LIFE TEST PERFORMANCE OF A PHILIPS RHOMBIC-DRIVE

REFRIGERATOR WITH BELLOWS SEALS

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ABSTRACT

In February 1979, four Stirling cycle cryogenic refrigerators, developed by Philips Laboratories for the Johns Hopkins University/Applied Physics Laboratory, were launched into orbit aboard the P78-1 spacecraft. The refrigerators were designed to cool the detectors of two identical gamma-ray spectrometers to 77°K reliably for one year. Since launch, the refrigerators, still in orbit, have individually accumulated from 5,000 to over 20,000 hours of operation.

The refrigerators have met, and in some instances exceeded the predicted life. However, telemetry data indicates that the operating temperatures have been degrading with time. Specifically, the Lockheed Palo Alto Research Laboratory, the monitor of the spectrometers' performance, reported a 0.4°K/day short-term temperature degradation, and a 16°K increase per year. Although these increases are within acceptable limits, Philips Laboratories initiated efforts designed to minimize, or to eliminate the reported degradation.

As part of those efforts, a refrigerator identical to those in orbit was built, with one significant modification: flexible metal bellows between the crankcase and the working volume to prevent possible contaminants from migrating into the cold region. During the life test of the modified refrigerator, the temperature increase during the first three month run was 0.022°K/day, a negligible level. As of October 1982, the unit has accumulated over 12,300 hours of operation.

INTRODUCTION

Cryogenic refrigerators are normally subject to two failure modes: catastrophic mechanical breakdowns and degradation of the operating temperatures. The refrigerators addressed in this paper have operated in space for three (3) years with no mechanical breakdown, the design goal having been one year. The operating temperatures, however, have degraded with time. This degradation has been attributed to two causes: a gradual loss of working gas by leakage past or through elastomeric static seals, and contamination of the working gas by volatile products originally present in the drive elements housed in the refrigerator crankcase.

The loss of working gas through the static seals can be significantly reduced or eliminated by using metallic seals or welded flanges, respectively. Maintaining the purity of the working gas, however, is a difficult problem. Philips Laboratories (PL), in an attempt to solve that problem, has modified the design of the four (4) refrigerators currently oribiting on the P78-1 spacecraft. Specifically, the new design approach makes use of metallic bellows to separate the working space from the crankcase, thus preventing contaminants from reaching the working space.

The new approach has been comparatively successful. This paper describes the new design and presents the experimental results attained. The work presented was fully funded by Philips Laboratories.

BACKGROUND

In 1973 Philips Laboratories, under contract to the Johns Hopkins University/Applied Physics Laboratory (JHU/APL), began to develop a miniature Stirling cycle cryogenic refrigerator capable of operating for one (1) year in space. The refrigerator was to cool the germanium detector of a gamma-ray spectrometer which was designed, flown and monitored by the Lockheed Palo Alto Research Laboratory. For maximum energy resolution, the germanium detector had to be cooled to approximately 77°K; this temperature level was to be reached and maintained as efficiently as possible using a mechanical refrigerator.

In addition to the operating life and efficiency requirements, the refrigerator had to be relatively free of vibrations. Specifically, the amplitude of its cold surface motion had to be less than 10 microns in any direction. To meet this requirement, the inertial forces induced by the reciprocating parts of the refrigerator, i.e., by the piston and by the displacer, were counterbalanced with the aid of a rhombic drive (ref. 1). The bearings of the drive, contained in the crankcase, were lubricated with a low vapor pressure grease; the low vapor pressure was to minimize the formation of gaseous contaminants; the use of a grease rather than a liquid was to help prevent lubricant migration away from the bearings.

One of the attractive features of the rhombic drive, in addition to its balanced configuration, is the absence of side loads on the reciprocating elements and seals. This feature helps minimize seal wear; it also enhances the use of bellows adjacent to the piston as a method of hermetically isolating the working space from the crankcase. Such isolation could prevent even the minimal gaseous contaminants generated by the lubricant from migrating from the crankcase into the working space. Therefore, the original refrigerator design included bellows type metal seals.

However, several bellows failed during the preliminary performance tests. Diagnostic analyses suggested that the failures were induced by high stresses which resulted from non-uniform bellows cross-sections. The solution, obviously, was to select bellows having acceptably uniform cross-sections. However, a non-destructive selection method was time consuming, and its application would have jeopardized the timely delivery of the refrigerators. Therefore, it was decided to omit the bellows from the deliverable units, and rely solely on the conventional reinforced-Teflon compression type seals for separating the crankcase from the working space. The decision was confirmed by test results which indicated that the outgassing of the low vapor pressure lubricant, and the associated contamination of the working gas, was lower than anticipated, and could therefore be tolerated.

Indeed, tests with the first refrigerator without bellows showed no oil vapor contamination. However, after approximately 1,000 hours of operation, its cold production began to deteriorate, and its operating temperature continued to increase. Upon warm-up and disassembly of the refrigerator, several droplets of water were found on the displacer, suggesting that the temperature degradation was caused by water contamination. This was confirmed by the results achieved when more stringent purging and filling procedures were adopted. Specifically, by using a vacuum system to evacuate the working space, and by raising the refrigerator envelope to 140°F during the purging procedure, the rate of operating temperature degradation was reduced from 0.9°K/day to 0.4°K/day. The latter rate was acceptable to the ultimate user. Therefore, using the method just described, the remaining refrigerators were purged, successfully tested, and delivered.

Of the six refrigerators built (ref. 2), one was placed on life test at JHU/APL, four were integrated with the experiment on the P78-1 satellite (ref. 3), and launched into space in February 1979, and one was retained as a spare. No mechanical failures were experienced with any of the refrigerators (ref. 4, 5); however, the temperature degradation problem remained, although the rate of degradation was significantly lower than that experienced at the outset of the program. As expected, outgassing products were still being generated in the refrigerator crankcase, and the conventional seals did not prevent their migration into the working space.

