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FINAL REPORT

MASTER

ADVANCED THERMOELECTRIC POWER SYSTEM

AEC Contract AT(30-3)-217

Subtask 5.1

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I. SUMMARY

Westinghouse Research Laboratories were awarded a sub-contract from The Martin Company in April, 1958, to develop a thermoelectric power conversion system as part of the SNAP Program of the U. S. Atomic Energy Commission. The power system was to be fueled with a radioisotope heat source, and contain a power flattening device for maintaining constant power output over the life of the generator. The generator, designated SNAP-IIIA, was to be completed and delivered to The Martin Company by December 31, 1958.

The generator was delivered to Martin on January 28, 1960. The generator operates at somewhat less than one percent overall efficiency, has a power output of approximately 1.45 watts and a specific power of 0.142 watt per pound. The power flattening device did not perform to expectations.

A second generator, designated SNAP-IIIB, was delivered to Martin by Westinghouse New Products Laboratories in March 1960. It produces a maximum power of 1.6 watts, and has a maximum efficiency of 1.20% and a specific power of 0.32 watts per pound (exclusive of the weight of the heat source).

II. INTRODUCTION

Under The Martin Company prime contract AT(30-3)-217 with the A.E.C., a sub-contract was awarded to Westinghouse Research Laboratories for the development of a thermoelectric power conversion system in April, 1958. The experience and technology gained by Westinghouse Research Laboratories in performance of BuShips Contract NOBS 72361 was to be applied to The Martin Company generator. This generator was later designated SNAP-III A.

The statement of work in the contract called for the design of a complete thermoelectric generator package, requiring no repetitively moving parts, capable of operating in a vacuum environment and of being fueled with a radio-isotope heat source. The power conversion system was to employ a variable heat dump mechanism to maintain constant generator voltage for a period of six months. The power conversion system also was to include an inverter to convert the low voltage, direct current output from the thermoelectric generator to provide power to a specified vehicle in the form required, and with the required regulation. The system was to be completed by December 31, 1958. The entire contract, including all reports, was to be completed by January 31, 1959.

III. HISTORY OF SUBCONTRACT

The delivery date of the SNAP-IIIA generator was revised to January 31, 1959. In January, it became apparent that the delivery date would not be met. It was mutually agreed by Martin and Westinghouse that no further payments would be made under the terms of the contract after January 1959, and that Westinghouse would complete the generator prior to April 1959, using Westinghouse funds as required. The justification for the revised date was based upon the fact that the Westinghouse SNAP-IIIA generator was to use more advanced thermoelectric materials than the previous one made by Minnesota Mining and Manufacturing Company. At this time, the 3M generator had been fabricated, delivered to Martin and then fueled with a radioisotope heat source.

The thermoelectric materials in the Westinghouse generator were to be capable of continuous operation with a hot junction temperature of 650°C. This would give the unit a high cold junction and heat rejection temperature, but still make a reasonably high efficiency possible. This would result in an advanced unit that had some favorable degree of comparison with the 3M device which used lead telluride.

The generator was not completed in April 1959, and on May 20th Martin recommended to the AEC that the delivery date be revised to August 30, 1959. On August 12th, Westinghouse informed Martin that it was unable to completely assemble the thermoelectric panels into the generator structure, and was transferring the partially complete generator to the New Products Laboratories for assembly. The completion date was given as December 1, 1959.

The New Products Laboratories completed the generator early in December 1959. On December 10, 1959, Westinghouse demonstrated the SNAP-IIIA generator for Martin personnel. Martin was to accept delivery of the generator following this. During the demonstration the valve controlling the heat dump mechanism failed. It was decided that Westinghouse would repair the generator and deliver it to Martin on December 14th. The generator was delivered on December 16th. The valve, however, again failed to operate properly. The unit was returned to Westinghouse on December 23rd. Martin requested that the generator be repaired and returned to Martin with an accompanying operating manual and drawings by February 1, 1960.

The generator was repaired and delivered complete with the drawings and operating manual on January 28, 1960.

