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STUDY OF EXTRATERRESTRIAL DISPOSAL OF RADIOACTIVE WASTES PART II

by R. E. Hyland, M. L. Wohl, R. L. Thompson, and P. M. Finnegan
Lewis Research Center
Cleveland, Ohio

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STUDY OF EXTRATERRESTRIAL DISPOSAL

OF RADIOACTIVE WASTES

Part II

Preliminary Feasibility Screening Study of Extraterrestrial Disposal of Radioactive Wastes in Concentrations, Matrix Materials, and Containers Designed for Storage on Earth

by R. E. Hyland, M. L. Wohl, R. L. Thompson, and P. M. Finnegan

Lewis Research Center

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1. INTRODUCTION

AEC has initiated a program aimed at providing near-term and long-term solutions to the problems associated with the handling and management of radioactive wastes. Battelle-Northwest has been requested to conduct studies and to make evaluations of all currently envisioned long-term waste management methods.

The objective of these efforts is to identify feasible long-term waste management systems and their components; identify the research and development necessary for their establishment; and estimate the schedule and costs associated with selected systems. In addition, these studies will be used as the basis for providing a discussion of alternatives in the statement of environmental impact required for authorization of a Federal waste repository project.

The concepts to be studied include:

(1) The application of alternate geologic storage techniques.

(2) An international off-shore repository.

(3) Storage in the seabed.

(4) Use of the permanent ice caps.

(5) A ten-mile deep hole.

(6) A deep cavity generated by a nuclear device.

(7) Extraterrestrial transport.

(8) Transmutation.

(9) Other methods as yet unidentified.

NASA has been requested by the AEC to study the feasibility of extraterrestrial transportation of radioactive wastes. More specifically, NASA has been requested to study the extraterrestrial transport of at least three types of radioactive waste materials:

1. Radioactive wastes in concentrations, matrix materials, and containers currently designed for storage on Earth.

2. Actinide wastes with 0.1 and 1 percent contamination by other radioactive wastes.

3. The third type to be defined later in the study.

The general approach in each of these studies will be similar. The studies will be divided into several phases. The first phase is a preliminary feasibility screening study. This phase will establish the maximum amount of the particular radioactive waste that could be transported to space per launch. It will also establish the minimum cost of disposing of this particular waste in space and estimate the number of launches required per year. The effect of integration of the package with a vehicle and accident conditions will not be treated in this phase. The waste disposal container will be designed considering primarily normal operation. The primary emphasis will be on heat transfer, radiation shielding, and criticality. If this preliminary feasibility screening study indicates that the cost is reasonable, then a phase II feasibility study will be conducted which will include integration with the launch vehicle and consideration of all the safety aspects of the study. If the phase I study indicates that this maximum waste payload and minimum cost system may not be feasible, then the phase II study will be postponed until other more promising space disposal systems are considered.

If the method appears feasible after the phase II feasibility study, then the third phase of the study would be conducted. This phase would identify the research and development necessary to demonstrate feasibility and estimate the schedule and costs associated with the development and operation of the system.

This report describes the results of the phase I preliminary feasibility screening study for the first class of radioactive wastes, that is, the radioactive wastes in concentrations, matrix materials, and containers currently designed for storage on Earth.

2. DESCRIPTION OF WASTE PRODUCTS, MATRIX MATERIALS AND CONTAINERS

2.1 Description of Waste Products

The radioactive wastes in this report are the fission products that remain after processing as indicated in references 1 and 2 followed by a ten-year hold in temporary storage. This processing separates the fission products from the unfissioned fuel, structural materials, and the actinide class of radioactive wastes. However, the fission products after processing still contain small amounts of these materials. Their effects are considered negligible in this report.

Figure 2-1 shows how the activity (curies/gm) and the thermal power (watts/gm) of the fission products vary with time after discharge from the reactor. Both have decayed by about a factor of ten by the end of the ten-year hold in temporary storage. At that time about half the heat is generated by three isotopes, ^{90}Y, ^{137}Cs, and its daughter ^{137}Ba.

Table 2-1 shows the characteristics of fission products from light-water reactors (LWR) and from liquid metal fast-breeder reactors (LMFBR). For the purposes of this study the important characteristics are the amount of fission products per MWe day and the thermal power and activity per gram of fission products. LMFBR waste products have less thermal power and activity per gram because the isotopic distribution of the fission products produced by fast and thermal reactors are somewhat different. In addition, the amount of fission products produced per MWe day is less for the LMFBR because the expected efficiency of the plant is expected to be higher, 40 percent compared to 33 percent for the LWR. For reference, the LMFBR produces 2.64 gm/MWe day compared to 3.23 gm/MWe day for the LWR.

2.2 Description of Matrix Materials

Four types of solid-matrix materials designed for storage on Earth are described in Table 2-2 (ref. 3). The four types are spray melt, pot calcine, phosphate glass, and fluid-bed calcine. The spray melt was selected for this study. It was selected because its activity (curies per unit volume) is high, yielding a more compact disposal package. In addition (1) it has a tough structure compared to crumbly, brittle, and granular structure of the other materials permitting it to remain intact in case of impact, (2) it has a high maximum stable temperature, 1170 K compared to 1170, 770, and 870 K for the other materials, allowing it to operate at higher temperatures thus permitting larger diameters and higher payloads, and (3) it has a comparatively high-thermal conductivity, 1.8 watts/m(K) compared to 0.5 and 1.8 for the other materials, permitting high heat removal rates or large diameters without exceeding centerline temperatures.

Spray melt appears to be the best of the four candidate matrixes presently available but it has several drawbacks from the space disposal viewpoint. It is desirable to have a material with a higher thermal conductivity, higher maximum stable temperature, and higher values of curies per unit volume. Any future studies should consider other matrix materials when they become available.

2.3 Description of Fission Product Storage Containers

The containers designed for Earth storage of fission products in the above matrix materials are cylinders. The cylinders are made of a non-reactive material which would be stainless steel for pot calcine and either stainless steel or mild steel for the spray melt, phosphate glass, and fluid bed calcine. Diameters of 6 to 24 inches and lengths of 8 to 10 feet are being considered (ref. 3). The diameter for Earth storage is selected primarily to assure the maximum centerline temperature of the matrix material is below the maximum stable temperature. The centerline temperature will be higher for the larger diameters. The lengths are selected on the basis of requirements such as loading, handling, and maintenance.

In the design of a cylindrical container for space disposal the diameters will also be selected to assure that the temperature of the matrix material does not exceed the maximum stable temperature, which is 1170 K for spray melt. The diameter of the vessels will, however, be permitted to exceed 24 inches if this is advantageous. The length of the cylinder will be determined by the maximum payload of the launch vehicle or the space tug, whichever is limiting. Table 3-1 shows the maximum allowable payload weights for the candidate combinations of payload, tug, and launch vehicle. The information in this table will be discussed in the next section.

Figure 2-2 is a schematic drawing of the cylindrical containers configured for space disposal. The fission products are contained in the inner stainless steel cylinder. This cylinder is surrounded by a depleted uranium gamma shield. The cylinder with the gamma shield is then inserted in an outer stainless steel radioactivity containment vessel. Both the inner and outer vessels are welded and helium leak checked for tightness. For the purposes of this study all materials are assumed to be in intimate contact so that the temperature drop across the interfaces can be neglected. This is an optimistic assumption and the effect will have to be checked if the concept warrants a phase II feasibility study.

The uranium shield was selected because it gave the lowest shield weight. However, uranium changes phase (α to β) when its temperature goes above 930 K and the phase change causes the material to expand prohibitively. The maximum normal operating temperature is about 600 K. The feasibility of using depleted uranium for the gamma shield would be reconsidered in the phase II study because abnormal and emergency conditions may cause the shield temperature to exceed the phase change temperature.

3. PAYLOADS, COSTS, AND DESTINATIONS FOR CANDIDATE SPACE VEHICLES

This subject is discussed in detail in reference 4 "Space Transportation Considerations for Disposal of Radioactive Wastes" by J. Ramler, R. Thompson, and S. Stevenson. This section summarizes some of the pertinent information in this report and discusses the reasons for selecting the shuttle as the launch vehicle and Earth escape as the destination for this study.

The candidate destinations starting with the highest ΔV requirements and lowest payloads are: direct solar impact, direct solar escape, solar impact via Jupiter, solar escape via Jupiter, solar orbit, solar orbit via Venus, solar orbit via Mars, Earth escape and Earth orbit. The candidate expendable vehicles starting with the highest payload capability are: Saturn V/Centaur, Saturn V, and Titan III E/Centaur. There is one shuttle design but two types of shuttle launches. One is a single shuttle launch which carries both the payload and the tug. The tug transports the payload from low Earth orbit to its final destination. The other requires two or more shuttle launches. One carries the payload. The other shuttle or shuttles carry one tug each. The payload and tug (or tugs) rendezvous and are assembled in low Earth orbit. The tugs may be either expendable or reusable.

Table 3-1 shows the payloads and costs for the candidate destinations and candidate launch vehicle and tug combinations. This table shows that direct solar impact is not possible with today's vehicles. It also shows that the shuttle is the most economical launch system.

The shuttle was therefore selected as the launch vehicle. Earth escape[1] was selected as the destination for this phase. High Earth orbit permits carrying about the same payload but was not selected because this destination was considered to be too near the Earth. This was an arbitrary decision and will be re-evaluated with other promising destinations in later phases of the study when other aspects, in addition to payload, are considered in the selection of the destination.

The trajectories used to calculate the above payloads were not dog-legged. Dog-legged trajectories may be required to avoid potential impact on land after abort during ascent. Dog-legging the trajectory requires more fuel and, if the shuttle is fully loaded, the payload decreases. When the trajectories are dog-legged, the payload for the single shuttle launch may be reduced more than that for the dual launch as follows: In the single launch case, the shuttle is fully loaded and thus the final payload decreases for missions with a dog-leg. In the dual case the tug-carrying shuttle is fully loaded but the waste carrying shuttle is only partially loaded, 34 000 pounds, compared to a maximum allowable of 62 000 pounds. The payload is limited to 34 000 pounds because the maximum the tug can put into Earth escape orbit is 31 000 pounds (the 3000 pound difference is due to structures that remain in the shuttle). Thus, 28 000 pounds of additional fuel could be carried for the dog-leg maneuver without reducing the payload. The second shuttle with the tug may not have to be dog-legged since land impact of the tug is less hazardous. If the shuttle with tug is not dog-legged, the

[1]Earth escape is a solar orbit obtained by one burn from Earth orbit. The important characteristic of this orbit is that it intersects the Earth's orbit and introduces the possibility of Earth impact. Solar orbit refers to orbits about the Sun which are either inside or outside the Earth orbit with negligible probability of impacting the Earth.

maximum payload for the dual launch mode will not be much lower than 31 000 pounds. This is the main reason for looking at the dual shuttle launch mode of operation. Without such a potential advantage the single shuttle would be preferred because it is a less complicated launch mode.

The cost comparison was made using existing expendable vehicle designs. If space disposal appears feasible, then the development of an expendable vehicle should also be considered. Cost savings may result due to mass production and potentially higher payload capacity.

4. ANALYSIS

The phase I analysis has two main parts. First, determination of the maximum amount of fission products that could be carried in the shuttle-orbiter-tug vehicle to earth escape. Second, calculation of the launch cost per pound, per curie, per MWe day, and per kw-hr electric to establish the effect of launch cost on the electric generating cost. The number of launches required in 1985 and 2000 are also estimated. If the effect on electric cost makes the system potentially not feasible, then the phase II feasibility study would be postponed until phase I studies on potentially more promising waste-matrix-container systems have been completed.

If the results of the phase I study indicate this waste-matrix-container combination to be potentially feasible, then a phase II feasibility study would be conducted which would include design for in-shuttle cooling and for off-normal, emergency and accident conditions and would consider shuttle safety environment, abort, re-entry, impact, and heating after impact. The following sections describe the design criteria, procedure, and assumptions for the phase I analysis.

