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NOVEMBER 1, 1962

PRE-OPERATIONAL REPORT OF
A BEARING COMPONENT
MATERIAL IRRADIATION TEST

(Title Unclassified)

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Astronuclear Laboratory
Westinghouse Electric Corporation

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PRE-OPERATIONAL REPORT OF
A BEARING COMPONENT
MATERIAL IRRADIATION TEST

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ABSTRACT

A series of dry lubricant bearing materials will be irradiation tested in the GETR. The preparation of this test is discussed in the body of this report.

SUMMARY

A series of solid lubricants of WSe₂, Cu and Teflon; WSe₂, Ag and Teflon; MoSe₂, Ag and Teflon; WSe₂, Bronze and Poly-imide; MoSe₂, Bronze and Poly-imide; WSe₂, Bronze and Poly-imide;; 404C Stainless Steel and MoSe₂ were developed at the Westinghouse Research Laboratory.¹ These dry solid lubricants have an application in the control drum bearing of the NERVA reactor control system. In order to determine the behavior of these lubricants in a radiation field, and therefore select the best material for this application, a screening test has been designed using the shuttle tube irradiation facility in the GETR. The fabrication of capsules that provide a hydrogen atmosphere and an evacuated atmosphere for these types of solid lubricants were designed and fabricated. The design of these capsules and a description of the fabrication along with the parameters of the irradiation tests are discussed.

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1. INTRODUCTION

The NERVA reactor has an application for a high torque small displacement ball bearing in the control drum actuator system. The lubrication of this control drum bearing in a high radiation field is a problem area. A series of experiments designed to screen dry lubricant bearing materials for this application has been designed. As a result of these screening tests, it is planned that in the future one of the materials will be selected for this application; and a bearing cage of this material will be fabricated, installed in a control drum bearing and operated in a dynamic test at an irradiation facility.

2. DESCRIPTION

The descriptions of the various dry lubricant bearing materials are included in Table I. An activation analysis and resultant shielding requirements are included in Appendix I. One capsule containing specimens of each material has an internal environment of hydrogen at atmospheric pressure. One capsule containing specimens of each material has an internal vacuum of approximately 10^{-6} TORR. The individual low pressures are dependent on the outgassing of individual specimens and are specified in Table II which includes data on pre-irradiation testing. The design of the capsule fabricated for the purpose of irradiation of these specimens is detailed in Figure 1.

3. TEST AND FACILITY CONDITIONS

It is desired that the ball bearing material be tested in a simulated environment of one hour full power operation of the NERVA reactor. To this end, the test environment includes a fast neutron flux of 1.9×10^{13} n/cm²sec which is the available flux at the GETR and an integrated fast flux of 5.4×10^{18} nvt which is based on the calculated flux at the control drum bearing. The facilities at the GETR for accomplishing this shuttle tube capsule irradiation are described in the literature. The requirements for the capsule itself were determined by GETR specifications of a standard capsule design SPEC PV 231543 supplied by General Electric Company. The capsule itself was designed to be inserted in a stagnant water tube of 100° F allowing an internal temperature in the specimens of less than 550° F.

4. SPECIMEN AND CAPSULE PREPARATION

The specimens were hand polished in alcohol in order that the composition of the specimens would not be influenced by the preparation. A series of photomicrographs were made indicating the structure of the materials before irradiation. These photomicrographs (Figures 2 through 7) are representative of the structure

TABLE I
DESCRIPTION OF TEST MATERIAL

CAPSULES	SPECIMEN MATERIALS	NUMBER OF SPECIMENS PER CAPSULE	AVERAGE WEIGHT OF ONE SPECIMEN (GRAMS)
A-1, A-2	3:1 WSe ₂ - 60 Cu By Vol: 60% Cu 30% Teflon 10% WSe ₂	3	23.5
A-3, A-4	2:1 WSe ₂ - 70 Ag By Vol: 70% Ag 20% Teflon 10% WSe ₂	1	29.7
A-5, A-6	3:1 MoSe ₂ - 70 Ag By Vol: 70% Ag 22.5% Teflon 7.5% MoSe ₂	1	28.3
B-1, B-2	2:1 WSe ₂ - 40 Bronze By Vol: 40% Bronze 40% Poly-imide 20% WSe ₂	3	19.9
B-3, B-4	2:1 MoSe ₂ - 40 Bronze By Vol: 40% Bronze 40% Poly-imide 20% MoSe ₂	3	18.9
B-5, B-6	2:1 WSe ₂ - 60 Bronze By Vol: 60% Bronze 26.7% Poly-imide 13.3% WSe ₂	3	22.8
C-1, C-2	440C Stainless Steel MoSe ₂ Coating on Ends 5000 Angstroms Thick	2	24.3

