NUCLEAR BATTERY-THERMOCOUPLE TYPE
SEVENTH QUARTERLY PROGRESS REPORT
JULY 1, 1958 TO SEPTEMBER 30, 1958

MASTER

B. C. Blanke

U. S. Army Signal Corps Contract No. R-65-8-99811-SC-01-91

U. S. Department of the Army Project No. 3-99-15-102

U. S. Army Signal Research and Development Laboratories, Ft. Monmouth, N.J.

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SEVENTH QUARTERLY PROGRESS REPORT
JULY 1, 1958 TO SEPTEMBER 30, 1958

B. C. Blanke

Date: 30 September 1958

Issued: JAN 6 1959

The object of this contract is to conduct research on radioactive materials and thermocouples suitable for the direct conversion of heat to electrical energy.

U. S. Army Signal Corps Contract No. R-65-8-99811-SC-01-91

U. S. Army Signal Research and Development Laboratories Technical Requirement Nos. P. R. and C. 58-ELS/R-3705, 58-ELS/O-3861 (S)

U. S. Department of the Army Project No. 3-99-15-102

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MONSANTO CHEMICAL COMPANY
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PURPOSE

Radioactive materials and thermocouples suitable for use in a system for the direct conversion of heat to electrical energy will be investigated. Isotopes having suitable characteristics will be determined, heat sources will be designed, and prototype batteries will be constructed.

ABSTRACT

Calculations were made to estimate the minimum amounts of isotopes as the element or appropriate compound which had sufficient power output to raise their temperatures to 200°C and 2300°C. Construction has begun on a second battery similar to the one described in MLM-CF-58-7-19.

CONFERENCES

John Birden and B. C. Blanke of Mound Laboratory visited Messrs. Schroeder, Denton, and Jerencsik of Ohio Semiconductors Company to discuss problems in preparing semiconductor materials such as bismuth telluride for battery use. No method of preparation compatible with design size is presently known.

B. C. Blanke attended the Navy-sponsored Conference on Thermoelectric Materials. George Hunrath of the U. S. Army Signal R and D Laboratories, who also attended the conference, authorized construction of a second 50-milliwatt battery.

FACTUAL DATA

Thirty-three isotopes having nuclear properties entitling them to consideration as possible heat sources were previously selected, and were listed in report MLM-CF-57-4-34. In the present report, these isotopes are further considered to determine the maximum temperature they could develop as a function of physical size. To maximize the temperature, the isotopes were assumed to have a minimum surface area per unit volume (spherical), and all heat losses other than radiation were a minimum or zero. An arbitrary emissivity of 0.85 was assumed in all cases because measured emissions were not available. Extremes of temperature were selected as 200°C and 2300°C. Below 200°C, the efficiency of the generators made from available materials falls off rapidly. Above 2300°C, it would be extremely difficult to find a satisfactory material to encapsulate the radioactive isotope.

The method of calculation is straightforward. The Stefan-Boltzman relationship states that the heat loss, q , in calories per second for a black body is:

$$q = \sigma AT^4 \quad \text{where } \sigma = \text{Stefan-Boltzman constant}$$

$$A = \text{Surface area, cm}^2$$

$$T = \text{Temperature, } ^\circ\text{K}$$

For non-black bodies, an emissivity factor ϵ is added

$$q = \epsilon \sigma AT^4$$

Evaluating: $\epsilon = 0.85$

$$\sigma = 4.96 \times 10^{-8} \text{ Kcal-hr}^{-1}\text{m}^{-2}\text{T}^{-4}$$

$$\sigma = \frac{4.96 \times 10^{-8}}{3.6 \times 10^4} = 1.378 \times 10^{-12} \text{ cal-sec}^{-1}\text{cm}^{-2}\text{T}^{-4}$$

[σ value from Jakob, Heat Transfer, John Wiley and Sons, New York, 1949]

$$A = 4\pi r^2 \quad r = \text{the radius of the assumed sphere of isotope in cm.}$$

$$\text{Or } q = 0.85(1.378 \times 10^{-12}) 4\pi r^2 T^4 \text{ cal-sec}^{-1}$$

The heat output of the various isotopes had been previously calculated in terms of watt-cm⁻³. If the total volume of the sphere, V_t , is isotope alone, the heat, W_t , is:

$$W_t = V_t k = \frac{4}{3}\pi r^3 k \quad \text{where } k = \text{isotopic heat output in watt-cm}^{-3}$$