4.1 Design Criteria

For this phase of the study three classes of criteria are considered: radiation dose levels, matrix material temperature limits, and shuttle payload limits. In the double shuttle launch where the payload and tug are placed in orbit on separate launches, the maximum payload is determined not by the shuttle but by the tug. The tug limit is based on what payload it can take to a destination or put on a trajectory.

Radiation dose levels. - Dose levels in three situations were considered:

Shuttle crew	2.5 mrem/hr in the crew compartment which corresponds to 10 rem/hr at 3 meters from the center of the container
Shuttle instrument dose for unmanned shuttle	10^7 rad to the nearest instrumentation which corresponds to 500 rem/hr at 3 meters from the center of the container
After accident public exposure	1 rem/hr at 3 meters from the center of the container

Temperature limits. - Calculated spray melt matrix material temperature shall not exceed 1100 K which is 70 K below the maximum stable temperature for spray melt.

Shuttle payload limits for Earth escape. -

Single shuttle launch	Payload	17 000 lbs
	Structure on payload	500
	Structure in shuttle	3 000
	Tug	44 500
	Total	65 000
Two shuttle launch		
Shuttle 1	Tug	59 000
	Structure in shuttle	3 000
	Total	62 000

Shuttle 2	Payload	30 000
	Structure on payload	1 000
	Structure in shuttle	3 000
	Total	34 000 lbs

4.2 Procedure and Assumptions for Waste Container Design

The steps for a phase I design of a container and shield which meets the normal operation dose, temperature, and payload criteria are listed below:

1. Select a set of container diameters in the range-proposed for Earth storage. Diameters of 6, 12, 18, 24, and 28 inches were selected.
2. Calculate the radiation and heat source for a selected activity concentration and container diameter.
3. Calculate gamma shield thickness for one of the dose criteria assuming uranium metal as the shield material.
4. Calculate the surface temperature of the container in orbit assuming an emissivity of 0.8.
5. Calculate the temperature in the center of the matrix material assuming no temperature drop across the material interfaces.
6. Calculate the weight per unit length of payload where payload is the fission product, matrix material, containment cylinder, and shield.
7. Calculate the weight of the end shields and containment vessel end caps and subtract from the allowable payload to get the weight of the center section of the payload.
8. Calculate the length of the cylinder which makes the payload weight equal the payload criteria.
9. Calculate the weight of fission products per launch.
10. Perform above calculations for three dose rate constraints, three activity concentrations and for single and double shuttle launches.

4.3 Procedures and Assumptions for Calculation of Space Transport Cost

The cost of space disposal of radioactive wastes can be divided into several categories.

(1) Temporary storage on Earth.

(2) Separation, concentration, and preparation of wastes in matrix materials.

(3) Design and fabrication of the space disposal container system and assembly of wastes and matrix material into the container.

(4) Shipment of wastes to the launch site.

(5) Space transportation cost.

This report is concerned with only one of these costs - the space transportation cost. The space transportation costs begin when the payload is delivered to the launch site. The major space transportation costs end when the payload gets to its destination. The costs, however, may not go to zero at this time. There may be additional monitoring costs depending on the disposal destination.

The other (all of the above) costs will have to be determined before a complete economic analysis can be made. The purpose of the present analysis is to determine the relation of the space transportation cost to the cost of generating electricity. Specifically, the space transportation cost will be compared with the bus-bar cost of electricity which is assumed to be 8 mills/kw-hr.

The factors that affect the space transport cost to the electric consumer are:

(1) Launch cost including shuttle and tug.

(2) Destination and gross payload.

(3) Ratio of radioactive waste to gross payload.

(4) Interest on funds collected and set aside for space disposal at the end of Earth storage time.

(5) Radioactive waste Earth storage time.

The steps for a phase I economic analysis are:

1. Determination of the gross payload for the candidate destination which is Earth escape in this study. Gross payload is defined as the weight of the waste container system delivered to the destination and includes all structures and auxiliary systems fixed to the container.

2. Determination of the net waste container payload by substracting the weights of the structures and auxiliary systems fixed to the waste container from gross payload.

3. Determination of the amount of fission products that can be carried in a container whose weight including the shielding equals the net payload.

4. Determination of the launch cost including shuttle and tug.

5. Determination of the cost per curie of fission products transported to space.

6. Determination of the discounted space transportation cost per curie disposed, that is, determine the amount of money per curie that could have been put in a trust fund for space transportation. This assumes that the consumer was charged for space transportation when he used the electricity and that the money was put in a trust fund and compounded at current interest rates.

7. Determine the amount of electricity (MWe days) that was generated per curie disposed.

8. Determine the cost of space transportation of wastes in units of mils per kw-hr of electricity.

9. Compare the cost of space transportation from step 8 (mills/kw-hr) to the bus-bar generating cost of 8 mills per kw-hr.

5. RESULTS AND DISCUSSION

This section has four main parts. Part one establishes the net payload and launch cost as a function of the destination and launch vehicle. The next part describes the design of the waste payload package and discusses the effect of the design parameter on the dimensions of the container, the container temperature and thermal power, and the amount of fission products per launch. The third part describes the launch costs in mills per kilowatt hour of electricity and discusses the effect of container design parameters, earth storage time, and interest rates on the mill/kw-hr cost. The fourth part estimates the required number of shuttle flights per year to 2010 AD and discusses the effect of the destination and the design parameters on the number of launches.

5.1 Gross Payload and Launch Cost

For this phase I feasibility screening study Earth escape was selected as the disposal destination and the shuttle was selected as the launch vehicle. Gross payload is defined as the waste container plus the structure attached to it. At this time single and dual shuttle operations appear to have equal feasibility and are both considered. In single shuttle operation both the waste payload and tug are carried in the same shuttle. In dual shuttle operation one shuttle carries the waste payload and the other carries the tug. The following table summarizes the payload and cost data for Earth escape.

Vehicle	Gross payload, wt. (lb)	Launch cost, $	Cost per pound of gross payload, $/lb
Single shuttle	17 500	11 M	628
Dual shuttle launch	31 000	21 M	677

Payload and Cost Data for Earth Escape

The costs per pound of gross payload are $628 and $677 and are essentially the same within the accuracy of this study. The selection of single shuttle or dual shuttle operation will be made at a later time and will depend on additional considerations, for example, ratios of waste weight to gross payload weight (this tends to increase with increasing gross payload), effect of dog-legging the trajectory (this tends to reduce the single shuttle payload more), the complexity of the dual operation compared to single shuttle operation and safety considerations.

For reference, Table 3-1 shows the payloads and costs for the other candidate launch vehicles and destinations. The candidate destinations starting with the highest ΔV requirement (lowest payload) are: direct solar impact, direct solar escape, solar impact via Jupiter, solar escape via Jupiter, solar orbit, solar orbit via Venus, solar orbit via Mars, Earth escape, and Earth orbit. The candidate expendable vehicles starting with the highest payload capability are: Saturn V/Centaur, Saturn V, and Titan III E/Centaur.

When selecting the candidate destination and launch vehicle, other factors besides payload and launch cost must be considered. For example, the Jupiter, Venus, and Mars fly-by missions require less ΔV but more accurate instrumentation and control than the more direct missions. In addition, Jupiter, Venus, and Mars are in the proper positions for launch for only about one month every 12, 19, and 25 months, respectively. Thus the fly-by missions would require all the launches for the 12 to 25 month period be made in about one month. This would require several launches per day during about a 1/2 hour launch window. More detailed discussion of these aspects can be found in reference 4.

Earth escape, Earth orbit, and solar orbit result in the highest payloads per vehicle but each has drawbacks that must be investigated. In the case of Earth escape the possibility of re-encounter with the Earth at some future time must be made negligibly small for thousands of years due to the long-life of the waste materials. In the case of Earth orbit the possibility of interference with other space activities must be studied and made acceptable. Solar orbit reduces these problems but requires additional burns later in the mission as does Earth orbit. Solar system escape would eliminate these problems but would be costly. These types of considerations are discussed by Ramler, Thompson, and Stevenson in reference 4. More detailed analysis of this type, integrated with safety and economic analysis is required before a destination can be firmly selected.

5.2 Waste Payload Design

The physical features of the waste, matrix materials, and containers are described in Section 2, Table 2-2, and figures 2-1 and 2-2. The design procedures and assumptions for the container and shield were described in sections 4.1 and 4.2. The results of the parametric analysis of these designs are presented in figures 5-1 through 5-8 and are discussed below.

There are three main categories of design criteria:

(1) Radiation dose rates of 1, 10, and 500 rem/hr at three meters from the container centerline.

(2) Centerline temperature less than 1170 K which is the maximum stable temperature for the spray melt matrix.

(3) Gross payload weight: 17 500 pounds for single shuttle and 31 000 pounds for dual shuttle operation.

Additional independent parameters are:

(1) Radioactivity concentration in the matrix to a maximum of 10 curies/cc.

(2) Earth storage time.

The dependent parameters are:

(1) Diameter of the waste plus matrix material.

(2) Diameter of the outer containment vessel.

(3) Length of the container.

(4) Payload thermal power.

(5) Containment system outer surface temperature.

(6) Amount of radioactive waste in the container.

Diameter of waste matrix. - This diameter was determined the requirement that the matrix centerline temperature not exceed the maximum stable temperature of the spray melt matrix material which is 1170 K. Figure 5-1(a) and (b) show the design point diameter for the matrix material to be about 28 inches for an activity concentration of 10 curies/cc and a radiation dose of 10 rem/hr and 500 rem/hr. The matrix diameter is the same for both dose rates due to two compensating effects. First, the lower dose rate requires a thicker shield and, for the same matrix material diameter, the temperature drop through the thicker shield is higher. Second, the thicker shield makes the outer container diameter larger and this reduces the surface heat flux and the surface temperature. These two effects essentially cancel each other and the 28 inch matrix material diameter satisfies the maximum centerline temperature requirement independent of dose in the range considered, which was 1 rem/hr to 500 rem/hr.

Diameter of outer containment vessel. - This diameter was determined by the gamma shield thickness for the three dose rates considered and a 1 inch thick impact shield as outer shell. The shield material was depleted uranium and its normal operating temperature was about 600 K. The uranium shield thickness, for the design dose rates of 1, 10, and 500 rem/hr were 4.5, 3.5, and 2 inches, respectively. These thicknesses were determined by the comparison method, using data from reference 5. For all doses the matrix material diameter was 28 inches and the inner containment vessel thickness was 1/2 inch. Figure 5-2 shows the outer diameter as a function of dose rate. The outer diameter is 40, 38, and 35 inches for dose rates of 1, 10, and 500 rem/hr.

Length of container. - Figure 5-3 shows the length[2] of the container as a function of the dose rate and for single and dual shuttle payloads of 17 000 and 30 000, respectively. The lengths for a 17 000 pound payload and for dose rates of 1, 10, and 500 rem/hr are 2.59, 3.33, and 5.21 feet, respectively. The length for a 30 000 pound payload and for dose rates of 1, 10, and 500, rem/hrs are 5.09, 6.35, and 9.63 feet, respectively.

Thermal power. - Since the matrix material diameter is a constant and independent of the dose rate, the thermal power generated per foot

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[2]The length includes the active matrix plus the end shielding and container thicknesses.

of cylinder is also a constant of 6 kw/ft. The length of the container is determined by the allowable payload and the radiation dose as discussed in the previous section. Figure 5-4 shows the thermal power as a function of dose rate for single and double shuttle launches. The thermal power for a single shuttle payload of 17 000 pounds and dose rates of 1, 10, and 500 rem/hr are 9.6, 15.1, and 27.8 kilowatts, respectively. The thermal powers for a dual shuttle payload of 30 000 pounds and for the same dose rates are 24.6, 33.2, and 54.3 kilowatts.

Containment vessel outer surface temperature. - The power per foot of capsule is a constant as discussed in previous sections. The surface temperature is then a function of the dose rate which defines the container diameter and radiating area per foot. Figure 5-5 shows the surface temperature as a function of dose rate. The surface temperature for dose rates of 1, 10, and 500 rem/hr, 3 meters from the container centerline was 480, 500, and 525 K, respectively.