It should be noted that following the removal of the bellows seals from the six deliverable refrigerators, Philips Laboratorires initiated a bellows testing program. Of the twenty pair of bellows available, six pair were randomly selected for endurance testing. The first two sets failed before achieving 1.0×10^6 cycles, which was determined to be the minimum number of cycles required to indicate the bellows reliability. One set having reached 1.0×10^6 cycles, continued on to exceed 5×10^8 cycles. These favorable results, and the failure to eliminate the contamination problem by improved purging methods, suggested that the bellows sealing approach be reevaluated by conducting tests on an actual refrigerator.

DESCRIPTION OF REFRIGERATOR

To evaluate the performance of the refrigerator/bellows seal combination, Philips Laboratories fabricated the refrigerator shown in figure 1, which was both thermally and physically equivalent to those delivered to JHU/APL, except for the addition of bellows seals. As an aid to the reader, the major characteristics of the refrigerator and some of its performance parameters, although previously published, are given in table I. It should be noted that the cold production and input power levels can be tailored, within certain limits, to specific operational temperature requirements.

A cross-sectional view of the refrigerator is shown in figure 2a along with an enlarged view of the bellows seal area shown in figure 2b. As indicated, two bellows are used in a nested, or concentric configuration. One end of each bellows is hermetically connected to a stationary element of the refrigerator; the others are hermetically connected to the reciprocating elements, i.e., one to the piston rod, the other to the displacer rod. The major characteristics of the two bellows are given in table II. Each side of the bellows seal arrangement, that is, both the crankcase and the working space, are pressurized (with helium) to $4.8 \times 10^5\ Nm^2$, reducing the pressure differential across the seal to essentially zero.

TEST PROGRAM AND RESULTS

The tests were run at a refrigerator speed of 1,000 rpm, with heat loads of 0.3 watts and 1.5 watts at the lowest and intermediate temperature levels respectively. The heat-rejection flange, the area where the heat of compression had to be dissipated, was maintained at 300°K $\pm$ 2°K. Testing commenced in January 1981. Although it was intended to run the test continuously, several interruptions were experienced, due to instrumentation failures, power outages, and the need to periodically recalibrate certain instruments.

For 800 hours of initial operation, data is available for comparing the output temperature stability of three (3) refrigerators which had no bellow seals, with the test refrigerator containing bellows. Specifically, the three refrigerators which had conventional seals were tested at Philips Laboratories prior to delivery to JHU/APL. The comparison is given in figure 3; it is obvious that the output temperatures of the refrigerators which had conventional seals, designated S/N 1 through S/N 3, degraded with use, while that of the test unit, designated PL, remained relatively constant. Since the four units were identical in every respect except for the method of separating the crankcase from ther working space, it is evident that the significant improvement in performance was due to the bellows seal.

It should be noted that a helium leak in the crankcase developed after the test was initiated. It was assumed that the leak was the result of static elastomeric seal relaxation. The associated loss of helium pressure, 3.5×10^4 Nm^2, was compensated for on a weekly basis. No attempt was made to repair the leak, since it had no effect on the bellows seal tests being conducted. However, as a precautionary step, the pressure in the working volume was monitored to insure no changes in the working pressure occurred. Indeed, no changes occurred; consequently there was no need to replenish the helium pressure in the working space.

The test described in this paper ran for over 12,300 hours. The performance of the refrigerator in that interval is summarized in the graph of figure 4. Some noteworthy events which occurred during the test period are highlighted next.

- During the first 3,064 hours of continuous running, the temperatures at both cold stages varied within a 5°K band. The monitoring instrumentation, the power input to the motors and to the cold finger heaters were reset, and testing resumed. During the next 1,360 hour continuous test period, the operating temperatures remained within the original 5°K band. At that point, that is, after a total of 4,424 hours of operation, the refrigerator was taken off the test stand for demonstration at a meeting.

- Following its reactivation, the test ran for another 1,702 hours (i.e., 5,944 total operating hours) before a power failure.

- The one year minimum expected operating life was attained with a temperature increase of 10°K on the lowest temperature cold surface and 7.5°K increase on the intermediate temperature cold surface. This translates to an average temperature rise of 0.027°K/day and 0.020°K/day, respectively. These rises were attributed to seal wear, inasmuch as no decrease in the operating pressure was experienced in the working space.

- After 1,660 additional operating hours, i.e., 10,420 hours total, the temperature increased at the coldest stage from 80°K to 87°K, and at the intermediate stage from 138°K to 142°K. The test was stopped; the refrigerator was allowed to warm up to ambient temperature, and the external surface of the cold finger checked for possible frost, since there was a suspicion that the vacuum level surrounding it was not adequate. No conclusions could be reached, and the refrigerator was placed on test again. Following 1,068 additional hours, i.e., 11,488 hours total, the temperatures were at 86.5°K (coldest surface) and 142°K (intermediate surface).

- After 854 hours of additional operation, i.e., 12,342 hours total, both cold finger temperatures showed a significant increase; this was accompanied by a light tapping noise from the cold finger. The testing was stopped, the refrigerator depressurized, and the cold finger removed to expose the displacers. Wear debris from the piston and displacer seals appeared to be minimal, although some particles had evidently migrated through the first stage displacer to the second stage. However, part of the second stage displacer seal, which is a Rulon band, had lifted from the titanium shell, a failure ascribed to fatigue at the epoxy joint (figure 5). The motion of the displacer seal rubbing against the inner face of the cold finger forced a corner of the seal down over part of the first stage displacer shoulder. This corner formed a wedge between the displacer shoulder and the inner shoulder of the cold finger; hence the loss of cold production and the tapping noise.

- The piston and first stage displacer seals, although worn, showed potential for lasting perhaps a further twelve months of operation.

The bellows will undergo further testing to determine their life capabililty.

The second stage displacer seal was replaced, and the refrigerator placed on test again. At this writing, the unit, and the original bellows seal, have accumulated over a thousand hours of additional operation.

PERFORMANCE CHARACTERISTICS

Following the delivery of the six (6) refrigerators to JHU/APL, but prior to the initiation of the test described above, Philips Laboratories subjected the unit shown in figure 1 to off-design point tests. Specifically the off-design tests were to generate information for applications where the refrigeration requirements were different from those shown in table I. To generate such information, two major refrigerator parameters were varied: heat load on the cold stages, and operating pressure. The results are presented in figures 6, 7 and 8.

