Sorption Cryocooler Development for the Planck Surveyor Mission

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ABSTRACT We are developing metal-hydride based sorption cryocoolers for the Planck Surveyor mission. The sorption coolers work by thermally cycling a metal-hydride to absorb and desorb hydrogen gas, which is used as the working fluid in a Joule-Thomson refrigerator. Pressure ratios of 100:1 or more can be achieved by varying the temperature of the compressor by a factor of 2–3. The major advantages of sorption coolers are that they are truly vibration-free and can be readily scaled to perform over a wide range of cooling powers. We present here a review of sorption cooler operation, important factors in the design of coolers, and the details of the design of a 20 K cooler system for the Planck mission.

KEYWORDS: sorption, cryocooler, Joule-Thomson, metal hydride

1 INTRODUCTION

Increased use of cryogenic detectors in astrophysics applications, particularly in space missions, is driving the development of long-lived, closed-cycle cryocoolers in order to provide continuous low temperatures without the need for stored cryogens. Closed-cycle coolers can have significant advantage over stored-cryogen by substantially reducing the payload mass required to achieve a desired temperature on-orbit, while at the same time increasing the lifetime of the cryogenic mission. The reduced mass can result in much smaller launch costs and leave a larger part of the mass budget available for improved science instruments, if desired, and the increased lifetime has obvious benefits for the science return from a given mission.

Mechanical cryocoolers are somewhat more developed for aerospace applications, but they suffer from two major disadvantages relative to sorption coolers. They produce mechanical vibrations, which can produce spurious signals on ultra-sensitive cryogenic detectors, and they are limited in scalability: they cannot be reduced below a certain minimum mass and input power due to limitations in the ability to fabricate the moving parts. Sorption cryocoolers, which use physi- or chemisorption to pump and compress the working fluid in a Joule-Thomson cryocooler, eliminate both of these problems, while maintaining the beneficial properties of closed-cycle, continuous cryocoolers.

Sorption coolers have been in terrestrial use for many years and operate over a wide variety of temperature ranges. Typical applications include charcoal-pumped helium refrigerators used in low temperature physics laboratories. Recently, however, with the 1996 flight of the Brilliant Eyes Ten Kelvin Sorption Cryocooler Experiment (BETSCE) [1] aboard the NASA Space Shuttle Endeavour, sorption cryocoolers have been demonstrated to work in a microgravity environment. BETSCE demonstrated a single-cycle, re-usable sorption cryocooler for achieving temperatures near 10 K by using $LaNi_{4.8}Sn_{0.2}$ and ZrNi sorbent beds with hydrogen gas (solid hydrogen at low temperatures) as the working fluid.

We are developing an 18 K continuous-cycle sorption cryocooler based on similar materials for the Planck Surveyor mission to map the anisotropy of the cosmic microwave background. The cooler will provide 20 K cooling of the Low Frequency Instrument, as well as providing 18 K precooling for the colder stages of the High Frequency Instrument.

2 Metal Hydrides and the Cooler Cycle

Metal hydrides, which are the basis for the compressors used in the Planck coolers, obey a pseudo vapor pressure equation $\ln P = B - A/T$, where P is the effective vapor pressure of hydrogen, B and A are constants, and T is the temperature of the material. The materials typically show some hysteresis, and the values for A and B are slightly different for absorption and desorption. What makes the metal hydrides useful is that the pressure of the hydrogen can be varied over a very wide range by relatively small temperature changes. As can be seen in Figure 1, the pressure can be varied between 0.1 bar and 100 bar with a temperature change of only 240 K (from 273 K to 513 K). The absorption of hydrogen by all practical storage alloys involves the release of heat (i.e., exothermic reaction) that must be removed if the sorbent is to remain isothermal. When two solid phases (i.e., the starting metal and hydride phases) are present, the hydrogen pressure remains nearly constant as hydrogen is either added or removed at a fixed temperature as shown in Figure 1. The long-term stability of a sorption cryocooler is primarily defined by the repeatability in the hydrogen absorption and desorption of the sorbent alloy during temperature cycling. At higher temperatures and pressures most hydrogen storage alloys exhibit internal disproportionation reactions involving formation of more stable phases (i.e., LaH_x) that greatly alter the absorption pressure and storage capacity.

