

RADIATION EXPOSURE TO THE ORBITING LUNAR STATION AND LUNAR SURFACE RELATED TO REUSABLE NUCLEAR SHUTTLE OPERATIONS

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ABSTRACT

The radiation environment created by the Reusable Nuclear Vehicle (RNS) in performing its normal mission functions while in the lunar vicinity and the impact of that environment on the Orbiting Lunar Station (OLS) and/or the lunar surface are examined.

Trajectory data, representative of nominal lunar arrival and departure maneuvers, reflecting the unique operating characteristics of the nuclear engine, provide the basic geometry model for the evaluation of the radiation exposures. Other factors included in the evaluation are the operating source term (neutron and gamma radiation), shutdown source term (fission point gamma radiation), view angle (shielding effects of stage and engine hardware), separation distance, exposure interval, time after shutdown, and prior reactor operating history.

To permit recovery of the impulse available from the coolant flow required by the high decay heat rates at reactor shutdown, the main engine LOI burn is terminated with the RNS in elliptical orbit and the coolant impulse used to circularize the orbit and complete OLS rendezvous. This circularization maneuver may take up to 40 hours or more, depending on the percent of cooldown impulse recovery planned. Radiation exposures at the OLS were evaluated for two conditions: (1) final orbit insertion 10 km ahead of the OLS, and (2) 10 km behind the OLS assuming a 90-percent cooldown impulse recovery about 12 hours of cooling).

Radiation exposures to the OLS during the lunar orbit departure burn (TEI) were evaluated for RNS startup 10 km behind the OLS and 10 km and 20 nm ahead of the OLS. Exposures received at the OLS for these cases are higher than for the LOI burn, since the reactor operation occurs much closer to the OLS, indicating greater initial separations will normally be desirable.

Lunar surface exposures from the operating reactor were evaluated for both the arrival and departure burns and while there is little probability that manned bases would lie along the paths in which measurable exposures would be recorded, the analyses do indicate the need to consider this possibility in planning such operations.

Conclusions supported by the analyses and recommended operational constraints for the RNS are presented.

One of the recommendations contained in the Space Task Group Report to the President (September 1969) was for continued lunar exploration with significantly increased capability and flexibility. Critical to achieving the proposed goals of the program will be the establishment of an Orbiting Lunar Station (OLS) and development of a space transportation system with emphasis on low cost and maximum payload flexibility. A major element being considered for the proposed system is the Reusable Nuclear Shuttle (RNS) designed to transport men, spacecraft, and supplies between earth orbit and lunar orbit as well as to other space destinations.

The NERVA nuclear engine, presently being developed, represents a major advance in propulsion and provides the basis for the RNS concept definition and mission operation planning used in this study. Nuclear engines differ considerably from chemical engines in operating characteristics and also represent a source of ionizing radiation which must be considered when planning any operations in their vicinity. To confirm the feasibility of using the RNS for lunar shuttle operations the effects on the OLS and lunar surface were examined for normal lunar arrival and departure maneuvers.

Trajectory data and reactor operating history for lunar orbit arrival and departure developed during the Nuclear Systems Definition Study (Contract NAS 824715) and the Lunar Mission Safety and Rescue Study (Contract NAS 9-10969) provided the basis for the evaluation.

The OLS is assumed to be in 60 nm polar orbit. Current planning does not call for actual docking of the RNS with the OLS; therefore, on lunar arrival it will only be necessary to inject into orbit in the near vicinity of the OLS from which position payload exchange can be accomplished either with lunar tugs or with propulsion units contained within the payload itself.

An RNS-OLS separation distance has not been established; however, it must satisfy two conditions: (1) the RNS must not be located so as to interface with operations around the OLS such as lunar lander arrivals and departures, and (2) it should be sufficiently distant that radiation from the engine, even in the worst attitude would not restrict activities at the OLS. Two RNS positions were used in the evaluation, 10 km ahead of and behind the OLS, which should satisfy the first condition.

