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INTERIM NUCLEAR ANALYSES IN SUPPORT OF
E/STS 2-3 SITE LAYOUT ACTIVITIES

MASTER

DECEMBER 1966

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Approved by:

J. A. Vreeland, Manager
Nuclear Analysis
REON

Technical Staff
REON

Prepared by:

H. O. Whittum, Manager
E/STS 2-3 Design Analysis

E. A. Warman, Manager
Shielding Analysis

G. Garriington
Shielding Analysis

D. R. Rogers
Shielding Analysis

DISTRIBUTION STATEMENT

TABLE OF CONTENTS

	Page
I. <u>INTRODUCTION</u>	1
II. <u>SCOPE OF STUDY</u>	2
III. <u>ANALYTICAL MODELS, METHODS AND SOURCES</u>	3
A. ANALYTICAL MODELS.....	3
B. ANALYTICAL METHODS.....	5
C. SOURCES OF RADIATION.....	6
IV. <u>RESULTS</u>	6
A. FULL POWER OPERATING RADIATION ENVIRONMENT.....	6
1. <u>Unshielded Engine Operation</u>	9
2. <u>Effects of Side Shield Thickness - Operation</u>	9
3. <u>Budgetary Study Shielded Configuration - Operation</u>	15
4. <u>Effect of LH₂ Level in Tank - Shielded Configuration</u>	19
B. SHUTDOWN RADIATION ENVIRONMENT	
1. <u>Unshielded Engine - Radiation Levels After Shutdown</u>	25
2. <u>Effects of Side Shield Thickness - After Shutdown</u>	32
3. <u>Budgetary Study Side Shield - After Shutdown</u>	32
C. CREDIBLE ACCIDENTS.....	37
1. <u>Extrapolation of Kiwi TNT Data to E/STS 2-3</u>	44
2. <u>Extrapolation of Phoebus 1A-321 Data to E/STS 2-3</u>	46
3. <u>Comparison of Radiation Levels from a Bare Shutdown Engine With Scaled Up Kiwi TNT and Phoebus 1A-321 Data</u>	50

TABLE OF CONTENTS (Contd.)

	<u>Page</u>
4. <u>Notes on the Character of Fission Product Release and Deposition for Kiwi TNT and Phoebus 1A-321</u>	54
5. <u>Estimate of Radiation Exposure During Egress from Escape Tunnel</u>	56
D. <u>EVAPORATION POND AND RETENTION BASIN STUDIES</u>	58
1. <u>Retention Basin</u>	61
2. <u>Evaporation Pond</u>	63
V. <u>CONCLUSIONS</u>	66
VI. <u>SUMMARY</u>	70
LIST OF FIGURES.....	72
LIST OF TABLES.....	76
LIST OF REFERENCES.....	77

I. INTRODUCTION

This report presents the results of nuclear analyses performed during the first three month period of preliminary design activities for Engine/Stage Test Stand (E/STS) 2-3. These analyses are intended to provide supportive nuclear data for the site layout engineering effort. Nuclear data for the test stand design effort will be the subject of a later document.

The information contained herein updates and supersedes some of the results and conclusions reached in the Budgetary Study Report¹ which covered the conceptual design of E/STS 2-3 for budgetary planning purposes. In general, the present analyses are more exhaustive than those of Reference 1 and place extensive reliance on computer code solutions as opposed to hand calculations. New areas of investigation have been pursued which are additive to those previously considered. More definitive reference data have been acquired and applied to the credible accident analysis in order to develop substantial analytical evaluations of the accident conditions postulated by the Design Criteria².

The referenced design criteria² replace a previous version of these criteria³ and contain a classified supplement which describes the analytical models and classified source material for these studies. This report therefore conveys only the unclassified results which are associated with the use of these classified data, thus allowing for some brevity in the present publication.

Only obvious conclusions are reached on the basis of the results reported. For the most part, this report provides working information for evaluation of site layout considerations. Decisions which are the prerogative of the Architect-Engineer are specifically avoided.

All normal operating and shutdown calculations are based on a 5,000 Mw NERVA configuration with a 230,000 lb. LH_2 Ground Test Module (GTM)⁴. The corresponding operating radiation levels for 10,000 Mw operation can be arrived at by multiplying these results by the ratio of the power (i.e. 2). The shutdown radiation levels following 45 minutes operation at 10,000 Mw can be obtained by multiplication by the ratio of the integrated powers (i.e. $\frac{45 \text{ min. @ } 10,000 \text{ Mw}}{30 \text{ min. @ } 5,000 \text{ Mw}} = 3$). In interpreting these results it should be emphasized that the criteria call for application of a factor of three (3) to all operating radiation levels and a factor of five (5) for all radiation levels after shutdown. For 10,000 Mw operation, then, a total factor of 6 must be applied to the 5,000 Mw nominal values reported herein. Following 45 minute operation at 10,000 Mw a total factor of fifteen (15) is required. In general, these later conditions will be found to be controlling. The 5,000 Mw data are reported because a 5,000 Mw engine configuration is closer to fruition and therefore more design data are known about it. The above scaling factors from a preliminary 5,000 Mw engine design to an unspecified 10,000 Mw configuration should prove to be conservative. In general, the application of the safety factors of 3 and 5 respectively should yield conservative results with the possible exception of those data which are based on current fission product release predictions.

II. SCOPE OF STUDY

Four distinctly different conditions have been analyzed: (1) operating radiation environment, (2) normal shutdown radiation environment, (3) credible accident and (4) evaporation pond, retention basin radiation environment. The operating and shutdown radiation environments are given for both the unshielded condition and with the 6 ft. borated water Budgetary Study shield in place.

Neutron and gamma radiation levels are also presented for 2 and 4 feet thick borated water shields to provide an assessment of radiation levels with varying shield thickness. The effects associated with the variations in LH_2 level, in the GTM tank, as a function of time during a firing have been analyzed to arrive at integral doses for a specific run, rather than relying on full power/empty tank data which formed the basis of the conceptual budgetary study.

Only ground deposited activity for the accident conditions has been considered to date. Ground deposition for normal operation has not been included. Source terms and distributions have not yet been predicted for either case. A cursory review of nuclear radiation from the plume during operation indicates that this source should be small compared to sources studied for reasonably long (i.e. in the order of several minutes)² delays between fission and release of the fission products.