Amount of radioactive waste in the container. - The weight and amount of radioactivity per foot of capsule is the same for all capsules because the activity concentration is constant at 10 curies/cc and the waste in matrix diameter is constant at 28 inches. The amount of fission products per container is a function of the maximum allowable payload and the dose criteria. Figures 5-6 show the amount of fission products in the container in curies and the packaging weight ratio for single and dual shuttle launches and for radiation dose rates from 1 to 500 rem/hr at 3 meters from the container centerline. The number of Megacuries for dose rates of 1, 10, and 500 rem/hr at 3 meters are 1.91, 3.02, and 5.56 for single shuttle payloads of 17 000 pounds. The number of Megacuries for a dual shuttle payload of 30 000 pounds for the same dose rates are 4.90, 6.62, and 10.9.

5.3 Space Transportation Cost

The factors that affect the space transportation cost and the procedures and assumptions for calculating that cost are described in

Section 4.3. The purpose of the analysis is to estimate the space transportation cost to the electric power consumer and to compare this cost to the electric cost, which is 8 mills per kw-hr at the bus-bar and 24 mills per kw-hr average to the residential consumer.

The effect on the transportation cost of each of the main parameters in the cost analysis will be determined. The parameters, the baseline values for the parameters, and range of variation of the parameters are listed in table 5-1. The effect of a parameter will be determined by varying the parameter, keeping the other parameters fixed at the baseline value. The results are presented in table 5-2 and the effect of the following parameters on the space transportation cost are discussed below:

(1) Destination
(2) Dose rate
(3) Earth storage time
(4) Space disposal fund interest rate
(5) Activity concentration

Effect of destination on cost. - The gross payload and the cost per pound of gross payload are presented in table 3-1 for the candidate destinations and the required vehicles. Gross payload is defined as the waste container and the structure attached permanently to it. The ratio of radioactive waste to gross payload depends on the character of the waste and the design of the container. The cost per pound of gross payload for the candidate destinations is listed below:

Earth escape, \$/lb of gross payload	628
High Earth orbit	628
Solar orbit via Mars or Venus	794
Solar orbit	800
Solar escape via Jupiter	3500
Solar impact via Jupiter	4700
Direct solar escape	4420
Direct solar impact	Payload is zero with existing vehicles

The effect of the destination on space transportation cost in terms of mills per kW hr electric is presented in table 5-2 for several destinations. The cost for Earth escape, solar orbit, and solar escape is 4, 5, and 28 mills/kw-hr.

Effect of dose rate. - The effect of varying the dose rate from 1 rem/hr to 500 rem/hr was determined for the Earth escape destination and is shown in figure 5-7. The cost per pound of waste delivered for the 10 rem/hr dose is 65 percent of the 1 rem/hr cost. The cost for the 500 rem/hr dose is 33 percent of the 1 rem/hr cost.

Effect of Earth storage time. - The effect of Earth storage times of 10, 20, and 40 years was determined and is shown in figure 5-8. The cost to the electric customer goes down as the storage time increases primarily due to the increased interest accumulated on the disposal fund. The cost of storing the material is small compared to the interest on the fund and is neglected in this analysis. The activity of the waste decreases with time which also tends to reduce the cost of disposal (less shielding, more waste payload). However, unless the nonradioactive decayed materials are removed from the waste to keep the curies per cc near the original level, the shield weight savings will be small. Time affects the cost in another and more significant way. Interest on the funds set aside for waste disposal increase much faster than the fission products decay. The time for 10 year old fission products to decay by half is about 30 years. The money doubling time is about 10 years at a seven percent interest rate. The effect on cost due to fission product decay during storage is neglected. Only the effect of interest on money in the disposal fund is considered. The cost per pound of waste delivered for the 20 year storage case was about half the 10 year cost and the 40 year storage time was about 1/8 of the 10 year cost. At a 7 percent interest rate the charge to the customer is reduced by half for each ten year storage time. Therefore, a storage time can be found for each destination which will make the initial charge to the electric consumer acceptable.

Effect of space disposal interest rate. - The interest on the space disposal fund can affect either the space transportation cost or the required storage time. The effect of interest rates of 5, 7, and 10 percent were determined and are shown in figure 5-8. The cost at a 7 percent interest rate for materials stored ten years in about 1.3 times that at 10 percent and about 80 percent of that at 5 percent. To get the same transportation cost at 5 and 10 percent as for 7 percent with a storage time of 10 years requires a storage time of about 14 years at 5 percent and 7 years at 10 percent.

Effect of activity concentration. - Increasing the concentration of the radioactive waste has a strong effect on the transportation cost but the amount the concentration can be increased is limited. Doubling the concentration would reduce the cost by about 45 percent. In general, the gain is not this great because the diameter must be reduced to keep the centerline temperature below the maximum stable temperature. The base case in this study had a concentration of 10 curies per cc and the full density fission products have a density about 26 curies/cc after 10 year storage. Thus going to full density fission products would reduce the costs by possibly more than half. The costs could be further reduced by removing the gamma emitters and/or the high thermal energy emitters and launching the harmful wastes that remain. The cost of launching separated radioactive wastes will be considered in later reports.

5.4 Number of Shuttle Launches per Year

The production rate of ten-year old fission products as a function of years from 1970 to 2000 is shown in figure 5-9. The amount of fission products that can be carried per launch is a function of

(1) Destination
(2) Dose rate
(3) Fission product concentration

Figure 5-10 shows the number of launches per year to 2010 AD for Earth escape, single or double launch mode, Earth storage for ten years, and three dose levels. In 1985 the required number of launches for dose levels of 1, 10, and 500 rem/hr at 3 meters from the package center are 300, 210, and 115, respectively. The effect of the other parameters on the number of launches per year is shown in table 5-2. The payload to Earth orbit is about equal to the payload to Earth escape and the number of launches is also similar. The payload to solar escape is about 10 percent of the payload to Earth escape and the number of launches would be increased accordingly. Increasing the Earth storage time to 40 years decreases the total activity by 50 percent. The number of launches is decreased accordingly if the fission product concentration is assumed to be maintained at 10 curies/cc thus keeping the curies per launch constant (i.e., more grams of fission products for the same dose level with longer storage time). An additional decrease in launch frequency could be obtained by removing the decayed isotopes after a long storage time.

It appears that launching of all fission products at an early time period results in a higher cost and high launch frequency. Both can be avoided by holding for a longer time followed by separation.

6. CONCLUSIONS

For this report all of the fission products (i.e., no separation) were considered for space disposal after being stored in Earth-storage facilities for 10 years. The fission products were assumed to be mixed in a solidified matrix material and contained in cylinders. These cylinders were sized based on the temperature limits on the matrix material and shielded to reduce the radiation dose rate to levels ranging from 1 to 500 rem/hr at 3 meters from the center of the package. In this report the impact of accidents on safety was not considered, and thus the conclusions obtained pertain only to the package as designed for normal operations. This implies minimum cost and maximum quantity of fission products per payload. The payloads were based on results of a previous study (ref. 4) in which the shuttle was selected as the lowest-cost vehicle. The destinations chosen for the report for comparison were Earth escape, Solar orbit, and Solar escape. The following conclusions were obtained from the results presented.

1. Matrix material such as spray melt can be used without exceeding temperature limits on matrix, but materials with higher thermal conductivity would be more desirable. Diameters of 28 inches or less were acceptable but not optimum based on fission products per package or cost.

2. The cost in terms of mills per kw hr electric, of space disposal of fission products (after 10 year temporary storage) in matrix materials and containers currently designed for Earth disposal and shielded (1 rem/hr) is 4, 5, and 28 mills per kw hr for Earth escape, solar orbit, and solar escape, respectively. This compares to 8 mills per kw hr bus-bar cost and about 24 mills per kw hr average consumer cost.

3. A major factor effecting cost was the Earth storage time. Assuming 7 percent interest on the funds set aside for space disposal, the cost to the electric consumer of space disposal is reduced by a factor of 2 for each 10 years of storage time. If the fission products are stored for 40 years prior to launch then the cost to the electric consumer are 0.5, 0.6, and 3.5 for Earth escape, solar orbit, and solar escape, respectively. There is, therefore, for each destination, a storage time that will make the initial charge to the electric consumer acceptable. Based on a normal operating condition design for solar escape, a storage time of more than sixty years is required to make the space disposal charge less than 10 percent of the bus-bar electric cost.

4. Large changes in dose rate are required to significantly affect the cost. Increasing the dose at 3 meters from the center of the package from 1 to 500 rem/hr results in factor of 3 reduction in cost.

5. The number of shuttle launches would exceed a launch per day within 5 years after the program was initiated if the material was launched as prepared for Earth storage and held for 10 years without further processing.

Inasmuch as fission products will decay with time, both the space transportation cost and number of launches can be reduced considerably by increasing hold time. Large reductions in launch costs might possibly be achieved if the fission products are separated and only, say, the actinides are launched into space. The actinides, in particular, present a special hazard if they are permanently stored on the Earth because they have such very long half-lives. The extent to which this principal hazard can be reduced at low launch cost warrants further study.

REFERENCES

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3. Schneider, K. J.: Solidification and Disposal of High-Level Radioactive Wastes in the United States. Reactor Tech., vol. 13, no. 4, Winter 1970-71, pp. 387-415.
4. Ramler, J.; Thompson, R. L.; and Stevenson, S.: Study of Extraterrestrial Disposal of Radioactive Wastes. Part I. Proposed NASA Technical Memorandum.
5. Jaeger, R. G., ed.: Engineering Compendium on Radiation Shielding. Vol. III. Springer-Verlag, 1970, pp. 21-23.
6. Anon.: Potential Nuclear Power Growth Patterns. Rep. WASH-1098, USAEC, Dec. 1970.

TABLE 2-1. - FISSION PRODUCT YIELDS FROM TYPICAL POWER REACTORS

	LWR	LMFBR
Power density per ton of fuel loading	30 Mwt/metric ton	58 Mwt/metric ton
Thermal energy yield per ton of fuel loading	33 000 Mwt-days/metric ton	33 000 Mwt-days/metric ton
Efficiency	33 percent	40 percent
Electric energy yield per ton of fuel loading	10 900 Mwe-days/metric ton	13 200 Mwe-days/metric ton
Fission product mass per ton of fuel loading	3.51×10^{4} gm/metric ton	3.49×10^{4} gm/metric ton
Fission product mass per Mwe-day	3.23 gm/Mwe-day	2.64 gm/Mwe-day
Fission product activity after 10 year hold	28.5 curies/Mwe-day	21.2 curies/Mwe-day
Radioactivity per gram after 10 year hold	8.83 curies/gm	8.03 curies/gm
Gamma ray	3.0 curies/gm-0.7 Mev E_{avg}	
Beta ray	5.8 curies/gm-0.4 Mev E_{avg}	
Fission product thermal power/gm after 10 year hold	0.0286 watts/gm	0.023 watts/gm

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TABLE 2-2. - CHARACTERISTICS OF WASTE IN MATRIX MATERIALS

DESIGNED FOR STORAGE ON EARTH

	Pot calcine	Spray melt	Phosphate Gl.	Fluid-bed calcine
Form hardness	Cake, crumbly soft	Single, tough mold hard	Single, brittle mold very hard	Amorphous-granular moderate
Leachability in water, gm/cm^2 day	1.0 to 10^{-1}	10^{-3} to 10^{-6}	10^{-4} to 10^{-7}	1.0 to 10^{-11}
Fission-prod oxides in mixture, mole %	Up to 80	Up to 30	Up to 25	Up to 50
Thermal condition, watt/M(K)	0.25 to 0.5	0.8 to 1.8	0.7 to 1.8	0.2 to 0.5
Density, gm/cc	1.1 to 1.5	2.7 to 3.5	2.7 to 3.0	1.0 to 1.7
Maximum stable temperature, K	~1170	~1170	~770	~870
Container material	Stainless steel	Mild or stainless steel	Mild or stainless steel	Mild or stainless steel
Maximum curies/cc	~10	~9	~7	~8

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TABLE 3-1. - CANDIDATE LAUNCH VEHICLES, DESTINATIONS, COSTS, COSTS PER POUND OF PAYLOAD

Candidate launch vehicle and tug combinations	Launch cost[a]	Destinations									
		Earth orbit or Earth escape		Direct solar escape		Solar impact via Jupiter		Solar escape via Jupiter		Solar orbit	
		Payload, wt (lb)	Cost per pound, $/lb	Payload, wt (lb)	Cost per pound, $/lb	Payload, wt (lb)	Cost per pound, $/lb	Payload, wt (lb)	Cost per pound, $/lb	Payload, wt (lb)	Cost per pound, $/lb
Shuttle (1) and reusable tug (1)	11 M	17 500	628	0	0	0	0	0	0	10 400	1058
Shuttles (2) and reusable tug (1)	21 M	31 000	677	0	0	0	0	0	0	15 500	1355
Shuttles (2) and reusable tug (2)	22 M	37 300	590	0	[b]0	0	0	0	0	27 700	794
Shuttle (1) and expendable tug (1)	25 M	24 000	1041	2 700	9 259	5 300	4 717	7 000	3571	19 400	1288
Saturn V/Centaur	200 M	108 000	1852	16 400	12 195	25 700	7 782	32 000	6250	84 200	2375
Saturn V	200 M	10 000	2000	0	0	12 400	16 130	20 100	9950	78 000	2564

[a]Cost does not include guidance for tug.

