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PASADENA, CALIFORNIA

MEMORANDUM #1

PERFORMANCE CHARACTERISTICS OF A SILICON-GERMANIUM RTG IN LONG-TERM OPERATION

April 29, 1969

Prepared For:
Jet Propulsion Laboratory
Pasadena, California

JPL CONT. GP-505381

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This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

INTRODUCTION

The on-board power source for auxiliary power is obviously a critical component of all spacecraft. In planning for a mission it is necessary to select the power source that best satisfies overall requirements from stand-points of cost and technical objectives. For deep space probes, within present-day state-of-the-art, thermoelectric power sources offer overall advantages not to be found with most other forms of energy conversion. Several different technologies, however, exist even within thermoelectric energy conversion, the applicability of each technology depending on the scope and intent of the mission being planned. It is in this respect that radioisotope thermoelectric generators that use silicon-germanium alloy thermoelements and associated technology are probably the most ideally suited power sources for the production of highly reliable very long term power.

Questions closely related to those of power supply selection pertain to the characterization of the performance of the supply with respect to electrical load conditions and operating time. Because such information for very long operating times either does not exist or is not readily available for most thermoelectric systems, including those that use silicon-germanium alloys, a preliminary investigation has been undertaken to characterize the performance of a typical radioisotope fueled silicon-germanium thermoelectric generator in operation for times up to 12 years. Information resulting from this investigation should be useful from several standpoints. First, the input typically to be expected into a voltage converter hooked onto the terminals of the RTG is clearly indicated. This will facilitate the selection and design of the converter. Second, mission planners will obtain a fairly good idea of the type of power profile available, including projected degradation rates. Third, the investigation highlights generator temperature conditions that must be carefully considered in a detailed power source design.

DESIGN CONSIDERATIONS

A partial design was formulated for a silicon-germanium radioisotope thermoelectric generator in order to illustrate the typical operating behavior of such a generator in long-term operation. Approximate design goals for the generator were a total power level in the 80 to 120 watt range, load voltage of the order of 28 volts, operating time of 12 years and beginning life (BOL) hot junction temperature of about 1000°C. Because power degradation in a radioisotope thermoelectric generator usually depends on the combined effects of fuel decay and thermoelectric module degradation, for long operating times it is desirable to use fuels with very long half-lives. Plutonium (238)-oxide was accordingly selected for design purposes as the fuel for the generator.

The heat rejection components, viz. the radiator, of a space power supply are generally treated as a part of the supply in a detailed design optimization because of a first-order bearing on performance and weight. Because the present design was not formulated for a specific application, it being intended only as an illustration of the behavior of a typical silicon-germanium RTG in long-term operation, the question of heat rejection was not treated in detail in the present case. Inasmuch as the cold sides of thermoelectric generators used in space applications frequently operate in the 200 to 300°C range, it was arbitrarily decided to design the present power supply for a cold junction operating temperature of about 260°C. Although this temperature is fairly representative, it is recognized that in an actual design the cold side would very likely operate at a somewhat different temperature.

The thermoelectric property data used in the present investigation for the silicon-germanium alloys has been derived from various material studies performed under AEC (the SNAP-10A program) and NASA (Contract No. NAS 5-3410) sponsorship.

Needless to say, the data for operating times of the order of 12 years is not actual measured data, but rather data obtained from extrapolations based on observed solid state processes occurring in silicon-germanium alloys. Although perhaps not exact, the extrapolations are believed to quite accurately depict the behavior of silicon-germanium alloys in long-term operation.

The analytical model used to design the RTG considered most thermal and electrical processes in fair detail. A few simplifying assumptions, however, were made in order to speed up the computations. The effects due to Thomson heat generation (absorption) in the thermoelements were neglected, as were the effects due to transverse heat flow in the thermocouple heat receptors (hot shoes). The latter were assumed to be made of a silicon-molybdenum alloy; the silicon-germanium thermocouples were thus assumed to be of the Air-Vac type which normally are radiatively coupled to a heat source. In the present study, because of its limited scope, no consideration was given to questions of the heat source. Extraneous losses in the electrical and thermal circuits were taken into account in an approximate and yet fairly representative manner. Thermal shunt losses through insulation surrounding the thermoelements, assumed to be Min - K 2020, were treated quite rigorously.