III. ANALYTICAL MODELS, METHODS AND SOURCES

A. ANALYTICAL MODELS

The basic engine model is as described in Reference 2 with a minimum reflector thickness and no flight type shield above the reactor. The only significant shielding associated with the engine is the self-shielding of the core, as described for one current 5,000 Mw configuration⁵ and the attenuation provided by the side reflector, bottom support region, and top support plate. The facility model is as described in Figure 1, with the ground elevation represented on a flat plane surface. An air density of $1.09 \times 10^{-3} \text{ gm/cm}^3$ was used throughout this study.

The separation distance between the LH_2 inner tank bottom and the reactor center is 18 feet 3 inches (based on an engine station "O" to tank bottom separation of approximately 40 inches.) The distance from the reactor center to the top of the side shield is 32-feet in this model, as shown in Figure 1. The tank model is based on a Lockheed configuration⁶.

B. ANALYTICAL METHODS

Direct gamma radiation and fast neutron fluxes are calculated with the QAD-P5 point kernel integration code⁷, as modified by REON for the computations involving neutron moments coefficients. Neutron spectra are computed by selected S_n codes. These computer calculations are augmented in some cases by hand calculations, where only approximate order-of-magnitude evaluations are reported. Gamma ray scattering in air and in the hydrogen contained in the ground test module tank, is calculated with the aid of the GGG computer program⁸. Gamma ray energy flux and particle flux to dose conversion factors, attenuation coefficients, and polynomial buildup factors are based on the data compiled by Capo^{9,10}. It should be noted that the GGG program, as supplied by Los Alamos, has been modified by REON to incorporate the same polynomial buildup expressions as are employed in the QAD calculations.

Initial neutron scattering hand calculations have been performed based on the neutron Albedo methods programmed in the NEUSCAT¹¹ computer code. For the purposes of calculating air scattering the GH_2 and air above the reactor are broken up into intervals ranging from 0-18° and 3° intervals from 18°-30°. A single solid angle of 30° to 90° is used to calculate air scattering for the unshielded case. (Note: The Budgetary Study side shield configuration results

in a 30° cutoff angle drawn from the core center to the top of the side shield). A relatively fine air scatter grid is used out to a radius of 4,500 feet from the core center. A water buildup factor, based on the equivalent number of relaxation lengths in air, is computed in the QAD calculation of the gamma radiation leakage in the 30° to 90° interval for the shielded cases.

C. SOURCES OF RADIATION

The sources of radiation are described elsewhere², however, equivalent point sources of radiation were developed for the scattering calculations. These sources are presented in Table 1.

The fission product inventory program FPIC¹² is used to supplement Perkins and King decay data¹³. The sources given in Table 1 are based on the Perkins and King values.

Secondary sources of gamma radiation were also computed for the side shield and LH₂ based on the neutron leakage fluxes shown in Figure 2 and the leakage spectra provided by the Design Criteria.

IV. RESULTS

A. FULL POWER OPERATING RADIATION ENVIRONMENT

As noted earlier, the full power operating radiation environment associated with a 5,000 Mw engine was calculated with the aid of a number of computer codes and hand calculations. The comparable 10,000 Mw operating levels are twice those reported herein. The factor-of-3 conservatism required for both power levels has not been included in the results reported here.

TABLE I
Equivalent Point Sources of Gamma Radiation

Photon Energy E (Mev)	5,000 Mw Operation Equivalent S_0 (Photons/sec)		1 Hour After 30 Minutes at 5,000 Mw Equivalent S_0 (Photons/sec)		24 Hours After 30 Minutes at 5,000 Mw Equivalent S_0 (Photons/sec)	
	Side Leakage $\alpha = 90^\circ$	End Leakage $\alpha = 0^\circ$	Side Leakage $\alpha = 90^\circ$	End Leakage $\alpha = 0^\circ$	Side Leakage $\alpha = 90^\circ$	End Leakage $\alpha = 0^\circ$
7.5	2.09×10^{17}	8.59×10^{16}				
6.5	4.14×10^{17}	1.67×10^{17}				
5.5	1.15×10^{18}	4.45×10^{17}				
4.5	3.66×10^{18}	1.30×10^{18}				
3.5	7.66×10^{18}	2.52×10^{18}				
2.8	4.79×10^{18}	1.42×10^{18}	3.30×10^{16}	1.01×10^{16}	1.27×10^{13}	3.85×10^{12}
2.5	6.97×10^{18}	2.03×10^{18}	6.53×10^{16}	1.95×10^{16}	2.14×10^{14}	6.40×10^{13}
2.0	1.05×10^{19}	2.78×10^{18}	7.12×10^{16}	1.93×10^{16}	2.88×10^{15}	7.84×10^{14}
1.5	1.42×10^{19}	3.16×10^{18}	2.08×10^{17}	4.70×10^{16}	1.65×10^{15}	3.74×10^{14}
1.0	2.14×10^{19}	3.59×10^{18}	1.79×10^{17}	3.04×10^{16}	3.16×10^{15}	5.36×10^{14}
0.7	3.48×10^{19}	4.62×10^{18}	3.62×10^{17}	4.84×10^{16}	1.75×10^{16}	2.33×10^{15}
0.3	2.38×10^{19}	1.54×10^{18}	1.12×10^{17}	7.05×10^{15}	5.25×10^{15}	3.29×10^{14}
TOTAL	1.295×10^{20}	2.37×10^{19}	1.03×10^{18}	1.82×10^{17}	3.07×10^{16}	4.42×10^{15}

NOTE: α = Meridian angle

FIGURE 2

Fast Neutron Flux and Gamma Dose Rate Leakage
@ 5,000 Mw on 7.5 Ft. Meridian Ring

1. Unshielded Engine Operation

Figure 3 gives the unshielded gamma ray dose rate as a function of distance to 1,000 feet from an operating 5,000 Mw engine. The total dose rate is broken down into direct engine leakage contribution (with no air buildup factors) and the contributions from air scattering in the solid angles from 0° to 30° and 30° to 90° . Ground scattering and air capture gamma contributions are not included in these calculations. The data are based on no LH_2 in the propellant tank. Figure 4 presents the fast neutron flux (E_n 0.1 Mev) for the same unshielded conditions. Neutron air scattering is not treated explicitly but is accounted for partially by the moments calculations. Figure 5 presents the total gamma ray dose rate and fast neutron dose rate (E_n 0.1 Mev) up to 9,000 feet from an unshielded 5,000 Mw operating engine. The gamma dose rate can be seen to be clearly the dominant contribution.

2. Effects of Side Shield Thickness - Operation

The attenuation of operating gamma radiation provided by 2, 4, and 6 feet thick borated water side shields is shown in Figure 6. It should be noted that secondary gamma radiation sources in the borated water are included in all cases.