At equilibrium, the isotopic heat output must equal the heat radiated

$$W_t = 4.186 q \text{ (converting watts to calories)}$$

Or

$$\frac{4}{3}\pi r^3 k = 0.85 (1.378 \times 10^{-12}) 4\pi r^2 T^4$$

$$\text{Solving for } r: \quad r = \frac{3 (1.378 \times 10^{-12}) 0.85 (4.186) T^4}{k} \quad \text{cm}$$

$$= 1.471 \times 10^{-11} T^4/k$$

$$\text{At } 200^\circ\text{C} \quad T^4 = 5.006 \times 10^{10}$$

$$r = \frac{7.364 \times 10^{-1}}{k} \quad \text{cm}$$

$$\text{At } 2300^\circ\text{C} \quad T^4 = 4.383 \times 10^{13}$$

$$r = \frac{6.447 \times 10^2}{k} \quad \text{cm}$$

Table 1 shows the results of these calculations. For most of the isotopes, compounds which could be the chemical form used in a heat source are also included. In the case of krypton, values are considered as related to a one cubic centimeter volume at STP ignoring the pressure changes with temperature when confined to this volume.

Those isotopes which could feasibly be produced in a nuclear reactor were selected from the list and further calculations were made to determine the maximum temperature each could develop as a function of physical size. The nuclear reactions necessary, and the reactor irradiation time and flux densities assumed are listed together with the results of the calculations in Tables 2 and 3 below. The heat sources are assumed to be composed of the isotope in question unseparated from the parent material. In Table 2 the parent is assumed to be pure prior to irradiation. In Table 3 the parent is assumed to be irradiated as it occurs in nature, i.e., mixed (in most cases) with other isotopes of the same element.

Table 1

HEAT SOURCE SIZE AS A FUNCTION OF TEMPERATURE FOR SELECTED ISOTOPES

Isotope as Elements or Compounds	Density, ρ g/cm ³	Isotope Power		Heat Source Radius, cm	
		watts/g	watts/cm ³	200°C	2300°C
Sulfur-35	2.07	1.69×10^1	3.50×10^1	2.11×10^{-2}	1.84×10^1
FeS	4.84	2.51	1.22×10^1	6.06×10^{-2}	5.31×10^1
Argon-42	1.783 g/l				
Calcium-45	1.55	1.06×10^1	1.64×10^1	4.48×10^{-2}	3.92×10^1
CaF ₂	3.18	3.13	9.96	7.39×10^{-2}	6.47×10^1
CaO	3.40	5.79	1.97×10^1	3.74×10^{-2}	3.28×10^1
Nickel-63	8.90	1.06×10^{-2}	9.43×10^{-2}	7.81	6.83×10^3
Krypton-85	3.708 g/l	6.31×10^{-1}	2.34×10^{-3}	3.15×10^{-2}	2.76×10^5
Strontium-89	2.6	9.97×10^1	2.59×10^2	2.84×10^{-3}	2.49
Strontium-90	2.6	9.58×10^{-1}	2.49	2.96×10^{-1}	2.59×10^2
Sr + Sr ⁹⁰ + Y ⁹⁰	2.6	4.55×10^1	1.18×10^2	6.22×10^{-3}	5.45
Yttrium-91	5.51	9.09×10^1	5.01×10^2	1.47×10^{-3}	1.29
YF ₃ + 1/2H ₂ O	No Data	3.05×10^1			
YCl ₃	2.8	1.93×10^1	5.40×10^1	1.36×10^{-2}	1.19×10^1
Y ₂ O ₃	4.84	2.84×10^1	1.38×10^2	5.35×10^{-3}	4.69
Cadmium-113	8.65	8.53×10^{-1}	7.38	9.98×10^{-2}	8.74×10^1
CdO	6.95	6.54×10^{-1}	4.20	1.75×10^{-1}	1.54×10^2
Tin-121m	7.28	5.88×10^{-1}	4.28	1.72×10^{-1}	1.51×10^2
Tin-123	7.28	2.72×10^1	1.98×10^2	3.72×10^{-3}	3.26