[b]Shuttle (2), expendable tug (1), and reusable tug (1) 8140 lb, cost/lb = $4420.

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TABLE 5-1. - RANGE OF PARAMETERS FOR SPACE TRANSPORTATION COST ANALYSIS

Parameter	Baseline value	Range
Destination and gross payload		Solar orbit (10 400 lb)
Single shuttle	Earth escape (17 500 lb)	Solar escape (2700 lb)
Dual shuttle	Earth escape (31 000 lb)	Solar orbit (15 500 lb)
		Solar escape (2700 lb)
Dose rate at 3 meters from container center	1 rem/hr	10 and 500 rem/hr
Launch cost		
Single shuttle	11 million dollars	No range
Dual shuttle	21 million dollars	
Earth storage time	10 years	20 and 40 years
Interest on space disposal fund	7 percent	5 and 10 percent
Activity concentration	10 curies/cc	20 and 40 curies/cc

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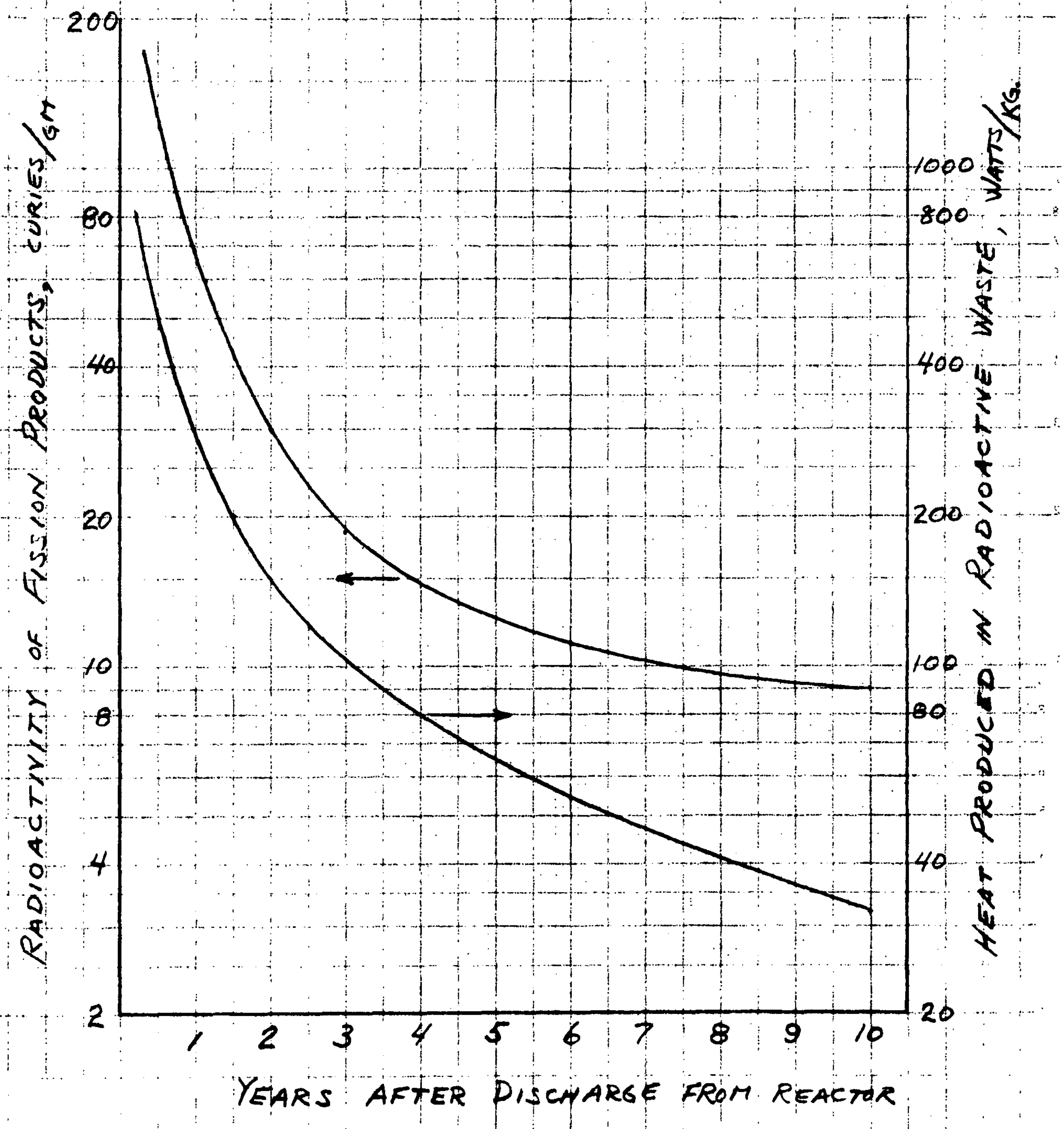
TABLE 5-2. - RESULTS OF SPACE TRANSPORTATION COST ANALYSIS FOR SINGLE SHUTTLE

Parameters for single shuttle launch mode	Cost			Amount of fission products per launch		Number of shuttle launches	
	Mills per kilowatt hour	Percent increase over base rate		Pounds	Megacuries	1985	1995
		Bus-bar at 8 mills	Consumer at 24 mills				
Baseline parameter case, Earth escape 1 rem/hr, 10 yr, 7%, 10 curies/cc	4	50	17	380	1.52	285	1520
Destination							
Solar orbit	5	62	21	304	1.21	342	1825
Solar escape	28	350	116	58	.23	1860	9900
Dose rate at 3 meters from container center							
10 rem/hr	2.6	32	11	600	2.45	180	960
500 rem/hr	1.3	16	5.5	1120	4.57	97	520
Earth storage time							
20 years	2.1	26	9	380	1.52	----	----
40 years	.53	6.6	2.2	380	1.52	----	----
Interest on space disposal fund							
5 percent	4.9	61	20	380	1.52	285	1520
10 percent	3.1	38	13	380	1.52	285	1520
Activity concentration							
20 curies/cc	2.1	26	9	730	2.96	150	790

FIG. 2-1. FISSION PRODUCT ACTIVITY AND THERMAL POWER AS A FUNCTION OF TIME AFTER PROCESSING SPENT FUEL ELEMENTS



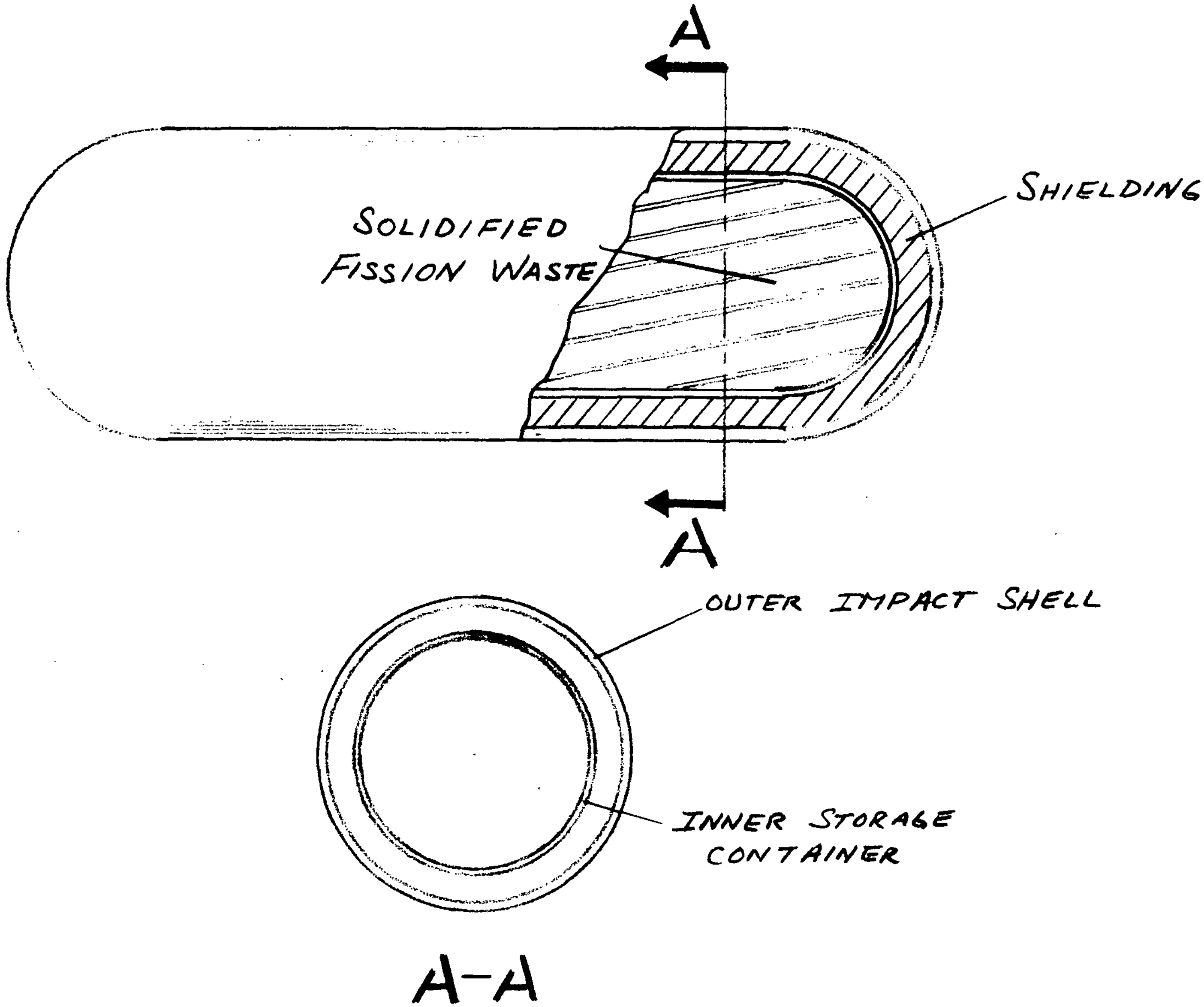


Figure 2-2 Typical Radioactive Container and Shielding for Space Disposal.

Fig. 5-1a Temperature at Center of Cylindrical Containers Containing Fission Product Waste Material Stored for 10 Years . Shielded with depleted uranium for 10rem/hr at 3 meters from the center of the cylinder.

