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PACKED-ROD REGENERATOR MATRICES Final
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FINAL REPORT

JPL Contract No. 955884

EVALUATION OF CERAMIC PACKED-ROD
REGENFRATOR MATRICES

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December 1981

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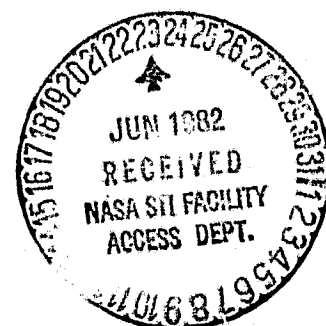


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I. SUMMARY

An extensive evaluation of a modified Model 21 cryocooler with various regenerator matrices is reported. The matrices examined are 0.015" diam Pb spheres and 0.008", 0.015", and 0.030" diam rods of a 0.2%-SnCl₂-doped ceramic labelled LS-8A. Specific heat and thermal conductivity data on these rod materials are also reported (literature data exist on the Pb spheres).

The primary goal of these studies was to overcome the chronic pulverization/dusting problem common to Pb spheres. This goal was achieved: During a 1000-hr life test with 0.008" diam rods there was no degradation of the refrigerator performance, and a subsequent examination of the rods themselves revealed no evidence of breakage or pulverization.

The load-temperature characteristics for the rod-packed regenerators were inferior to that for the Pb spheres, the effect being to shift the Pb-spheres load curve up in temperature. This temperature shift was 5.0, 7.4, and 11.6K for the 0.008", 0.015", and 0.030" diam rods, respectively (i.e., the no-load, second stage temperatures were 12.4, 14.8, and 19.0K, respectively, compared to 7.4K for the Pb spheres case).

The ordering of the load curves obtained with the three rod diameters is explained as being due primarily to the diminished volumetric specific heat and enthalpy of the rods in the higher temperature portion of the regenerator compared to Pb spheres (the measured packing fractions are included in these analyses). For the 0.030" diam rods, the slow thermal relaxation time (~38ms) and small surface area compound the reduced specific heat and enthalpy.

Packing fractions ~80% were obtained with the rod-packed regenerators compared to 61% for the Pb sphere regenerator. The insertion of fine copper screens in the rod-packed regenerators did not affect the packing fraction and resulted in improved performance in the case of the 0.015" diam rods. This is due to the turbulent conditions obtained with the screens (estimates of the Reynold's Numbers indicate that the He flow through the packed-rod

regenerators without screens is laminar). Metallizing the 0.030" diam rods to improve the heat transfer coefficient resulted in degraded refrigerator performance.

The conclusions reached from these studies are reinforced by the finding that the optimum operating conditions determined for both the Pb-spheres and the packed-rod regenerators are the same: 3.3 Hz coldhead speed and 190 psid pressure drop.

The most confusing finding in this study was that the extruded rods of 0.2%-SnCl₂-doped LS-8A had a significantly lower specific heat than that of the bulk material on which the program was based. Surprisingly, extruding rods of undoped LS-8A results in dramatically increased specific heat values which are larger than, or equivalent to, Pb spheres, 2-31K. It is suggested that a pressure-induced phase transformation occurs during extrusion to explain these results.

Whatever the cause of this extrusion effect, the clear recommendation from this study is to evaluate these undoped rods in the Model 21 regenerator. It is anticipated from this study that such rods would not only alleviate the Pb-sphere-pulverization problem but also result in improved refrigerator performance.

II. INTRODUCTION

The effectiveness of regenerators in Stirling-cycle type refrigerators depends critically on matching the volumetric specific heat of the regenerator matrix material to the volumetric specific heat of the working fluid. This effectiveness in turn plays the dominant role in determining the refrigerator efficiency.¹

In cryocoolers, the working fluid is He gas, and because He gas retains a large specific heat at low temperatures, small Pb spheres have commonly been used as the regenerator matrix material. The reasons for this usage are that Pb has a large volumetric specific heat at low temperatures (Debye temperature $\approx 110\text{K}$), and the packing fraction for spheres is large (theor. 68%). Also, the use of spheres insures a small thermal conductance loss across the regenerator because of the point-contact thermal resistance between the spheres.

Mechanically, Pb spheres are undesirable due to the chronic pulverization that occurs in reciprocating regenerators. This pulverization leads to segregation and gas channeling which not only degrade the performance of the cryocooler but also often result in machine failure (We remark that in our tests here we observed evidence for pulverization in a Pb-sphere regenerator after only 80 hours of operation.). Often a small amount of Sb is alloyed with Pb to improve the hardness, but the improvement gained is marginal at best.

The possibility of replacing Pb spheres with a new ceramic, labelled LS-8A, led to the first JPL-funded study in this series (JPL Contract No. 955446, Evaluation of a High-specific-heat Ceramic as a Possible Replacement for Pb in Regenerators). It was known prior to this first contract that the LS-8A ceramic had a low-temperature, volumetric specific heat equivalent to Pb and a hardness about 13 times larger than Pb.² The goal of this first study was to evaluate doped versions of LS-8A to examine the resulting hardness and low-temperature thermal properties, and the dopants selected were SnCl_2 , CsI, and AgCl. Also, double dopings ($\text{SnCl}_2 + \text{CsI}$) were examined,

and the doping levels ranged from 0.1 to 2.0%.²

Although the dopants increased the hardness of LS-8A by up to 20%, a more dramatic and unexpected improvement took place in the specific heat. Specifically, the SnCl_2 dopant had a remarkable effect in increasing the specific heat, and an analytical model was developed based on which the 0.2%- SnCl_2 -doping level was determined to be the optimal level.²

Going further, it was determined that rods rather than spheres of this doped LS-8A would be appropriate regenerator matrix materials. That is, the thermal conductance of a column of Pb spheres was measured,³ and based on thermal conductivity measurements of the doped LS-8A it was found that the thermal conductance loss across a rod regenerator would actually be smaller than that across an equivalent Pb-sphere regenerator. There are several compelling reasons for considering a packed-rod regenerator:

- (1) The packing fraction is about 50% larger than for spheres (theor., 91%);
- (2) The rod arrangement is inherently more stable mechanically than the sphere arrangement; and (3) The LS-8A can be continuously extruded.²

The present contract, the second in the JPL-funded series, was based on evaluating 0.2%- SnCl_2 -doped LS-8A rods in an actual cryocooler (Model 21, Cryogenic Technology, Inc.). Additionally, some of these rods were evaluated in the Model 350 refrigerator at JPL. Three rod diameters were studied (0.008, 0.015, and 0.030-in diam.), and the Model 21 was modified to allow for both speed and pressure-drop variations. The measurements here involved load curves under these various conditions, and the specific heats and thermal conductivities of the three rod-diameter materials were measured, 2-30K. Additionally, the Model 21 was thoroughly characterized with Pb spheres in the regenerator to provide base-line data.

III. EXPERIMENTAL METHODS

Specific Heat and Thermal Conductivity

The methods used for measuring thermal properties have been documented previously.² In the studies here, however, thermal properties were measured on small rods rather than on bulk samples, so the sample-preparation techniques were different.

For thermal conductivity measurements, the sample consisted of several (~20-50) rods bundled so that the heat flow was parallel to the rods' axes. This bundling was accomplished by stacking the rods in a section of a 1/8" diam. plastic straw, varnishing the exposed ends of the bundle, then removing the straw when the varnish cured (G.E. 7031 varnish). Two carbon resistors were hollow ground with a 1/8" diam. grind to fit over the bundle saddle-fashion, and about 2 cm of the manganin leads for these thermometers were tempered to the bundle at the thermometer locations. A heater was wrapped on one end of the bundle (~300 Ω), and the other end of the bundle was Ag-epoxied to a copper mounting stud which bolted into the reservoir of the calorimeter. The linear-heat-flow measurement method was used, as discussed previously.²

A specific heat sample was prepared by "potting" several short sections (≤ 5 mm) of the rod material into a 3/8" diam. pellet using the 7031 varnish. A Teflon mold was used, and care was taken to use the maximum amount of rod material and the minimum amount of varnish. After the pellet cured, the heater, thermometer, etc were fixtured and the sample measured, as reported previously.² The actual weight of the rods in the sample was determined by dissolving the sample with the 7031 solvent after the measurement, separating and rinsing the rods and weighing them. Although the G.E. 7031 varnish has a rather large specific heat at low temperatures, the addenda contribution to the specific heat was typically <15%.

Model 21 Refrigerator

The Model 21 refrigerator is a two-stage machine, and calibrated germanium resistance thermometers were mounted on both stages. These thermometers were measured by the four-lead, potentiometric method wherein

the current (10 μ A) was supplied by a constant current source and the voltage displayed on a digital voltmeter.

A 25- Ω heater (resistance calibrated 7-30K) was mounted on the second stage for measuring load curves, and this heater was powered by a constant current source. This load current was measured by displaying the voltage drop across a series, 1k Ω , standard resistor on the digital voltmeter.

In all the measurements made on the Model 21, the voltage outputs from the two germanium thermometers were displayed on a chart recorder and the measurements recorded when the thermometers indicated stability. In general, the lowest temperatures were recorded since any transients or instabilities in the entire system would act to increase the stage temperatures. It was established early in the study that these minimum temperatures were reproducible from run to run and from day to day.

The pressure-drop variations were achieved by the use of a pressure by-pass manifold between the inlet and outlet pressure lines. The speed variations were achieved using a stepping motor, and a schematic diagram of the stepping motor is shown in Figure 1.

Finally, a 3/8-in thick Pb shim was added to the second stage to dampen the temperature excursions; this shim does not, however, otherwise affect the operation of the refrigerator.

In all the tests with the Model 21 using both Pb spheres and the doped LS-8A rods, the temperature of the hot end of the second stage remained fairly constant, 30-31K, and so is not reported in the sections below.

STEPPING MOTOR POWER SUPPLY WIRING DIAGRAM

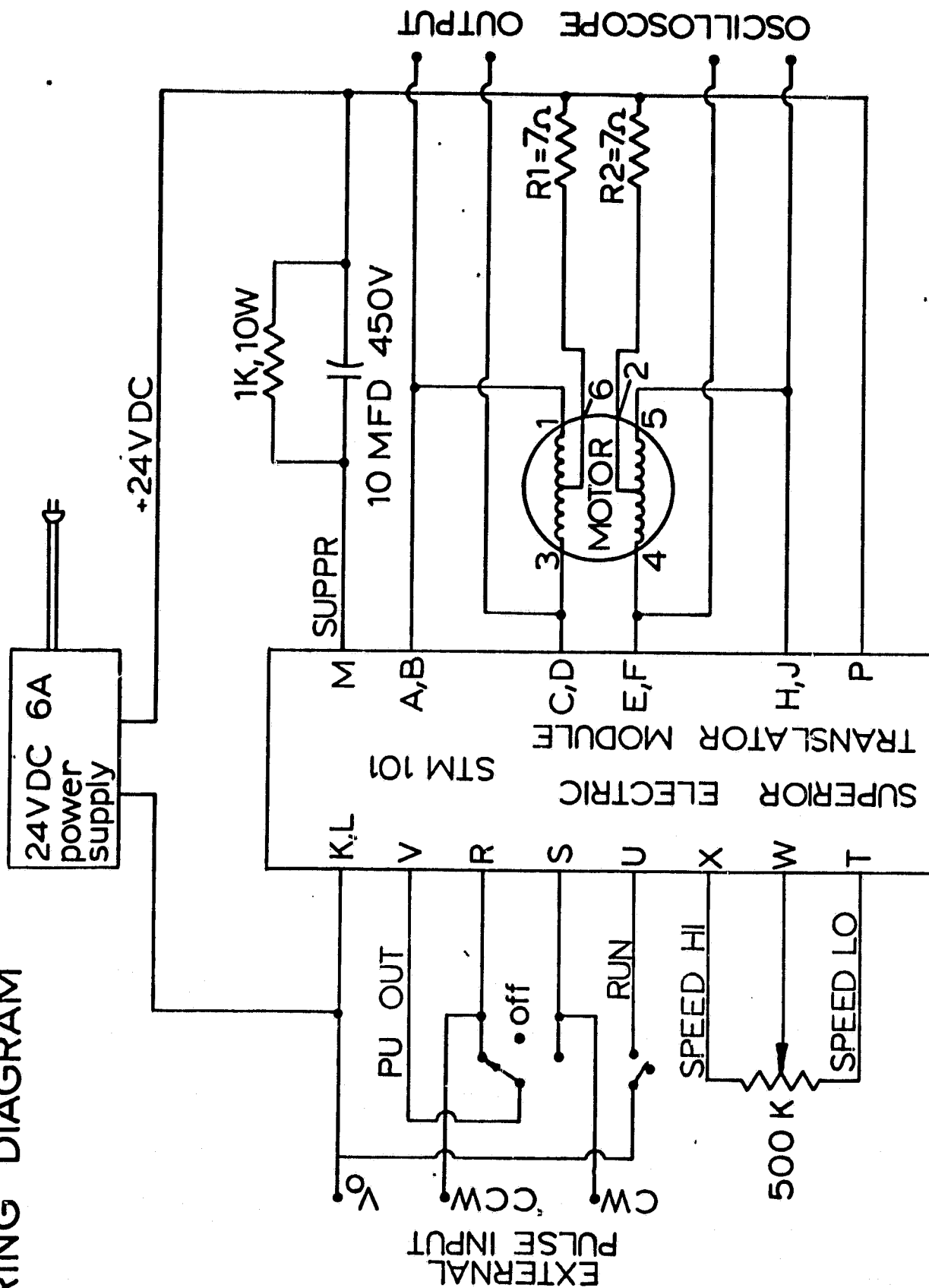


FIGURE 1. Schematic Diagram of the Stepping Motor used for Speed Variations in the Model 21.

IV. EXPERIMENTAL RESULTS - REFRIGERATOR TESTS

Pb Sphere Regenerator

The first phase of our study was to gain experience with and characterize the Model 21 with the as-received Pb spheres in the regenerator. In Figure 2 are shown load-curve data measured on two different days, and the circles and triangles represent the second-stage minimum temperatures, as discussed above. The error bars represent the temperature excursions, but as seen in Figure 2 the minimum second-stage temperatures reproduce very well. The operating conditions shown in Figure 2 are the manufacturer's specifications (3.3 Hz and 190 psid).

The next step was to measure the second-stage temperature as a function of speed and pressure under no load conditions, and these data are shown in Figure 3: First, the speed was held constant at 3.3 Hz and the pressure drop varied from 100 to 190 psid; and second, with the pressure drop maintained at 190 psid, the speed was varied from 1 to 5 Hz.

The Figure 3 data show that the nominal operating conditions are very nearly the optimum conditions also. As the pressure drop decreases from 190 psid, the second stage temperature rapidly increases to about 15K. Conversely, as the speed is increased or decreased from about 2.5 Hz, the second stage temperature also increases.

The speed data in Figure 3 indicate a broad minimum in the second stage temperature centered at 2.5 Hz. Below 2 Hz, the temperature rapidly increases to 12K, demonstrating how critically the refrigerator performance depends on the mass-flow rate.

The next step was to measure load curves under non-optimal conditions. One intuitively suspects that the optimum load curve (i.e., minimum temperatures at maximum power levels) will be obtained for those operating conditions which give the minimum temperature under no-load conditions. Such is indeed the case, as seen in Figure 4 and 5. In Figure 4 are shown load curves at 190 and 140 psid maintaining the speed at 3.3 Hz, and in Figure 5

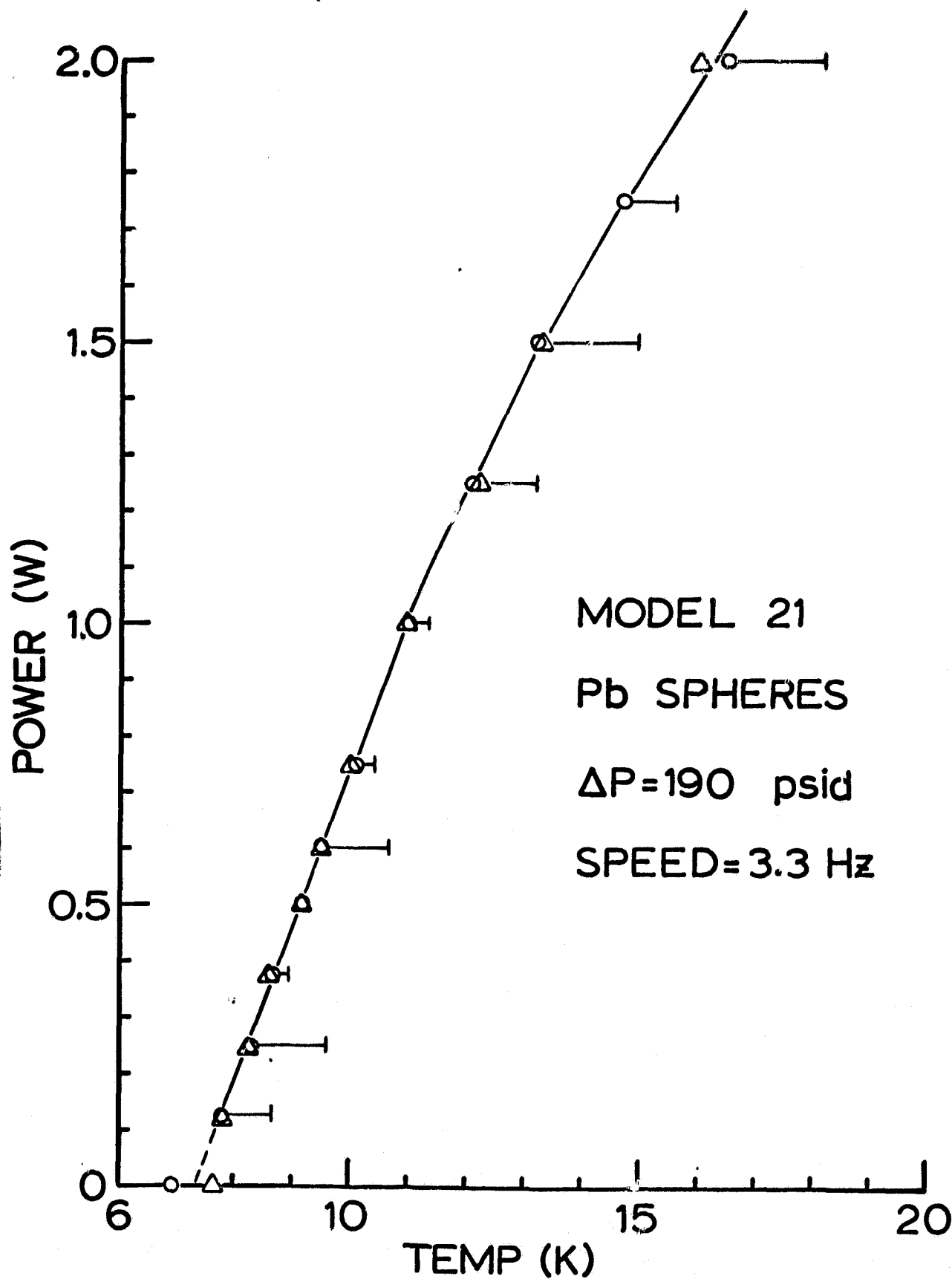


FIGURE 2. Power-Temperature Characteristic of Model 21 with 0.015" diam Pb spheres.

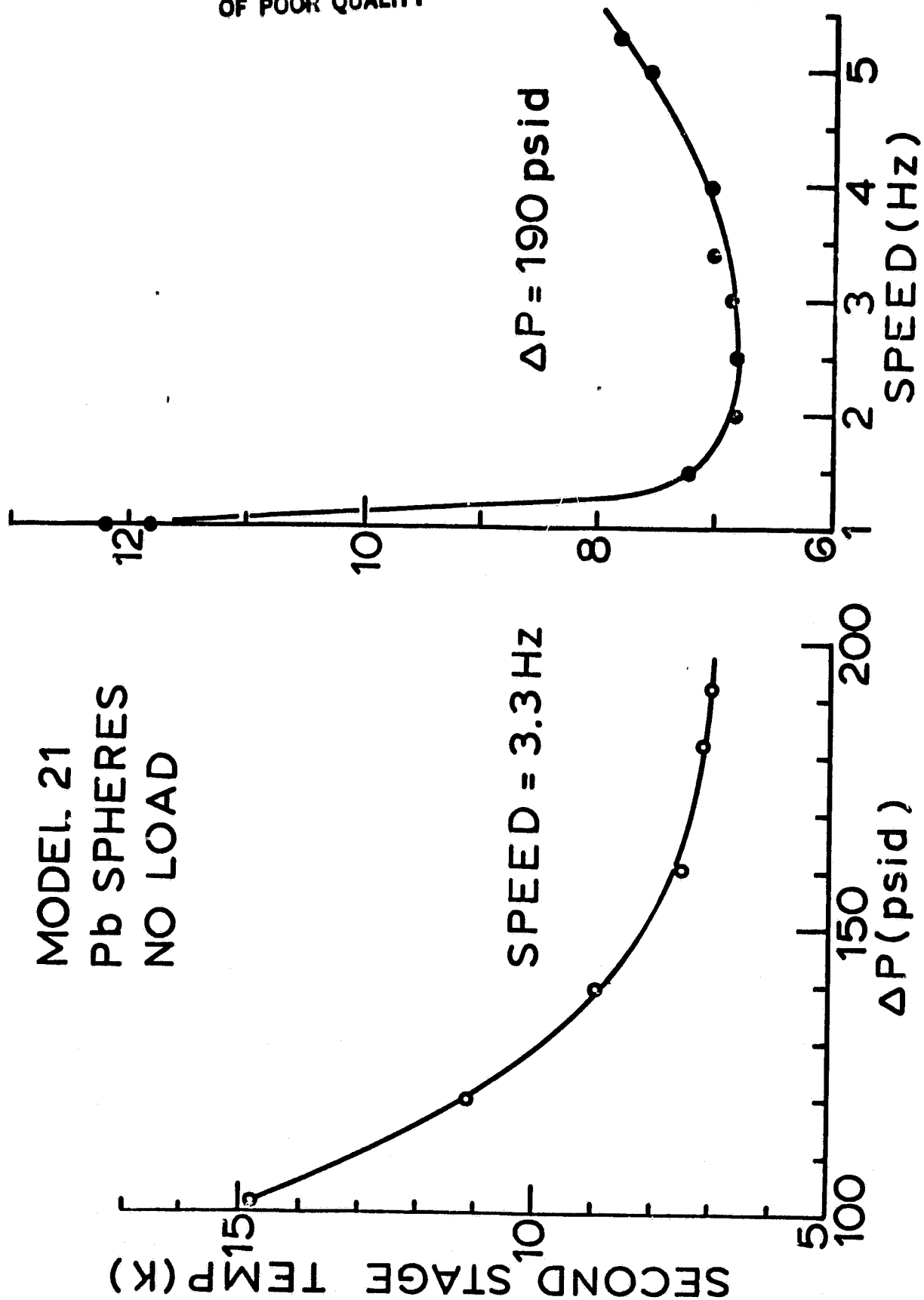


FIGURE 3. Dependence of the Model 21 second-stage Temperature on Pressure-drop and Speed Variations for the Pb-sphere regenerator.

