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ABSTRACT

HPF is an ultra-stable, precision radial velocity near infrared spectrograph with a unique environmental control scheme. The spectrograph will operate at a mid-range temperature of 180K, approximately half way between room temperature and liquid nitrogen temperature; it will be stable to sub-milli-Kelvin(mK) levels over a calibration cycle and a few mK over months to years. HPF's sensor is a 1.7 micron H2RG device by Teledyne. The environmental control boundary is a 9 m^2 thermal enclosure that completely surrounds the optical train and produces a near blackbody cavity for all components. A large, pressure-stabilized liquid nitrogen tank provides the heat sink for the system via thermal straps while a multi-channel resistive heater control system provides the stabilizing heat source. High efficiency multi-layer insulation blanketing provides the outermost boundary of the thermal enclosure to largely isolate the environmental system from ambient conditions. The cryostat, a stainless steel shell derived from the APOGEE design, surrounds the thermal enclosure and provides a stable, high quality vacuum environment. The full instrument will be housed in a passive 'meat-locker' enclosure to add a degree of additional thermal stability and as well as protect the instrument. Effectiveness of this approach is being empirically demonstrated via long duration scale model testing. The full scale cryostat and environmental control system are being constructed for a 2016 delivery of the instrument to the Hobby-Eberly Telescope. This report describes the configuration of the hardware and the scale-model test results as well as projections for performance of the full system.

Keywords: Cryostat, environmental control, precision radial velocity, Habitable-zone Planet Finder

1. INTRODUCTION

One of the principal requirements for precision radial velocity (RV) instrument is a high degree of stability in the full optical train. As such, it has become standard practice to fiber-feed these instruments so that they are away from the telescope and to enclose the optics in a vacuum chamber (see *Figure 1*) to essentially eliminate convective and minimize conductive connection to the ambient environment. Even with a well-executed vacuum environment, thermal stability likely remains the main source of environment-related RV errors; there are also mechanical, vacuum quality, vibration, and other environmental influences that can detract from the theoretical RFV precision. Other major components of the error budget (for bright sources) are calibration precision and scrambling to reduce modal noise. Though the latter two are of order similar to environmental influences as contributors to RV precision, no further discussion of them will be

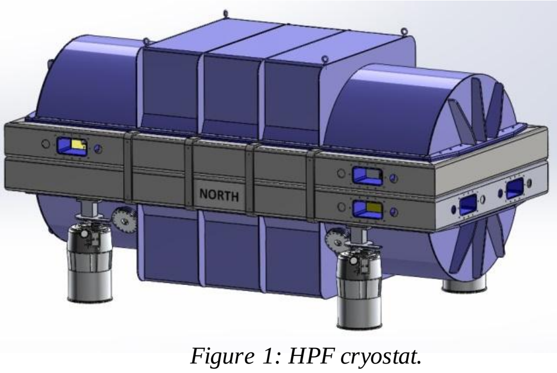

Figure 1: HPF cryostat.

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included in this work. Related HPF contributions to these Proceedings are provided for each of these topics.

Section 2 of this report summarizes the thermal control approach and its implementation, and then provides component-by-component descriptions. Section 3 provides the empirical results of scale model testing. Section 4 provides conclusions and planned activities in the near future.

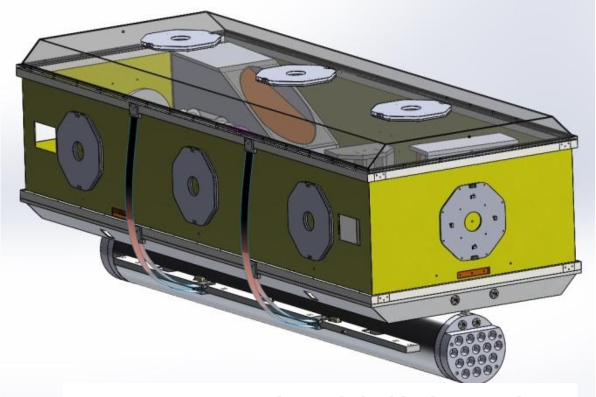

Figure 2: HPF Thermal shield (shown with transparent upper hood) with heater panels, thermal straps, and LN2 tank.

2. CRYOSTAT AND THERMAL CONTROL SYSTEM

A cryogenic vacuum chamber houses the HPF optics and detector systems in a moderately high vacuum environment to allow the system to be cooled to around 180K and remain stable thermally. The H2RG detector is designed to be a low noise system when operated at below about 120K. The thermal background must also be maintained at sufficiently low temperature to ensure that thermal blackbody radiation is sufficiently suppressed for the 1.7µm cut-off detector. Moderately high vacuum ($<10^{-6}$ Torr) is also essential for eliminating thermal convection or gross molecular transport of energy which would preclude thermal stability at the mK level. The cryogenic vacuum system with a 180K system operating temperature, plus a cold finger directly coupled to the liquid nitrogen reservoir meets the full set of these operating constraints. *Figure 1* shows the solid model of the cryostat. The system design is based on the APOGEE cryostat which is in long-term, stable operation at Apache Point Observatory.

