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EVALUATION OF LINEAR POLYETHYLENE AND FIBERGLASS REINFORCED EPOXY FOR USE AS IRRADIATION CAPSULES

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ABSTRACT

Sealed plastic capsules have been irradiated in unsealed metal rabbits (irradiation containers) in the NASA Plum Brook Reactor hydraulic rabbit facilities. The purpose was to determine the operating limits for the irradiation of experiments in these capsules.

Both linear polyethylene and fiberglass reinforced epoxy capsules were tested. The operating limits for the irradiation of experiments in polyethylene capsules have been defined. The epoxy capsules became highly radioactive when irradiated and failed at lower levels of exposure (5×10^{10} ergs/g H_2O) than the polyethylene capsules.

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EVALUATION OF LINEAR POLYETHYLENE AND FIBERGLASS REINFORCED EPOXY FOR USE AS IRRADIATION CAPSULES

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SUMMARY

Sealed polyethylene and fiberglass reinforced epoxy capsules were irradiated in the NASA Plum Brook Reactor hydraulic rabbit facilities, RA-8 and RD-5, to determine the operating limits for irradiation of experiments in these capsules. The effects of irradiation were determined on the capsule softening temperature, thermal conductivity, and burst strength. After irradiation, the capsules were leak-checked and the pressure inside the sound capsules was determined.

For the polyethylene capsules (see Table 1 for parameters), the following operating limits were established:

a. Maximum specimen temperature in contact with capsule wall - 395^{o}K (250^{o}F). This corresponds to a heat flux of 10,000 watts/m^2, (3170 btu/hr-ft^2). Table 2 gives gamma heating rates in water in the test holes.

b. Maximum pressure buildup in the capsule from gas production of the polyethylene and sample - limited to burst strength of the polyethylene as a function of dose. Figure 1 shows the dose limits in RD-5 for empty capsules and for capsules containing various amounts of non gas producing solids. A sample calculation is presented to show the method to be used to account for pressure buildup due to gas-releasing samples.

c. Liquid samples and gas emitting solid samples where it is desired to retain the gases in the capsule may not be irradiated in RA-8. Empty capsules (1.5 cm^3 free volume) may be irradiated in RA-8 to a dose of $8.5x10^{10}$ ergs/g(H_2O) without the interior becoming contaminated. Solid non-gas emitting samples may be irradiated in RA-8 with a free capsule volume of 0.55 cm^3 to a dose of $7x10^{10}$ without becoming contaminated.

The probability of a polyethylene capsule not failing if irradiated within these operating limits is 0.95. Failure is defined as loss or contamination of the specimen.

The fiberglass reinforced epoxy capsules became highly radioactive when irradiated and failed at lower exposures than the polyethylene.

INTRODUCTION

Plastic capsules provide a convenient means for sealing specimens for irradiation testing in hydraulic rabbits when specimen contact with the primary cooling water and/or contamination from metal (aluminum) rabbits cannot be tolerated. Examples are the production of pure tracers and irradiation of specimens for neutron activation analysis. Since it is difficult to predict the capsule performance from the published information on the radiation effects of the materials, we tested polyethylene and epoxy containers to establish their operating limits in the Plum Brook Reactor (PBR) hydraulic rabbit facilities.

The effects of irradiation dose, material supplier, and material age on the following physical characteristics of the polyethylene capsules were determined: softening point, thermal conductivity, burst strength, and integrity. The amount of hydrogen gas released to the interior of the capsule during irradiation was determined for two temperatures. The hydrogen is produced by irradiation induced reactions in the polyethylene.

The above measurements enabled operating limits to be established in terms of specimen temperature in contact with the capsule wall, which also established the heat flux at that temperature, and pressure buildup within the capsule, which is a function of dose. The probability of a capsule not failing when operated within these limits was determined.

The epoxy capsules became highly radioactive and failed at much lower exposures than the polyethylene, so no operating limits were established for them.

APPARATUS AND PROCEDURES

REACTOR

The NASA Plum Brook Reactor is a light-water cooled and moderated reactor designed for operation up to a thermal power of 60 megawatts. A plan view of the reactor core is shown in Figure 2.

All the irradiations were performed in vented metal rabbits in the RD-5 and RA-8 test facilities (see Figure 2). The neutron flux and gamma heating data in the two test facilities are shown in Table 2. The methods used to determine the neutron flux and gamma heating are also given in Table 2. The primary cooling water temperature ranged between 322^oK (120^oF) and 333^oK (140^oF) and the pressure ranged between 8.95×10^5 and 1.03×10^6 n/m^2 (130 and 150 psig). The primary water pH ranged between 6 and 7 and the conductivity was less than 1 μ mho/cm.

MATERIALS

The material used in the polyethylene irradiations is commonly called linear or high temperature polyethylene. More specifically, the material is Type III, Class "A" conforming to ASTM specification 1248-65T.

The material was purchased from three different vendors. Three batches of material were ordered and delivered at three month intervals from one vendor to study the effect of aging. It was noted at the time of the first delivery that one of the materials did not conform to our specifications. The material was tested, however, to see if it would perform adequately. The polyethylene capsule design is shown in Figure 3.

The material used for the epoxy irradiations was a glass base-epoxy resin cured with an aromatic hardener. The material conformed to ASTM specification #D-709 "Specifications for Laminated Thermosetting Materials". The material is Type IV, Grade G-10, as specified by D-709. This material is also specified in Military Specification Mil-P-18177 as type GEE.

TESTING

The following tests were performed on the irradiated and unirradiated polyethylene. Only the leak test was performed on the epoxy capsules.

Vicat Softening Temperature

The softening temperature of the material was measured on a Vicat Softening Point apparatus. In this test, the temperature of the material is raised until a needle with a one mm^2 flat point and one kg load sinks into the material.

Thermal Conductivity

A special apparatus was used to measure the change in the thermal conductivity of the capsules. In this test the capsule is immersed in a water bath. A heater is placed inside the capsule to boil the water and maintain a constant temperature within the capsule. Heat flows through the capsule wall to the surrounding water bath. The thermal conductivity of the capsule is determined by the rate of temperature rise in the water bath.

The thermal conductivity of the polyethylene was also measured on a Colora-thermoconductometer. A separate irradiation of flat specimens was made for these tests. The thermoconductometer works as follows: A flat cylindrical sample of the material to be tested is placed between containers of liquids having a suitable boiling point difference (10^{o}-20^{o}K). The liquid with the higher boiling point is heated electrically. The heat passes through the sample and boils the second liquid. The quantity of heat passing through the sample is proportional to the volume of liquid evaporated. Calibration samples of known thermal conductivity are used to construct a calibration diagram. The thermal conductivity values of subsequent samples can be read directly from this calibration diagram.

