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MEMORANDUM # 5

PERFORMANCE CHARACTERISTICS of TYPICAL SILICON-GERMANIUM RTG's in AIR OPERATION

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prepared for

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INTRODUCTION

Radioisotope thermoelectric generators (RTG's) used on unmanned spacecraft for auxiliary onboard electrical power are commonly fueled prior to launch. Unless special provisions are made to modify the environment on the launch pad, this means that prior to and during launch there is a period of time that the RTG's operate in an air environment at essentially standard temperature and pressure (STP) conditions. The effects of such air operation on RTG performance are basically of two types. First, the air environment temporarily modifies RTG performance from its design vacuum values by changing the external and in an unsealed system also the internal heat transfer characteristics of the RTG. Subsequent vacuum operation is unaffected by these temporary changes in RTG operating environment and the RTG will exhibit its original design performance in an eventual space environment. Second, operating in an air environment may permanently modify the physical characteristics of certain components of the RTG such that design performance values are not recovered in a subsequent vacuum operation. Mechanical strength characteristics of certain RTG components may also be affected. Permanent changes in RTG operating behavior as a result of air expossure are usually associated with irreversible chemical and/or physical processes caused by reactions and interactions with oxygen.

Because oxygen poses a serious problem to RTG's that use lead and tellurium compounds and alloys, it is accepted practice with devices of this type to hermetically seal them. Prior to final sealing, such devices are frequently also back-filled with an inert gas in order to reduce the volatility of the thermoelectric material. The result of this procedure is that neither permanent nor temporary effects usually occur internal to telluride RTG's as a result of air operation. In air, however, the external heat transfer characteristics of the RTG are modified by an enhanced heat rejection rate from the outer surface of the device because radiation heat transfer is supplemented by convection. In air the RTG consequently operates at hot and cold side temperatures and thus also a performance level that are lower than the vacuum design values. In order for this effect to be only temporary, it is necessary to use materials for the

RTG casing and radiator, including radiator emittance coating, that are insensitive to oxygen.

The air operation of silicon-germanium RTG's presents a situation somewhat different from that encountered with telluride generators. Unlike lead and tellurium compounds and alloys, silicon-germanium alloys, are not adversely affected by operation in air. This is also true of the most common silicon-germanium thermocouple configuration, the so-called Air-Vac thermocouple, that uses components which in their respective general ranges of operating temperature are not adversely affected by air,i.e. by oxygen. Inasmuch as volatility either is not a problem with silicon-germanium Air-Vac thermocouples, it may appear that silicon-germanium RTG's designed for operation in space vacuum require neither hermetic sealing nor any other modifications to also permit pre-launch and launch operation in air. Whether this is really true or not depends on the sensitivity to air of silicon-germanium RTG components other than the Air-Vac thermocouples. Because relatively little effort has been expended to date on the design and even less on the development of silicon-germanium RTG's, the effects of air operation on RTG performance have never been investigated in any detail for silicon-germanium systems. Nevertheless, because of their proven relative stability of performance and reliability, it is namely silicon-germanium Air-Vac thermocouples that probably will be used in second-generation RTG's intended for use in future extended-lifetime space missions. It is the purpose of the present memorandum therefore to conduct a preliminary investigation of the effects of air operation on silicon-germanium RTG performance and to highlight the areas that require further clarification. In terms of the temporary and permanent effects discussed above, the primary intent of the present study is to consider the former of these in some detail and to point out in a general manner some more important of the possible latter-type effects. Because in some applications power is required from the RTG even during the launch phase, another and related purpose of the present study is to determine the amount of such power available from typical silicon-germanium RTG's in air operation.

RTG MODEL

For purposes of the present study, a configuration typical of finned cylindrical RTG's has been assumed for the silicon-germanium generator. A cylindrical radioisotope fuel capsule is surrounded around its periphery by silicon-germanium Air-Vac thermocouple modules. A small gap separates the thermocouple hot shoes from the surface of the fuel capsule; the thermocouples thus receive heat from the fuel capsule by means of thermal radiation. The Air-Vac thermocouple cold stacks terminate in studs which enable the attachment of the thermocouples to a cylindrical generator casing by means of screws. For enhanced rejection of waste heat from the cold side of the generator, radiation fins are attached around the periphery of the generator casing. The two ends of the RTG are terminated by end caps that include thermal insulation and structural members for the support of the radioisotope fuel capsule. Thermal insulation also completely surrounds individual thermocouple legs in the void area between the hot shoes and the cold sides (electrical interconnects) of the thermocouples. Power leads from the RTG are brought out through one of the end caps.

Silicon-germanium Air-Vac thermocouples are schematically illustrated in Figure 1. The n- and p-type silicon-germanium thermoelements are attached on one end to a silicon-molybdenum alloy hot shoe (heat collector) and on the other end to a cold stack that includes stress compensation members, electrical interconnects that complete the electrical path to adjacent thermocouples, and an electrical insulator that isolates the thermocouple from the generator casing. The cold stack terminates in a stud that contains a threaded screw receptacle. As already indicated, for purposes of minimizing thermal shunt losses, the n- and p-type silicon-germanium thermoelements are surrounded by thermal insulation.

The radioisotope fuel capsule is assumed to be of the high temperature refractory-type and is encased in a graphite re-entry shell. For purposes of the present treatment, as will be seen below, it is not necessary to consider the detailed construction of the fuel capsule. As concerns air operation of the RTG, the primary point of significance about the fuel capsule is its outer graphite shell because unprotected graphite is not compatible with a high temperature air environment.