2.1 Technical approach and system overview

Thermal stability at mK levels: provided by an actively controlled thermal shield which completely surrounds the optical bench and all mounted components including the detector system. See *Figure 2*. Control is provided by custom temperature monitoring and heater driver electronics (described below) developed by Matt Nelson of the University of Virginia (UVa) IR instrument group. The thermal control system involves a thermal shield heat balance consisting of thermal radiation at about 2.5-3watts/m^2 (a relatively stable heat source shown as curve in *Figure 3*) and heaters positioned around the thermal shield providing approximately 0.3 watt/m^2 as the variable heat source (octagonal, surface-mounted shapes in *Figure 2* and represented as small double-ended arrows in *Figure 3*). Thermal straps to the LN2 tank provide the heat sink (four of 16 shown); these straps are slightly over-sized to balance the input radiation, with the thermal equilibrium temperature settling at 5-10K below the desired operating temperature (three strap

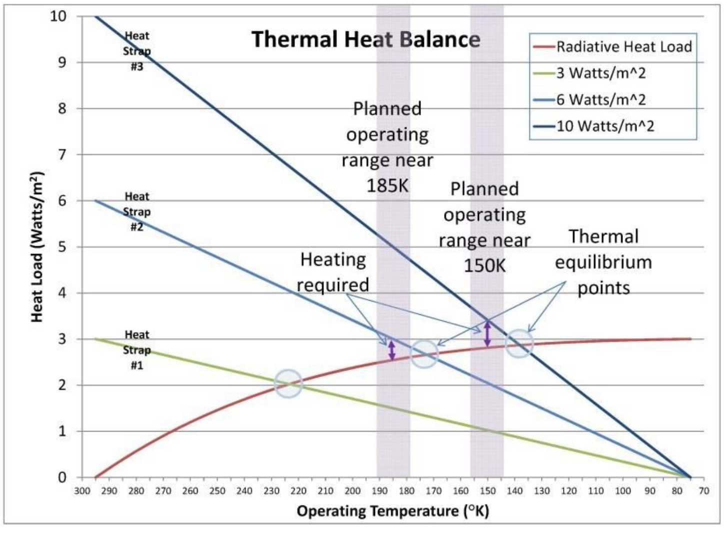

Figure 3: Thermal heat balance showing three selected sizes of thermal straps and their thermal equilibrium points(intersections circled) with radiative heat loads (lower curve).

sizes illustrated below), so the variable heaters are used to make up the difference. *Figure 3* illustrates this balance; strap #1 is too small for a useful operating temperature, strap #2 is sized for operation near 185K, and strap #3 is sized for 150K. HPF will operate at or near 180K and straps will be sized accordingly at about 1.5 watts each.

Mechanical stability: a rigid, flat optical bench is provided for mounting optical components and the detector system. This bench is a simple surface that allows straight-forward integration of massive components like the grating, camera, and off-axis parabolic mirrors. The bench is surrounded by a light-tight thermal shield which both serves as a stray (thermal) light barrier, but also as an environmental control boundary. Environmental controls prevent temperature-induced changes to the opto-mechanical system. The optical bench and radiation shield are suspended from the box beams by thermally and mechanically isolating flexures. The LN2 tank is not connected in any rigid manner to the optical bench, so mechanical load changees in the tank due to boil-off are not transmitted to the bench. The bench will be supported with a three-point (possibly four-point) mount that is attached to the frame of the cryostat. The cryostat is floated on air legs to minimize vibration of optical components.

Normal operation: the LN2 tank is the ultimate heat sink for the environmental control system; it is also is directly connected to the detector via a cold finger. As such, the LN2 tank thermal stability is required to be significantly better than availed by nominal LN2 saturation temperature variations experienced when an LN2 tank is vented to ambient; barometric pressure causes temperature variations of 100-200 mK on hour timescales. To avoid ambient barometric pressure effects, the HPF system LN2 boil-off is passed into a manifold to warm the cold gas, and then through an absolute pressure-referenced back-pressure regulator which maintains upstream (LN2 saturation) pressure stable to about 1% of nominal atmospheric variability. This steady saturation pressure in the LN2 tank will yield a correspondingly stable saturation temperature which is expected to be of order a few mK variation (~1% of ambient) over long time scales.

Action	3-Way Valve (#1)	Warm-up Valve (#3)	3-Way Valve (#2)	HPF Xfer Valve (#4)	Warm-up Valve (#5)	Backpressure
Fill Storage Dewar	Energized Fill Dewar	Deenergized closed	Deenergized Vent LN2	Energized open	Energized closed (after 180s)	Auto Throttled
Standby	Deenergized Fill Tank	Deenergized closed	Deenergized Vent LN2	Deenergized closed	Deenergized open	Auto Throttled
Fill LN2 Tank	Deenergized Fill Tank	Energized open (60s)	Energized Press LN2	Deenergized closed	Deenergized open	Auto Throttled

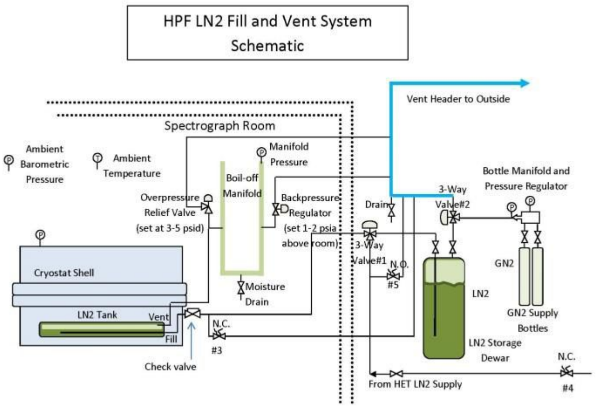

Figure 4: Fill and vent system plumbing diagram.

