Cryostat Design and Construction at the IRTF

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Abstract

Over the past 6 years the instrumentation team at the NASA Infrared Telescope Facility(IRTF) has designed and built 3 major facility instruments, two cameras and a spectrometer, for use by the infrared astronomical community. We will report on many new techniques for cryostat construction that have been developed that deviate from traditional practices. These include aluminum electron beam welded vacuum and cryogenic enclosures, rectangular cryostat formats, use of closed cycle coolers and their performance, use of all aluminum structures, optimization of cryogenic performance without super insulation, activated charcoal getters, and opto-mechanical mounting. Cryostat performance data and methods for estimating cryostat performance will also be included.

Introduction

Detecting infrared radiation for detailed scientific study is much like locating a dropped pin at a rock concert. Noise due to the background radiation from ambient temperature optical systems swamps the small infrared signal of interest. As infrared detectors improved, background levels had to be reduced to allow the detector improvements to be realized. To reduce the background levels the optics filters and baffles had to be cooled below 100K in most cases. The detectors also needed cooling for optimum performance usually to temperatures lower than that required by the optics. Thermos like instruments were devised to hold vessels of liquid cryogens such as nitrogen and helium in an evacuated environment that reduced the thermal conduction due to gas conduction and radiation loading from the ambient temperature outer vacuum jacket. Optical components are then bolted to the cryogen vessels and typically surrounded by cold radiation shields. Liquid cryogenic instruments are often called dewars while the more general term cryostat describes any instrument that works at cryogenic temperatures in an ambient environment.

Cryostat design for astronomical instrumentation is a multi-disciplinary activity, involving mechanical, optical, thermal, and electronic engineering skills that has most often been learned on the job at one of the university astronomical centers. Design philosophy and approach vary greatly between different design groups often with debates of religious proportions. Undoubtedly some of the statements made in this paper will be deemed heretical, but the deviations from tradition allow a development of the craft through both successes and failures.

Design Philosophy

The design philosophy of the IRTF instrument team is a result of the experience gained during the building of about a dozen IR instruments and from lessons learned from some of the pioneers in infrared astronomical instrumentation such as Don Hall, Eric Becklin, Rich Capps, Robert Joseph, Alan Tokunaga, Charlie Telesco and some younger pioneers Mark Shure, John Rayner, Tom Greene and John Lugten. These scientists have provided the scientific direction and personal drive to make sure that the instruments performed useful and desired measurements as well as bringing, to the team, important technical ideas from experiences at other institutions that could be studied and developed by our technical staff.

Listed below are the key points framing the IRTF instrument design philosophy:

Have a clear scientific goal for the instrument.

Design and optimize the optics first.

Understand the fundamental limitations of the instrument design.

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Design a cryostat around the optics that:

- Maximizes ability to work on the instrument.
- Minimizes cold mass
- Minimizes overall size
- Minimizes iterative cold tests or alignments
- Is very stiff
- Provide multiple defenses against light leaks
- Has a hands off hold time of 24 hours
- Has a cool down time of less than 10 hours
- Provides a clean vacuum environment

To achieve a superb instrument the scientific goals must enter into most of the decisions made. A team member usually the PI must have a deep understanding of the scientific goals and must participate daily with the team throughout the term of the project as the advocate from the scientific perspective. Specific observing problems are useful as guides for making technical decisions.

Our projects are divided roughly in thirds. The first third being full concept development, the second being detailed design and the third being assembly, testing, and optimization. The concept development begins with framing the scientific goals and designing the optics and choosing the detector. This is followed by concept development for the cryostat, electronics, computers, and software. The optics will frame the cryostat and tolerancing of the optics will yield the mechanical tolerances required. The detectors chosen and the required instrument performance specifications will drive the electronics and software requirements.

As the concept develops, analysis of the optics will allow an understanding of the issues that will limit the performance of the instrument. Sometimes the sky and telescope background levels are so large that it is relatively easy to achieve background limited operation, a fundamental limit. More often other effects can limit the performance. Some spectrometers have required background levels at the detector of as little as 1 photon per second making treatment of potential light leaks crucial. Other instruments have extremely tight mechanical or optical element positioning requirements. Understanding the issues that will limit performance beyond a fundamental limit must be understood before the concept phase is complete. There should be a design review near the end of the concept phase to catch issues missed at a time when changes can still be made easily.

The last group of design philosophy points concerns the cryostat design specifically. We feel strongly that the instrument should be easy to work on. Once operational the most worked on areas have been the detector area, as we upgrade or optimize detectors, and filter wheels which seem to always need just one more filter. We try to make access to these areas as easy as possible. To access the detector no optics should need to be removed and to change filters nothing should need to be removed other than access covers. We avoid nested boxes.

During the concept development the instrument often grows in size, increasing expense and difficultly of handling, cooling and manufacturing. Keeping a focus on minimizing cold mass helps combat the expanding instrument and keep this problem under control.

We try to keep the overall instrument size small to maximize the efficiency of working with the instrument. If you are pumping the instrument down on a Saturday and need two people to carry the instrument to the pump instead of one this represents a considerable cost. As with cold mass, putting some creative energy into keeping the size down will result in a instrument that is easier to use.

You must estimate the number of cold tests or iterative cold alignments that will be required. We find with our large instruments that we can only accomplish one cooldown a week. If a design is allowed that requires 5-10 cool down tests, two and a half months could be occupied with cooldown tests. This is not only a schedule issue but a cost issue as well. Minimizing cooldown tests by combining tests and designing such that they are not required will save a lot of time and money. Most important is that the cold tests be thought out and planned for.

Early dewars were not stiff enough in the mechanical mounting of the guts of the dewar. Often the whole cold assembly would move as the telescope and instrument were tipped around the sky. New techniques discused later have greatly improved rigidity. This requirement has been especially important for high resolution spectrometers where the wavelength calibration can change with small movements in the cold part of the cryostat.

If it is a sin to build an instrument that is not background limited then light leaks are the devil. The most insidious aspect of light leaks is trying to find them. Many cooldown experiments can be expended trying to pin down a light leak. The best solution is to get rid of them in the beginning through proper design. At 5 and 10 microns even a pin hole can produce an overwhelming light leak. In any critical area we design in two separate serial shields or light blocks. Covers that will be removed more than a couple of times require more attention so that they can be replaced every time maintaining the light tightness.

