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SNAP 7D

Strontium-90 Fueled Thermoelectric Generator Power Source Thirty-Watt U.S. Navy Floating Weather Station

Final Report

MASTER

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Martin Marietta Corporation

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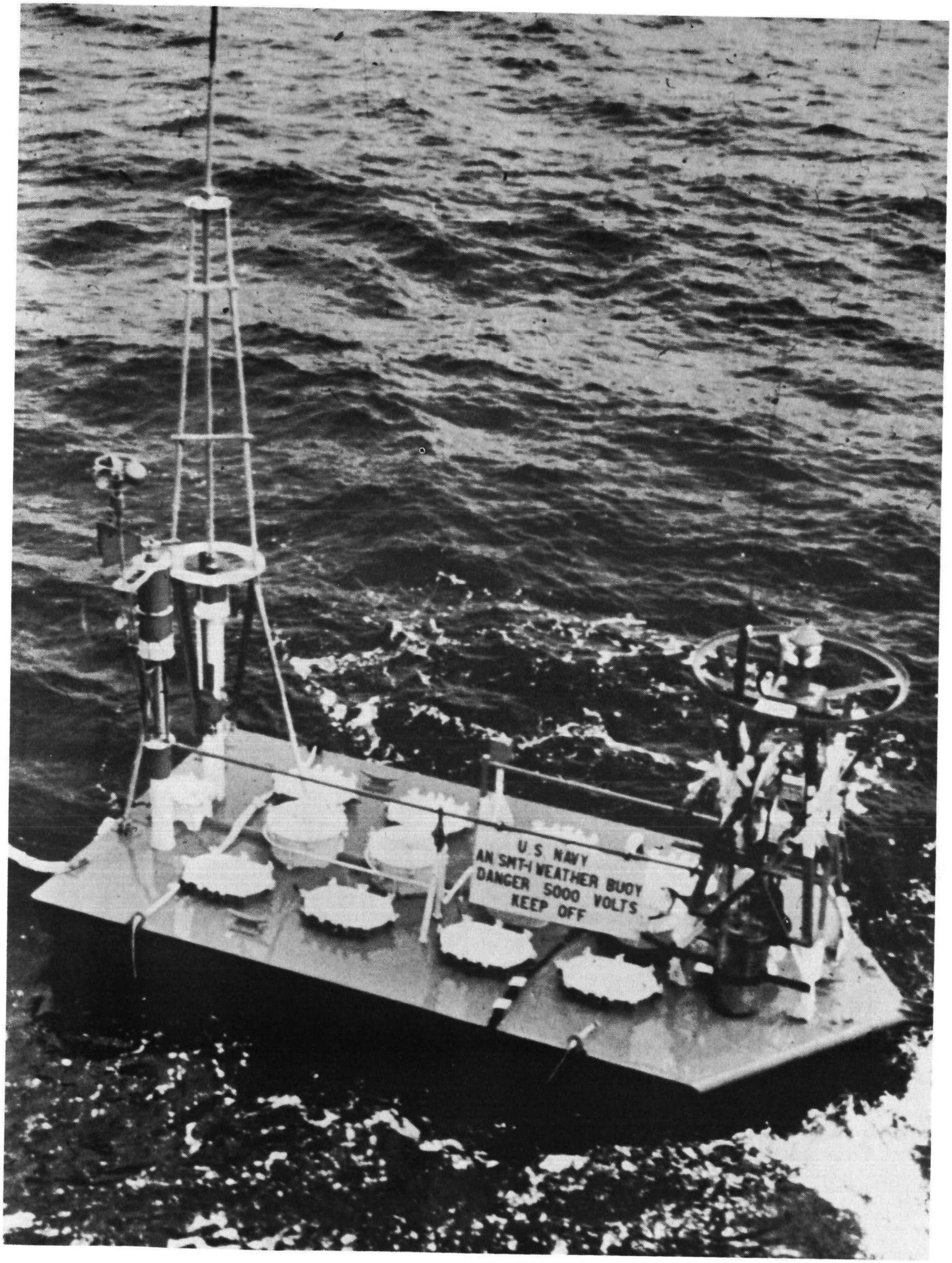

SNAP 7D
U. S. Navy Floating Weather Station with Sr-90 Fueled Generator

FOREWORD

This is the final report on the thirty-watt system for a modified U. S. Navy NOMAD-class weather buoy. This report has been prepared for the U. S. Atomic Energy Commission in compliance with Contract AT(30-3)-217. The work discussed herein was completed by the Martin Company, a division of the Martin Marietta Corporation.

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SUMMARY

The objectives of the SNAP 7D program were to design, manufacture, test and deliver a thirty-watt electric generating system for a modified U. S. Navy NOMAD-class weather buoy to be stationed in the Gulf of Mexico. This report describes the sixty-watt strontium-90 thermoelectric generator, the relay panel, the batteries, and the installation of the system in a boat-type buoy.

In addition to delivering the power supply, many tests were required for the SNAP 7D system to demonstrate its conformance to the contract statement of work. The electrical tests of the generator and of the system, the shock and vibration tests, and the tests at the environmental temperature extremes are discussed in detail.

I. INTRODUCTION

A radioisotope-fueled thermoelectric generator system has been developed by the Martin Company, a division of the Martin Marietta Corporation, for the Atomic Energy Commission (Contract AT (30-3)-217, SNAP 7 Program). This system will provide electrical power for a U.S. Navy 30-watt floating weather station which will automatically broadcast local weather conditions at regular intervals from a location in the Gulf of Mexico.

The system was designed to operate in the environmental extremes that are anticipated for this type of installation, to operate without attendance or maintenance for periods of two years, and to have a useful life of 10 years when maintained in accordance with contractor's instructions (Ref. 1).

The SNAP 7D System consists of a thermoelectric generator, a relay panel, and a battery pack to serve as a reservoir for the storage of electrical energy. The system design and operating parameters are in accordance with the Statement of Work (Ref. 2).

II. PHYSICAL DESCRIPTION

The generator, relay panel, and battery pack are to be installed in a modified U. S. Navy Nomad-class weather buoy. The arrangement is shown in Fig. 1.

A. SYSTEM INSTALLATION

The generator is located in the center well of the buoy between bulkheads Nos. 3 and 4 with the center of gravity as low as possible. An inner deck has been added to the buoy to form the generator compartment below the inner deck and the relay panel-battery compartment between decks. A tube connects the hatch and inner deck to provide access to the lower compartment while maintaining watertight compartments. The lower compartment is filled with transformer oil which transfers the heat from the generator into the boat structure and thus into the surrounding water. The tube between the decks serves as an expansion chamber for the oil.

The relay panel is mounted to the aft bulkhead in the compartment between decks. This position was selected as a convenient location for making the system hookup; the panel is mounted where it is not likely to be damaged by personnel climbing into the compartment.

The battery pack is mounted directly to the inner deck. This mounting arrangement protects the batteries from the temperature extremes. Since the oil in the generator compartment is in contact with the underside of the inner deck, the inner deck will remain close to the outside water temperature.

B. THERMOELECTRIC GENERATOR

The SNAP 7D thermoelectric generator consists of a Sr-90 heat source, a thermoelectric conversion circuit, a heat rejection system, and a biological shield. Figure 2 shows the configuration of the generator.

The Sr-90 heat source, 1435 watts at beginning of life, will power the generator for a minimum of ten years. The isotope fuel is formed into flat discs and sealed within Hastelloy-C cylindrical containers. Fourteen fuel containers are installed in a Hastelloy-C fuel block which is used to conduct the heat energy to the thermoelement hot junctions. The flat surfaces of the fuel block that contact the thermoelements are covered with thin strips of mica to electrically insulate the thermoelements and still allow the heat to transfer.

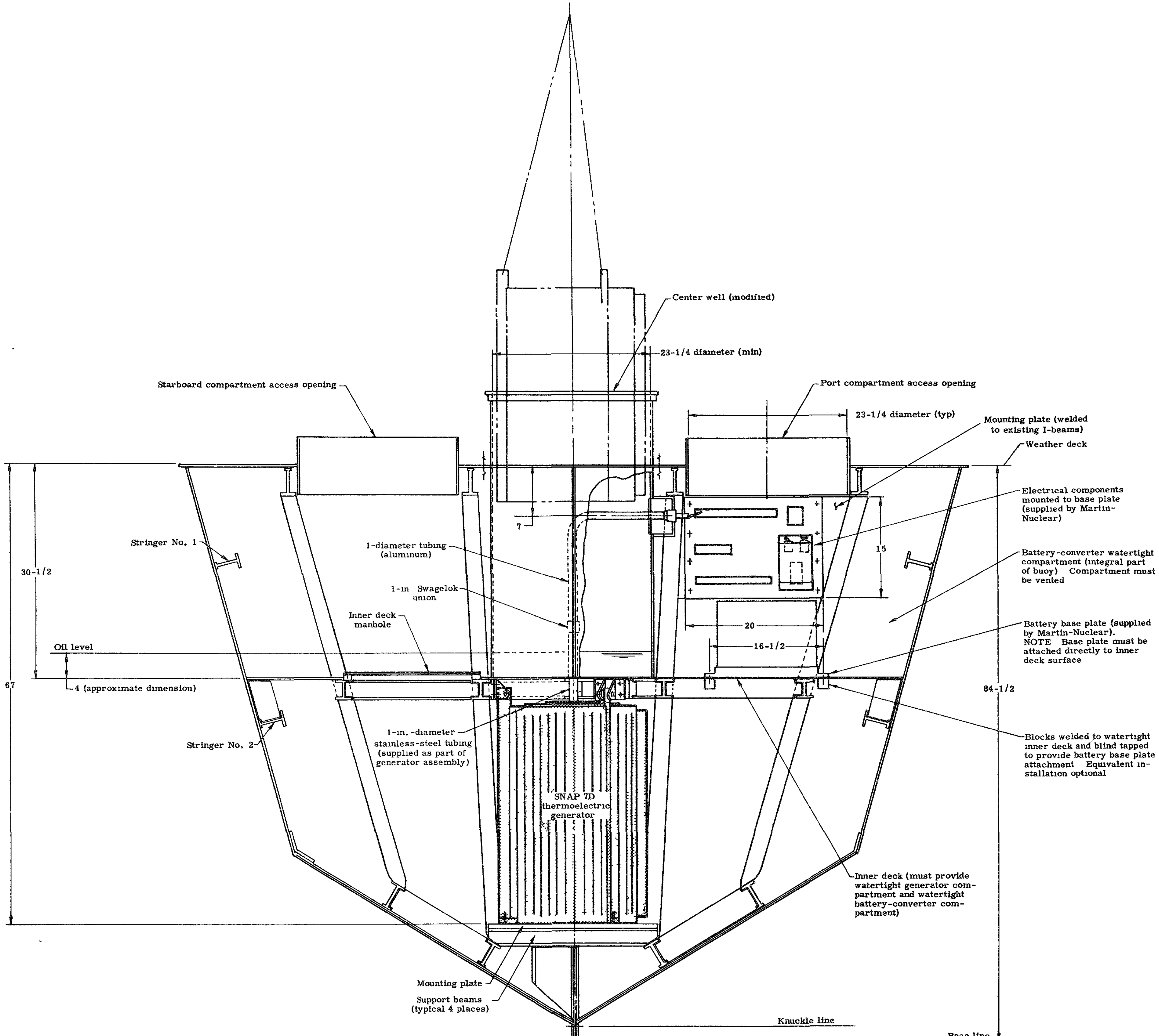

Fig. 1. SNAP 7D Installation

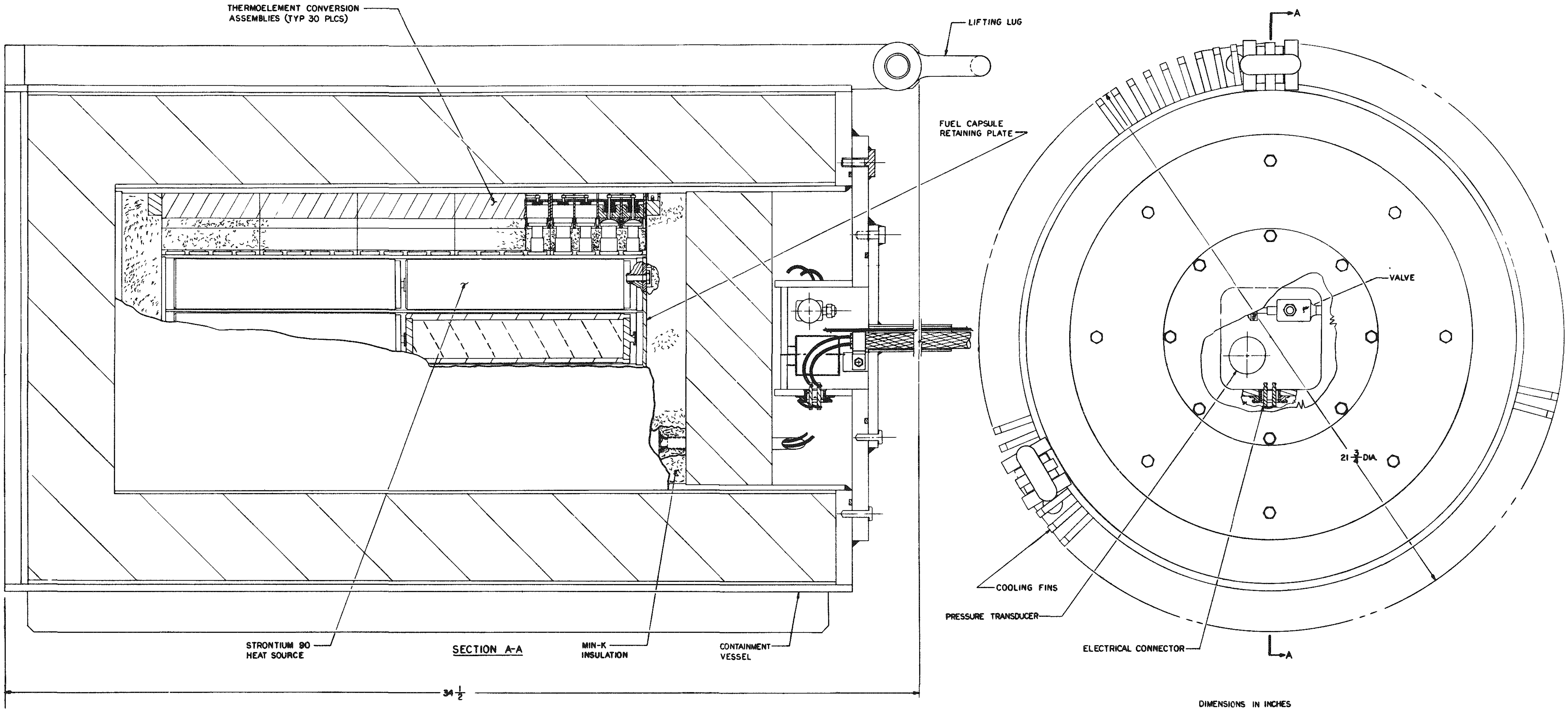

Fig. 2. SNAP 7D 60-Watt Generator

In constructing the thermoelectric couple, a pair of thermoelements are joined together by an iron shoe that serves as the hot junction connection which transfers heat from the fuel block to each lead telluride thermoelectric element (see Fig. 3). A copper cap is soldered to the cold end of each element to conduct heat from the element and to serve as an electrical connection. Martin "Hard Coat" aluminum hardware is used to conduct heat from the copper cap to the heat sink. The hard coat serves as an electrical insulation.

One hundred twenty pairs of thermoelements are used to convert a part of the Sr-90 decay heat to electrical power. Four pairs are assembled into a module. Five modules are assembled into a vertical strip; and six equally spaced strips are assembled into a generator (see Fig. 4). The remaining volume around the fuel block is filled with Johns-Manville Min-K insulation.

The fuel, fuel block, thermoelectric elements, and associated hardware are contained within a Hastelloy-C can which is surrounded on the sides and bottom by a radiation shield of depleted uranium. The uranium is completely encased in Hastelloy-C. A close fitting uranium plug is inserted into the inner can on top of the generator assembly to complete the radiation shielding. The shielding thickness is sufficient to satisfy Interstate Commerce Commission (ICC) shipping and handling requirements. A Hastelloy-C cover is welded over the inner can to complete the generator assembly.

Due to the possible hazards associated with the use of a radioisotope, very stringent requirements were placed on isotope containment. The Sr-90 isotope, used in the titanate form, is virtually insoluble. Discs of the compacted and sintered isotope were sealed in Hastelloy-C containers. Hastelloy-C was chosen because of its very good structural qualities and its excellent corrosion resistance. It was calculated that the fuel container would retain the strontium titanate for over 1000 years if submerged in seawater. This would be true even if the corrosion rate were twice that found through tests at the Wrightsville Beach Corrosion Center, N. C. The Hastelloy-C fuel container in conjunction with the generator housing can be considered as double containment.

A comprehensive safety study has been made on all aspects of the generator fueling, handling, and servicing. This study is covered in a separate safety report (Ref. 3).

The generator housing is evacuated, flushed, and back-filled with inert gas. It is necessary to remove all air from the housing in order to prevent harmful oxidation of the thermoelements at elevated temperatures. The internal pressure is adjusted to approximately 31 inches Hg absolute. By changing the gas at maintenance periods and replacing

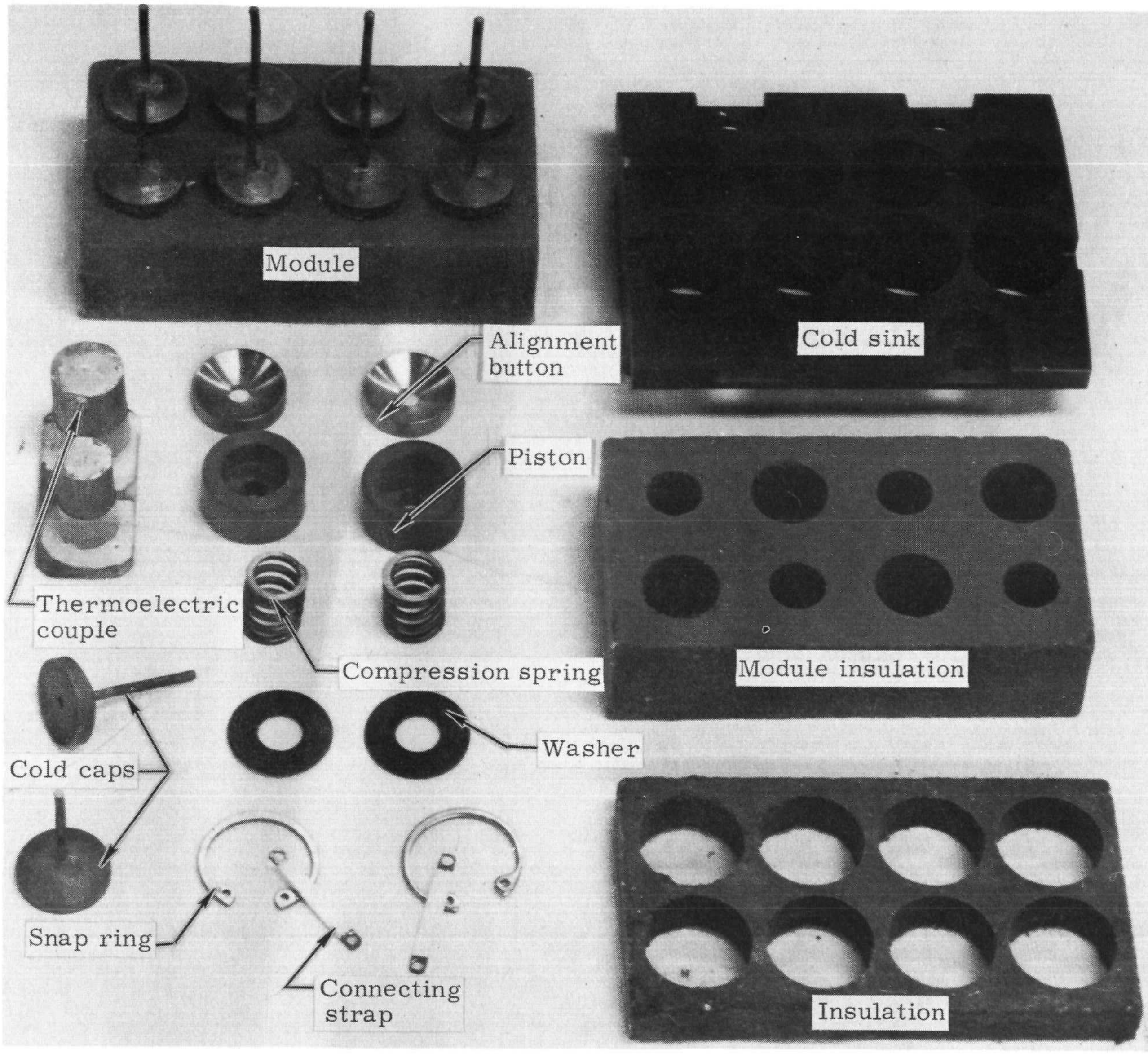

Fig. 3. SNAP 7D Thermoelement Module Components

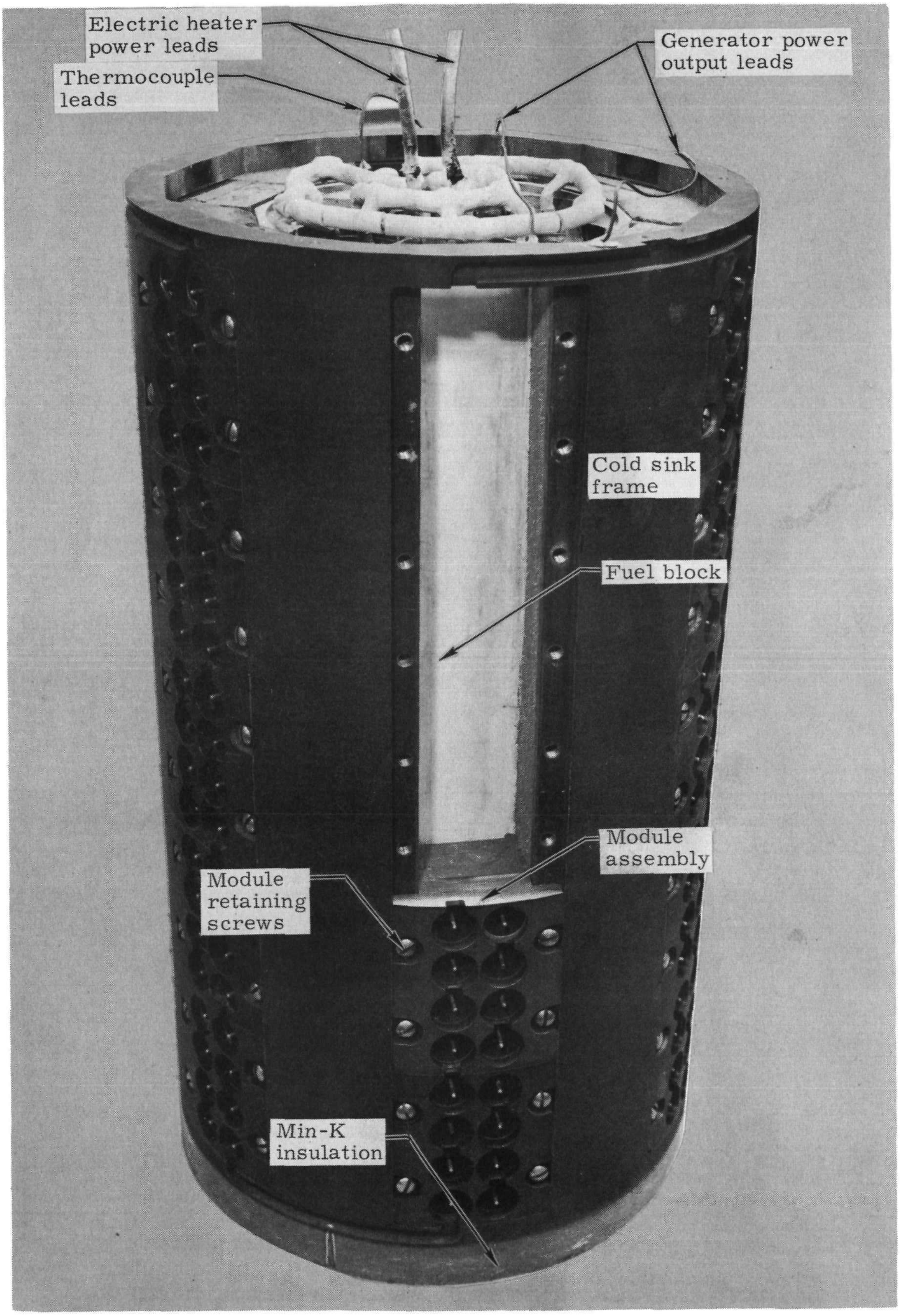

Fig. 4. SNAP 7D Thermoelectric Modules Assembled in Electrically Heated Generator

it with a gas that has lower thermal conductivity, it is possible to obtain a stepwise power flattening method. This method alleviates the thermal output reduction from the isotope as it decays and thus allows the generator to meet design power requirements for a 10-year period.