DESIGN CONFIGURATION

In order to obtain the desired performance characteristics within the specified operating constraints, design studies indicated that the RTG would have to make use of 256 Air-Vac type silicon-germanium thermocouples in a series-parallel arrangement. The dimensions of individual thermocouple components are as follows:

Thermoelement length	2.54 cm
Cross-sectional area	
n-type thermoelement	0.2101 cm^2
p-type thermoelement	0.1168 cm^2
Hot shoe area	4.00 cm^2
Radiator area per couple	15.00 cm^2

Because the radiator area per couple considerably exceeds the hot shoe area per couple, the implication is that the generator has either a finned cylindrical configuration or has a remote radiator to which the heat is transported by heat pipes or by a liquid metal loop. As stated above, for the purposes of the present study, it was not necessary to perform detailed heat rejection analyses.

It should be noted that the given design configuration is within present state-of-the-art silicon-germanium Air-Vac thermocouple technology as regards component dimensions. Because the present investigation was not concerned with the detailed design of a complete RTG, however, it should be recognized that the configuration is not the result of extensive trade-off studies normally performed and therefore does not necessarily represent some so-called "optimum" design.

RTG PERFORMANCE CHARACTERISTICS

The performance of the silicon-germanium RTG for operating times up to and including 12 years is illustrated in Figures 1 to 4. Figure 1 shows plots of load voltage and power output as functions of load current for four different operating times: beginning of life, 1500 hours, 5 years and 12 years. A variety of load ressistance values are indicated on the plots. It is noted from Figure 1 that the power and voltage degradation of the RTG depends on the load resistance. For example, in order to have the RTG produce maximum power at the end of life, a load resistance of about 10 ohms is required. At that load resistance, the beginning of life power output, although close to it, is not at its maximum.

From Figure 1 it is seen that the total power degradation experienced by the RTG in 12 years of operation is of the order of 15 to 20 percent. A part of this degradation is due to fuel decay, with the remainder due to the n-type silicon-germanium alloy which undergoes dopant precipitation as a function of time. The latter phenomenon is well documented and understood, and as a consequence may be minimized through thermocouple design which enables excess power to be initially dissipated in the thermoelements. As time goes on, relatively more power will be dissipated in the load, with the result that the power profile as a function of time will be flattened. In order to approximately illustrate the relative contributions of the fuel and the silicon-germanium alloys to the total power decrease, the following table shows the total heat input into the 256 thermocouples and the figure-of-merit of the silicon-germanium alloy as functions of time:

Time	Heat Input-Watts	Figure-of-Merit/°C
Initial	1382	$6.27 \times 10^{-\cancel{8}4}$
1500 Hours	1380	6.01 "
5 years	1330	5.79 "
12 years	1262	5.64 "