The hold time and cooldown requirements are based on convenience. A hold time of 24 hours allows convenient operation of the cryostat during engineering and at the telescope. Shorter hold times usually result in some one driving up to the telescope or into the lab at strange hours to prevent a warm up. Longer than 24 hours is unnecessary and makes the instrument larger than needed. Cooldown times are usually limited by the optics and filter cooldown times although in our spectrograph the large grating is the slowest. We shoot for a hands on cool down of less than 6 hours so that it can be accomplished in one day and a temperature stabilized cooldown time of less than10 hours since the optics and filters will take this long there is no sense cooling down faster.

The detectors used in these instruments cost typically $50,000 to $100,000. We had a strong desire to upgrade our vacuum quality. Optics or detectors would sometimes become contaminated in our early instruments. This could not be tolerated with potentially irreplaceable detectors. This is discussed below in the cryostat performance section.

Cryostat design specifics

Enough philosophizing. In our desire to produce an instrument consistent with the design philosophy we have made changes and improvements in the way in which we build cryostats. The significant issues are discussed below.

A Square peg in a Round Hole

Liquid cryogen dewars have mostly been made in a cylindrical shape in order to get the most strength for a given mass of materials and reduced cost by using stock tubing. Since the cryostats are operated under vacuum the vacuum jackets must withstand the atmospheric pressure pushing in, and any cryogen can within the vacuum enclosure must withstand the pressure pressing out from it's inside. Using a cylindrical cryogen can allows thinner walls witnessed by the rigidity of a one liter soda bottle under pressure. So why mess with square vacuum structures? In about 1980 Rich Capps designed a new photometer dewar, for the IRTF, patterned after a photometer at NOAO called the Blue Toad. The new design was called the Two Tummy Toad(TTT) since it had two cryogen cans to the Blue Toad's one. The experience with the TTT taught us a few important lessons.

Square dewars are perfectly reasonable especially for small dewars where the small surface areas do not result in significantly more mass being used.

Square format dewars are much easier to work on. Access through large covers on both sides of the cold structure were a great improvement. Independent access to the detector compartment and an easily changed filter wheel were also major improvements.

The cost of building a square dewar is somewhat higher than a cylindrical dewar about 20-30 % due mostly to increased mill work and decreased lathe work.

The square layout was much more flexible in design allowing the cryostat to be built around the optics as opposed to folding and modifying the optics to fit into a constrained space.

While a cylinder seems like a more efficient shape the packing density or percentage of used space was higher in the square designs.

As new and larger instruments started being designed the pressure on the large flat plates increases and wall thickness must increase as well. Table 1 shows the thickness required for square plates. The shaded areas exceed reasonable limits for the aluminum. Based on the minimum thickness required for mounting screws and window mounting 0.5 inches is our preferred vacuum jacket wall thickness, although sometimes this is weight relieved in areas without screws. As table 1 shows 0.5 inch aluminum is appropriate for plates as big as 18"x18".

E-Beam welding

The design flexibility was a big advantage of the rectangular format cryostat. We decided to maximize this design flexibility by learning how to make vacuum jackets, cold structures and cryogen cans out of flat plates welded together. This allows easily stretching the size of the components to fit the optical design without the constraints of available tube sizes, hogging depths and extruded can sizes. We started experimenting with electron beam welding with a lot of help from Electron Beam Welding Inc. We found that plates from 1/100 inch to 1/2 inch were easily welded into boxes with near perfect leak tightness. In nearly 20 applications now only one can failed to be leak tight and that leak was extremely small and could not be traced to the weld. It was a hogged liquid helium can with an e-beam welded cover. Since then we have always used 6 plates for helium cans as it was suggested that small bubbles get extruded into long skinny capillaries in a block of material that the hogging would cut through. In plates the capillaries would be along the plates so that when the ends are welded the capillaries would get sealed. Figure 1 shows typical joints for e-beam welding. For best results the joints should be very tight with a gap around .001 inches. A step is needed to prevent the molten metal from pouring out during welding. The welds are deep and narrow effectively fusing the two plates through the entire thickness with no filler material and since this is done in a vacuum the weld is very clean. Even penetration welds can be made as shown in figure 1. The welds leave a rough surface. A second pass can be requested that turns the weld into a shinny bead typically 1/4 inch wide for a 1/2 inch deep weld. The welds can then be machined with no worry of creating leaks. They can only be seen in by polishing the metal or by etching it, as in anodizing presumably due to the difference in crystalline structure. 6061 aluminum is not appropriate for e-beam welding as a lack of silicon causes cracks in the welds. We use 2219 for all e-beam welded pieces but mount pieces made from 6061, that are not to be e-beam welded, on these structures as the thermal contraction is very similar.

Cost of E-beam welding is about $100 per weld but varies greatly depending on the specific problem and the number of times that the e-beam vacuum welding tank must be vented. Additionally we usually heat treat the welded pieces to remove residual stress and allow for accurate machining. This most often has been done by Alum-A-Therm at a relatively modest price. The vacuum jacket plates can be polished before the welding, for reduced emissivity and surface area. When we have the vacuum jacket anodized we have the inside masked since anodizing greatly increases surface area, and therefore outgassing as well as increasing emissivity. In this form they are much easier to deal with than trying to polish the inside of a box after assembly.

E-beam welding has opened up our design possibilities greatly. Virtually any shape that can be conceived can be constructed. L shaped work surface/cryogen can and a square annular nitrogen can are examples of unusual structures that were achieved. The switch from all copper to all aluminum is greatly appreciated by our machinists and instrument technicians since aluminum is much easier to machine and screws holes rarely strip. It is also much easier to keep a low emissivity surface on aluminum than copper.

