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CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

715-24

PROGRESS REPORT NO. 33

FOR A PROGRAM OF

THERMOELECTRIC GENERATOR TESTING

AND

RTG DEGRADATION MECHANISMS EVALUATION

Submitted to

The US Department of Energy
Division of Advanced Nuclear Systems and Projects
Washington D.C.

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The Jet Propulsion Laboratory
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Pasadena, California

December 1979

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FOREWORD

This report is submitted to the Department of Energy covering work conducted under Interagency Agreement No. E(04-3)-959 by the Jet Propulsion Laboratory and documents all activities covering the period of October and November 1979 performed under the technical direction of Mr. Patrick O'Riordan Power Systems Section, Space and Terrestrial Systems Branch of the DOE Division of Advanced Nuclear Systems and Projects.

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SECTION I

SUMMARY

The n-type selenide legs after 10,600 hours continue to show agreement with the 3M Co. published data.

In the ingradient testing after 11,378 hours the n-legs show comparable performance to the reported 3M data. The new design p-type legs were placed on test.

The remaining MHW generator on test Q1-A has accumulated 19,567 hours and performance remains stable. Three 18 couple modules S/N-1, 2, and 3 previously tested at RCA were received for JPL test and evaluation. S/N-1 has 1,700 hours testing at JPL with results indistinguishable from those at the end of RCA testing in 1977.

The performances of LES 8/9 generators are following DEGRA predications after 31,824 hours.

The performance of the Voyager 1 and 2 RTGs is reported after 19,577 hours and 20,122 hours of operation, respectively.

SECTION II

SELENIDE TECHNOLOGY EVALUATION

A. THERMAL CONDUCTIVITY TESTS

The long-term testing of the n-type legs has been continued, using calorimeters similar to those used for the p-type legs (see reports #26, 5/78 and #27, 8/78 for experimental details). The legs operate over a temperature gradient of T_H = 800°C and a maximum T_C = 250°C and have accrued approximately 10,600 hours of operation. The thermal conductivity values for the four legs are shown in Figure 1 and normalized to the original value (K_0 = 20 hours) in Figure 2, as a function of operating time. The thermal conductivity values for three of the four legs has remained relatively stable; the thermal conductivity of #4 shows an upward trend of perhaps 3%/1,000 hr. These tests are continuing.

B. INGRADIENT TESTING

Ingradient testing of the three remaining n-type. Gd-Se legs (Nos. 1, 3, 4) was interrupted during August and September to prepare the station to receive additional test furnaces for the new p-type legs. The refurbished station was returned to service 10/10/79. The performance data for the n-type legs is updated in Figures 3 through 6; 11,378 hours of testing had accrued 12/5/79 (see pp 9, 14, Progress Report #27 for experimental details).

Four unsegmented p-type Cu_2Se legs of more recent design using Astroquartz silica fiber and Min-k slurry wrapping were placed on test 10/10/79 in the refurbished station. Figures 7 through 10 show the data to 12/5/79 with 1,147 hours test time. (See Progress Report #25 for experimental details.)