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TABLE II

PRE-IRRADIATION TEST DATA

CAPSULE NUMBER	SPECIMEN NUMBER	ENVIRONMENT	WEIGHT GMS.	DIAMETER INS.	LENGTH INS.	HARDNESS	DENSITY GM/CC
A-1	A-1-1	Hydrogen	23.5584	0.6262	0.6998	R _h - 67	6.91
	A-1-2	@ 14.7 PSIA	23.5438	0.6262	0.6991	R _h - 72	6.91
	A-1-3		23.3532	0.6263	0.6995	R _h - 62	6.85
A-2	A-2-1	Vacuum	23.6194	0.6263	0.700	R _h - 68	6.92
	A-2-2	2.4 x 10 ⁻⁶	23.3808	0.6263	0.6988	R _h - 66	6.86
	A-2-3	TORR	23.4099	0.6263	0.7003	R _h - 72	6.86
A-3	A-3-1	H ₂ @ 14.7 PSIA	29.7712	0.6261	0.6984	R _l - 84	8.75
A-4	A-4-1	Vac, 1.6 x 10 ⁻⁶ TORR	29.6828	0.626	0.6997	R _l - 84	8.71
A-5	A-5-1	H ₂ @ 14.7 PSIA	28.1183	0.6263	0.6997	R _l - 74	8.24
A-6	A-6-1	Vac, 1.4 x 10 ⁻⁶ TORR	28.4299	0.6264	0.6999	R _l - 84	8.33
B-1	B-1-1	Hydrogen @	18.2261	0.6269	0.6989	R _h - 85	5.34
	B-1-2	14.7 PSIA	17.6968	0.6264	0.6985	R _h - 86	5.19
	B-1-3		18.1711	0.6271	0.6986	R _h - 92	5.32
B-2	B-2-1	Vacuum	19.9839	0.6266	0.6985	R _h - 87	5.86
	B-2-2	2.2 x 10 ⁻⁶	20.0648	0.6266	0.6996	R _h - 85	5.88
	B-2-3	TORR	19.8727	0.6265	0.6991	R _h - 83	5.83
B-3	B-3-1	Hydrogen	18.1583	0.6270	0.6995	R _h - 89	5.31
	B-3-2	@ 14.7 PSIA	17.9512	0.6268	0.6993	R _h - 84	5.26
	B-3-3		18.1297	0.6271	0.6994	R _h - 89	5.31
B-4	B-4-1*	Vacuum	19.5465	0.6268	0.6998	R _l - 95	5.72
	B-4-2	5.2 x 10 ⁻⁷	19.8085	0.6266	0.6987	R _h - 80	5.81
	B-4-3*	TORR	19.6966	0.6266	0.6998	R _l - 98	5.77
B-5	B-5-1	Hydrogen	23.2299	0.6269	0.6997	R _h - 97	6.80
	B-5-2	@ 14.7 PSIA	22.7679	0.6266	0.6999	R _h - 97	6.67
	B-5-3		22.7898	0.6266	0.6999	R _h - 98	6.67
B-6	B-6-1	Vacuum	23.1527	0.6268	0.6999	R _h - 95	6.78
	B-6-2	4.0 x 10 ⁻⁷	22.7601	0.6268	0.6998	R _h - 92	6.66
	B-6-3	TORR	22.9226	0.6266	0.6999	R _h - 91	6.71
C-1	C-1-1	Hydrogen @	24.3961	0.6243	0.6324	R _c - 56	7.97
	C-1-2	14.7 PSIA	24.3461	0.6242	0.6309	R _c - 56	7.96
C-2	C-2-1	Vacuum	24.3694	0.6243	0.6314	R _c - 56	7.96
	C-2-2	9.5 x 10 ⁻⁶ TORR	24.3408	0.6242	0.6308	R _c - 56	7.96

*Samples chipped on first hardness impression.

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MATERIAL: CAPSULE ALUMINUM 1100-0
 TUBING AL - 1100-0 .3125 O.D.
 .050 WALL THICKNESS
 COPPER FOIL - .010 THICKNESS
 WELDING: HELI - ARC

SPX-M-1 BEARING COMPONENT TEST CAPSULE

Sample A-1-1
3:1 WSe₂ - 60 Cu
Teflon (dark material)

Figure 2

12X mag.

Sample A-3-1
2:1 WSe₂ - 70 Ag
Teflon (dark material)

Figure 3

12X mag.

Sample A-5-1
3:1 MoSe₂ - 70 Ag
Teflon (dark material)

Figure 4

12X mag.

Sample B-1-1
2:1 WSe₂ - 40 Bronze
Poly-imide (dark material)

Figure 5

12X mag.

Sample B-3-1
2:1 MoSe₂ - 40 Bronze
Poly-imide (dark material)

Figure 6

12X mag.

Sample B-6-3
2:1 WSe₂ - 60 Bronze
Poly-imide (dark material)

Figure 7

12X mag.

