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Estimates of the Radiation Environment for a Nuclear Rocket Engine

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ABSTRACT

Ambitious missions in deep space, such as manned expeditions to Mars, require nuclear propulsion if they are to be accomplished in a reasonable length of time. Current technology is adequate to support the use of nuclear fission as a source of energy for propulsion; however, problems associated with neutrons and gammas leaking from the rocket engine must be addressed. Before manned or unmanned space flights are attempted, an extensive ground test program on the rocket engine must be completed. This paper compares estimated radiation levels and nuclear heating rates in and around the rocket engine for both a ground test and space environments.

INTRODUCTION

Knowledge of the neutron and gamma ray effective dose equivalent and heating rates in and around the rocket engine is important in the selection of materials and in determining the optimum configuration of engine components. Our model of the rocket engine is based on the PHOEBUS[1] and NERVA[2,3,4] designs developed and tested in the 1960s. While space reactor technology has advanced greatly, little has been accomplished in the deployment of nuclear powered rockets since the early 1970s. More recent designs may differ somewhat from the LSU model, but there are enough similarities so that our estimates should be of use to today's designers.

Capture gamma rays and reflected leakage radiation from the reactor core make the ground test environment more severe than that encountered when the engine operates in the vacuum of outer space. [illegible] standards for environmental protection as well as to minimize radiation exposure to personnel. Because of the high radiation levels, such facilities should be located in isolated areas and incorporate a high degree of sophistication in the application of remote systems technology.

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DISCLAIMER

THE RADIATION TRANSPORT MODEL

Many of the reactor designs used in earlier nuclear rocket projects are not readily available in the open literature, so we used the materials description from Reference 1 and the critical facility mockup dimensions from Reference 2 to describe the reactor and other engine components. Two-dimensional, discrete ordinates (S_8-P_3) transport calculations were [illegible] obtain the radiation environment.[5] Multigroup cross sections for coupled neutron-gamma transport calculations were obtained from the VELM libraries.[6] Nuclear heating rate estimates are based on the ISOPLOT4 module in the DOGS code package developed at ORNL.[7]

The engine model and key dimensions used in our radiation transport analysis are shown in Figure 1. The reactor includes a shield internal to the aluminum pressure vessel, a radial reflector, and support structures above and below the core. Cooling of the core and all other components within the pressure vessel is provided by a flow of hydrogen; the heated hydrogen is expelled through the nozzle to impart thrust to the entire space vehicle. The Hastelloy-X nozzle is cooled by a portion of the hydrogen flow. Regions inside the pressure vessel are characterized by extremely high temperature gradients perpendicular to the direction of coolant flow. The internal shield protects engine components located above the reactor; the original shield material called BATH, described in Reference 8, is approximated by a mixture of boron and aluminum. It is located about 6 cm above the top of the core and extends 6 cm beyond its lateral surface.[4]

