N76-19182

10. REFURBISHMENT OF THE CRYOGENIC COOLERS FOR THE SKYLAB EARTH RESOURCES EXPERIMENT PACKAGE

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SUMMARY

Two of the Skylab Earth Resources Experiment Package (EREP) experiments, S191 and S192, required a cold temperature reference for operation of a spectrometer. This cold temperature reference was provided by a subminiature Stirling cycle cooler. However, the failure of the cooler to pass the qualification test, coupled with the fact that the cooler manufacturer had gone out of business made it necessary for the additional cooler development, refurbishment, and qualification to be done by the Lyndon B. Johnson Space Center (JSC). Because of the exclusive nature of the contracts between the cooler manufacturer and the experiment contractors, no drawings, assembly procedures, or manufacturing specifications were available. Furthermore, no replacement components were available for the limited number of existing coolers in the EREP program. These facts made the development of adequate procedures for both disassembly and reassembly of the cooler mandatory. Also, since these coolers were flight items, a strict quality assurance program had to be implemented. A description of the failures and the cause of these failures for each of the coolers is presented. The solutions to the various failure modes are discussed along with problems which arose during the refurbishment program. The rationale and results of various tests are presented. The successful completion of the cryogenic cooler refurbishment program resulted in four of these coolers being flown on Skylab. The system operation during the flight is presented.

INTRODUCTION

The primary objective of the Skylab mission was the study of the earth. This earth survey included agriculture, forestry, oceanography, hydrology, geology, and geography. The EREP contained the scientific instruments to conduct the investigation of these various disciplines. Two of the experiments within the EREP group were designed to investigate the infrared region of the electromagnetic wave spectrum. The S191 Infrared Spectrometer performed controlled experiments in the applicable region of the spectrum on ground sites actively acquired and tracked by the flight crew. The S192 Multispectral Scanner gathered quantitative high spatial resolution line-scan imagery data on radiation reflected and emitted by selected ground sites. One of the

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features which each of these experiments had in common was their use of a nearly identical cryogenic cooler to refrigerate the infrared detector.

CYCLE DESCRIPTION

Before presenting a detailed description of the cooler, it is helpful to briefly review the operation of the cooler. Any refrigerator operating on the Stirling cycle principle must have a compression volume at a warm temperature and an expansion volume at some colder temperature. The relationship between these two volumes must be such that a fixed quantity of working fluid (helium in this case) is made to alternately pass from one volume to another through a regenerative heat exchanger. This is shown in Figure 1, which illustrates the four basic processes of an idealized Stirling cycle. In the isothermal compression process of Figure 1-A, the compression piston moves upward while the expander piston remains stationary at its top position. Heat is rejected at the compressor head (the aftercooler heat exchanger) at an intermediate temperature. Figure 1-B illustrates a constant-volume heat transfer process in which heat is stored in the regenerator. In Figure 1-C, isothermal expansion occurs by a downward movement of the expander piston with the compressor piston stationary. Heat is absorbed (from the infrared detector) at the low temperature in the cold-end heat exchanger. The cycle is completed (Figure 1-D) by a constant-volume heat transfer process in which the working fluid travels from the expansion volume to the compression side. During this process, the working fluid extracts the heat stored in the regenerator during the previous constant-volume heat transfer process.

COOLER DESCRIPTION

The cooler, shown in Figure 2a, is a subminiature Stirling cycle refrigerator which uses helium as the working fluid and has a cooling capacity of approximately 1 watt at $90^{o}K$ ($-297^{o}F$). Physically, the cooler is 6.35 cm (2.5 inches) in diameter and approximately 30.5 cm (12 inches) long, and weighs approximately 2.7 kg (6 lbs). The cooler consists of four working sections; they are as follows: (Figure 2b)

a. Cold end assembly, including the cold end heat exchanger and regenerator.

b. Cylinder head assembly, including the after-cooler heat exchanger.

c. Cylinder block assembly, including pistons and crank assembly.

d. Drive motor assembly and gear case.

The cold end assembly contains the refrigerating surface, which is in good thermal contact with the infrared detector. This section of the machine operates at approximately 90°K (-297°F). The cold end assembly also contains the regenerator which is the heart of a Stirling cycle refrigerator. The effectiveness of a regenerator is defined as the ratio of energy actually absorbed to the energy which could be ideally absorbed. It can be shown (Reference 1) that if the effectiveness for the regenerator is less than 94 percent, there will be no net refrigeration. Hence, great care must be exercised in working with the regenerator.

The cylinder head assembly contains the after-cooler heat exchanger. The after-cooler heat exchanger, which absorbs the heat of compression from the helium gas, consists of several very small copper tubes brazed into a bundle and inserted into the aluminum cylinder head. Heat rejection is by conduction through the heat exchanger walls and cylinder head to the cooler outer shell and finally, through the mounting brackets to the spacecraft structure.

