ACCOMMODATION OF NUCLEAR POWER AND PROPULSION CONCEPTS

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INTRODUCTION

The use of nuclear systems for propulsion and power are being examined as system options for implementing the lunar and Mars human exploration missions currently being studied by NASA. Systems might include nuclear electric propulsion (NEP) and nuclear thermal rocket (NTR) vehicles, operating reactors on coorbiting platforms, radioisotope thermoelectric generators, and others. The space station, as a transportation node, would have to store, assemble, launch, and refurbish elements containing these systems. Care must be taken to safeguard humans from the radiation imposed by these systems, in addition to the naturally occuring background of the space environment. Key issues need to be identified early to enable their proper consideration in planning activities and the baseline space station design. A study was conducted over the past year with Texas A&M University to identify and explore key issues and quantify findings in a way useful to the Space Station Program.

INTRODUCTION

- THE HUMAN EXPLORATION INITIATIVES BEING PROPOSED BY NASA MAY REQUIRE POWER AND PROPULSION CAPABILITIES THAT ONLY NUCLEAR SYSTEMS CAN PROVIDE
- SPACE STATION FREEDOM, AS A TRANSPORTATION NODE, WILL HAVE TO ACCOMMODATE THESE SYSTEMS
- KEY ISSUES SHOULD BE IDENTIFIED EARLY TO ENABLE PROPER INCORPORATION IN PLANNING ACTIVITIES AND IMPACT TO BASELINE SPACE STATION DESIGN
- STUDY CONDUCTED OVER THE PAST YEAR WITH TEXAS A&M UNIVERSITY (DEPT. OF NUCLEAR ENGINEERING) TO IDENTIFY AND EXPLORE KEY ISSUES AND QUANTIFY FINDINGS IN A WAY USEFUL TO THE SPACE STATION PROGRAM

OBJECTIVE

IDENTIFY SPACE STATION OPERATIONAL IMPLICATIONS, SAFETY ISSUES, AND SYSTEM IMPACTS ASSOCIATED WITH THE ASSEMBLY, LAUNCH, AND REFURBISHING OF NUCLEAR-POWERED VEHICLES AND OTHER NUCLEAR COMPONENTS OPERATING NEAR OR STORED AT THE SPACE STATION

STUDY ORGANIZATION/APPROACH

This chart shows the study organization and the analysis approach taken. The potential radiation sources, both man-made and natural, were identified and treated with respect to the recommended radiation dose limits for astronauts working in space. The issues pertaining to human interaction with each of the radiation sources were identified and operating parameters for keeping radiation exposure within the recommended limits were formulated.