To minimize mission velocity requirements trans-lunar trips will normally be scheduled to coincide with opportunities for coplanar earth departure and lunar arrival. Such opportunities occur twice each lunar month, although trip frequency would probably not exceed one every 54.6 days. Earth return opportunities permitting coplanar arrival in earth orbit will also be selected; however, to avoid extended waiting time in lunar orbit, most lunar departures will require some out-of-plane maneuvers. These departures will normally be performed

using a 3-impulse maneuver to minimize energy requirements, although single burn departures may be selected if the total plane change requirement is less than 20 degrees.

RADIATION ENVIRONMENT CREATED BY THE NUCLEAR ENGINE

The radiation environment related to normal engine operations will be most severe during periods when the reactor is operating at full power (1575 mw) and both neutron and gamma radiation are present. The intensity will depend on distance from the reactor and the presence of intervening mass such as shielding and stage and engine components. These effects are shown in Figures 1 and 2. These data were generated using the Common Radiation Analysis Model (CRAM)*. The sharp reduction in dose rate in the forward sector (0 to 15 deg) is related to the NERVA engine internal shield. Neutron dose rates assumed an RBE (radiobiological equivalent) factor of 8.

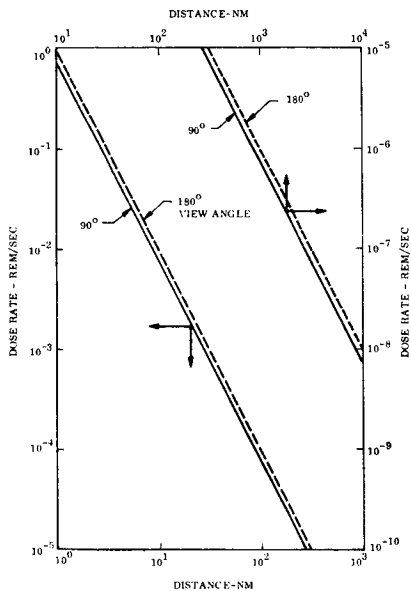


Figure 1 - Dose Rate (Neutron and Gamma) vs Separation Distance From the Operating NERVA Engine

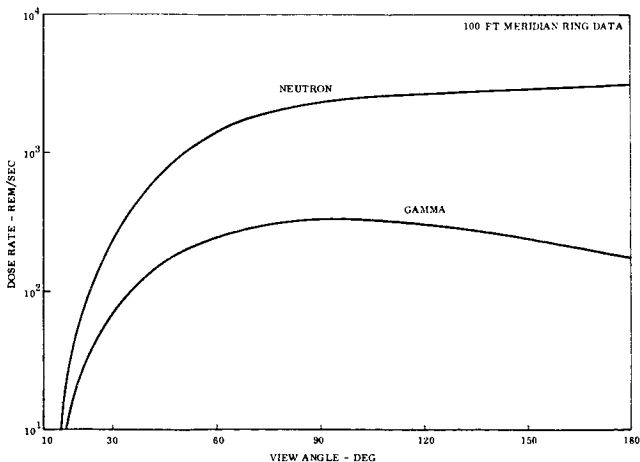


Figure 2 - Dose Rate vs View Angle for the Operating NERVA - 100 ft Meridian Ring Data

When the reactor is shutdown and the source of neutrons eliminated, the radiation environment created by the engine will be considerably diminished, consisting primarily of gamma radiation due to fission product decay in the core. Since the fission product source term is dependent on reactor operating history, time after shutdown, distance, and view angle, all these factors must be considered in the definition of the environment. Figures 3 and 4 give the dose-distance data following shutdown in lunar orbit for the first shuttle trip. Operating history assumed full power cycles of 1773 seconds and 367 seconds at leave earth and arrive moon with a 4-1/2 day coast between. The effect of view angle is presented in Figure 5. From these data it can be seen that the dose rate at 100 ft (30.48 meters) 100 seconds after shutdown is 20.5 R/sec, or more than two orders of magnitude less than the combined neutron-gamma dose rate of 3325 R/sec at the same distance during full power operation. Furthermore, at the end of the first day this rate will have dropped an additional 3 orders of magnitude.