The LN2 system is also supplied with an auto-fill system to maintain the LN2 tank (~100 liters) mostly full in an effort to further stabilize the heat sink temperature; after 24 hours of boil-off at about a 15 liters/day rate, the partially empty tank will be refilled each morning after daily calibrations. Cold charges of LN2 will also be used, if necessary, to minimize the thermal transient caused by filling via warm lines and with 'warm' LN2 (at 2-3 atmospheres saturation pressure/temperature). Additional testing will be conducted to evaluate the necessity for this additional set of precautions. *Figure 4* shows the piping system necessary for auto-fill and cold charging of LN2.

Cooldown and heatup: cooldown of the massive optical bench is accomplished by a LN2 circulation line that is attached at various points to the underside of the optical bench. Cooldown without a forced heat removal system would otherwise be by radiation cooling to the thermal shield; this radiative cooling mode would require 2-3 weeks to achieve operating temperature, too long for reasonable control of required testing and maintenance cycles. By flowing LN2 through the circulation line, cooling to near operating temperature is expected to take approximately 2 days. At least one week will then be needed for system to equilibrate and stabilize at planned operating temperature. Cooling systems will be sized to avoid the possibility of the detector cooling at rates greater than a fraction of a degree per minute.

Maintenance access: the lid and bottom of the cryostat are removable without disturbing the optics for instrument integration and subsequent maintenance. O-rings seal each cover to the box beams. Corner jacks will be used to suspend the cryostat while the bottom is removed and/or during normal maintenance access.

2.1.1 Temperature monitoring

The UVa temperature sensing solution is based around a fundamental excitation circuit that has been in use at UVa on various instruments for a combined service life of over a decade. The basic sensing solution is based on a constant current drive of a forward biased diode. The ideal diode equation can be manipulated to show that the forward voltage drop on a diode driven with a constant current is inversely linearly dependent on the voltage of the diode junction. This type of temperature sensor has several advantages over other sensor types such as resistive temperature devices (RTD's), and thermocouples. In particular the devices can be driven at very low drive currents while still producing a macroscopic voltage that is relatively easy to measure without significant design of a signal conditioning and amplification circuit. That same large signal also allows for a significantly lower calibration problem due to large cabling impedance common to cryogenic applications. The low drive current and large signal also allows for application of a diode sensor with a 2-wire connection vs. 3 or 4-wire connections common to other devices, providing in-situ calibrations of the devices are done. Finally, calibration is far simpler in that the device response is linear, and multipoint calibrations are not needed for accurate results over a fairly broad range of temperatures. The circuit designed for this combines a temperature compensated constant current source with an 18 bit Sigma-Delta A/D converter with a programmable gain amplifier. In practice this setup run with a gain of 4 provides A/D coverage over the temperature range of room temperatures to LN2 temperatures with unresolved noise in the system, and 1.2 mK resolution. (Plot can be provided if needed). Enough data has also been collected to determine that room temperature swings of a few K in the compensation circuit are not detectable in measurement results at the mK level.

The board utilizes 4 separate excitation circuits combined with an analog multiplexer and 4 input A/D converter to provide coverage of a total of 16 sensors. One sensor is reserved for measurement of the circuit board temperatures, allowing 15 separate sensors per board on the instrument.

The diodes used are 1N914/1N4148 devices which are embedded in either a small copper or aluminum block with thermal epoxy. These devices have proven reliable over many years of service, but could be easily replaced with diode sensors specifically built for cryogenic temperature sensing.

In addition, the devices used are based off the I2C instrument bus, and can be jumper programmed to different addresses allowing up to 4 boards to co-exist on the same bus to allow for a large number of sensors. In addition the board carries a secondary A/D converter with full differential inputs allowing for various other sensors such as strain gauges and thermocouples to be added easily. Some of the inputs can also be used for sensing of on-board environmental sensors for relative humidity and barometric pressure. Mounting for one of two different barometric sensors is provided.

2.1.2 Heater control

The heater circuit currently being used at UVa for the scale model tests is a new design based on a power op-amp and a power sensing IC. The idea was to provide a low power driver with a smooth linear output instead of an on/off or power chopped circuit, both of which could broadcast significant noise inside an instrument. The power sensing IC measures current across a sensing resistor, as well as the high side voltage driving the heating element. It then combines both voltages to provide a control signal proportional to the power being dissipated by the heating element.

This control signal is then provided to the - input of the op-amp as a feedback signal. The + input is controlled by an on-board 16 bit D/A converter, and it is this signal that then provides a linear power control for the heating element.