The present treatment assumes a specific RTG design that may be considered fairly representative of second generation silicon-germanium RTG's. An initial power output of 180 to 200 watts at a load voltage in the 20 to 30 volt range is specified for the system. This assures that after long operating times, of the order of 10 to 15 years, the system produces at least 150 watts of output power. The implied power degradation in that time includes that due to fuel decay as well as that due to the thermocouples themselves. *

Initial thermocouple hot and cold junction vacuum design operating temperatures have been set at about 1700 and 600°F respectively. The former of these temperatures is compatible with the high temperature capabilities of refractory fuel capsules currently in development and the latter approximately corresponds to minimum weight RTG's. It is realized of course that rather than being arbitrarily selected as here, system operating temperatures for an actual RTG are usually derived from detailed performance and weight optimization studies. Inasmuch as the primary intent of the present study is to consider the operation of a typical silicon-germanium RTG in air, it suffices to use a design that although not optimum for any specific application is nevertheless quite representative; hence the simplified procedure used here.

Design considerations indicate that the stated RTG power and voltage requirements are approximately satisfied with a system in which the radioisotope fuel capsule is surrounded by six thermoelectric modules, each module consisting of 50 silicon-germanium Air-Vac thermocouples in a 2x25 array. Although the six modules are connected electrically in series, each module is internally hooked in a series-paralled arrangement. The overall diameter of the fuel capsule, including re-entry shell, is assumed to be 3.5 inches. The silicon-molybdenum hot shoes are assumed to be square with a side length of one inch. A 0.040" gap separates adjacent hot shoes. It is assumed that the silicon-germanium thermoelements are one inch long and that the relative cross-sectional areas of the n- and p-type elements are at a ratio of 1.8. Even though this area ratio is usually optimized in each detailed design calculation, for simplicity in the present case it has been fixed at the indicated value because it is known from experience that area ratios of this order optimize silicon-germanium thermocouple performance in typical applications. The absolute values

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* See Memorandum #1 prepared by Resalab Scientific for the Jet Propulsion Laboratory.

of thermoelement cross-sectional areas are determined from performance requirements, the assumed thermocouple and RTG design configurations and the operating temperatures already given for the RTG and from the fuel loading of the radioisotope capsule. The latter is set at a quantity capable of initially yielding 3250 thermal watts. The void space between the hot and cold sides of the Air-Vac thermocouples and surrounding the thermocouple legs is filled with thermal insulation. As discussed in the following section, two different types of thermal insulation will be considered for this purpose.

In view of the above design considerations, the overall dimensions of the RTG turn out to be some 30 inches of length and a diameter slightly in excess of six inches. Six equally spaced radiation fins of 2.5 inch length surround the outer periphery of the generator casing. It should again be pointed out that the assumed RTG configuration has not been either weight or efficiency optimized for any specific mission requirements. Being fairly representative of typical silicon-germanium RTG's, the assumed configuration is, however, completely adequate for persent purposes.

AIR OPERATION OF THE RTG

In order to determine the effect of air operation on the performance of the RTG, the following sequence of performance calculations has been carried out in detail. Assuming a specific thermal insulation for the generator and the design configuration discussed in the preceeding section, the absolute values of thermoelement cross-sectional areas have been calculated such that in vacuum operation the RTG yields some 200 watts of electrical power output at a load voltage of 28 volts when operating at hot and cold junction temperatures of about 1700 and 600°F respectively. The determination of thermoelement cross-sectional areas completely specifies the RTG design. Using this fixed design and the fixed amount of input heat of 3250 watts, the performance of the generator as a function of load current can now be established. The resultant RTG performance and operating temperature values fully describe the operation of the RTG in a vacuum environment.

In order to assess the performance of the RTG in air, it is necessary to account for two effects that depend on operating environment. First, making a worst case assumption of an unsealed system, the heat transfer characteristics inside the RTG are modified because of changed values of insulation thermal conductivity and because of enhanced heat transfer from the fuel capsule to the thermocouples. Second, the heat rejection rate from the radiator and case of the RTG to the environment is changed because in air operation radiative heat transfer is supplemented by convection. The former of these conditions generally results in smaller temperature differentials across the thermoelements because insulation conductivity in air is usually higher than it is in vacuum. The reduced amount of heat flowing through the thermocouple legs results in a decreased temperature differential across them. The latter condition generally causes the radiator and the surface of the outer casing of the RTG to operate at lower temperatures in air than they do in vacuum. The net result is that in air the RTG operates at lower temperatures and lower performance level than it does in vacuum. Although all RTG temperatures are generally lower in air operation than they are in vacuum, as a result of the two effects just mentioned, it is the hot side temperatures that are usually reduced more than the cold side temperatures.

As stated, waste heat from the RTG in air operation is rejected from the radiator and generator casing by a combination of thermal radiation and convection. Of the two possible modes of convection heat transfer, forced convection of course results in more enhanced cooling and consequent lower radiator temperatures than natural convection. For purposes of the present study, however, it has been assumed that forced convection is not utilized and therefore that only natural convection heat transfer takes place in addition to radiation. Making the further assumption that while operating in air, the RTG is oriented with its main axis along the vertical, it may be calculated * that convective heat transfer from the RTG is in the turbulent range. Using appropriate heat transfer equations, it is possible to relate RTG radiator temperatures to the heat rejected from the RTG. The heat rejected from the RTG is equal to the total available heat reduced by the amount converted to electrical power. In the present calculation, it has been necessary to resort to

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* See Elements of Heat Transfer by M. Jakob and G.A. Hawkins, chapt. VII, John Wiley & Sons, Inc, New York 1954

an, iterative method because the electrical power produced by the RTG depends on its operating temperatures and, as just pointed out, the operating temperatures in turn depend on the amount of electrical power produced. Because of their iterative nature, the present calculations also enable the accurate accounting of the temperature dependance of the properties of the thermal insulation and the thermoelement materials.

Temperature integrated values of appropriate properties are introduced after each iteration to correspond to the temperatures determined in the preceeding iteration. After a sufficient number of iterations, usually three or four, all dependent variables in the problem converge to their self-consistancy values, thereby completing the calculation.

