NASA Contract Report CR-189180

Nuclear Safety for the Space Exploration Initiative

Terry E. Dix
Rockwell International
Rocketdyne Division
Canoga Park, California

November 1991

Prepared for
Lewis Research Center
Under Contract NAS3 25808

NASA

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1.0 SUMMARY

A preliminary hazards analysis of a nuclear reactor power system for surface power generation on the moon and Mars as part of the Space Exploration Initiative has been performed. The rigor and scope of the analysis was consistent with the conceptual state of the 1988 System Design Review SP-100 Reference Flight System design for the potential applications and the current detail of the mission descriptions. The objective of the study was to identify potential hazards arising from nuclear reactor systems for use on the lunar and martian surfaces, related safety issues, and resolutions of such issues by system design changes, operating procedures, and other means. This study does not address safety issues for a reactor which is part of a propulsion system. However, the use of such a system will have an impact on the mission profile and this has been taken into account.

All safety aspects of nuclear reactor systems from prelaunch ground handling to eventual disposal were examined consistent with the level of detail for SP-100 reactor design, launch vehicle and space transport vehicle designs, and mission descriptions. The analysis of missions to the moon and Mars has been conducted by concentrating on events not previously covered in past aerospace nuclear safety studies. Information from those previous aerospace nuclear safety studies was used where appropriate.

Safety requirements for the SP-100 space nuclear reactor system were compiled from available published documents. Mission profiles for typical lunar and martian flights were defined with emphasis on activities after low earth orbit insertion. Accident scenarios were then qualitatively defined for the new mission phases. Safety issues were identified for all mission phases with the aid of simplified event trees. Safety issue resolution approaches of the SP-100 program were compiled. Resolution approaches for those safety issues not covered by the SP-100 program were identified. Additionally, the resolution approaches of the SP-100 program were examined in light of the moon and Mars missions.

The key results of the study are summarized in Table 2-1. This table presents the governing requirements and the resolution approaches identified to meet the requirements. Each of the safety issues listed in Table 2-1 are summarized below including the resolution approaches.

Decay Heat Removal

The SP-100 Reference Flight System uses the primary coolant loop and the auxiliary coolant loop systems to remove decay heat from the reactor core after shutdown. These systems have been designed for operation in zero-g space. A steady state analysis was performed to determine the feasibility of designing a primary heat transport loop with the capability of removing reactor decay heat by natural convection. The study was based upon an SP-100 reactor operating on the lunar surface with either a Brayton or a Stirling power conversion subsystem. Temperature differences developed across the reactor as a function of height and pipe diameter for one second and 50 seconds after shutdown were on the order of 100 C to 200 C for a configuration of 6 m from reactor to heat exchanger with 8 cm diameter pipe. Thus, excessive temperatures would not occur if the reactor design used natural

Table 1-1
Summary of Resolution Approaches to Key Safety Issues of Nuclear Reactors as Planet Surface Power Systems for the Space Exploration Initiative
(Sheet 1 of 2)

Safety Issue	Requirement	Resolution Approach
Decay heat removal	Low risk	Use containment vessel for loss of coolant accident; use natural convection otherwise.
Reactor control	Low risk	Investigate need for poison-backed reflectors to reduce backscattering by close proximity shielding.
Disposal	Low risk	Use methods with minimum astronaut interaction; provide adequate long term safe disposal with minimum risk.
Criticality	Subcritical in all credible accident conditions	Neutron absorbers; design to survive new launch and transport vehicle accident environments; use expendable launch vehicles so reactor is above solid rocket boosters.
End-of-life shutdown	Low risk	Automatic, single fault tolerant clock mechanism; irreversible power interruption to control actuators.
Radiation exposure release	ALARA	Need radiation exposure limits and controls for all power sources (stationary and mobile); must consider all potential missions.
Mars environment	Low risk	Use reliable coatings on or isolation from the martian environment of refractory metals; consider using lower temperature materials (stainless steel, etc.) compatible with the martian environment.
High speed impact on the earth, moon and Mars	Low risk	Design reactor to survive earth reentry intact; rely upon highly reliable transfer vehicle guidance systems for moon and Mars.

Table 1-1
Summary of Resolution Approaches to Key Safety Issues of Nuclear Reactors as Planet Surface Power Systems for the Space Exploration Initiative
(Sheet 2 of 2)

Safety Issue	Requirement	Resolution Approach
Return flyby trajectories to the moon and Mars	Low risk	Eject nuclear reactor into space to avoid inadvertent earth reentry or design highly reliable transfer vehicle to accommodate excess return mass during earth orbit insertion.

convection in the primary coolant loop should the secondary heat transfer loop fail to provide a heat sink.

A potential method to accommodate a loss of coolant accident is containment of the primary coolant loop inside a guard vessel. The guard vessel would be designed so that the captured coolant would cover the reactor and decay heat would be rejected by heat pipes attached to the guard vessel wall. A cursory steady state thermal analysis for a lunar application resulted in a temperature drop from the reactor to the guard vessel on the order of 525 C to 550 C. However, the analysis indicated that it is possible to remove the decay heat by boiling. For Mars, the pressure inside the guard vessel would have to be kept at or below the martian atmospheric pressure so that the lithium saturation temperature would be well below the normal operating temperature of the reactor. A transient analysis is required to estimate peak fuel cladding temperatures to verify this method of accommodating a loss of coolant accident.

Reactor Control

Reactor control with BeO reflectors may not be adequate for a man-rated reactor. Leakage out the reactor may be significantly reduced by a man-rated shield in close proximity to the reactor. Poison-backed reflectors may be required to reduce the backscattering produced by the shield. An analysis is required.

Currently, the possibility of astronauts performing maintenance or repair activities is remote. As such, consideration should not be given to a reactor design which allows for replacement and maintenance of reflectors, safety rods, and reflector and rod drive mechanisms.

Inadvertent reactor startup must be prevented by use of lock mechanisms to maintain shutdown rods inside the reactor core and reflectors in their least reactive position.

Disposal

The problem of safe disposal of the used nuclear reactor core is a complex issue. The problem involves fuel and fission product containment, radiation exposure and diversion. Three disposal schemes were examined: 1) storage in place, 2) storage away from the power production area, and 3) insertion into a parabolic trajectory. Disposal by insertion into a parabolic trajectory from the moon and Mars has the potential for accidents during launch from the planet surface and boost from orbit around the planet. These accidents may leave the planet surface or the orbit contaminated. An unplanned retrieval from orbit will create circumstances for additional accidents and significant radiation exposure to astronauts if their presence is required. Disposal by launching the used reactor core to a nuclear safe orbit about the moon or Mars would result in the used reactor presenting a hazard for future flights.

Lunar and Mars surface disposal, i.e., storage in place or away from the power production area, eliminates the hazards associated with schemes that require launching from the planet surface for disposal. However, environmental safety concerns become important for long periods of time. During long storage times, provisions must be made to restrict access to the storage areas and provide for passive decay heat removal.

Any method of surface storage of the used nuclear reactor fuel would be dependent upon the need to remove the used core from the power production area for such purposes as reusing portions of the existing power system versus the ability to safely remove the used core without overexposing the astronauts or contaminating the environment while removing the spent fuel. This issue has been considered should the decision be made in the future to require the removal of the reactor from the vicinity of the base. A commitment to permanent human occupation of the lunar surface may require removal of the used reactors from the base area to avoid clustering these radioactive sources around the base. Spent fuel removal could be accomplished by means of robots to prevent astronaut exposure. Should the use of robots to remove the fuel fail, remedial efforts may be required; these should minimize astronaut exposure. Spent reactor fuel stored on Mars would be required to withstand the martian environment for many years. A risk assessment must be performed to assist in determining which disposal scheme is best. The disposal strategy must have minimum astronaut interaction and adequate long term safe storage with minimum risk.

Criticality

The SP-100 is being designed to remain subcritical during launch accidents by providing sufficient negative reactivity and the structural capability to retain this negative reactivity. Neutron absorber rods will be locked into place inside the reactor core at launch to be removed only upon the startup command. These rods have been designed to keep the reactor core subcritical under all postulated reactor configurations resulting from explosions, projectiles, fragments, and shrapnel. Hydrocode analyses by General Electric (Ref. I-1) have been performed to verify the rods will remain in the reactor core during the explosion environments resulting from failures of the space shuttle. Nuclear reactor accommodation of the explosion environments possible during any phase of the moon and Mars missions is not known at this time due to the lack of sufficient design detail of the launch, transfer, and excursion vehicles. The use of an expendable launch vehicle may eliminate solid rocket motor casing fragments as a safety concern since the reactor should be located above any fragment field generated in an explosion of the launch vehicle.

Larger launch vehicles have been proposed for the moon and Mars missions. When sufficient design details are forthcoming, data characterizing the environments resulting from launch vehicle failures will have to be generated and compiled in the same manner as has been done for the Space Shuttle and the Titan IV. These new environments and failure rates will then be used to design the SP-100 or any other reactor to remain subcritical in these environments. The reactor system will be required to maintain subcriticality in the new launch vehicle explosion environments. The SP-100 program has shown that the fuel and safety rod alignment is maintained in the explosion environments radial implosion, lateral overpressure load against one side of the reactor, axial overpressure load, SRB fragment impact, shrapnel impact, and secondary impact.

End-of-Life Shutdown

End-of-life shutdown is a safety issue because a nuclear reactor that fails to shutdown may preclude access to the power production site to emplace a replacement reactor. Final shutdown should be accomplished by a clock mechanism which will activate at a preset time set prior to operation. The clock mechanism must be single fault tolerant. It must operate independently of the reactor operating mode or the power conversion subsystem operation. It must also irreversibly interrupt the power supply to the reactor control drives, both safety rods and reflectors.

Radiation Exposure

Radiation exposure control during operation and maintenance will involve shielding, distance, and time wherever practical. The particular radiation exposure limits for astronauts has not been clearly defined.

Radiation exposure controls for astronauts need to include the effects of all sources of natural and man-made radiation, both stationary and mobile. Past shielding studies for stationary and mobile systems have ignored the presence of sources of man-made radiation in addition to the reactor. An allocation of exposure to natural and man-made radiation is required. An analysis must be performed of potential astronaut activity on the surface of the moon and Mars to characterize the potential for exposure of the astronauts to man-made radiation sources. From this characterization, an optimum dose limit allocation between mobile and stationary man-made radiation sources can be made.

The characterization of astronaut activities for the purpose of dose limit allocations must include all potential missions. A dose limit based upon a 30 day astronaut stay will result in astronaut overexposure during the

600 day lunar mission dress rehearsal for the missions to Mars. Dose limits should be based upon the longest potential astronaut stay expected during the lifetime of the nuclear reactor surface power system.

Dose limits have not been suggested based upon a realistic and complete set of dose plane locations. Dose limits for man-made radiation emanating from surface nuclear reactors have been proposed for the habitat area at various distances from the power production area (e.g., 1 km and 5 km), at arbitrary distances, and at the inner-most point of the radiator panels. Proper sizing and comparison of shielding alternatives will require the allocation of dose limits at prescribed locations. Various astronaut activities will require them to perform duties at the habitat area, at the launch/landing site, at the soil processing plant, and at locations away from the outpost which will require travel outside the protection of the habitat on surface rovers. A total dose limit must be recognized as the summation of the doses acquired from the various locations at which astronauts will be performing their duties. Also, dose limits should be separated into nominal and emergency limits. A nominal limit should reflect the diversity of duties required of an individual astronaut. Emergency limits should be set to reflect the availability of an excursion vehicle for outpost abandonment in addition to the consequences to the astronauts of power system failure.

Mars Environment

In addition to the CO_2 atmosphere, the martian soil has been found to contain oxidants. The martian soil is periodically entrained and suspended in the atmosphere by surface winds. Also, H_2SO_4 and HCl aerosols are believed to be present in the wind blown dust. Reactor materials will be required to withstand the CO_2 atmosphere and these oxidants and acids during operation and long term storage if final disposal is on the surface of Mars.

Research is required for material compatibility with the martian environment. Coatings such as silicide for refractory metals need to be investigated for long term reliability. Reactor designs using alternate materials, such as stainless steel, which operate at lower temperatures and are compatible with the martian environment need to be considered. Isolation of the refractory materials from the martian environment should be investigated as a potential solution. The refractory metals could be encased in a vessel which supports a vacuum or inert atmosphere between the outside vessel and the inner refractory materials, e.g., encase the primary coolant loop piping in a stainless steel tubing with a vacuum between them.

High Speed Impact on the Earth, Moon and Mars

High speed impacts are possible during a flight to the moon or Mars. High speed impacts on the lunar and Mars surfaces may occur during moon/Mars orbit insertion and descent to the surface. They may also occur during launch from the earth and upon return to the earth should the space vehicle fail to orbit the moon or Mars and return to the earth. The issue of a return to earth without orbiting the moon or Mars is discussed below under the safety issue of return flyby trajectories. An additional possibility for lunar surface impact may occur if nuclear electric propulsion is used and the trans-lunar orbit requires a gravity assist flyby of the moon. Impact speeds may be as high as planet approach velocities since the moon has no atmosphere and Mars has too little atmosphere to adequately slow down the spacecraft. The reactor is unlikely to survive such an impact on the moon or Mars. The risk to the mission from this type of accident will have to be estimated taking into account flight path angle, incoming velocity, and the aerobrakes. Highly reliable transfer vehicle guidance systems will minimize risk. The reactor must be designed to survive earth reentry so that the risk to the general population is insignificant.

Return Flyby Trajectories

Flights to the moon and Mars are likely to use trans-lunar and trans-mars trajectories which will allow return to earth should the space vehicle propulsion system fail to function for orbit insertion. This type of trajectory would be failsafe. If a failure in the propulsion system used for orbit insertion around the moon or Mars is detected during the trans-lunar or trans-Mars trajectory phase of the mission or the system fails to operate when commanded, a return flyby trajectory would allow the space vehicle to return to earth with little or no additional thrusting for retrieval of astronauts and cargo. The propulsion system may be either chemical or nuclear. The term return flyby trajectory has been used to denote a trajectory from the earth to the moon or Mars which would not require a significant thrust at the moon or Mars to insert the space vehicle into a trajectory which will return the space vehicle to the earth. The returning space vehicle would contain the original cargo, including the surface power system reactor. The potential exists for the returning space vehicle to reenter the earth's atmosphere should the propulsion system failure preclude an earth avoidance maneuver. Reactor earth reentry survival in a subcritical configuration will have to be guaranteed so that the risk to the general population is insignificant.

The preferred resolution to reduce the risk to the general population to an insignificant level would be ejection of the nuclear reactor at some time in the return flyby trajectory when such an action poses very little threat to the general population. This would be the most likely means of reducing the threat since a return flyby trajectory would probably call for ejection of the cargo and unused propellant since transfer vehicles do not appear to be designed for insertion into low earth orbit with such a large mass. It is not clear that the propulsion system for the SEI space vehicles would be capable of earth orbit insertion with the full cargo. The return trajectory should have a perigee altitude of at least 1000 km in case ejection of the reactor fails. If ejection of the reactor is not possible, the transfer vehicles would have to be designed to accommodate this mission abort scenario. The transfer vehicle would have to be designed so that the aerobrake, or the attached excursion vehicle, could safely insert the spacecraft into orbit about the earth. The particular flight maneuvers associated with earth orbit insertion should be chosen to minimize risk to the general population. Because the reactor will not be operated until it is emplaced on the surface of the moon or Mars, mission risk will not be aggravated by a fission product inventory. The safety issue of a nuclear propulsion system as part of this returning space vehicle was not addressed since it was outside the scope of this task.

Loss of Power to Habitat

This issue is not normally considered a nuclear safety issue. It has been included here because it does have an impact on the safety of the astronauts. The following discussion will have some application to any central power system used on the moon and Mars.

In all cases where the nuclear reactor is shutdown due to a failure and in some cases where power is reduced, the habitat will not have sufficient power to maintain life support systems. It is the responsibility of the power system designer to prevent a power system response which will place the astronauts in a life threatening situation. An uninterruptible power source must be provided which will maintain minimum life support capabilities.

Habitat power requirements in the case of nuclear reactor shutdown or power-down will be time dependent based upon the response of the habitat life support systems to a loss of power. An analysis must be performed to identify the power needs of systems after a nuclear reactor power system shutdown or power reduction.

A reliability, availability, and maintainability (RAM) analysis is required of all surface power systems (including extravehicular mobility units) with respect to meeting the life support requirements of the astronauts. These life support requirements would include maintenance of the excursion vehicle to provide the astronauts the option to abandon the outpost. The goals of the RAM analysis must be consistent with the purpose of the outpost and the restrictions placed upon any emergency options due to the remoteness of the outpost from earth and the harsh environment in which the outpost exists.

Reactors designed for low earth orbit applications are typically required to meet reliability goals. Reliability goals are used for systems which are not repairable. The nuclear reactor power system for the moon and Mars may have some degree of repairability. Also, the availability of power to the astronauts is most important. As such, it would seem that an availability goal is more appropriate. A nuclear power system should be designed with an availability goal(s) for power to sustain life support systems and other vital power consumers as a part of a total power management and distribution system of stationary and mobile power sources. A RAM analysis is advised.

Recommendations

The scope of this study was to identify safety issues associated with the use of nuclear reactors as lunar and martian surface power systems for the Space Exploration Initiative. Resolution approaches to the safety issues were identified without an extensive analytical assessment. Resolution options were selected based upon previous analyses as appropriate. Where there was inadequate information, data requirements and the methods to acquire the data were identified. The following paragraphs discuss follow-on tasks.

Shielding options cannot be properly evaluated at this point in the Space Exploration Initiative. There is no comprehensive criteria against which to evaluate and select the best option. A study should be performed to characterize astronaut activities for the purpose of establishing dose limit allocations. This study would define a global dose limit and then proceed to allocate portions of this limit to the various activities astronauts will perform. Admittedly, there is not enough data for a definitive set of criteria, but there is enough data on mission activities to perform a parametric analysis with the intent to bound the solution and reduce the number of options. Additional data requirements can be identified. Shielding impacts on mission activities can be identified to eliminate the potential for dose requirements that would eliminate critical mission elements.

The next step in evaluating mission risk would be the construction of complete event trees with projected accident probabilities based upon the best available failure rate data on the launch vehicle and the space vehicles used to transfer the reactor from earth orbit to the surface of the moon or Mars. This step would identify failure rate data requirements. All mission phases would be analyzed to allow a comprehensive comparison. Missing data could be provided by data on similar systems and components operating in similar environments. In combination with estimates of radiation source terms, the event trees would be used to identify high risk contributors, by using a relative risk index, that may have a large impact on nuclear reactor and power conversion system design. The relative risk evaluation would begin the process of identifying dominant mission risk contributors early in the design process to preclude significant design changes during subsequent design efforts when such changes would have a severe adverse effect on system development. The relative risk index can be used to identify the dominant risk contributors without the need to determine absolute mission risk.

The safety requirements listed in this study are primarily for a payload launched on the Space Shuttle. The unmanned mission safety requirements are the result of an initial cursory evaluation of SP-100 mission safety requirements and their applicability to potential SEI missions. The additional manned mission requirements were identified as part of this study. A thorough evaluation of the applicability of the unmanned mission safety requirements is needed to eliminate unnecessary requirements and to identify missing requirements. The launch vehicles proposed for the SEI missions are primarily expendable boosters. A study is required to ensure that the safety requirements for these expendable launch vehicles have been identified.

2.0 INTRODUCTION

In the 90-day Space Exploration Initiative (SEI) study conducted by the National Aeronautics and Space Administration, power requirements and duty cycles for the planetary (lunar and martian) surface systems were estimated. A major conclusion of the study was the requirement for a nuclear reactor to supply electrical power to planetary surface systems with duty cycles having power demands during the lunar night.

The object of this task order was to report the results of a study to investigate the safety issues associated with using a reactor as a source of electrical energy to power planetary surface systems identified during the 90-day study. This safety investigation defined mission profiles for nuclear reactor applications on the moon and Mars. Accident scenarios and environments were postulated. A qualitative safety assessment was performed.

The most advanced space nuclear reactor design program is the SP-100 program. The SP-100 reactor power system is being designed for generic missions in orbit around the earth and not specifically for missions on the surfaces of the moon and Mars. This study evaluated and resolved safety issues associated with the missions to the moon and Mars. The effects of planet surface application on the SP-100 design were noted.

This report begins with a summary of the results of the study in Chapter 2. This is followed by a discussion of nuclear reactor applications on the moon and Mars in Chapter 3. Basic mission sequences for flights to the moon and Mars are then presented. Mission phases for operation on planetary surfaces and final disposal are also included. Next, the lunar and martian environments are described since these environments have safety implications.

The current safety requirements for the SP-100 reactor system are presented in Chapter 4. This includes a list of safety requirements documents.

Chapter 5 presents the defined mission profiles for the lunar and martian flights. The basis for these flights are the results of the 90-day study and feedback during Task Order reviews. Further details have been added to allow a reasonable identification of potential accidents. Separate mission profiles have been defined for flights to the moon and Mars. The mission profiles covered activities from fuel fabrication to disposal.

Potential accident scenarios and environments were identified for the lunar and martian mission profiles. These scenarios and environments are presented in Chapter 6. From the accident scenarios and environments, safety issues were identified. The safety issues are presented in Chapter 7.

Safety issue resolution approaches are presented in Chapter 8. The depth of the safety analysis and resolution approaches is commensurate with the level of detail found in the results of the 90-day study. This chapter contains a brief summary of SP-100 program resolution approaches. It also contains the results of an assessment of the lunar and martian mission elements not previously examined.

Chapter 9 presents a brief list of recommendations to enhance the safety of a nuclear reactor throughout the various phases of the lunar and martian missions.

3.0 NUCLEAR REACTOR APPLICATION ON MARS AND THE MOON

The potential need for a nuclear reactor power system was identified in the 90-day study to provide the electrical power required as the outposts' power demands evolve into the hundreds of kilowatts. Also, a nuclear reactor power system has a mass advantage over photovoltaic systems on the moon because the length of the lunar night makes dedicated energy storage for photovoltaic systems heavy. The reactor system could be part of a centralized power production system wherein transmission cables would connect the reactor with the other major areas of the lunar and martian outposts. The reactor power system could also be a stand-alone unit dedicated to a specific application. The location of the unit and the means to transmit the power to the application will be dependent upon the amount of human interaction at the site of the application.

The safe use of a nuclear reactor as an electrical power source on the moon and Mars requires the system designer to consider all phases of the mission, not just that part of the mission when the reactor is operating on the surface of the planet. The design must be analyzed for potential harmful effects to the general population, the environment of the earth, and mission personnel during all mission phases.

As a starting point in this analysis, the safety analyst must be knowledgeable of the circumstances to which his system will be subject during the mission phases. This chapter begins with a discussion of basic mission profiles defined for this study. The basic missions to the moon and Mars have been defined assuming continuous occupation of the surface of the planet and reuse of transportation vehicles. The discussion includes potential perturbations from these basic mission profiles to provide a comprehensive safety assessment. Alternate mission sequences include direct launch to the moon and Mars, transport vehicle assembly in low earth orbit away from the space station, reactor emplacement on the surface of the planet or buried, intermittent outpost occupancy, and disposal by surface or away-from-surface strategies (detailed mission profiles are presented in Chapter 4). This is followed by a section on the lunar and martian environment as they pertain to safety.

The flight plans for missions to the moon and Mars are currently under evaluation. To provide a basis for a safety evaluation of the use of a nuclear reactor as a power source for surface systems on the moon and Mars, basic mission sequences have been assumed. The basis for the basic mission sequences defined for this study was Reference Approach A (Ref. III-1). Reference Approach A was chosen because it appeared to contain the greatest level of activity, as opposed to Reference E, and thus would provide a comprehensive treatment. Variations of these basic mission sequences have been defined in this study to include the latest proposals by NASA and other potential alternatives. The details of the mission sequences are in Chapter 4.

During the exploration of the moon, flight plans will change with lunar outpost evolution. As the lunar outpost evolves to decrease dependency on earth, flight plans will include reuse of systems, e.g., the lunar transfer vehicle and the lunar excursion vehicle (LEV). Prior to the establishment of the lunar excursion vehicle servicer on the moon, the lunar transfer and excursion vehicles will be flown in an expendable mode. With the addition of the LO_2 plant on the moon, the transfer and excursion vehicles will be flown in a reusable mode.

Flights to Mars will follow much the same pattern as the lunar flights. The one significant exception is the first manned flight. For a chemical propulsion system, both transfer and excursion vehicles will be flown in an expendable mode with the transfer vehicle aerobrake, if used, jettisoned at Mars. The flight crew will transfer to an Apollo-like reentry vehicle for direct reentry to earth. The transfer vehicle will either be lost in space or burnup upon reentry to earth. If the propulsion system is nuclear-based, the returning astronauts may enter into an earth orbit on all missions including the first. This first manned flight with a chemical propulsion system is mentioned for the sake of completeness. The long flight times to Mars involved with chemical propulsion will likely preclude the use of chemical-based rocket engines. In any case, there is always the possibility of using an Apollo-like reentry capsule on a Mars mission regardless of the propulsion system; throwaway nuclear rocket engines may be used and return to earth may be by direct reentry in an Apollo-like capsule without the use of a propulsion system for orbit insertion.

3.1 LUNAR OUTPOST

The typical delivery of cargo and crew to the lunar outpost, Figure 3-1, will begin with launches of lunar payload, crew, and propellants from earth to Space Station Freedom. At Space Station Freedom, these items are loaded onto the lunar transfer vehicle. The lunar transfer vehicle subsequently rendezvous with the lunar excursion vehicle in lunar orbit. Payload, crew, and the necessary propellants are transferred to the lunar excursion vehicle. The lunar excursion vehicle subsequently descends to the lunar surface. The lunar transfer vehicle returns to Space Station Freedom. Servicing and maintenance of the lunar transfer vehicle will be performed at Space Station Freedom while the same will be performed for the lunar excursion vehicle at the lunar outpost. Alternatives to this basic mission sequence are direct launch to the moon, e.g., Apollo flights; launch to low earth orbit for assembly of the lunar transport vehicles; direct descent to the lunar surface; and the use of expendable vehicles.