The board itself has 8 separate channels corresponding to the 8 outputs of the D/A converter which is controlled over the I2C instrument bus mentioned in the previous section. Cost implementation is in the range of $20-$30 per channel plus board costs of about $40 each, and multiple boards can be controlled on the same bus similarly to the previous section.

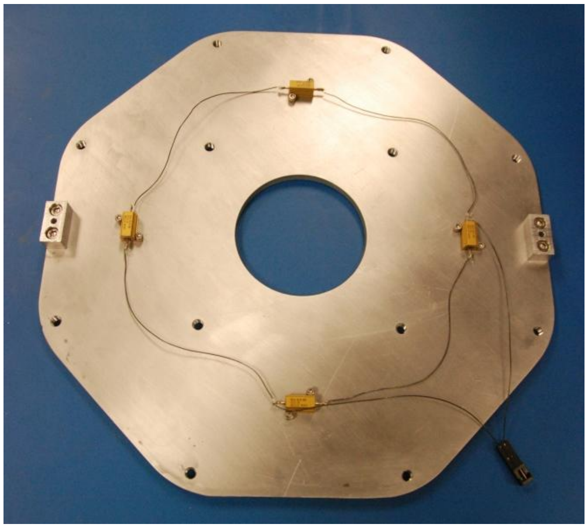

Figure 5: Heater control panel with set of Vishay 5watt power resistors. A protective cover plate will protect separate the heaters and wiring from the MLI blankets. The controlling temperature sensor will be opposite the large center hole on the inside of the thermal shield wall.

Overall Implementation: The full PID feedback control of the system happens entirely in software which has already been developed at UVa and is currently running the test setup (described in Section 3), and is based around software components that have been in use for many years. Compute power is not significant due to the low data rates needed for this type of control, and can be anything from a low cost embedded processor to a small PC.

2.1.3 Heat source (resistive heaters)

A set of four wire wound power resistors (Vishay Dale) are mounted to an octagonal base plate to constitute an interchangeable heater element. See *Figure 5*. Kapton thin film heaters could also be used, but difficulties with replacing a faulty unit advised for a different approach. The set of 5 watt heaters will only operate at 1-2% of heater rating – the heaters are connected in parallel-series so that the overall resistance matches the original scale model tests that used a single heater. The base plate also distributes the power delivered and acts as a low-pass thermal filter for the very slow response needed in the operational system. Control temperature is sensed on the opposite side of the thermal shield wall as seen by the optical train. A thin aluminum cover is employed over the heater element to protect the wiring and MLI blankets. Fourteen heater elements will be employed in the HPF design; another several channels of thermal control are to be available for emergent control needs. 24 total channels (three 8-channel boards) of heater-driver electronics will be installed. Temperature monitoring will consist of 30 total channels of the UVa electronics (two 15-channel cards) along with at least one Lakeshore eight channel monitoring unit which will serve as an independent thermal standard.

2.2 Heat sink (LN2 tank via thermal straps)

LN2 tank is suspended off of the box beams and is physically located below and outside of the lower cover of the thermal shield. The tank has charcoal getter assemblies mounted to its ends, and is completely enclosed in MLI blankets to minimize thermal (radiation) losses to ambient. The tank is mounted on G10 hangers which break the thermal conduction path while allowing the distal from fill/vent connections end of the tank to thermally contract approximately a centimeter along it long axis when cooled to LN2 temperature. The tank is serviced by a fill and a vent line and is maintained at or slightly above atmospheric pressure. Level monitoring and control are provided by a dedicated system as used for the APOGEE cryostat.

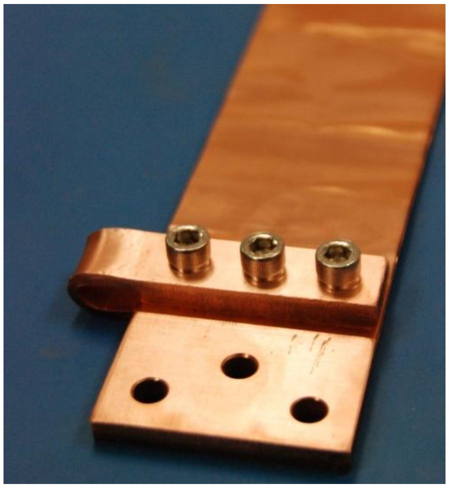

Figure 6: A terminal block on a thermal strap.

A set of 16 thermal straps, sized for about 1.5 watts each to provide a 180K operating temperature, are provided to connect the LN2 tank below fluid level (the ultimate heat sink is the LN2) with a distributed set of attachment points on the thermal shield. Since there is more potential thermal uniformity provided by a larger number of attachment points, a trade was made with the number of straps required to achieve thermal performance specifications and the operational constraints of a large number straps. Section 2.7 below shows the results of this choice. *Figure 6* shows the terminal block for a single strap; the three bolts clamp a set of copper ribbons sized for the thermal load expected.