The cylinder block assembly contains the compression and expansion cylinders plus all of the important mechanisms in the cooler. Figure 3 shows a detailed view of this assembly. A single crankshaft is utilized to drive both the compressor and expander pistons. In order to achieve the constant volume processes required for proper operation, the compression and expander pistons are approximately 90° out of phase. This phase angle is very important for the optimum performance of the cooler. The phenolic extension on the expansion piston is to provide a long heat path between the relatively hot piston rings and the cold working fluid. The pistons have four basic components; they are as follows:

a. An aluminum body,

b. A Rulon (glass filled Teflon) sleeve over the aluminum body,

c. Two full-circle Rulon compression rings and,

d. O-rings behind the Rulon compression rings to prevent gas leakage between the ring and the aluminum body.

The pistons are connected to the piston rods with wrist pins; the wrist pin bearings are needle bearings while the rod bearings and the main crankshaft bearings are ball bearings. These bearings are all packed with a commercial grade, high temperature hydrocarbon lubricant.

A 96-tooth bevel ring gear (shown in Figure 3) is attached to the crankshaft with eight screws, which are staked. The ring gear has a reduction ratio of four which results in a nominal crankshaft speed of approximately 1500 r/min. Both the ring gear and pinion gear are coated with molybdenum disulfide dry lubricant. The entire crankshaft/piston assembly is attached to the cylinder head assembly by screws through the main bearing hangers. The bearing hangers contain pilot pins for gross alignment; shims are used to complete the precision alignment of the pistons in the cylinder.

The drive motor assembly contains the 28V d.c. motor which operates at approximately 6000 r/min or 4500 r/min. The two speeds are a requirement for the S192 experiment; S191 operates only at the higher speed. The power consumption ranges from a maximum of 45 watts operating at high speed to a minimum of 28 watts when operating at low speed. The pinion gear is mounted to the motor shaft and the set screws are safety-wired. The gear case is utilized to mate the motor drive assembly to the cylinder block assembly.

Since a long shelf life for the coolers is required, an outer case is installed over the entire cooler to prevent helium leakage. The original outer case design was an aluminum cylinder with a bimetallic joint at each end. The aluminum section provides for good heat rejection, while the stainless steel permits the outer case to be welded to the cooler. The electrical leads are soldered to a ceramic feed-through connector contained in a stainless steel end cap. The end cap is welded to the motor end of the unit making the entire cooler hermetically sealed (Figure 2a).

Physically, the only external difference between the S191 cooler and the S192 cooler is the design of the front mounting flange. In operation, the startup procedure for both coolers is the same; the motor is set to the high speed, and 28V d.c. is applied to the motor. The S191 runs continuously in this configuration. The detector temperature is controlled at a constant 82°K (-312°F) using an electrical resistor on the detector. The S192 operates differently. Once the detector reaches 90°K (-297°F), a controller in the experiment switches the motor to low speed and reduces the voltage simultaneously. The detector temperature is then controlled at approximately 92°K (-293°F) by automatically varying the motor voltage, which varies the motor speed and consequently the cooling capacity.

COOLER PROGRAM BACKGROUND

In Janualy 1972, the cooler was undergoing component qualification testing at the S191 contractor's facility. This qualification test was for both the S191 and S192 coolers. A large portion of the qualification testing, including vibration, electromagnetic interference (EMI), exposure, etc., had been successfully accomplished. There had been some problems with the thermal performance of the S191 coolers earlier, but the S192 units were operating satisfactorily. However, during qualification testing in a thermal vacuum environment, the S191 cooler experienced several runs with degraded performance and finally failed to start. At this point in time, the manufacturer of the cooler had gone out of business, thus it was not possible to procure additional coolers nor, more importantly, was there anyone available to conduct a failure investigation and perform the necessary corrective action. The cooler program was on a very close schedule and the qualification failure had significant impact. In order to meet the Skylab launch date, the flight cooler had to be delivered to the experiment contractor by June 1972.

The S192 coolers failed while in systems test at the experiment contractor's facility in April 1972. The primary result of the failure was the inability to cool the infrared detector to its required operating temperature. Three coolers failed within a two-week period of time. For this experiment, the flight cooler was required in July 1972, to phase into Skylab checkout without impacting the launch schedule.

Thus, JSC faced a situation where a functioning cooler was not available for either S191 or S192; the cooler was not qualified; and the schedule was critical. These facts necessitated two concurrent programs.

First, JSC embarked on a cooler refurbishment program which included additional development activities, the qualification test program, and the delivery of the required flight hardware. Because of the exclusive nature of the contracts between the cooler manufacturer and the experiment contractors, drawings, assembly procedures, manufacturing specification or names of component vendors (e.g., bearing manufacturer) were not available. Furthermore, the true performance capabilities of the cooler, including the off-nominal performance characteristics, were not available. Finally, no replacement components were available for the eight coolers in this program.

The parallel program involved the procurement of a new cooler from an alternate source. This new design had increased weight and electrical power requirements; it also entailed major changes in both the S191 and S192 cooler/experiment interfaces. In view of these facts, in addition to the Skylab budget constraints, this contracted effort was terminated as soon as the success of the JSC refurbishment effort was demonstrated.