There will be both piloted and cargo-only flights as identified in Ref. III-1. A limited exploration program may have astronauts on every flight. A piloted flight will deliver cargo and a four man crew to the lunar surface with subsequent return of the crew and a limited amount of cargo. A cargo flight will deliver only cargo with the lunar transfer vehicle left on the surface or returned empty. Both flights will use common lunar transfer and excursion vehicles. Direct launch and descent missions may use what would be defined as a single vehicle with stages. A piloted flight will require the addition of a crew module while the cargo flights will use only some type of cargo pallet. Cargo flights where the lunar transfer and excursion vehicles

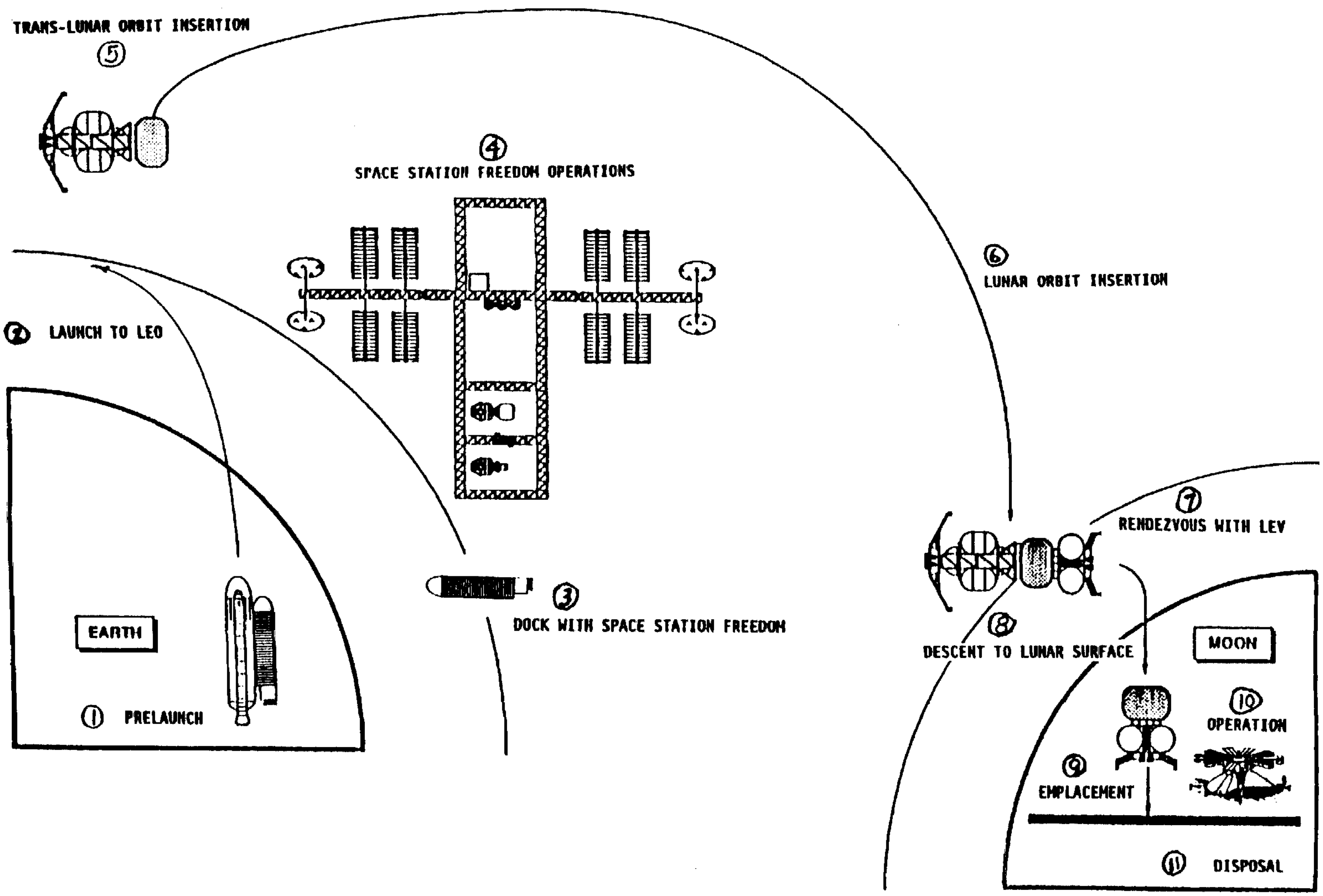

Figure 3-1 Lunar Mission Profile (Ref. III-2).

are expended will provide the maximum transfer of mass to the lunar surface. Piloted flights will likely use an earth-to-moon trajectory which will allow a safe return to the earth should the propulsion system fail to allow proper insertion into an orbit about the moon. The trajectory would allow the astronauts to fly behind the moon and then return to the earth with little or no thrusting. The assumption has been made that an Apollo-like reentry would be required at the earth. The disposition of the rest of the cargo and space vehicle is unknown; the cargo and vehicle would either fly past the earth, orbit, or enter the atmosphere.

Heavy-lift launch vehicles will be utilized to deliver the lunar payloads, vehicles, and propellants to Space Station Freedom in the basic mission sequence. These same vehicles, or variations, would be used to deliver material to low earth orbit or to launch directly to the moon. The launch vehicles will be either a derivative of the Shuttle or a version of the Advanced Launch System, Figure 3-2. Both launch vehicles will have a payload shroud large enough to allow lunar transfer and excursion vehicles to be launched virtually intact during the early expendable flights. One launch will deliver the lunar transfer and excursion vehicles and two subsequent launches will deliver the necessary lunar transfer and excursion vehicle propellants. Early piloted flights will have the lunar transfer and excursion vehicles, Figure 3-3, packaged to be launched on a single heavy-lift vehicle. The package will contain a fully fueled lunar transfer vehicle core propulsion/avionics module, the aerobrake central core and peripheral segments, the lunar transfer vehicle crew module, the lunar excursion vehicle crew cab, and a partially fueled lunar excursion vehicle. The Shuttle will deliver crew and cargo. All early flights will expend the lunar transfer and excursion vehicles. Direct launch and descent flights will have launch configurations similar to early expendable flights but with fully fueled vehicles.

At Space Station Freedom, the eight peripheral aerobrake segments will be attached to the central core of the lunar transfer vehicle and the combination examined for structural integrity. The aerobrake will be refurbished and verified after each flight up to a total of five flights. Similar work is assumed performed at a low earth staging orbit not at Space Station Freedom.

Two heavy-lift vehicles will deliver to Space Station Freedom the expendable propellant tanks for the lunar transfer vehicle. Two of the propellant tanks will be jettisoned after trans-lunar orbit injection and the remaining two will be jettisoned in low lunar orbit. The same sequence of propellant tank delivery and empty tank ejection was assumed when a low earth staging orbit was used in place of operations at Space Station Freedom. A direct launch mission was assumed to also jettison empty fuel tanks.

When the lunar excursion vehicle is reused, cryogenic propellants and consumables will be transferred from the lunar transfer vehicle. LO_2 mined on the lunar surface will be used by the lunar excursion vehicle when available; LH_2 will always originate from earth.

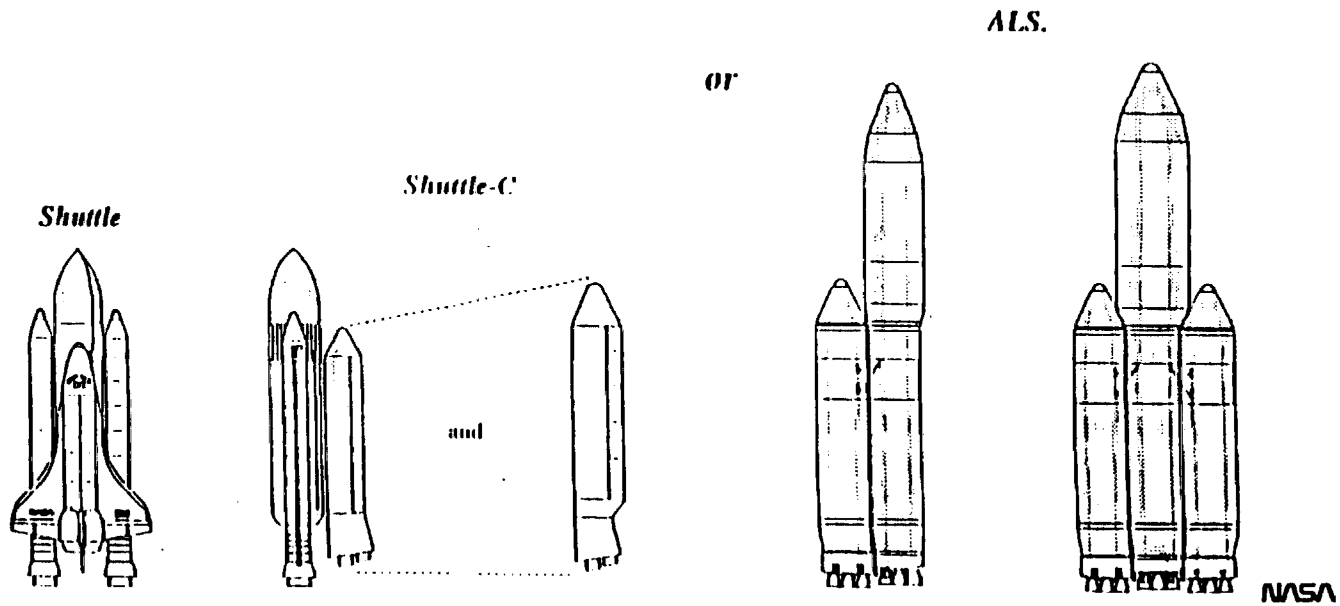

Figure 3-2 Lunar Heavy-Lift Launch Vehicle Options (Ref. III-3).

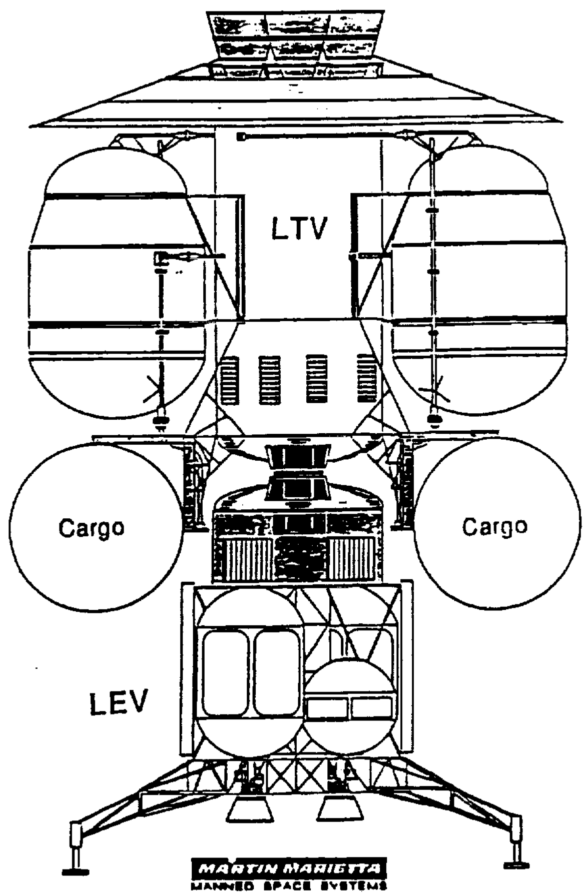

Figure 3-3 Lunar Transportation System (Ref. III-4).

An automated rendezvous and docking system is provided in the lunar transfer vehicle for rendezvous with a lunar excursion vehicle in lunar orbit and with Space Station Freedom upon return from the moon. This system will have manual override provisions for piloted flights.

The reused lunar excursion vehicle, Figure 3-4, will be based on the lunar surface or stored in lunar orbit. On the lunar surface it will be covered by a thermal tent and out-gassing will be controlled by the lunar excursion vehicle servicer stationed at the launch area. The legs and landing pads will be provided with height control for landing on unimproved areas. The excursion vehicle engines will provide single engine-out capability. They will be fueled with LH_2 and LO_2.

An expended lunar excursion vehicle was assumed to be left in lunar orbit.

3.2 MARTIAN OUTPOST

Delivery of crew and cargo to Mars in the basic mission sequence is very similar to delivery to the moon. The flight profile is shown in Figure 3-5. Payload, crew, and propellants are launched from earth to Space Station Freedom where transfer and excursion vehicles are assembled, inspected, and fueled. The assembled vehicles are then inserted into a transfer orbit to Mars. At Mars the vehicles separate and use aerobrakes for Mars capture. In orbit, the vehicles rendezvous and the crew transfers from the transfer vehicle to the excursion vehicle. Descent to the martian surface is accomplished by aerobrake and descent engines. The aerobrake is jettisoned during reentry. Once on the surface, the crew lives in a habitat which has been delivered as cargo either on the same excursion vehicle or a previous one. Ascent from the surface will be accomplished using an upper stage of the excursion vehicle. This part of the excursion vehicle will rendezvous with the orbiting transfer vehicle to transfer crew and cargo for the return trip to earth. Capture at earth will be accomplished by transfer vehicle aerobrake. The transfer vehicle will then rendezvous with Space Station Freedom for refurbishment.

Flight maneuvers include injection into the trans-Mars orbit, aerobrake capture at Mars, and descent and landing at Mars. The return portion of the mission involves ascent from the martian surface, rendezvous in martian orbit with the transfer vehicle, injection into the trans-earth orbit, and capture at earth. The two captures will be accomplished by aerobraking. Aeromaneuvering of the excursion vehicle will allow cross-range landing capability for an out-of-plane (orbital) landing site. The early piloted expeditionary missions will use an Apollo-like reentry capsule for the crew to reenter directly to the surface of the earth. The nominal entry velocities at Mars and earth are 8.5 kilometers per second and 12.5 kilometers per second, respectively. An aborted mission is expected to see a larger earth reentry velocity.

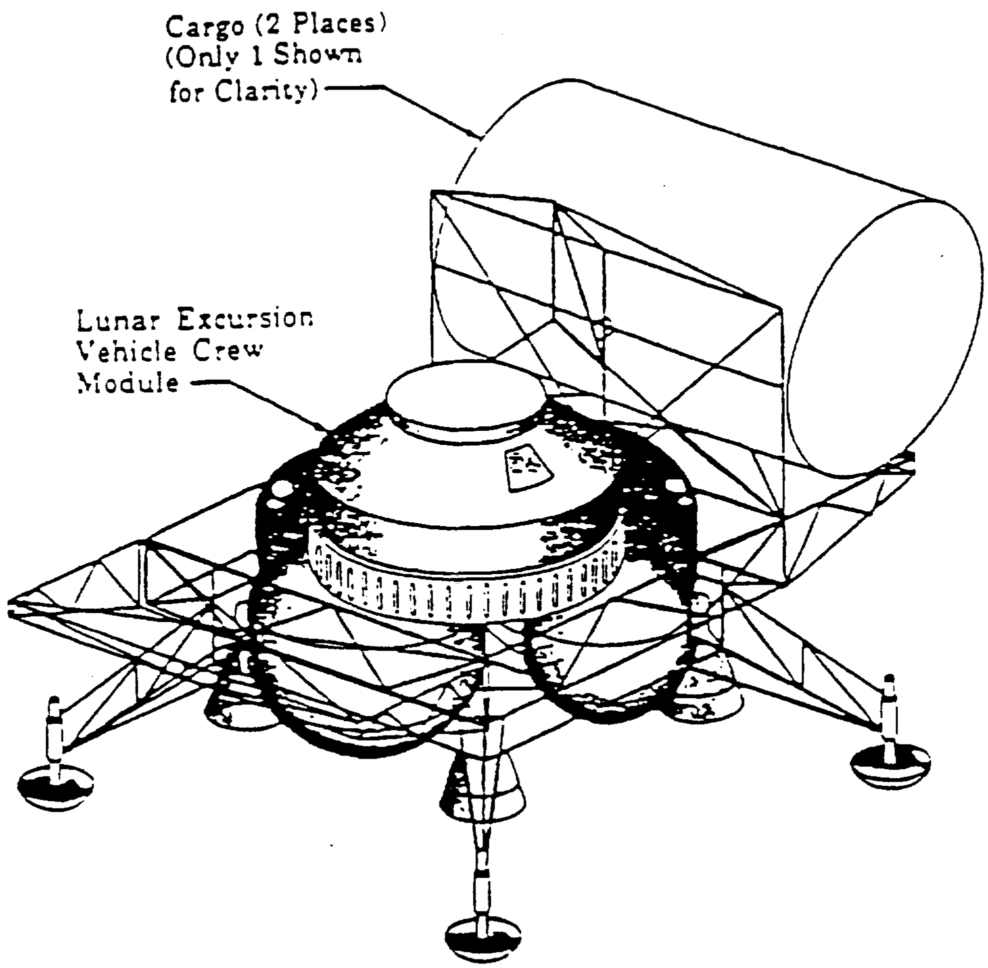

Figure 3-4 Lunar Excursion Vehicle (Ref. III-1).

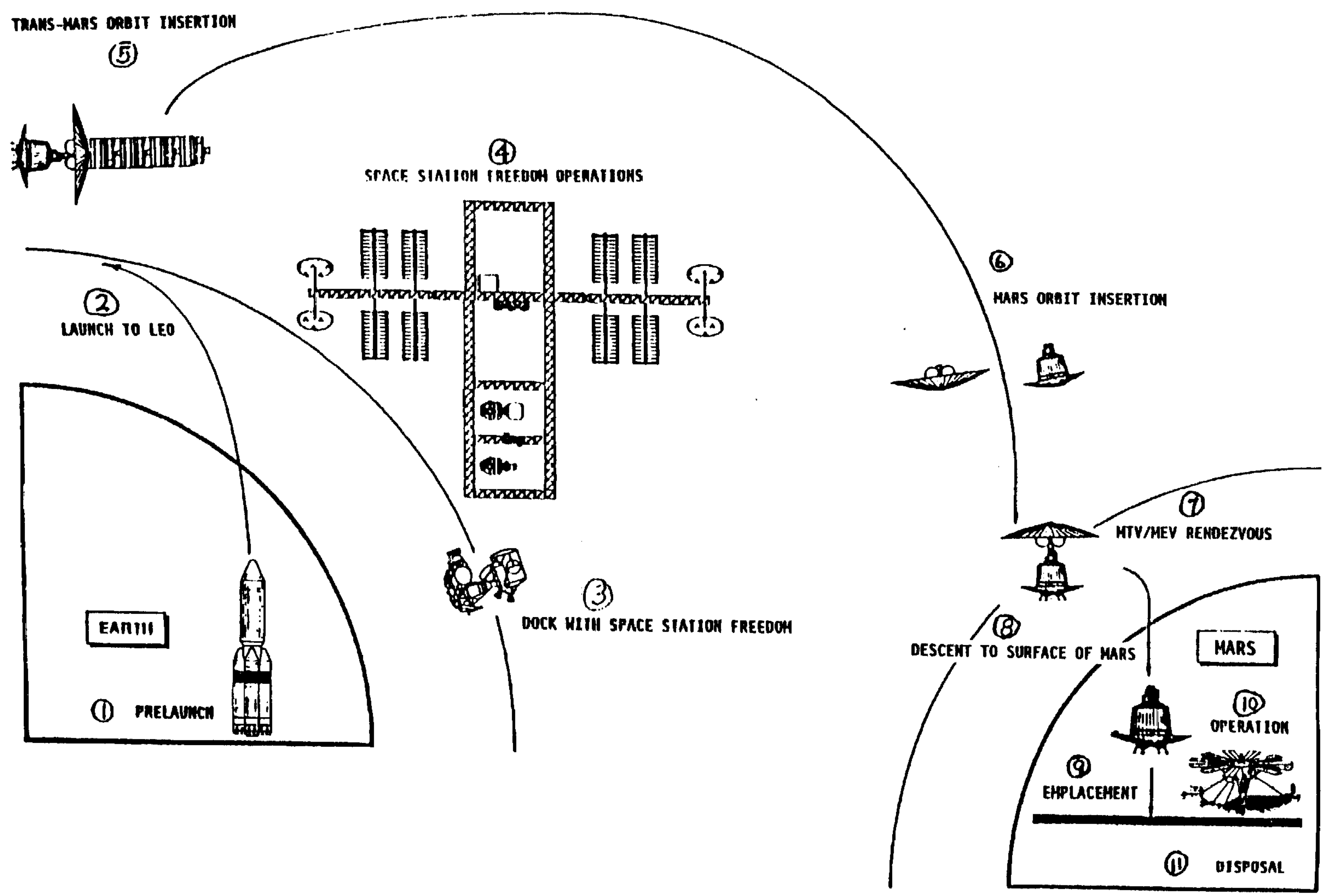

Figure 3-5 Mars Mission Profile (Ref. III-2).

Alternatives to the basic mission sequence maneuvers include direct launch and descent to Mars with a single transfer vehicle from earth to Mars and back. Transfer vehicle assembly may be performed in low earth orbit in place of Space Station Freedom. Also, chemical transfer vehicle engines may be replaced with nuclear propulsion engines. A potential nuclear electric driven trans-Mars orbit trajectory can be seen in Figure 3-6. A nuclear thermal driven transfer vehicle would follow a trajectory similar to that of the basic mission sequence. The assumption was made that all nuclear propulsion driven transfer vehicles would not use an aerobrake for insertion into orbits around the earth and Mars.

As with the lunar flights, there would be piloted and cargo flights to Mars. A limited exploration program may involve only flights with cargo and astronauts. Cargo flights will be composed of excursion vehicles only. There will be no orbiting transfer vehicle. The excursion vehicles will separate at Mars and be captured by means of the aerobrakes, if used. For the first cargo flight, the excursion vehicles may descend to the martian surface and remain there. For all flights, the lower stage of the excursion vehicle will be expended. It appears that the upper portion of excursion vehicles will be operated in an expendable mode. All piloted flights will likely use trajectories that allow the crew to fly by Mars and return to earth should the mission be aborted due to propulsion failure with little or no thrusting. The possibility exists that similar flyby trajectories may be used for cargo flights to recover the cargo and space vehicle. It is not clear how the returning space craft would be captured by the earth's gravity to orbit about the earth since a failed propulsion system may also preclude use of a propulsion system for orbit insertion about the earth. The possibility is included for completeness. If the decision is made to not recover the space vehicle and cargo from an aborted mission, there will be no nuclear reactor returning to the earth and thus, no safety issue.

Launch vehicles for the exploration of Mars will be a larger class of heavy-lift vehicles with roughly double the capacity of the lunar heavy-lift vehicles. Conceptual designs are shown in Figure 3-7. An obvious observation is that this class of launch vehicles will have payloads located above the solid rocket boosters. In a launch explosion, fragments from the solid rocket boosters should not be a safety concern. The possibility that the Space Shuttle may be used to lift cargo to Space Station Freedom, if it is used as a staging area, should not be ignored. The Space Shuttle was mentioned (Ref. III-1) as a means to lift cargo for the lunar missions and the potential for the same strategy for martian flights may exist.

The transfer vehicle consists of a core vehicle and an expendable injection stage fueled by LH_2 and LO_2, Figure 3-8. Subsequent to injection into the trans-Mars orbit at Space Station Freedom, the injection stage is jettisoned. The injection stage consists of five core propulsion systems of engines and propellant tanks with the potential for three additional strap-on propellant tanks. The strap-on propellant tanks will be the same configuration as the core system tanks.

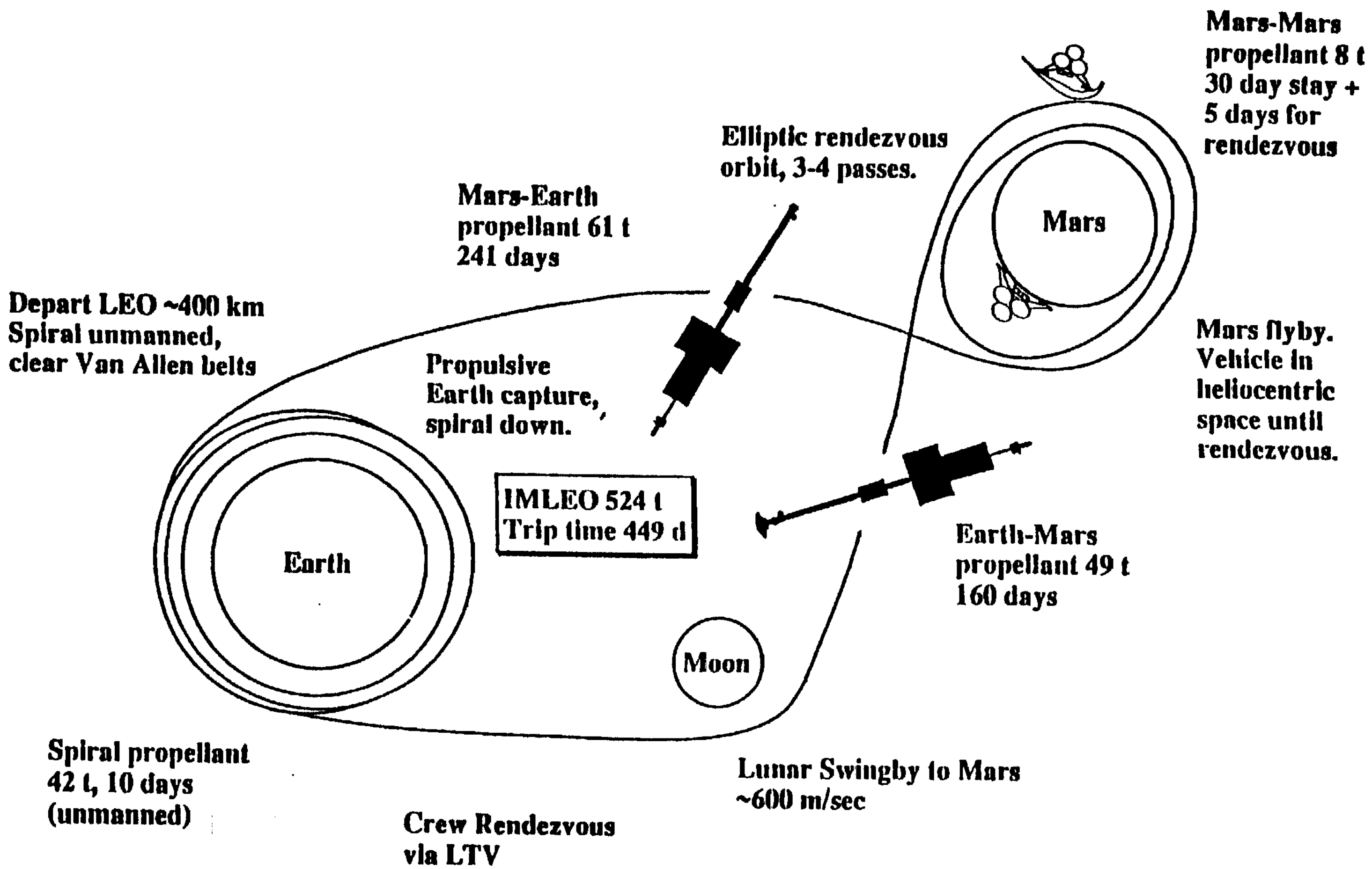

Figure 3-6 Mars Mission Profile for Nuclear Electric Propulsion (Ref. III-2)

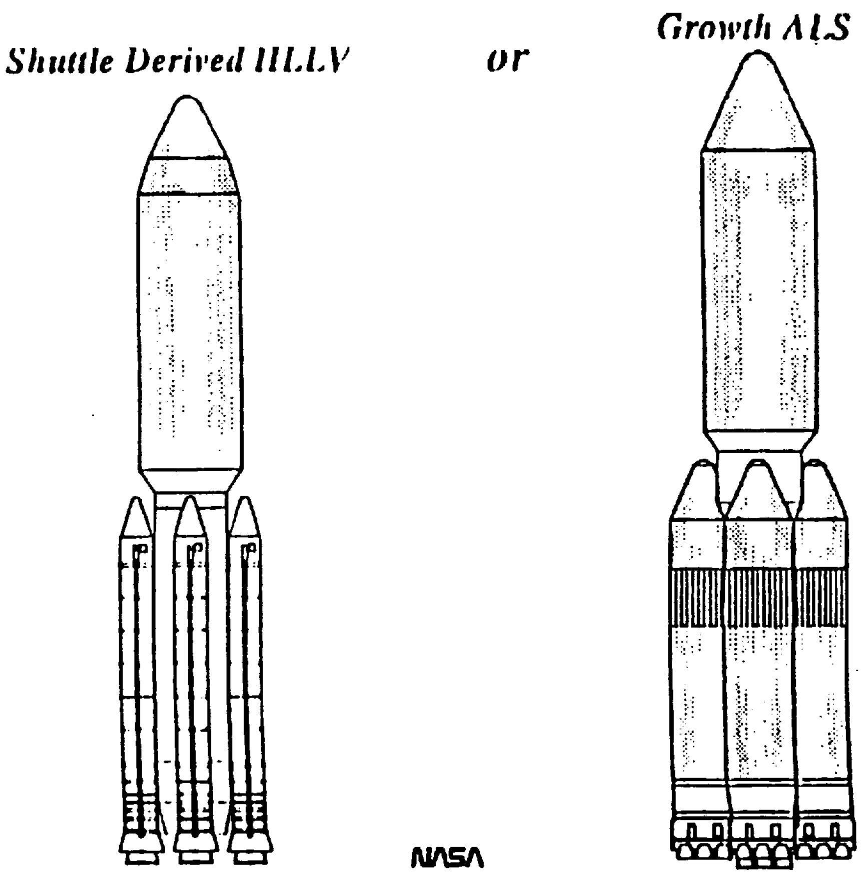

Figure 3-7 Mars Heavy-Lift Launch Vehicle Options (Ref. III-3).