The attenuation of fast neutrons as a function of borated water side shield thickness is presented in Figure 7. Such deep neutron penetration problems are generally susceptible to considerable inaccuracies. For this reason, a check on the calculational technique was made with experimental data on deep penetration of neutrons in borated water solutions, at the Oak Ridge Lid Tank Shielding Facility (LTSF), as reported by Warman¹⁴. These data include

FIGURE 3

FIGURE 4

FIGURE 5

FIGURE 6

FIGURE 7

fast neutron tissue dose measurements to depths of 110 cm. The same experiments show the excellent agreement between the fast neutron flux in plain water and borated water at these large penetrations. Therefore, Oak Ridge Bulk Shielding Reactor (BSR) data for plain water¹⁵ were used to extend the experimental data from 110 cm to 180 cm (6 feet). Figure 8 shows how these experimental data agree (with no normalization of the BSR to LTSF values). The QAD water moments calculation for the LTSF configuration (with disc source) can be seen to result in excellent agreement with the measured data. No normalizations were made to either the calculated or measured data. This comparison shows the calculation of deep penetration to be better than the most optimistic anticipations.

The same water moments method was used for the side shield calculations reported in Figure 7. However, beryllium moments are used to calculate the engine leakage fluxes. The fast fluxes incident on and emerging from the side shield are obtained by normalizing the water moments fluxes to the beryllium moments fluxes at the shield's inside surface. This procedure allows for use of the best available prediction of engine leakage and shield leakage fluxes.

3. Budgetary Study Shielded Configuration - Operation

Figure 9 gives the gamma ray dose rate to 1,000 feet from a 5,000 Mw operating engine with the 6-foot thick Budgetary Study borated water shield. Scatter over the shield can be seen to be a major contributor in this case. Figure 10 shows the gamma ray and fast neutron dose rates to 10,000 feet from the 5,000 Mw engine shielded by 6-feet of borated water, for an empty propellant tank condition.

FIGURE 8

FIGURE 9

FIGURE 10

Fast Neutron and Gamma Ray Dose Rate From
Operating Engine vs Horizontal Distance
from Core Center - 5,000 Me

- Notes: (1) Exhaust products from ground deposition and cloud passage not included
(2) Ground scattering not included
(3) No LH_2 propellant in tank

4. Effect of LH_2 Level in Tank - Shielded Configuration

All of the data reported above are based on no LH_2 in the tank. In actual practice, however, this liquid hydrogen has a considerable effect on the scattering over the side shield. This effect has been evaluated and the results are presented below. In addition, LH_2 capture gamma radiation contributes to the shielded case when the LH_2 level is above the height of the side shield.

Figure 11 presents the gamma dose rates which result from LH_2 (n, γ) capture reactions, when there is at least 10% of LH_2 in the tank. Data are given for the unshielded case and the Budgetary Study shield case. Figure 12 shows the operating gamma dose rates resulting from a combination of leakage out the side shield, air scatter from 27° to 30° and LH_2 captures. These dose rates prevail for most of the run duration.

Figure 13 and 14 respectively show how the liquid level varies with LH_2 weight and the angle drawn from the core center to the top edge of the LH_2 in the GTM tank. Figure 15 gives the liquid level vs run time with a flow rate of 300 lbs (LH_2)/sec and a starting weight of 230,000 lbs. Figure 16 shows the tangent angle vs run time. At this flow rate, a total run time of 767 seconds is required to empty the tank. The maximum tangent angle is 27.3° . This angle is applicable for run times less than 690 seconds. For run times greater than this, the tank is emptied very quickly with a concomitant reduction in the tangent angle to 0° with no LH_2 .

The variation in air and GH_2 scattered gamma dose rate with variations of LH_2 level in the tank is represented in Figure 17 as a plot of

FIGURE 11
 LH_2 Capture Gamma Dose Rates vs Distance from 5,000 Mw Engine

FIGURE 12

FIGURE 13

RN-TM- 0415

FIGURE 14

FIGURE 15

dose rate vs tangent angle for various separation distances. When the data of Figure 16 are combined with those of Figure 17, plots of dose rate vs run time can be made, for various separation distances, as shown in Figure 18.

Integration under the curves in Figure 18 results in the total gamma dose at the specified locations for a run in which the tank is emptied at full flow rate/full power conditions. If the run is terminated with residual LH_2 in the tank, lower doses are obtained, as presented in Table 2. The differences between using these data rather than the full power empty tank dose rates reported in the earlier sections are seen to be relatively insignificant.

Finally, the effects of plume radiation, cloud passage and ground deposition cannot be ignored for large separation distances where the direct and air scattered contributions represent low dose rates and doses. These effects will be evaluated after release rates and spatial distributions have been predicted.

B. SHUTDOWN RADIATION ENVIRONMENT

1. Unshielded Engine - Radiation Levels After Shutdown

The unshielded gamma ray dose rate is given in Figure 19 for points out to 1,000 feet from a shutdown engine one hour after operation at 5,000 Mw for 30 minutes. The same information is conveyed in Figure 20 for an engine which has been shutdown for 24 hours following operation at 5,000 Mw for 30

FIGURE 16
Tangent Angle
vs
Run Time

FIGURE 17 DOSE RATE vs TANGENT ANGLE

RN-TM-0415

FIGURE 18: DOSE RATE VS TIME

RN-TM-0415

TABLE II

Integrated Gamma Doses for Various
Run Times and Residual LH_2 Levels

Run Time (Sec)	Residual LH_2 (lbs)	Tangent Angle (Degrees)	Integrated Gamma Dose (rads)							
			100 Feet		500 Feet		1000 Feet		5000 Feet	
			w/ LH_2 Capture	w/o LH_2^* Capture	W	W/O	W	W/O	W	W/O
690	20,000	27	770	690	24	17	3.8	2.3	.34	.18
728	5,500	24	810	730	25	18	4.0	2.5	.35	.19
757	3,300	21	840	760	26	19.1	4.3	2.6	.36	.20
763	1,300	18	850	770	26	19.3	4.3	2.6	.36	.20
767	0	0	850	770	26	19.4	4.4	2.7	.36	.20

*W and W/O LH_2 Capture indicates whether or not LH_2 (n, γ) capture gamma contributions have been added to the direct plus air scatter values.

FIGURE 19

FIGURE 20

minutes. These data are extended to 10,000 feet in Figure 21 for both the 1 hour and 24 hour cases.