The effects of the heat load (including no load) on the operating temperatures of the two cold stages are given in figures 6 and 7. In the former, the heat load on the coldest stage was varied from 0 to 1 watt of heat, with the intermediate stage left unloaded. In the latter, the approach was reversed: the coldest stage was not loaded, while the load on the intermediate stage was varied from 0 to 2 watts of heat. In both instances, three operating pressures were used: 4.8×10^5 Nm^2, 5.5×10^5 Nm and 6.2×10^5 Nm^2, with the operating speed maintained constant at 1000 rpm.

Figure 8 illustrates the cold production capabilities of the refrigerator using different heat loads on both stages to obtain identical temperatures. This was accomplished by selecting various loads for the intermediate stage to achieve specific temperatures, i.e., 100°K, 120°K, and 140°K. The heat loads on the cold stage were adjusted so that these same temperatures were achieved, and heater power was measured.

SUMMARY

As of October 1982, the test refrigerator has accumulated over 12,300 hours of operation, including long periods of continuous runs. The bellows, with the initial life test data included, have flexed for 1.4×10^9 cycles. During the operational periods cited above the temperature of the cold surfaces remained within the range specified for the refrigerators which were delivered to JHU/APL.

TABLE I.--MAJOR REFRIGERATOR CHARACTERISTICS AND PERFORMANCE

Item	Results
Cold Production	0.3 W @ < 90°K; 1.5 W @ 140-170°K
Input Power	< 30 W
Speed	1000 rpm
Vibration of Cold Surface	3.3 μm
Acoustic Noise	< 48 dBA at 91 cm with a 40 dBA background
Size	15 cm x 18 cm x 30 cm
Weight	5.5 kg w/o electronics; 7.2 kg with electronics
Residual Torque Due to Starting/Stopping	Virtually zero

TABLE II.--MAJOR BELLOWS CHARACTERISTICS

Item	Outer Bellows	Inner Bellows
O.D. (mm)	44.2	24.1
I.D. (mm)	33.0	14.5
No. of Convolutions	16	21
Convolution Pitch (mm)	2.7	2.1
Wall Thickness (mm)	.14	.12
Material	Nickel, gold plated	

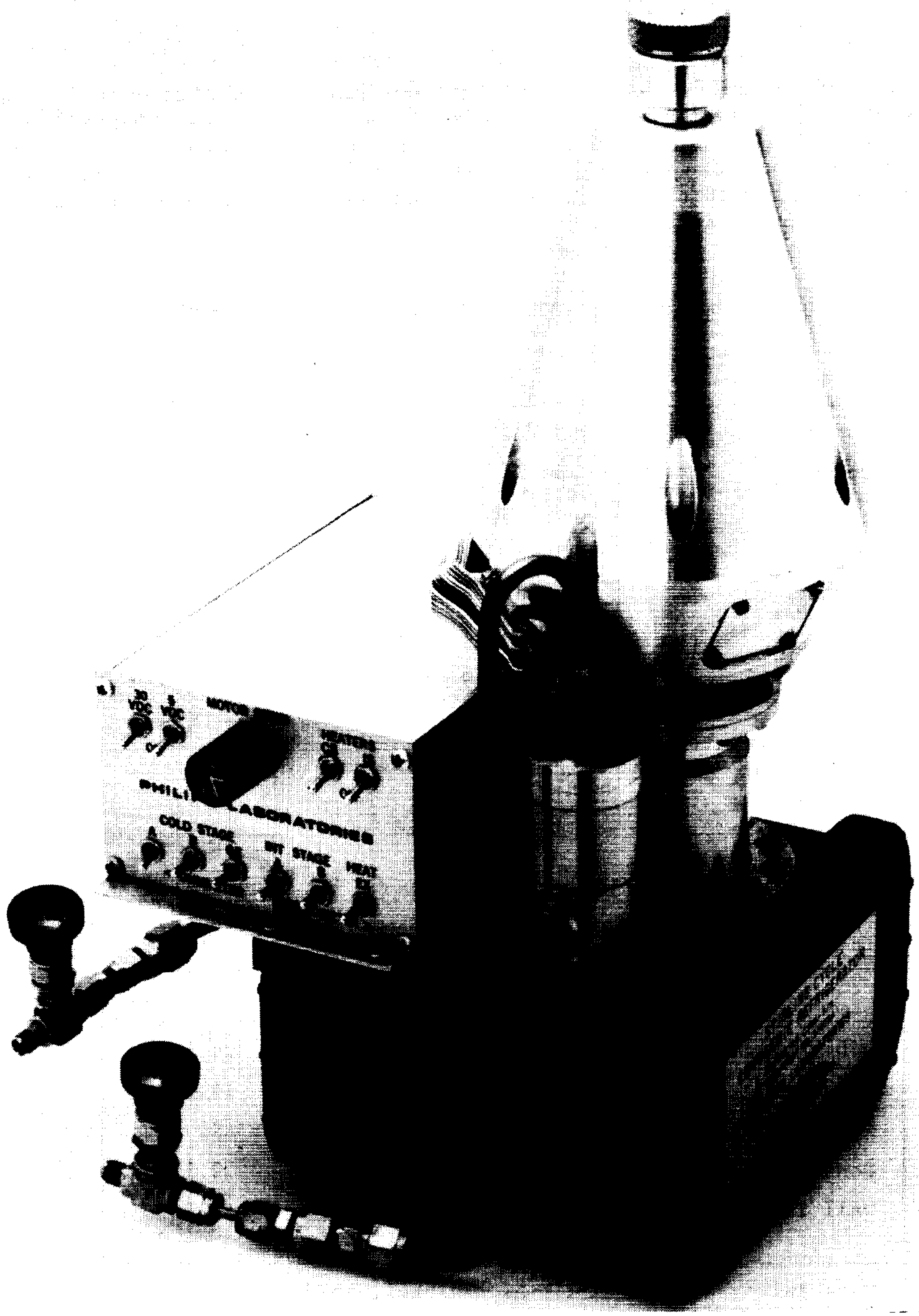

Figure 1. Fully instrumented Stirling cycle refrigerator used for testing.