Table 1 (Continued)

HEAT SOURCE SIZE AS A FUNCTION OF TEMPERATURE FOR SELECTED ISOTOPES

Isotope as Elements or Compounds	Density, ρ g/cm ³	Isotope Power		Heat Source Radius, cm	
		watts/g	watts/cm ³	200°C	2300°C
Cerium-144 + Pr-144	6.90	2.36×10^1	1.63×10^2	4.52×10^{-3}	3.96
CeO ₂	7.3	1.66×10^1	1.21×10^2	6.08×10^{-3}	5.33
Ce ₂ O ₃	6.95	8.66	6.02×10^1	1.22×10^{-2}	1.07×10^1
CeF ₃	6.16	1.21×10^1	7.47×10^1	9.86×10^{-3}	8.64
Promethium-146	6.9 (Cerium)	4.06	2.80×10^1	2.63×10^{-2}	2.30×10^1
Pm ₂ O ₃ (Assumed)	No Data	1.50			
Promethium-147	6.9 (Cerium)	5.09×10^{-1}	3.51	2.10×10^{-1}	1.84×10^1
Pm ₂ O ₃ (Assumed)	No Data	1.90×10^{-1}			
Samarium-151	7.8	4.21×10^{-3}	3.28×10^{-2}	2.24×10^1	1.96×10^4
Sm ₂ O ₃	7.43	1.56×10^{-3}	1.16×10^{-2}	6.35×10^1	5.56×10^4
Europium-149	6.9 (Cerium)				
Eu ₂ O ₃	No Data				
Europium-152	6.9 (Cerium)	7.69×10^{-2}	5.31×10^{-1}	1.39	1.22×10^3
Eu ₂ O ₃	No Data	2.87×10^{-2}			
Europium-154	6.9 (Cerium)	4.75×10^{-1}	3.28	2.25×10^{-1}	1.97×10^2
Eu ₂ O ₃	No Data	1.78×10^{-1}			
Europium-155	6.9 (Cerium)	5.38×10^{-1}	3.71	1.98×10^{-2}	1.74×10^2
Eu ₂ O ₃	No Data	2.02×10^{-1}			
Gadolinium-148	6.9 (Cerium)	3.23×10^{-1}	2.23	3.30×10^{-2}	2.89×10^2
Gd ₂ O ₃	7.4	1.20×10^{-1}	8.84×10^{-1}	8.33×10^{-1}	7.29×10^2

Table 1 (Continued)

HEAT SOURCE SIZE AS A FUNCTION OF TEMPERATURE FOR SELECTED ISOTOPES

Isotope as Elements or Compounds	Density, ρ g/cm ³	Isotope Power		Heat Source Radius, cm	
		watts/g	watts/cm ³	200°C	2300°C
Thulium-170	6.9 (Cerium)	1.35×10^1	9.31×10^1	7.91×10^{-3}	6.93
Tm ₂ O ₃ (Assumed)	No Data	5.21			
Thulium-171	6.9 (Cerium)	2.67×10^{-1}	1.84	4.00×10^{-1}	3.50×10^2
Tm ₂ O ₃ (Assumed)	No Data	1.03×10^{-1}			
Lutecium-174	6.9 (Cerium)	1.29	8.90	8.27×10^{-2}	7.24×10^1
Lu ₂ O ₃	No Data	4.99×10^{-1}			
Tungsten-185	19.3	9.72	1.88×10^2	3.93×10^{-3}	3.44
WO ₂	12.11	7.05	8.54×10^1	8.62×10^{-3}	7.55
Tungsten-188	19.3				
WO ₂	12.11				
Osmium-194	22.48				
Thallium-204	11.85	1.04	1.23×10^1	5.98×10^{-2}	5.23×10^1
Lead-210 + Bi-210 + Po-210	11.3	3.00	3.39×10^1	2.17×10^{-2}	1.90×10^1
Polonium-208	9.4	3.69×10^1	3.47×10^2	2.12×10^{-3}	1.86
Polonium-209	9.4	4.44×10^{-1}	4.17	1.77×10^{-1}	1.55×10^2
Polonium-210	9.4	1.43×10^2	1.35×10^3	5.47×10^{-4}	4.82×10^{-1}
Curium-242	17.0 (est.)	1.20×10^2	2.04×10^3	3.61×10^{-4}	3.16×10^{-1}
Curium-244	17.0 (est.)	2.73	4.64×10^1	1.59×10^{-2}	1.39×10^1