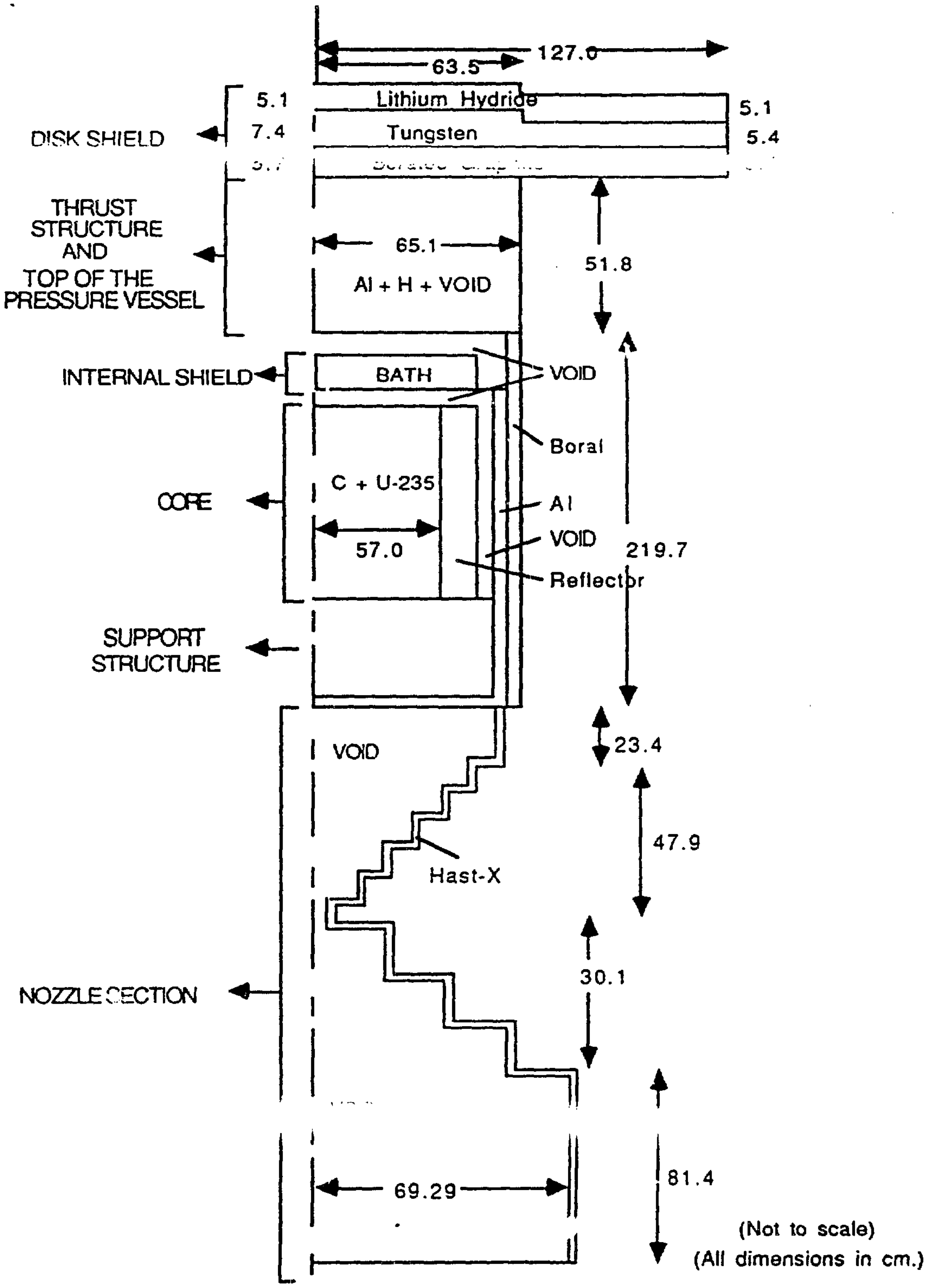
There is a disk shield external to the pressure vessel; its main function is to reduce the mission dose to the crew who would be located tens of meters away on the other side of the propellant tank that contains a time-varying level of liquid hydrogen. This 127 cm radius disk is composed of layers of borated graphite, tungsten, and lithium hydride. It is similar to the shields considered in Reference 4 except that tungsten replaces the lead used in earlier designs. Neutron and gamma heating rates in this shield are of concern in both space and ground test environments.

PREDICTED RADIATION LEVELS

Fluxes in 22 neutron and 10 gamma ray energy groups are calculated throughout the model for a fission power of 1000 Watts. Effective [illegible] Anterior-Posterior conversion factors in ICRP-51. The space environment is simulated by the specification of a vacuum boundary around the engine model. The ground test environment is simulated by using a white boundary condition below the nozzle extension. Engine testing in the 1960s incorporated clamshell side shields around the reactor and a thick shield above it. Such a configuration greatly increases the heating rates of all components within the shielded volume. If the engine is suspended in a test stand without additional shielding, more accurate measurements of

Figure 1

Radiation Transport Model of the Nuclear Rocket Engine



leakage radiation may be made. Also, nuclear heating rates are reduced significantly, especially at high power operation.

Figure 2 presents the isodose equivalent rate plots around the engine in the flight environment; the rates include contributions of both neutrons and photons. Total effective dose equivalent rates normalized to one kilowatt of fission power are given in Table I for the flight environment for key locations in the model. Heating rates in microwatts per cubic centimeter at the same locations are shown in Table II. For the ground test configuration, these rates are increased by about 4% at the nozzle throat and by a factor of two at the bottom of the model. There is no effect above the bottom of the core. Prompt fission and secondary gammas produced in the engine model are included but fission and activation products are not. Since nuclear rocket missions entail relatively short periods of operation, photons from radionuclides should be much less intense than those from prompt fission and neutron capture sources. Therefore, radiation levels and heating rates in these tables can be scaled linearly with the fission power developed in the core.

