



ARTIFICIAL HEART PUMP (ADDITIONAL ENDOGENOUS HEAT) PROGRAM

FINAL REPORT
(July, 1966 through June, 1967)

N. E. Davis, C. H. Davenport, and D. P. Kelly



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MIAMISBURG, OHIO

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**N. E. Davis
C. H. Davenport
D. P. Kelly**

Issued: January 27, 1969

MONSANTO RESEARCH CORPORATION

A Subsidiary of Monsanto Company

MOUND LABORATORY

Miamisburg, Ohio

operated for

UNITED STATES ATOMIC ENERGY COMMISSION

U S GOVERNMENT CONTRACT NO AT 33-1664-53

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I. SUMMARY

Three plutonium-238 radioisotope-powered heat sources were developed and fabricated at Mound Laboratory for use by Thermo Electron Engineering Corporation (TEECO) in the Artificial Heart Pump (Additional Endogenous Heat) Program. These sources contained doubly encapsulated plutonium-238 metal; two had a thermal power of $15(+2-0)$ W and one had $25(+0-2)$ W. Details of the design, fabrication, and testing of the heat sources are given in this report.

Two of the heat sources (one 15-W and one 25-W) were shipped to TEECO for use with special heat exchangers in implantation experiments on dogs at Boston City Hospital. These tests have been under way since July, 1967. The third heat source (15-W) was fabricated for in-house testing at Mound Laboratory.

II. INTRODUCTION

The total implantation of long-term energy sources for cardiac prostheses is ultimately desirable. Radioisotopes have been considered for this type of energy source. However, because all of the heat from a radioisotope source cannot be converted into mechanical energy by a heat engine, considerable heat must be removed from the body. Therefore, studies relating to the transfer of this additional endogenous heat were necessary for the further development of the overall artificial heart pump program.

A. PROGRAM BACKGROUND

Because of the interest in the Artificial Heart Pump (Additional Endogenous Heat) Program, the subject was discussed early in 1966 by personnel from the Atomic Energy Commission, Division of Isotopes Development (AEC/DID), Washington, D. C., and the National Heart Institute (NHI), Bethesda, Maryland. This ultimately led to the awarding of a program contract by NHI to the Thermo Electron Engineering Corporation (TEECO) of Waltham, Massachusetts [name since changed to Thermo Electron Corporation (TECO)].

Subsequently, additional discussions were held concerning various responsibilities within the program. It was decided that Monsanto Research Corporation at Mound Laboratory, Miamisburg, Ohio, would supply the radioisotope heat sources. The heat source design criteria included:

1. Thermal power output of 15(+2-0) W and 25 (+0-2) W for the two heat sources required.
2. An overall heat source design (both materials and dimensions) compatible with the heat exchanger.
3. Consideration of the radiation level in the heat source design in view of the bio-medical application.

Mound effort in this program was initiated during July, 1966, and was completed in June, 1967.

B. PARTICIPANTS AND FUNCTIONS

The Artificial Heart Pump (Additional Endogenous Heat) Program was sponsored by the U. S. Atomic Energy Commission (Division of Isotopes Development), Washington, D. C., and the National Institutes of Health (National Heart Institute), Bethesda, Maryland. The responsibility for implanting

the radioisotope heat sources was assigned to Boston City Hospital.

The following is a list of organizations involved in the fabrication and implantation of the heat sources for this program and their respective functions (see Appendix A for further details).

U. S. Atomic Energy Commission

1. Division of Isotopes Development (DID)
AEC funding and guidance in the development of the radioisotope heat sources.

Other U. S. Government Agencies

1. National Heart Institute (NHI)
Funding and guidance for the Additional Endogenous Heat Program.

Industrial Organizations

1. Monsanto Research Corporation, Mound Laboratory
Final design and fabrication of the radioisotope heat sources.
2. Thermo Electron Engineering Corporation
Design of the overall system, and testing related to the Additional Endogenous Heat Program

Hospitals

1. Boston City Hospital
Implantation of the radioisotope heat source-heat exchanger assemblies and subsequent monitoring.

III. RADIOISOTOPE HEAT SOURCE

A. DESIGN CONCEPTS

1. Radioisotope Fuel It was necessary that the radioisotope fuel used in the heat sources for this program meet both medical and physical requirements. Since these sources would be implanted within living systems, the radiation characteristics of the fuel were extremely important. Also, it was essential that the fuel and the encapsulation materials be compatible to preclude any possibility of fuel escape at the operating temperature of the heat source ($\sim 620^{\circ}\text{F}$ or 327°C maximum, in vivo). As noted previously, the thermal power requirements for the fuel in the two heat sources were $15(+2-0)$ W and $25(+0-2)$ W.

Plutonium-238 metal was chosen as the fuel form because it met all of the requirements. This radioisotope is particularly desirable for the application in view of its long half-life (87.4 yr). In addition, the metal has a lower specific neutron emission rate than plutonium-238 dioxide, another fuel form often used in heat source fabrication. The metal is produced at Mound Laboratory¹ from feed material received from the reactor site and has the typical isotopic composition shown in Table 1.

Table 1

TYPICAL ANALYSIS FOR ISOTOPES IN PLUTONIUM^e

<u>Plutonium Isotope</u>	<u>Average Abundance (wt%)</u>
238	80.0
239	16.5
240	2.5
241	0.8
242	0.08

2. Capsules In addition to the capsule-fuel compatibility requirement, several design criteria for the capsule components received careful consideration. Since the heat source is fixed in the heat exchanger during the implantation, compatibility of the construction materials used for the heat source and heat exchanger was necessary. An additional requirement for the outer capsule material was that it remain corrosion-free in air at surface temperatures up to 550°F (288°C). The overall capsule was

designed for a 5-yr lifetime. Tantalum and Haynes alloy No. 25 were chosen for the inner and outer capsules, respectively, since these materials met all of the stated criteria.

The design parameters which were stated by TEECO for the heat source dimensions were 0.6 in. (1.52 cm) in height by 1.75 in. (4.44 cm) in diameter. The final heat source design included a height of 0.58 in. (1.47 cm) and a diameter of 1.61 in. (4.09 cm) with a nominal 4° taper. This taper provided for the proper fit of the heat source into the heat exchanger. Figure 1 shows the inner and outer capsule components prior to assembly. Figure 2 shows an assembled heat source and an early model TEECO heat exchanger. Various characteristics of these heat sources are indicated in Table 2.

B. FABRICATION OF HEAT SOURCES

The initial step in this work involved fabrication of the capsule components at Mound Laboratory. Samples of the capsule materials were submitted for chemical analysis to verify the composition of the materials used in fabricating these components. The results of these analyses are shown in Table 3. In addition, the components were dimensionally gaged and inspected. Several sets of components were allocated for use in the weld development program. The weld parameters established for these capsules were then used in the fabrication of the fueled heat sources.

In preparation for fabrication of the heat sources, all necessary equipment and materials were placed into an argon atmosphere glove box. The plutonium was received from the Metal Production Group at Mound Laboratory in the form of a metal button. The area and equipment used for plutonium metal production are shown in Figure 3.

The plutonium metal was removed from its transfer container and placed into a small quartz casting tube, which was in turn placed into a larger quartz casting tube. A quartz cover was then placed over the larger tube, thus enclosing the plutonium metal. A vacuum line was attached to a fixture on the cover, and the entire assembly was placed into a vertical electrical resistance furnace. A chromel-alumel thermocouple was placed in the furnace between the larger quartz tube and the furnace wall. A vacuum was applied to the assembly and electrical power was switched on for the furnace. The plutonium was maintained at 1472°F (800°C) for 30 min to ensure complete melting. At the end of this time the vacuum was shut off and the assembly was taken out of the furnace and cooled for 15 min. The plutonium was then removed from the casting tube and weighed; weight adjustments were made so that the proper amount of fuel would be available for the heat source.

The fuel was inserted into an inner capsule in an argon atmosphere glove box; a lid was welded on the capsule using TIG (tungsten-inert gas) welding. Figure 4 illustrates a typical TIG welding facility. The fueled inner capsule was decontaminated using standard health physics procedures,

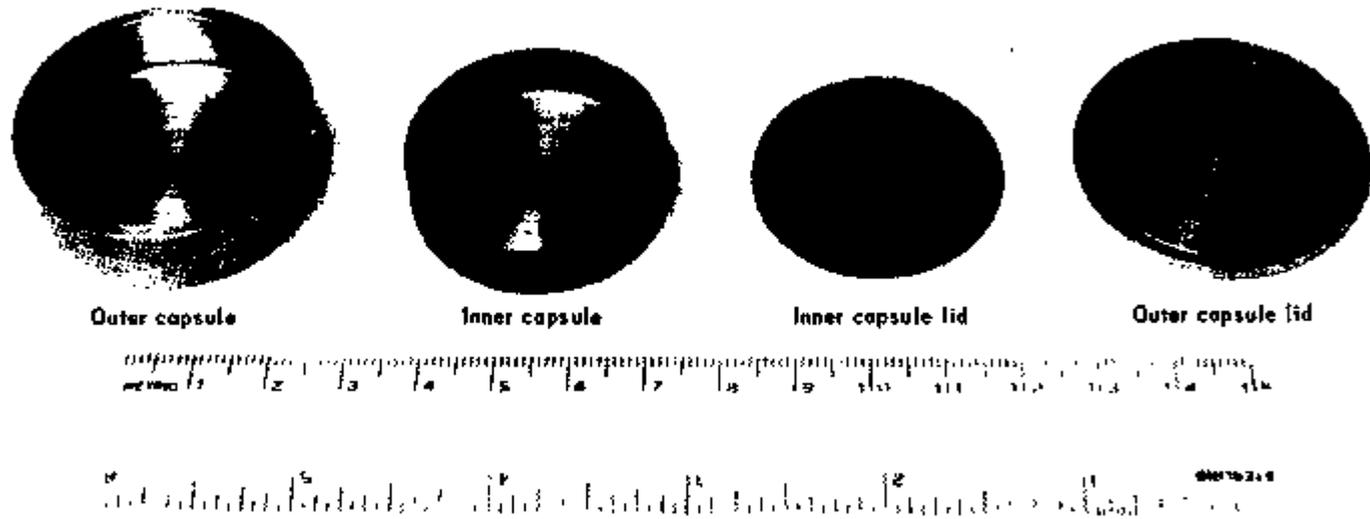


FIGURE 1 - Capsule components for artificial heart pump heat source.