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of the materials to be irradiated. No photomicrographs of the four stainless steel specimens were taken. Hardness measurements were made on all specimens, and these measurements are included in the pre-irradiation test data. The specimens were then rolled in a copper sheet designed to provide a thermal conducting medium between the specimen and the capsule (shown in Figure 8) in order that the allowable internal temperature of the specimen will not be exceeded. The heat transfer calculations are included in Appendix II. The problems involved in providing a vacuum inside the capsule necessitated an aluminum 1100 to copper to kovar seal to glass connection so that a connection to the vacuum system could be made, and the internal pressures could be monitored on a test capsule. These vacuum transition joints are shown in Figure 9. A test capsule has been monitored at the Westinghouse Research Laboratory and has successfully maintained an internal pressure of 1.7×10^{-8} TORR.

5. FABRICATION, TESTING AND SEALING OF CAPSULES

A. FABRICATION

1. The original design of the test capsule required that 6061 AL be used throughout fabrication. The reason that this grade of aluminum was chosen was its availability in tubing sizes applicable to the capsule design, even though a choice could be made between 6061 and 1100 Aluminum as stated in GETR specifications. During development of the capsule design, two problems were encountered which prohibited the use of 6061 AL. The first was its inability to provide a leak tight seal during the pinchoff, and the second difficulty was the poor welding characteristics as compared to the 1100 AL. The body of the capsule was machined from solid bar stock as no tubing of this series of aluminum was available without a special order.
2. The capsules were Heli-arc welded with argon used as the inert gas. The transition tube was first welded to the top end cap and then this assembly welded to the capsule body. The specimens were then inserted and the bottom plug welded. The capsule was cooled for the final weld to prevent overheating of the specimens. After each weld, the joint was helium leak checked with a VEECO Mass Spectrometer Helium Leak Detector with a sensitivity of one part helium to 10^7 parts air. Each component was evacuated to 9×10^{-6} mm/hg and sprayed with helium. The same model leak detector MS-9A was used throughout fabrication to determine capsule integrity.

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Figure 8
Bearing Capsule Assembly

Figure 9

Vacuum Transition Joint

B. TESTING

1. A test capsule was fabricated with the same dimensions as a service capsule, but the bottom plug was replaced with a transition joint for determining the integrity of the pinchoff.
 - a. The transition joint (Figure 9) was a device which was used for connection to the high vacuum system; and in the case of the test capsule, it was utilized also for connection to a high vacuum Bayard-Alpert ion gauge. It consisted of leak-tight transitions from 1100 Aluminum to copper to a kovar seal to glass.
 - b. The test capsule was welded, leak checked and installed on a vacuum system. The capsule was baked-out at 450° while evacuating. At a pressure of 1×10^{-8} mm/hg, the aluminum was pinched off approximately $7/8$ inch from the capsule end. The vacuum gauge at the other end was then observed for vacuum loss. After 24 days, no rise in pressure has been noted.
 - (1) The pinchoff device is a mechanical apparatus used successfully for sealing of copper evacuation lines on experimental electronic tubes. Its adaptability to aluminum was proven by repetitious sealing off and leak testing various grades of aluminum.

C. SEALING

1. After final assembly and leak test the service capsules will be either evacuated or filled with hydrogen and sealed. A protective sleeve will be installed over the protruding pinchoff tip maintaining an overall length of 4 inches.
 - a. Capsules A-2, A-4, A-6, B-2, B-4, B-6 and C-2 will be installed in the vacuum system and evacuated while baking out at 450° F. At 10^{-6} mm/hg or lower the capsule will be sealed.
 - b. Capsules A-1, A-3, A-5, B-1, B-3, B-5 and C-1 will be evacuated to 10^{-5} mm/hg and backfilled with hydrogen at 14.7 PSIA and sealed.
 - c. The protective sleeve is an aluminum split collar held in position over the protruding tip by aluminum rivets.

D. CAPSULE ENVIRONMENT

The vacuum system used for evacuation of the capsule is an all glass system utilizing a mercury diffusion pump and liquid nitrogen cold trap.

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After installation on the vacuum system, the capsules were baked out at 450° F for about four hours and forty minutes while evacuating. The total evacuation time was approximately 18 hours. The bake-out time and temperature were limited by the specimens and the AL-Cu transition joint.

The hydrogen filled capsules were not fitted with the glass transition but were evacuated on a general duty vacuum system with provisions for back filling with hydrogen.

The pinchoff device previously described was used on both the evacuated and the filled capsules. The device exerts an external pressure on the tube forming a cold welded seal.

The planned pressure for the evacuated capsules was 1×10^{-8} TORR. This pressure was attained in the test capsule which was an empty cylinder of the same design as the service capsules except that it had a vacuum gauge at one end. The pressure in the seven service capsules at time of pinchoff had a range of 9.5×10^{-6} to 5.2×10^{-7} TORR. The vacuum obtainable in any particular capsule was limited by the outgassing characteristics of the composition tested.

6. PRE-IRRADIATION EXAMINATION

Pre-irradiation examinations of the capsules were conducted, and a checklist provided by General Electric Company was followed in guaranteeing that the capsules meet all of the conditions necessary for the shuttle tube of the GETR. The sum total of all pre-irradiation examinations for Westinghouse requirements on the specimens are included in Table 2. Friction wear characteristics of these dry lubricant component composites are included in the literature.¹

7. POST-IRRADIATION TESTING

All of the pre-irradiation testing will be duplicated after irradiation plus other tests. This will include gas chromatography, specimen removal, weights, visual examination and photography, metallographic study, dimensional survey, hardness testing and a friction wear test.