FAILURE DESCRIPTION AND CORRECTIVE ACTION

Because the observed failure characteristics of the S191 cooler could have been due to several failure modes, the disassembly and inspection of the cooler was very methodical. The gas pressure was measured and gas analysis was performed. It was determined that the outer case did not have a proper shrink fit. The initial disassembly inspection showed large quantities of electric motor carbon brush particles. When the motor was removed, it was discovered that the brushes were so badly worn that the lead wire inside the brush had worn a groove in the commutator. The probable cause of the failure was excessive brush wear. This resulted from choosing a brush which could not provide the proper lubrication of the commutator when operating in the dry helium atmosphere. The cooler performance degradation (prior to the final failure) was probably the result of contamination of the working fluid by brush material.

The corrective action was to redesign the motor; this included the design of a new brush which would operate properly in a helium environment. A number of the materials in the motor were changed to materials which would not out-gas as readily. The final corrective action was to incorporate the necessary quality assurance provisions in the cooler assembly procedures to preclude contamination.

When the S192 coolers were disassembled, one minor internal difference from the S191 cooler was noted. This difference was a small part secured by the main bearing hanger screw (see Figure 4a). Because of the manner in which this piece was attached, an adverse moment was imparted to the main bearings. This resulted in a premature failure of the main bearings and one of the rod bearings; the other main and rod bearings were affected, but to a lesser degree. This was the primary failure on all of the S192 coolers. Since the original function of the part in question could not be determined, it was decided to leave the part in place, but modify the mounting fixture to alleviate the adverse moment. The modification is shown in Figure 4b. The final corrective action for the S192 was to replace the original electric motors with those which had been redesigned for S191.

REFURBISHMENT PROGRAM

The preliminary activity of the JSC refurbishment program included the initial disassembly of a failed cooler and the determination of the physical characteristics. Two S191 coolers were originally delivered, a failed cooler and a disassembled cooler. The components from the disassembled cooler were used to determine the physical characteristics of the cooler components. After an extensive study of these components, a complete set of drawings was prepared. Since these coolers were flight items, a strict reliability and quality assurance program had to be implemented.

Concurrent with the component evaluation, the disassembly of the failed cooler was initiated. Since no drawings or disassembly procedures were available at this time, the disassembly of the cooler was performed very meticulously. Still photographs and movies were taken of each disassembly step. This information was used as the basis for writing both the disassembly procedure and the assembly procedure. Although drawings of the physical components were in work, a majority of the tolerances, alignments, and materials used were unknown. A program was initiated to determine materials used for piston rings, sleeves, o-rings, and lubricants. Since the source of the original bearings was not known, an investigation was performed to determine the availability of the required bearings. Then a program was initiated to determine the type of bearing lubricant and the lubricant packing density required for optimum operation. Regenerator flow checks were made before and after disassembly to ensure proper reassembly. Extensive tests were also performed on the original piston sleeves and rings. These tests included "blow-by" tests and "pull-through" tests to evaluate the mechanical fit of the pistons in the cylinders.

After all of the subassembly tests and procedures had been determined, the assembly procedures were written. These procedures contained the step-by-step operations required to physically assemble the cooler components and instructions for various component level tests required prior to assembly. Although the majority of the assembly was straightforward, several sections were extremely critical. The most important of the areas was the block/crankshaft assembly. The criticality of this assembly was in the bearing alignment and the proper ring and pinion gear alignment. A fixture was manufactured in-house which provided for the measurement of gear mesh, and the gears were then shimmed to provide the proper tolerances.

During the course of the refurbishment program, certain failures were encountered which required component modification and are discussed below.

Outer Case.- During the installation of the first bimetallic outer case, it was discovered that a leak had developed at the bimetallic joint. The remaining bimetallic cases were examined by X-ray and dye penetrant techniques and found to contain flaws which were aggravated by the outer case installation, which was a shrink fit. However, extensive thermal analyses indicated that the heat transfer characteristics of the cooler were not adversely affected by the use of an all stainless steel case. Therefore, stainless steel outer cases were manufactured at JSC for both the S191 and S192 coolers.

End Cap.- Problems were encountered during the program with the end cap leakage. This leakage normally occurred around the electrical connector and was probably caused by repeated welding on the same end cap each time a cooler was refurbished. Therefore, the task of designing and procuring a new type of end cap was assigned to the S192 experiment contractor. These end caps were procured, delivered, and used on the S192 flight coolers and the S191 flight backup cooler. The S191 prime flight cooler was delivered with the original end cap.

Piston Rings.- When the S192 cooler was reassembled and tested, its performance still would not meet the necessary requirements. Intensive examination revealed that the Rulon piston rings were out-of-round. This condition was probably a result of the bearing failures. The corrective action for this failure was fabrication of new piston rings. However, this required an extensive effort to develop a "piston-fit" test which would provide the ring clearances necessary to achieve proper cooler performance. (The S191 flight unit was delivered with the original rings and sleeves.)