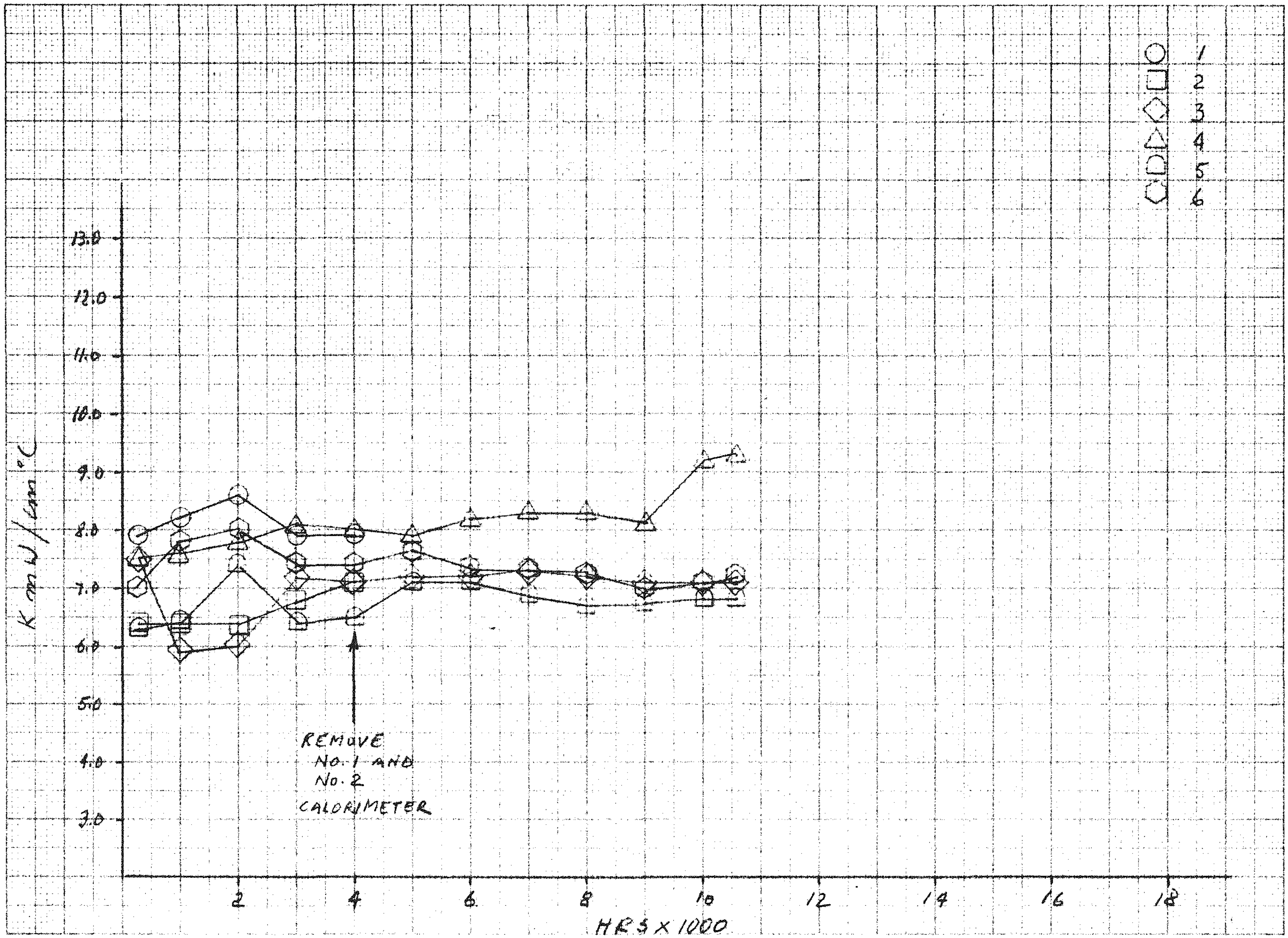

Figure 1. Thermal Conductivity Test N-Type

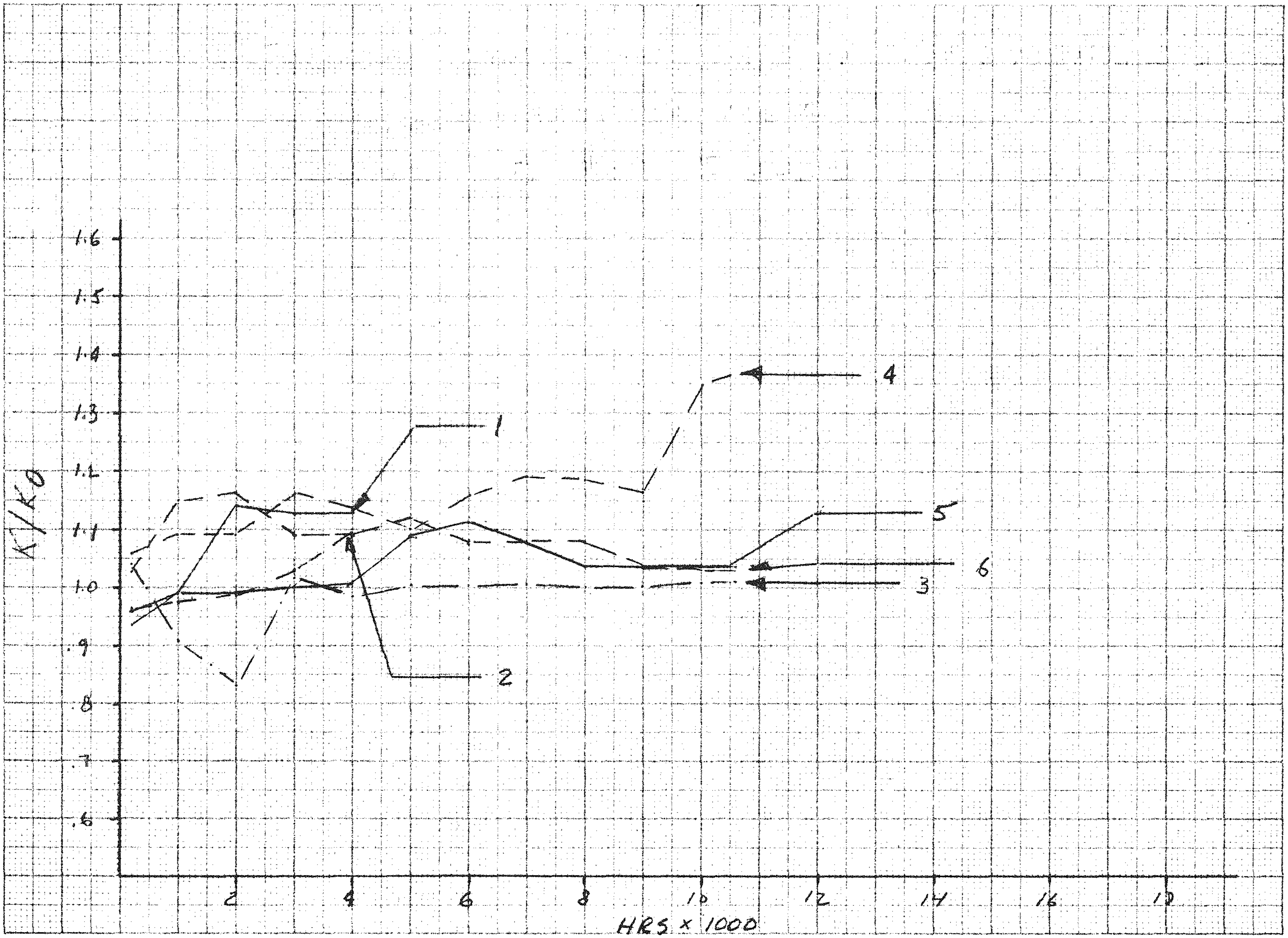

Figure 2. Thermal Conductivity Test N-Type, Normalized

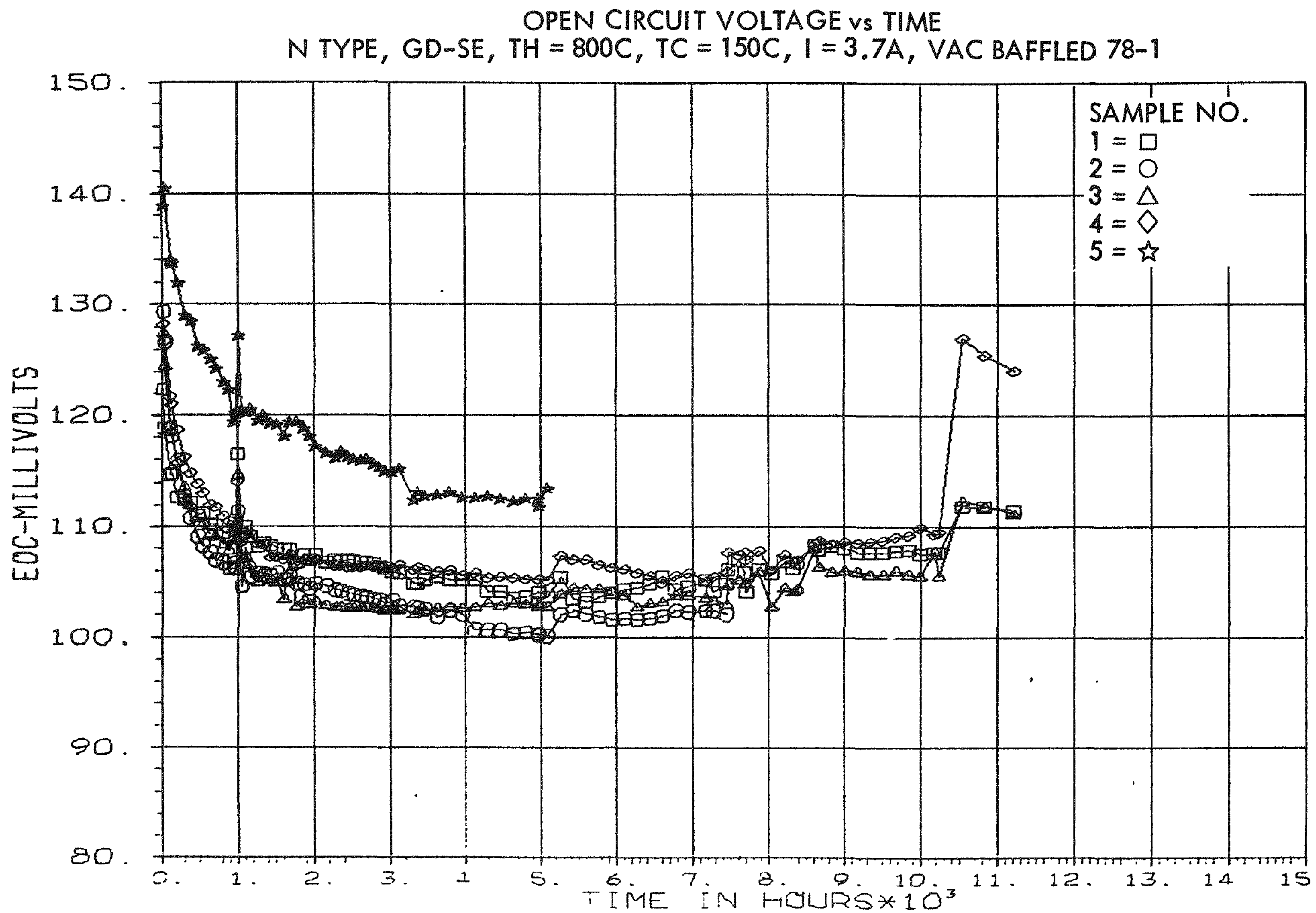

Figure 3. O/C Voltage vs Time N-Type, Gd-Se T_H=800C, T_C=150C, I=3.7A

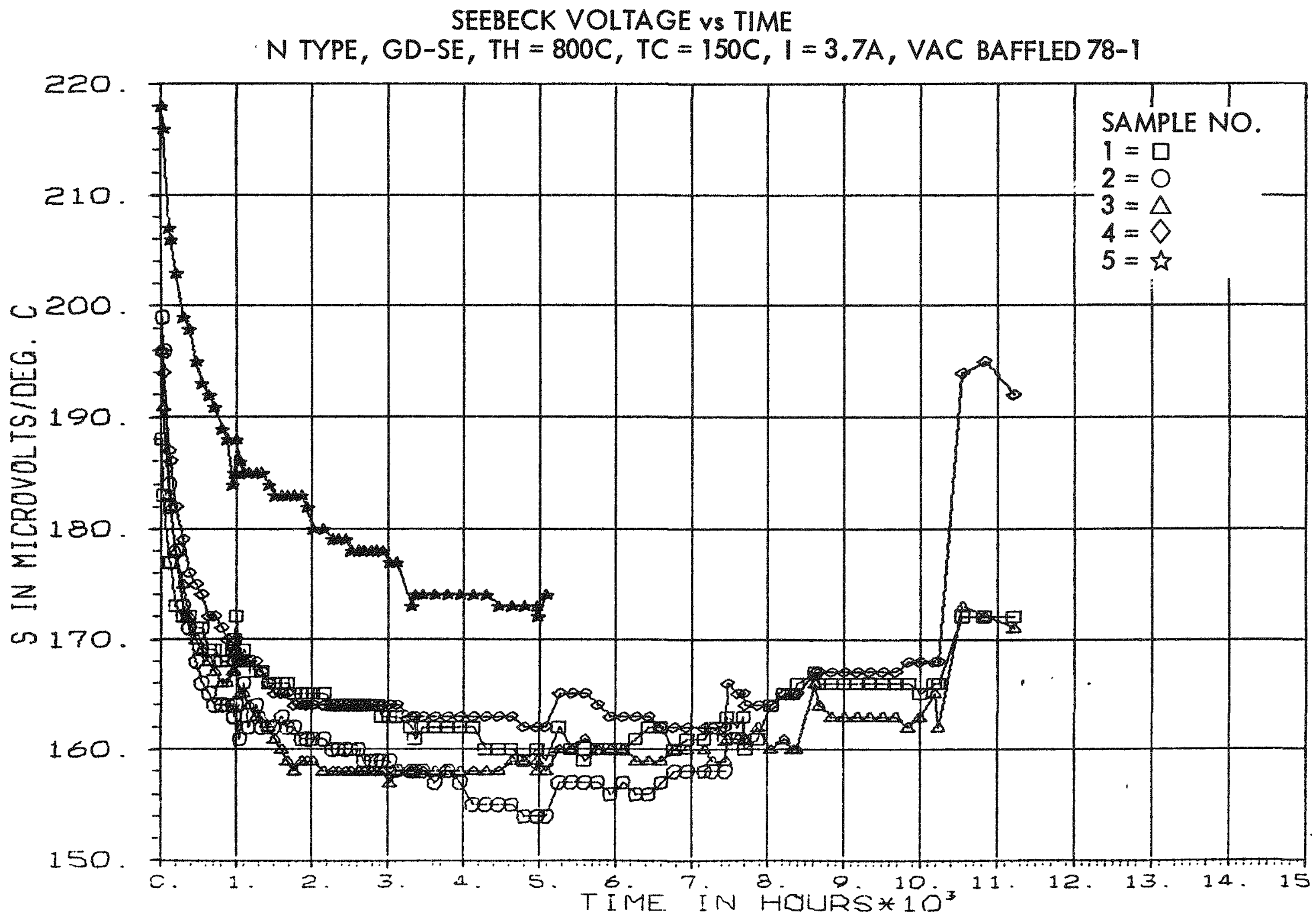

Figure 4. Seebeck Voltage vs Time N-Type, Gd-Se T_H=800C, T_C=150C, I=3.7A

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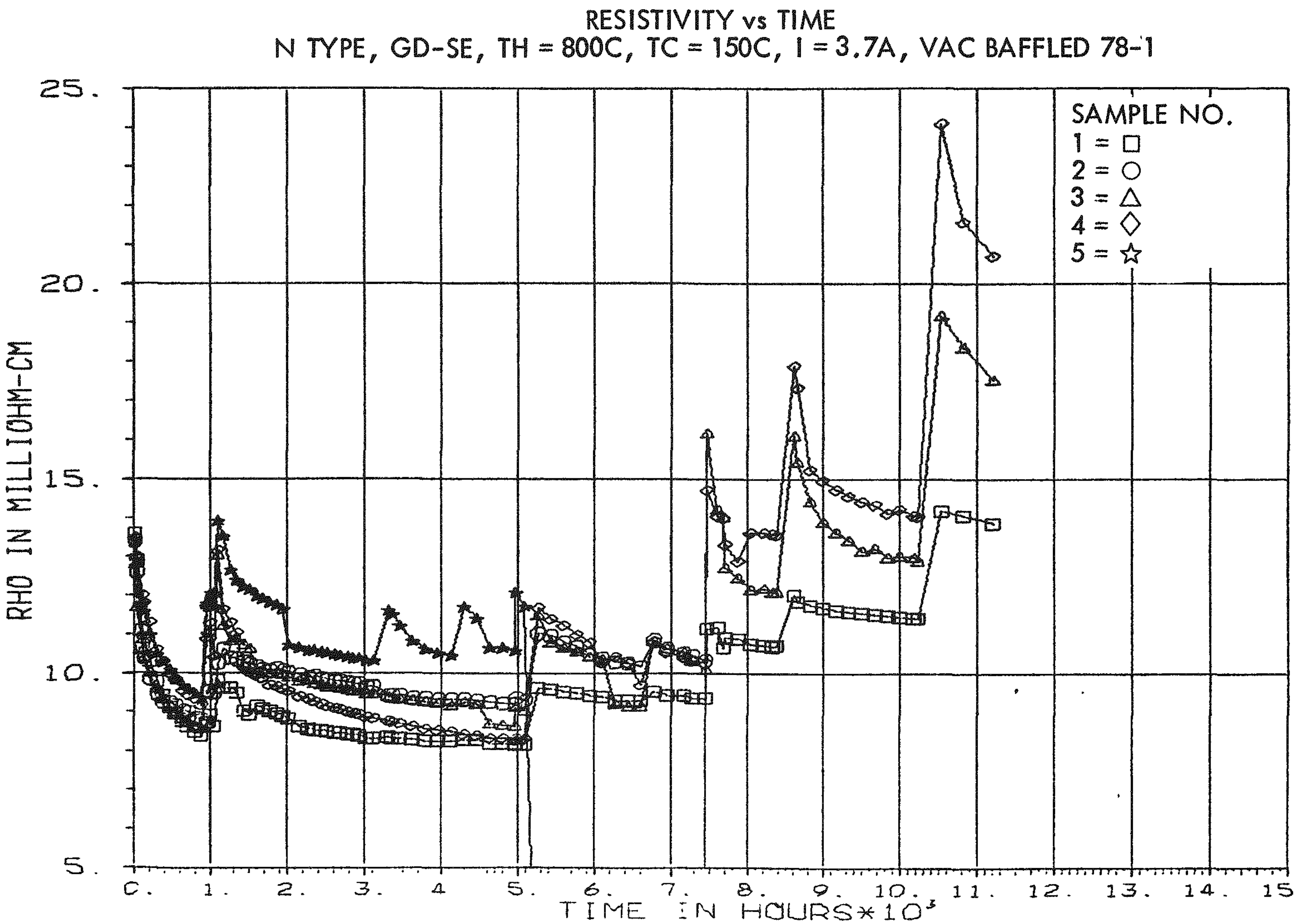

Figure 5. Resistivity vs Time N-Type, Gd-Se T_H=800C, T_C=150C, I=3.7A

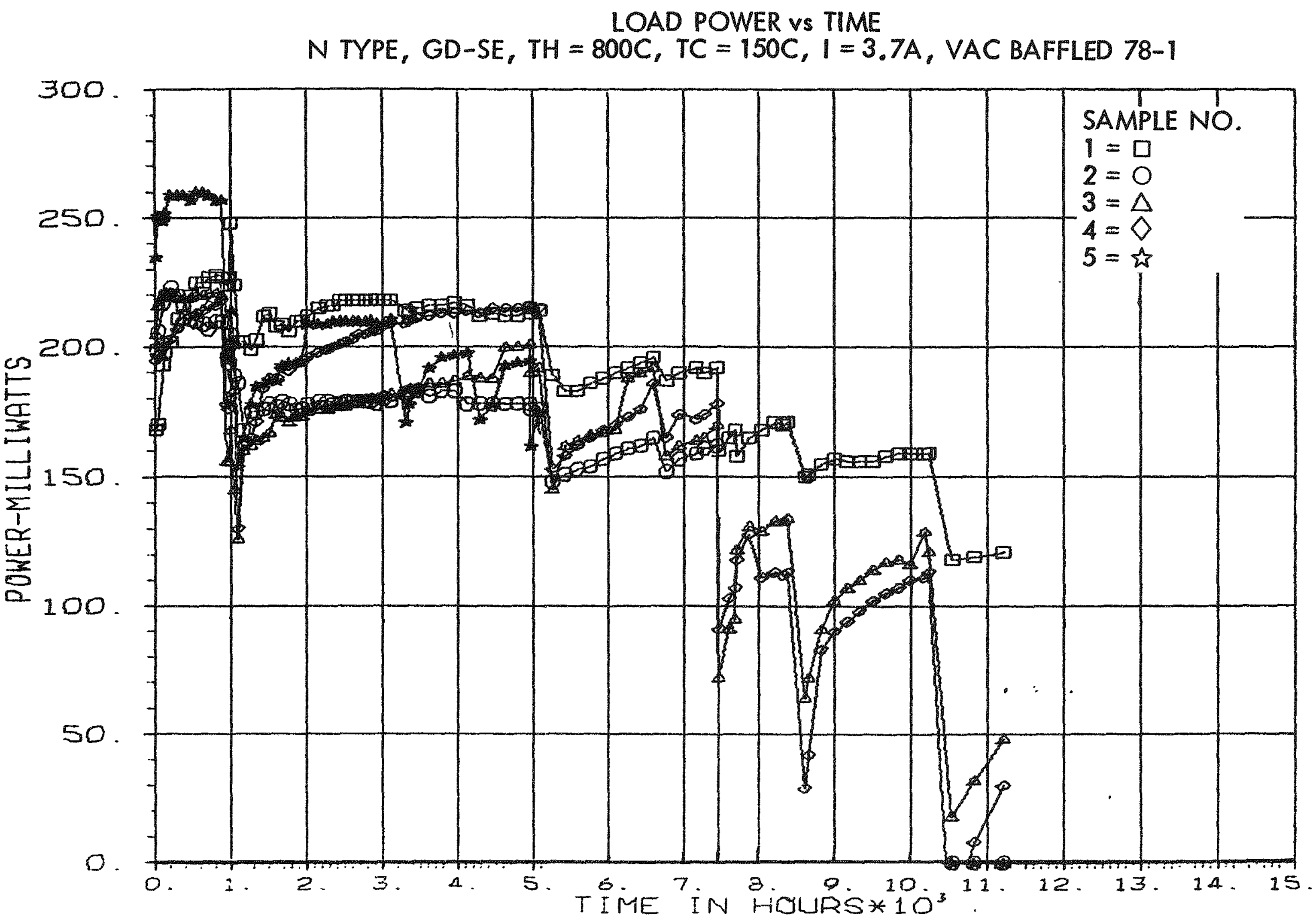

Figure 6. Load Power vs Time N-Type, Gd-Se T_H=800C, T_C=150C, I=3.7A

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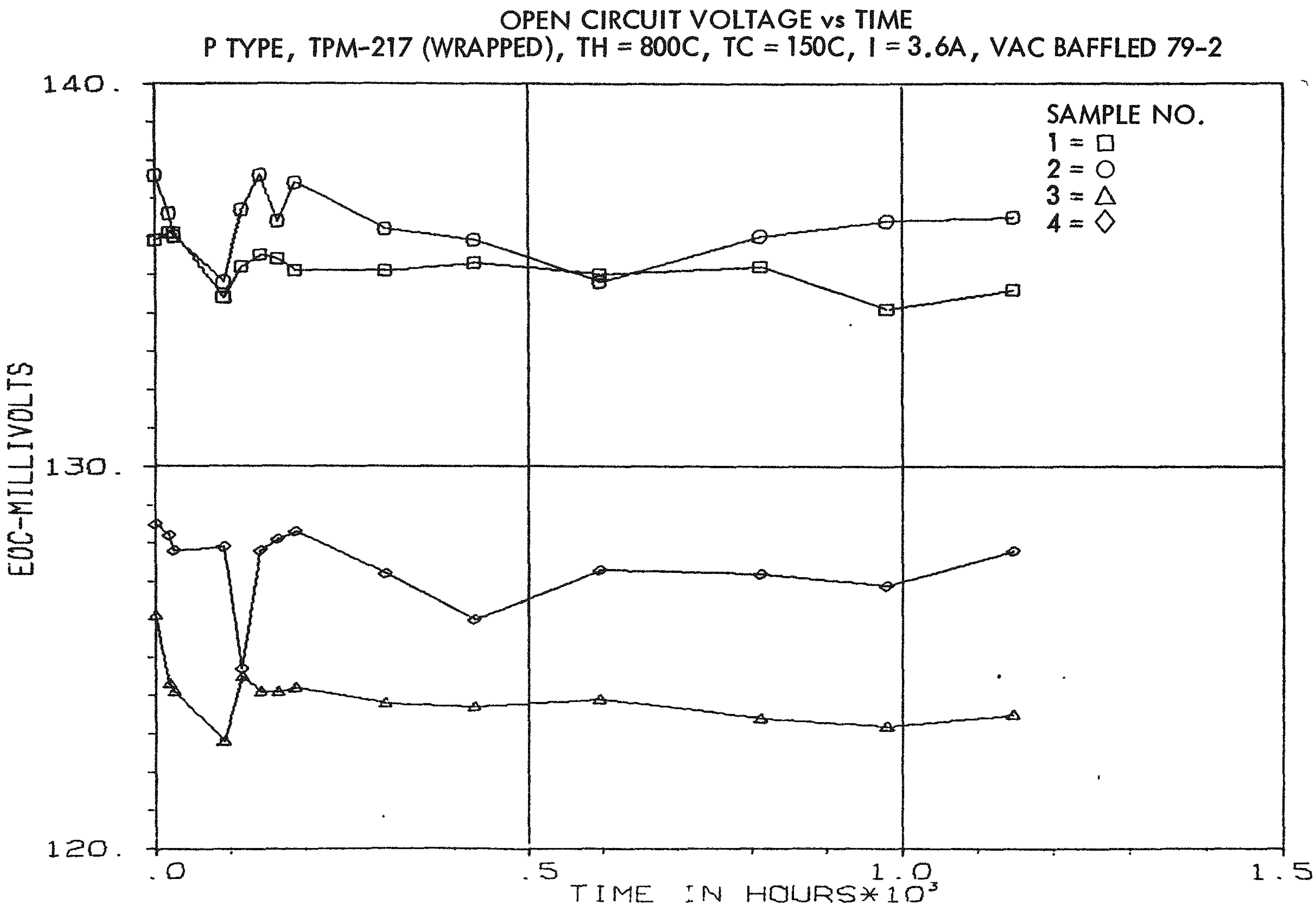

