NASA NEEDS AND TRENDS IN CRYOGENIC COOLING

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INTRODUCTION

There are increasing numbers of NASA space instruments that require cryogenic cooling to accomplish their objectives. These include instruments for Earth observation, atmospheric science, gamma-ray and X-ray astronomy, infrared astronomy, and basic research. Potential future space applications for cryogenic cooling include instruments for high energy astronomy, radio-astronomy, relativity measurements, and a variety of instruments and systems employing superconducting devices.

The elements of the instruments that may require cooling are radiation detectors, optical components, baffles, or in some cases, the whole instrument. Cryogenic cooling is necessary to provide the required detector response, reduce pre-amplifier noise, and/or reduce background radiation.

The objectives of the discussion herein are to indicate the projected NASA needs in spaceborne cryogenic systems and to describe recent results from NASA cryogenic cooling technology efforts. Much background information has been extracted from References 1 and 2. However, the emphasis will be placed upon future cryogenic cooling applications. Only areas where there are large efforts and significant projected needs will be covered.

INSTRUMENT SYSTEM NEEDS

Earth Observation

Observation of the Earth's surface from satellites* is accomplished at wavelength bands for which the Earth's atmosphere is transparent. Two of these "clear air" bands are from .3 - 2μm and from 8 - 14μm. The former band is utilized to measure reflected sunlight from the Earth while the latter is used to detect the Earth's radiant emission.

Earth observation in the .3 - 2μm band does not usually require cryogenic cooling. In the 8 - 14μm regime, cryogenic cooling of the detector and, perhaps some optical components, is required.

The most common form of detector used by NASA to-date for the 8 - 14μm band has been Hg Cd Te. Cryogenic cooling of the detectors has been accomplished with radiant coolers.[3] For example, the AVHRR (Advanced High

*Satellites are defined here as free-flying spacecraft, unattached to the Shuttle or a space platform or station.

Resolution Radiometer) aboard the TIROS series of spacecraft utilizes a radiant cooler to maintain Hg Cd Te detectors at 95°K. The Landsat-D spacecraft, which was launched in 1982, employs a radiant cooler to provide 87°K for the Thematic Mapper instrument Hg Cd Te detectors. The instrument cooling loads for the cited examples are 35 mW and 85 mW, respectively. Schematic of typical radiant coolers are shown in Figure 1.

The Earth observation instruments to-date are usually scanner type--i.e., there is a moving mirror which scans a swath of the Earth normal to the orbit plane. The input radiation for each mirror position is separated into the desired wavelength bands and focused on single detectors, each appropriately designed and doped for the particular wavelength.

A new concept for Earth observation instruments utilizes a large number of detectors arranged in a line to essentially take a "picture" of a swath of the Earth at each orbital position, at a particular wavelength band.

The prime advantage of linear array systems over scanner systems is the potential for improved spectral and spacial resolution. This occurs because each detector has a much larger integration time over a partiuclar swath of the Earth.

The thermal band (i.e., ~12μm) of a multi-linear array (MLA) instrument might consist of 2,000 Hg Cd Te detectors and associated electronics. Typical cooling requirements are on the order of several watts at 90 - 100°K. The mid-infrared (3-6μm) band and perhaps the 1-2.5μm band would also require cryogenic temperatures with cooling loads of 1 or more watts.

Mission lifetime for an MLA instrument would be at least 3 years. Thus, it is clear that a closed cycle refrigerator would be of extreme benefit for a linear array instrument and is probably the only practical cooler for it. Figure 2 is a schematic of the NASA/GSFC, long-lifetime, Stirling cycle cooler, presently being developed, coupled to an MLA-type instrument.

The MLA class of instruments, then, clearly require coolers with larger capacity than present day scanning instruments. It is unclear, however, when the NASA MLA instruments will be developed and operational.

Atmospheric Science

Measurements of the atmosphere composition, temperature, pressure and wind are made at a variety of wavelengths for which the atmosphere is not transparent. These measurements fall into two general categories--direct emission and occultation instruments. In the first case, radiometric measurements are made directly at the particular emission wavelength of the constituent of interest. In the second case, the absorption lines from an emission source, such as the sun, are observed through the limb* of the atmosphere.

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*Limb measurements refer to observing from the spacecraft in a direction tangent to the Earth and through the atmosphere.

Examples of previous atmospheric science instruments are the LRIR (Limb Radiance Inversion Radiometer) which was placed in orbit aboard Nimbus-6, and LIMS (Limb Infrared Monitoring of the Stratosphere) which was aboard Nimbus-7. The LRIR measured Earth-limb radiance in four spectral bands ranging from 8.6 to 27μm. The LIMS obtained stratospheric data in six bands ranging from 6.08 to 17.24μm. In both cases, Hg Cd Te detectors were employed.

Both the LRIR and LIMS instruments utilized a two-stage, solid cryogen cooler produced by Lockheed Palo Alto Research Laboratories. The primary cryogen was methane at a nominal temperature of 65°K and an instrument heat load of 52 mW. The secondary stage employed ammonia at a nominal temperature of 152°K with a instrument heat load of 91 milliwatts.