The gamma ray dose rate varies substantially with time after shutdown, as evidenced by the data in Figure 22. In this figure, the dose rate, at a point 33 feet from the shutdown engine, is given as a function of time after shutdown from 1 hour to 400 hours. It should be noted that all shutdown data in this interim report are based only on fission product decay in the core. Activation sources have not been included; nor has any attempt been made to incorporate subcritical fission multiplication due to photoneutrons. This latter effect could be significant for the 1 hour decay case and should be dominant for very short times after shutdown (i.e. several minutes). At 33 feet from the unshielded engine, an operating gamma dose rate of 1.83×10^7 rad(c)/hr exists. One hour after 30 minutes of operation at 5,000 Mw the dose rate is 1.18×10^5 rad(c)/hr. It has decayed to 2.73×10^3 rad(c)/hr 24 hours after shutdown.

2. Effects of Side Shield Thickness - After Shutdown

The attenuation provided by 2, 4, and 6-feet of borated water is shown in Figures 23 and 24, respectively, for 1 hour and 24 hours decay after shutdown following a 30 minute run at 5,000 Mw.

3. Budgetary Study Side Shield - After Shutdown

The contrast between the data in Figures 23 and 24 and the full power gamma transmission shown in Figure 6, is obviously due to the softer spectrum associated with the decay sources. During operation, the gamma transmission for 6 feet of borated water is 2.0×10^{-3} of the unshielded values. At one hour after shutdown it has decreased to 3.8×10^{-4} , and at 24 hours after shutdown it has decreased further to 1.5×10^{-4} . The shield is thus 13 times

FIGURE 21

Unshielded Gamma Ray Dose Rate vs Distance 1 and 24 Hours
After 30 Minutes at 5,000 Mw (No Propellant in the Tank)

FIGURE 22

FIGURE 23

Attenuation of Shutdown Gamma Radiation
 1 Hr. After 5,000 Mw Operation for 30
 Min. with 2, 4, and 6 Ft Water Side
 Shields (Note: Air Scattering Over
 Shield Not Included)

FIGURE 24

more effective for 24 hour decay gamma attenuation than it is for operating gamma leakage suppression.

Figures 25 and 26 give the 1 hour and 24 hour gamma dose rates vs distance out to 1,000 feet from a shutdown engine with a 6 feet thick borated water side shield following 30 minutes operation at 5,000 Mw. Figures 27 and 28 give the 1 hour and 24 hour dose rates to 7,000 feet from the engine with the 6 feet thick Budgetary Study shield. The air and GH_2 gamma scattering over the side shield (0° - 30°) is seen to be the major contributor for the after-shutdown conditions.

All of these data are based on the premise that no LH_2 will be in the GTM tank after shutdown. In actual fact, however, some LH_2 will probably be used for post shutdown cooling. The effects of this LH_2 on leakage radiation is very great due to the fact that the scatter over the shield is the dominant contribution. Attention is called to the data on liquid level as a function of weight and tangent angle, as reported earlier in Figures 13 and 14. Based on this information, the total gamma ray dose rates, at various distances, are plotted in Figures 29 and 30 as a function of residual LH_2 weight for the 1 hour and 24 hours decay sources respectively. The latter case (24 hours) gives some indication of the shielding provided by LH_2 either left in the tank specifically for shielding purposes, at the conclusion of a run, or pumped into the tank after shutdown.

C. CREDIBLE ACCIDENTS

The Design Criteria² specifies the following accident conditions for a reactor power excursion or core meltdown:

FIGURE 25

FIGURE 26

FIGURE 27
Gamma Ray Dose Rate vs Distance with 6 Ft. Water Shield
1 Hour After 30 Minutes at 5,000 Mw

FIGURE 28

Gamma Ray Dose Rate vs Distance with 6 Ft. Water
24 Hours after 30 Minutes at 5,000 Mw

FIGURE 29

Gamma Ray Dose Rate Vs. Tangent Angle and Weight
of Residual LH₂ in GTM Tank for Various Distances from
Shielded Engine 1 hr. after 30 Min. @ 5,000 mw

FIGURE 30

(1) A reactor power excursion resulting in reactor pressure vessel rupture, nozzle loss and scattering of core pieces to the exhaust duct, tank shield, engine compartment and surrounding area.

(2) Core meltdown assuming 20 percent core vaporization and resulting damage to the test position, including rupture of the run tank.

These criteria have been interpreted¹ as requiring scaled up studies of the Kiwi Transient Nuclear Test experience and available data from the loss of coolant accident associated with the Phoebus 1A-321 test. Both the Kiwi TNT and Phoebus 1A-321 experimental results have been scaled up directly in proportion to the fission product source strengths of these tests to those one hour after a 5,000 Mw reactor operation for 30 minutes and 20,000 Mw operation for 45 minutes. The differences between those following the instantaneous fissions in Kiwi TNT are properly accounted for as shown in Figure 31. Ground depositions from the Kiwi TNT experiment in the downwind directions are evaluated in addition to the crosswind conditions which were discussed in the Budgetary Study. The earlier work was based on rather sketchy preliminary data^{16,17} whereas the present work reflects more recent available information^{18,19,20,21} in addition to the earlier information.

1. Extrapolation of Kiwi TNT Data to E/STS 2-3

The Kiwi Transient Nuclear Test was a deliberate nuclear destruction experiment of a prototype nuclear rocket engine. A nuclear transient was induced in a virgin reactor by the rapid insertion of reactivity accomplished by modification of the control drums permitting rapid rotation not anticipated in E/STS 2-3. The transient produced 3.1×10^{20} fission burst with two-thirds of the fission product activity being transported away by the effluent cloud. The data have been scaled up to reflect E/STS 2-3 conditions of 10,000 Mw operation for 45 minutes or 5000 Mw operation for 30 minutes.

FIGURE 31

The TNT Dose Rate Survey Isodose Rate Contours at One Hour Post Event are presented in Figures 19 and 20 of LA-3519-MS²⁰. Based on these data, the 205° direction is described as downwind and a 90° direction was selected as crosswind. Using these isodose rate contours, plots of the dose rate as a function of distance are obtained. If these data are then adjusted upward consistent with E/STS 2-3 fission product inventories given in Figure 31, the dose rate distribution about E/STS 2-3 following a 5,000 Mw 30 minute run by 1 hour, 5 hours, and 24 hours is shown in Figure 32. Comparable data for a 45 minute, 10,000 Mw run are shown in Figure 33. These Kiwi TNT gamma source decay rates are based on adjustment of the scaled up sources by the Perkins & King gamma ray spectrum and decay rates following instantaneous fission.