The present study has considered silicon-germanium RTG's with two different types of thermal insulation, a multi-foil insulation and a high temperature fibrous insulation. In the case of both thermal insulations, the design of the RTG has first been formulated on the basis of the vacuum performance requirements discussed above. The performance of the RTG in air operation has then been determined for both cases by making allowances for convective heat transfer from the radiator, as already discussed, and the changed thermal conductivity of the thermal insulation in an air environment.

As may be expected, the effect of air on insulation thermal conductivity is markedly different for the two types of insulation considered in the present study. The foil-insulation is assumed to consist of metal foils separated by opacified paper spacers. The thermal conductivity values used for the foil-insulation are thoses associated with insulation in which the metal foils are made of nickel. Although other metals may equally be considered for this insulation, for purposes of the present study the choice of metal makes little difference because thermal conductivity values in both air and vacuum are only relatively slightly dependent on the metal. For use in an actual RTG, it is of course important to select a foil-insulation that is capable of prolonged operation at design operating temperatures in vacuum and in an unsealed RTG is also capable of operating in an air environment prior to launch. Although foil-insulation that uses nickel foils has this ability at reasonably high temperatures, there is some question whether long-term vacuum operation in [illegible] 0 to 1800°F temperature region is possible without foil degradation. Foils [illegible] refractory metals, such as molybdenum, of course are ideally suited for high temperature vacuum operation. Because of the formation of highly volatile oxides, however, unprotected refractory metal foil-insulations undergo permanent damage in RTG's that operate in air. Therefore, although not of great importance for the purpose of establishing RTG operating characteristics in air, the choice of foil-insulation for an actual RTG becomes very critical in formulating an acceptable final RTG design. More will be said about this below.

It has been found by Reid * that thermal conductivity values of foil-insulations (viz., those that use nickel foils and copper foils) are higher in air than they are in vacuum by more than a factor of fifteen at the approximate operating temperatures considered in the present study. The primary reason for this is heat conduction by air across radiation interfaces in the foil-insulation. A secondary effect is the oxidation of the nickel foils which causes changes in the emissivity characteristics of the nickel. The oxidation is however reversible because a return to high vacuum results in dissociation of the oxide and recovery of initial thermal conductivity values.

Even though the bulk thermal conductivity of foil-insulations greatly differs in air and in vacuum, in an actual thermoelectric device this difference is not quite as great because penetrations in the form of thermocouple legs modify the effective thermal conductivity of the foil-insulation. The immediate area surrounding thermocouple legs must be filled with insulation that electrically separates the legs from the metal foils in order to prevent elecrical shorting of adjacent thermocouples. The net result of having two insulations of different thermal conductivities in parallel is that the effective thermal conductivity of the overall insulation surrounding the thermocouple legs lies inbetween the values of the two individual insulations. Because the insulation inserted between the thermocouple legs and the foil-insulation is usually much poorer (higher thermal conductivity) than the foil-insulation, the effect

* "Air Exposure of Multifoil Insulation Systems" by R.L. Reid, ASME Publication No. 68-HT-50, 1968.

of penetrations is to considerably increase the effective thermal conductivity of the foil-insulation. This effect of course increases with increasing differences in the bulk thermal conductivity values of the two insulations in parallel. For this reason effective vacuum thermal conductivity values of the foil-insulation are considerably more modified than are the air values. Normally it is necessary to resort to complicated heat transfer calculations in order to determine the precise effect of penetrations on the effective thermal conductivity of foil-insulation in any given application. This has not bee done in the present case, and instead it has been assumed that the effective thermal conductivity of the foil-insulation is double its bulk value in vacuum and is the same as its bulk value in air. The justification for these assumptions is that generally in the case of configurations such as the one in the present study, the effect of penetrations on the thermal conductivity of the foil-insulation is of the order just assumed.*

Unlike the case of foil-insulations, the effect of atmosphere on insulation thermal conductivity is not especially great in the case of fibrous insulations. For purposes of the present study, it has been assumed that the fibrous insulation used in the silicon-germanium RTG is Min-K 2020. Min-K 2020 is a high temperature insulation capable of long-term operation at temperatures up to 1800°F in both air and vacuum. One reason for its development, in fact, has been its use in silicon-germanium RTG's. Even though not great, the thermal conductivity of the Min-K 2020 insulation does have a slight dependence on it's operating environment. Its conductivity values in air have been fairly well determined up to average operating temperatures of the order of 1600°F. Several studies have been conducted on the determination of the corresponding thermal conductivity values in vacuum, but unfortunately the results have not been completely conclusive. In one study** it was found that the vacuum conductivity of Min-K 2020 insulation was some 20 percent less than in air, a result

* Private Communication, F. Notaro, Linde Division, Union Carbide Corporation.

**Final Report, Report No. ALO-2661-12, Contract No. AT (29-2) - 2661, J.O. Collins, Johns - Manville, Manville, New Jersey.

that may be expected on the basis of theory. In another study, however, it was found that at high temperatures the thermal conductivity of Min-K 2020 in vacuum exceeded that in air by about 5 to 10 percent. Because the former result appears more reasonable, it is thermal conductivity values derived in the first mentioned study that have been used for Min-K 2020 insulation in the present investigation. As already mentioned, operation in air up to temperatures of about 1800°F has no adverse permanent effect on the thermal conductivity of Min-K 2020. This insulation is therefore well suited for use in unsealed silicon-germanium RTG's that undergo pre-launch operation in air. Because fibrous insulations generally have higher vacuum thermal conductivities than foil-insulations, it is generally RTG's that use the latter insulations, however, that exhibit slightly better performance in space applications. Which type insulation is used in an actual RTG depends primarily on questions of pre-launch air operation. As pointed out above, unlike fibrous insulations, it is foil-insulations that are subject to permanent damage when operating in air. Because it is usually possible to eliminate this difficulty by selecting foils that are capable of air operation, by flushing the RTG with an inert atmosphere on the launch pad or by temproarily sealing the RTG prior to launch, it is the better performance potentially available from foil-insulated RTG's in vacuum that in recent years has oriented the insulation preference in that direction. For completeness, however, the present study has also considered fibrous insulated silicon-germanium RTG's.