The primary method to select an alloy for a sorption compressor is based upon the equilibrium pressure-composition-temperatures (PCT) plots of the hydrogen absorption and desorption. The pressure range given in Figure 1 for $LaNi_{4.8}Sn_{0.2}H_x$ is particularly attractive for use in the compressor beds of sorption coolers used to produce cold tip temperatures around 20 K. The pressure plateaus in Figure 1 are

FIGURE 1. Absorbtion Isotherms for $LaNi_{4.8}Sn_{0.2}H_x$.

broad and reasonably flat, which promotes both good reversible storage capacity and uniform cold-stage temperature. Additionally, tin substitution has been shown to greatly enhance the stability of the hydride phase during thermal cycling [2], which is the factor most likely to limit performance life of the compressor. Due to these properties, $LaNi_{4.8}Sn_{0.2}H_x$ was selected as the sorbent for use in the sorption compressor beds for the Planck mission.

The properties of the sorbent material used in the compressor directly affect the performance of the cryocoolers. The reversible hydrogen storage capacity defines the size and mass of the sorbent beds necessary to provide a given amount of hydrogen. The base temperature and efficiency of the Joule-Thomson refrigerator being driven by the compressor is a function of the low-pressure sorption pressure; a lower pressure of absorption at a given temperature will enable the refrigerator to reach a lower cold-tip temperature. The heat of desorption determines the heater power necessary to extract the stored hydrogen from the sorbent, and the degradation and reversibility properties determine the ultimate lifetime of the sorption compressor.

The rigorous requirements being imposed on the temperature stability at the cold-stage of the Planck sorption coolers raises issues with the sorbent materials. Deviations in alloy composition and stoichiometry can significantly alter both the absorption-desorption plateau pressures and their slopes across hydride composition. The preparation of high- purity and very homogeneous alloys is thus necessary if appropriate operating cold-tip temperatures are to be achieved and maintained while a bed absorbs hydrogen. It is also important to optimize the Sn content in the $LaNi_{5-y}Sn_yH_x$ alloy between $0.2 < y < 0.3$ to ensure that operating conditions are satisfied and to enhance robustness during thermal cycling. While the $LaNi_{4.8}Sn_{0.2}H_x$ alloy showed no sign of degradation from tests in the BETSCE project, the much more extended (i.e., $\sim 10^4$ cycles per year) temperature cycling of the beds for the Planck coolers require more thorough characterizations of degradation behavior under conditions that simulate compressor bed operation.

The box labelled A-B-C-D overlaid on the sorption isotherms of Figure 1 indicates an idealized sorption cooler cycle. A continuous-cycle sorption compressor system is made by running several individual sorption compressors, each filled with metal hydride, in parallel. The individual compressors in a continuous system are phased so that there is always at one compressor desorbing at high pressure to supply gas to the Joule-Thomson expander, and at least one compressor absorbing to maintain the low pressure side of the system at a constant pressure. A typical system will be composed of a number of individual compressors so that some may be heating and cooling while the others absorb and desorb.

3 Planck Cooler Design

Figure 2 shows a schematic of a complete sorption cooler system that will be used on the Planck spacecraft. Two identical systems will be used to provide redundancy and eliminate the sorption cooler as a single-point failure mode. The compressor assemblies, comprising the two complete sets of compressors along with their ballast volumes, check valves, and electronics systems are located on the warm spacecraft bus. The assemblies are attached to a radiator that cools passively to 280 K in order to provide a heat sink for cooling the compressors to their adsorption temperature and exhausting the heat of absorption. Each assembly is composed of five identical sorption compressors, each filled with metal hydride and provided with a gas gap heat switch for coupling to and decoupling from the 280 K radiator.

Each compressor is connected to the high and low pressure sides of its plumbing system through check valves (indicated in the figure by arrows, which indicate the direction of flow), which allow gas flow through the system in a single direction only. In addition to the compressors, there is a high-pressure ballast tank connected to the high pressure side of the system to damp out oscillations of the high pressure gas, and a sixth sorbent bed, held at the absorbing temperature of the other five, but always open to the low pressure side of the system to damp out pressure fluctuations of the low pressure gas. At any time, one compressor is hot and desorbing, one compressor is cooling down, one compressor is heating up, and two compressors are cold and absorbing. By cycling each of the beds through the possible states, we can maintain continuous cooling.