Figure 7. O/C Voltage vs Time P Type, TPM-217 (Wrapped) T_H=800C, T_C=150C, I=3.6A

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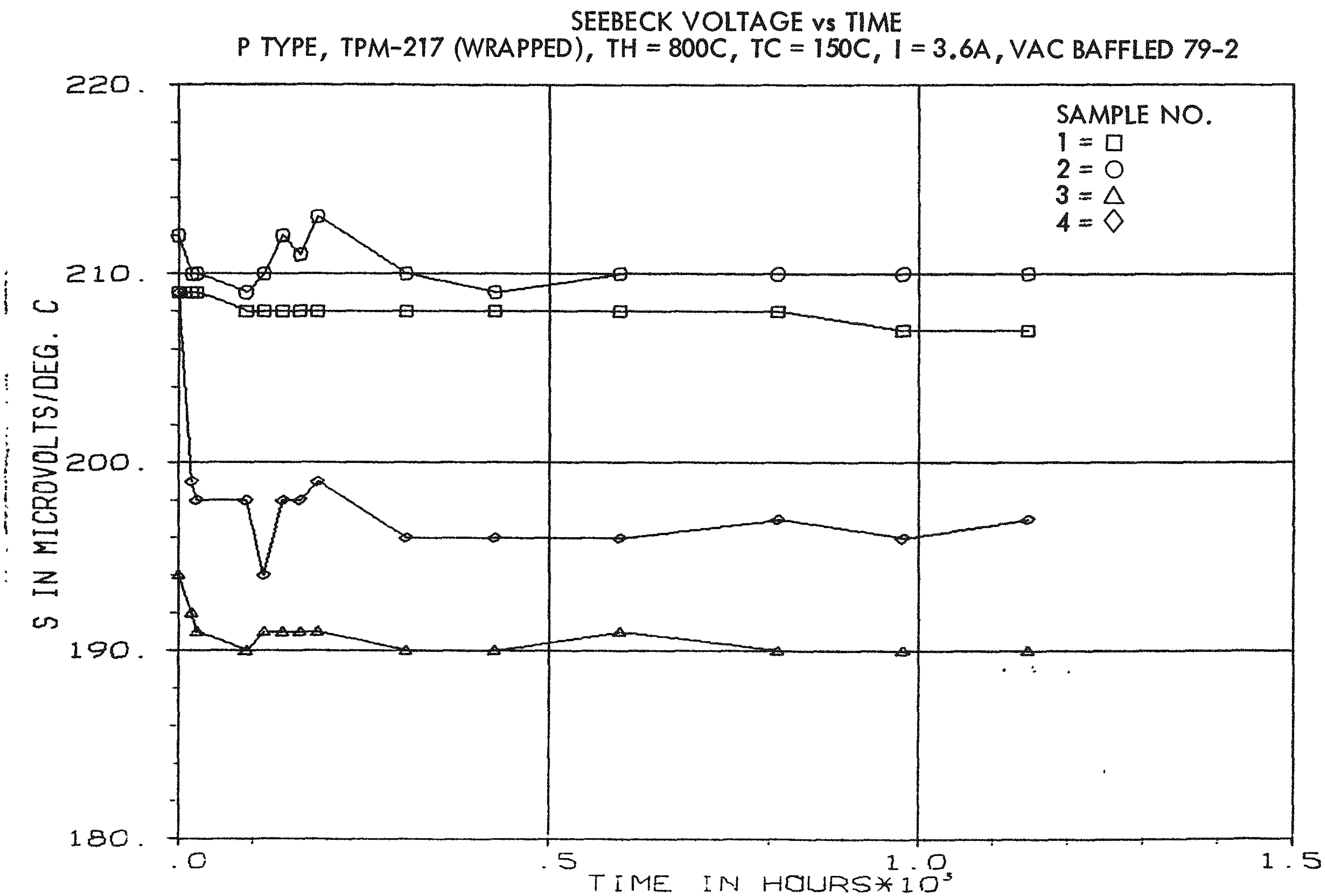

Figure 8. Seebeck Voltage vs Time P Type, TPM-217 (Wrapped) T_H=800C, T_C=150C, I=3.6A

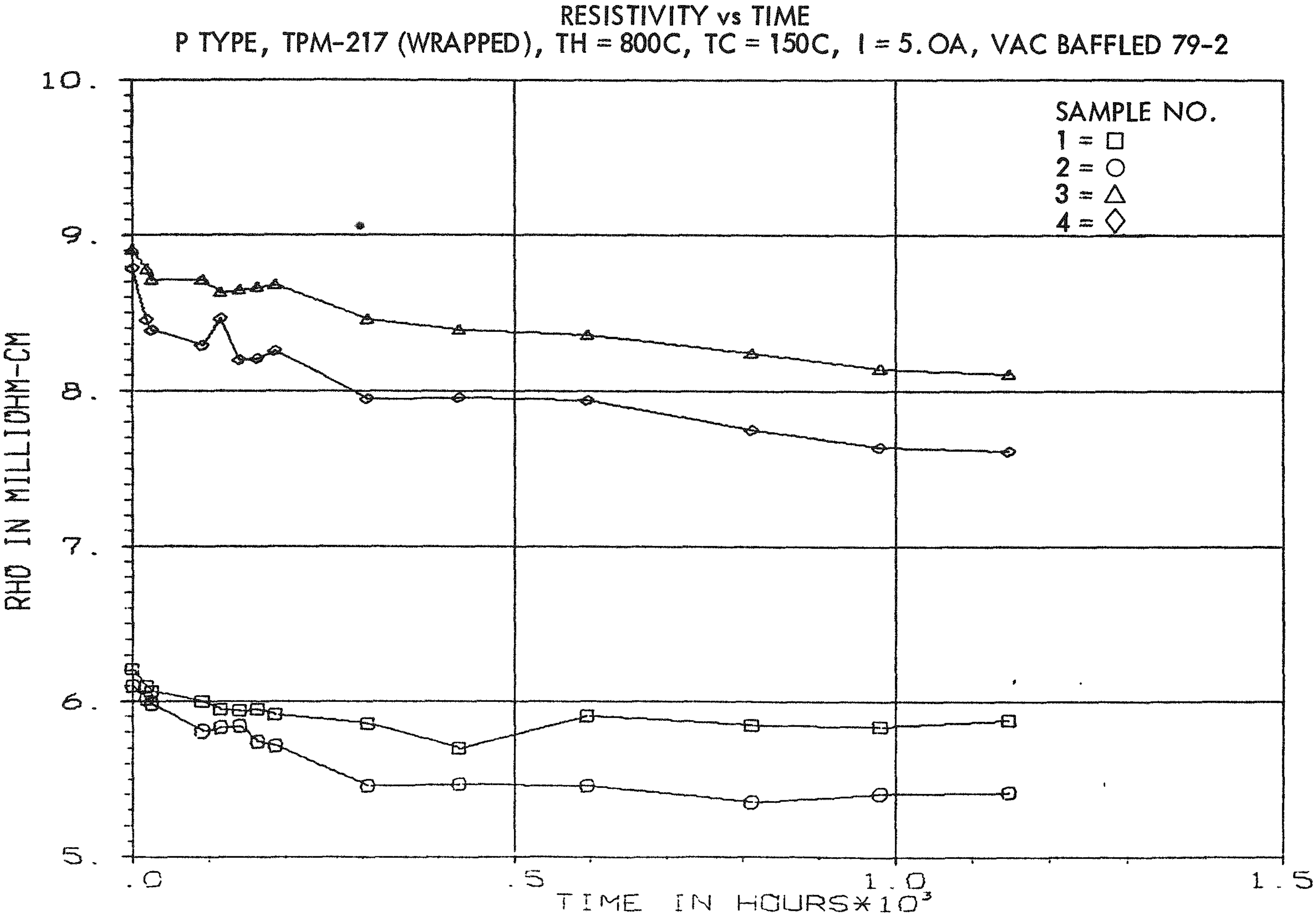

Figure 9. Resistance vs Time P Type, TPM-217 (Wrapped) T_H=800C, T_C=150C, I=3.6A

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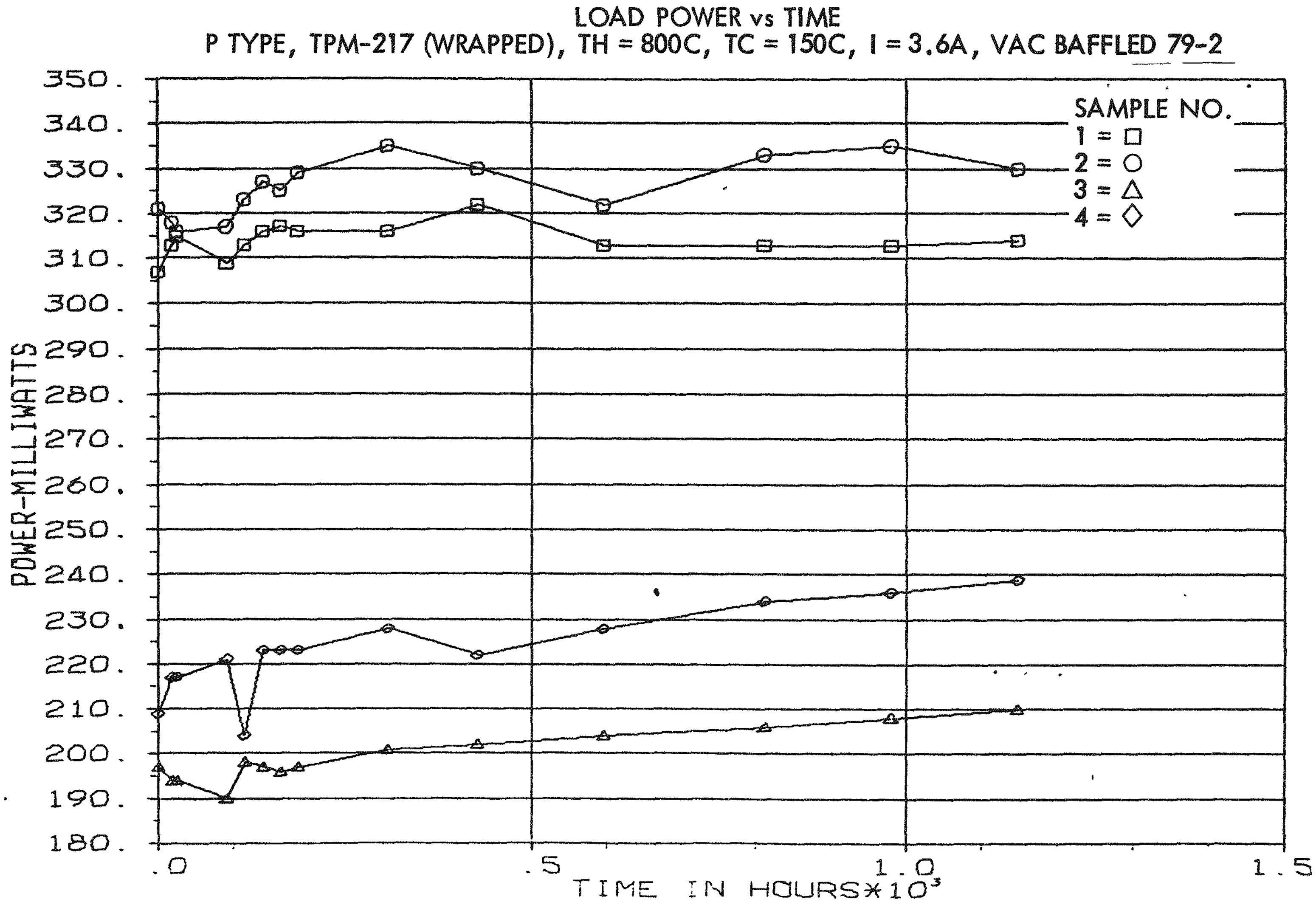

Figure 10. Load Power vs Time P Type, TPM-217 (Wrapped) T_H=800C, T_C=150C, I=3.6A

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C. THERMOPHYSICAL PROPERTIES AND COMPATIBILITY TESTS

This section includes isothermal weight loss measurements on six of the new-type wrapped p-legs with load current and temperature as variables. New isothermal experiments with n-type legs in oxygen and in CO atmospheres were started during this reporting period; weight loss results are reported over a temperature range of 800°C to 1050°C.