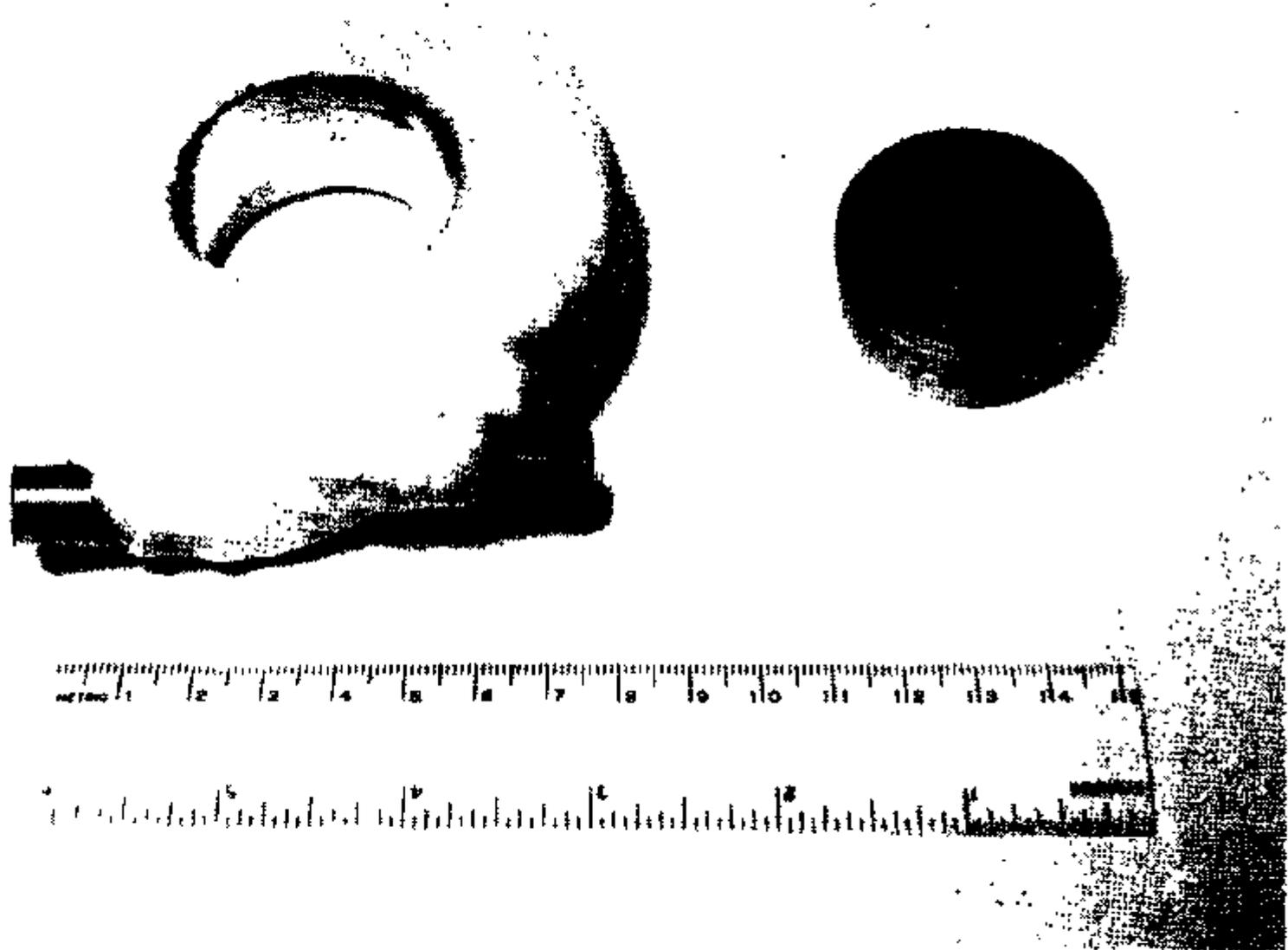


FIGURE 2 - Artificial heart pump heat exchanger and heat source.

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Table 2

CHARACTERISTICS OF HEAT SOURCES FOR ARTIFICIAL HEART PUMP

General Information

Number of Sources Fabricated to Date - - - - - 3*

<u>Fuel Data</u>	<u>15-W Heat Source</u>	<u>25-W Heat Source</u>
Fuel Form	Plutonium Metal ^b	Plutonium Metal ^b
Thermal Power per Source (W)	15(+2-0)	25(+0-2)
Fuel Weight per Source (g, nominal)	26.6	44.4
Fuel Volume per Source (cc, nominal)	2.1	3.6

Capsule Data

	<u>Inner Capsule</u>	<u>Outer Capsule</u>
Material	Tantalum	Haynes alloy No. 25
Overall Height (in., nominal)	0.35	0.58
Overall Diameter (in., nominal)	1.426	1.610
Wall Thickness (in., nominal)	0.030	0.090
Cap Thickness (in., nominal)	0.020	0.110
Internal Volume (cc, nominal)	7.2	--
Welding	TIG	EB

*Two delivered to TEECO, one (15 W) retained at Mound Laboratory

^b See Table 1 for isotopic composition

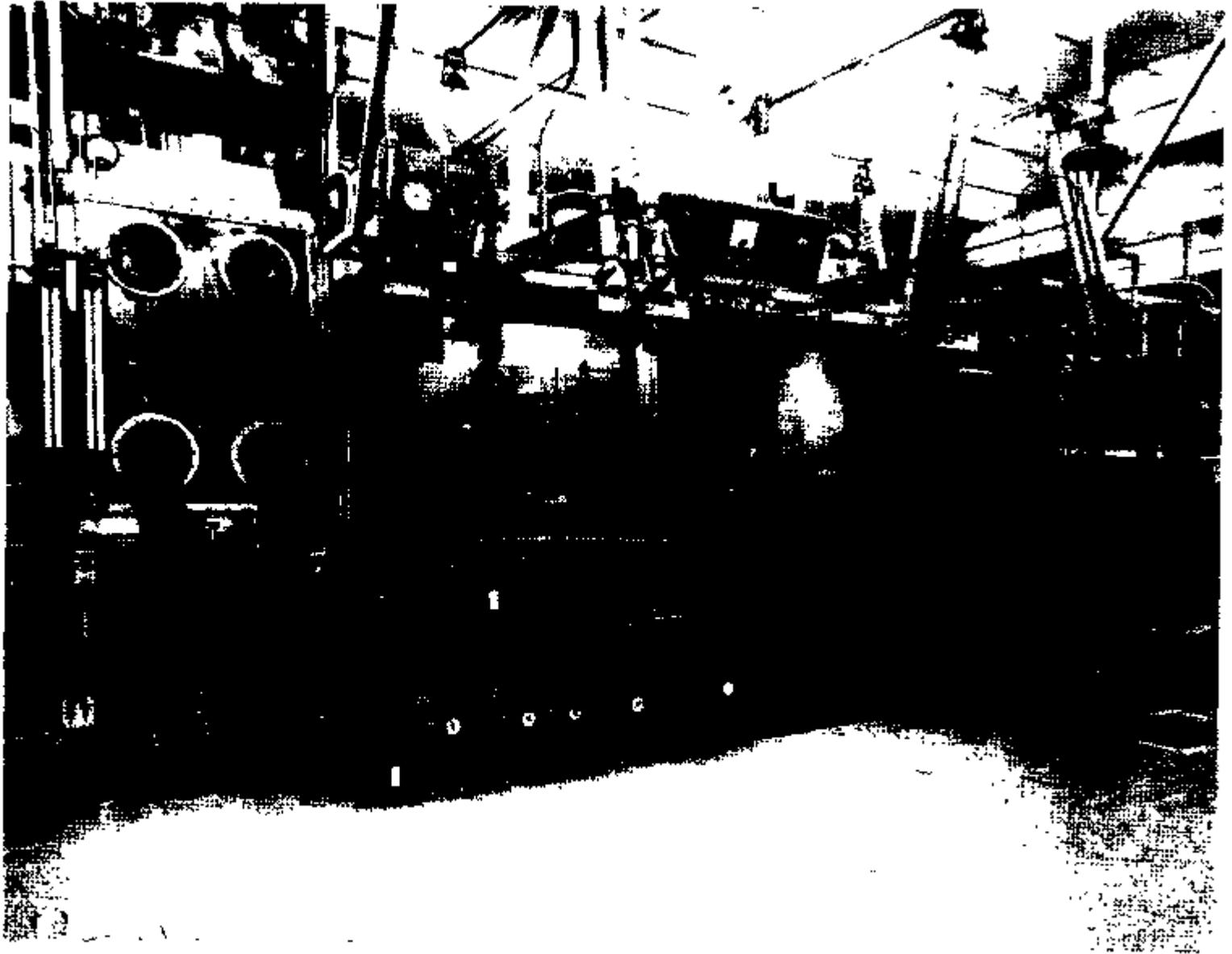


FIGURE 3 - Plutonium-238 metal production facility at Mound Laboratory.