Table 2

HEAT SOURCE SIZE AS A FUNCTION OF TEMPERATURE^j
Irradiation of Pure Parent Isotope
Assumed

Isotope or Probable Compound	Required Reaction	Irradi- ation Time ^h days	Density of Target g/cm ³	Isotope Power		Heat Source Radius, cm	
				watts/mole of target	watts/cm ³ of target	200°C	2300°C
Sulfur-35 FeS	$_{16}\text{S}^{34} + \text{n}^1 \rightarrow \text{S}^{35} + \gamma$	180	2.07	1.27×10^{-1}	7.73×10^{-3}	9.52×10^1	8.34×10^4
			4.84	4.81×10^{-2}	6.84×10^{-3}	1.08×10^2	9.42×10^4
Calcium-45 CaF ₂ CaO	$_{20}\text{Ca}^{44} + \text{n}^1 \rightarrow \text{Ca}^{45} + \gamma$	360	1.55	5.28×10^{-1}	1.86×10^{-2}	3.96×10^1	3.47×10^4
			3.18	2.83×10^{-1}	2.05×10^{-2}	3.60×10^1	3.15×10^4
			3.40	3.87×10^{-1}	2.99×10^{-2}	2.46×10^1	2.16×10^4
Nickel-63	$_{28}\text{Ni}^{62} + \text{n}^1 \rightarrow \text{Ni}^{63} + \gamma$	360	8.90	3.02×10^{-2}	4.34×10^{-3}	1.70×10^2	1.49×10^5
Krypton-85	$_{36}\text{Kr}^{84} + \text{n}^1 \rightarrow \text{Kr}^{85} + \gamma$	360	3.708 ^b	2.50×10^{-2}	1.10×10^{-6}	6.67×10^5	5.84×10^8
Strontium-89	$_{38}\text{Sr}^{88} + \text{n}^1 \rightarrow \text{Sr}^{89} + \gamma$	180	2.6	2.43×10^{-4}	7.18×10^{-6}	1.03×10^5	8.98×10^7
Cadmium-113m CdO	$_{48}\text{Cd}^{112} + \text{n}^1 \rightarrow \text{Cd}^{113\text{m}} + \gamma$	180	8.65	1.37×10^{-4}	1.06×10^{-5}	6.96×10^4	6.09×10^7
			6.95	1.20×10^{-4}	7.44×10^{-6}	9.90×10^4	8.67×10^7

Table 2 (Continued)

HEAT SOURCE SIZE AS A FUNCTION OF TEMPERATURE^j
 Irradiation of Pure Parent Isotope
 Assumed

Isotope or Probable Compound	Required Reaction	Irradi- ation Time ^h days	Density of Target g/cm ³	Isotope Power		Heat Source Radius, cm	
				watts/mole of target	watts/cm ³ of target	200°C	2300°C
Tin-121m	${}_{50}^{120}\text{Sn} + {}_0^1\text{n} \rightarrow {}_{50}^{121\text{m}}\text{Sn} + \gamma$	360	7.28	2.06×10^{-6}	1.25×10^{-7}	5.89×10^6	5.16×10^9
Tin-123	${}_{50}^{122}\text{Sn} + {}_0^1\text{n} \rightarrow {}_{50}^{123}\text{Sn} + \gamma$	360	7.28	4.66×10^{-3}	2.76×10^{-4}	2.67×10^3	2.34×10^6
Europium-155	${}_{62}^{154}\text{Sm} + {}_0^1\text{n} \rightarrow {}_{62}^{155}\text{Sm} \xrightarrow{\beta^-} {}_{63}^{155}\text{Eu}$	30	6.9 ^c	3.17×10^{-2}	1.42×10^{-3}	5.19×10^2	4.54×10^5
Eu ₂ O ₃			6.9 ^d	2.74×10^{-2}	6.15×10^{-4}	1.20×10^3	1.05×10^6
Thulium-170	${}_{69}^{169}\text{Tm} + {}_0^1\text{n} \rightarrow {}_{69}^{170}\text{Tm} + \gamma$	90	6.9 ^c	2.37×10^2	9.68	7.61×10^{-2}	6.66×10^1
Tm ₂ O ₃ ^a			6.9 ^d	2.08×10^2	4.24	1.74×10^{-1}	1.52×10^2
Thulium-171	${}_{68}^{170}\text{Er} + {}_0^1\text{n} \rightarrow {}_{68}^{171}\text{Er} \xrightarrow{\beta^-} {}_{69}^{171}\text{Tm}$	90	4.77 ^e	2.54×10^{-1}	7.13×10^{-3}	1.03×10^2	9.05×10^4
Tm ₂ O ₃ ^a			8.64 ^f	2.23×10^{-1}	5.66×10^{-3}	1.30×10^2	1.14×10^5