Capsule Burst Test

The capsules were tested to determine their burst strength. One end of the capsule was cut off at the weld. The open end was slipped over 0.635 cm (¼") stainless steel tubing and clamped. The stainless steel tubing was connected to a coil of copper tubing which surrounds the capsule. The copper tubing permits preheating of the gas and provides an isothermal environment for the capsule. The assembly is then heated in a furnace to a testing temperature of $352^{o}K$ ($175^{o}F$). This is the average capsule wall temperature when the capsule interior temperature is $395^{o}K$. At the test temperature, the capsule is pressurized until it fails. The pressure at which it fails is defined as the burst strength.

Capsule Leak Test

The capsules were weighed before and after irradiation to determine if the capsule leaked. The capsules were also leak-tested before and after irradiation by placing the capsule in a water-filled flask. A vacuum of $9.5x10^{4}n/m^{2}$ (28" of Hg) was pulled on the flask. The presence of bubbles coming from the capsule indicated a leak.

Gas Analysis

The amount and composition of the gas in the capsules after irradiation were measured on a gas chromatograph. The sampling method was to break the capsule in a helium-filled sealed chamber of known volume. A sample of gas taken from the chamber was analyzed on the gas chromatograph. From these data, the amount of the different gases in the capsule was calculated. Since the capsule volume was known, the pressure at the operating temperature in the capsule also could be calculated.

RESULTS

AGE AND SUPPLIER

Polyethylene material for these tests was ordered from three suppliers. In addition, three batches of material were ordered at three month intervals from one of the suppliers. Five separate batches of material were used to study the effect of material age and supplier. One of the batches did not have the same appearance as the other materials. Preirradiation testing revealed that this material had a lower burst strength and vicat softening temperature and did not meet the ASTM specifications. During irradiation, containers made from this material failed at a high rate. These containers did not have sufficient strength to withstand the primary cooling water pressure and collapsed. The other four batches of material appeared equal during pre- and post-irradiation testing. An analysis of variance treatment of the data revealed that there is no significant difference, at the 95% confidence level, between batches B-1, C-1, C-2, and C-3. There was no significant difference, at the 95% confidence level, between the ages and between the suppliers studied. For this reason, the data from these four batches of material are treated as one. The data from the inferior material, batch A-1, is included in the tables but not the graphs or discussion.

VICAT SOFTENING TEMPERATURE (TABLE 3)

The average preirradiation value of the softening temperature is 395°K ± 6°K (252°F ± 11°F). After irradiation to an absorbed dose of 1×10^{11} erg/g H_2O the average softening temperature of the polyethylene irradiated in the RD-5 facility had increased to 425° ± 22°K. The increase in the softening temperature did not appear to be affected by the difference in dose rate between RD-5 and RA-8. It is evident from Table 3 that there is a large increase in the data scatter as well as the average softening temperature value. In our testing we noted that in some cases the plastic was split by the flat needle rather than penetrated by it. The material split because it became embrittled. If the material split the measured vicat point value would be lower than the actual value of the softening temperature. This accounts for the scatter in the data at higher exposures. For our operating limits, the maximum specimen temperature in contact with the capsule wall will be the softening point of unirradiated polyethylene.

THERMAL CONDUCTIVITY (TABLES 4 and 5)

Two methods were used to evaluate the change in thermal conductivity of the polyethylene. These methods are discussed under "TESTING". The capsule type specimens gave a higher value of thermal conductivity than the published value and the flat specimens a lower value. In both of our tests, the thermal conductivity of the polyethylene dropped about 20% during irradiation. The drop in thermal conductivity occurred almost immediately. After the initial drop, the conductivity increased with irradiation. The initial decrease in thermal conductivity may be due to an observed dull coating formed on the polyethylene during irradiation. For our operating limits the lowest measured average value, (6.0×10^{-4} cal/sec/°C cm), was used to calculate the heat dissipation through the container wall. For the maximum allowable specimen temperature in contact with the capsule wall, this thermal conductivity yields a maximum heat flux of 10,000 watts/m^2 (3170 btu/hr-ft^2).

BURST STRENGTH (TABLE 6, FIGURE 1)

The average pre-irradiation value of the burst strength was $3.0 \pm 1.1 \times 10^6$ n/m^2 (440 ± 160 psig). Initially the burst strength increased with irradiation. A maximum of $4.5 \pm 2.0 \times 10^6$ n/m^2 (600 ± 290 psig) was reached at an absorbed dose of 4.3×10^{10} ergs/g H_2O in RD-5. The burst strength then decreased with irradiation to an average strength of $1.9 \pm 0.3 \times 10^6$ n/m^2 (280 ± 40 psig) at an absorbed dose of 1×10^{11} ergs/g H_2O in RD-5. Because the burst strength of the capsules decreases more rapidly as a function of dose in RD-5 than RA-8, the RD-5 data is quoted here and used to establish the Safe Container Pressure. For our operating limits the lower limit curve on Figure 1 is used as the plot of Safe Container Pressure values. This is the pressure that the container can withstand 95% of the time without failing, i.e., average minus 2 σ .

GAS ANALYSIS (TABLE 8, FIGURE 1)

A total of sixty-two (62) polyethylene capsules were irradiated to study the rate of pressure buildup in the capsules. The pressure buildup is caused by the evolution of hydrogen from the polyethylene. Some of the capsules were irradiated empty and some contained metal specimens. The metal specimens were solid cylinders bored to the proper mass to heat the area they contacted to 395°K. (Lead specimens were used in RA-5 and aluminum specimens were used in RA-8.)

It is difficult to anticipate the effect of irradiation temperature on the pressure buildup in the capsules. There are two mechanisms for the formation of H_2 (Ref. 3). The first involves the scission by a single radiation event of adjacent C-H bonds on the same molecule forming an unsaturated bond C = C and two hydrogen atoms. This mechanism is independent of temperature. The second mechanism involves the scission of C-H bonds on different molecules and the formation of a cross link C - C bond between them. This method is highly temperature dependent between $\sim$ 300 and 430°K. The permeability of polyethylene to permanent gases is dependent on the number of cross links (Ref. 4). Thus, as the irradiation temperature is increased, the amount of hydrogen formed is increased but the permeability of the polyethylene is decreased. It is difficult to quantify these opposing effects and predict the overall effect of temperature on the amount of H_2 diffusing into the capsule interior.