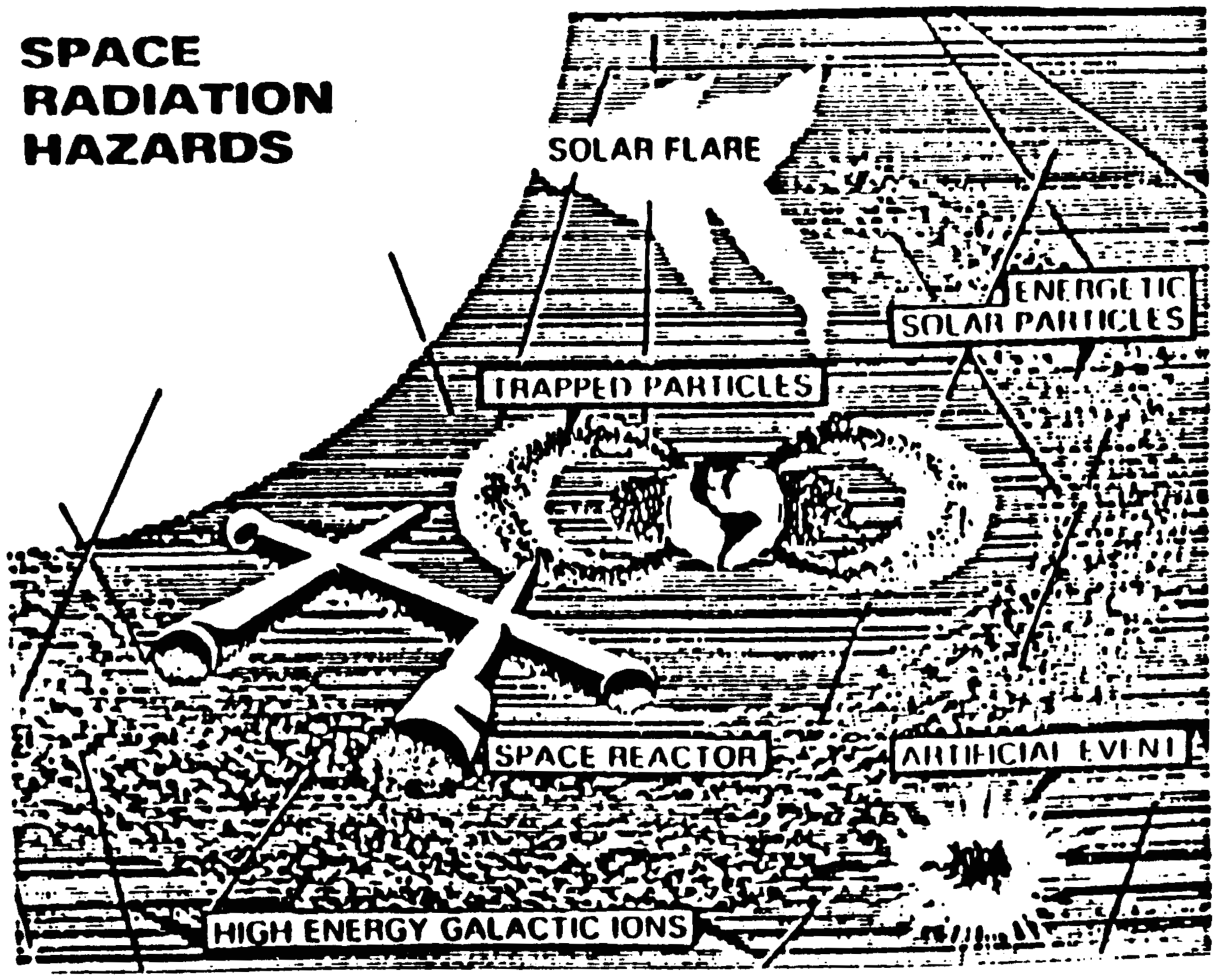
STUDY ORGANIZATION/APPROACH

- HUMAN RADIATION EXPOSURE CONSIDERATIONS
  - NATURAL SPACE RADIATION ENVIRONMENT
  - POTENTIAL MAN-MADE RADIATION SOURCES IN SPACE
  - RECOMMENDED HUMAN RADIATION EXPOSURE STANDARDS
  - RADIATION DOSE BUDGETS FOR SPACE STATION FREEDOM CREW
- SERVICING/PARKING OF NUCLEAR POWERED SPACE TRANSFER VEHICLES
  - NUCLEAR ELECTRIC PROPULSION (NEP) AND NUCLEAR THERMAL (NTR) VEHICLES
  - LAUNCH/RETURN CONSIDERATIONS
  - PRELIMINARY DESIGN OF A PORTABLE REACTOR SHIELD
- PROXIMITY OF OPERATING REACTORS TO SPACE STATION
  - EVA IN VICINITY
  - DISTANCE FROM SPACE STATION
- STORAGE AND HANDLING OF RADIOISOTOPE POWER SOURCES
- STORAGE AND HANDLING OF FRESH AND PREVIOUSLY OPERATED REACTOR CORES AT SPACE STATION
- POTENTIAL FOR MATERIAL ACTIVATION NEAR OPERATING REACTORS
- CONCLUSIONS

SPACE RADIATION HAZARDS

Space presents a significant radiation environment whether mad-made sources are in the vicinity or not. The major constituents of naturally occuring radiation consist of high energy protons from solar flares, galactic cosmic rays (protons and heavier nuclei), trapped particles in the earth's magnetic field (protons and electrons in the inner and outer Van Allen radiation belts, respectively) and other solar-related proton sources. A spacecraft venturing into interplanetary space would be exposed to all these sources. The low earth orbit (LEO) environment at the space station is, however, much more benign because the earth's magnetic field deflects high energy proton emissions from the sun. The natural radiation experienced at the space station is caused by trapped protons at the lower edge of the inner Van Allen radiation belt. The cumulative radiation experienced by a space station crewman on a six-month tour of duty would be about half the recommended annual dose for a space worker or one-quarter the annual dose if on a three-month tour of duty per year. Man-made or artificial radiation sources (primarily gamma rays and neutrons) would add to the background and the sum of the two would have to be kept within the recommended limits.

SPACE RADIATION HAZARDS



TYPES OF HAZARD

HIGH DOSES YIELD:
- RADIATION SICKNESS AND DEATH IN 1 TO 8 WEEKS
- CATARACTS

NON-LETHAL DOSES YIELD:
- CANCER
- MUTATIONS
- FETAL ABNORMALITIES

NCRP PROPOSED STANDARDS

Current radiation protection guidelines for NASA space personnel were formulated in 1970. The career limit was set at 4 Sv (400 rem) to the blood forming organs (BFO). Since that time, our knowledge of both radiation risks and of the natural space environment has improved. In addition, the space population has changed in its distribution with respect to age and gender. For these reasons, the National Council on Radiation Protection and Measurements (NCRP) has reexamined NASA's earlier guidelines and is currently recommending the dose limits shown in this table (NCRP 1989).

The career limits correspond to a 3% lifetime excess risk of fatal cancer where a career is assumed to be approximately 10 years. Annual and 30-day limits are also specified as to prevent nonstochastic radiation effects such as bone marrow depletion, cataracts, and skin erythema; for nonstochastic effects, the severity increases with increasing dose, and there is a threshold dose below which the response is not detected clinically. As indicated in the table, an individual may receive 0.5 Sv to the blood forming organs in a given year of space activity, yet cannot receive more than one half the annual limit in any 30-day period.

RECOMMENDED DOSE LIMITS FOR SPACE WORKERS

- National Council on Radiation Protection and Measurements (NCRP)
- Radiation Dose Limits corresponding to a 3% Lifetime Excess Risk of Fatal Cancer

	Dose Equivalent (Sv)		
	Bone Marrow	Lens	Skin
Career	1.0 - 4.0*	4.0	6.0
Annual	0.50	2.0	3.0
30 Day	0.25	1.0	1.5

*Age and sex dependent limits

STUDY APPROACH

(1) For each scenario, calculate cumulative doses as a function of various operational parameters.

