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SNAP III

Final Performance Test Summary

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MND-P-2398

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FOREWORD

This report has been prepared by The Martin Company as partial fulfillment of Task 3 for Fiscal Year 1961. It summarizes the results of performance, parametric and life tests undertaken through June 1960 on the SNAP III, radioisotope-fueled, thermoelectric generator. The Task 3 program was conducted by The Martin Company under Contract AT(30-3)217 from the United States Atomic Energy Commission.

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SUMMARY

SNAP III, a 3- to 5-watt electrical generator, was designed as a proof-of-principle device in the development of radioisotope powered, thermoelectric power conversion systems. A program involving five development areas was employed in achieving this aim. These areas were:

- (1) Generator development, fuel encapsulation and handling techniques.
- (2) System safety studies.
- (3) System dynamic tests.
- (4) System parametric performance tests.
- (5) System life tests.

In this report, particular attention was given to fuel encapsulation and handling techniques, system safety studies, system parametric performance tests and system life tests. Reference is made to two other reports which describe, in detail, the SNAP III operational testing and dynamic testing of the unit.

I. INTRODUCTION

During the early stages in the development of thermoelectric materials, the idea was expressed that radioactive decay processes would provide an excellent source of thermal energy for conversion via thermoelectric techniques. Several radioactive isotopes with reasonably long half lives and high specific heat-to-volume ratios were available, and their decay heat could produce the high temperatures necessary to effect the large temperature difference required across the active length of a thermoelement.

The Martin Company, under contract to the U.S. Atomic Energy Commission, designed and developed the SNAP III generators to combine these two compatible features into a direct conversion device which would be an excellent replacement for the normal storage battery in certain selected applications. The primary purpose of this program was to determine practical isotope handling requirements and to assure that a generator so powered would produce the necessary amount of electricity with reasonable efficiency and reliability.

This report describes the results of the program. The data and experience obtained on SNAP III generators is presented, not as a separate entity in itself, but as proof-of-principle data that can also be applied to other thermoelectric direct conversion devices.



II. GENERAL DESIGN DESCRIPTIONS

The SNAP III 3M-1-G series thermoelectric generators were produced by Minnesota Mining and Manufacturing Company (3M) and isotopically fueled by The Martin Company.

The SNAP III generators of the type shown in Fig. 1 are right cylinders with spherical ends. They are 5-21/64 inches high and 4-53/64 inches in diameter. The nominal electrical output is about 3.5 watts for a heat input of 65 watts or an overall efficiency of over 5%.

Design details of the generator are shown in Fig. 2.

The spun copper shell housing the generator mechanism has a wall thickness of 0.030 inch and is constructed in two sections. The top closing dome contains a gas fill tube and power input electrical leads (electrically heated units only). The lower case contains a gas fill tube, electrical output and thermocouple leads and the generator thermoelectric structure. The two sections are soldered with a lead-tin solder using an induction heating coil. The complete generator weighs 3.8 pounds.

Fifty-four lead telluride thermoelectric elements are under axial compression between an aluminum right cylinder and a stainless steel collector hub. These elements are approximately 0.225 inch in diameter and 1 inch long. Twenty-seven elements are N-type containing lead iodide doping, and 27 have sodium doping and are of the P-type. The elements are electrically connected in series, alternating N- and P-types.

The series electrical continuity on the cold side is obtained by using an insulating washer between the element cold shoe and the aluminum cylinder and then connecting element pairs with copper wire which is soldered to the cold shoes. The cold shoes are soldered to each element with tin-bismuth solder.

The series electrical continuity on the hot side is obtained by pressing each pair against a common iron shoe. Each shoe is separately insulated from the stainless steel hub by coating the hot collector hub with an interface of aluminum oxide. The pressure electrical contact is obtained by spring loading each element axially with a 2-pound spring load located in the cold aluminum ring. Screw caps permit individual element spring loading adjustments. With the arrangement described, an average pair cold shoe-to-cold shoe electrical resistance of less than 0.05 ohm could be achieved with the generator at room temperature.

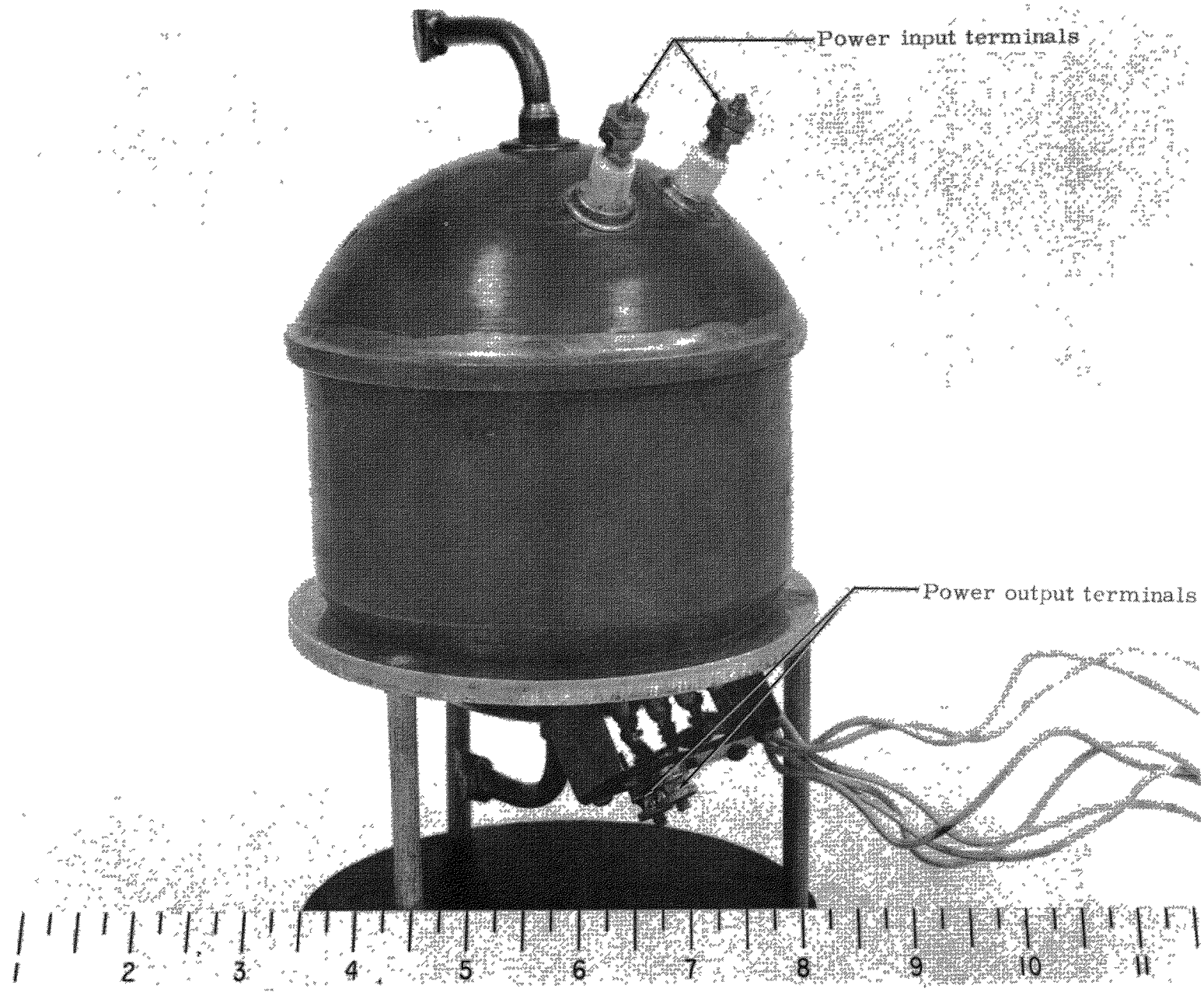


Fig. 1. Thermoelectric Generator No. 1-G-4

MND-P-2398

The isotope source is sealed in a welded canister which is then sealed in the generator capsule. This capsule is inserted in the stainless steel collector hub. The capsule is made of molybdenum with a pressure tight plug or of Haynes 25 alloy with a welded plug. This capsule has a 4-degree taper on the outer surface so it can be easily removed when the generator is defueled. It also ensures better thermal contact with the collector hub. For electrically heated sources, a Watlow Firerod heater cartridge, rated at 115 volts and 125 watts, was inserted in the source capsule.

Polonium-210 was selected as the fuel for this type generator because of its high specific alpha and low gamma activities. This facilitated ease of handling and demonstration. This isotope has a specific power of 144 thermal watts per gram of pure material and a half life of 138 days. It is a reactor-produced radionuclide and can be readily separated from the target material by chemical methods.

Mica sleeves are placed on each element. Their primary purpose is to reduce sublimation of the element near the hot end. In addition, there is a slight increase in element strength.

Normally, three thermocouples are provided in a generator to measure cold shoe, hot shoe and source temperatures.

The internal cavities of the generator are filled with a powdered thermal insulator. This insulator is Min-K 1301. Solid machined Min-K is used in both end caps. To completely fill all remaining voids, powdered Min-K was added while vibrating the generator. Various gases with a small amount of reducing hydrogen or a vacuum atmosphere complete the interior composition. The type of gas and pressure will be explained in Chapter V.

III. FUEL ENCAPSULATION AND HANDLING TECHNIQUES

One of the major phases of this program was to demonstrate that isotope fueling of a thermoelectric generator was feasible and to delineate guide lines and procedures to follow to accomplish this task. Various items in developing handling procedures arose and are discussed in this section.

The most obvious problem was the necessity for a dry containment box which would permit generator fuel loading or unloading and provide the three following functions:

- (1) Contain any radioactive spillage. This required a dry containment box negative pressure and gas outlet absolute filters.
- (2) Provide a reducing atmosphere. Introduction of a 1200° F isotope heat source into a generator would cause oxidation at the critical hot junction. To maintain clean, low resistance pressure contacts, a reducing atmosphere was required in the generator at the time of source insertion.
- (3) Enable manipulation of the tools for opening, sealing and leak checking of the SNAP III generators.

The second problem was safe containment of the isotope fuel. The Polonium-210 alpha emitter was purchased from Monsanto Chemical Company, Mound Laboratories. This fuel is fabricated in a double encapsulated canister, the outer canister measuring 0.369 inch in diameter and 1.314 inches in length at 800° F. This canister was placed in a 4-degree tapered capsule which was sealed and inserted in the generator heat source cavity. Electrical Watlow heaters were installed in the tapered capsule for the initial electrically heated tests of the generators.

Two fuel capsules for the 1-C-1 and 1-G-1 generators* were fabricated from molybdenum coated with Colomony No. 5 flame spray coating to reduce corrosion. Both capsules were sealed with a Lee plug. This stainless steel closure plug is ribbed externally and has a tapered insert to expand and seal the Lee plug under a pressure of 700 psi.

During the refueling process of the 1-G-1 generator, the Lee plug was found to be loose. The source canister was removed and found free of physical surface defects. A Health Physics check disclosed a large alpha

*See Chapter IV for generator identification.

radiation count within the disassembly dry containment box. Subsequent inspection by Mound Laboratories revealed that the source was not leaking but that weld oxidation caused some of the surface metal to flake off. This permitted polonium entrapped in the weld to escape. Complete decontamination is difficult with this type of source fabrication. However, with normal isotope handling precautions, this contamination is not a serious problem.

Removal of the isotope fueled capsule from the 1-G-1 generator stainless steel source cavity could not be accomplished without severe damage to the generator. It was removed by longitudinally sawing the collector. No evidence of molybdenum-stainless steel bonding was apparent. The "freeze-up" was caused by different coefficients of expansion of the fuel capsule and generator fuel capsule housing (Mo and SS), respectively. The molybdenum had a lower coefficient of expansion than the stainless steel, and when the generator was heated initially, the capsule depressed further into the tapered hole. As the fuel capsule temperature reduced due to isotope decay, the collector contracted about the capsule and prevented normal capsule removal.

During the structural tests on the isotope fuel capsule, the molybdenum capsule with a Lee-type plug was found to be unsatisfactory for strength and corrosion resistance. Out of this program evolved the Haynes 25 alloy capsule. The 1-G-4 generator, loaded in May 1960, used the Haynes 25 alloy capsule with a welded closure plug. This capsule permitted easier refueling and more positive isotope containment.

Welding of Haynes 25 was conducted in a helium atmosphere under 30 psi pressure. Due to the small diameter of the welded seam, initial difficulty was experienced by a blowout of the molten metal due to pressure buildup inside the closed capsule. An additional welding step was then used which consisted of increasing the helium atmosphere pressure at the moment of closing the welded circle. This reduced the differential pressure and produced isotope-containing capsules with highly successful welds. These capsules have withstood high forces during impact tests without rupturing.

Removal of spent Polonium-210 fuel capsules was conducted in a manner simulating a heavy wall capsule rupture. The slight negative pressure required in the dry box was obtained by a suction ventilation system drawing through an absolute filter. The inert atmosphere used was nitrogen. This prevented any generator hot shoe oxidation during source capsule removal. Health Physics monitoring was utilized during each step of the capsule removal.

Welding of the Haynes 25 capsule was accomplished in a helium atmosphere at 30 psi. This entrapped helium provided a thermal bond between the isotope canister and capsule and also permitted a vacuum leak check of the welded capsule. The capsule was placed in a vacuum-tight container connected to a vacuum system and a helium leak detector.

Experience gained during this program has shown that isotopically fueled generators can be fueled, defueled and handled safely with a high degree of confidence.



IV. GENERATOR HISTORIES

A brief history of each generator is presented in this section. This provides background data and a more complete description of the generators developed during this program.