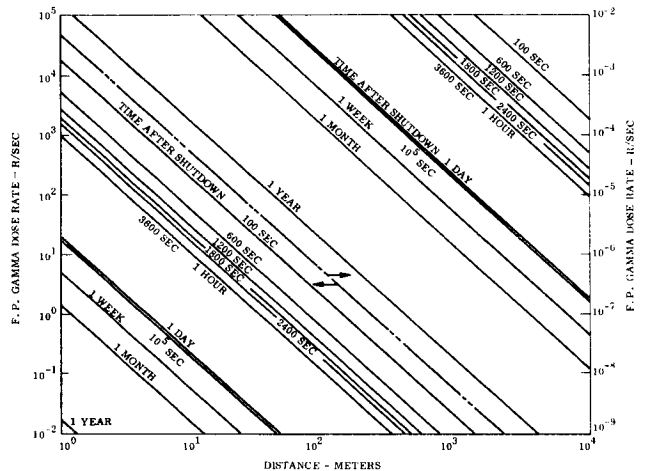


Figure 3 - Fission Product Gamma Dose Rate vs Distance From the Unshielded NERVA Core Following Shutdown in Lunar Orbit

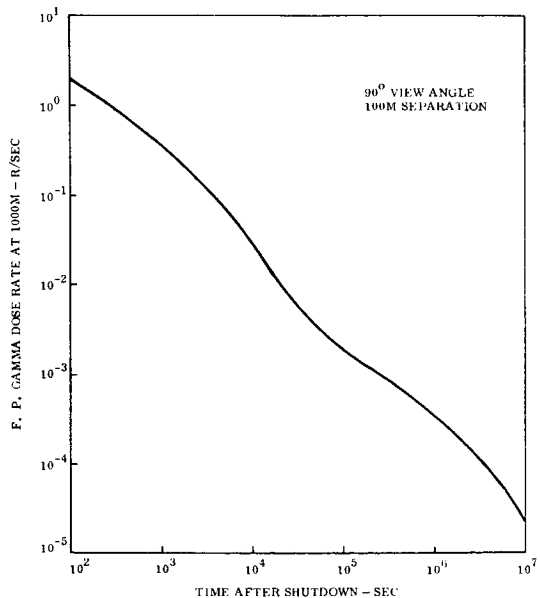


Figure 4 - Fission Product Gamma Dose Rate vs Time After Shutdown From the NERVA Core - LOI Burn

For the first 10 to 20 hours after shutdown the fission product source term will be dominated by the short-lived fission products from the last burn and not until a week or more has elapsed will the build up of greater inventories of longer lived fission products related to multiple burns have any pronounced effect on the source strength. Since the operations evaluated in this study are concerned with relatively short decay times, results based on the first trip analysis can be accepted as representative of subsequent trips as well.