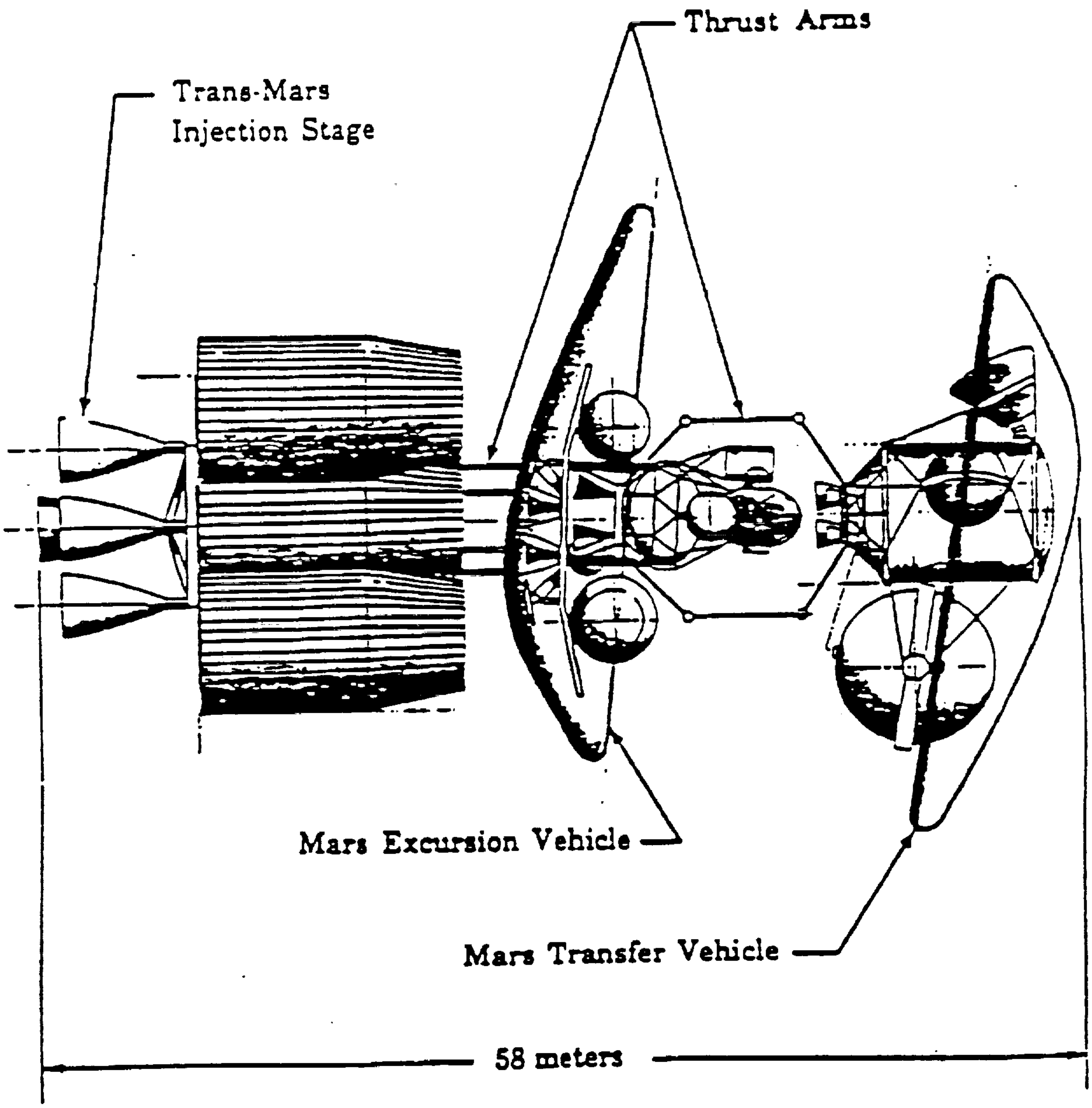

Figure 3-8 Mars Transportation System (Ref. III-1).

The large aerobrake on the transfer vehicle will be used for capture at Mars and the earth on missions subsequent to the early expeditionary missions which will use an Apollo-like reentry vehicle upon return to earth. Aerobrake lift will provide trajectory control and drag will slow the vehicle. The aerobrake heat shield will be designed to survive high-velocity earth reentry and capture. Transfer vehicle propulsion for return to earth from Mars will be provided by four engines of the design developed for the lunar transfer vehicle.

The excursion vehicle, Figures 3-8 and 3-9, consists of two rocket stages and an aerobrake. The aerobrake is identical in shape and size to the transfer vehicle aerobrake. It will provide lift to maneuver from parking orbit to a landing site on the surface of Mars. It will also contain a heat shield for capture at Mars. No mention was made whether this heat shield would survive earth reentry. Landing legs are deployed and the descent engines are ignited after the aerobrake is jettisoned. The five descent engines of the lower stage and the three ascent engines of the upper stage will provide single engine-out capability. They will be fueled with LH_2 and LO_2.

Nuclear propulsion concepts for the transport vehicle are shown in Figures 3-10 and 3-11. The nuclear thermal engine would burn for a very short time in the vicinity of the earth and Mars. Hydrogen would be the propellant. Nuclear electric propulsion was assumed to require continual operation of the engine during the trans-Mars and trans-earth trajectories. Another assumption made was that crew rendezvous was necessary outside the van Allen radiation belts. The nuclear electric propulsion system would require weeks to traverse the radiation belts from low earth orbit. The nuclear electric powered transport vehicle would have to use a low earth orbit for cargo and propellant transfer.

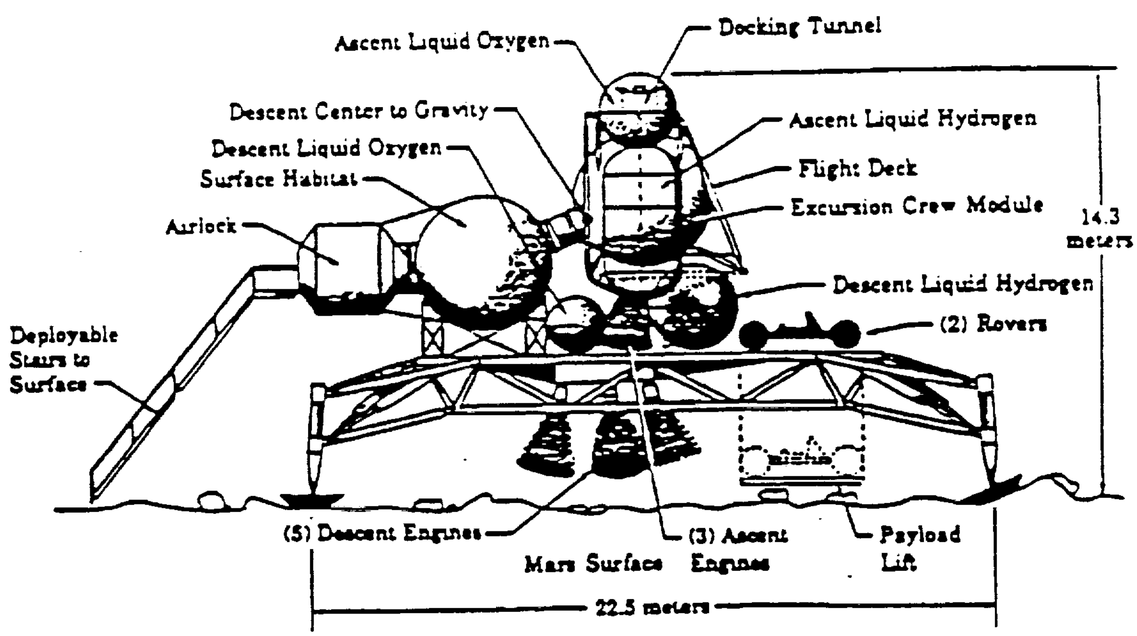

Figure 3-9 Mars Excursion Vehicle (Ref. III-1).

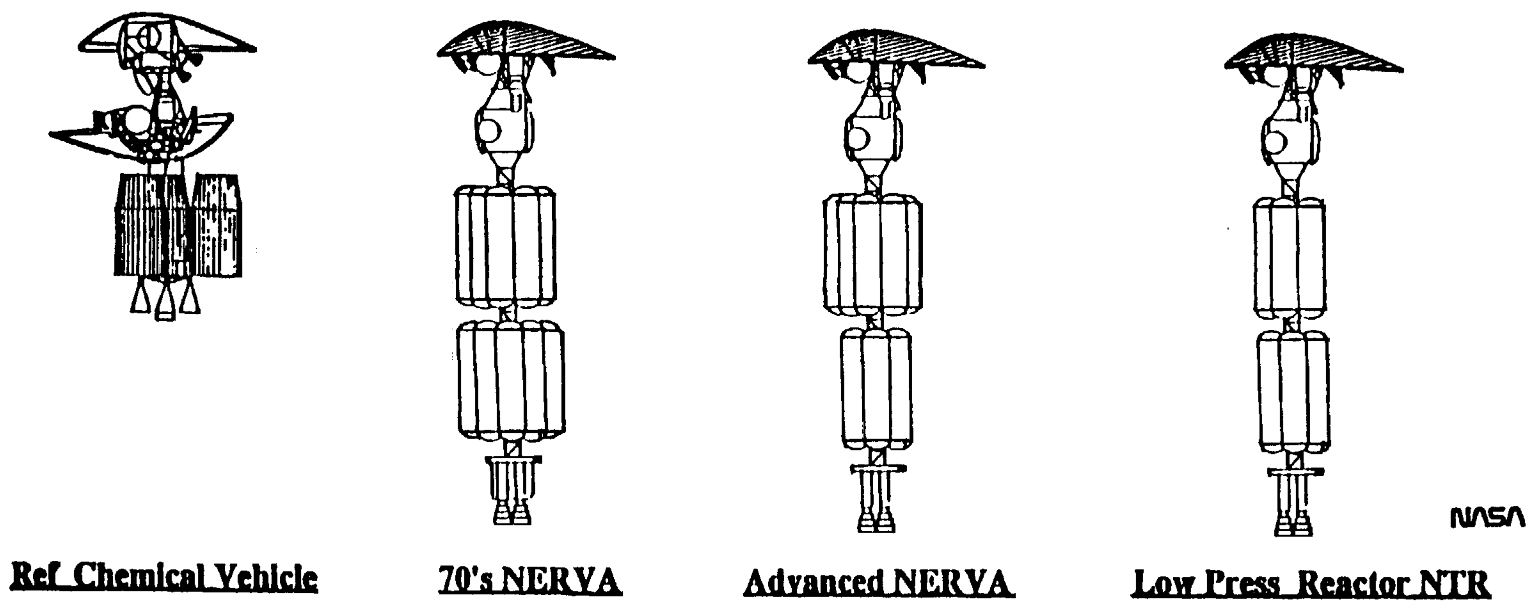

Figure 3-10 Mars Transport Vehicle Using Nuclear Thermal Propulsion (Ref. III-6).

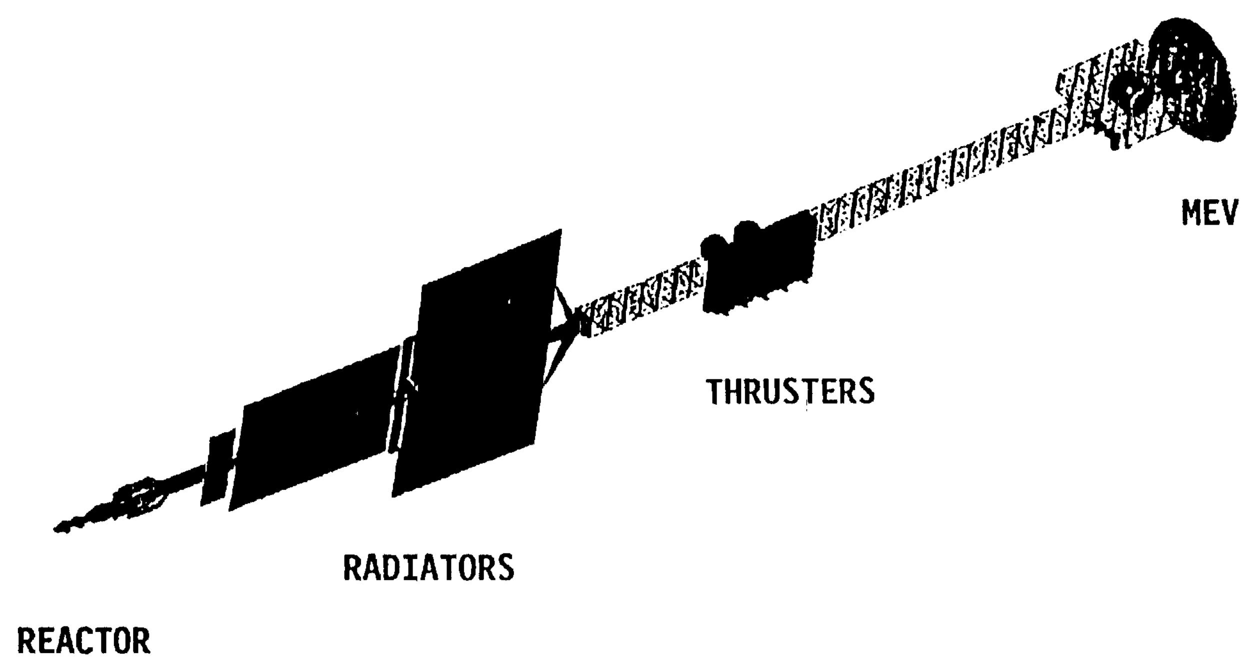

Figure 3-11 Mars Transport Vehicle Using Nuclear Electric Propulsion (Ref. III-5).

4.0 SAFETY REQUIREMENTS

The following is a list of safety requirements compiled from the SP-100 space nuclear reactor program.

1. The maximum individual radiation dose to the public shall be 0.5 rem/yr. The limit for operations personnel is 5 rem/yr.

2. Subcriticality shall be positively maintained assuming any credible single failure or initiating event during all normal assembly, transportation, handling, prelaunch, launch ascent, deployment, orbit acquisition, end of life, and permanent storage orbit operations.

3. The reactor shall have effective intrinsic negative reactivity feedback for positive power and temperature excursions.

4. The reactor shall be designed to ensure with high confidence the permanent subcriticality of the reactor at the final shutdown. This final shutdown shall activate automatically, shall be irreversible, and shall not be initiated or rendered inoperable by any credible single failure or initiating event.

5. The reactor shall remain subcritical under the following conditions:
   a) Core internal structure and vessel generally intact with all exterior components removed and with all possible combinations of soil and water filling and surrounding the core.
   b) Core internal structure and vessel generally intact with compaction along the pitch lines of the pins to produce pin-to-pin contact, all exterior components removed, and all possible combinations of soil and water filling and surrounding the core.
   c) Core internal structure and vessel generally intact with compaction along the pitch line of the pins to produce pin-to-pin contact, the normal exterior components and reflectors compressed around the core; the exterior absorber material, if any, in its normal shutdown position; and the core containing it original coolant or any possible combinations of soil and water.
   d) Core internal structure and vessel generally intact with compaction along the pitch line of the pins to produce pin-to-pin contact, all exterior components removed, and aluminum surrounding the core containing its original coolant.
   e) Core internal structure and vessel generally intact with all exterior components removed and the vessel

exposed to a solid propellant fire.

6. The unirradiated nuclear fuel shall pose no significant environmental hazard.

7. Engineered safety features shall be designed and built to conform to STS-1 (QA Assurance) and STS-2 (Reliability Engineering).

8. The coolability of the reactor shall be assured with high confidence for all credible accident conditions to maintain the structural integrity and thereby the predictability of the desired reactor behavior during final shutdown.

9. The reactor protection system shall
   a) have two independent systems not subject to common cause failure to reduce reactivity to a subcritical state,
   b) have the capability to sense conditions requiring shutdown,
   c) have an automatic shutdown capability,
   d) be independent of the reactor control system except for the neutron absorber (core-internal) and reflector elements and their actuators,
   e) have fault detection sensors with capability for test during reactor operation,
   f) have a fault detection system not subject to single point failure,
   g) have a fault detection system not subject to common cause failures with systems and conditions upon which it is called to activate in case of their failure,
   h) be failsafe, and
   i) have adequate shutdown margin.

10. The reactor designer shall conduct a safety test and analysis program to assess reactor response to postulated credible accidents.

11. The reactor control system shall
    a) require a positive coded signal for reactor startup,
    b) be capable of controlling power escalation to full power,
    c) be capable of reducing power to a full shutdown mode,
    d) be capable of controlling power and temperature excursions, and
    e) be capable of operation in a directed positive shutdown mode.

12. Operating conditions requiring automatic shutdown are failure of the reactor control system, exceeding nuclear fuel design temperature limits, and failure of the reactor control and/or safety systems communications system.

13. Test and inspection programs for design and manufacture shall include a plan to verify the design concept, to show conformance to safety specifications, and to provide data for quality control of manufacturing or engineered safety features.

14. No planned reentry.

15. The reactor shall survive an inadvertent reentry in a subcritical configuration with internal neutron shutdown absorbers intact in a contiguous reactor core.

16. Following intact inadvertent reentry, the reactor shall be designed to produce effective burial of radioactive materials present upon impact on water, soil, or pavement-grade concrete.

17. The reactor control and safety systems communications system shall be composed of two independent subsystems with the capability to monitor and/or control the status of the reactor, the reactor control system, the power conversion system, and all safety systems.

18. Independent electrical power shall be provided to the reactor control and protection systems and their communications system. These systems must operate independent of the reactor operating mode or power conversion system operation. Independent electrical power must be provided to safety related systems for a minimum of 24 hours following failure of the power conversion system.

19. Quantities of toxic materials are to minimized.

20. The power system shall be designed to prevent a significant release and dispersal of toxic materials during normal operations in all mission phases with the potential for human interaction with the system and when the system is exposed to environments associated with credible failures and accidents during these operations. Possible releases to the atmosphere will be held within on-site and off-site tolerance levels established by the appropriate regulatory authority.

21. The instrumentation system shall provide, through reactor control, protection and safety systems communication system, signals to allow continuous determination of 1) the reactor power level and rate of change; 2) the fuel temperature; 3) the positions of the control and reflector elements; and 4) the status of the reactor control system, the reactor protection system, the power conversion system, and the independent electrical power source.

22. Individual risk due to a mission shall be subject to ALARA considering economic, technical and social factors.

23. The risk to the general population shall be subject to ALARA considering economic, technical and social factors.

24. Design margins must reflect consideration of normal mission operation system failure rates, accident probabilities and environments.

25. Safety Technical Specifications must be prepared for approval by the Department of Energy.

26. The reactor design shall enhance the ability to detect, locate, and recover Special Nuclear Material.

27. The power system shall comply with NSTS 1700.7B and KHB 1700.7 safety requirements for STS payloads.

28. NHB 8071.1, JSC 18327, and AFSD SD-YV-0068 shall apply to the design for fracture control of payloads launched on the Space Shuttle. (The appropriate requirements for other launch vehicles will apply for launch with those vehicles).

29. NSTS 14046 shall apply for structural design verification.

30. MSFC-SPEC-522 shall apply for control of stress corrosion cracking.

31. The design shall be in accordance with JPL 601-4 (Aerospace System Safety Guidelines).

32. MIL-STD-1576 shall apply for electro-explosive devices.

33. Fission products shall be contained within fuel pins through permanent disposal.

34. Local fault propagation in reactor internals and core assemblies shall be minimized due to flow blockages or flow restrictions.

35. Fuel design specifications shall not be exceeded.

36. Potential meteoroid and space debris damage shall be assessed per NASA SP-8042.

37. The power system shall be designed with reactivity limits to assure the effects of postulated reactivity accidents can neither result in damage to the coolant boundary nor disturb the core, support structures, or other reactor internals.

38. The maximum programmable rate of change of reactor power over the full power range shall be 1.5% of full rated power

per minute.

39. Safety rod insertion probability shall be greater than 0.999.

40. Minimum voltage limits shall be set on critical loads bus external to the reactor controller.

41. The power system shall be failsafe upon loss of power from the launch vehicle.

42. The reactor monitoring systems shall include alarm indications signalling the presence of abnormal conditions while inside the STS payload bay and during pre-launch operations.

43. Beryllium structures shall comply with NASA-JSC Letter ES2-47-87.

44. NSTS defined Category 1 Hazards shall be two fault tolerant.

45. NSTS defined Category 2 Hazards shall be single fault tolerant.

46. Software shall be subject to NSTS fault tolerance requirements.

47. Normal power system functions shall not cause ignition of an assumed flammable payload bay atmosphere during reentry, landing and post-landing operations. (This is a requirement for launch in the NSTS).

48. Any mechanical interface with the launch vehicle shall be capable of withstanding launch loads, abort loads (NSTS) and orbit injection loads (NSTS).

49. Moving mechanical assemblies shall be designed per DoD-A-83577.

50. Structural verification shall be performed as per AFSD SD-YV-0067.

51. Contamination of launch vehicle materials by refractory materials used in the nuclear power system shall not cause launch vehicle material loss of ductility or loss of material thickness by erosion.

52. Power system manufacturing processes shall meet safety and environmental regulations.

53. Batteries for the power system shall be designed in accordance with NSTS 1700.7 and JSC 20793.

54. Pressure vessels are to be compatible with room temperature assembly and integration.

55. Composite structures shall comply with NSTS 1700.7.

56. The test connector to permit ground monitoring of reactor instrument and control system status shall be independent of the telemetry data stream and must be accessible in the stowed launch configuration.

57. There shall be no planned release of hazardous materials during NSTS operations.

58. The reactor power system design must comply with NHB 8060.1B.

59. Pre-launch repairs shall be performed in accordance with KHB 1700.7 and MIL-STD-1472.

60. Lightning protection shall be provided per JSC 07636.

61. Power system wiring shall tolerate 200% of expected current load without exceeding insulation temperature rating.

62. Electronics performing safety functions must be capable of withstanding SVS-11501 environments and comply with DoD-E-8983.

63. System design shall provide protection of personnel per MIL-STD-1472.

64. Maximum EMR fields while the power system is inside the NSTS cargo bay shall comply with JSC 07700, Volume XIV, Attachment 1.

65. EVA required activity for the power system shall comply with JSC 10615.

66. Power system elements shall be designed or marked to prevent connection in a reverse mode.

67. Power system drawings shall include critical item designations per SP-100 CIL instructions.

68. All reactor operations shall be supervised by qualified personnel trained for reactor operation.

69. All main power returns shall be carried within a supply line as a twisted, shielded pair.

70. The design shall have an overload protection limit of 55 amperes.

It should be noted that the above requirements are primarily for launch on the NSTS. Launch with a vehicle other than the NSTS will require the system designer and safety function to meet comparable requirements for that launch vehicle.

Additional safety requirements would include that the reactor is not operated in a power production mode until emplaced on the moon or Mars (Ref. III-1) and the maximum individual radiation dose from lunar and martian operations be dependent upon the overall mission risk and total dose from natural and man-made radiation sources (Refs. IV-1, IV-2, IV-3, and IV-4). The National Council on Radiation Protection has proposed an individual dose guideline of 50 rem/yr from all radiation sources (Ref. IV-1). Power cable design and placement at the outposts shall prevent astronaut contact with the cables or prevent astronaut electrocution if contact is made. Also, power reductions and reactor scram shall not result in the loss of critical life support systems which would result in the loss of life prior to the restart of the reactor power system or the use of supplementary power sources.

The requirements from the SP-100 program are for an unmanned mission. For manned missions, the requirements listed in the preceding paragraph are required in addition to those for unmanned missions. The unmanned mission requirements are the result of an initial cursory evaluation of SP-100 mission safety requirements and their applicability to potential SEI missions. The additional manned mission requirements were identified in this study. A thorough evaluation of the applicability of the above unmanned mission safety requirements is needed to eliminate unnecessary requirements and to identify missing requirements. The requirements listed in this chapter are primarily for a payload on the Space Shuttle. The launch vehicles proposed for the SEI missions are primarily expendable boosters. A study is required to ensure that the safety requirements for these expendable launch vehicles have been identified. Finally, as launch vehicle designs and mission definitions mature, the safety requirements presented have to be reassessed for applicability and completeness.

A list of safety related documents is presented in Table 4-1.

Table 4-1
Safety Related Documents
(Sheet 1 of 3)

Document Number	Title
AFR 127-4	Investigating and Reporting US Air Force Mishaps
AFR 127-12	Air Force Occupational Safety, Fire Protection and Health (AFOSH) Program
AFR 160-132	Control of Radiological Health Hazards
AFR 161-8	Control and Recording Procedures - Occupational Exposure to Ionizing Radiation
AFSD SD-YV-0067	Structural Design Verification Requirements for DoD Shuttle Payloads
AFSD SD-YV-0068	Fracture Control Requirements for DoD Shuttle Payloads
DoD-A-83577	Assemblies, Moving Mechanical, for Space Vehicles, General Specifications
DoD-E-8983	Electronic Equipment, Aerospace, Extended Space Environment, General Specification
DOE Orders on Nuclear Safety	Various titles (e.g., 5480.6 - Safety of Department of Energy-Owned Nuclear Reactors)
ICD 2-19001	Shuttle Orbiter/Cargo Standard Interfaces
JPL 601-4	Jet Propulsion Laboratory Flight Projects Safety Guidelines and Requirements
JSC 07636	(lightning protection)
JSC 10615	EVA Description and Design Criteria
JSC 18327	Fracture Control Guidelines for STS Payloads
JSC 20793	Manned Space Vehicle, Battery Safety Handbook

Table 4-1
Safety Related Documents
(Sheet 2 of 3)

Document Number	Title
JSC Letter ES2-47-87	(Johnson Space Center letter on beryllium fracture control)
KHB 1700.7	Space Transportation System Payload Ground Safety Handbook
KHB 1860.1A	KSC Ionizing Radiation Protection Program
MSFC-SPEC-522	Design Criteria for Controlling Stress Corrosion Cracking
MIL-STD-1472	Human Engineering Design Criteria for Military Systems, Equipment, and Facilities
MIL-STD-1522	Standard General Requirements for Safe Design and Operation of Pressurized Missile and Space Systems
MIL-STD-1576	Electroexplosive Subsystem Safety Requirements and Test Methods for Space Systems
NASA SP-8013	Meteoroid Environment Model - 1969 (Near earth to lunar Surface)
NASA SP-8042	Meteoroid Damage Assessment, NASA Space Vehicle Design Criteria (Structures)
NCRP Report No. 98	Guidance on Radiation Received in Space Activities
NHB 8060.1B	Flammability, Odor, and Offgassing Requirements and Test Procedures for Materials in Environments That Support Combustion
NHB 8071.1	Fracture Control Requirements for Payloads Using the National Space Transportation System (NSTS)
NSTS 14046	Payload Verification Requirements

Table 4-1
Safety Related Documents
(Sheet 3 of 3)

Document Number	Title
NSTS 1700.7b	Safety Policy and Requirements for Payloads Using the Space Transportation System
OSNP-1	Nuclear Safety Criteria and Specifications for Space Nuclear Reactors
SP-100 Program Safety Technical Specifications	Reference Flight System Specification (SE002)
10CFR20	Code of Federal Regulations, Title 10, Part 20 - Standards for Protection Against Radiation

5.0 MISSION PROFILES

The process of identifying safety issues for the use of a nuclear power system on the moon or Mars is a multistep process. To be comprehensive, the safety analyst must become familiar with all aspects of the potential application. Subsequently, potential hazards must be identified. The analyst must then assess the response of the nuclear power system to these hazards. From this response assessment, the analyst can estimate potential radiation and toxic material sources that would be hazardous to humans. Using models which simulate the transport of these hazards to humans, the analyst can estimate the risk to the general population and to the environment of the mission.