(2) Indicate range of operations which can be considered "safe".

- Most permissive (dose budget)
- Most restrictive (ALARA)

RADIATION EXPOSURE BUDGETS FOR SPACE STATION CREWS

We can compare these dose limits to natural doses received in LEO. At SSF at an inclination of 28.5°, doses to the BFO delivered over a 30-day period range from a low of 0.015 Sv at an altitude of 450 km during solar maximum to a high of 0.053 Sv at 500 km during solar minimum (Nachtwey 1989). If the station were allowed to vary its altitude over several years so as to achieve a constant atmospheric drag, an average 30-day radiation dose of 0.01 Sv can be achieved. Dose rates thus range from a low of 0.01 Sv/month (best case conditions) to a high of 0.05 Sv/month (worst case conditions). The primary contributor to radiation doses in LEO is energetic protons trapped within the Earth's lower magnetic field.

By subtracting an estimate of natural dose from the NCRP limits, an "allowable radiation dose budget" for individual crew members is obtained. This dose budget could be expended through exposures from man-made sources such as nuclear reactors or medical examinations. It is current radiation protection practice to ensure that such exposures are kept "As Low As Reasonably Achievable" (ALARA). Nevertheless, mission planners should be cognizant of the operational limits imposed by these allowable dose budgets. Consequently, we have defined two dose budgets: LBAD-st and LBAD-lt. The acronym LBAD stands for Lower Bound on Available Dose and is obtained by subtracting from the NCRP limits, an upper estimate of the natural dose at SSF (0.05 Sv in 30 days). The suffixes "st" (short-term) and "lt" (long-term) correspond to the NCRP's 30-day and annual dose limits to the blood forming organs, respectively. Thus, LBAD-st is calculated as (0.25 Sv/mo - 0.05 Sv/mo) = 0.20 Sv in 30 days. Assuming a six-month crew rotation at space station, the LBAD-lt is calculated as [0.50 Sv/yr - (6 mo./yr.) (0.05 Sv/mo.)] = 0.20 Sv in 180 days.

If the LBAD-lt is prorated over a full 180-day crew rotation period, only 0.033 Sv from man-made sources would be allowed within any 30-day period; thus, the LBAD-lt is more restrictive than the LBAD-st. The LBAD-st is a more appropriate limit when considering short-term, infrequent exposures such as during extravehicular activity (EVA) near a

RADIATION DOSE BUDGETS FOR SSF CREW
(6 Month Duty Tour)

- Natural Radiation Doses at SSF:
  - ranges from 0.01 to 0.05 Sv/mo

- Lower Bound on Available Dose (LBAD)

  (Benchmark dose level contrived to identify problem thresholds)

Dose Budget = Max. Dose Limit - Dose from Nat. Space Env.

1) Short-term exposures (LBAD-st)

   Dose Budget = 0.25 Sv/mo - 0.05 Sv/mo
   = 0.20 Sv in 30 days

2) Continuous or long-term exposures (LBAD-lt)

   Dose Budget = 0.50 Sv/y - (6 mo/y)(0.05 Sv/mo)
   = 0.20 Sv in 180 days

LAUNCH AND RECOVERY OF NUCLEAR POWERED VEHICLES IN SPACE STATION VICINITY

MARS MISSION SCENARIOS WITH NUCLEAR POWERED VEHICLES

Two reference scenarios were considered in this study. In the first scenario, a cargo vehicle utilizing an NEP propulsion system were assumed to make a 1810 day round trip to Mars starting from LEO. The power system employed a single SP-100 reactor scaled by a factor of 10.4 to a power level of 25 MWt. The vehicle spent 150 days in orbit around Mars with the reactor operating at 0.4 MWt and a total of 373 days coasting at a power level of 0.2 MWt. Operating neutron and gamma fluxes for this reactor were obtained by scaling values calculated for the SP-100 reactor.

In the second scenario, a personnel vehicle utilizing an NTR propulsion system was assumed to make a 486 day round trip to Mars also starting from LEO. Trans-Mars Insertion (TMI) was performed by a stage containing a Phoebus-class reactor which was discarded upon completion of the TMI burn. A NERVA-class reactor was used during the remaining burns operating at a power level of 1575 MWt. The vehicle spent 30 days in Mars orbit with the NERVA reactor at 0.4 MWt and a total of 456 days coasting with a housekeeping power level of 0.2 MWt.

For these two mission scenarios, the total integrated power for the NEP reactor was 32,310 MWth-days of which 96.5% was consumed by the propulsion system. The total integrated power for the second stage NTR reactor was 210.3 MWth-days of which only 50.9% was consumed by the propulsion system. Thus, even though the NTR reactor has a rated thermal power ~ 60 times that of the NEP reactor, its total integrated power was over 150 times smaller. Fission product inventories and their associated gamma radiation levels are dependent, not only upon the total integrated power, but upon the time history of reactor operation. At short shutdown times, the gamma source term of the NTR reactor will be dominated by the decay of short-lived radionuclides produced during the Earth Orbital Capture (EOC) burn. At longer shutdown times, the gamma source terms of both reactors will be dominated by longer-lived radionuclides, and the fission product inventory of each will become a stronger function of the total integrated power than of the specific time history of reactor operation.

To show the contribution to the fission product build-up due to the production of housekeeping power, a second NTR scenario was run with zero housekeeping power production (reactor shutoff during coast). The effect on cooldown time is shown on a later chart.