RESULTS AND DISCUSSION

As discussed in the preceeding sections, the method of determining the effect of air operation on the performance of silicon-germanium RTG's in the present study has been the design of RTG's with foil and fibrous insulations for vacuum operation at hot and cold junction temperatures of about 1700 and 600°F respectively. Design goal for the RTG's has been a power output of about 200 watts at a nominal load voltage of 28 volts. The RTG's are assumed to be unsealed so that in air operation it is not only the heat transfer rate from the radiator but also the heat transfer rate through the thermal insulation inside the RTG that is modified. The temperatures and performance levels of the RTG's in air operation have been determined by assuming natural convective cooling of the radiators (in addition to radiation cooling) and by using insulation thermal conductivity values corresponding to an air environment.

Figure 2 shows the performance of a foil-insulated silicon-germanium RTG in air and in vacuum as a function of generator load conditions. As expected, the performance of the generator in air is considerably less than it is in vacuum. Nevertheless, even in air operation considerable amounts of electrical power are available from the RTG. It is seen that some 80 percent of the begining-of-life power is available from an unsealed foil-insulated silicon-germanium RTG on the launch pad. Load voltage for a fixed impedance load is reduced by only about 10 percent in air operation.

The hot and cold junction temperatures of the foil-insulated RTG in air and vacuum operation are shown as a function of load current in Figure 3. It is noticed that the hot junction temperature decreases by some 200 to 300°F in going from vacuum operation to air operation. The corresponding decrease in cold junction temperature is only of the order 100 to 120°F. As already explained, whereas the change in the cold junction temperature primarily reflects the enhanced cooling due to convective cooling of the radiator, in air the change in the hot junction temperature also shows the additional effect of increased thermal conductivity of the foil-insulation that surrounds the thermocouple legs and insulates the end caps of the RTG.

Probably the most significant thing to be noted about Figure 3. is that at the load current (about 6.5 amperes) corresponding to the maximum power point of the RTG in air operation, the hot junction temperatures of the silicon-germanium Air-Vac thermocouples are about 1460°F. The corresponding cold junction temperatures are about 470°F. In air operation of the generator the multi-foil insulation in the RTG will accordingly operate at temperatures approximately in this range. Because of thermal end losses the hot junctions of the thermocouples along the axis of the RTG will exhibit a parabolic temperature distribution. It may be estimated that whereas in the present case the average thermocouple hot junction temperature in air operation is about 1460°F, the maximum will be of the order of 1500°F. The foil-insulation in the RTG will therefore have to be able to operate in air at temperatures up to 1500°F if the RTG is left unsealed during pre-launch operation. As already mentioned, refractory metal foils are not satisfactory at such temperatures. Nobel metal foils and possibly also nickel foil may be used. If refractory metal foils are to be used, they must be protected from the air by special coatings or by sealing of the RTG and/or introduction of an inert gas flush. The corresponding maximum fuel capsule re-entry shell surface temperature will be about 1600°F for air operation. Because unprotected graphite is not compatible with an air environment at such elevated temperatures, the graphite re-entry shell that usually surrounds the radioisotope fuel capsule must be protected from reaction with oxygen by application of a coating. Alternatively, sealing of the RTG and/or flushing with an inert gas on the launch pad is once again a possibility. The high temperature air operating difficulties with foil-insulation and fuel capsule re-entry shell are further amplified if the RTG were to operate in an open-circuit mode. From Figure 3. it is seen that thermocouple hot junction temperatures and accordingly also the re-entry shell surface and foil-insulation temperatures rise by about 200°F in going from maximum power output to open-circuit operation.

As concerns the cold side components of the RTG, it is believed that no problems should be encountered as a result of air operation at temperatures of the order of those indicated by Figure 3. Even though the cold stacks of Air-Vac thermocouples contain some materials, such as tungsten, that are not compatible with oxygen at high temperatures, air operation at temperatures in the 400 to 500°F range should not result in any adverse effects for periods of time not excessively long (about 1000 hours).

The corresponding performance values and operating temperatures for a Min-K 2020 insulated silicon-germanium RTG in air and vacuum operation are shown in Figures 4 and 5. As compared to the case of a foil-insulated generator, it is noted that the effect of air operation on RTG performance is considerably less for fibrous insulation. It is also noted, however, that the vacuum performance level for the fibrous insulated RTG is somewhat lower than that of the foil-insulated

RTG. Whereas the cold side operating temperatures in the two cases are about the same, the hot side temperatures of the fibrous insulated RTG exceed those of the foil-insulated generator by about 100°F. As mentioned in the preceeding section, this is acceptable as concerns the air operation of Min-K 2020. Because of the higher operating temperatures, the possible problems associated with reaction of oxygen with the graphite re-entry shell are magnified, however, in the case of the fibrous insulated RTG. Aside from this particular potential problem, no other problems are anticipated with the air operation of an unsealed fibrous insulated silicon-germanium RTG.