A number of p-type samples have been isothermally operated at different temperatures and current gradients. The measured weight losses from these samples is shown in Figure 11. To determine the sublimation baffling effectiveness which the wrapping of these samples afforded, the measured weight loss rate is compared with the unwrapped weight loss rate in Figure 12. This comparison indicates that the wrap which was used effectively reduced the weight loss by a factor of ~1000. Throughout the test sequence it was noticed that some of the samples would lose contact with the electrodes. This was particularly the case for samples which exhibited the higher weight losses. Initially, the samples were contacted with 150 lbs/square inch spring pressure. This was subsequently increased to 300 lbs/square inch, which seemed to prevent the loss of contact. Figures 13 - 18 show the six samples of the time of the latest weight measurement. All of the stepped caps became unbonded (this occurred after the first weight loss measurement (~24 hrs of operation). In addition, sample No. 5 (900°C at $i\ell/A$ = 11.0 Amp/cm) lost its wrap partially and testing of this sample had to be discontinued. The remaining samples are continuing on test. From the data obtained thus far, it would appear that a substantial reduction of weight loss is being achieved by the 3M wrapping technique. The data also suggest however, that the losses which do occur are primarily

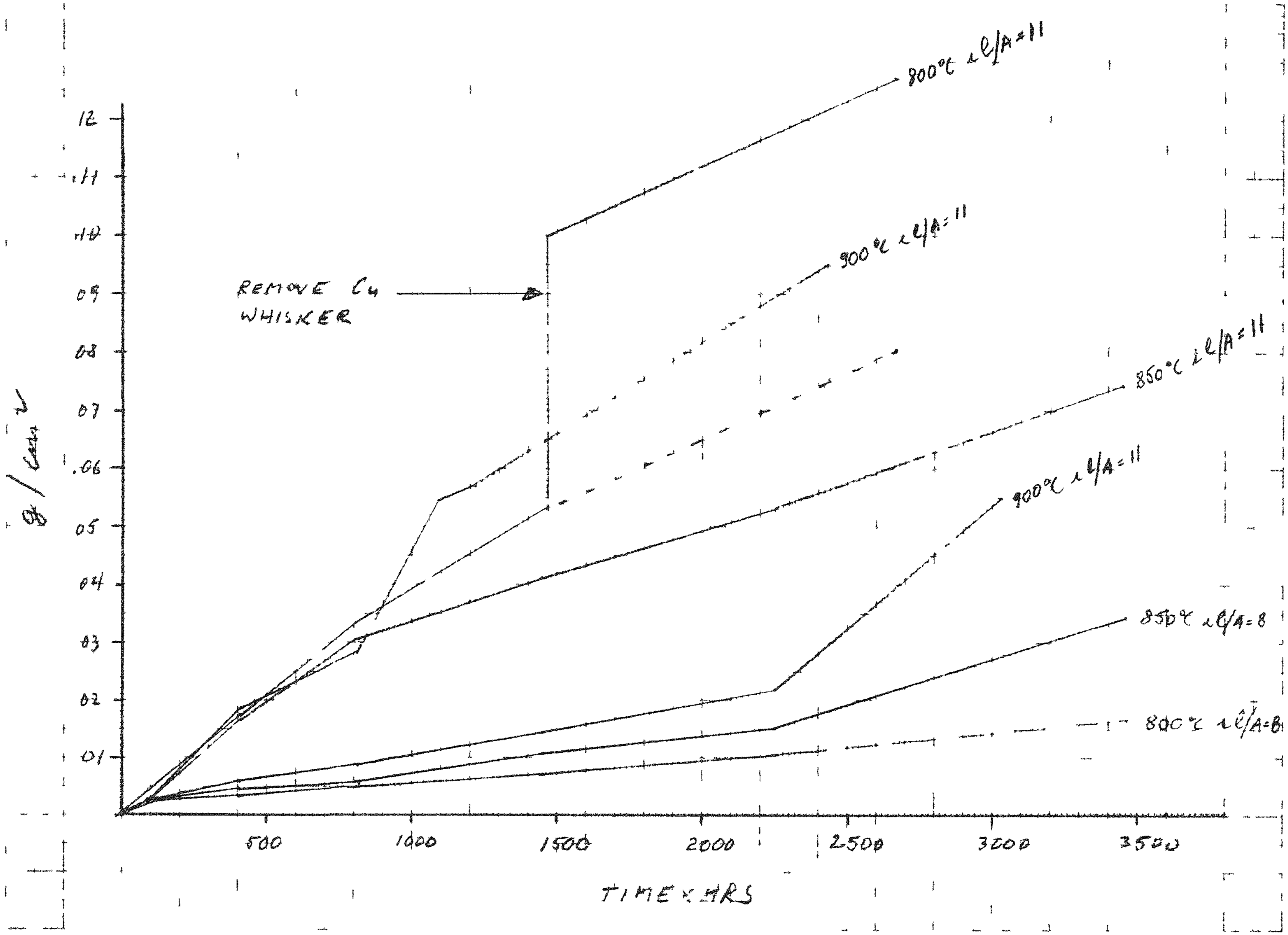

Figure 11. Isothermal Sublimation with Current, P-Type Legs

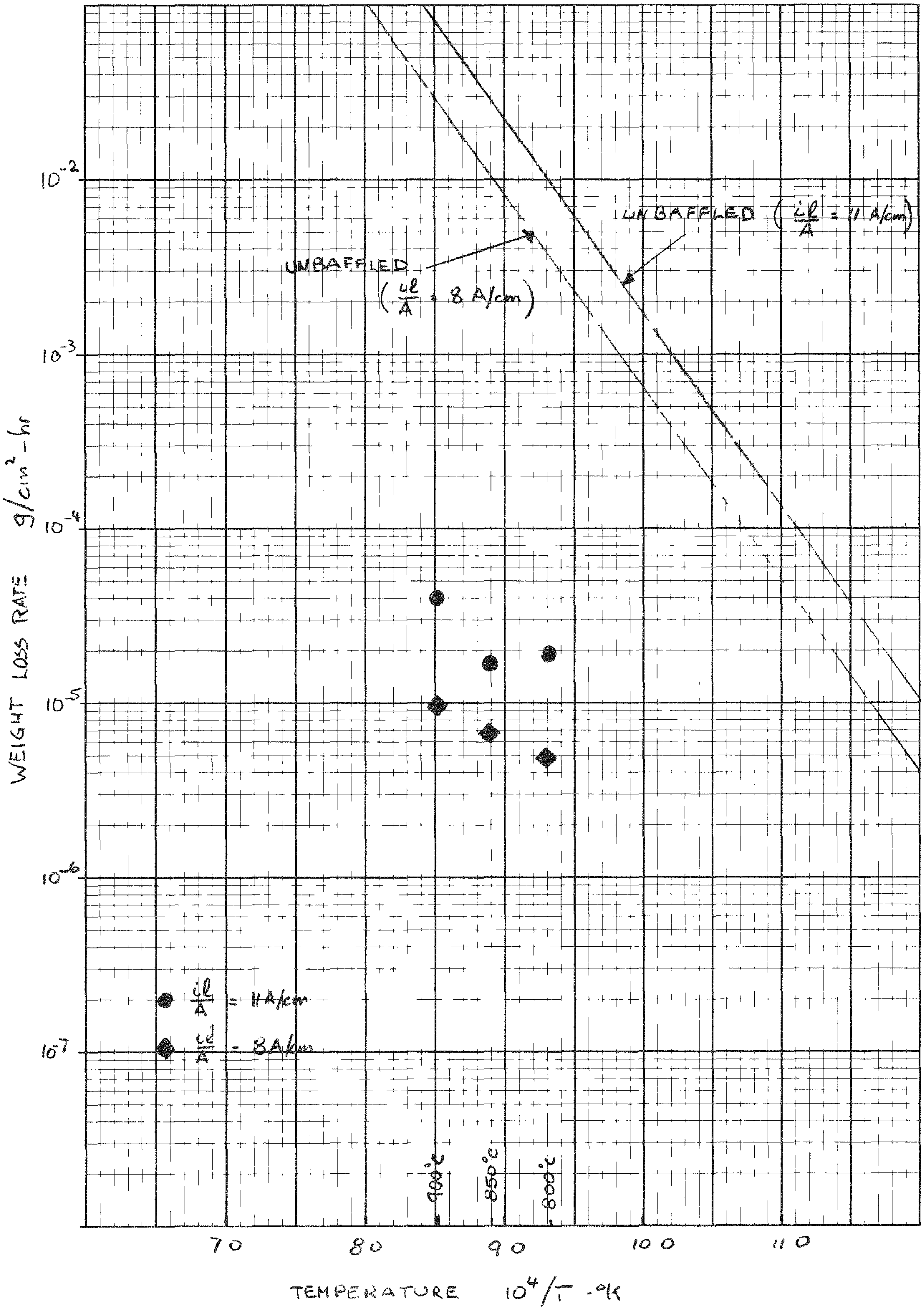

Figure 12. Weight Loss Rate for Wrapped P-Type Legs Compared With Unbaffled Rate

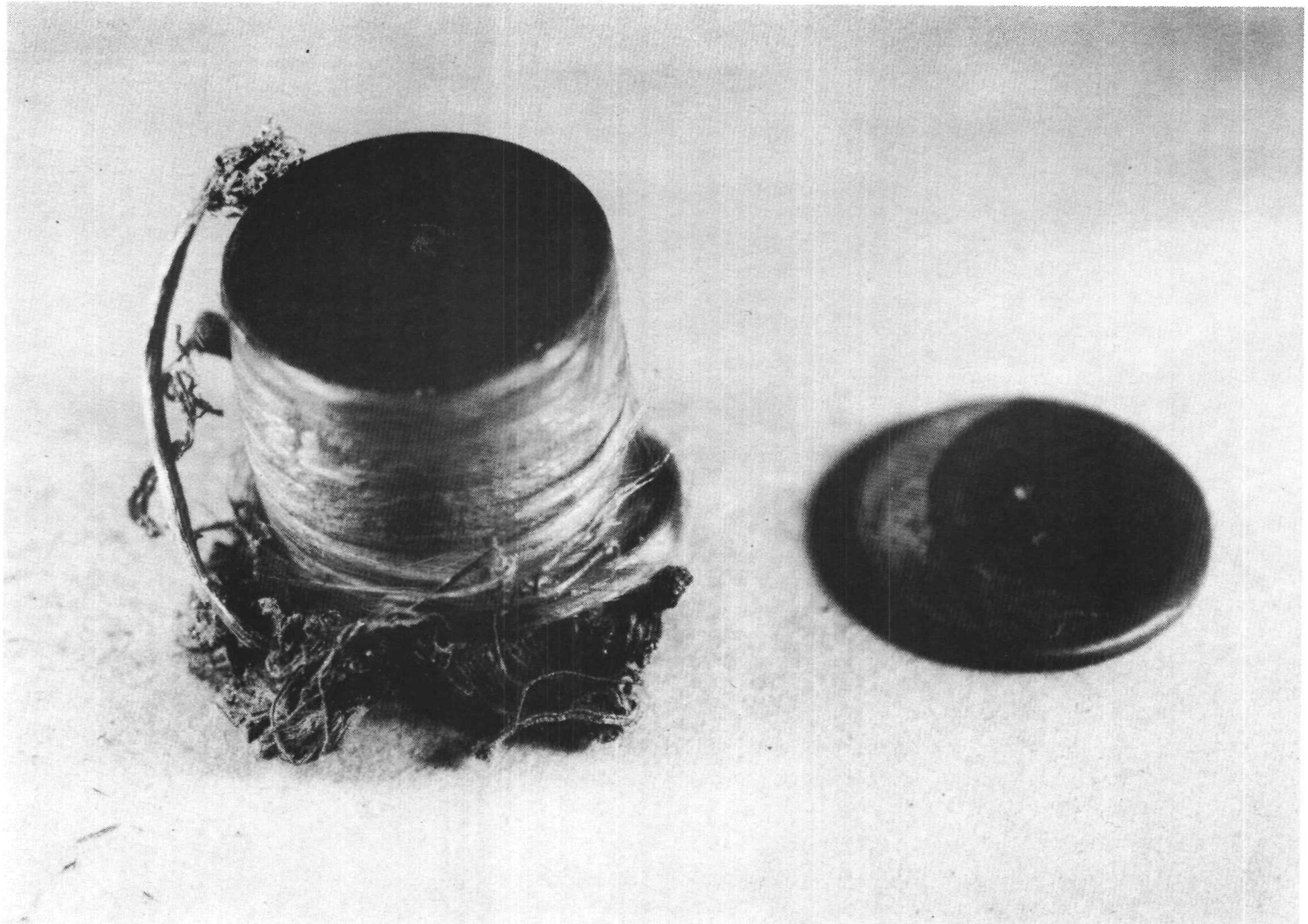

Figure 13. Isothermal Weight Loss Leg No. 1 800°C il/A=11

Figure 14. Isothermal Weight Loss Leg No. 2 800°C il/A=8

Figure 15. Isothermal Weight Loss Leg No. 3 850°C il/A=11

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Figure 16. Isothermal Weight Loss Leg No. 4 850°C il/A=8

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Figure 17. Isothermal Weight Loss Leg No. 5 900°C il/A=11

Figure 18. Isothermal Weight Loss Leg No. 6 900°C il/A=8

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from the top interface surface (the stepped cap to leg contacting area). This may result in an increased electrical resistance across this interface with potential open circuit failure. Increasing the contacting pressure may obviate this problem. However, the wrap, particularly as it becomes saturated with sublimed material, might negate the beneficial effect of the increased pressure. A remaining area of concern will be the longivity of the wrap itself. Further testing and analysis will be required to ascertain the viability of the sublimation suppression scheme for long term operation.

Compatibility tests on n-type GdSe legs with oxygen at 2×10^{-5} Torr were started earlier at 800, 850, and 900°C. Three new tests at 950, 1000, and 1050°C were started. Plots of the results over the first few hundred hours are shown in Figure 19. The loss rate curve observed in vacuum at 1000°C is drawn in for comparison. The early results indicate a large effect for O_2 at 2×10^{-5} Torr pressure level.

A second set of 6 n-type GdSe legs are under isothermal test in a CO atmosphere at 2×10^{-5} Torr, with a legs at 50°C temperature intervals from 800 to 1050°C. The results shown in Figure 20 tend to indicate that there is little or no interaction between GdSe and CO in this temperature range. The line in the figure showing the loss rate in vacuum is reasonably close to the values so far measured in CO atmosphere.