A. 3M-1-C-1 GENERATOR

The original SNAP III generator was manufactured by Minnesota Mining and Manufacturing Company for the AEC and delivered to The Martin Company in late 1958. After initial tests, using an electrical heater to determine operating characteristics and internal gas fill procedures, this generator was isotopically fueled with approximately 1600 curies of Polonium-210 provided by Mound Laboratories (Monsanto Chemical Company). The internal gas was 75% N₂ and 25% H₂ at 15 inches of mercury absolute pressure.

The radioisotope fueled and electrically evaluated 1-C-1 generator was delivered to the AEC on 12 January 1959.

The generator was returned to The Martin Company on two more occasions. A neutron measurement was made in March 1959. The neutron count of less than 2 mr/hr was found to be due to a (α ,n) reaction with the slight oxygen contamination in the Polonium-210 fuel. During April 1959, the generator was evacuated to check the gas integrity of the shell and refilled again with 1/2 atmosphere of 75% N₂ and 25% H₂. The generator was returned to the AEC on 25 April 1959.

B. 3M-1-G-1 GENERATOR

The second isotopically heated generator was fueled with a 1738-curie Polonium-210 source in April 1959 and delivered to the AEC. The original output of this unit was approximately 2.5 watts with a Seebeck voltage of 3.5 volts. During March 1960, this generator was returned to The Martin Company for refueling after the Polonium-210 had decayed to approximately 220 curies (3 half lives).

Figure 3 shows the output characteristics of this generator when it was received by The Martin Company in March 1960. Operation of the generator appeared normal except for the low input power.

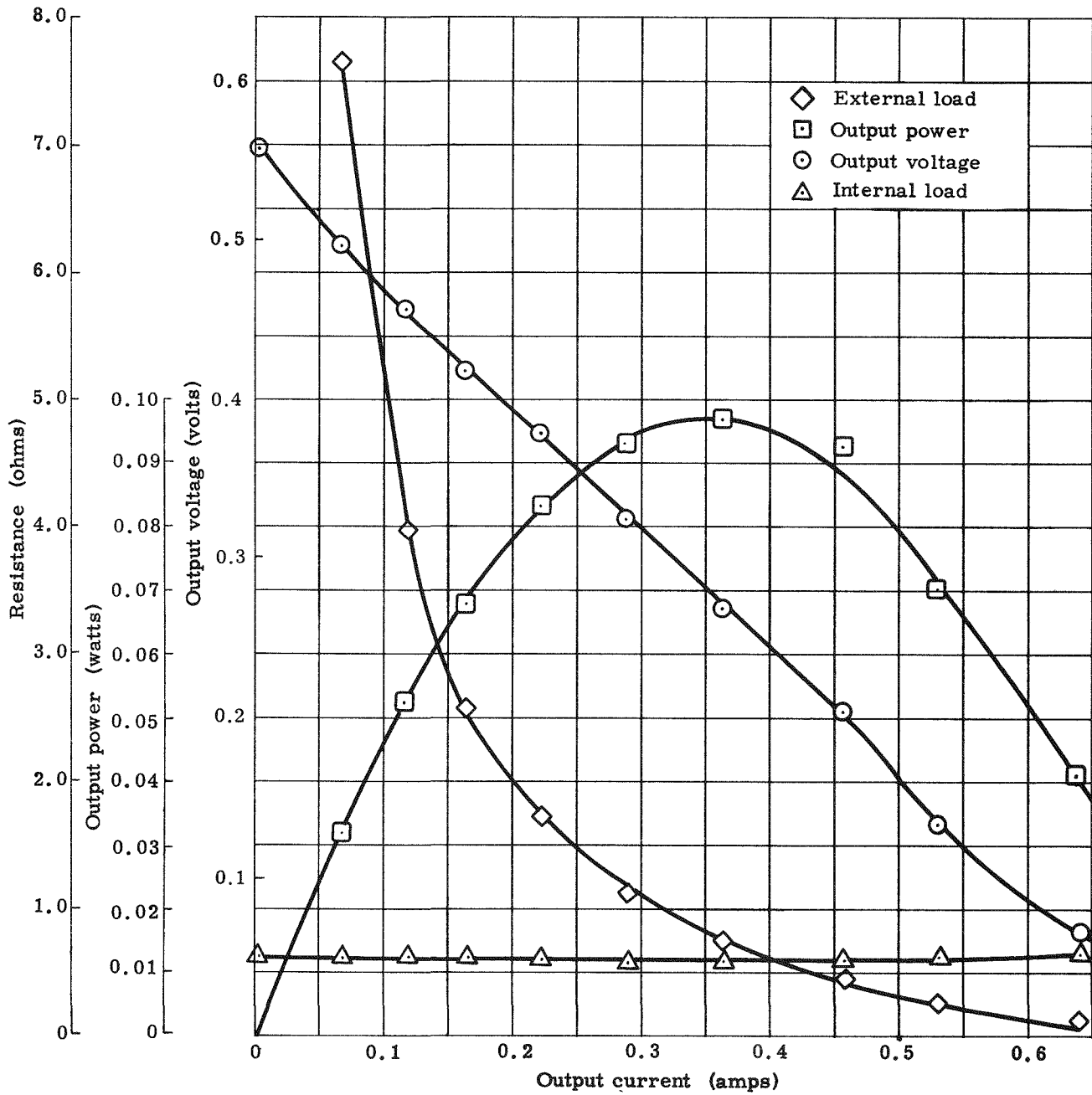


Fig. 3. Performance of 1-G-1 Generator after Three Half Lives of Po-210 Decay

In April 1960, an attempt was made to defuel this generator. The molybdenum fuel capsule could not be separated from the stainless steel hot shoe collector. During the various unsuccessful attempts, the generator elements failed structurally and the capsule was removed intact with the stainless steel collector. The capsule was returned to Mound Laboratories for inspection and disposal.

C. 3M-1-G-3 GENERATOR

This generator was completed in May 1959 for use in parametric tests. On 21 August 1959, the generator failed after approximately 465 hours of operational testing at various input power levels. At failure, the unit had been operating with 65 watts input power for 14 hours. This generator had been operated by the manufacturer at 68.6 watts input prior to delivery.

Internal inspection revealed one broken P-type element and other P-type elements which had rotated approximately 1/8 of a revolution. Sublimation of the elements had deposited large crystals on the element mica sleeves and colder element areas.

The generator was repaired by The Martin Company. The P-type elements were machined to the proper size and the hot junction collector was recoated with aluminum oxide. The reassembled generator was used for completion of the parametric tests.

Shell gas leakage in the outer container at the closing solder joint on the 1-G-3 generator was a problem. Many attempts were made to correct this condition but the low creep strength of lead-tin solder at 200° F under differential pressures greater than 1 atmosphere prevented complete gas containment. At completion of the parametric tests, the generator was disassembled for a careful internal resistance measurement of the various components.

D. 3M-1-G-4 GENERATOR

The 1-G-4 generator to be used for dynamic testing was completed in July 1959. Prior to these tests, it was used for two months for parametric studies employing an electrical heater. It was then used for dynamic testing over a span time of 6 months. Performance of this generator is shown in Fig. 4.

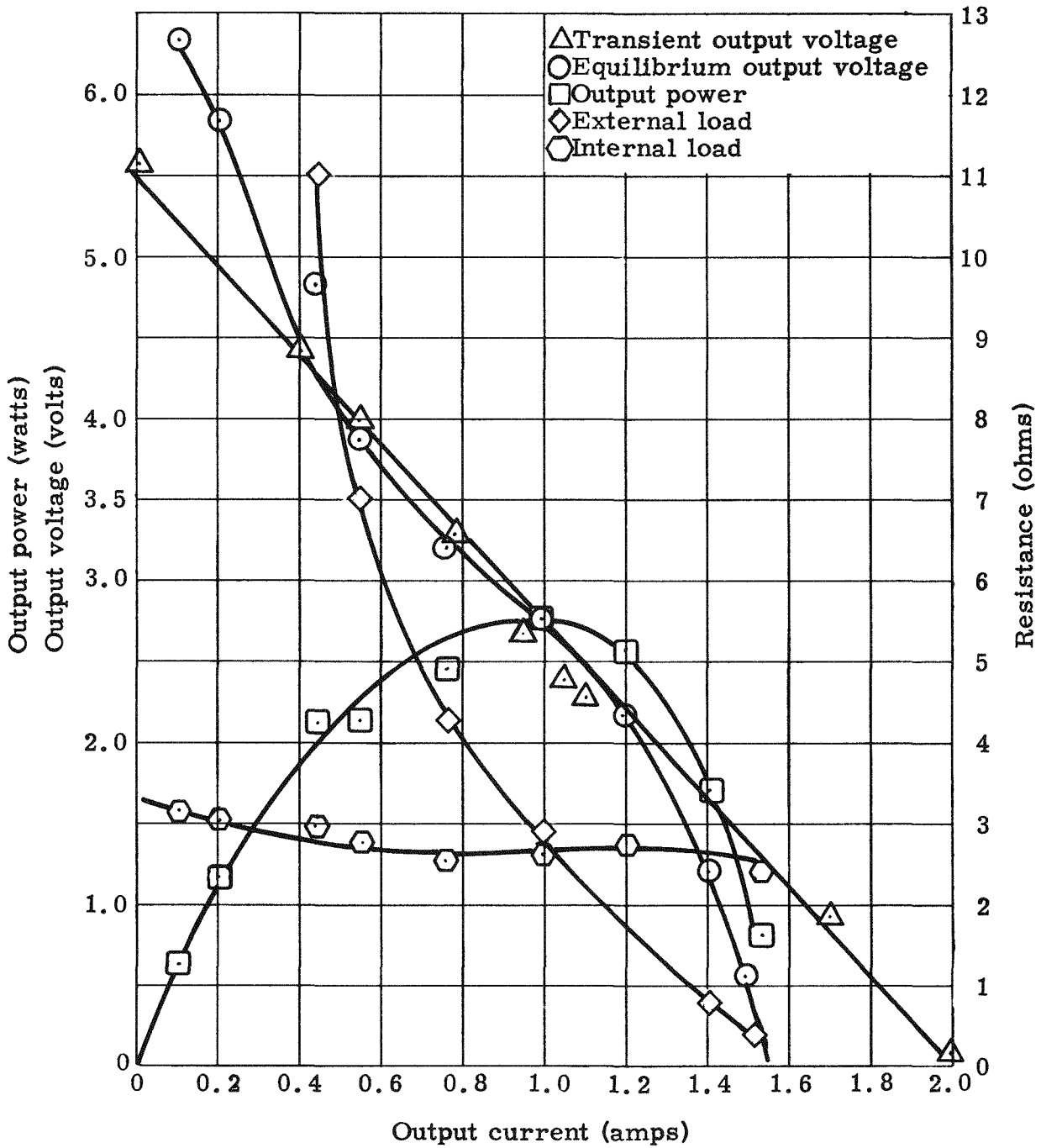


Fig. 4. Performance of 1-G-5 Generator at 65 Watts Input Power

After completion of the dynamic tests, the generator was again checked under normal room environment conditions to determine performance prior to loading with an isotopic fuel. The 1-G-4 was fueled with approximately 2100 curies of Polonium-210. The fueled generator was checked electrically at external loads which resulted in 1150° F or less hot shoe temperature. It was then delivered to the AEC for immediate use at the Miami scientific meeting in early May 1960.

E. 3M-1-G-5 GENERATOR

The 1-G-5 generator was received along with the 1-G-4 for similar dynamic tests. It, too, was used initially for parametric testing during the summer of 1959.

Following the dynamic tests, it was also considered for the 1-G-1 replacement as an isotopically fueled generator. Due to its slightly lower maximum power output (compared to the 1-G-4) and a slight erratic behavior at higher load currents, this generator has not been used for any other tests to date. Figure 5 presents the generator characteristics at 65 watts power input.

F. 3M-1-G-10 GENERATOR

The 1-G-10 generator was received by The Martin Company on 18 January 1960 for SNAP III life test evaluation. It was filled with 95% argon and 5% hydrogen at 1 atmosphere by the manufacturer (Minnesota Mining and Manufacturing Company). The generator, as received, had about a 6% efficiency.

Approximately 6 days of electrical tests were conducted to determine the electrical and environmental parameters. The life test power input was determined to be that open circuit condition which produced 1100° F hot shoe temperature. Thus, an input of 67 watts and optimum load resistance of 4.5 ohms were set for continuous generator operation. The generator, through 23 August 1960, had operated continuously for 7 months under these conditions.