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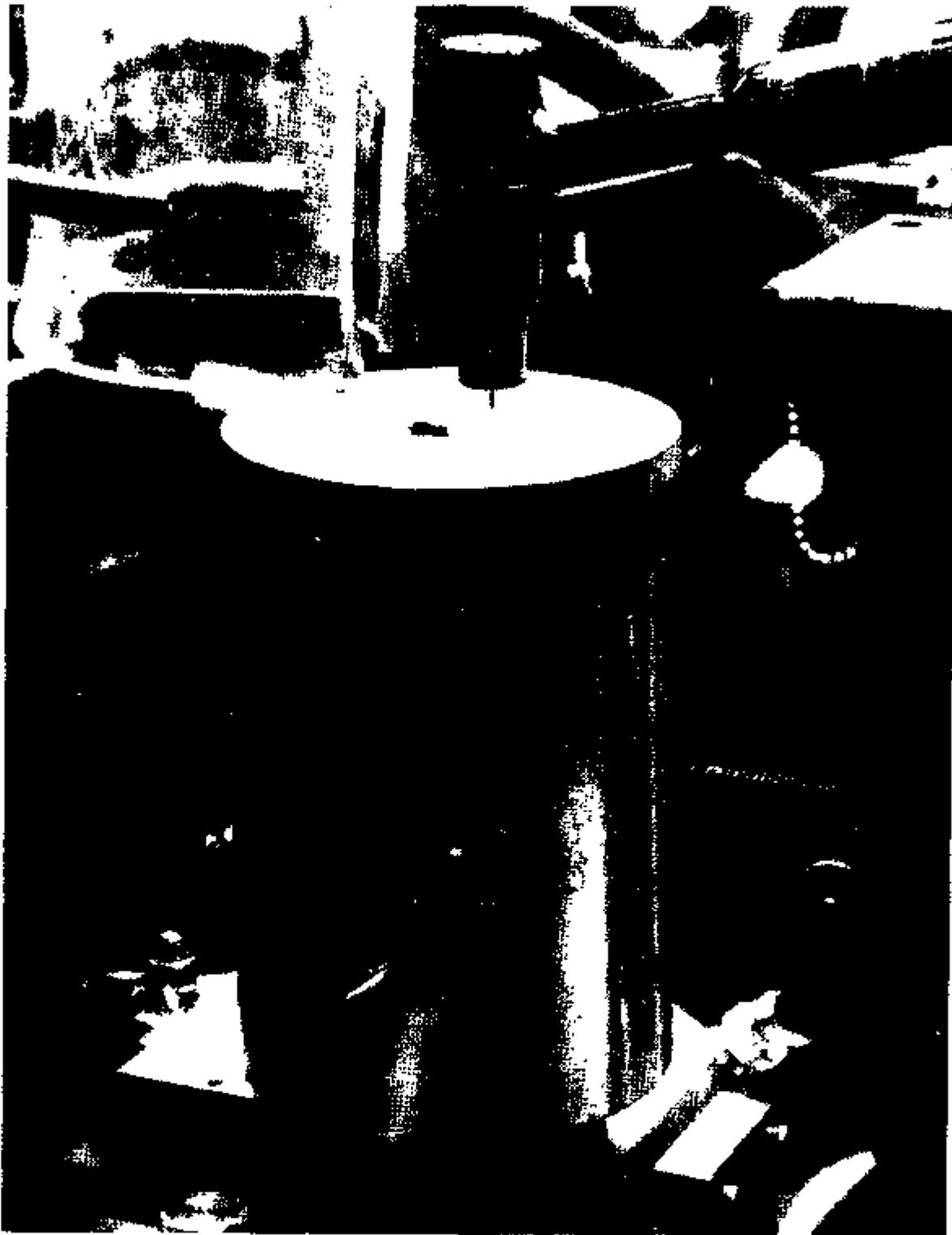


FIGURE 4 - Typical TIG welding facility at Mound Laboratory.

Table 3

CHEMICAL ANALYSIS OF CAPSULE COMPONENTS

Element	Tantalum (inner capsule)		Element	Haynes alloy No. 25 (outer capsule)	
	Specified (wt %)	Analysis (ppm)		Specified (wt %)	Analysis (wt %)
Fe	*	10	Cr	19-21	19.5
Si	*	5	Ni	9-11	10.2
Mo	*	5	W	14-16	14.7
Nb	*	10	Fe	3 (max.)	2.76
Al	*	<0.5	Si	1 (max.)	0.03
Ta	99.9	Balance	Co	Balance	Balance

*No individual impurity shall exceed 800 ppm.

visually inspected, and helium leak tested (see Section III.C). The inner capsule was then inserted into an outer capsule and a closure lid was welded in place using an EB (electron beam) welder. The EB welding facility which was used is shown in Figure 5. The fabricated heat source was decontaminated if necessary, visually inspected, helium leak checked, calorimetered, and radiographed. Radiation characteristics were determined for the heat source and several physical tests were also conducted (see Section III.C).

In addition to fabricating the three fueled heat sources, two test capsules were fabricated for use in free drop and percussion tests (see Section III.C). Lead was placed in both capsules before they were welded. The capsule for the free drop test contained a weight of lead equivalent to that of the plutonium metal present in the 25-W heat source; the capsule for the percussion test contained a volume of lead equivalent to that of the plutonium metal in the 25-W heat source. Both test capsules were welded using the weld parameters previously established.

In addition to the welding associated with the fabrication of the heat sources and test capsules, one example weld was performed prior to and after fabricating the heat sources. Details on the metallographic examination of these welds are presented in the next section.



FIGURE 5 - EB welding facility at Mound Laboratory.

C. TESTS AND EVALUATIONS

No formal quality control for the fabrication of the heat sources was required because of the desired program schedule. However, several tests were performed relating to the fabrication, and details are given in the following sections.

1. Helium Leak Checking A VEECO MS-9 mass spectrometer leak detector was used to measure the leak rate of both the fueled inner and outer capsules. These capsules were first pressurized with helium at 300 psig (20 atm) for 30 min and the pressure was then released. The capsules were placed under vacuum in a chamber monitored by a leak detector which previously had been calibrated with a standard leak. The results indicated that the capsules had a leak rate less than the sensitivity of the detector (5.8×10^{-9} standard cc of helium/sec).

2. Metallography Dummy capsules were welded using the same weld parameters employed in fabricating the heat sources. These capsules were cut open just below the lid to include some of the capsule wall. The weld area was cross-sectioned along a diameter, mounted, polished, and etched to bring out the weld profile. Photographs of the typical weld profile of the inner and outer capsules are shown in Figures 6 and 7, respectively.

3. Radiography The heat sources were radiographed to detect fabrication defects (if any) and to determine the integrity of the capsule welds. An iridium-192 source was used to produce the required gamma radiation; Figure 8 illustrates the radiographic equipment employed. The radiographs showed complete weld integrity and no visible defects for any of the heat sources. A typical radiograph is shown in Figure 9.

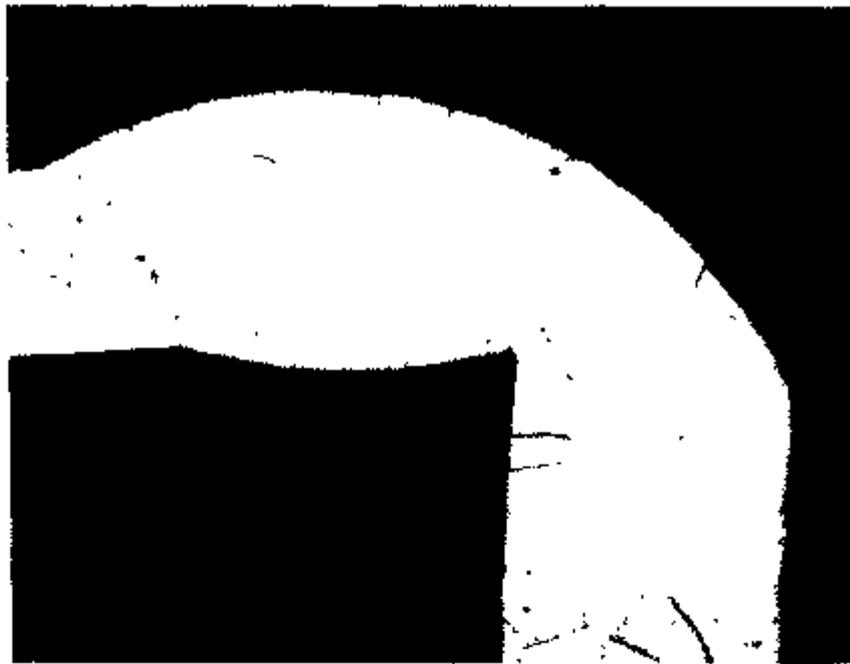
4. Calorimetry The thermal power of each completed heat source was determined by standard calorimetric methods. The results are given in Table 4.

Table 4

THERMAL POWER OF HEAT SOURCES FOR ARTIFICIAL HEART PUMP

<u>Heat Source Identity</u>	<u>Power*</u> <u>[W (th)]</u>	<u>Date Measured</u>
15-1	16.126	5-6-67
15-2	15.835	5-8-67
25	24.038	5-5-67

*95% confidence level.



Right
Half



Left
Half

FIGURE 6 - Typical weld profile of inner capsule.