Earlier Westinghouse realized that a new approach could be followed in the overall generator design which could result in improved performance, and decided unilaterally to build such a generator, again at no additional cost to the Government. The new design was termed SNAP-IIIB, and was delivered to Martin on March 10, 1960. It differed appreciably in configuration from SNAP-IIIA, but showed only an incremental improvement in performance as demonstrated by Westinghouse data. The AEC then determined that neither SNAP-IIIA nor SNAP-IIIB offered enough of an advance in thermoelectric generator technology to warrant further testing or evaluation by Martin, and work was therefore terminated on this program.

IV. DESIGN AND PERFORMANCE OF SNAP-III A

A. Description of Generator

The generator is shown in Fig. 1. It weighs 10.18 pounds with the electrical heater and approximately 7 pounds without the heater. The "N" elements are lead telluride and the segmented "P" elements consist of germanium telluride at the hot junction end and zinc antimonide at the cold junction end. The "P" and "N" elements are mechanically bonded to a plate which then forms an insulated pressure contact against the hot junction. By so doing, the problem of high electrical contact resistance at the hot junction is eliminated. This is probably the most outstanding feature of the generator. The assembly of the generator is shown in Fig. 2. As shown in Fig. 2, the generator consists of four sections located symmetrically around the cylindrical heat source; two thermoelectric ladders located 180 degrees apart, and two heat dump sections also located 180 degrees apart.

The generator was designed to use an isotope heat source and therefore has a heat dump mechanism that regulates the power output during the life of the generator as the isotope power decays. The design life of the generator is approximately equal to one half-life of the isotopic heat source. Theoretically, the gas-heat dump mechanism should be disposing of one-half of the power output from the isotope at the beginning of life, and no heat at the end of life. From the beginning of life, the generator must leak the gas in such a way as to match the exponential decay of the isotopic heat source over the half-life.

The heat dump mechanism operates on the thermal conductivity-pressure relationship of gases. Argon was chosen for this generator, its pressure varying from 1 atmosphere (760 mm of Hg) down to 0.07 mm of Hg.

The electrical heater is a 400-watt, 115-volt, a-c unit with a stainless steel outer jacket. The only thermocouple is attached to the outside surface of the heater.

The hot junctions are capable of continuous operation at a heater temperature of 540°C (1000°F)* with no expected ill effects. For short periods of time (i.e., during thermal transients, etc.) the heater temperature can go as high as 600°C (1110°F).

*Since there is only one thermocouple in the generator, and this is on the electrical heater, there is no way of knowing what is the actual hot junction temperature. Similarly with the cold junction, the temperatures recorded are those on the outside of the generator and not the actual cold junction temperature.

SNAP III A THERMOELECTRIC GENERATOR

Figure 1

"SNAP III A THERMOELECTRIC GENERATOR"

Figure 2

B. Generator Performance

The SNAP-III A thermoelectric generator was tested by the New Products Laboratories of Westinghouse prior to delivery to Martin-Nuclear. The results of these tests were made available to Martin when the generator was delivered and are the basis for the Tables. Martin-Nuclear has not tested the generator.

Two sets of performance data are shown in Tables 1 and 2. A one-hour time interval was allowed between readings to ensure that a steady state equilibrium condition existed.

TABLE 1

WESTINGHOUSE SNAP-III A PERFORMANCE DATA

Item	Run					
	Number					
	1	2	3	4	5	6
Argon pressure (mm Hg)	760	760	760	7.5	0.5	0.07
Bell jar pressure (mm Hg)	10	0.06	0.018	0.015	0.013	0.013
Heater temperature*(°C)	577	537	541	537	539	544
Cold junction temperature*(°C)	224	229	227	216	202	172
Heat dump temperature*(°C)	234	229	230	219	198	175
Internal resistance (m_{ω})	482	468	467	434	400	385
Power input (w)	169	157	163	144	98	91.5
Power output (w)	1.78	1.45	1.41	1.13	.795	.83
Voltage, Open circuit (v)	1.85	1.65	1.62	1.4	1.13	1.13
Voltage, load (v)	0.54	0.53	0.52	0.47	0.41	0.41
Efficiency (%)	1.05	0.925	0.865	0.785	0.81	0.908

Data taken on December 11, 1959

* See preceding footnote.