A new NASA atmospheric science satellite presently being designed is the Upper Atmosphere Research Satellite (UARS). This spacecraft accommodates 11 instruments, 2 of which utilize cryogenics. It is anticipated that the UARS will be launched in 1988.

The UARS Cryogenic Limb Array Etalon Spectrometer (CLAES) instrument will utilize a solid hydrogen cooler for cooling 23 Si (Ga) detectors and the spectrometer optics to 12°K. The cooler vent line will vapor cool the telescope baffle to 130°K. The 12°K Si (Ga) detectors, together with the low instrument background temperature, provide very sensitive measurements of atmospheric constituents with emission spectra in the 3.5 - 13μm regime. The cooling load to the 12°K hydrogen is .3 W, while the baffle load is 2.4 W.

The CLAES cooler will be the first to utilize solid hydrogen in space, although ground testing of a small flight-type, solid cryogenic cooler has been successfully accomplished.[5] A schematic of the CLAES solid hydrogen cooler is shown in Figure 3. The anticipated weight of the system is 354 Kg, including 78 Kg of hydrogen.

The low temperature requirement of the instrument limited the cooler design to either solid hydrogen or supercritical helium. Hydrogen was selected over helium because of its higher cryogenic cooling efficiency, which becomes critical for a system with an 18 month lifetime requirement. A 10°K, closed-cycle cooler would offer very significant weight benefits over the solid hydrogen cooler, as well as a longer lifetime. However, a 10°K, long-lifetime, closed-cycle cooler is not yet developed.

A second cryogenic instrument that will be aboard the UARS spacecraft is the Improved Stratospheric and Mesospheric Sounder (ISAMS). The ISAMS has 12 spectral channels over the 4 - 100μm regime.

The ISAMS infrared channels will be cooled by two Stirling cycle coolers that are presently being developed. Although nothing has been published, the coolers will employ linear drive motors and dry lubricated pistons. Required capacity of each machine will be 1 watt at 80°K. The minimum lifetime requirements for the coolers is 18 months.

The UARS and other future atmospheric science missions once again demonstrate the need for a long-lifetime mechanical cooler. In addition, in the case where a stored cryogen system is expedient to employ, methods for extending lifetime for a given size cooler must be developed. For example, a large fraction of the heat leak between a stored cryogen cooler outer vacuum shell and the inner cryogen tank is by conduction through the support structure connecting the shell to the tank. This structure is required for the cooler system to survive launch loads, but is considerably overdesigned for orbital conditions. The development of a structural system that could essentially disengage after the cooler is in orbit would reduce the heat load to the cryogen and greatly extend cooler lifetime.

Infrared Astronomy

For NASA infrared astronomy missions, liquid helium cooling is essential. The first of the infrared astronomy missions will be the Infrared Astronomy Satellite (IRAS), which is to be launched into a polar orbit in January 1983. This joint U.S., Netherlands, and U.K. satellite system utilizes doped silicon detectors to survey the sky and to make selected point source measurements in a wavelength range of 8 to 129μm.

The IRAS will utilize a 540 liter, 1.8°K, superfluid helium dewar manufactured by Ball Aerospace Systems Division. As shown in Figure 4, the superfluid helium is contained in a torroidal-shaped, 5083 aluminum main cryogen tank. The infrared telescope system fits into the center of the torroid and is mounted to the telescope mounting ring. Structural support is achieved through nine fiberglass-epoxy bands which terminate at the main shell. Additional thermal protection is provided by three vapor-cooled shields and multilayer insulation in the vacuum space. The main shell will operate at about 200°K via radiant cooling in orbit to further reduce heat leaks to the cryogen tank. Liquid-to-vapor phase separation in zero gravity is accomplished by a porous plug located at the entrance to the vent line. The dewar cover, which is jettisoned during the initial stages after achieving orbit, utilizes a supercritical helium tank to reduce its heat leak. From ground test data and mathematical modeling, the operational orbital lifetime for the IRAS dewar is predicted to be about 7 months.

The same basic IRAS dewar will be used for the Cosmic Background Explorer (Cobe) mission, which has recently been approved as a new NASA program. Modifications to the IRAS dewar for Cobe include deletion of the aperture cover tank, additional support straps for Shuttle launch (versus Delta for IRAS), improved valves, and a lower main shell temperature.

In addition to photoconductor detectors (as on IRAS), Cobe will utilize infrared bolometers. Consequently, it is desirable to operate the dewar at as low a temperature as possible, which is 1.6°K.

Future infrared astronomy missions indicate the need for even lower temperatures for bolometers. One mission is the Shuttle Infrared Telescope

Facility (SIRTF). This facility will fly as an attached payload to the Shuttle (Figure 5). The basic cooling system will consist of a combination of liquid helium and supercritical helium cryostats. However, an instrument attached to the facility will be capable of carrying its own "booster" cooling system as well. The facility, then, will make multiple flights with a different complement of instruments on each flight.