MARS MISSION SCENARIOS WITH NUCLEAR POWERED VEHICLES

- NEP CARGO MISSION
  - 25 MW_{th} REACTOR 5 MW_e OUTPUT
  - 1810 DAYS TOTAL
  - 150 DAYS AT MARS
  - 1287 DAYS AT HIGH POWER (25 MW_{th})
  - 523 DAYS AT LOWER POWER (0.2, 0.4 MW_{th})
- NTR PILOTED SPRINT MISSION
  - 1575 MW_{th} REACTOR, 75,000 LBS. THRUST
  - 3 BURNS: MOC, TEI, EOC (TMI PERFORMED WITH EXPENDABLE STAGE)
  - 486 DAYS TOTAL TRIP TIME
  - 30 DAYS AT MARS
  - 98 MINUTES OF HIGH THRUST OPERATION
- TWO NTR CASES:
  1. DUAL MODE: REACTOR RUN AT LOW LEVEL FOR HOUSEKEEPING POWER DURING COAST AND AT MARS
  2. REACTOR FOR PROPULSION ONLY

LAUNCH OF NUCLEAR POWERED VEHICLES IN SPACE STATION VICINITY

THE SSF CREW'S RADIATION EXPOSURE WILL NOT EXCEED THE MAXIMUM RECOMMENDED 30-DAY LIMIT IF THE LAUNCH (TANGENTIAL THRUST) OF THESE VEHICLES IS CONDUCTED SUCH THAT:

- THE NEP INITIALLY LAGS SSF BY 3 km
- THE NTR INITIALLY LEADS SSF BY 7 km

RETURNED NUCLEAR POWERED VEHICLE (NEP OR NTR) IN SSF VICINITY

In the scenarios, the vehicle arrives in LEO at some large distance from the station. After a variable period of reactor cooldown, the vehicles are then towed to some variable parking distance. It is after this variable shutdown time that we calculate integrated 4-hour EVA doses at close distances from the reactor and integrated 30-day and 180-day parking doses at relatively larger distances. The 4-hour doses represent those that might be received during EVA unloading operations, while the 30-day and 180-day doses represent those that might be received by the crew living at SSF. The 4-hour EVA and 30-day doses are compared to the maximum recommended 30-day dose (one half the major annual dose) while the 180-day dose is compared to the maximum long-term exposure (annual) dose. Both reactors are treated as point sources with no vehicle or shadow shielding. The shutdown gamma dose rates were computed as the product of the operating gamma dose rate and the ratio of shutdown to operating gamma source strengths (LaBauvre et al. 1982). Gamma flux-to-dose equivalent conversion factors were obtained from Report 43 of the International Commission on Radiation Units and Measurements (ICRU 1988).

The following charts address these issues quantitatively by addressing the following cases:

1. How long after the NEP or NTR reactor is shutdown and at what distance from SSF can the vehicle be parked while maintaining 6-month cumulative doses to SSF below recommended limits? Here the long-term limit of 0.2 Sv applies for doses received from the reactor. When combined with doses received from natural radiation sources, the total 6-month cumulative dose would equal 0.5 Sv, or the annual recommended dose limit.

2. How long after the NEP or NTR reactor is shutdown and at what distance from SSF can the vehicle be parked while maintaining the 30-day cumulative dose below recommended limits? Here the short-term limit applies (0.2 Sv in 30 days from the reactor or 0.25 Sv total). This case represents a scenario in which the vehicle might be moved in close to SSF for 30 days for unloading and refurbishing, but would then be moved away so as not to exceed for long-term limit.

3. How long after the NEP or NTR reactor is shutdown and at what distance from the reactor can a 4-hour EVA be performed while maintaining doses below the short-term (30-day) limit?

RETURNED NUCLEAR POWERED VEHICLE (NEP OR NTR) IN SPACE STATION VICINITY

ISSUE: DOES A RETURNED NEP OR NTR (SHUTDOWN) REACTOR PARKED NEARBY PRESENT A RADIATION HAZARD TO SSF PERSONNEL?

CONCLUSION: NOT IF PROPER SAFETY PRECAUTIONS ARE TAKEN.

SOLUTIONS:

- SHUT DOWN THE REACTORS FOR SUFFICIENT TIME TO KEEP DOSES WITHIN RECOMMENDED LIMITS

  1) DOSE TO SPACE STATION CREW AT A GIVEN DISTANCE FROM VEHICLE
     - OVER 6-MONTH DUTY TOUR
     - BRING VEHICLE INTO CLOSE PROXIMITY FOR 30 DAYS, THEN MOVE AWAY