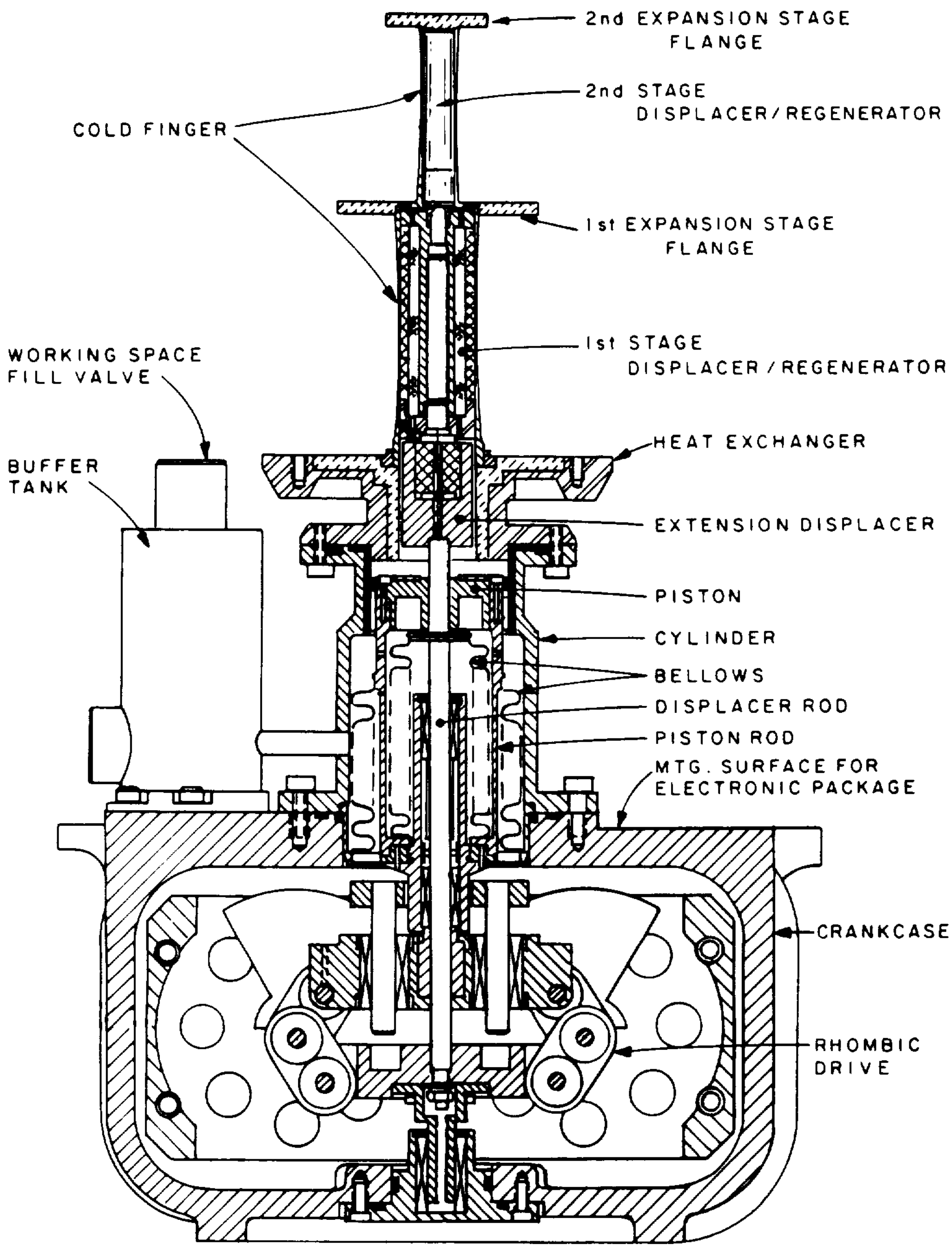

Figure 2a. Cross-sectional view of refrigerator.