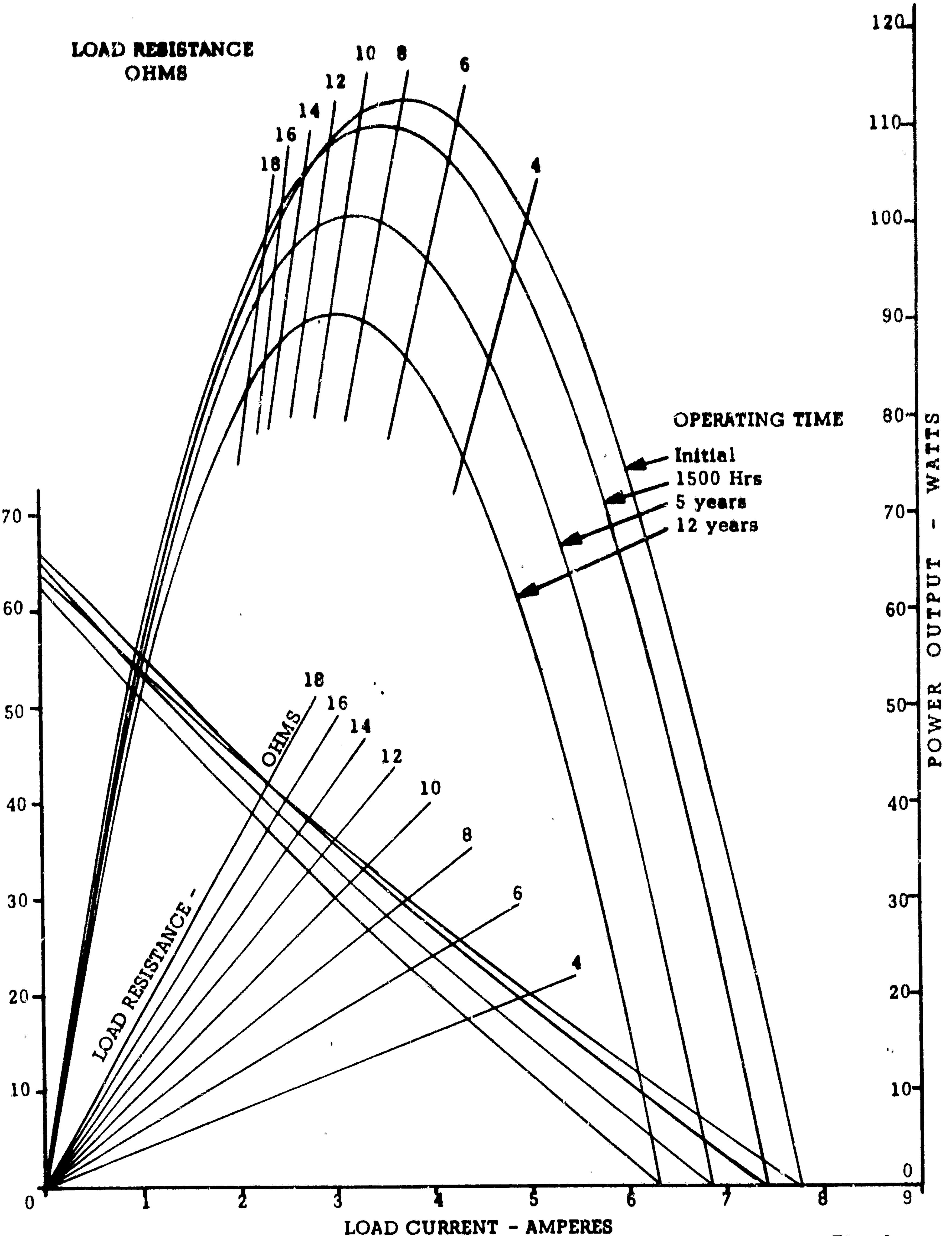
It is seen that the heat input decays by some 8.6 percent and the figure-of-merit decreases by about 10 percent in 12 years of operation. Considering the number of thermocouples and the hot shoe area per thermocouple, it is observed that the incident heat flux is of the order of 1.3 watts/cm^2, a value well within the range of those possessed by most actual systems.

The corresponding plots of thermocouple hot and cold junction temperatures as functions of load current are shown in Figures 2 and 3, respectively. It is noted that at the beginning of life the hot junction temperature is close to 1000°C at the maximum power point. Under open circuit operating conditions, however, the hot junction temperature rises to temperatures in the vicinity of 1200°C. Such temperatures are somewhat excessive, not only as regards the Air-Vac thermocouples, but also from the standpoint of most radioisotope fuel capsules that might be considered for use with a silicon-germanium RTG. This condition indicates that in a detailed RTG design, it will be necessary to not only consider the system at its operating point, but also to evaluate its characteristics under open circuit operation.

Figure 4 shows plots of open circuit voltage as a function of hot junction temperature for the silicon-germanium RTG. This plot, in conjunction with Figures 1 and 2, enables the determination of instantaneous open circuit voltage for the RTG under any operating conditions. If the circuit were to open, however, the operating temperatures would shift to those shown in Figure 2 at zero load current. The time involved in this depends on the thermal characteristics of the whole RTG. Because the present treatment has not considered the design of the total RTG, it is not possible to accurately predict the time constant for transients. Based on approximate analyses, however, it has been concluded that 30 minutes may be used as a representative time constant for such phenomena.

SUMMARY

The present investigation has considered the performance of a typical silicon-germanium RTG in operation for operating times up to and including 12 years. The performance of the generator has been studied from the standpoints of electrical and thermal characteristics under a variety of load conditions. Although the primary emphasis of the investigation has been on long-term effects, short-term transient phenomena have also been approximately considered. It is concluded that RTG performance degradation, including fuel decay, will be less than 20 percent in 12 years of operation.