Table 2 (Continued)

HEAT SOURCE SIZE AS A FUNCTION OF TEMPERATURE^j
 Irradiation of Pure Parent Isotope
 Assumed

Isotope or Probable Compound	Required Reaction	Irradi- ation Time ^h days	Density of Target g/cm ³	Isotope Power		Heat Source Radius, cm	
				watts/mole of target	watts/cm ³ of target	200°C	2300°C
Tungsten-185	${}_{74}^{184}\text{W} + {}_0^1\text{n} \rightarrow {}_{74}^{185}\text{W}$	180	19.3	2.65	2.78×10^{-1}	2.65	2.32×10^3
WO ₂	+ γ		12.11	2.26	1.49×10^{-1}	4.96	4.34×10^3
Thallium-204	${}_{81}^{203}\text{Tl} + {}_0^1\text{n} \rightarrow {}_{81}^{204}\text{Tl}$	360	11.85	6.32	3.69×10^{-1}	2.00	1.75×10^3
	+ γ						
Polonium-210	${}_{83}^{209}\text{Bi} + {}_0^1\text{n} \rightarrow {}_{83}^{210}\text{Bi}$	360	9.8 ^g	8.12×10^{-1}	3.81×10^{-2}	1.93	1.69×10^3
	$\xrightarrow{\beta^-} {}_{84}^{210}\text{Po}$						

a Assumed

b g/liter(STP)

c Density of cerium

d Density of cerium oxide

e Density of erbium

f Density of erbium oxide

g Density of bismuth

h Irradiation flux is 10^{14} n/cm²/sec in each case.

j Values may differ from those given in MLM-CF-4-34 because of assumed flux and irradiation time changes.

Table 3

HEAT SOURCE SIZE AS A FUNCTION OF TEMPERATURE^j
 Irradiation of Naturally - Occurring Parent
 Assumed

Isotope or Probable Compound	Required Reaction	Irradi- ation Time ^h days	Density g/cm ³	Per Cent of Pure Parent in Natural Target	Isotope Power		Heat Source Radius, cm	
					watts/mole of target	watts/cm ³ of target	200°C	2300°C
Sulfur-35	$_{16}^{34}\text{S} + _0^1\text{n} \rightarrow$ $_{16}^{35}\text{S} + \gamma$	180	2.07	4.215	5.35×10^{-3}	3.45×10^{-4}	2.13×10^3	1.87×10^6
FeS			4.84		1.95×10^{-3}	2.95×10^{-4}	2.50×10^3	2.19×10^6
Calcium-45	$_{20}^{44}\text{Ca} + _0^1\text{n} \rightarrow$ $_{20}^{45}\text{Ca} + \gamma$	360	1.55	2.07	1.09×10^{-2}	4.22×10^{-4}	3.10×10^4	1.53×10^6
CaF ₂			3.18		5.60×10^{-3}	4.44×10^{-4}	1.66×10^3	1.45×10^6
CaO			3.40		7.79×10^{-3}	6.61×10^{-4}	1.11×10^3	9.76×10^5
Nickel-63	$_{28}^{62}\text{Ni} + _0^1\text{n} \rightarrow$ $_{28}^{63}\text{Ni} + \gamma$	360	8.90	3.66	1.11×10^{-3}	1.68×10^{-4}	4.38×10^3	3.83×10^6