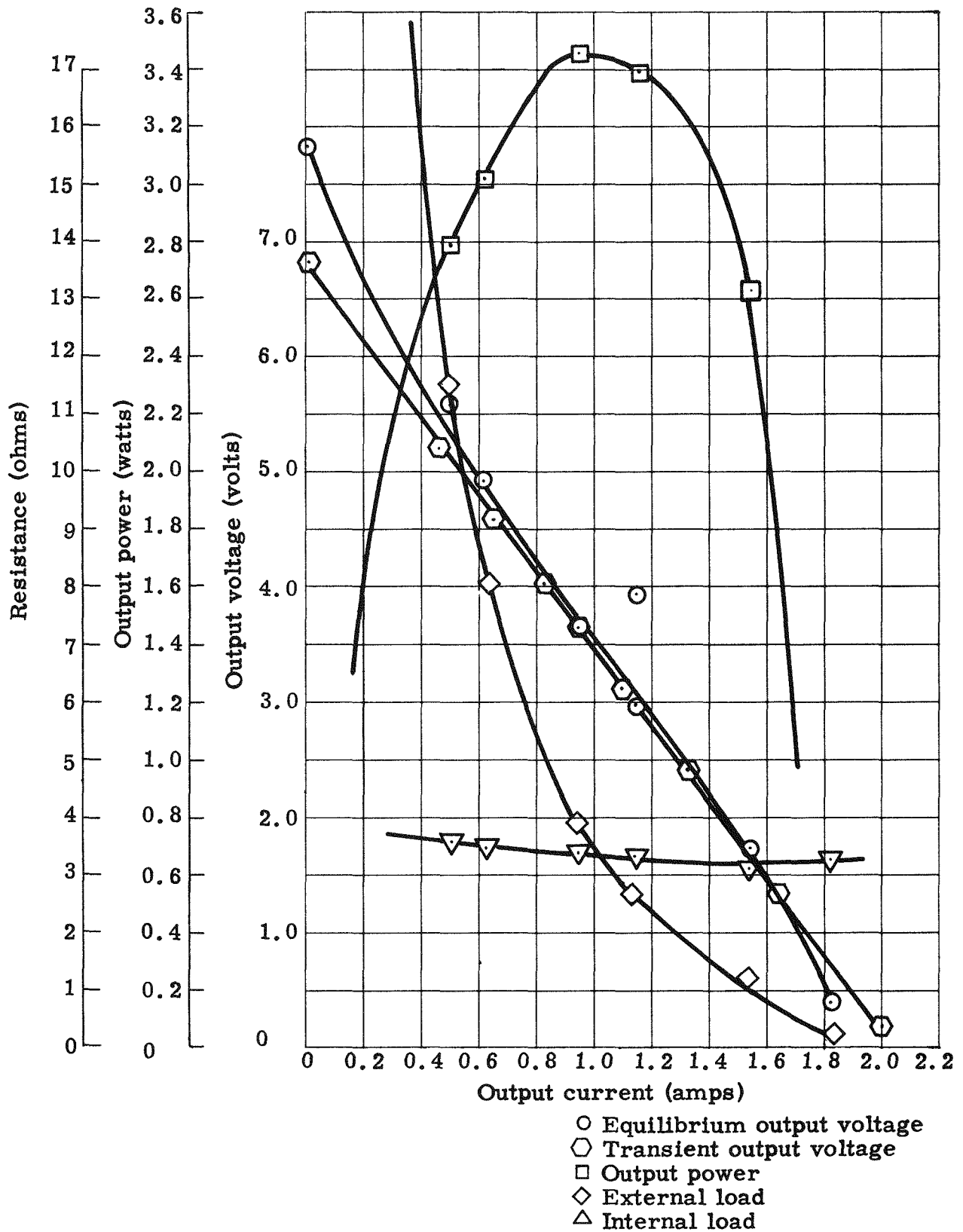


Fig. 5. Performance of 1-G-4 Generator at 65.3 Watts Input Power

V. SYSTEMS TESTS

A. RADIOISOTOPE SAFETY

Radioisotope safety studies for the SNAP III generator consist primarily of those associated with normal handling or use of a fueled generator in connection with personnel and personnel-induced generator failures. The safety controls for fuel encapsulation and generator loading were covered in Chapter III. The safety analyses and tests associated with a fuel capsule rupture due to earth atmosphere re-entry or rocket launch failures have been explored to a great extent and are reported in Ref. 1.

The two areas of radioisotope safety that will be discussed are Health Physics requirements and helium pressure buildup in the Polonium-210 capsule.

1. Health Physics Requirements

Three SNAP III generators have been fueled with Polonium-210. The quantities of fuel ranged from 1600 curies for the 1-C-1 to 2100 curies for the 1-G-4. Polonium-210 is an alpha emitter. The primary radiation hazard during generator handling is, therefore, gamma radiation or bremsstrahlung.

Typical gamma and neutron radiation intensities for the 1-G-4 generator fueled with 2100 curies of Polonium-210 and unshielded were:

Gamma

Surface of heat capsule (r/hr)	1.5
Surface of generator outer shell (mr/hr)	400
One foot from generator shell (mr/hr)	60
One meter from generator shell (mr/hr)	6

Neutron

Two inches from generator shell	Less than 2 mr/hr
---------------------------------	----------------------

These radiation data show that there is a relatively small radiological hazard connected with handling of a fueled generator. Normal transportation is accomplished inside a cask. When a generator is set up for operation, and personnel do not spend appreciable time (less than 8 hours per day) within one meter of the generator, the dosage received would be below tolerance. As the fuel decays with a half life of 138 days, the quoted dose levels would also decrease at the same decay rate.

The slight neutron radiation originates from a slight contamination of the Polonium-210 (oxygen, etc.) causing an (α, n) reaction from the alpha particles of polonium. As seen in the table, this is well below tolerance.

The requirements of Health Physics in monitoring fueled generators must not be overlooked. As stated, there is appreciable gamma radiation and a slight amount of neutron radiation. Location of the fueled generators must be known and any personnel conducting extensive work with or near the generator should be controlled as to total amount of exposure. In general, handling should conform to Title 10 of the Code of Federal Regulations, Part 20.

2. Helium Pressure Buildup in the Po-210 Capsule

The thermal energy source for SNAP III consists of two cylindrical stainless steel containers containing Polonium-210. Both containers are housed in a right cylindrical canister of stainless steel. This container is further encased in a heavy walled, tapered receiver capsule. The latest configuration of this tapered receiver is a seal-welded capsule of Haynes 25 alloy.

A study was conducted to determine the internal helium pressure buildup throughout the lifetime of a SNAP III generator that is fueled with Polonium-210, which is an alpha or helium nucleus emitter.

By determining the number of helium nuclei emitted from the Polonium-210 as a function of time and fuel temperature as a function of time, ambient temperature, disintegration rate and thermal efficiency, the pressure parameters were determined by the ideal gas law.

Table 1 shows time versus pressure resulting from this analysis. Initial conditions were as follows:

- (1) Eight hundred and thirty-two curies of ${}_{84}\text{Po}^{210}$ in each capsule initially.
- (2) Initial source temperature of 644°K .

- (3) Ambient temperature of 300° K.
- (4) Half life of Po-210 of 138.4 days.
- (5) A gas volume of 0.266 cm³ in each container.

TABLE 1

Calculated Helium Pressure in Internal Canister
as a Function of Time

<u>Time</u>	<u>Pressure (psi)</u>
1 week	87
1 month	332
1 year	1190
3 years	1200

Examination of the inner stainless steel, polonium-fueled canisters has shown no failure or deformation. However, due to the high theoretical pressure buildup, the two inner fuel containers have been enclosed within an additional stainless steel canister.

B. THERMOELECTRIC HOT JUNCTION TEMPERATURE CONTROL

The primary cause of generator performance degradation has been an increase in internal resistance at the hot junction contacts between the elements and hot shoes. The thermoelectric material used in SNAP III generators is made from lead telluride, which has a significant sublimation characteristic above 1150° F at 1 atmosphere absolute pressure.

For isotope-fueled generators, the initial fuel thermal output must be such that at normal operating external load conditions, the hot shoe will not exceed 1150° F. With the relatively short half life of Polonium-210 (138 days), this critical period would be prevalent for less than the first month after fueling. During storage or transportation, precautions should be taken to keep the output terminals shorted to take advantage of the higher rate of Peltier cooling and, hence, minimum possible hot junction

temperature. Overheating can then be obtained only by insulation of the exterior shell.

Figures 6 and 7 present the output parameters and element junction temperatures of the newly fueled 1-G-4 generator with 2100 curies of Po-210. Under short circuit equilibrium conditions, the hot junction temperature was 1089° F as compared to 1148° F for the maximum power output.

As a point of interest, it was found that the temperature decreased still further when the newly fueled 1-G-4 generator was placed inside the steel shipping cask under short circuit conditions. This was due to the close proximity of the generator outer shell and the cask inner wall, coupled with the larger external cask heat transfer surface. This temperature decrease amounted to 77° F at the hot junction.

C. DYNAMIC TESTS

The electrically heated SNAP III generator, 1-G-4, was subjected to vibration, acceleration and shock intensities simulating the conditions for the third stage and payload of the Vega vehicle and the WS-117L vehicle. Generator performance and efficiency were analyzed for each orthogonal plane of test. Details of the test results may be found in Ref. 2.

The generator shell, internal structure and pressure, and the hot and cold junction temperatures were not affected during the test.

During mechanical environmental testing, a-c ripple was evident in the generator d-c output. This phenomenon may have been caused by elastic deformations within the generator, due to the environmental forces. The most severe a-c ripple was observed when the generator was vibrated on an axis along the hub centerline. This ripple disappeared after the completion of each test cycle.

The generator operated approximately 300 hours during the entire test program. Efficiency varied slightly during the vibration cycle. The average recovery time was approximately 5 minutes. In the acceleration and shock phases, there was a negligible variation in efficiency. The average efficiency variation for the entire test was less than 5% of the overall generator performance.

These tests of the SNAP III-type thermoelectric generator proved that it is a rugged device capable of satisfactorily withstanding mechanical environmental conditions of space vehicle launching.

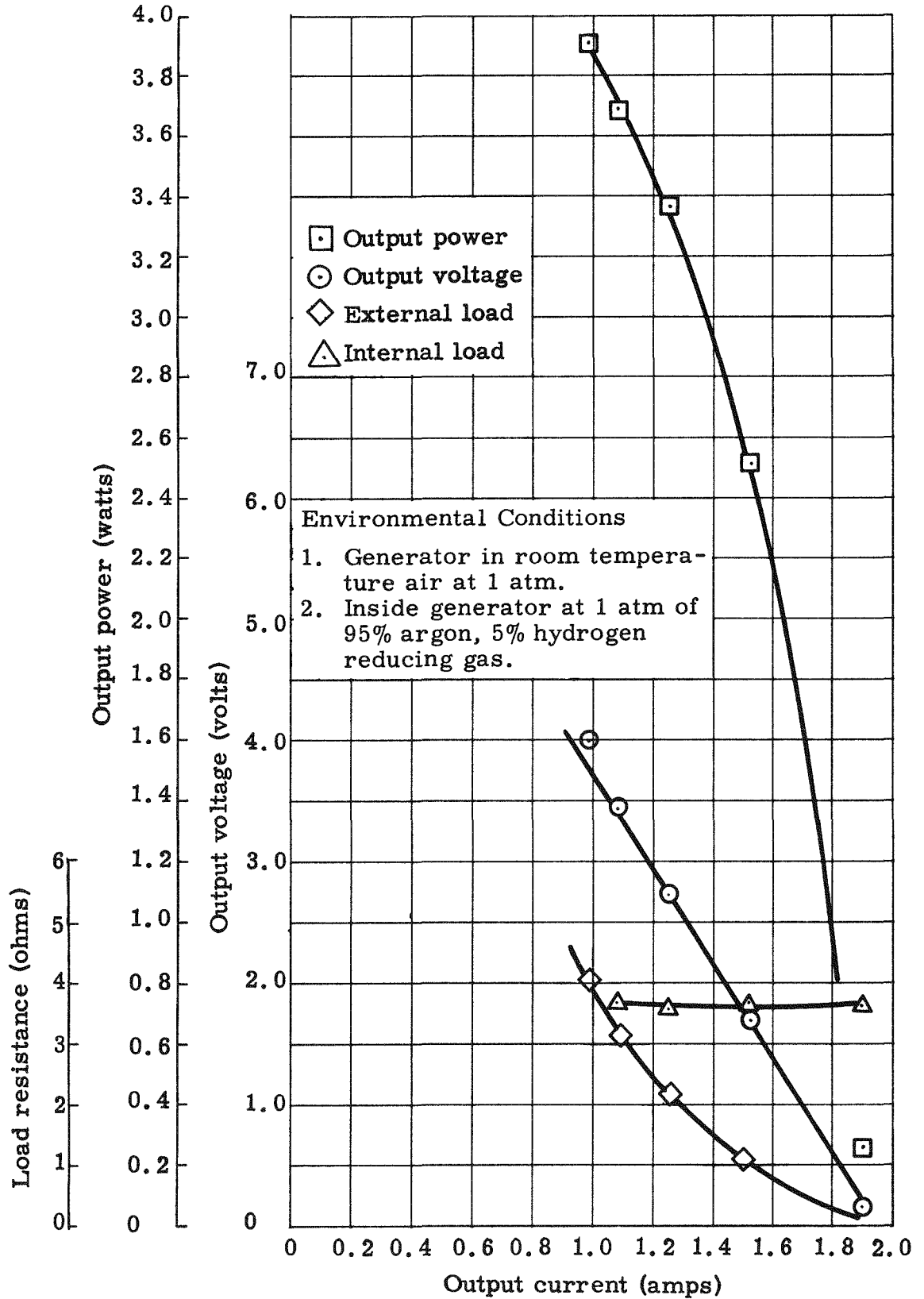
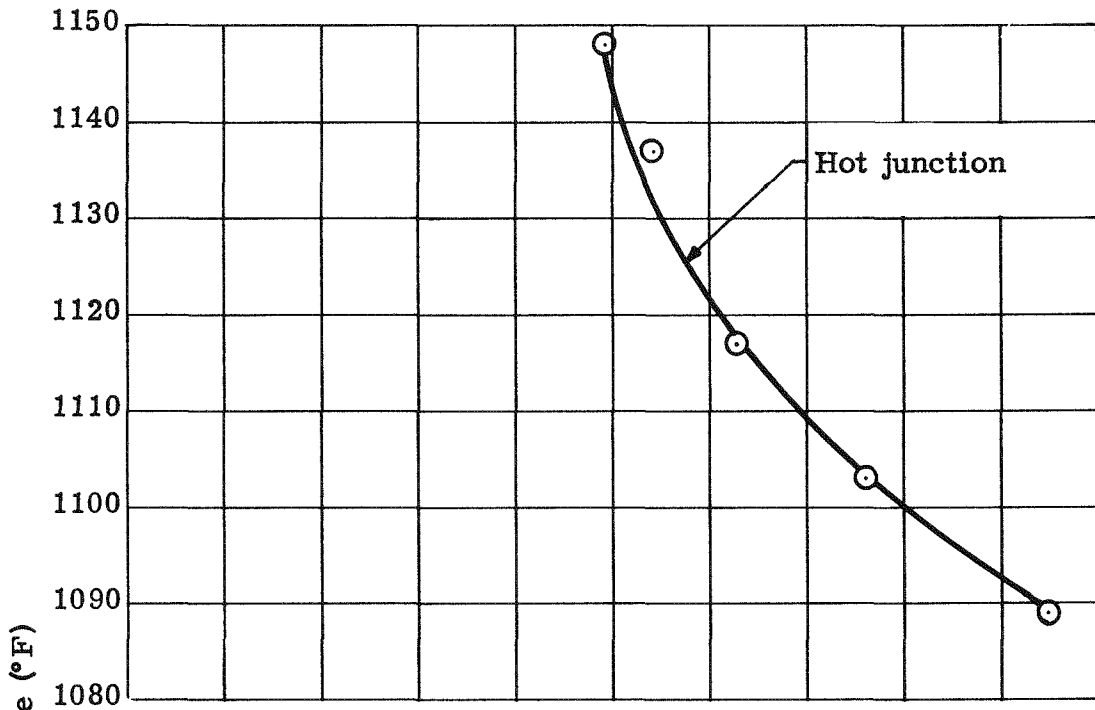