The thermal shield (*Figure 2*) is a 3003 Al enclosure which is actively controlled thermally to provide a stable environment for the optical system and optical bench which are fully enclosed by it. The shield is surrounded by MLI blankets to reduce radiation heating of the shield to around 3 watts/m^2. Mounted to the outside of the shield (approximately every 0.6 m^2) is a heater element with a temperature sensor inside the shield opposite the location of the heater; this heater/sensor combination allows for precision thermal control of this location on the shield, independently of every other such part section of the shield. The thermal shield is suspended in the cryostat by thermally resistant mountings to the optical bench; since there is minimal differential temperature between the bench and shield, little if any conductive heat flow is experienced between these components. The stable thermal configuration of the shield provides an unchanging radiative environment for the optical system, eliminating any thermal driver that could change the temperature of the system.

2.4 MLI blankets

12-layer MLI blankets will cover the entire thermal shield, as well as the thermal straps. A separate set of blankets will also be used on the LN2 tank to minimize LN2 boil-off and excessive LN2 usage. Thermal modeling which assumed 12-layer blanket throughout showed the top and bottom panels of the thermal shield to run hotter than the rest of the shield as a result of the thermal strapping being unevenly distributed between the sides and top of the shield for practical accessibility reasons (the area per thermal strap is almost double on top and bottom compared to side panels). To mitigate the uneven temperature distribution, the upper hood blankets will be double thickness (24 layers); the modeled performance of the bottom panel did not account for the large solid angle obstructed by the LN2 tank which is essentially will supply zero thermal radiation because of the underlying LN2 tank temperature. Lab tests will reveal if additional thermal insulation of the bottom panel will be needed. Based on the blanket design and thermal performance experienced by APOGEE, a net thermal load of approximately 30 watts is expected for the entire HPF system.

2.5 Vacuum shell and vacuum control

The vacuum shell is a stainless steel welded, 3.0m x 1.4m x 1.5m, 2.5mT enclosure that, along with the LN2 tank, forms the vacuum boundary of the cryostat. The shell consists of three pieces: 1) the box beams which include of two layers of 0.15m x 0.20m stainless square tubes which are welded together and are penetrated by a series of penetrations for fibers and instrument services, 2) the lower hood which surrounds the LN2 tank and lower portion of the thermal shield, and 3) the upper hood which surrounds the upper portion of the thermal shield.

A pair of oversized charcoal getters are attached to the LN2 tank ends, outside of the thermal shield as shown in *Figure 2*. A small thermal shield covered with small MLI blankets will radiatively isolate the getters while still allowing molecular transport via a labyrinth system. Since the tank is maintained in the mostly-full state for long term operations, the getters remain at LN2 temperature and in full operational use. An identical design in APOGEE has allowed a three-year operational run with vacuum maintained better than 1 x 10^{-6} Torr. Dual pressure indicators monitor vacuum performance. Long-term quality vacuum is essential for maintaining the stability of the HPF optical system.

2.6 Spectrograph enclosure

An insulated room will house the spectrograph at the HET. This room will be passively maintained, with outside room temperature being controlled by HVAC to 16+0.5C. No heat source(s) will be allowed in the room, so the enclosure will act as a thermal buffer to the thermal cycling of the HVAC system. The floor will be concrete slab with significant thermal mass which will act to stabilize internal temperature. Electronics cabinets and LN2 systems will be outside of the room and are represented as the boxes and tanks on the facing wall. HEPA filters will be installed in the room in case the instrument needs to be opened for maintenance; normal operation will be with HEPAs off.

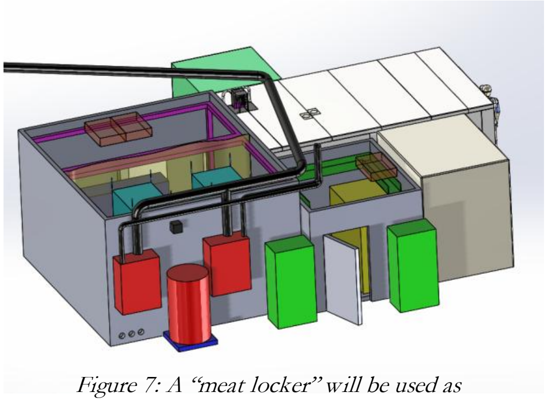

Figure 7: A "meat locker" will be used as the spectrograph enclosure in the lower level off the HPF. Room is illustrated as open-topped large room. A smaller room will house all calibration equipment including the laser frequency comb.

All calibration systems, including the laser frequency comb, will be housed in an adjacent room that will be actively cooled if necessary. As in the main spectrograph enclosure, all electronics cabinets will remain outside of the room.

2.7 Thermal modeling

SolidWorks thermal modeling was used to evaluate thermal profiles and performance of the thermal shield. These models allowed various configurations of thermal straps and heater placements to be optimized, and thermal gradients to be minimized. Figure 8 shows an optimized thermal profile of the thermal shield; blue thermal straps are installed to represent the heat sink and heater panels set at operating temperature of 180K are shown in the design position.

