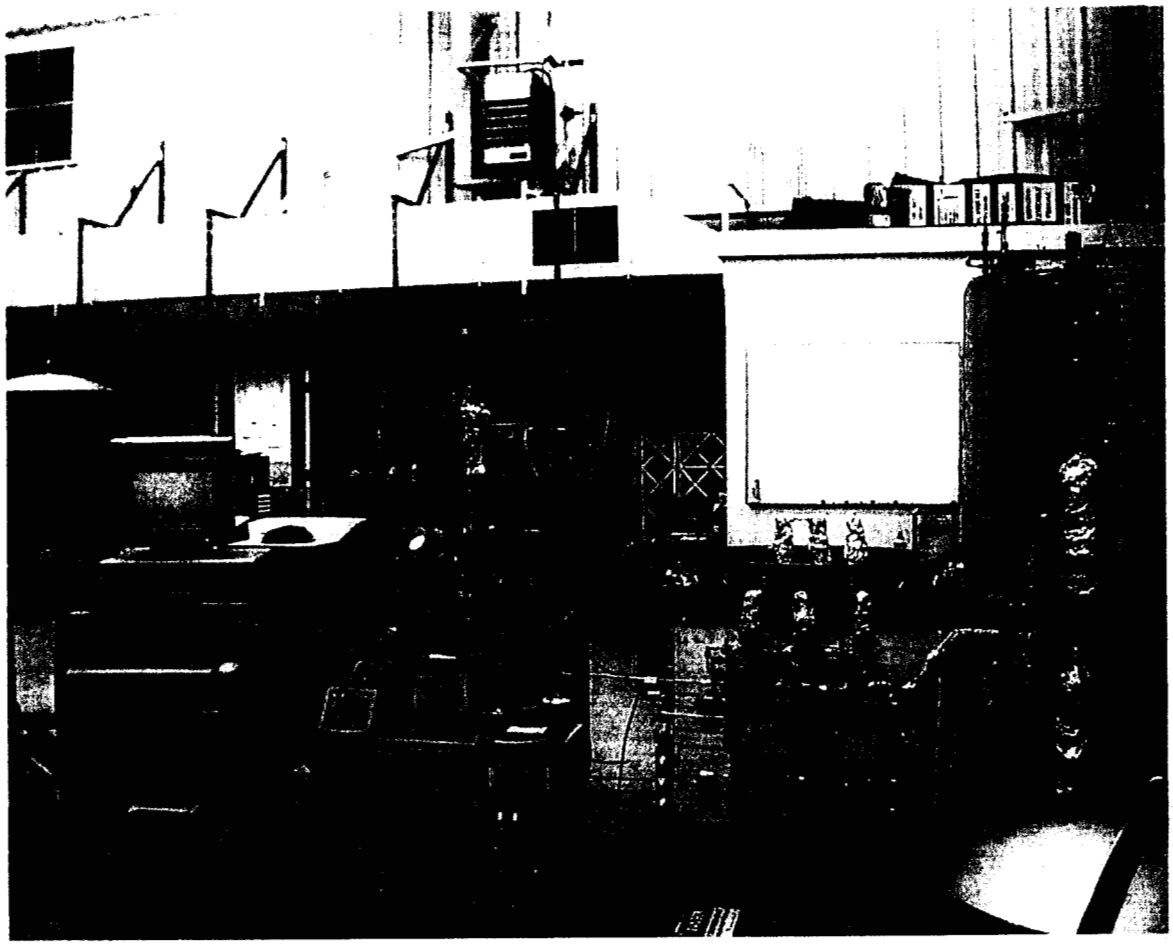

Figure 3. The LifeCycle apparatus

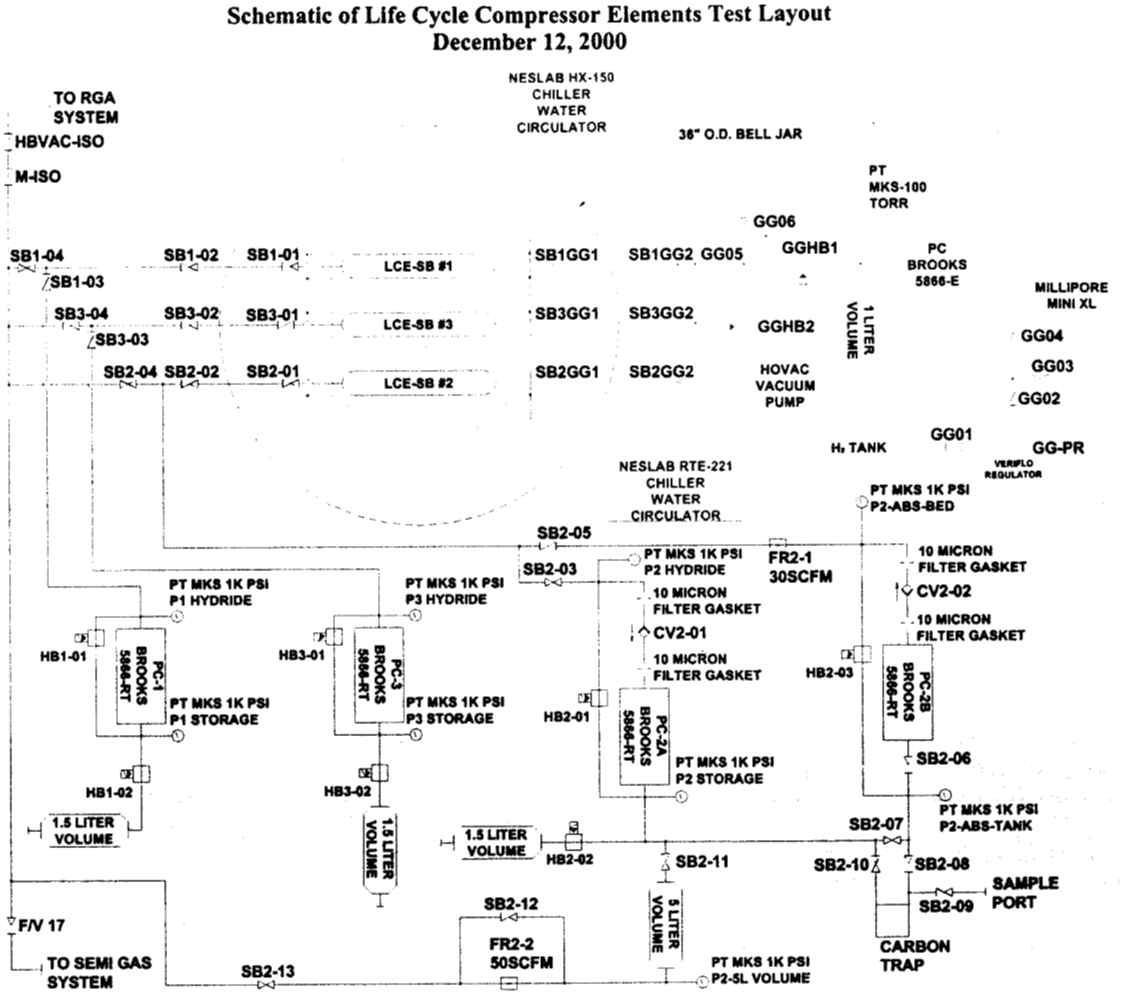

Figure 4. Schematic of LifeCycle apparatus gas handling system