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2. Letter of L. O. Richs to N. Bifano, WANL-TMI-166 ()

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APPENDIX I
ACTIVATION ANALYSIS
AND
SHIELDING REQUIREMENTS

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1. ACTIVATION ANALYSIS AND SHIELDING REQUIREMENTS

A. ACTIVATION ANALYSIS

An activation product inventory for each type of capsule after decay times of 0 and 24 hours was calculated, and the results are listed in Table I-1. These calculations were based on the following equation:

$$A = \frac{N\phi f (1-e^{-\lambda t_1}) (e^{-\lambda t_2})}{3.7 \times 10^{10}}$$

where

ϕ = Neutron flux (n/cm²sec)

A = Activity of specimen in curies

N = Number of atoms of target nuclide in specimen

σ = Activation cross section (Barns)

f = Fractional isotopic abundance of target nuclide

λ = Decay constant of the nuclide

t_1 = Irradiation time

t_2 = Decay time

1. CONDITIONS OF CALCULATIONS

The following assumptions were made in calculating activation product inventories:

a. Primary constituents of specimens contained no impurities.

b. Neutron flux are uniform throughout specimen.

c. Irradiation conditions:

Thermal neutron flux = 10^{14} n/cm²sec

Fast neutron flux = 1.9×10^{13} n/cm²sec

Irradiation time = 79 hours

d. Activation of hydrocarbon materials in specimens was neglected. Pure beta emitting isotopes were also neglected.

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*Flux attenuation of 0.1 was assumed
which is an approximation to the
self-attenuation of the specimen.

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TABLE I-1

ACTIVATION PRODUCTS INVENTORY OF SPECIMENS (CURIES/CAPSULE)

Isotope	WSe ₂ - 60 Cu		WSe ₂ - 60 Bronze		WSe ₂ - 40 Bronze		MoSe ₂ - 40 Bronze		WSe ₂ - 70 Ag*		MoSe ₂ - 70 Ag*		440C SS	
	t ₂ =0hr	t ₂ =24hr	t ₂ =0hr	t ₂ =24 hr	t ₂ =0hr	t ₂ =24 hr	t ₂ =0hr	t ₂ =24 hr	t ₂ =0hr	t ₂ =24hr	t ₂ =0hr	t ₂ =24hr	t ₂ =0hr	t ₂ =24hr
W ¹⁸¹	0.022		0.023		0.037									
W ¹⁸⁵ (1.7m)	29.4		30.2		49.7				0.909					
W ¹⁸⁵ (74d)	0.876	0.81	0.90	0.83	1.48	1.46			0.0276	0.0274				
W ¹⁸⁷	451.	225.5	463.	231.5	760.	380.			12.1	6.05				
Se ⁷⁵	0.045	0.043	0.047	0.045	0.075	0.072	0.0439	0.0437	0.0013	0.0013				
Se ⁸¹ (18m)	24.12		24.87		40.5		18.7		0.705		0.410			
Se ^{83m} (69s)	0.435		0.450		0.732		0.338		0.0127		0.0074			
Cu ⁶⁴	4,350	1,190.	3,890.	1,060.	2,600.	708.	2,600	708.						
Cu ⁶⁶	930.		830.		555.		555.							
Sn ¹¹³			0.022		0.015		0.015							
Sn ¹²³ (40m)			17.4		11.6		11.6							
Sn ¹²⁵ (9.5m)			0.898		0.60		0.60							
Mo ⁹⁹							1.28	1.21			0.0457	0.0356	0.338	0.330
Mo ¹⁰¹							2.07				0.01535		0.062	
Ag ¹⁰⁸ (2.3m)									895.		895.			
Ag ¹¹⁰ (253d)									0.36	0.359	0.36	0.359		
Ag ^{110m} (245)									2,080		2,080.			
Fe ⁵⁸													0.644	0.511
Cr ⁵⁰													7.61	7.42
Cr ⁵⁴													114.	
Mn ⁵⁵													95.	
Si ³⁰														
TOTAL	5,788	1,416	5,260	1,292	4,023	1,089	3,200	709	2,988	6.41	2,976	0.395	217.7	8.26

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Specimens will be wrapped with copper foil 0.010 inches thick by 2 7/8 inches wide to provide copper positioning of the specimens within the aluminum capsule and to satisfy heat transfer requirements. The mass of the copper foil used will be 114 gm, and the mass of the aluminum capsule is 32 gms. Activation products resulting from irradiation of the capsule and foil are as follows:

<u>ISOTOPE</u>	<u>DECAY TIME</u>	
	<u>0 HR</u>	<u>24 HR</u>
Al ²⁸	442 c	
Mg ²⁷	1.05 c	
Na ²⁴	0.212 c	0.070 c
Cu ⁶⁴	8,810 c	2,405 c
Cu ⁶⁶	1,881 c	

B. SHIELDING REQUIREMENTS

The cask illustrated in the attached sketch is an available General Electric cask and is to be utilized as a shipping container for the capsules. The cask cavity is large enough to accommodate fourteen (14) capsules. Shielding calculations were performed to determine the adequacy of the cask as a shipping container.