Comparisons between the results of the Kiwi TNT type accident conditions and the Phoebus 1A-321 conditions (both scaled to E/STS 2-3 integrated powers) are made in Sections IV.C.3 of this report, along with comparisons with bare core dose rate vs distance relationships. Data relative to the TNT ground deposition patterns in addition to these comparisons are included in Section IV.C.4. Interpretations of all of these data are made later in Section V.

2. Extrapolation of Phoebus 1A-321 Data to E/STS 2-3

The Phoebus 1A-321, Experimental Plan 4, full power reactor test was conducted at a power level of approximately 1050 Mw for 10.8 minutes. Near the termination of the run, a loss of coolant occurred which resulted in the rapid overheating of the core and expulsion of 5-8% of the core through the nozzle. This test represents a loss of coolant accident in which considerable experimental data were obtained and which is similar to an incident postulated in the E/STS 2-3 criteria.

FIGURE 32

FIGURE 33

The scale-up of the Phoebus 1A-321 data to E/STS 2-3 conditions can be accomplished by adjusting the deposition dose rates reported for the estimated time of cloud passage to dose rates at one hour after the test, and scaling to E/STS 2-3 in the same manner as was described for Kiwi TNT. Such scaling adjusts dose rates for differences in fission product inventory between Phoebus 1A-321 conditions and E/STS 2-3 conditions.

The deposition dose rates corrected to the estimated time of cloud passage are reported in Figure 26 of Reference 21. It was reported in Reference 21 that winds at run time were southerly at 6 to 15 knots through 10,000 feet MSL. On this basis, a cloud velocity of 10 mph was assumed for purposes of correcting Phoebus 1A-321 deposition dose rates to that following 1 hour decay. Table 3 depicts the adjustment of Phoebus 1A-321 deposition data at time of cloud passage to 1 hour after the test using fission product gamma decay data from Figure 28.

TABLE III

Adjustment of Phoebus 1A-321 Downwind
Deposition Dose Rates to One Hour Decay

<u>Distance from Test Point (Ft.)</u>	<u>Estimated Time of Cloud Passage (Min.)</u>	<u>Deposition Dose Rate at Time of Cloud Passage (R/hr)</u>	<u>Deposition Dose Rate After One Hour Decay (R/hr)</u>
2000	2.5	1.7×10^1	1.7×10^0
4000	5.0	5.5×10^1	7.62×10^0
8000	9.0	5.4×10^1	1.06×10^1
12000	13.0	2.5×10^0	5.73×10^{-1}
16000	18.0	9.2×10^{-2}	2.77×10^{-2}

The downwind direction was established at approximately the 310° direction and the crosswind direction was selected at the 270° direction. Due to the uncertainty associated with attempts to establish the time of cloud passage in the crosswind direction, since the cloud did not travel in that direction, the crosswind deposition dose rate was determined from the isodeposition contour shown in Figure 20 of Reference 21. It was assumed that the ratio of crosswind to downwind dose rates would be unaffected by the decay from the time of cloud passage to the one hour decay time (i.e. same radioactive decay rate in the crosswind and downwind directions).

The Phoebus 1A-321 dose rates were then adjusted upward to represent the E/STS 2-3 fission product inventory based on the variations in intensity for appropriate operation and decay times and power levels. The resultant E/STS 2-3 dose rates, scaled up from Phoebus 1A-321 data, are presented in Figures 34 and 35, for 5,000 Mw for 30 minutes and 10,000 Mw operation for 45 minutes considering 1 hour, 5 hours, and 24 hour decay for both downwind and crosswind conditions in each case.

3. Comparison of Radiation Levels from a Bare Shutdown Engine With Scaled Up Kiwi TNT and Phoebus 1A-321 Data

Figure 36 presents a comparison of the radiation levels, as a function of distance from the test stand, for a bare shutdown engine and those resulting from a scale up of the Kiwi TNT and Phoebus 1A-321 downwind and crosswind measurements. These data are based on one hour decay following 30 minutes of operation at 5,000 Mw. These conditions following 45 minutes of operation at 10,000 Mw can be arrived at by multiplying all of the curves in Figure 36

FIGURE 34

FIGURE 35

FIGURE 36

by a factor of three (3). As was noted earlier, an additional factor of five (5) is required², in either case, in order to make comparisons of these data with the access criteria.

Use of the downwind data can be seen to result in extremely large dose rates as compared to the crosswind or bare engine values. A bare engine is roughly equivalent to the crosswind conditions at some locations.

The relative shapes of the dose vs distance curves are quite remarkably different for the various cases. Since an exposure is predicated for one hour after an accident, in these cases wind direction cannot be predetermined with a great deal of accuracy. However, if the decay associated with times greater than one hour is considered, after an excursion (such as the Kiwi TNT) or loss of shield water accident (such as the bare engine), then the dose rates for these cases in Figure 36 would be lower by an amount roughly equivalent to that shown in Figure 31. Of course, the Phoebus 1A-321 type of accident may have a controlled favorable wind direction; since the loss of coolant accident is predicated to occur during a full power run (which would only be conducted with favorable winds). However, sudden wind reversals could occur which would increase the importance of the downwind data for the core meltdown scale up core as in the case of Phoebus 1A-321 release.

4. Notes on the Character of Fission Product Release and Deposition for Kiwi TNT and Phoebus 1A-321

In the Kiwi TNT incident, it is estimated that approximately 66% of the fission products created were transported away from the test point by the effluent cloud and the remaining 33% were distributed in the form of core fragments dispersion in the test area, with most of this radioactive material being deposited within a few hundred feet²⁰.

In the Phoebus 1A-321 loss of coolant accident approximately 5-8% of the core is estimated to have rapidly exited²¹ through the nozzle, at the end of a 10.8 minute power run²¹. A preliminary evaluation estimated 20-25% of the core was rapidly expelled¹⁷. The 5-8% figures are believed to be the best available estimates.

Isodose and isodeposition patterns were measured for both events¹⁷⁻²¹ and these data are used extensively in this analysis.

The observed differences between the Kiwi TNT and Phoebus 1A-321 dose rate vs distance scale up to E/STS 2-3 conditions can be explained by an investigation of the distributions of the ground depositions. In the case of the Phoebus (core meltdown) scale up roughly 80% of the ground deposition within 128,000 feet occurred within the first 10,000 feet of the test point. For the Kiwi (Excursion) scale up, less than 5% of the ground deposition within 128,000 feet occurred within the first 10,000 feet. See Figure 39.