The generator is designed to operate with the water temperature around the buoy ranging from 28° to 80° F. The gas fill is selected to give the newly fueled generator a hot junction temperature of approximately 950° F when the generator is surrounded by 80° F water. Ninety-nine vertical fins attached to the outer shell of the generator housing hold the surface temperature to within 31° F of the water temperature.

C. BATTERY AND RELAY PANEL

The battery pack and relay panel are installed in the compartment formed between decks on a specially modified Nomad-class weather buoy. The compartment is weathertight, but it is vented to prevent a possible buildup of explosive vapors in case a battery should severely outgas.

1. Battery

The battery is a 170-ampere-hour nickel-cadmium type (Gulton Industries P/N 3VO-170P) which provides high-current service. The battery pack consists of three batteries which provide a nominal potential of 12 volts. The cells are of the sealed type and thus it is not necessary to add water. The seals are reinforced by encapsulation in epoxy. The only exposed surfaces are the two battery terminals and the cell pressure release valve discharge orifices.

The batteries have been factory-tested with a continuous current of 10 amperes, which is far in excess of any current requirements of the system, without harmful effects or without pressure venting through the pressure relief valves. If the pressure relief valves should open during generator operation, they will automatically close again and the operation of the batteries will continue. A nylon rupture disc is located on the valve for the purpose of indicating any action of the pressure relief valve.

The large batteries were selected to allow for 72 one-hour-interval weather station transmissions. Sealed cells were selected to ensure a two-year maintenance-free system. The use of these large-capacity sealed cell batteries made direct-current charging feasible. It was found that the generator could be coupled directly to the battery, since the generator would stabilize within the desired charging voltage range and the batteries could dissipate the excess energy as heat without incurring any damage.

2. Relay Panel

The United States Navy personnel responsible for the development of the weather station equipment requested an emergency system be installed to switch the navigation light from the SNAP 7D system to a reserve set of batteries to be furnished by the Navy. An analysis of the system backed up by test indicated that it would be desirable to switch over to the reserve batteries if the generator output fell below 36 watts. Since the generator stabilizes at 12 volts, this meant that the cutoff point should be set at 3 amperes. A current sensing relay was installed which would trigger a second relay capable of handling the high current involved. In order to avoid the high voltage drop across the current-sensing relay, it was necessary to install a silicon rectifier which essentially bypasses the current-sensing relay once the signal has been sent to the rectifier. The weather station load will remain on the SNAP 7D system at all times.

Two terminal strips have been added to the relay panel for convenience in hooking up the system. With the panel mounted in place it is only necessary to connect the generator output leads, the thermocouple leads, the battery leads and the leads to put the system into operation. A shunt has been provided on the panel to supply the signal to the current-sensing relay and for convenience in measuring generator current.

III. THERMOELECTRIC ANALYSIS

A. SELECTION OF THERMOCOUPLE MATERIAL

The choice of thermoelectric material operating over a specified temperature range is generally determined by its figure of merit (Z). The efficiency of a thermoelectric material is expressed by its figure of merit. Those materials exhibiting the highest figures of merit will perform the conversion of heat to electricity at the highest efficiency. The high cost of radioisotopes makes the radioisotope-fueled thermoelectric generator operating efficiency extremely important. The figure of merit is expressed as:

$$Z = \frac{\alpha^2}{k\rho}$$

where

α = Seebeck coefficient

k = thermal conductivity

ρ = electrical resistivity

The figure of merit will also vary with temperature and impurity content of the material.

Although the figure of merit is the basic parameter for material choice, it is certainly not the sole consideration. Other factors involved in the choice are fabricability, the structural stability of the material, its resistance to corrosive atmospheres, and its bonding characteristics.

Lead telluride was selected by virtue of its high figure of merit within the generator temperature range. Although lead telluride is brittle, its good structural stability sanctions its use in a properly designed generator. In addition, lead telluride deteriorates rapidly in air at high temperature. These deficiencies must be considered in the design of the thermoelement containment vessel and support structure.

The lead telluride thermoelectric material is "doped" with carefully controlled amounts of impurities. The type of impurity doped into the lead telluride determines whether the element will be P-type or N-type. The P-type lead telluride element contains 0.81 atomic percent of free tellurium, and is doped with an electron acceptor such as sodium which tends to increase the number of positive current carriers. The N-type element contains 0.71 atomic percent of free lead, and is doped with a donor material such as lead iodide to increase the concentration of negative carriers. Since the current flows in opposite directions in N and P elements, the elements are arranged in pairs with ends connected electrically at a constant temperature.

The concentration of the impurity affects the properties of the thermoelectric material. For example, the temperature at which the material reaches its maximum figure of merit increases with increasing impurity concentration. The concentrations employed in the lead telluride elements manufactured by the Martin Company for the SNAP 7D generator were 0.060 weight percent sodium and 0.055 weight percent lead iodide. The statistically averaged data associated with the properties of these elements are presented in Table 1.

B. THERMOELECTRIC EFFICIENCY AND ELEMENT SIZING

After the selection of the thermoelectric material, the number of elements and their dimensions must be determined. The number of elements is determined by the requirements of the load required of the generator. The dimensions of the elements depend on the material properties and the designer's choice. The thermoelement properties listed in Table 1 were used in these determinations.

The heat-to-electricity conversion efficiency of a thermoelectric generator operating between specified hot and cold junction temperatures is given by:

$$\eta = \frac{\Delta T_t}{T_h} \cdot \frac{\frac{x}{x+1}}{1 + \frac{K\,(R_c + R_i)\,(x+1)}{\alpha^2\,T_h} - \frac{\Delta T_t \left(1 - \frac{R_i}{2\,(R_i + R_c)}\right)}{T_h\,(1+x)}}$$

TABLE 1

Summary of Data* Associated with Thermoelectric Properties of Martin-Manufactured Thermoelectric Elements

	N-Element	P-Element	Composite
Seebeck voltage (μv/°C)	196	171.4	--
Resistivity (μohm-cm)	1131	3532	--
Contact resistivity (μohm-cm^2)	464	1299	--
Thermal conductivity (watts/cm-°C)	0.0194	0.0200	--
Figure of Merit (°C^{-1})	1.75×10^{-3}	1.13×10^{-3}	1.40×10^{-3}

*Based on hot and cold end temperatures of 700° K and 335° K.

where

K = thermoelement thermal conductance (watts/°C)

$$\left[K = (k_N A_N + k_P A_P) \frac{1}{\ell}\right]$$

where k = thermal conductivity (watts/cm-°C)

A = cross-section area (cm^2)

ℓ = element length (cm)

$$R_c = \frac{C_P}{A_P} + \frac{C_N}{A_N} \doteq \text{contact resistance (ohms)}$$

where C = contact resistivity (ohm-cm^2)

$$R_i = \left(\frac{\rho_N}{A_N} + \frac{\rho_P}{A_P}\right)$$

ℓ = thermoelement resistance (ohms)

ρ = resistivity (ohm-cm)

R_e = load resistance (ohms)

T_h = hot junction temperature (°K)

ΔT_t = temperature difference between thermocouple ends (°C)

x = the ratio $R_e/R_i + R_c$

α = $\alpha_N + \alpha_P$ = combined Seebeck coefficient (v/°C)

Subscripts P and N refer to P- and N-type elements.

The derivation of the above expression will not be clarified in this report. For an explanation of thermoelectric theory and the derivation, the reader is referred to standard texts on the subject of thermoelectricity (Ref. 4).

In order to achieve maximum thermoelectric efficiency there is an optimum ratio of load resistance to the sum of thermoelement and contact resistance which must be maintained. This ratio is given by

$$x_{opt} = \left[1 + \frac{\alpha^2 T_h}{K(R_c + R_i)} - \frac{\alpha^2 \Delta T_t \left(\frac{R_i}{2} + R_c \right)}{K(R_c + R_i)^2} \right]^{1/2}$$

The ratio of element diameters (N; P), assuming equal length, is also important in obtaining optimum efficiency and can be calculated by finding the ratio of diameters that will make the product $K (R_c + R_i)$ a minimum. The other important factor in generator design is the open circuit voltage, "e", of the generator, which is expressed by

$$e = N\alpha \Delta T_t$$

where N is the number of thermoelectric couples.

Employing the equations listed above, the thermoelectric design of the generator may be completed. The operating characteristics of the generator are determined completely by using the previous three equations and the insulation heat losses calculated by the relationships in Chapter IV. The thermoelement length was arbitrarily specified as one inch (2.54 cm) for this generator. The generator characteristics listed in Table 2 are derived from the input data. Although a small portion of the P-elements used in the generator were not manufactured by Martin Marietta Corporation and have properties different than those of the Martin element, the difference is too small to appreciably affect generator performance.

Although the end-of-life power output is only 49 watts, it can be increased by reducing the heat losses through the insulation as the power output decreases with time. At the same time the periodic maintenance of electronic gear is performed, the gas in the generator can be changed from pure helium to less conductive inert gases.

The end-of-life power as used above is defined as that power which the generator is expected to deliver at the end of 10 years.

TABLE 2

Generator Physical and Operational Characteristics

	N-Type	P-Type
Thermoelement		
Length (cm)	2.54	2.54
Diameter (cm)	1.10	1.44
End-of-life thermal power (watts)		1075 (based on initial fuel loading)
Insulation losses (see Chapter IV) (watts)		154
Thermoelement efficiency (%)		5.22 (end of life)
Generator efficiency (%)		4.55 (end of life)
Power output (watts(e))		49
Element pairs (number)		120
Open circuit voltage (volts)		16.1
Load voltage (volts)		8.64

IV. THERMAL ANALYSIS

The analysis of heat flow and temperatures within the SNAP 7D thermoelectric generator is presented in two steps: (1) external analysis--determination of the outer shell temperature of the generator; (2) internal analysis--determination of the temperature differences between the heat source, hot junction and cold junction as a function of the output of the heat source. The outer shell temperature is used to determine the base temperature for generator operation; thus, from the outer shell temperature the internal temperatures are established. The thermal analysis determines the amount of heat required to maintain the desired temperature difference between hot and cold junctions and the design of the generator shell which will prevent overheating of the interior.

The most critical temperature in the generator is the hot junction temperature. Lead telluride elements will deteriorate at an appreciable rate by sublimation at temperatures greater than 1000° F. For a generator such as SNAP 7D with a ten-year operating life, the maximum tolerable hot junction temperature was chosen as 980° F. This maximum fixes the hot junction temperature for initial operation, which, assuming no change in generator thermal properties, results in a calculated end-of-life temperature of 800° F.

The first step in thermal analysis is to determine the ambient conditions in which the generator will operate. The outer surface of the generator can then be designed to fix the generator temperature base so as to maintain the internal temperatures at desired levels. A minimum outer surface area is fixed by the design of the generator. Additional heat rejecting surface can be added in the form of cooling fins if required to reduce the outer shell temperature.

A thermal study was made to determine the best location for radiation shielding. Although it results in greater generator weight, the shield was placed outside the generator cold junction. Placing the shielding between the heat source and hot junction, which would result in a minimum shield weight, would increase the surface area of the fuel block reducing the hot junction temperature and increasing the insulation area, thereby lowering generator efficiency.

The generator must be adaptable to operation in two different environments: (1) When the surrounding air temperature may go as high as 125° F in an enclosed space during shipment of the generator. (However, the generator may be short-circuiting during shipment, greatly lowering the hot junction temperature due to Peltier cooling.) (2) The environment present when the generator is in its aluminum boat. The generator was designed to operate under the latter condition; therefore, this analysis must assure that the hot junction temperatures under the former condition will not exceed that anticipated in the latter.

A. TEMPERATURE DURING SHIPMENT

Examination of the operating characteristics of the generator showed that a surface temperature of 200° F would maintain the internal temperatures at safe levels during shipment while the generator was short-circuited. The surface of the generator was thus designed to maintain a temperature of 200° F with the anticipated initial heat output of 1546 watts. The heat lost from the surface is given by:

$$q_{total} = q_{conv} + q_{rad} = 1546 \text{ watts}$$

where

q_{conv}	=	$h_c A_c \Delta T$ (heat rejected by convection)
q_{rad}	=	$h_r A_r \Delta T$ (heat rejected by radiation)
h_c	=	convection film coefficient
h_r	=	radiation heat-transfer coefficient
T_s	=	surface temperature of generator (absolute scale)
T_r	=	environmental temperature (absolute scale)
A_c	=	convective heat-transfer area
A_r	=	radiation heat-transfer area
ΔT	=	$T_s - T_r$.

The generator surface consists of a cylinder approximately 19 inches in diameter and 32.75 inches high with 99, 1-1/2-inch long fins running longitudinally on the curved surface of the cylinder. The number of fins is determined by the 200° F maximum temperature.

The radiant heat-transfer area, A_r, is taken to be approximately the area of the cylinder with its diameter taken as 22 inches (including fin length), including the top surface and excluding the bottom.

$$A_r = 17.80 \text{ ft}^2$$

The convection heat-transfer area is the area of the cylinder, excluding the bottom, plus the surface area of the fins multiplied by the fin efficiency. The fin efficiency is given by Ref. 5:

$$e_s = \frac{1}{\sqrt{2\epsilon}} \tanh \sqrt{2\epsilon}$$

where

e_s = fin efficiency

ϵ = $W_c^{3/2} \sqrt{h_c/kA}$

A = cross-sectional fin area = $25\ W_c$

W_c = $W + \delta$

δ = one-half the fin thickness = 0.125 inch

W = fin length = 1.5 inches

k = thermal conductivity of fin material

= 6.5 Btu/hr-ft-°F

h_c = convective heat-transfer coefficient

$\cong$ $0.27\ \Delta T^{0.25}$ (Ref. 6)

= 0.79 Btu/hr-ft^2-°F.

Fin efficiency, e_s, is found to be 83%; thus the total convective heat-transfer area, A_c, is:

$$A_c = 15.50 + 0.519\ N$$

The radiant heat-transfer coefficient is given by:

$$h_r = \frac{\sigma \epsilon_s \left[(T_s)^4 - (T_r)^4 \right]}{T_s - T_r} \quad \text{(Ref. 7)}$$

where

σ = Stefan-Boltzmann constant

ϵ_s = surface emissivity.

Adding the radiative and convective heat losses, setting the total equal to 1546 watts, and solving for N results in a minimum requirement of 84 fins. To incorporate a safety factor into the design, 99 fins were employed. For the actual initial heat input of 1435 watts, the surface temperature will not exceed 190° F under 125° F ambient conditions.

B. INSULATION HEAT LOSSES

The surface of the fuel block which is not covered by thermoelement hot junctions must be thermally insulated to reduce parasitic heat losses which lower generator operating efficiency. Min-K 1301 is used as the thermal insulation. It was chosen because of low thermal conductivity, good structural qualities and machinability. The insulation fits tightly between the fuel block and the heat sink which rests against the cold junctions, preventing motion of the fuel block. The mean insulation depth, selected as a good design compromise between thermal efficiency and generator fabricability, is 1.5 inches.

A thermal conductivity of 0.0190 Btu/hr-ft-°F was selected for calculating end-of-life thermal losses through the insulation. This corresponds to Min-K 1301 with a gas fill of about 85% argon, 15% helium. The calculated total heat loss at end of life is 154 watts including 18 watts lost through mica insulators protecting the thermoelements. An approximate solution can be obtained from the following relationship:

$$q = \frac{6 \pi r_1 r_2 k \Delta T_i}{r_2 - r_1}$$

where

q	=	insulation loss
r_1	=	inner radius of insulation
r_2	=	outer radius of insulation
k	=	thermal conductivity of insulation
ΔT_i	=	temperature difference across insulation.

C. EXCESSIVE THERMAL POWER IN FUEL

Since strontium-90 is a fission product, it contains other strontium isotopes which are separated chemically with the Sr-90. The other active strontium isotope is Sr-89, a shorter lived isotope (half-life: 51 days), which may produce as much as 80 times the heat output of Sr-90 when discharged from the reactor. Although holding time will generally be allotted so that the Sr-89 fraction will decay to a very low level, production schedules indicate that appreciable amounts might be present when the generator is loaded. The output of the Sr-89 could cause temporary overheating of the thermoelectric elements if it were not given proper consideration. The heat produced by Sr-89 beta emissions cannot be considered as part of the thermal power requirement since its duration is very short.

Figure 5 illustrates the combined thermal output of Sr-89 and Sr-90 for 245,400 curies of the heavier isotope as a function of time after discharge from the reactor. The atomic ratios were arbitrarily chosen as 0.64 and 0.20, representing estimates of upper and lower limits of Sr-89 content. The content in the encapsulated isotope fuel will depend on the actual atomic ratio at discharge (a function of irradiation time) and the age of the waste which supplied the strontium. With the proper use of conducting gas in the thermal insulation, the excess heat can be released over the first few months of generator life without detriment to its performance. The maximum Sr-89 content as specified for the SNAP 7D fuel, 90 watts, can easily be handled.

D. ANALYSIS OF GENERATOR INSTALLATION

Although the original design calculations for the SNAP 7D generator (see Ref. 8) assumed a water environment with 80° F maximum temperature, the final disposition of the generator has resulted in some-

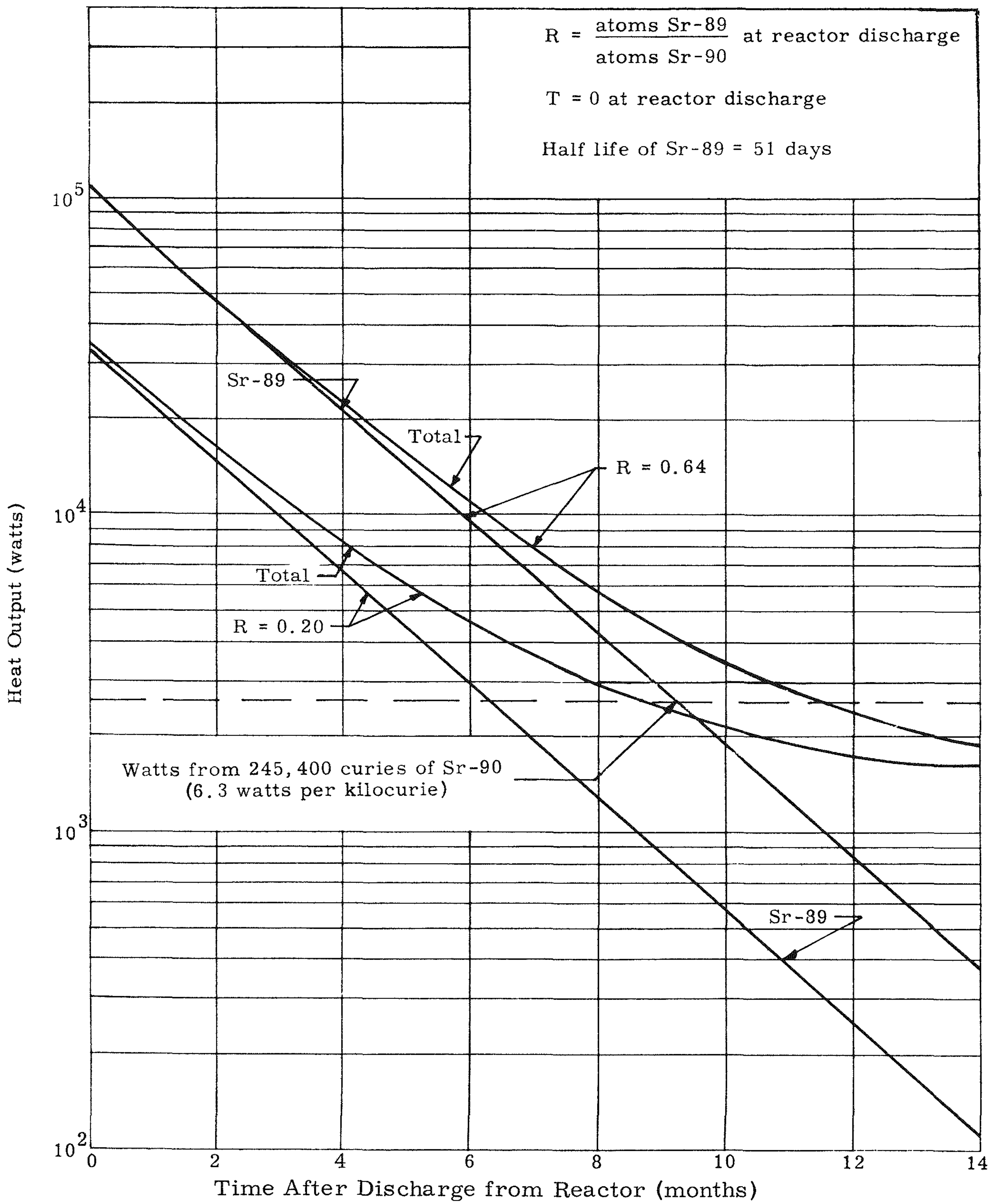

Fig. 5. Effect of Strontium-89 on Heat Output of SNAP 7 60-Watt Generator

what altered ambient conditions. The maximum beginning-of-life surface temperature of the generator, submerged in oil in its aluminum boat, has been calculated as 111° F (see Appendix A). At end of life, this maximum temperature will have dropped to 103° F.

The cold junction temperature at the beginning of life will thus be approximately 180° F instead of the 160° F originally estimated. The end-of-life cold junction temperature will be 156° F rather than the 143° F used in the thermoelectric analysis. This change, however, will not affect the end-of-life power output, since a rise of 20° F in both hot and cold junctions will not appreciably affect operating parameters.