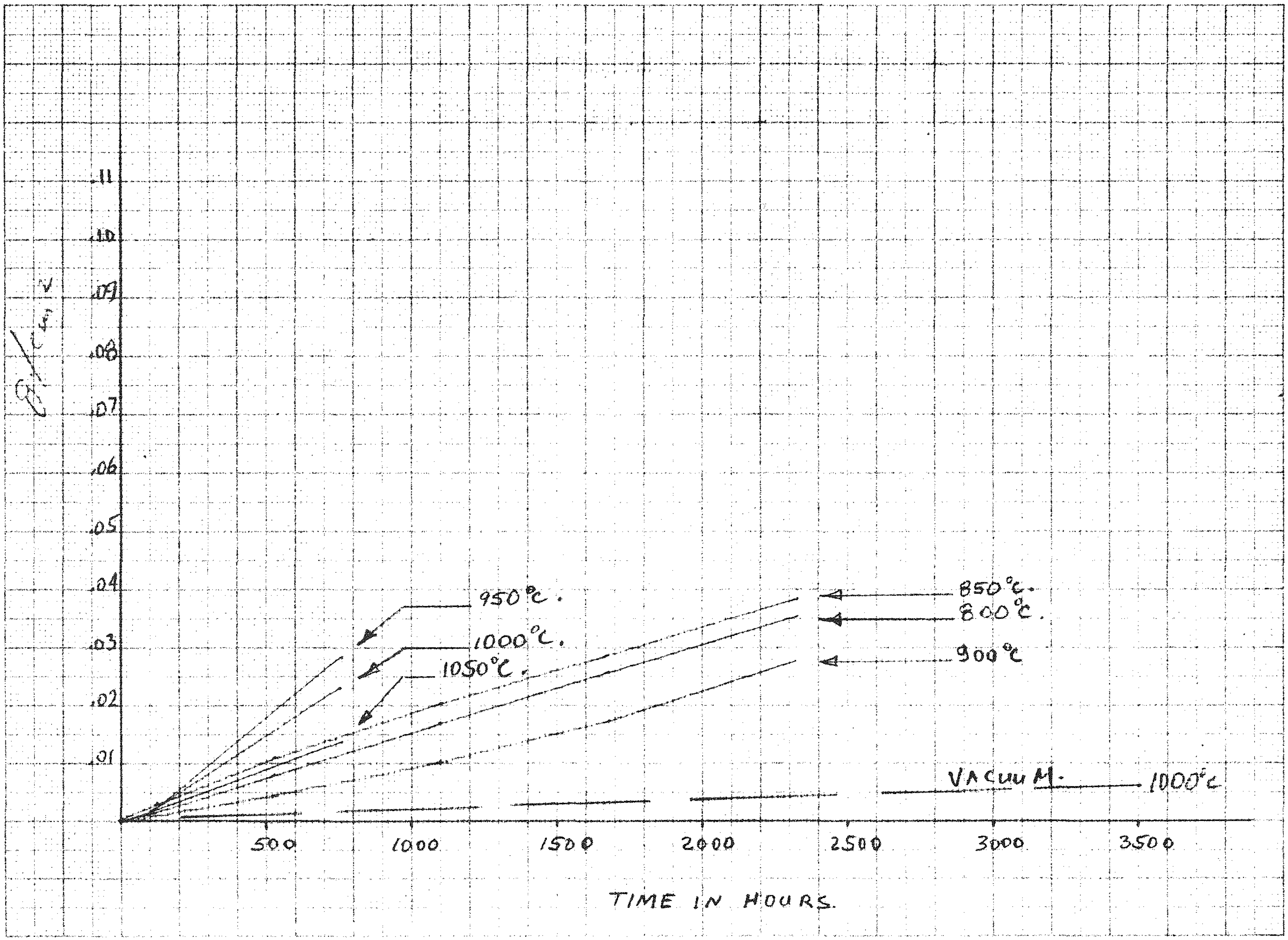

Figure 19. Isothermal Weight Loss N-Type O_2 Environment, 10^{-5} Torr.

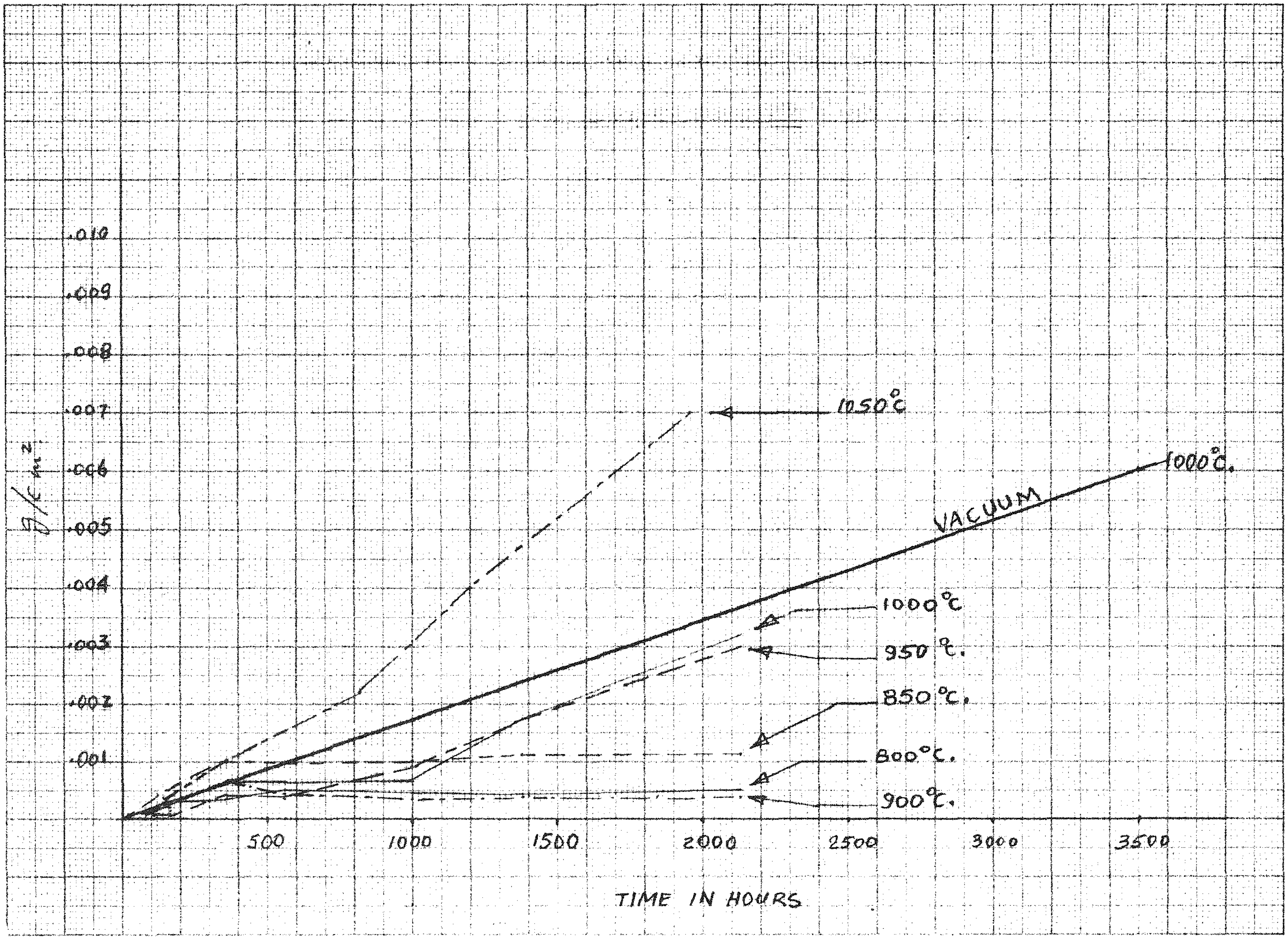

Figure 20. Isothermal Weight Loss N-Type CO Environment, 10^{-5} Torr.

SECTION III

THERMOELECTRIC GENERATOR TEST AND EVALUATION

Thermoelectric generators, representing recent and advanced technology, assembled with lead telluride, TAG-85 and silicon-germanium materials are being tested at JPL. These generators are: The HPG (PbTe) and the generator Q1-A (SiGe), representative of the MHW type generators. Three 18 couple modules (S/N-1, S/N-2, and S/N-3) that were extensively tested at RCA were received for JPL evaluation in support of the Galileo Program. The S/N-1 generator was on test during this reporting period, and work on a station for S/N-3 is in progress. Test results will appear in subsequent reports. One important question to be dealt with is the evaluation of storage effects on the thermoelectric modules.

A. HIGH PERFORMANCE GENERATOR HPG S/N-2

This generator has operated for a total time of 47,809 hours. During the last 1,951 hours of operation, the generator power out has decreased by 1.61%. Presently the generator power out is 124.2 watts. The generator open circuit voltage has also decreased slightly to its present value of 24.70 volts ±0.05 volts; the internal resistance has increased 0.01 ohm to 1.17 ohms. The generator hot and cold junction temperatures are unchanged since the last report: AVG $\overline{T}_H$ = 1021°C ± 3°C and the AVG $\overline{T}_C$ = 366°C ± 2°C.

The generator degradation rate for the last 5,000 hours of operation was 0.44% per 1,000 hours. The generator history is illustrated in Figure 21.

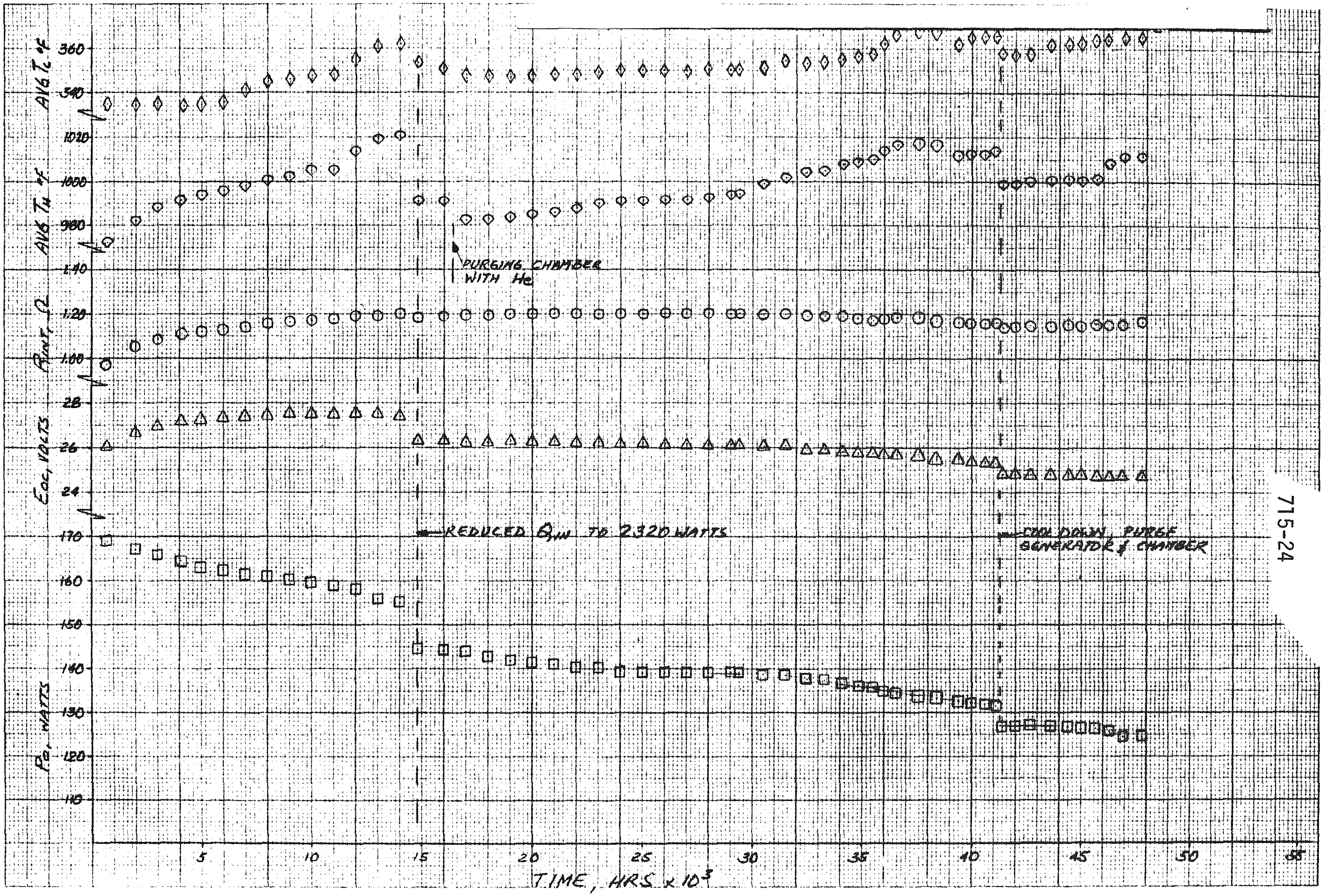

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Figure 21. HPG S/N-2 History

B. MHW GENERATOR Q1-A

This generator has operated for a total time of 19,567 hours. During the last 2,643 hours of operation the generator power out has decreased by 1.30 watts. Presently the generator power out is 133.5 watts. The generator open circuit voltage has slightly decreased and internal resistance has slightly increased in that time (E_{oc} = 57.10 volts and R_{int} = 6.10 ohms). The generator heat source temperature is unchanged, but the case temperatures have slightly increased: AVG $\overline{T}_H$ = 1032°C, AVG $\overline{T}_C$ = 263°C.

The generator degradation rate for the last 5,000 hours of operation was 0.30%/1,000 hours. The generator life history is illustrated in Figures 22 and 23. Figure 24 shows power out vs $\sqrt{\text{time}}$.

C. 18 COUPLE MODULES S/N-1, 2, 3

Three 18 couple modules, S/N-1, -2, -3, originally tested for about 18,000 hours by RCA and, since 1977, stored at room temperature were sent to JPL for test and evaluation. Two arrived with broken heater leads, but S/N-1 was apparently undamaged. S/N-1 was placed on test as soon as possible at the same conditions as those used in prior testing, i.e., 1130°C hot shoe temperature. A new heater was obtained for S/N-3; preparation of another test station for this generator was nearly completed during this reporting period. Operation of S/N-2 is not contemplated.