As an initial step in this process, this study has identified potential hazardous environments for the nuclear power system which could results in hazards to humans and the environment. No attempt has been made to eliminate hazards, and thus, safety issues, by a quantitative assessment of the probability of an event or the response of the nuclear power system and the resulting hazardous source. The next step in the safety process would be the determination of the probabilities of events leading to hazardous environments for the nuclear power source and the characterization of these environments.

In order to identify potential hazardous environments for the nuclear power system, the application (nuclear power source of electricity on the moon and Mars) has been defined as allowed by available information. The process of defining the application required descriptions of the potential mission profiles. With these descriptions, including all reasonable possibilities, potential hazardous environments for the nuclear power system could be identified. Hazardous environments for humans were also identified as part of this process. Chapter 5 presents descriptions of the potential mission profiles and Chapter 6 presents potential hazardous environments for the nuclear power system and the astronauts based upon the mission profiles described in this chapter. In this manner, safety issues can be identified in a comprehensive manner. As stated previously, the next step beyond this study would be to assign event probabilities and characterize environments to allow a quantitative assessment as to the relative risk involved. Obviously, events with very low probability and safe reactor response would be eliminated as safety issues.

Mission profiles for lunar and martian missions have been defined. A basic mission profile has been assumed for each mission. The basic lunar mission is based upon operation of transfer and excursion vehicles in a reusable mode. The martian basic mission profile describes operations with chemical rocket engines and aerobrakes and with an expendable excursion vehicle. Potential alternate activities in a mission phase are also discussed. The basic mission profiles with alternate mission phase activities were selected to minimize the number of mission profiles examined but allow a comprehensive assessment of safety issues.

5.1 LUNAR OUTPOST

The top-level definition of the mission profile for a lunar flight has been defined as shown in Table 5-1. This closely follows lunar mission

Table 5-1
Lunar Mission Profile

Mission Phase	Mission Activity
1	Pre-launch
2	Launch to low earth orbit
3	Low earth orbit space vehicle assembly
4	Trans-lunar orbit insertion
5	Lunar orbit insertion
6	Rendezvous with lunar excursion vehicle
7	Descent to lunar surface
8	Emplacement
9	Operation and maintenance
10	Disposal

sequences defined by the National Aeronautics and Space Administration in References III-1 and V-1 with the exception of phase 3. The exception was final assembly of the lunar mission space vehicle in low earth orbit but not at the space station. Figure 3-1 contains a drawing of a typical lunar flight profile as defined in References III-1 and V-1. This mission profile replaced the mission phases dock with space station Freedom and space station Freedom operations with low earth orbit space vehicle assembly operations. These replaced mission phases are included in the analysis as options since the possibility exists the space station mission in the future may include operating as a rendezvous platform for the Space Exploration Initiative. The following text in this section will present a more detailed description of the above phases in the lunar mission profile.

Pre-launch

The detailed mission profile for the pre-launch phase of the lunar mission is shown below in Table 5-2. It was assumed that control of the fuel was limited to the Department of Energy until received at the launch site. A similar procedure was followed for the Radioisotope Thermoelectric Generators for Galileo where the Department of Energy fabricated the fuel, assembled the generators, tested them, and provided transportation between Department of Energy sites and Kennedy Space Center. The Department of Energy delivered the generators to an appropriate storage facility at the launch site. Intraplant transfer, when it was required, was arranged by the launch site controlling authority. The Department of Energy would manufacture the fuel pellets,

Table 5-2
Pre-launch Mission Phase Activities

Sequence	Mission Phase Activity
1	Fabrication and assembly of reactor
2	Zero power testing of reactor
3	Package and ship reactor to launch site
4	Mate reactor with balance of power system, if required
5	Inspect and test
6	Store power system
7	Integrate power system with launch vehicle
8	Transport launch vehicle to pad and inspect
9	Load cryogenic propellants
10	Activate telemetry
11	Ignite liquid propellant engines

insert the pellets into the fuel rods, and insert the rods into the reactor vessel, load the lithium, and seal the vessel. The unfueled reactor vessel would have been shipped to a Department of Energy site by the power system supplier for insertion of the fuel rods and lithium. The Department of Energy would then transport the reactor to the launch site where it would become the responsibility of the user agency, the launch agency and the power system supplier as authorized by the launch site controlling authority. At the launch site, the reactor would be inspected and placed into a storage facility. The activities required at the launch site would be dependent upon the reactor configuration as shipped to the launch site. The configuration of the reactor at this time would depend upon zero power testing requirements, transportation limitations, and launch site assembly limitations. This study did not investigate possible configurations. The most likely reactor configuration delivered to the launch site would be a complete nuclear power system ready to be mated to a payload or launch vehicle as required. Handling of the reactor at the launch site was assumed limited to system checkout tests to determine any damage due to transportation from the Department of Energy to the launch site and any checkout due to final power system assembly performed at the launch site, e.g., dry run mating checks, physically and electrically mating the reactor with any balance of the power system not attached, component checkout after mating, and final loading into the launch vehicle payload bay. Checkout of the primary heat transfer loop would likely be performed at a Department of Energy facility where the majority, if not all, of the power system was assembled. It is doubtful that a significant amount of power system assembly would be performed at the launch site. At all other times, the reactor would be in the launch site storage facility. Ground handling at the launch site will require the use of transport systems and lift cranes. Access control would be provided through physical barriers and procedures.

Launch to Low Earth Orbit

Boost to low earth orbit will be accomplished by either of three launch vehicles, the current space shuttle, a heavy-lift derivative of the space shuttle, or an advanced launch systems (ALS) vehicle. Since the launch sequences are slightly different between the space shuttle types and the ALS, two mission profiles have been defined for this phase. The profiles for this phase are shown in Tables 5-3 and 5-4 for the ALS vehicle and the space shuttle-type vehicle, respectively. This phase of the mission is the same as missions previously studied during the Galileo/Ulysses (Ref. V-2), DIPS (Ref. V-3), and SP-100 programs (Refs. V-4 and V-5) and will be discussed only briefly since safety assessments have been performed as part of these programs. The phase begins with either liftoff of a liquid-propellant-fueled-only launch vehicle or the ignition of the solid rocket motors and ends with either the separation of the payload from the ALS vehicle or the opening of the shuttle-type vehicle payload bay doors. These launch and ascent sequences have been extensively defined for the Galileo and SP-100 programs and the same sequences are assumed here.

An upper stage was assumed. Initial crew flights may involve partially fueled excursion vehicles. For later flights when the excursion vehicles would be reused, this will not be the case. It was assumed that any launch of an excursion vehicle in the reusable mode would be without propellants. Cargo flights will launch the propellants separately from the excursion and transfer vehicles. Launch configurations for shuttle-derivative vehicles will require the reactor to be located at an elevation occupied by a portion of the solid rocket boosters, see Figure 3-2. The launch configuration for an ALS boost to low earth orbit will have the reactor above the boosters.

The usual convention is to break this mission phase into additional phases. For a shuttle launch, this means the following phases: launch (prior to liftoff), stage 1 ascent (from liftoff until the boosters are jettisoned), and stage 2 ascent (after booster jettison until Orbital Maneuvering System burn number 1) (Ref. V-2). For an unmanned launch vehicle, this results in the mission phases launch (from liftoff to booster jettison) and ascent (liquid stage burns including any upper stage) (Ref. V-3). For purposes of this study, these phases have been lumped into one with the intention of minimizing the repetition of extensively published results of past safety studies (Refs. V-2, V-3, V-4, and V-5). Results pertinent to this study will be summarized and included for completeness.

Direct launch to the moon would involve transport vehicle(s) fueled at launch. The anticipated launch vehicle is either a shuttle-derivative or ALS booster. The events for this mission phase would be the same as those listed in Tables 5-3 and 5-4.

Table 5-3
Advanced Launch System Launch Phase Activities

Sequence	Mission Phase Activities
1	Liftoff
2	Clear tower
3	Roll maneuver
4	Pitchover maneuver
5	Staging sequence command
6	Stage I ignition
7	Booster separation
8	Payload fairing unlatch and jettison
9	Staging sequence command
10	Stage I separation
11	Stage II ignition
12	Staging sequence command
13	Stage II retrofire and separation

Table 5-4
Shuttle-derivative Vehicle Launch Phase Activities

Sequence	Mission Phase Activities
1	Solid rocket booster ignition
2	Liftoff
3	Clear tower
4	Roll maneuver
5	Pitchover maneuver
6	Staging sequence command
7	Solid rocket booster separation
8	Main engine cutoff
9	External tank jettison
10	Orbital Maneuvering System first burn
11	Coast
12	Orbital Maneuvering System second burn
13	Payload bay doors open

Low Earth Orbit Space Vehicle Assembly

The mission profile for this phase of the lunar mission depends upon the launch vehicle. It was assumed that the space shuttle or a derivative would be capable of delivering the payload to the assembly point without assistance.

A space tug or an upper stage was assumed to be required to deliver the ALS payload. The resulting profiles are shown below in Tables 5-5 and 5-6 for the ALS and the shuttle-derivative, respectively. The payload has been assumed separated from the ALS.

Table 5-5
Mission Phase Low Earth Orbit Space Vehicle Assembly Activities (ALS)

Sequence	Mission Phase Activities
1	Space tug dock with payload, if used
2	Space tug/upper stage maneuver and first burn
3	Space tug/upper stage final burn
4	Release from space tug/upper stage
5	Inspection for damage
6	Lunar transfer vehicle and lunar excursion vehicle assembly, if required
7	Lunar transfer vehicle and lunar excursion vehicle fueling, if required
8	Attach cargo to lunar transfer vehicle

Table 5-6
Mission Phase Low Earth Orbit Space Vehicle Assembly Activities (Shuttle-Derivative)

Sequence	Mission Phase Activities
1	Space Shuttle Orbital Maneuvering System burns
2	Remove payload from shuttle bay
3	Inspection for damage
4	Lunar transfer vehicle and lunar excursion vehicle assembly, if required
5	Lunar transfer vehicle and lunar excursion vehicle fueling, if required
6	Attach cargo to lunar transfer vehicle

All propulsion is assumed by means of cryogenic propellants with two burns required. Low thrust engines will be used for maneuvering. Either a space tug (e.g., Orbital Maneuvering Vehicle) will dock with the ALS payload and deliver it to the assembly point or an upper stage will be used. The payload in the shuttle bay will be removed at the assembly point. The space tug will be remotely controlled. The orbit lifetime for the payload will be short for purposes of safety assessment, i.e., a failure resulting in the payload stranded in orbit will lead to reentry.

The post-launch inspection of the power system will likely be performed in parallel with the many other lunar transfer vehicle assembly and maintenance operations. The activities in this phase are those which begin after the cargo has been separated from the launch vehicle and end with the completion of the assembly of the lunar transfer vehicle with lunar cargo. Major activities include the assembly/refurbishment of the aerobrake, maintenance of the propulsion system, and attachment of the fuel tanks and cargo. Propellants are LO_2 and LH_2. It was assumed the fuel tanks would be attached to the lunar transfer vehicle prior to the cargo based upon Figure 3-4. The sequence of events may mirror those on the ground where fueling is last. Flights to the moon with the lunar excursion vehicle in the reusable mode would require the cargo be attached to the lunar transfer vehicle and not the excursion vehicle. There is the possibility early in the initiative that cargo may be launched attached to the lunar excursion vehicle.

Assembly of the transportation vehicles may occur at Space Station Freedom should the mission of the space station be expanded in the future. The mission profiles may be as shown in Tables 5-7 and 5-8 for an ALS and a shuttle-derivative launch vehicle, respectively. Assembly at the space

Table 5-7
Mission Phase Dock with Space Station After ALS Launch Activities (option)

Sequence	Mission Phase Activities
1	Space tug dock with payload
2	Space tug maneuver and first burn
3	Space tug final burn
4	Dock with Space Station Freedom
5	Disassemble payload and attach to space station as required
6	Inspection for damage
7	Lunar transfer vehicle and lunar excursion vehicle assembly, if required
8	Lunar transfer vehicle and lunar excursion vehicle fueling, if required
9	Detach cargo from space station, if required
10	Attach cargo to lunar transfer vehicle

Table 5-8
Mission Phase Dock with Space Station after Shuttle Launch Activities (option)

Sequence	Mission Phase Activities
1	Space Shuttle Orbital Maneuvering System burns
2	Shuttle dock with Space Station Freedom
3	Remove payload from shuttle bay
4	Attach payload to Space Station Freedom
5	Inspection for damage
6	Lunar transfer vehicle and lunar excursion vehicle assembly, if required
7	Lunar transfer vehicle and lunar excursion vehicle fueling, if required
8	Detach cargo from space station, if required
9	Attach cargo to lunar transfer vehicle

station would result in essentially the same activities as for space vehicle assembly in low earth orbit with the exception of the detachment of the cargo from the space station. The potential exists for a direct launch to the moon was defined as shown in Table 5-9. The use of a single transportation vehicle would not involve the transfer of cargo at either the low earth orbit assembly point or the space station.

Table 5-9
Mission Phase Direct Launch to Moon (option)

Sequence	Mission Phase Activities
1	Separate from launch vehicle
2	Maneuver for trans-lunar orbit insertion
3	Lunar transport vehicle burn
4	Jettison empty propellant tanks
5	Coast to lunar orbit insertion

Trans-Lunar Orbit Insertion

The activities during this mission phase are shown in Table 5-10. The

Table 5-10
Trans-Lunar Orbit Insertion From Low Earth Orbit Space Vehicle Assembly Mission Phase Activities

Sequence	Mission Phase Activities
1	Maneuver for orbit insertion
2	Transfer vehicle engine burn
3	Empty propellant tanks jettisoned

activities begin with the initial maneuvering prior to the thrusting required for insertion into the trans-lunar orbit. After the burn, the emptied lunar transfer vehicle propellant tanks are jettisoned. Flight is by an automated control sequence. Propellants are LO_2 and LH_2.

If the space station assembly option is exercised, this mission phase would begin with a space tug maneuvering to dock with the assembled lunar transfer vehicle, with or without the lunar excursion vehicle, see Table 5-11.

Table 5-11
Trans-Lunar Orbit Insertion From Space Station Freedom Mission Phase Activities (option)

Sequence	Mission Phase Activities
1	Separation from Space Station Freedom
2	Dock with space tug
3	Space tug maneuver and first burn
4	Space tug final burn
5	Release from space tug
6	Maneuver for orbit insertion
7	Transfer vehicle engine burn
8	Empty propellant tanks jettisoned

The space tug docks with the lunar transfer vehicle, thrusts to separate the lunar transfer vehicle from the space station in conjunction with the release of the transfer vehicle by the space station, and subsequently maneuvers to place the transfer vehicle in an orbital configuration for insertion into the trans-lunar orbit. The space tug undocks and returns to the space station prior to the lunar transfer vehicle engine burn for trans-lunar orbit insertion and empty propellant tank jettison.

Lunar Orbit Insertion

After coasting in the trans-lunar orbit, the lunar transfer vehicle would maneuver to provide the proper thrust vector for lunar orbit insertion. The LH_2 and LO_2 fueled engines would fire until the lunar transfer vehicle is in lunar orbit. The empty lunar transfer vehicle propellant tanks would then be jettisoned. As with the tanks jettisoned in the previous phase, the trajectories of the expelled tanks must be defined to assure they will not become hazards to the reactor. The activity sequence is shown in Table 5-12. An automated control system will be used with astronaut override.

Table 5-12
Lunar Orbit Insertion Mission Phase Activities

Sequence	Mission Phase Activities
1	Maneuver for orbit insertion
2	Lunar transfer vehicle engine burn
3	Empty propellant tanks jettisoned

Rendezvous with Lunar Excursion Vehicle

In this mission phase, the lunar excursion vehicle will approach the lunar transfer vehicle for docking. The transfer of cargo will be provided by an automated system on the lunar excursion vehicle or the lunar transfer vehicle. Cargo will be unlocked from the transfer vehicle, pulled or pushed to the excursion vehicle, and locked into place on the excursion vehicle. A typical cargo transfer system may be as shown in Figure 5-1. Initial flights will not require this sequence since the cargo will already be attached to the excursion vehicle launched with the transfer vehicle and mated at Space Station Freedom or in low earth orbit. LH_2 will then be transferred from the transfer vehicle to the excursion vehicle. LO_2 is assumed provided from mining operations on the lunar surface. Until lunar mining of LO_2 is producing the necessary quantities, early flights will require the lunar transfer vehicle provide LO_2 for the excursion vehicle. Also, prior to the permanent habitation of the lunar base and the decision to reuse excursion vehicles, flights will arrive with the transfer and excursion vehicles mated and the excursion vehicle fueled. At this time, the excursion and transfer vehicles will be flown in an expendable mode. Subsequent to fueling, the excursion vehicle will undock from the transfer vehicle and maneuver away from

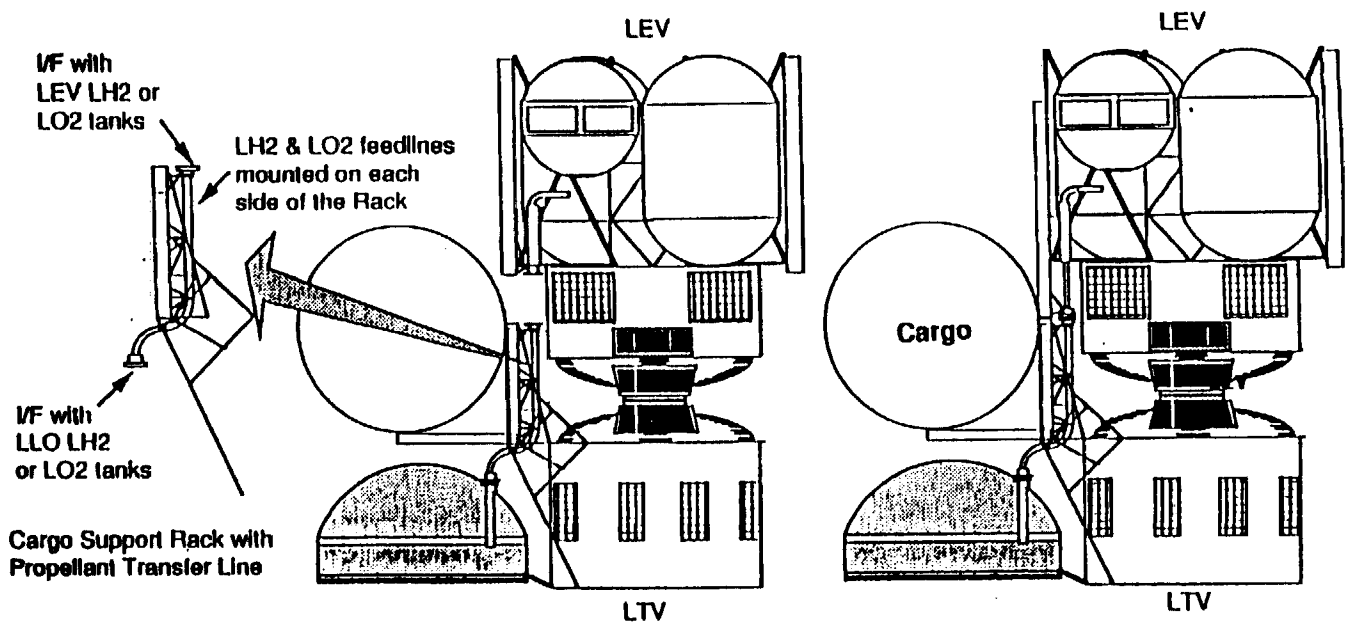

Figure 5-1 Cargo and Fuel Transfer From LTV to LEV (Ref. III-4)

the transfer vehicle for the descent to the lunar surface. This sequence of events are shown in Table 5-13. An automated control system was assumed.

Table 5-13
Rendezvous with Lunar Excursion Vehicle Mission Phase Activities

Sequence	Mission Phase Activities
1	Lunar transfer vehicle maneuver for docking with excursion vehicle, if required
2	Lunar transfer vehicle dock with lunar excursion vehicle, if required
3	Transfer cargo and LH_2/LO_2, if required
4	Separation of lunar transfer and excursion vehicles

Descent to Lunar Surface

Descent to the lunar surface will be accomplished using the lunar excursion vehicle LO_2 and LH_2 engines with automated control. The engines will burn until touchdown. The burn sequence will involve two burns like any other orbit transfer. The sequence is shown in Table 5-14. The landing area will not be prepared in the early flights. Sequence 5 represents any maneuvering just prior to touchdown. A mission profile for direct descent to the lunar surface was defined as shown in Table 5-15. A single vehicle would not involve the separation of the LTV and the LEV.

Emplacement

The reactor will be either be placed in an excavation, shielded by a berm, or left on the surface, or some combination of these options. For purposes of this study, a reference sequence for emplacement by placement in an excavation or berm was defined as shown in Table 5-16. This sequence of events represents operation subsequent to the arrival of the lunar excursion vehicle payload unloader (LEVPU) on the lunar surface and with the presence of astronauts. After inspection and connection of telemetry, the cargo will be secured by the LEVPU and detached from the lunar excursion vehicle. The LEVPU will then lift the cargo from the lunar excursion vehicle and transport it to a site near the launch pad for temporary storage. The reactor will be stored temporarily as required. The reactor will be inspected prior to transport to the excavation site. At the excavation site the reactor will be lowered into the excavation. If an upper shield is required to cover the excavation, it will be attached at this time. The power conversion system will be assembled

Table 5-14
Descent to Lunar Surface Mission Phase Activities
(Post-LTV/LEV Rendezvous)

Sequence	Mission Phase Activities
1	Maneuver for descent burn
2	Ignite lunar excursion vehicle engines (two burns)
3	Descent maneuvering
4	Touchdown on lunar surface
5	Lunar excursion vehicle engine cutoff

Table 5-15
Descent to Lunar Surface Mission Phase Activities
(direct descent)

Sequence	Mission Phase Activities
1	Separation of lunar transfer and excursion vehicles as required
2	Maneuver for descent burn
3	Ignite lunar excursion vehicle descent engines (both burns)
4	Descent maneuvering
5	Touchdown on lunar surface
6	Lunar excursion vehicle engine cutoff

as required. The activities required for assembly were not defined in detail due to the absence of a final system design. The reactor assembly was assumed to require connection to the power conversion subsystem, connection of the reactor instrumentation and control circuitry, and connection of the auxiliary power supply. These activities would be supplemented with inspections and subsystem and component testing. Testing at this time was assumed to be limited to devices that are driven by electrical power and do not involve a critical reactor configuration. System tests would be performed subsequent to startup following power system assembly. A radiation survey would be performed prior to continuous full power operation to verify analytical estimates of the radiation field emanating from the reactor used for shielding design.

Table 5-16
Emplacement in an Excavation and/or Behind a Berm Mission Phase Activities

Sequence	Mission Phase Activities
1	Inspection for damage
2	Connect telemetry to surface transport vehicle (LEVPU, other?)
3	Offload from LEV
4	Transport to temporary storage, if required
5	Inspection damage
6	Transport to excavation
7	Lower into excavation, configure and inspect for damage and contamination
8	Connect to power conversion subsystem and inspect
9	Connect reactor instrumentation and control as required and inspect
10	Connect to startup power source, if required
11	Startup
12	Test
13	Radiation survey

Emplacement on the surface of the moon was assumed to involve the activities shown in Table 5-17. This list of activities would be different should the nuclear power system land on the moon at the location where it will be operated without removal from a lunar lander. In this case, there will likely be a visual inspection for damage followed by any assembly required and connection to the power grid, or directly to the application. The commands for deployment and startup would then be issued. Startup tests and a radiation survey would then be performed prior to full power operation. The number of activities will be reduced if the system is self-contained and only requires connection to the power grid followed by deploy and startup commands.

Surface emplacement will require distance or lunar soil to attenuate the radiation from the reactor to meet the radiation dose requirements of Chapter 4. Placement of the power system inside a crater or excavation will allow the reactor to be placed closer to the habitat area. Lunar soil will act as a shield. Surface placement with line-of-site to the habitat area will require the power system to have an integral shield or be located sufficiently far from the habitat to meet radiation dose limitations. Operation of an unshielded reactor is not a viable option since the large habitat-to-reactor distances required would severely limit astronaut activities and the additional power cable length and mass required would be prohibitive.

Table 5-17
Emplacement on Surface Mission Phase Activities

Sequence	Mission Phase Activities
1	Inspection for damage
2	Connect telemetry to surface transport vehicle, as required (LEVPU, other?)
3	Offload from LEV, as required
4	Transport to application site, if required
5	Inspection for damage
6	Connect to power conversion subsystem and inspect, if required
7	Connect reactor instrumentation and control as required and inspect, as required
8	Connect to startup power system, if required
9	Erect radiation zone barrier, if required
10	Startup
11	Test
12	Radiation survey

Operation and Maintenance

The operation and maintenance phase of the lunar mission profile begins after the initial power-up to full power. Mission phase activities are shown in Table 5-18. The sequence may be repeated many times prior to the conclusion of this mission phase.

Astronaut interaction with the reactor would be limited to maintenance and control supervision if an active load following strategy is adopted. Astronauts would be involved in the maintenance and repair of non-nuclear equipment as allowed by the design and working conditions. Maintenance and repair may involve astronauts in the power production area, in the vicinity of the reactor. Whether the reactor must be shutdown for repairs to the power generation system will depend upon the shielding design and the nature of the failure. Access to restricted areas near the reactor will have to be precluded by some physical or administrative means, e.g., fence, warning beacon, and permissible travel lanes.

Table 5-18
Operation and Maintenance Phase Activities

Sequence	Mission Phase Activities
1	Operate at constant power or active load following
2	Shutdown
3	Maintenance
4	Astronaut activities at site
5	Startup
6	Test
7	Power up

Disposal

Disposal alternatives for the reactor at end-of-life will depend upon detailed evaluations of disposal strategies. Three strategies have been defined: 1) disposal in place on the moon, 2) disposal away from the power production area, and 3) insertion into a parabolic orbit. The mission phase profiles are shown in Tables 5-19 through 5-21.

All alternatives begin with the final shutdown of the reactor. After shutdown, auxiliary power is supplied to the power system to monitor the status of the reactor while astronauts perform any necessary activities associated with disconnection of the bus to the reactor control system to permanently shutdown the reactor. This auxiliary power will also be used while astronauts disconnect the power conversion subsystem and radiators from the reactor if so desired. For disposal away from the power production area, the used reactor would remain in place for fission product decay if this is necessary. After a sufficient period of time to reduce radiation to safe levels, the reactor would be encased in a shielded cask for transport away from the power production site. The reactor would be hauled by an unpressurized manned/robotic rover on a transport cart to the disposal site or the launch pad. These operations, plus handling at the disposal site and the launch pad, were assumed to require minimal astronaut involvement. Any disposal by burial may require a decay heat removal system unless the reactor can lose decay heat sufficiently in-place prior to burial. Burial may be delayed until years after final shutdown if desired.