The preceding activation analysis indicates that the WSe₂ - 60 Cu capsules represent the worst case with respect to shielding requirements; and, therefore, are the only ones considered in the following calculations:

1. CONDITIONS OF CALCULATIONS

The following assumptions were made in calculating the shielding adequacy of the cask:

- Cask contains twelve (12) WSe₂ - 60 Cu capsules that have decayed for 24 hours.
- Activity is uniformly distributed in volume of cask cavity.
- Source of activity is a right cylinder having the same dimensions as the cask cavity.
- Source is isotropic.

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The dose rate from a cylindrical source at point P is given by:

$$\phi = \frac{BSvR_o^2}{2(a+Z)} F(\theta, b_2) \text{ when } \theta_1 = \theta_2 = \theta$$

where

ϕ = Scalar flux ($\text{cm}^{-2}\text{sec}^{-1}$)

B = Dose buildup factor for lead

Sv = Source strength of volume source ($\text{Mev}/\text{cm}^3\text{sec}$)

R_o = Radius of cask cavity (cm)

a = Thickness of lead (cm)

A = Effective self-attenuation distance (cm)

$$F(\theta, b_2) = \int_0^\theta e^{-b \sec \theta'} d\theta'$$

$$b_2 = b_1 + \mu_s Z$$

$$b_1 = \mu_i t_i$$

μ_i = Linear absorption coefficient of lead (cm^{-1})

t_i = Thickness of lead (cm)

μ_s = Linear absorption coefficient of source (cm^{-1})

$$\theta = 29^\circ$$

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Dose rates at the surface of the cask calculated by the above method for the isotopes of concern are listed in Table II-2.

TABLE II-2

<u>ISOTOPE</u>	<u>DOSE RATE (MR/HR)</u>
$^{185}_{74}\text{D}$	1
$^{187}_{75}\text{Se}$	2.4
$^{64}_{24}\text{Cu}$	545.0
$^{24}_{11}\text{Na}$	<u>67.5</u>
TOTAL	615 MR/HR

Based on the assumptions made, the dose rate at the surface of the cask exceeds the permissible limit of 200 mr/hr imposed by applicable shipping regulations. However, because of the considerable margin of conservatism inherent in the assumptions, it is felt that the cask is adequate for shipping the bearing and component test capsules. If necessary, capsules will be retained for further decay until the dose rate at the surface of the cask is within acceptable limits.

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Figure 1-1
SHIPPING CASK

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APPENDIX II

HEAT TRANSFER

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2. HEAT TRANSFER

The following section covers the heat transfer considerations necessary to assure compliance with GETR limitations. The calculations include heat generated by direct gamma radiation (at one watt per gram) and heat generated due to activation in the specimens, supports and capsule.

A. NOMENCLATURE

μ	=	Poisson's ratio
T_1	=	Specimen centerline temp. - $^{\circ}\text{F}$
T_2	=	Specimen surface temp. - $^{\circ}\text{F}$
T_3	=	Support inside temp. - $^{\circ}\text{F}$
T_4	=	Support outside temp. - $^{\circ}\text{F}$
T_5	=	Capsule inside temp. - $^{\circ}\text{F}$
T_6	=	Capsule outside temp. - $^{\circ}\text{F}$ (ambient water temp.)
Q	=	Heat generation rate in specimen - Btu/hr ft ³
$\bar{Q}$	=	Heat generation rate in specimen - Watts/gm
q	=	Heat flux - Btu/hr ft
w	=	Specimen weight - ft.
r_s	=	Radius of specimen - ft.
r_{co}	=	Capsule outside radius - in.
r_{ci}	=	Capsule inside radius - in.
A_s	=	Cross sectional area of specimen - ft ²
k_c	=	Conductivity of copper - Btu/hr ft $^{\circ}\text{F}$
k_s	=	Conductivity of specimen - Btu/hr ft $^{\circ}\text{F}$
k_a	=	Conductivity of aluminum - Btu/hr ft
h_j	=	Coefficient of contact - Btu/hr ft ² $^{\circ}\text{F}$
R_s	=	Thermal resistance of copper foil - hr ft $^{\circ}\text{F}/\text{Btu}$

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E_a = Energy absorbed in sample per disintegration, Mev.

d_s = Diameter of specimen - in.

d_{ci} = Diameter of capsule inside surface - in.

d_{co} = Diameter of capsule outside surface - in.

l_c = Length of capsule - in.

t = Thickness of capsule - in.

l_{cu} = Length of copper supports - in.