The above evaluation of the location of the ground deposited fission product activity from Kiwi TNT data is based on the fraction of the ground deposited activity and its radial distance from the test point. This was determined using scale-up data based on the earlier referenced experimental fission product isodeposition contours.

When the two incidents are put on the same basis for E/STS 2-3 conditions (e.g. 1 hour after 45 minutes at 10,000 Mw) the effects of the relatively larger close in deposition for the Phoebus type accident are evident, as shown in Figure 36. This demonstrates the importance of the deposition patterns, since the Phoebus 1A-321 incident resulted in only a 5-8% total

inventory release compared to 100% for Kiwi TNT (66% long range distribution and much of the rest in large fragments close in). The release of a large inventory of fission products such as results from a scale up to E/STS 2-3 conditions yields maximum dose rates when distributed locally as in the Phoebus 1A-321 case where distances between 5,000 and 10,000 feet are involved and the core pieces located on the stand are diminished by air attenuation and distance. It may, therefore, be concluded from Figure 36 that within 5000 feet maximum dose rates result from scaled up Kiwi TNT data and beyond 5000 feet Phoebus 1A-321 scale up produces maximum dose rates.

The source deposition was evaluated using a planimeter to determine the surface area inside each of the isodose contours. The exponential midpoint value in each of the isodose contours was selected and the product of ground deposited activity and area was determined to establish relative number of curies for each contour area. The relative activity in each of the 5000, 8000, and 32,000 ft. radial line areas was also determined from this procedure. The results are presented in Figure 37 showing integrated deposited activity as a function of radial distance considering a total representation at the 128,000 ft. radial line. The same procedure was employed to determine the relative ground deposited activity from a Phoebus 1A-321 release using isodeposition contours presented in Figure 3 and 4 of Reference 21.

5. Estimate of Radiation Exposure During Egress from Escape Tunnel

An estimate has been made of the personnel exposure associated with egress from an escape tunnel following the two previously discussed types of credible accidents. Shielded loading of an escape vehicle and a vehicle

FIGURE 37

speed of 40 miles per hour are assumed escape conditions. Figures 38 and 39 respectively give the resultant doses to personnel as a function of distance from the test point to the origin of the vehicle evacuation. It is intended that these data serve as a rough estimate of integrated personnel exposures for various escape tunnel lengths. The data are, of course, subject to the same reservations as all of the Kiwi TNT and Phoebus 1A-321 type accident scale up information conveyed in this report. The downwind and crosswind information is presented, for both cases, to allow for some assessment of the range of variations which result from the pure scale up procedure.

D. EVAPORATION POND AND RETENTION BASIN STUDIES

A brief study was undertaken in relation to the radiation associated with the design of an evaporation pond and retention basin. This work was terminated as a result of the decisions reached in the 1 November 1966 Technical Review Meeting²².

Prior to the 1 November meeting, preliminary analyses were performed to evaluate the influence of the retention basin and evaporation pond upon the site layout considering the worst likely conditions anticipated during normal operation. The following assumptions were applied (based upon existing criteria at that time):

(a) For a 10,000 Mw run for 45 minutes it was assumed that 1% of the gross fission products is released into the exhaust coolant water as gaseous fission products, and is uniformly mixed in the water.

(b) For the same run it was assumed that 3% of the total fission product inventory is released as particulate fission products.

FIGURE 38

FIGURE 39

Cumulative Percent of Ground Deposited Activity Within 128,000 Ft.
vs. Radial Distance from the Test Point for Phoebus and Kiwi TNT

(c) The source activity of the retention basin was determined assuming that all the particulate fission products released were deposited at the bottom of the retention basin and all the gaseous fission products released remained uniformly distributed in the retention basin water. It was further assumed that the retention basin water is drained prior to each run.

(d) The source activity of the evaporation pond was determined assuming that all the fission products released are deposited in the evaporation pond and that the pond was evaporated to dryness after 30 days following each run.

These were maximum conditions to be inferred from those criteria.

1. Retention Basin

Based upon these assumptions, the dose rate from the retention basin as a function of distance and decay time were determined considering homogeneously distributed gaseous fission products as a series of self-absorbing truncated cone sources whose surface areas are equivalent to that of the basin, and considering the particulate fission products as distributed over the bottom of the basin shielded by the retention basin water.

It was determined that the depth of water in the retention basin would be 9 feet if 5.9×10^6 gallons of water were released to the 525 foot by 125 foot basin²³. This thickness was subsequently used as the water shield for the particulate fission products at the bottom of the basin, and for the height of the gaseous fission product truncated cone sources.

The gaseous fission product dose rate versus distance was determined by representing the retention basin water by 3 self-absorbing truncated cone sources²⁴ whose combined surface area is equivalent to that of the basin. It was assumed that the gaseous fission products were uniformly distributed throughout the water. The gaseous fission product source strength was obtained from earlier descriptions of U²³⁵ fission product gamma ray spectra¹³ and employed as follows:

$$\phi_r = \frac{BS_v}{2\mu_s K} \left[E_2(b_1) - E_2(b_3) + \frac{E_2(b_3 \sec \theta)}{\sec \theta} - \frac{E_2(b_1 \sec \theta)}{\sec \theta} \right]$$

where:

S_v = fission product source strength, Mev/cc-sec

B = dose buildup factor

μ_s = linear absorption coefficient for water, cm^{-1}

K = conversion factor from Mev/cm^2 to mr/hr

$b_1 = \sum \mu_i t_i$

μ_i = linear absorption coefficient for air, cm^{-1}

t_i = thickness of air between the retention basin and the detector point, cm

$b_3 = b_1 + \mu_s h$

h = depth of water, cm

$\theta = \tan^{-1} \frac{r}{t_i}$

r = radius of the truncated core, cm

$$E_2(b_n) = b_n \int_{b_n}^{\infty} \frac{e^{-t}}{t^2} dt$$

The resultant gamma ray dose rate from the truncated cone representation, using a 6-energy group source representation, are presented in Figures 40 and 41 for variations in decay time from 1 to 3000 hours. The three truncated cone sources were deployed along an east-west line consistent with the retention basin orientation. The results are presented for dose rate distributions in the north-south direction as well as the east-west direction.

The contribution from the particulate fission products is based on the assumption that they are located at the bottom of the retention basin. Disc source representations shielded by 9 feet of retention basin water were used for these calculations. The source strengths for these calculations were also obtained from Reference 13. It was observed that the contribution from this source was negligible compared to that from the gaseous fission products due to the 9-foot water shield thickness.