LOAD RESISTANCE OHMS
18
16
14
12
10
8
6
4
OPERATING TIME
Initial
1500 Hrs
5 years
12 years
LOAD RESISTANCE - OHMS
18
16
14
12
10
8
6
4
POWER OUTPUT - WATTS
LOAD CURRENT - AMPERES
0
1
2
3
4
5
6
7
8
9
10
20
30
40
50
60
70
0
10
20
30
40
50
60
70
80
90
100
110
120

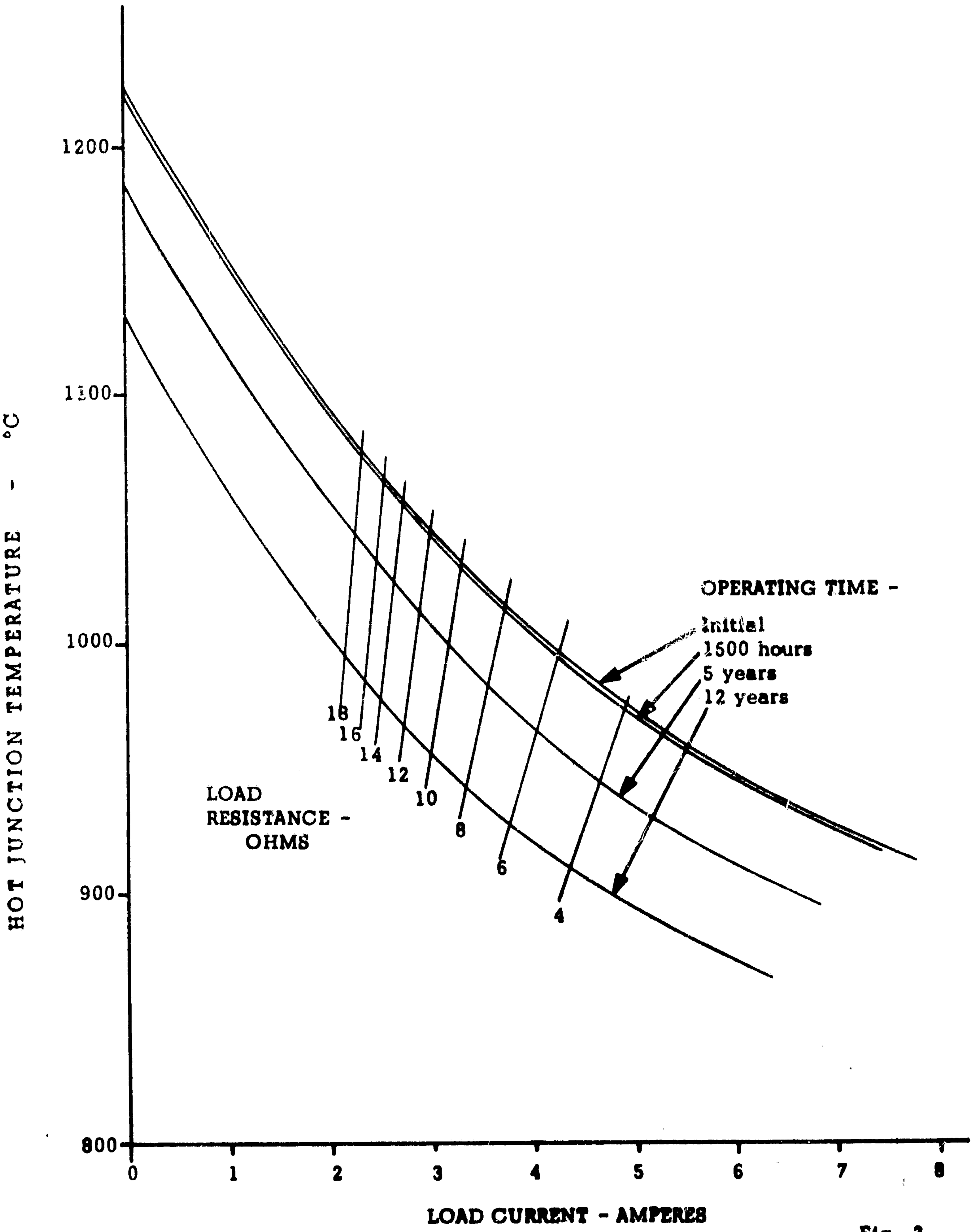
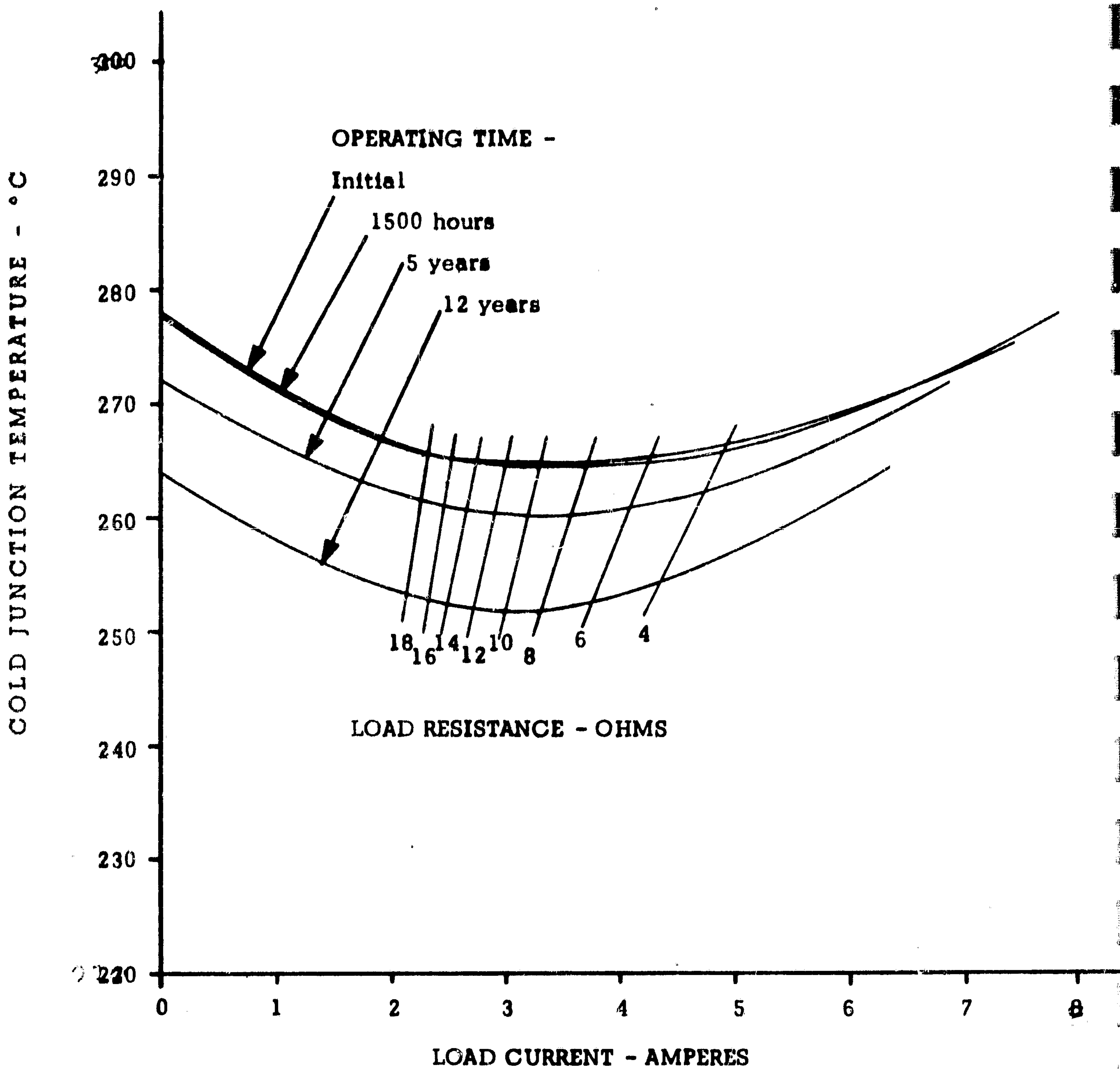