The reduction of the electrical power requirement due to the elimination of the dc-to-dc voltage converter allowed a reduction in the heat input at the beginning of life. Instead of the previously calculated figure of 1546 watts, electrical testing of the generator showed that a minimum of 1380 watts was required at beginning of life. This reduction permitted initial operation with lower insulation losses than previously calculated.

The hot junction temperature, with the generator submerged in a tank of water and skin temperature of 86° F, was measured as 934° F. With a skin temperature of 111° F, the hot junction will go to 959° F, still safely below the limit of 980° F.

The change in actual operating conditions from the original concept resulted from the decision to mount the generator in the aluminum boat containing the weather station apparatus rather than submerge it directly in water. Thus, instead of only one convective film temperature drop between generator surface and the water, there are now three: a drop from generator surface to oil bath, from oil to boat hull, and from boat hull to water.

Although using water rather than oil inside the boat would lower the generator surface temperature, oil was chosen to reduce the possibility of corrosion and evaporation within the boat. The complete description of the generator surface temperature analysis can be found in Appendix A.

V. FUELING AND SHIELDING REQUIREMENTS

A. FUEL FORM

Strontium-90 with its relatively long half-life (27.7 years) was selected as the radioisotope to provide the thermal energy for the SNAP 7D system. The titanate form ($SrTiO_3$), a stable ceramic compound with extremely low solubility in sea water, is used.

It was necessary to fix the fuel volume prior to the detail design of the generator because of the long lead time required for chemical processing of the fuel. Assuming a 5% overall conversion efficiency, producing 60 watts after 10 years, the fuel requirement at the start of life was 1546 thermal watts. Based on the original estimate of 0.5 watt/cm^3, a total volume of 3100 cm^3 was required.

The fuel pellet diameter selected was the same as that used in the SNAP 7A and 7C programs. The required fuel cavity length was computed based on this diameter. Fourteen fuel capsules are used for ease of fabrication and handling (see Fig. 6). The capsules are arranged in the fuel block as follows: two capsules are located in the center hole; twelve capsules are located in six holes equally spaced around the center hole.

The fuel capsules are made of Hastelloy-C, selected for its structural and corrosion properties. Each capsule has a button protruding from its top surface to facilitate remote handling in the hot cells and loading into the generator.

B. FUEL LOADING

The actual fuel loading requirements were based on tests with electrically heated generators. The maximum fuel loading is limited by the hot junction temperature of the thermoelements. The minimum amount of Sr-90 is based on the system power requirement at the end of 10 years. The fueling specification called for a maximum thermal input of 1470 watts, and a minimum thermal input of 1380 watts due to Sr-90 only.

The generator was fueled at the Oak Ridge National Laboratory (ORNL) on June 12, 1962. Table 3 shows the fuel loading for each capsule, the maximum capsule leakage rate, and the degree of contamination after cleaning.

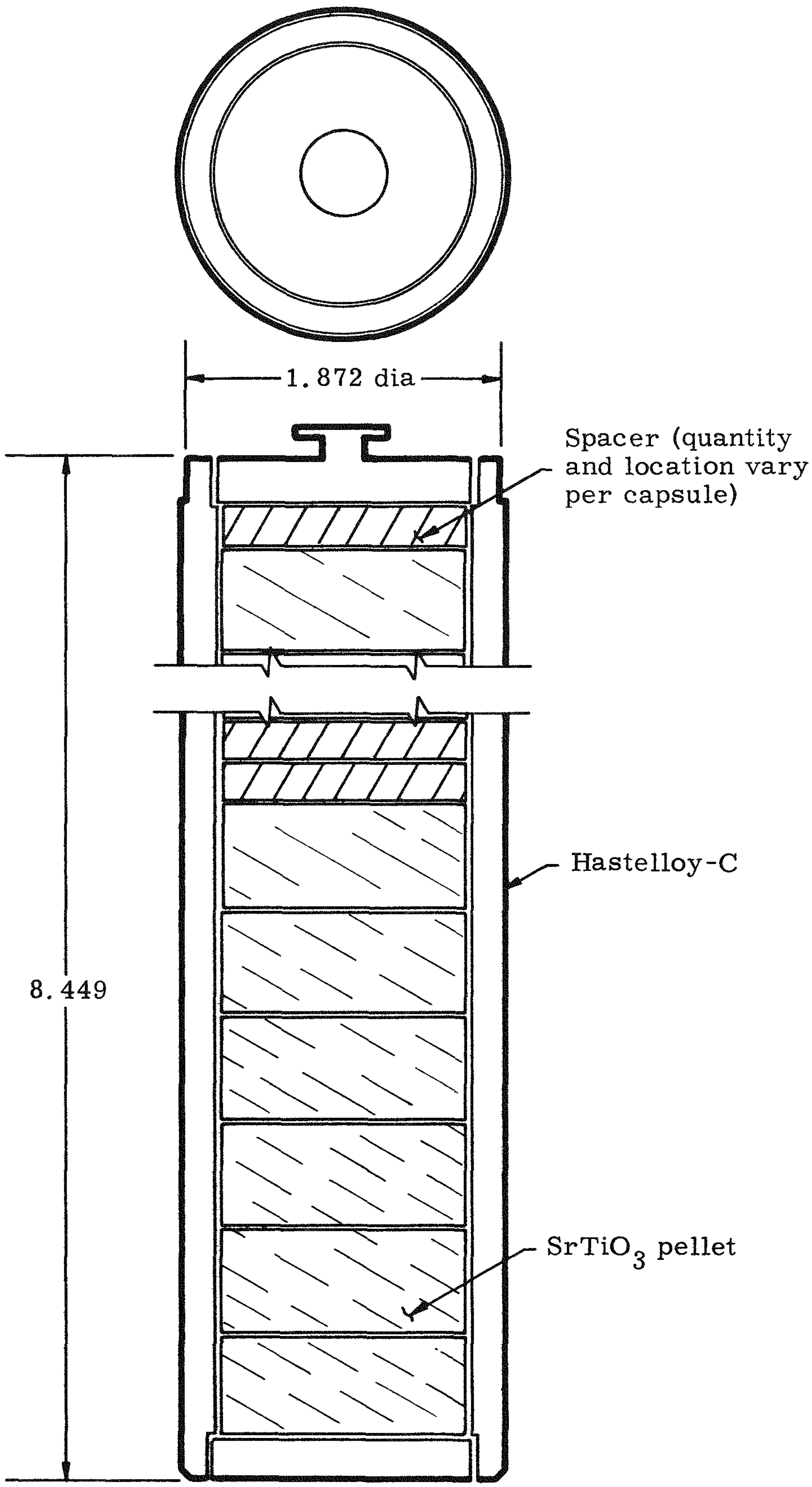

Fig. 6. Fuel Capsule

TABLE 3

Capsule Fuel Loading Data (fueling of generator at ORNL on June 12, 1962)

Capsule No.	Watts Sr-90	Leak Rate (cm^3/yr)	Smear Count (dpm--entire surface)
1	117.6	3.4	1300
2	116.3	<0.75	220
3	113.1	<0.38	180
4	114.3	<0.75	80
5	115.9	<0.75	300
6	115.4	<0.75	760
7	115.5	<0.23	260
8	118.1	<0.26	100
9	113.5	0.81	60
10	115.0	<0.75	900
11	116.4	<0.75	50
12	115.2	<0.75	70
13	25.0	0.44	160
	1411.3		4980

Due to the higher power density of the fuel pellets, 1386 watts (Sr-90) were loaded into twelve fuel capsules. This satisfied the minimum loading requirement; however, in order to offset the thermal gradient experienced in the lower end of the fuel block, an additional 25 watts were placed in the bottom of the thirteenth capsule. In each capsule spacers were used to take up the void volume. The use of liners in the fuel capsules was authorized. This permitted double decontamination, and it proved very helpful in obtaining clean capsules.

The twelve fuel capsules were loaded in the six outer holes in the fuel block. The thirteenth capsule was loaded in the bottom of the center hole; and the fourteenth capsule (empty) was loaded in the top of the center hole to act as a spacer.

C. SHIELDING REQUIREMENTS

Gamma radiation dose rates were originally based upon a fuel loading of 280,000 curies of Sr-90. Each of the fourteen capsules was assumed to contain 20,000 curies. Dose rates were calculated by means of an IBM 7090 computer using values for the bremsstrahlung radiation determined as explained in Appendix B.

Calculated dose rates for one capsule without additional shielding and for fourteen capsules loaded into a fuel block are given in Table 4.

Depleted uranium was used as the shield material to reduce the dose rate from the generator to 10 mr/hr at a distance of one meter from the envelope of fuel pellets. This material was chosen because its use resulted in a smaller overall size and weight than iron, lead, or tungsten. The thicknesses determined are:

Shield	Thickness (in.)
Top	3.2
Side	3.25
Bottom	3.2

This work was done before the work described in Appendix B was performed. Consequently, as explained in the Appendix, the thicknesses are too thick by about two half-value layers. This amounts to about 1/2 inch when uranium is the shield material. A comparison of measured and calculated dose rates is given in Table 5. The calculated values in this table have been adjusted to reflect the actual fuel loading of 224,000 curies and the actual thickness of shielding materials.

TABLE 4

Calculated Dose Rates for Single Capsule and Fuel Block

	Dose Rate at Center of Side (r/hr)	Dose Rate at Ends (r/hr)
One capsule		
At surface	38,000	26,400
One meter from surface of fuel pellets	56	24
14 capsules in fuel block		
At fuel block surface	22,000	14,000
At one meter from envelope of fuel pellets	130	67

TABLE 5

Radiation Data on Fueled Generator

Complete Assembly	Measured (mr/hr)	Calculated (mr/hr)
Contact		
Top	15	11.6
Sides	11	13.8
Bottom	20	17.1
At one meter		
Top	2	1.15
Sides	2	2.1
Bottom	2	1.16

Detector in well in contact with shield plug-- 60 mr/hr.

Detector at top without generator cover--35 mr/hr.

Measured and calculated dose rates agree within a factor of two, which is considered good in shielding work. The difference between measured and calculated values is probably due to differences in location of points at which calculations were made and readings taken, and also to differences between model used for design calculations and actual generator construction. It may be concluded that the shield for the 60-watt generator is conservative.

The shielding is adequate to meet ICC regulations for an unescorted radioactive shipment (10 mr/hr maximum at one meter and 200 mr/hr maximum at the surface).

A complete safety analysis report on the use of strontium-fueled thermoelectric generators has been prepared and is given in Ref. 3.

VI. GENERATOR ASSEMBLY

The SNAP 7D generator is assembled as follows: The Hastelloy-C fuel block is centrally positioned within the aluminum cold sink frame and held in place by corner blocks of Min-K insulation. A base plate of Min-K insulation is used to support the aluminum cold sink and fuel block. The base plate holds the fuel block in a vertical position, and also thermally insulates the fuel block from the generator housing.

P- and N-type lead telluride thermoelements are cast for the generator and are assembled into thermoelectric couples. One P-type and one N-type element are bonded to a common iron shoe to form a couple (see Fig. 3). A short mica sleeve is cemented around each element to add to its structural integrity. The elements in a couple are pushed through a section of Min-K insulation. Four couples are used to make a thermoelectric module. A copper cold cap with an electrical terminal is soldered to each thermoelement to complete the basic module. A thin sheet of mica is then placed beneath the iron shoes to electrically insulate the shoes from the fuel block and to allow the couples to slip as the fuel block grows due to differential expansion.

The module is carefully fitted into one of the slots in the aluminum cold sink frame, and an additional piece of Min-K insulation is fitted over the module. A cold sink bar is placed over the module and secured with four screws. An alignment button is placed on each cold cap to compensate for the axial and angular misalignment. A piston is inserted into the cold sink bar over each alignment button to provide a path for heat transfer. A compression spring is installed in every piston and retained with a washer and snap ring. This keeps the iron shoes in intimate contact with the fuel block for maximum heat transfer. Five of these modules are installed in each of six vertical strips; a total of thirty modules are inserted in the generator.

The couples in a row are connected in series by copper connecting straps. The rows, in turn, are connected in series by copper wire with high temperature insulation.

The generator assembly is housed in a biological shield. The shield consists of a cylinder with a closed lower end made of depleted uranium and encased in Hastelloy-C and with a nickel-plated uranium plug closing the upper end of the cylinder. A Hastelloy-C cover completes the assembly.

When the generator is tested, the cover is bolted in place with O-ring seals. After the generator is fueled and the checkout of the fueled generator is completed, the cover is welded in place. The bolts are replaced by welded-in plugs.

An inert atmosphere is maintained in the generator to prevent oxidation of the thermoelements at elevated temperatures. The fill gas is varied to control the thermal conductivity through the insulation in the generator. The usual gases used are argon and helium, or mixtures of the two.

VII. ELECTRICAL SYSTEM

The SNAP 7D electrical system is designed to store the electrical energy supplied by the nuclear-powered thermoelectric generator. The low current from the generator is used to maintain the charge on a storage battery. The battery, in turn, is capable of supplying the high current required by the flashing light and weather station equipment upon their periodic demand. Since the generator is sized for end-of-life operating conditions, the generator power output will always exceed the integrated power demands and will normally maintain the battery in a fully charged condition.

In case of a generator failure, it is desirable to switch the flashing light which marks a navigational hazard to a reserve battery system. A relay system has been devised which senses generator output current, and will automatically transfer the flashing light load to the reserve batteries if the generator output current falls below a predetermined value.

A. BATTERY

The electrical storage system is a rechargeable 12-volt battery pack capable of supplying a high rate of discharge during short periods of time. The battery pack (see Table 6) consists of three series-connected batteries. A battery is composed of three nickel-cadmium cells of the sealed type. The seals are backed up by encapsulation in epoxy. The only exposed surfaces are the two battery terminals and the cell pressure-release valve orifices.

The pressure-release valves are safety elements used only to prevent rupture of cell and battery, and damage to adjacent equipment in case of accident. The orifice is covered externally by a nylon film which, by rupturing, will serve as an indicator as to whether or not the safety valve has operated. The valves are of a reclosing design which will permit the cells to continue in service as sealed units if the fault causing the overpressure is of a temporary nature.

Causes of overpressure can be grouped into three general classes:

(1) Internal short circuit. The pressure will be caused by boiling of the electrolyte with the heat developed. In general, the reaction will be violent and the cell will be permanently damaged.

(2) Reverse charge. This is the result of reversed connection to a charger or by overdischarge of the battery. If the loss of electrolyte is not too great, the cells may be cooled and restored with normal charging techniques.

TABLE 6

Battery Data

Capacity (rate)	170 AH at 2 hr
Voltage (volts, nominal)	3.6
Open-circuit voltage charged (volts)	Approximately 3.9
Open-circuit voltage discharged (volts)	Less than 3.75
Cutoff voltage (volts)	3
Nominal charging voltage (volts)	4.20
Maximum continuous discharge rate (amp)	850
Maximum peak current (amp)	2000
Temperature range (°F)*	20 to 100
Maximum continuous overcharge rate (amp)	7
Factory test (amp)	10
Recommended initial charge rates (amp)	5
Minimum ampere hours required for full charge	340

*This battery can deliver a very large part of its power at temperatures below 0° F, but charging must never be done with battery or ambient temperature below 20° F to avoid excessive pressure. At temperatures above 100° F, noticeable loss of capacity (temporary) will begin to take place, although charge and overcharge may be made safe as far as pressure is concerned. This cell should not be subjected to temperatures above 150° F in storage or operation.

(3) Overcharge beyond rated maximum values. The future serviceability of the battery will depend on the degree of overcharge.

One other feature of sealed cells is that a reduced charging rate should be used after the cells have been off charge for periods of a day or more. Failure to observe this precaution can result in overpressure.

B. RELAY PANEL

The relay panel is composed of a current sensing relay, a switching relay, a reset switch, a shorting switch, a shunt, and terminal strips to facilitate the system connections.

The current-sensing relay has been adjusted to make contact if the current from the generator falls below three amperes. The resulting signal is fed into a silicon rectifier which acts as an electrical gate and which conducts the current around the current-sensing relay to the switching relay. The switching relay transfers the navigation light to the reserve battery system. A diagram of the system wiring is presented in Fig. 7.

There is a large voltage drop, approximately 9 volts, across the current-sensing relay when the points close. If the signal were fed directly into the switching relay the relay would not actuate due to insufficient available voltage. The silicon rectifier eliminates the voltage drop across the current-sensing relay from the circuit, and thus the full potential of 12 volts is available to actuate the switching relay. Resistors, a capacitor, and a diode are added to the circuit to control current flow.

A multi-contact switching relay was selected in order to obtain a relay that could handle high currents but would not consume large amounts of power. Normally the navigation light operated from the batteries supplied with the SNAP 7D system, and is wired to one side of the switching relay. When the generator current drops below 3 amperes, the navigational light is switched from the system batteries to the reserve batteries. The weather station load remains on the SNAP 7D system batteries at all times.

The navigation light does not switch back to the system batteries automatically. A manual reset button has been provided for this purpose. In order to reset the switching relay, it is necessary that the generator current be at least three amperes.

A shorting switch has been provided for convenience. This switch will short out the generator output, but it will not alter battery operation.

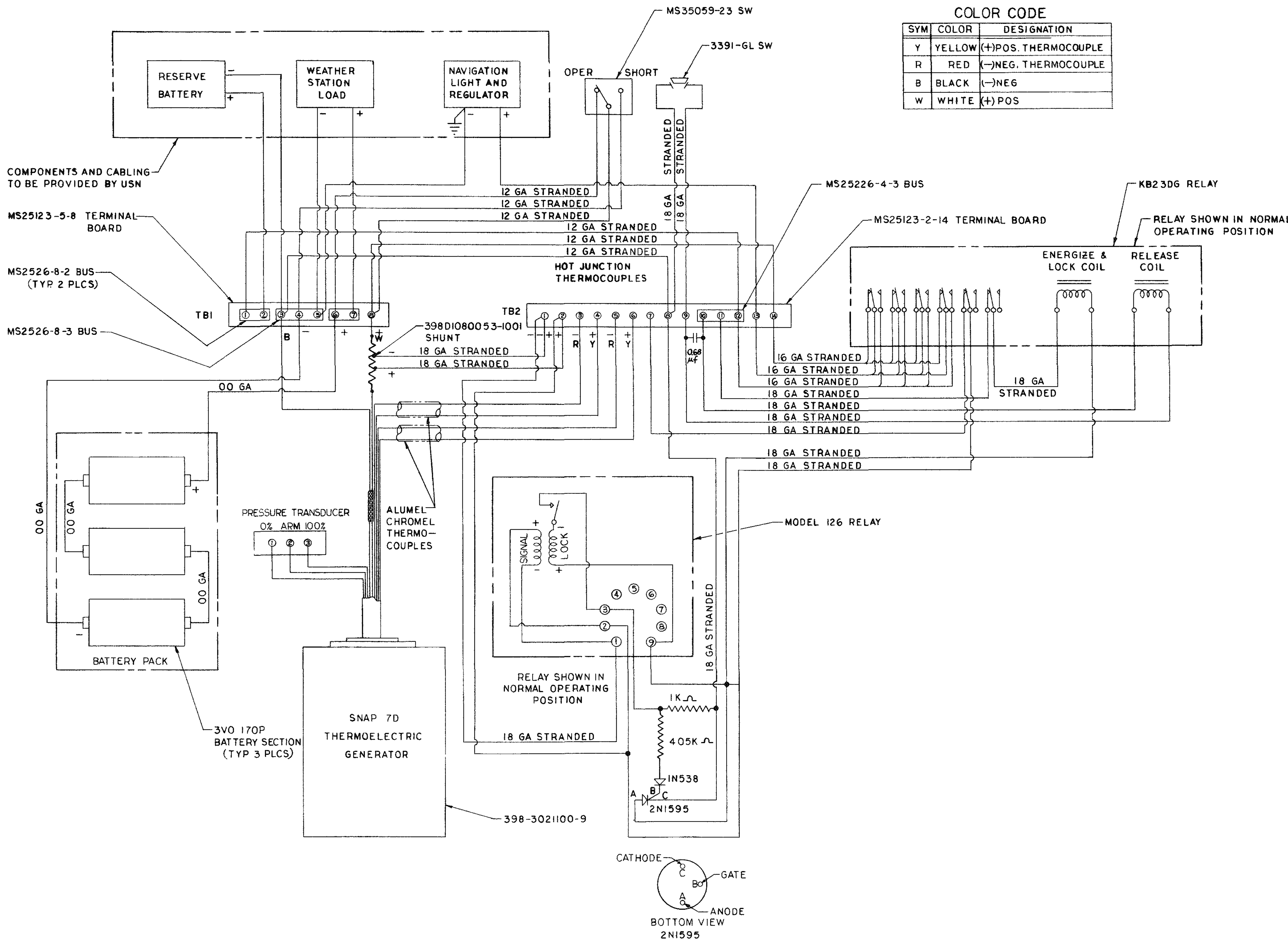

Fig. 7. SNAP 7D Wiring Diagram

A 5-ampere, 50-mv shunt has been placed in series with the generator output lead. The drop across the shunt is measured in millivolts, and can be converted to amperes by dividing by ten. This is used to read the generator output current and to supply the signal for the current-sensing relay.

Terminals have been provided on the relay panel to facilitate the reading of the pressure transducer. This device is a variable potentiometer which responds to gas pressure changes within the generator.

VIII. SNAP 7D OPERATIONAL TESTS

The SNAP 7D generator and system were thoroughly tested prior to fueling. The objectives of the tests were to determine the fuel loading limitations, the generator performance data, the compatibility of the system, and compliance with the Statement of Work (Ref. 2).

A. DESCRIPTION OF TESTS

1. Generator

The generator tests were initiated on March 28, 1962. Erratic instrumentation readings indicated that a problem existed. External examination failed to reveal the problem, so the generator was removed from its housing. It was found that a major percentage of the couples had a broken element and that the breakage was predominant in the ends of the generator. There were also indications that some of the terminals on the elements had shorted to the housing. It was concluded that the problem was due to differential expansion (Ref. 9). The couple terminals were shortened as a solution to radial expansion. As a solution to longitudinal expansion, the coefficient of friction between the couples and the fuel block was reduced to the point where the sliding stress on the elements was below the allowable stress limit. This was done by adding a thin sheet of mica between the fuel block and the couple shoes. The generator was then reassembled and the tests resumed without further incident.

Parametric tests were performed with helium and argon for beginning of life and end of life, respectively. These tests were to determine the maximum amount of fuel that should be used and to determine the minimum amount of fuel that would supply the required power after 10 years of operation.

For shock and vibration tests the generator was filled with argon (1.05 atmospheres) and a power input of 1000 watts was supplied with electric heaters. The voltage across a resistive load was monitored to determine possible deviation of generator output during environmental testing. (See Section IX for the environmental test data.)

The generator was operated at approximately matched load with four different electrical power inputs for each of the following internal gas fills:

(1) 100% argon.

(2) 20% argon-80% helium.

(3) 40% argon-60% helium.

(4) 100% helium.

The gas change recommendations to power-flatten the generator over its life are derived from these data.

2. Battery and Relay Panel Tests

Initial tests were performed to determine the stabilized operating point of the battery for a one-hour and a two-hour load cycle. The batteries were connected to the relay panel and a power supply for this test. Dummy loads were used to simulate the navigation light and the weather station equipment.