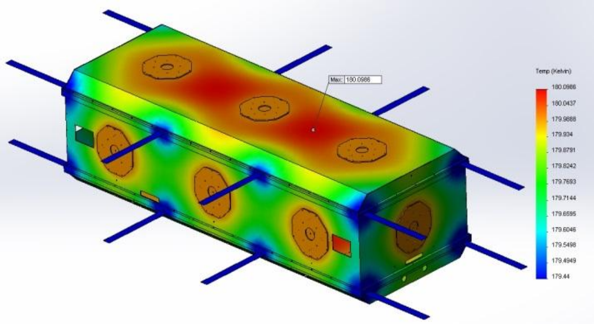

Figure 8: A terminal block on a thermal strap.

Modeling results show only a 0.6K temperature spread from coolest points (179.5K) where thermal straps attach to warmest(180.1K) at 'hot spot' which is furthest from thermal strap attachment points. The warmer top and bottom will be mitigated somewhat as described in MLI section above. Even with stable temperature distributions as shown, the optical bench as modeled shows no perceptible thermal gradient (<0.1mK). A 1K ambient change produces 10mK change in the 'hot spots' but no measurable change in the optical bench temperatures.

Empirical results from the scale model tests validate this model.

3. SCALE MODEL TESTING

Overview:

The following brief summary and referenced figures document a series of tests done at UVa to test the thermal control scheme envisioned for HPF. The 1/3rd to 1/4th scale model tests of the HPF environmental enclosure ("the box") have were conducte over a year-long period. The model itself was constructed as an analog of the thermal shield and optical bench in HPF; the temperature monitoring and heater control electronics were refined during this year to near-flight (final) configurations. *Figure 9* (attached) shows the test apparatus and labels some of the discussed components.

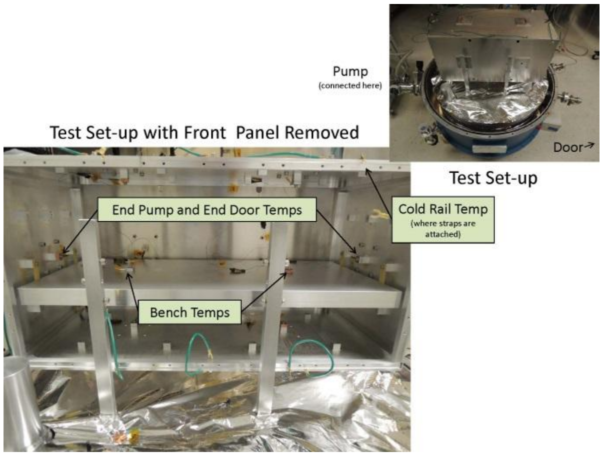

Figure 9: Scale model test apparatus.

Cooldown of test apparatus:
Cold Cycle #1 ran from November 2012 until early-December and was near stability for only a few days. Cold Cycle #2 began in mid-December 2012 and ran for over six months; cooldowns took several weeks to reach stability, demonstrating the need for forced cooldown (with LN2) of the bench in the designed HPF "flight" system. Bench was stabilized by adjusting wall temperatures in an exponential hunt around the approximate bench temperatures (absolute temperature calibration not accurately done for bench sensors) until stable temperatures were achieved. Operation at a repeatable control temperature (say 180K) was shown to require improvements in sensor calibration as well as some procedural requirements to achieve this operational constraint in a reasonable short time after cooldown starts.

Controlled zone temperature stability: All controlled zones (one foot square areas of the box with heater panel and temperature sensor at its center) achieved 1-3mK stability over durations of order a few 10^2s (five to ten minutes) and <1mK over durations over 10^3s (twenty minutes). The shorter duration fluctuations are insignificant control system patterned hunting. Stable temperatures were achieved within 5-10 minutes of step changes and maintained indefinitely except for two unplanned control computer freeze-ups. A new control computer was installed and no additional anomalies were seen over a six month period. See *Figure 10* for a typical five day stretch of testing.

Cold rail stability: The cold straps attach around the edges of the box onto what we call the cold rail – a thickened frame of the box for attaching the walls to each other (box monocoque design is similar to the thermal shield in flight hardware design) and distributing the cold sink effect more evenly. The cold rail is the furthest in distance, and thus temperature, from the controlled zone temperature sensor. This temperature fluctuation provides a sense of the maximum departure of the environmental enclosure from a black body cavity as the "tilt" of the temperature gradient varies. The cold rail varied of order 10mK daily and a similar amount over 5-10 minutes during LN2 tank fills. Major reasons for this fluctuation are:

a. LN2 tank level decreases and corresponding cold plate temperature increases of 300-400mK/day due to boil-off and the heat load on the cold plate. See Figure 4. The configuration of the test apparatus is different in a significant way than the flight LN2 tank configuration in that the cold straps tap

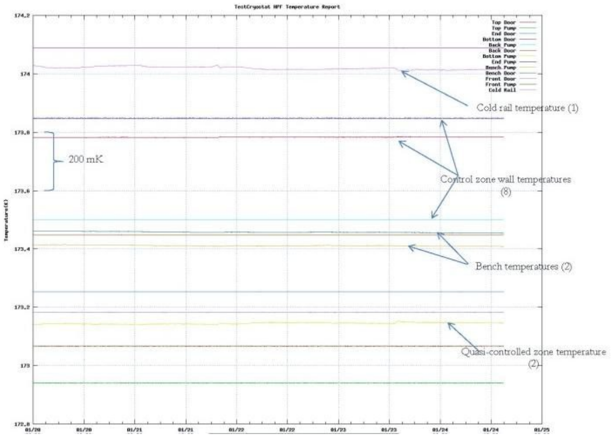

Figure 10: Five days of a test run.

off of the “unwetted” cold plate in test configuration and the LN2 level falls away from the cold plate in between fills, whereas in the flight configuration, the cold straps will tap off below the liquid level of the LN2 tank. The heat sink temperature seen by the straps will not vary due to boil-off between fills in this configuration.