HOT JUNCTION TEMPERATURE - °C
1200
1100
1000
900
800
0
1
2
3
4
5
6
7
8
LOAD CURRENT - AMPERES
OPERATING TIME -
Initial
1500 hours
5 years
12 years
LOAD RESISTANCE - OHMS
18
16
14
12
10
8
6
4

Fig. 2



COLD JUNCTION TEMPERATURE - °C
300
290
280
270
260
250
240
230
220
OPERATING TIME -
Initial
1500 hours
5 years
12 years
18
16
14
12
10
8
6
4
LOAD RESISTANCE - OHMS
0
1
2
3
4
5
6
7
8
LOAD CURRENT - AMPERES

Fig. 3

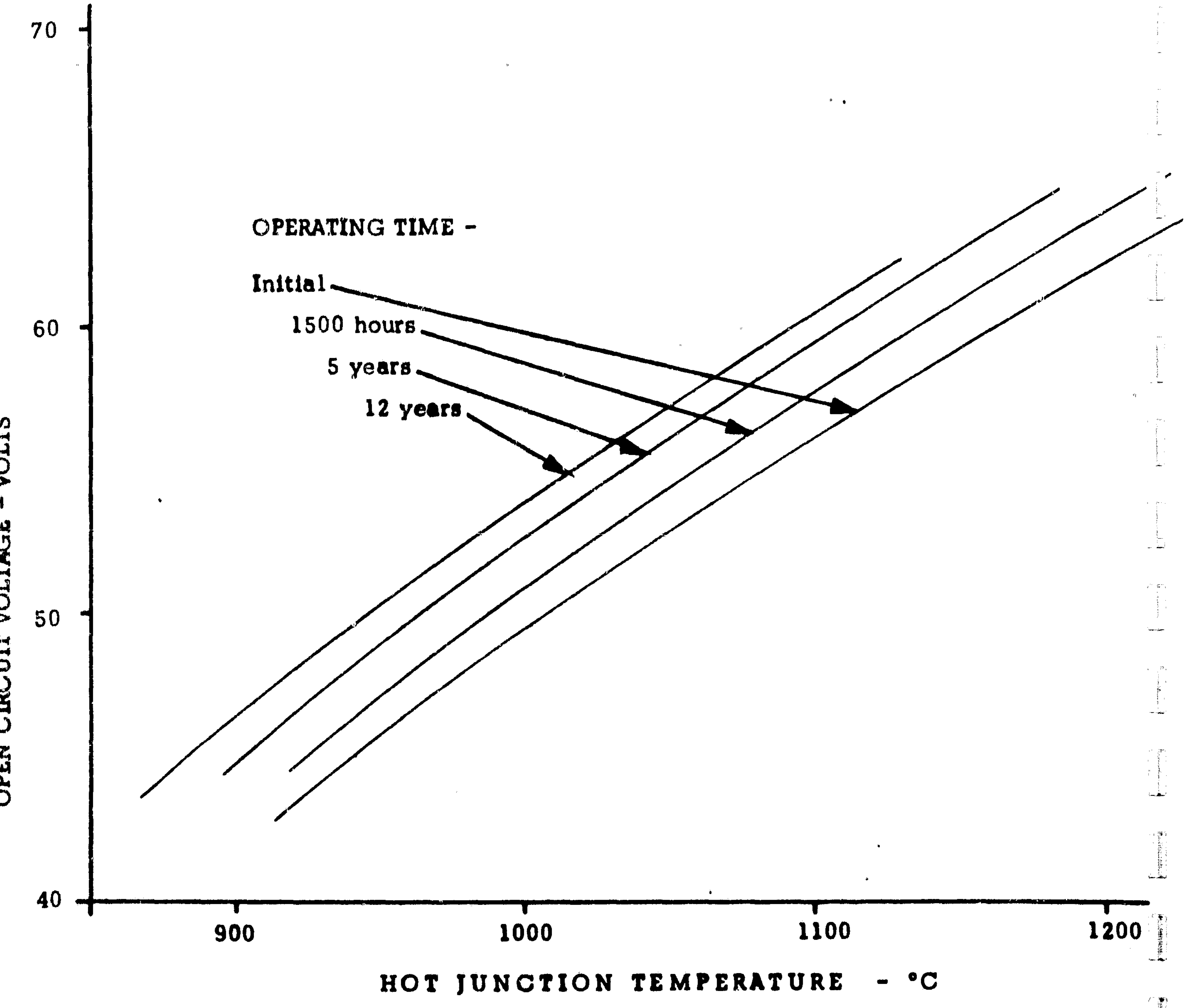

OPERATING TIME -
Initial
1500 hours
5 years
12 years
70
60
50
40
OPEN CIRCUIT VOLTAGE - VOLTS
900
1000
1100
1200
HOT JUNCTION TEMPERATURE - °C

Fig. 4