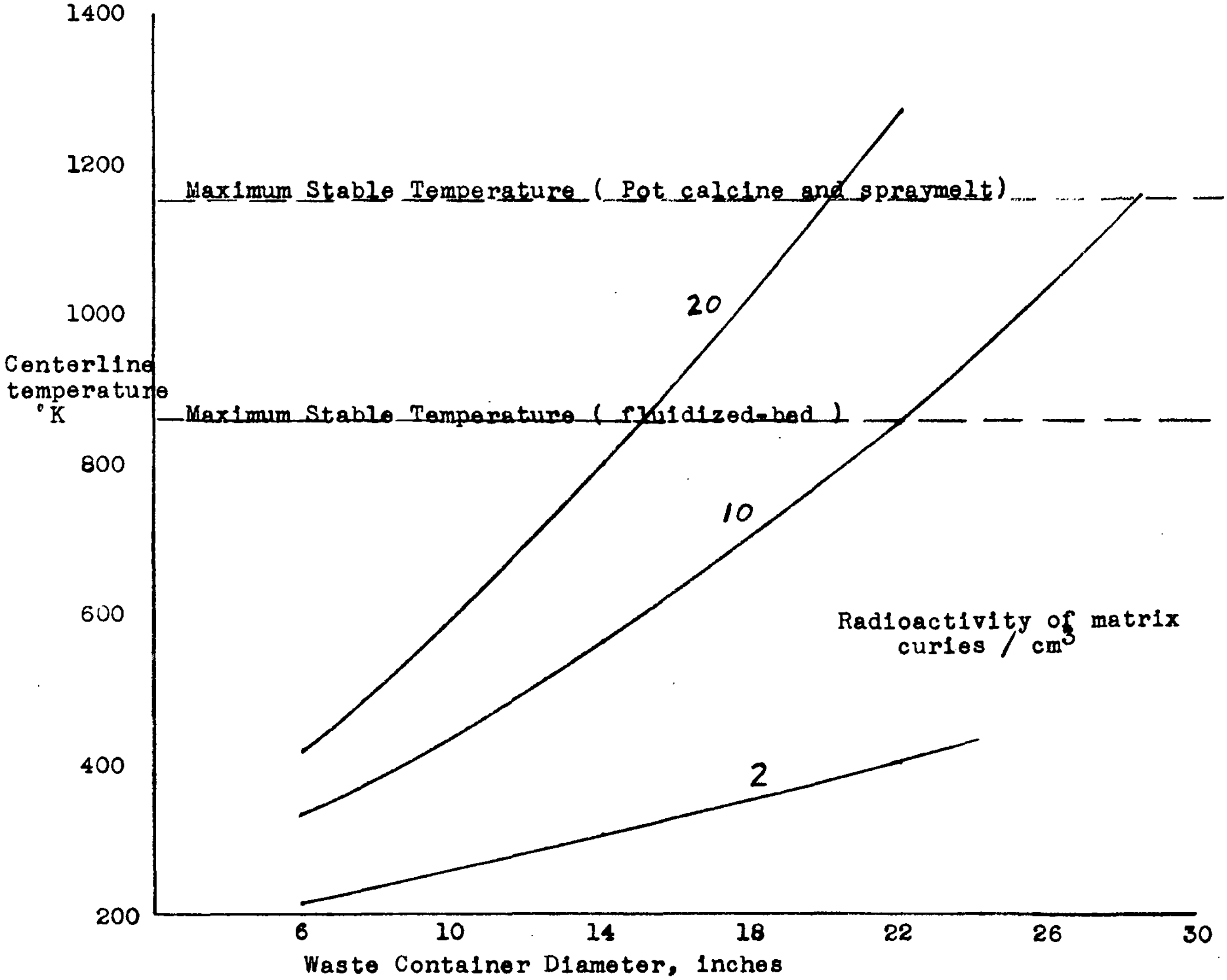
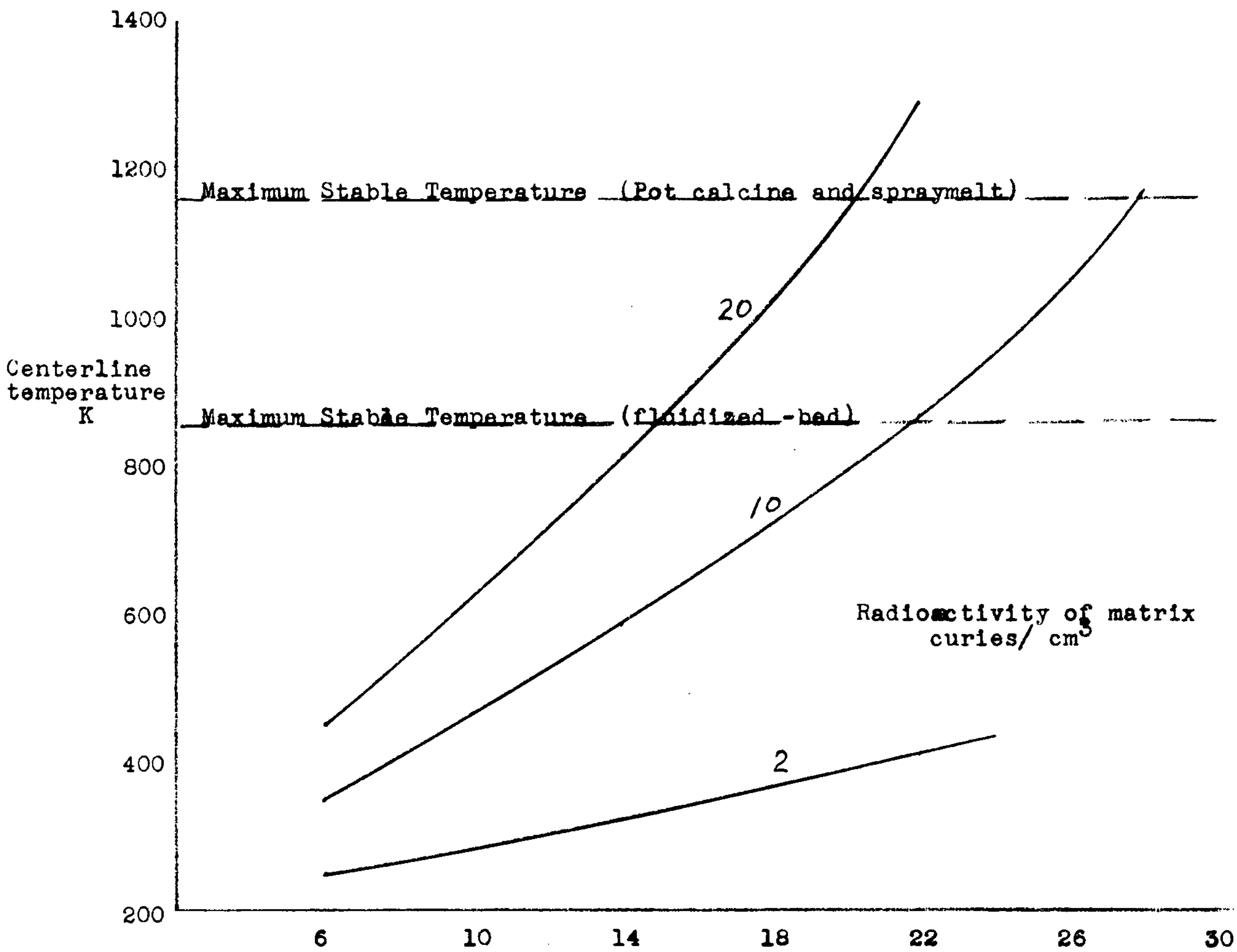


Fig. 5-1b Temperature at Center of Cylindrical Containers Containing Fission Product Waste Material Stored for 10 Years. Shielded with depleted uranium for 500rem/hr at 3 meters from the center of the cylinder.

(k = 1.7 watts/meter -°K)



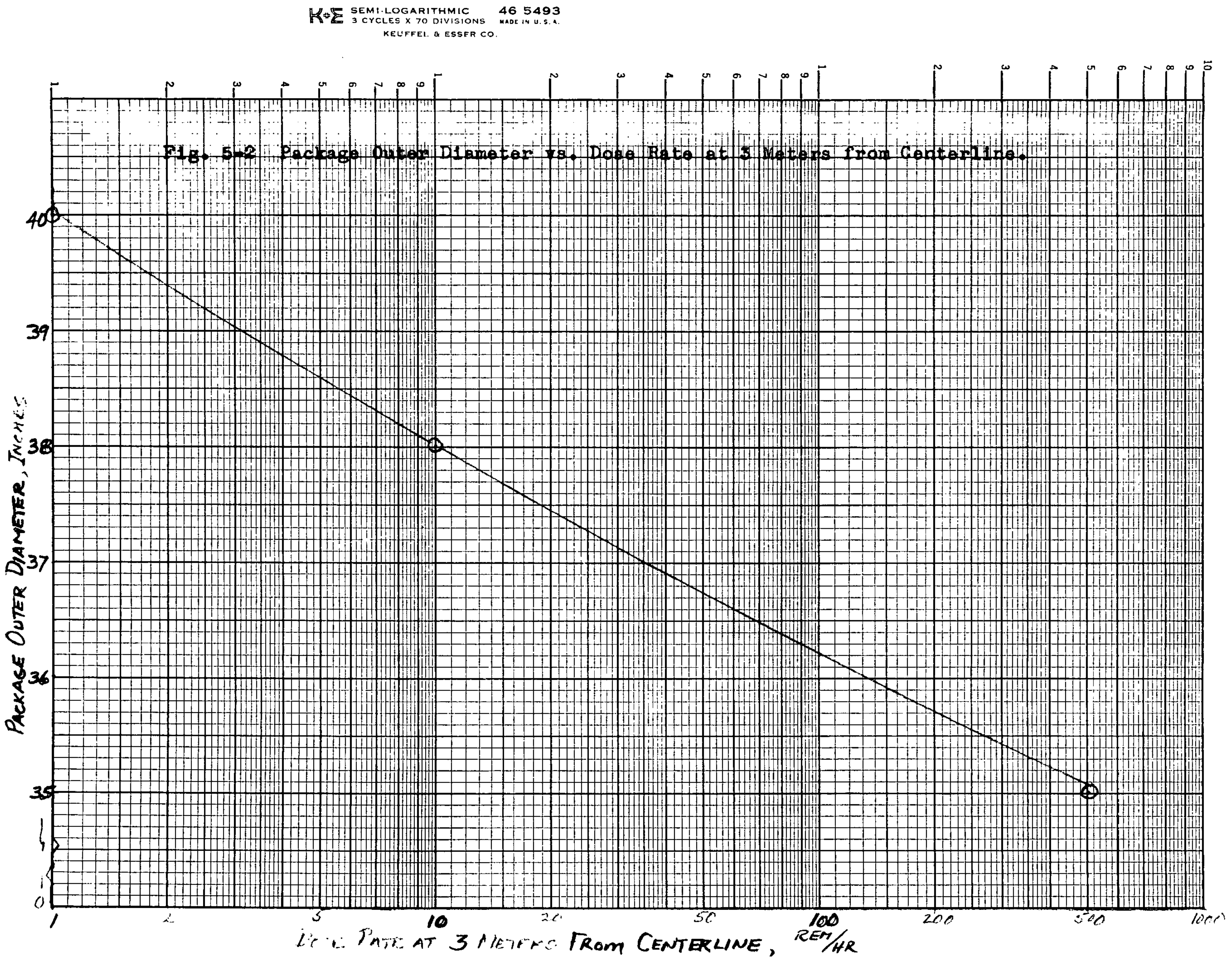


Fig. 5-2 Package Outer Diameter vs. Dose Rate at 3 Meters from Centerline.