3. Integrated System Tests

The generator was placed in a cold box with provisions for cooling and operated under simulated system conditions for 30 days. The battery and relay panel were located in a second cold box. The system was loaded with a cyclic resistive load which simulated the weather station load and with an equivalent continuous resistive load to simulate a flashing navigation light. The test was performed in this manner so that temperature tests for the generator, battery, and relay panel could be conducted simultaneously with the 30-day system test. A timer was set to cycle the load every three hours for the entire test. Pertinent data were recorded several times daily. The electrically heated SNAP 7B generator, installed in a biological shield, was used for this test so that SNAP 7D fueling would not be delayed. The generator was placed in an open top container with a mixture of antifreeze and water for simulation of the actual generator installation. Ambient air temperatures were controlled to provide generator coolant temperatures of 28°, 50°, and 80° F. The generator was operated for one week at each of these thermal conditions and operation data were recorded daily.

The temperature of the cold box in which the battery and panelboard were located for temperature tests was controlled at ambient temperatures of 28°, 55°, and 80° F for one week at each temperature. Battery charge voltage and current were recorded at least once a day throughout the entire test. The simulated weather station load was cycled every three hours and the equivalent flashing light load was continuous at 4.85 watts.

Acceptance tests were performed with the integrated system on July 3, 1962. The simulated weather station load was cycled four times. A variable series resistor was switched into the circuit between the generator and battery. This resistance was increased to decrease the current output from the generator to cause the switch to transfer the GFE flashing light to the reserve battery. The operation of this switch was demonstrated twice. The flashing light was replaced with a 19.2-ohm resistive load to conclude the tests.

B. TEST RESULTS

1. Generator Tests

a. Electrically heated performance

Maximum allowable fuel at beginning of life for the SNAP 7D generator with a helium atmosphere was found to be 1470 watts total of Sr-90 and Sr-89. To meet design requirements, the minimum Sr-90 at beginning of life was determined to be 1380 watts. The actual Sr-90 fuel load was 1411 watts; this fuel load will provide an isotope power input of 1275 watts at the end of four years. After 10 years, the isotope power will be 1100 watts. A graph of predicted isotope power input and generator output power is shown in Fig. 8.

Parametric data and temperatures for an electrical power input of 1480 watts with a helium fill is shown in Figs. 9 and 10. Similar data for an argon gas fill with 1080 electrical watts input is included in Figs. 10 and 11. To obtain those required isotope loadings given in the preceding paragraph, subtract 10 watts from the electrical input power to allow for external electrical losses. Figure 12 shows a plot of hot junction temperature versus electrical power input, the effect short circuit has on temperature, and the corresponding internal resistance.

Results of the gas change tests showing temperature versus electrical power input for internal gas fills of pure helium, 40% helium-60% argon, 20% helium-80% argon, and pure argon are included in Fig. 13. The pure helium and pure argon information has been extrapolated to input power versus output power, and appears in Fig. 14.

b. Isotope fuel performance

The generator was fueled with 1411 watts of Sr-90 and 24 watts of Sr-89 for a total isotope thermal power input of 1435 watts. This thermal input provided similar generator performance characteristics to an electrical power input of 1445 watts. Initial parametric data for the isotope-fueled generator is shown in Figs. 15 and 16.

2. Battery Performance

Results of initial tests on the battery were erratic, and appeared to follow no logical pattern. As the cyclic off time for the load was decreased, battery charge voltage increased. Sufficient time for stabilized performance under this condition was not available.

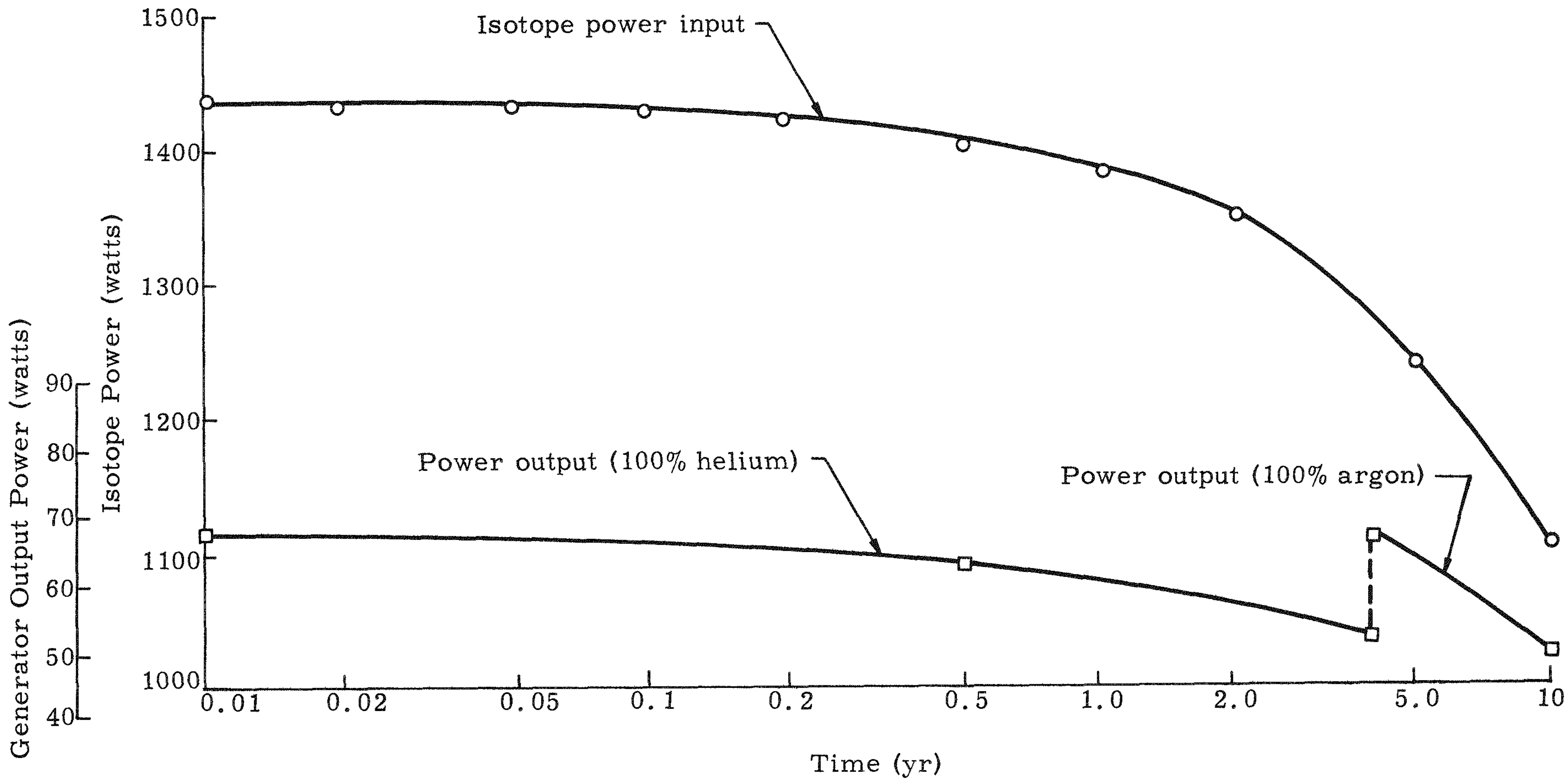

Fig. 8. SNAP 7D Generator Isotope Power Input and Predicted Power Output

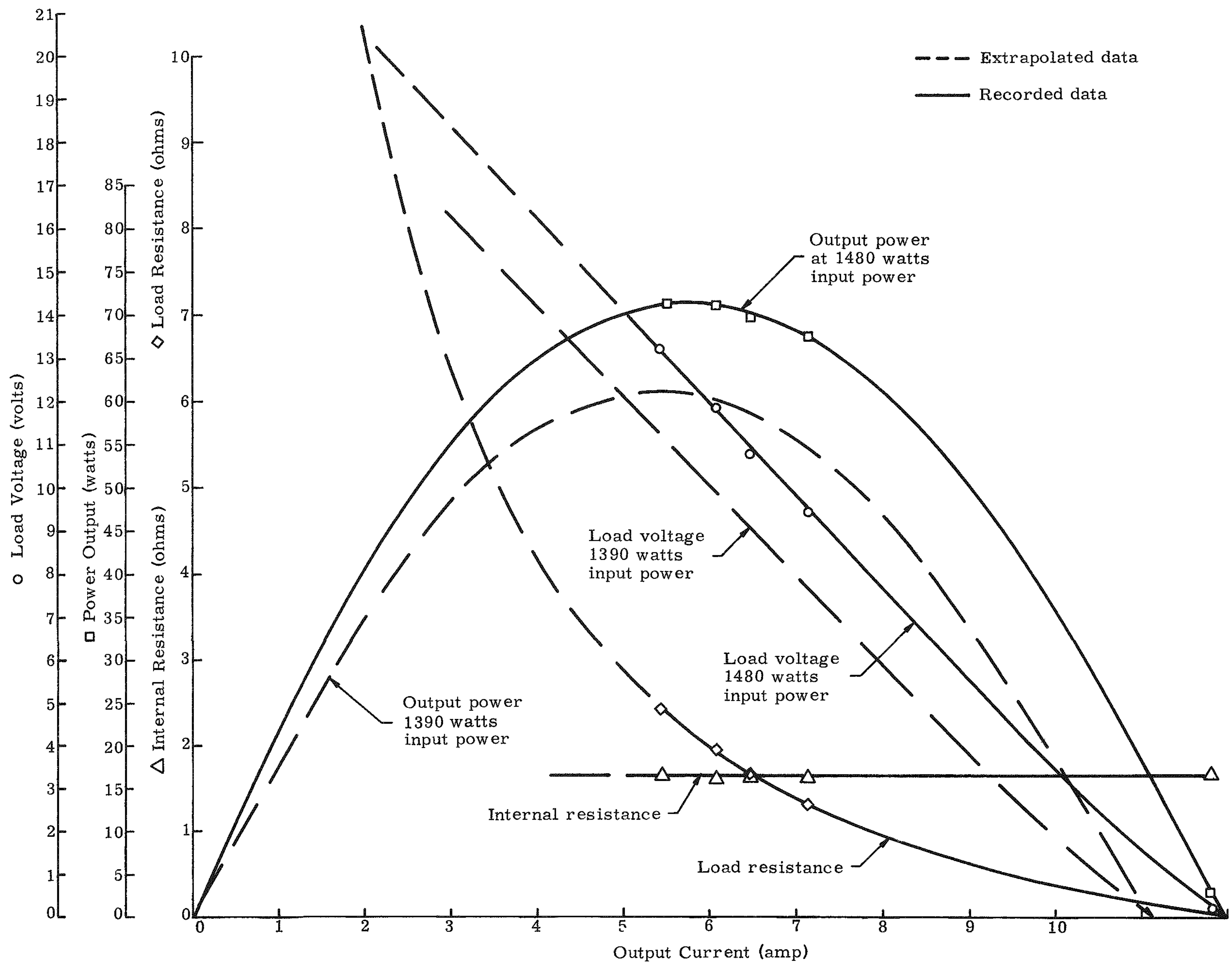

Fig. 9. No. 1 60-Watt Generator--Parametric Data at Start of Life (Electrical Power Input: 1480 Watts; Internal Gas: Pure Helium)

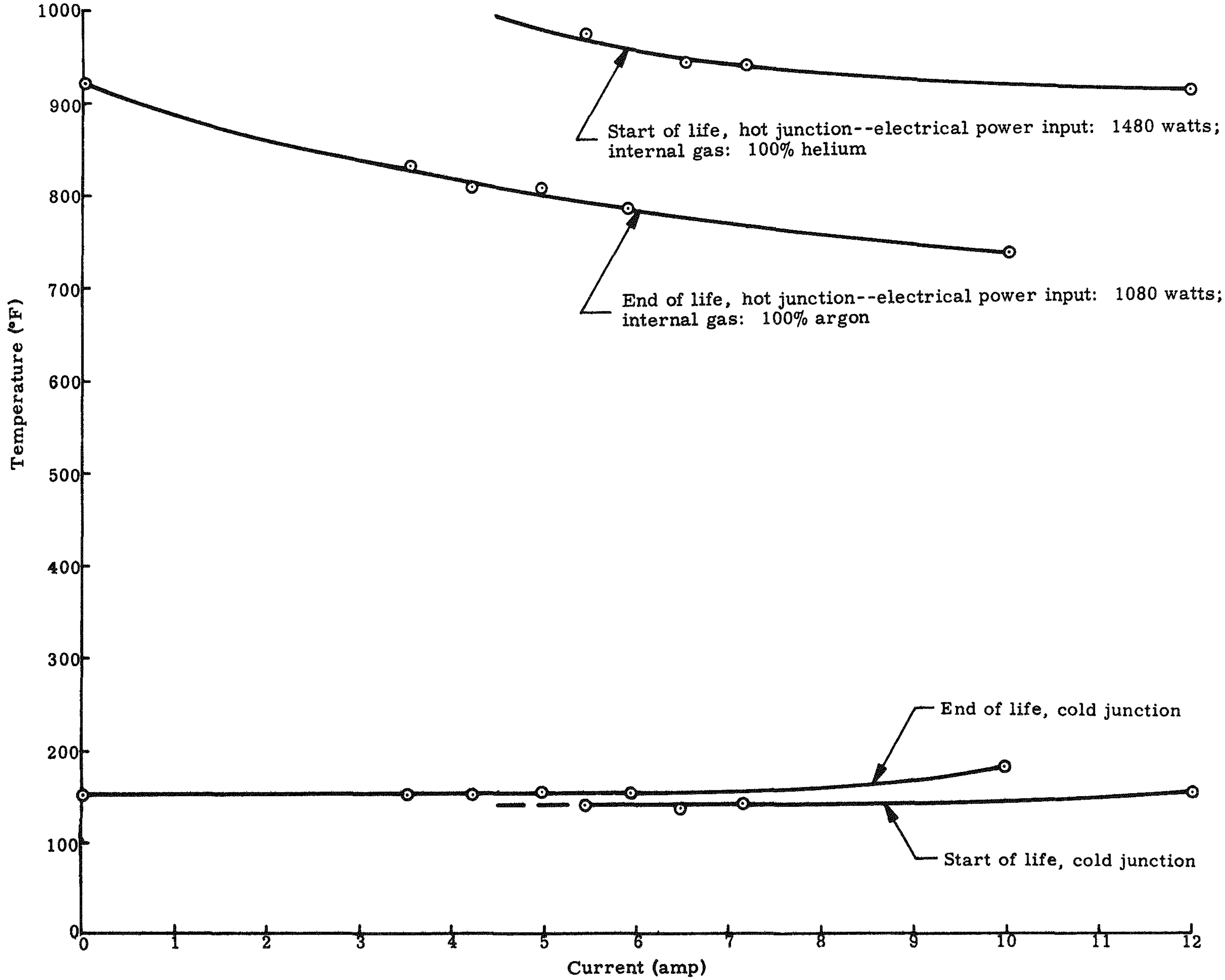

Fig. 10. SNAP 7D 60-Watt Generator--Hot Junction Temperature Versus Current

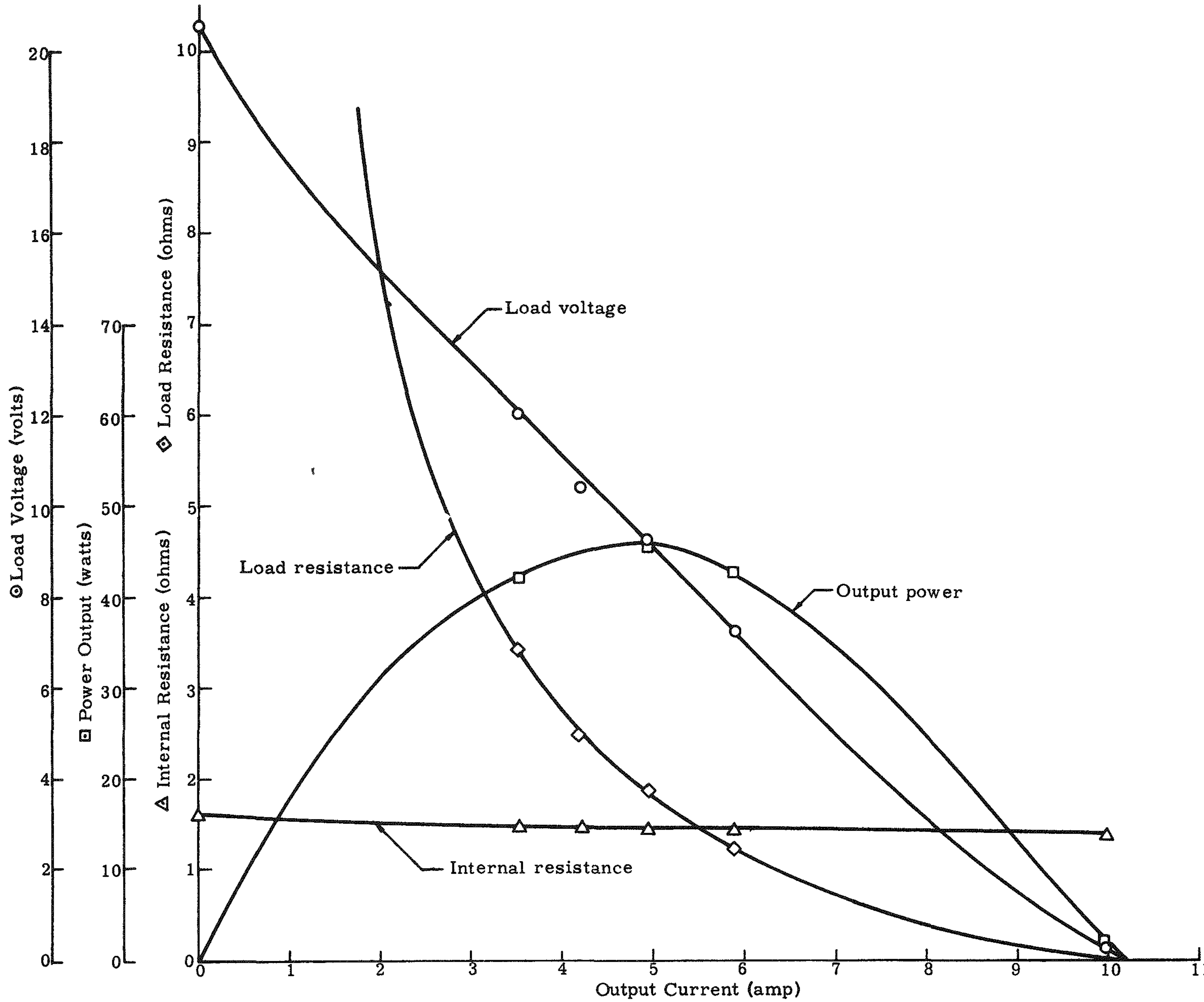

Fig. 11. SNAP 7D 60-Watt Generator--Parametric Data at End of Life (electrical power input: 1080 watts; internal gas: pure argon)

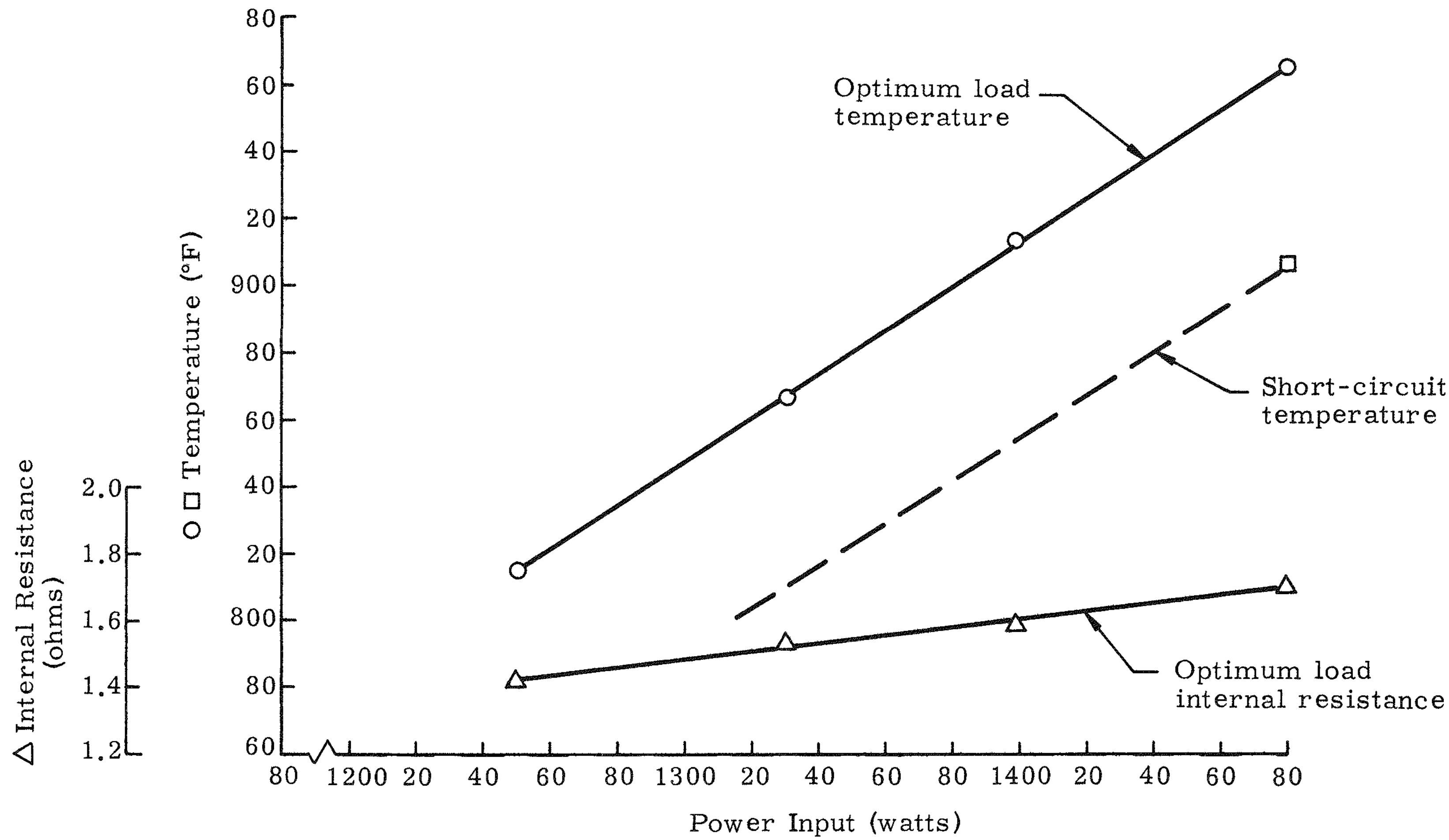

Fig. 12. No. 1 60-Watt Generator--Hot Junction Temperatures Versus Electrical Power Input (Internal Gas: 100% Helium)