Fig. 6. Performance of 1-G-4 Generator after Fueling with 2100 Curies of Po-210



Environmental Conditions

1. Generator in room temperature air at 1 atm
2. Inside generator at 1 atm of 95% argon, 5% hydrogen reducing gas

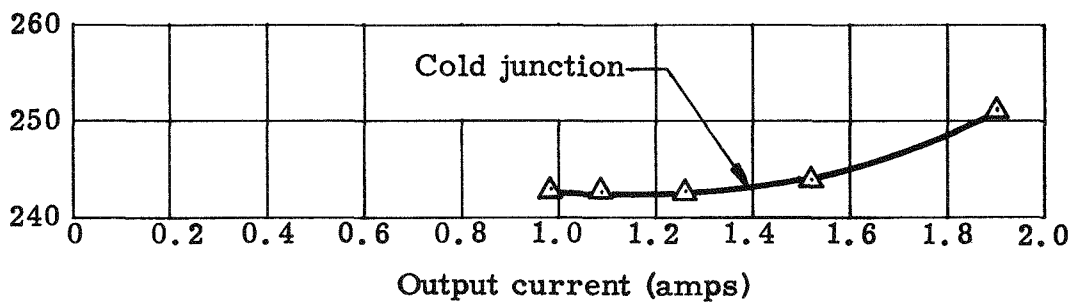


Fig. 7. Hot and Cold Junction Temperatures of 1-G-4 Generator after Fueling with 2100 Curies of Po-210

D. PERFORMANCE

Performance evaluations were conducted on the 1-G series thermoelectric generators. These tests were made to determine the effect of the many variable parameters on generator output. The parameter changes studied were:

- (1) Power input.
- (2) Internal gas composition.
- (3) Internal gas pressure.
- (4) External environment.
- (5) External load resistance.

All of these independent parameters collectively effect generator performance. The tests were therefore conducted to study generator behavior under one variable parameter condition.

Due to the relatively large thermal capacity of the generator, a change of load (or other parameter) required approximately 90 minutes for the generator to stabilize on a new point. For these equilibrium points, stabilization was considered complete if three readings of power output and junction temperatures spaced 10 minutes apart exhibited no change greater than meter accuracy.

Transient data, when taken, are considered to be generator performance figures during short period load changes. A short period is less than 10 seconds. As will be shown later, equilibrium and transient performance are quite different under the same equilibrium external load conditions, due to the Peltier, Thomson and Joule effects on the element circuit.

Because of the interrelationship of the independent parameters on generator performance, it was considered necessary to reproduce the complete output current versus voltage output and load resistance for each generator environment condition. It is from these various characteristic curves that conclusions will be reached as to the performance dependency on the independent parameters.

1. Power Input Parameter

Several SNAP III generators were used to obtain performance data as a function of power input. The primary purpose was to determine if these thermoelectric generators were adversely affected in terms of efficiency at high power inputs. It is conceivable that the generators would

reach a power maximum due to the maximum point in the curve of Seebeck coefficient versus average temperature of the element. Since Seebeck coefficient is a function of the various temperatures of the thermoelectric element and this temperature distribution is not known exactly, the power output was determined experimentally.

A typical plot of output voltage versus output current with the parameter of power input is shown in Fig. 8. It is to be noted that these data approximate straight lines within the region of 30 to 90% of projected short circuit current and tend to intersect at a point. The slope of these constant input power curves is the negative of the load resistance (R_m) that gives maximum power output.

All constant input power lines of Fig. 8 can be expressed by:

$$V = MI + b$$

where

V = output voltage

M = line slope

b = output voltage at zero output current

I = output current.

The output power (P) is the product of voltage and current output
or

$$P = V I = MI^2 + bI$$

The maximum power output occurs at $\frac{dP}{dI} = 0$.

So

$$\frac{dP}{dI} = 2 MI + b = 0$$

or

$$I = \frac{b}{2M} \text{ at maximum power output.}$$

But

$$I = \frac{V}{R} = \frac{b}{2M}$$

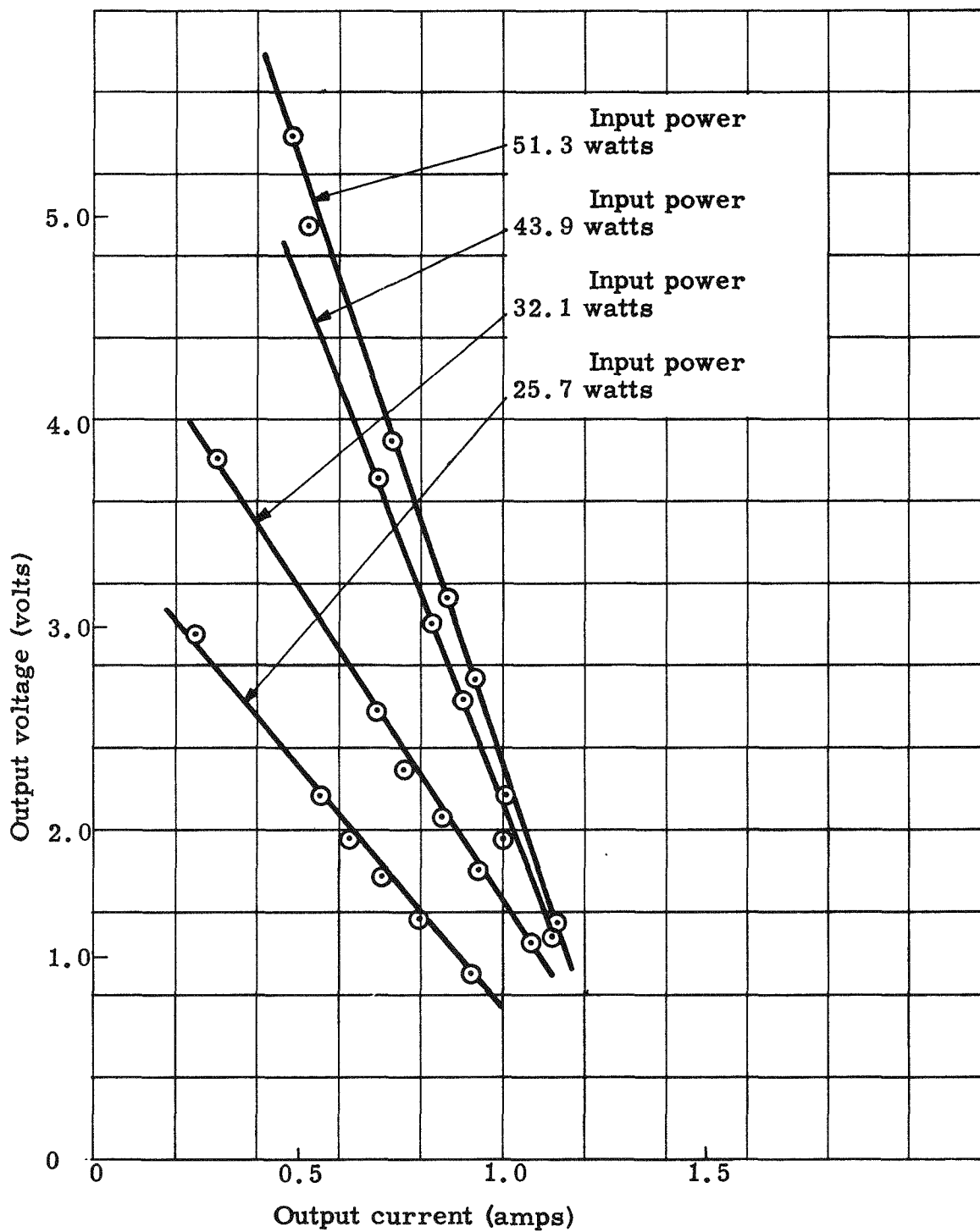


Fig. 8. Performance of 1-G-3 Generator External and Internal Vacuum Conditions

So that, at maximum power output,

$$V = \frac{b}{2} \text{ and } R = -M.$$

A plot of generator differential temperature (hot junction minus cold junction temperature) versus power input is shown in Fig. 9. This ΔT for optimum load resistance also varies almost linearly with power input up to 80% of maximum power input.

The end point variations of these curves are a function of the degree of Peltier cooling for the thermoelectric elements and a function of the change in Seebeck coefficient and electrical resistivity with temperature due to the rapid increase in resistivity at these temperatures. This would result in lower output currents. The Seebeck voltage also reaches a maximum before the element is altered from a metallurgical standpoint and this would result in less efficient voltage production. These two effects (less efficiency in current and voltage output) will cause the generator efficiency to decrease. However, it appears that the maximum power output is governed only by the high temperature properties of the thermoelectric element. These characteristics can be seen in Fig. 10.

From these data, generator characteristics are as follows for a variable thermal input:

- (1) Power output is nearly linear except at the end points of the power output versus power input curve.
- (2) There is a maximum in efficiency.
- (3) ΔT is nearly linear.
- (4) Open circuit voltage is essentially linear.
- (5) A linear α (Seebeck coefficient) can be implied by the characteristics of Items 3 and 4.
- (6) Short circuit current is nearly constant.
- (7) A linear but increasing internal resistance results from Items 4 and 6.

From the preceding characteristics, it can be stated that for constant internal and external atmospheres, the increasing power input will cause an increasing average temperature which will give rise to an increasing internal resistance. This increased internal resistance (R_{int}) will then

All values at external load resistance (R_{max}) to give maximum power output

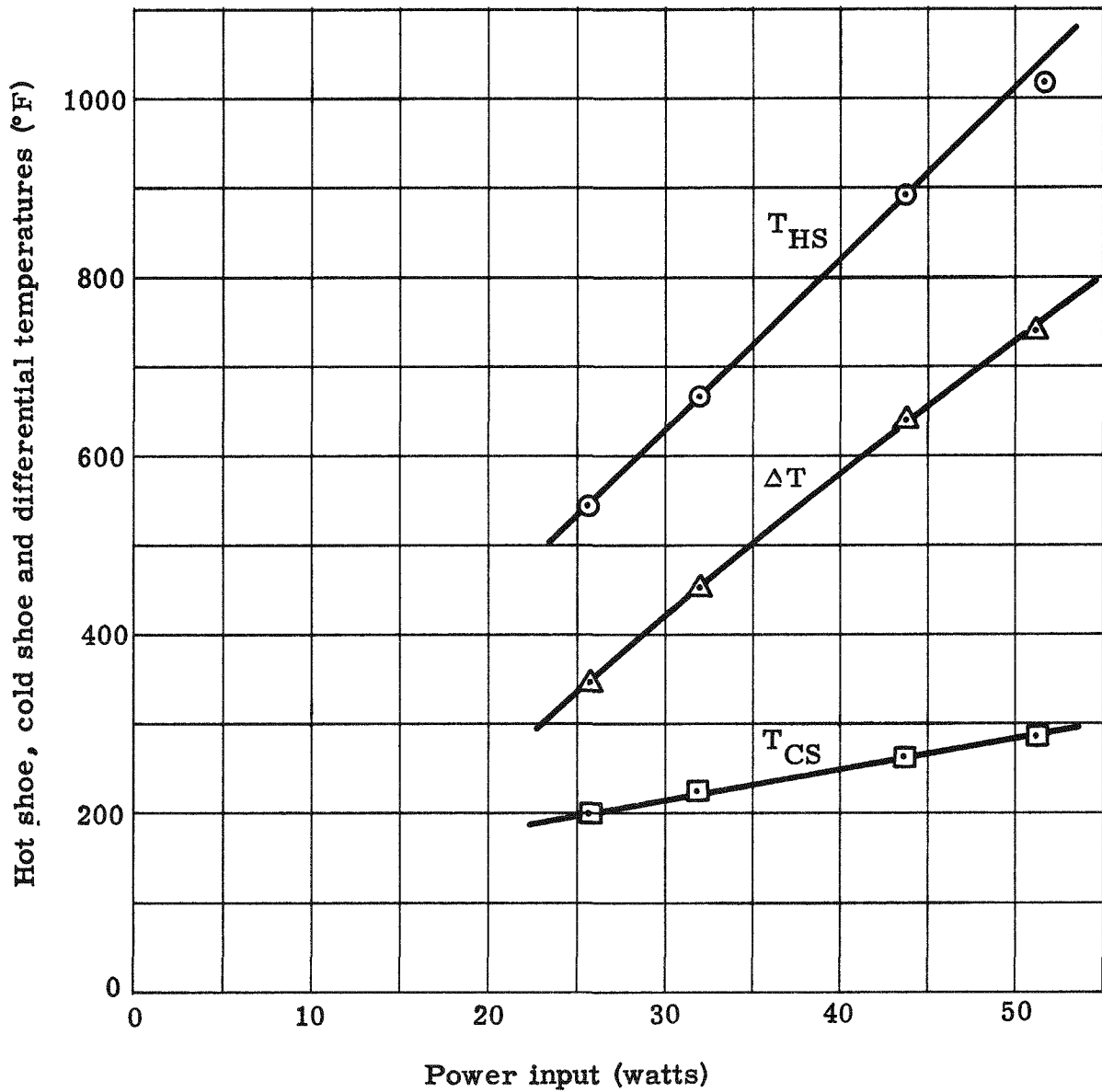


Fig. 9. Performance Characteristics of 1-G-3 Generator with External and Internal Vacuum Conditions