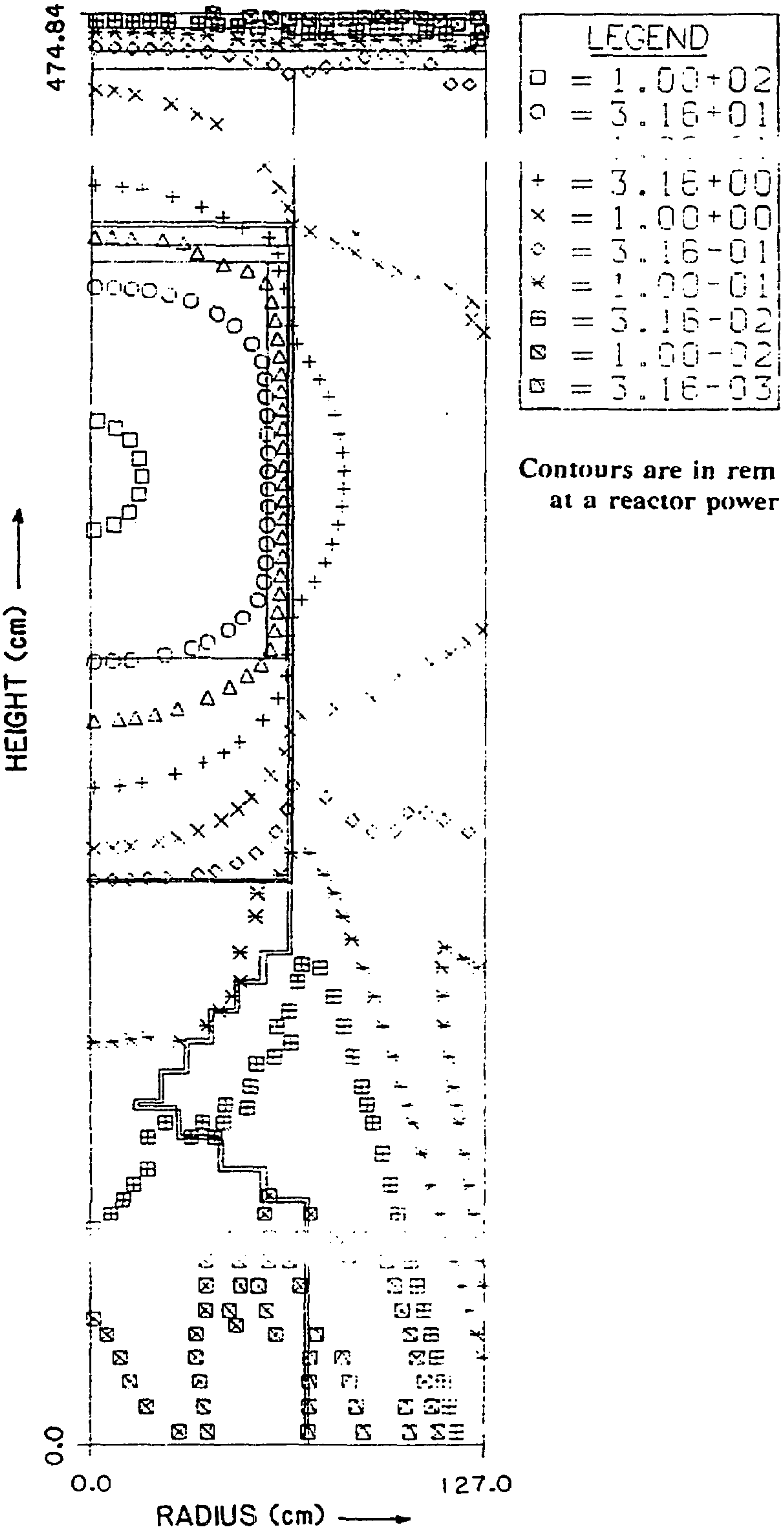
Engines considered in Reference 4 produced up to 75,000 pounds of thrust from 1564 Megawatts of fission power. At this power, heating rates in the lithium hydride in the disk shield would be about 0.13 Watts/cc at the center to 0.01 Watts/cc at the edge for operation in outer space. Nuclear heating can place restraints on both power and operating times, thus influencing mission profiles. Assumptions of initial temperatures and power-time operating sequences strongly affect the temperatures in the components. Of particular concern are the temperatures within the lithium hydride.