It is clear that some of the instruments that will fly with SIRTF will carry ultra-low temperature coolers to provide bolometer temperatures of .1 to .3°K. Greatly increased bolometer performance will result at these ultra-low temperatures.

One other infrared astronomy mission is the Small Helium-Cooled Infrared Telescope that will fly aboard the Shuttle in 1984. The requirements for this system, however, are not technology drivers. The technology drivers for infrared astronomy missions are the need for lower tempratures for infrared bolometers and long-lifetime dewars for future free-flyer and space station instruments.

Other Liquid Helium Systems

There are other NASA payloads that will require liquid helium. These include, for example, the Gravity Probe B Satellite, the Superfluid Helium Properties Experiment, and possible future payloads employing superconducting components. The cryogenic needs for these systems are similar to those of infrared astronomy.

X-Ray and Gamma Ray Astronomy

Cryogenic cooling is required for X-ray spectrometer instruments for both the detectors (e.g., Si(Li)) and Field Effect Transistors (FETs). The temperature requirement is about 100-120°K for the detector and 130°K for the FETs.

The High Energy Astronomical Observatory-B (HEAO-B) utilized a two-stage, solid methane/ammonia cooler for its X-ray instrument. Launched in 1978, the cooler maintained a nominal 80°K primary temperature and 150°K secondary temperature for 11 months. The cooler was manufactured by Ball Aerospace Systems Division.

A future X-ray observatory that is in the planning stages at NASA is the Advanced X-ray Astronomical Facility. Although the instruments have not yet been selected for this satellite, it is likely that at least one will require cryogenic cooling.

In the area of gamma ray astronomy, the HEAO-C satellite was launched in 1979. This satellite utilized the same cooler design as HEAO-B to perform X-ray and gamma ray spectroscopy. However, the HEAO-C cooler achieved a lifetime of only 8 months.

For both the HEAO-B and C satellites, it is clear that a long-lifetime, closed cycle cooler would have been a tremendous asset. Of course, a much larger stored cryogen cooler, which is more feasible in the Shuttle era, would also have helped. Additionally, a launch support release mechanism for the stored cryogen system would have extended lifetime by several months. With possible higher heat loads and longer lifetime requirements of future X-ray and gamma ray instruments, it is clear that a closed cycle cooler will be required.

Space Station

NASA is presently proposing the development of a space station. Although the exact nature of the station has not been defined, it would appear that resupplying cryogens to scientific payloads may be a reasonable thing to do. This could take the form of "refueling in space" or replacement of a cooler and/or instrument. In one sense, this may alleviate the cryogen lifetime problem; however, from a cost and risk viewpoint, one would want to have a long service interval. The cryogenic system design drivers and needs for a space station system are essentially unknown at this time.

Summary of NASA Needs

It is clear there is a pressing need for a long-lifetime, closed cycle cooler. A device of this nature in the 65°K temperature range would find wide spread utilization for earth observation, and X-ray and gamma ray astronomy missions. A 10°K, closed cycle cooler would find application for atmospheric science instruments. Another potential use would be to provide the cooling for radiation shields and the inner support structure of stored cryogen systems for both instruments and long-term storage of cryogenic propellants in space.

For infrared astronomy and other liquid helium systems, improvement in lifetime of the cryogenic systems is needed. The development of structural support release systems for dewars would certainly be of great benefit. It is also about time to consider closed cycle liquefaction systems for space.

Additionally, for infrared astronomy missions, flight-worthy ultra-low temperature systems, such as a helium-3 and adiabatic demagnetization refrigerators, will be needed.

The refueling of Orbit Transfer Vehicle cryogenic propulsion systems is already in NASA's plans. A cryogenic fluid transfer technology experiment should fly aboard the Shuttle in the late 1980's. This technology may also be of use in developing systems for the servicing of cryogenic coolers from a space station.

RECENT PROGRESS IN NASA TECHNOLOGY PROGRAMS

Reference 1 summarizes the progress in NASA efforts to develop the technology to satisfy the stated needs. The following is a brief discussion of significant progress since Reference 1 was published.

The most exciting achievement over the past year has been the successful testing of the first model of the NASA/Goddard long-lifetime, 5W, 65°K, Stirling cycle cooler (Figure 6). This cooler, which is being developed for NASA by Philips Laboratories, utilizes magnetic bearings to eliminate rubbing of the piston and displacer against the cylinder walls. Additional design features include (1) linear drive systems for both the piston and displacer, (2) elimination of organic materials and the resultant contamination inside the working volumes, (3) electronic control of piston/displacer axial motions and phase angle, and (4) dynamic balance.

As of this writing, the cooler has successfully completed over 300 hours of operation and 100 start/stop cycles. All performance design goals have been met. Details of the latest test results are in Reference 6.