The initial indications from the operation of S/N-1 are that little or no change in the generator has taken place since it was last operated by RCA. The hot shoe thermocouples no longer function, so replication

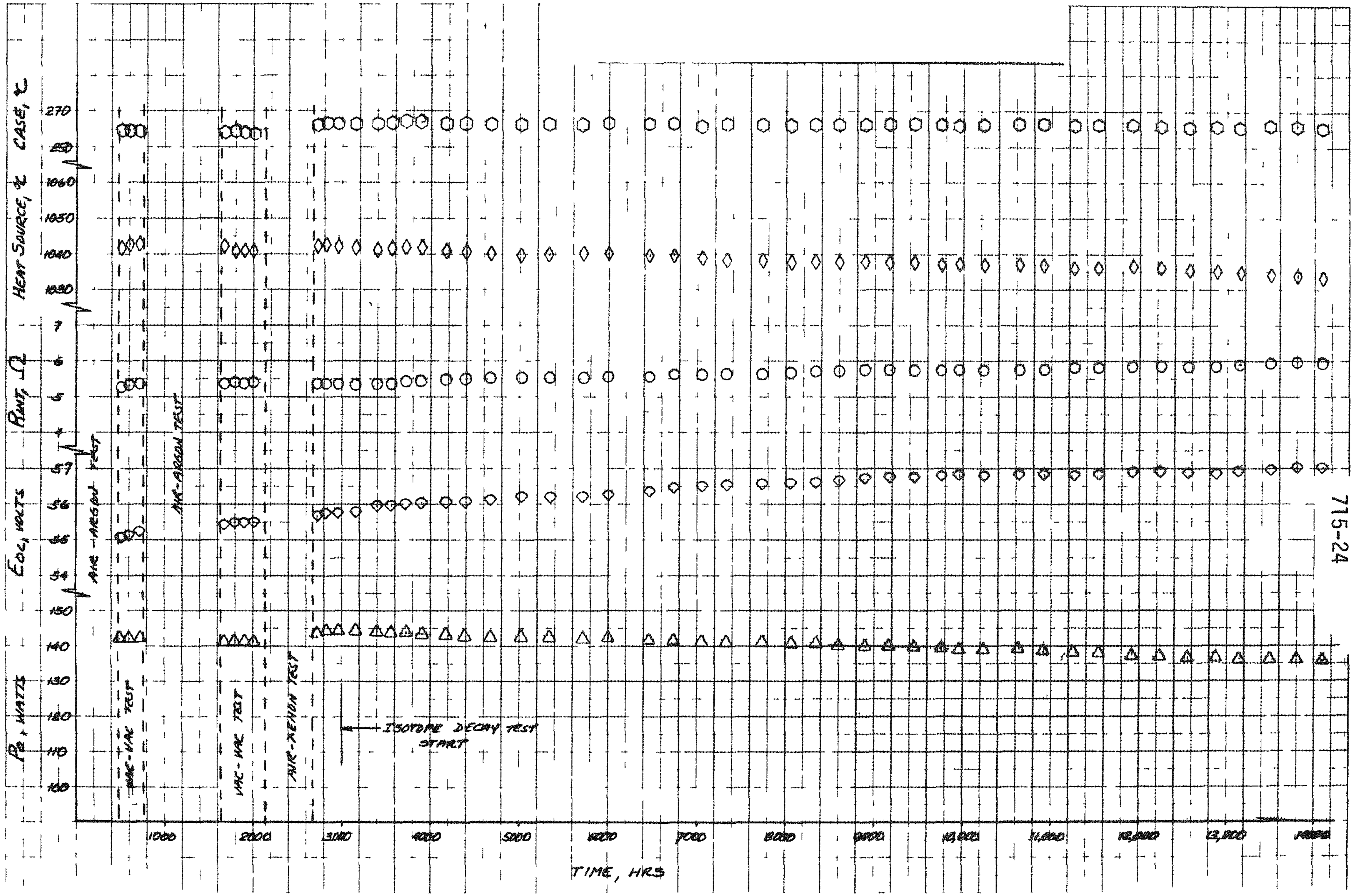

Figure 22. Q1-A History

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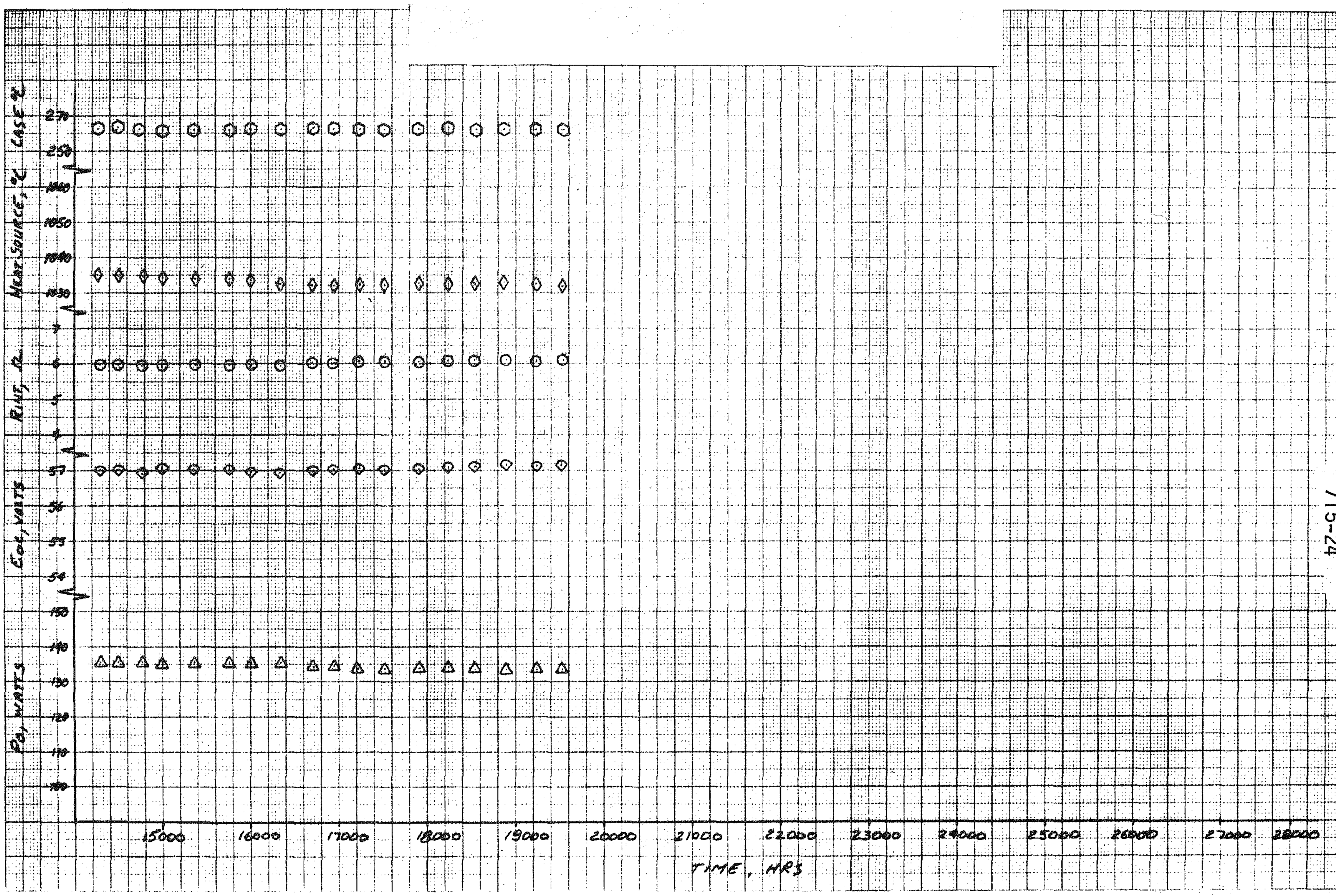

Figure 23. Q1-A History

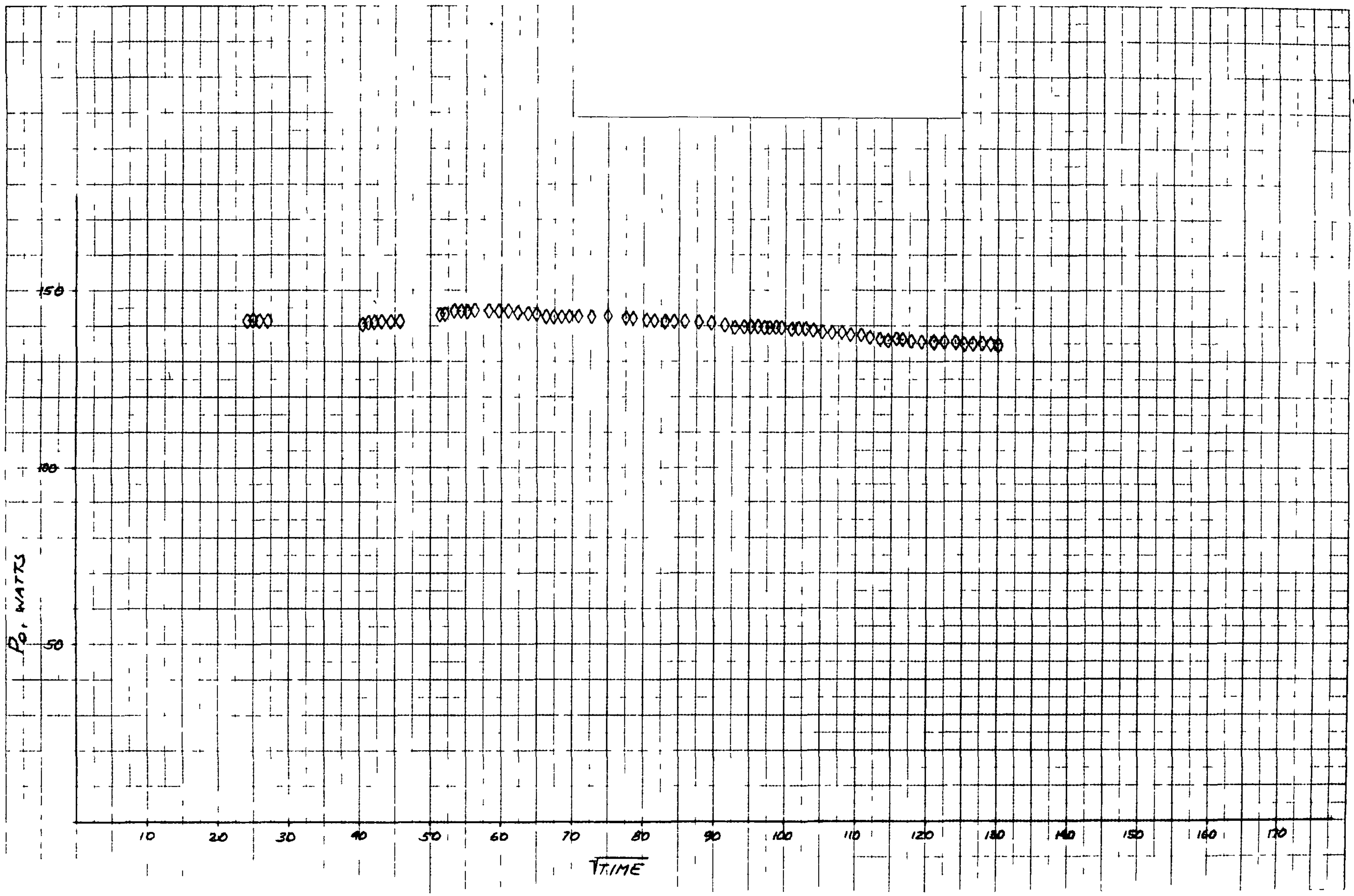

Figure 24. Q1-A Power Out vs $\sqrt{Time}$

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of conditions of operation were confined to using the same heater input power. The operational history at JPL for the first 1,700 hours is shown in Figure 25. Parametric test results are shown in Figure 26. The results of comparing the present test with RCA's data using computer extrapolation will be presented in a later report.