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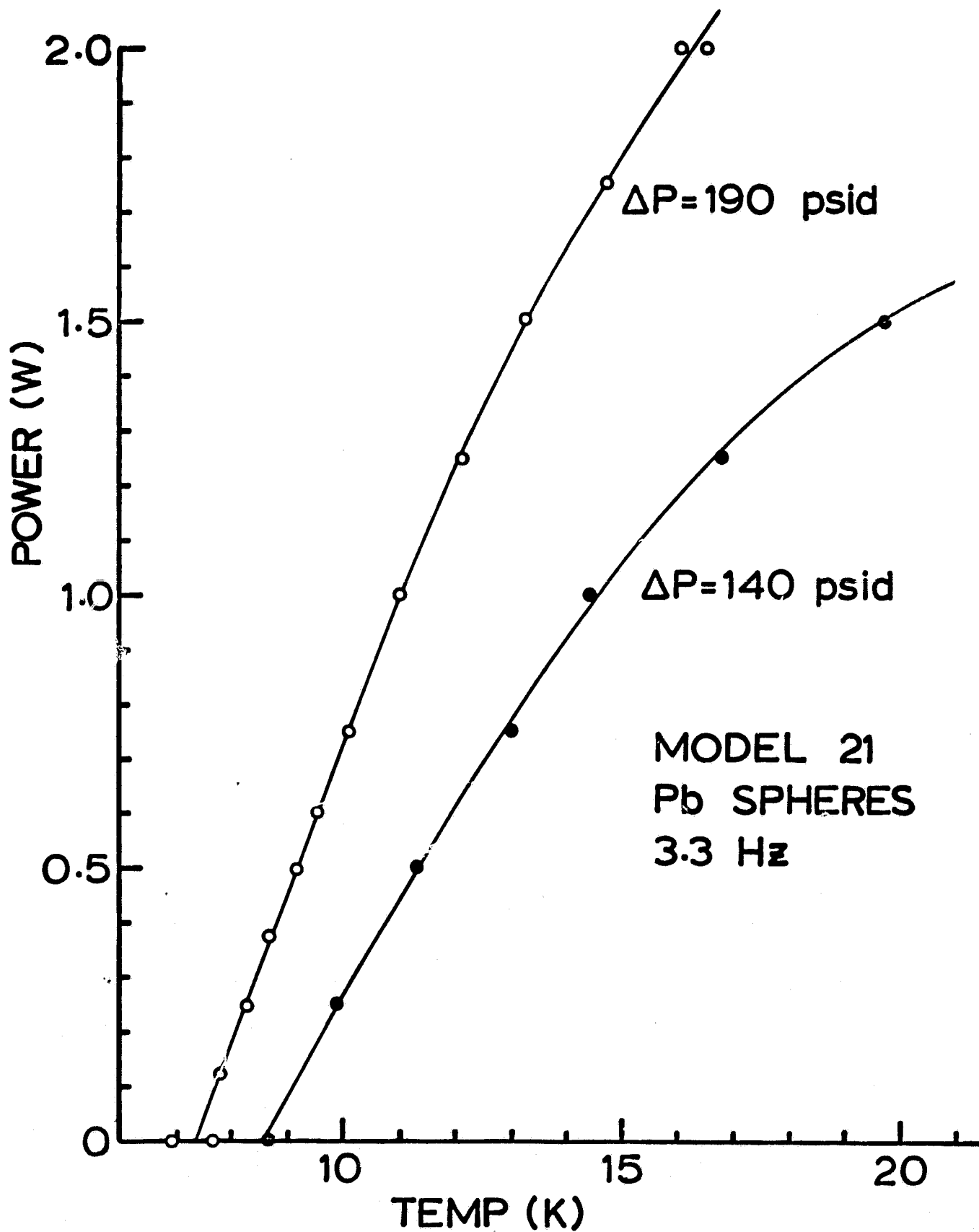


FIGURE 4. Model 21 load curves at 190 and 140 psid with the speed maintained at 3.3 Hz, Pb-sphere regenerator.

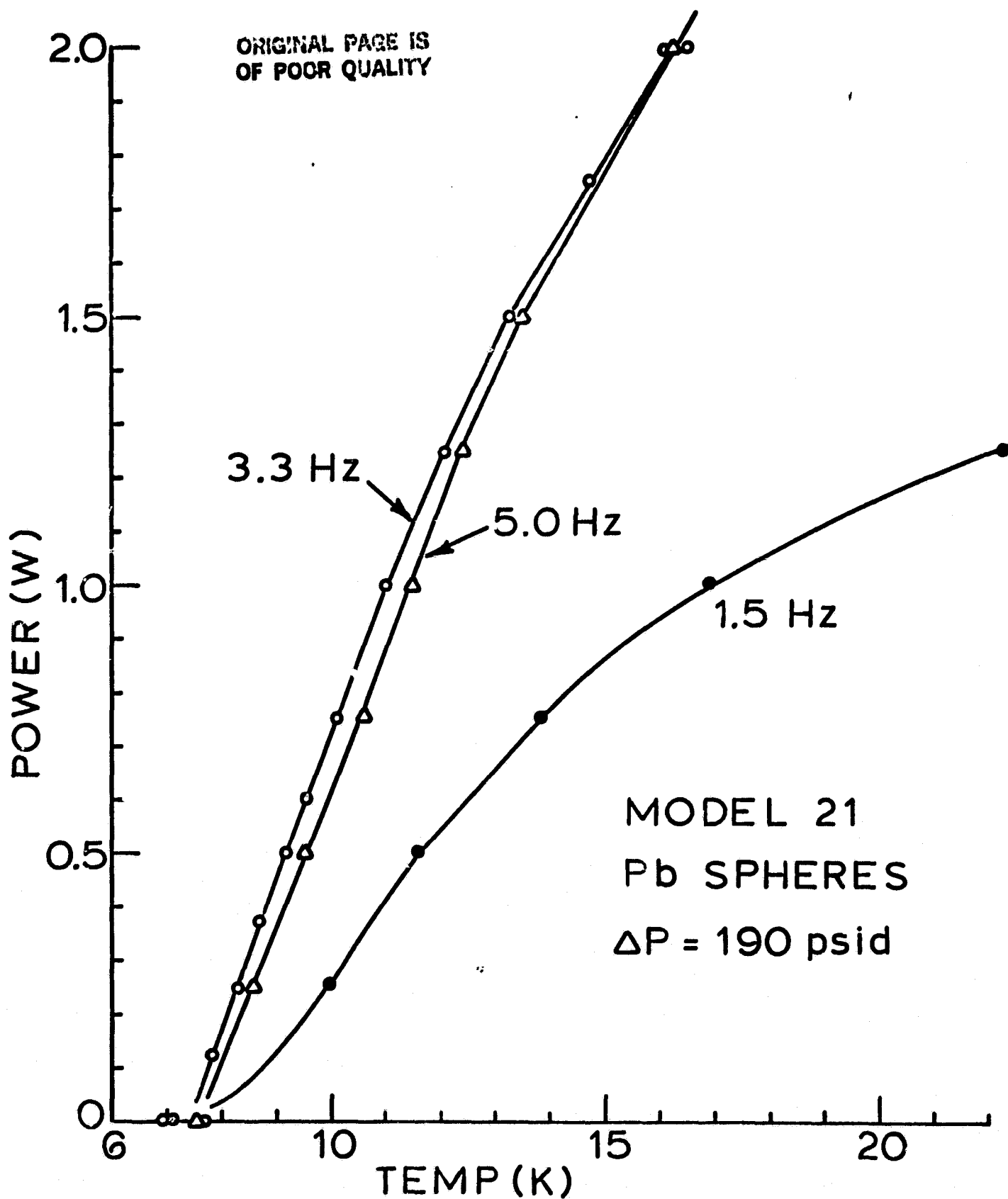


FIGURE 5. Model 21 load curves at 1.5, 3.3, and 5.0 Hz with the pressure drop maintained at 190 psid, Pb-sphere regenerator.

are shown load curves at 1.5, 3.3, and 5.0 Hz maintaining the pressure drop at 190 psid.

The Figure 4 data show that the load curve rapidly degenerates when the pressure drop is decreased from 190 psid, and these data correlate well with the data in the left-hand plot of Figure 3.

The Figure 5 data are somewhat surprising on comparison with the right-hand plot of Figure 3. That is, from Figure 3 the no-load, second stage temperature at 1.5 Hz is below the 5.0 Hz temperature, yet in Figure 5 there is a major degradation in the load curve at 1.5 Hz compared to either 3.3 or 5.0 Hz. Apparently, the 1.5 Hz mass-flow rate is just large enough to yield a low, zero-power temperature but not large enough to support loaded conditions.

The Pb spheres were removed from the regenerator and weighed. The estimated filling factor was $61.7 \pm 1.1\%$. The felt pads, which are placed at the top and bottom of the Pb-sphere column, showed a dull grey stain when the regenerator was opened. The total running time with the Pb-sphere regenerator was about 80 hours.

0.015" Diameter Rods Regenerator

The rods of 0.2%- SnCl_2 -doped LS-8A were received as extruded sections, 3-4 ft. long. These sections were cut into regenerator rods 2.75 in. long with a razor blade, and a nitrogen anti-static gun was used to de-dust the rods prior to loading in the regenerator. The kerf-loss from this rod-cutting provided rod material for preparing thermal conductivity and specific heat samples.

Following the tests with Pb spheres, the regenerator cartridge was cleaned, and clean felt spacers were inserted. A total of 450 rods were loaded into the regenerator, corresponding to a packing factor of $78.2 \pm 0.3\%$.

The first step was to measure the load curve at 3.3 Hz and 190 psid (i.e., the optimal conditions for Pb spheres), and these data are shown in

Figure 6. As seen, the load curve is significantly inferior to the Pb-spheres curve. Interestingly, the slopes of the two load curves are practically identical near 15K (0.2W/K).

After about 20 hours of these tests, the regenerator was opened and examined and the bundle of rods was pulled half-way out and rotated. A few broken rods were replaced, and undoubtedly these had been broken in the first loading. Consequently, the data shown in Figures 7, 8, and 9 are referenced as "First Loading" and "Second Loading".

The Figure 7 data show the results of no-load variations in the speed and pressure drop on the second stage temperature. These results are very similar to the Pb-spheres results, Figure 3, and indicate that the optimal operating conditions for the Pb spheres are also optimal for these rods.

Figures 8 and 9 show load curves for these rods under various speed and pressure drop conditions. The no-load speed variation, Figure 7, indicates a minimum at 2.5 Hz, but as seen in both Figures 8 and 9 there is a significant loss in performance at 2.6 Hz. The major difference between Figures 8 and 9 is the difference in pressure drops (194 and 161 psid), and it is clear that the performance degrades rapidly as the pressure is reduced below 190 psid.

The performance of the Model 21 refrigerator with the 0.015¹-in diam rods as shown in Figures 6-9 was considerably inferior to the performance with Pb spheres. It was suggested by W. A. Steyert that if copper screens were placed in the rod regenerator, two advantages would be gained: (1) Flow would be made more turbulent, and (2) The screens would constitute isothermal planes.

Fine mesh copper screen was obtained from W. A. Steyert and cut into 3/8"-in and 5/8"-in diam screen, the latter for delivery to the JPL. After cutting, the screens were given an oxygen anneal⁴ to improve the low-temperature thermal conductivity.

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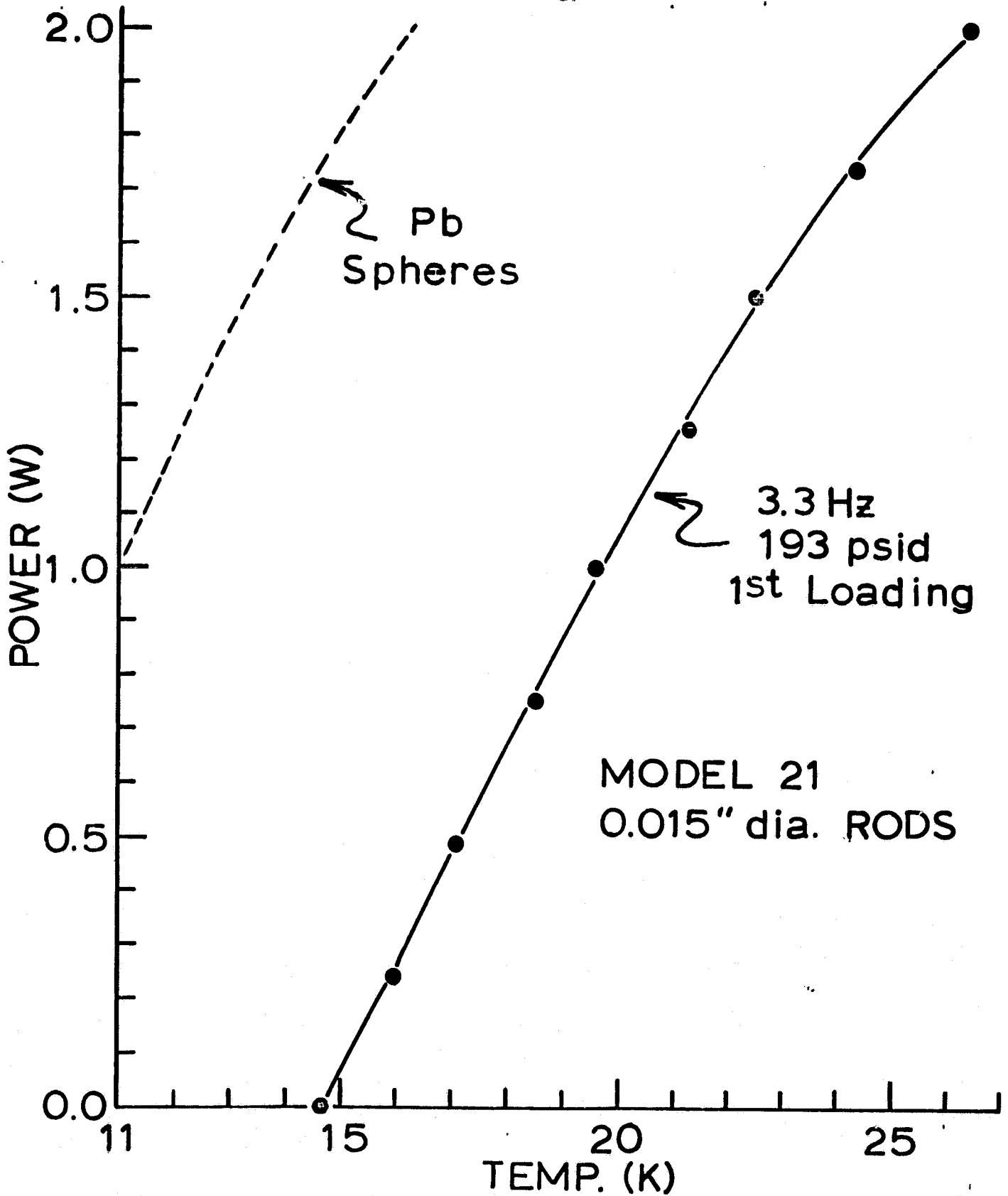


FIGURE 6. Load Curve for full-length, 0.015" diam rods at 3.3 Hz, 193 psid, compared to Pb spheres.

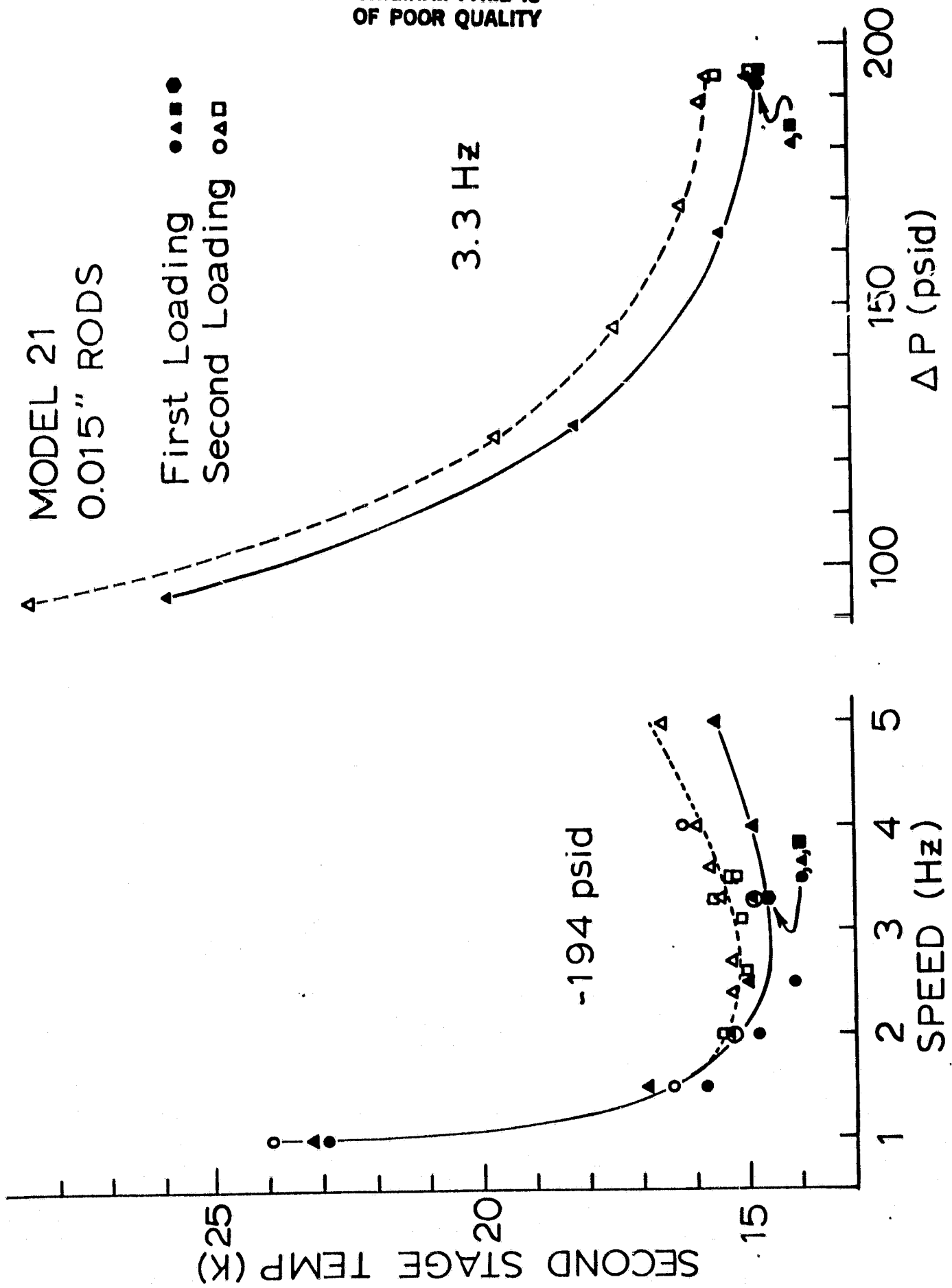


FIGURE 7. Variation of second-stage temperature (no-load) for 0.015" rods with speed and pressure. The symbols refer to different rod loadings (see text). Compare with Figure 3.