The next step in the long-life, Stirling cycle cooler program is to develop a second 65°K, 5W model of the cooler. The second model will improve the technology of the system to a level where a flight program would commit to using it. Follow-on plans include extending the technology to lower temperature (12°K) machines.

Results have also been reported during the past year in the development of stored cryogen system structural release systems. For example, Reference 7 describes the design of a NASA 3-year, liquid helium dewar utilizing the Lockheed Passive-Orbital-Disconnect-Strut System. Another NASA contract to design a structural release system has recently been awarded to Ball Aerospace Systems Division.

The systems being developed are the passive type, as illustrated in Figure 7. In the series passive design, the launch load is transmitted through the pin between the tubular structural support and end fitting. When in orbit, there is only a thin fiberglass band connecting the end fitting and tube, and there is a clearance around the pin. In this way, the thermal conductance in orbit is very low. In the parallel design, the thin outer tube is the in-orbit support, while during launch, the central structural member supports the load. These "bumper" type systems do not require any activation other than the launch loads themselves. More work is needed to flight qualify these systems.

Work has also progressed over the last year in the development of adsorption coolers. Tests have begun on a $LaNi_5$ adsorption type Joule Thomson refrigerator that achieves 29°K. This system offers advantages for outer planet missions, where radioactive power system waste heat is available and a 77°K first stage temperature can be achieved via radiant cooling. Details of these results are in Reference 8.

Additional NASA work of significance over the past year includes studies on the development of a zero-g, .3°K, ^{3}He system. The results of experiments on a copper matrix fluid retention system for such a device are reported in Reference 9.

CONCLUSION

A variety of NASA needs in cryogenic cooling has been identified. Efforts to provide the technology for these needs have produced outstanding results. However, much remains to be done.

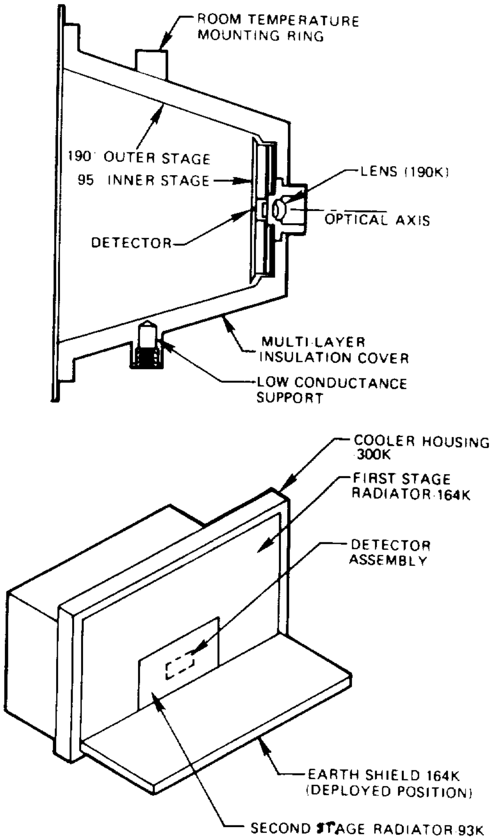

Figure 1. Radiant Coolers: A.D. Little (top), ITT (bottom).