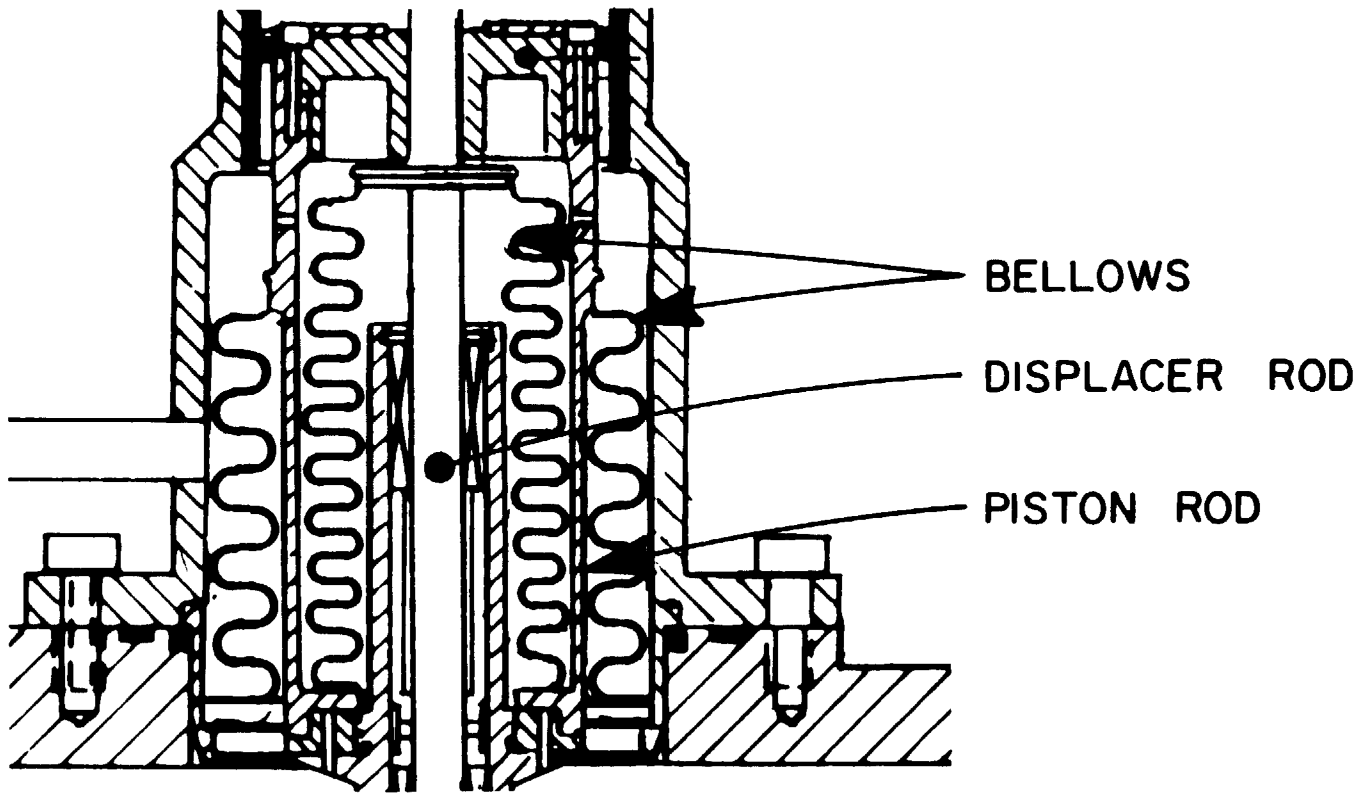

Figure 2b. Closeup of bellows seal area.

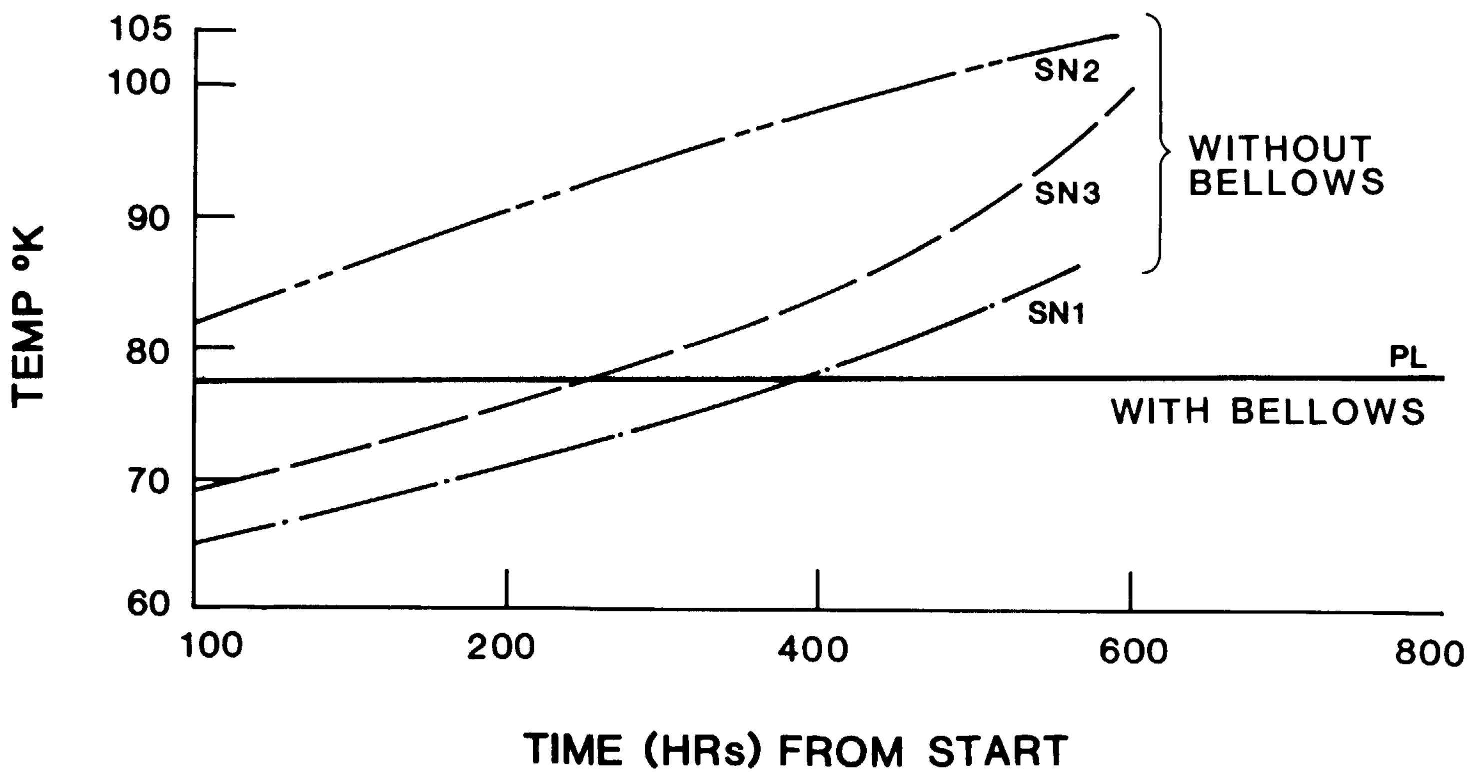

Figure 3. Cold-end temperature vs. operating time for first 800 hours.