2. Evaporation Pond

It was assumed that 4% of the total fission product inventory was all deposited in the evaporation pond which was evaporated to dryness after 30 days following each run (see Table 3). The condition of 30 days decay represents a case of maximum dose rate, since prior to that time shielding is provided by the water.

The dose rate contribution to the facility from the evaporation pond 30 days after a run was determined using a point source representation, with three source energy groups, for dose point locations at large separation distances.

FIGURE 40

FIGURE 41

TABLE 3

Evaporation Pond Fission Product Source Strengths

<u>Gamma Energy (Mev)</u>	<u>Source Strength (Mev/sec)</u>
0.5	7.96×10^{14}
1.5	4.58×10^{14}
2.5	8.00×10^{12}

The gamma ray dose rate from the evaporation pond is presented in Figure 42 for distances greater than 1000 feet from the source, based on a point source representation.

These calculations regarding the retention basin and evaporation pond dose rates were performed to evaluate rough-order-of-magnitude contributions.

V. CONCLUSIONS

Dose rates vs distance and dose rates vs time, both during operation and after shutdown or accidents, have been provided. The combinations of these parameters are left to designers, especially as they relate to compliance with design criteria such as personnel access. Sufficient data are reported to facilitate such evaluations by persons whose primary discipline is not nuclear analysis.

A number of conclusions can be reached relative to the data presented herein and differences with the earlier analyses which were a part of the budgetary study. Some of these conclusions are as follows:

FIGURE 42
Evaporation Pond Dose Rate vs Distance

Distance from Source - Feet

(1) During operation, an empty tank assumption appears to be appropriate since calculations with varying LH_2 levels do not significantly affect operational dose rates at most distances considered. This is based on a very rough treatment of LH_2 (n, γ) capture gamma sources with no consideration of the products of these reactions as sources of concomitant air scatter contributions. That is to say that air scatter from the LH_2 capture gamma sources would be additive to the data reported herein.

(2) Borated water capture gamma radiations represent less than 1% of the leakage gamma levels with a 6 ft. thick shield. These sources represent roughly 20% of the leakage levels for a 2 ft. thick shield.

(3) Neutron dose contributions are small, even for the unshielded case. However, deep penetration of neutrons is shown to have been adequately treated. Such deep penetration calculations sometimes prove to be a significant problem, depending on the neutron to gamma ratio. Even for the 1,000 Mw development engine, bare engine neutron leakage calculations are less accurate than the gamma analyses.

(4) During operation, air scatter over the budgetary study side shield is important only in the vicinity of 500 to 2000 feet.

(5) After shutdown, air scatter over the budgetary study side shield is the dominant contributor out to about 2500 feet. The direct radiation leakage from the side shield predominates at large separation distances.

(6) The air scatter contributions are generally much higher than those reported in the earlier budgetary study. The direct values are virtually the same.

(7) The air scatter and LH_2 capture contributions are very sensitive to changes in the height of the side shield relative to the core center and tank bottom separation distances. Raising or lowering of the stage firing position or side shields may have a marked effect on the radiation leakage rates.

(8) The employment of more recently published data, for the Kiwi TNT and Phoebus 1A-321 accident condition evaluations, results in higher radiation levels than predicted for crosswind conditions (Budgetary Study).

(9) The use of downwind data results in scaled up dose rates for E/STS 2-3, which are orders of magnitudes higher than have been used in the facility design to date. Based on downwind conditions, the TNT type accident is the worst case studied out to approximately 5,000 feet; beyond that point the core meltdown accident scale up was dominant with virtually no difference in radiation levels from 5,000 to 10,000 feet.

(10) Dose rates from 100 rad/hr to more than 10,000 rad/hr exist from roughly 10,000 feet in to 1000 feet, for these two accident types, with one hour decay after each accident, based on a fission product inventory from 30 minutes operation at 5,000 Mw. An inventory from 45 minutes operation at 10,000 Mw would result in comparable dose rates from 300 rad/hr to 30,000 rad/hr. A safety factor of at least five (5), as specified in the criteria, must be applied to these numbers. A higher safety factor would not be inappropriate for these type scale-up calculations.

(11) It appears evident that an energy release lower in magnitude than the TNT release could constitute a worse radiation accident, due to the fact that such a large fraction of the TNT released fission products went off site.

(12) Analyses indicate the Kiwi TNT and Phoebus 1A-321 scale up cases probably do not represent maximum credible accidents, since the residual radiation levels are strongly dependent on the on-site deposition patterns and the relative amounts of on-site and off-site fission product release. Although containment is offered by the side shield, the open ended configuration poses unique containment problems. This could result in higher or lower residual radiation levels than are arrived at by a pure scale-up.

(13) The Phoebus type scale-up is very misleading in that it is based on an upward firing release to the atmosphere.

(14) In general, at large distances from the test stand (i.e. several thousand feet) normal operations could result in effluent release and ground deposition which would be higher in magnitude than the direct and scattered radiation, both for the operating and shutdown conditions. This determination cannot be made definitive until more source term and release rate data are available and duct (and/or scrubber) design is formulated..

VI. SUMMARY

In summary, the radiation environments associated with operation, shutdown and limited accident conditions have been analyzed to provide nuclear data for site layout considerations. Nuclear data relative to test stand design will be the subject of a later document.

Evaluations of the Kiwi TNT and Phoebus 1A-321 scale up conditions provide important information relative to the effects of local (on site) radioisotope deposition. Due to the relatively small amounts of local deposition associated with these incidents, it can be inferred that these

quite possibly do not represent maximum credible accidents, and therefore should not dictate site layout considerations.

Analyses are in progress relating to the radiation levels associated with alternate fission product deposition patterns, in order to establish the worst accident case for the various site layout considerations.

On site (NRDS) radioactive contamination can be considerable, from either the operating or accidental fission product releases. Nuclear analyses are required to establish the extent of possible contamination and risks to site personnel. The nuclear radiation levels and ingestion and inhalation hazards at E/STS 2-3 and other NRDS locations (such as the A&E building) cannot be determined at present due to the lack of information relative to release rates, ducting, scrubbing and dispersion of radioactants.