  2) DOSE TO EVA ASTRONAUT NEAR VEHICLE

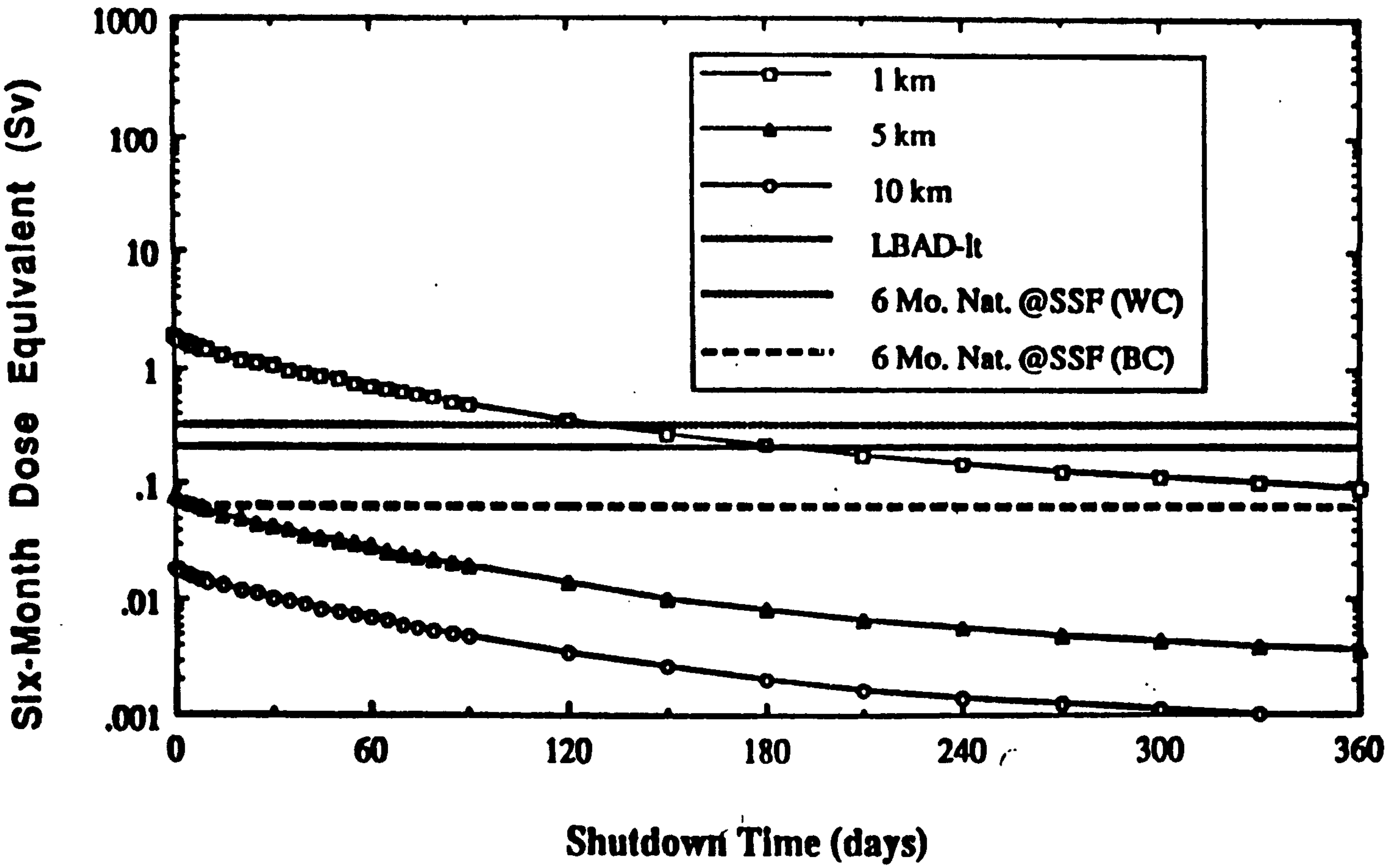
- USE A PORTABLE REACTOR SHIELD STORED AT SSF

SIX-MONTH PARKING DOSE TO SSF PERSONNEL FROM AN NEP VEHICLE REACTOR AFTER SHUTDOWN

This chart represents the dose received by the SSF crew (ignoring the small amount of shielding provided by the walls of the aluminum modules) in six months after an initial NEP reactor shutdown time.

The long-term limit ($LBAD_{lt}$) applies and allows for a cumulative dose of 0.20 Sv in six months. This is shown as the solid line. The point at which the cooldown curves cross this line represent the reactor cooldown times required to limit doses to within the six-month radiation dose limit. The curves are shown with distance from the space station as a parameter. For example, the NEP requires > 180-day cooldown time before it can be parked 1 km from the space station for 6 months. The dose falls off rapidly with distance, and results indicate the vehicle can be brought to 5 km from SSF within the first day and parked for 6 months. The other horizontal lines represent the worst case (WC) and best case (BC) natural radiation at the space station orbit as explained earlier.