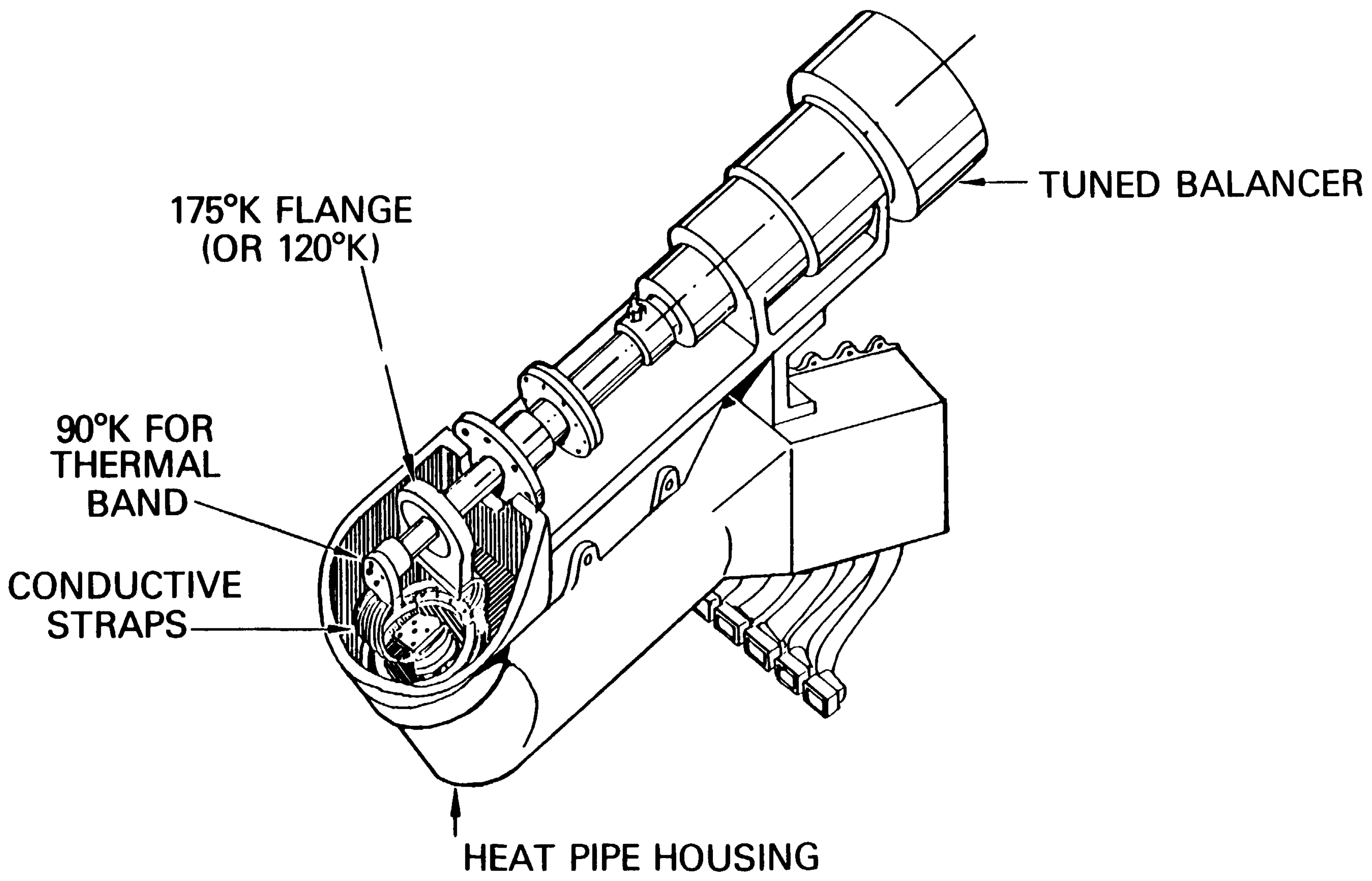

Figure 2 MLA Instrument Coupled to a Stirling Cooler (extracted from Reference 4)