Cryostat performance

At the same time that developments were being made in the construction of cryostats, work was ongoing studing the performance of our cryostats in terms of cryogen hold time, or heat load on the cold structures, and quality of vacuum in terms of absolute pressure and internal cleanliness. The cryogenic performance is determined by three main factors. First is the pressure in the vacuum, second is the thermal radiation loading from the vacuum jacket falling on the cold structure and third is solid conduction through the cold structure mechanical supports. The first two terms usually dominate. A detailed description of these and other cryostat building issues is found in the book Cryogenic Engineering[1] which is an excellent reference for cryostat design. The first problem that emerged was that the vacuum needed to be around 10^{-4} Torr. This was not always achieved in our early instruments. These instruments were assembled using GE varnish, white thermal compound and were not very clean. This was our first step to get rid of any outgasers, anything soft or gooey was replaced, and vented screws were used throughout but still the performance was less than we expected. We started experimenting with aluminized mylar foil, also called super insulation. We had been wrapping 5-10 layers of aluminized mylar around all cold surfaces and found that the dewars worked better right after being wrapped and slowly degraded over months. Upon closer examination we found that we were not getting the expected reduction in radiation loading of 1 over the number of layers plus one, but that we were getting about a factor of two improvement regardless of the number of layers. Additionally we found the dewars pumped out many times faster and maintained a better vacuum without the superinsulation. Without superinsulation the hold time was reduced due to the high emissivity of the copper structures that we used in our early instruments. A paper by Scurlock and Saull[2] described the problem that we were having. In order for the super insulation to work each layer must be thermally isolated from the next. This is very difficult to achieve with mylar due to outgassing and the resultant gas conduction between layers. If the pressure between the layers is higher than around 10^{-4}Torr the layers become thermal linked and the only advantage of the super insulation is the decrease in emissivity caused by the outer layer. It seems that most of our early instruments were operating with the gas conduction the dominant heat transfer mechanism between the vacuum jacket and the cold surface and that the layers of superinsulation were acting like layers of blankets. Scurlock and Saull have demonstrated superb performance, more than 10 times better than our results, using ten layers of metallic aluminum foil each spaced with a layers of fiberglass matt that had been impregnated with activated charcoal. We do believe that multilayer insulations can work but that our implementation was not working correctly. Given the successes of the ebeam welding experiments we were building our next dewar using all polished aluminum surfaces and decided to do the first cold tests without superinsulation.

ProtoCAM[3] our 1-5.5 micron prototype camera was the first volunteer. It was built with an e-beam welded vacuum jacket, nitrogen can and helium can, all of 2219 aluminum. The inside of the vacuum jacket and the outside of the cold structure were polished with a buffing wheel until you could make out a wavy reflection. We were quite surprised with the performance. The most obvious difference was the vacuum pump down time. We were able to turn on the diffusion pump in about 15 minutes and achieved a pressure that would allow cooldown in about two hours. This typically took overnight with previous designs. The first cool down yielded the second surprise. The nitrogen boil off was significantly lower than previous designs that were substantially smaller. At the same time the helium boil off was about twice what it should have been. After some head scratching we realized that we had left a slit opening in the radiation shield that surrounded the helium can, of about 0.5 inches by 3 inches, uncovered. This amount of 300K radiation "seen" by the helium can was enough to account for the excess helium boiloff. The next cool down we covered the slit to the helium can and cooled it down again. The helium boil off had decreased to the expected level but the nitrogen boiloff had increased. We cooled it down one more time this time with the slit covered with a plate spaced above the radiation shield that would block the direct view of the 300K vacuum jacket but still allow area around the edges for cryopumping access to the helium can. The helium boiloff went up slightly and the nitrogen boiloff down slightly but a much smaller effect than before. This underscored a few important points.

A helium can does not insure good vacuum unless an adequate path is provided to the helium can surface. The mean free path of a molecule at these pressures is 5 inches or so meaning that the cryopumping rate is related to the area of straight path access to the pumping surface.

Even with our efforts to increase the vacuum quality, and a large helium can, our dewar was still witnessing significant thermal load due to gas conduction. Vacuum quality should still be improved.

That a dewar could be built with no superinsulation and all polished aluminum structures, performing slightly better than a traditional copper and superinsulation constructed dewarwith the additional payoff of many times faster pump down times and presumably a cleaner vacuum.

While the nitrogen performance could probably have been improved with some super insulation the dewar met it hold time requirements and none was added. The improvement in pump down speeds has made the instrument so much easier to use. We have designed all dewars since that time the same way and have no desire to use superinsulation.

It should be noted that with ProtoCAM we switched from zeolite to activated charcoal for a getter. The activated charcoal getters are made like closed cycle cooled cryopumps. A sheet of copper is covered with a layer of Eccobond 286 epoxy and then covered with activated charcoal pellets. After the epoxy is set the charcoal is brushed to remove any loose particles and mounted charcoal side down on 4 metal spacers with about 1/4 of an inch space above the nitrogen can. The black charcoal will heat up and stop getting if 300K radiation falls on it so it must face a cold surface. This type of getter has a few advantages over zeolite getters. The activated charcoal will fully outgas at room temperature, so it does not need to be heated like zeolite. Secondly baskets of zeolite produce white dust caused by the pellets rubbing on each other which can coat optics. The flat plate getters are also easier to make and mount. Our experience with ProtoCAM has shown that this type of getter works well for years with no attention. We see no degradation in boil off rates even after being cold for over two weeks.

One other experience that supports this thinking was found at the University if Minnesota as shown to me by Terry Jones, an astronomer and instrument builder there. They have a bolometer dewar that uses only 0.2 liters of liquid helium, which they pump on, to reduce the temperature reducing the helium level to 0.1 to 0.13 liters. This dewar will hold the approximately .1 liters of pumped helium for 5 days. An astounding performance! Their secret? Gold plating of all surfaces, no superinsulation and ion pump to achieve a vacuum of 10^{-7}Torr.

Floating shields

The idea behind the superinsulation is that of a floating shield. If you have two infinite parallel plates at different temperatures in a vacuum, call the heat transfer due to radiation between the plates, Q. If you float a third plate between them it will equilibrate to a temperature between the temperature of the two plates. The colder of the first two plates will now only see the radiation from the floating plate which is cooler and therefore the heat transfer will be lower. Q will decrease as the inverse of the number of floating plates plus one. One floating shield will reduce the heat transferred by radiation by a factor of two. The reason that the multi layer superinsulation didn't work for us is that the layers were not floating but were coupled through gas conduction to the cold surface.

We decided to try a true floating shield in our most recent instrument NSFCAM a 1-5.5 micron camera which was a bit larger than Cshell. We wanted to use the same cooler but felt we were getting to close to the cooler's capacity. We built a floating shield out of 1/8 inch thick aluminum plate and surrounded most of the cold structure. This was not a light tight shield. It had large holes for access to hardware and shafts, but it covered about three quarters of the cold structure surface area. If the shield were connected to nothing it would reach a temperature half way in power between the 300K vacuum jacket and the 77k cold structure. This is about 250k. The shield was connected to the fiberglass support tabs at the place that we calculated the fiberglass would be 250k. The cooling power was measured by disconnecting the closed cycle cooler and measuring the boil off of the precharge can. With the floating shield (which did equilibrate to 252k) the cooling load was 11 watts and without the shield it was 15 watts. While not a factor of two decrease it was consistent with the areal coverage of the shield. It seems like something for nothing but it works.