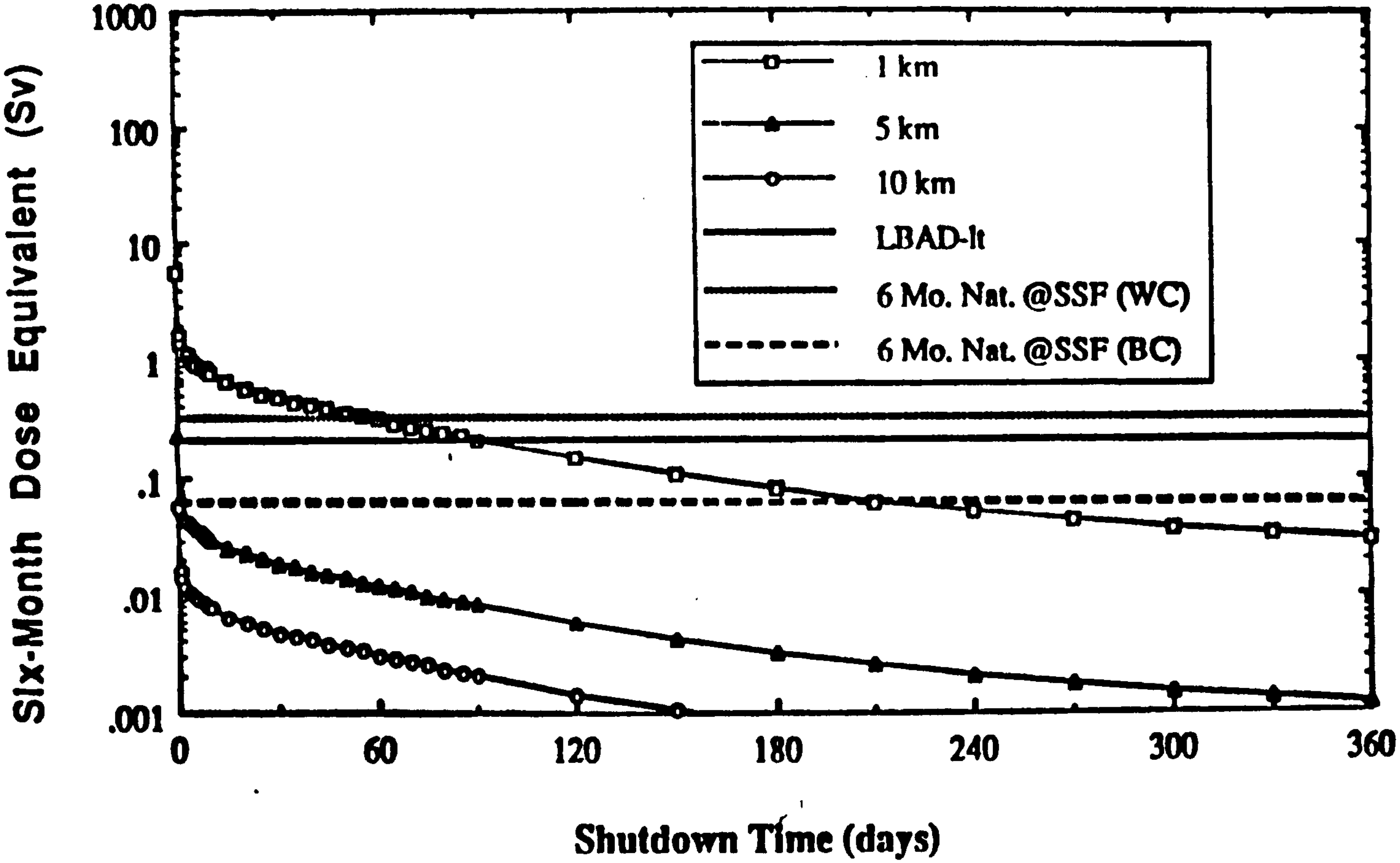
SIX-MONTH PARKING DOSE TO SSF PERSONNEL FROM NEP REACTOR AFTER SHUTDOWN (OUTSIDE SHADOW SHIELD)



SIX-MONTH PARKING DOSE TO SSF PERSONNEL FROM AN NTR REACTOR AFTER SHUTDOWN

These curves are similar to the NEP case except that the NTR cools off somewhat faster due to its shorter operating time history and can be moved into the SSF proximity sooner. For example, the NTR can be moved to 1 km of the space station for six months after a cooldown time of 90 days (compared to NEP's 180 days). As with the NEP, it is safe to move within a few kilometers of the space station almost immediately after the vehicle arrival. Initially upon return and shutdown, the NTR is "hotter" than the NEP due to the very high power earth orbit capture (EOC) burn just performed. Within a few days, however, dose rates around the NTR reactor fall below those around the NEP reactor at comparable distances.