The data for RD-5 in Table 8 points out two important considerations. First, as more of the capsule is filled with material, bringing the filled portion up to 395°K, the amount of gas diffusing into the capsule decreases for a given exposure. In spite of this decreased diffusion, a very high rate of capsule failures was experienced at 7.8×10^{10} and 1.0×10^{11} ergs/gm H_2O. This behavior could be the result of a sudden increase in the diffusion rate near 7.8×10^{10} ergs/gm H_2O or a decrease in the strength of the capsules below those given in Figure 1 for empty capsules. The latter mechanism seems most plausible. The amount of cross-linking that has occurred at a given dose is higher at the higher irradiation temperature. Also, the amount of H_2 trapped in the material is higher resulting in higher internal stresses in the capsule wall. However, the possibility of a sudden increase in diffusion rate cannot be ruled out. As the internal stresses increase due to the trapped H_2, the internal energy may reach the threshold for a new diffusion mechanism.

These considerations make it necessary to make the exposure limits of the capsules dependent upon the free volumes remaining in the capsules after the samples are added. Based on the data in Table 8, such limits have been established in Figure 1 for capsules partially filled with lead. Although a lower density material than lead may be a worse case than lead, we do not have data to determine how much worse. It is believed that the limits on Figure 1 are conservative enough to account for this situation.

A sample calculation for establishing dose limits for gas-producing samples in RD-5 is presented later in this report.

The data for RA-8 indicates that the capsules were leaking gas above $\sim 2x10^{10}$ ergs/g H_2O. However, no leaks could be detected by the post-irradiation examination and the capsules appeared sound. Thus, liquids that have a significant vapor pressure and gas emitting solid samples where it is desired to retain the gases in the capsule may not be irradiated in RA-8. Empty capsule (1.5 cm^3 free volume) may be irradiated in RA-8 to a dose of $8.5x10^{10}$ ergs/g (H_2O) without the interior being contaiminated. Solid non-gas emitting samples may be irradiated in RA-8 with a free capsule volume of 0.55 cm^3 to a dose of $7x10^{10}$ ergs/g (H_2O) without becoming contaminated.

The pressure buildup in the capsules must be considered when removing an irradiated experiment. If the experiment sample is a powder and delicate, the gas should be vented or the capsule opened in a closed chamber.

CAPSULE LEAK TEST (TABLES 7 AND 8)

Below an absorbed dose of $1x10^{11}$ erg/g H_2O, eight of the 168 empty polyethylene capsules tested leaked. Of the twenty-nine empty capsules irradiated to an absorbed dose of $1x10^{11}$ to $2x10^{11}$ ergs/g H_2O eleven failed. Based on this data, the probability that a single capsule will not fail when irradiated up to $1x10^{11}$ ergs/g (H_2O) is $1 - \frac{8}{168}$ or 95.2%.

If "n" capsules are irradiated the probability none will fail is $(P)^n$ or $(.952)^n$. There is a significant increase in failures above an absorbed dose of $1x10^{11}$ ergs/g H_2O.

For the capsules containing specimens the dose limit was established (Figure 1) at the dose at and below which no failures occurred. This is considered to give at least a 0.95 probability of non failure.

The apparent in-pile leakage of the gas out of the capsules irradiated in RA-8 were not considered capsule failures with respect to solid samples. However, liquid samples cannot be irradiated in this facility if their vapor pressures are significant at the irradiation temperature.

EPOXY

Empty epoxy capsules were irradiated in the RA-8 and RD-5 test facilities. The range of exposure in these facilities was from an absorbed dose of $2.5x10^{10}$ ergs/g H_2O to $4x10^{11}$ ergs/g H_2O. All of the capsules irradiated in RA-8 (the higher flux test facility) failed. Only the capsule irradiated to an absorbed dose of $5x10^{10}$ ergs/g H_2O or less in the RD-5 facility did not fail. The cause of failure was due to the separation of the glass cloth laminations.

The probable cause of the failures in the RA-8 test facility at lower exposures than the RD-5 test facility was attributed to the higher temperature in this facility.

The capsules were also highly radioactive after irradiation which would limit their usefulness as experiment containers. For these reasons no further irradiations with this material are planned.

SAMPLE CALCULATION FOR GAS PRODUCING SAMPLES IN RD-5

Bases:

Irradiation position - RD-5

Capsule Free Volume - 1 cm^3

Gas produced by sample - equivalent to 0.25×10^6 n/m^2, pressure rise in 1 cm^3 free volume

From Figure 1:

Dose limit (non gas-producing sample) = 0.58×10^{11} ergs/g(H_2O)

Corresponding apparent pressure = 2×10^6 n/m^2

Total pressure (with gas-producing sample) = $2 \times 10^6 + 0.25 \times 10^6 = 2.25 \times 10^6$ n/m^2

Dose permitted equivalent to this total pressure = 0.5×10^{11} ergs/g (H_2O)

Note:

A correction can be made to this calculated dose permitted value to allow for the reduced gas from the capsule due to the dose being reduced from 0.58×10^{11} to 0.5×10^{11} ergs/g (H_2O). The empty capsule pressure buildup vs. dose curve may be used for this iterative correction. Also, the entire calculation may require iteration since gas production is usually a function of dose.

CONCLUSIONS

The purpose of this program was to determine the operating limits for the irradiation of experiments in plastic capsules. Linear polyethylene and fiberglass reinforced epoxy capsules were irradiated in the Plum Brook Reactor to determine the effect of irradiation on the properties which affect their usefulness as irradiation capsules.

The controlling factors on the use of polyethylene were determined to be its softening point, $395^{o}K$ ($250^{o}F$), and the burst strength which is a function of dose (see Figure 1). The softening temperature places a limit on sample temperature in contact with the polyethylene and thus on the capsule heat flux. The burst strength places a limit on the permissible pressure buildup caused by the sample plus polyethylene during irradiation. The burst strength and the allowable dose for empty and partially filled capsules are presented in Figure 1.

There was an outleakage of gases from the polyethylene capsules irradiated in RA-8 above $2x10^{10}$ ergs/gm (H_2O). Because of this, liquids that have a significant vapor pressure and gas emitting solids, whose gases are to be retained, may not be irradiated in RA-8. Empty capsules (1.5 cm^3 free volume) may be irradiated in RA-8 to a dose of $8.5x10^{11}$ ergs/g (H_2O) without the interior becoming contaminated. Solid non-gas emitting samples may be irradiated in RA-8 with a free capsule volume of 0.55 cm^3 to a dose of $7x10^{10}$ ergs/g (H_2O) without becoming contaminated.