Low Temperature Start.- Testing of the S191 coolers revealed that a problem did exist on low temperature starts. Although the cooler would start, the cool-down times and minimum detector temperatures achievable were severely affected on starts which were performed at case temperatures of 288°K (60°F) or lower. This behavior was attributed to the different thermal expansion rates of the piston rings, sleeves, and cylinder walls. At the cold temperatures, the fit of the piston rings and sleeves in the cylinder did not provide compression. Tests indicated that if the piston rings were sized to provide proper compression at a case temperature of 280°K (45°F), the ring friction was excessive at the higher case temperature. Extensive thermal analysis of the normal mission duty cycle indicated the minimum case temperature would be approximately 293°K (67°F), thus an operational constraint of 292°K (65°F) for cooler starts was established.

FINAL ASSEMBLY AND CHECKOUT

When the assembly was complete, additional time was required to ensure satisfactory cooler performance prior to shipment. The procedures required after assembly, but prior to shipment of production units, are discussed below.

Helium Servicing.- These procedures specified the method for charging the cooler with helium prior to the bench and performance tests. This procedure was the same for both S191 and S192 coolers.

Bench Test.- This test provided (1) a run-in period to ensure proper ring and sleeve and motor brush seating, (2) a cooling capacity test to determine the cool-down time required to reach 90°K (-297°F) and (3) capacity test designed to determine the cold end temperature which could be maintained at 28V high speed, 24V high speed, and 24V low speed. In addition, the S192 bench test provided for a start with a cooler case temperature of 319°K (105°F) and a simulated mission profile.

Outer Shell Installation.- This procedure was the same for both experiment coolers. The procedure provided the methods for shrink fitting the outer case over the cooler and electron beam welding the flange and end cap to the outer case.

Performance Test.- After the outer shell had been installed, the helium servicing procedure was again performed, and the servicing tube was pinched to provide a hermetically sealed unit. The performance test was then performed. This test was essentially a repeat of the bench test, excluding the run-in, to verify that no cooler damage had occurred during the outer shell installation.

Final Acceptance Tests.- These tests were different on the S191 and S192 coolers because of the different design uses. The S191 test consisted of a nominal performance test (27V high speed, 317°K (110°F) environment), low voltage test (26V high speed, 317°K (110°F) environment), and a vibration test to determine the maximum displacement of the cold end during operation. The S192 acceptance test consisted of a nominal performance test (28.5V high speed start with a switch to 24V low speed at 90°K (-297°F) while maintaining a 297°K (75°F) environment), a high temperature-low voltage test (27.5V high speed start with a switch to 24V low speed at 90°K (-297°F) while maintaining a 314°K (105°F) environment), a low temperature-low voltage test (27.5V high speed start with a switch to 24V low speed at 90°K (-297°F) while maintaining a 286°K (55°F) environment and a cold end self-induced vibration test.

THERMAL QUALIFICATION TEST PROGRAM

The qualification test for the S191 coolers was performed at JSC White Sands Test Facility. The test was performed with the cooler installed in the S191 spectrometer. The test profile included temperature and voltage limits, minimum restart time, and nominal and off-limit mission duty cycles. The cooler performance for each of the tests was satisfactory except for the low temperature start. Although the cooler did start and cool down to the prescribed temperature at a case temperature of 288°K (60°F), the time required to achieve the operating temperature of 90°K (-297°F) was excessive. However, as previously mentioned, an operational constraint was imposed to reflect a minimum case temperature of 292°K (65°F); the retest for this condition was successfully accomplished. Since the operational conditions for the S191 were more severe than the S192, the qualification for the latter was by similiarity except for one test sequence. The low speed, high case temperature 314°K (105°F) condition was run with a simulated S192 experiment interface (i.e., heat pipe). This sequence completed the qualification testing for S192.

FLIGHT APPLICATION

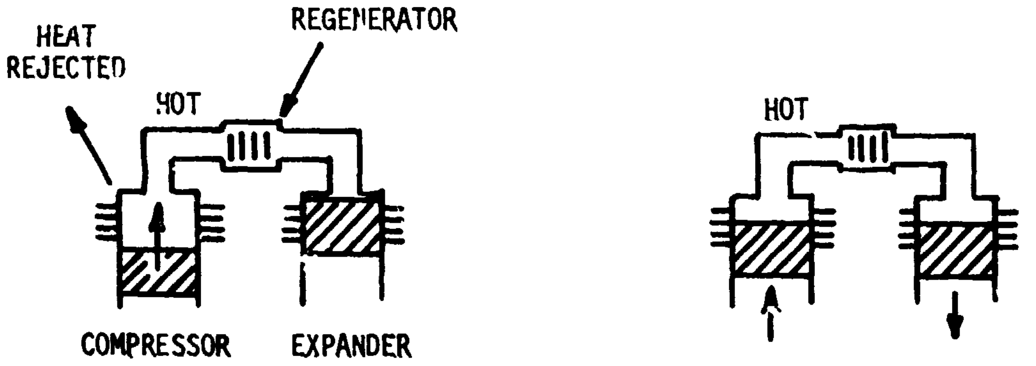
During the cooler refurbishment program, seven coolers were completely rebuilt a total of thirteen times. This included the three flight qualified coolers, two backup flight units, qualification unit, design evaluation test unit, life test cooler, and coolers for other types of test activities. For flight, the S191 had a primary flight unit and one backup cooler. The S192 experiment had two flight units, a primary and a spare which the crew could change; S192 also had a backup flight cooler. The S192 had a signal noise problem, so the backup cooler was taken up and installed by the crew of Skylab IV. The flight performance of all the coolers was excellent.