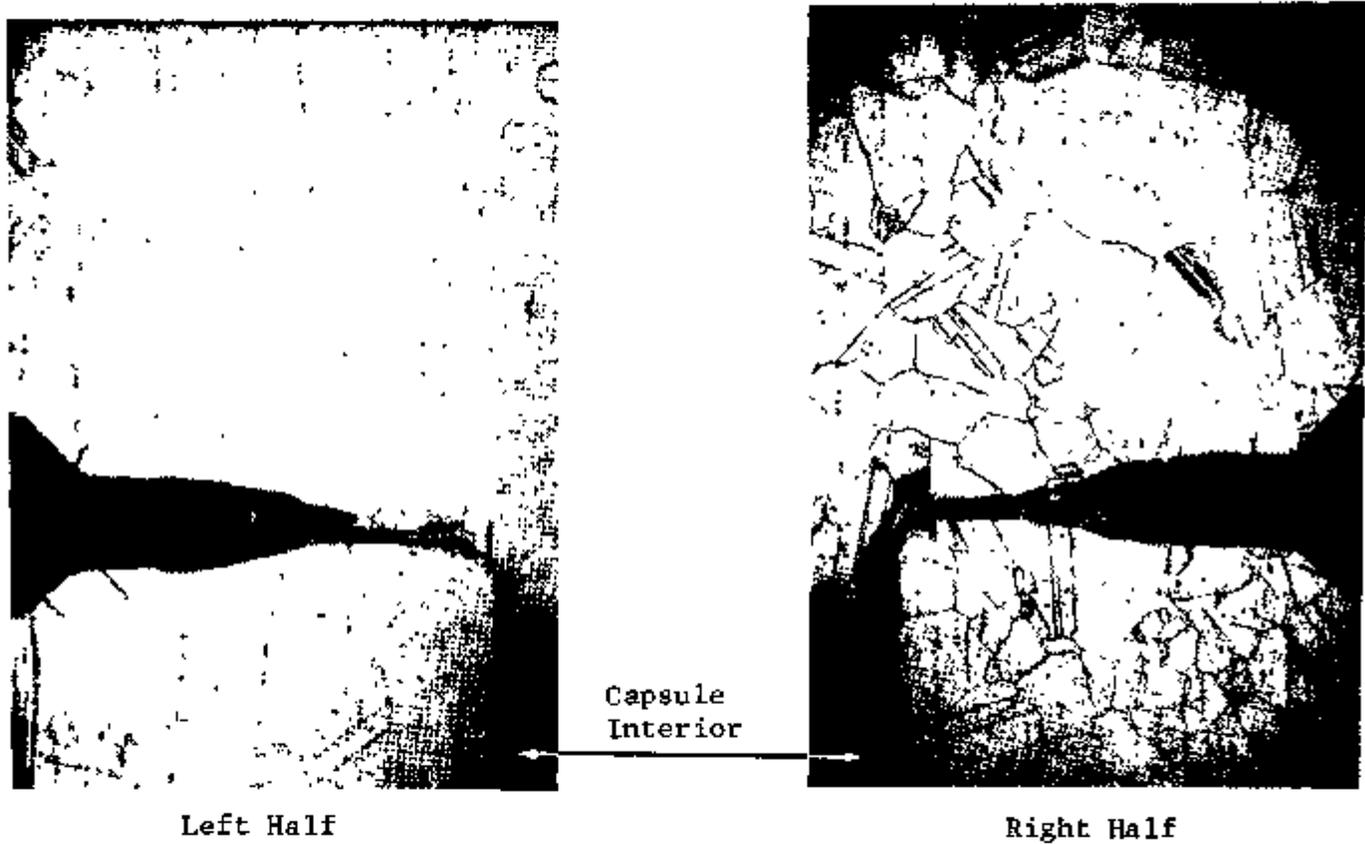


FIGURE 7 - Typical weld profile of outer capsule.
(magnification 30X)

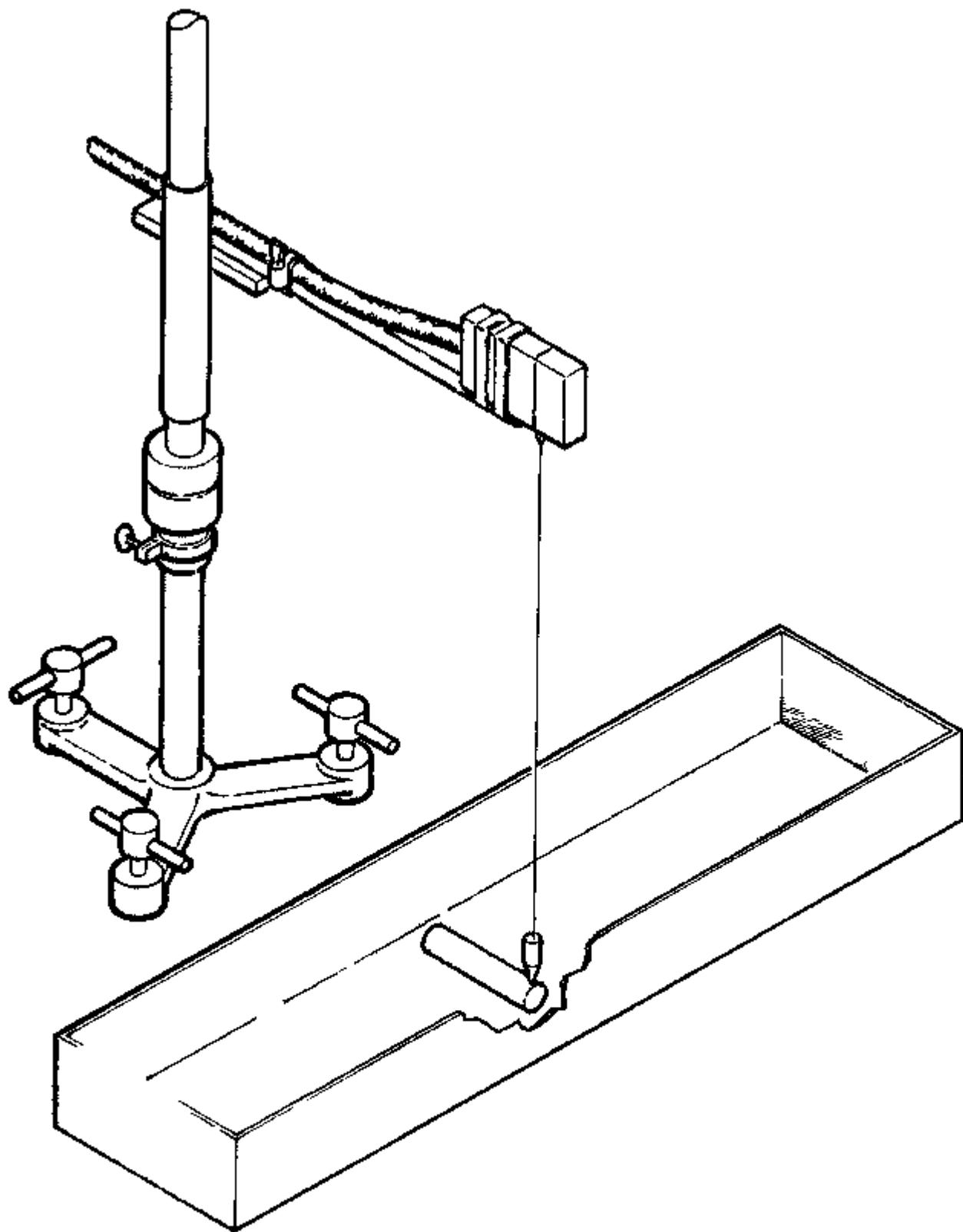


FIGURE 8 - Iridium-192 radiographic facility at Mound Laboratory.

5. Physical Testing The following tests, as defined in Title 10, Code of Federal Regulation (CFR), Part 71, Packaging of Radioactive Materials for Transport, Appendix D (July 22, 1966), were performed on the fueled heat sources or test capsules to determine whether the encapsulation satisfied the safety requirements for Special Form Licensed Material.

Free Drop A test capsule (see Section III-B) was dropped 30 ft (9.15 m) onto a flat concrete surface, where it struck on its top edge. The post test appearance, as shown in Figure 10, revealed only a few shallow nicks on the top edge. The capsule integrity was checked by pressurizing the capsule with helium at 300 psig (20 atm) for 30 min. The pressure was then released and the capsule was placed in a helium leak detector vacuum chamber. No leaks were detected within the sensitivity limits of the detector (8×10^{-9} standard cc of helium/sec.).

Percussion A steel rod, 1.0 in. (2.54 cm) in diameter and weighing 3 lb (1.4 kg), was dropped 40.0 in. (101.6 cm) onto the top surface of a second test capsule (see Section III-B). This capsule was placed on a 0.250 in. (0.635 cm) thick sheet of lead which was in turn placed on a flat concrete surface. The test capsule was subjected twice to the percussion test and essentially no degradation was incurred. Two shallow depressions were on the capsule where it had been struck by the rod; however, the maximum depth of the depressions was only 0.0011 in. (0.0028 cm). Figure 11 shows the post-test appearance of the capsule. A helium leak test on the capsule indicated no leakage within the sensitivity limits specified above.

Heating and Water Immersion For these tests, the two artificial heart pump heat sources scheduled to be sent to Boston City Hospital were used. These sources were first placed in a muffle furnace having an air atmosphere and were then heated to 1475°F (802°C) for 10 min. During the test, the heat sources acquired a thin amber-colored oxidation film but sustained no significant degradation.

The two sources were allowed to cool and then were immersed in water at room temperature for 24 hr. Following this treatment, the heat sources were again radiographed. The visual examination and radiographs indicated no loss of integrity for either heat source. The radiographs also showed that the plutonium metal essentially covered the entire circular cross-sectional area of the inner capsule.

Radiation Characteristics The total neutron emission rate, neutron dose rate, gamma dose rate, neutron spectrum, and gamma spectrum data were obtained for the Artificial Heart Pump heat sources. These radiation data are discussed in Appendix C.

After completion of the tests and evaluations described above, heat sources 15-1 and 25 were shipped to Boston City Hospital on June 30, 1967, and September 18, 1967, respectively.

15-1

15-2

25



FIGURE 9 - Typical radiograph of heat sources for the artificial heart pump.



FIGURE 10 - Capsule after free drop test.

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FIGURE 11 - Capsule after percussion test.

IV. OUTLOOK FOR THE ARTIFICIAL HEART PUMP HEAT SOURCE

A. IMPLANTATION OF ARTIFICIAL HEART PUMP HEAT SOURCES AT BOSTON CITY HOSPITAL

The three artificial heart pump heat sources fabricated at Mound Laboratory satisfactorily passed the various tests described in Section III.C. However, additional radiation testing was performed at Boston City Hospital prior to implanting heat sources 15-1 and 25. The results of these tests were favorable and indicated that implantation could proceed. Successful implants in dogs were made - the 15-W source on September 26, 1967, and the 25 W source on May 8, 1968 - and both dogs were surviving and healthy as of December 1, 1968. The animals are being monitored for physiological effects which could be attributed to the radioisotope heat sources. Since only preliminary evaluations have been made of the monitored data obtained to date, it is not yet possible to state if additional heat source implantations will be required in this study of the effects of additional endogenous heat.