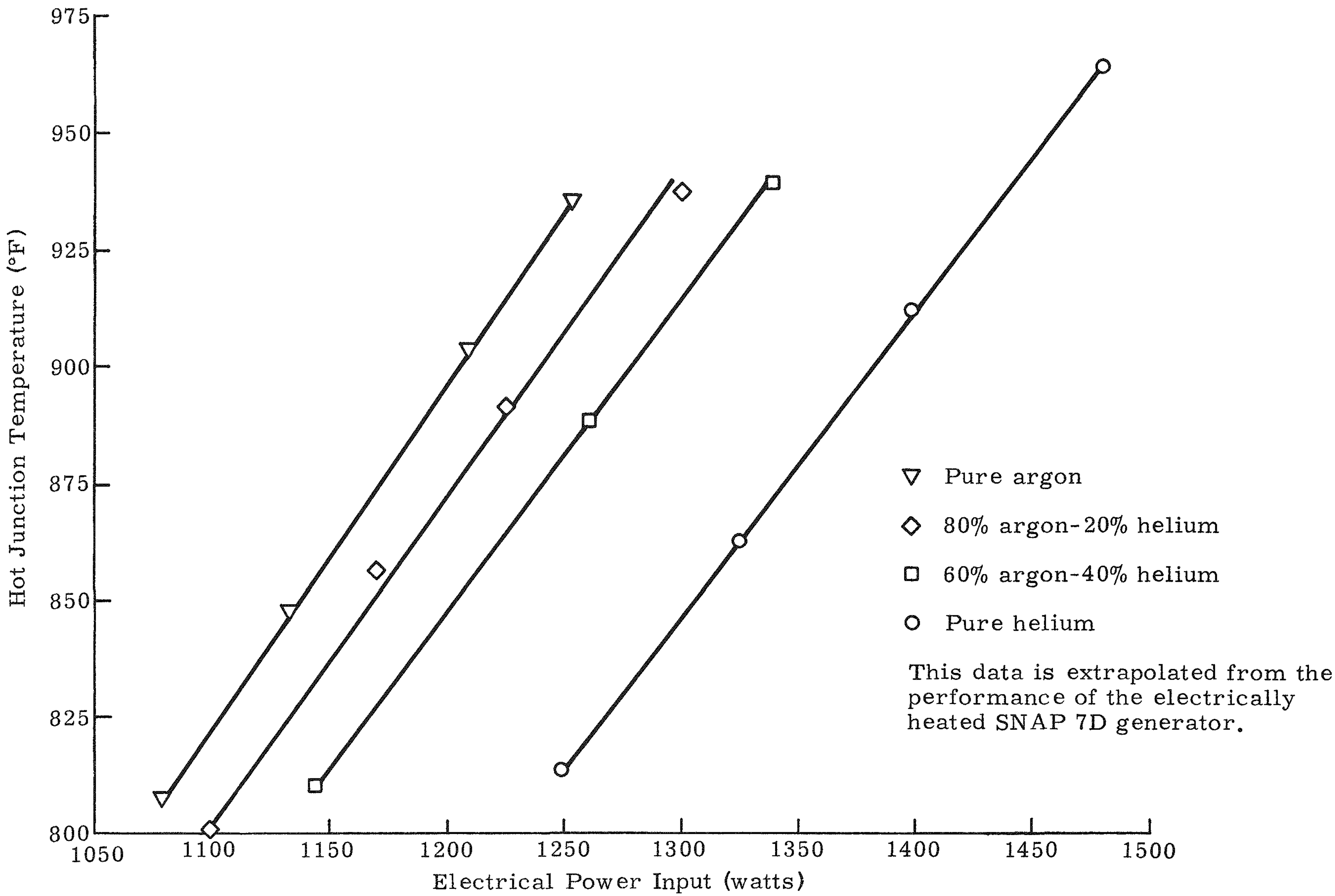

Fig. 13. SNAP 7D Generator--Hot Junction Temperature Versus Electrical Power Input at Optimum Load with Various Internal Gas Mixtures

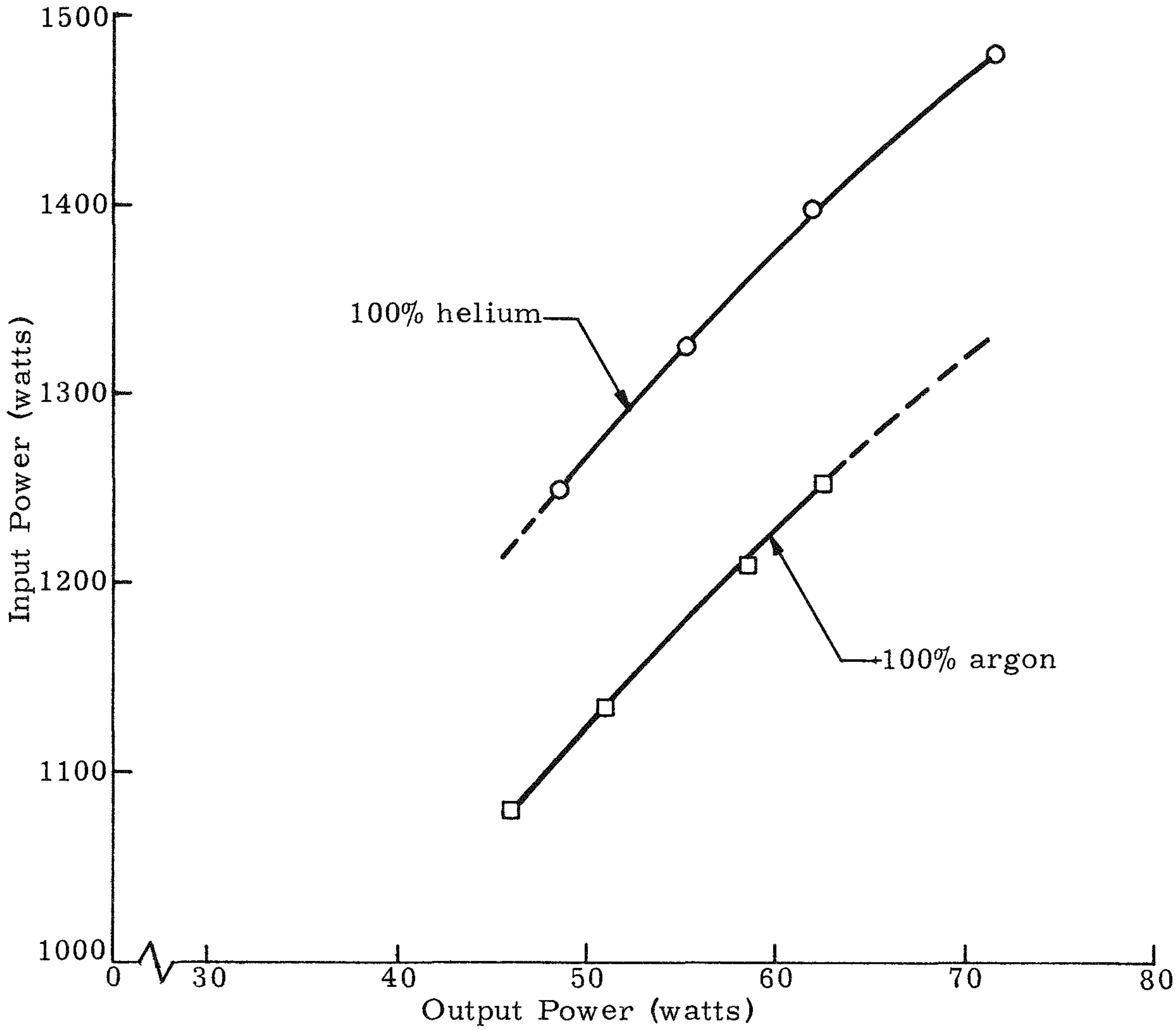

Fig. 14. SNAP 7D Generator Electrical Power Input Versus Power Output

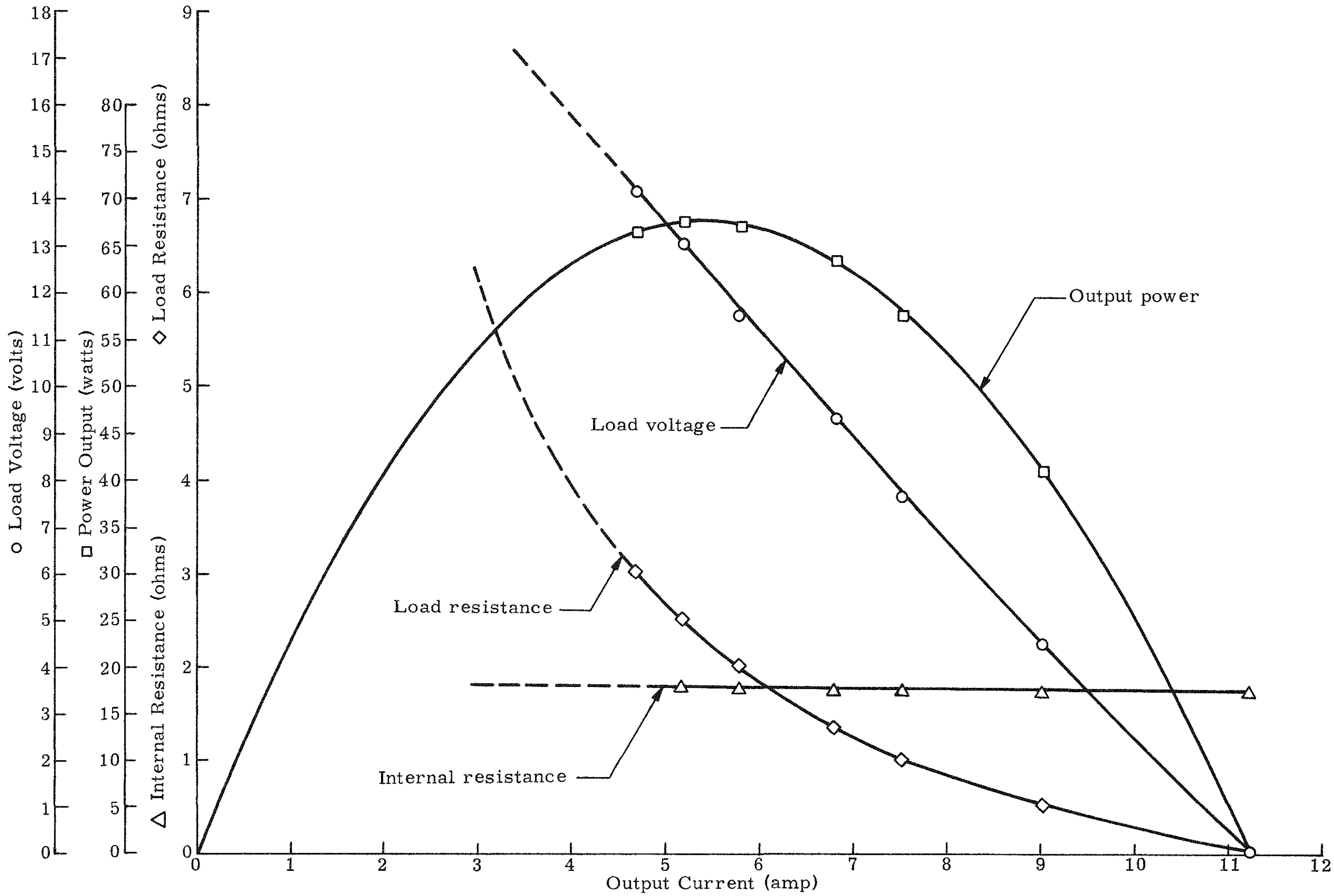

Fig. 15. SNAP 7D Generator (Fueled) Parametric Data (Internal Gas: Pure Helium; Water Temperature: 75° F)

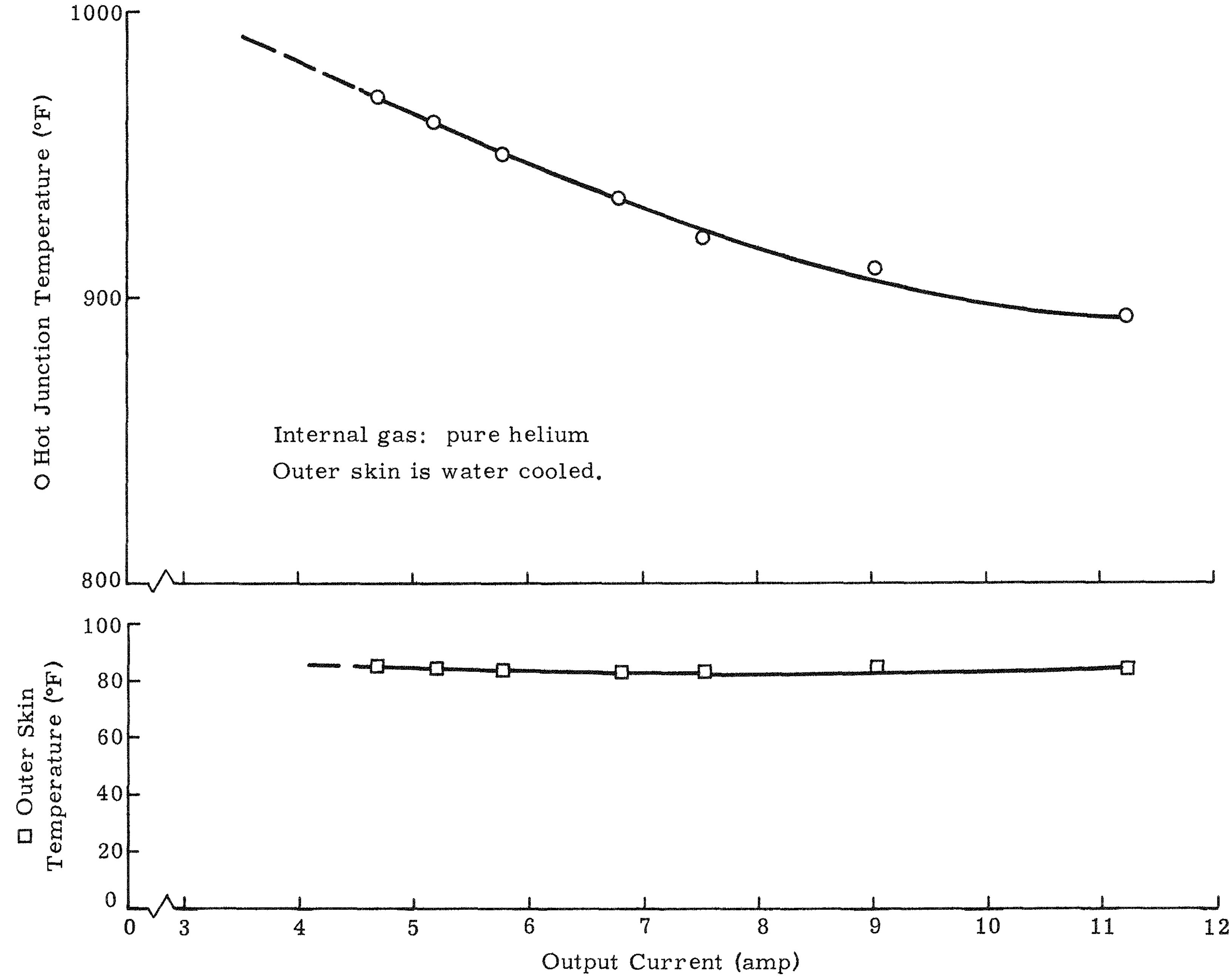

Fig. 16. SNAP 7D Generator (Fueled)--Hot Junction and Outer Skin Temperature Versus Output Current

From subsequent stabilized operation at each of three different ambient temperature conditions, the battery temperature coefficient was found to be -38.5 mv/°C. A plot of battery charge voltage versus ambient temperature is shown in Fig. 17.

3. System Tests

Temperature and voltage results of the system tests are shown in Figs. 18 and 19.

4. Acceptance Tests

Acceptance criteria for the SNAP 7D system is as follows:

a. Steady-state output voltage

(1)	At time of initiation of system operation and for two years thereafter.	12 ± 2 volts
(2)	Output with an external load of 19.2 ohms continuous.	9 volts min
(3)	Maximum RMS ripple voltage (including noise).	2.5% of output voltage

b. Stabilized cyclic load output voltage with the following cyclic loads: 12 ± 2 volts

(1) A load to simulate operation of the weather station equipment requiring a total time of three minutes. The initial surge current is 200 amperes and steady-state current is 50 amperes.

(2) A GFE flashing light.

c. Operation of the reserve battery switch shall be demonstrated at least twice.

All the above criteria were successfully demonstrated. Battery charge voltage after four consecutive cycles of the motor generator simulated load was 12.26 volts; this was a decrease of 0.14 volts. The battery voltage did not change from the original value of 12.40 volts when a 19.2-ohm load was switched into the circuit. The peak-to-peak ripple voltage was 0.005 volts. Based on peak-to-peak ripple, the ripple voltage was 0.04%. No effort was made to determine the actual RMS ripple percent, since it is extremely low. Stabilized battery voltage for the three-hour load cycle was 12.40 volts.

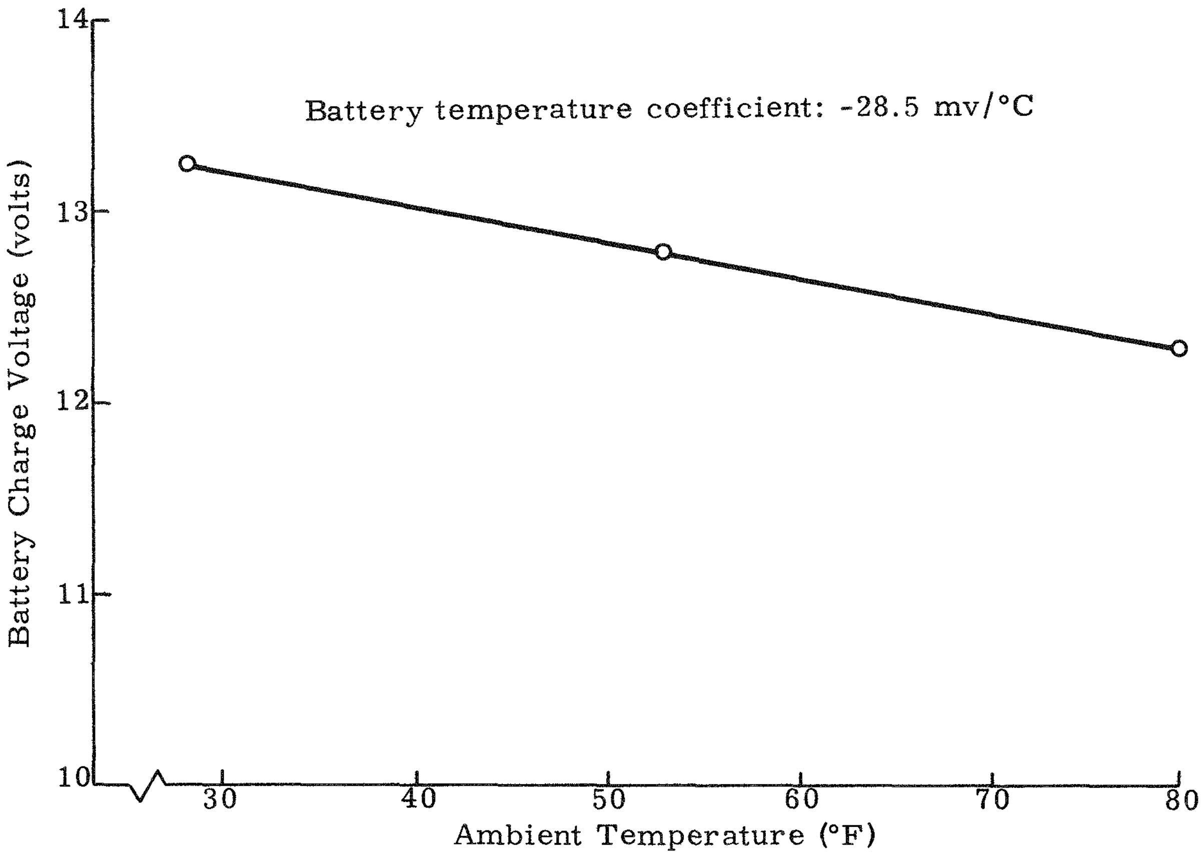

Fig. 17. SNAP 7D 30-Day System Test Battery Charge Voltage Versus Temperature

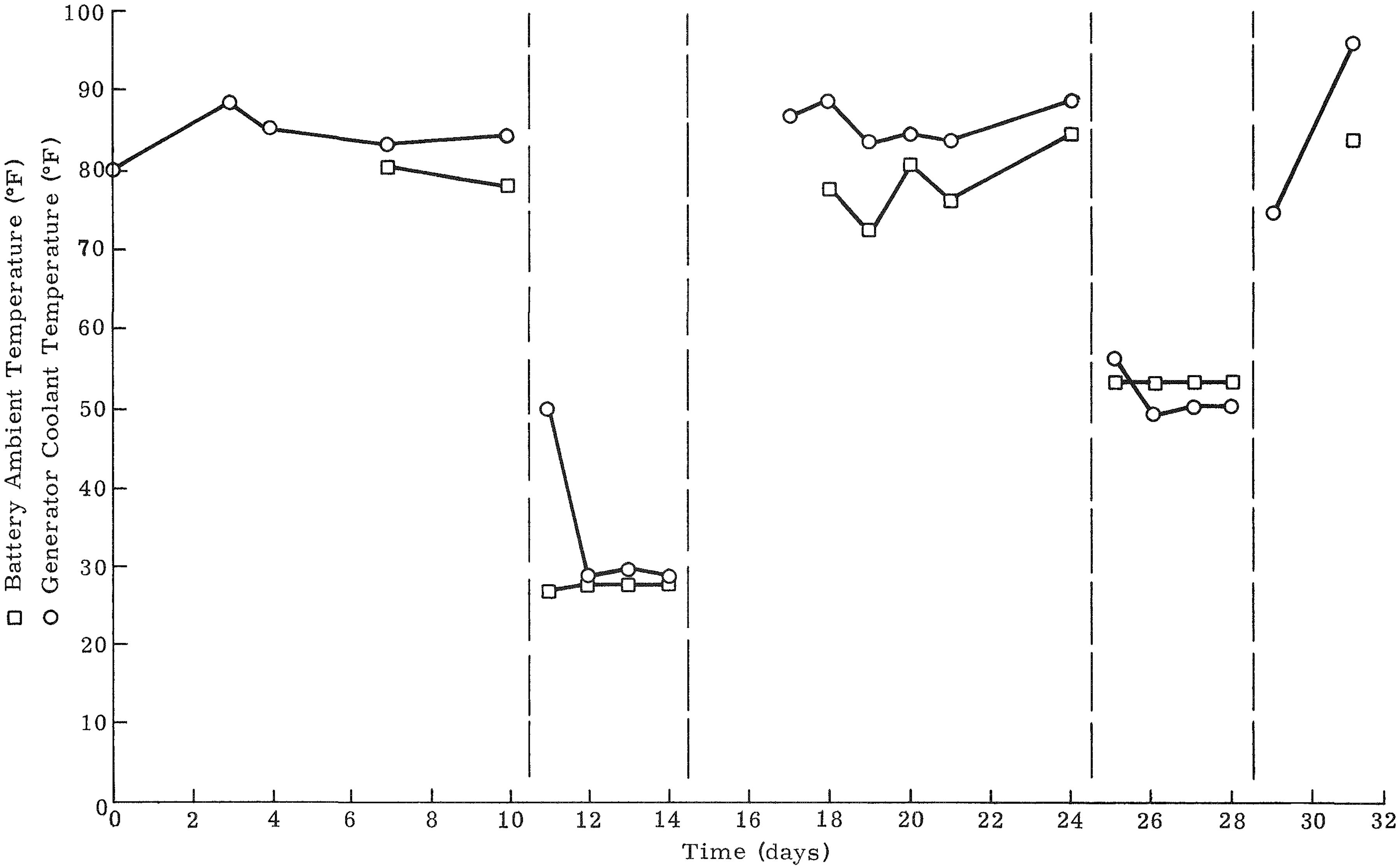

Fig. 18. SNAP 7D 30-Day System Test Battery and Generator--Ambient Temperature Versus Time