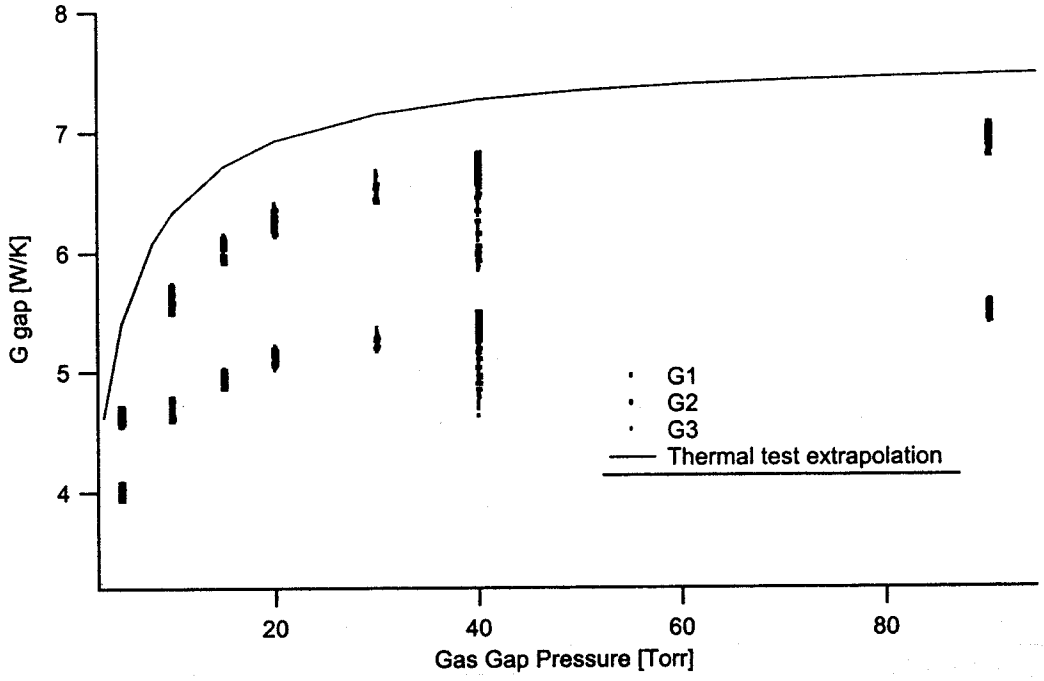

Figure 5. Conductance of the gas gap for the three compressor elements; CEs 2 and 3 are indistinguishable. The deviation measured for CE 1 is believed to be a thermometry problem.