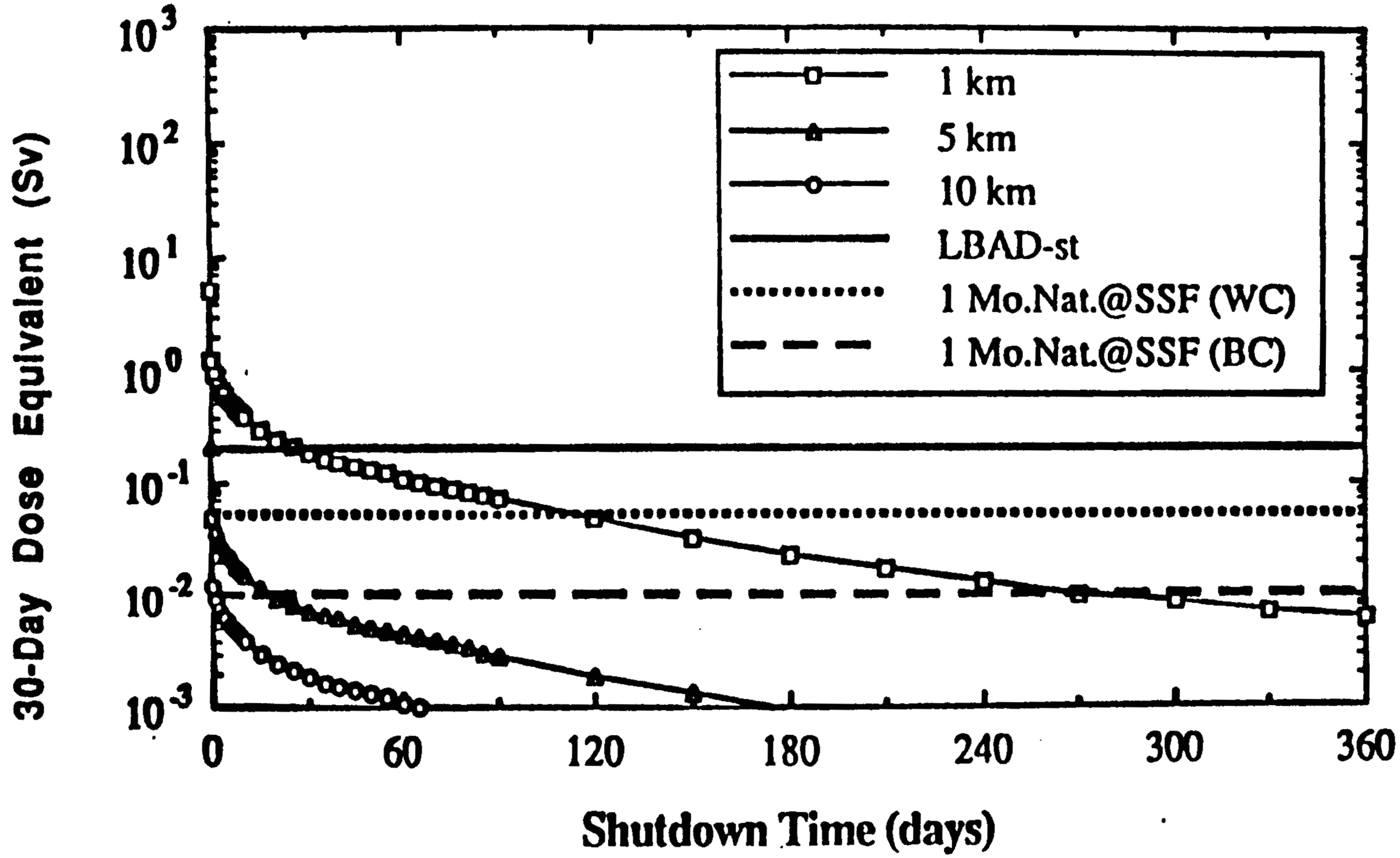
SIX-MONTH PARKING DOSE TO SSF PERSONNEL FROM NTR REACTOR AFTER SHUTDOWN (OUTSIDE SHADOW SHIELD)



30-DAY PARKING DOSE TO SSF PERSONNEL FROM NTR REACTOR AFTER SHUTDOWN

This curve demonstrates that, for the particular NTR scenario examined, the vehicle can be moved to 1 km from SSF for 30 days without exceeding the short-term limit after a cooldown period of 25 days.

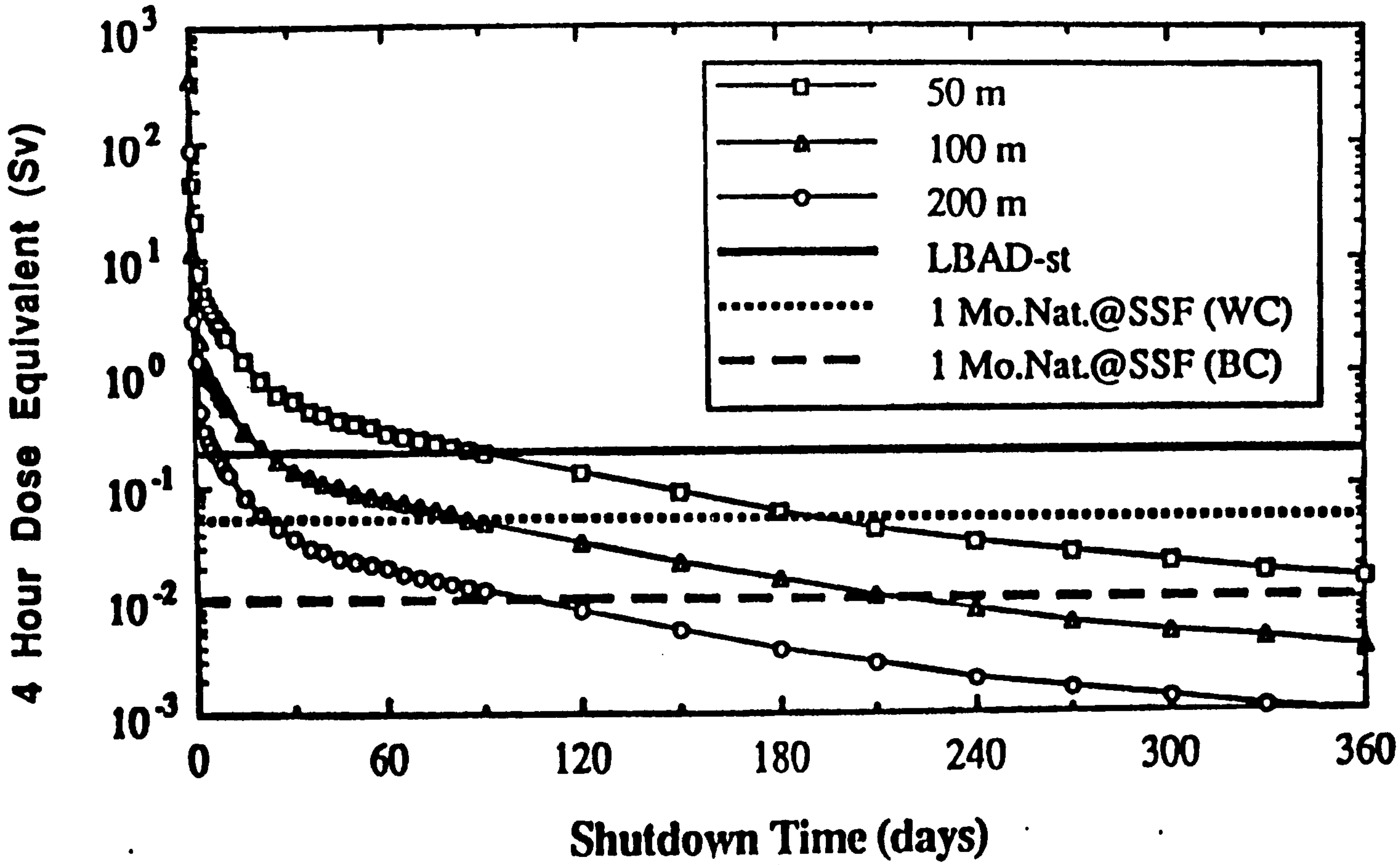
30-DAY PARKING DOSE TO SSF FROM NTR REACTOR AFTER SHUTDOWN (OUTSIDE SHADOW SHIELD)