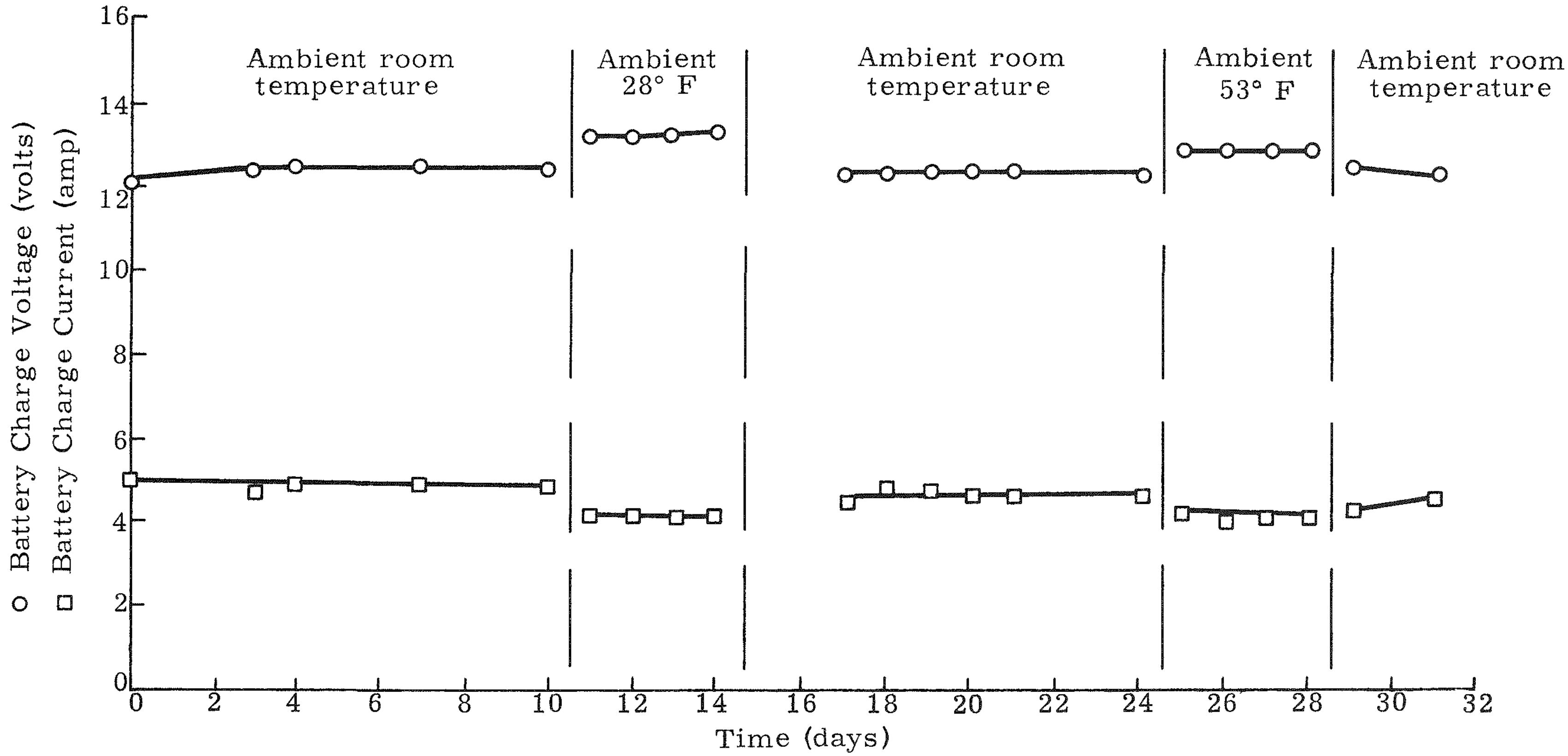

Fig. 19. SNAP 7D 30-Day System Test Battery Charge Voltage and Current Versus Time

Operation of the reserve battery switch was demonstrated twice, and each time the flashing light switched to the reserve battery when the generator output current was decreased to 3.0 amperes.

C. SYSTEM EVALUATION

1. Generator Tests

At the beginning of the SNAP 7D program, it was estimated that three gas changes would be required to attain a 10-year performance life for the generator. As a result of the percentage of Sr-90 in the isotope fuel, it was found that changing the gas to pure argon after four years would extend the useful life of the generator to 10 years. This will give a generator output power of 52 watts with helium after four years and 49 watts with argon after 10 years as indicated in Fig. 8.

2. Battery Tests

The erratic battery data obtained from initial tests are attributed to an improper "conditioning" of the battery prior to delivery to the Nuclear Division. Information from the vendor is that the negative plates probably were not properly formed before shipment from their plant. After initial operation, the batteries functioned properly.

3. System Tests

The variable ambient temperatures at approximately 80° F indicated in Fig. 18 are a result of varying ambient room temperatures. These ambient temperatures were measured by a thermometer suspended in each cold box. During early morning hours the ambient room temperature drops to approximately 75° F, and, in the afternoon, will increase to 95° F. During periods of operation with controlled cold box temperatures, no problems were encountered.

4. Acceptance Tests

All acceptance criteria were demonstrated and fulfilled. During acceptance tests it was found that the hot junction thermocouple on the top end of the generator did not indicate properly. A voltmeter indicated 1.3 volts across the thermocouple leads. One of the leads was shorted to the generator at a different point from that of the one where the thermocouple is attached. The thermocouples have since been changed to two other locations closer to the mid-point of the generator. These locations were selected to indicate better the maximum hot junction temperatures.

5. Conclusions and Recommendations

All components of the SNAP 7D system should function without attention for four years. The sensing mechanism which switches the navigation light from the SNAP 7D battery to the reserve battery is the least reliable part of the battery, in that moving contact points are required which are subject to corrosion and sticking. For future use, a solid-state switching device is recommended, although the existing system should satisfy the 10-year design objective. The solid-state device would consume more power and for that reason it was not used originally. The elimination of the converter requirement has increased the system efficiency, so the small extra amount of power required by the solid-state switching device would present no problems.

An internal gas pressure increase has been noted on the SNAP 7D generator. The pressure increases with time and has been noted on both the electrically heated and the fueled generator. This pressure increase has also been noted on the SNAP 7A and 7E and on the electrically heated SNAP 7B generators. It is believed that the gas is being liberated from the insulation by decomposition of the organic binders due to thermal and radiation effects. From recent gas analysis on the SNAP 7A, 7B, 7D and 7E generators, it appears that the gas is mostly hydrogen.

The effect of the hydrogen can readily be seen by comparing the thermal conductivity of hydrogen with that of the desired gas fill for the generator, remembering that the chosen fill gas controls the heat losses of the generator. The thermal conductivity of hydrogen is about 1.12 times that of helium, but it is about 10 times that of argon. This will only affect that portion of the heat that flows through the insulation (calculated at 154 watts with an 85% argon-15% helium gas fill).

The SNAP 7D is initially filled with helium, and the heat loss due to the hydrogen is therefore small. The important result is the effect on the output power, and this is less than 6 watts electrical as observed over an 8-month period. Therefore, the generator will deliver approximately 46 watts at the end of 4 years, instead of 52 watts if uncorrected. However, the system only requires 36 watts to operate, so the time of the recommended first gas change will not be affected.

It is not expected that the pressure created by the liberation of the gas will ever become serious. The maximum pressure noted in the SNAP 7 generators has been 17 inches Hg (gage). The generator can safely withstand pressures much higher than this; however, a gas change is recommended if the pressure should reach 25 psia. A pressure transducer (0 to 25 psia) has been installed on the generator to permit pressure readings after installation in the weather station buoy.

It is quite possible that no further gas will be liberated by the time of the first gas change. However, if the problem does still exist, then it is recommended that a gettering device be installed at that time.

A research program, under Contract AT(30-1)-3143, is in progress to determine the cause of the gas pressure buildup and the means for alleviating it.

IX. ENVIRONMENTAL TESTING OF SNAP 7D ELECTRICAL GENERATING AND STORAGE SYSTEM

Environmental qualification of the major system components is necessary because:

(1) The equipment, after exposure to normal accelerations and vibrations, must be operable and sustain no major damage from induced shock or vibration loads.

(2) The equipment must be capable of operation under the environmental conditions encountered at the installation site.

Tests were conducted under conditions set forth in applicable portions of the Statement of Work (Ref. 2).

A. DESCRIPTION OF TEST SPECIMENS

1. Generator

The operating model test generator consists of four basic items: an electric heat source (to simulate the isotopic heat source), a thermoelectric conversion circuit, a heat dissipation section, and a biological shield. The biological shield was not used for the mechanical environment tests.

The generation unit with its container was installed in a test fixture (with circulating water for cooling) for the vibration and shock tests. Temperature extreme tests were conducted with the unit assembled in its biological shield and submerged in a mixture of glycol and water to simulate heat-transfer properties.

2. Battery and Relay Panel

The complete relay panel was used for the environmental tests. One battery was used for the shock and vibration tests, since it was typical for the three batteries that make up the battery pack.

B. TEST CONDITIONS

The SNAP 7D thermoelectric generator, battery, and relay panel were subjected to vibration, shock, and temperature extremes in accordance with the following:

1. Vibration Tests

Since the SNAP 7B and 7D generators are identical, one model was subjected to the following environment (7B and 7D environmental requirements are identical):

(1) Vertical plane--5- to 300- to 5-cps sweep, in 15 min, at a ±3-g level or 0.060 ± 0.006 in. displacement, whichever is less.

(2) Repeat (1) for the two remaining orthogonal axes.

(3) Dwell at the most severe resonant condition, at the input level consistent with the frequency, for a period of two hours.

2. Shock Tests

The following requirement is identical for the SNAP 7B and 7D systems:

(1) Subject the specimen to two 3-g shocks having a 6-ms half-sine wave pulse, in each of the three principal orthogonal axes.

3. Temperature

(1) Generator--record performance and specimen temperature* after stabilization at the following ambient conditions:

(a) 28° F sea level pressure.

(b) 50° F sea level pressure.

(c) 80° F sea level pressure.

(2) Battery and relay panel--record performance and specimen temperatures after stabilization at the following ambient conditions:

(a) 28° F sea level pressure.

(b) 53° F sea level pressure.

(c) 80° F sea level pressure.

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*Specified temperatures are those of the immediate surrounding environment, in this case the glycol-water mixture.

C. TEST METHODS

1. Generator

Since the SNAP 7B and 7D generators are identical, one model was subjected to the environment as outlined in Section IX-B of this report.

a. Vibration

The generator and container were placed in the water-jacketed test fixture and positioned on the oil film table of the C-25HB electrodynamic shaker for testing to the conditions outlined in Section IX-B(1). Primary generator functions (input, output, and temperatures) were monitored throughout the test with the circuitry shown in Fig. 20. Figure 21 shows a typical installation on the oil film table.

b. Shock

The generator was secured to the table of the Barry Medium Impact Shock Machine for testing to the conditions outlined in Section IX-B(2), except that the level applied was 6 g instead of 3 g. Figure 22 shows a typical installation on the drop table.

c. Temperature

The generation unit was installed in its biological shield and placed in a tank filled with a solution of glycol and water. The tank with the generator was then positioned inside the 10- x 10- x 10-ft temperature chamber, and subjected to the conditions outlined in Section IX-B(3(1)). Performance was recorded at each stabilized condition.

2. Battery and Relay Panel

a. Vibration

The battery and relay panel were mounted to flat plate fixtures and tested independently to the conditions outlined in Section IX-B(1). Figures 23 and 24 show a typical installation on the C-25HB shaker of the relay panel and battery, respectively. The relay panel was powered during the tests and monitored to check performance.

b. Shock

The battery and relay panel were secured to the table of the Barry Medium Impact Shock Machine for simultaneous testing to the conditions outlined in Section IX-B(2), except the level applied was 6 g instead of 3g. Figure 25 shows a typical installation on the drop table.

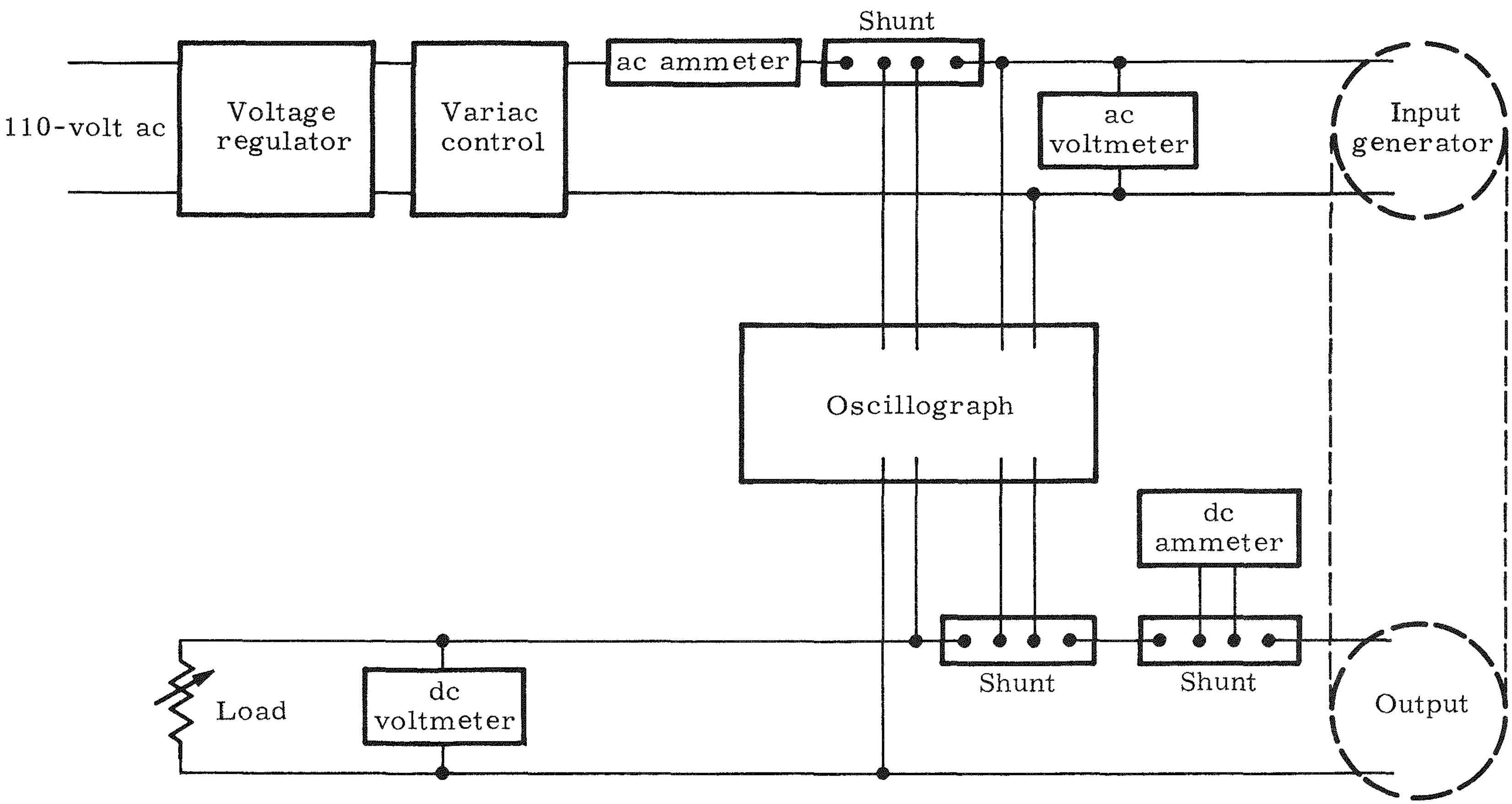

Fig. 20. SNAP 7D Generator Test Instrumentation Circuitry

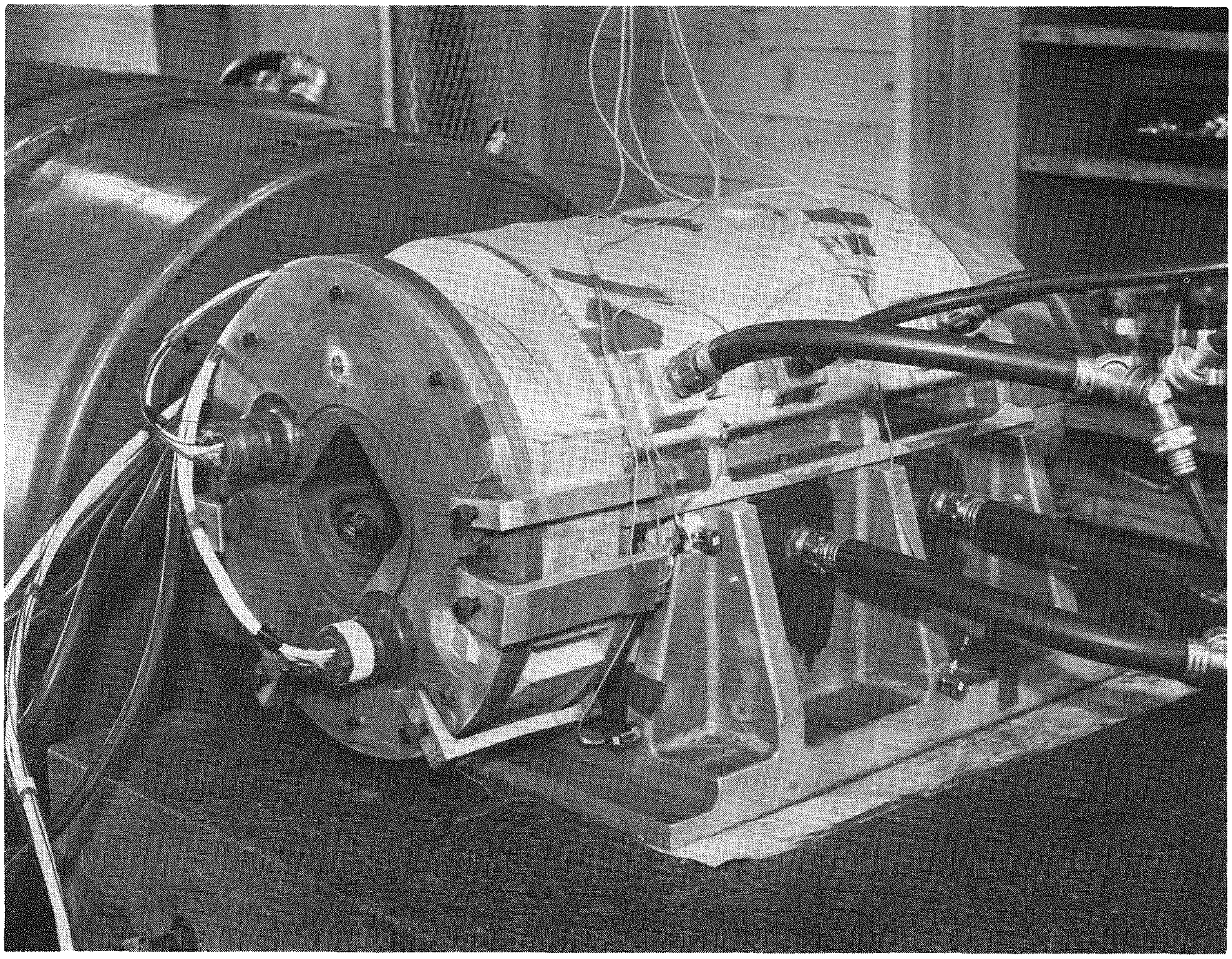

Fig. 21. SNAP 7D Generator Positioned on C-25HB Table for Horizontal (Plane I) Vibration Test

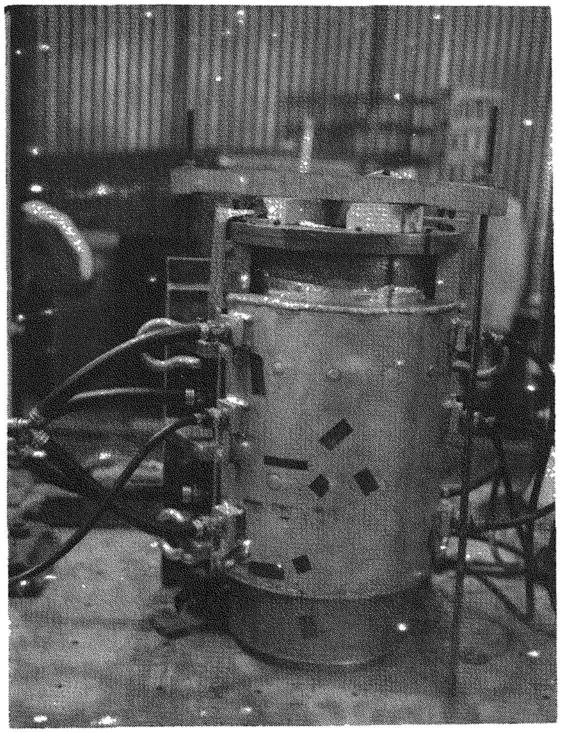

Fig. 22. SNAP 7D Generator Positioned on the Barry Impact Machine Table for Vertical Plane Shock

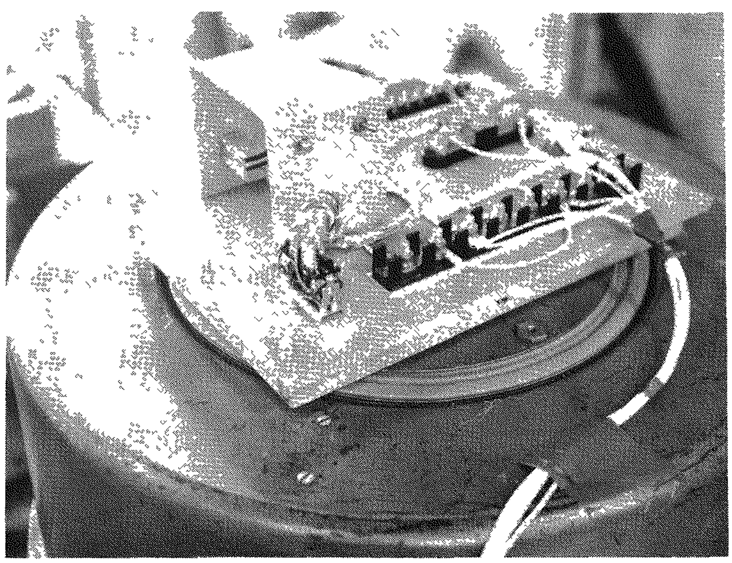

Fig. 23. SNAP 7D Relay Panel Mounted on C-25HB Shaker for Horizontal Plane Vibration

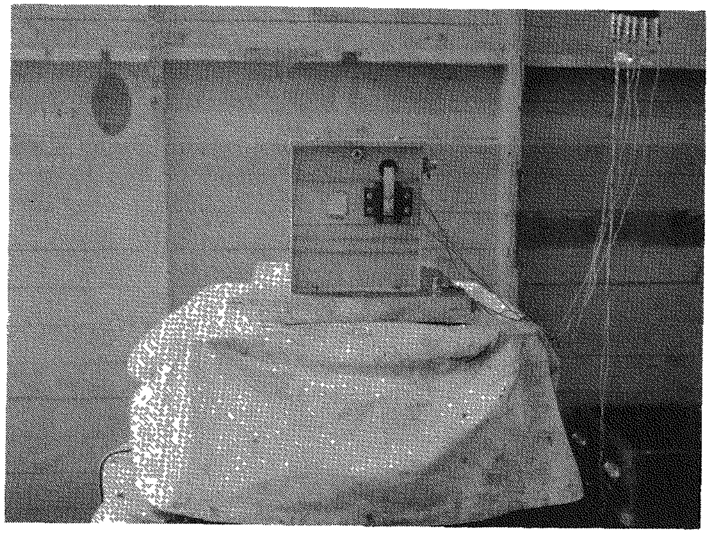

Fig. 24. SNAP 7D Battery Unit Positioned on C-25HB Shaker for Horizontal Plane Vibration

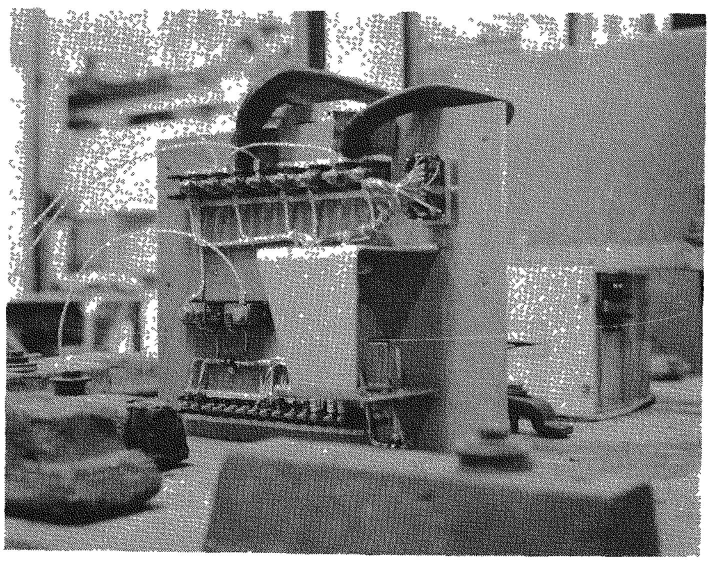

Fig. 25. SNAP 7D Battery and Relay Units Positioned on Barry Impact Machine Table for Horizontal Plane Shock

c. Temperature

The battery and relay panel were positioned in a small temperature chamber and subjected to the ambient temperatures outlined in Section IX-B(3b). This test was conducted in conjunction with the generator tests. Performance was recorded at each stabilized condition.