Table 3 (Continued)

HEAT SOURCE SIZE AS A FUNCTION OF TEMPERATURE^j
 Irradiation of Naturally - Occurring Parent
 Assumed

Isotope or Probable Compound	Required Reaction	Irradi- ation ⁿ Time days	Density g/cm ³	Per Cent of Pure Parent in Natural Target	Isotope Power		Heat Source Radius, cm	
					watts/mole of target	watts/cm ³ of target	200°C	2300°C
Krypton-85	${}_{36}\text{Kr}^{84} + {}_0^1\text{n} \rightarrow$ ${}_{36}\text{Kr}^{85} + \gamma$	360	3.708 ^b	56.9	1.42×10^{-2}	6.29×10^{-7}	1.17×10^6	1.03×10^9
Strontium-89	${}_{38}\text{Sr}^{88} + {}_0^1\text{n} \rightarrow$ ${}_{38}\text{Sr}^{89} + \gamma$	180	2.6	82.56	2.00×10^{-4}	5.93×10^{-6}	1.24×10^5	1.09×10^8
Cadmium-113m	${}_{48}\text{Cd}^{112} + {}_0^1\text{n} \rightarrow$ ${}_{48}\text{Cd}^{113\text{m}} + \gamma$	30	8.65	24.04	3.30×10^{-5}	2.54×10^{-6}	2.90×10^5	2.54×10^8
CdO			6.95		2.89×10^{-5}	1.70×10^{-6}	4.12×10^5	3.61×10^8
Tin-121m	${}_{50}\text{Sn}^{120} + {}_0^1\text{n} \rightarrow$ ${}_{50}\text{Sn}^{121\text{m}} + \gamma$	360	7.28	32.97	6.97×10^{-7}	4.28×10^{-8}	1.72×10^7	1.51×10^{10}

Table 3 (Continued)

HEAT SOURCE SIZE AS A FUNCTION OF TEMPERATURE^j
Irradiation of Naturally - Occurring Parent
Assumed

Isotope or Probable Compound	Required Reaction	Irradi- ation ^h Time days	Density g/cm ³	Per Cent of Pure Parent in Natural Target	Isotope Power		Heat Source Radius, cm	
					watts/mole of target	watts/cm ³ of target	200°C	2300°C
Tin-123	${}_{50}\text{Sn}^{122} + {}_0^1\text{n} \rightarrow$	360	7.28	4.71	4.19×10^{-4}	2.57×10^{-5}	2.87×10^4	2.51×10^7
	${}_{50}\text{Sn}^{123} + \gamma$							
Europium-155	${}_{62}\text{Sm}^{154} + {}_0^1\text{n} \rightarrow$	30	6.9^c	22.53	7.14×10^{-3}	3.24×10^{-4}	2.27×10^3	1.99×10^6
	${}_{62}\text{Sm}^{155} \xrightarrow{\beta^-} {}_{63}\text{Eu}^{155}$							
Eu_2O_3			6.9^d		6.17×10^{-3}	1.41×10^{-4}	5.21×10^3	4.56×10^6
Thulium-170	${}_{69}\text{Tm}^{169} + {}_0^1\text{n} \rightarrow$	90	6.9^c	100.0	2.37×10^2	9.68	7.61×10^{-2}	6.66×10^1
	${}_{69}\text{Tm}^{170} + \gamma$							
Tm_2O_3^a			6.9^d		2.08×10^2	4.23	1.74×10^{-1}	1.53×10^2

Table 3 (Continued)

HEAT SOURCE SIZE AS A FUNCTION OF TEMPERATURE^j
 Irradiation of Naturally - Occurring Parent
 Assumed