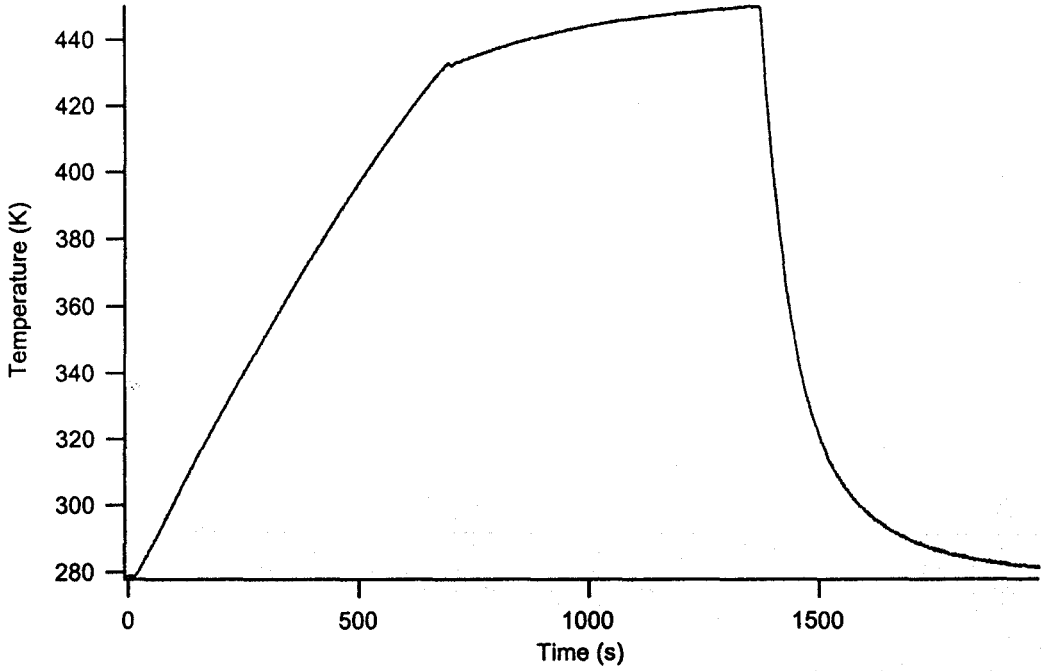

Figure 6. Time-temperature profile for heatup phase, desorption phase, and cooldown phase for CE#1. Each phase occupies 667 seconds in the present implementation.