All regulation of the sorption system is done by simple heating and cooling, with no active control of valves being necessary. Normal operation of the compressors can be done with only a minimum of active feedback: The heaters for the compressors

FIGURE 2. Schematic of the Planck sorption cooler system.

are controlled by a simple timed on-off heater system. In addition to the on-off heater power, each heater will have up to 30 W of additional heating supplied by a proportional controller in order to compensate for degradation of the hydride which might occur, as well as fluctuations in the spacecraft supply voltage.

The hydrogen flow lines pass through the intermediate radiators, cooled passively to 170 K, 105 K, and 57 K. This provides precooling of the hydrogen gas to the final radiator temperature of 57 K before passing through the J-T and cooling by expansion. The intermediate radiators, which are part of the telescope's passive cooling system, are arranged as v-grooves[3]. The cryostat assembly is comprised of the Joule-Thompson (J-T) expansion orifice, followed by three sequential heat exchangers. Hydrogen gas at high density, precooled by the last radiator stage, expands through the orifice, with a significant fraction of the fluid condensing as liquid. Some of the liquid is held in the first liquid reservoir (LR#1), which provides 18 K precooling for the RAL cooler. The reservoir has the form of an annular ring of sintered stainless steel with an axial hole, located within the tubing of the gas loop; heat is absorbed at the outer wall, evaporating hydrogen which flows back to the absorbent bed. Excess liquid beyond that required to saturate the first reservoir flows to the second (LR#2), which cools the LFI directly. A third reservoir (LR#3) is maintained above the hydrogen critical temperature, to flash any liquid which reaches it, providing an even flow of gas back to the sorbent bed. Each of the heat exchangers is filled with a high-surface-area wicking material in order to retain the liquid in the reservoirs without gravity. A tube-in-tube counterflow heat exchanger is located between the last liquid reservoir and the coldest passive radiator in order

FIGURE 3. Mechanical drawing of a single compressor for the Planck cooler.

to recover enthalpy from the exhaust gas stream.

The interface of the hydrogen sorption cooler with the lower temperature stage coolers provides the precooling required for efficient operation of the J-T expansion of helium in the RAL 4K cooler. High-pressure helium gas is supplied by a mechanical compressor located remotely; this fluid must be cooled to approximately 18 K. The temperature at this stage is the most demanding requirement on the sorption cryostat. The thermal interface is a simple block of conductive material on the RAL heat rejection stage, to which the first hydrogen heat exchanger is attached by mechanical fasteners. The L'Air Liquide dilution cooler for the HFI detectors interfaces thermally only to the RAL cooler, which allows precooling of the helium isotopes to 4 K and provides a cold thermal enclosure within which the dilution unit operates.

A single compressor bed, shown in figure 3 is comprised of two concentric cylinders closed with end caps. The inner of these tubes contains the hydride material and the outer forms a vacuum jacket around the inner cylinder. This vacuum jacket is used as a gas-gap heat switch by alternately filling and evacuating the jacket region. The single compressor beds are structurally fully redundant as a consequence of this double wall construction. Each compressor bed is 45 cm long and has an outer diameter of 3.8 cm. The hydrogen gas for the gas-gap heat switch, which will be described later, is supplied through a tube protruding from the side of the outer cylinder. A vent tube passes through the center of the hydride material to allow gas to flow out to the cryostat assembly. This vent tube is fabricated from sintered 316 stainless steel, and has a sub-micron porosity, which prevents the powdered hydride from entering the gas flow lines.

A helically shaped heater tube is located with the center line of the helix concurrent with the centerline of the device, passing through the hydride material.The helix provides a high large contact area between the heater and the hydride media, leading to good temperature uniformity. The additional length, as compared to straight heaters lowers the power density in the heater and increases the heater life life, with each unit length of heater under lower loads. Additional heat conduction to the hydride is provided by aluminium foam that fills the inner cylinder and makes a tight contact with the heater. The foam is 89% empty, and is cut to allow penetration by the various other components which are located in the inner cylinder.

The heater, thermocouple, and vent-tube leads run from the end cap of the inner cylinder to that of the outer cylinder. Each has a small bend for stress relief, isolates them from the launch load path. Therefore, the only elements taking significant load are those designed to be structural, load carrying elements. There are two of these structural end supports: one at either end of the tube assembly. At one end provision is made for thermal compliance, without strain, between the inner and outer tubes.