SUMMARY

The present study has been concerned with the pre-launch air operation of typical silicon-germanium RTG's designed for vacuum operation in space. The object of the present study has been the determination of the air operating characteristics of such RTG's and the highlighting of potential problem areas associated with air operation. Concrete RTG designs that utilize both metal foil-type as well as fibrous-type thermal insulations have been selected as a basis of the study. It has been assumed that the RTG's are unsealed to the atmosphere and that in air operation radiative heat rejection from the radiator is supplemented by natural convection. Some of the more interesting conclusions of the study may be summarized as follows:

1. A foil-insulated silicon-germanium RTG exhibits some 80 percent of its vacuum design performance in air operation. A fibrous-insulated RTG exhibits some 90 to 95 percent of its vacuum design performance in air operation.
2. As a result of air operation, no permanent damage to the cold sides of unsealed silicon-germanium RTG's is anticipated. This applies to both foil as well as fibrous insulated RTG's.
3. The foil-insulation in foil-insulated RTG's may be required to operate at temperatures as high as 1500°F in air. If the RTG is to be unsealed, it will be necessary to use foils that are not permanently damaged as a result of such operation. Nobel metal and possibly nickel foils should

be suitable for this purpose. Refractory metal foils, however, have to be protected from the air (oxygen).

4. No problems with fibrous insulation (Min-K 2020) are anticipated as a result of RTG operation in air.

5. The graphite re-entry shell of the radioisotope fuel capsule will operate at temperatures of the order of 1600°F or higher in air. In the case of both foil as well as fibrous-insulated RTG's this means that the graphite must be protected from reacting with oxygen.

In conclusion it may be stated that possible problem areas in the unsealed air operation of a typical silicon-germanium RTG are the foil-insulation and the graphite re-entry shell of the fuel capsule. The former of these problem areas may be eliminated by a judicious choice of metal for the foils of the insulation. The latter problem area may be eliminated by using a coating on the re-entry shell that is impermeable to oxygen. Alternatively, both problem areas may be eliminated by sealing the RTG during air operation or flushing it with an inert gas on the launch-pad. Finally, if forced convection instead of the natural convection assumed in the present study is used for cooling the RTG on the launch pad, it may be possible to decrease all RTG operating temperatures by several hundred degrees Fahrenheit. Even through this somewhat alleviates the potential problem areas associated with the air operation of the foil-insulation and the graphite re-entry shell, it does not completely eliminate them.