B. RECOMMENDATIONS

The 15-W heat source being retained at Mound Laboratory should be visually examined on a periodic basis and also should be tested for possible temperature degradation. The latter test should be conducted for at least one month at a temperature corresponding to that of the implanted heat source. Radiographic examination of the heat source before and after the test should be used to determine if any degradation occurred.

V. REFERENCES

1. F. D. Lonadier and J. S. Griffo, Ind. Eng. Chem., Process Design Develop., 3, 336 (1964).
2. S. G. Abrahamson, D. G. Carfagno, and B. R. Kokenge, Plutonium-238 Isotopic Fuel Form Data Sheets, MLM-1564 (October 31, 1968).

VI. ACKNOWLEDGMENT

The Artificial Heart Pump (Additional Endogenous Heat) Program at Mound Laboratory required extensive team effort and the use of many disciplines. The authors of this report wish to acknowledge all contributions made to the Program by their associates in Nuclear Operations, and particularly by those in the Production, Technology, and Quality & Reliability Departments. Appreciation is likewise extended to the gaging section, and various engineering groups at Mound Laboratory - also to the Atomic Energy Commission, Dayton Area Office - for their assistance.

VII. APPENDICES

APPENDIX A

INTERFACE DOCUMENT FOR ARTIFICIAL HEART PUMP (ADDITIONAL ENDOGENOUS HEAT) PROGRAM

I. General

A. Scope - This document provides the general description of the heat source responsibilities of the Thermo Electron Engineering Corporation, under contract PH 43-66-982 to the National Heart Institute, and responsibilities of Mound Laboratory (Monsanto Research Corporation) under contract to the Atomic Energy Commission through the Albuquerque Operations Office and under the program guidance of the Division of Isotopes Development, in accomplishing the program to study additional endogenous heat.

B. Classification - This program is unclassified with the following exceptions:

1. Fuel form production technology is Confidential, Restricted Data.
2. Capsule fabrication methods are Confidential, Restricted Data.
3. Any program or technique to improve the isotopic heat source (capsule) is Confidential, Restricted Data.

C. Communications

1. Technical communications from Mound and TEECO will be through N. E. Davis, Mound Laboratory, Miamisburg, Ohio, and R. J. Harvey, TEECO, Waltham, Massachusetts.
2. Copies of all correspondence will be furnished to:
 - a. E. E. Fowler, Division of Isotopes Development, USAEC
 - b. Dr. F. Hastings, National Heart Institute, NIH, HEW
 - c. E. A. Walker, Dayton Area Office, USAEC

d. W. E. Scoville, Albuquerque Operations Office, USAEC

3. Program scope modifications are subject to the approval of the sponsoring agency and inquiries will be directed to that agency with an information copy to the other agency.

<u>D. Reports Distribution</u>	<u>No. of Copies</u>
E. E. Fowler, Division of Isotopes Development	3
E. A. Walker, Dayton Area Office	1
W. E. Scoville, Albuquerque Operations Office	1
Dr. F. Hastings, National Heart Institute	2
N. E. Davis, Mound Laboratory	2
R. J. Harvey, Thermo Electron Engineering Corp.	2

II. Mound Laboratory Responsibilities

- A. Mound will design and fabricate a 25-W (th) and a 15-W (th) plutonium-238 fueled heat source in accordance with the specifications to be furnished by TEECO. Each unit will consist of a fuel pellet, corrosion barrier, and containment capsule.
- B. Mound will perform tests on the capsule to assure that welding techniques are of sufficient quality to produce uniform, repeatable joints.
- C. Mound will supply the necessary shipping container for transporting the capsules from Mound Laboratory to City Hospital, Boston, Massachusetts. A description of the shipping container will be furnished to TEECO by Mound.
- D. Mound will perform at least the following tests on the encapsulated heat sources and furnish the results of such tests to TEECO:
 1. Measure the thermal power output prior to shipping and upon return from City Hospital.
 2. Determine the neutron and gamma dose rates at the surface of the heat exchanger.
 3. Perform capsule assurance tests in accordance with Appendix D, Part 71, Packaging of Radioactive Materials for Transport, Rules and Regulations - Title 10 - Atomic Energy, dated July 27, 1966.
- E. Mound will supply the following data and information to TEECO:
 1. Illustrations of the final form, fit, and shape of the capsule.

2. Specifications on the outer capsule material.
3. Technical information to substantiate the adequacy of the capsules to support the license application for receiving these sources.

F. Mound will use its best efforts to deliver the sources by May 1, 1967.

G. Mound will prepare a monthly status letter covering the program. The status letter will discuss each assigned task. It will be available by the tenth of the month following the report period. Distribution will be as indicated in Part I.D.

III. Thermo Electron Corporation Responsibilities

A. TEECO will furnish to Mound the specifications for the capsules to be designed and fabricated by Mound.

B. TEECO will return the isotope heat sources and shipping containers to the AEC at Mound Laboratory, Miamisburg, Ohio, no later than November 1967, unless extended by mutual agreement of the AEC and NHI. It is understood that the capsules can be recalled at any time due to higher priority requirements or safety considerations.

C. TEECO will obtain all licenses required by applicable law and implementing regulations, including those of the AEC, with respect to activities contemplated under this program.

D. TEECO will provide a heat exchanger to Mound to be used in conjunction with the radiation measurements. The heat exchanger will be made available no later than seven weeks prior to source delivery.

E. TEECO will furnish all reports related to, or resulting in whole or in part from, the use of the isotope heat sources including but not necessarily limited to details of heat exchanger design, test procedure, and results of animal tests, to the Division of Isotopes Development, USAEC.

F. TEECO will furnish informal monthly status reports to the distribution indicated in Part I.D. TEECO is responsible for meeting minutes and trip reports which are to be included in these monthly reports after concurrence from Mound.

APPENDIX B

HEAT SOURCE RADIATION CHARACTERISTICS

Because of the end use of the artificial heart pump heat sources, the radiation characteristics of these sources are extremely important. The following properties were determined for the two heat sources to be implanted:

1. Neutron energy spectrum (for bare source)
2. Total neutron emission rate (for bare source)
3. Neutron dose equivalent rate (for bare source and for source in the heat exchanger)
4. Gamma dose equivalent rate (for bare source and for source in the heat exchanger)
5. Gamma energy spectrum (for bare source)

A. NEUTRON SPECTRA

The neutron energy spectrum was obtained using a stilbene crystal, fast neutron spectrometer. The detector was positioned on the source axis for these measurements. No spectrum measurements were made at other locations relative to the source because variations in the spectrum as a function of location would be insignificant. No spectrum measurements were made with the source in the heat exchanger since the presence of the latter would alter the spectrum only very slightly. The results of these energy measurements for both sources are shown in semi-logarithmic plots in Figures 1 and 2.

For each source, about 70% or more of the neutrons result from spontaneous fission of plutonium-238. The rest of the neutrons are from (α, n) reactions with impurities having low atomic numbers. Above about 5 MeV most if not all of the spectrum is due to spontaneous fission neutrons. The data for energies greater than 5 MeV have been fitted to a Maxwellian distribution, and the particular curve has then been extended into the low MeV region. The Maxwellian distribution is shown in Figures 1 and 2 as a solid line

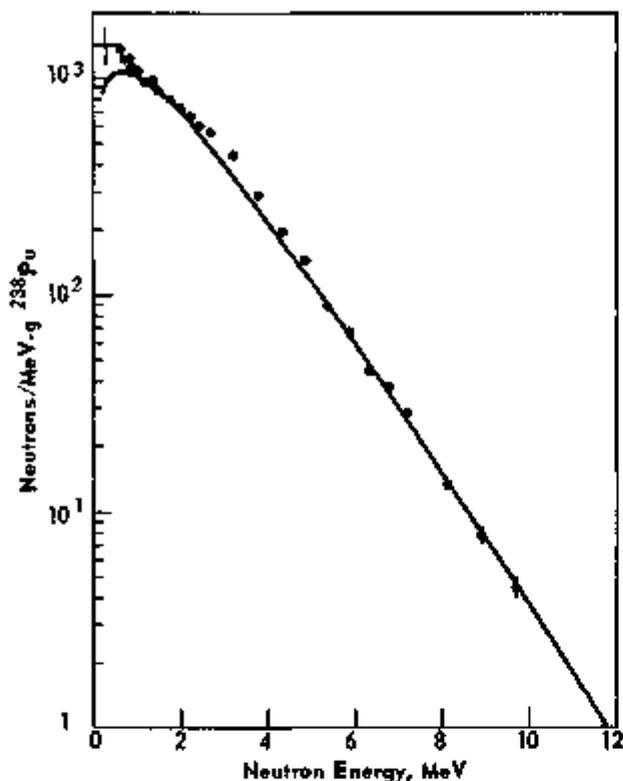


FIGURE 1 - Neutron energy spectrum for heat source 15-1.

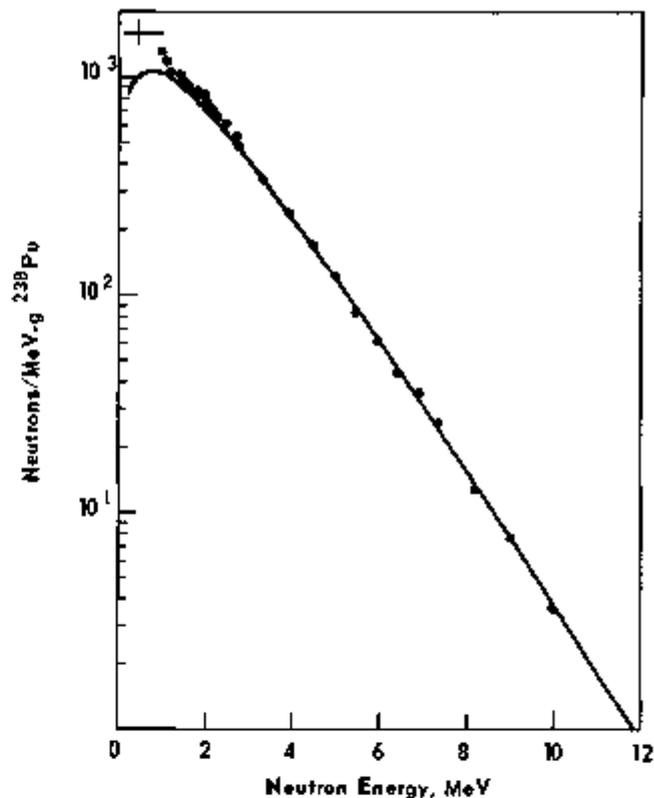


FIGURE 2 - Neutron energy spectrum for heat source 25.

and it represents approximately the spontaneous fission portion of each spectrum. The difference between the solid line and the measured spectrum is due to neutrons from (α, n) impurities. The lefthand data point in each measured spectrum was obtained by a difference calculation using data from two different detectors. The total neutron flux (all energies) incident on the crystal was determined from measurements with a long counter. The flux above the lower limit of detection for the spectrometer was obtained from the stilbene data. The difference between these two measurements is then this lefthand data point.