Table 5-19
Disposal in Place Storage Phase Activities

Sequence	Mission Phase Activities
1	Shutdown
2	Provide post-shutdown power
3	Disconnect reactor control system power
4	Disconnect reactor from power conversion system and radiators if desired
5	Restrict access to site

Table 5-20
Disposal on Moon Away From Power Production Area
Mission Phase Activities

Sequence	Mission Phase Activities
1	Shutdown
2	Provide post-shutdown power for reactor
3	Disconnect reactor control system power
4	Disconnect reactor from power conversion system and radiators if allowable
5	Allow radioactivity to decay, if required
6	Remove reactor from excavation as required
7	Transport reactor to disposal site
8	Bury reactor or leave on surface
9	Restrict access to disposal site

Table 5-21
Disposal by Parabolic Trajectory Phase Activities

Sequence	Mission Phase Activities
1	Shutdown
2	Provide post-shutdown power for reactor
3	Disconnect reactor control system power
4	Disconnect reactor from power conversion system and radiators if allowable
5	Allow radioactivity to decay
6	Remove reactor from excavation as required
7	Transport reactor to launch site
8	Mate with booster if necessary
9	Load reactor onto excursion vehicle
10	Launch to orbit
11	Offload reactor and booster from excursion vehicle (if mated on moon)
12	Mate reactor with booster if not already
13	Maneuver for parabolic orbit insertion
14	Booster engine burn

5.2 MARTIAN OUTPOST

The top-level definition of the mission profile for a martian flight has been defined as shown in Table 5-22. This closely follows martian mission sequences defined by the National Aeronautics and Space Administration in References III-1 and V-1. Figure 3-5 contains a drawing of a typical martian flight profile, Figure 3-6 for nuclear electric propulsion. The following text in this section will present a more detailed description of the above phases in the martian mission profile.

Pre-launch

For the purposes of this study, the profile for this phase of the martian mission has been assumed to be the same as the lunar Pre-launch mission phase.

Launch to Low Earth Orbit

For the purposes of this study, the profile for this phase of the martian mission has been assumed to be the same as the corresponding lunar mission phase with the exceptions that 1) the nuclear reactor power system will be launched on expendable launch vehicles with the martian transfer and excursion vehicles and 2) the expendable launch vehicle may use solid rocket

Table 5-22
Martian Mission Profile

Mission Phase	Mission Activity
1	Pre-launch
2	Launch to low earth orbit
3	Low earth orbit space vehicle assembly operations
4	Trans-Mars orbit insertion
5	Mars orbit insertion
6	MTV and MEV rendezvous
7	Descent to surface of Mars
8	Emplacement
9	Operation and maintenance
10	Disposal

boosters. Figure 3-7 shows the martian mission launch vehicle options.

<u>Low Earth Orbit Space Vehicle Assembly</u>

For the purposes of this study, the profile for this phase of the martian mission has been assumed to be the same as the lunar Low Earth Orbit Space Vehicle Assembly mission phase for the case where an expendable launch vehicle is used. There is the possibility that the nuclear reactor power system will be launched attached to the martian excursion vehicle in a configuration suitable for the flight to Mars.

Aerobrake(s), if used, will be assembled on the excursion vehicle(s) and the excursion vehicle(s) will be fueled as well as the transfer vehicle. Reference III-1 is not clear as to the use of martian excursion vehicles in a reusable mode. The lunar mission profile was assumed to apply. Regardless, propellants for the martian excursion vehicle(s) will likely originate from the earth or the moon, the assumption taken here.

<u>Trans-Mars Orbit Insertion</u>

For the purposes of this study, the profile for this phase of the martian mission was assumed to be the same as the lunar mission Trans-Lunar Orbit Insertion mission phase. Figures 3-8 and 3-9 illustrate the proposed martian transfer and excursion vehicles with Figure 3-8 showing an expected flight configuration. The exceptions are: 1) the possibility of nuclear electric propulsion may eliminate LO_2, 2) all vehicles are fully fueled, 3) the excursion vehicle(s) are always present, and 4) the flight path for nuclear electric propulsion may contain a flyby of the moon to gain energy in a gravity assist maneuver, see Figure 3-6.

Mars Orbit Insertion and MTV/MEV Rendezvous

The Mars Orbit Insertion flight profile is significantly different from the Lunar Orbit Insertion profile due to the separation of the transfer and excursion vehicles and the use of aerobrakes to shed energy. The activities for this mission phase are shown in Table 5-23. Prior to orbit insertion by aerobrake, the transfer and excursion vehicles are separated from the configuration as shown in Figure 3-8. The vehicles separately shed energy by an automated system until achieving the proper orbit. Subsequently, the vehicles rendezvous with the astronauts leaving the crew module of the transfer vehicle for the excursion vehicle crew module. Descent to the martian surface is then preceded by separation of the transfer and excursion vehicles. No cargo transfer from the transfer vehicle to the excursion vehicle was assumed, i.e., the cargo was assumed attached to the excursion vehicle at the vehicle assembly point in low earth orbit, or Space Station Freedom. This phase would be unnecessary for cargo missions since the excursion vehicles could descend directly to the surface of Mars.

Table 5-23
Mars Orbit Insertion Phase Activities

Sequence	Mission Phase Activities
1	Separation of transfer and excursion vehicles
2	Maneuver for aerobraking
3	Aerobrake into orbit
4	Maneuver for rendezvous
5	Transfer and excursion vehicle dock
6	Crew transfer to excursion vehicle
7	Separation of transfer and excursion vehicles

The use of nuclear propulsion would greatly affect this phase of the mission. Orbit insertion would be accomplished by rocket engine burn. A short burn near Mars was assumed for a nuclear thermal propulsion system. A nuclear electric propulsion system was assumed to have been operated constantly since insertion into the trans-Mars orbit except for vehicle rotation at mid-course. If constant thrusting is not the case, the electric thrusters will, however, be ignited far from Mars in any case. The significance of this point is the long lead time available for corrective action after failure of the nuclear electric propulsion system.

Descent to Surface of Mars

Descent to the surface of Mars is significantly different than descent to the lunar surface. This phase of the martian flight begins with a maneuver for descent and ends with engine cutoff after landing. The profile is shown in Table 5-24. The aerobrake is used initially to shed orbital energy but is jettisoned prior to ignition of the descent engine(s). The conditions under which the aerobrake is jettisoned are unknown at this time. A chemical or nuclear propulsion descent system may be an option. Shielding requirements may preclude the use of a nuclear system for manned flight. A nuclear descent stage would require a 4π shield to allow astronauts mobility on the surface. Descent was assumed to be controlled by an automated system.

Table 5-24
Descent to Surface of Mars Mission Phase Activities

Sequence	Mission Phase Activities
1	Maneuver for descent
2	Aerobrake
3	Jettison aerobrake
4	Descent engine ignition
5	Touchdown
6	Descent engine cutoff

Emplacement

For the purposes of this study, the profile for this phase of the martian mission has been assumed to be the same as the corresponding lunar mission phase.

Operation and Maintenance

For the purposes of this study, the profile for this phase of the martian mission has been assumed to be the same as the corresponding lunar mission phase.

Disposal

For the purposes of this study, the profile for this phase of the martian mission has been assumed to be the same as the corresponding lunar mission phase.

6.0 ACCIDENT SCENARIOS

Potential accidents for each phase of the lunar and martian mission profiles defined in Chapter 5 have been identified. Accident descriptions and characterization were qualitative only. There was no data available due to the conceptual nature of the launch vehicles and the lack of a specific nuclear reactor power system design for the moon and Mars. Nuclear reactor designs for the moon and Mars were assumed to be basically similar to SP-100.

Simplified event trees have been constructed for each mission phase as an aid to postulating reactor response to accidents. The accident scenarios and simplified event trees have been defined and constructed without regard to the safety design features implemented in the SP-100 program to preclude overlooking a new safety issue resulting from the differences in SP-100 missions and the SEI missions. The effects of the SP-100 program safety features will be assessed in chapter 8. Multiple use of a part of a tree does not mean consequences of the same magnitude nor that the events represented by the same descriptor are exactly identical. For example, the shipping accidents on route to reactor assembly and on route to the testing facility in Figure 6-1 represent events with individual fuel rods and an assembled reactor. A ruptured shipping container would potentially lead to either fuel rods in a critical configuration or damage to the reactor to result in a critical configuration. A critical configuration was assumed possible only after extensive damage to the shipping container, i.e., rupture of the container. A critical configuration was assumed to result in an excursion and the release of fission products. The trees were constructed in an abbreviated form with sufficient information to identify potential hazards. The accidents and simplified event trees were defined to be comprehensive to preclude design and procedure change suggestions that would potentially solve one safety issue and re-introduce another without notice.

A small discussion is presented at this point to place in perspective the following accident scenario descriptions. These descriptions are part of a radiological risk assessment process required for launch approval of a nuclear power source. Mission risk is assessed by probabilistic risk analysis techniques. The end product of the analyses is a quantitative assessment of the potential for human exposure to radiation levels above natural background as a result of the use of nuclear power sources in a space application. The analysis begins with the determination of mission events which have the potential to expose humans to radiation. Occurrence probabilities are then determined. Next, the consequences of these events are defined in terms of human exposure to radiation at various levels. Finally, the nuclear power system is evaluated on the basis of these analyses.

Accident scenarios are defined as part of the determination of mission events which have the potential to expose humans to radiation. For a particular mission, mission phases are defined to allow the systematic evaluation of normal procedures and mission events to determine the results of an abnormal event. This is followed by an analysis of aborts or failure modes for each mission phase to identify potential malfunctions, single or multiple, which can potentially affect the nuclear power source. For each of the malfunctions, subsequent nuclear power source environments and associated occurrence probabilities are defined. These environments are then sequenced in an event tree. This is followed by an assessment of the response of the nuclear power system to each of the adverse environments, e.g., launch pad explosion overpressure and fragment field. If the analysis indicates a potential for the uncontrolled exposure of humans to radiation, a radiation source term is defined. The state and location of the radiation source term is considered. When the source terms with associated probabilities have been defined, the human consequences of the source terms are analyzed by characterizing environmental dispersion and human uptake. The combination of the source term probabilities and the potential human uptake is then used to describe the mission risk.

The simplified event trees described in this chapter do not include the occurrence probabilities mentioned above. They are not detailed in that events of similar type but not necessarily the same consequence or probability have been combined. Nuclear system responses have been defined based upon similar accidents evaluated in previous safety analyses. The responses are the result of a cursory evaluation. No attempt has been made to estimate occurrence probabilities. The intent was to use the event trees to identify safety issues and not to discount any of them. Events which have catastrophic consequences for the nuclear power system may have extremely small occurrence probabilities making the event an insignificant contributor to mission risk. A new safety issue identified in this study should not impact design until occurrence probabilities, system response, and dispersion in the environment have been determined.

6.1 LUNAR OUTPOST

Prelaunch

Potential accidents for this mission phase are listed in Table 6-1. As noted in chapter 5, this mission phase ends prior to the ignition of the liquid engines. Also listed are the resulting accident environments. The accidents and environments subsequent to the receipt of the reactor at the launch site have been thoroughly examined in the Galileo/Ulysses (Ref. V-2), DIPS (Ref. V-3) and SP-100 (Refs. V-4 and V-5) programs. A few accidents prior to transportation of the reactor to the launch site have been included, e.g., zero power test control failure and beryllium release during fabrication.

For this mission phase, the corresponding simplified event tree can be found in Figure 6-1. It was assumed that a damaged reactor has the potential for an excursion due to the resulting configuration. At a minimum, a damaged reactor was assumed to release fuel without an excursion required due to fuel pin damage. A more detailed safety assessment is required to define degrees of damage. All impacts were assumed to have the potential for damage to the reactor. A reactor control failure during zero power testing was assumed to result in a runaway reaction leading to fuel pin failure. A decay heat removal failure during zero power testing was assumed to lead to excessive clad temperatures and fuel pin failure. An inadvertent reactor startup due to a spurious or inadvertent signal was assumed possible without a method to preclude such an occurrence. An inadvertent reactor startup was assumed to

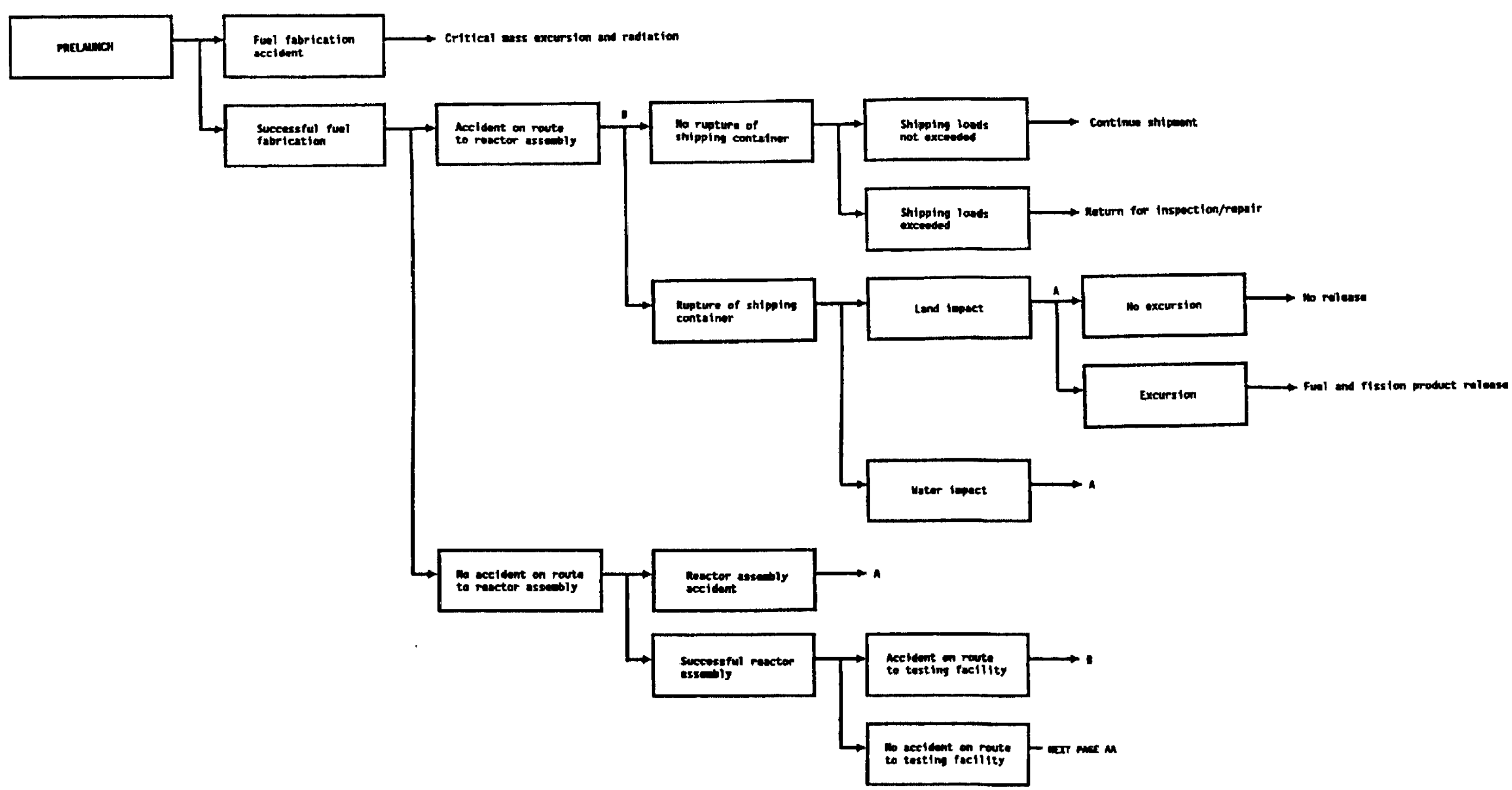

Figure 6-1 Simplified Event Tree for the Lunar Mission Phase Prelaunch

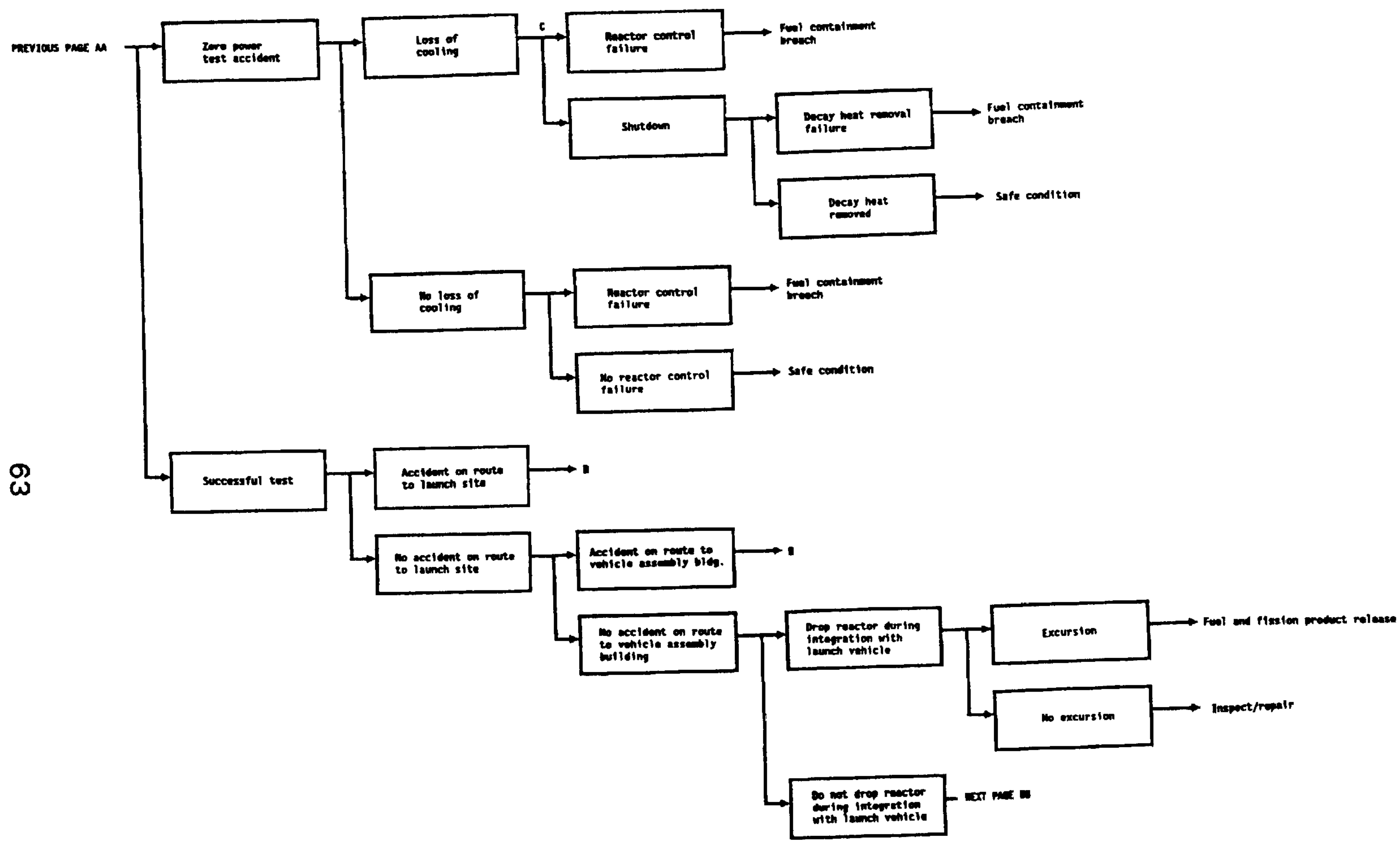

Figure 6-1 Simplified Event Tree for the Lunar Mission Phase Prelaunch (cont.)

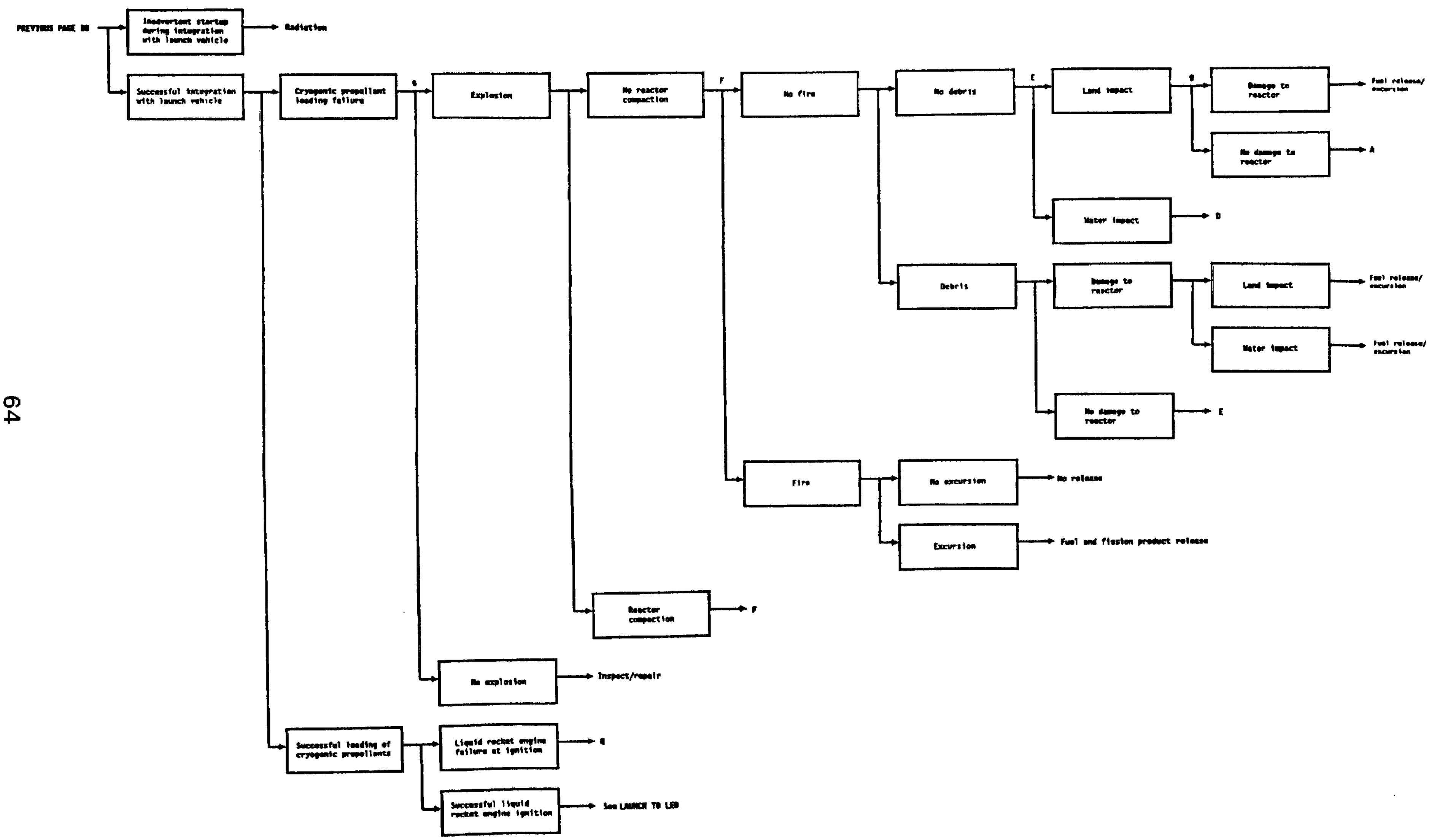

Figure 6-1 Simplified Event Tree for the Lunar Mission Phase Prelaunch (cont.)

Table 6-1
Lunar Mission Prelaunch Phase Accidents and Resulting Nuclear Reactor Environments

Accident	Reactor Environment
Drop reactor or fuel rod	Impact
Traffic accident	Impact Water submersion
Zero power test control failure	Excursion
Inadvertent reactor startup	N/A
Collision	Impact
Fire in storage facility	Fire
LO_2/LH_2 tank failure	Overpressure Shrapnel Fire
Aft compartment explosion (Shuttle-derivative)	Overpressure Shrapnel Fire
Failure of a liquid propellant rocket motor leading to an explosion	Overpressure Shrapnel Fire
Beryllium release during machining	N/A

provide a radiation field harmful to nearby personnel.

Launch to Low Earth Orbit

The accidents and resulting environments for this mission phase have been extensively studied during the Galileo/Ulysses (Ref. V-2), DIPS (Ref. V-3) and SP-100 (Refs. V-4 and V-5) programs for both the space shuttle and expendable launch vehicles (Titan). Accidents will be initiated from either a failure of the launch vehicle or the nuclear reactor structure to resist launch loads inside the payload bay. The nuclear reactor will be subject to impact, fire, overpressure, projectiles, and reentry. The potential exists for inadvertent reactor startup.