The S191 cooler had a problem during the early phases of the first Skylab mission. The problem was directly related to the loss of the solar cell panel on Skylab I. The temperature of the Multiple Docking Adapter (MDA), which contained the EREP, decreased significantly below its nominal operating temperature. This temperature reduction occurred because the heat dissipated from the EREP electronics and other subsystems was not available due to the reduced electrical power. A procedure was developed in real time to increase the cooler temperature; the unit then functioned properly. With the installation of the Skylab parasol, electrical power became available for operation of subsystems in the MDA. This increased the temperature in the MDA, and consequently, brought the cooler case and temperatures to its proper level. No further problems were encountered until the last 15 minutes of the S191 mission; at this point, the cooler performance started to degrade. The S191 was able to complete its mission, even with the degraded performance. Since the qualification design life of the cooler had been exceeded, the performance was considered out of specification, but not a failure.

The S192 primary cooler performed with no anomalies throughout its flight life. As mentioned previously, due to a signal noise problem, the backup cooler with a detector of a new design was installed by the Skylab IV crew. This eliminated the signal noise problem, which indicated that the source of the noise was not inherent in the cooler design. The backup cooler operated satisfactorily for the remainder of the mission.

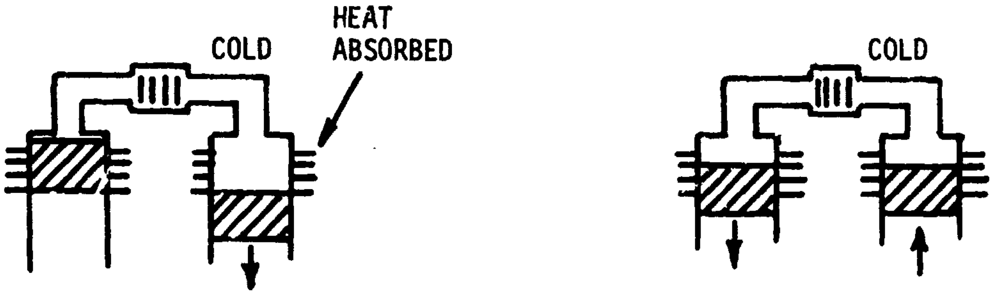
REFERENCES

1. Barron, R.: Cryogenic Systems. McGraw-Hill Book Co., Inc., 1966.



1-A. ISOTHERMAL COMPRESSION (Heat Rejected in After-cooler)

1-B. CONSTANT-VOLUME HEAT TRANSFER (Heat Transfer From Fluid to Regenerator)



1-C. ISOTHERMAL EXPANSION (Heat Absorbed From Infrared Detector)

1-D. CONSTANT VOLUME HEAT TRANSFER (Heat Transfer From Regenerator to Fluid)