D. TEST RESULTS

1. SNAP 7B, 7D Generator

a. Vibration

The generator was subjected to the vibration environment as outlined in Section IX-B(1). Figure 21 shows the generator in position for testing. Continuous functional monitoring indicated satisfactory performance. The output power changes, as shown in the data on Table 7, are a result of the changing cooling conditions (i.e., water flow and temperature).

No major vibration resonance was noted. The generator was then subjected to the two-hour vibration dwell in horizontal plane II (Fig. 20) at 55 cps with no adverse effects noted. Table 7 tabulated the functional data obtained during the vibration tests.

b. Shock

The SNAP 7B, 7D generator was positioned on the table of the Barry Medium Impact Shock Machine for two shock impulses in each of the three major axes (Fig. 26). Figure 22 shows a typical position for testing. The generator functioned properly throughout all six drop tests. No effect on, or discontinuity in, output power was recorded during the test. Table 8 tabulates the functional data obtained during the shock tests.

c. Temperature

The complete generator assembly (including the finned biological shield) was positioned in the temperature chamber and subjected to the temperatures outlined in Section IX-B(3) of this report.

2. SNAP 7D Battery and Relay Panel

a. Vibration

The battery and relay panel were individually subjected to the vibration environment outlined in Section IX-B(1). Figures 23 and 24 show

TABLE 7

Vibration Test Data

		Input			Output		
Date	Time	ACV	AC (amp)	Watts	DCV	DC (amp)	Watts
5/2/62	08:25	54.8	19.6	1075	11.2	3.7	41.5
	10:35	54.9	19.6	1080	11.25	3.75	42.0
	11:25	55.0	19.7	1085	11.25	3.75	42.0
	13:20	54.9	19.6	1080	11.30	3.80	43.0
	14:30	54.9	19.7	1080	11.30	3.80	43.0
	16:00	55.5	19.9	1100	11.30	3.80	43.0
	16:35	55.8	19.9	1110	11.30	3.80	43.0
5/3/62	09:15	55.0	19.7	1080	11.30	3.80	43.0
	10:40	54.8	19.6	1075	11.30	3.80	43.0
	13:35	54.1	19.4	1050	11.30	3.80	43.0
	14:05	54.0	19.3	1040	11.25	3.70	41.5
	15:20	54.0	19.3	1040	11.20	3.65	40.7
	16:20	55.0	17.7	1080	11.20	3.70	41.4

(1) Before vertical plane vibration
(2) After 3-g sweep
(3) Before horizontal plane vibration
(4) After 3-g sweep
(5) Before vibration in horizontal I plane
(6) After 2 g - 170 - 300 - 5 cps
(7) Before vibration horizontal II plane
(8) After 3 g - 5 - 300 - 5 cps
(9) One hour of two-hour dwell
(10) After two-hour dwell

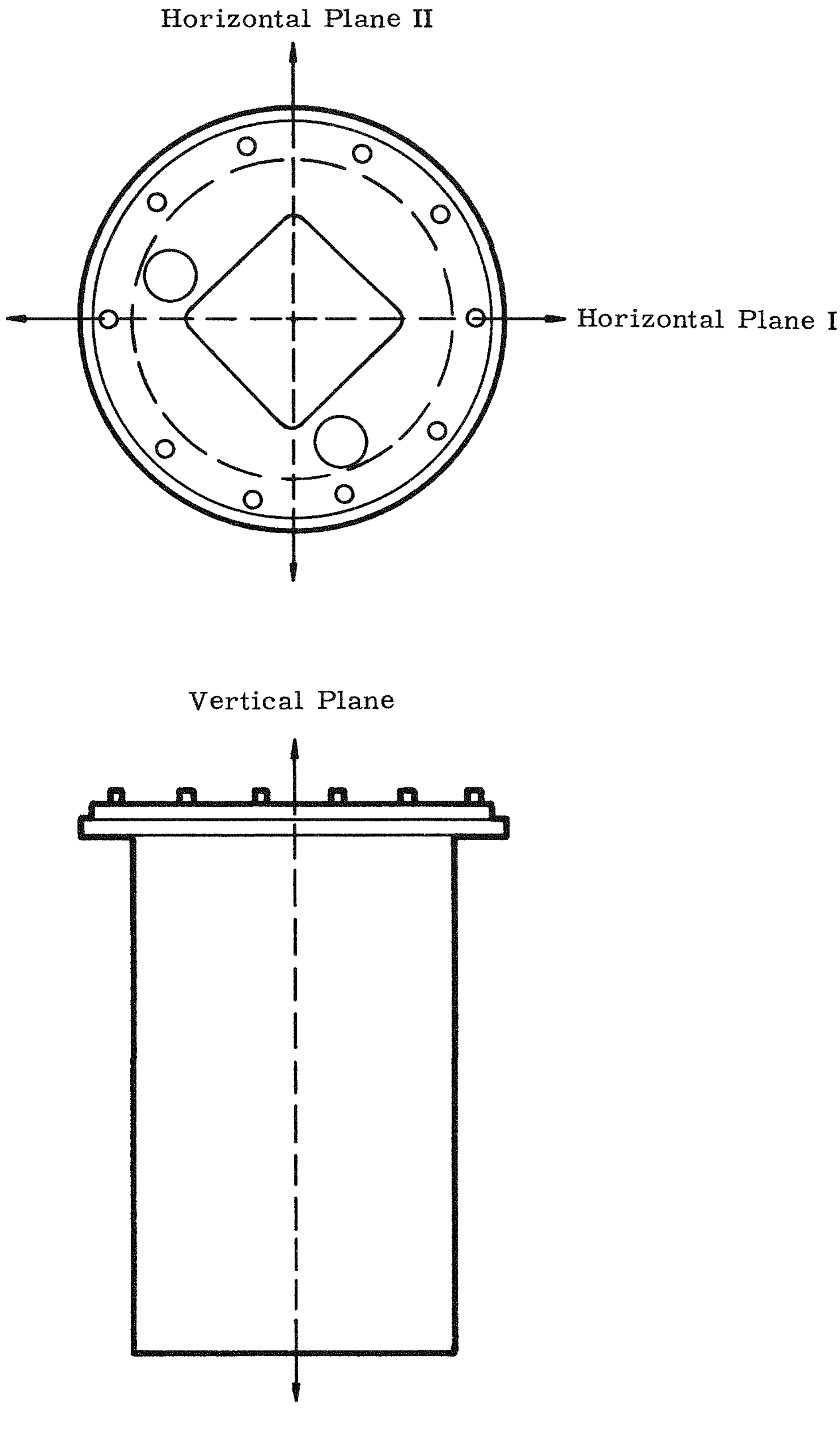

Fig. 26. Reference Axes for Vibration and Shock Tests (Snap-7B Thermoelectric Generator)

TABLE 8

Shock Test Data

		Input			Output		
Date	Time	ACV	AC (amp)	Watts	DCV	DC (amp)	Watts
5/4/62	02:00	54.5	19.45	1060	11.00	3.65	40.15
	04:00	54.8	19.45	1066	11.00	3.65	40.15
	06:00	55.0	19.50	1072	11.00	3.65	40.15
	08:30	54.5	19.50	1057	11.20	3.70	41.44
	13:00	54.2	19.40	996	10.70	3.50	37.45
	16:00	55.4	19.85	1099	10.90	3.60	39.24

(1) Before horizontal shock
(2) After all shock tests

typical test setups. Functional checks performed on the relay panel (check on dropout current) and the battery (charging capability after vibration) indicated satisfactory performance. Since no major resonant frequency was detected on either specimen, the two-hour dwells were conducted at 33 cps in the vertical axis. Table 9 tabulates the functional data obtained for the vibration tests.

b. Shock

The battery and relay panel were positioned on the drop table for simultaneous testing to the environment outlined in Section IX-B(2). Figure 25 shows the units positioned for testing. Functional checks performed before, during, and after each test (monitoring of relay functioning) indicated no structural damage or effects in the operation of the battery and relay system.

c. Temperature

The battery and relay panel were subjected to the temperatures outlined in Section IX-B(3) of this support. Data taken during this test is presented in Section XIII-C.

TABLE 9

SNAP 7D Battery and Relay Panel
Vibration Functional Test Data

Position Sweep	Drop-Out Current (amp) Before	After
Longitudinal	2.9	2.5
Lateral	2.6	2.4
Vertical	2.4	2.5
Resonance Dwell (two-hour dwell at 33 cps, 3 g)	2.5	2.4

APPENDICES

APPENDIX A

ANALYSIS OF GENERATOR SURFACE TEMPERATURE AT BEGINNING OF LIFE

Two temperature differences must be calculated. The first is that between the water and the hull of the boat, and the second is between the boat hull and the generator surface. (The generator is mounted in the aluminum boat as shown in Fig. 1 of this report.) In both calculations the same basic relationship is employed.

$$q = hA_c \Delta T$$

where

q is the heat transferred to the water

h is a convective heat-transfer coefficient

A_c is the convective heat-transfer area

ΔT is the temperature difference from fluid bulk to surface or surface to surface.

The convective heat-transfer coefficient is based on the properties of the fluids involved in the convection. The coefficient is a function of fluid thermal conductivity, thermal expansion, density, specific heat, and viscosity, and of the temperature drop across the fluid film at the solid surface.

The properties of the fluids are as follows:

Property	Water	Petroleum Base Electrical Insulating Oil
Density (lb/ft^3)	68.6	53
Thermal Conductivity (Btu/hr-ft-°F)	0.363	0.070
Viscosity (lb/hr-ft)	1.68	31.5
Specific Heat (Btu/lb-°F)	1	0.465
Thermal Expansion (°F^{-1}) (cubical)	1.15×10^{-4}	5.29×10^{-4}

The film drop from water to hull is estimated as 70° F, whereas that from hull to generator surface is estimated as 30° F. In order to determine the coefficient "h" for the water films, the following relationship is employed:

$$h = \frac{0.59k}{L} \left[\frac{L^3 \rho^2 g \beta \Delta T}{\mu^2} \left(\frac{C_p \mu}{k} \right) \right]^{0.25} \qquad \text{(Ref. 10)}$$

where

k	=	fluid thermal conductivity at film temperature (Btu/hr-ft-°F)
L	=	height of vertical surface (ft)
g	=	gravitational constant (4.17×10^8 ft/hr^2)
C_p	=	specific heat of fluid at film temperature (Btu/lb-°F)
β	=	thermal expansion coefficient (°F^{-1})
μ	=	fluid viscosity at film temperature (lb/hr-ft)
ΔT	=	temperature drop across film (°F)

The convective heat-transfer area is taken as the hull area enclosing the compartment containing the generator. The heat flow is 1435-55 or 1380 watts.

Solving

$$\Delta T = \frac{q}{h A_c}$$

$$= \frac{5083 \text{ Btu/hr}}{\left[27 \text{ Btu/hr-ft}^2\text{-°F}\right]} \quad \left[27 \text{ ft}^2\right]$$

$$\cong 7° \text{ F}.$$

For the temperature drop through the annular space containing the transformer oil, h is given by:

$$h = \frac{0.071\, k}{(L/x)^{1/9}} \left[\frac{x^3 \rho^2 g \beta \Delta T C_p}{\mu k} \right]^{1/3} \qquad \text{(Ref. 11)}$$

where

x = the distance between hull and generator (ft).

Because of the poorer convection properties of the oil, h is lower in this case. The convective area is taken as the generator cylindrical surface area without the fins which are of very low efficiency in the liquid. Solving for ΔT,

$$\Delta T = \frac{5083}{[15.6 \text{ Btu/hr-ft-°F}]} \quad [13.50 \text{ ft}^2]$$

$$\Delta T = 24° \text{ F.}$$

Thus, the total temperature difference between water ambient and generator surface is calculated as 31° F. Since the maximum water temperature in the Gulf of Mexico is estimated as 80° F, the maximum generator surface temperature will be 111° F.

APPENDIX B

SHIELDING KILOCURIE AMOUNTS OF STRONTIUM-90

I. INTRODUCTION

Strontium-90 is one of the radioactive isotopes used to generate heat for small auxiliary power systems. Kilocurie amounts of this isotope are required to produce several watts of heat. Since the decay sequence of Strontium-90 contains no nuclear gamma radiation, it would be easy to believe that no shielding is required. However, bremsstrahlung X-rays are present, and shielding must be provided for them. Most of the bremsstrahlung are generated when the beta rays are slowed down in the compound or mixture of which the fuel pellet is made. A smaller number are generated by the betas which escape the pellet and are slowed down in the cladding material.

Bremsstrahlung from Strontium-Yttrium-90 are usually measured by using small sources in the microcurie and millicurie range. These results invariably stress the large quantity of low energy gamma rays produced but do not give adequate distributions for the high energy end of the spectrum. These results are wholly inadequate for use in designing shields for high kilocurie amounts of Strontium-90. Calculated bremsstrahlung distributions indicate that heavier shielding is required than is indicated by experimental results obtained in measuring microcurie and millicurie amounts of Strontium-90.

To obtain a confirmation of the amount of shielding required for large Strontium-90 sources, Oak Ridge National Laboratory was requested to measure the attenuation by lead absorbers of the radiation from a 1000-curie source of strontium titanate. The purpose of this report is to compare the experimental results with calculated values.

II. BREMSSTRAHLUNG

The total intensity (number of photons times the photon energy) of bremsstrahlung from monoenergetic beta rays in thick targets is given by

$$I = kZE^2$$

where

I = bremsstrahlung intensity

k = constant

Z = atomic number of absorber

E = beta energy (Mev).

The spectral distribution of photons is a straight line function with the maximum photon energy equal to the beta ray energy (Ref. 12). The number of photons at the maximum energy is, however, zero. By equating the total intensity to the area of the triangle formed by the distribution curve and the coordinate axes, the number of photons at zero energy is easily found to be equivalent to 2EkZ. If the photon distribution is divided into energy groups, the average number of photons in each group is equal to the area under the distribution curve bounded by the energy limits of the range, divided by the energy increment.

Beta rays from isotope decay are not emitted monoenergetically but in spectral distributions which vary greatly for different isotopes (Ref. 13).

If the distribution of betas is known for a particular isotope, it may be broken into energy groups and the photon production for each group found.

By use of the curves in Ref. 13, the beta distribution of the nominal 2.2-Mev beta from the disintegration of Yttrium-90 was found. The results were normalized to have the area under the curve represent the distribution from one Yttrium-90 disintegration. As a check of these results, the average energy of the betas calculated from this curve was found to be 0.876 Mev which compares favorably with the value 0.90 Mev given in Ref. 14.

The beta distribution was divided into 10 equal energy groups; the number of betas in each group per Yttrium-90 disintegration is given in Table B-1. This grouping of betas was then used to calculate bremsstrahlung distribution. The energy grouping for the bremsstrahlung was chosen to be the same as that for the betas. The number of gammas for each group and the number of gammas divided by kZ are listed in Table B-1.

TABLE B-1

Grouped Spectral Distribution of Betas and Bremsstrahlung from Yttrium-90

Energy Group	Number of Betas per Yttrium-90 Disintegration	Number of Gammas ÷ kZ	Number of Gammas per Yttrium-90 Disintegration: As Used k = 0.0007 Z = 26	Number of Gammas per Yttrium-90 Disintegration: Adjusted k = 0.000175 Z = 26
2.2-1.98	0.0068	0.000157	2.97×10^{-6}	7.42×10^{-7}
1.98-1.76	0.0349	0.00143	2.70×10^{-5}	6.75×10^{-6}
1.76-1.54	0.0696	0.00611	1.155×10^{-4}	2.89×10^{-5}
1.54-1.32	0.1013	0.0180	3.404×10^{-4}	8.51×10^{-5}
1.32-1.10	0.1231	0.0425	8.035×10^{-4}	2.09×10^{-4}
1.10-0.88	0.1389	0.0924	1.747×10^{-3}	4.37×10^{-4}
0.88-0.66	0.1482	0.188	3.550×10^{-3}	8.87×10^{-4}
0.66-0.44	0.1469	0.385	7.286×10^{-3}	1.82×10^{-3}
0.44-0.22	0.1308	0.887	1.677×10^{-2}	4.19×10^{-3}
0.22-0	0.0993	3.50	6.612×10^{-2}	1.65×10^{-2}

Published values for the constant k vary widely from 0.4×10^{-3} to 1.1×10^{-3} (Ref. 12). One theoretical determination gives values one order of magnitude lower. The value 0.7×10^{-3} was used in the calculations presented here.

An effective value of Z = 26 was obtained for strontium titanate by using the following relation, found in Ref. 12:

$$Z_{eff} = \frac{N_1 Z_1^2 + N_2 Z_2^2 + N_3 Z_3^2 + \ldots}{N_1 Z_1 + N_2 Z_2 + N_3 Z_3 + \ldots}$$

where N_1, N_2, N_3, . . . are the atoms per cm^3 of the mixture having atomic numbers Z_1, Z_2, Z_3, . . .

The total intensity of bremsstrahlung from a distribution of beta energies is expressed by

$$I = kZ(E_{rms})^2 \doteq \sum_{\substack{\text{all} \\ \text{groups}}} N_i \overline{E}_i$$

or

$$(E_{rms})^2 \doteq \sum_{\substack{\text{all} \\ \text{groups}}} \frac{N_i}{kZ} \overline{E}_i$$

E_{rms} is the root mean square energy of the beta distribution; $\overline{E}_i$ is the average group energy of the bremsstrahlung, and N_i is the number of bremsstrahlung in the group. The root mean square energy of the betas was calculated and found to be 1.015 mev. The sum of the number of gammas, divided by kZ, multiplied by the average energy, was calculated and found to have a value of 1.217 mev. This is about 18% higher than the calculated $(E_{rms})^2$.

Reference 15 states that the dose rate from one curie of Strontium-90 is about the same as that from 12 mgm of radium, and the average energy of the bremsstrahlung is about 300 kev. The dose rate at one meter from 12 mgm of radium is 12 mr/hr. Using the distribution of bremsstrahlung given in Table B-1, the bare (without self-absorption and shielding) dose rate at one meter from one curie of Strontium-Yttrium-90 was found to be 12.53 mr/hr, and the average energy of the bremsstrahlung was calculated to be 236 kev.

The bremsstrahlung from the 0.5-Mev beta of Strontium-90 were not included since they will be in the low kilovolt range and will be attenuated rapidly in the first few mils of shielding.

III. SHIELDING PROGRAM

Dose rates were calculated by means of a generalized shielding program coded for the IBM 709. The source is divided into a number of point sources, and the program calculates the dose rate from each of these points. The program was coded to accommodate up to 400 source points and a maximum of 10 initial source energies. Path lengths through the various materials, along a line joining a point source and the dose point, are found and used to calculate relaxation lengths and buildup for each of the materials between these two points. The individual relaxation lengths are added to obtain the total relaxation length. Buildup along the individual path segments is defined as the infinite medium buildup factor minus one. The total buildup factor along the path from the source to the dose point is assumed to be one plus the sum of the individual buildups. Infinite media buildup factors are approximated by the sum of two exponentials.

The direct energy flux at the dose point is evaluated for each source energy and source position and converted to dose rates by the appropriate flux-to-dose conversion factor. The total dose rate is, of course, equal to the sum of the dose rates from each individual source point.

IV. DESCRIPTION OF EXPERIMENTS*

Dose rates from a 1000-curie source of Strontium-Yttrium-90 were measured by ORNL personnel. The kilocurie of Strontium-90 was contained in 65 grams of titanate powder which had been compacted and sintered to a density of 4.5 grams per cubic centimeter. The only radioactive contamination in the pellet was 305 millicuries of Cerium-144 at the time the measurements were made.

Measurements were made with a Cutie Pie Model 740 (Victoreen Instrument Company) and with a survey meter No. 2610A (Nuclear Instrument and Chemical Company) which had been calibrated by the ORNL Health Physics Department, using standard radium gamma sources.

The physical arrangement used when the measurements were made is shown in Fig. B-1. Two sets of measurements were made. Case I was made with the detector located 16-3/8 inches above the pellet when the pellet was shielded with a 1/8-inch Hastelloy-C plate and lead plates which varied in increments of 1/2 inch up to 6-1/2 inches. The measurements for Case II were made with the detector 19-1/4 inches above the

*This information was drawn freely from an advance copy of Ref. 16.