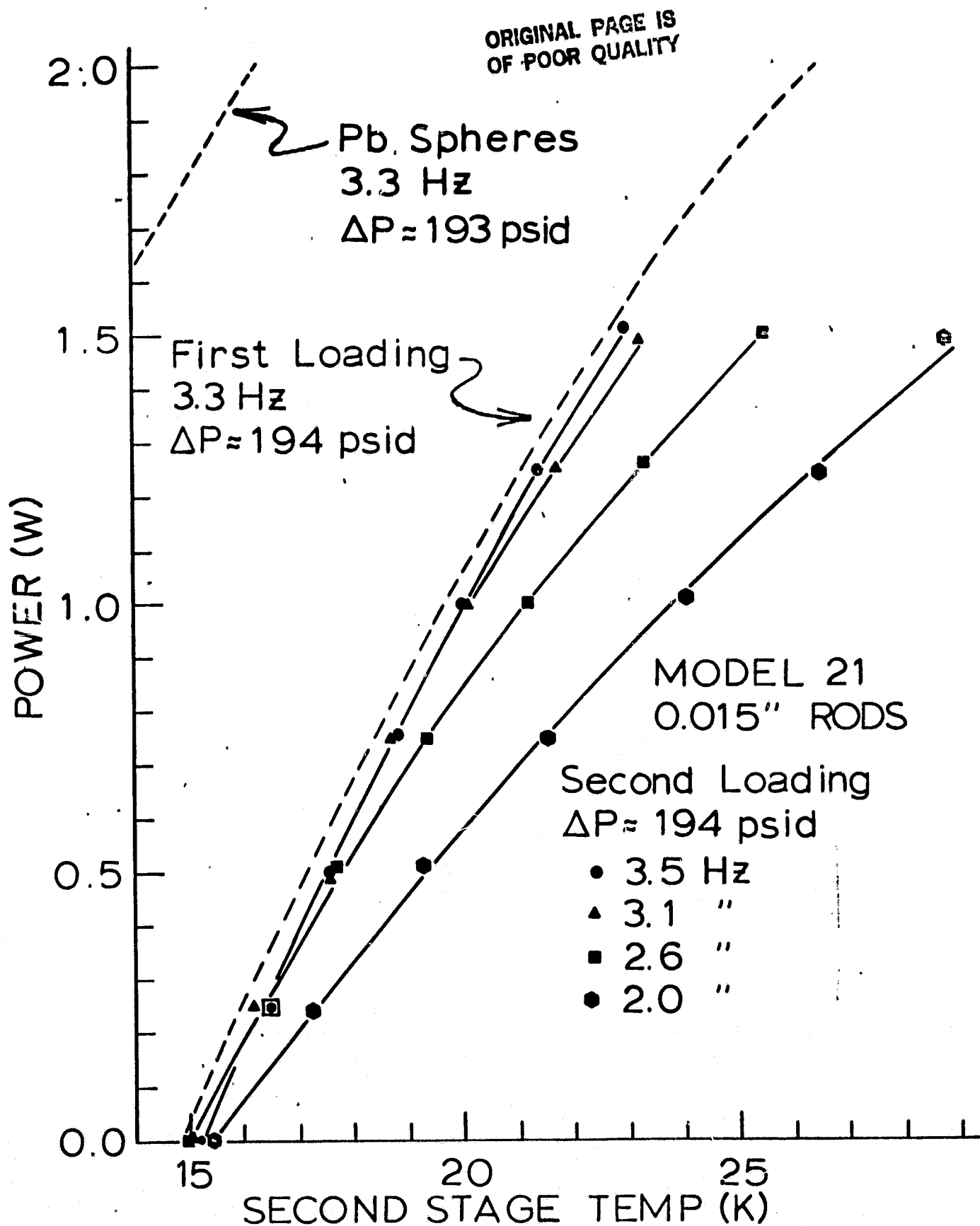


FIGURE 8. Load Curves for the 0.015" diam rod-packed regenerator, variable speed coldhead at constant pressure drop.

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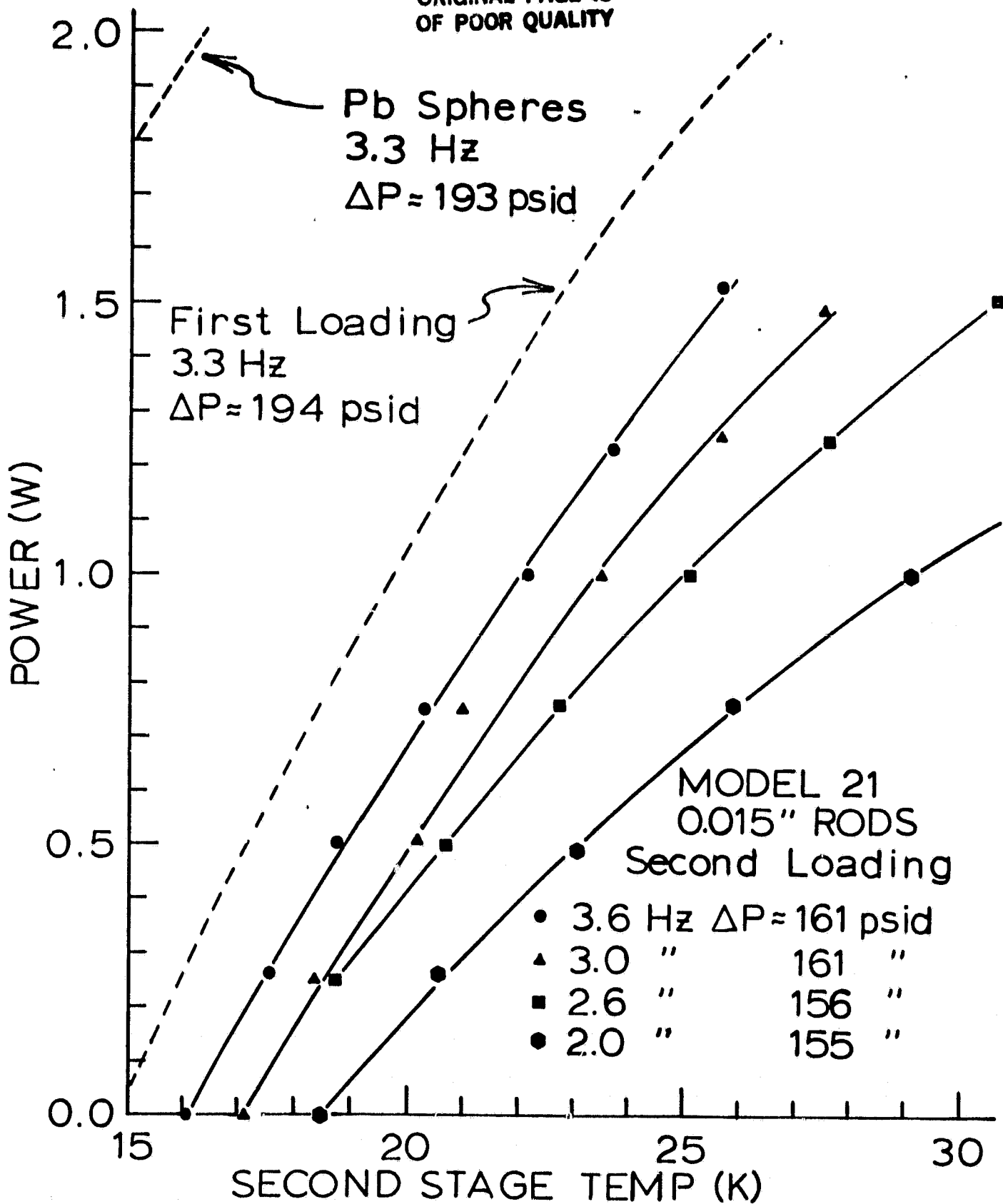


FIGURE 9. Load Curves for the 0.015" diam rod-packed regenerator at various coldhead speeds and pressure drops.

The regenerator was unloaded, and the rods were cut into "half-length" sections. The regenerator was reloaded with the half-length sections separated by two adjacent 3/8-in diam screens. The packing factor for this loading was $79.4 \pm 0.3\%$, showing that the procedure did not substantially affect the packing factor compared to the "full-length" case (78.2%). The antistatic nitrogen gun was always used to de-dust the rods for every loading.

The results obtained with these "half-length" rods are summarized in Figures 10-12 and compared to the "full-length" results. There is a significant improvement in the performance of the Model 21 due to the half-length rods with separating copper screens. This is particularly evident in Figure 12 where the load curve has increased ~40% compared to the "full length" curve.

These findings were pursued further: The regenerator was unloaded, the rods cut in half again to produce "quarter length" rods, and the regenerator reloaded with three copper screens between the rod bundles. The packing factor for these "quarter length" rods was $80.2 \pm 1.0\%$.

The results of the refrigerator tests with the "quarter length" rods are shown in Figures 13-15 where the data are compared to the "full length" and "half length" data.

The data in Figures 13-15 show a significant improvement in refrigerator performance on going to shorter rod segments with interspersed copper screens. For example, the "quarter length" load curve in Figure 15 is about 64% higher than the "full length" load curve.

These experiments completed the tests with the 0.015-in diam rods of 0.2%- SnCl_2 -doped LS-8A. A quantity of these rods sufficient to load the regenerator of the Model 350 was submitted to the JPL.

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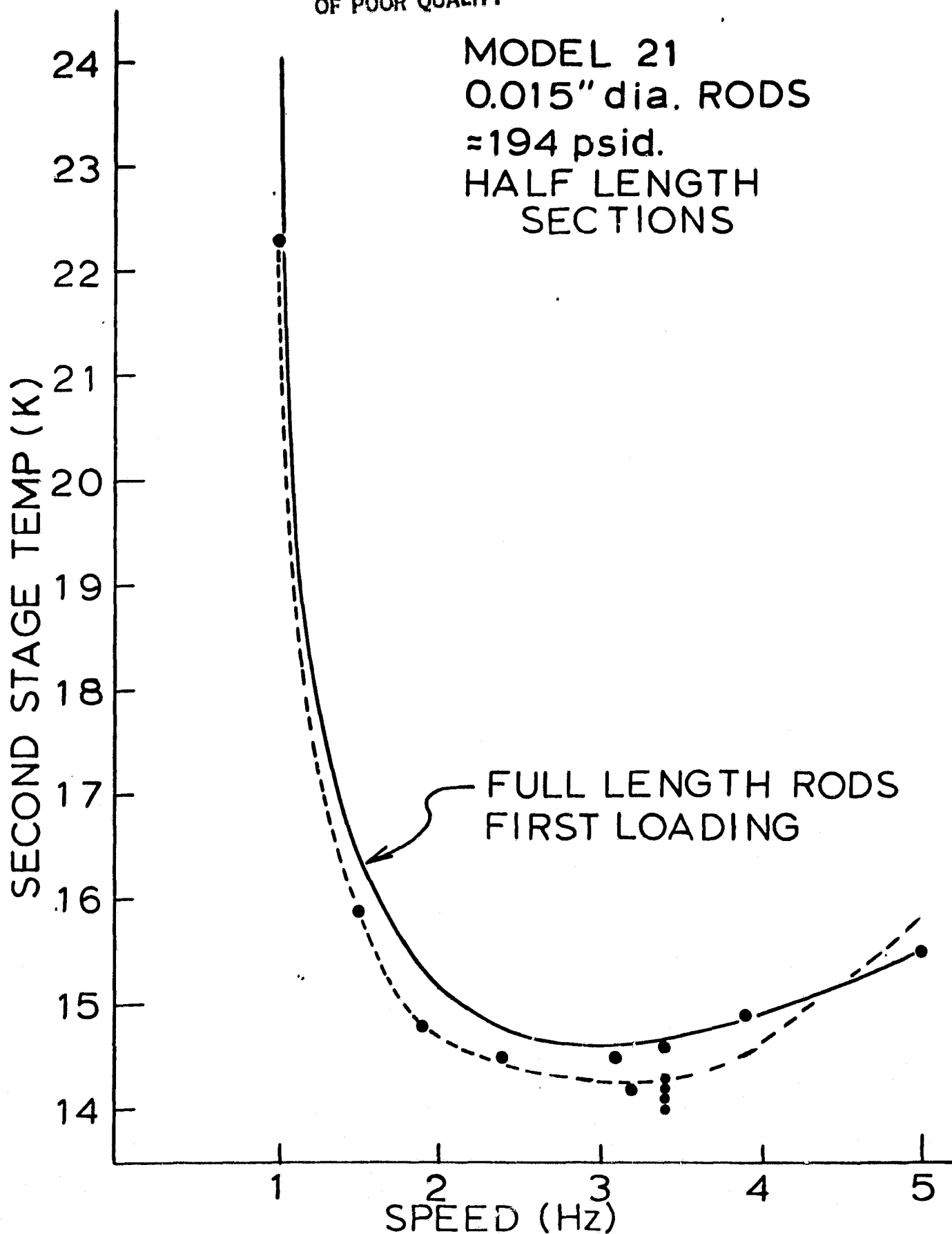


FIGURE 10. Comparison between full-length and half-length 0.015" diam rods, no load, constant pressure drop, variable speed.

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MODEL 21
0.015" dia. RODS
≈ 3.4 Hz
HALF LENGTH
SECTIONS

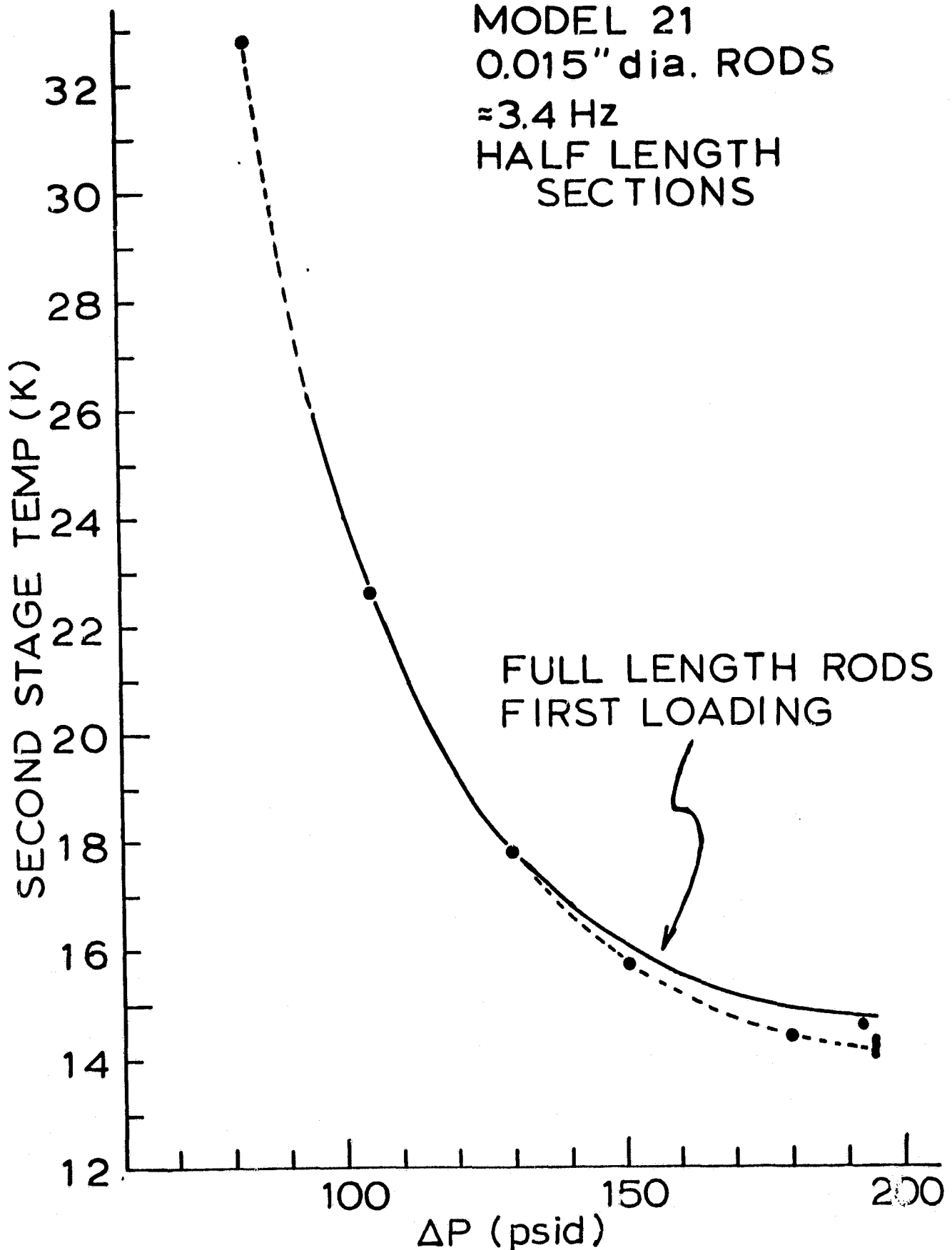


FIGURE 11. Comparison of full-length and half-length 0.015" diam rods, no load, constant coldhead speed, variable pressure drop.

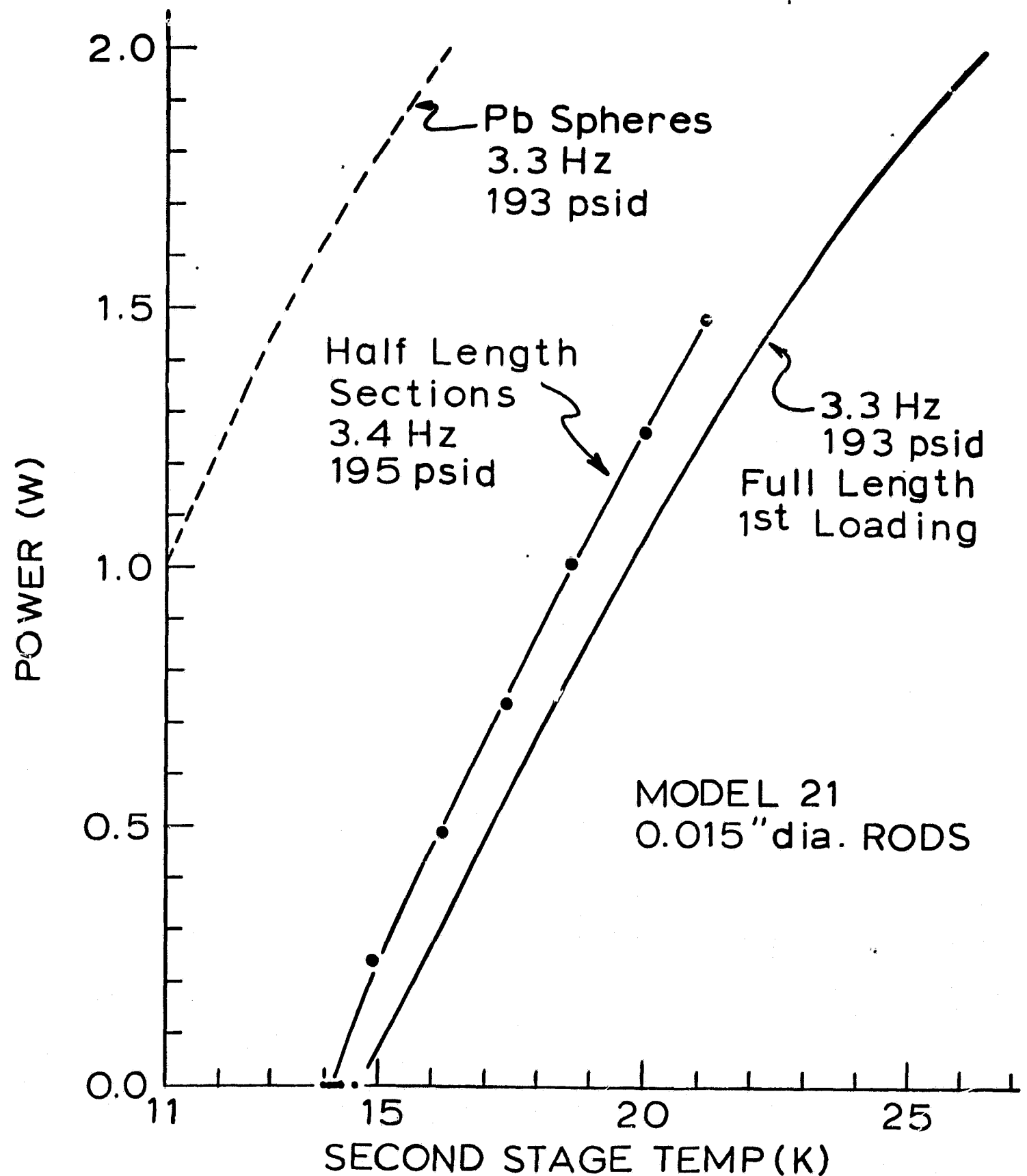


FIGURE 12. Comparison of load curves for full-length and half-length 0.015" diam rods at 3.3 Hz and 193 psid.

MODEL 21
0.015" dia. RODS
≈194 psid.