R_{ci} = Contact resistance - hr ft $^{\circ}\text{F}/\text{Btu}$

R_{co} = Contact resistance - hr ft $^{\circ}\text{F}/\text{Btu}$

k_{air} = Conductivity of air - Btu/hr $^{\circ}\text{F}$ ft

T_7 = Temperature of cask internal wall - $^{\circ}\text{F}$

S_r = Thermal stress in specimen - PSI

E = Young's modulus

a = Coefficient of linear expansion

A_i = Specimen activity of nuclide i per capsule, curies.

B. HEAT GENERATION DUE TO ACTIVATION

The activities of the nuclides in each sample were obtained from Table II-1. The heat generated in the specimen by each nuclide is calculated as follows:

$$\frac{\text{Heat generated}}{\text{Capsule}} = A_i \times E_a \times 3.7 \times 10^{10} \frac{\text{dps}}{\text{Curie}} \times 1.6 \times 10^{-13} \frac{\text{Watt-sec}}{\text{Mev}} \times 3.413 \text{ Btu/Watt-hr}$$

As a sample calculation for Cu-64 in samples A-1 or A-3,

$$\frac{\text{Heat generated}}{\text{Capsule}} = 4,350 \times 0.341 \times 3.7 \times 10^{10} \times 1.6 \times 10^{-13} \times 3.413 = 30 \text{ Btu/hr}$$

The heat generated by the other nuclides in each specimen was calculated in a similar way, and the results are shown in Table II-2.

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C. HEAT GENERATION DUE TO DIRECT GAMMA HEATING

The heat generation in the specimens, copper foil and aluminum capsule was calculated using the given heating rate of 1 watt per gram, and the total weights of the materials present. For example, for the three WSe₂ - 60 copper specimens:

$$\begin{aligned} \text{Heat gen./capsule} &= 1 \frac{\text{watt}}{\text{gram}} \times 23.5 \frac{\text{grams}}{\text{specimens}} \times 3 \frac{\text{specimens}}{\text{capsule}} \times 3.413 \text{ Btu/Watt hr} \\ &= 240 \text{ Btu/hr} \end{aligned}$$

For the gamma heat generated in the specimens, an attenuation factor of .9 was used to account for gamma attenuation in the capsule, specimens and copper support foil. This factor reduces the heat generated in the specimen due to direct gamma heating to 216 Btu/hr.

D. TEMPERATURES ATTAINED IN SPECIMENS

1. TEMPERATURE DROP IN SPECIMENS

The temperature distribution in the specimen is given by Glasstone,²⁻¹ page 662, as:

$$T - T_2 = \frac{Q}{4k_s} (r_s^2 - r^2) \quad 0 \leq r \leq r_s$$

with the following assumptions:

- a. Both direct gamma and activation heating in the specimen is uniform.
- b. No heat leaves the circular faces of the specimen.

The heat generation rate in the specimen being considered is calculated from the rates listed in Table II-1 as follows:

$$Q = \frac{86.1 + 216}{3\pi r_s^2} = \frac{302.1}{3\pi r_s^2 (.0583)} = \frac{550}{r_s^2} \text{ Btu/hr ft}^3$$

The temperature drop in the specimen is:

$$T_1 - T_2 = \frac{Q r_s^2}{4k_s} = \frac{550}{4k_s}$$

Values of k_s were determined experimentally for specimens A-3 and A-4, B-1 and B-2, and B-5 and B-6.²⁻² k_s was estimated for all other samples.

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TABLE II-1

SPECIMEN HEATING

Sample	Isotope	Maximum Activity,	Energy Deposited,	Maximum Heat Generated,	Direct γ Heating,
		<u>Curies</u> <u>Capsule</u>	<u>Mev</u> <u>Disintegration</u>	Btu/hr	Btu/hr
WSe ₂ -60 Cu					
	W ¹⁸⁵ (1.7m)	29.4	0.10	0.059	
	W ¹⁸⁵ (75d)	0.876	0.43	0.008	
	W ¹⁸⁷	451	0.92	8.4	
	Cu ⁶⁴	4,350	0.341	30.0	
	Cu ⁶⁶	930	2.54	<u>47.6</u>	
			TOTAL	86.1	216
WSe ₂ -60 Bronze					
	W ¹⁸⁵ (1.7m)	30.2	0.10	0.059	
	W ¹⁸⁵ (54d)	0.90	0.43	0.008	
	W ¹⁸⁷	46.3	0.92	8.60	
	Cu ⁶⁴	3,890	0.341	26.8	
	Cu ⁶⁶	830	2.54	42.5	
	Sn ¹²³	17.4	1.38	0.485	
	Sn ¹²⁵	0.898	2.17	<u>0.039</u>	
			TOTAL	78.5	210
WSe ₂ -40 Bronze					
	W ¹⁸⁵ (1.7m)	49.7	0.1	0.100	
	W ¹⁸⁵ (54d)	1.48	0.43	0.013	
	W ¹⁸⁷	760	0.92	13.80	
	Cu ⁶⁴	2600	0.341	17.90	
	Cu ⁶⁶	555	2.54	28.45	
	Sn ¹²³	11.6	1.38	0.323	
	Sn ¹²⁵	0.60	2.17	<u>0.026</u>	
			TOTAL	60.6	183