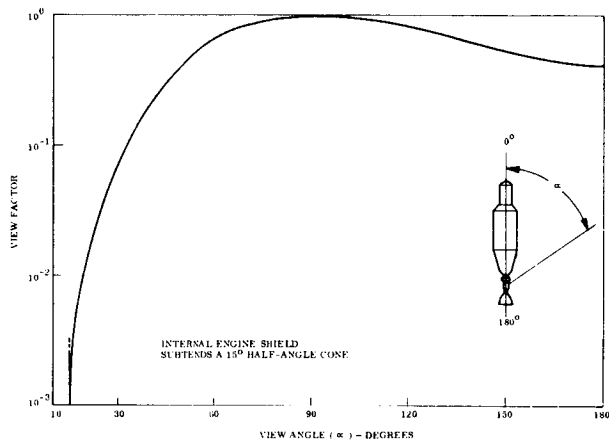


Figure 5 - Effect of View Angle on Fission Product Gamma Dose Rate

EFFECT OF DECAY HEAT ON RNS PROPULSIVE MANEUVERS

In addition to the radiation environment created by the decaying fission products in the reactor core, a considerable quantity of heat is released which must be removed to prevent damage to the engine. For example, at the end of shutdown (SCRAM) for a typical LOI burn the decay heat release is about 3.7×10^5 Btu/sec which would be sufficient to vaporize core material and destroy the engine if a continuous flow of coolant was not provided. After about 5 minutes the heat release rate will have dropped to about 6.8×10^3 Btu/sec and coolant can be provided at a much lower rate. In practice, to avoid the need for continuously reducing the coolant flow throughout the cooling period, an intermittent or pulsed flow technique is employed in which engine and reactor components are held within safe temperature limits by fixed flow pulses initiated when the upper temperature limit is reached and terminated when the lower bound is reached. These pulses are fairly uniform in thrust and duration, but decrease in frequency until the decay heat rate has dropped low enough to permit cooling by radiation alone, at which time active cooling can be terminated.

*Full Flow Flight Engine Common Radiation Analysis Model, "Aerojet General Corp., RN-S-0551, Sacramento California, 1969

For a typical LOI burn, cooling pulse trains will last from 25 to 40 hours and consume from 1500 to 2500 lb of propellant. To minimize the impact of this coolant demand on mission performance, most of the impulse produced will be applied toward the ΔV required for orbit insertion. The effect of the delayed impulse on the trajectory at lunar orbit arrival is shown in Figure 6, in which about 12 hours of cooling impulse recovery was used. Impulse from the cooling pulses not used for ΔV must be nullified to prevent orbit perturbation. In addition to minimizing the performance impact by utilizing coolant impulse for ΔV , an added benefit is realized in that the RNS-OLS separation distance during full power operation will be greatly increased over that which would result if little or no impulse recovery was planned.

A three-impulse departure maneuver, using a 36-hour intermediate ellipse to perform a 90-degree plane change maneuver, is illustrated in Figure 7. Although the intermediate ellipse and plane change may vary for different departures, only the first burn will occur close enough to the OLS or lunar surface to be of concern from a radiation standpoint.