Simplified event trees for the launch vehicle options shuttle-derivative and Advanced Launch System (ALS) are shown in Figures 6-2 and 6-3,

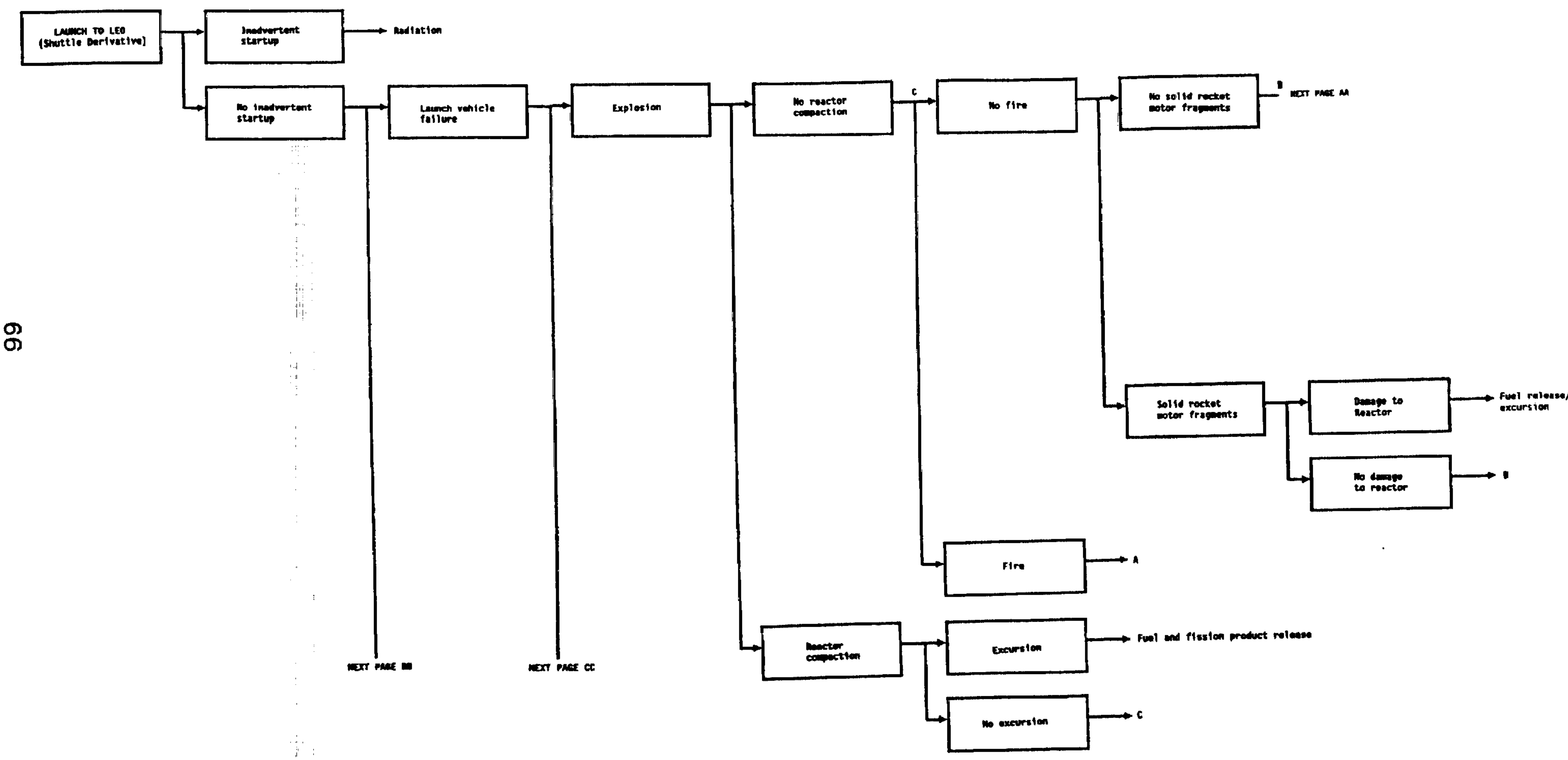

Figure 6-2 Simplified Event Tree for the Lunar Mission Phase Launch to Low Earth Orbit (Shuttle Derivative)

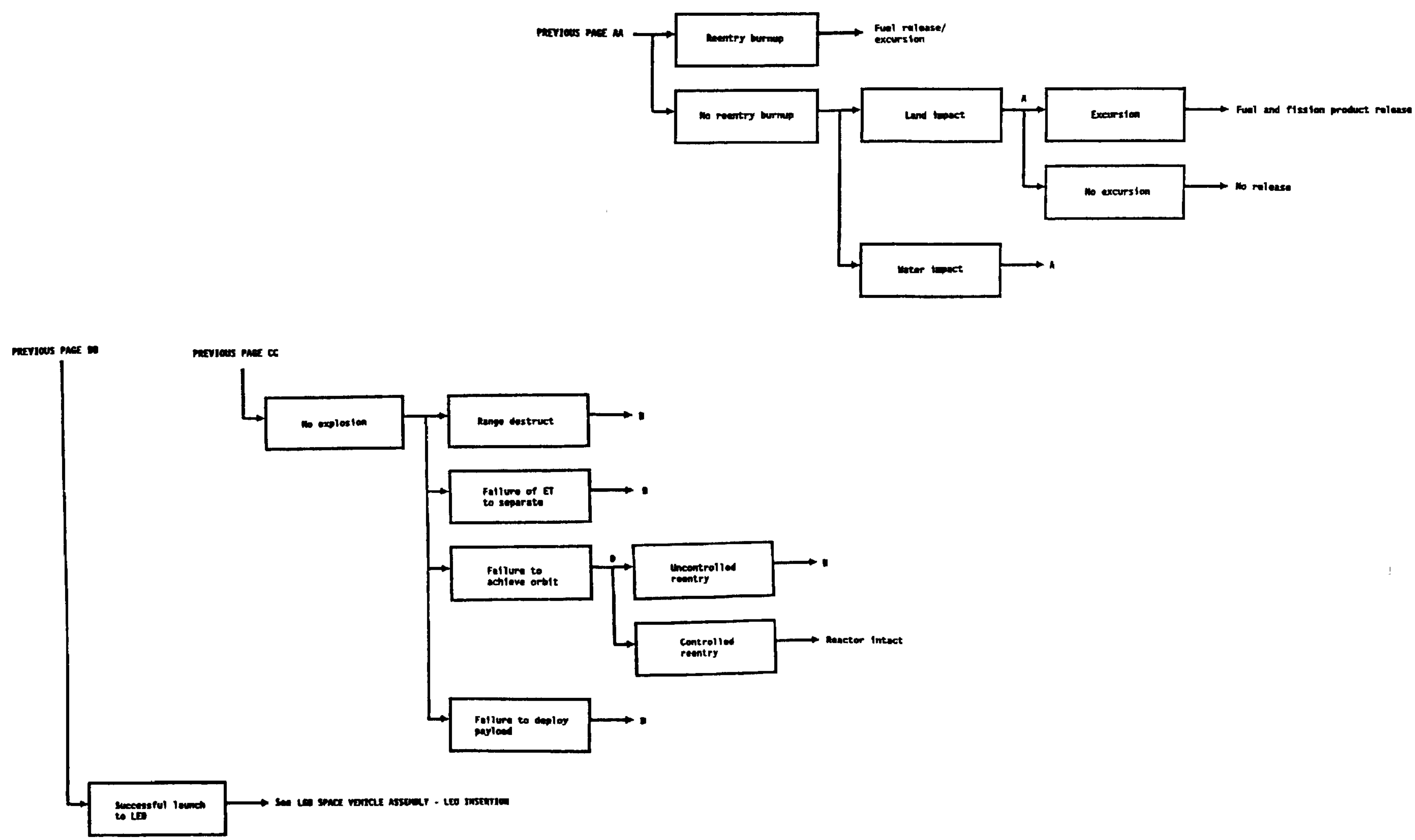

Figure 6-2 Simplified Event Tree for the Lunar Mission Phase Launch to Low Earth Orbit (Shuttle Derivative) (cont.)

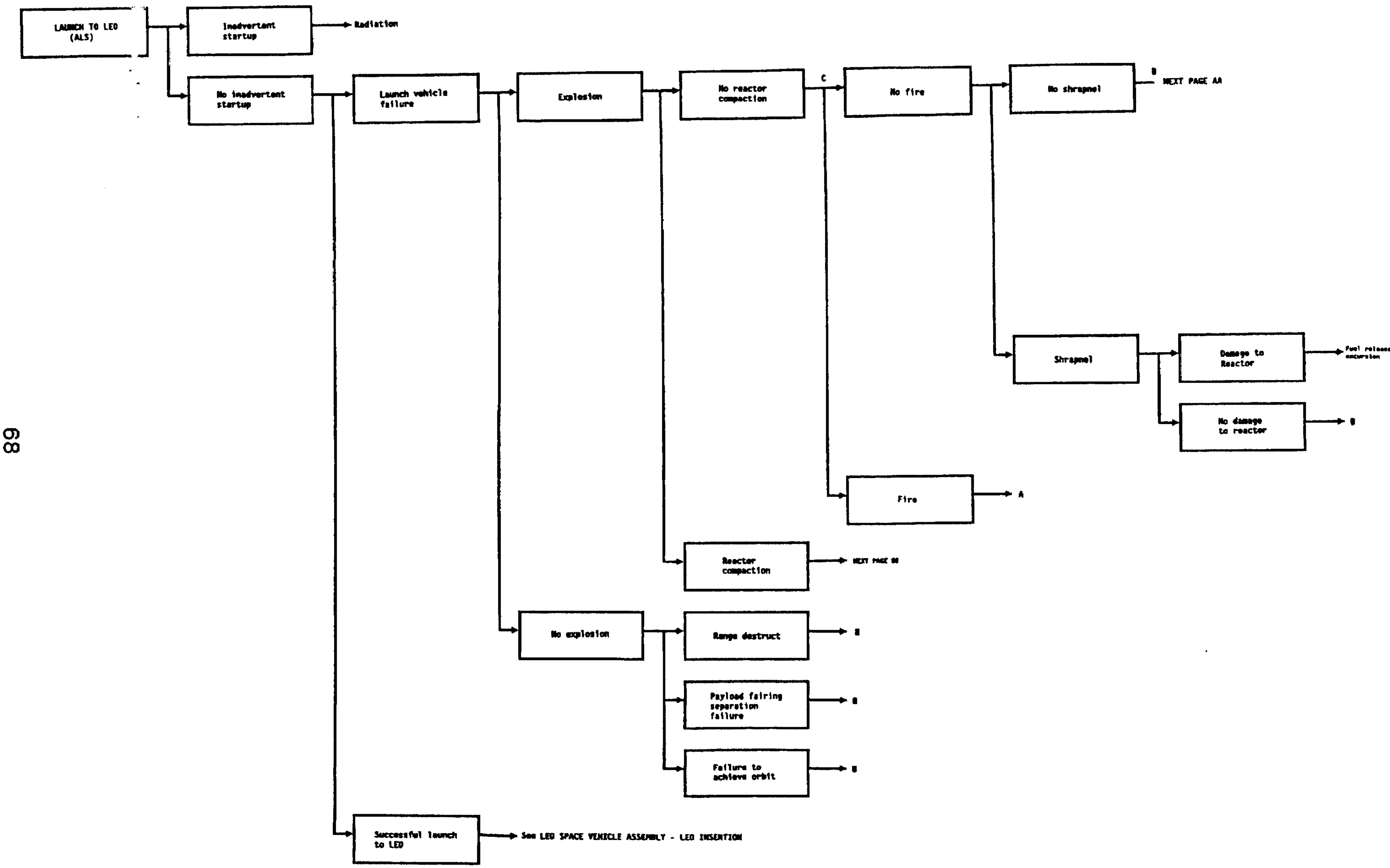

Figure 6-3 Simplified Event Tree for the Lunar Mission Phase Launch to Low Earth Orbit (Advanced Launch System)

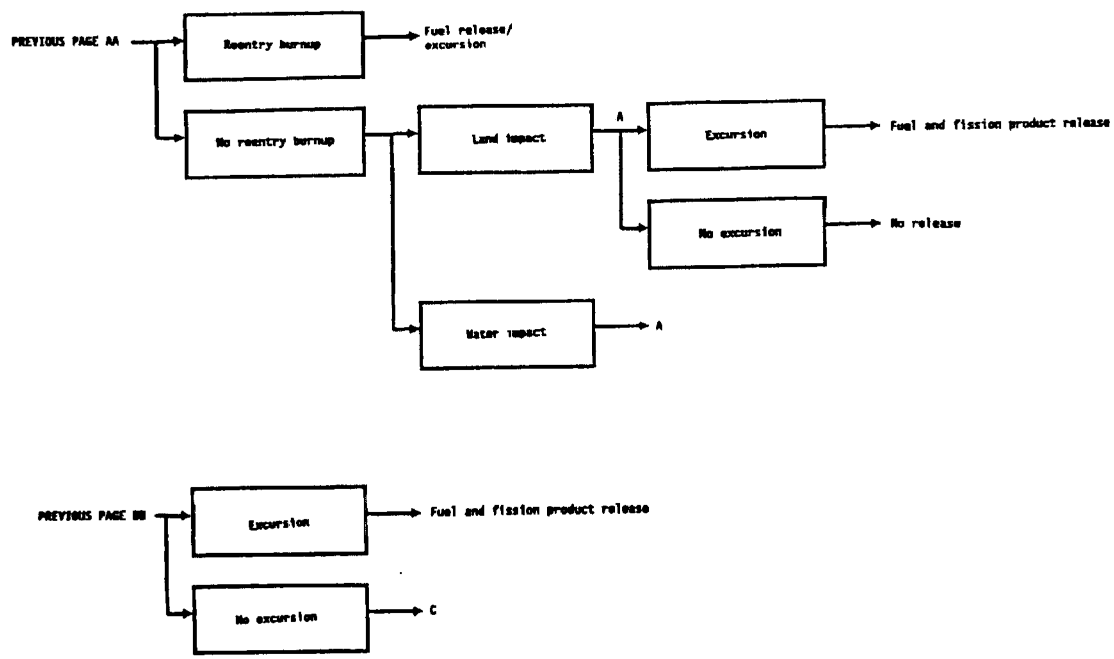

Figure 6-3 Simplified Event Tree for the Lunar Mission Phase Launch to Low Earth Orbit (Advanced Launch System) (cont.)

respectively. For clarification, the descriptor "Fire" represents the condition where a reactor may reach a critical configuration due to the thermal environment produced by burning fuel on the ground near the launch pad. No subsequent events take place. A fireball was assumed to not significantly damage the reactor in flight, i.e., the "No Fire" event. The condition of the reactor on the ground for the "Fire" event was not defined. In any case, there would either be fuel, and possibly fission products, released or not. Characterization of events in this mission phase was minimized since the SP-100 program has studied this phase in great detail. Sufficient detail has been included to determine that the current missions to the moon and Mars will not introduce new safety issues.

Low Earth Orbit Space Vehicle Assembly

Potential accidents are listed in Table 6-2. This mission phase has been divided into two sub-phases: 1) insertion into low earth orbit from launch and 2) assembly operations. Table 6-2 covers the first sub-phase. Low earth orbit insertion was assumed to require the shuttle Orbit Maneuvering System or an upper stage of the launch vehicle. Even though a space tug has been included in the analysis, a space tug will not likely be used since it would require a base for support which would be missing. The possibility does exist that an expendable space tug may be used and discarded after assembly of the transport system. Space tug failures would include an explosion of the propulsion system, engines and tanks, and guidance errors leading to orbits which will decay. Similar accidents are possible for cargo launched on a space shuttle-type vehicle where the Orbital Maneuvering System fails by explosion or guidance error. Any time during this phase, an inadvertent reactor startup command could be issued.

Table 6-2
Lunar Mission Low Earth Orbit Space Vehicle Assembly Phase (LEO Insertion) Accidents and Resulting Reactor Environments

Accident	Reactor Environment
Space tug/last stage of launch vehicle failure	Explosion Projectiles Reentry
Orbital Maneuvering System failure	Reentry
Assembly failure	Reentry
Collision	Impact Reentry
Inadvertent reactor startup	Inadequate heat sink

Failures of the space tug (e.g., Orbital Maneuvering Vehicle), upper stage, and the Space Shuttle Orbital Maneuvering System may result in projectiles and reentry, see Figures 6-4, 6-5 and 6-6. An explosion may result in reentry because of the relatively low altitude of the orbit. A guidance failure may result directly in reentry. Failure of a space tug to dock with the cargo would leave the nuclear reactor in low earth orbit. Orbital maneuvering to place the space vehicle components in close proximity for assembly have the potential for collisions. Collisions may occur between the reactor and various components of the transportation vehicles as the pieces are maneuvered for assembly. An excursion may occur whenever the reactor is damaged, a situation similar to a launch explosion. An inability to assemble the entire transportation system package with payload may leave the reactor stranded in low earth orbit if the power system cannot be recovered. Reentry may occur if the orbit has a short life and the reactor altitude cannot be maintained prior to a rescue mission. An inadvertent reactor startup command may find the reactor generating heat with the heat rejection subsystem not deployed or unable to reject heat to space because the power system is inside a payload fairing or other container. In this case, the reactor would not have an adequate heat sink which to reject heat. The fuel and fission products generated would be released if fuel clad failure occurred. Otherwise, the fission products would act as a radiation source during reentry and earth impact. Also, an unshielded reactor, i.e., the reactor design requires lunar regolith for shielding during operation, may produce a hazardous radiation field for any astronauts in the vicinity.

Operations in low earth orbit will include the handling of propellant tanks with large quantities of LO_2 and LH_2. Overpressurization of a propellant tank, if fuel transfer is required, or a collision during the process of attaching the fuel tanks to the transfer and/or excursion vehicles, may result in tank failure as indicated in Table 6-3. A considerable amount of activity will involve moving pieces of transfer vehicle components, e.g., aerobrake and propellant tanks, and cargo from temporary storage positions to the mission vehicle assembly area. This movement of material has the potential for a collision with the nuclear reactor power system. Inadvertent startup of the reactor is also a potential accident during this mission phase.

A propellant tank rupture due to the explosion of an unsuccessful fueling of the lunar transfer vehicle (LTV) and the lunar excursion vehicle (LEV) would produce a field of projectiles. These projectiles may separate the nuclear power system from the space station or the transfer/excursion vehicle. Astronaut retrieval may follow, assuming the reactor configuration subsequent to the accident was subcritical. A critical reactor configuration was assumed to lead to an excursion and/or fuel release. A collision of the nuclear power system and the various pieces of the transfer and excursion vehicles moved about during assembly would likely result in low speed impact without an excursion and possibly, reentry if the impact dislodges the reactor and it cannot be recovered. Depending upon the power system design, an inadvertent startup would result in the reactor overheating since the heat rejection subsystem would not be deployed or the reactor would not be integral with the rest of the power system. Another serious concern would be the exposure of astronauts to the radiation field generated by the reactor. If

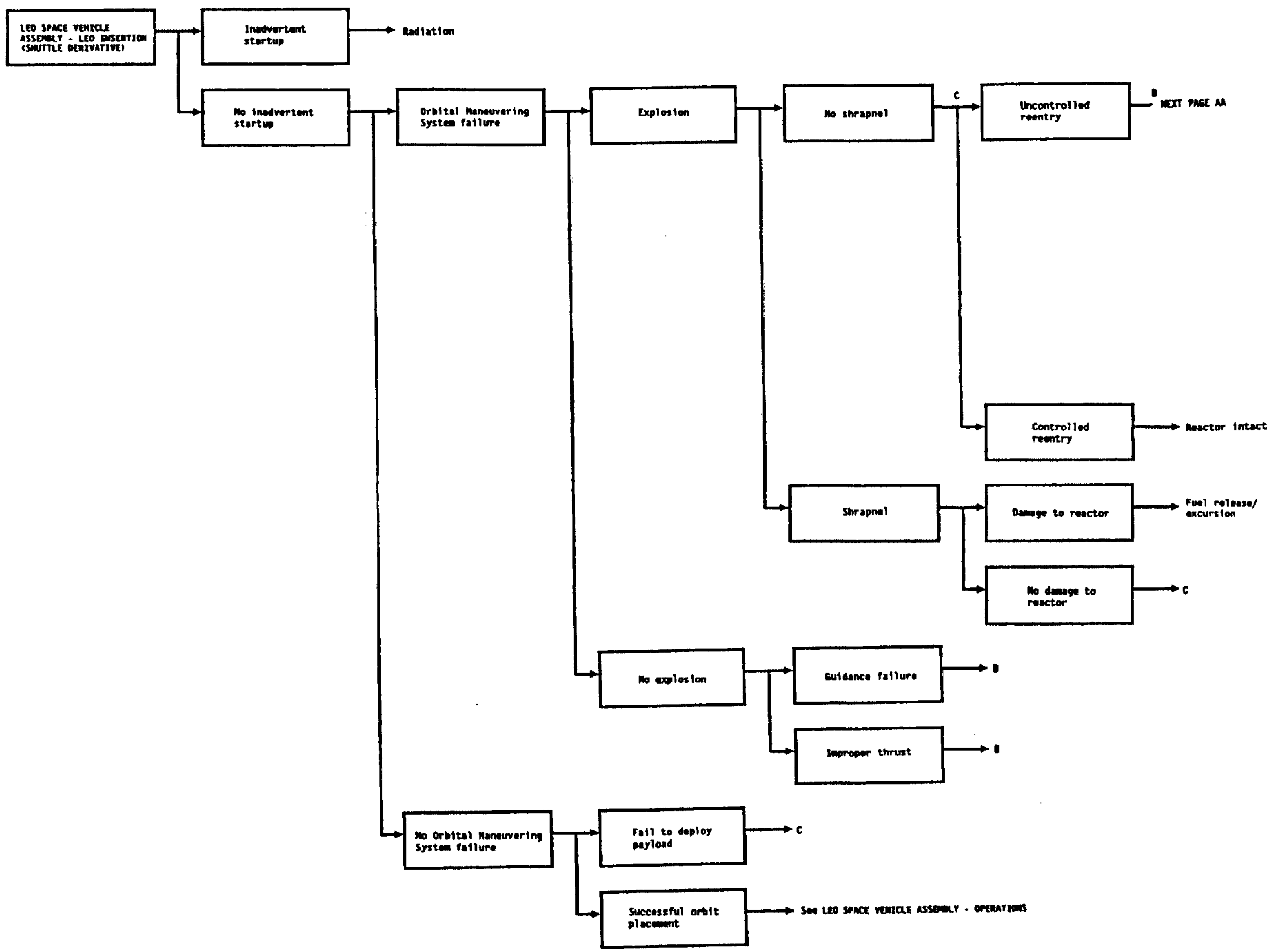

Figure 6-4 Simplified Event Tree for Lunar Mission Phase Low Earth Orbit Space Vehicle Assembly - LEO Insertion (Shuttle Derivative)

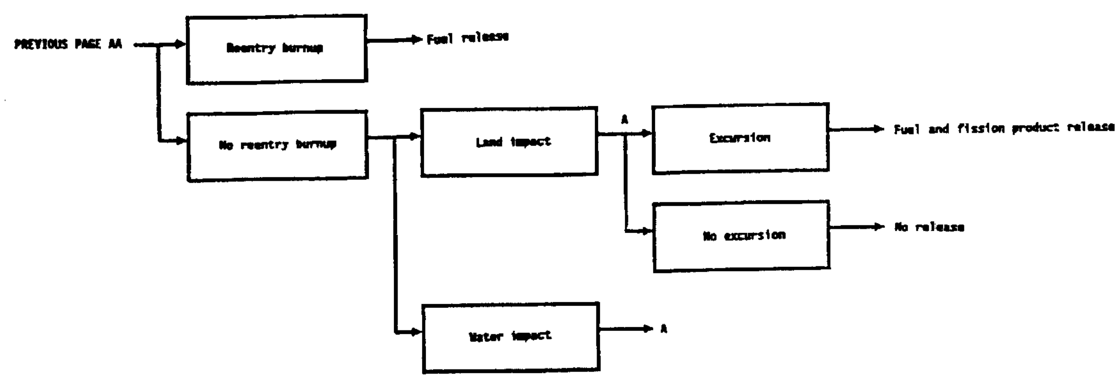

Figure 6-4 Simplified Event Tree for Lunar Mission Phase Low Earth Orbit Space Vehicle Assembly - LEO Insertion (Shuttle Derivative) (cont.)

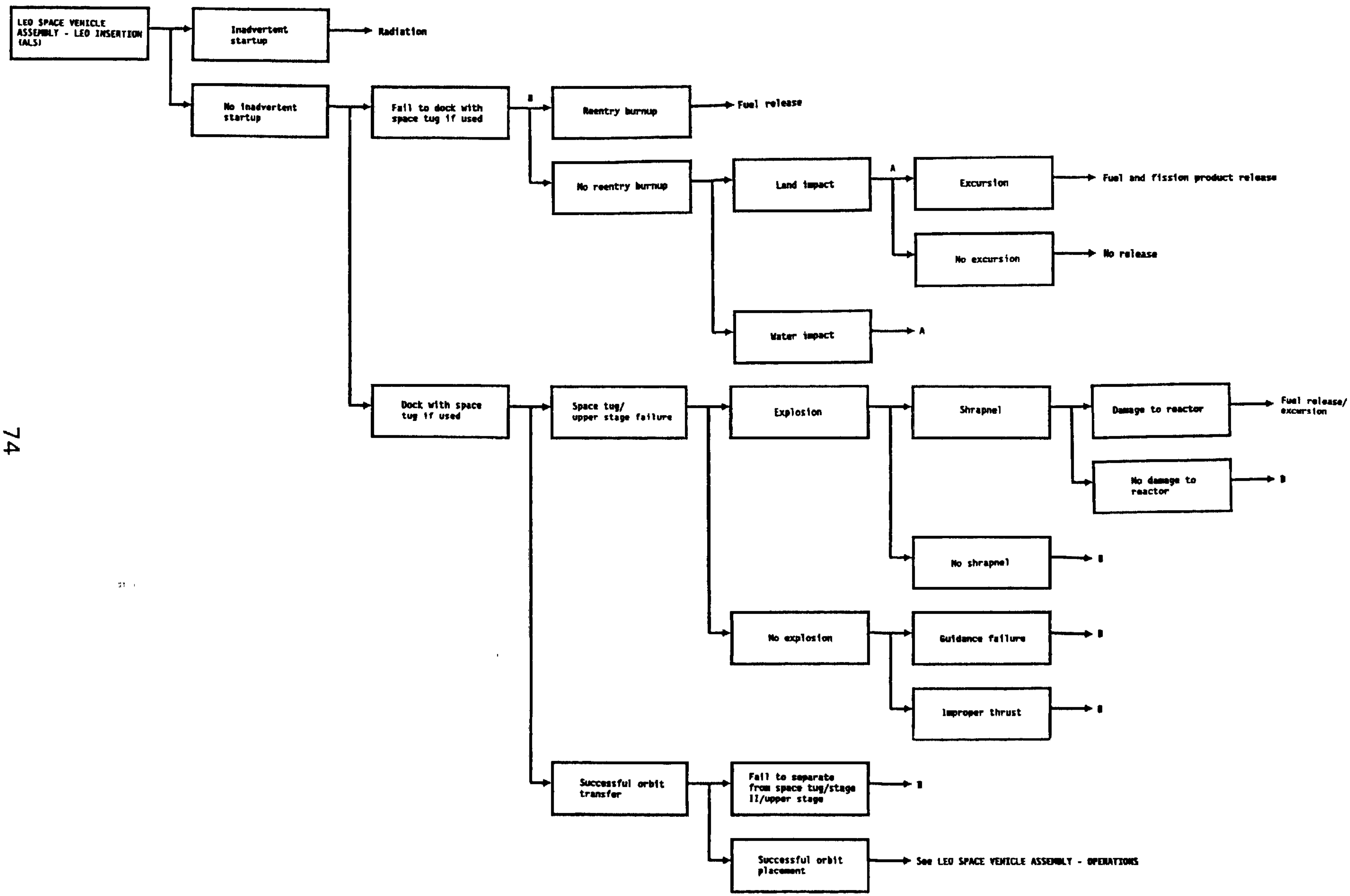

Figure 6-5 Simplified Event Tree for Lunar Mission Phase Low Earth Orbit Space Vehicle Assembly - LEO Insertion (Advanced Launch System)

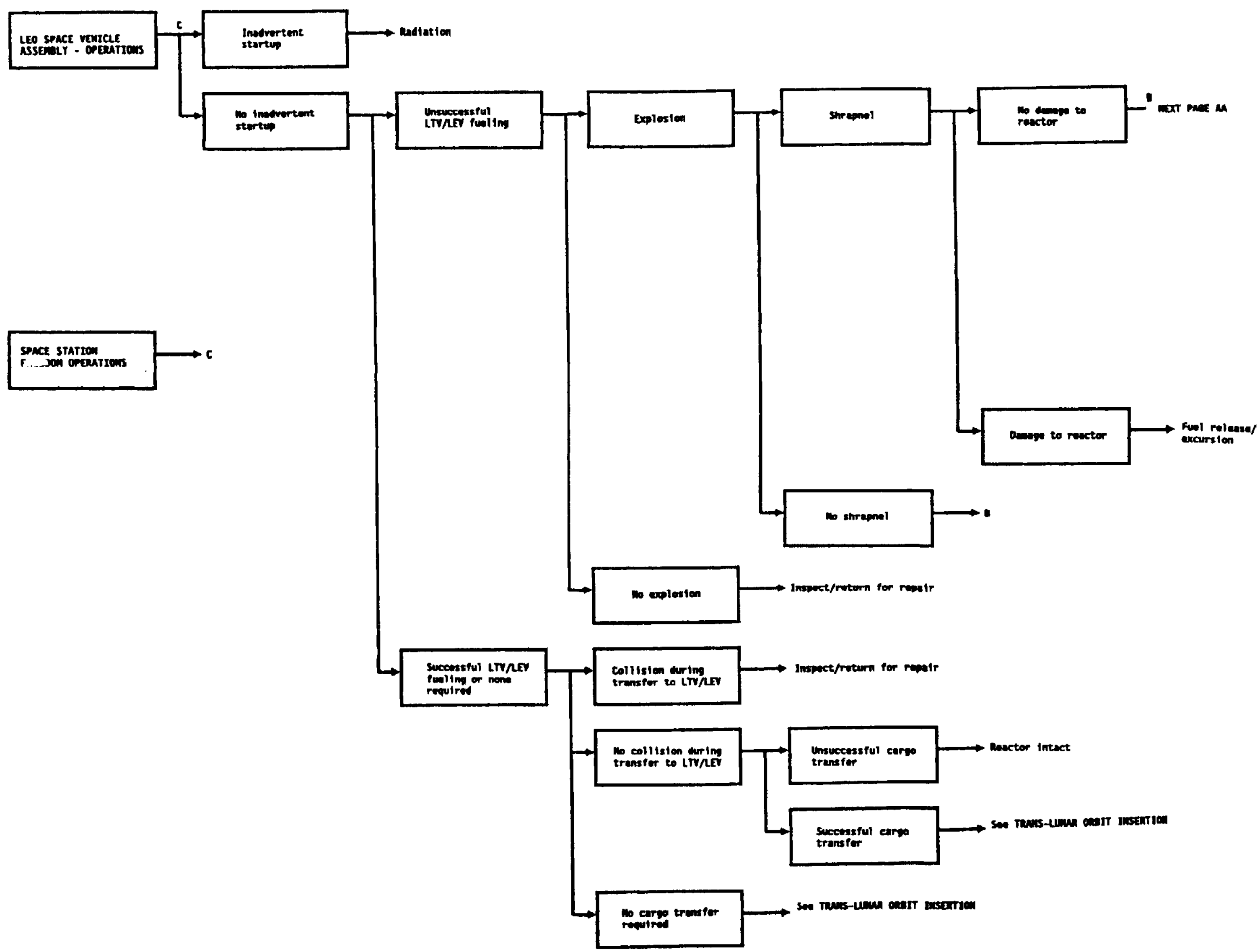

Figure 6-6 Simplified Event Tree for the Lunar Mission Phase Low Earth Orbit Space Vehicle Assembly - Operations

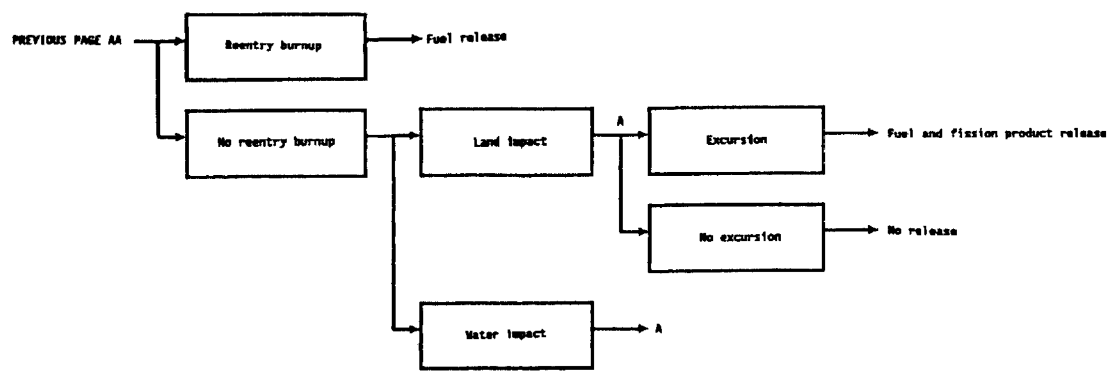

Figure 6-6 Simplified Event Tree for the Lunar Mission Phase Low Earth Orbit Space Vehicle Assembly - Operations (cont.)

the lunar emplacement scheme is to shield the reactor with lunar materials, operation at this time would subject astronauts to an inadequately shielded neutron flux.