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TABLL II-1

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HEATING (continued)

Sample	Isotope	Maximum Activity, Curies Capsule	Energy Deposited, Mev Disintegration	Maximum Heat Generated, Btu/hr	Direct γ Heating, Btu/hr
MoSe ₂ -40 Bronze					
	Cu ⁶⁴	2600	0.341	17.9	
	Cu ⁶⁶	555	2.54	28.45	
	Sn ¹²³	11.6	1.38	0.323	
	Sn ¹²⁵	0.60	2.17	0.026	
	Mo ⁹⁹	1.28	1.22	0.032	
	Mo ¹⁰¹	2.07	2.44	0.104	
			TOTAL	46.8	174
WSe ₂ -70 Ag					
	W ¹⁸⁵ (1.7m)	0.909	0.1	0.0018	
	W ¹⁸⁵ (54d)	0.0276	0.43	0.0024	
	W ¹⁸⁷	12.1	0.92	0.224	
	Ag ¹⁰⁸	895	1.72	30.9	
	Ag ^{110m}	0.36	0.64	0.0047	
	Ag ¹¹⁰	2,080	2.59	109.0	
			TOTAL	140.2	91
MoSe ₂ -70 Ag					
	Ag ¹⁰⁸	895	1.72	30.9	
	Ag ^{110m}	0.36	0.64	0.0047	
	Ag ¹¹⁰	2080.	2.59	109.0	
	Mo ⁹⁹	0.0457	1.22	.0011	
	Mo ¹⁰¹	0.01535	2.44	.0007	
			TOTAL	139.9	87
440C SS					
	Fe ⁵⁹	0.644	0.368	0.010	
	Cr ⁵⁵	1.14	2.8	0.129	
	Mn ⁵⁶	95.0	1.97	7.56	
	Mo ⁹⁹	0.338	1.22	0.015	
	Mo ¹⁰⁰	0.062	2.44	0.007	
			TOTAL	7.70	149

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TABLE II-2
ACTIVATION HEAT GENERATED IN CAPSULE

Isotope	Maximum Activity, Curies Capsule	Energy Deposited, Mev Disintegration	Maximum Heat Generated, Btu/hr	Direct Heating, Btu/hr
Cu ⁶⁴	8,810	0.341	60.5	
Cu ⁶⁶	1,881	2.54	96.5	388
Al ²⁸	442	2.96	25.6	
Mg ²⁷	1.05	1.79	Negligible	109
Na ²⁴	0.212	1.39	<u>Negligible</u>	
		TOTAL	182.6	

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For samples A-1 and A-2

$$k_s = 72.3 \text{ Btu/hr/ft } ^\circ\text{F}$$
$$T_1 - T_2 = \frac{550}{4 \times 72.3} = 1.90^\circ\text{F}$$

2. TEMPERATURE DROPS THROUGH CAPSULE AND SUPPORTS:

- a. The temperature drop through the specimen to copper contact is estimated (Mc Adams, P. 17)²⁻³ as follows:

$$R_{ci} = \frac{1}{h_j^2 \pi r_s} = \frac{1}{(1000)^2 (0.02605)} = .00611 \text{ hr } ^\circ\text{F ft/Btu}$$

with h_j estimated to be 1000. The temperature drop through this contact is:

$$T_2 - T_3 = 1730 (.00611) = 10.6^\circ\text{F}$$

since the heat flux is:

$$Q_{A_s} = 2\pi r_s^2 = \frac{302.1}{(3) (.0583)} = 1730 \text{ Btu/hr ft}$$

- b. The thermal resistance of the copper support itself is:

$$R_s = \frac{\ln(\frac{d_{ci}}{d_s})}{2\pi k_{cu}} = \frac{\ln(\frac{.870}{.625})}{2\pi (226)} = .000233 \text{ hr ft } ^\circ\text{F/Btu}$$

The maximum heat flux corresponding to this resistance is:

$$Q_A = \frac{86.1 + 216 + 60.5 + 96.5 + 388}{\frac{2.875}{12}} = 3540 \text{ Btu/hr ft}$$

Thus the temperature drop through the copper foil is:

$$T_3 - T_4 = 3540 (.000233) = 0.82^\circ\text{F}$$

- c. The temperature drop through the copper to capsule contact surface is estimated as follows:

$$R_{co} = \frac{1}{h_j^2 \pi r_{ci}} = \frac{1}{(1000)(2\pi)(.435)} = .00438$$

The temperature drop through this contact is: $T_4 - T_5 = 3540 (.00438) =$

$$15.5^\circ\text{F}$$

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- d. The resistance of the aluminum capsule is:

$$R_c = \frac{\ln\left(\frac{d_{ci}}{d_s}\right)}{2\pi k_{al}} = \frac{\ln\left(\frac{1.00}{.87}\right)}{2\pi(120)} = .000185$$

The heat flux corresponding to this resistance is:

$$Q_A = \frac{86.1 + 216 + 60.5 + 96.5 + 388 + 25.6 + 109}{3.1875} = 3680 \text{ Btu/hr ft}$$

Thus the temperature drop through the capsule itself is:

$$T_5 - T_6 = 3680 (.00185) = 0.68^\circ \text{F}$$

- e. The total temperature drop from the specimen centerline to the water is thus:

$$T_1 - T_6 = 1.90 + 10.6 + 0.82 + 15.5 + 0.68 = 29.5$$

- f. Assuming the water temperature is maintained at 110°F , the specimen centerline temperature will be 139.5°F . The results of the temperature drop calculations are listed in Table II-3.