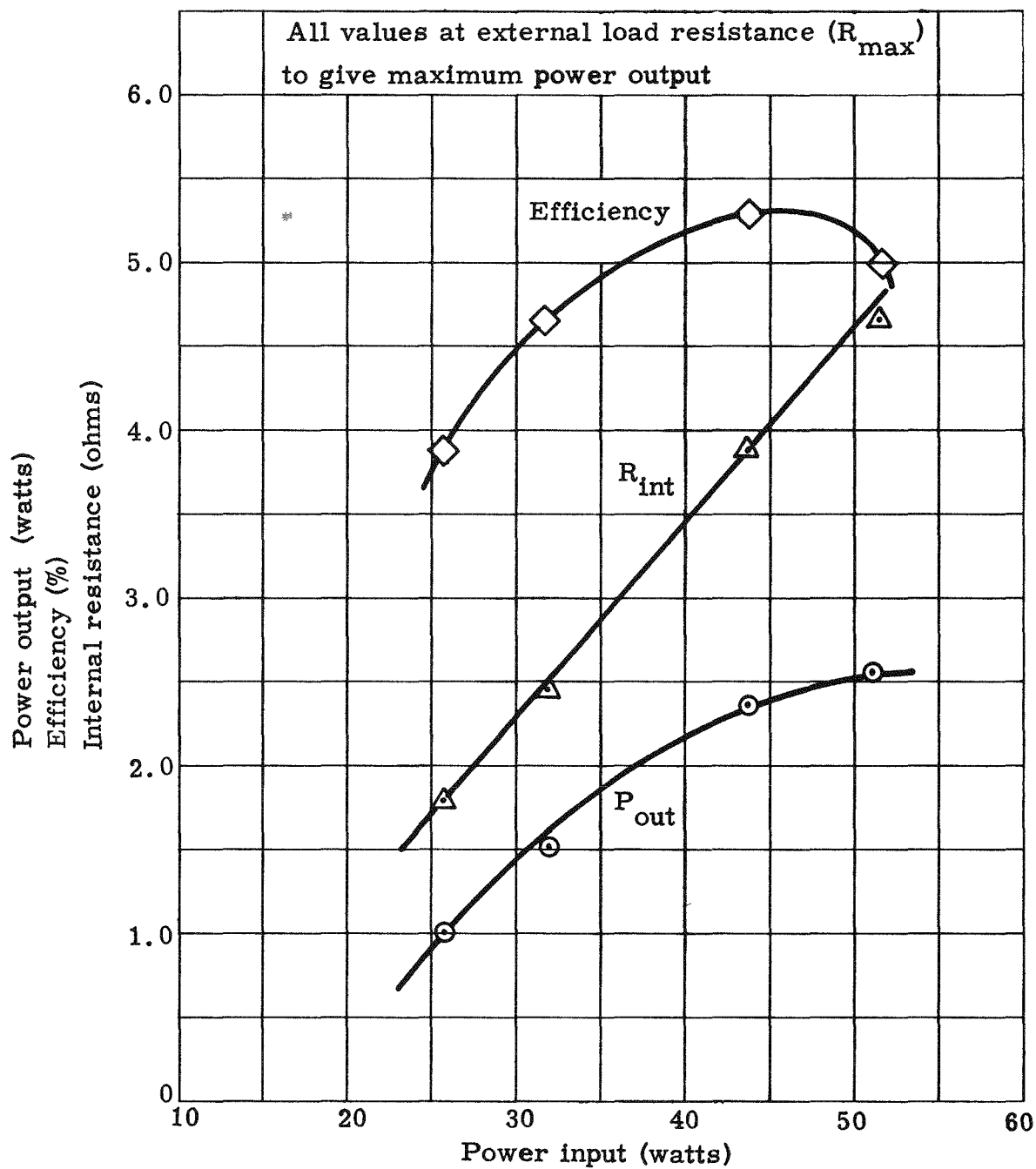


Fig. 10. Performance Characteristics of 1-G-3 Generator with External and Internal Vacuum Conditions

require an increase in the external load resistance (R_{\max}) to obtain a maximum power output. Therefore, $R_{\max} = \beta R_{\text{int}}$ for maximum power transfer. The value for β is not unity as in fixed parameter d-c electrical systems, but in this type generator it varied from about 1.1 to 1.5. Typical values of internal versus external resistance can be seen in Fig. 11. This characteristic of β being greater than one appears to be inherent in thermoelectric devices due to temperature dependency on variables such as resistivity and Seebeck coefficient.

2. Internal Gas Composition

The optimum internal atmosphere of a generator is dependent on several design parameters. Some considerations are as follows:

(1) Type of thermoelectric element material:

- Oxidation resistance
- Sublimation properties
- Element coating.

(2) Method of power flattening, if required, such as:

- Heat dump
- Controlled gas leak
- Variable external resistance.

(3) Thermal conductivity of gas in area of thermoelectric assemblies.

The present SNAP III generators consist of lead telluride elements surrounded by powdered Min-K insulation. The purpose of the insulation is to provide a low thermal conductivity in the generator and to prevent any convective heat transfer inside the generator.

The first consideration, Item 1, is therefore specified for SNAP III generators. Since lead telluride sublimates readily at low pressures, a gas is required. This generator is designed with only spring pressure hot shoe electrical contacts; therefore, reducing gas is desirable to maintain low contact resistances.

- ⊙ R = slope of E_o versus I_o
- ◇ R_{max} = external load at maximum power output
- R_{int} = internal resistance for maximum power output

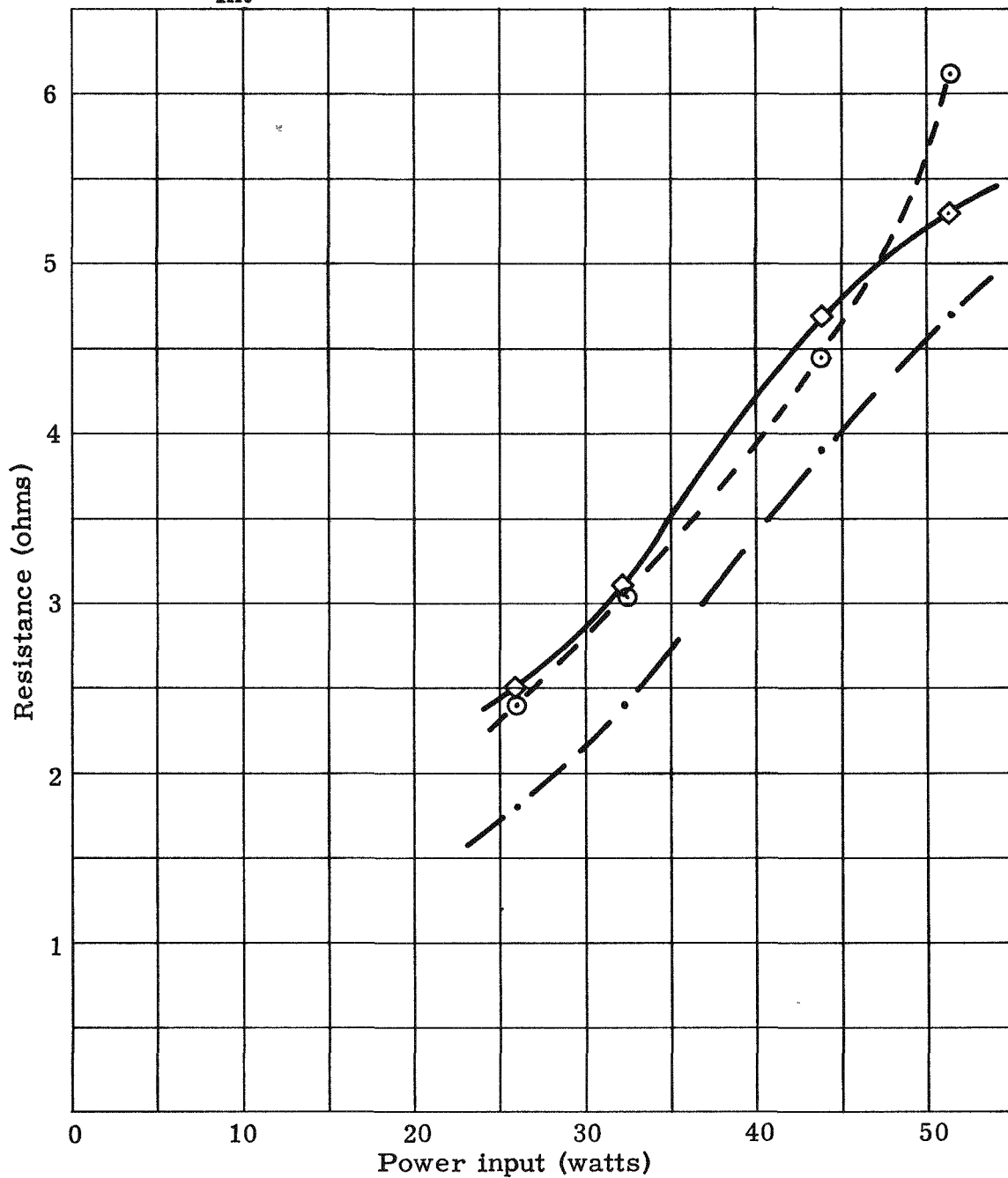


Fig. 11. Generator 1-G-3 Vacuum Internal and External--
Relationship $R_{max} = \beta R_{int}$

If the elements in a thermoelectric generator are coated to greatly reduce sublimation or oxidation, an internal vacuum would produce the best efficiency due to larger temperature differentials. Under these conditions or with an inert internal gas, the lead telluride elements may be exposed to a hot junction temperature of 1000° to 1100° F. With only lead telluride elements (no external coating), the maximum hot junction temperature should be held at about 900° F to prevent sublimation in a vacuum.

The power flattening consideration dictates the type of internal gas. Power flattening can be achieved by expelling source heat at a controlled rate to produce a constant power output, i.e., a constant ΔT across the element. If this heat loss is conducted primarily through the generator, the gas thermal conductivity will decrease as the pressure decreases. This, therefore, dictates an inert gas such as helium which has a relatively high thermal conductivity at one atmosphere compared to the value at near vacuum.

The third consideration is a combination of element material and gas conductivity. If a gas pressure is needed and heat dumping is not required, the inert gas of lowest thermal conductivity is a best choice, i.e., a gas similar to argon.

The four types of internal atmospheres used in SNAP III generators are shown in Table 2.

TABLE 2
Internal Atmospheres of SNAP III

<u>Internal Gas</u>	<u>Thermal Conductivity at 32° F (Btu/hr-ft-°F)</u>
85% N ₂ , 15% H ₂	0.0248
95% A, 5% H ₂	0.0133
85% He, 15% H ₂	0.0818
Vacuum	--

At a 47-watt power input, the 1-G-3 generator had the following efficiencies for a vacuum external to the generator and internal gases as listed.

TABLE 3
Performance Variation for Various Internal Atmospheres

<u>Internal Environment</u>	<u>Efficiency (%)</u>	<u>Power Output (watts)</u>
1 atmosphere--85% N ₂ , 15% H ₂	2.24	1.05
Vacuum	2.77	1.30
1 atmosphere--95% A, 5% H ₂	2.36	1.11

From Table 3, the data show that power output and efficiency are functions of the thermal conductivity of the internal gas.

3. Internal Gas Pressure

A study of the internal gas pressure parameter was conducted. An internal vacuum is the most efficient for power output and the simplest to use for space applications. In SNAP III generators, maximum power output can be obtained with an internal gas pressure. Hot junction temperature in excess of 900° F does not cause rapid sublimation or oxidation at the element shoe interface under these conditions.

The 1-G-3 generator was used for parametric tests at various internal gas pressures ranging from essentially vacuum conditions to 30 inches of mercury absolute. External atmospheres employed were vacuum and one atmosphere of air. Both tests were conducted inside a vacuum bell jar, radiating to a black body sink at tap water temperatures. Complete characteristic curves were obtained as described earlier in this chapter. Vacuums used were less than 50 microns of mercury absolute.

Figures 12 through 14 show the variation of various thermal and electrical output properties as functions of internal pressure of 85% nitrogen and 15% hydrogen. Power input for all points was approximately 48 ± 0.5 watts.