TABLE 2

WESTINGHOUSE SNAP-IIIA PERFORMANCE DATA

Item	Run Number						
	1	2	3	4	5	6	7
Argon pressure (mm Hg)	760	100	50	25	5	1	0.07
Bell jar pressure (mm Hg)	0.035	0.012	0.013	0.013	0.013	0.013	0.013
Heater temp. (°C)	537	542	539	537	533	536	547
Cold junction temp. (°C)	225	223	220	214	200	184	170
Heat dump temp. (°C)	226	226	222	219	204	186	176
Internal resistance (m Ω)	480	473	467	454	429	398	389
Power input (w)	151	149.5	144	139.5	120	106	95
Power output (w)	1.42	1.36	1.27	1.22	1.02	0.86	0.805
Voltage, open circuit (v)	1.65	1.60	1.54	1.49	1.32	1.17	1.16
Voltage, load (v)	0.52	0.51	0.50	0.49	0.45	0.42	0.42
Efficiency (%)	0.94	0.91	0.88	0.875	0.85	0.81	0.85

Data taken on December 14 & 15, 1959

These data are indicative of the performance of the generator. Because a complete set of operational data is not available, it is difficult to make many specific observations concerning the generator.

For almost every measurement reported, the temperature of the radiator of the heat dump mechanism is several degrees higher than the temperature of the radiator in the vicinity of the cold junction.

Regardless of whether the measurements are made with high argon pressures or low pressures, the heat flux through the heat dump mechanism is greater than that through the thermoelectric portion of the generator. Since the areas of the two sections are about equal, the flow through the heat dump mechanism constitutes a high loss that reduces the efficiency of the generator and creates a secondary effect in that the cold junction temperature is raised because of the flow of heat from the heat dump areas to the cold junction area. This in turn reduces the ΔT of the thermoelectric elements and hence reduces the efficiency even more. This is probably the most significant reason for the low efficiency of the generator.

The purpose of the power flattening device is to maintain a relatively constant power output over the life of the generator, which is approximately equal to the half-life of the radioisotope. Thus when the internal gas pressure is one atmosphere (760 mm) the power input required to produce a given power output should be approximately twice that at an internal gas pressure of 0.07 mm. The data reported in Tables 1 & 2 are inconclusive in this respect in that neither the power output nor the output voltage could be held constant as the gas pressure was reduced from one atmosphere to its lowest value of 0.07 mm of Hg. One can observe from the data that the power input was adjusted so as to maintain the hot junction temperature (heater temp.) at a relatively constant value equal to its maximum. This produces the highest power output for any particular gas pressure. However, the power output dropped off as the gas pressure was decreased. It can be surmised that if the test had been conducted such that the power input was decreased in an exponential manner simulating the power input from an isotopic heat source (as the gas pressure varied from 760 to 0.07 mm of Hg), then the power output and voltage would have fallen off even more rapidly than they did in the case reported in Tables 1 & 2. Thus, it may be inferred that the power flattening characteristics of the generator are minimal.

As was reported in the previous chapter, the weight of the generator, including the heater or heat source, is 10.18 pounds. The maximum power output, with the heater temperature in the vicinity of 540°C, is 1.45 watts. This yields a specific power of 0.142 watts per pound.

V. DESIGN AND PERFORMANCE OF SNAP-IIIB

A. Description of Generator

Although the fundamental principle of operation of this unit is the same as that of SNAP-IIIA, a number of significant modifications in design were made to improve performance. As a consequence the geometry of the generator was changed markedly. Figures 3 and 4 depict the external configuration of the unit, and Figure 5 shows the internal arrangement of the components.