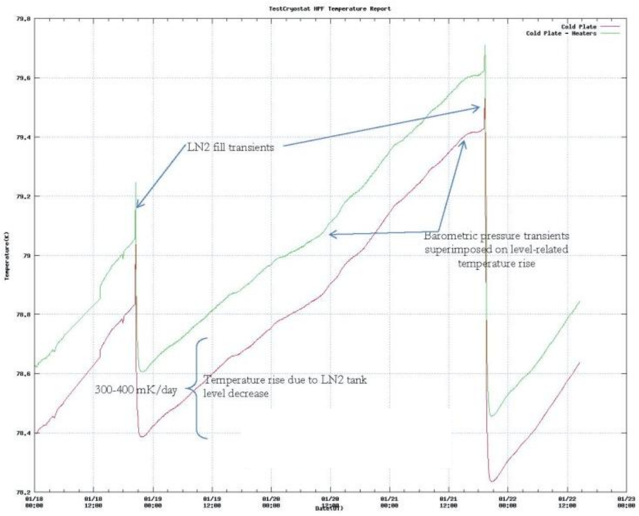

Figure 11: Thermal transients caused by LN2 tank fills and cold plate above liquid level. These transient will have mitigation measures in HPF.

b. Barometric pressure changes caused LN2 saturation temperature to vary by ± 100mK per day. These changes were superimposed on the steadily rising cold plate temperature due to tank level effect described above. See figure 4.

c. Short duration spikes of 200mk in LN2 tank/cold plate temperature were seen during LN2 tank “warm fills.” See *Figure 11*. (Although this temperature spike had little effect on enclosure or bench temperature in this test set-up, the flight configuration will (and APOGEE does) experience significant temperature spikes on the detector which is tightly coupled thermally to the LN2 tank.) The LN2 storage Dewar being used to resupply the experiment is auto-pressurized to 20-25psig with its own boil-off as is standard practice in LN2 systems. This causes the saturation temperature of the stored liquid to rise by a few K above the experiment LN2 saturation temperature which is dictated by (much lower) barometric pressure in the lab. An alternate, more traditional explanation of the temperature spike is due to “hot” gas flowing across the surfaces of the tank during fills as the hoses and hardware come down to LN2 temperatures during the fill. In the flight configuration, the supply Dewar will be kept at ambient pressure/temperature until a fill is initiated. GN2 will be used to quickly charge the storage Dewar as the motive force for filling; this quick pressurization will sub-cool the liquid (temperature significantly below saturation temperature) and prevent the temperature spike in the LN2 tank. When the fill is completed, the storage Dewar will be vented again to atmosphere. A pre-fill cooldown of the fill piping may also have to be implemented if the latter explanation is operative.

d. Print through on cold plate temperature of 3-5mK per 15-20 minutes was seen due to UVa lab ambient temperature changes affecting the walls of the test Dewar. This high frequency, small magnitude fluctuation should have no impact on either the scale model or the flight configuration systems; a longer-term drift in spectrograph room temperature (e.g. seasonal) could have a long term impact. Probably the biggest cause of this print-through is the poor MLI design around the cold plate which eventually was rectified. Another flight configuration mitigating action will be that the spectrograph room will be a thermally controlled “meat locker” which will be subject to a fraction of the ±1-2K room temperature variations in the UVa lab and the direct impingement of the HVAC exhaust on one side of the test Dewar shell.

All of these parameters, individually and collectively changing heat sink thus cold rail temperature, did not preclude our achieving bottom line bench temperature stability as described below.

Bench Stability: This bottom-line component demonstrated <1 mK stability for stretches of a day and 1-3mK for a multi-week period during which there were no upset conditions (temperature had reached equilibrium, control system operating stably, vacuum stable below 10^{-6} Torr). ***It is almost trivial to maintain better than 10mK and it is possible to achieve the goal of 1mK bench stability with our environmental control scheme on a scale model bench that has a factor of a few smaller mass-to-area***

ratio than the flight configuration (which makes the scale model a factor of a few less stable – i.e. in the conservative direction).