The fiberglass reinforced epoxy capsules became highly radioactive when irradiated and failed at lower exposures ($5x10^{10}$ ergs/g H_2O) than the polyethylene. These capsules will not be used at the Plum Brook Reactor Facility.

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TABLE I

POLYETHYLENE CAPSULE PARAMETERS

Overall length	5.5 cm
Outside Diameter	1.0 cm
Inside Diameter	0.6 cm
Internal Length	5.0 cm
Internal Wall Area	10.0 cm^2
Internal Volume	1.5 cm^3
Wall Thickness	0.16 cm
ΔT_{max}	62^oK
Maximum Heat Flux through the Wall	10,000 $watts/m^2$
Thermal Conductivity	$6.0x10^{-4}$ $cal/sec/^oC$ cm

TABLE 2

FLUX AND GAMMA HEATING IN THE PBRF RABBIT FACILITIES AT 60 MW

	RD-5 RBH = 16"	RD-5 RBH = 28"	RA-8 RBH = 16"	RA-8 RBH = 28"
Thermal, $n/cm^2/sec$	1.4×10^{13}	1.1×10^{13}	9.6×10^{13}	2.0×10^{14}
Epithermal Neutrons, E .5ev - .1 Mev	5.6×10^{11}	4.9×10^{11}	1.3×10^{13}	2.2×10^{13}
Fast Neutrons, $E > .1$ Mev ($n/cm^2/sec$)	4.6×10^{11}	4.0×10^{11}	9.6×10^{12}	1.6×10^{13}
Fast Neutrons, $E > 1$ Mev ($n/cm^2/sec$)	2.3×10^{11}	2.0×10^{11}	4.8×10^{12}	8.0×10^{12}
Fast Neutrons, $E > 2.9$ Mev ($n/cm^2/sec$)	2.4×10^{10}	2.1×10^{10}	8.6×10^{11}	1.4×10^{12}
Gamma Heating, watts/gm H_2O	.4	.4	1.5	2.5

<u>Uncertainties at 95% Level of Confidence</u>:

1) Thermal flux	$\pm$ 10%
2) Epithermal flux	$\pm$ 60%
3) Fast flux > .1 Mev	$\pm$ 40%
4) Fast flux > 1 Mev	$\pm$ 25%
5) Gamma heating	$\pm$ 22%

1) The thermal flux reported is the average 2200 meters/sec thermal flux measured in the Plum Brook Reactor during cycles 80 through 85. One-half percent cobalt wires with an effective cross-section of 37.2 barns were used in these measurements.

2) The epithermal flux was determined by assuming a 1/E spectrum exists. Previous measurements in these core locations show that this is a good assumption.

3) The integral and differential fast flux values were derived from RP-4, a one-dimensional, 71-group diffusion calculation. The calculations were normalized by using the experimentally determined integral fast flux. The fast flux was monitored with a nickel wire. The effective cross-section used for nickel was .40 barns. The differential flux versus energy groups are shown in figures 4 and 5.

4) The gamma heating measurements were performed in the Plum Brook Mock-Up Reactor. Fe_2SO_4 was used as the gamma dosimeter.

TABLE 3
VICAT SOFTENING POINT (^{o}K) OF POLYETHYLENE

Material	Exposure in RD-5, RBH = 20"									Exposure in RA-8, RBH = 24"						
	Time (hours)									Time (hours)						
	0	1/2	1	2	3	4	6	7	8	0	1/8	1/4	1/2	1	1-1/2	2
	Absorbed dose (ergs/g H2O)x10^{11}									Absorbed dose (ergs/g H2O)x10^{11}						
	.00	.07	.14	.29	.43	.58	.87	1.04	1.16	0	.11	.21	.43	.85	1.27	1.71
A-1	359 354 359 353 343 398 362 351 354	355 359	359 374	364 374 361	368 364	387 363 398 357	399 405	--	405							
B-1	389 399 399 399 398 394 399 394 399	386 385	352 407	383 405 403	405 425	422 411 398 403	436 405 435		463							
C-1	398 400 389 397 399 392 384 397 395 397	385 422	394 396 377 403 403 403 399	374 405 402 407 403 402 405 405	407 405	436 436 403 407 372 405 402 394	390 421 416 420 445 407 405 410	426 443 421 404 425	449	252 ± 6 (10)	389 389 394 397 397 396 394 391 394 391	403 405 403 401 403 391 392 394 393 392	403 403 408 408 403 396 395 397 396 396	422 450 457 392 414 400 383 414 398 393	441 391 391 406 392 389 396 393 386 399	391 402 405 421 342 419 464
C-2	396 394 394 394 393	386 404	394 403	390 384 398	409 398	412 403 432 401	423 465 459		436							
C-3	394 394 394 393 394	385 403	393 403	394 409 401	407 403	417 426 407 410	414 421 400		389							
Averages, ± 2σ	395 ± 6	395 ±27	394 ±31	398 ±19	407 ±16	410 ±49	422 ±41	425 ±22	434 ±59	395 ± 6	394 ± 6	398 ±11	400 ±10	418 ±52	400 ±31	419 ±48

TABLE 4

THERMAL CONDUCTIVITY OF POLYETHYLENE CAPSULE SPECIMENS

Cal/sec/^{o}C/cm x 10^{4}

Exposure in RD-5

RBH = 20"

Absorbed dose (ergs/g H_2O)x10^{11} :	0	.07	.14	.19	.29	.43	.58	.87
Time (hours) :	0	1/2	1	1.33	2	3	4	6
<u>Material</u>								
A-1	8 8 7 9 9 10 9 9 8 8							
B-1	10 10 10 8 9 8 10 10	4 7	6.5 8	9	9	8	8	6
C-1	10 10 8 8 9 8 10 10 10	6 8	9 7	8	9 7	7.5	7.5	9
C-2	--	8 8	9 7	9	8.5 8	7	7	8
C-3	--	8 8	9 7	10	8.5 8	8	7	8
Average $\pm$ 2σ	9.0 $\pm$ 1.0	7.1 $\pm$ 1.5	7.8 $\pm$ 1.1	9.0 $\pm$ .8	8.3 $\pm$ .7	7.6 $\pm$ .5	7.4 $\pm$ .5	7.7 $\pm$ 1.3

TABLE 5

THERMAL CONDUCTIVITY OF FLAT POLYETHYLENE SPECIMENS

Cal/sec/^{o}C/cm x 10^4

Exposure in RD-5
RBH = 24"