The relatively large uncertainty for this point results from taking the difference between two numbers of approximately the same size. The error bars for all of the other data points represent \pm one standard deviation and were calculated from counting statistics only. Where no error bar is shown, it is smaller than the printed data point. The two spectra have the same general features. However, there are small differences between the spectra; the differences were expected since the two sources have slightly different specific neutron yields.

B. TOTAL NEUTRON EMISSION RATE

The total neutron emission rates of these sources were determined with the use of a long counter and a $^{239}\text{PuBe}(\alpha, n)$ standard source calibrated at the National Bureau of Standards. A geometric integration

was done for each source to account for the anisotropy of emission. A correction was made to account for the difference between the long counter response to these heat sources and to the standard source. Another correction was made to take into account the change of yield with time for the standard since the calibration at the National Bureau of Standards (this change was due to the ingrowth of americium-241 from the decay of plutonium-241 present in the standard source). The total neutron emission rates for each source on May 18, 1967, were:

Source 15-1 1.02×10^6 n/sec $\pm 5\%$

Source 25 1.60×10^6 n/sec $\pm 5\%$

The $\pm 5\%$ is an estimate of the absolute uncertainty. The specific yield of source 15-1 was 3.58×10^3 n/sec/g of plutonium-238 and for source 25 it was 3.76×10^3 n/sec/g. The neutron flux anisotropy $E(\theta)$ (defined as the ratio of the flux at a given angle relative to the source axis of symmetry to the average of the spatially integrated flux) was measured for several angles and these results are summarized in Table 1.

Table I

ANISOTROPY FACTORS FOR NEUTRON FLUX CALCULATIONS

Anisotropy Factor E (θ)

θ Value	For Heat Source 15-1		For Heat Source 25	
	Without Heat Exchanger	With Heat Exchanger	Without Heat Exchanger	With Heat Exchanger
0°	1.10	1.23	1.19	1.27
90°	0.89	0.69	0.88	0.70
180°	1.14	1.26	1.21	1.29
270°	0.89	0.83	0.88	0.83

C. NEUTRON DOSE RATE

A factor for converting from the neutron fluence to the dose equivalent for heat sources 15-1 and 25 was obtained by using the neutron spectra and the recommended maximum permissible exposure to neutrons of different energies as given in Table 2 of the National Bureau of Standards Handbook 63. The factor so obtained for heat source 15-1 was $(3.16 \pm 0.16) \times 10^{-5}$ mrem/n/cm² and for heat source 25 it was $(3.11 \pm 0.13) \times 10^{-5}$ mrem/n/cm².

The neutron dose equivalent rate was calculated at several points on the source axis of symmetry by using the following equation which assumes a planar neutron source:

$$DE = \frac{QC}{2\pi R^2} \left[A \ln \frac{\sqrt{R^2 + H^2}}{H} + B \left(1 - \frac{H}{\sqrt{R^2 + H^2}} \right) \right] \quad (1)$$

where

DE = the neutron dose equivalent rate,

R = the radius of the plutonium volume,

H = the distance from the midplane of the plutonium volume,

Q = the total neutron emission rate of the source,

C = the factor given above for converting from fluence to dose,
and

A and B = constants.

To obtain the above equation, the following approximate relationship was used for the anisotropy factor:

$$E(\theta) = A + B |\cos \theta| \quad (2)$$

The assumption was made in Equation (1) that all scattering takes place within the plutonium volume, even if it may actually have occurred within the source container or the heat exchanger. The effect of this assumption should be slight and, if anything, may make the calculated values slightly high.

The dose at the curved side surface of the heat exchanger was calculated at two reference positions (90° and 270°). These calculations used the actual source dimensions, but the results obtained were within 2% of the result obtained when a point source is assumed. Because it is much simpler, the following expression was used for the neutron dose equivalent rate from a point source.

$$DE = \frac{QE(\theta) C}{4\pi H^2} \quad (3)$$

In the latter case, H is the distance between the axis of symmetry and the edge of the heat exchanger and is 4.3 cm. The other factors are as defined above.

Table 2 is a summary of the calculated neutron dose equivalent rates for both sources using the previously mentioned equations. The uncertainty for all values, except for the case of contact with a surface of the source, is estimated to be about $\pm 20\%$. The uncertainty for those calculations at a source surface is approximately $\pm 40\%$.

Table 2

CALCULATED ABSORBED NEUTRON DOSE RATE
(mrem/hr)

<u>Location</u>	<u>Heat Source 15-1</u>		<u>Heat Source 25</u>	
	<u>Without Heat Exchanger</u>	<u>With Heat Exchanger</u>	<u>Without Heat Exchanger</u>	<u>With Heat Exchanger</u>
On top surface, $\theta = 0^\circ$	420	440	710	740
On bottom surface, $\theta = 180^\circ$	850	870	1320	1330
On axis, 3 cm from top of surface	55	61	94	100
On axis, 10 cm from top of surface	8	9	14	14
On axis, 100 cm from top of source	0.10	0.11	0.16	0.17
On surface of heat exchanger at $\theta = 90^\circ$		37		59
On surface of heat exchanger at $\theta = 270^\circ$		44		70

D. GAMMA EQUIVALENT MEASUREMENTS

Gamma dose equivalent rate measurements were conducted for heat sources 15-1 and 25 using several sizes of Condenser-R meters. The sources and detectors were held approximately 4 ft (1.2 m) from the floor and 6 ft (1.8 m) from the closest wall by an aluminum rod framework. The measured values were plotted as a function of distance from the center of the plutonium fuel. Each curve was then extrapolated to the surface of the source. This extrapolation was made by using the theoretical variation of dose equivalent rate as a function of distance along the source axis. This relationship is shown in Figure 3 for a thin disc source having a radius of 1.73 cm. Figures 4 and 5 show gamma dose equivalent measurements and extrapolations to the surface of the source using the theoretical curve. Measurements, using gamma dosimetry film and Condenser-R meters, were made on heat source 15-2 in order to check the agreement with the

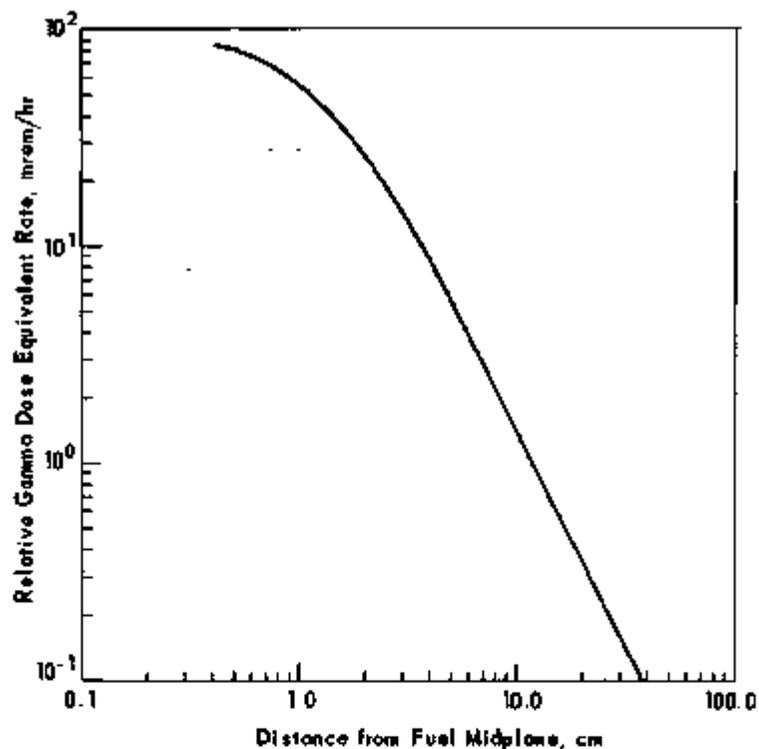


FIGURE 3 - Variation of gamma dose equivalent rate as a function of distance along the heat source axis.

theoretical curves at distances close to the source. These measurements and the theoretical curve agree with each other to within at least 1 cm of the fuel center. The gamma dose equivalent rate at the side of each source was obtained by extrapolation from the measured values assuming the dose varied inversely as the square of the distance. Figures 6 and 7 show the dose measurements at the side of the sources.

Table 3 presents the gamma dose equivalent values for each source. The values at the surface of the source have an estimated uncertainty of about $\pm 40\%$, while the uncertainty for all other values is approximately $\pm 20\%$. The large uncertainty at the surface of the heat source is due mainly to the uncertainty in the extrapolation from the measured values.

E. GAMMA SPECTRA MEASUREMENTS

Gamma spectra measurements were made on heat sources 15-1 and 25 using a NaI(Tl) scintillation detector 3 in. in diameter by 3 in. in height. Each source was mounted with its flat surfaces parallel to the incident face of the detector. The distance from source to detector was adjusted to produce about 10% or less dead time in the pulse height analyzer. The spectra were measured in two energy ranges. One range covered approximately 0 to 900 keV and the other 0.2 to 2.7 MeV. Results for heat source 25 are shown in Figures 8 and 9. The gamma spectrum for heat source 15-1 was quite similar to that for 25; therefore, only the latter spectrum has been included.