SECOND STAGE TEMP (K)

--- FULL LENGTH RODS
-- HALF
— QUARTER

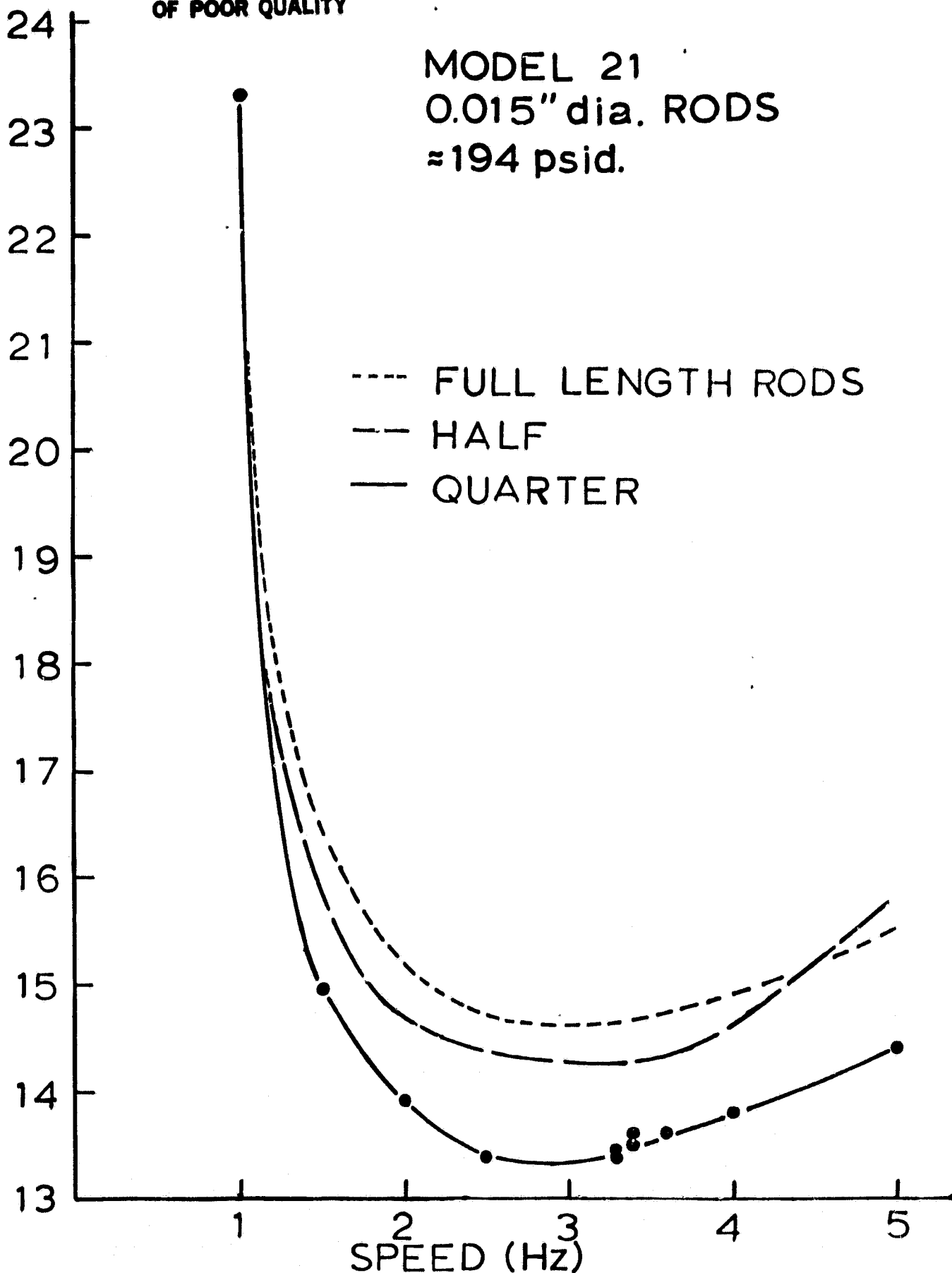


FIGURE 13. Dependence of the Model 21 second stage temperature upon speed variation for full-length, half-length, and quarter-length 0.015" diam rods, no load, 194 psid.

MODEL 21
0.015" dia. RODS
≈ 3.4 Hz

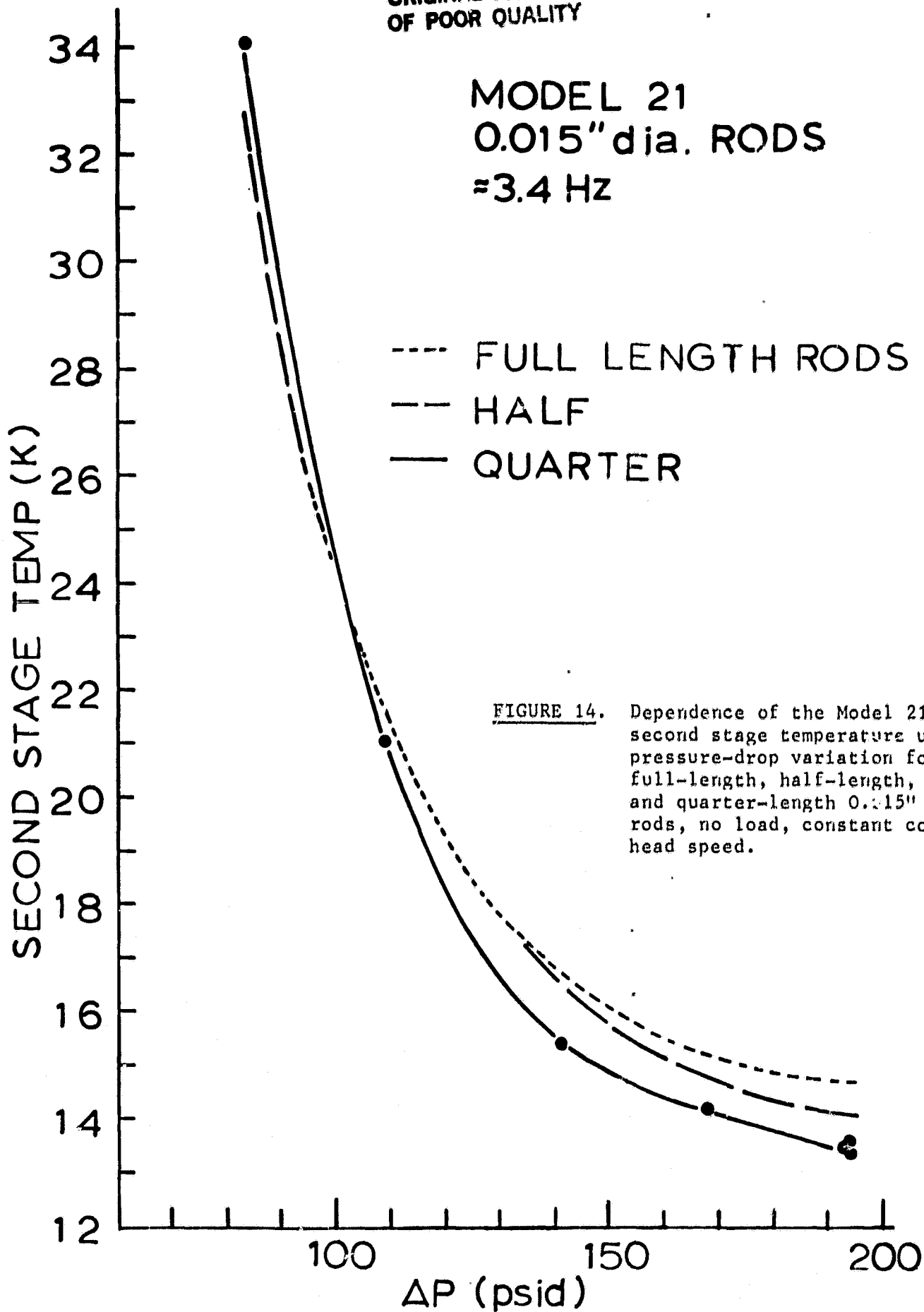


FIGURE 14. Dependence of the Model 21 second stage temperature upon pressure-drop variation for full-length, half-length, and quarter-length 0.015" diam rods, no load, constant cold-head speed.

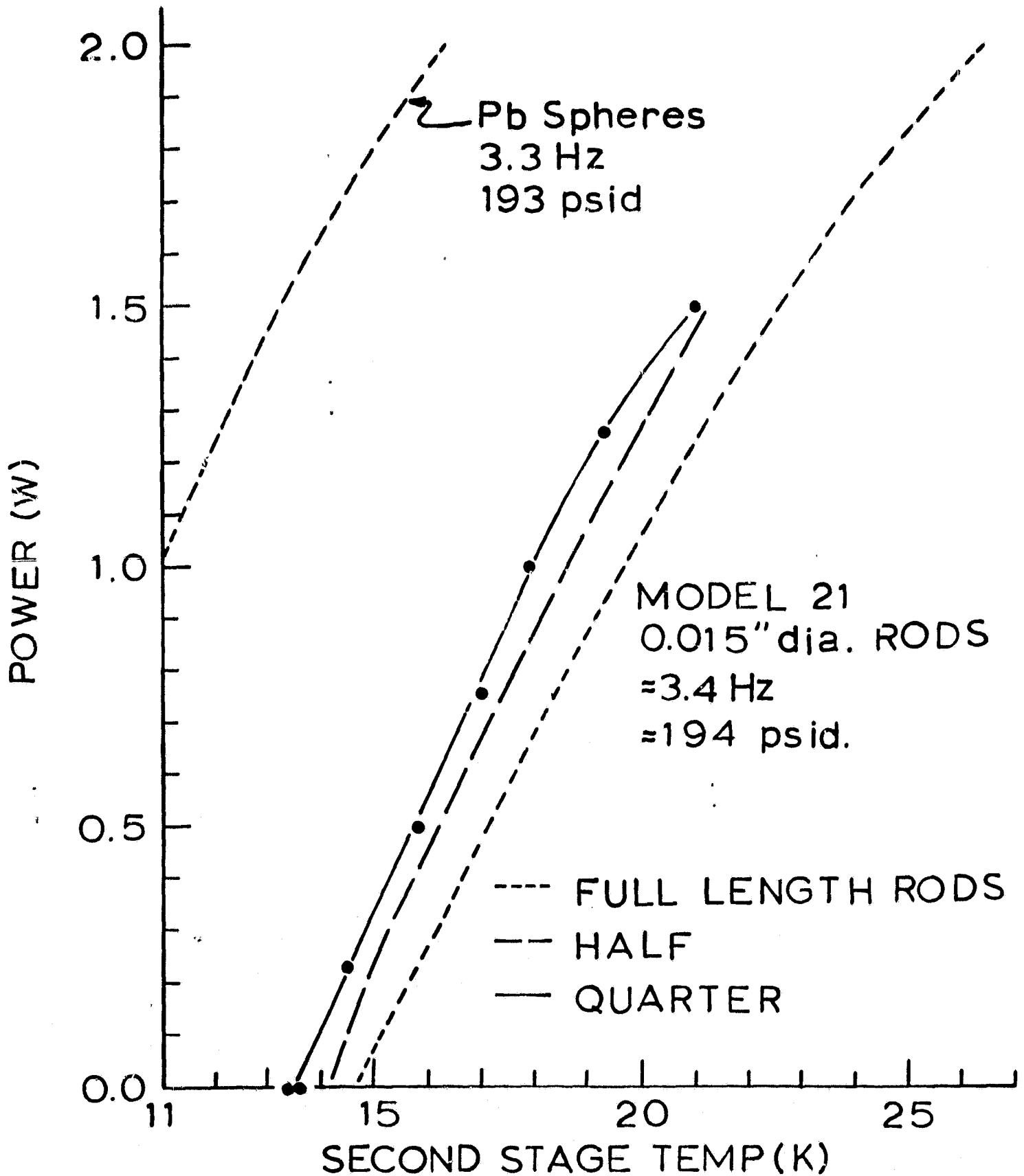


FIGURE 15. Load Curves of the Model 21 for full-length, half-length, and quarter-length 0.015" diam rods at 3.4 Hz and 194 psid.

0.030" Diameter Rods Regenerator

The testing program for these 0.030" diam rods of 0.2%-SnCl₂-doped LS-8A was an outgrowth of our findings on the 0.015" diam rods discussed above, the goal being to discern trends between the .015" and 0.030" rod results.

The program here was to test "full-length" and "half length" rod regenerators, and the procedures used were the same as with the 0.015" rods above. The packing factors obtained were: "full-length", 80.5%; "half-length", 79.4%. These packing factors compare favorably to those obtained with the 0.015" rods.

The test results obtained on the "full-length" rod regenerator are shown in Figures 16-18, where comparisons are made with both the Pb-spheres and 0.015"-rods regenerators. As seen, the refrigerator performance continually degrades in going from Pb spheres to the 0.015" rods to the 0.030" rods.

These results with the 0.030" diam rods suggest that the thermal diffusivity with these larger rods may be a problem, but this had been examined earlier² and it had been concluded that thermal diffusivity should not be compromised at this large rod diameter (see also below). The suggestion was made, therefore, that perhaps the heat transfer coefficient between the surface of the rod and the He gas was poor.

To examine this heat-transfer aspect, a nichrome coating was evaporated on the full-length rods, and the .030" rods were ideal for this because far fewer rods (~120) were involved than would have been involved with the 0.015" diameter. Three evaporations were required to coat the rods, the rods being rotated between evaporations.

The test results obtained with these coated, full-length rods and with the "half-length" rods are shown in Figures 19 and 20 compared to the uncoated, full-length rod results. These results show only marginal improvement in going to "half-length" rods and a significant degradation due to the nichrome coating.

MODEL 21
≈ 194 psid

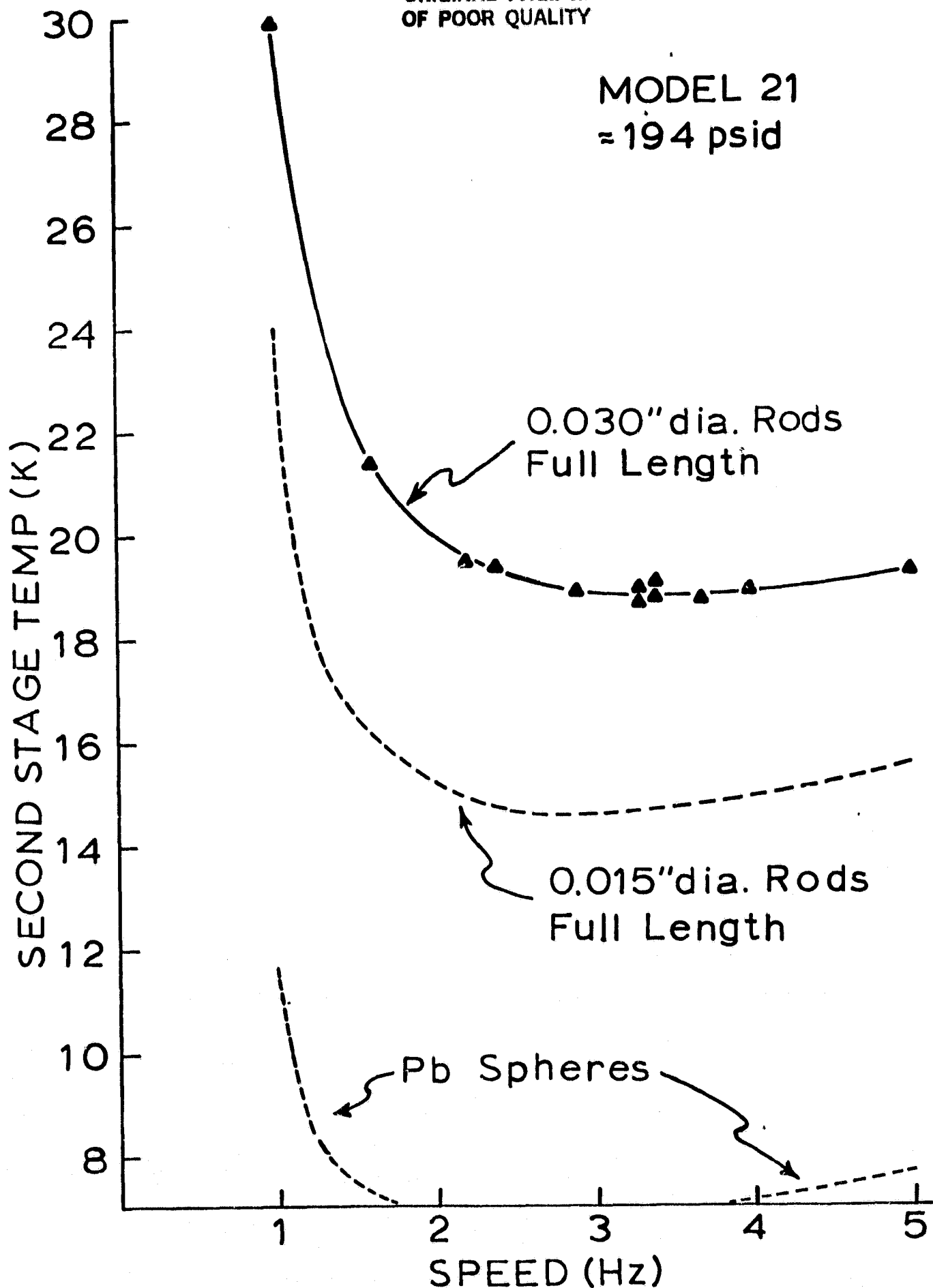


FIGURE 16. Comparison of the second-stage-temperature dependence on coldhead speed for Pb spheres and full-length rods of 0.015" and 0.030" diam at constant 194 psid pressure drop and no load.

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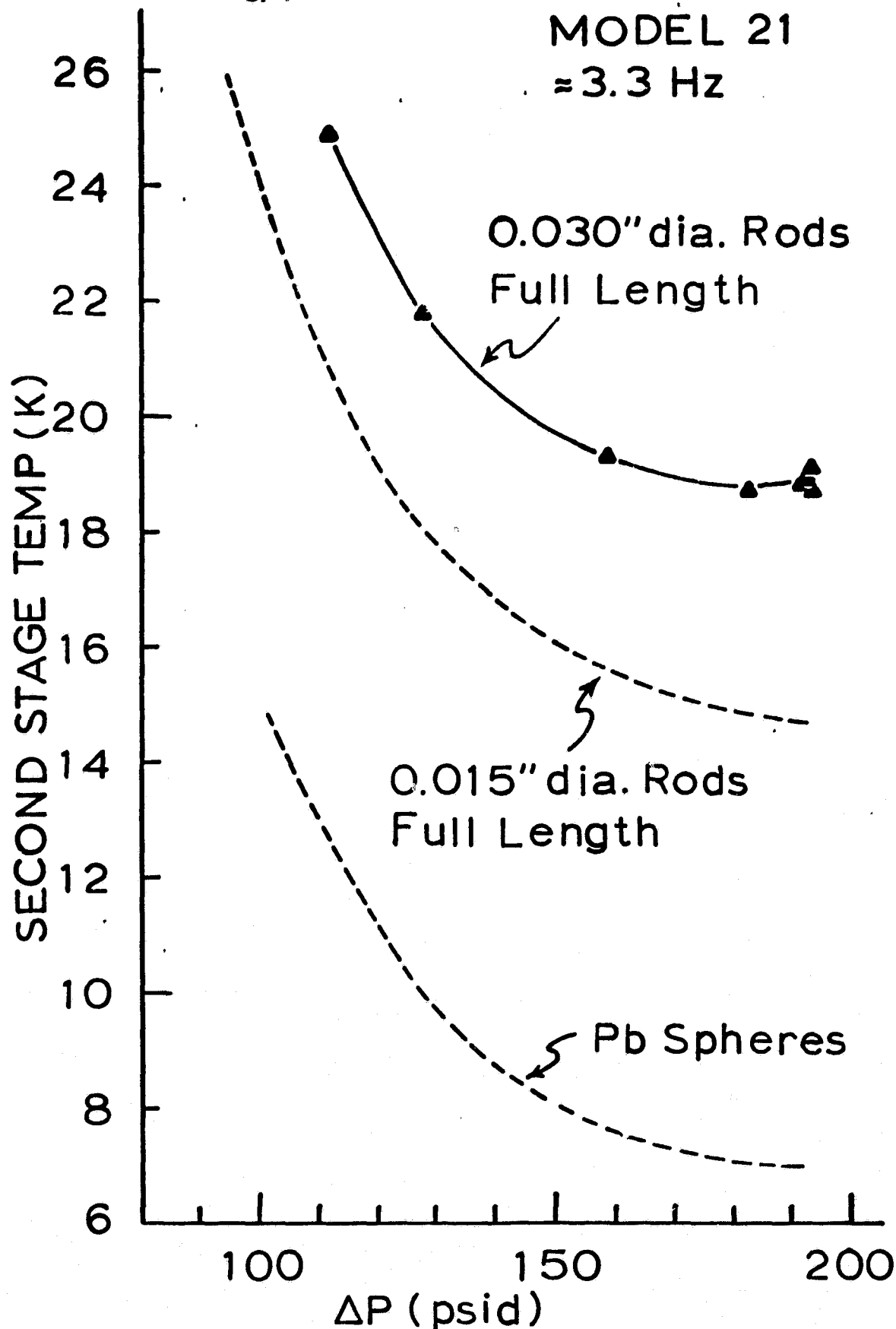


FIGURE 17. Comparison of the second-stage-temperature dependence on pressure drop for Pb spheres and for full-length rods of 0.015" and 0.030" diam at constant speed and no load.