Absorbed dose (ergs/g H_2O) x 10^{11} :	0	.07	.14	.29	.58	1.16
Time (hours) :	0	1/2	1	2	4	8
	7.2	5.2	5.8	7.1	6.0	7.5
	7.1	5.5	5.8	7.4	6.7	7.8
	8.0	5.7	7.5	6.5	6.1	7.2
	6.7	5.8	7.9	6.6	6.3	7.2
	6.9	6.0	6.9	7.2	6.8	7.6
	6.8	6.9	6.9	7.2	7.0	7.6
	6.8	6.9	6.2	6.6	7.2	7.5
	7.9		6.4	6.6	6.8	7.6
	7.9		6.6		6.6	
			6.7		6.7	
Average 2σ	7.3 $\pm$ 1.1	6.0 $\pm$ 1.3	6.7 $\pm$ 1.4	6.9 $\pm$ 0.7	6.6 $\pm$ 0.8	7.5 $\pm$ 0.4

TABLE 6
BURST STRENGTH OF POLYETHYLENE CONTAINERS
newton/meter^2 x 10^{-6}

Material	Exposure in RD-5 RBH = 20"									Exposure in RA-8 RBH = 24"						
	Time (hours)									Time (hours)						
	0	1/2	1	2	3	4	6	7	8	0	1/8	1/4	1/2	1	1-1/2	2
	Absorbed dose (ergs/g H2O)x10^{11}									Absorbed dose (ergs/g H2O)x10^{11}						
	0	.07	.14	.29	.43	.58	.87	1.04	1.16	.00	.11	.21	.43	.85	1.27	1.71
A-1	1.8 1.1 1.1 1.0 1.3 1.3	1.4 1.0	1.1	1.0	1.4											
B-1	2.8 3.3 2.9 2.6 3.2 1.4	4.3 3.3	3.2 4.1	3.9 3.1 5.4	5.4 4.9	4.8 3.3 3.2	3.1 2.3 2.1		0.7							
C-1	2.1 3.2 3.7 3.0 3.0 3.5 3.2	3.7 4.0	4.2 2.8 4.6 4.8 4.6 4.7 4.7	3.8 4.7 3.4 4.2 5.4 4.7 4.3 3.9	4.9 4.7	2.4 3.7 3.7 2.9 2.6 3.7 3.2 3.0	3.2 3.2 2.5 2.9 2.4 2.7 2.8 2.6	1.7 1.8 2.0 1.9 2.1	1.7	Same as RD-5 data 3.0 ± 1.1	2.6 4.1 4.1 3.2 3.0 4.8 4.2 3.9 1.4 3.7	4.8 3.8 3.7 3.5 1.8 4.2 2.9 4.7 4.7 4.9	3.1 2.5 3.0 3.3 3.8 3.8 3.6 3.0 2.6 2.3	2.1 2.2 2.7 3.0 2.3 3.2 2.3 2.1 2.3 2.5	1.9 2.6 2.8 2.3 0.6 1.7 2.2 1.2 2.6 2.1	0.7 0.9 0.7 1.1 1.7 1.7 1.3 2.2 1.6
C-2	3.1 3.3 3.7	3.6 4.0	4.2 3.1	4.5 3.2 3.5	5.0 4.5	2.6 3.7 2.6	3.5 2.0 1.8		1.5							
C-3	2.7 3.3 3.4	2.9 3.1	4.4 4.1	3.8 5.4	2.1 4.5	4.1 3.3 3.5	2.7 1.5 2.2		1.7							
Avg of B-1, C-1, C-2 &C-3	3.0 ± 1.1	3.6 ± 1.0	4.1 ± 1.3	4.2 ± 1.5	4.5 ± 2.0	3.3 ± 1.2	2.6 ± 1.1	1.9 ± 0.3	1.4 ± 0.9	3.0 ± 1.1	3.5 ± 2.0	3.9 ± 2.0	3.6 ± 1.2	2.5 ± 0.8	2.0 ± 1.4	1.3 ± 1.1

TABLE 7

INTEGRITY OF EMPTY POLYETHYLENE CAPSULES IRRADIATED IN RD-5 AND RA-8

Exposure in RD-5 (RBH = 20"):								
Absorbed Dose (ergs/g H_2O)x10^{11}	.07	.14	.29	.43	.58	.87	1.04	1.16
Time (hours)	1/2	1	2	3	4	6	7	8
Number of Capsules Irradiated	17	18	22	8	26	17	5	9
Number of Capsules Failed	1	0	1	0	0	0	0	0
Exposure in RA-8 (RBH = 24"):								
Absorbed Dose (ergs/g H_2O)x10^{11}	.11	.21	.43	.85	1.71			
Time (hours)	1/8	1/4	1/2	1	2			
Number of Capsules Irradiated	15	15	15	15	15			
Number of Capsules Failed	0	0	0	6	11			

NOTE: This table does not include any data from material A-1.

TABLE 8

MEASURED PRESSURE BUILDUP (GAGE)

$n/m^2 \times 10^{-6}$

Exposure (erg/g H_2O)x10^{-11}		Sample	Free Vol. (cm^3)	Relative Gas Released	Calculated Pressure* $n/m^2 x 10^{-6}$ (395°K)
RD-5	.07	Air	1.5	.35	.35
"	.07	"	1.5	.35	.35
"	.14	"	1.5	.51	.51
"	.29	"	1.5	.72	.72
"	.29	Lead	1.3	.43	.50
"	.29	"	1.0	.30	.45
"	.29	"	1.0	.33	.49
"	.29	"	0.8	.22	.41
"	.29	"	0.8	.18	.34
"	.58	Air	1.5	.95	.95
"	.58	"	1.5	.86	.86
"	.58	Lead	1.3	.89	1.02
"	.58	"	1.3	0.95	1.09
"	.58	"	0.8	0.44	.82
"	.58	"	0.8	0.49	.92
"	.78	"	1.3	1.54	1.78
"	.78	"	1.3	Leaked	Leaked
"	.78	"	1.3	"	"
"	.78	"	1.3	"	"
"	.78	"	1.3	"	"
"	.78	"	1.3	"	"
"	.78	Air	1.5	1.38	1.38
"	.78	"	1.5	1.33	1.33
"	.78	"	1.5	1.15	1.15
"	.78	"	1.5	1.41	1.41
"	1.0	Lead	1.3	1.25	1.44
"	1.0	"	1.3	Leaked	Leaked
"	1.0	"	1.3	"	"
"	1.0	"	1.3	"	"
"	1.0	"	1.3	"	"
"	1.0	"	1.3	"	"
"	1.0	Air	1.5	1.56	1.56
"	1.0	"	1.5	Leaked	Leaked
"	1.0	"	1.5	1.68	1.68
"	1.0	"	1.5	1.58	1.58
"	1.16	"	1.5	1.11	1.11