The outer tube assembly is primarily fabricated of 6061-T6 aluminum. This is done for ease of conduction between the outer tube and the thermal sink to which the outer tube is attached. This outer tube also provides the primary structural attachment point for the single compressor bed. Electrical and plumbing attachments are handled from the three tubes at one end of the device described earlier.

Nearly all of the parts of the compressors and the gas-handling system which come in contact with hydrogen are made of 316L vacuum arc remelt stainless steel which has been electropolished on the surfaces exposed to the hydrogen. This choice of material also serves to prevent the degradation of the compressors structural parts by reaction with the hydrogen. There are two components which are made of other materials. The aluminium foam, which provides heat conduction to the hydride in the compressor, and the seals of the check valves, which are made of viton.

The gas gap heat switch[4] is used make and break thermal contact between each of the compressor beds and the radiator, by varying the pressure in a narrow gap over several orders of magnitude. Two regimes are distinguished by different ranges of the Knudsen number, defined as the ratio of the mean free path of a molecule to a characteristic dimension, in this instance the distance between the two surfaces. Knudsen numbers above 1 correspond to a mean free path larger than the distance between the plates so that collisions with the walls are more likely than collisions with other molecules; this is the molecular regime. When the Knudsen number is below 0.01 intermolecular collision predominates and the heat transfer is determined by the momentum transfer in the gas: the regime is called the viscous or continuum regime. Above a certain pressure, determined by the molecular characteristics, the thermal conductivity approaches a constant value. For Knudsen numbers between the two limits the transition regime is defined.

The two order of magnitude variation in Knudsen number across the transition regime corresponds to roughly two orders of magnitude change in the thermal conductance. A gas gap heat switch will operate primarily across this regime by changing the pressure (density) of the gas between two surfaces. The switching is performed by varying the pressure of a gas which has a high thermal conducttivity and can be reversibly stored. Hydrogen and hydrides are a suitable combination;hydrogen has a very high thermal conductivity and hydride materials capable

FIGURE 4. Gas-gap heat switch configuration and thermal circuit schematic.

of reversible hydrogen storage are readily available.

The general configuration of a gas gap heat switch is shown in Figure 4.

At least three hydrogen storage materials will be tested for potential use in the Planck compressors: Uranium, ZrNi and SAES St172. The SAES St172 alloy has already been tested and used as a reversible hydrogen pump for up 500 cycles with no substantial changes in the behavior. It can also be manufactured in single, mechanically solid pieces, eliminating the need for porous containers to retain the hydride. Each gas gap heat switch is expected to draw less than 10 W and maintain a temperature difference across the gap of about 7-8 K.

A dynamic numerical simulation of the compressor system has been developed and used to determine sizing of the compressor beds and predict their performance. The model is run using the SINDA/FLUINT [5] Thermal Analyzer with special FORTRAN subroutines to include the details of the hydride properties, and divides each bed into circumferentially symmetric nodes, with 90 axial nodes and 8 radial layers for each compressor. The details of the model account for simultaneous adsorption and desorption in different parts of the compressor due to pressure and temperature variations in the compressor.

The only forcing functions of the model are the heaters and gas-gap heat switches, both of which are simple on-off functions which switch at prescribed times. The model simulates the response of the system to the timed heating and cooling of the compressor beds, which are coupled to each other via the ballast tank, the cold-head, and the check valves, which open and close based on instantaneous pressure differences between the compressors and the ballast tank (high pressure side), or the compressors and the cold head (low pressure side). Cryostat details have not yet been included in the model, but will be developed to match the real cryostat design as it develops. The cryostat model and the compressor model can then be coupled and used to predict the performance of the complete system as built and under various other conditions.