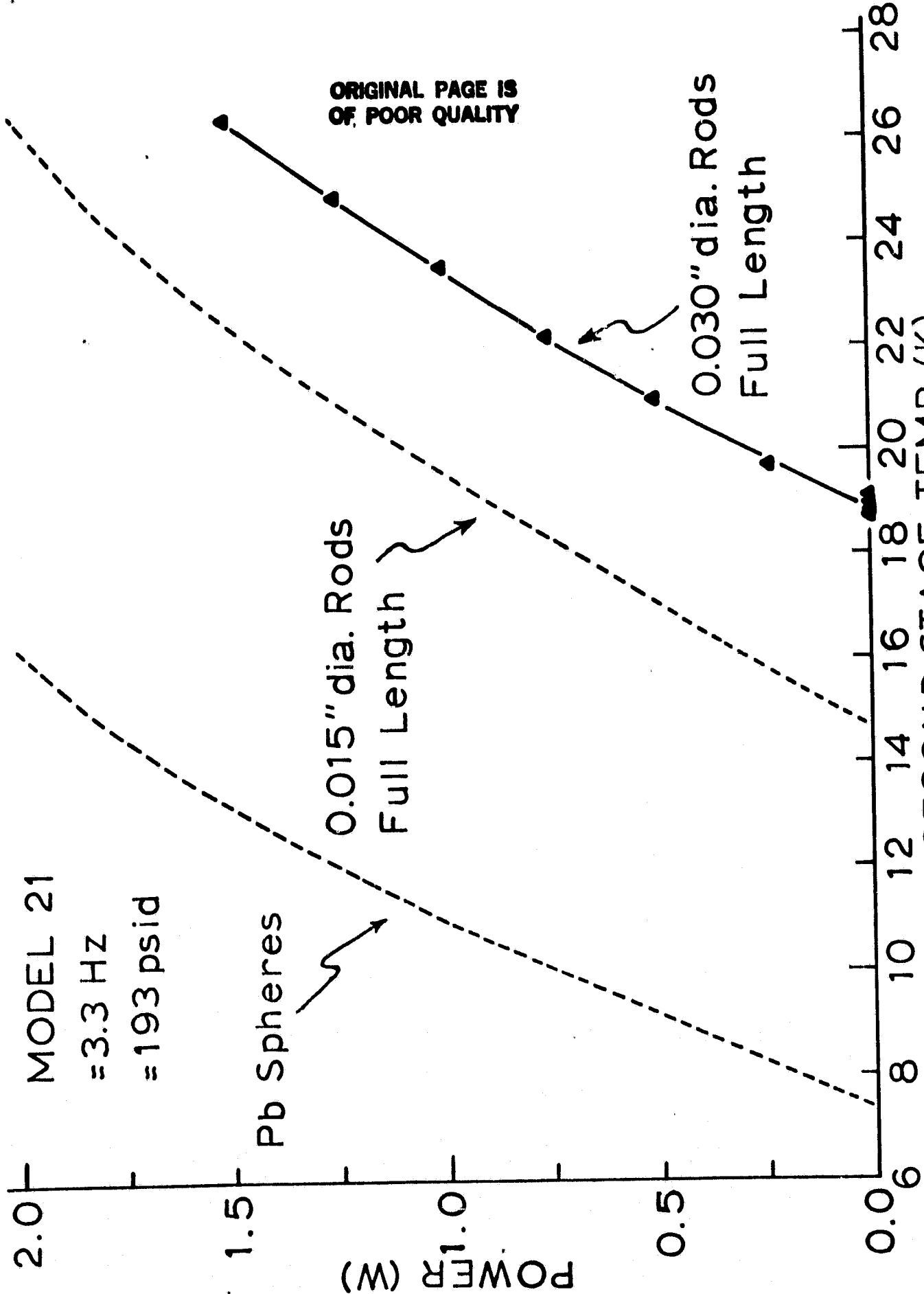


FIGURE 18. Comparison of load curves for full-length, 0.015" and 0.030" diam rods at 3.3 Hz and 193 psid.

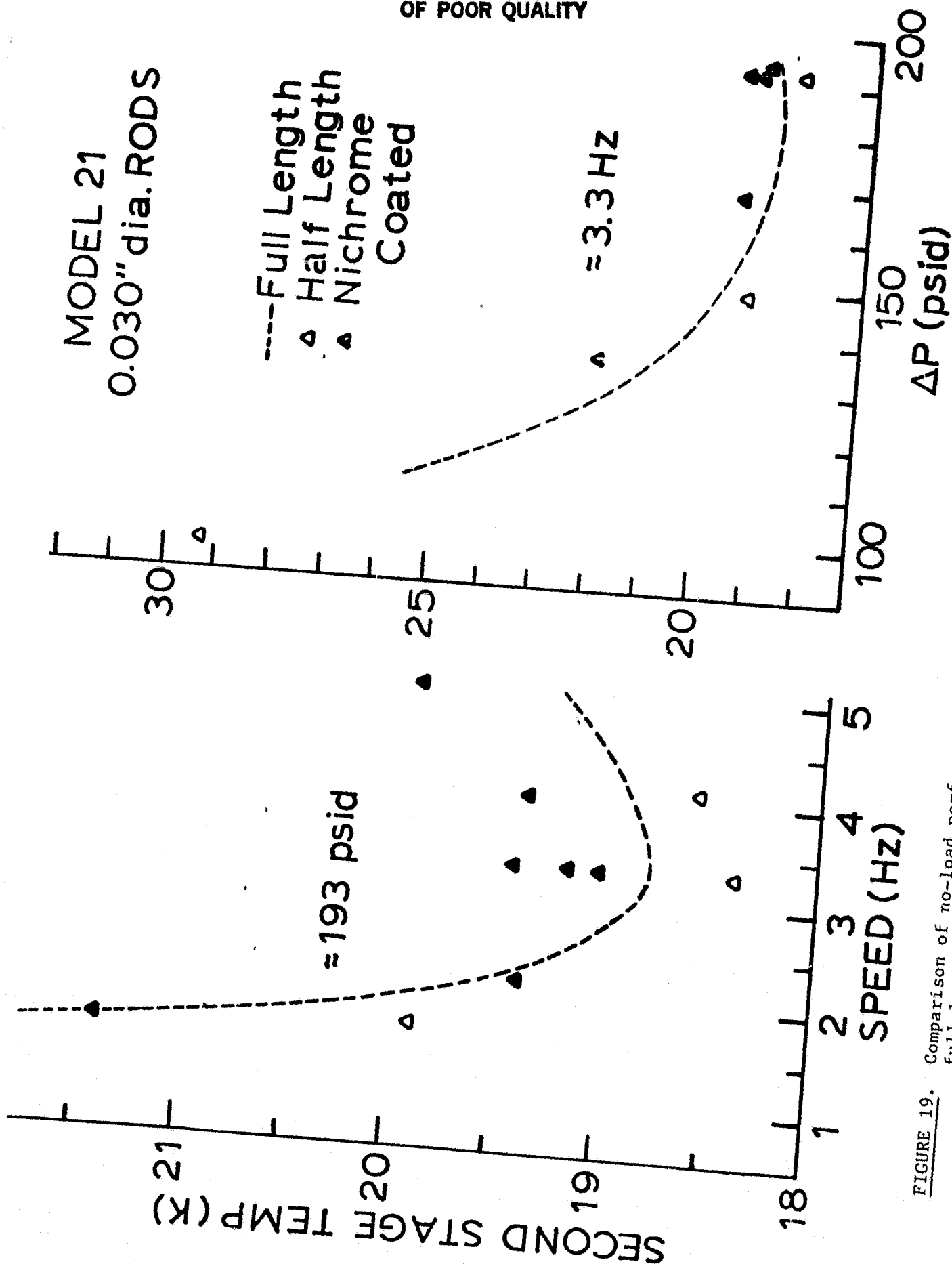


FIGURE 19. Comparison of no-load performance for full-length, half-length, and nichrome-plated full length 0.030" diam rods, as functions of speed and pressure drop.

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MODEL 21
0.030" dia. RODS

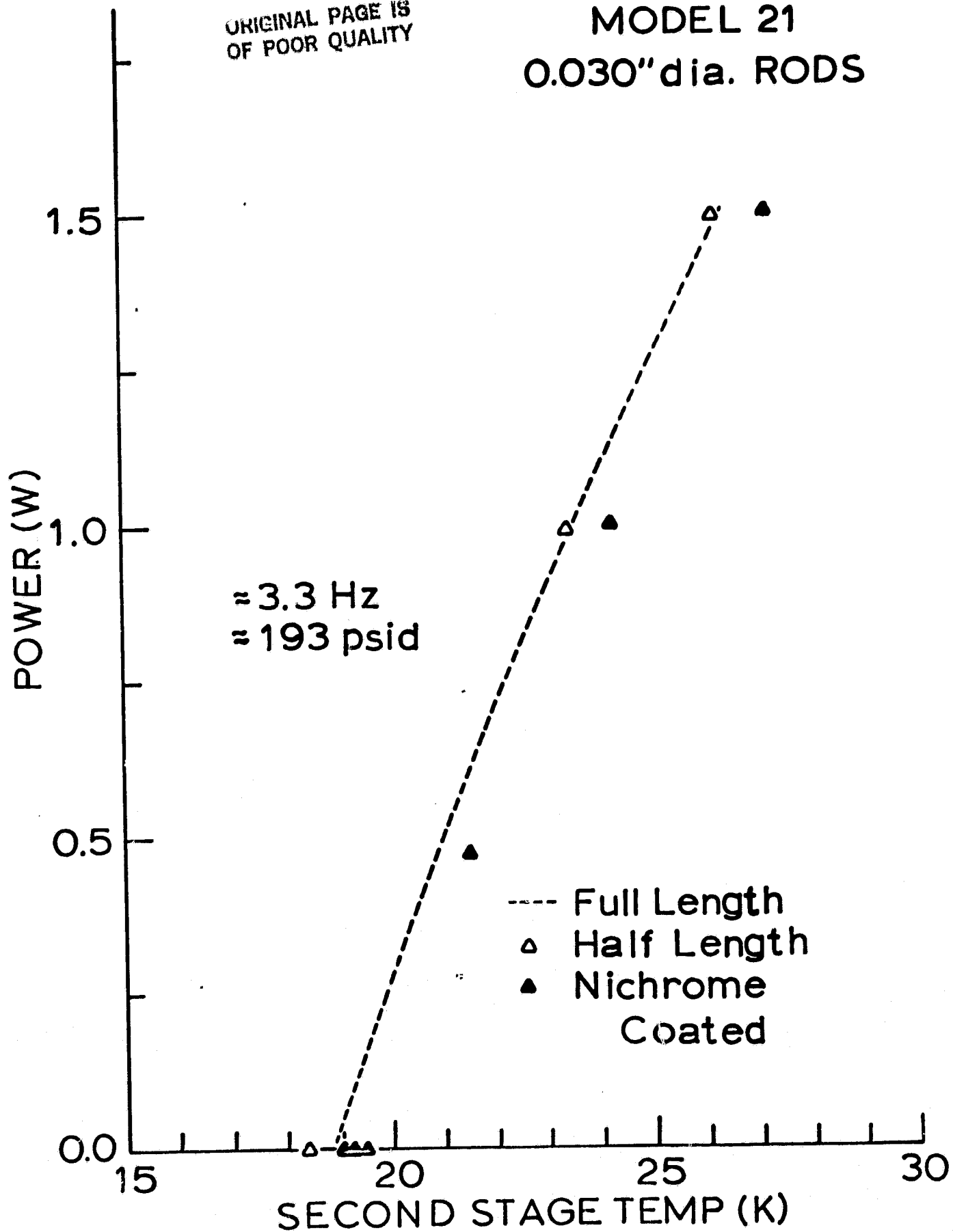


FIGURE 20. Load curves for various 0.030" diam rods: Full-length, half-length, and nichrome-plated at 3.3 Hz and 193 psid.

These tests concluded our study of the 0.030" diam rods of 0.2%-SnCl₂-doped LS-8A. A quantity of these rods sufficient to load the regenerator of the Model 350 was shipped to the JPL.

0.008" Diameter Rods Regenerator

Because the various rod modifications had been studied with the 0.015" and 0.030" rods, only the full-length rods of 0.008" diameter were studied. Moreover, since these rods were received late in the contract and a 1000-hr life test was planned with these rods, only one regenerator loading was allowed.

The de-dusted rods were loaded into the Model 21 regenerator, and a packing factor of 82.4% was obtained. The test results on these 0.008" rods are shown in Figures 21-23, and comparisons are made with the 0.015" rods.

As seen, there is a considerable improvement in the refrigerator performance with the 0.008" diam rods. As with the 0.015" and 0.030" diam rods, the optimum operating conditions are the same as for the Pb spheres, and the Figure 23 load curve for the 0.008" rods represents more than a 100% improvement over the 0.015" rod load curve. And finally, as seen in Figures 21 and 22, the optimum operating conditions for these rods are essentially the same as for the Pb spheres.

1000-Hr Life Test With The 0.008" Rods Regenerator

The coldhead-compressor system was set at the optimum operating conditions (3.3 Hz, 192 psid), and the refrigerator was run continuously for 1000 hrs. At approximately 150-hr intervals, the load characteristics were measured, and the resulting data are shown plotted in Figures 24-26.

Figure 24 shows the variation of the no-load second-stage temperature with time. The pressure drop varied somewhat during the life test, and these pressure variations are also shown in Figure 24. The temperature variations match the pressure variations very well.

Figures 25 and 26 summarize the load characteristics during the 1000-hr test. There was some variation in the applied power in these tests, and

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MODEL 21
192 psid

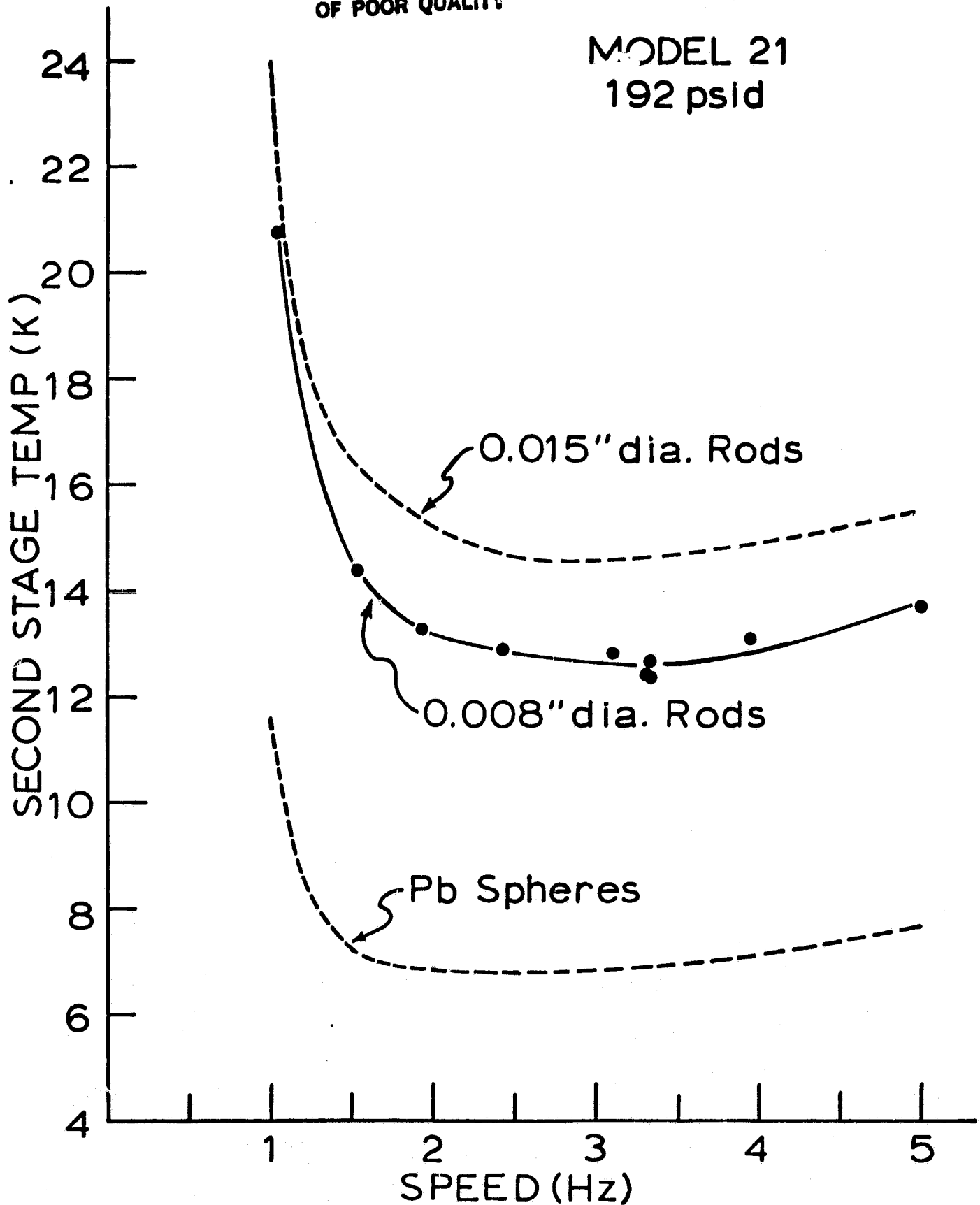


FIGURE 21. Comparison of no-load, speed variations on the second-stage temperature for Pb spheres, 0.015" and 0.008" diam rods at 193 psid.

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MODEL 21
3.3 Hz

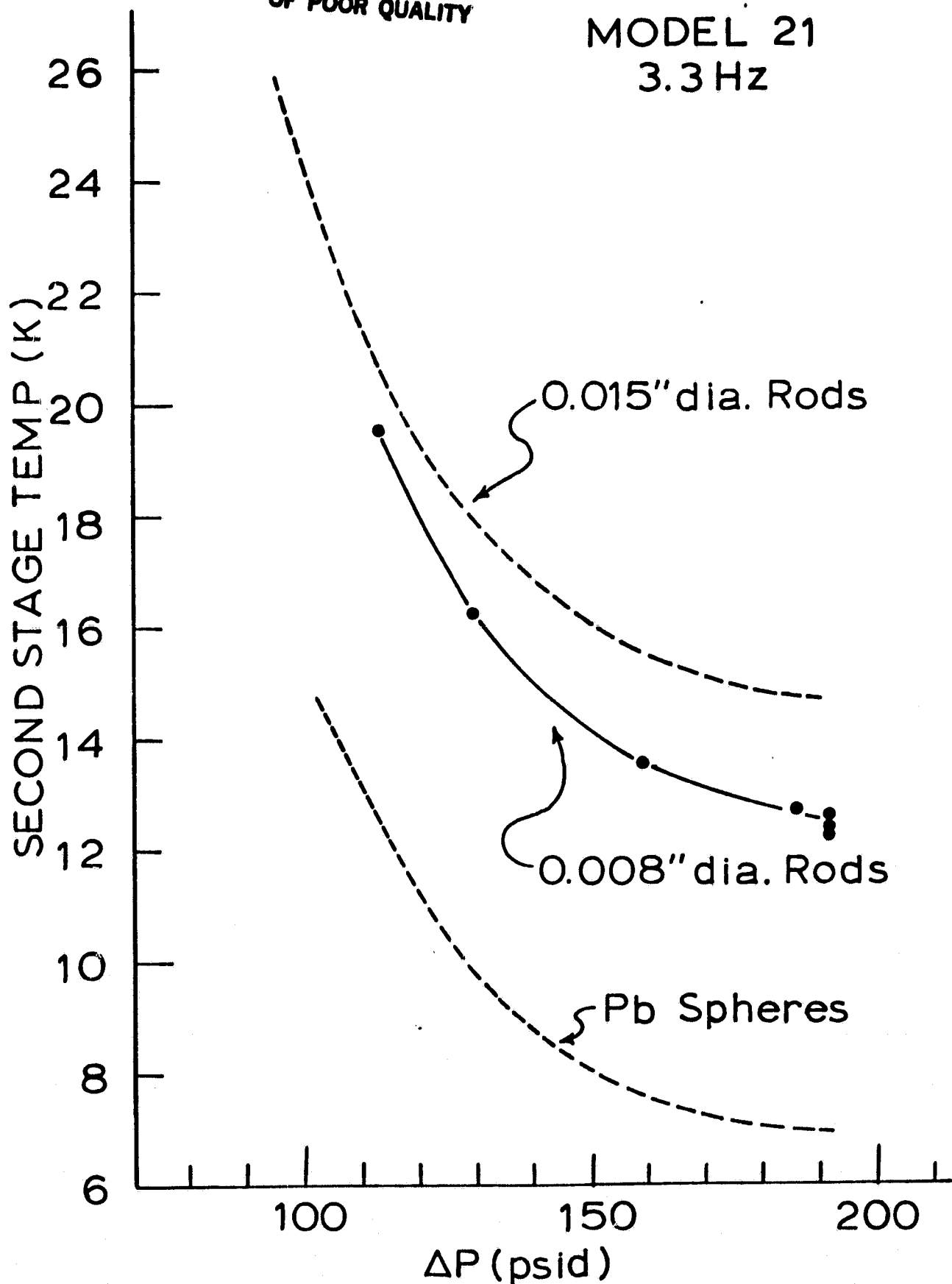


FIGURE 22. Comparison of no-load, pressure-drop variations on the second-stage temperature for Pb spheres, 0.015" and 0.008" diam rods at 3.3 Hz.