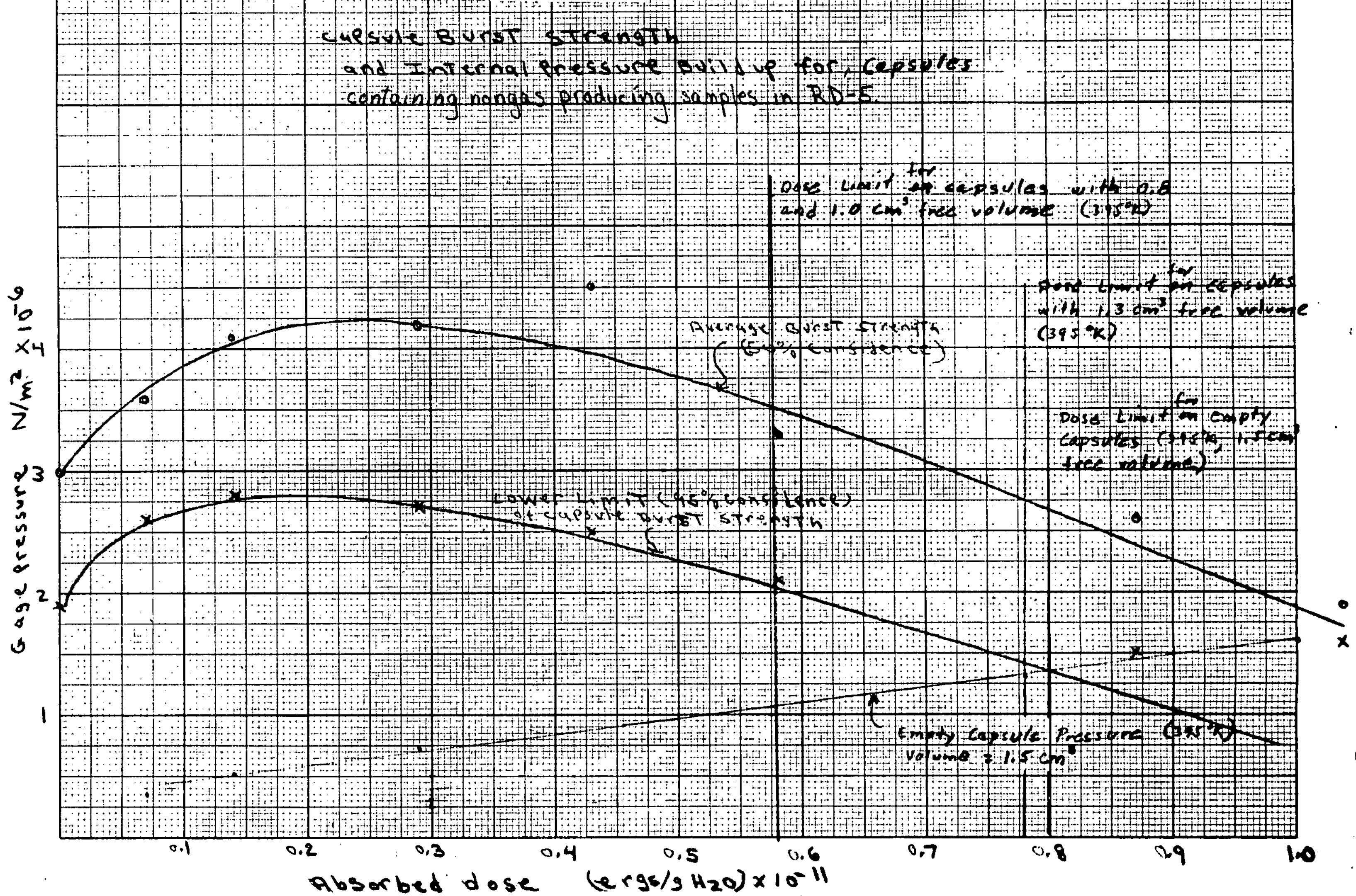
* Calculated from H_2 and N_2 content of capsule.

Table 8:

Exposure (erg/g H_2O)x10^{-11}		Sample	Free Vol. (cm^3)	Relative Gas Released	Calculated Pressure* n/m^2x10^{-6} (395^oK)
RA-8	.11	Air	1.5	.34	.34
"	.11	"	1.5	.47	.47
"	.21	"	1.5	.48	.48
"	.21	"	1.5	.50	.50
"	.21	"	1.5	.44	.44
"	.21	Al	0.5	.15	.45
"	.21	"	0.5	.19	.56
"	.34	"	.55	.05	.15
"	.34	"	.55	.08	.23
"	.34	"	.55	.07	.21
"	.34	Air	1.5	.17	.17
"	.34	"	1.5	.11	.11
"	.43	"	1.5	.16	.16
"	.50	Al	.55	.05	.15
"	.50	"	.55	.07	.20
"	.50	"	.55	.05	.15
"	.50	Air	1.50	.03	.03
"	.50	"	1.50	.15	.15
"	.71	Al	.55	.02	.05
"	.71	"	.55	.05	.15
"	.71	"	.55	.06	.19
"	.71	Air	1.50	.16	.16
"	.71	"	1.50	.19	.19
"	.85	"	1.5	.49	.49
"	.85	"	1.5	.17	.17
"	1.71	"	1.5		Leaked

* Calculated from H_2 and N_2 content of capsule.