LIST OF FIGURES

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
1	Configuration for Nuclear Analysis of 5,000 Mev NERVA Engine and 230,000 Lbs. (LH ₂) Ground Test Module in E/STS 2-3	4
2	Fast Neutron and Gamma Dose Rate Leakage at 5,000 Mw on 7.5 Ft. Meridian Ring	8
3	Unshielded Gamma Ray Dose Rate vs Distance from Operating 5,000 Mw Engine (No Propellant Tank)	10
4	Unshielded Fast Neutron Flux vs Distance from Operating 5,000 Mw Engine (Direct with no Scattering)	11
5	Fast Neutron and Gamma Ray Dose Rate from Operating Engine vs Horizontal Distance from Core Center - 5,000 Mw	12
6	Attenuation of 5,000 Mw Engine Leakage Gamma Radiation in Water Side Shield	13
7	Fast Neutron Attenuation in Borated Water Side Shield	14
8	Comparison of QAD Fast Neutron Dose Rate Calculations with Dose Rates Measured in Borated Water (1.34% by Weight) in the LTSF Configuration Tank Water	16
9	Gamma Ray Dose Rate vs Distance with 6 Ft. Water Shield (5,000 Mw Engine)	17
10	Fast Neutron and Gamma Ray Dose Rate from Operating Engine vs Horizontal Distance from Core Center - 5,000 Mw	18
11	LH ₂ Capture Gamma Dose Rates vs Distance from 5,000 Mw Engine	20
12	Operating Dose Rate vs Separation Distance with More Than 10% LH ₂ in Tank	21
13	Weight of LH ₂ in Run Tank vs Fluid Level (Based on LMSC-A830249)	22

LIST OF FIGURES (Contd)

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
14	Liquid Level Above the Bottom of the Tank Along the Tank Axis vs the Angle Tangent to the Liquid	23
15	Liquid Level vs Run Time	24
16	Tangent Angle vs Tun Time	26
17	Dose Rate vs Tangent Angle	27
18	Dose Rate vs Time	28
19	Unshielded Gamma Ray Dose Rate vs Distance 1 Hr. after 30 Min. at 5,000 Mw (No Propellant Tank)	30
20	Unshielded Gamma Ray Dose Rate vs Distance 24 Hr. After 30 Min. at 5,000 Mw (No Propellant Tank)	31
21	Unshielded Gamma Ray Dose Rate vs Distance 1 and 24 Hours After 30 Minutes at 5,000 Mw (No Propellant in Tank)	33
22	Gamma Ray Dose Rate vs Time after Shutdown	34
23	Attenuation of Shutdown Gamma Radiation 1 Hr. After 5,000 Mw Operation for 30 Min. with 2, 4, and 6 Ft. Water Side Shields (Air Scattering Over Shield Not Included)	35
24	Attenuation of Shutdown Gamma Radiation 24 Hrs. After 5,000 Mw Operation for 30 Min. with 2, 4, and 6 Ft. Water Side Shields (Air Scattering Over Shield Not Included)	36
25	Gamma Ray Dose Rate vs Distance with 6 Ft. Water Shield 1 Hr. After 30 Min. at 5,000 Mw	38
26	Gamma Ray Dose Rate vs Distance with 6 Ft. Water Shield 24 Hrs. After 30 Min. at 5,000 Mw	39
27	Gamma Ray Dose Rate vs Distance with 6 Ft. Water Shield 1 Hour After 30 Min. at 5,000 Mw	40
28	Gamma Ray Dose Rate vs Distance with 6 Ft. Water Shield 24 Hours after 30 Min. at 5,000 Mw	41

LIST OF FIGURES (Contd)

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
29	Gamma Ray Dose Rate vs Tangent Angle and Weight of Residual LH_2 in GTM Tank for Various Distance from Shielded Engine 1 Hr. After 30 Min at 5,000 Mw	42
30	Gamma Ray Dose Rate vs Tangent Angle and Weight of Residual LH_2 in GTM for Various Distances from Shielded Engine 24 Hr. After 30 Min. at 5,000 Mw	43
31	Gamma Source Decay from Kiwi TNT, Phoebus 1A-321, and E/STS 2-3 10,000 Mw and 5,000 Mw Inventory	45
32	Dose Rate vs Distance Scaled from a Kiwi TNT Type Transient for One-Hour, 5 Hours, and Twenty-Four Hour Decay Following 5,000 Mw E/STS 2-3 Operation for 30 Min.	47
33	Dose Rate vs Distance Scaled from a Kiwi TNT Type Transient for One-Hour, 5 Hours, and Twenty-Four Hour Decay Following 10,000 Mw E/STS 2-3 Operation for 45 Min.	48
34	Dose Rate vs Distance Scaled from a Phoebus 1A-321 Type Accident for one Hour, Five Hours, and Twenty-Four Hour Decay Following 5,000 Mw E/STS 2-3 Operation for 30 Min.	51
35	Dose Rate vs Distance Scaled from a Phoebus 1A-321 Type Accident for One Hour, Five Hours, and Twenty-Four Hour Decay Following 10,000 Mw E/STS 2-3 Operation for 45 Min.	52
36	Gamma Ray Dose Rate Comparison of Bare Core with Scaled Up Kiwi TNT and Phoebus 1A-321 Data, 1 Hour After 30 Min. Operation at 5,000 Mw	53
37	Integrated Exposure of Personnel vs Origin of an Escape Vehicle Traveling at 40 mph in Terms of Distance from the Test Point Based on Scale Up of Kiwi TNT to E/STS 2-3 Operation of 10,000 Mw for 45 Min.	57
38	Integrated Exposure of Personnel vs Origin of an Escape Vehicle Traveling at 40 mph in Terms of Distance from the Test Point Based on Scale Up of Phoebus 1A-321 Data to E/STS 2-3 Operation of 10,000 Mw for 45 min.	59

LIST OF FIGURES (Contd)

<u>Figure No.</u>	<u>Title</u>	<u>Page</u>
39	Cumulative Percent of Ground Deposited Activity Within 128,000 Ft. vs Radial Distance from the Test Point for Phoebus and Kiwi TNT	60
40	Gamma Dose Rates vs Distance from Retention Basin Due to 1% Gaseous Fission Products Uniformly Distributed in the Water (Source = 3 Truncated Cones in Series) i.e. North or South	64
41	Gamma Dose Rates vs Distance from Retention Basin Due to 1% Gaseous Fission Products Uniformly Distributed in the Water (Source = 3 Truncated Cones in Series) i.e. East or West	65
42	Evaporation Pond Dose Rate vs Distance	67

LIST OF TABLES

<u>Table No.</u>	<u>Title</u>	<u>Page</u>
I	Equivalent Point Sources of Gamma Radiation	7
II	Integrated Gamma Doses for Various Run Times and Residual LH ₂ Levels	29
III	Adjustment of Phoebus 1A-321 Downwind Deposition Dose Rates to One Hour Decay	49

LIST OF REFERENCES

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