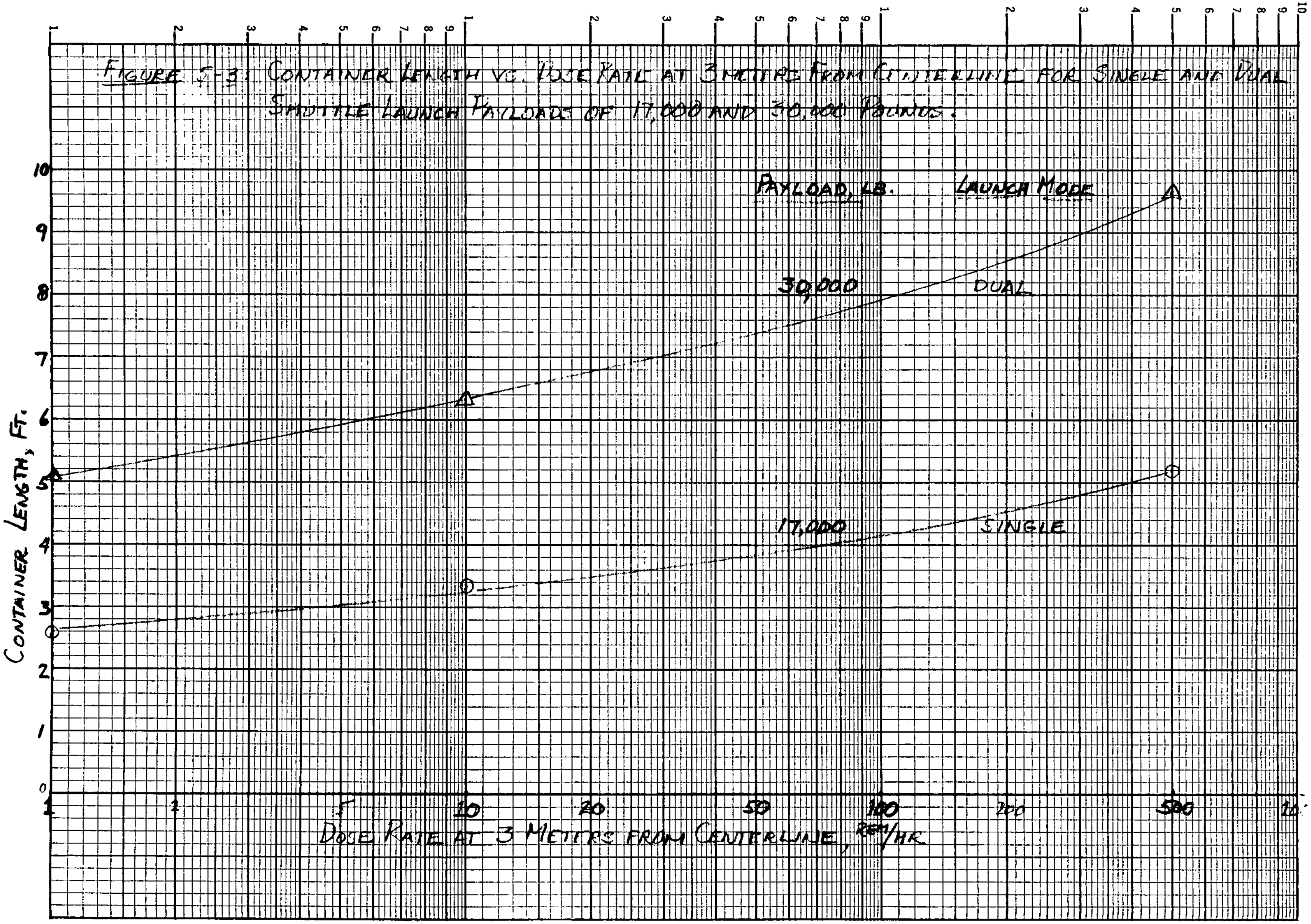


FIGURE 5-3: CONTAINER LENGTH VS. DOSE RATE AT 3 METERS FROM CENTERLINE FOR SINGLE AND DUAL SHUTTLE LAUNCH PAYLOADS OF 17,000 AND 30,000 POUNDS.

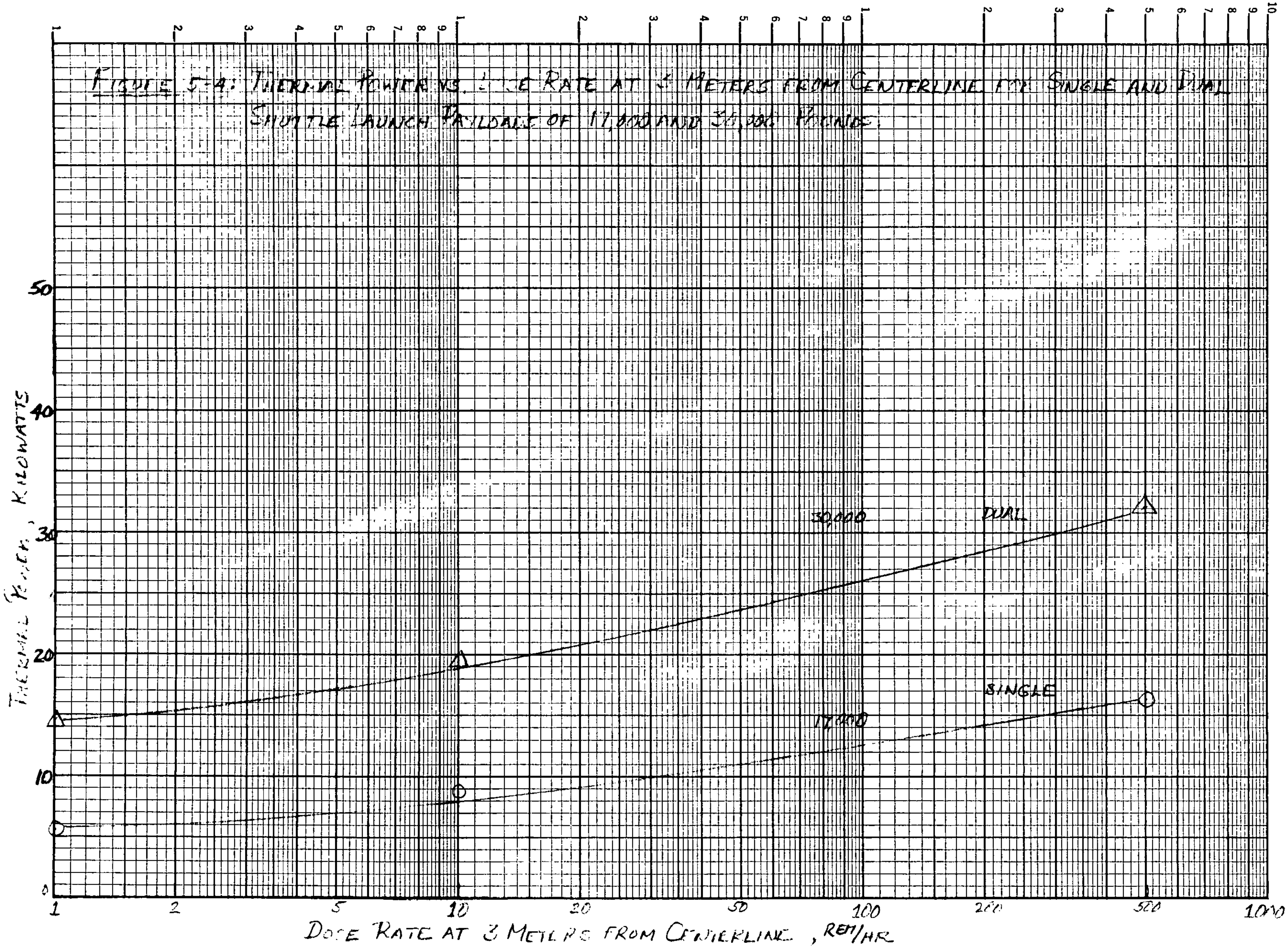
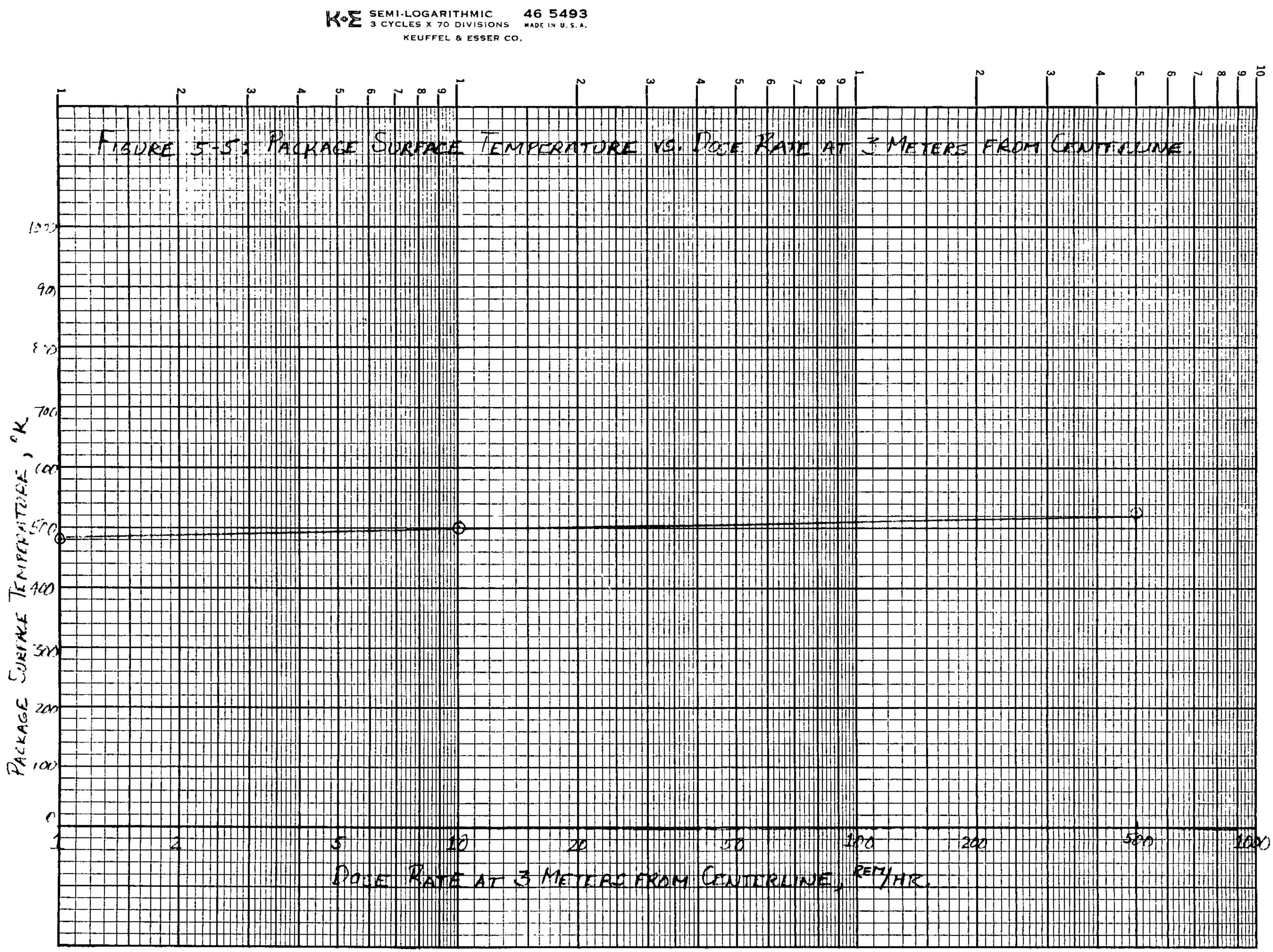


FIGURE 5-4: THERMAL POWER VS. DOSE RATE AT 3 METERS FROM CENTERLINE FOR SINGLE AND DUAL SHUTTLE LAUNCH PAYLOADS OF 17,000 AND 30,000 POUNDS.


K+E SEMI-LOGARITHMIC 46 5493
3 CYCLES X 70 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.
FIGURE 5-5: PACKAGE SURFACE TEMPERATURE VS. DOSE RATE AT 3 METERS FROM CENTERLINE.
PACKAGE SURFACE TEMPERATURE, °K
1000
900
800
700
600
500
400
300
200
100
0
1
2
5
10
20
50
100
200
500
1000
DOSE RATE AT 3 METERS FROM CENTERLINE, REM/HR.