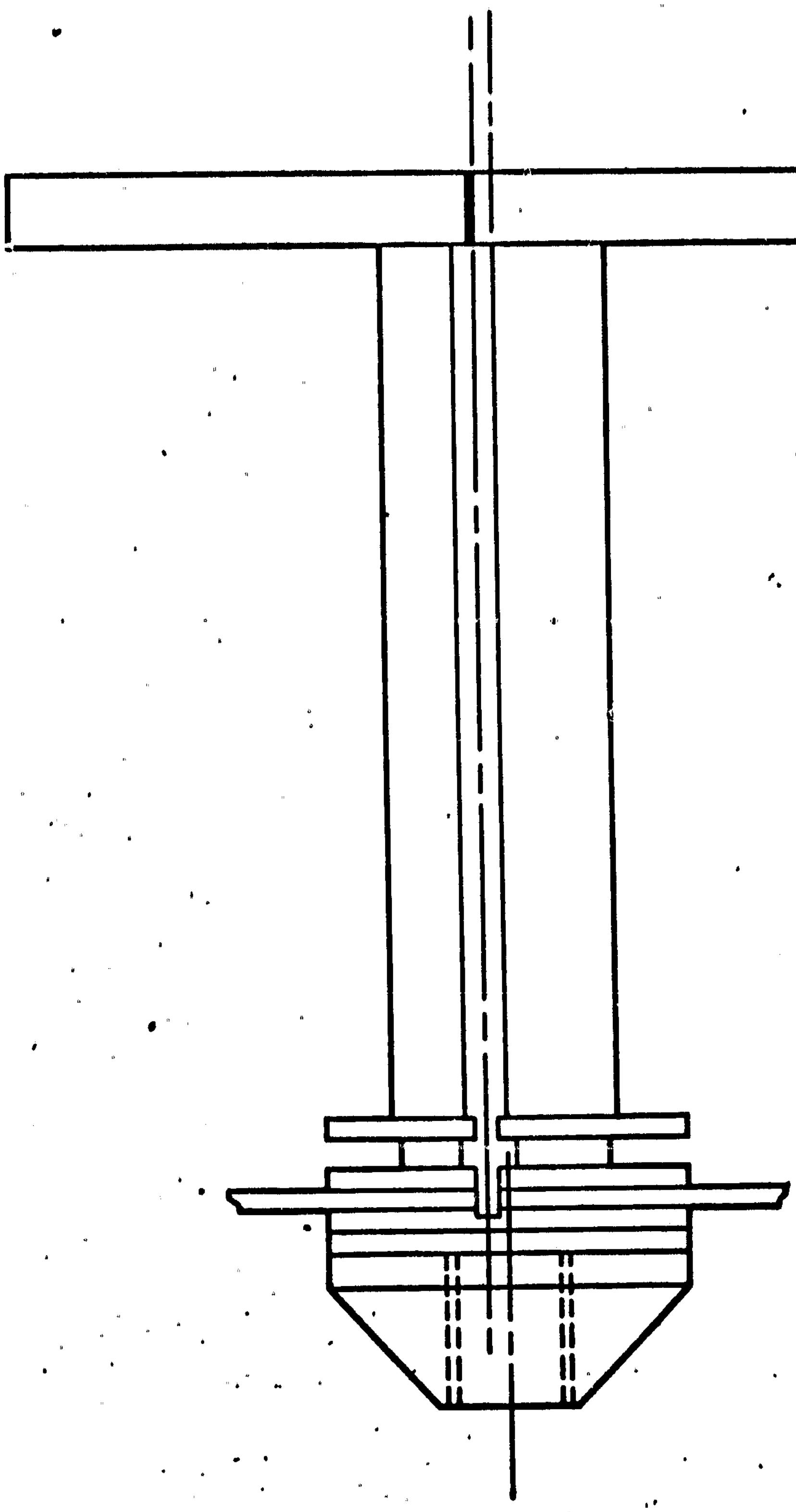


FIGURE 1

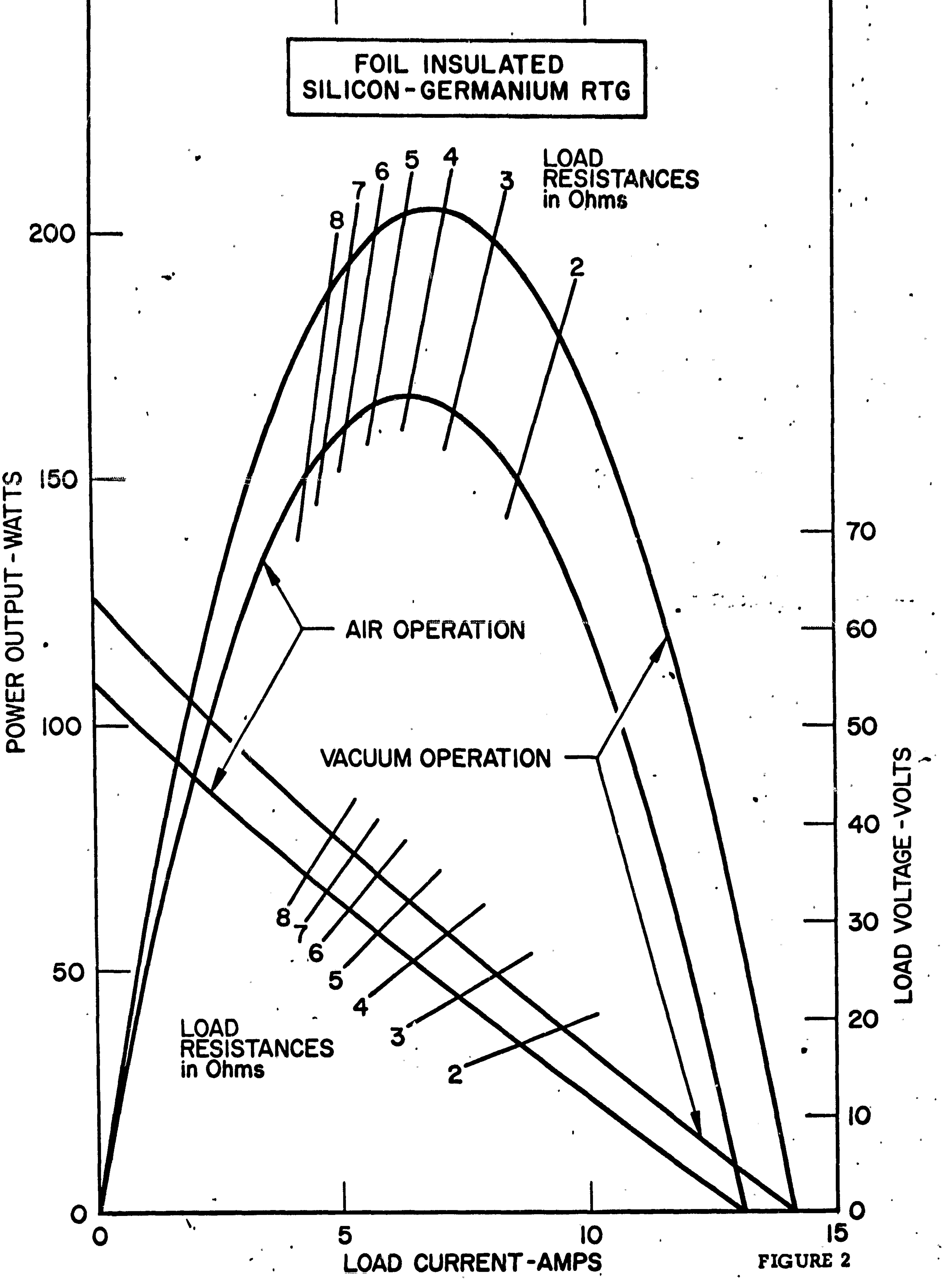

FOIL INSULATED
SILICON-GERMANIUM RTG
LOAD RESISTANCES in Ohms
8
7
6
5
4
3
2
AIR OPERATION
VACUUM OPERATION
8
7
6
5
4
3
2
LOAD RESISTANCES in Ohms
POWER OUTPUT-WATTS
0
50
100
150
200
LOAD VOLTAGE-VOLTS
0
10
20
30
40
50
60
70
LOAD CURRENT-AMPS
0
5
10
15