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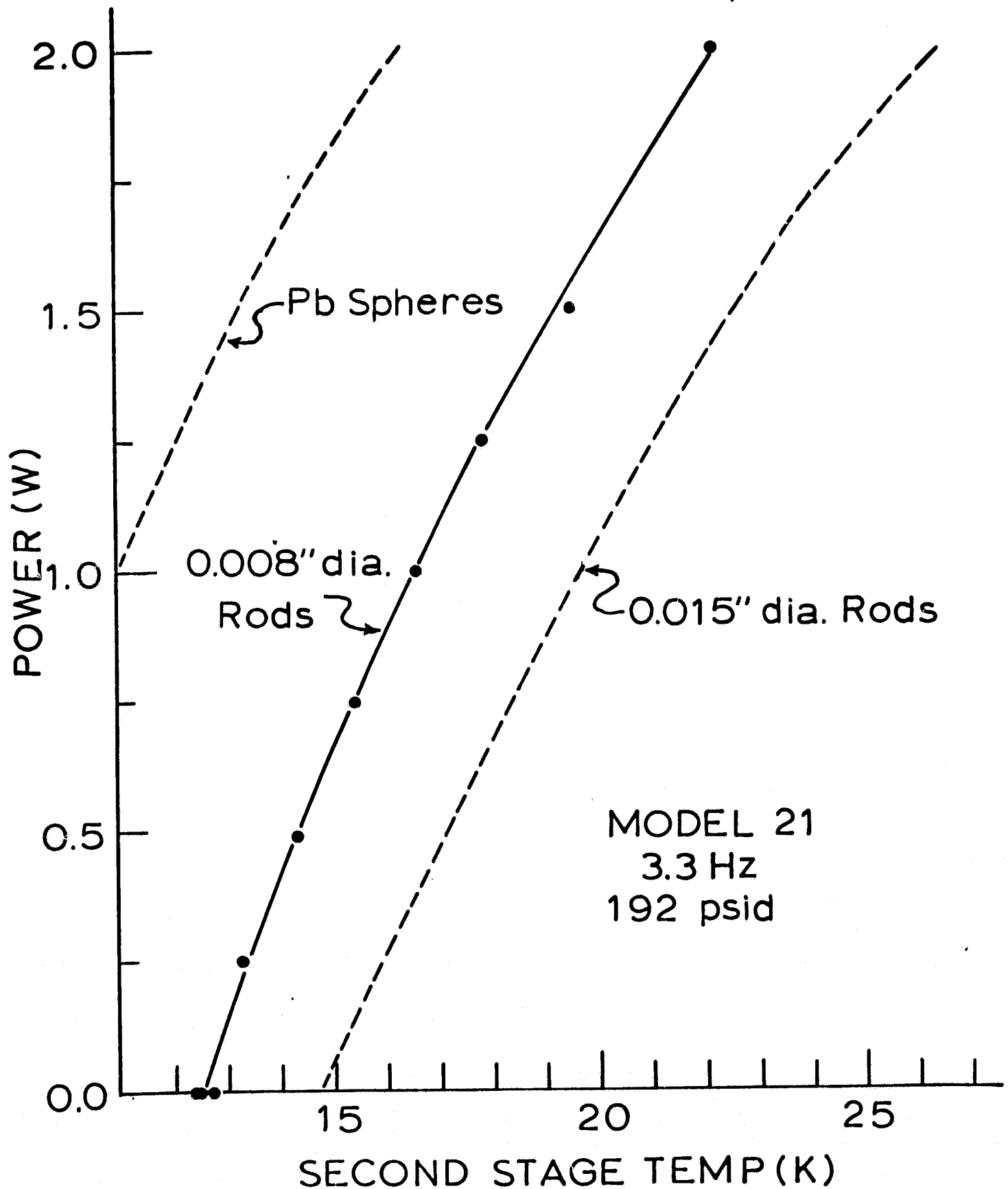
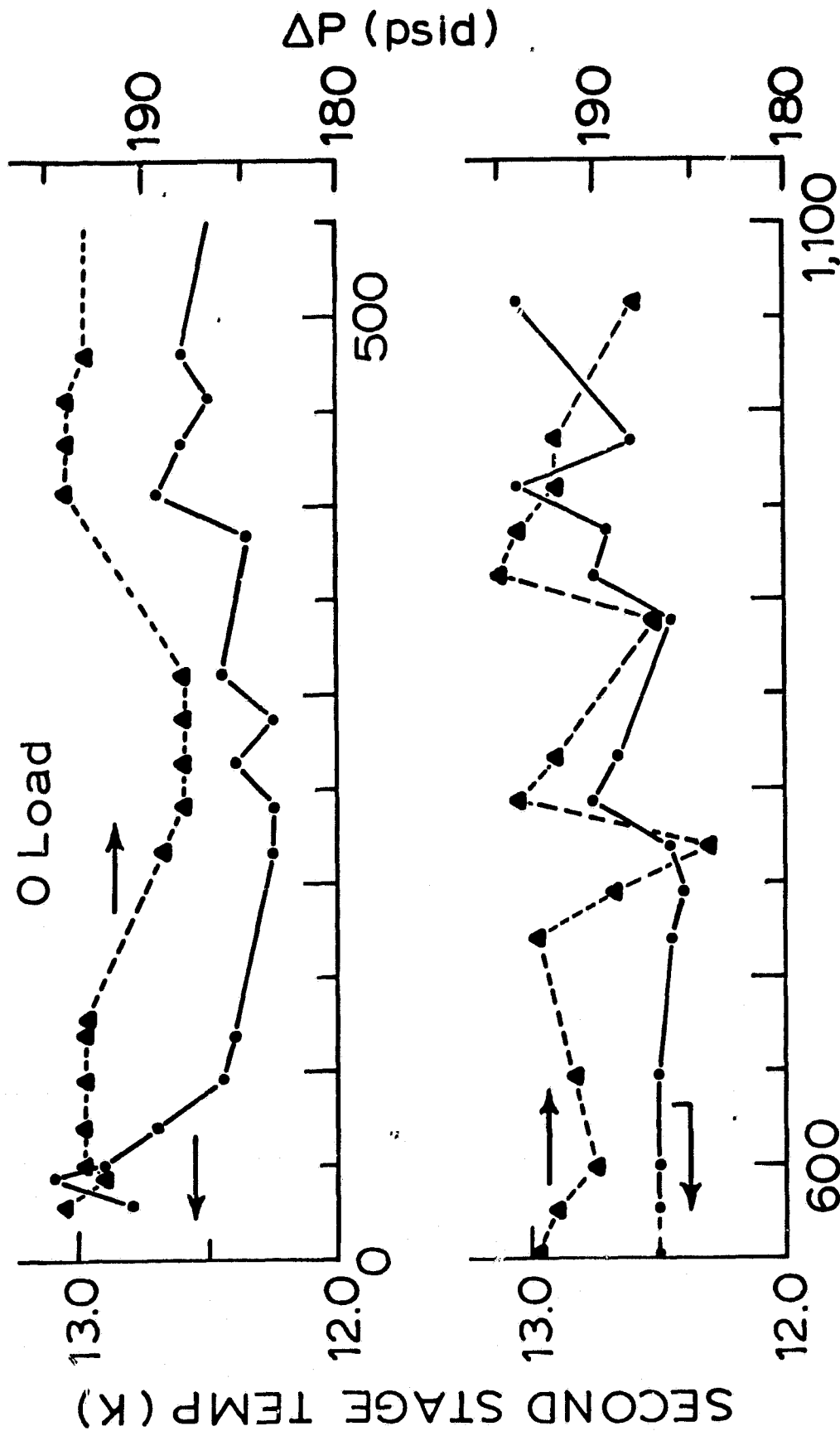


FIGURE 23. Comparison of load curves for Pb spheres, 0.008" and 0.015" diam rods at 3.3 Hz and 192 psid.

MODEL 21
0.008" dia. RODS

3.3 Hz
0 Load



OPERATING TIME (HRS.)

FIGURE 24. Lifetime characteristics of the Model 21 with 0.008" diam rods, no-load, 3.3 Hz conditions.

MODEL 21
0.008" dia. RODS

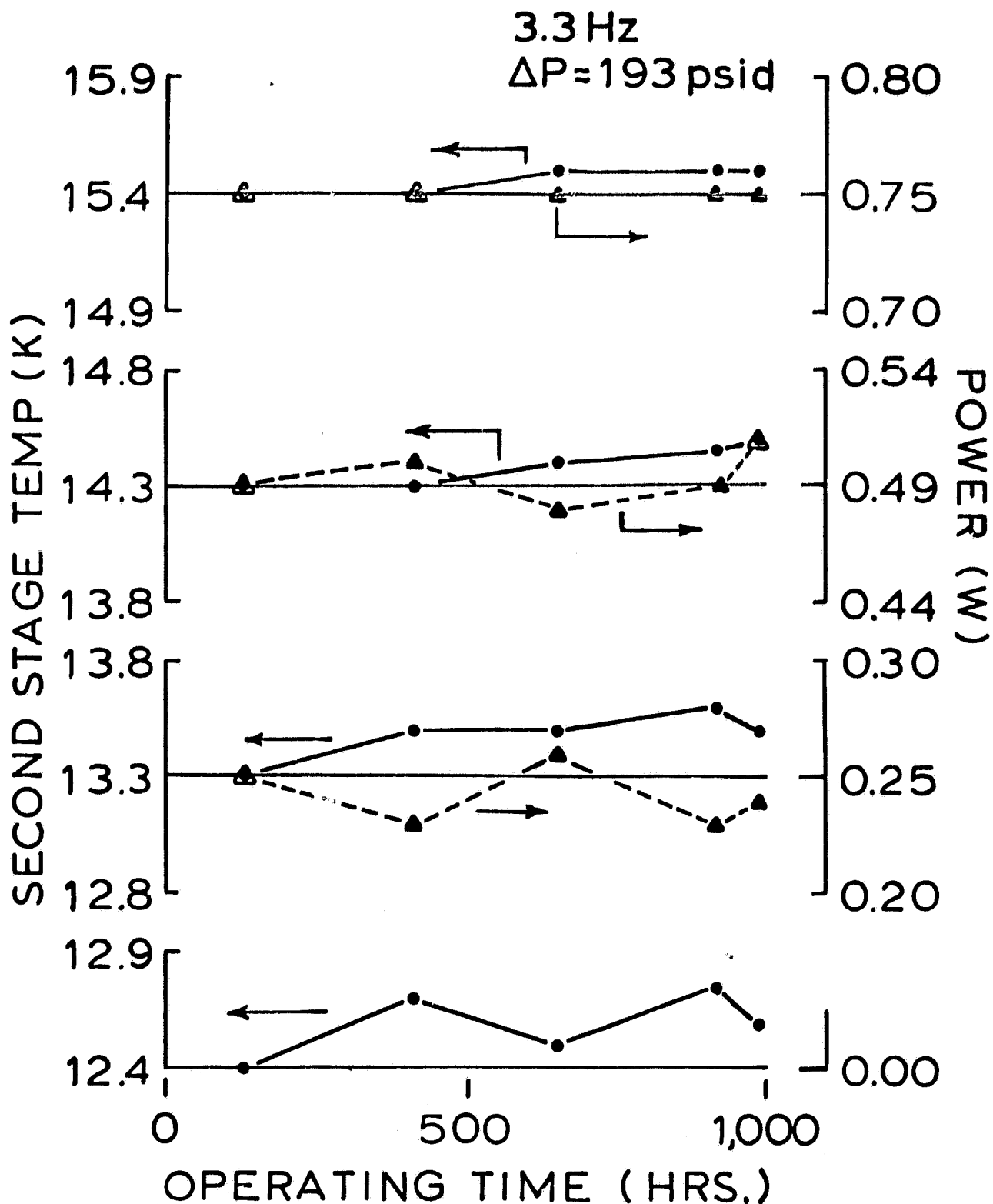


FIGURE 25. Lifetime characteristics of the Model 21 with 0.008" diam rods for power levels up to 0.75 Watts, 3.3 Hz and 193 psid.

MODEL 21
0.008" dia. RODS

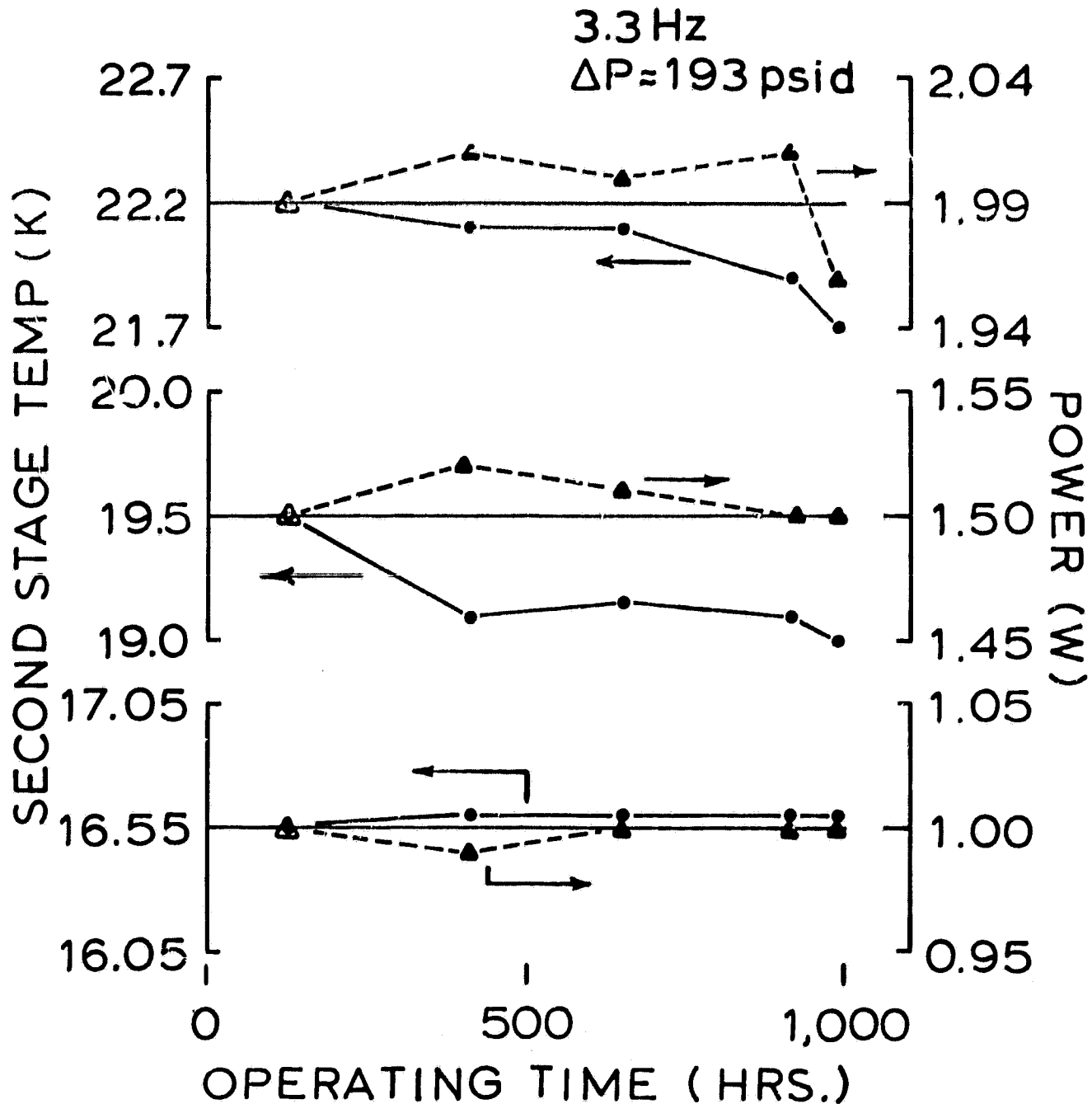


FIGURE 26. Lifetime characteristics of the Model 21 with 0.008" diam rods for power levels between 1.0 and 2.0 Watts, 3.3 Hz and 193 psid.

these power variations are also shown in Figure 25 and 26. In general, the load-temperature characteristics track very well (note, in particular, the 2.0 W curve in Figure 26).

The conclusion here is that there was no apparent degradation in the performance of the refrigerator during this 1000-hr life test.

Following this test, the regenerator was opened and examined. There was no apparent pulverization or breakage of the 0.008" rods. This is particularly significant because the test with these rods was the most demanding given the large number of rods and their fragility compared to the 0.015" or 0.003" rods.

There was a slight yellow stain on the felt pads following this life test; whether this was due to incomplete de-dusting prior to the initial loading or to abrasion during the test cannot be determined.

A photograph of felt pads and of some of the 0.008" rods is shown in Figure 27.

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FIGURE 27. Regenerator-filter felt pads and 0.008" diam rods after 1000-hr test run. The pad on the left is clean and unused. At center and right are pad sides which were, respectively, toward and away from the regenerator rod bundle during the test run.

V. EXPERIMENTAL RESULTS-THERMAL PROPERTIES

Specific Heat

A composite plot of the volumetric specific heats of the 0.008", 0.015", and 0.030" diam rods of 0.2%-SnCl₂-doped LS-8A is shown in Figure 28. For comparison, the specific heat of the bulk material is also shown in Figure 28. The data are plotted as C/T^3 for convenience because both C and T^3 are changing by several orders of magnitude on this temperature range.

It is immediately clear from Figure 28 that the extruded rods have a smaller specific heat than the bulk material, suggesting that the extrusion process itself has a deleterious effect on the specific heat. There are two possible causes for this effect: (1) The SnCl₂ dopant is driven into the grain boundaries, or (2) A pressure-induced phase transformation is occurring.

This was pursued by annealing the 0.015" diam rods for 22 hr at 370°C and measuring their specific heat. These data are shown in Figure 29 where the data for bulk LS-8A, both doped and undoped, are also shown for comparison.

The Figure 29 data show that annealing the rods only marginally improves the specific heat. Moreover, the specific heat of the doped LS-8A rods is practically the same as the specific heat of bulk, undoped LS-8A.

We happened to have on hand a small amount of 0.015" diam rods of undoped LS-8A, and the specific heat of these undoped rods was measured in the hope of understanding the effect of extrusion on the thermal properties. These specific heat data are shown in Figure 30 together with specific heat data on the doped 0.015" rods and on bulk LS-8A, doped and undoped.

The Figure 30 data reveal a very confusing result: The undoped rods have specific heat properties similar to bulk, doped LS-8A, whereas the doped rods act like bulk, undoped LS-8A.

These Figure 30 results obviously suggest a mixup in the doped and undoped rods. Consequently, both sets of rods were subjected to chemical

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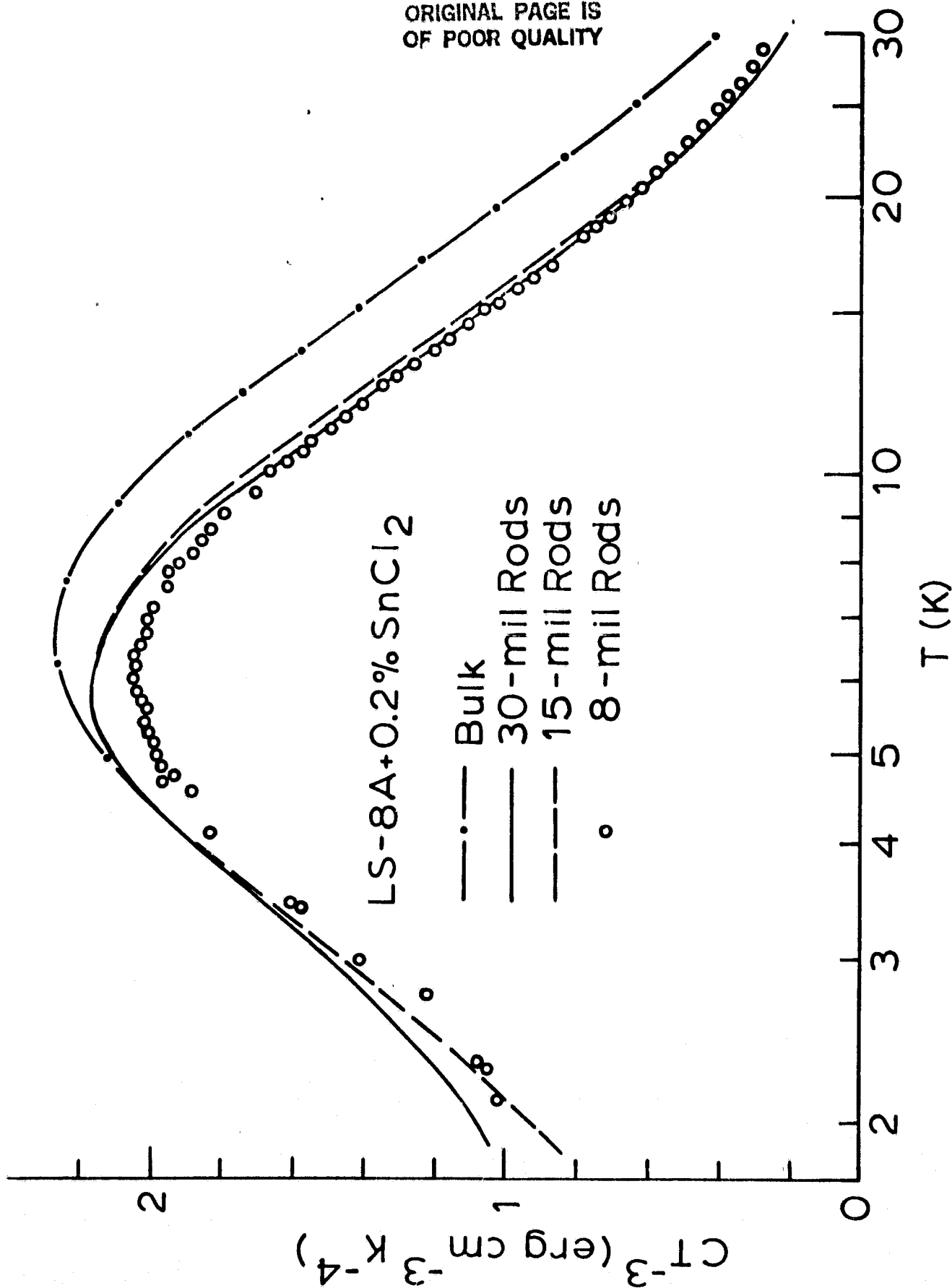


FIGURE 28. Comparison of the volumetric specific heats of the 8-, 15-, and 30-mil rods of LS-8A + 0.2% SnCl₂ with that of the bulk material.