Figure 5 shows the compressor pressure, the high-pressure ballast tank pressure,

FIGURE 5. Predicted behavior of the Planck compressor system.

the heater power, and the compressor temperature for a single compressor as a function of time for the system starting from a cold start. The other compressors start and stop on their regular schdules, resulting in the 800 s period of oscillation of the pressure in the high pressure ballast tank, but data for only one individual compressor are shown. At the beginning of the cycle, the heater goes on at 165 watts to heat the compressor up to its desorption temperature. The temperature and pressure of the bed and high pressure tank can be seen to rise as the compressor heats. At 800 s, the heater power is reduced to maintain a constant pressure in the compressor during desorption. The pressure of the high pressure bed can be seen to settle down to oscillations about 59.25 atm, with the range of variation about 1% of the total pressure. The hydrogen gas flow at the cold tip is the product of the mass flow rate and the cooling power per unit flow rate. Both of these increase with increasing pressure, resulting in a 2% variation over the 800 s cycle. The temperature variations of the cold head cannot be accurately predicted without knowledge of the heat capacity at the cold head, but by by using high heat-capacity materials can be reduced to a smaller fraction than the variations in the cooling power. Measurements made on the breadboard system will be used to compare to the model and produce further refinements of the model's ability to predict real performance.

Some aspects of the real system are not included directly in the model, but have been accounted for in the system design and will be monitored as the system is built and tested. The system is expected to degrade slowly over a period of years, reducing the reversible storage capacity of the hydride; it has been oversized by 50%

in order to make up for the expected rate of degradation and provide the expected 5 year lifetime of the cooler system. The inherent slope of the hydride pressure plateaus, combined with the degradation of the hydride is expected to lead to a slow increase in the cold-head temperature. Adding proportional control to the compressors to maintain constant pressure (rather than constant temperature), as well as regulating the temperature of the cold-head, has been baselined to alleviate this. We also expect that degradation of the emissivities in the gas gap heat switch will lead to higher heat losses from the compressor. A 20% margin has been added to the heater power, which, when combined with the proportional control, should be sufficient to maintain compressor performance for the full mission lifetime.

4 Summary and Conclusions

We have presented the general principles of sorption coolers and details of the development of the metal hydride sorption cooler system for the Planck mission. The coolers will provide continuous 18 K and 20 K cooling for the HFI and LFI instruments, respectively. Very complete numerical models have been developed to aid in the design of the coolers. The breadboard compressors are presently in fabrication and will be used for life testing of the materials and performance testing of the design.