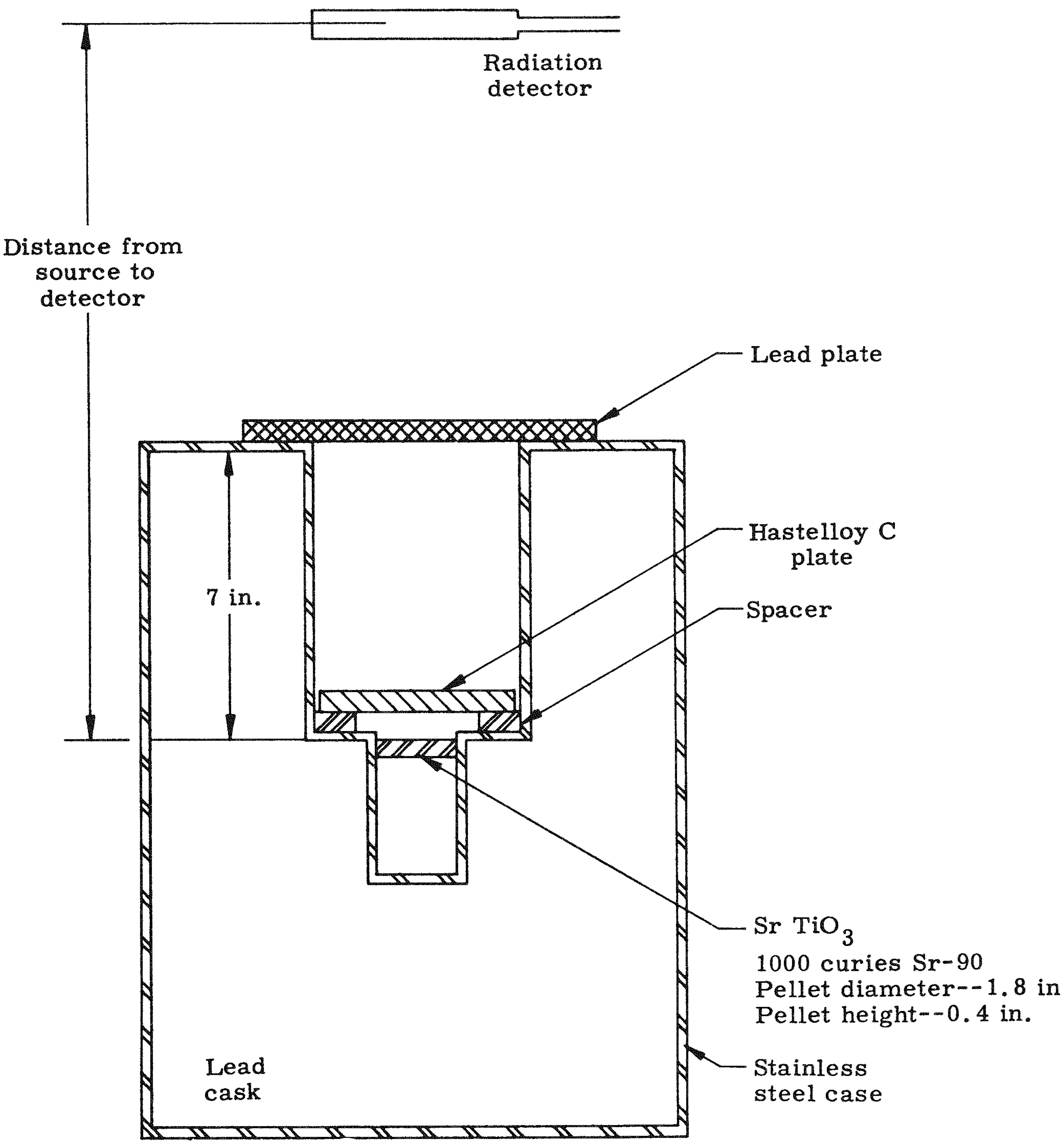

Fig. B-1. Physical Arrangement Used in Measuring Dose Rates pellet when it was shielded with 1/2 inch of Hastelloy C and various thicknesses of lead. The results of these experiments are plotted in Fig. B-5 and B-6.

V. RESULTS OF CALCULATIONS

The accuracy of point-by-point approximations to integrals depends upon the number of points used. To determine the number of points to use to obtain reasonably accurate results, several problems are run with different numbers of points. Experience has shown that comparatively few points are required to have the third and fourth significant figures in agreement with the results from a greater number of points. To determine the number of source points to use for the present problem, the source was divided into 5, 10, 20 and 40 points. The circular cross section of the fuel pellet was divided into 5 and 10 approximately equal areas, as shown in Fig. B-2 and B-3, and the height was divided into 1, 2 and 4 equal divisions. Calculated results are given in Table B-2. After examining these results, it was decided to run the remainder of the problems with 20 source points. Dose rates versus thickness of lead shielding are tabulated in Table B-3 and are plotted in Figs. B-5 and B-6. Table B-3 also contains the contribution to total dose rate from the 305 millicuries of Cerium-144 present in the strontium pellet. As with Strontium-90, most of the gamma radiation associated with Cerium-144 is bremsstrahlung radiation. The bremsstrahlung radiation from Cerium-144 results from the 2.97-Mev beta of Praseodymium-144. The higher energy beta of Praseodymium-144 causes the bremsstrahlung to be more penetrating than the bremsstrahlung of Yttrium-90. If the contribution from Cerium-144 to Strontium-90 dose rates were limited to a percentage of the Strontium-90 dose rate, the allowable amount of cerium would vary with the shield thickness. To illustrate this point, it was assumed that a 10% increase in dose rate would be acceptable. The curies of Cerium-144 per curie of Strontium-90 were calculated for various thicknesses of lead shielding and are plotted in Fig. B-4.

VI. COMPARISON OF RESULTS AND CONCLUSIONS

Examination of Figs. B-5 and B-6 shows that the calculated results are higher than the experimental results by an almost constant amount. Analysis of the data shows the calculated results are higher than the experimental results by a factor of about 4.

This could be caused by either of two items used in the calculations. One of these could be the curie strength, and the second, the product

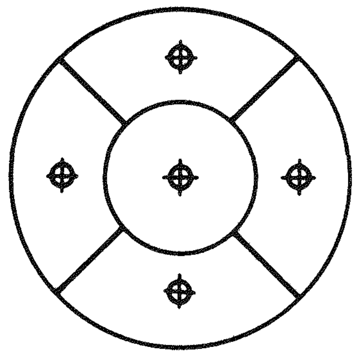

Fig. B-2.
Source Point Configuration--
Five Divisions

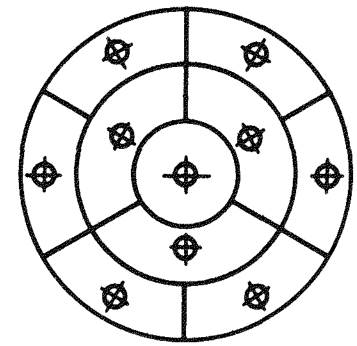

Fig. B-3.
Source Point Configuration--
10 Divisions

TABLE B-2

Comparison of Dose Rates for Various Numbers of Source Points

Number of Divisions in Circular Area	Number of Divisions in Height	Total Number of Source Points	Dose Rate* No Lead (mr/hr)	Dose Rate* 1/2-in. Lead ($mr/hr \times 10^4$)	Dose Rate* 5-in. Lead (mr/hr)
5	1	5	38.181	1.0144	6.6837
	2	10	38.318	1.0146	6.6937
	4	20	38.354	1.0146	6.6963
10	1	10	38.175	1.0142	6.6787
	2	20	38.311	1.0143	6.6890
	4	40	38.347	1.0144	6.6914

*Detector--16-3/8in. from pellet;
Self absorption in pellet and 1/8-in. Hastelloy

TABLE B-3

Calculated Dose Rates Versus Thickness of Lead
for Comparison with ORNL Data--
Self Absorption + Hastelloy-C + Lead

Thickness of Lead (in.)	Dose Rates (mr/hr) Sr-Y-90* 1000 Curies	Ce-144* 305 Millicuries	Sr-Y-90** 1000 Curies
1/2	1.015×10^{4}	23.6	5.61×10^{3}
1	3.828×10^{3}	12.0	2.08×10^{3}
1-1/2	1.575×10^{3}	6.4	8.47×10^{2}
2	6.81×10^{2}	3.5	3.62×10^{2}
2-1/2	3.03×10^{2}	1.9	1.60×10^{2}
3	1.38×10^{2}	1.045	7.26×10
3-1/2	6.38×10	0.575	3.34×10
4	2.98×10	0.316	1.55×10
5	6.70	0.0952	3.47
6	1.54	0.0285	8.00×10^{-1}
7	3.64×10^{-1}	0.00851	1.87×10^{-1}

*Distance, source to detector = 16-3/8 in.
Hastelloy-C thickness = 1/8 in.

**Distance, source to detector = 19-1/4 in.
Hastelloy-C thickness = 1/2 in.

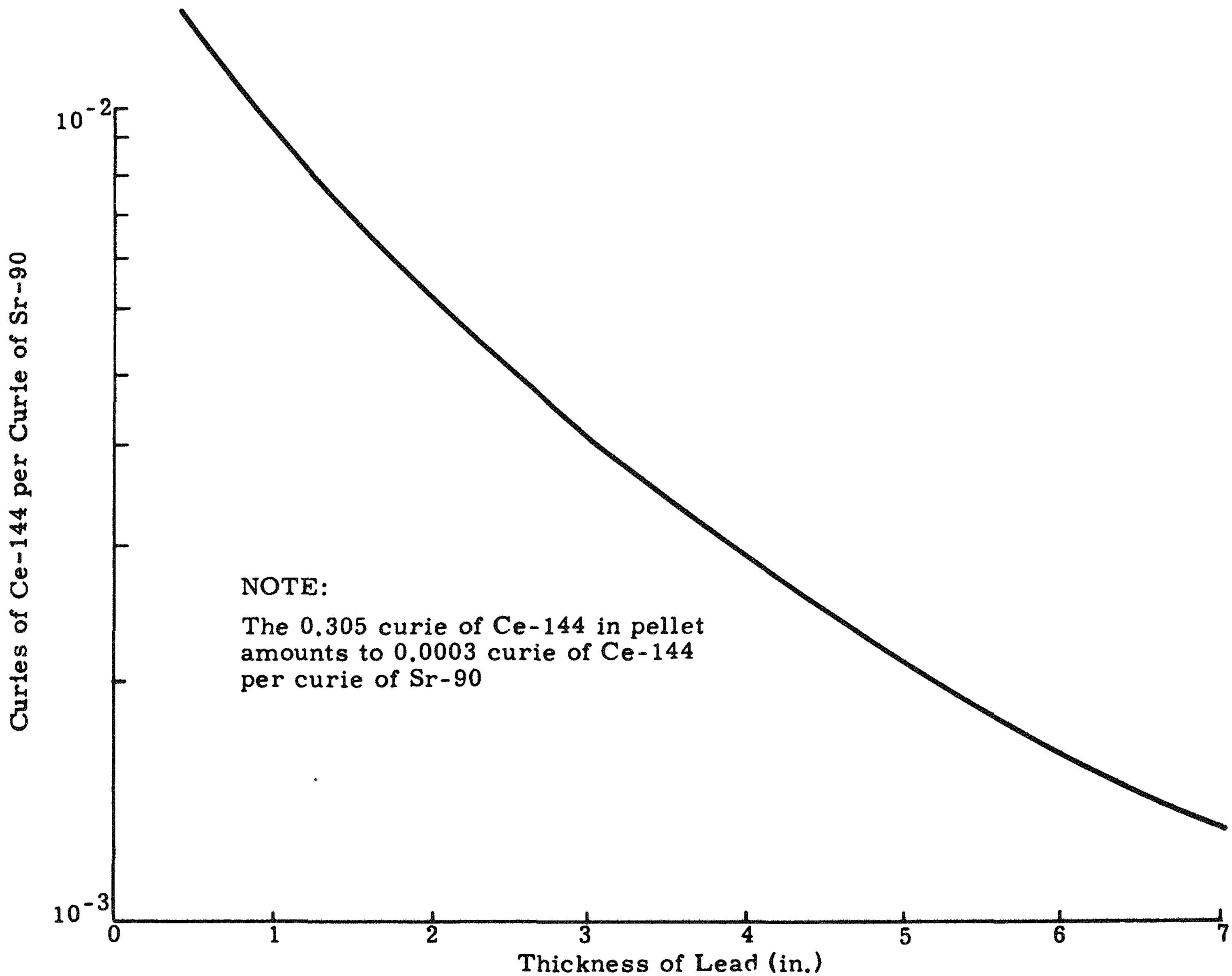

Fig. B-4. Curies of Ce-144 per Curie of Sr-90 Required to Increase Strontium-90 Dose Rate by 10%

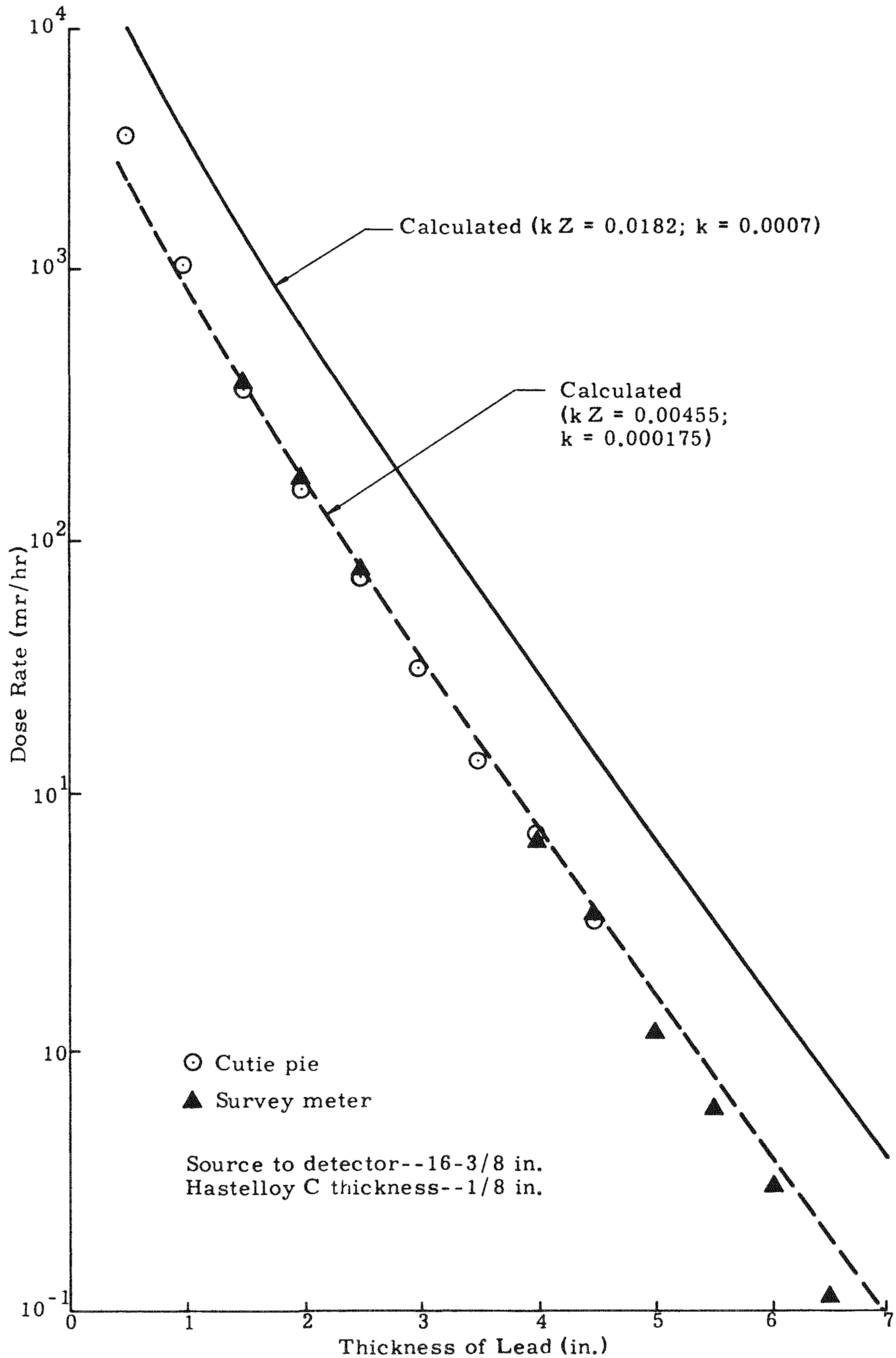

Fig. B-5. Measured and Calculated Dose Rates for Case 1

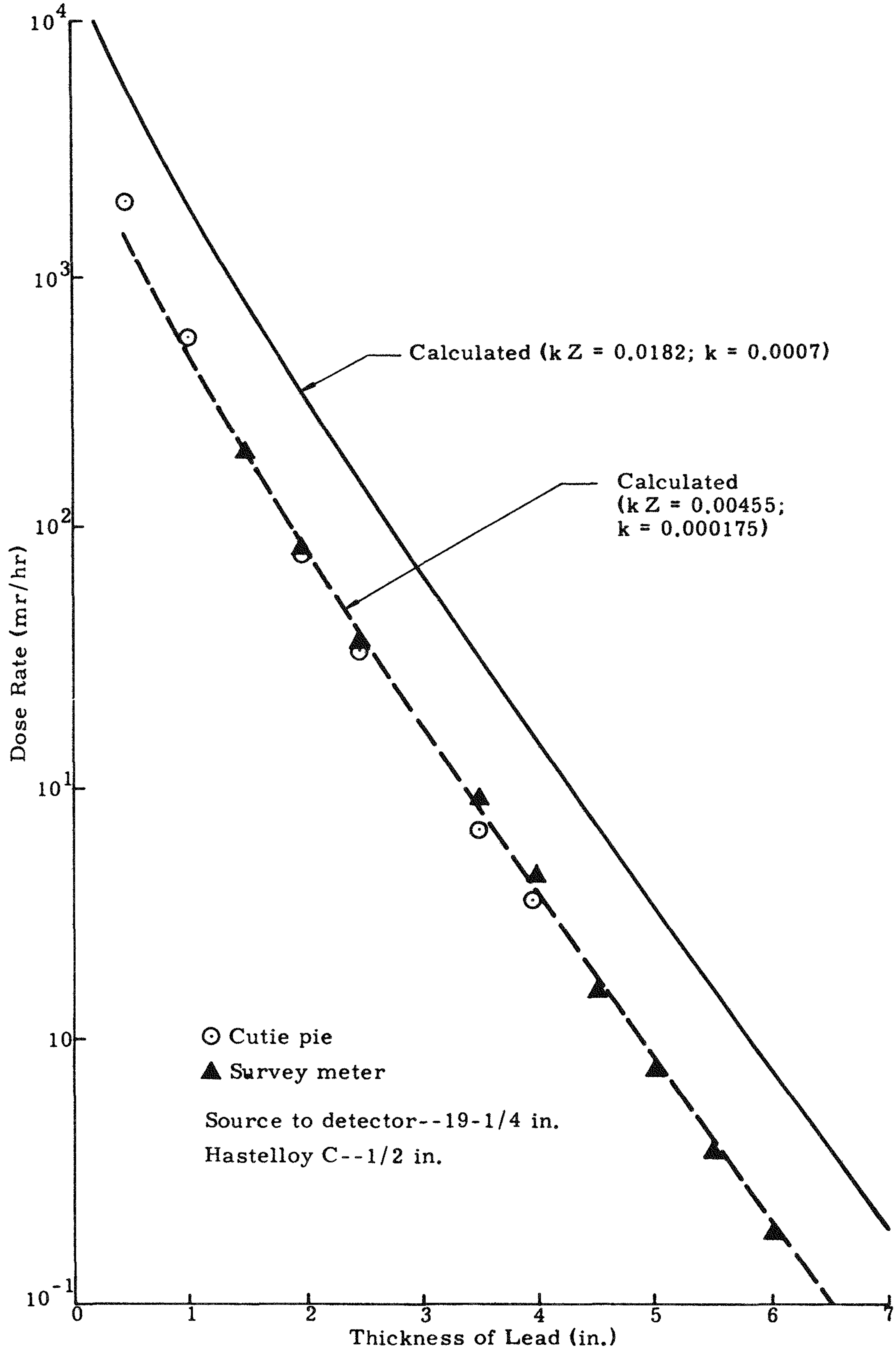

Fig. B-6. Measured and Calculated Dose Rates for Case 2 kZ which enters into the bremsstrahlung calculation. The curie strength used should be close to the stated amount since care was exercised to determine the amount of Strontium-90 present in the pellet. When the spread of values given the k is considered (Ref. 12) it would be safe to assume that the factor kZ used in the calculations is incorrect. The factor kZ will be corrected to obtain agreement between calculated and experimental results.

The originally calculated values were divided by 4 and plotted as the dashed curves in Figs. B-5 and B-6. These curves are in close agreement with the experimental points.

The value of kZ used to make the original calculations is 0.0007 x 26 = 0.0182, and the value which gave the dashed curve is 0.00455. If it is assumed that the calculated effective Z of 26 is correct, the value of k would become 1.75×10^{-4}. The number of gammas per disintegration of Yttrium-90, using the adjusted value of kZ, is tabulated in Table B-1.

The Cerium-144 present in the pellet while the experiments were being performed did not contribute appreciably to the Strontium-90 dose rates. Depending upon the shield thickness, the amount of cerium present in the pellet could be increased by factors between 4 and 40 to have a 10% increase in dose rate.

APPENDIX C

SNAP 7D ENGINEERING DRAWINGS, WEIGHTS AND DIMENSIONS

Title	Number
System	
Installation	398D1080000
Installation layout	398D1080050
Battery specification	398D1080051
Electrical system	398D1080052
Electrical components installation	398D1080053
Generator	
Plug-flange screw holes	398-3021021
Cap screw	398-3021029
Generator, biological shield assembly	398-3021100
Cylinder	398-3021101
End plate	398-3021102
Fuel block	398-3021104
Plate, fuel block	398-3021105
Shield	398-3021106
Shield block	398-3021107
Insulation strip	398-3021108
Insulation block	398-3021109
Thermoelectric elements	398-3021110
Shoe, hot junction	398-3021111
Details--cold junction	398-3021112
Piston	398-3021113
Washer	398-3021114
Frame--heat sink	398-3021115
Module bar--heat sink	398-3021116

Title	Number
Insulation--corner strip	398-3021117
Insulation--plate	398-3021118
Wire guide	398-3021120
Electrical connector	398-3021122
Connector mount	398-3021123
Schematic diagram	398-3021124
Connecting bar	398-3021125
Nameplate	398-3021127
Spacer	398-3021130
Fuel capsule assembly	398-3021131
Biological shield container	398-3021141
Operating model assembly	398-3021142
Generator cover assembly	398-3021143
Hot shoe--element assembly	398-3021145
Cold cap assembly	398-3021146
Thermoelectric module assembly	398-3021147
Heat sink assembly	398-3021148
Container--operating model	398-3021149
Shipping Pallet	
Shipping pallet	398-3021026
Generator--pallet shipping assembly	398-3021050

SNAP 7D ELECTRICAL GENERATION
SHIPPING PACKAGES

Item	Envelope Dimensions (in. high)	Weight (lb)
Generator mounted on shipping pallet	60 x 48 x 60	5000
Batteries mounted to battery plate	24 x 36 x 18	250

Item	Envelope Dimensions (in. high)	Weight (lb)
Swagelok fittings, tube, cable, electrical panel, assembly, miscellaneous	48 x 48 x 18	100

ACTUAL SNAP 7D COMPONENT WEIGHTS

	(lb)
Generator	
Biological shield and cover	4186.5 (calculated)
Top shield plug	202 (calculated)
Fuel capsules	62.5
Generator (internal parts)	238 (calculated)
Electrical panel assembly	19
Batteries	243
Cable	5.5

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