Figure 1



Capsule Burst Strength and Internal pressure Build up for Capsules containing nongas producing samples in RD-5.
Dose Limit for capsules with 0.8 and 1.0 cm³ free volume (395°K)
Dose Limit for capsules with 1.3 cm³ free volume (395°K)
Average Burst Strength (50% confidence)
Dose Limit for empty capsules (395°K, 1.5 cm³ free volume)
Lower Limit (95% confidence) of capsule burst strength
Empty Capsule Pressure (395°K) Volume = 1.5 cm³
Gage pressure N/m² × 10⁻⁶
Absorbed dose (ergs/g H2O) × 10⁻¹¹
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
1
2
3
4

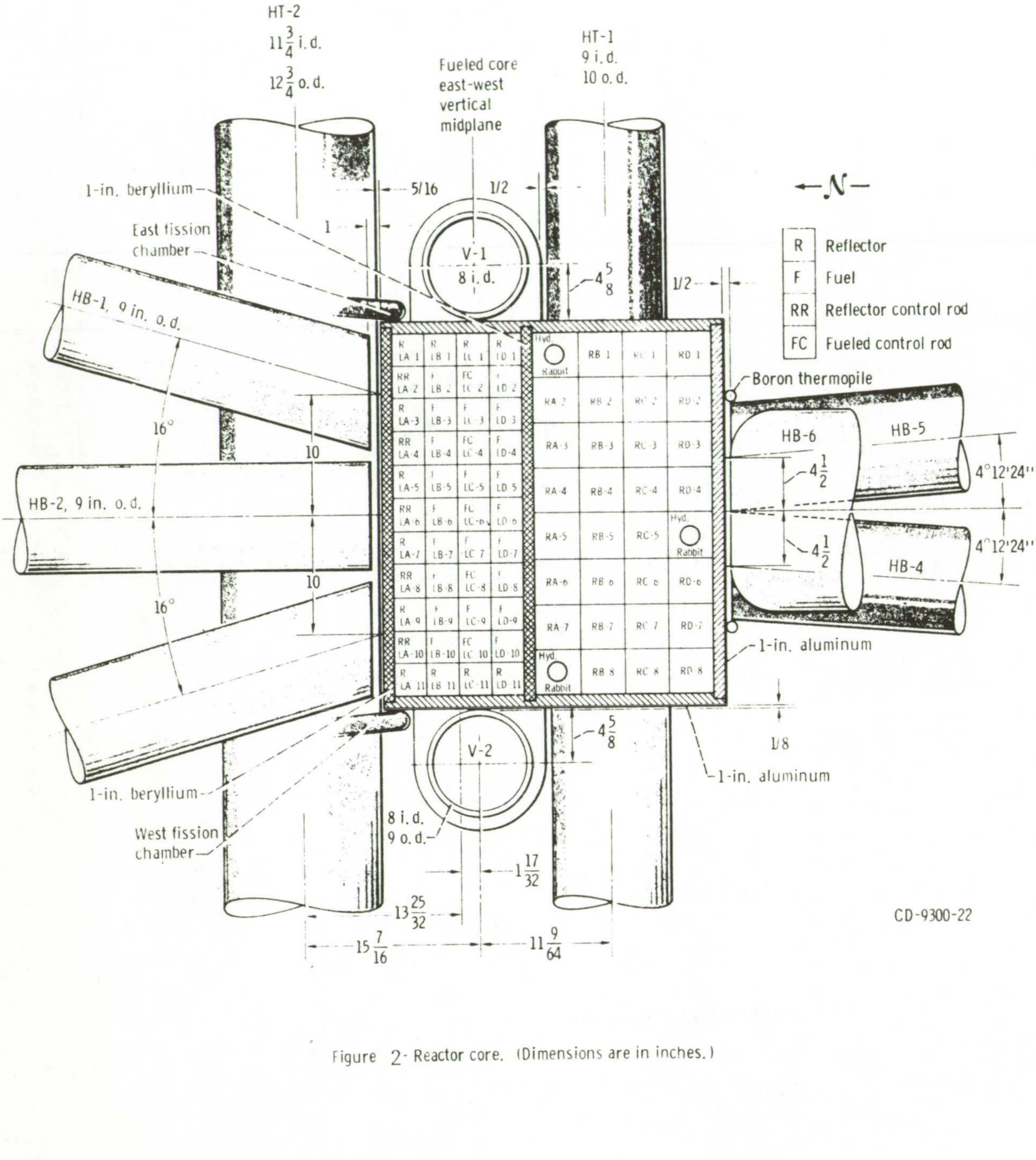
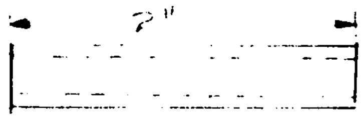
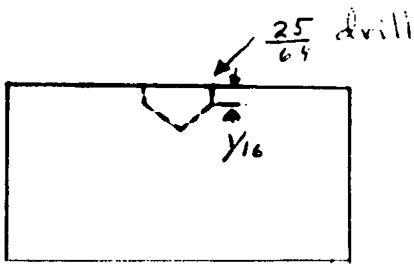


Figure 2 - Reactor core. (Dimensions are in inches.)

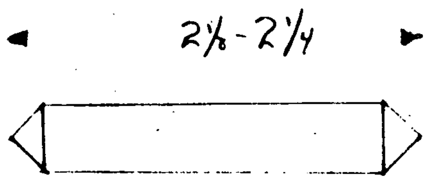


3/8" Tubing, 1/1C" Wall

1/8 dia - 1/4 long
Polyethylene rod



Aluminum Mold



Completed container

MATERIAL:

Linear Polyethylene ASTM Type III, Class "A"

FABRICATION:

1. Cut tubing to 2" length.
2. Place .1 to .2g polyethylene in the aluminum mold.
3. Heat until clear - 400°F.
4. Press tubing 1/16" into mold.
5. Hold five sec.
6. Cool mold in water.
7. Repeat steps 2-6 with other end.
8. Leak check capsule.