Table 6-3
Lunar Mission Low Earth Orbit Space Vehicle Assembly Phase (Operations) Accidents and Resulting Reactor Environments

Accident	Reactor Environment
Propellant tank failure during LTV/LEV fueling	Explosion Projectiles Reentry
Collision	Impact Reentry
Inadvertent reactor startup	Inadequate heat sink

An option for this mission phase is the assembly of the space vehicle at Space Station Freedom, Figures 6-7 and 6-8. The potential accidents for this option are much the same as for assembly of the space vehicle in low earth orbit. The major exception is the maneuvers used to dock with the space station. They will replace the maneuvers in low earth orbit to place the various components of the payload and transportation system in close proximity for assembly. Failure to dock may occur when the space tug attaches to the cargo which has been boosted by an expendable launch vehicle or when the space tug and cargo or shuttle attempts to dock with Space Station Freedom. For this mission phase, the assumption was made that the space tug would not dock with the space station but the cargo would be directly attached to the space station. The space tug would then separate from the cargo after confirmation of cargo attachment to the space station. During any of these docking maneuvers, a collision between the cargo and the space tug and/or space station may occur. If the cargo and space tug are unable to dock with the space station, an alternate procedure would have to be used to retrieve the cargo. A similar situation may occur if the space shuttle would fail to dock with the space station or the space tug would fail to separate from the cargo after docking with the space station. A collision may result in impact with the space tug, the space shuttle, or the space station structure. Representative accidents for this option are listed in Table 6-4.

The potential accidents for operations at the space station would be quite similar as those for space vehicle assembly in low earth orbit, see Table 6-3, but with the addition of potential collisions of the reactor and propellant tanks with the space station. There will still be the potential for collisions between the reactor and elements of the transportation system.

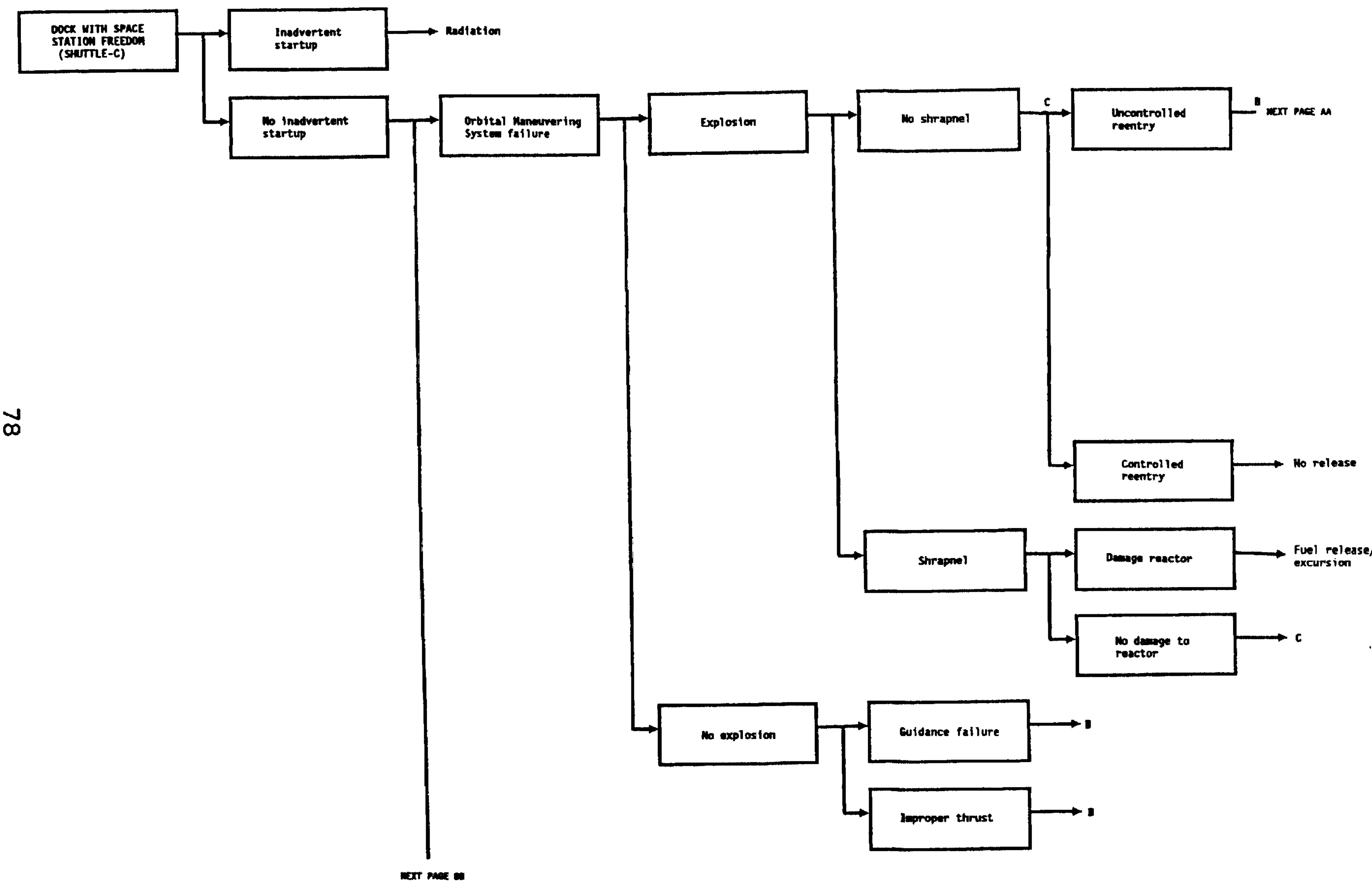

Figure 6-7 Simplified Event Tree for the Lunar Mission Phase Dock With Space Station Freedom (Shuttle Derivative)

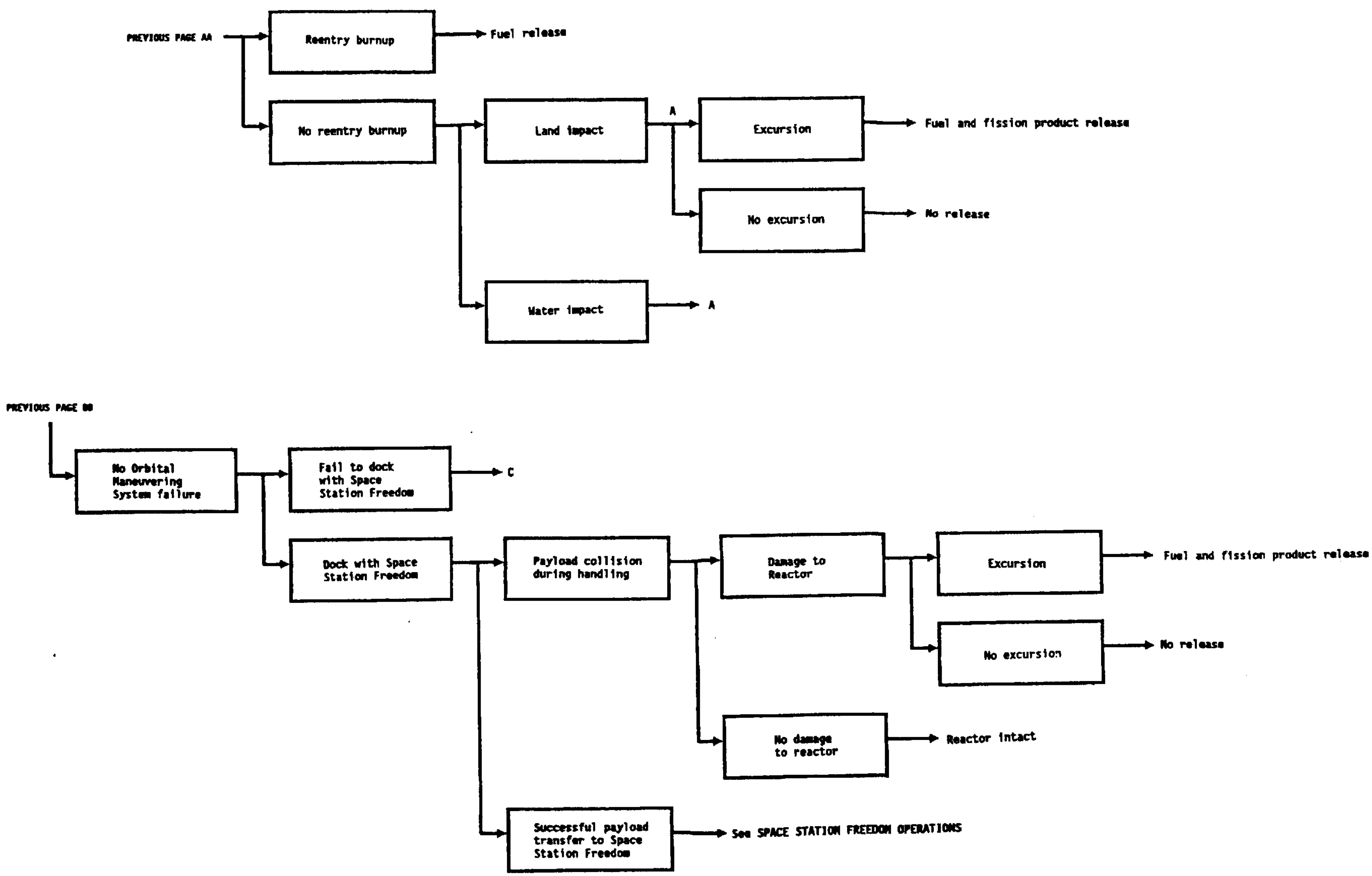

Figure 6-7 Simplified Event Tree for the Lunar Mission Phase Dock With Space Station Freedom (Shuttle Derivative) (cont.)

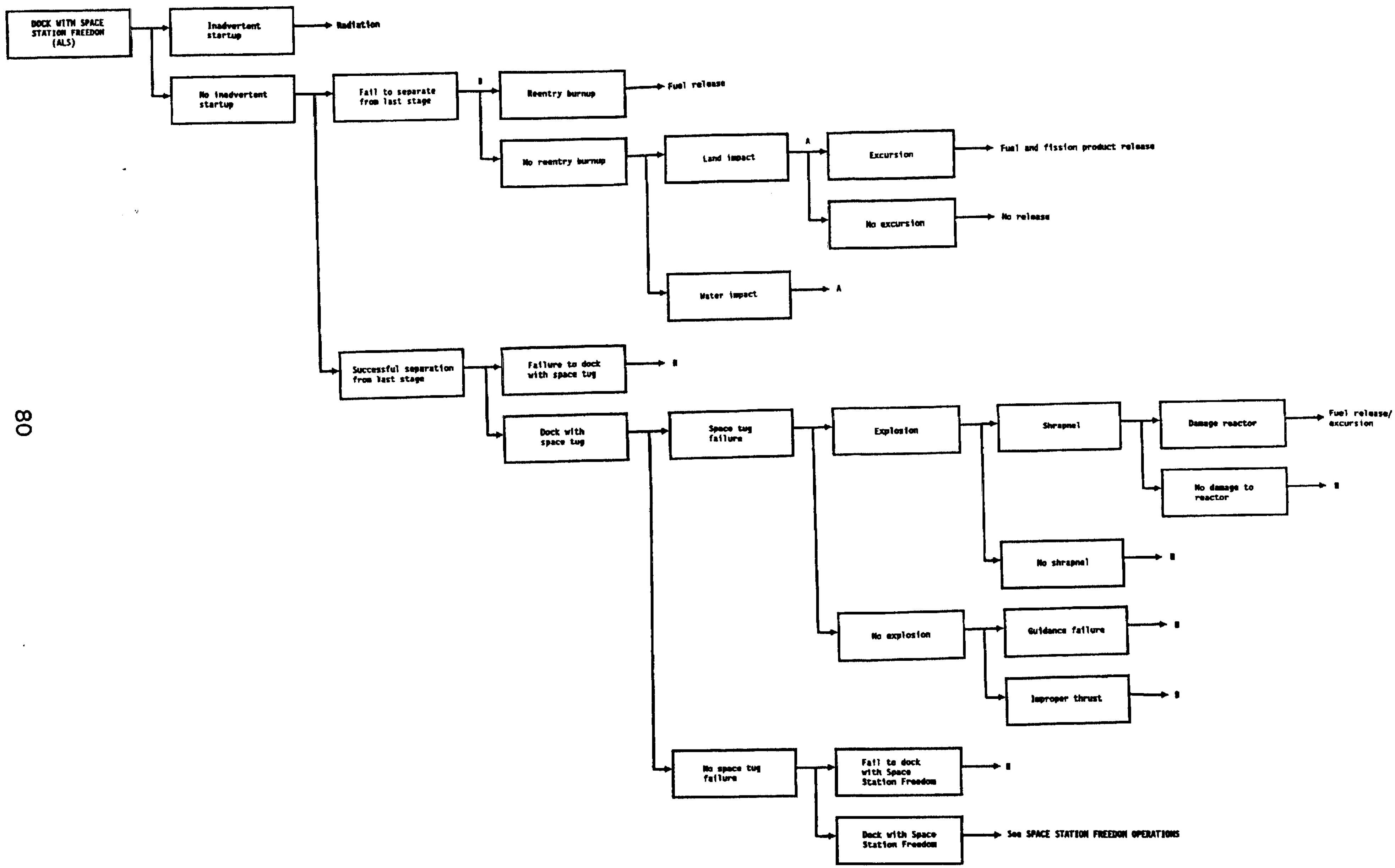

Figure 6-8 Simplified Event Tree for the Lunar Mission Phase Dock With Space Station Freedom (Advanced Launch System)

Table 6-4
Lunar Mission Dock With Space Station Freedom Phase Accidents and Resulting Reactor Environments (option)

Accident	Reactor Environment
Space tug failure	Explosion Projectiles Reentry
Orbital Maneuvering System failure	Explosion Projectiles Reentry
Docking failure	Reentry
Collision	Impact Reentry
Inadvertent reactor startup	Inadequate heat sink

The corresponding simplified event tree is also shown in Figure 6-6.

A direct launch to the moon would not involve any assembly operations in low earth orbit. Because of this, the accidents would be limited to inadvertent reactor startup and failure of the lunar transfer vehicle to insert the payload into the trans-lunar orbit, see Figure 6-9. The resultant possible reactor environments may be an inadequate heat sink, an explosion, projectiles, and reentry to earth if the resultant trajectory passes too close to the atmosphere.

Trans-Lunar Orbit Insertion

Potential accidents during this phase include a collision of the transfer vehicle and cargo with Space Station Freedom after separation, Table 6-5. Orbit insertion from low earth orbit not at the space station would not have the potential for collision with the space tug used to undock the lunar transportation system from the space station. Also, space tug failures during orbit maneuvers would be eliminated. The maneuvering by the space tug prior to trans-lunar orbit insertion was assumed performed by the lunar transportation system. Collision of the transfer vehicle and cargo and the jettisoned propellant tanks may also occur after orbit insertion. Such a collision was assumed to lead to an explosion, see Figure 6-10. The lunar transfer vehicle may fail for such reasons as tank rupture, engine explosion, engine failure to ignite or shut down, loss of thrust, or guidance error. A failure of the exhausted propellant tanks to separate from the transfer

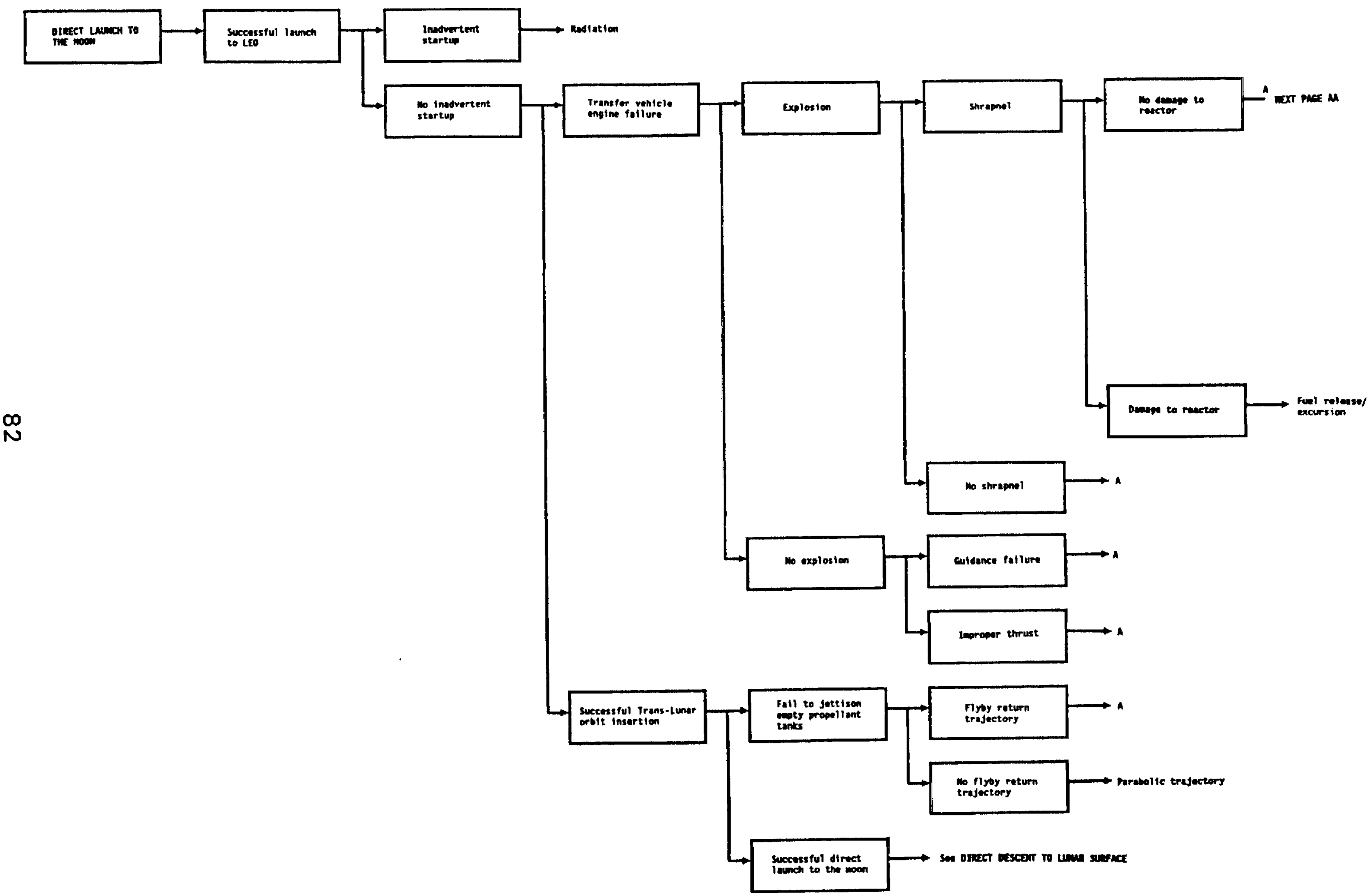

Figure 6-9 Simplified Event Tree for the Lunar Mission Phase Direct Launch To The Moon

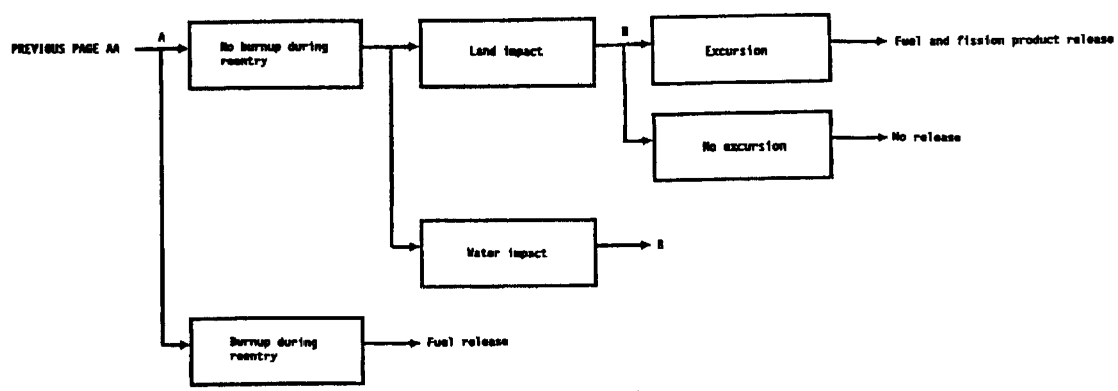

Figure 6-9   Simplified Event Tree for the Lunar Mission Phase Direct Launch To The Moon (cont.)

Table 6-5
Trans-Lunar Orbit Insertion Phase Accidents and Resulting Reactor Environments

Accident	Reactor Environment
Lunar transfer vehicle and space tug failure	Projectiles Reentry
Collision with space tug	Impact
Failure of empty propellant tank to separate	Reentry
Inadvertent reactor startup	Inadequate heat sink

vehicle may be a safety problem depending upon contingency plans for such an event. If sufficient rocket fuel is provided for lunar orbit insertion with the empty tanks attached, there will be no safety concern. However, if the contingency plan is to allow the transfer vehicle to return to earth without attempting lunar orbit insertion, the possibility of earth reentry exists. An inadvertent reactor startup command may be issued.

Collisions may lead to impact of the reactor and/or an explosion. A failure of the transfer vehicle and the space tug may result in a projectile field due to an explosion followed by reentry. A damaged reactor may result in an excursion of the reactor in orbit or during reentry and impact. As stated above, a failure to jettison an empty propellant tank(s) may result in reentry. An operating reactor would pose a hazard to a flight crew. It was assumed that the reactor would be sufficiently far from the space station to not be a hazard to astronauts at the space station. An operated reactor may pose a hazard to the public. If the reactor can be shut down, it may not pose a significant problem. If, however, the reactor cannot be shutdown or it operates to the point of fuel release, it will pose a hazard to astronauts if retrieval is required and to the public if retrieval is not possible and it is stranded in low earth orbit. This last safety problem is common to all mission phases where the potential for reentry occurs. The reactor itself would not be part of a fully assembled and deployed system and, hence, would not have an adequate heat sink because it was insulated from space.