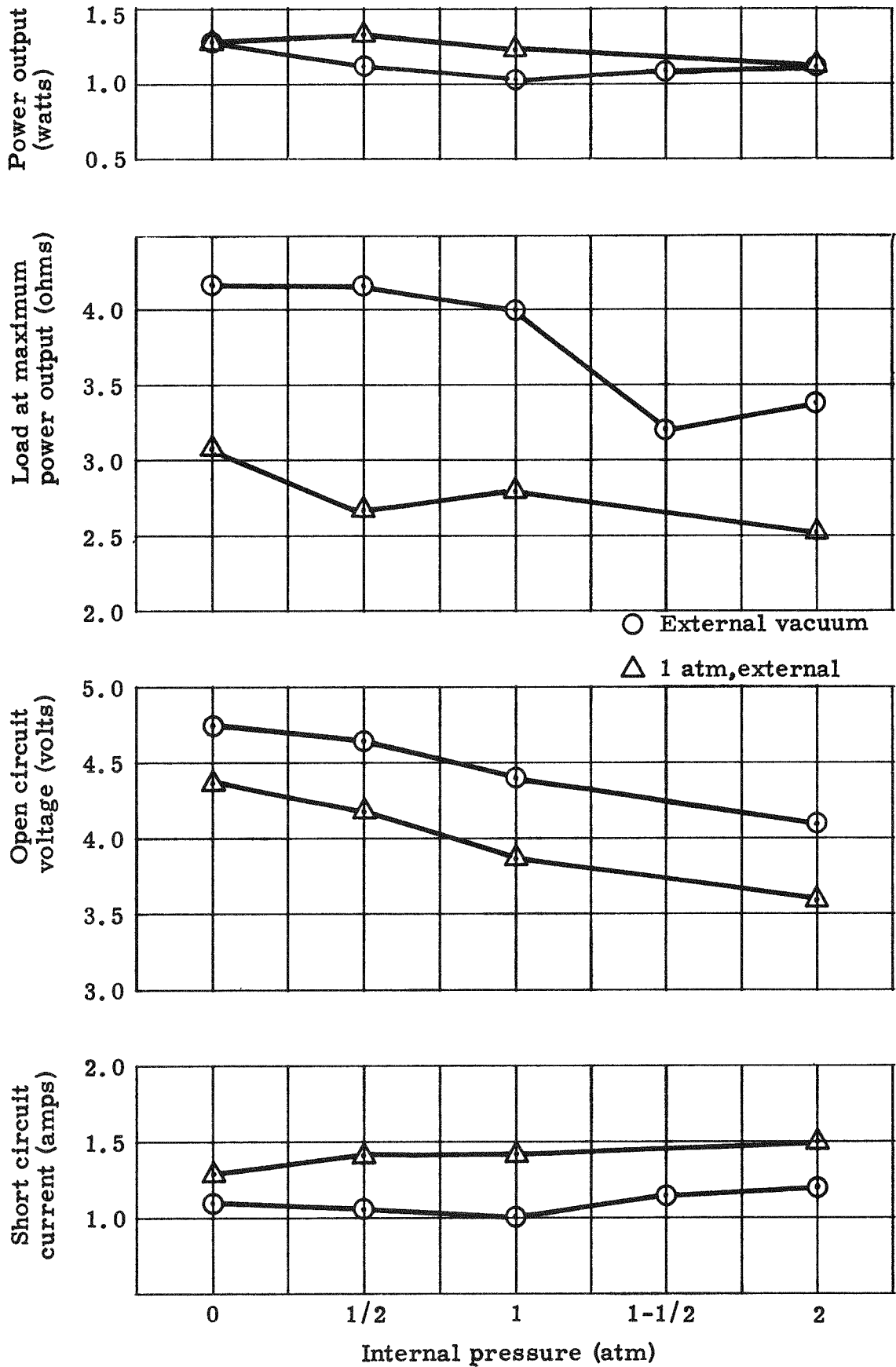


Fig. 12. Generator 1-G-3 Electrical Parameter Comparisons versus Internal Pressure of 85% N₂, 15% H₂

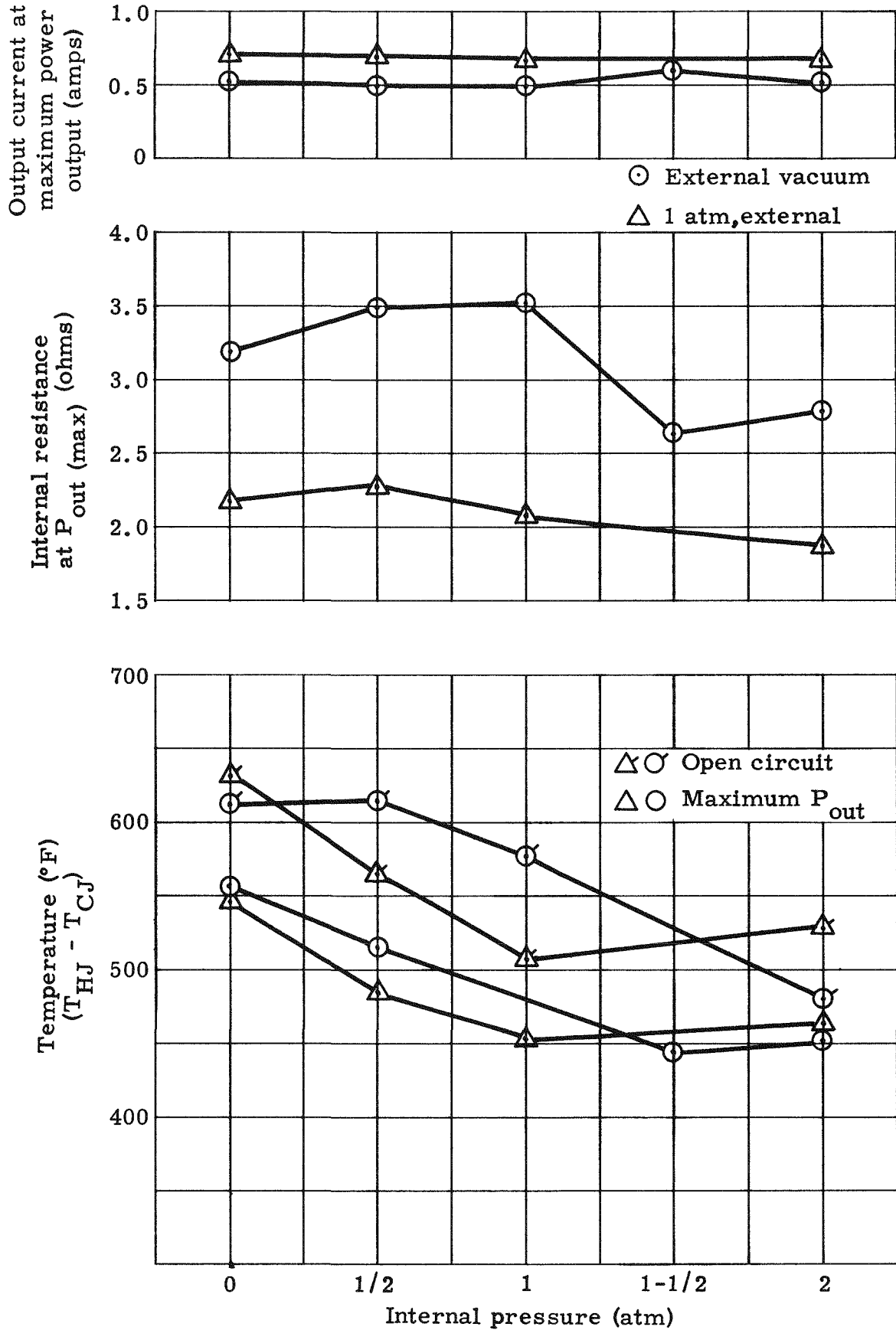


Fig. 13. Generator 1-G-3 Electrical and Thermal Comparison versus Internal Pressure of 85% Nitrogen, 15% H_2

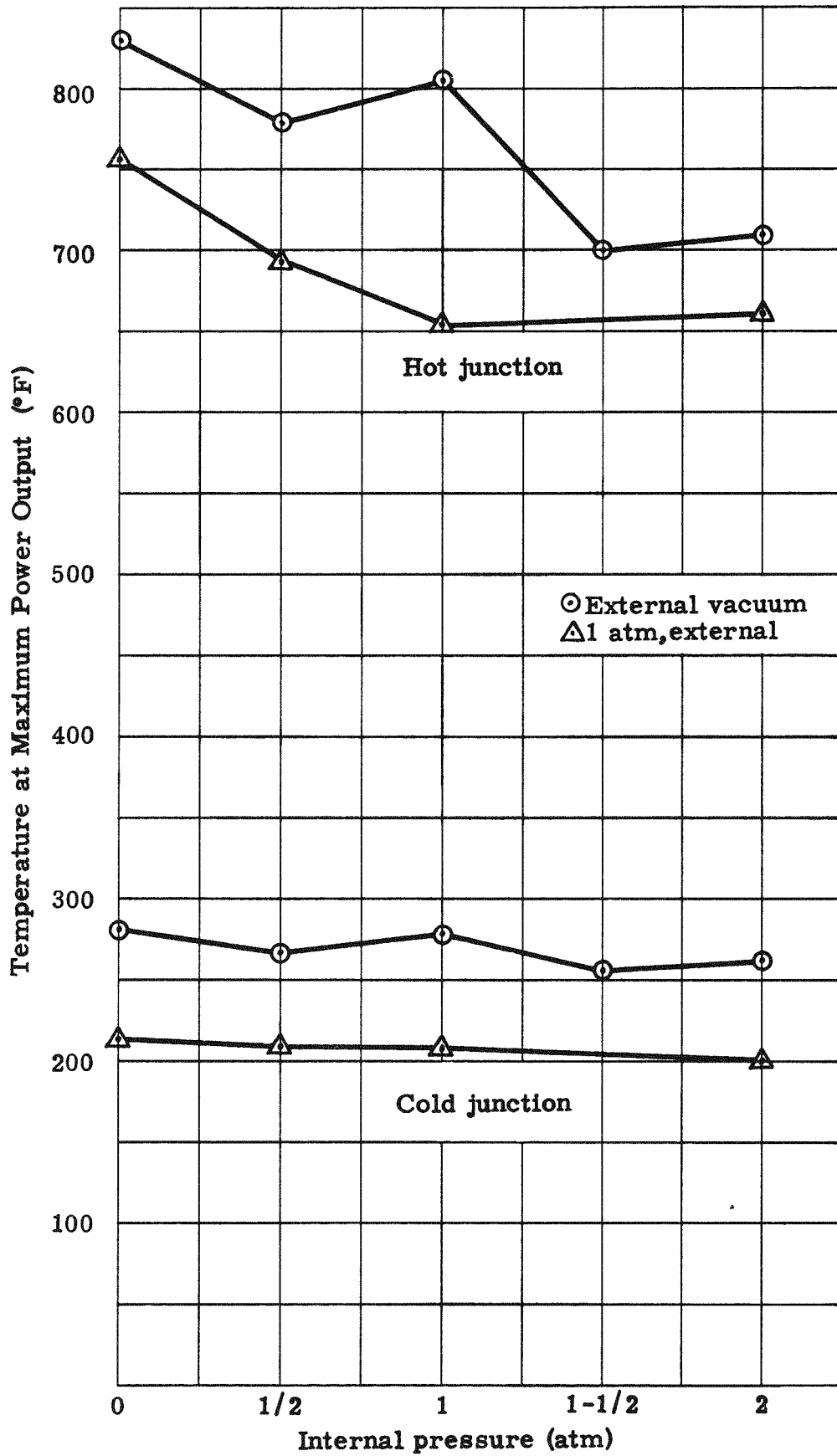


Fig. 14. 1-G-3 Generator Thermoelectric Junction Temperature versus Internal Atmosphere (85% N₂, 15% H₂)

It should be noted that a decrease in ΔT and mean temperature results with an increasing pressure. This, in turn, causes the elements to decrease in both Seebeck voltage and internal resistance and therefore a lower matching external load resistance at maximum power output. This leads to a slight increase in short circuit current. The total effect is that power output decreases slightly with an increase in internal pressure.

A comparison of operational values at various internal pressure conditions as compared to those obtained in vacuum is shown in Table 4.

TABLE 4
Percentage Performance Changes for Various
Internal Pressures (85% N₂-15% H₂)
as Compared to Vacuum (Internal)

External pressure, atmospheres	0	1	0	1	0	1	0	1
	1/2		1		1-1/2		2	
Internal pressure, atmospheres	1/2		1		1-1/2		2	
Power output, watts	-12.0	+3.8	-20.0	-3.9	-15.0	X	-13.0	-7.7
Maximum power load, ohms	0	-14.2	-4.2	-9.7	-21.5	X	-18.0	-18.4
Open circuit voltage, volts	-2.1	-4.5	-7.4	-11.8	X	X	-15.0	-18.2
Short circuit current, amperes	-4.5	+9.2	-9.1	+9.2	+4.5	X	+9.1	+15.4
Internal resistance, ohms	+9.4	+4.5	+9.4	-4.5	-17.2	X	-12.5	-13.6
ΔT at maximum power, °F	-7.5	-11.3	X	-20.8	-20.1	X	-19.0	-18.8

From Table 4, it can be seen that the variation in performance is on the order of 15% lower for 2 atmospheres internal pressure (85% N₂ - 15% H₂) than that for a vacuum internal environment.

4. External Generator Environment

The generators were tested in one atmosphere air and a vacuum, both radiating to a black body sink at tap water temperature. This test apparatus resulted in stable cold junction temperatures.

Figures 12 and 14 and Table 4 show the variation of output parameters for the two external environments. It can be seen that the outer vacuum conditions appreciably raised the generator average temperatures to 60° F above the values for normal room conditions. This caused a marked increase in internal resistance (30%) and Seebeck voltage (8%). Increased internal resistance lowers the output current and output power slightly and requires a higher load for highest efficiency operation.

5. External Load

The data in this report were taken from complete characteristics plots. All controllable conditions were constant whereas the external load was varied. This procedure produced a curve similar to Fig. 15. All output parameters are plotted against load current. Each test was started at short circuit and the load was then increased incrementally to describe the electrical and thermal characteristics of the generator for all other independent parameters. The electrical and thermal characteristics were considered constant when data were reproduced over a 20-minute period.

The load was an ohm maximum variable resistor maintained under constant ambient conditions. An output switch provided an open circuit, short circuit and load capabilities.