APPLICATIONS OF CONTRIBUTON THEORY

A technique called "Contributon Theory" can be used to identify the channels followed by neutron or gamma dose-response as it is transported from the reactor core to the top of the disk shield.[10] Contributons are defined to be those special particles that are actually responsible for generating the response observed at some detector. Figure 3 shows the spatial distribution of the response being carried by contributons in transit from the sources in the core to a "dose detector" located along the top of the disk shield. It can be seen that virtually all of the dose originates from the top few centimeters of the core. The streamlines show that most contributons directly penetrate the shield, causing the peak at the centerline along the top of the disk. There is also a secondary peak in the dose distribution beyond the core radius. The streamlines show that this dose is carried by contributons that leak radially from the core and are scattered by surrounding materials. Contributon Theory should be very helpful when analyzing the more complex radiation flow that would be expected if radial shields enclose the engine in a ground testing configuration.

Figure 2

Isodose Equivalent Rate Contours for the Flight Environment



Contours are in rem per second at a reactor power of 1 kW

Table I

Total Dose Equivalent Rates in Rem per Second per Kilowatt

Location	Centerline	Outer Radius
Top of the Disk Shield	0.0153	0.0020
Bottom of the Disk Shield	0.8872	0.2880
Top of Pressure Vessel	5.680	0.9823
Top of the Core	13.63	4.783
Center of the Core	-	41.20
Bottom of the Core	29.51	9.442
Bottom of Pressure Vessel	0.2345	0.0394
Throat of the Nozzle	0.0666	0.0743
Bottom of the Nozzle	0.0059	0.0023