Cryostat Performance Data

Shown in table 2 is the cryostat performance data for a sample of the instruments that we have built. Note that the closed cycle cooled cryostats have an excellent vacuum due to the larger cold getter as described below. Looking at the heat load per square inch it is apparent that all of our instruments have fairly similar performance. The best performance is witnessed with an all polished aluminum construction using a floating shield, which is also our preferred configuration in terms of construction ease and ease of service.

We feel no pressing need to improve on these performances although, from the data presented by Scurlock and Saull, heat loads as low as 0.3 mW per square inch are achievable using 10 layers of aluminum foil spaced with activated charcoal impregnated fiberglass paper. These ten layers appear to work as they should reducing the heat load by about a factor of 11. More than a factor of 10 reduction in our heat loads would allow significant reduction in cryogen can sizes and closed cycle cooler capacities and should be pursued. Certainly multiple layer floating shields, like those that we have made are reasonable to produce. Stated simply, we can achieve performance equal to or better than traditional copper superinsulation cryostats with an all aluminum construction resulting in a much better vacuum environment, yet performance could still be substantially improved.

Closed Cycle Coolers or Liquid Cryogens?

Closed cycle cryogenic refrigeration units are compressor driven, gas expansion coolers that use ultra pure helium as the working gas. A cooling head is attached to the cryostat. The cooling head has one or two stages providing cooling at around 77K and 20 K. The cooling power levels are large compared to what we are familiar with using liquid cryogens. Around 25 watts at 77K and 5 watts at 20K. The power at 20K is particularly attractive since it would take about a 150 liter helium can to provide this level of cooling with a 24 hour hold time. These systems may seem large and possibly too complex for astronomical instrumentation but they have been shown in a few instruments to be a good choice[4,5,6]. As the size of the instrument starts to get large, say over 1-2 cubic feet liquid cryogens get increasingly cumbersome. The size of the cryogen cans for large dewars is significant and, especially if liquid helium is used, the cost and logistics headache of ordering cryogens is considerable. For some sites dealing with liquid helium is deemed too difficult and they will not do it. A rule of thumb might be if your instrument is about the size of the cooler (the CTI model 350 is about 6 x 12 x 17 inches) and/or you need temperatures below 65K then you should consider using a cooler.

About the same time that ProtoCAM was being developed a much larger instrument was being designed. Cshell[5] is a 1-5.5 micron high resolution spectrograph. With a 4x9 inch grating and two IR detectors we knew we had to move beyond our old designs and decided to use a closed cycle cooler. After much study we selected the CTI model 350 as our cooler. The selection was based on reliability, service, vibration levels and cooling power. Other good coolers were available some with advantages that we liked. An additional influence was the excellent support we received from the CTI technical staff understanding vibration and cryopumping.

There were three main questions we had regarding the implementation of the closed cycle coolers. First would the vibrations affect the instrument performance, second would we be able to couple the cooler to the cold structure with adequate efficiency yet not transmiting vibration and third could we deal with the waste heat produced by the compressor at 14,000 feet altitude. In short all of these questions were easily dealt with.The waste heat was handled by ordering the liquid cooled compressor and connecting it to our floor chiller system at the telescope.

The vibration problem was, also far less of a problem than we expected. Our experience with single element photometers made us extremely sensitive to vibration and microphonic pickup noise. Early experiments at the United Kingdom Infrared Telescope demonstrated that the then new infrared arrays were not measurably sensitive to vibrations. This was good news and meant that our main worry regarding vibrations would be our optics mounting. We set as a design requirement that all optical mounts have a resonant frequency of greater than 300 Hz. The vibrations from the closed cycle coolers come from two main sources. One is a piston that is driven up and down as part of the gas expansion process. This piston is in the cooling head right on the instrument. The second vibration source is the 60 Hz motor used to open and close the valves on the cooling head. Some coolers use gas compression to stop the piston at the end of it's travel. Other coolers as in the CTI 350 use a yoke to drive the piston off of a cam on the motor. This greatly reduces the vibration from the piston which cycles at about a 1 Hz rate. Some coolers use a DC motor to drive the valves and the yoke, this may be an advantage. The dominant vibration power from the CTI 350 is from the ac motor at around 60 Hz. We designed a support for the CTI 350 cooling head that consisted of a welded metal bellows surrounded by a ring of neoprene rubber. The rubber ring does two things. It supports the cooler under the vacuum induced pressure of a couple hundred pounds and, since it was tuned to have a resonant frequency of 12 Hz, it provides substantial reduction of the transferred vibrational energy. A diagram of the closed cycle cooler assembly is shown in figure 2.

While we could easily calculate the amount of copper required to pass the heat needed to maintain the cold structure temperature, we were unsure of how to model the interfaces between the cooling strap and the cold structure and the cooler. This also turned out not to be a problem. It is important to remember that conductivity between two metal surfaces is only a function of pressure not surface area. If you put enough force on the interface you can get the conductivity of the bulk material. Our strap was made from 30 strips of soft annealed OFHC copper averaging 6 inches in length, 2 inches wide and 0.005 inches thick with copper blocks e-beam welded to the ends. The closed cycle cooler end of the strap is attached to the cooler with six 10-32 screws. The cold structure end of the strap is attached to the cold structure with six 1/4-20 screws. All screws were equipped with Belleville washers meant to take up the differential contraction caused by the stainless screw and copper block. We feel that the washer probably do nothing because we crush them when tightening the screws. We tighten these screws to the maximum you can with a allen wrench. This is a bare copper on aluminum interface and we see no significant temperature drop across the interface.

The second stage of the cooler is connected to the detectors using a 1/8 inch copper wire that is bussed along the cold structure on low conductivity fiberglass standoffs, about 10 inches, behind a radiation shield until it penetrates the detector compartment through a, black painted, fiberglass disk. The line to the detector is electrically isolated by putting a piece of mica in the chain. We can achieve a temperature of 20 K at the detector with this setup. The temperature of the detector is regulated with a temperature controller using heating resistor and temperature sensor on the cold finger directly behind the detector.