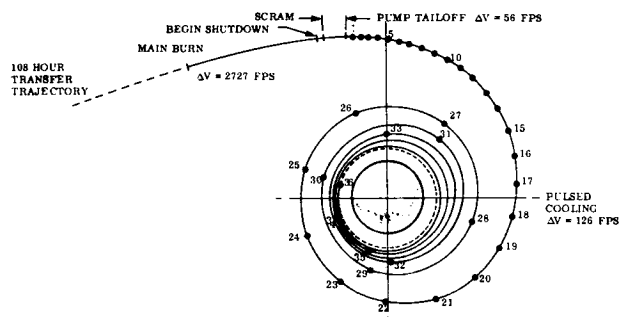


Figure 6 - Lunar Orbit Insertion Using Cooldown Pulses

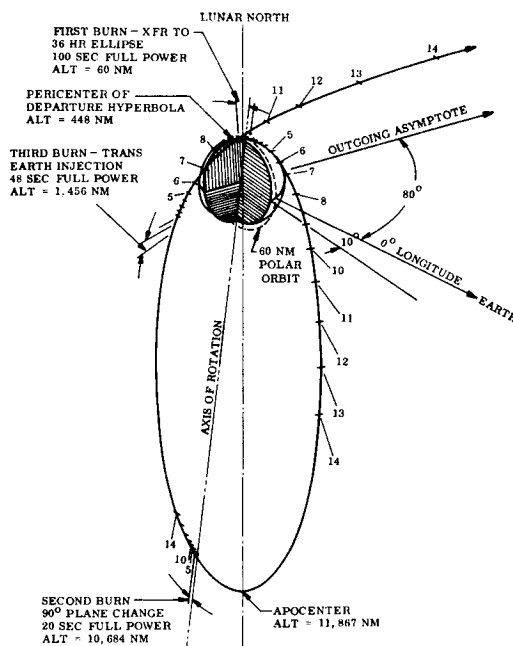


Figure 7 - Typical Three-Burn Lunar Departure With 90° Plane Change

RADIATION EXPOSURE TO THE OLS DURING
NORMAL RNS LUNAR MISSION OPERATIONS
- LUNAR ORBIT INSERTION

The integrated neutron and gamma dose levels which would be received at the OLS during RNS lunar orbit insertion were evaluated for two conditions previously mentioned; (1) final LOI 10 km ahead of the OLS, and (2) 10 km behind the OLS.

During the main engine burn the separation distance (RNS to OLS) and view angle for both cases are virtually the same and are presented in Figure 8. The total dose delivered to the OLS during the period from startup to SCRAM was computed to be 1.94×10^{-4} Rem, of which 1.44×10^{-4} Rem was attributable to neutrons and 5.03×10^{-5} Rem to gamma radiation.

Almost coincident with shutdown the view angle becomes less than 15 deg for both cases and remains so during most of the cooldown insertion. Thus, even though the RNS-OLS distance is diminishing, the protection provided by the engine internal shield effectively eliminates any radiation problem at the OLS. Separation distance and view angle for the latter half of the case in which final LOI occurs 10 km behind the OLS are shown in Figure 9. View angle for the alternate case is also shown.

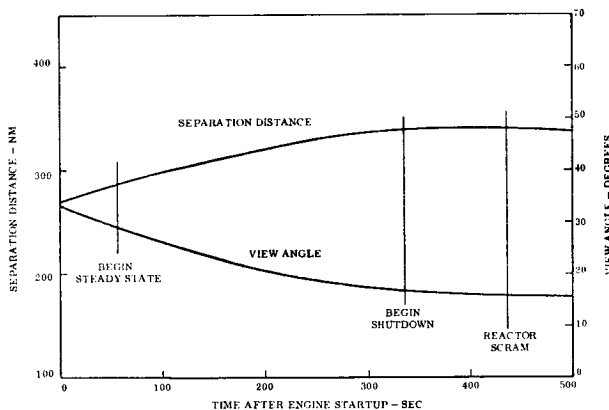


Figure 8 Separation Distance and View Angle Between OLS and RNS During LOI Burn

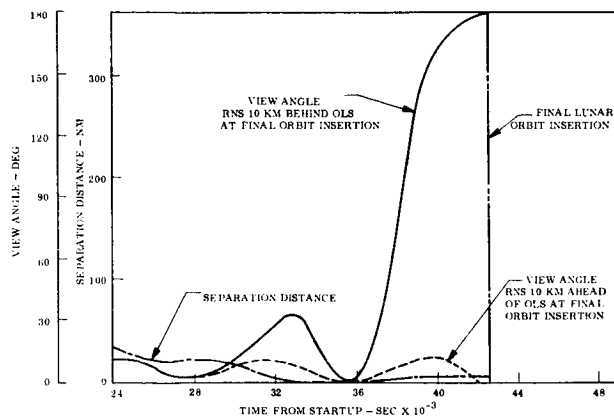


Figure 9 View Angle and Separation Distance to OLS During Cooldown Phase of RNS LOI Maneuver

For arrival 10 km behind the OLS a total fission product gamma dose of 7.03×10^{-3} Rem, roughly 36 times the dose received during the main burn, will be received at the OLS. Most of this dose will be delivered during a 20-minute interval (37,800 to 39,000 seconds) when the RNS is making a close passage with the OLS (1.5 nm) and the view angle is in the 60 to 140-deg range.

For the alternate arrival condition, 10 km ahead of the OLS, the RNS would not pass the OLS during the maneuver and would always remain oriented such that the OLS is within the engine shield cone, effectively eliminating any measurable dose at the OLS.