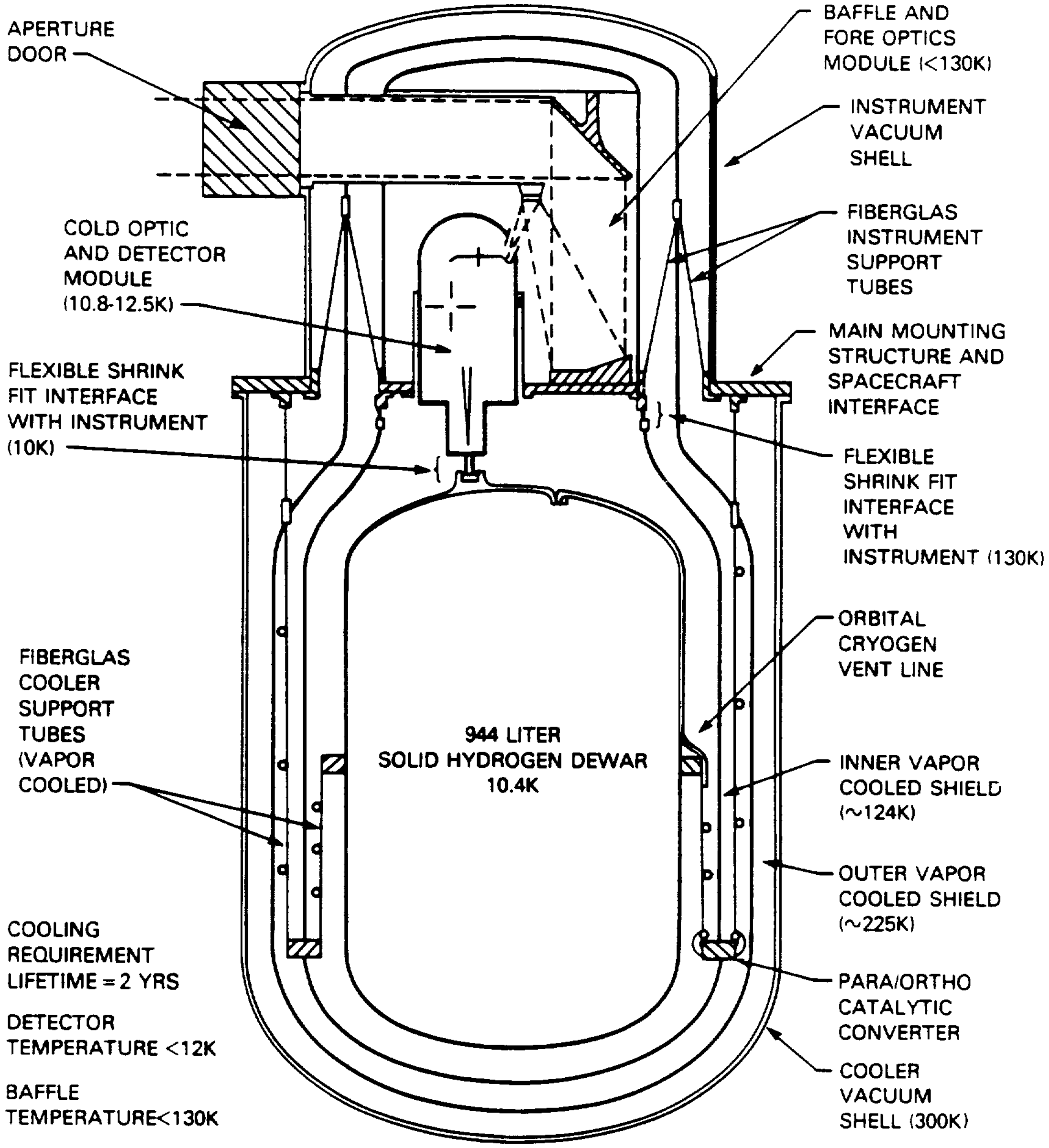

Figure 3 CLAES Solid Hydrogen Cooler Concept

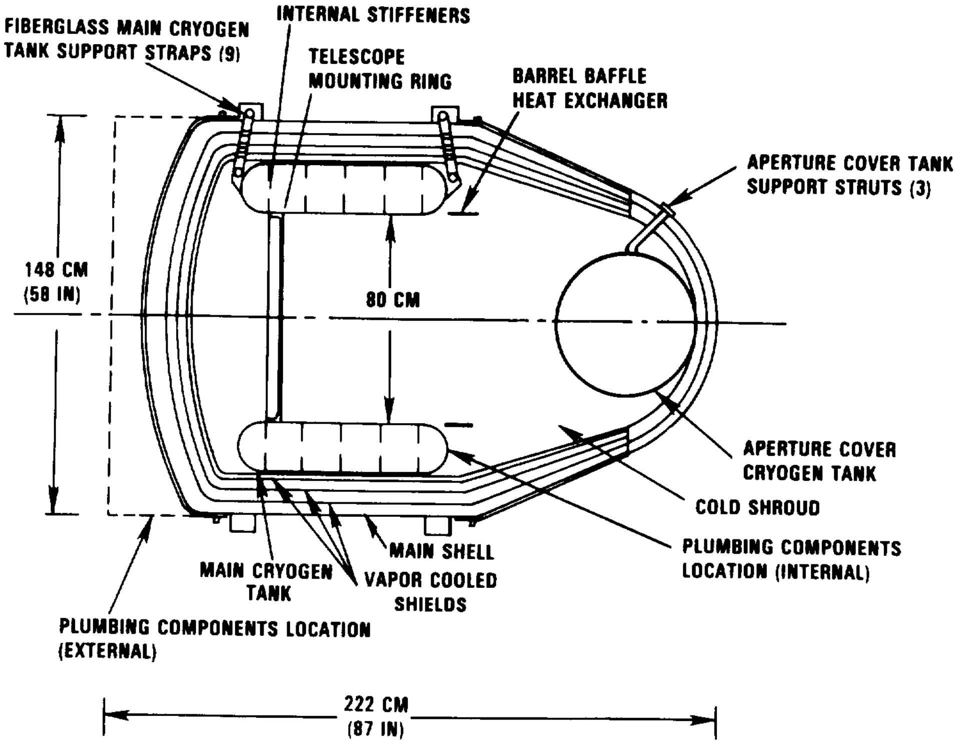

Figure 4. IRAS Superfluid Helium Dewar.