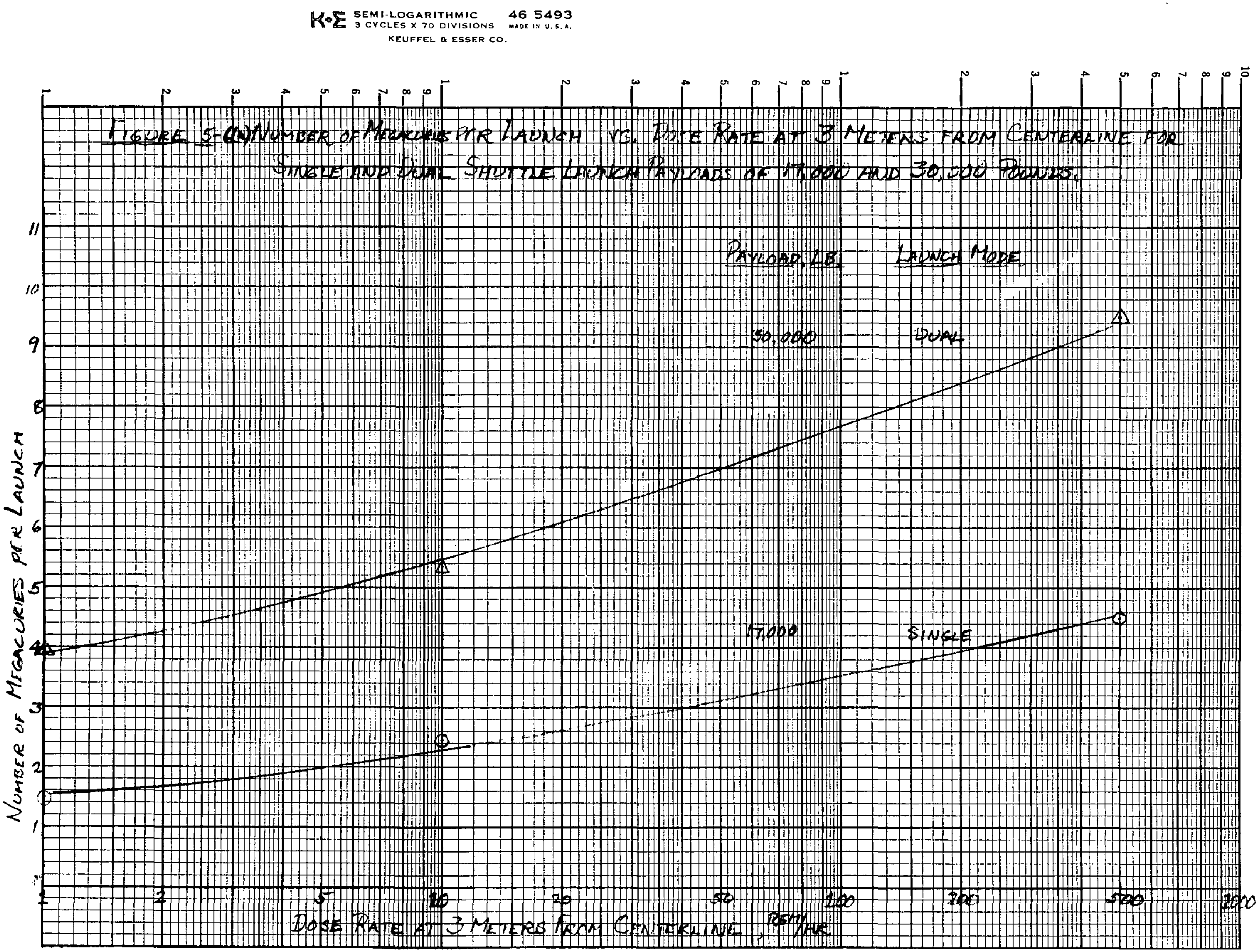
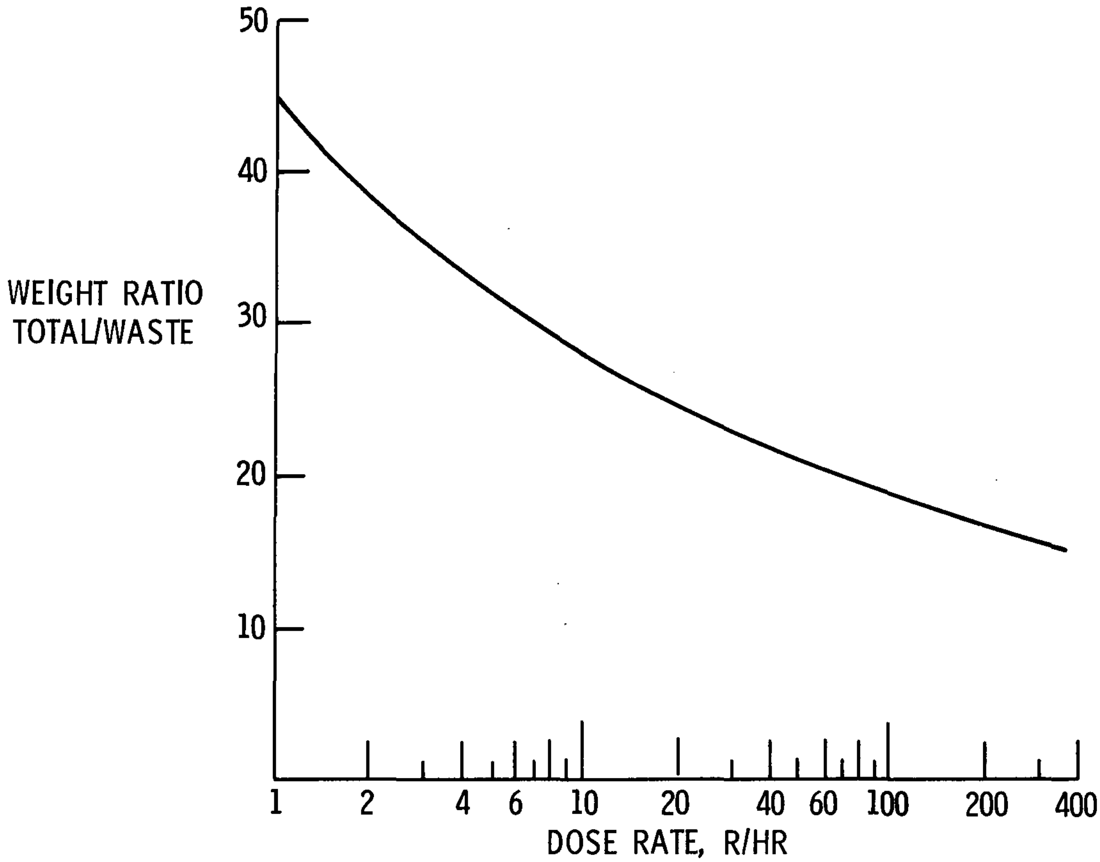


FIGURE 5-(4) NUMBER OF MEGACURIES PER LAUNCH VS. DOSE RATE AT 3 METERS FROM CENTERLINE FOR SINGLE AND DUAL SHUTTLE LAUNCH PAYLOADS OF 17,000 AND 30,000 POUNDS.

Fig. 5-6b PACKAGING RATIO FOR ALL FISSION PRODUCTS - PHASE I
ASSUMING 10-YR EARTH STORAGE



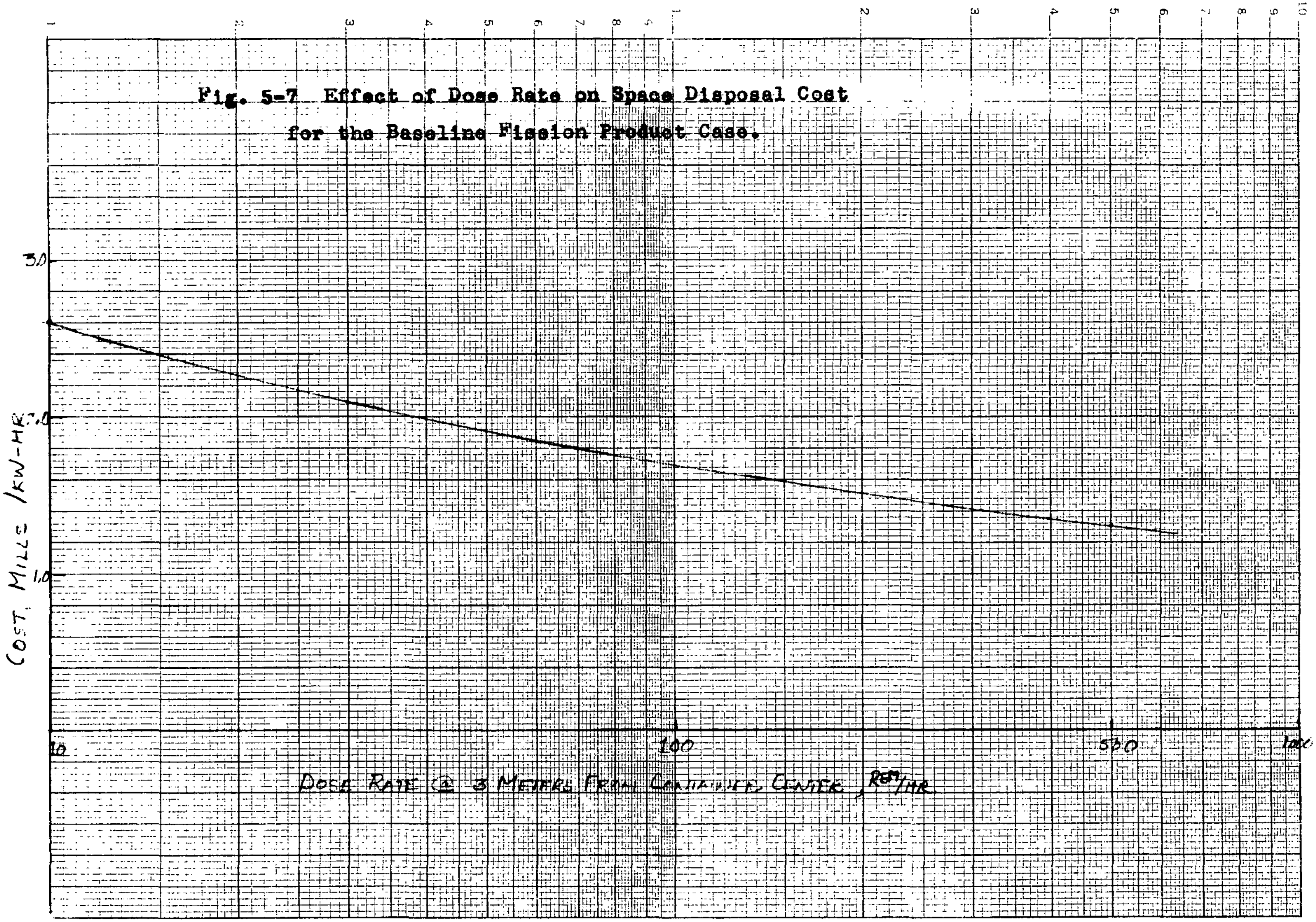


Fig. 5-7 Effect of Dose Rate on Space Disposal Cost for the Baseline Fission Product Case.

K+E SEMI-LOGARITHMIC 2 CYCLES X 131 DIVISIONS 46 5133 KEUFFEL & ESSER CO.