Cooldown time using a closed cycle cooler alone would take many days for a large instrument. For this reason we have included a 1-2 liter liquid nitrogen can on the cold surface that we call the precharge can. Using the precharge can and a pressure feed nitrogen setup we can cool the instrument in about five hours. We did not intend to use the precharge can after cooldown but we found that the temperature would drift with the cooler alone. We could adjust the helium pressure in the compressor, effectively adjusting the cooling capacity, such that the cooler was taking most of the cooling load and then by topping off the precharge can once a day the boiling nitrogen in the can would regulate the temperature. Our conclusion is that unless you use a cooler with 5-10 times the capacity of what you need and use active temperature control of the cold structure that there may be unacceptable temperature drifts. The use of the precharge can for temperature regulation is an efficient compromise if stocking liquid nitrogen is no problem.

Since we felt we had far more cooling capacity than we need we decided to add a cryopumping getter to the closed cycle cooler to improve the vacuum. Our getter consisted of two concentric copper cylinders mounted on the second stage of the cooler covered inside and out with a layer of Eccobond 286 epoxy into which we embedded activated charcoal pellets as described above. We also added a radiation shield from the first stage of the cooler that surrounded the second stage getter to prevent the black pellets from heating up. This first stage radiation shield was also coated on the inside with epoxy and charcoal. The getter works very well achieving a vacuum level of around 10^{-6} Torr. We cannot say which getter, the 10k or 77k one is working better or if both are necessary.

In summary our experience with closed cycle coolers is entirely positive. In the lab being able to cooldown anytime without regard to liquid helium availability or cost has allowed much more work to get done. At the telescope we have found that we can leave an instrument cold for weeks using a thermos of nitrogen a day. Probably all of our instruments will be closed cycle cooled from now on.

Mechanical

Cryostats are mechanical beasts and there are many aspects of the mechanical design. Most have been discussed before so we will only discuss a few aspects that we feel are most noteworthy in our designs.

Fiberglass tabs

A perennial problem with early cryostats was internal flexure. The use of orthogonally oriented fiberglass tabs first introduced to us by John Lacy of the university of Texas at Austin(some people call them Lacey Tabs although he claims that he didn't invent them). Refer to figure 3 for a diagram of the tab implementation. The goal with a cold structure support is that the cold structure be held rigidly yet still allow for the considerable thermal contraction of the cold structure. Using four tabs, as shown,to connect the cold structure to the vacuum jacket achieves this. The tabs are flexible in only one direction. The four tabs are arranged such that a vector normal to the surface of each tab intersect. This intersection point becomes the fixed point as the cold structure contracts. The tabs can be oriented in a way to allow any point on the cold structure to remain fixed with respect to the vacuum jacket as the cold structure cools. We usually put the fixed point on the incoming light path. This tab arrangement is deceivingly strong. Very thin tabs can be used to support large cantilevered masses in a predicable manner. We use the tab arrangement to mount cryogen cans, large closed cycle cooled cold masses, and detector assemblies. For large structures the tabs are about 2 x 3 x 1/16 inches and for small structures we use tabs made from electronic circuit board fiberglass about 1/4 inch wide and 1/2 to 1 inch long.

We also use fiberglass neck tubes for any liquid cryogen cans, sometimes with stainless bellows if contraction movement is required. One of the main reasons for using fiberglass neck tubes is electrical isolation. By having only fiberglass connections between the vacuum jacket and the cold structure we can maintain a true single point ground which we feel is very important. Our neck tubes have been manufactured by Spaulding Composites. The tubes are not all leak tight and must be tested but the prices are very reasonable and they will do custom sizes.

Lens mounting

Image quality of large telescopes has greatly improved in the past few years and as a result the requirements of optical systems has become much more stringent. Lens positioning requirements for diffraction limited imaging has translated to mechanical positioning specifications of, on the order of, a few thousands of an inch. The difficulty is that many of the infrared optical materials contract different amounts and at much different rates than the aluminum. If you make a hole only a few thousandths over the size of the lens, during cool down, the hole will contract much faster than the lens and you will crush the lens. If you open up the hole to allow for the cool down contraction the hole is too big to meet the positioning requirements. We investigated using Invar for lens mounting but still had cooldown troubles. The mount that we have designed to address this problem is shown in figure 4 . The mount uses two radial pads that provide the radial positioning with a leaf spring opposite to keep the lens in contact with the pads. The differential expansions must be calculated to determine the correct warm positions of the pads such that the lens will shift to the correct position when cold. The result is positioning accuracy as good as the lens edge tolerance and no chance of damage to the lens. The axial clamping of the lens is accomplished using a aluminum ring machined to leave three springy fingers that press the lens down onto three axial support pads under the lens with a force of 1-2 pounds. This design has worked well in three applications now.

Light Tight Feedthroughs

With cryostats requiring background flux levels of around 1 photon/second in an environment that is literally about a billion times that obviously light tightness must be taken seriously. Any feedthrough in the radiation shield must be absolutely light tight. Most feedthroughs are easily handled with careful design, rotary feedthroughs are more difficult. We have designed a small light tight cryogenic rotary feedthrough that mounts in the radiation shield. The feedthrough has been demonstrated to be tight to the few photon per second level. A drawing of the feedthrough is shown in figure 5 . It is basically a barrel with two rotational tongue and grooves on either side. The grooves are a little oversized to allow the grooves to be painted black.

Some would say that we should use cold motors so that we would have no feedthroughs. Cold motors allow no penetrations and allow the entire cold guts to be removed intact and be operated outside of the vacuum jacket. They also allow a motor to be placed in an area where exiting shafts to a warm motor would be inconvenient or impossible. These are strong arguments for cold motors. There are disadvantages however. First is that the instrument can only be operated by computer as there are no external shafts that could be turned by hand. This is mostly a problem in the lab while doing engineering tasks. We often find it an advantage to be able to turn the shafts by hand. Secondly in the case of a mechanism failure, especially a cold only failure, there is no way to collect information about the failure. You must just guess at the problem. You cannot turn the shaft and feel the problem. Seeing the motor turn is of great help when trouble shooting the hardware and software of the motor drives and limit switches. Thirdly it violates one of our design philosophy concepts that is to minimize cold mass. And lastly we have an excellent rotary feedthrough. The wires used to power the steppers are difficult to cool and can emit liight in a dark compartment and would have to be shielded. We are experimenting with cold motors although we do not expect to move to them completely but use them in applications where they are required.

Bearings

We make extensive use of stainless ball bearings in our aluminum mechanisms. The bearing must have a loose slip fit, when mounted in aluminum structures, to avoid excessive preload when cold. We have had a few bearing failures where balls actually cracked in half but these were caused but inproper assembly of the mechanisms. We have recently been experimenting with a impregnated molybdenum disulfide coating done by E/M Corp using a process called Microseal with good results. We have been using this coating on bearings and gears.