Figure 1. Fundamental Thermodynamic Processes for Stirling Cycle Refrigerator

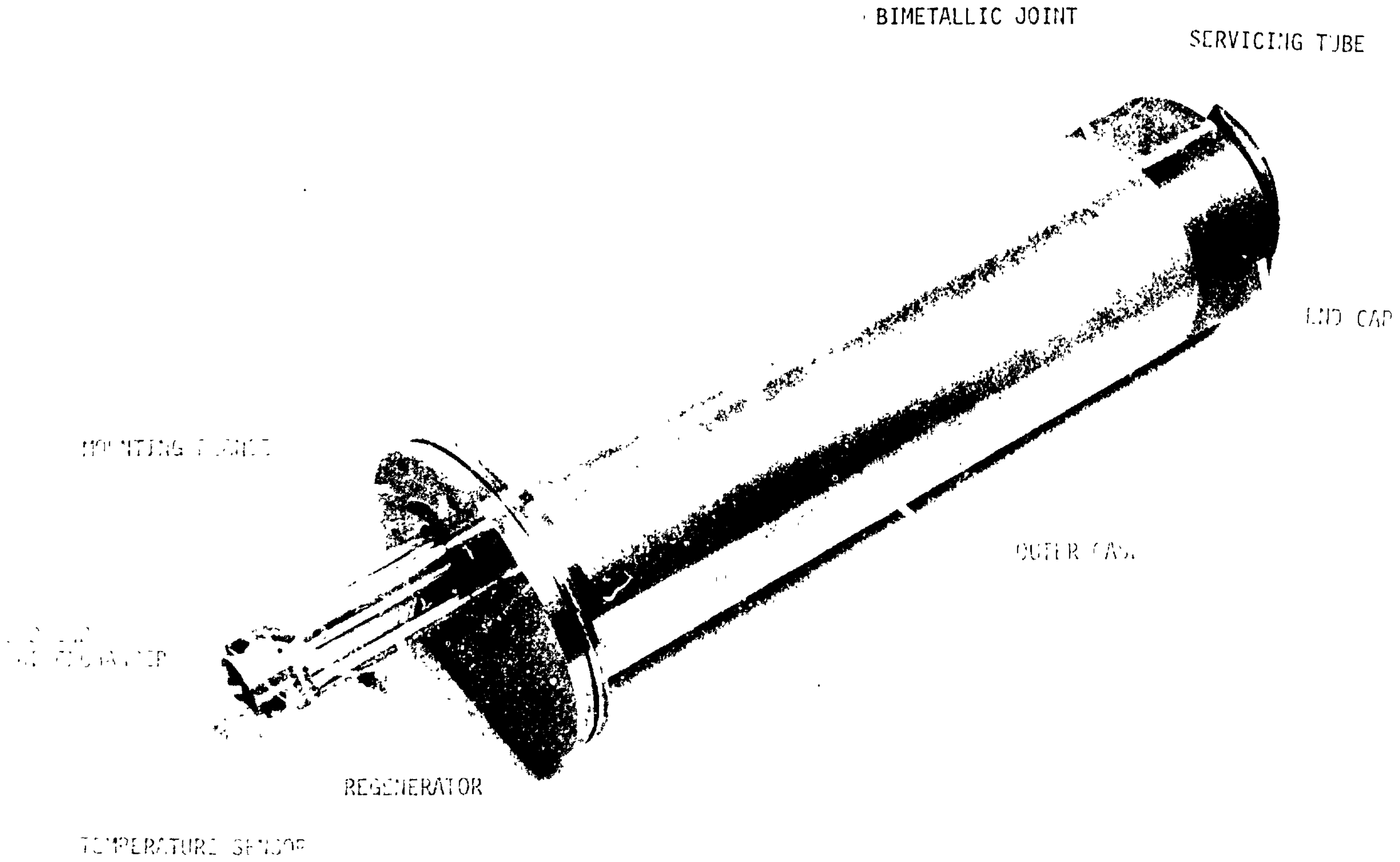


Figure 2a. Overall View of S191 Cryogenic Cooler

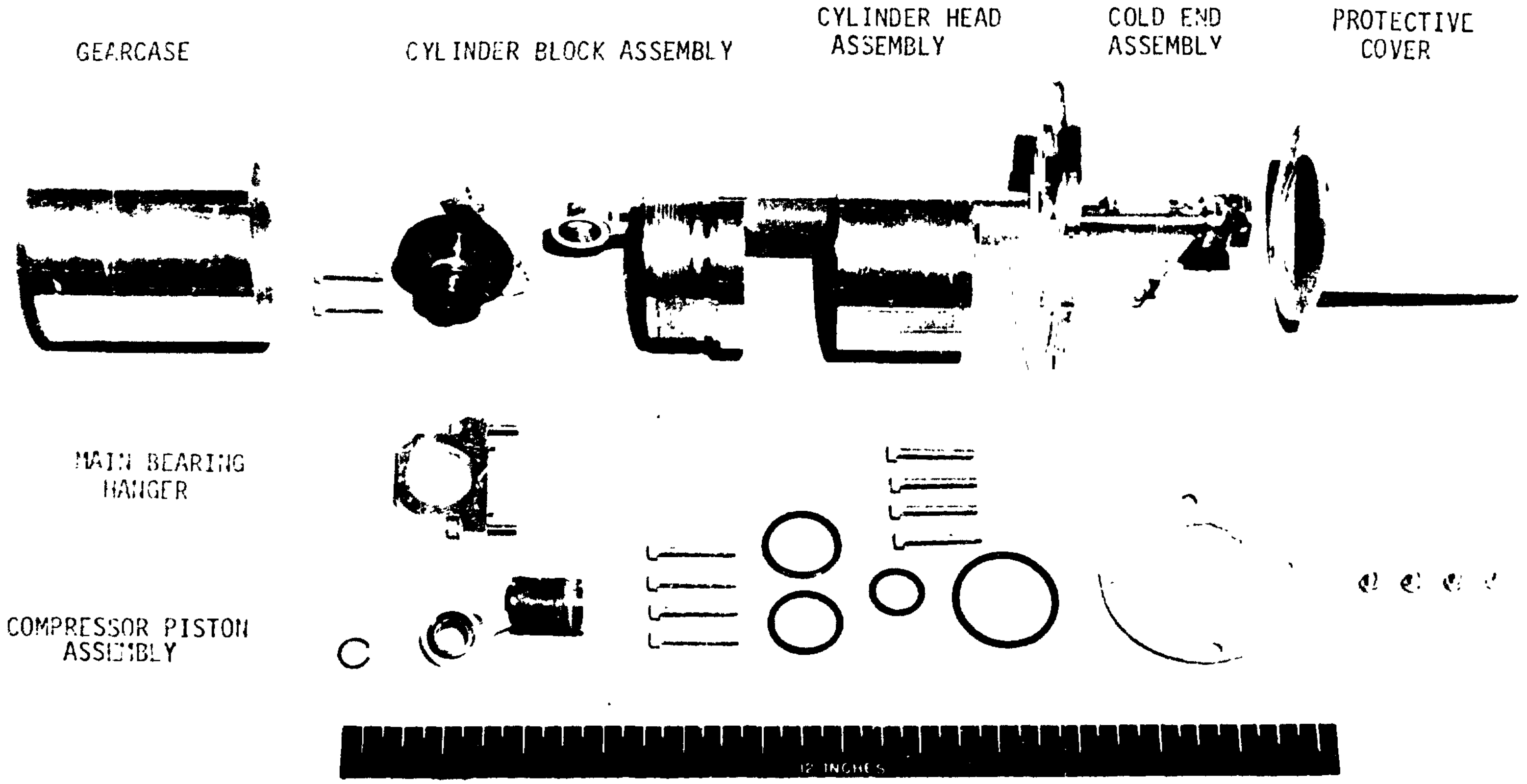


Figure 2b. Exploded View of S191 Cryogenic Cooler (Less Drive Motor and Outer Case)