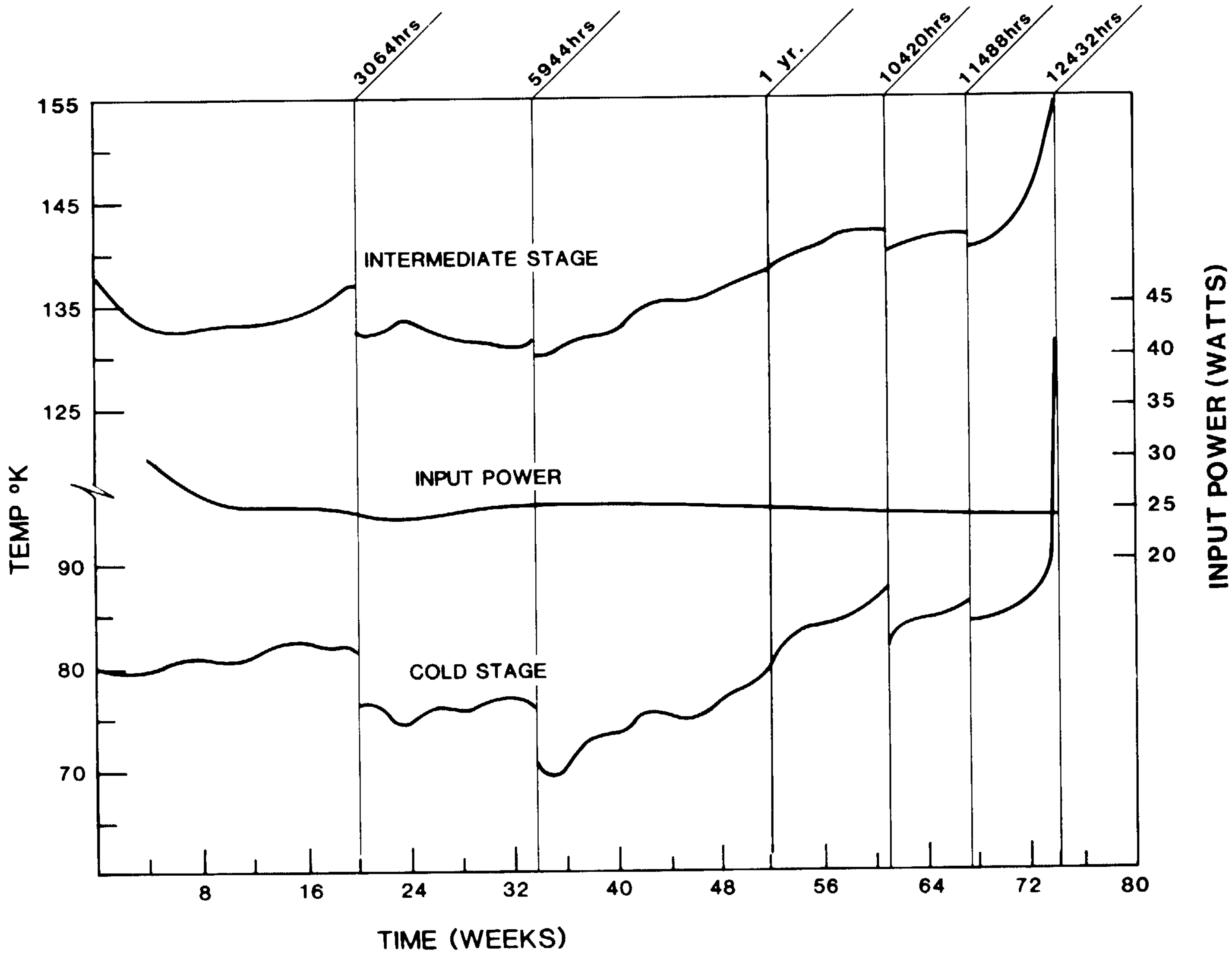

Figure 4. Operating temperatures and input power versus elapsed time.