Summary

We have presented some of our developments in the art of cryostat design. This is clearly still an art creeping toward an understood technology. Clearly there is still room for vast improvements in our designs and we will continue to improve them. We feel that we have a solid, predicable and workable design that meets our present requirements. We hope that the sharing of our knowledge will be of some help to others working at this craft.

Acknowledgements

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List of vendors

The following is a list of the vendors that we have found for hard to find cryostat build materials and processes.

Alum-A-Therm (aluminum heat treating)
Gorden Ritter
7474 Garden Grove Blvd.
Westminister, CA 92683
800-447-6077
741-895-2754 fax

CTI (closed cycle coolers)
Kelvin Par
266 Second Ave.
Waltham, Mass. 02254
617-890-9400

Electron Beam Welding
6940 Hermosa Circle
Buena Park,CA 90620
714-670-9119
714-522-0926 fax

U-C Components, Inc. (vented screws)
2330 Old Middlefield Way Suite 16
Mountain View, CA 94043-2408
415-964-3827

E/M Corporation (Microseal impregnated solid lubricants)
6940 Farmdale Av.
North Hollywood, CA 91605
213-875-0101

Emerson & Cummings, Inc. (Eccobond 286 Epoxy good for nearly any cryogenic application)
Woburn, MA 01888
617-938-8630

Ferrofluidics Corp. (rotary vacuum feedthroughs)
40 Simon Street
Nashua, NH 03061
603-883-9800
603-883-23080 fax

Helical Corp. (makers of helical cut solid flex couplings)
P.O. Box 1069
Santa Maria, CA 93456
805-928-3851
805-928-2369 fax

Metal Flex Welded Bellows, Inc. (Closed cycle cooler bellows with o-ring flange)
Robert Guyer
P.O. Box 513
Derby Line, VT 05830
802-334-5550
802-334-5318 fax

Spaulding Composites, Co. (Fiberglass cryogenic neck tube material)
2000 South Hoefner Ave. (Ask for fine weave G-10 custom neck tube)
Los Angeles, CA 90040 (made on a solid mandrel)
213-685-6710
213-722-4670 fax

References

1. B.A. Hands Editor, Cryogenic Engineering, Chapter 4, Academic Press, Orlando, Florida,1986

2. R. G. Scurlock and B. Saull, "Development of multi-layer insulations with thermal conductivities below 0.1 micro Watt/cm deg K",Sixth International Cryogenic Engineering Conference, page 249

3. D. W. Toomey, M. Shure, E. M. Irwin, M. E. Ressler, "ProtoCAM- An Innovative IR Camera for Astronomy", SPIE Instrumentation in Astronomy VII, Volume 1235, pages 69-81, 1990

4. J. T. Rayner, M. A. Shure, D. W. Toomey, P. M. Onaka, A. J. Denault, W. E. Stahlberger,D. Watanabe, K. Criez, L. Robertson, D. Cook, M. J. Kidger, "Design of a new 1-5.5 micrometer infrared camera for the NASA Infrared Telescope Facility", SPIE Infrared Detectors and Instrumentation, vol. 1946 pages 490-501, 1993.

5. A. T. Tokunaga, D. W. Toomey, J. Carr, D.N.B. Hall, "Design for a 1-5 micrometer cryogenic echelle spectrograph for the NASA IRTF", SPIE Instrumentation in Astronomy VII, Volume 1235, pages 131-143, 1990

6. C.M. Mountain, D.J. Robertson, T.J. Lee, R. Wade, "An Advanced Cooled Grating Spectrometer for UKIRT", SPIE Instrumentation in Astronomy VII,vol. 1235 part 1, pages 25-33, 1990

Table 1 Flat Plate Defelection Under Vacuum

Deflection and Stress of Aluminum Plate Subject to 14.7 psi

Cavedoni 5/26/92

yield strength = 35,000 psi
ss = simple support
fx = fixed support

Square Plate 4" x 4"

		0.125	0.25	0.375	0.5	0.75
DEFL (ss)	inches	0.0085	0.0011	0.0003	0.0001	0.0000
DEFL (fx)	inches	0.0026	0.0003	0.0001	0.0000	0.0000
STRESS	psi	4,608	1,152	512	288	128

Square Plate 6" x 6"

		0.125	0.25	0.375	0.5	0.75
DEFL (ss)	inches	0.0431	0.0054	0.0016	0.0007	0.0002
DEFL (fx)	inches	0.0133	0.0017	0.0005	0.0002	0.0001
STRESS	psi	10,368	2,592	1,152	648	288

Square Plate 8" x 8"

		0.125	0.25	0.375	0.5	0.75
DEFL (ss)	inches	0.1363	0.0170	0.0050	0.0021	0.0006
DEFL (fx)	inches	0.0419	0.0052	0.0016	0.0007	0.0002
STRESS	psi	18,432	4,608	2,048	1,152	512

Square Plate 12" x 12"

		0.125	0.25	0.375	0.5	0.75
DEFL (ss)	inches	0.6901	0.0863	0.0256	0.0108	0.0032
DEFL (fx)	inches	0.2123	0.0265	0.0079	0.0033	0.0010
STRESS	psi	41,472	10,368	4,608	2,592	1,152

Square Plate 16" x 16"

		0.125	0.25	0.375	0.5	0.75
DEFL (ss)	inches	2.1810	0.2726	0.0808	0.0341	0.0101
DEFL (fx)	inches	0.6711	0.0839	0.0249	0.0105	0.0031
STRESS	psi	73,728	18,432	8,192	4,608	2,048

Square Plate 18" x 18"

		0.125	0.25	0.375	0.5	0.75
DEFL (ss)	inches	3.4936	0.4367	0.1294	0.0546	0.0162
DEFL (fx)	inches	1.0750	0.1344	0.0398	0.0168	0.0050
STRESS	psi	93,312	23,328	10,368	5,832	2,592