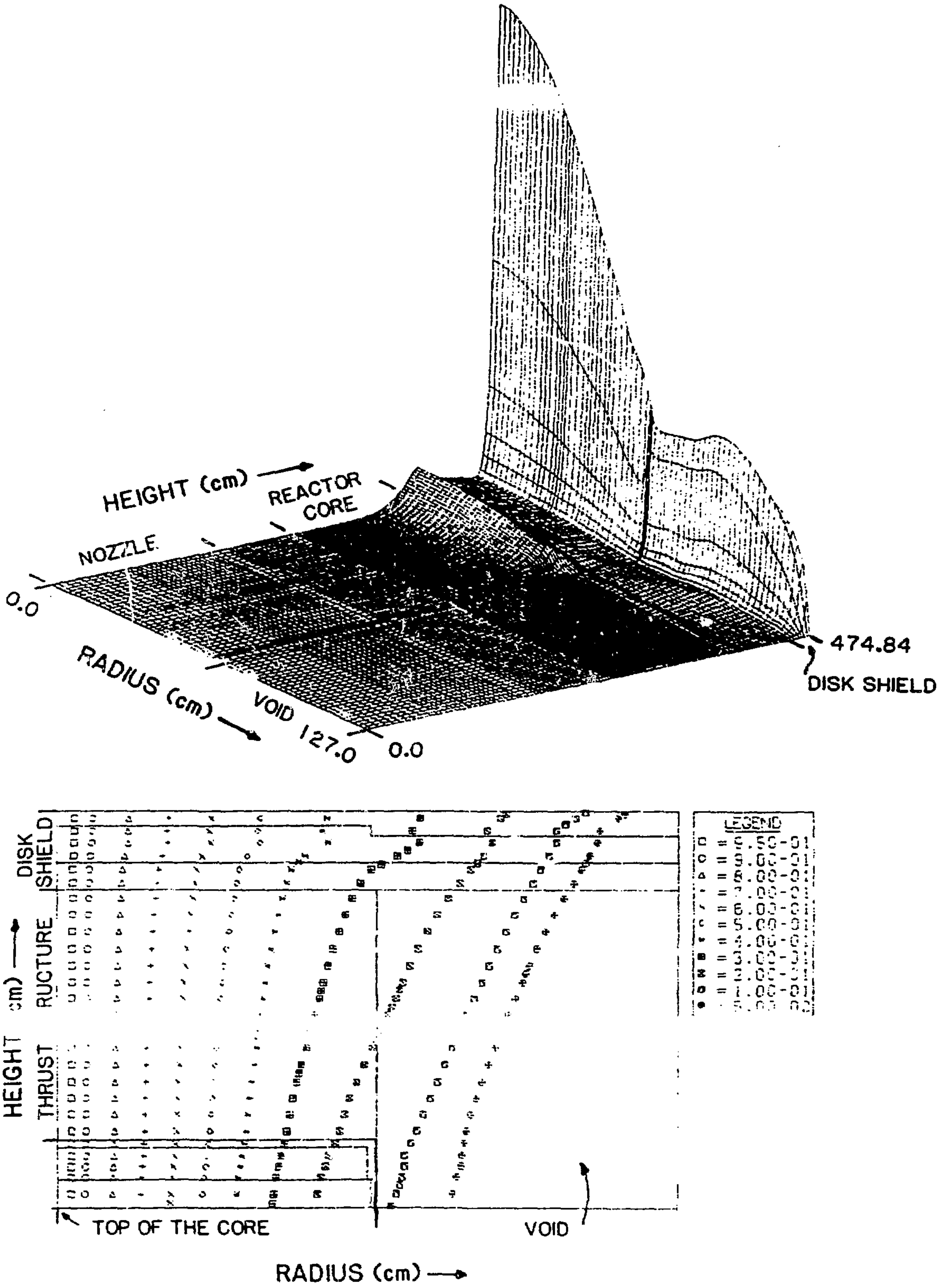
Table II

Total Heating Rates in Microwatts per CC per Kilowatt

Location	Material	Centerline	Outer Radius
Disk Shield	LiH	0.0853	0.00918
Disk Shield	W	4.21	1.25
Top of Pressure Vessel	Al	7.724	2.195
Middle of Internal Shield	Al	10.6	2.98
Pressure Vessel Wall	Al	-	18.31
Bottom of Pressure Vessel	Al	-	0.0331
Throat of Nozzle	Hast-X	-	0.1648
Bottom of Nozzle	Hast-X	-	0.0087

Figure 3

Contributon Response Flux Distribution and Response Streamlines



THE POSTSHUTDOWN ENVIRONMENT

Production of fission and activation products during power production complicates post-test activities as well as space operations such as docking at manned space stations. The ORIGEN-S program was used to estimate the inventory of radionuclides built up in the engine for ten minutes of operation at one kilowatt of thermal power.[11] These data are of use in predicting radiological consequences of releases to the atmosphere during testing as well as for estimating radiation fields near the engine. Ten minutes was selected as a reasonable time for powered operation because nuclear rocket mission profiles generally feature relatively short periods of operation separated by long intervals of time.

Table III shows the gamma dose equivalent rates opposite the axial centerline of the core as functions of distance from the exterior surface of the pressure vessel and decay time. These rates can be scaled linearly with the thermal power developed by fission during reactor operation. A multigroup point kernel microcomputer program, MICROSHIELD, was used to estimate these rates.[12] The twelve gamma energy group structure in the ORIGEN-S output was incorporated in the calculations; a buildup factor appropriate to the beryllium reflector was selected. The rates given in Table 3 are appropriate to the space environment. Reflection from the materials below the engine would increase them somewhat for the ground test environment. The magnitude of the increases depend on the distances from the ground and the engine, as well as on the materials below the test article. Neutron activation of the ground and the test stand would increase the gamma dose rates after reactor shutdown.

A plot of the gamma dose rate as a function of postshutdown decay time is shown in Figure 4; rates are normalized so that they can be used at any distance. The initial steep slope can be characterized by a half-life of 2.3 minutes; beyond 60 minutes, a half-life of approximately 114 minutes is appropriate.

SUMMARY

To assist in the design of ground test facilities and flight hardware, we have developed a nuclear rocket engine model for [illegible], even at low power operation, are significant from a standpoint of protection of personnel; these are of less concern for materials damage. However, neutron and gamma ray heating rates are important in engine design, especially during ground test operation.