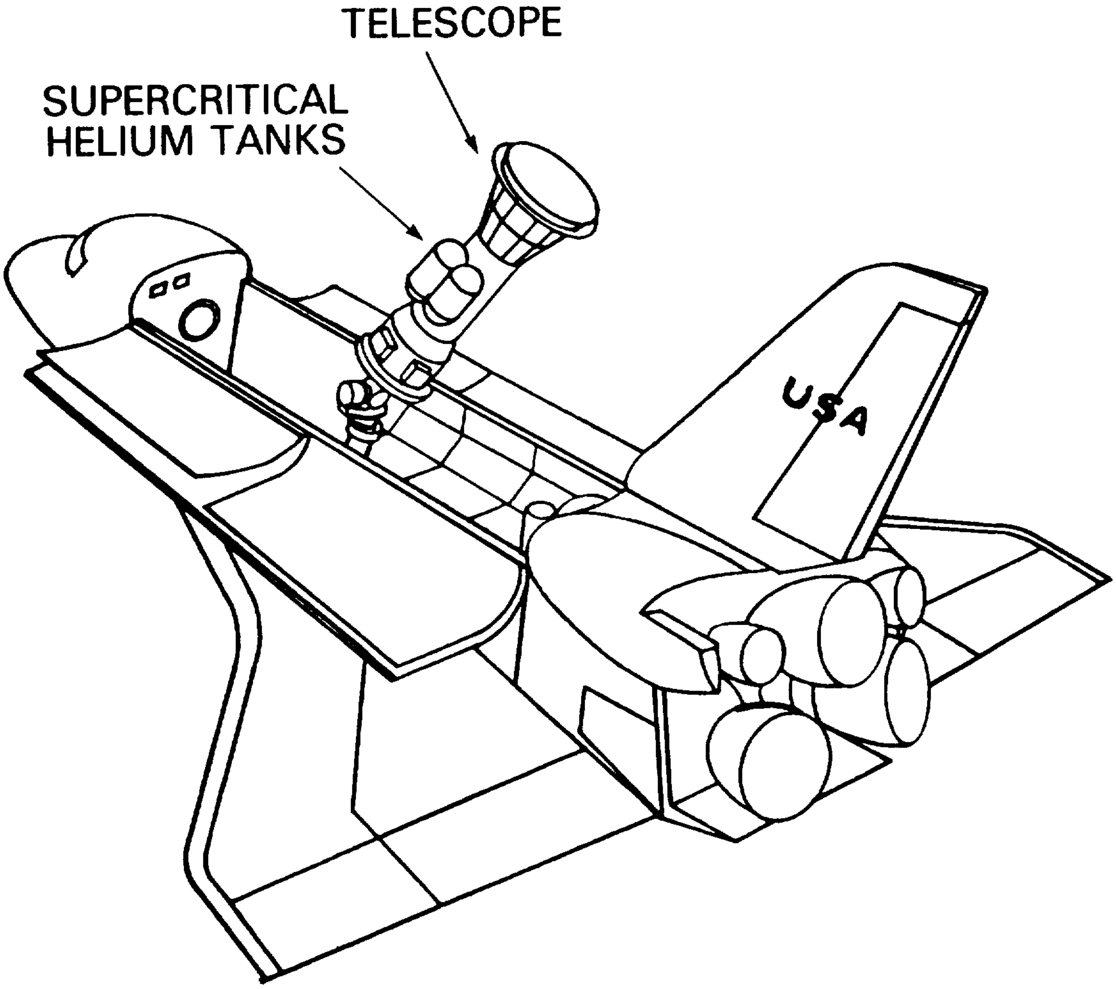

Figure 5. SIRTF Concept.