Table 2 Cryostat Cryogenic Performance

Instrument	type of instrument	area of 77k 77k surface sq. inches	total 77k heat load watts	heat load per area mW/sq in	configuration
Two Tummy Toad	photometer	184	2.70	14.67	Two copper cans, LN2 and LHe, 5-10 layer Al mylar
CGAS	1-5 spectrometer	275	3.20	11.64	Two copper cans, LN2 and SN2, 8 layer Al mylar
ProtoCAM	1-5.5 camera	397	3.80	9.57	Two cans polished aluminum, LN2 and LHe, no insulation
Cshell	1-5.5 spectrograph	930	12.00	12.90	All Polished aluminum, closed cylce cooled
NSFCAM w/o floating shield	1-5.5 camera	1203	15.00	12.47	All Polished aluminum, closed cycle cooled
NSFCAM w/ floating shiled	1-5.5 camera	1203	11.00	9.14	All polished Al w/ floating shield, closed cycle cooled

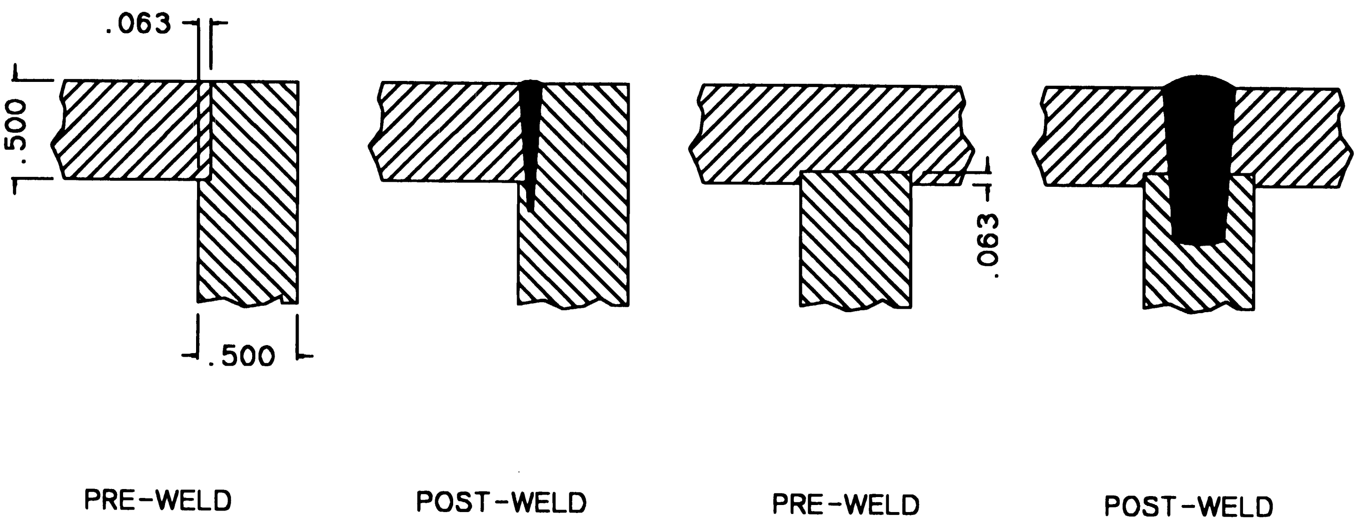


FIGURE 1: CONFIGURATIONS USED IN ELECTRON BEAM WELDING

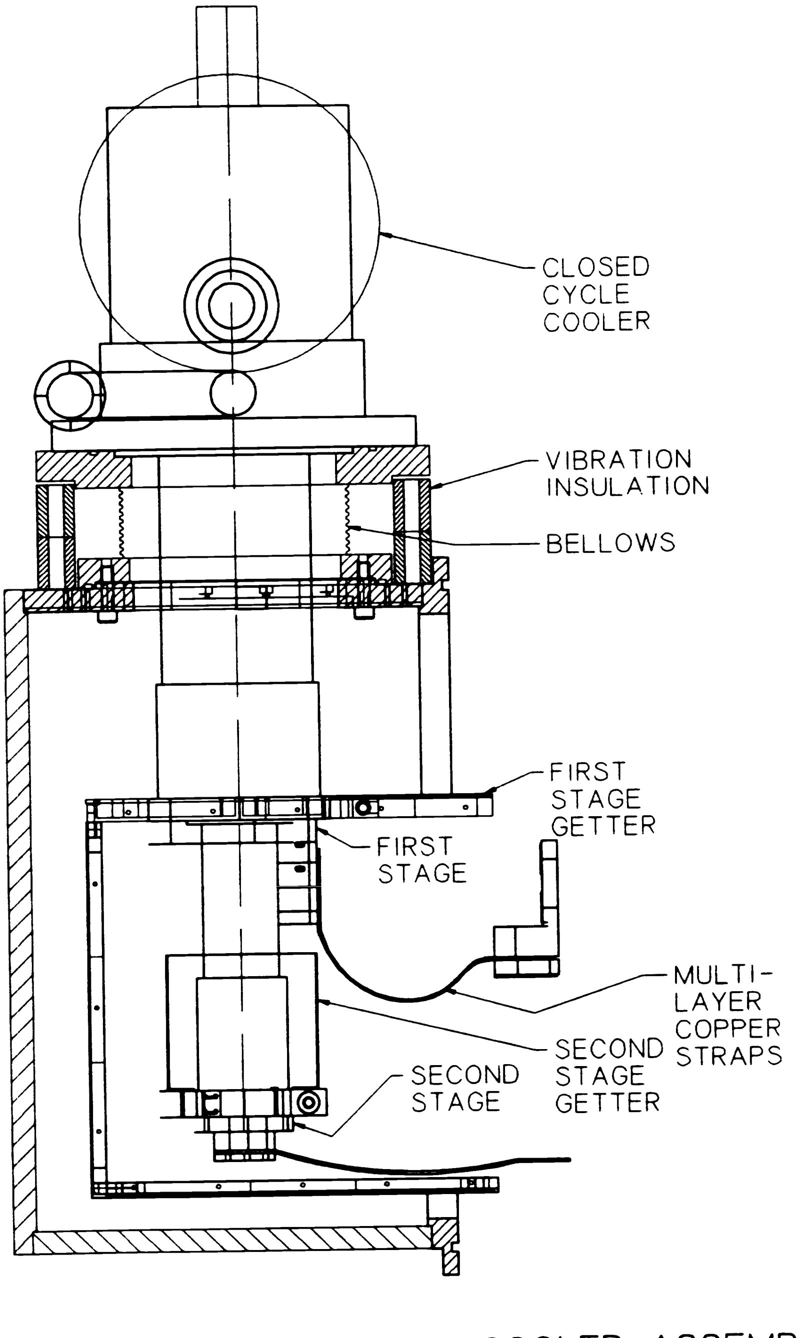
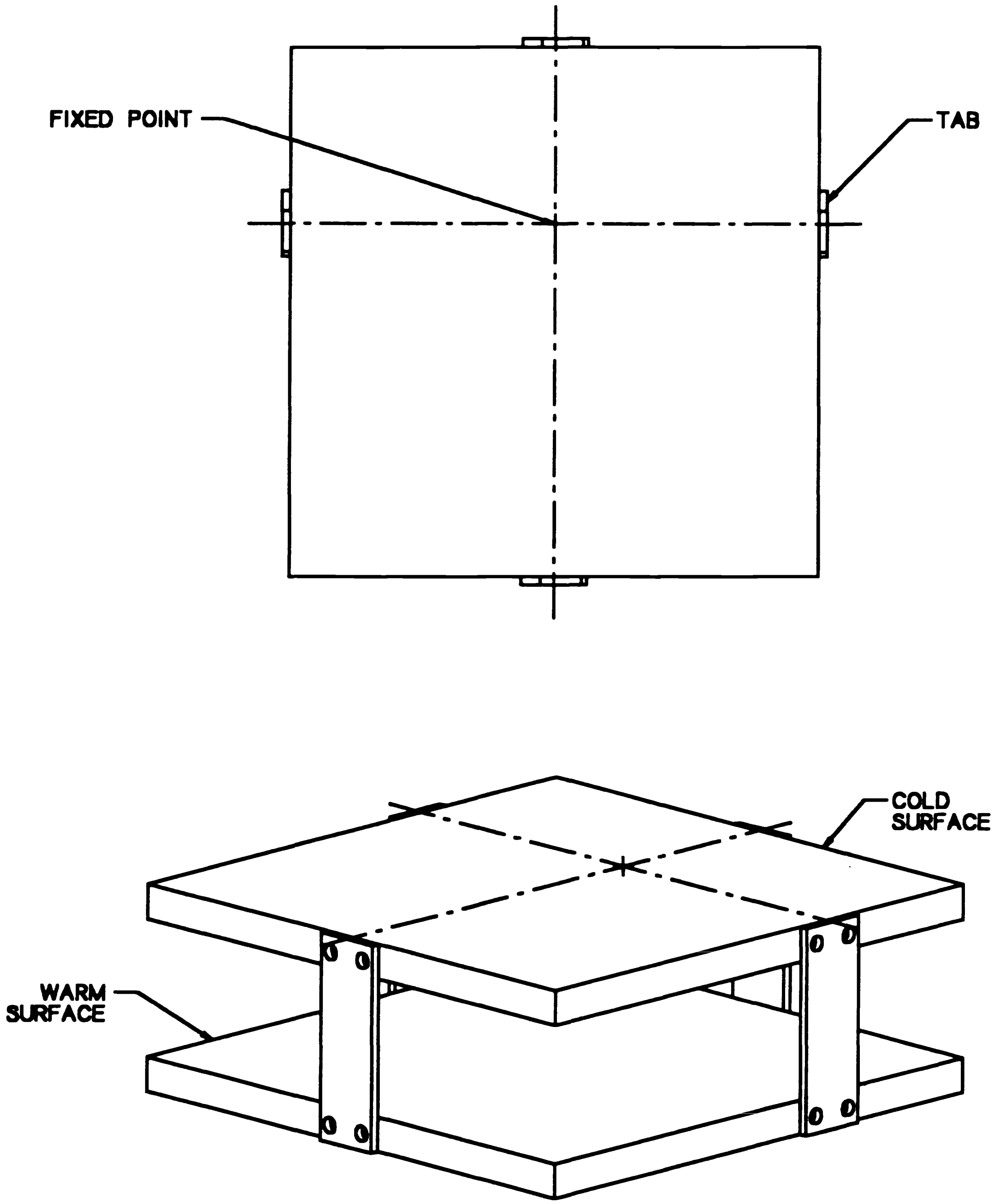


FIGURE 2: CLOSED CYCLE COOLER ASSEMBLY



REPRESENTATIVE IMPLEMENTATION

FIGURE 3: FIBERGLASS TAB SUPPORTS

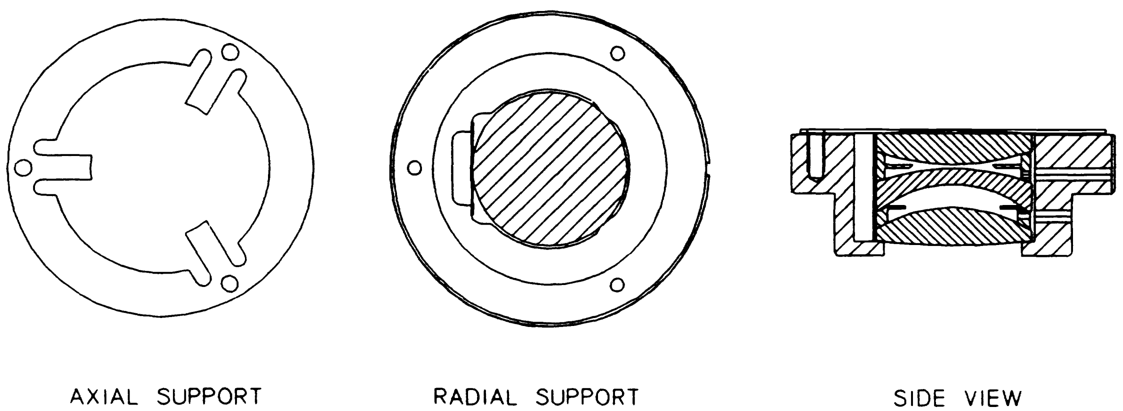


FIGURE 4: CROYOGENIC LENS MOUNT

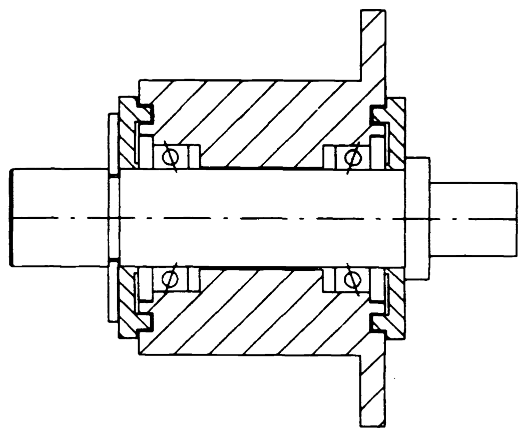


FIGURE 5: LIGHT TIGHT FEED THROUGH