Figure 3. S191 Cylinder Block Assembly

NOTE: NOT TO SCALE - EXPANDED
TO SHOW DETAILS

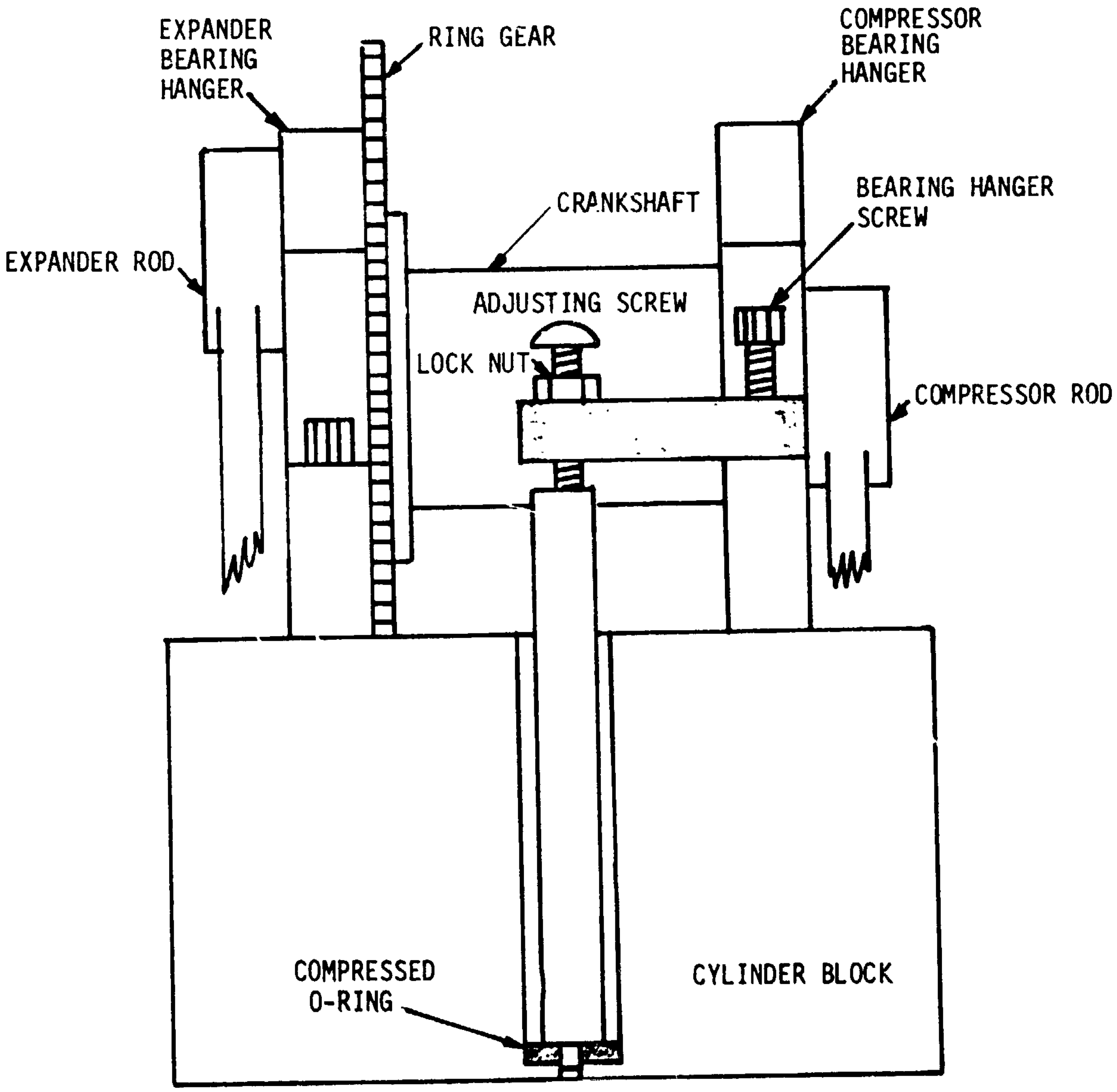
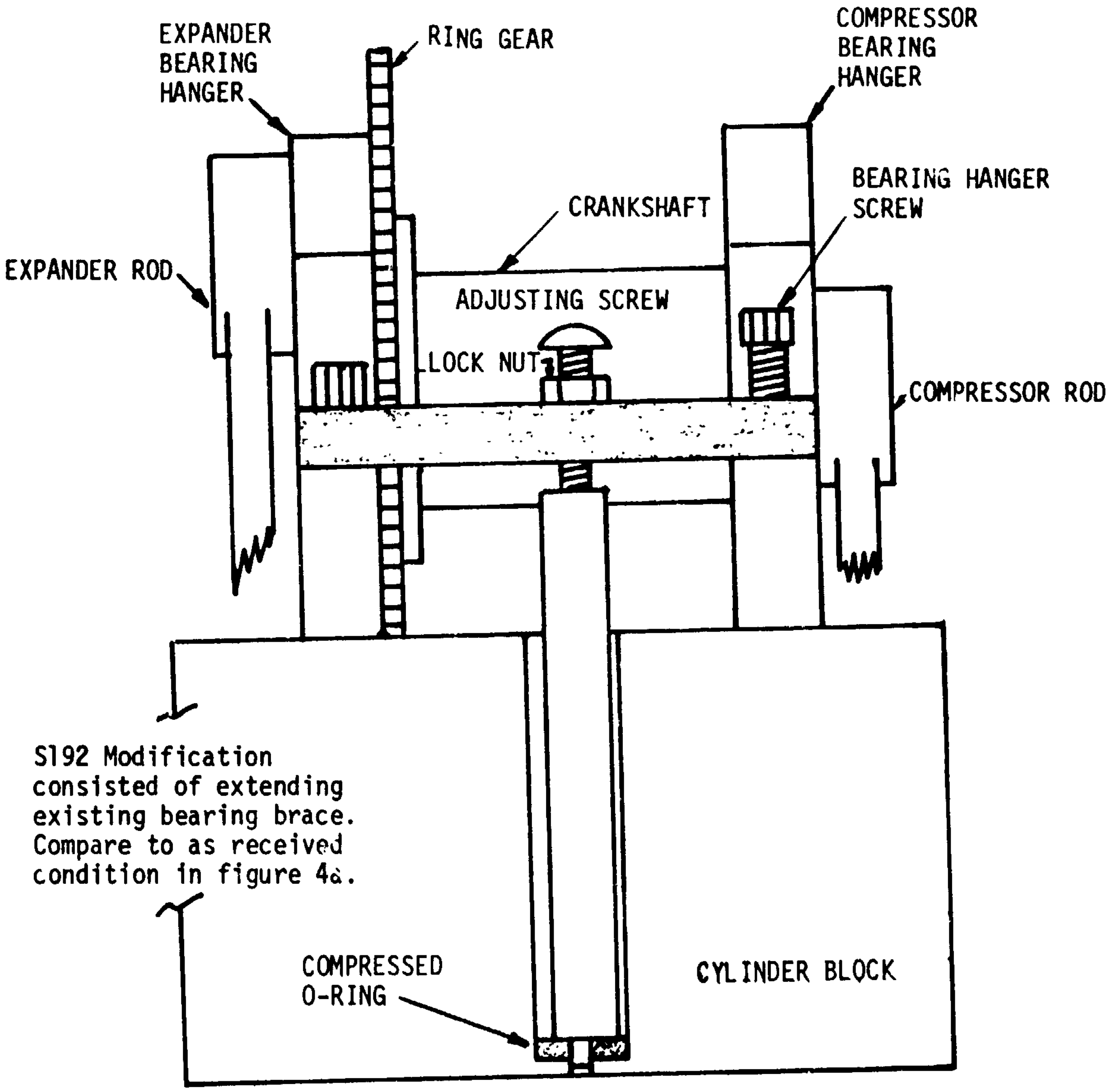


Figure 4a. S192 Cooler Main Bearing Support (As Received)



NOTE: NOT TO SCALE - EXPANDED
TO SHOW DETAILS

S192 Modification consisted of extending existing bearing brace. Compare to as received condition in figure 4a.

Figure 4b. S192 Cooler Main Bearing Support (As Required)