After the equilibrium curve was described, the optimum load was set on the generator. A transient curve was obtained at the optimum load by variable loading of the generator for 10 seconds. As shown in Fig. 16, the slope of this straight transient E versus I curve is always less than the equilibrium E versus I curve.

The equilibrium E versus I curve is generally a straight line with end point variations which are peculiar to each generator. Normal usage of a generator would be about midrange of the linear portion of this curve. These end point variations are functions of the degree of Peltier cooling of the thermoelectric elements. Near the open circuit conditions, there is only slight cooling. The generator mean temperature and ΔT , therefore, rise appreciably. The reverse occurs under short circuit conditions. This can be seen in Fig. 17. Peltier cooling is also the primary cause of the decreased slope of any transient E versus I curves.

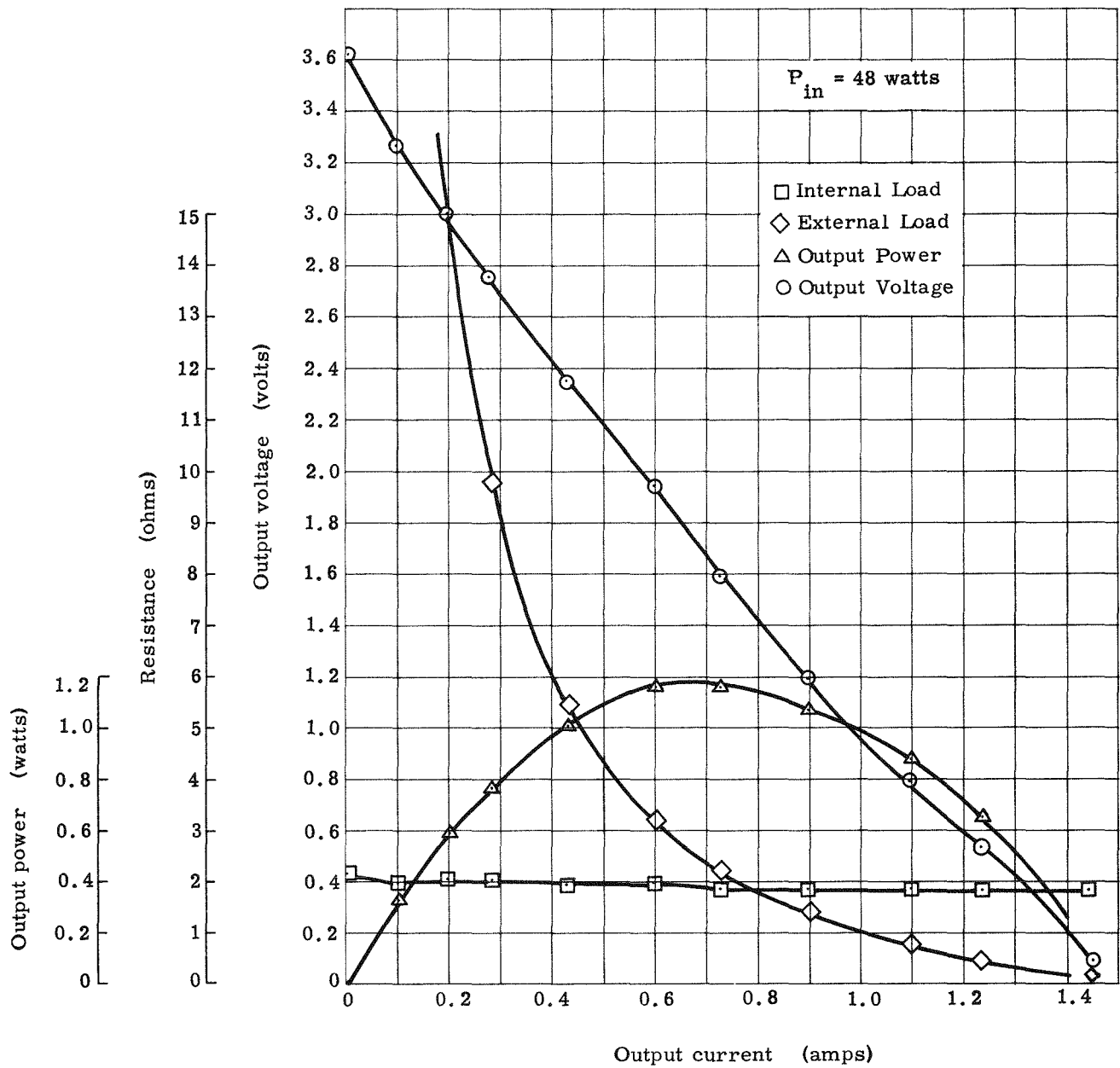


Fig. 15. 1-G-3 Stabilized Generator Performance at Two Atmospheres Internal (85% N_2 , 15% H_2) and One Atmosphere of Air External

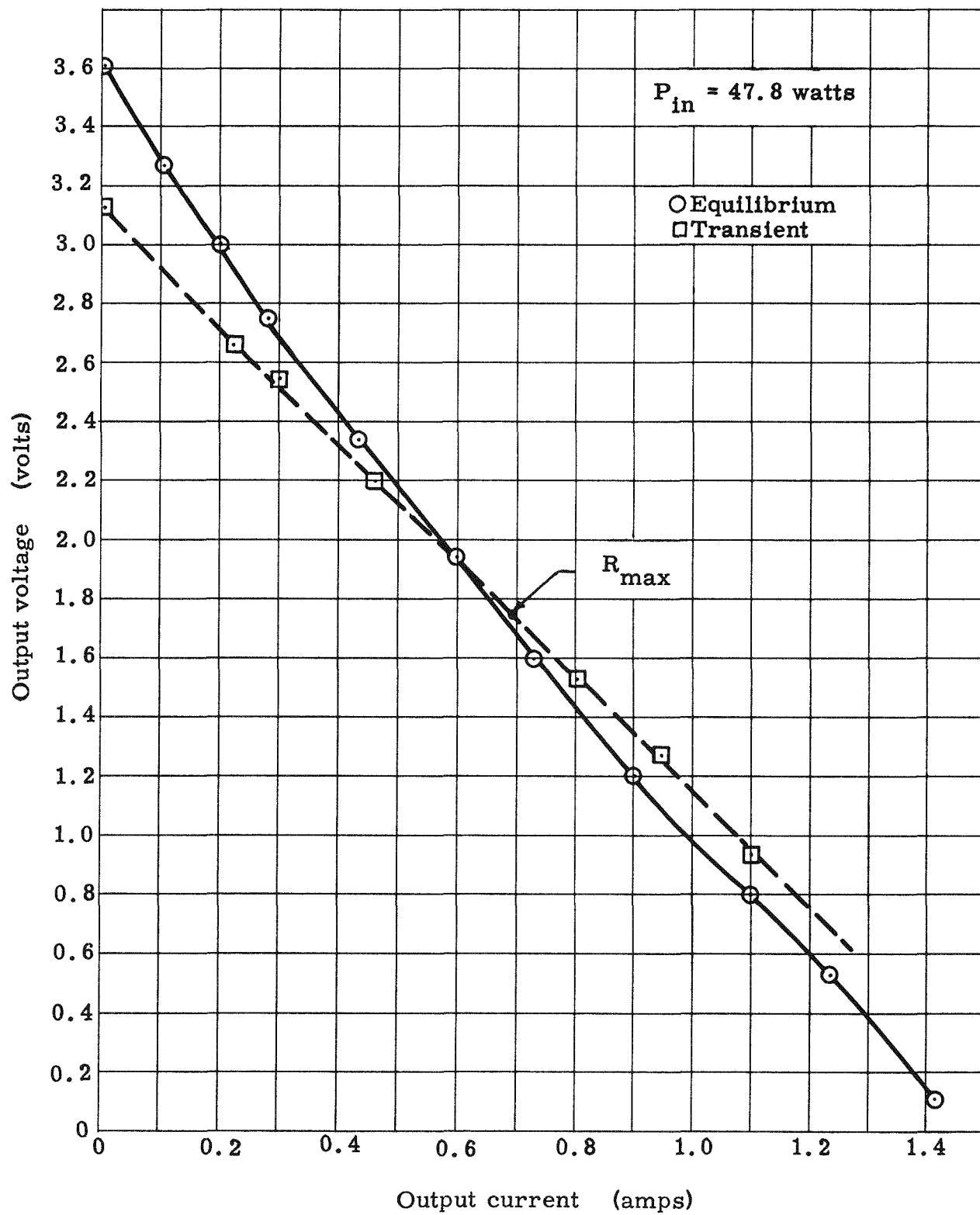


Fig. 16. 1-G-3 Generator Performance at Two Atmospheres Internal (85% N_2 , 15% H_2) and One Atmosphere Air External

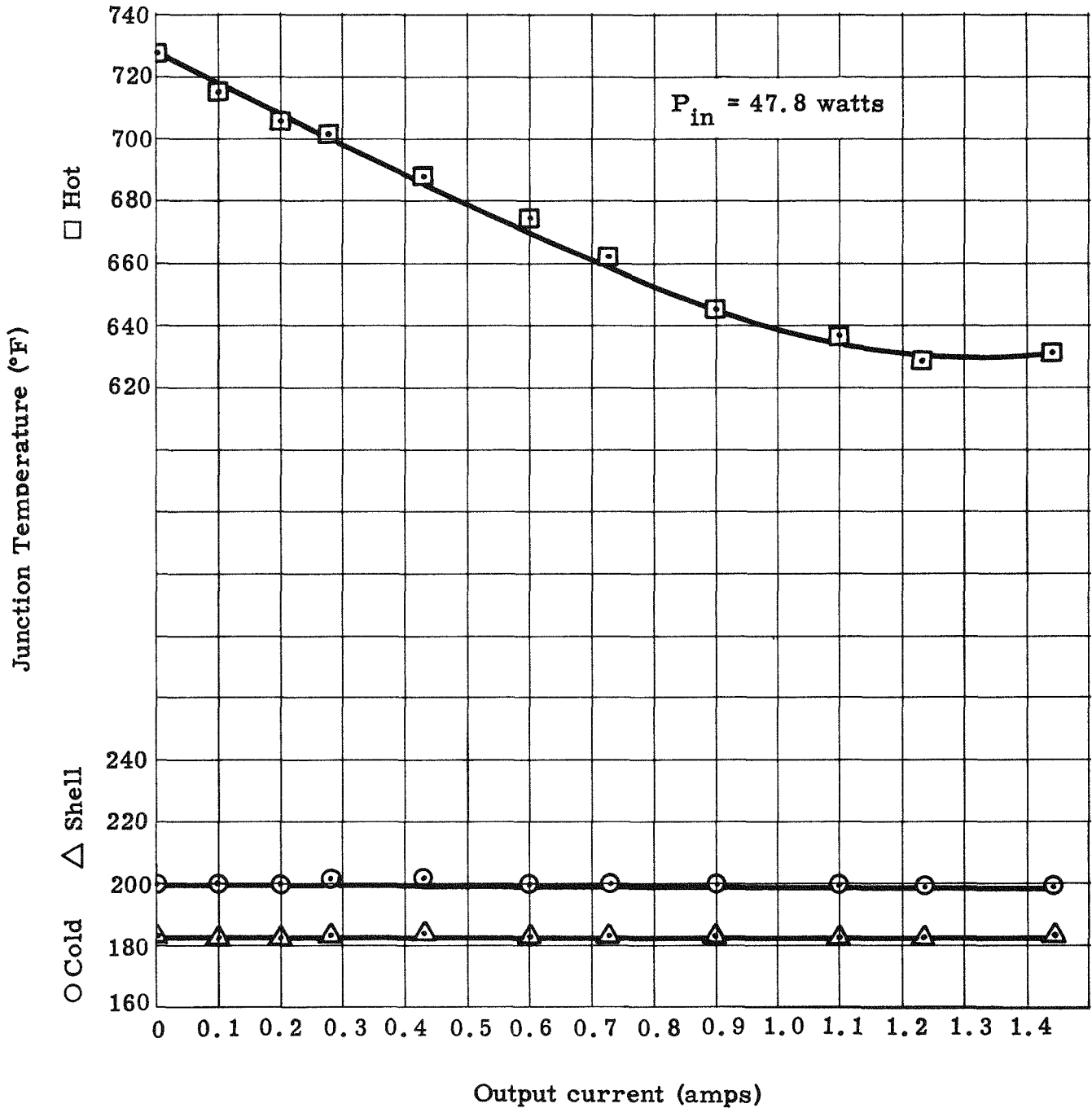


Fig. 17. 1-G-3 Generator Performance at Two Atmospheres Internal (85% N₂, 15% H₂) and One Atmosphere of Air External.

Thermoelectric generators, like temperature independent devices, pass through a maximum power output point for a given power input. However, in a thermoelectric generator, this maximum power transfer does not occur at a load resistance equal to the internal resistance but at $R_{\max} = \beta R_{\text{int}}$. This characteristic was explained in Chapter V.

6. Operational Test Difficulties

Measurements have shown that a large portion of the internal resistance in a SNAP III generator may occur at relatively few pressure contacts on the P-type element hot shoe. Under heat and pressure, the thermoelectric elements tend to metallurgically bond to the iron shoe, thus maintaining a low electrical bond resistance. Because of element sublimation and possible oxidation, the elements decrease in length and should the compression spring used on the cold shoe tend to bind, the hot junction contact resistance will increase with time. A high generator resistance occurred during the final test of the 1-G-3 generator. The output was noted to be erratic and low. Subsequent inspection of the generator at isothermal conditions revealed that one hot shoe P-type element contact had 4 ohms resistance and another was over 0.5 ohm. This accounted for 90% of the total generator resistance. Instances of cracked elements were also noted; however, the resistance of a cracked element is not appreciably increased if pressure contact is maintained.