E. THERMAL STRESSES IN SPECIMEN

The thermal stress in a solid cylinder (of infinite length) with unrestricted ends is given by NAA-SR-Memo-1740²⁻⁴:

$$S_r = \text{Max. tensile stress} = \frac{Ea Q r_s^2}{8 k_s (1-\mu)} = \frac{Ea (T_1 - T_2)}{2 (1-\mu)}$$

This formula can be used only as a very rough estimate since the specimens are not homogeneous, and material properties E , a and k_s can be estimated only roughly. Using the calculated temperature drops and the properties of the base metal (bronze),

$$S_r = \frac{(16 \times 10^6)(10.2 \times 10^{-6})(1.90)}{2 (1-0.35)} = 368 \text{ psi.}$$

Using the given temperature drop and the properties for poly-imide plastic,

$$S_r = \frac{(2.5 \times 10^6)(2.3 \times 10^{-5})(1.90)}{2 (1-0.3)} = 78 \text{ psi.}$$

The calculated values of thermal stress indicate that specimen failure is not probable.

TABLE II-3

SPECIMEN AND CAPSULE THERMAL DATA

Element	Btu/hr Produced	Q_{rs}^2 Btu/hr/ft	k_s Btu/hr/°F ft	T_1-T_2	QA_s	T_2-T_3	QA_2	T_3-T_4
WSe ₂ -60 Cu	302.1	550	72.3	1.90	1730	10.6	3540	0.82
WSe ₂ -60 Bronze	288.5	525	13.6	9.65	1650	10.1	3480	0.81
WSe ₂ -40 Bronze	243.6	443	13.4	8.15	1390	8.50	3290	0.77
MoSe ₂ -40 Bronze	220.8	402	13.4	7.51	1261	7.70	3160	0.74
WSe ₂ -70 Ag	231.2	1261	11.5	27.4	3960	24.2	3240	0.75
MoSe ₂ -70 Ag	226.9	1240	11.5	27.0	3900	23.8	3220	0.75
440C SS	156.7	428	26	4.12	1345	8.22	2930	0.68

TABLE II-3
SPECIMEN AND CAPSULE THERMAL DATA (continued)

Element	QA ₃	$T_5 - T_6$ °F	$T_1 - T_6$ °F	Centerline Temp., °F	(Q/A)Max.	Sr ₁ psi. Base Metal Plastic
WSe ₂ -60 Cu	3080	0.57	29.5	139.5	12,160	368 78
WSe ₂ -60 Bronze	3030	0.56	36.4	146.4	12,000	1,125 396
WSe ₂ -40 Bronze	2990	0.55	32.5	142.5	11,450	950 335
MoSe ₂ -40 Bronze	2910	0.54	30.4	140.4	11,170	875 308
WSe ₂ -70 Ag	2950	0.55	67.3	177.3	11,300	2,590 1,176
MoSe ₂ -70 Ag	2930	0.54	66.3	176.3	11,250	2,500 1,133
440C SS	2710	0.50	26.4	136.4	10,400	171 —

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F. HEAT FLUX AT CAPSULE SURFACE

The capsule outside area is .0806 ft², and the total heat generated in the capsule is calculated from the constituents in Tables II-1 and II-2. Thus the maximum heat flux at the capsule surface is:

$$(q/A)_{\text{Max.}} = \frac{(86.1 + 216 + 60.5 + 96.5 + 388 + 25.6 + 109)}{0.0806}$$

$$(q/A)_{\text{Max.}} = 11,420 \text{ Btu/hr ft}^2$$

Taking into account the conservative assumptions employed, the actual heat flux will not exceed the specified 12,000 Btu/hr ft².

G. HEAT REMOVAL AFTER TEST

Calculations of temperatures attained in the capsules after removal from the reactor indicate that the temperature of the specimens will not exceed approximately 184° F in the shipping cask assuming a one-day cooling period in stagnant water.

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- 2-2 Letter of B. L. Rugh to N. Bifano, October 3, 1962.
- 2-3 Mc Adams, W. H., Heat Transmission, Pub: Mc Graw-Hill, 1954.
- 2-4 Gingrich, J. E., Shimazaki, T. T., Steady State Temperature and Thermal Stress Distributions in Plates, Cylinders and Spheres with Uniform Internal Heat Generation, NAA-SR-Memo-1740.

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