EVA DOSE FROM NTR REACTOR AFTER SHUTDOWN

The curves for the shutdown NTR reactor are shown here. In order to achieve the same integrated doses at the same distances as for the NEP case, a reactor shutdown time of only 90 days is needed for the NTR reactor. At shutdown times less than approximately 10 days, the gamma doses due to the NTR reactor are greater than those due to the NEP reactor at the same distance. This difference can be attributed to the NTR reactor's higher power level and its correspondingly greater inventory of short-lived radionuclides produced during the final earth orbit capture (EOC) burn. At shutdown times greater than 10 days, doses due to the NEP reactor are greater, yet both continue to decrease with increasing shutdown time.

EVA DOSE FROM NTR REACTOR AFTER SHUTDOWN (OUTSIDE SHADOW SHIELD)



RADIOISOTOPE POWER SOURCES AT THE SPACE STATION

Radioisotope power sources such as radioisotope thermoelectric generators (RTG's) have been used by the U.S. space program for many years. The standard unit produces about 250 watts of electrical power and is safe to handle for short periods of time. The space station, as a transportation node, may have to store these devices or systems containing these devices for longer periods of time. A preliminary examination of the safety issues associated with RTG's at the space station was made. The results indicate that beyond a few meters from several RTG units, the SSF crew would receive less than their maximum allowed dose in a 6-month period. The devices could be stored somewhere on the truss structure, preferably as far away as possible to minimize the dose. The RTG's are cylindrical in form and, therefore, are directional in their radiation fields. The radial direction is the more critical, so the RTG's should be stored with the radial direction away from the space station modules.

STORAGE OF RADIOISOTOPIC POWER SOURCES ON SSF

ISSUE: DOES THE PRESENCE OF RADIOISOTOPIC POWER SOURCES REPRESENT A RADIOLOGICAL HAZARD TO THE SSF CREW?

CONCLUSION: ONLY FOR VERY SMALL SEPARATION DISTANCES OF LARGE NUMBERS OF POWER SOURCES.

SOLUTION:

1) STORE UNITS ON A BOOM
2) ORIENT UNITS TO MINIMIZE DOSE
3) EMPLOY PORTABLE RADIATION SHIELD

EXAMPLE: THE 6-MONTH AXIAL DOSE FROM AN RTG UNIT DOES NOT EXCEED THE DOSE BUDGET FOR SEPARATION DISTANCES IN EXCESS OF 6 METER.

MULTIPURPOSE PORTABLE RADIATION SHIELD

- REDUCE RADIATION HAZARDS DURING LAUNCH AND RETURN OF MARS VEHICLES.
- ENHANCE EVA CAPABILITIES NEAR SHUTDOWN AND OPERATING REACTORS.
- FACILITATE STORAGE AND HANDLING OF RADIOISOTOPIC POWER SOURCES AT THE SPACE STATION.
- REDUCE DOSES FROM THE NATURAL SPACE ENVIRONMENT. THIS WILL INCREASE RADIATION DOSE BUDGETS FOR CREW MEMBERS POSSIBLY LEADING TO GREATER FLEXIBILITY IN CREW ROTATION SCHEDULING.

CONCLUSIONS

- SPACE STATION FREEDOM CAN BE USED AS A TRANSPORTATION NODE FOR SPACE NUCLEAR-POWERED VEHICLES.
- NUCLEAR POWER SOURCES CAN BE USED IN SSF VICINITY.
- RADIOISOTOPIC POWER SOURCES CAN BE STORED AND/OR USED ON SSF.
- NONE OF THESE ACTIVITIES POSE AN UNACCEPTABLE RADIOLOGICAL HAZARD PROVIDED PROPER PRECAUTIONS ARE TAKEN.
- A PORTABLE RADIATION SHIELD IN LEO WOULD PROVIDE FOR INCREASED OPERATIONAL FLEXIBILITY.