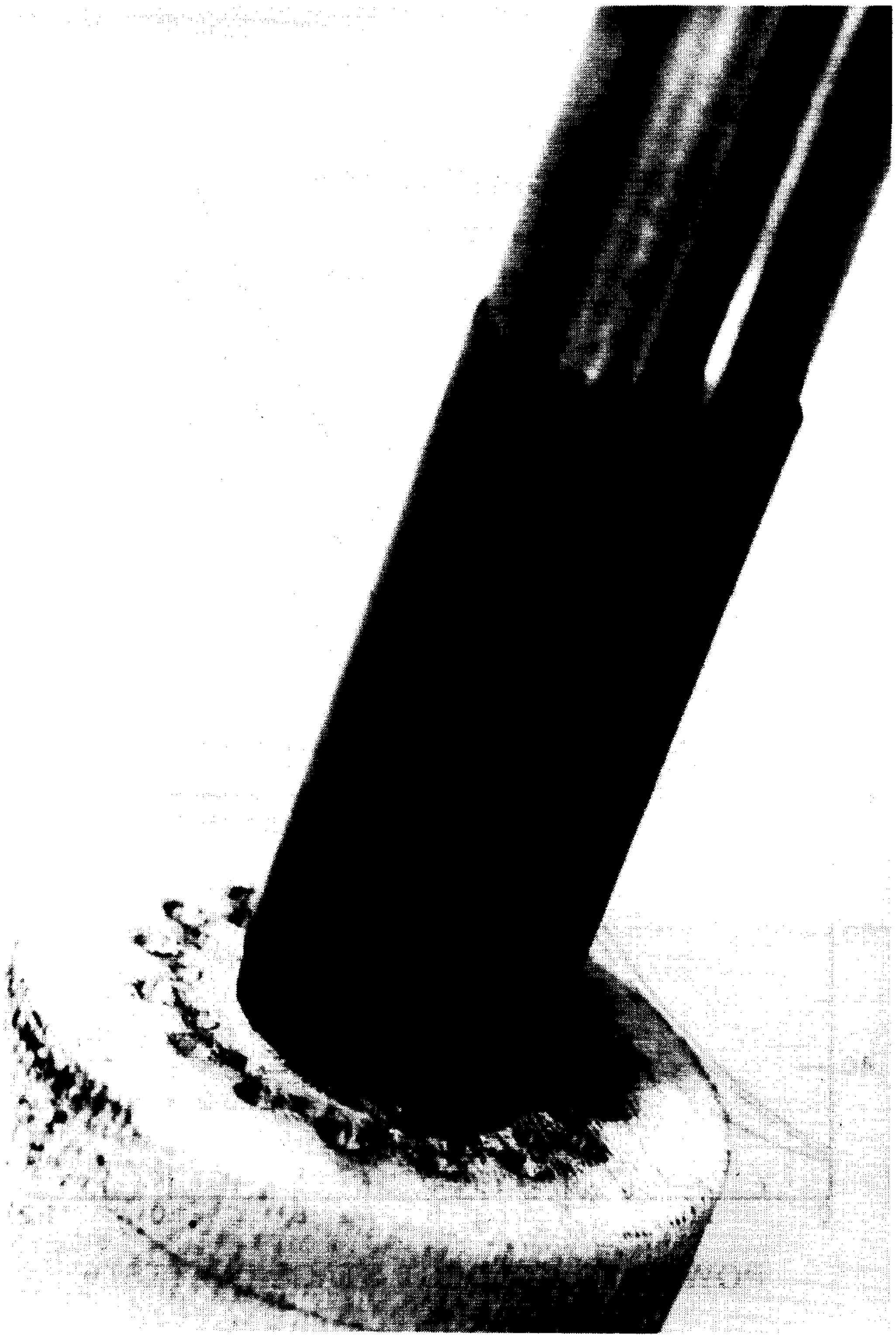

Figure 5. Photograph of the damaged seal.

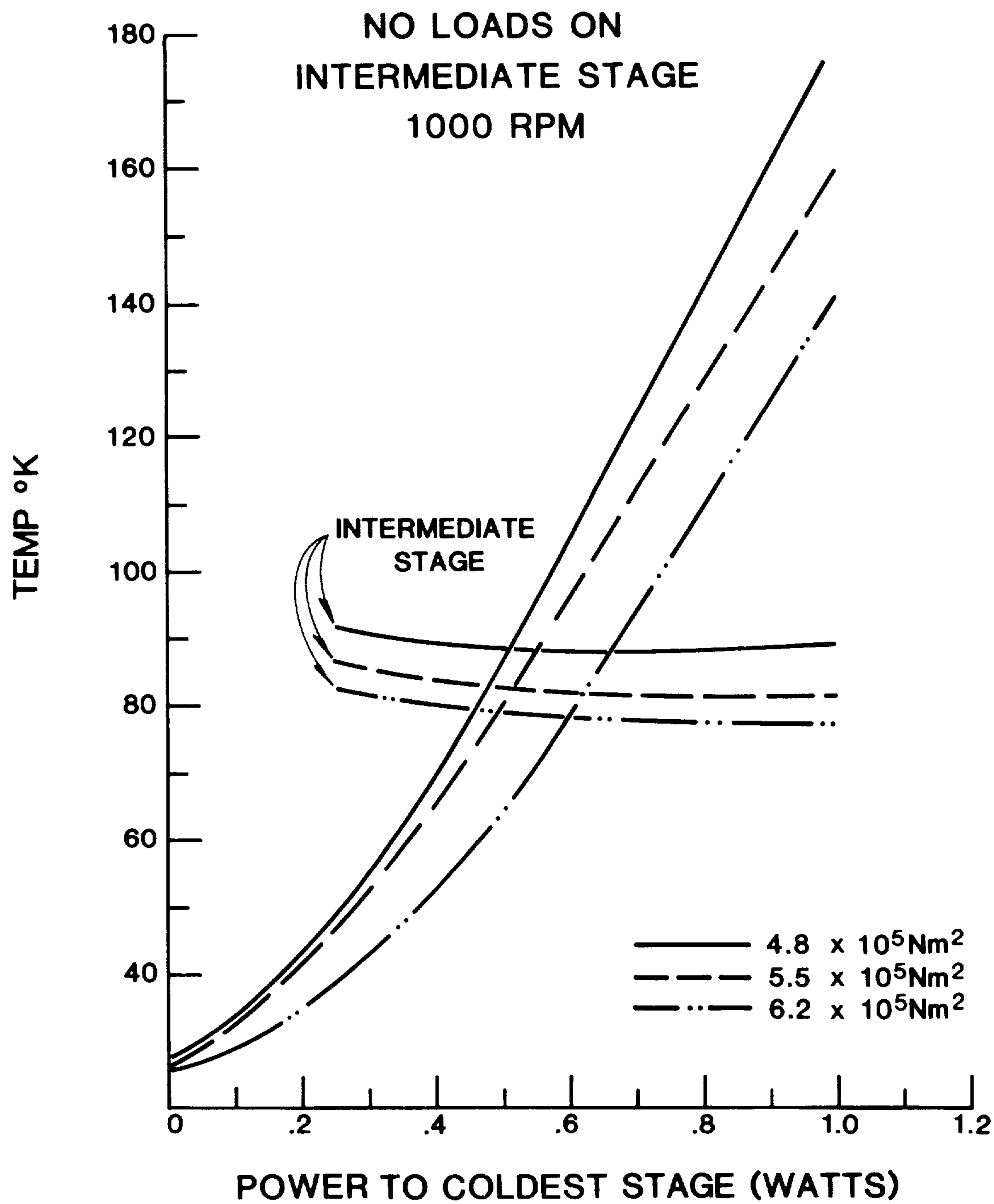

Figure 6. Intermediate-stage temperature vs. heater power to coldest stage.