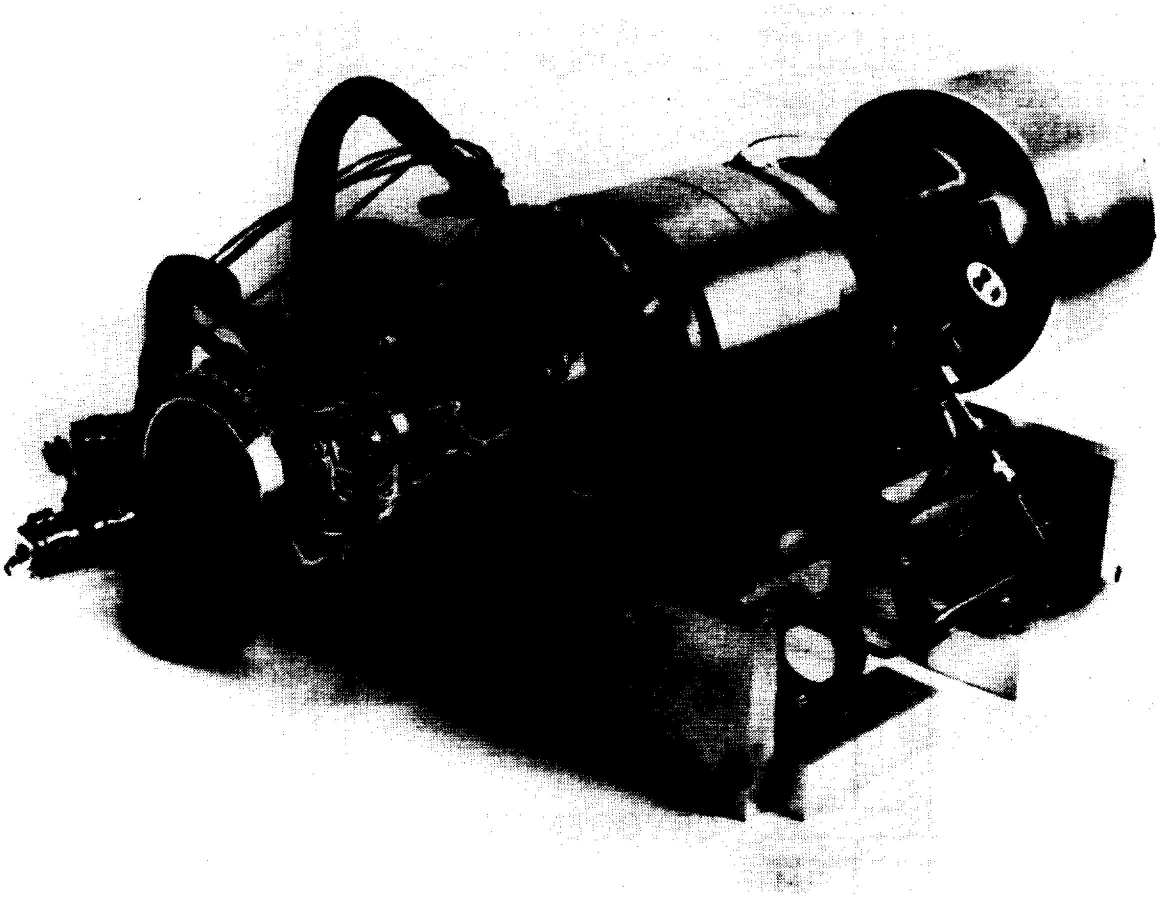

Figure 6. Photograph of NASA Stirling Cycle Cooler developed by Philips Laboratories.

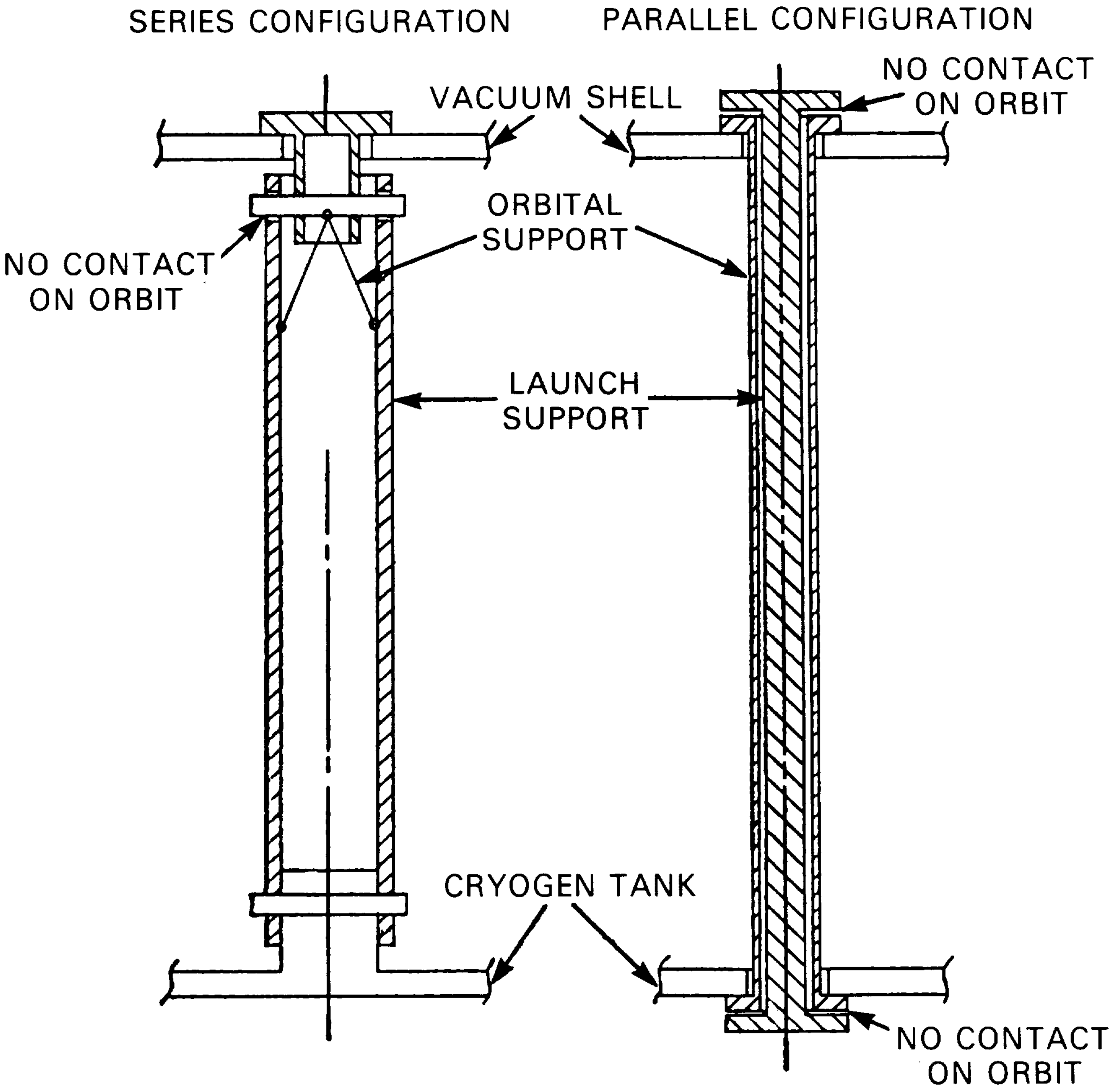

Figure 7. Series and Parallel Launch Support Release System for Stored Cryogen Systems.

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