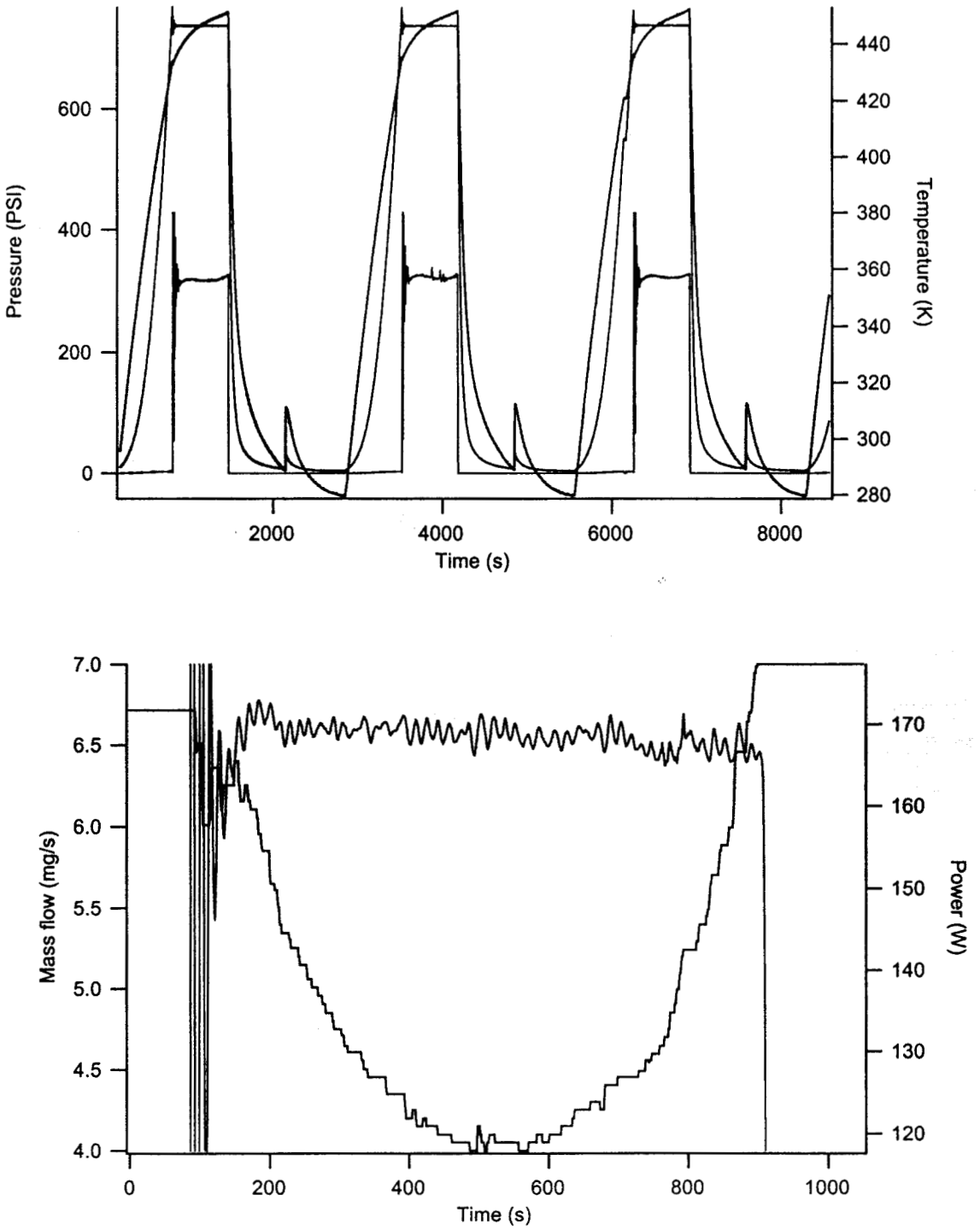

Figure 7. a) time dependence of the pressure, temperature, and mass flow from CE#1; b) the power profile and resulting mass flow. The mass flow is constant to within 1%, except for the large spike at the beginning of the desorption phase, which is due to oscillation in the valve controller.