The changes in design of particular note include:

1. Thermal isolation of the heat dump mechanism from the thermoelectric cold junction area, to overcome the loss in efficiency observed for SNAP-IIIA;
2. Provision for enclosure of the thermoelectric elements in a separate, constant pressure, reducing atmosphere, so that the thermal contact between the thermoelectric ladder and the radiator surface is enhanced and is constant over the life of the generator;
3. More compact mounting of the thermoelectric elements in a single cylindrical array.

Other characteristics stated by Westinghouse are listed in Table 3.

TABLE 3

CHARACTERISTICS OF SNAP-IIIB

Weight (exclusive of heat source)	5 lbs.
Number of couples	17 (P - GeTe + ZnSb) (N - PbTe)
Operating temperatures	$T_{hot} - 480^{\circ}\text{C}$ $T_{cold} - 190^{\circ}\text{C}$
Power output at maximum power transfer	1.6 watts
Output voltage	1.44 volts
Efficiency	0.88% at start of life 1.20% at end of one half-life

Fig. 3. SNAP-III B Thermoelectric Generator

Fig. 4. SNAP-III B Thermoelectric Generator

SNAP IIIB Thermoelectric Generator

B. Performance of Generator

No details on the performance of the generator over extended periods of time, or on the operation of the heat dump mechanism, have been provided by Westinghouse. However the figures quoted in Table 3 indicate that only marginal increases in efficiency over SNAP-III A performance have been obtained. It is possible that the heat dump mechanism operates well and flattens the output power over the life of the generator. *

* NPED Report F-6930-19(1) states: "SNAP-IIIB has been extensively tested; the control system performs adequately and the model demonstrates feasibility of concept."

VI. COMPARISON WITH OTHER SNAP-III GENERATORS

The performance of a typical Minnesota Mining and Manufacturing Co. SNAP-III thermoelectric generator is presented here as a basis of comparison. It should be remembered that the 3M generator does not include a power flattening mechanism as do the Westinghouse SNAP-IIIA and IIIB designs.

TABLE 4 *

Minnesota Mining and Manufacturing Co.
SNAP-III Thermoelectric Generator Performance Data

Hot junction temperature	594°C (1100°F)
Cold junction temperature	110°C (230°F)
Power-in	77.6 watts
Power-out	4.6 watts
Voltage optimum load	4.0 volts (d-c)
Efficiency	5.9%

* Data taken from T. E. Gen. #3M-1G10

A comparison of the data in Table 4 with the data contained in Tables 1, 2, and 3 reveals the relative difference in performance. SNAP-IIIA and IIIB, designed to use more advanced thermoelectric materials capable of higher hot junction temperature operation, do not operate at hot junction temperatures as high as that of the 3M SNAP III. Other differences in performance characteristics are apparent. The approximate specific power of an isotope fueled SNAP-III generator is 0.67 watts per pound, whereas the specific powers of the electrically heated SNAP-IIIA and IIIB generators are 0.142 and 0.22 watts per pound, respectively.

VII. CONCLUSIONS

The most significant design advance resulting from this program is the bonding of the thermoelectric elements to a plate at the hot junction, thereby reducing or eliminating the electrical contact resistance at the hot junction. This is the most serious drawback in other SNAP-III thermoelectric generators. Information on the bonding technique employed has not been released by Westinghouse.

Since no data have been furnished on the operation of the heat dump mechanism, we are unable to evaluate its functioning and reliability. However, it is recommended that such a device sense the hot junction temperature and control it at a constant value, rather than attempt to control power output by sensing the cold junction temperature.

Other features of the two generators do not appear to constitute significant improvements by comparison with SNAP III and related devices for which a substantial amount of experimental data has been accumulated.

VIII. REFERENCES

Details of SNAP IIIA and IIIB analysis, design, performance, and operation may be found in the following Westinghouse New Products Laboratories reports.

- A. "SNAP III Thermoelectric Generator", Report No. F-6930-19(1), by D. A. Forejt, April 30, 1960
- B. Instruction Manual - SNAP IIIA, January 25, 1960
- C. Instruction Manual - SNAP IIIB, March 9, 1960

Detail and assembly drawings for the two generators are on file at The Martin Company.