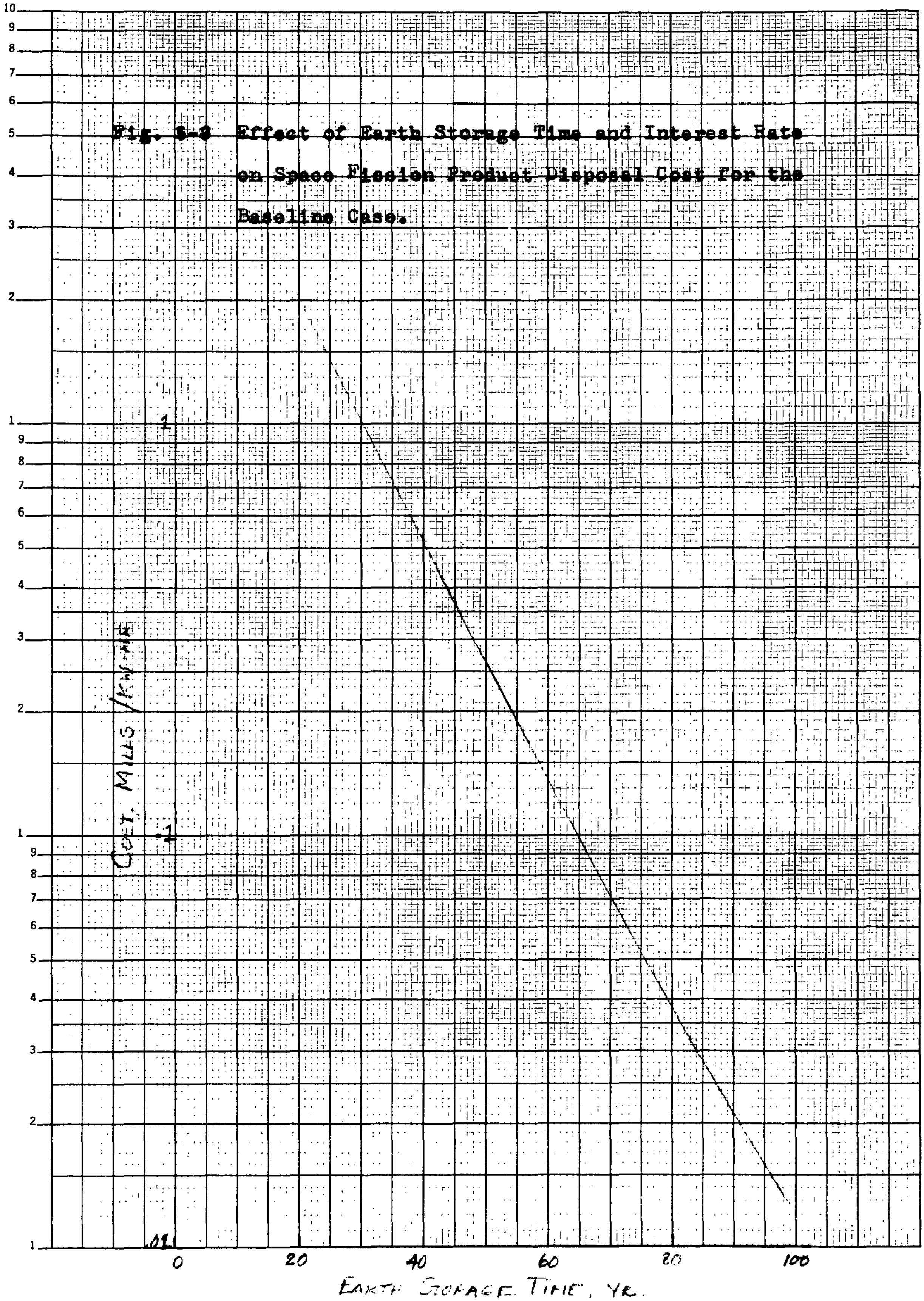


Fig. 6-2 Effect of Earth Storage Time and Interest Rate on Space Fission Product Disposal Cost for the Baseline Case.

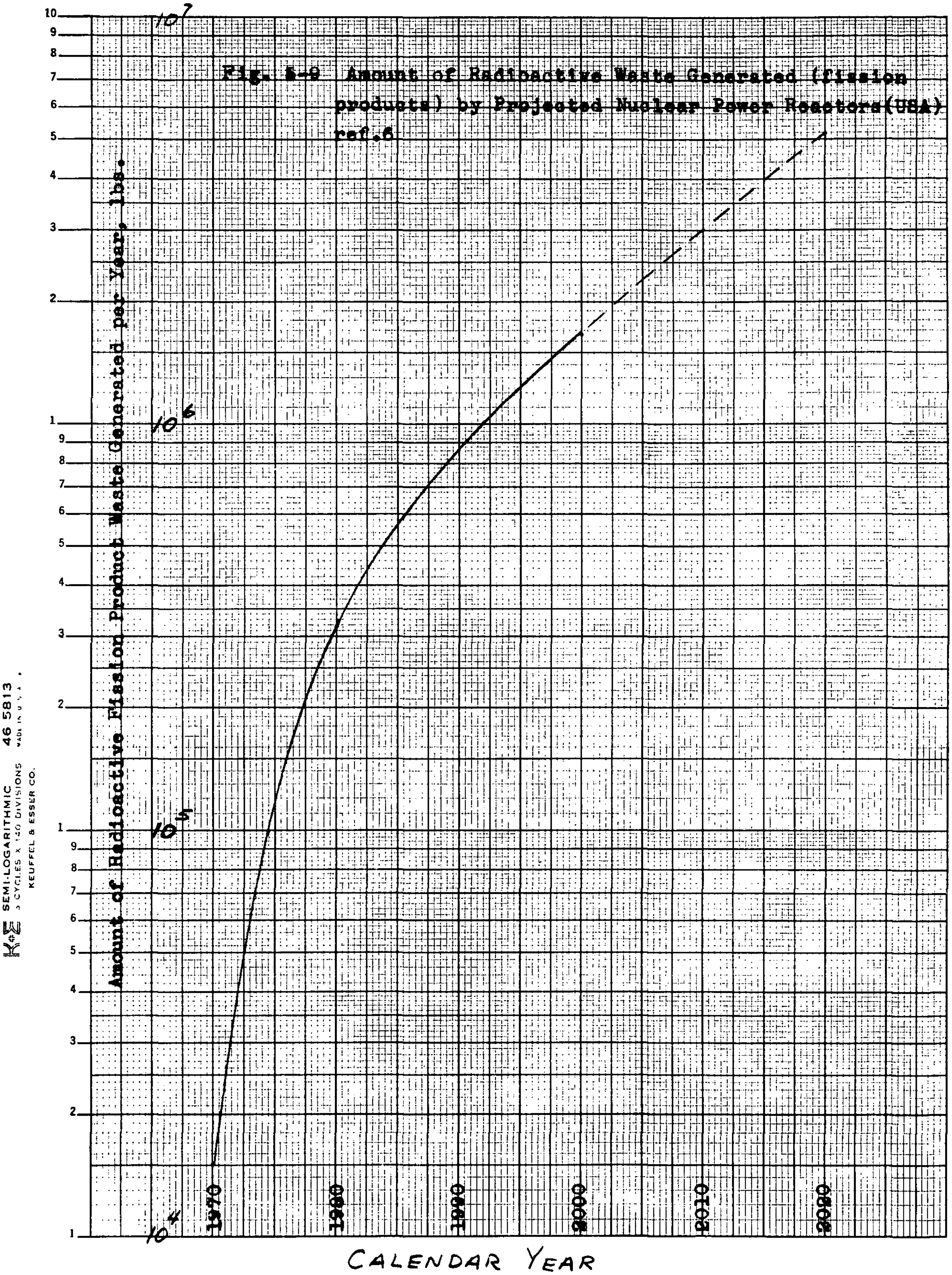


Fig. 5-9 Amount of Radioactive Waste Generated (fission products) by Projected Nuclear Power Reactors (USA) ref.6

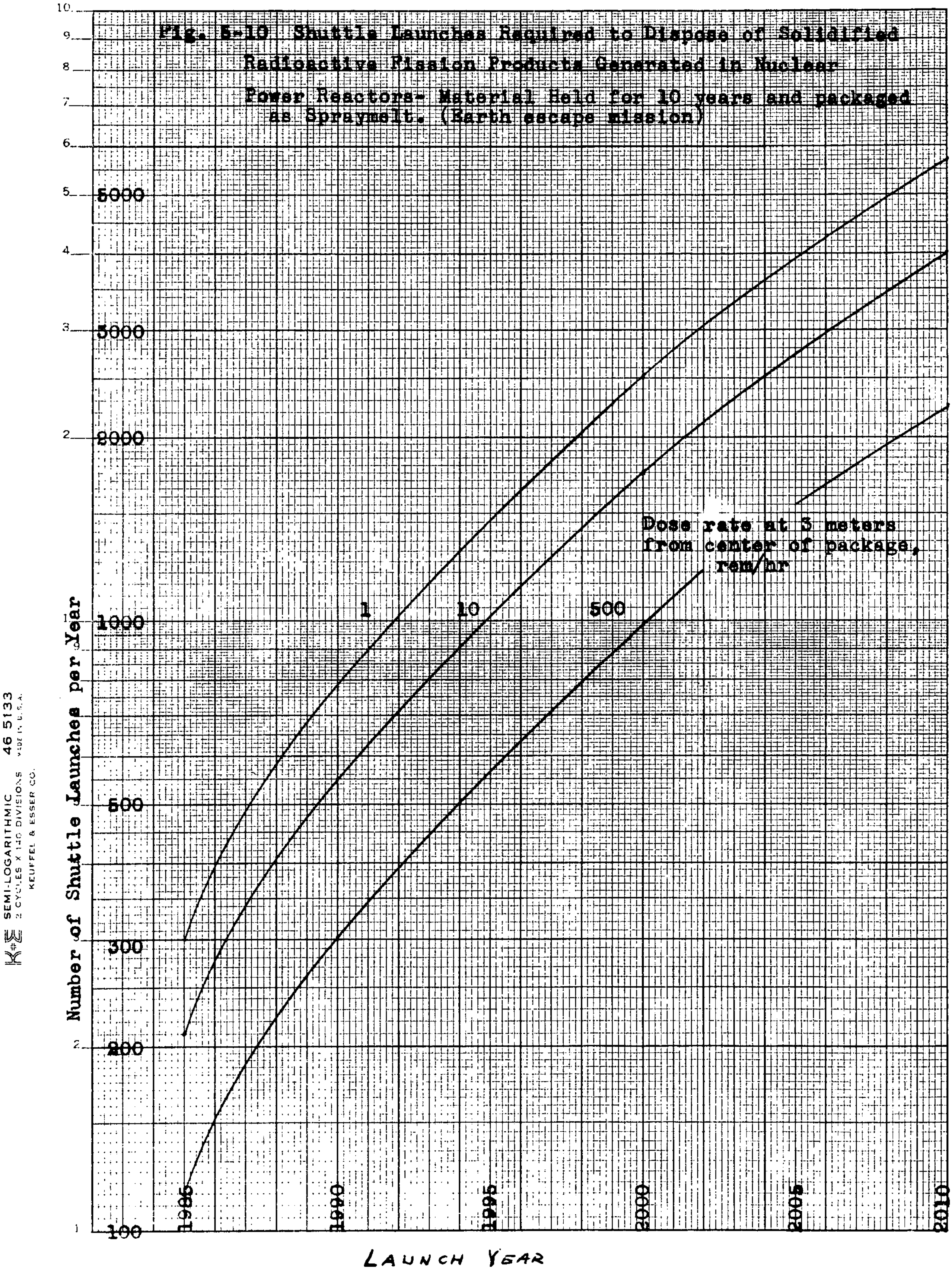


Fig. 5-10 Shuttle Launches Required to Dispose of Solidified Radioactive Fission Products Generated in Nuclear Power Reactors- Material Held for 10 years and packaged as Spraymelt. (Earth escape mission)
Number of Shuttle Launches per Year
5000
3000
2000
1000
500
300
200
100
1
10
500
Dose rate at 3 meters from center of package, rem/hr
1985
1990
1995
2000
2005
2010
LAUNCH YEAR
SEMI-LOGARITHMIC 46 5133
2 CYCLES X 140 DIVISIONS MADE IN U.S.A.
KEUFFEL & ESSER CO.