FIGURE 2

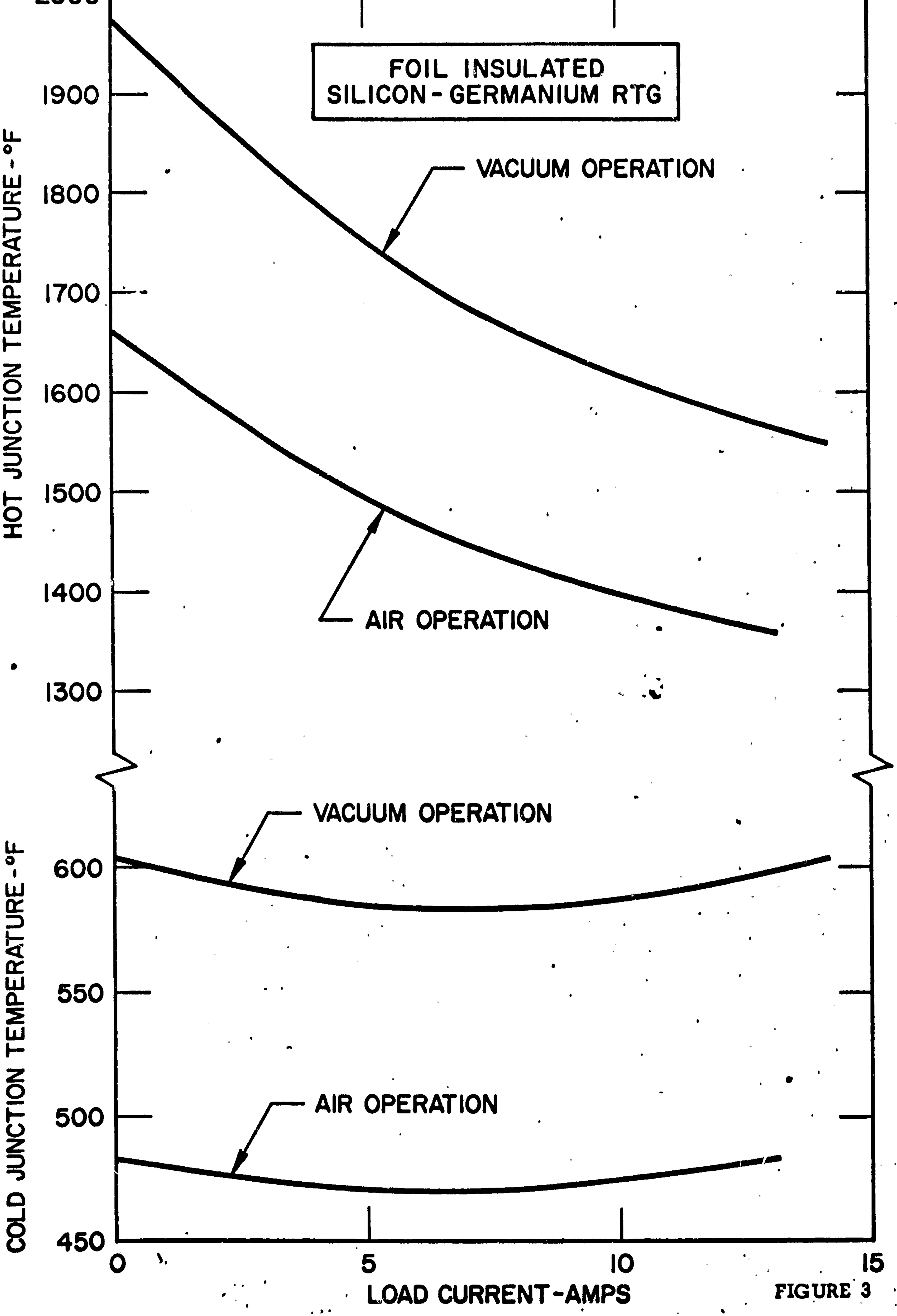
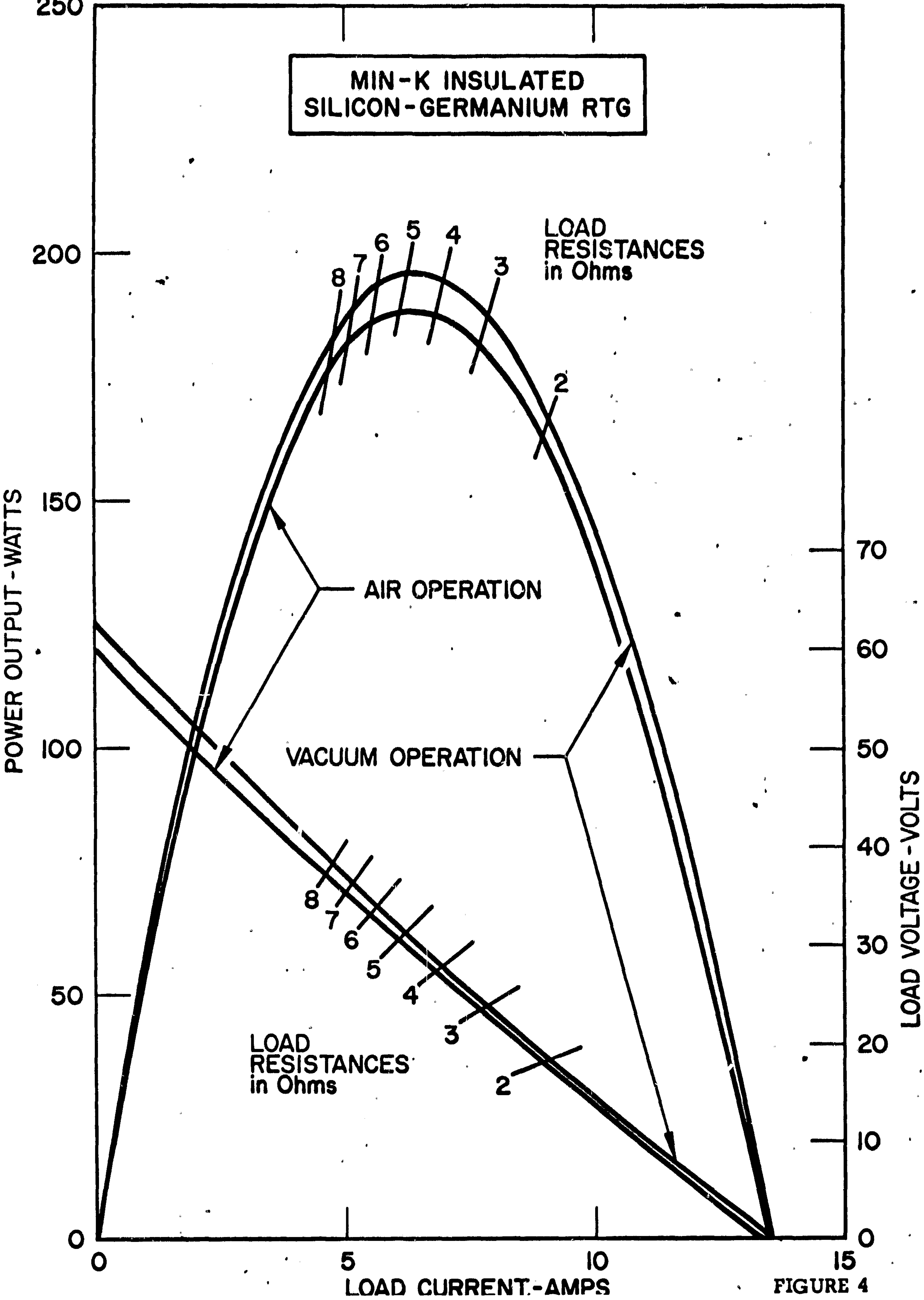