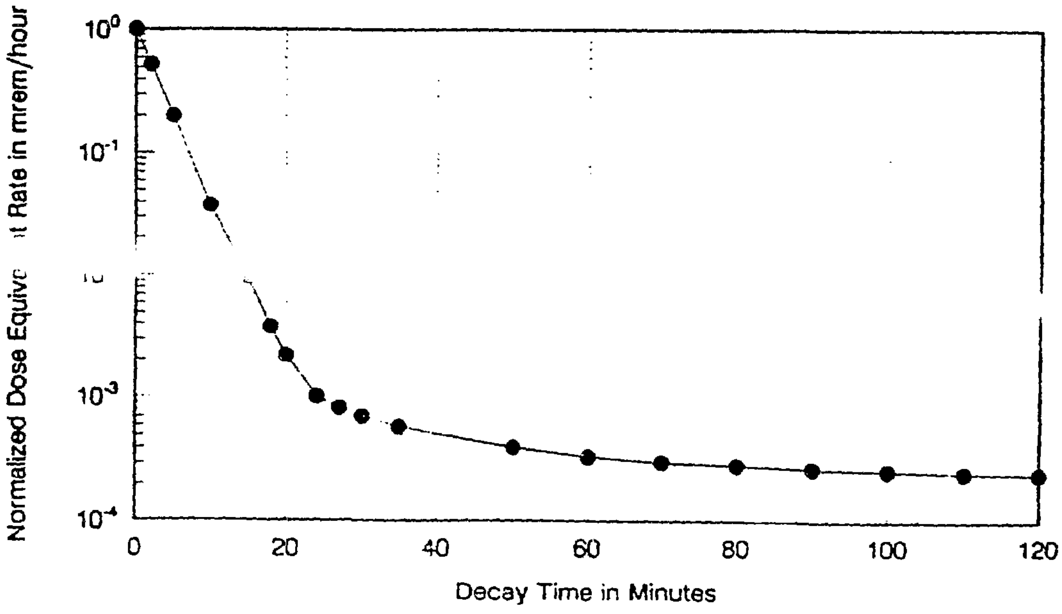
Table III

Postshutdown Gamma Ray Dose Equivalent Rates in mr per Hour

Distance from Surface (cm)	Decay Time in Minutes 0	5	15
5	2986	628	[illegible]
35	1639	345	17.3
85	738	155	7.8
135	407	86	4.3
185	255	54	2.7
235	175	37	1.8
285	127	27	1.3
335	96	20	1.0
485	60	13	0.6
635	30	6	0.3
935	14	3	0.2
1135	10	2	0.1
1435	6.1	1.3	0.06
1935	3.4	0.7	0.03

Figure 4

Normalized Dose Equivalent Rates Versus Decay Time



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REFERENCES

1. R. E. MALENFANT, The External Gamma Radiation Environment from the KIWI, PHOEBUS, and PEEWEE Reactors, *Proceedings of the National Symposium on Natural and Manmade Radiation in Space*, NASA Technical Memorandum X-2440, 440 (January 1972).

2. M. A. CAPO and S. L. ANDERSON, Application of Transport Techniques to the Analysis of NERVA Shadow Shields, *Proceedings of the National Symposium on Natural and Manmade Radiation in Space* , NASA Technical Memorandum X-2440, 449 (January 1972).

3. J. C. COURTNEY, N. A. HERTELENDY, and B. A. LINDSEY, Radiation Heating in Selected NERVA Engine Components, *Proceedings of the National Symposium on Natural and Manmade Radiation in Space* , NASA Technical Memorandum X-2440, 460 (January 1972).

4. E. A. WARMAN, et. al., *The Final Report of the Shield System Trade Study-Volume 1, Book 2*, Aerojet Nuclear Systems Company, Sacramento, CA (July 1970).

5. W. A. RHOADES and R. L. CHILDS, *An Updated Version of the DOT4 One-and Two-Dimensional Neutron/Photon Transport Code*, Oak Ridge National Laboratory Report ORNL-5851 (1982).

6. C. Y. FU and D. T. INGERSOLL, *VELM61 and VELM22: Multigroup Cross Section Libraries for Sodium-Cooled Reactor Shield Analysis*, Oak Ridge National Laboratory Technical Memorandum ORNL/TM-10302 (April 1987).

7. D. T. INGERSOLL and C. O. SLATER, *DOGS-A Collection of Graphics for Support of Discrete Ordinate Codes*, Oak Ridge National Laboratory Technical Memorandum ORNL/TM-7188 (1988).

8. J. A. DEMASTRY and T. P. MERRICK, Irradiation Effect Studies on NERVA Materials, *Proceedings of the National Symposium on Natural and Manmade Radiation in Space*, NASA Technical Memorandum X-2440, 595 (January 1972).

9. International Commission on Radiological Protection, *Data for Use in Protection Against External Radiation*, ICRP Publication 51, Pergamon Press, New York, NY (March 1987).

10. M. L. WILLIAMS, Generalized Contributon Response Theory, *Nucl. Sci. Eng.*, 62, 355 (1991).

11. O. W. HERMAN and R. W. WESTFALL, ORIGEN-S: SCALE System Module to calculate Fuel Depletion, Actinide Transmutation, Fission Product Buildup and Decay, and Associated Radiation Source Terms, as described in Section F7, *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation*, NUREG/CR-0200, Vol. 2 (January 1982, Rev. June 1983 and December 1984).

12. C. E. NEGIN, G. WORKU, and V. R. FRICKE, *MicroShield Version 3A: A Microcomputer Program for Shielding Analysis and Dose Assessment*, Grove Engineering, Inc. Rockville, MD (1988).