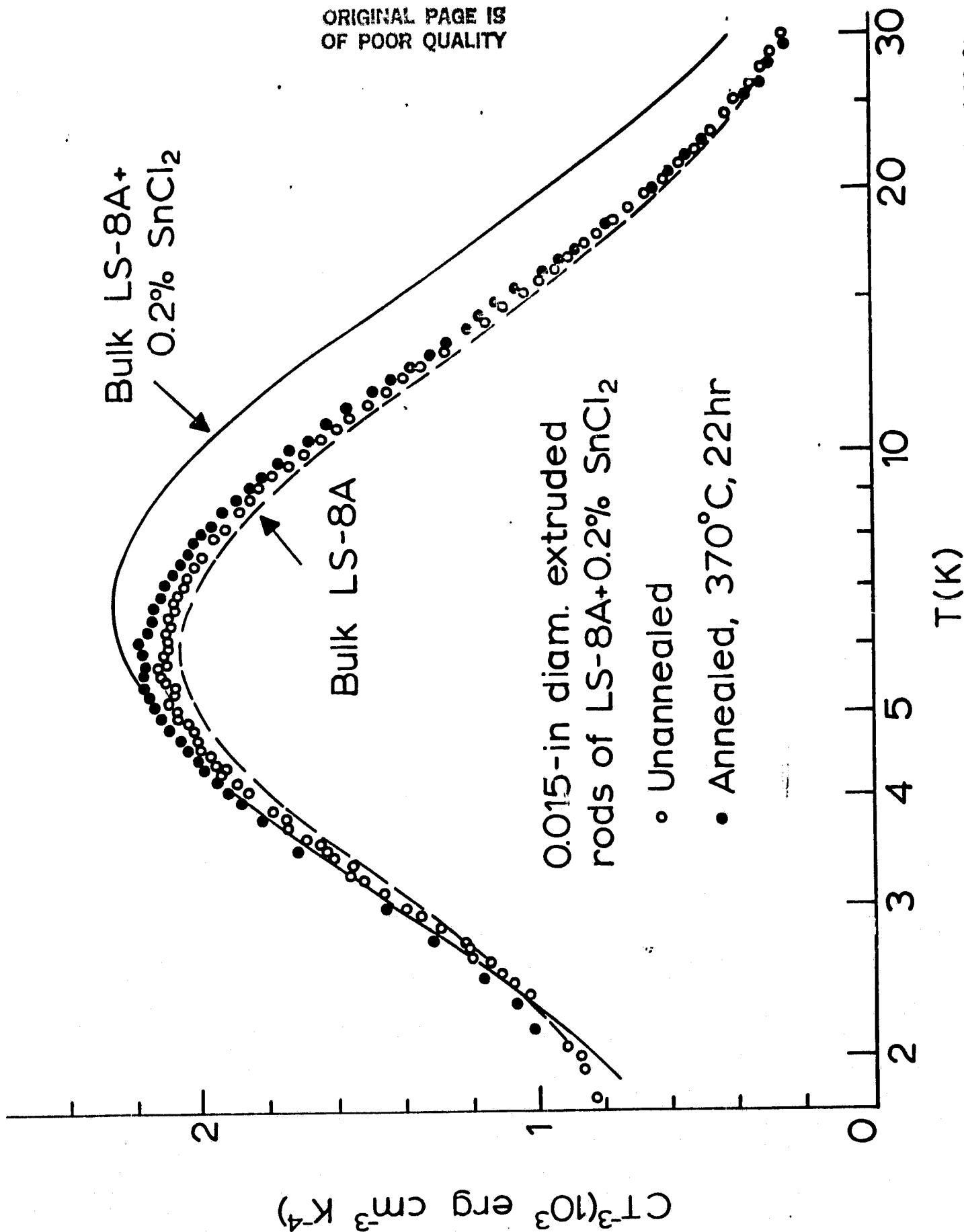


FIGURE 29. Specific heat of LS-8A + 0.2% SnCl₂ in bulk and rod form compared to bulk, undoped LS-8A.

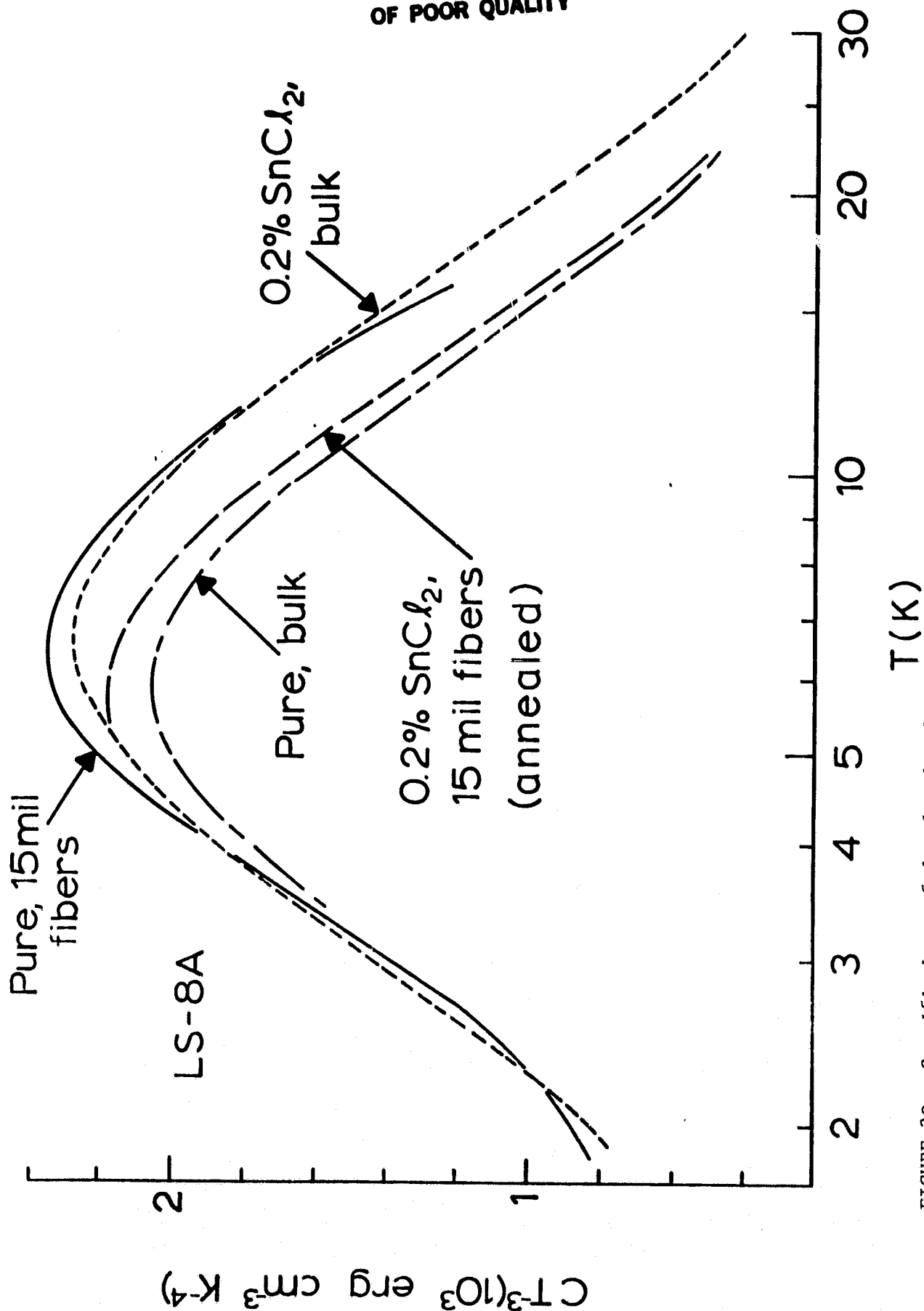


FIGURE 30. Specific heat of doped and undoped LS-8A in bulk and 15-mil-diam rod form.

analyses to detect the presence or absence of the SnCl_2 dopant. These chemical analyses confirmed that the "doped" rods did indeed contain 0.2% SnCl_2 and that the "undoped" rods did not even contain traces of SnCl_2 .

To re-confirm these surprising results, a small, fresh batch of undoped 0.015" diam rods of LS-8A was measured, and these specific heat results are shown in Figure 31. These data confirm that extruding undoped LS-8A has a very beneficial effect on the specific heat.

Thermal Conductivity

Thermal conductivity data on 0.008", 0.015", and 0.030" diam rods of 0.2%- SnCl_2 -doped LS-8A are shown in Figure 32 compared to the bulk thermal conductivity. As one would expect, the peak thermal conductivity progressively decreases as the sample dimension decreases due to increased boundary scattering.

The effect of annealing on the thermal conductivity was also examined (see Specific Heat section, above), and these data are shown in Figure 33. There is a marked increase in the peak thermal conductivity with annealing, corresponding to the slight increase in specific heat on annealing (Figure 29). Apparently, the extrusion process causes some crystalline damage that can be annealed out.

Finally, the thermal conductivity of undoped 0.015" diam rods was measured, and these data are shown in Figure 34. Here we see again the same behavior as with the specific heat -- namely, the undoped rods behave as the doped bulk and vice versa. These Figure 34 data are a valuable confirmation of this unexpected finding.

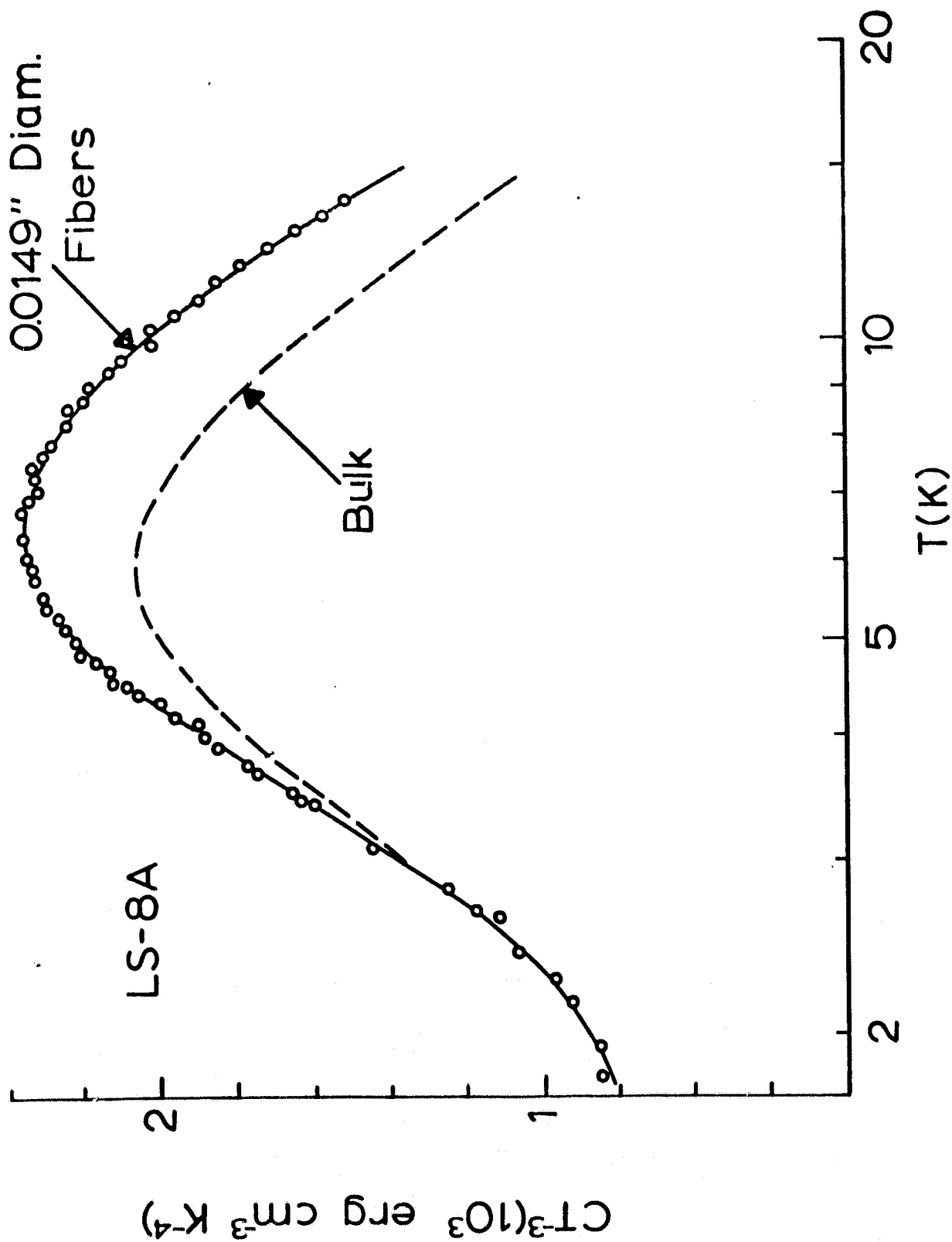


FIGURE 31. Confirmation data on the effect of extruding undoped LS-8A on the specific heat.

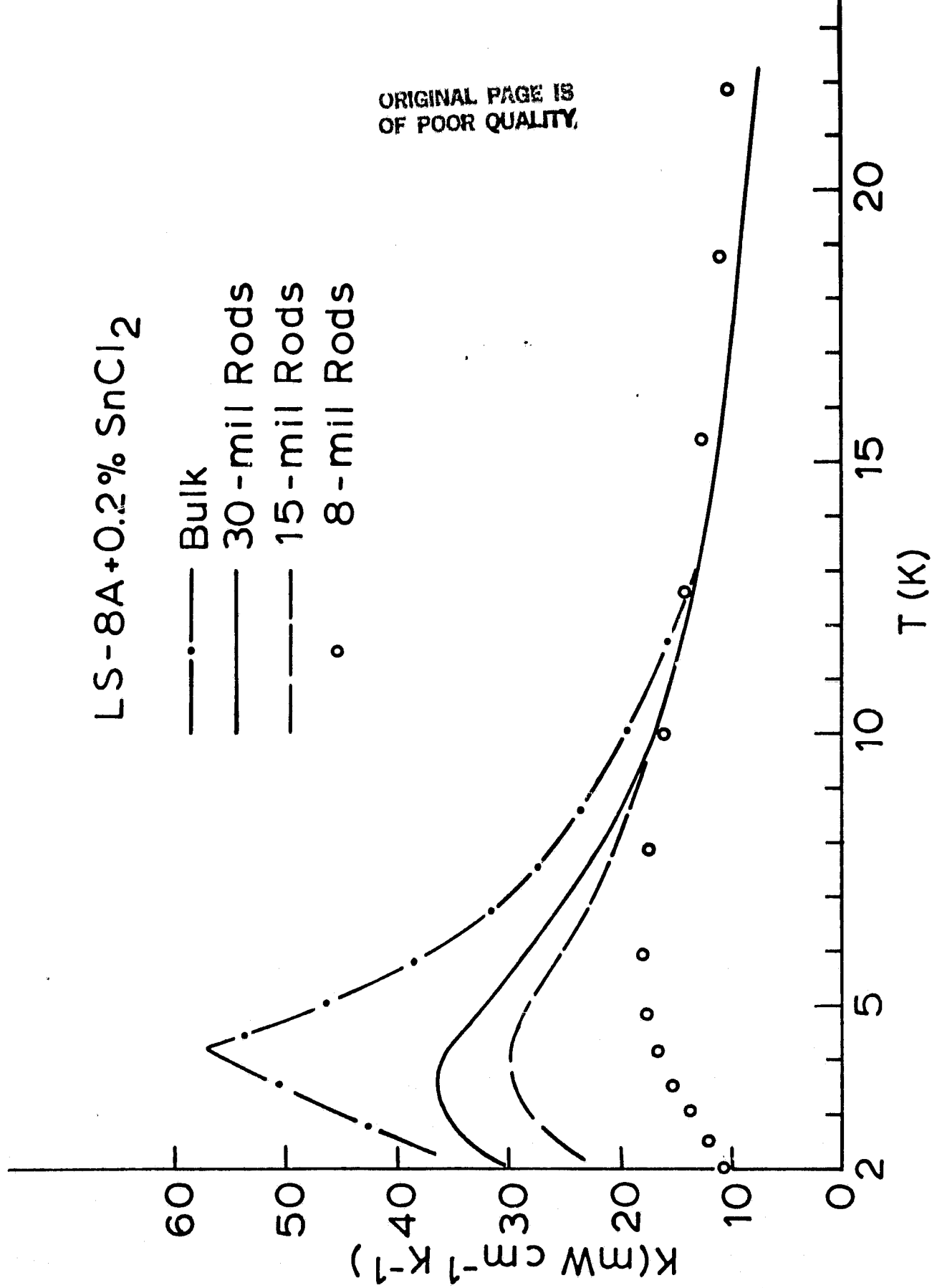


FIGURE 32. Comparison of the thermal conductivities of the 8-, 15-, and 30-mil rods of LS-8A + 0.2% SnCl₂ with that of the bulk material.

LS-8A + 0.2% SnCl₂

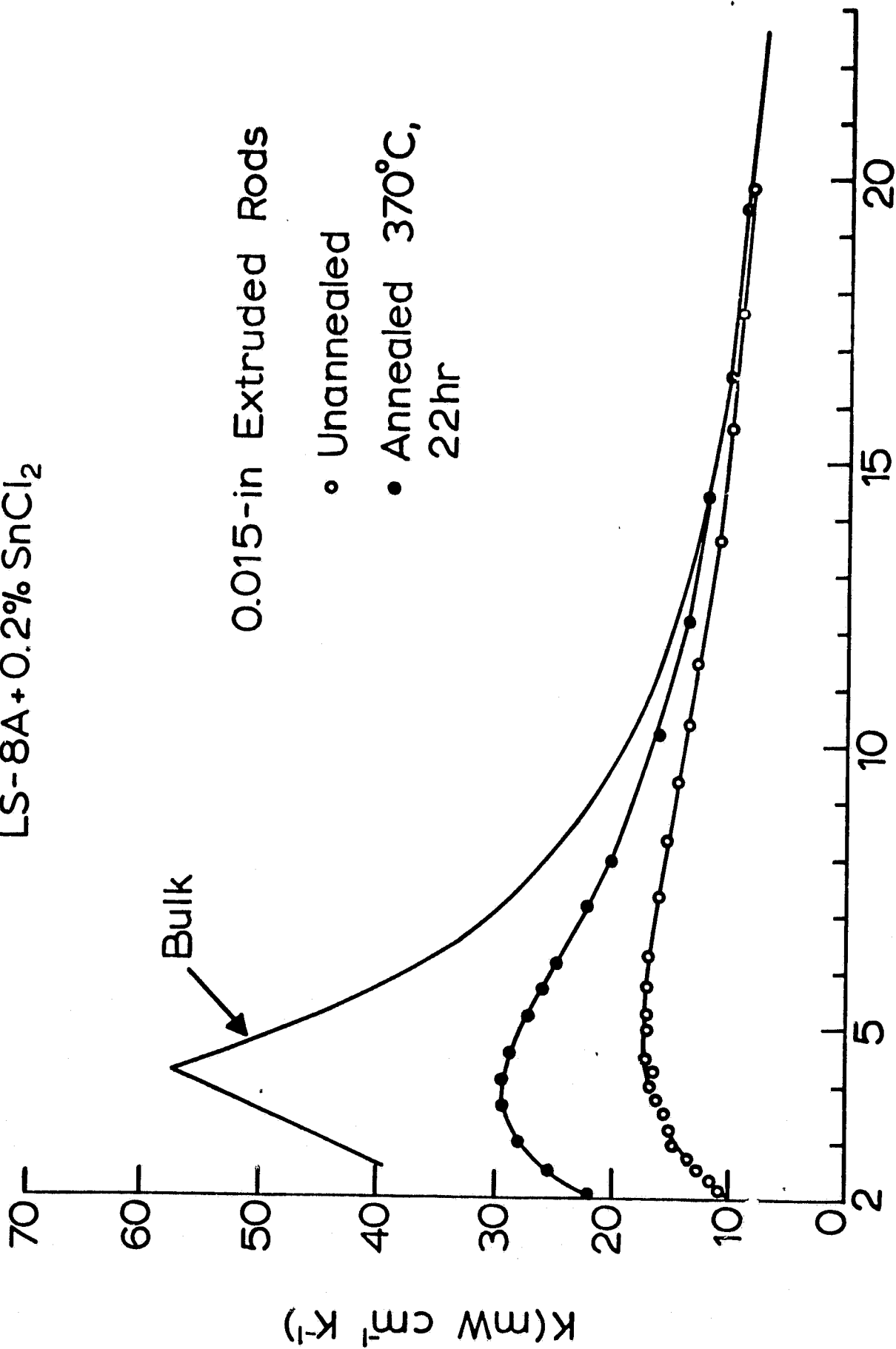


FIGURE 33. Thermal conductivity of 0.2% SnCl₂-doped LS-8A rods of 15-mil diam showing the effect of annealing.