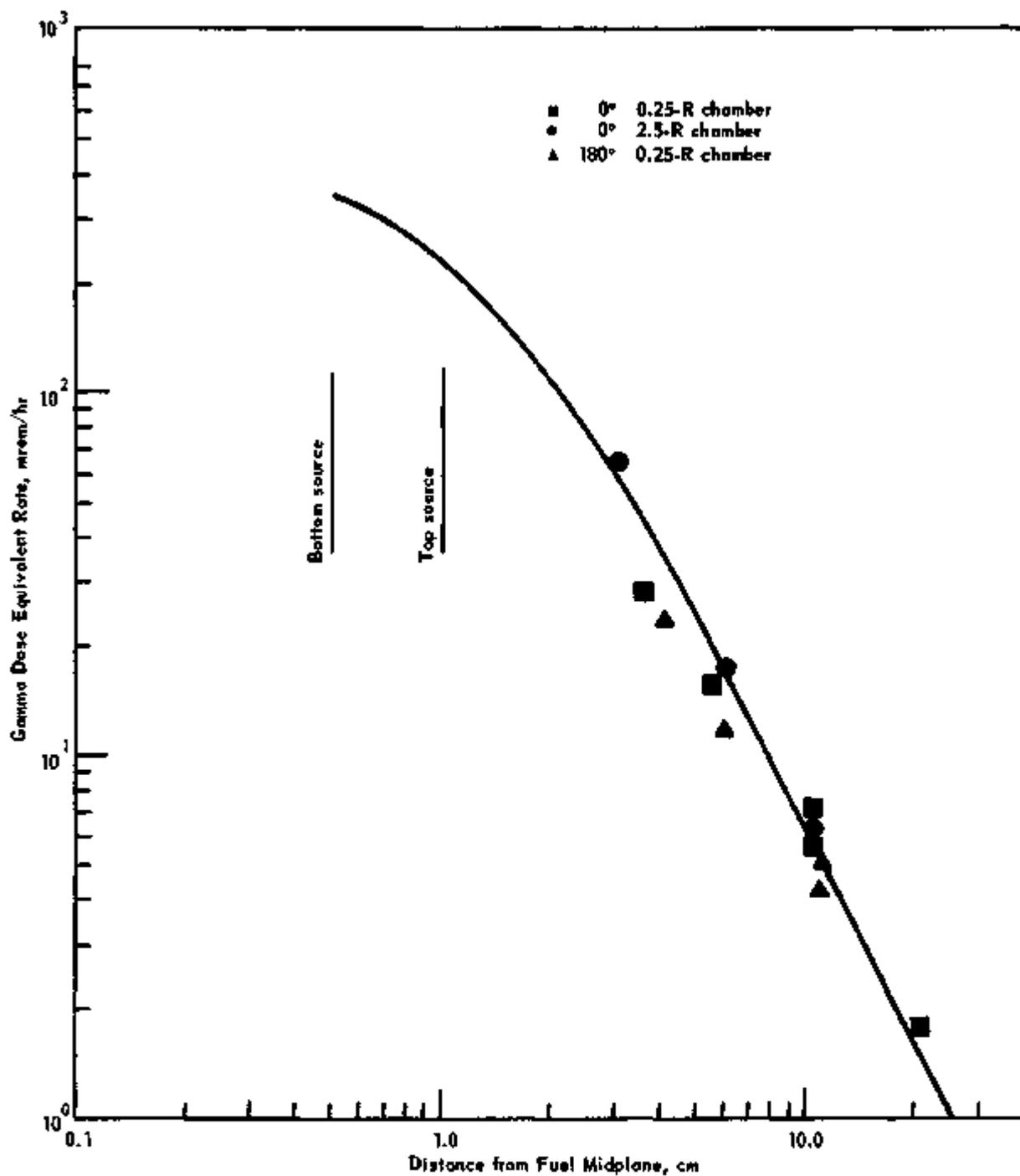


FIGURE 4 - Measured gamma dose equivalent rate as a function of distance along the axis of heat source 15-1.

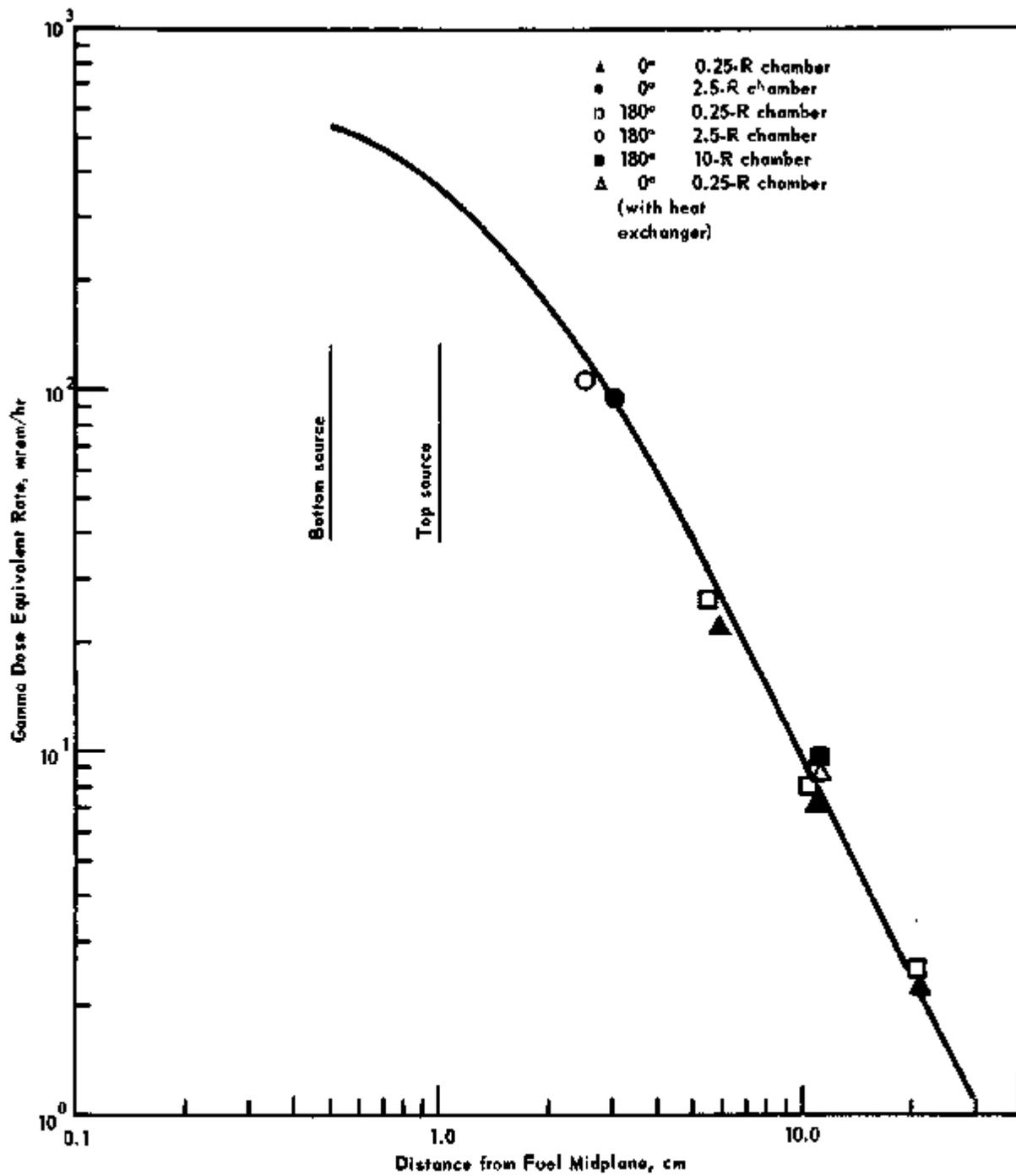


Figure 5 - Measured gamma dose equivalent rate as a function of distance along the axis of heat source 25.

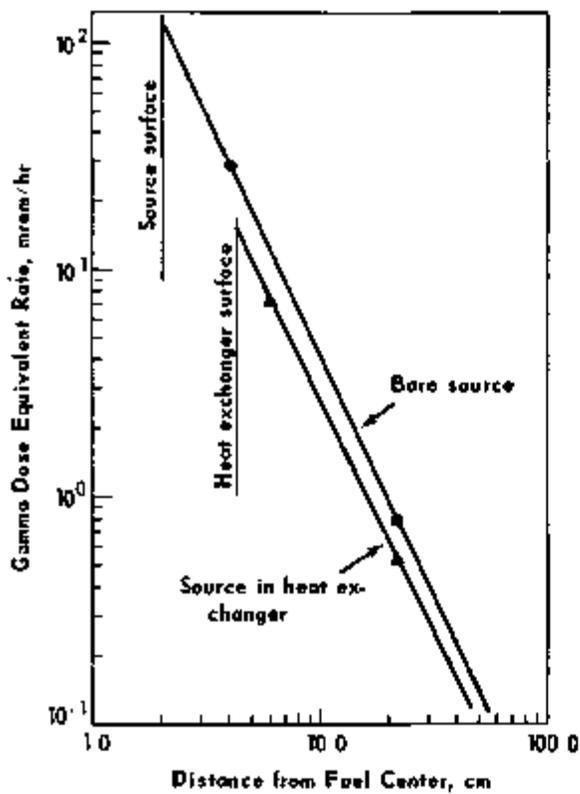


FIGURE 6 - Measured gamma dose equivalent rate at the side of heat source 15-1 and heat exchanger.