FOIL INSULATED
SILICON-GERMANIUM RTG
HOT JUNCTION TEMPERATURE-°F
1900
1800
1700
1600
1500
1400
1300
VACUUM OPERATION
AIR OPERATION
COLD JUNCTION TEMPERATURE-°F
600
550
500
450
VACUUM OPERATION
AIR OPERATION
0
5
10
15
LOAD CURRENT-AMPS

FIGURE 3



MIN-K INSULATED
SILICON-GERMANIUM RTG
LOAD RESISTANCES in Ohms
8
7
6
5
4
3
2
AIR OPERATION
VACUUM OPERATION
8
7
6
5
4
3
2
LOAD RESISTANCES in Ohms
POWER OUTPUT - WATTS
0
50
100
150
200
250
LOAD VOLTAGE - VOLTS
0
10
20
30
40
50
60
70
0
5
10
15
LOAD CURRENT - AMPS

FIGURE 4

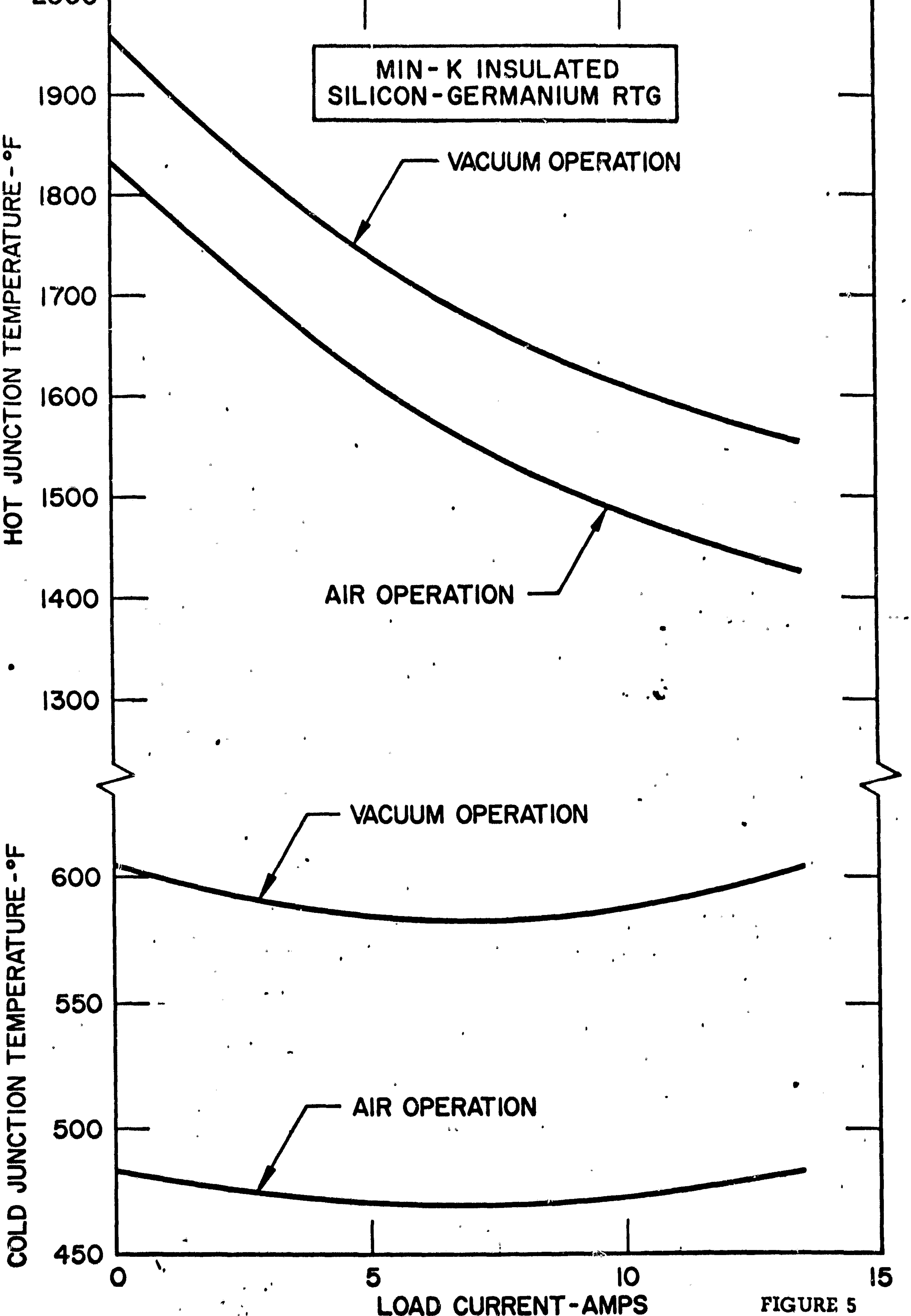

MIN-K INSULATED
SILICON-GERMANIUM RTG
VACUUM OPERATION
AIR OPERATION
VACUUM OPERATION
AIR OPERATION
HOT JUNCTION TEMPERATURE - °F
COLD JUNCTION TEMPERATURE - °F
1900
1800
1700
1600
1500
1400
1300
600
550
500
450
0
5
10
15
LOAD CURRENT - AMPS

FIGURE 5