Increasing the separation distance at final LOI would have little effect on the fission point gamma dose if arrival behind the OLS is selected, unless the distance was increased to the point that the close passage was eliminated. It can reasonably be concluded then that unless mission conditions dictate otherwise, arrival of the RNS ahead of the OLS would normally be selected.

LUNAR ORBIT DEPARTURE

The lunar orbit departure operation may be accomplished using a single-burn or a 3-burn maneuver, depending on the amount of plane change required to satisfy the trans-earth injection (TEI) conditions. During the 3-burn departure the second and third burns will occur at such high altitudes (see Figure 7) that no effective dose will be received at the OLS.

The neutron and gamma dose received at the OLS was evaluated for three departure startup conditions; RNS 10 km behind the OLS, RNS 10 km ahead of the OLS, and RNS 37 km (20 nm) ahead of the OLS.

Separation distances and view angles for startup 10 km ahead of and 10 km behind the OLS are presented in Figures 10 and 11. Startup 37 km ahead would be similar to the 10 km ahead case except that the distances would be greater by about 15 nm.

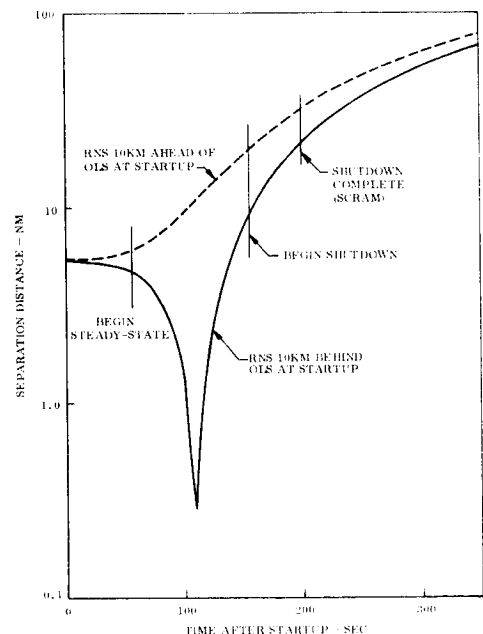


Figure 10 RNS-OLS Separation Distance During Fast Burn of the 3-Burn Lunar Departure Maneuver

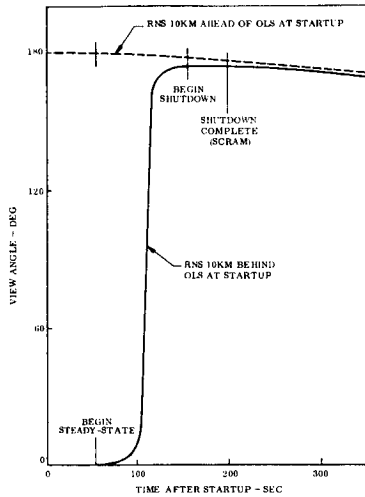


Figure 11 RNS View Angle From OLS During First Burn of Three-Burn Lunar Departure Maneuver

Integrated neutron and gamma doses at the OLS for these cases will be:

Position at Startup	Neutron Dose	Gamma Dose
10 km behind OLS	42.9 Rem	5.41 Rem
10 km ahead of OLS	2.52 Rem	0.139 Rem
37 km ahead of OLS	0.266 Rem	0.015 Rem

The high dose for the case where startup occurs 10 km behind the OLS results from the very close OLS passage (about 0.29 nm) during the reactor operating period. The benefits of even modest increases in separation distance are readily apparent from the other two cases evaluated.

The high neutron and gamma doses during engine operation for startup behind the OLS could be eliminated if the initial distance was increased to about 30 nm (56 km); however, a close OLS passage would still be required when fission product gamma rates are near maximum. Additionally, the risk of collision during the flyby would also represent an undesirable hazard.