Isotope or Probable Compound	Required Reaction	Irradi- ation Time ^h days	Density g/cm ³	Per Cent of Pure Parent in Natural Target	Isotope Power		Heat Source Radius, cm	
					watts/mole of target	watts/cm ³ of target	200°C	2300°C
Thulium-171	${}_{68}^{170}\text{Er} + {}_0^1\text{n} \rightarrow$	90	4.77 ^e	14.9	3.78×10^{-2}	1.08×10^{-3}	6.83×10^2	5.98×10^5
	${}_{68}^{171}\text{Er} \beta^- \rightarrow {}_{69}^{171}\text{Tm}$							
Tm ₂ O ₃ ^a			8.64 ^f		3.31×10^{-2}	8.54×10^{-4}	8.62×10^2	7.55×10^5
Tungsten-185	${}_{74}^{184}\text{W} + {}_0^1\text{n} \rightarrow$	180	19.3	30.6	8.11×10^{-1}	8.51×10^{-2}	8.65	7.58×10^3
	${}_{74}^{185}\text{W} + \gamma$							
WO ₂			12.11		6.91×10^{-1}	4.55×10^{-2}	1.62×10^{-1}	1.42×10^4
Thallium-204	${}_{81}^{203}\text{Tl} + {}_0^1\text{n} \rightarrow$	360	11.85	29.5	1.86	1.08×10^{-1}	6.83	5.98×10^3
	${}_{81}^{204}\text{Tl} + \gamma$							
Polonium-210	${}_{83}^{209}\text{Bi} + {}_0^1\text{n} \rightarrow$	360	9.8 ^g	100.0	8.12×10^{-1}	3.81×10^{-2}	1.93	1.69×10^3
	${}_{83}^{210}\text{Bi} \beta^- \rightarrow {}_{84}^{210}\text{Po}$							

Table 3 (Continued)

HEAT SOURCE SIZE AS A FUNCTION OF TEMPERATURE^j
Irradiation of Naturally - Occurring Parent
Assumed

NOTES:

- a Assumed
- b g/liter (STP)
- c Density of cerium
- d Density of cerium oxide
- e Density of erbium
- f Density of erbium oxide
- g Density of bismuth
- h Irradiation flux is 10^{14} n/cm²/sec in each case.
- j Values may differ from those given in MLM-CF-4-34 because of assumed flux and irradiation time changes.

A second battery having the same characteristics as previously reported in MLM-CF-58-7-19 having a power output after six months of 50 milliwatts at 4.8 and 1.2 volts is being constructed. As this battery will be used for demonstration purposes, certain modifications of the outer case and a biological shield for transporting and demonstrating will have to be made.

With the heat source containing 1200 curies of polonium, the radiation at the surface of the battery case will have a maximum of 2.26 roentgens per hour and a safe working distance of 116 centimeters for an eight-hour working day. At the end of six months the surface radiation will decrease to 0.92 roentgens per hour and the working distance for an eight-hour working day to 71.5 centimeters. One inch of lead surrounding the battery would cut the level of radiation at the surface to 2.5 milliroentgens per hour which is one third the maximum level approved by the Atomic Energy Commission. The battery can be removed from the lead shielding for inspection and demonstration.

The initial thermal output of the radioactive source will raise the external temperature of the unshielded case by 89 to 92°C above room temperature when the case is cooled solely by ambient air. Introduction of a finned case cover would decrease this temperature and also make it more difficult for a person handling the battery to receive an excessive radiation dose.

CONCLUSIONS

Calculations giving the size of a sphere of pure isotope required to give a heat source temperature of 200°C and 2300°C indicate that most of the 33 isotopes listed would be acceptable. The most notable exceptions are nickel-63, krypton-85, samarium-151, all europium isotopes, and thulium-171. These would require very large amounts to reach the higher temperature.

From the point of view of canning parent isotope and subsequently irradiating it for use as a heat source, only thulium-170 (Tm-169), tungsten-185 (W-184), thallium-204 (Tl-203), and polonium-210 (Bi-209) show much promise, although sulfur-35 (S-34) may have some possibilities. If naturally-occurring isotopes are canned and then irradiated, tungsten is an unlikely heat source.

Polonium-210 is the only isotope in Table 2 or 3 having the distinct advantage of being chemically separable from the parent isotope. In view of the relatively low polonium yield it is unlikely that the unseparated bismuth and polonium would be used as a heat source.

PROGRAM FOR THE NEXT INTERVAL

The demonstration battery will be completed, and a review of the isotope heat source will be made.

IDENTIFICATION OF KEY PERSONNEL

Bertram C. Blanke	(260 hours)
Kenneth C. Jordan	(173 hours)
John H. Birden	(520 hours)
John L. McKinney	(520 hours)