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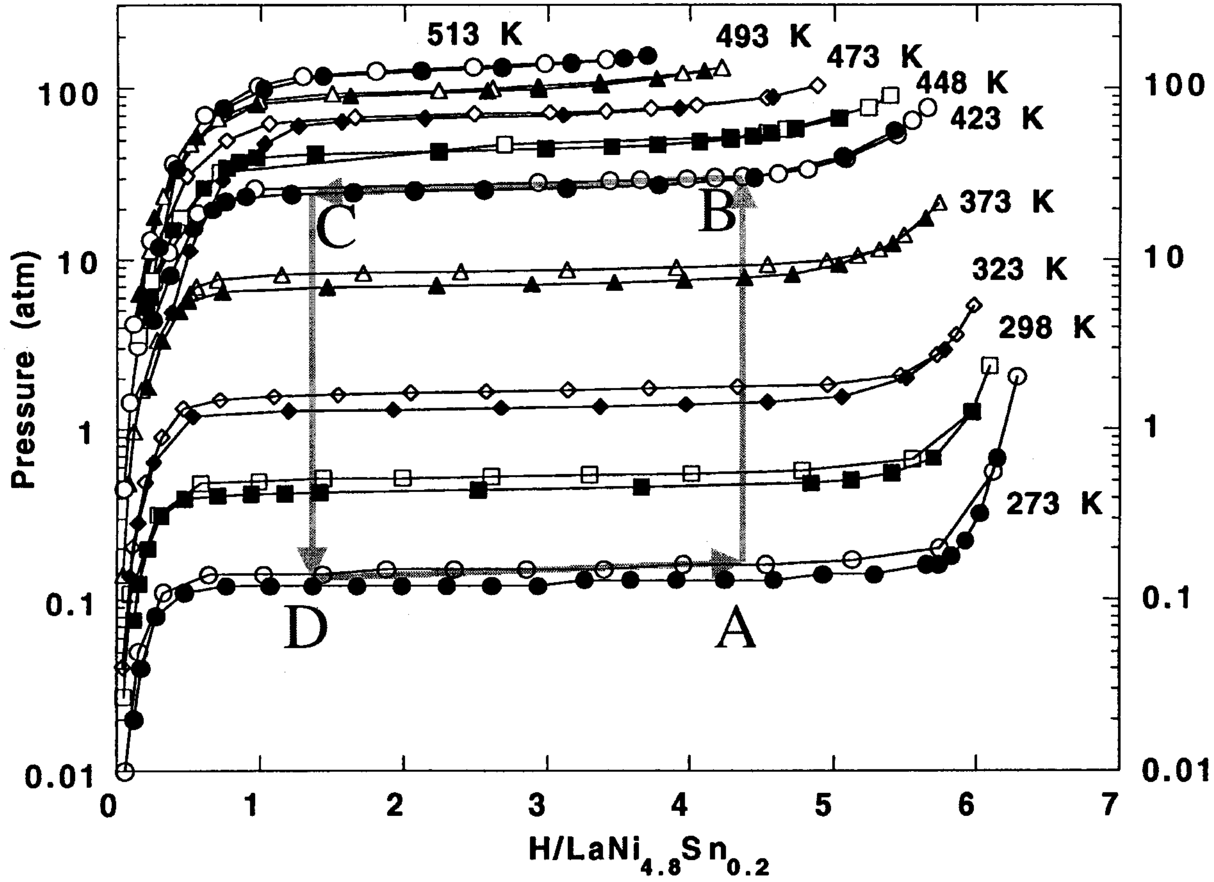
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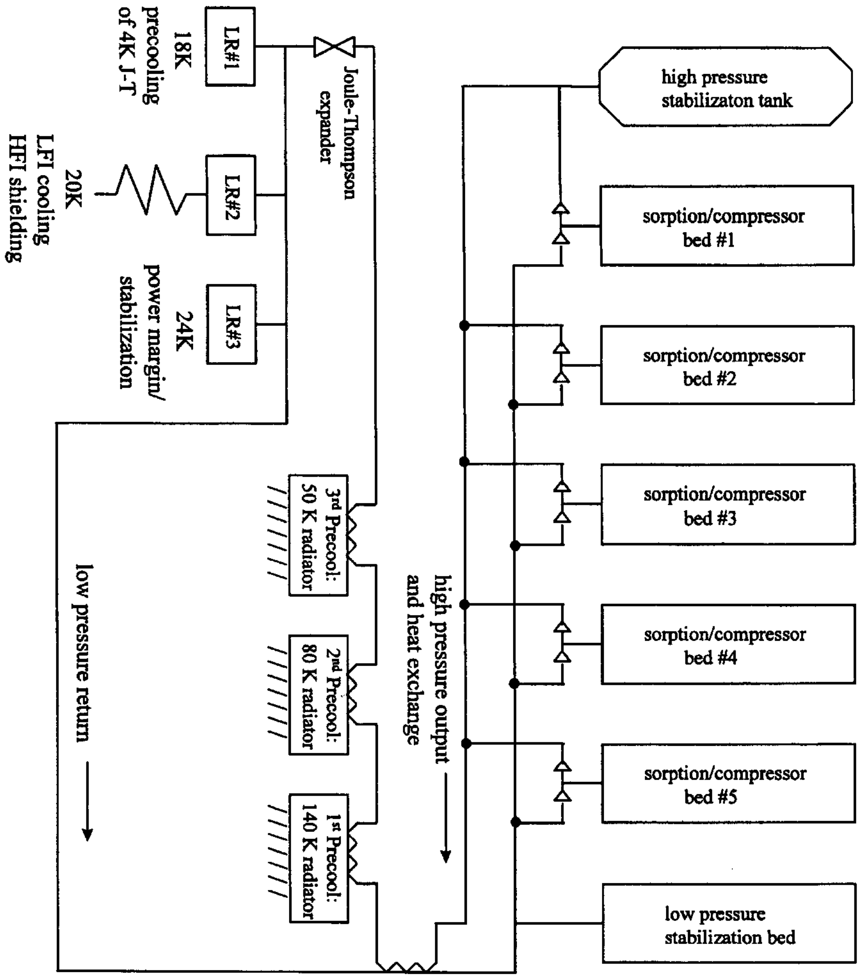
493 K
473 K
448 K
423 K
373 K
323 K
298 K
273 K
A
B
C
D
Pressure (atm)
0.01
0.1
1
10
100
0
1
2
3
4
5
6
7
H/LaNi$_{4.8}$Sn$_{0.2}$