The analyses support the conclusion that if startup near the OLS was required, a position ahead of it in orbit would be favored. A distance of at least 20 nm would be desirable. On the other hand, since the RNS requires no direct OLS support for the TEI maneuver, a more desirable condition for startup would be with the RNS beyond the lunar horizon (about 680 nm for 60 nm orbit altitudes) such that the engine burn could not be seen at the OLS and none of the low altitude operation would occur near the OLS. RNS transfer to such an orbit position can be accomplished at minimal expense in terms of ΔV during the waiting period in lunar orbit.

RADIATION EXPOSURE DURING RNS RESIDENCE IN LUNAR ORBIT

On arriving at the moon the nuclear shuttle will be divested of its outbound payload by lunar tugs or using propulsion units in the payload itself. Sometime prior to departure an earth-return payload will be delivered to the RNS and docked to it. Residence time of the RNS in lunar orbit can vary from about 4 days to as much as 30 days, during which time no NERVA engine operation will be required. During this period the RNS will maintain a

nose-to-the-sun orientation, which in the worst case could result in a 90-deg OLS view angle for the entire period.

From Figure 3 it can be seen that the average dose rate would be less than 5×10^{-8} R/sec, which over the full 30 days would only result in a dose at the OLS of 0.13 Rem. From a fission product gamma radiation standpoint the 10-km separation appears more than safe. No hazards would be associated with this standby period, except in the event of an RNS system malfunction.

RADIATION EXPOSURE TO LUNAR SURFACE DURING RNS ARRIVAL OR DEPARTURE

Men or installations on the lunar surface along the RNS trajectory trace could be exposed to radiation during periods of nuclear engine operation for the lunar arrival and departure burns. The most severe arrival situation would involve a single-burn LOI maneuver in which a minimum recovery of after-cooling impulse was planned. This type of insertion would result in the lowest altitude during the burn. For evaluation, an incoming trajectory was selected for which no after-cooling impulse recovery was employed. Such an approach is represented pictorially in Figure 12. RNS altitude at the beginning of steady-state operation is about 85 nm. Neutron and gamma doses delivered to various positions along the surface track were evaluated using the separation distance and view angle data given in Figures 13 and 14.

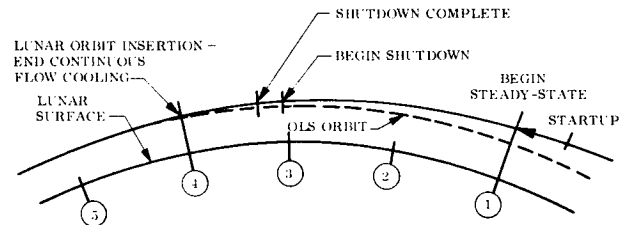


Figure 12 Relative Location of Lunar Surface Positions With Respect to RNS Incoming Trajectory - Low Altitude Approach

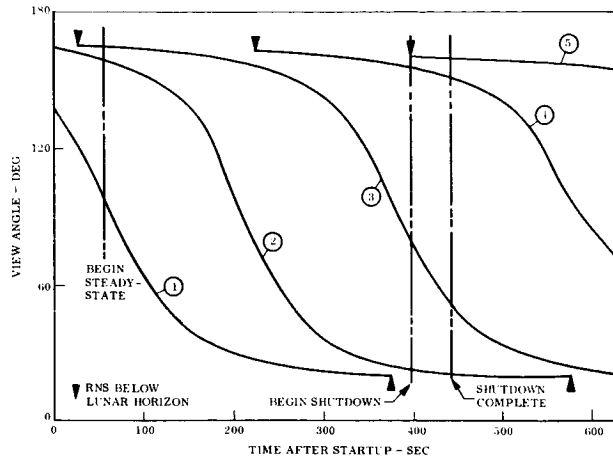


Figure 13 RNS View Angle From Indicated Surface Positions During Low Altitude LOI Burn