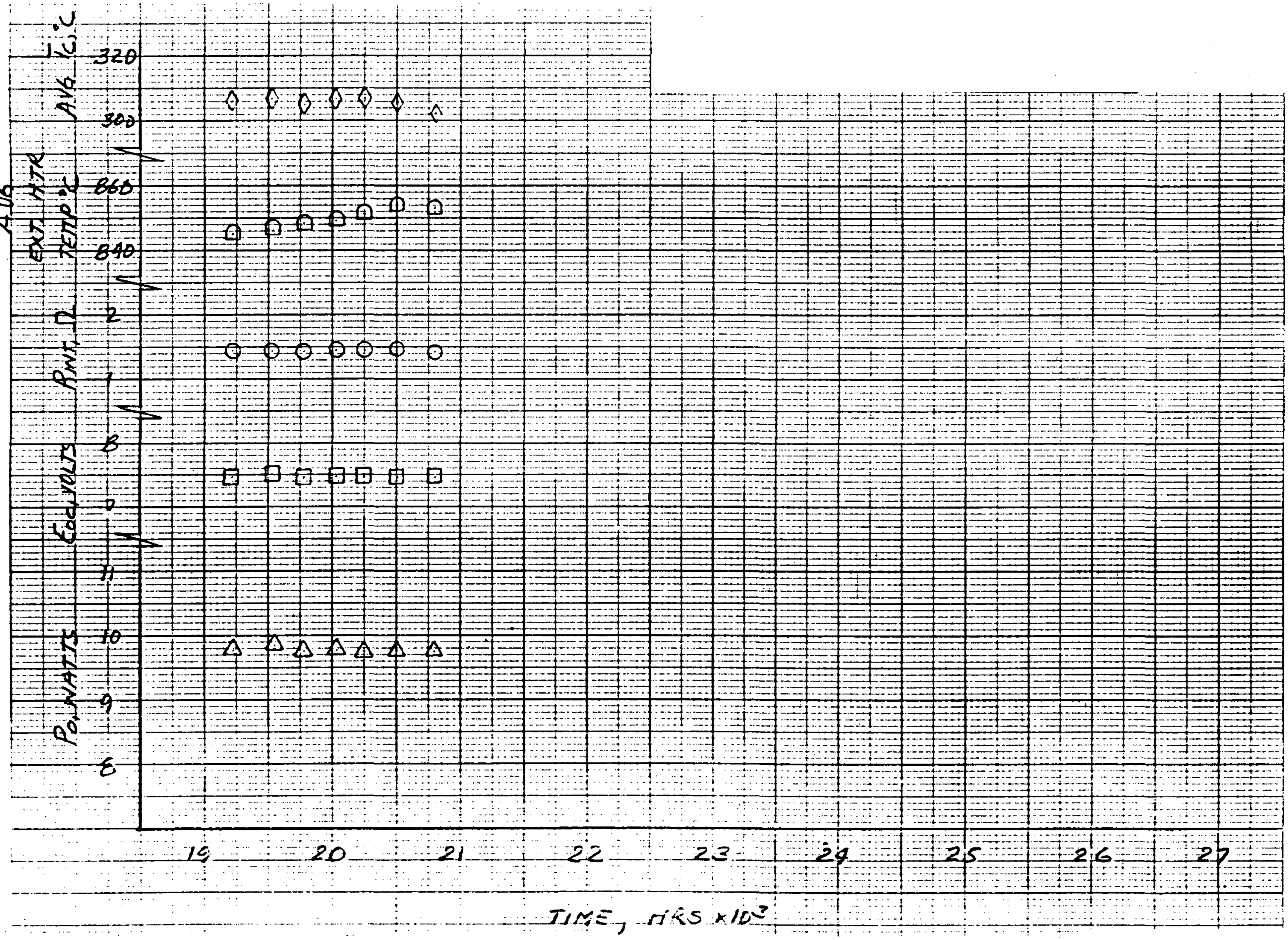

Figure 25. 18 Couple Module S/N-1 Test History

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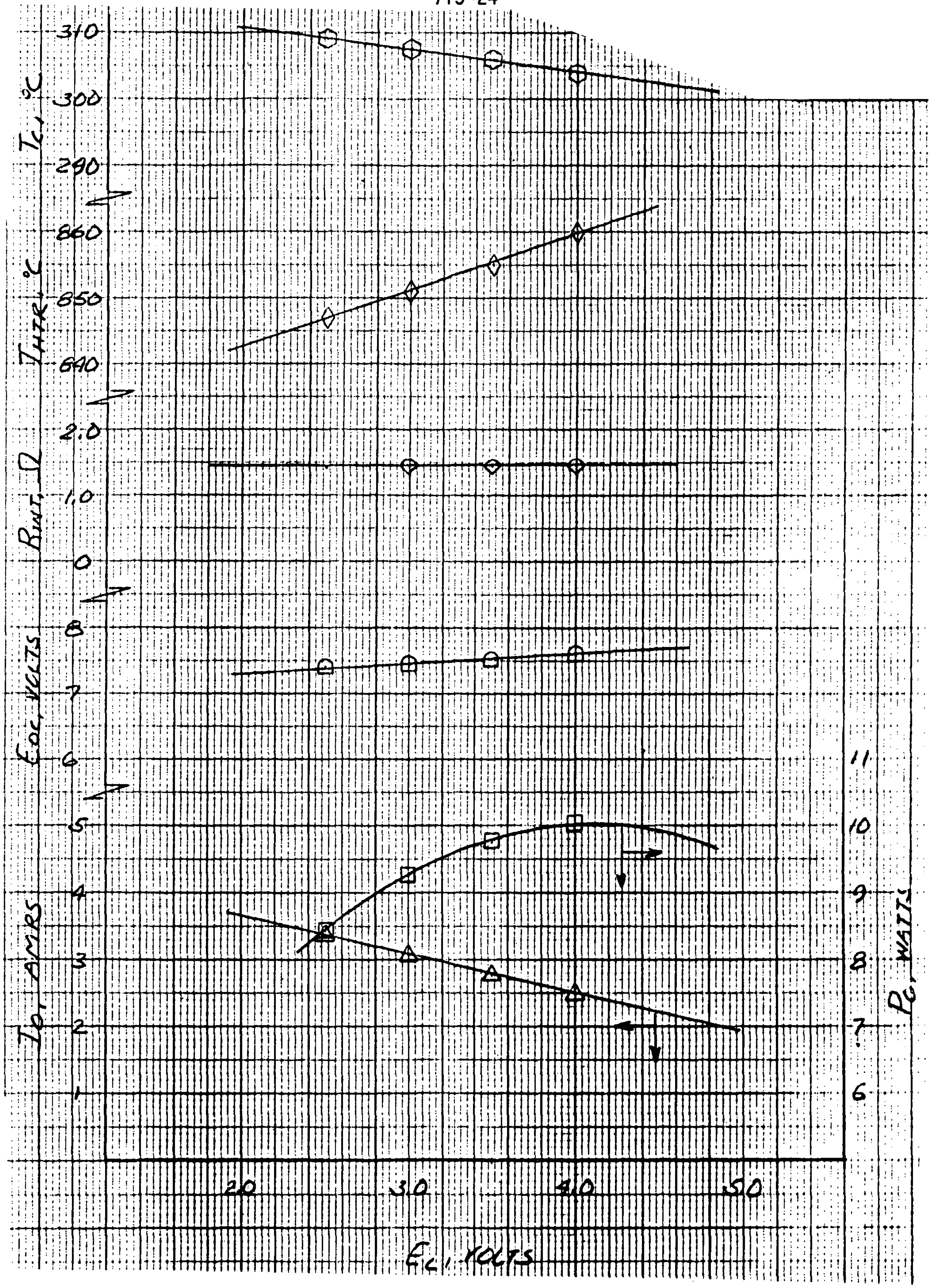

Figure 26. 18 Couple Module S/N-1 Parametric Test

SECTION IV
MHW FLIGHT PERFORMANCE

A. POWER PERFORMANCE COMPARISONS FOR LES 8 AND 9 RTGS

This information is furnished by Lincoln Laboratories on a quarterly basis. The power output of the four LES 8 and 9 RTGs has been compared with the calculated output of DEGRA2 up to a mission time of 31,824 hours, for a total of over 3-1/2 years of operation. The comparison is shown in Figures 27 and 28. For details of the DEGRA calculations, the reader is referred to Progress Reports Nos. 20, 22, 23, 1977. Based on the initial performance of these RTGs, the BOM age of RTG-1 on LES-8 and RTGs-1 and 2 on LES-9 was 1,500 hours and the BOM age of RTG-2 on LES-8 was 500 hours. The degradation rate of RTG-1 on LES-8 and RTG-2 on LES-9, (Figure 27), show excellent agreement with the DEGRA calculation using a silicon nitride coating lifetime of 100,000 hours. RTG-1 on LES-9 has a slightly higher degradation rate, but still shows reasonably good agreement with the 100,000 hours coating lifetime curve. RTG-2 on LES-8, (Figure 28), shows excellent agreement with the DEGRA calculation using a silicon nitride coating of 100,000 hours.

B. POWER PERFORMANCE OF VOYAGER 1 AND 2 FLIGHT RTGS

This information is provided by the Voyager Flight Project at JPL. The six thermoelectric generators which provide the power for the Voyager spacecraft are of the same type and design as are used on the LES-8 and LES-9 spacecraft. A comparison of the Voyager RTGs power output versus that predicted by DEGRA has been made. For details of the DEGRA calculations the reader is referred to Progress Report Nos 23, 25, and 29. Based on the initial performance of the RTGs on both Voyager 1 and 2,

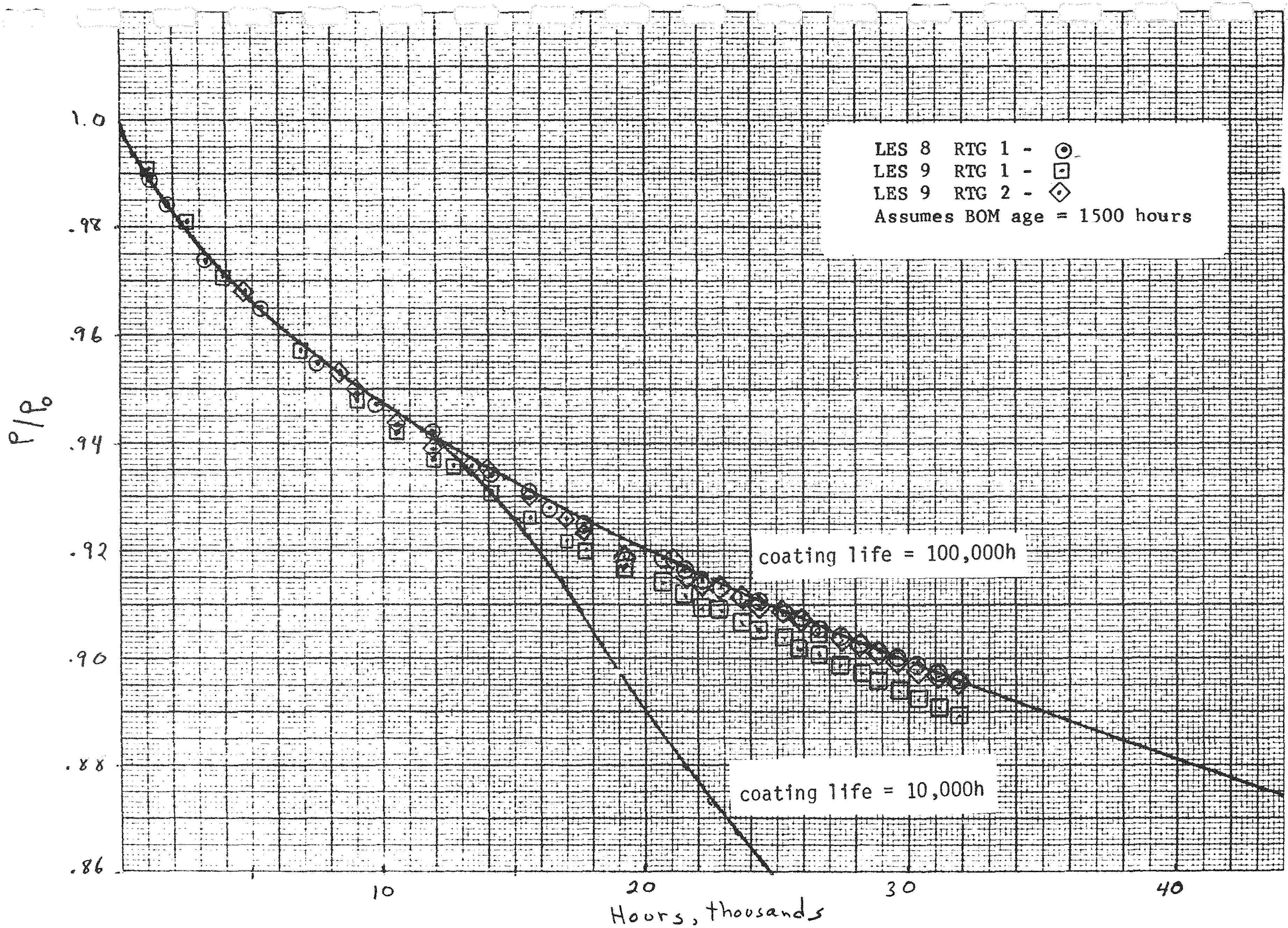

Figure 27. Comparison of LES 8/9 RTG Power with DEGRA

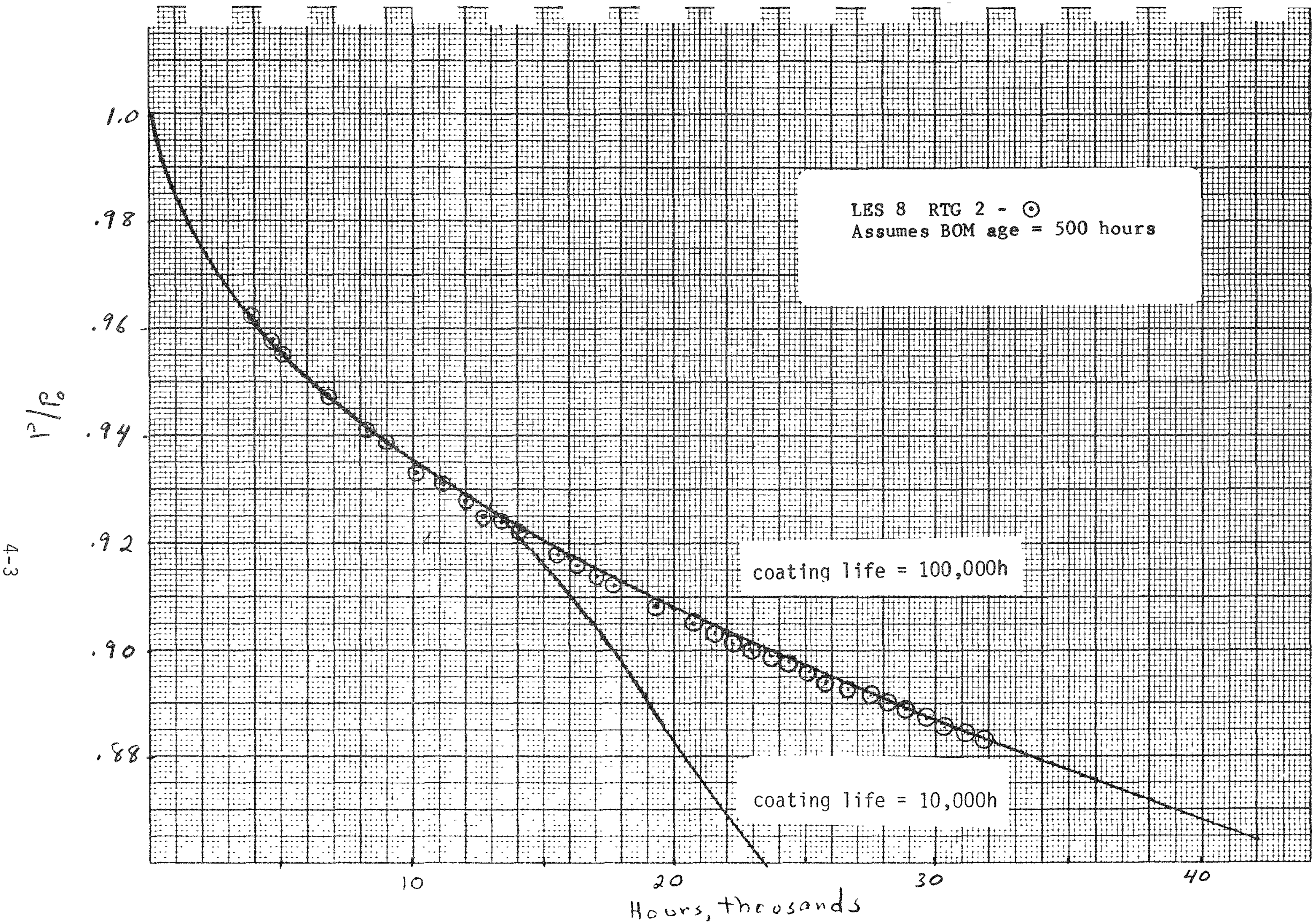

Figure 28. Comparison of LES 8 RTG Power with DEGRA

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the BOM age of all the RTGs was determined to be 1,500 hours. The ratio of the output power to the original power at launch (P/Po)of the RTGs on Voyager 1 and Voyager 2 is compared to the DEGRA data normalized to a Beginning Of Mission (BOM) "age" of 1,500 hours in Figures 29 and 30. The degradation rate of the RTGs 2 and 3 on Voyager 1 shows excellent agreement with the DEGRA calculations using a silicon nitride coating lifetime of 100,000 hours (Figure 27). The degradation rate of RTG 1 has fallen below but appears to parallel the coating lifetime curve of 100,000 hours (Figure 27). The degradation rate of the two RTGs on Voyager 2 also show excellent agreement with the DEGRA calculations using a silicon nitride coating lifetime of 100,000 hours (Figure 28). For information the plots of the "raw" data versus time, as previously reported, for Voyager 1 and Voyager 2 are shown in Figures 29 and 30. The accrued time and power output of the RTGs is listed as follows:

VOYAGER - 1

Total operation time - 19,577 hours

Last period of operation = 1,680 hours

RTG-1	F-8		145.47 watts
RTG-2	F-6		146.33 watts
RTG-3	F-9		148.07 watts
RTGs Total		=	439.87 watts

VOYAGER - 2

Total operation time - 20,128 hours

Last period of operation = 1,680 hours

RTG-1	F-10	149.68 watts
RTG-2	F-12	147.41 watts
RTG-3	F-11	Telemetry - Not Operating