Fig 1


high pressure stabilizaton tank
sorption/compressor bed #1
sorption/compressor bed #2
sorption/compressor bed #3
sorption/compressor bed #4
sorption/compressor bed #5
low pressure stabilization bed
high pressure output and heat exchange
low pressure return
Joule-Thompson expander
LR#1
LR#2
LR#3
18K precooling of 4K J-T
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24K power margin/ stabilization
3rd Precool: 50 K radiator
2nd Precool: 80 K radiator
1st Precool: 140 K radiator

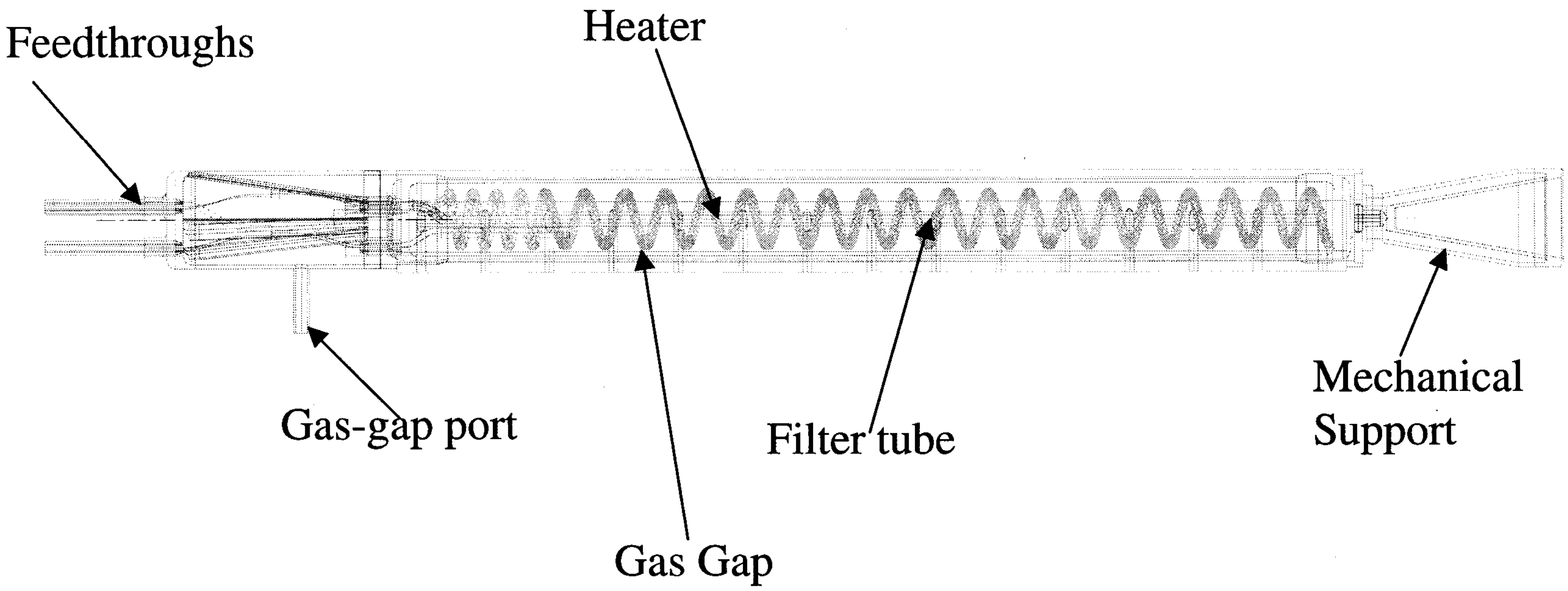
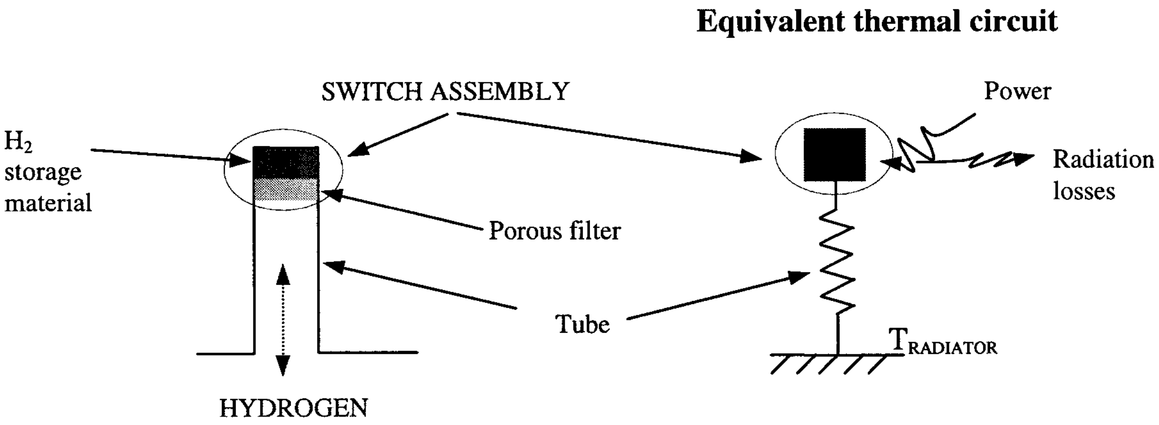