Long-duration stability testing revealed three additional factors that must controlled to achieve our mK stability goal for year-long timeframes. These factors are as follows:

a. **Control computer/software/electronics robustness**: This integrated system must be developed with multi-year, stable operation in mind. See Figure 3. Although upsets and/or system failures do not have severe consequences, in that the system can be easily recovered to near-original conditions, the long time-constants of the system may result in several weeks of lost observations or observations outside of the planned mK stability regime. Ongoing system stability enhancements and additional long-duration stability testing will address or at least inform the magnitude of this systemic failure mechanism. Final configuration will also require a dedicated UPS to power the entire environmental control system, including heaters, for hours to days.

b. **Vacuum quality:** This parameter has arisen as a significant factor in achieving design stability. High quality vacuums (better than a few x 10^{-6} Torr, for example) allowed the successful results recorded above. When vacuum deteriorated to the worse than 10^{-5} Torr, though, the cold straps and isolated bench were “short circuited” by molecular transport and the bench temperature drifted increasingly rapidly to 10mK/day and beyond as vacuum deteriorated. In the test box case, this drift was toward colder temperatures, though MLI changes (and the flight configuration) could easily result in this drift being toward warmer temperatures. Flight hardware is being designed to use the APOGEE-heritage oversized charcoal adsorbers (getters) that have provided a stable vacuum at better than 1 x 10^{-6} Torr for 1.5 years and running. This should completely mitigate the HPF vacuum quality issue.

c. **Frontal barometric pressure changes:** There were two significant rapid frontal passages during the extended test. During both of these events the control system was unable to manage required temperature stability on the bench. It is uncertain why these fluctuations with a large dP_{atm}/dt led to worse stability compared to the cold plate daily fluctuations from cryogen boil-off. However, there is a strong correlation and stabilizing cryogen temperatures to this effect may be essential for overall bench temperature control.

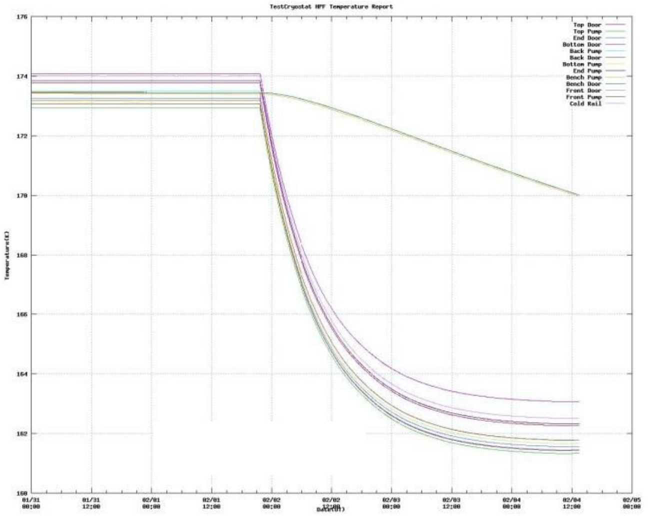

Figure 13: Back-to-nature transient after de-energizing control system.

Back-to-nature test and warm-up of test apparatus:

Due to deteriorating vacuum, Cold Cycle #2 was terminated by de-energizing temperature control electronics. See *Figure 13*. Wall temperatures were allowed to drift downward to the natural thermal equilibrium point around 162K while the bench lost about 1K/day; no further LN2 fills were conducted, allowing the LN2 tank to boil dry on February 5th and temperatures then to rise. See *Figure 14*. Once charcoal adsorber temperature reached about 140K, the trapped gas in the adsorber was released and vacuum deteriorated to around 100mTorr – peak heat-up rate was induced by molecular transport immediately followed this release. Peak rate achieved was <0.1K/minute on the walls which have the highest area-to-volume ratio (possibly a good limiting case for detector back-to-nature heat-up rates). Around five days were required for box and bench temperatures to reach ambient after vacuum rose to the 100-200mTorr level. See Figure 8. Figure 9 shows the bench and wall temperatures at ambient with no control and a poor vacuum to illustrate the nominal environment.

Conclusions:

The HPF environmental design scheme appears to be capable of establishing new thermal stability standards for large-scale experimental apparatus. Scale model tests to date have demonstrated the capability to achieve mK stability over durations of months, which is a good start but a factor of 10 short of the requisite long-term performance. A number of improvements are being implemented based upon the results of testing which should continue to improve the final system design.

Confidence in long-term performance will also be gained through long term thermal testing of the final system before optics are installed.

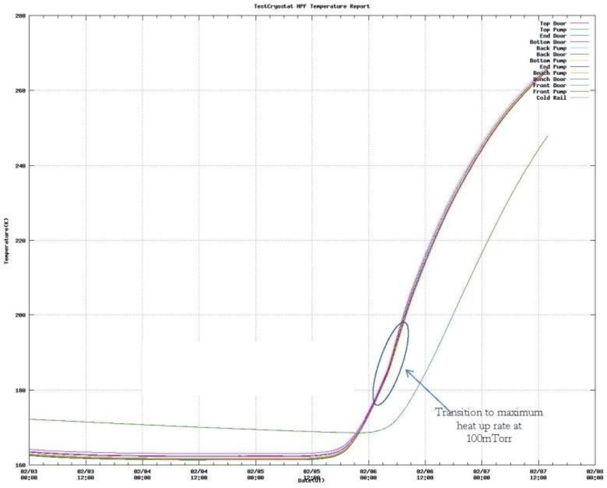

Figure 14: Back-to-nature transient after running out of LN2.