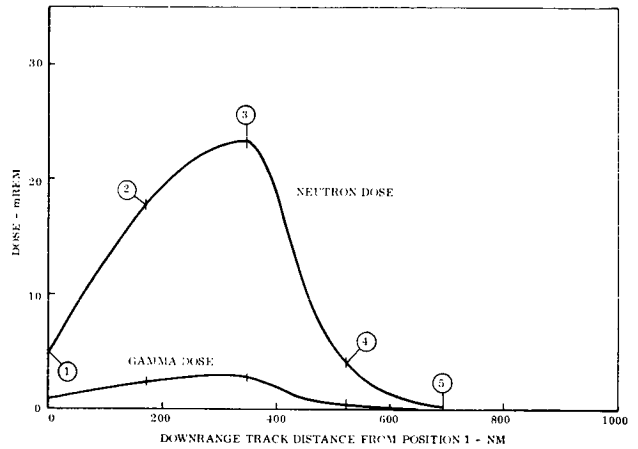


Figure 15 Neutron and Gamma Dose to Lunar Surface During Low Altitude LOI Maneuver

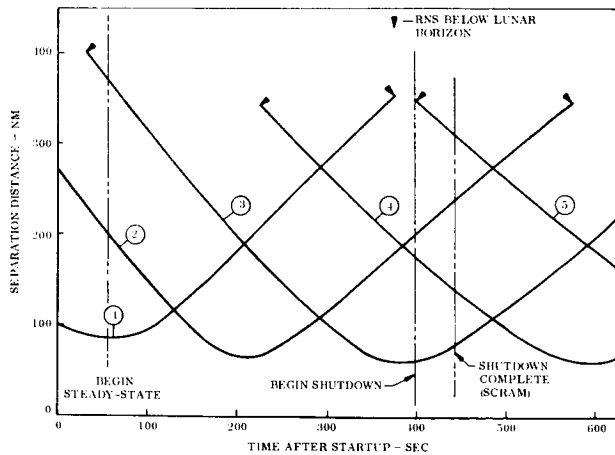


Figure 14 Line of Sight Distance to RNS From Indicated Surface Positions During Low Altitude LOI Burn

The neutron and gamma doses received along the ground track reach maximums of 2.35×10^{-2} Rem and 2.9×10^{-3} Rem at position 3, vertically below the RNS at shutdown (see Figure 15). Uprange positions 1 and 2 benefit from the change in view angle after the overflight, while downrange positions 4 and 5 benefit from increased range, and even more important are hidden by the lunar horizon during the early portion of the burn with position 5 not coming into view until shutdown is initiated.

Normal LOI burns will start at altitudes of about 125 nm and shutdown at about 95 nm, in which case the lunar surface dose will be reduced to perhaps one-third to one-half the values computed for the low altitude approach. Lunar orbit departure burns, on the other hand, would always start at 60 nm and remain low during most of the burn. For three-burn departures the first burn would rarely exceed 100 seconds duration; however, for single-burn departures burn times of 300 to 400 seconds could be required, most of which time the RNS would be at or near the 60 nm altitude. Although a specific case was not evaluated, the similarity to the low altitude arrival case suggests that the surface exposures would not be too different, although peaks might be slightly higher due to the slightly lower altitude during full power operation.

In any event, surface doses from either LOI or TEI burns do not appear high enough to be of concern unless experiments with sensitive measurement instruments were involved and then only if they happened to be located at very specific locations.

SUMMARY AND CONCLUSIONS

The analyses quite clearly support the conclusion that there is nothing in the RNS lunar operation either related to radiation or unusual operating constraints which would challenge its feasibility or practicability in supporting advanced lunar exploration. With the exception of the lunar orbit insertion maneuver, in which the engine cooldown extends the time interval for the maneuver, the nuclear and chemical shuttle operations would be nearly the same. Separation distances in orbit between the RNS and OLS will probably be established more on the basis of clearance required for other OLS operations than for control of radiation environment. Radiation exposures related to normal RNS operations at either the OLS or on the lunar surface do not reach levels high enough to be of concern, either for a single trip or for the accumulated dose from multiple trips.