POLYETHYLENE CAPSULE

Figure 3

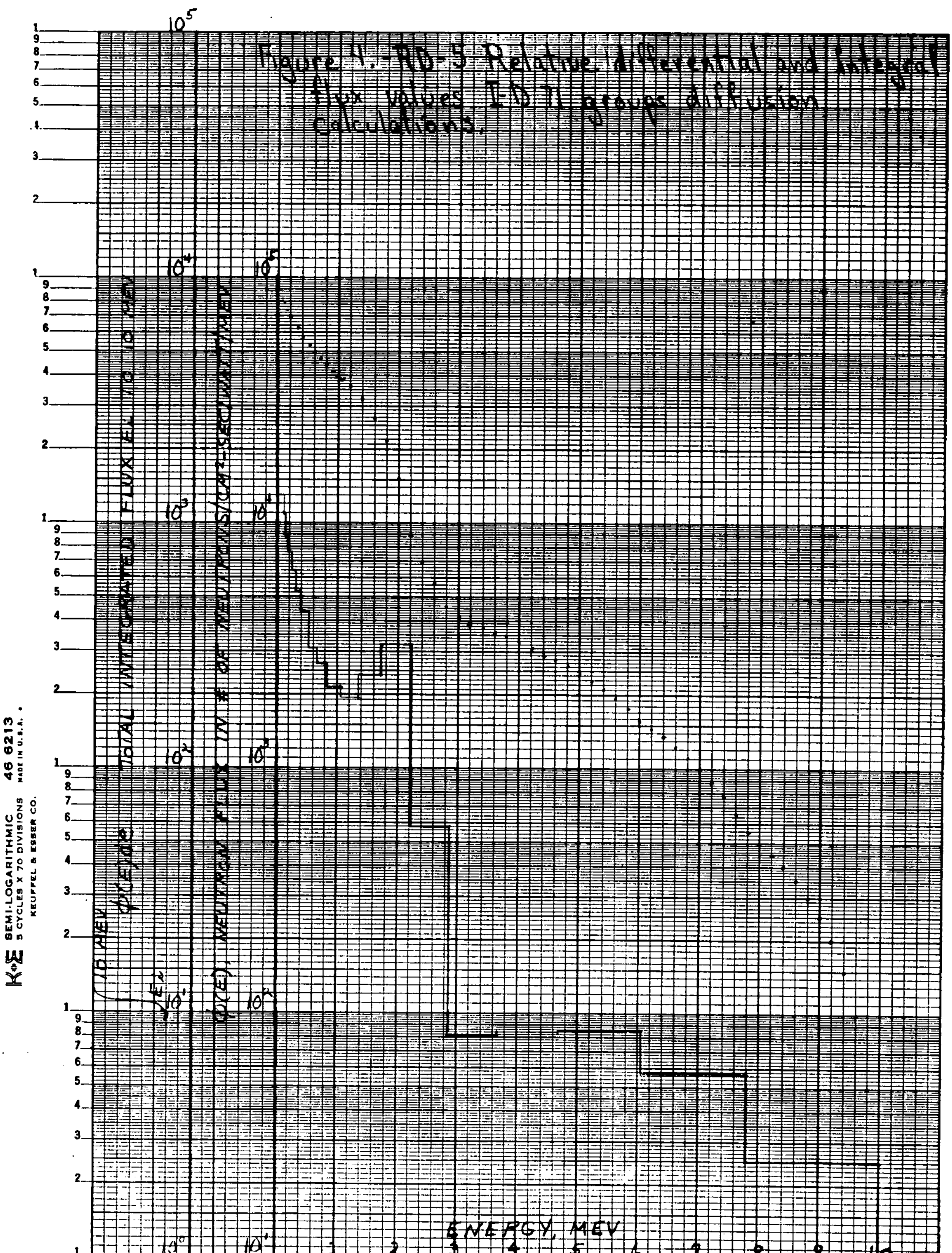


Figure 4-RD-5 Relative differential and integral flux values I-D 11 groups diffusion calculations.

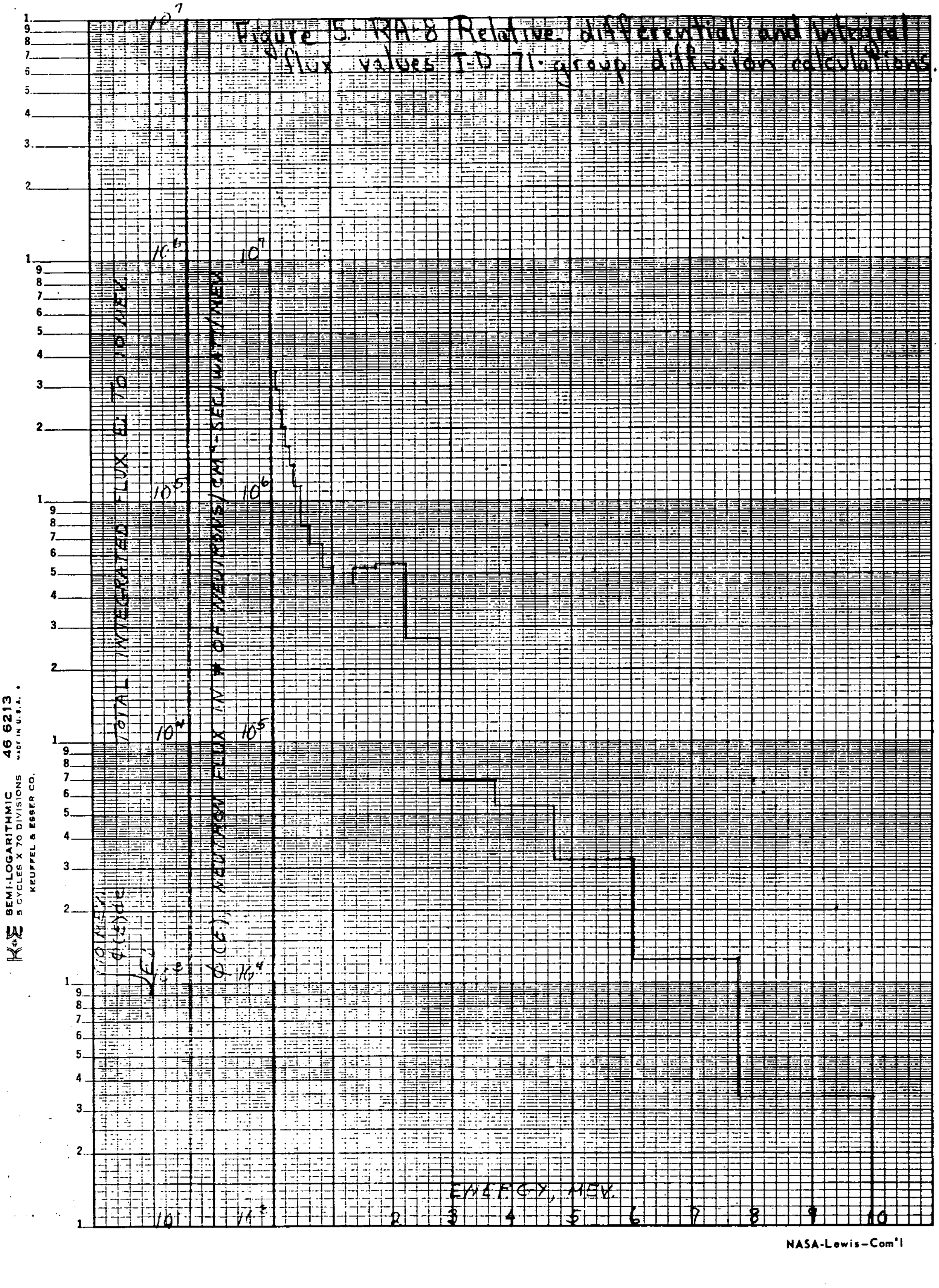


Figure 5. RA-8 Relative differential and integral flux values 1-D 71-group diffusion calculations.