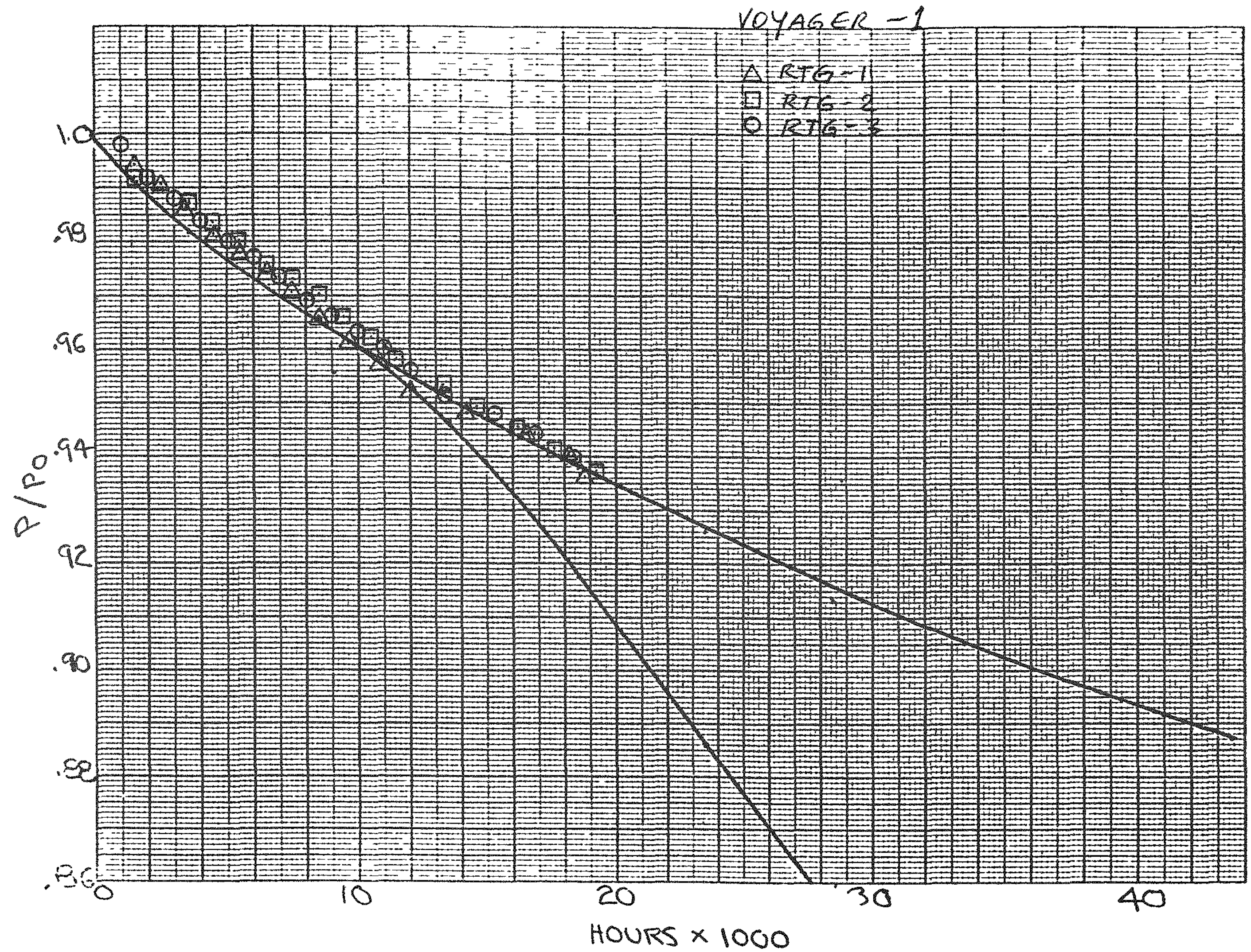

Figure 29. Comparison of Voyager 1 RTG Power with DEGRA

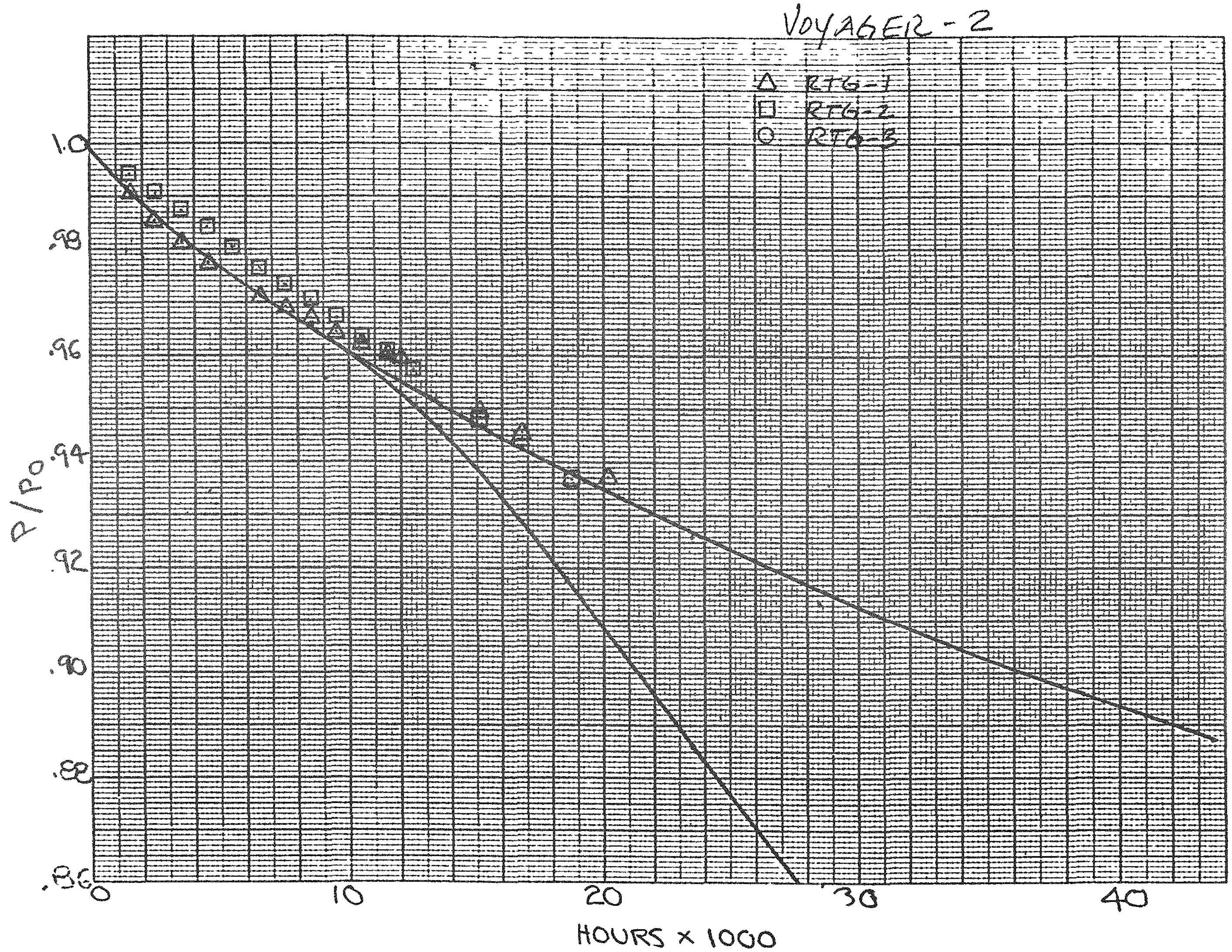

Figure 30. Comparison of Voyager 2 RTG Power with DEGRA

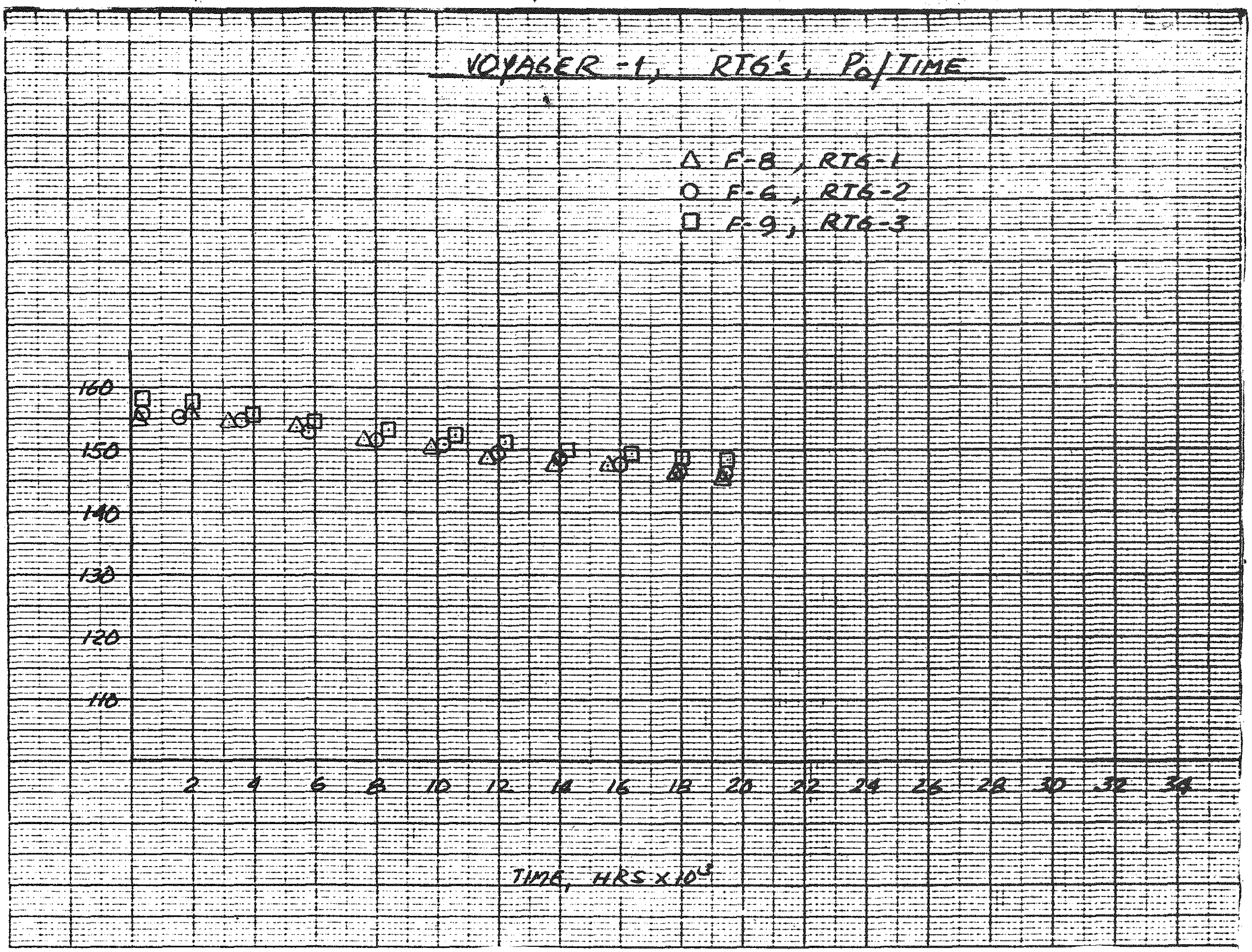

Figure 31. Voyager 1 RTG Power vs Time

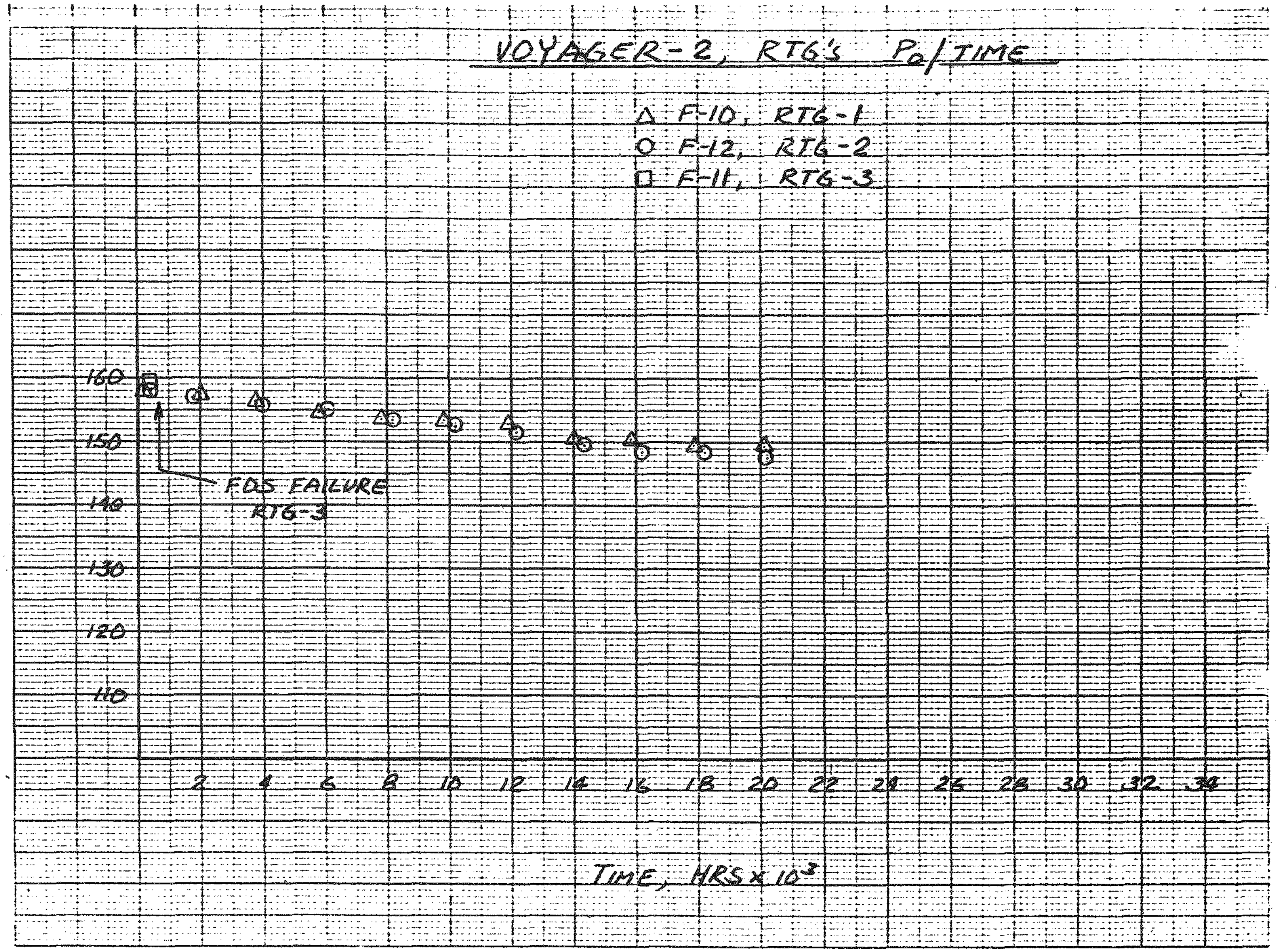

Figure 32. Voyager 2 RTG Power vs Time