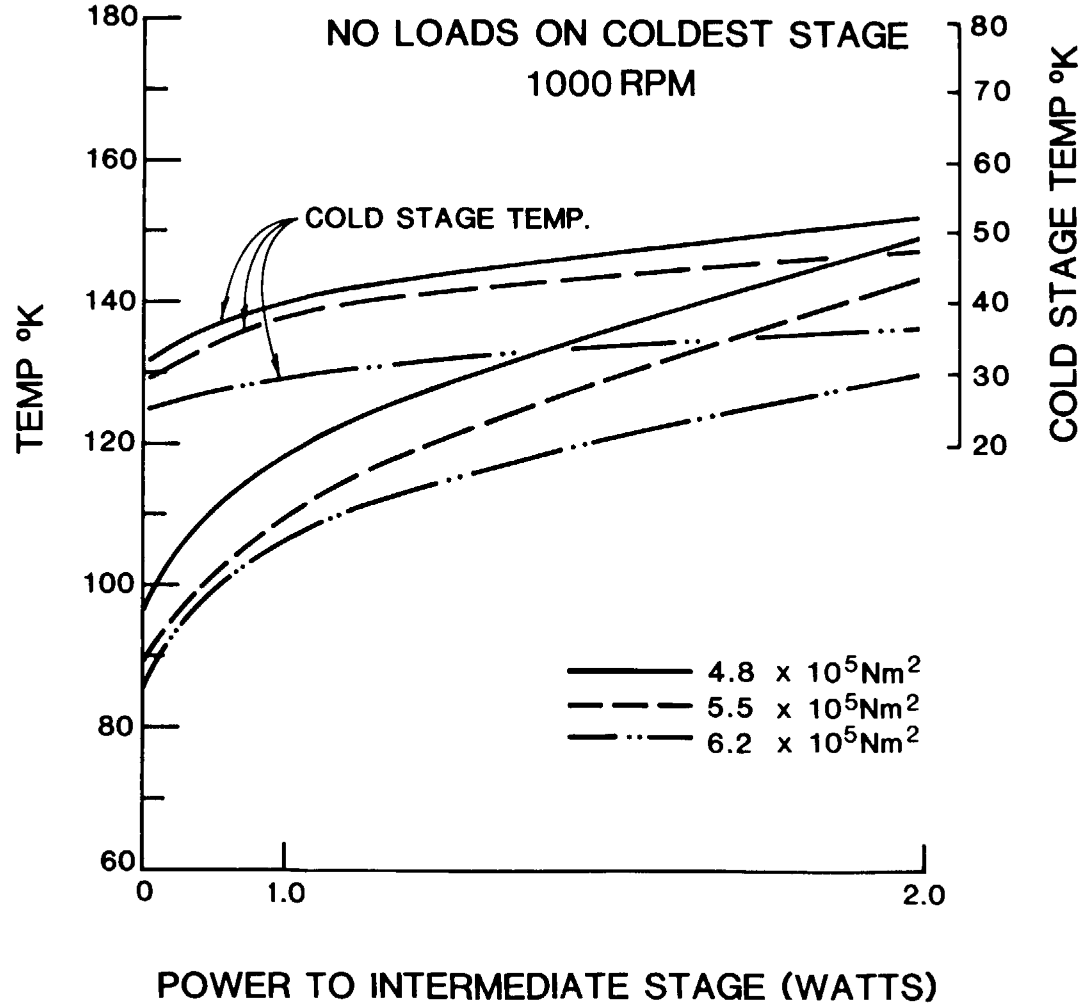

Figure 7. Coldest stage temperature vs. heater power to intermediate stage.

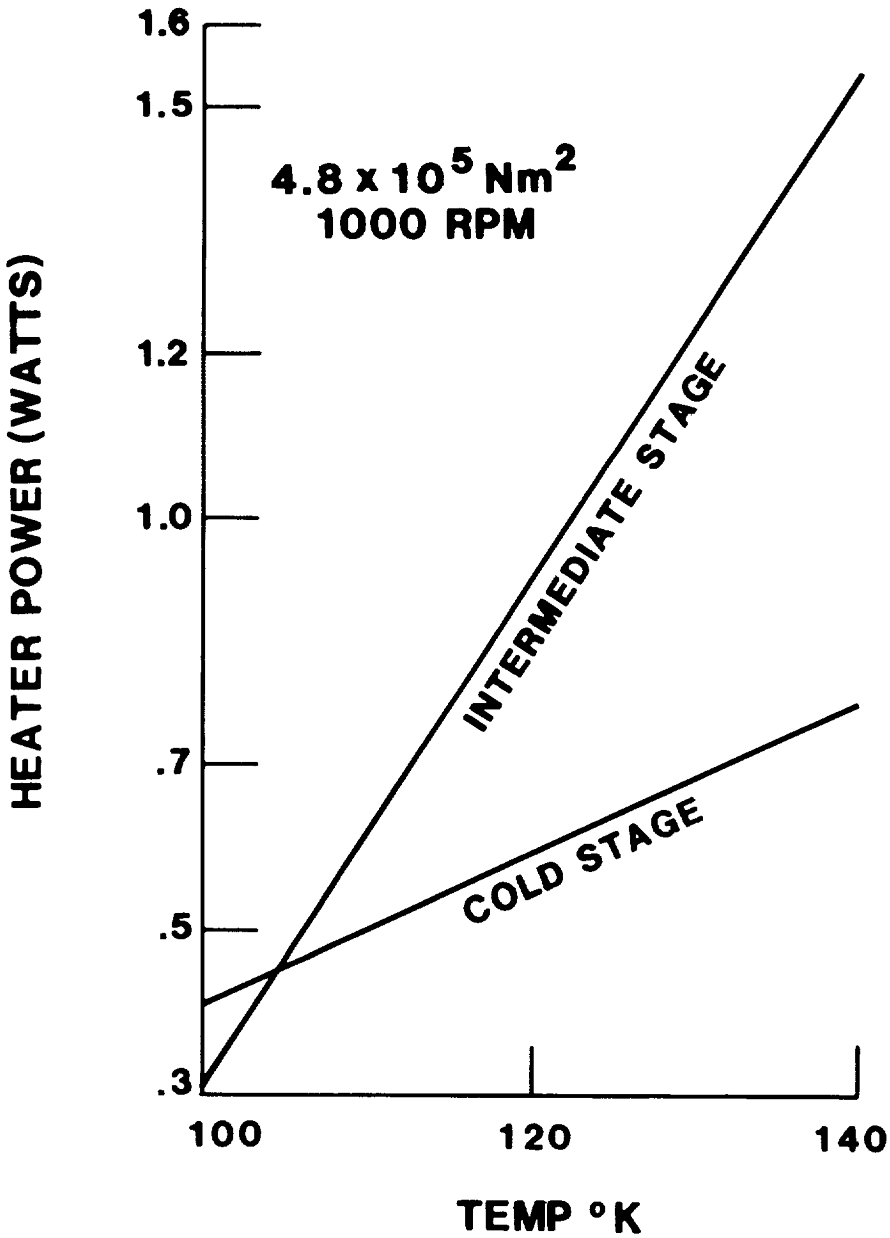

Figure 8. Cold production vs. heater loads.

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