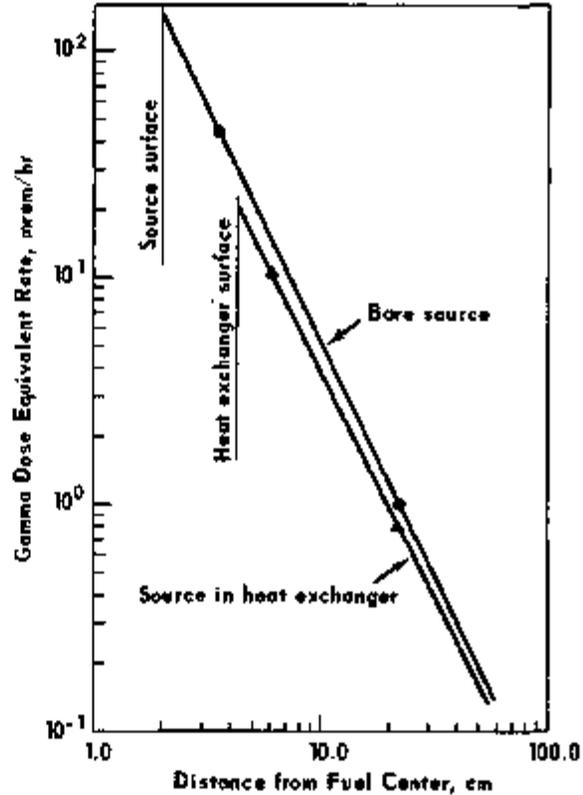


FIGURE 7 - Measured gamma dose equivalent rate at the side of heat source 25 and heat exchanger.

Energy
(keV)

70
100
153
203
336
767
2614

Probable Origin

^{238}Pu
 ^{238}Pu
 ^{238}Pu
 ^{238}Pu
 ^{237}U
 ^{238}Pu
 ^{208}Tl

The gamma rays seen in the spectra are typical of those found in NaI(Tl) spectra of plutonium-238 metal sources measured previously.

Table 3

GAMMA DOSE MEASUREMENTS AND CALCULATIONS
(mrem/hr)

<u>Location</u>	<u>Heat Source 15-1</u>		<u>Heat Source 25</u>	
	<u>Without Heat Exchanger</u>	<u>With Heat Exchanger</u>	<u>Without Heat Exchanger</u>	<u>With Heat Exchanger</u>
<u>At Surface</u>				
Top	230	235	360	365
Bottom	355	360	550	560
Side	135	14 ^a	145	19.5 ^a
<u>10 cm from Surface</u>				
Top	5.1	-	8.5	-
Bottom	5.6	-	9.2	-
Side	2.8	1.3 ^a	3.4	1.8 ^a

^a Reference point is surface of heat exchanger.

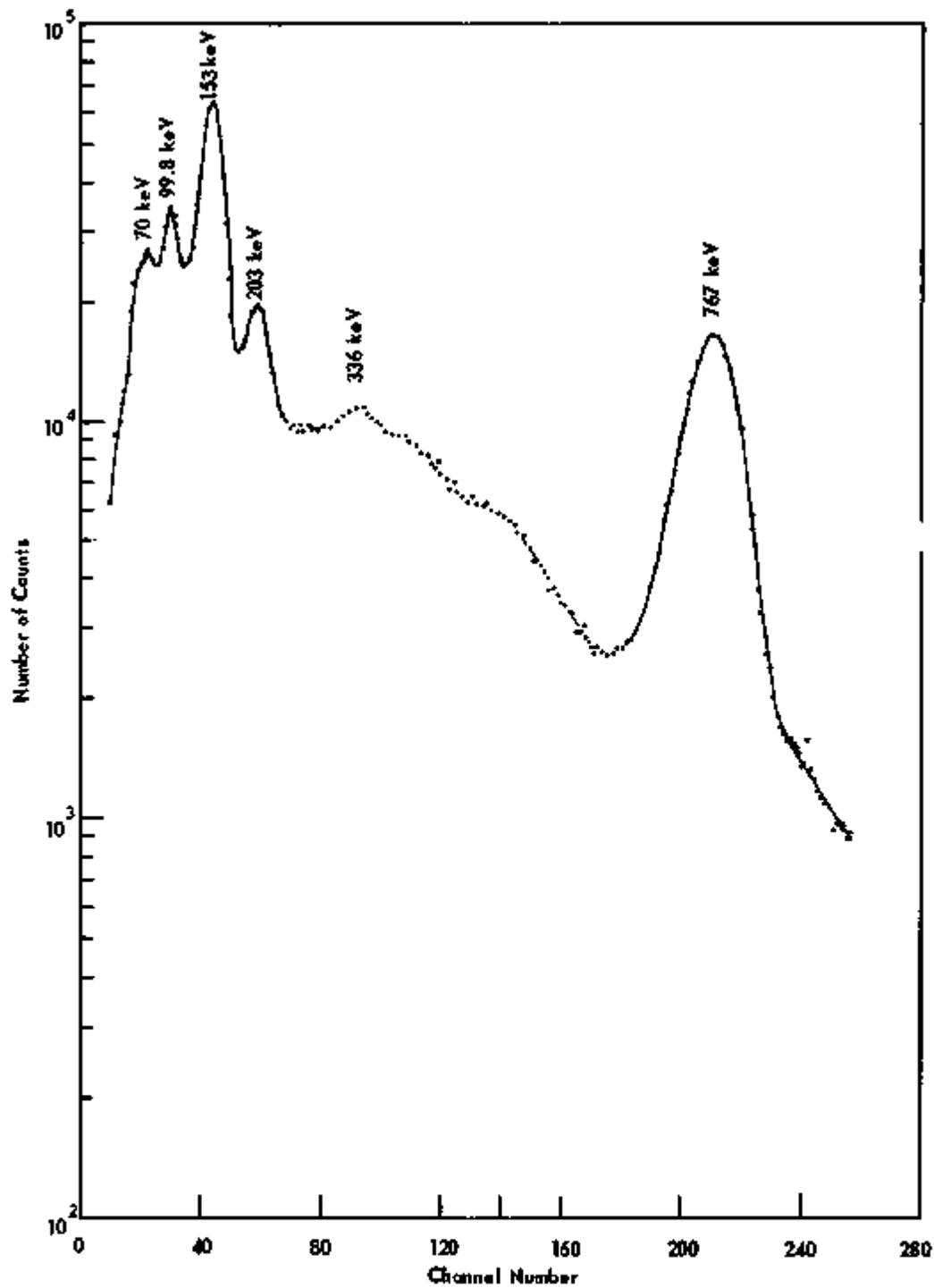


FIGURE 8 - Gamma energy spectrum for the heat source 25.
(0-0.9 MeV range)

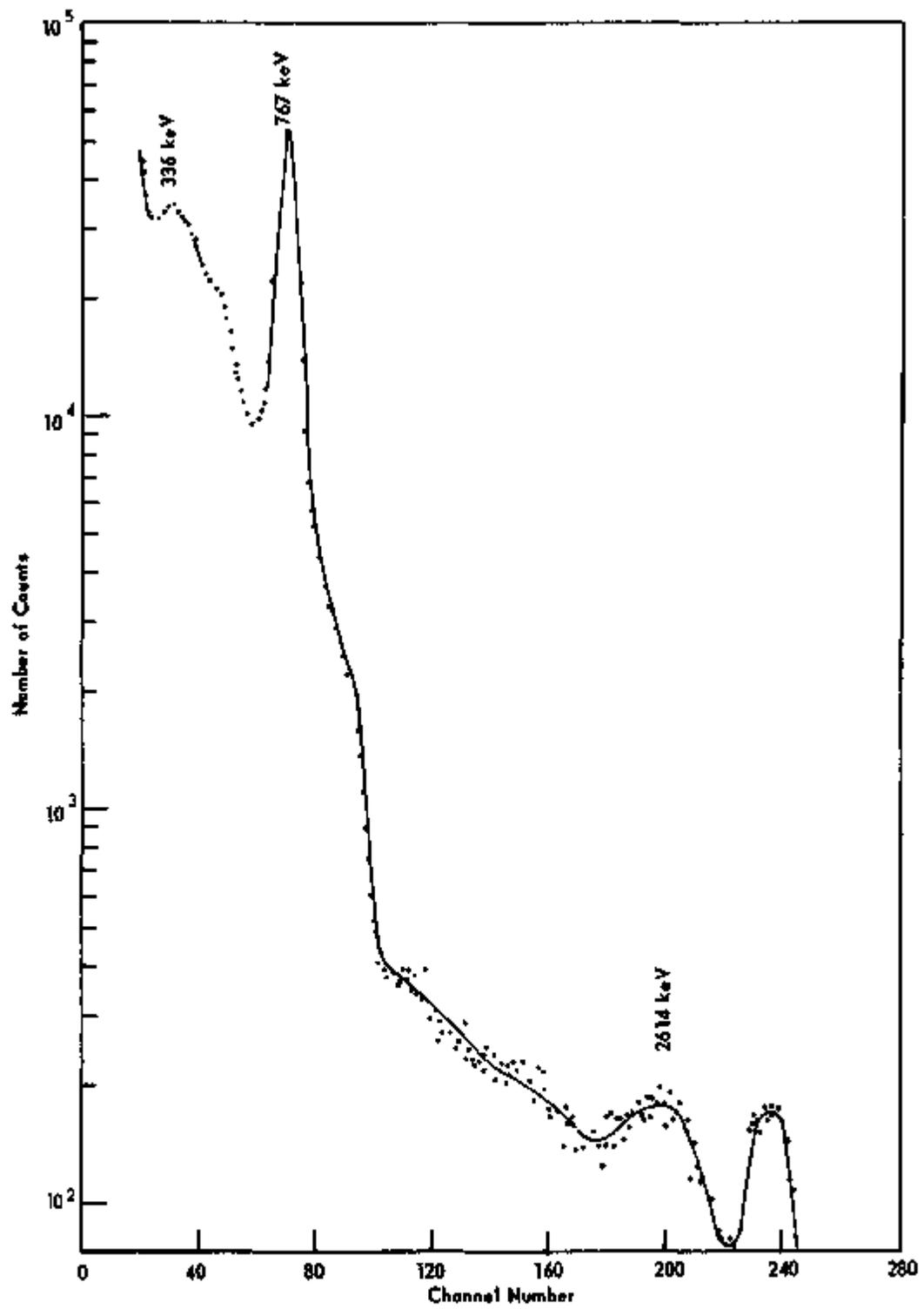


FIGURE 9 - Gamma energy spectrum for the heat source 25.
(0.2-2.7 MeV range)