Difficulty was experienced on the 1-G-3 generator because it leaked through the outer shell closing seam. This occurred under conditions of differential pressures greater than 1 atmosphere. The leaking was noted only when external vacuum conditions were present. Inspection revealed that the closing seam fit tolerance was too great to obtain maximum-strength, soldered joints. Under conditions of 200° F shell temperatures or greater and high differential pressures (greater than 1 atmosphere absolute), the solder would creep and small leaks would develop. A high melting point lead-tin solder (600° F) maintained a seal for a period of time but did not completely solve the leakage problem. Additional mechanical strength should be added to the closing seam for SNAP III generators when they are to be operated under differential pressures greater than 1 atmosphere absolute.

7. Instrumentation

All generators evaluated in this program utilized thermocouples on the hot and cold thermoelectric junctions, heat source and shell. Read-out of thermocouples was accomplished with potentiometers with an accuracy of 1/2% or better.

Heater electrical power was regulated at 60-cps, 117-volt line power. Input power was adjusted by variable a-c autotransformers. The input power parameters were recorded on meters with an accuracy of 1% or better.

Output power was controlled by a knife-type switch which permitted normal load, short circuit or open circuit operation. Output parameters were recorded using meters with an accuracy of better than 1%.

Internal and external pressures were recorded by use of a manometer for nonvacuum pressures. Vacuum pressures were recorded from thermo-couple-type vacuum gauges.

Vacuum pressures were maintained below 50 microns (50×10^{-6} meter of mercury) in a system which permitted regulation of both internal and external vacuum pressures.

E. LIFE TEST

A SNAP III life test evaluation was initiated on 26 January 1960 with a new generator, the 3M-1-G-10. The life test is scheduled for completion in December 1960. At the completion of the life test, an addendum to this report will be submitted that will include the remainder of the data and any conclusive observations. The generator data as furnished to The Martin Company by the manufacturer were as follows:

Power input, watts	77.6	Heat source, °F	1178
Open circuit, volts	7.6	Hot junction, °F	1100
Maximum power voltage, volts	4.0	Cold junction, °F	230
Maximum power output, watts	4.6	Internal gas at 1 atmosphere, %	95 argon 5 hydrogen
Efficiency, %	5.9		

This generator was initially operated to define the life test operating point for power input and optimum load resistance. The power input was specified by that power which resulted in a 1100° F hot junction temperature under open circuit conditions. This resulted in a power input of 66.6 watts. A characteristic curve was then produced for generator output parameters. The optimum load was determined to be about 4.5 ohms.

For the actual life test, the generator was mounted in an enclosure which permitted free convective cooling but eliminated room drafts. The input power is regulated at 117-volt ac, 60-cycle power, adjusted by a variable autotransformer. Electrical readouts are recorded from meters of 1% or better accuracy. Temperatures are recorded by use of a 1/2% accurate potentiometer.

Figures 18 and 19 are generator parameters as functions of time in days. A study of these graphs shows that both ΔT and internal resistance have changed. Assuming element resistivity changes very little for a small ΔT change (about 50° F), a decrease in ΔT and an increase in internal resistance must be independent events and not functions of Peltier cooling. At present, it appears that the thermal conductivity and internal resistance of the generator are increasing at a slow but constant rate.

Generator degradation is not a function of any element Seebeck voltage change. Table 5 illustrates this fact.

TABLE 5
Life Test Generator Seebeck Voltage Versus Time

<u>Date</u>	<u>Open Circuit (volts)</u>	<u>Temperature</u>		<u>Seebeck Coefficient (mv/°F)</u>
		<u>Hot Shoe (° F)</u>	<u>Element ΔT (° F)</u>	
2/6/60	6.46	958	728	8.88
4/4/60	6.22	928	703	8.87
6/5/60	6.15	915	683	9.00

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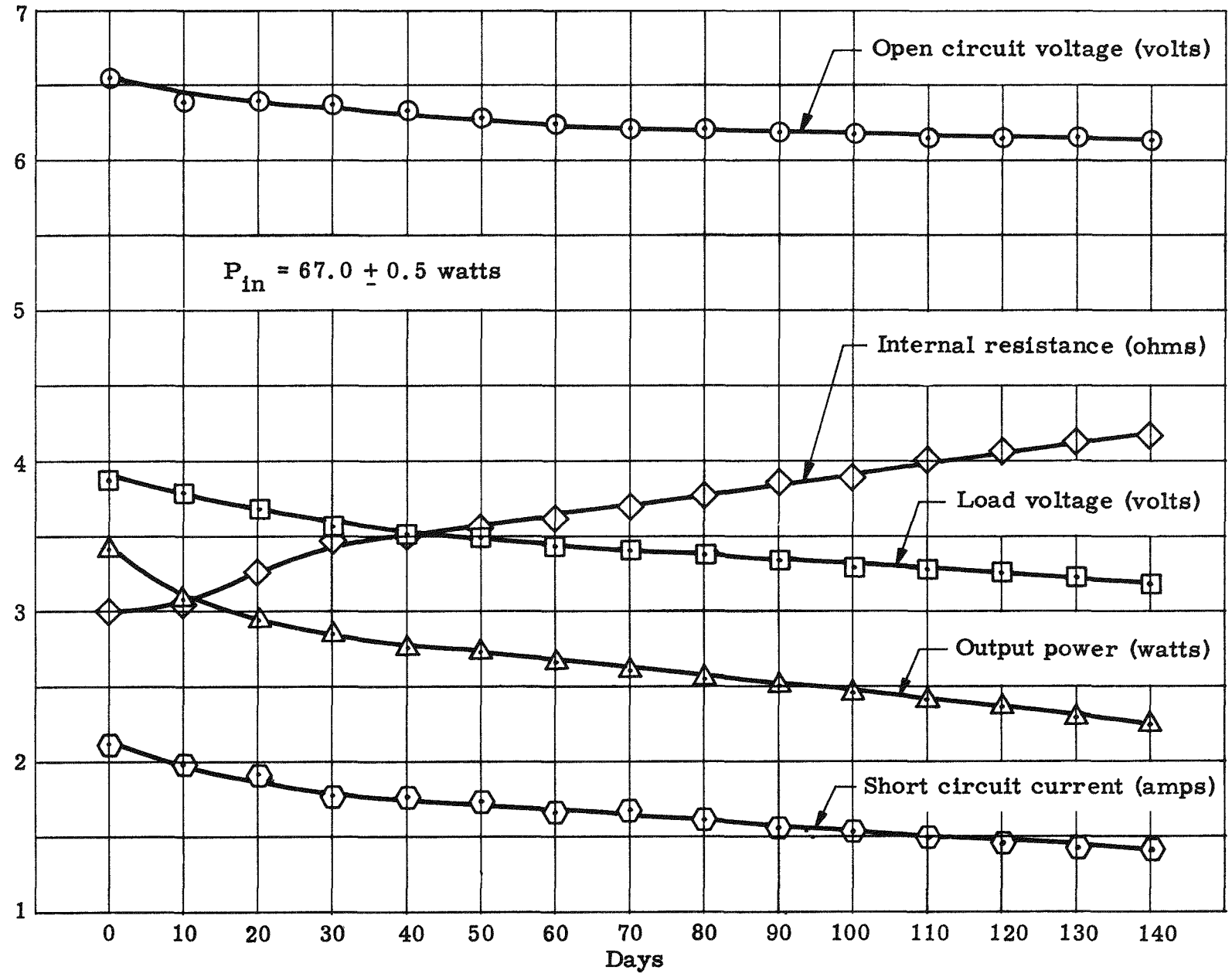


Fig. 18. 1-G-10 Generator Life Test Output Parameters

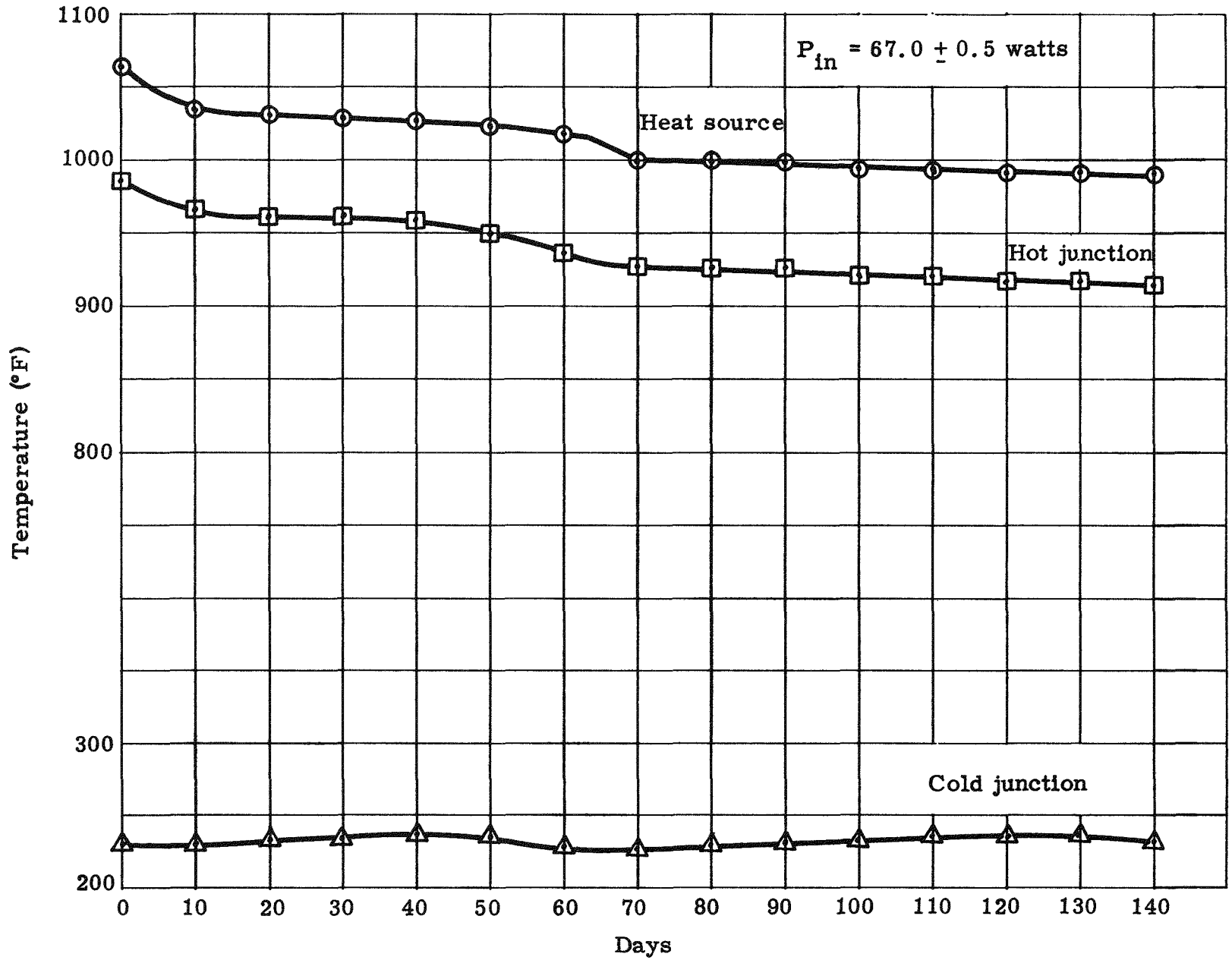


Fig. 19. 1-G-10 Generator Life Test Junction Temperatures

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VI. CONCLUSIONS

Polonium-210 was used as the fuel for the isotope-powered SNAP III generators. This was purchased from Mound Laboratories in welded stainless steel canisters and encapsulated in either molybdenum or Haynes-25 by The Martin Company. Capsule preparation and sealing was accomplished in a 30-psi helium atmosphere by either welding or insertion of an expandable metal plug under 700-psi pressure. The generator loading procedures were designed to prevent oxidation of the internal generator mechanism at all times after the insertion of the 1200° F fuel.

The radiation safety considerations associated with an isotopically fueled generator were not serious. The alpha particle emitting isotope resulted in bremsstrahlung gamma radiation below dangerous levels but required normal low activity isotope handling precautions. The dose rate of newly fueled generators was about 60 mr/hr at a distance of 1 foot from the generator shell.

SNAP III generators proved to be of rugged design in shock, vibration and acceleration tests and withstood shock loads of 50 g. The electrically heated generators exhibited a slight ripple in the direct-current output due to elastic deformations within the generator during the shock test cycle. In all cases, however, the generator returned to pretest efficiencies within 5 to 10 minutes after the test was completed.

Performance of the SNAP III generators was studied under parametric changes of power input, internal gas composition and pressure, external environment and external load. The power input versus power output characteristics were linear except that, at the higher power inputs above 45 watts, the temperature-dependent thermoelectric element parameters caused the efficiency to decrease from a maximum value of 5.3%. Efficiency versus internal gas composition and pressure are related to the thermal conductivity of the gas. Vacuum internal conditions are desirable for a thermoelectric element configuration which will not sublime at elevated temperatures. The external environment was a constant temperature heat sink, and generator performance varied as the element properties vary at the different average temperatures. Maximum power output of 2.55 watts at an efficiency of 5.0% was achieved near a matched internal and external resistance of 4.7 and 5.3 ohms, respectively. It has been found that the thermal properties of the generator cause the matched external load to be 1.1 to 1.5 larger than the internal resistance.

One generator has operated continuously for over 5 months under constant load and electrical power input. The initial system efficiency at 67 watts power input was 5.15% which reduces to 3.45 watts power output. A generator efficiency degradation of approximately 0.36% per month has been noticed during the first 5 months of operation. It is believed that this is caused by both an increase in internal resistance and in overall generator thermal conductivity.

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