Feedthroughs
Heater
Gas-gap port
Filter tube
Mechanical Support
Gas Gap

Fig 3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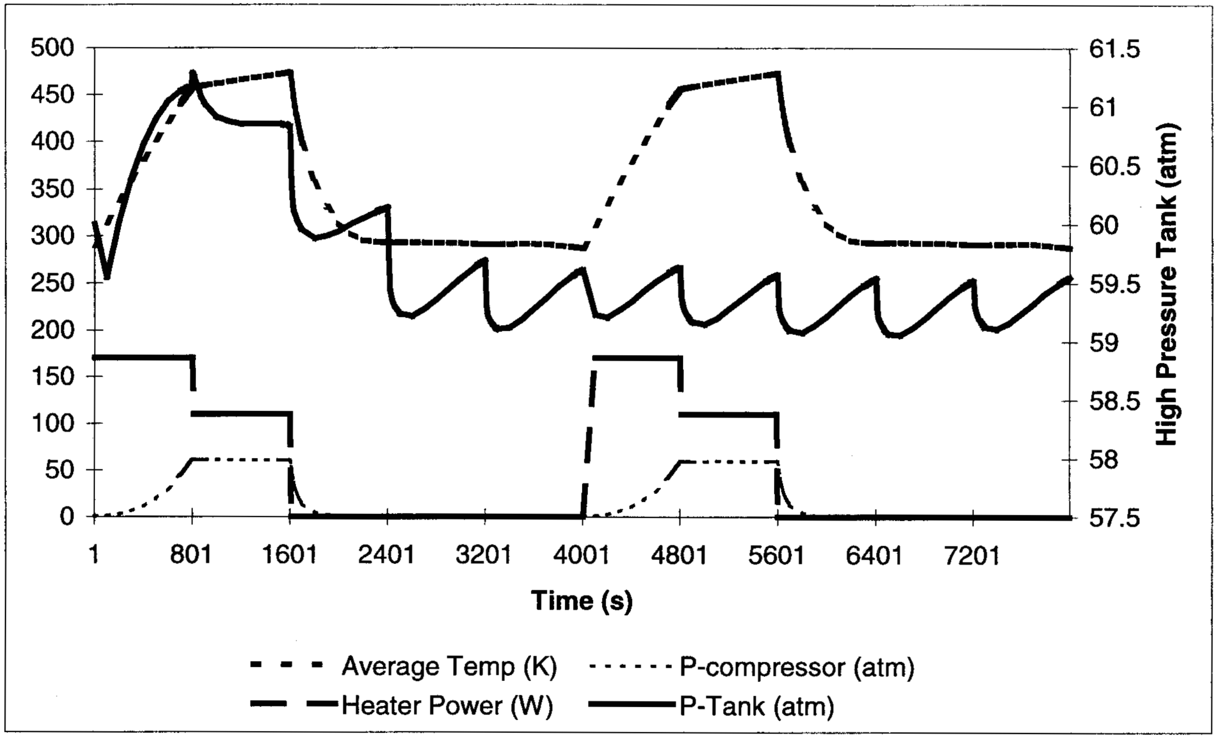
H_2 storage material
Porous filter
Tube
HYDROGEN
Power
Radiation losses
$T_{RADIATOR}$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3201
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4801
5601
6401
7201
Time (s)
61.5
61
60.5
60
59.5
59
58.5
58
57.5
High Pressure Tank (atm)
Average Temp (K)
P-compressor (atm)
Heater Power (W)
P-Tank (atm)