LS-8A

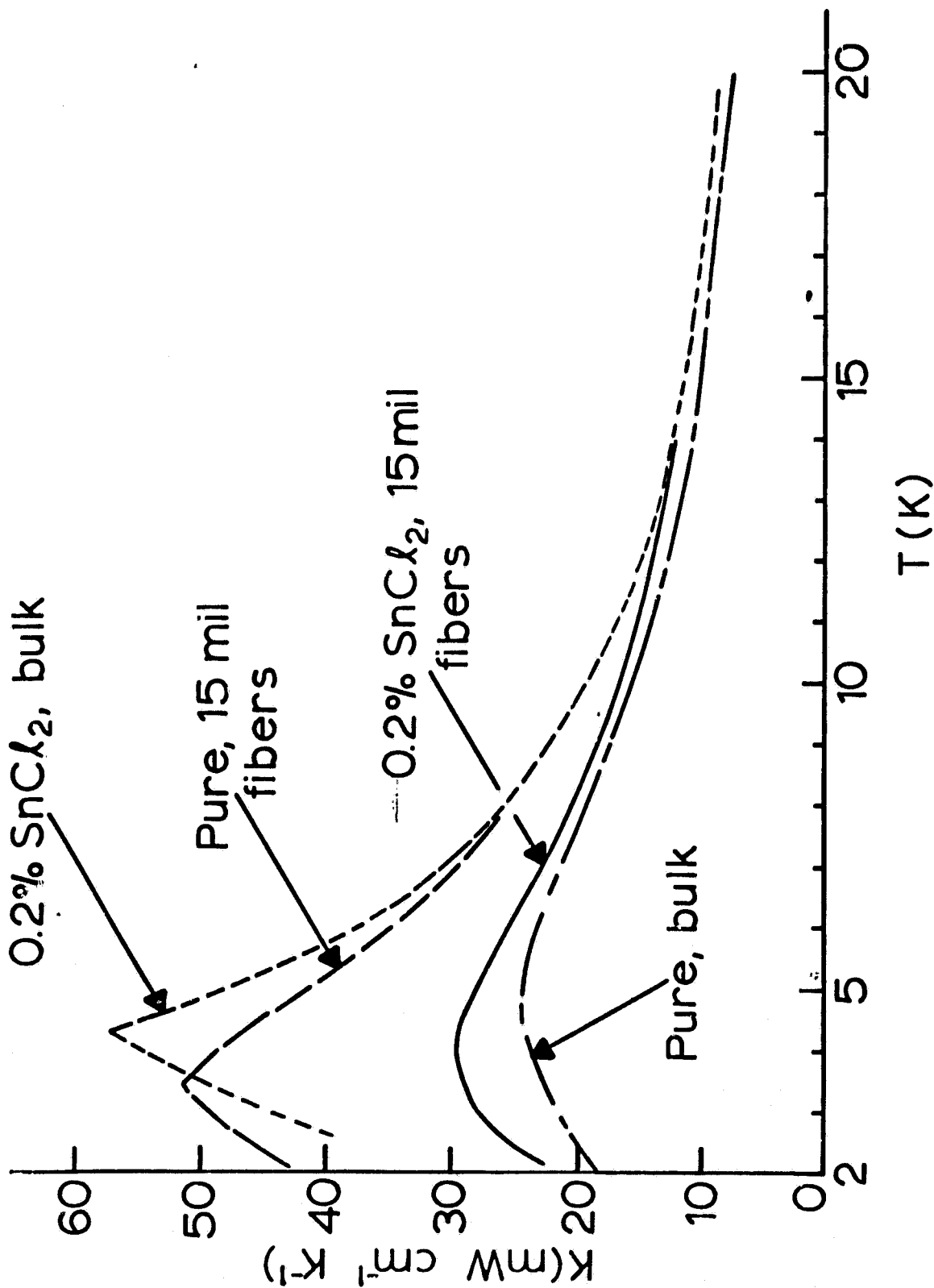


FIGURE 34. Thermal conductivity of doped and undoped LS-8A in bulk and 15-mil-diam rod form.

VI. ANALYSES AND DISCUSSION

In the above sections, an exhaustive study of the performance of the Model 21 refrigerator has been presented with the regenerator filled with Pb spheres and with rods of SnCl_2 -doped LS-8A of diameters 0.008", 0.015", and 0.030" (Figures 2-27). In addition, the thermal properties of these rods were thoroughly measured (Figures 28-34). In this section we will attempt to analyze these data.

The first step in our analysis will be to develop a table of relevant operating and thermal properties. Two important parameters are the Reynold's Number and the thermal relaxation time:

1. Reynold's Number. The Reynold's Number is defined by:

$$PN = VD\rho/\mu \quad (1)$$

where V is velocity, D is the channel diameter, ρ is the density, and μ is the viscosity. For He gas at ≈ 10 atmos and $\approx 15\text{K}$, $\rho \approx 0.035 \text{ gm/cm}^3$ and $\mu \approx 35$ micropoise. For the velocity at the optimum 3.3 Hz speed, the gas travels through the regenerator in ≈ 0.15 sec, and since the regenerator is 6.6 cm long, $V \approx 43 \text{ cm/sec}$. Finally, the ratio of channel diameter to rod diameter is ²

$$(\sqrt{3}/\pi - \frac{1}{2})^{\frac{1}{2}} = 0.23 \quad (2)$$

The Reynold's Numbers for the three size rods are listed in Table I. The Reynold's Number analysis is valid only if the mean free path of the He atoms is small compared to the channel diameter. The mean free path is given by

$$\ell = (nd^2\pi\sqrt{2})^{-1}$$

where n is the density of He atoms and d is the atomic diameter. From ρ above, $n \approx 5.3 \times 10^{21} \text{ cm}^{-3}$ and $d \approx 10^{-8} \text{ cm}$. Consequently, $\ell \approx 4 \times 10^{-7} \text{ cm}$, which is orders of magnitude smaller than the channel size.

2. Thermal Relaxation Time. A sphere of radius r equilibrates (i.e., $\approx 98\%$) in a characteristic time

$$\tau = 4r^2/\pi^2 k \quad (3)$$

where k is the thermal diffusivity, $k = K/C$, K and C being the thermal conductivity and gravimetric specific heat, respectively. For estimating τ from Eq. (3), we have taken the no-load, minimum temperature of the second stage under optimal conditions for each case and used K and C at that temperature. Equation (3) has been applied to the cylindrical rods also as the numerical factors for rods and spheres are about the same. These relaxation times are listed in Table I. The K and C data are taken from the literature where K for bulk Pb was used.^{3,5}

Also listed in Table I are the minimum, no-load second-stage temperatures, the second-stage temperatures at 1 W load, the filling factors, the approximate channel sizes, and the surface area ratio (ratio of surface area of rods or spheres to the container volume).

As we've seen above, the refrigerator performance progressively degrades in going from Pb spheres to 0.008" rods to 0.015" rods to 0.030" rods, and from Table I the relaxation times τ show a corresponding trend. However, except for the 0.030" rods these τ -values are much smaller than the "blow time" at 3.3 Hz, 150 msec, so it appears unreasonable to ascribe the refrigerator performance entirely to the variation in relaxation times. Moreover, the variation of the second-stage temperature with speed for the 0.030" rods should show an improvement at slower speeds if the relaxation time were troublesome, yet from Figure 16 the temperature variation with speed is practically the same as for Pb spheres (except for a scale factor) and is essentially flat from 2-5 Hz.

The Reynold's Numbers in Table I indicate that except for the 0.030" rods the flow in the regenerator is essentially laminar. One would expect

Table 1
Operating Parameters for (a)
Sphere and Rod Regenerators

Parameter	Pb Spheres (b)	Rod Diameters (c)		
		.008"	.015"	.030"
Minimum No-load Temp.	7.4K	12.5K	14.8K	19.0K
1-W Load Temp.	10.9K	16.6K	19.6K	23.5K
Reynold's Number	-	401	750	1500
Channel Size	~0.007"	~0.002"	~0.003"	~0.007"
Thermal Equil., τ (d)	0.010ms	0.74ms	4.5ms	38ms
Surface-Area Ratio	272	454	241	121
Filling Factor, f	61.7%	82.4%	78.2%	80.5%

- (a) At optimum conditions (3.3 Hz and 190 psid).
- (b) 0.015" diam, Sb-doped.
- (c) Full length, no copper screen spacers.
- (d) Estimated at the minimum, no-load temp.

that as the flow becomes more turbulent, the thermal impedance due to boundary layers would be reduced and the refrigerator performance would be improved. Since at speeds above about 4.4 Hz the flow through the 0.030" rod regenerator should be turbulent ($Re > 2000$), one would expect by this argument that the refrigerator performance would improve dramatically at higher speeds for these rods, but such is not the case (Figure 16). Moreover, the performance of the refrigerator with a copper screen between "half-length" 0.030" rods was not improved compared to "full-length" rods, Figure 20.

On the other hand, with the 0.015" diam rods there was a progressive improvement in the refrigerator performance in going from full-length to half-length to quarter-length rods, Figure 15, and certainly the dominant effect of the separating fine copper screens was to act as turbulizers.

Another feature evident from Table I is the increasing channel size for increasing rod diameter. The concern here is that the larger the channel size, the more inefficient will be the heat transfer between the He gas and the regenerator matrix since the He atoms have further to diffuse. Yet, on strictly geometric considerations, the effective channel size for the 0.030" rods is equivalent to that for the Pb spheres (bcc packing).

The surface-area ratios in Table I show that the 0.030" diam rods have a surface area less than half that of the Pb spheres, and this is probably the most compromising problem with these diameter rods. The surface area of the 0.015" diam rods is equivalent to that of the Pb spheres, and for the 0.008" diam rods the surface area is almost double that of the Pb spheres.

We are, of course, dealing with complex phenomena in the regenerator matrix wherein all the above parameters play an interactive role. The gas flow through the Pb spheres is certainly very turbulent, and this turbulence may overcome the effect of the large channel size, whereas the same cannot be said for the rod regenerators. The heat transfer coefficient between the He gas and the matrix material is certainly a critical parameter which

we can only speculate on in the case of the rods. It has been demonstrated that a metallic coating on the rods actually degrades the refrigerator performance, Figure 20. One suspects, however, that if the heat transfer coefficient for the rods were seriously inferior to that for the Pb spheres, the performance of the refrigerator with the rods would not be so similar to the performance with the Pb spheres (e.g., optimum operating conditions, identical power-temperature slopes).

Turning next to the measured thermal properties of the rods, the thermal conductivity data of Figure 32 show that there is little difference between the thermal conductivities of the various rod diameters above about 10K (note that all second-stage temperatures were >10K for the rod regenerators).

The specific heat data, however, show significant differences between the various rod diameters. These data are collected in Figure 35 (note the volumetric basis), where the packing factors, f , from Table I have been taken into account. The Figure 35 data are limited to temperatures 15-31K for three reasons: (1) The second-stage temperatures achieved with the rod regenerators are generally >15K; (2) The volumetric specific heats of all these rod materials are equal to, or greater than, that of Pb spheres below about 15K; and (3) We intuitively suspected that specific heats were being "lost" at the higher temperatures in the regenerator. Also shown in Figure 35 are the measured data for 0.015" diam Pb spheres³ using the Pb-sphere packing factor in Table I.

The Figure 35 data show unmistakably that the specific heat for the doped LS8A rods falls considerably below that of the Pb spheres in the higher temperature range of the regenerator. The C/T^3 plot somewhat masks how significant this reduction is. For example, at 25K, the Pb-spheres specific heat is about 33% higher than the 0.030"-rod specific heat. Significantly, the specific heat data for the (doped) 0.008" rods in Figure 35 is larger than for the 0.015" and 0.030" rods, and the specific heat of undoped 0.015" rods is larger than, or equivalent to, that of the Pb spheres on the 15-30K temperature range. We shall return to these findings below.

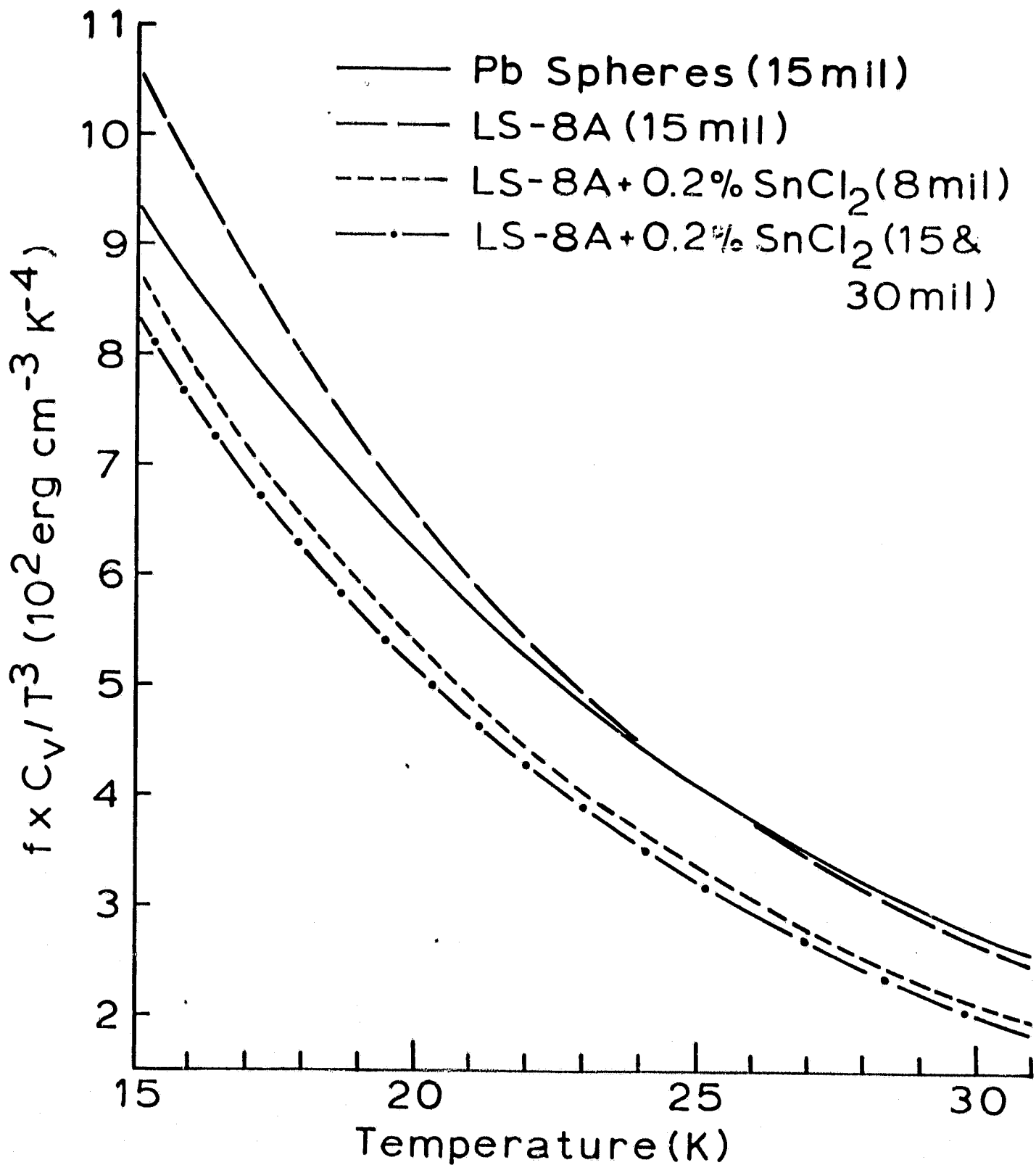


FIGURE 35. Comparison volumetric specific heats of the LS-8A rod materials and Pb spheres

The He gas flowing through the regenerator exchanges heat with the matrix material over a range of temperatures throughout the regenerator, and so the specific heat at any one temperature is not as important as the integral of the specific heat -- that is, the enthalpy. The specific heat data in Figure 35 were numerically integrated to yield the enthalpy relative to 15K, and these enthalpy data are shown in Figure 36.

The Figure 36 data show that with the doped rods of LS-8A there is a considerable "loss" of enthalpy in the regenerator, 15-31K, compared to the case of Pb spheres. Also, this enthalpy loss is more serious for the 0.015" and 0.030" rods than for the 0.008" rods of doped LS-8A. Interestingly, the undoped rods have an enthalpy relative to 15K that is everywhere larger than that for Pb spheres.

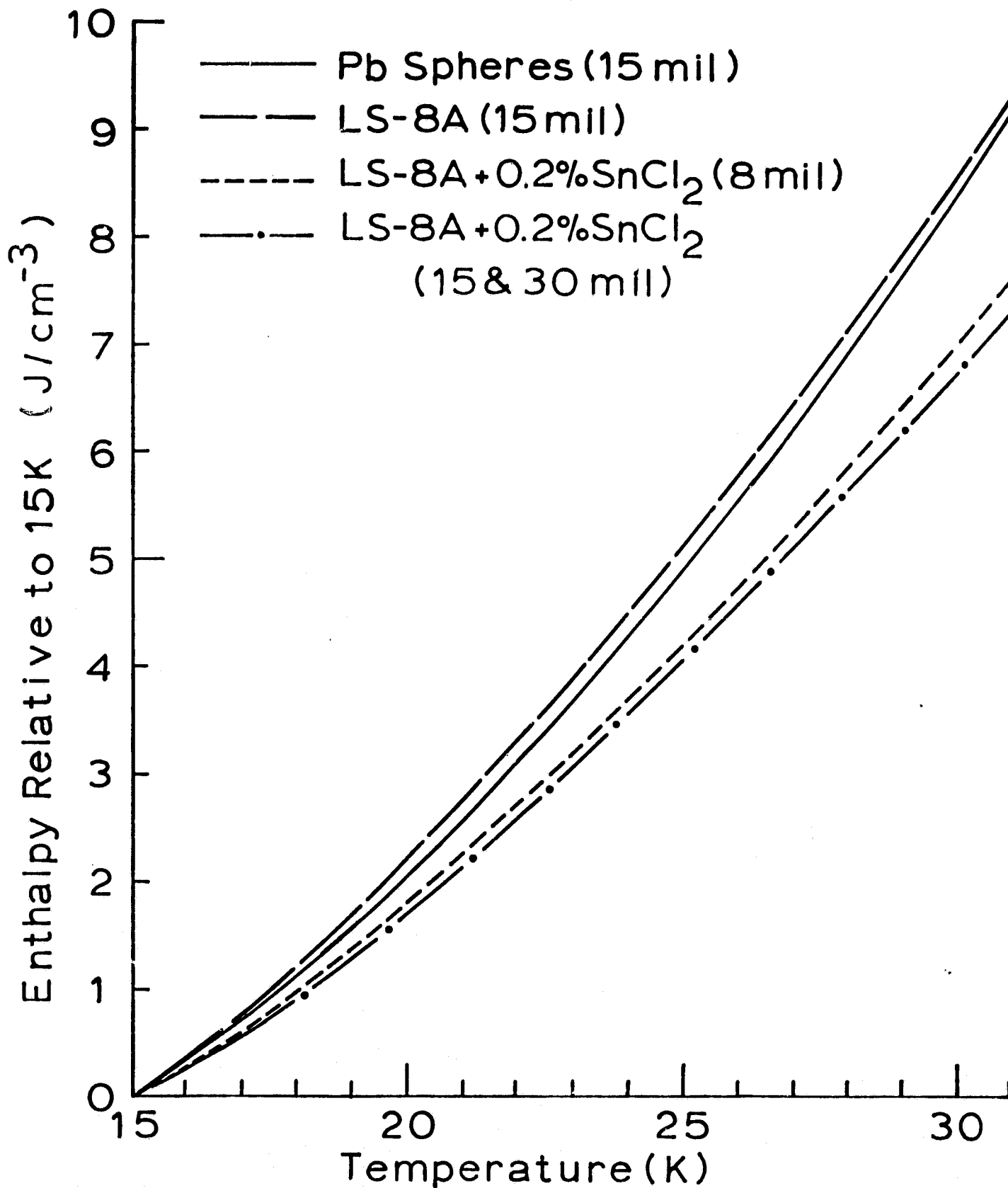


FIGURE 36. Comparison enthalpy data calculated from the specific heat data in Figure 35.

VII. CONCLUSIONS AND RECOMMENDATIONS

The data presented above point to the following conclusions regarding the performance of the Model 21 refrigerator with the rods of 0.2%-SnCl₂-doped LS-8A in the refrigerator:

1. The chronic pulverization/dusting problem associated with Pb spheres can apparently be solved by using rods of LS-8A.
2. The power-temperature load characteristics for the doped LS-8A rods are the same as for Pb spheres except for a shift up in temperature: +5K for 0.008" diam rods; +7.4K for 0.015" diam rods; and +11.6K for 0.030" diam rods.
3. The optimum operating conditions for the Pb spheres and for all the rod diameters are the same (3.3 Hz and 190 psid).
4. The primary reasons that the 0.008" diam doped rods perform better than the larger diameter rods are the increased specific heat and enthalpy compared to the other rods (Figures 35 and 36) at the upper end of the regenerator and the large surface area.
5. The primary reasons the 0.030" diam doped rods perform poorly compared to the smaller diameter rods are the combination of reduced specific heat, smaller surface area, and slower thermal relaxation time.
6. The insertion of fine copper screens with high thermal conductivities significantly improves the performance of the rod-regenerators due primarily to the turbulence caused by these screens in the He gas flow.

The findings here clearly suggest a study of the undoped 0.015" diam rods of LS-8A in the Model 21. The compelling reasons for this recommendation are:

1. The undoped rods have specific heats and enthalpies larger than, or equivalent to, that of Pb spheres over the range 2-31K.
2. The demonstrated absence of significant pulverization/dusting with the 0.008" diam doped rods will be true for the undoped 0.015" rods also.
3. The 0.015" diam rod geometry has a favorable thermal relaxation time, a surface area equivalent to 0.015" diam Pb spheres, and these rods are convenient to handle.

Acknowledgement

The authors are grateful to Dr. C. F. Clark for assistance in reducing the thermal properties data and to W. Pierce for assistance with the stepping motor for the Model 21.

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