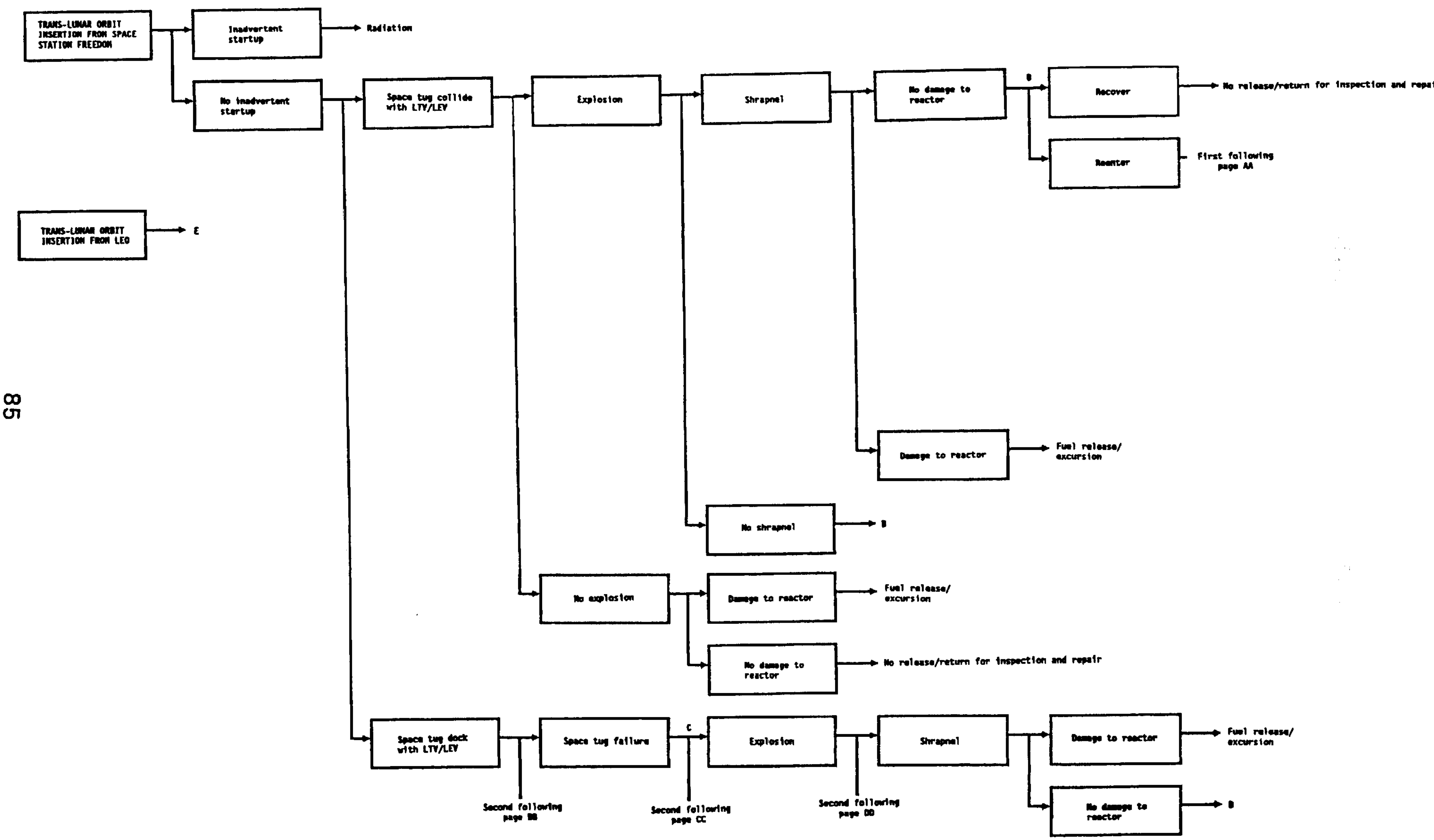

Figure 6-10 Simplified Event Tree for the Lunar Mission Phases Trans-Lunar Insertion From Space Station Freedom and LEO

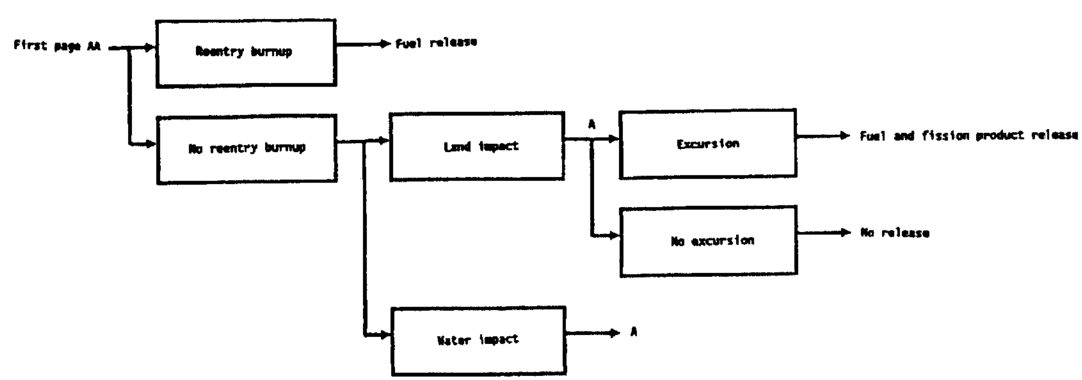

Figure 6-10 Simplified Event Tree for the Lunar Mission Phases Trans-Lunar Insertion From Space Station Freedom and LEO (cont.)

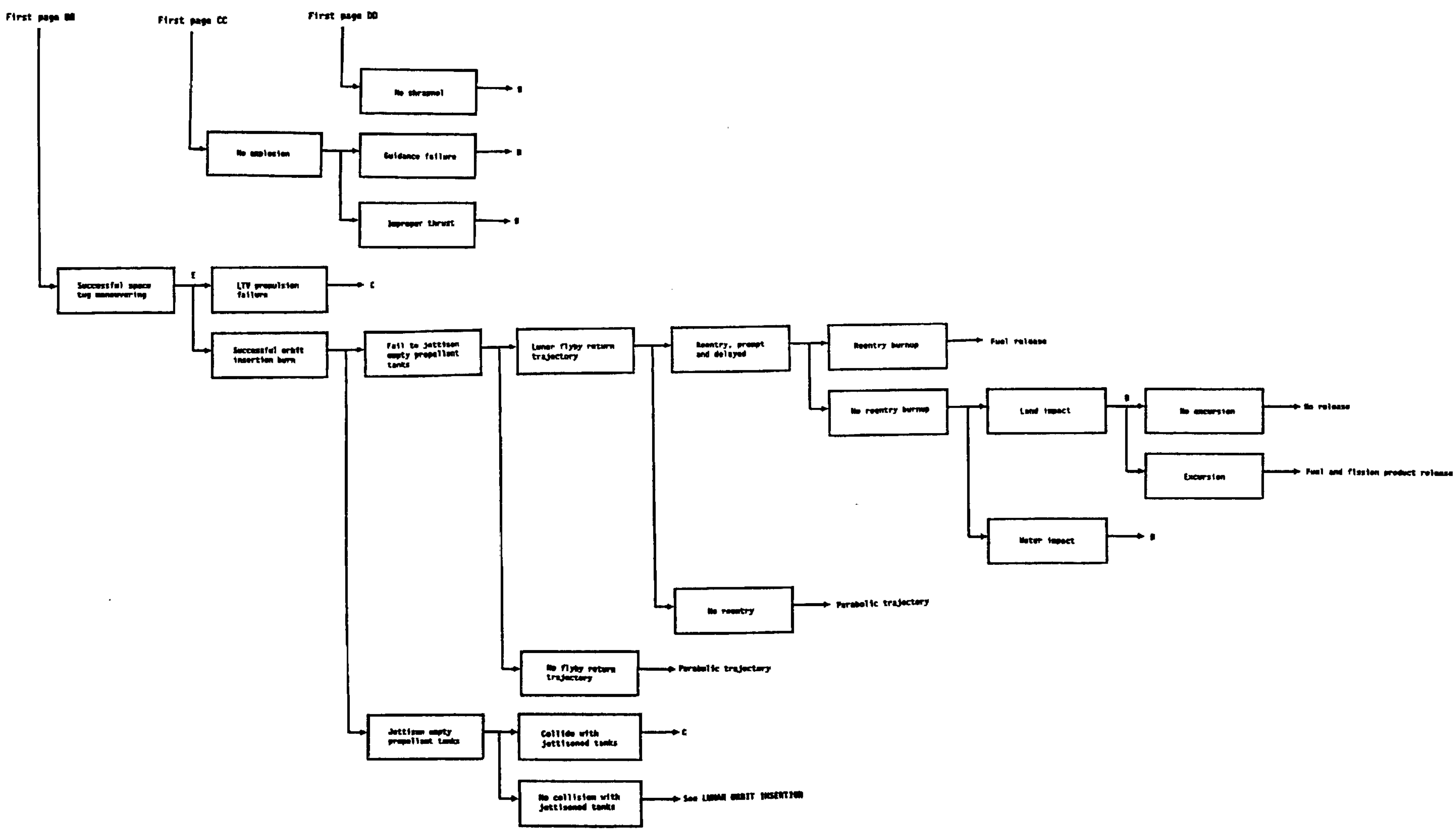

Figure 6-10 Simplified Event Tree for the Lunar Mission Phases Trans-Lunar Insertion From Space Station Freedom and LEO (cont.)

Lunar Orbit Insertion

Failures of the lunar transfer vehicle have been lumped into a single accident in Table 6-6. Lunar transfer vehicle failures can include loss of thrust, failure to ignite engines, engine explosion, failure of engines to shut down, and guidance error. As usual, an inadvertent startup command may be received.

An explosion of the lunar transfer vehicle engines may result in a field of projectiles plus rupture of LO_2 and LH_2 propellant tanks with additional

Table 6-6
Lunar Orbit Insertion Phase Accidents and Resulting Reactor Environments

Accident	Reactor Environment
Lunar transfer vehicle failure	Explosion Reentry Projectiles Impact
Inadvertent reactor startup	Inadequate heat sink

projectiles, see Figure 6-11. As noted previously, a damaged reactor may result in fuel release and possibly, an excursion. A failure of the rocket engine to ignite or very early loss of thrust may lead to a return to earth and reentry if the trans-lunar orbit has a return trajectory intersecting the earth. Improper thrust vector control may result in lunar surface impact. Impact on the surface of the moon was assumed to result in complete destruction of the reactor. The impact, without the benefit of an atmospheric drag, would be at high speed, likely much greater than earth reentry terminal speed. An inadvertently operating reactor may pose a hazard to a flight crew. As previously discussed, the reactor would not be configured for operation and would not have an adequate heat sink.

A direct descent to the lunar surface option would have the potential for the same accidents as lunar orbit insertion with the exception of the separation of the transfer and excursion vehicles if a single transportation vehicle was not used (see Figure 6-12). If the transfer and excursion vehicles did not separate, the transportation vehicles and payload may return to earth on a flyby trajectory, where the earth return leg of the trans-lunar orbit intersects the earth. An explosion of the descent vehicle during descent may lead to fuel release or possibly an excursion with the fuel and excursion fission products released upon impact with the lunar surface.

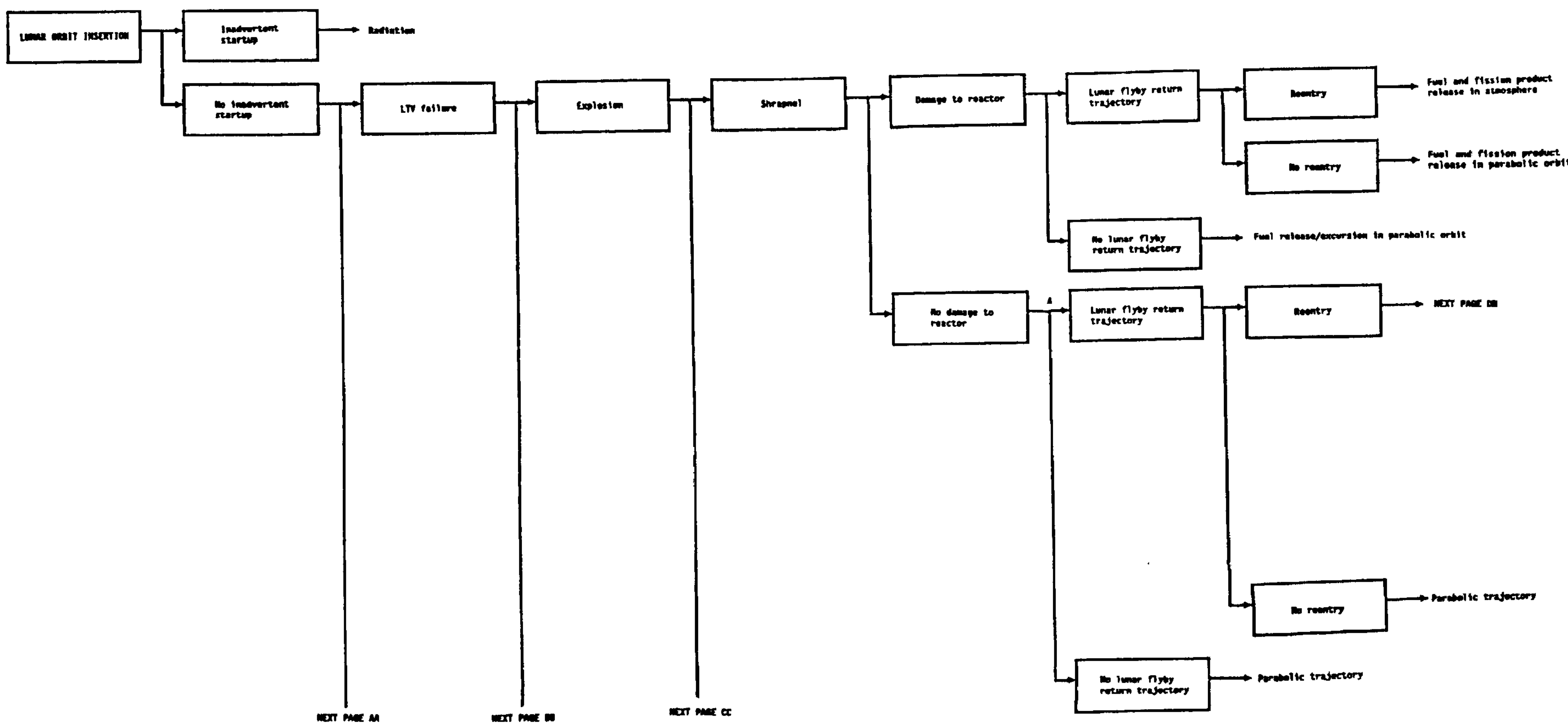

Figure 6-11 Simplified Event Tree for the Lunar Mission Phase Lunar Orbit Insertion

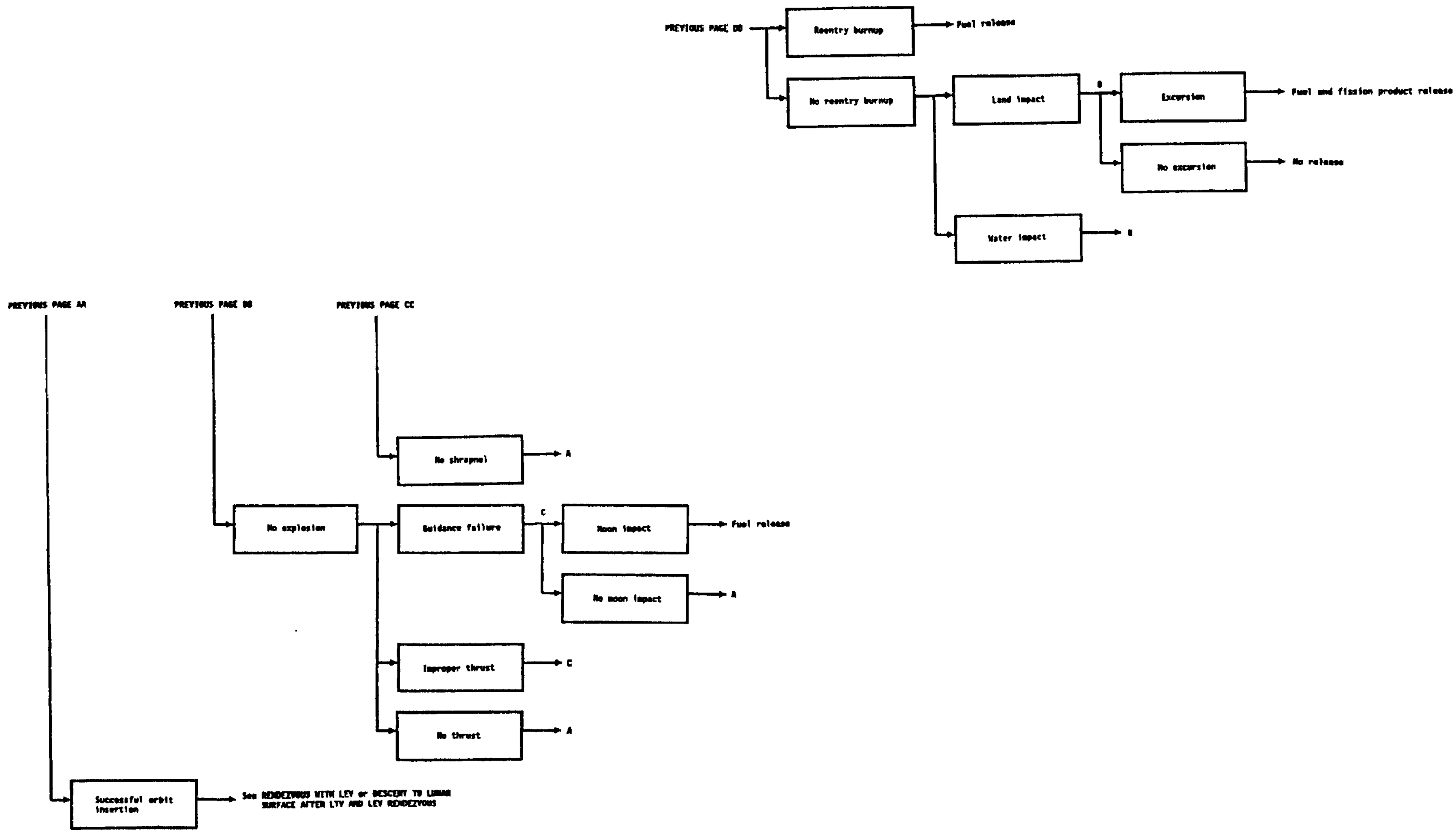

Figure 6-11 Simplified Event Tree for the Lunar Mission Phase Lunar Orbit Insertion (cont.)

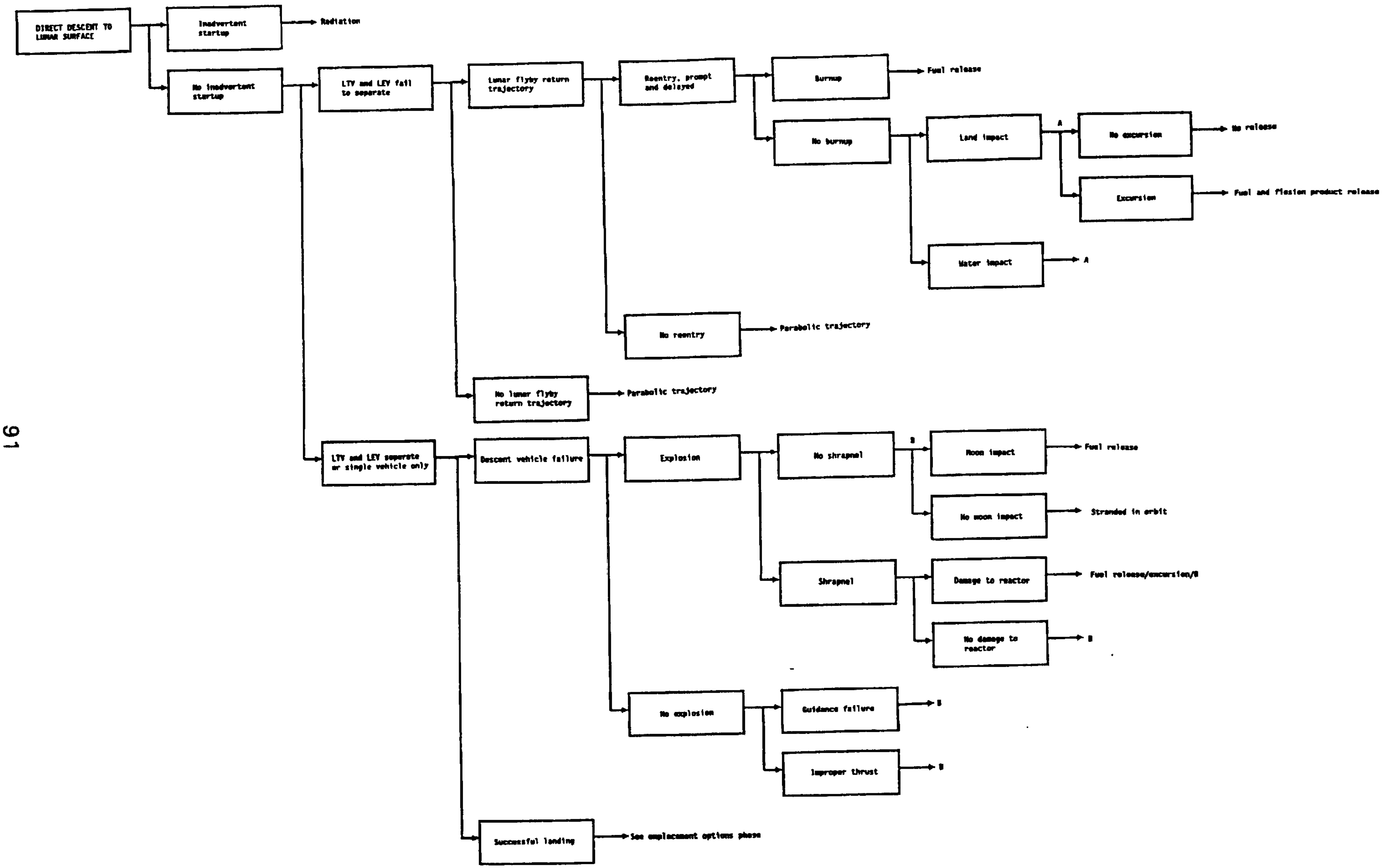

Figure 6-12 Simplified Event Tree for the Lunar Mission Phase Direct Descent to Lunar Surface

Rendezvous With Lunar Excursion Vehicle

Potential accidents for this phase of the lunar mission are listed in Table 6-7. Collisions could occur during the docking maneuver and after the lunar transfer and excursion vehicles have separated prior to excursion vehicle descent to the lunar surface. Failures to dock, undock, and transfer cargo and propellants to the excursion vehicle may not immediately present safety problems but, a procedure and the means would be required to recover the reactor. An inadvertent reactor startup is possible.

Table 6-7
Lunar Mission Rendezvous With LEV Phase Accidents and Resulting Reactor Environments

Accident	Reactor Environment
Collision	Impact Explosion Projectiles
Failure to dock or undock	Stranded in orbit
Failure to transfer cargo or LH_2/LO_2	Stranded in orbit
Inadvertent reactor startup	Inadequate heat sink

A collision may result in reactor impact, an explosion, and projectiles. Fuel may be released to orbit after a collision and explosion with an excursion a possibility, Figure 6-13. The docking, undocking, and cargo or LO_2 and LH_2 transfer failures would lead to the reactor stranded in orbit. Retrieval may or may not be practical. Propellant tank rupture due to an unsuccessful propellant transfer from the LTV to the LEV would produce projectile fields. An inadvertent startup of the reactor could lead to a hazardous radiation field to a flight crew and an overheated nuclear power system if it is unable to adequately reject heat because it is inside a fairing or other such container.

Descent To Lunar Surface

Table 6-8 lists potential accidents and the resulting reactor environments for this phase of the lunar mission. A failure of the lunar excursion vehicle may occur due to a guidance error, a loss of thrust, a descent engine explosion or failure to ignite or re-ignite, or an attitude control failure upon landing. Guidance errors, loss of thrust, and attitude

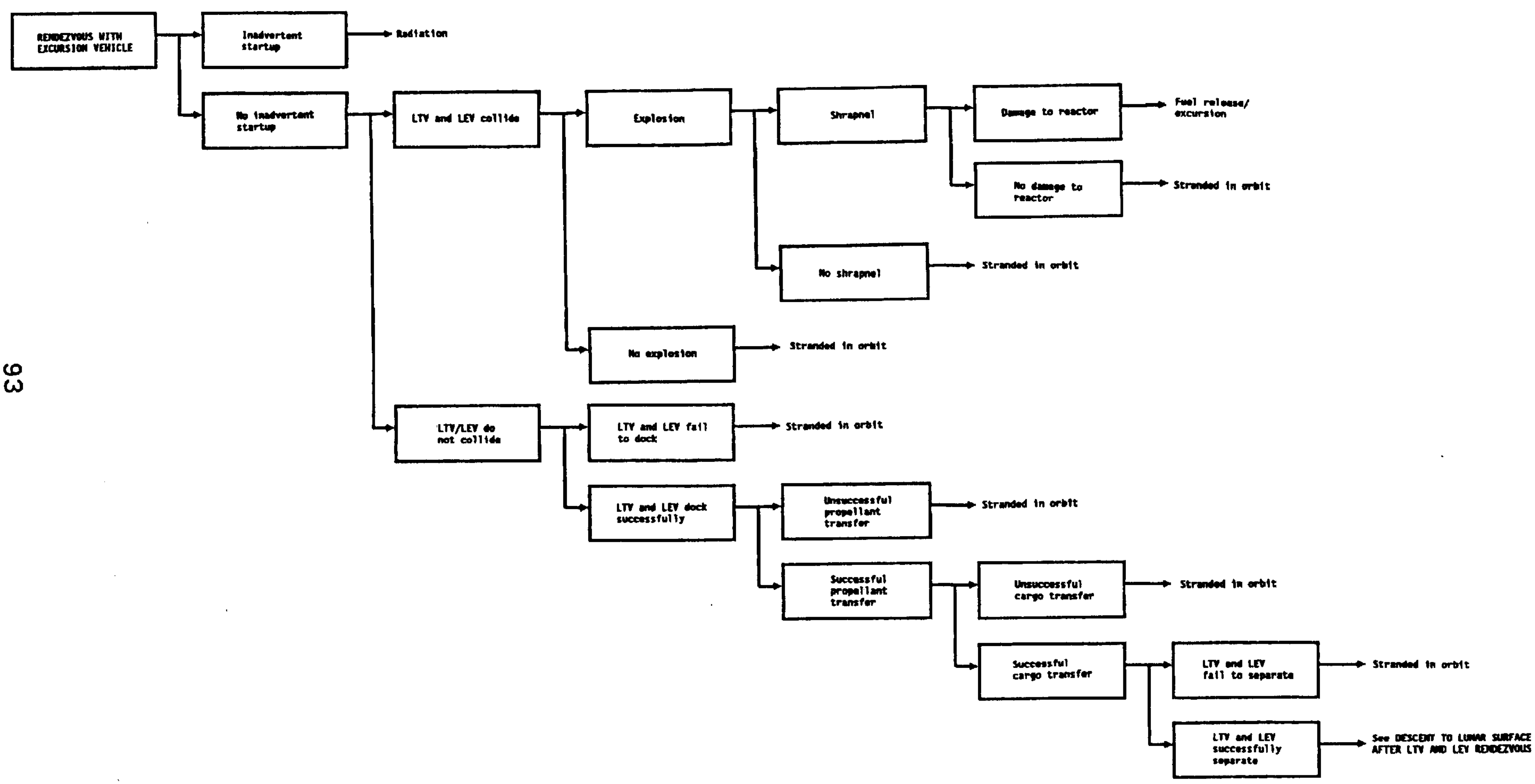

Figure 6-13 Simplified Event Tree for the Lunar Mission Phase Rendezvous with Lunar Excursion Vehicle

Table 6-8
Descent to Lunar Surface Phase Accidents and Resulting Reactor Environments

Accident	Reactor Environment
Lunar excursion vehicle failure	Impact Projectiles Stranded in orbit Burial in regolith Explosion
Inadvertent reactor startup	Inadequate heat sink

control failure may lead to impact on the lunar surface with fuel released as shown in Figure 6-14. No allowance was made for mitigating circumstances in near-surface low-speed impacts. An engine explosion would produce a field of projectiles. A damaged reactor was assumed to release fuel with the possibility for an excursion. The added notation /A denotes that the reactor may also impact the surface of the moon, i.e., the accident is not over. No ignition of the descent engines would leave the reactor stranded in orbit. An inadvertent reactor startup would present a radiation hazard to the flight crew. The reactor would also be unable to adequately reject heat. Subsequent fuel cladding failure was assumed.

Direct descent to the lunar surface has been discussed previously in the mission phase Lunar Orbit Insertion.

Emplacement

Accidents during this phase are dependent upon the emplacement scheme. Common to the emplacement schemes are the potential accidents dropping the reactor to the lunar surface if offloading from the lunar excursion vehicle and/or emplacement in an excavation is required, colliding the reactor with other cargo or the lunar excursion vehicle during offloading, inadvertent reactor startup, reactor control failure during startup and test prior to full power operation. Not included in the simplified event trees is the possibility of excessive emitted radiation due to inadequate shielding discovered during a site survey. The assumption was made that proper engineering design resulted in adequate shielding. A summary of these accidents for the emplacement schemes where the reactor would be emplaced in an excavation or surrounded by a berm is shown in Table 6-9. Potential accidents for the emplacement schemes where the reactor is left on the surface of the moon are also shown in Table 6-9. Impact accidents will be at low speeds.

Low speed impacts will result if the reactor collides with the lunar excursion vehicle or is dropped during unloading of the reactor at the landing

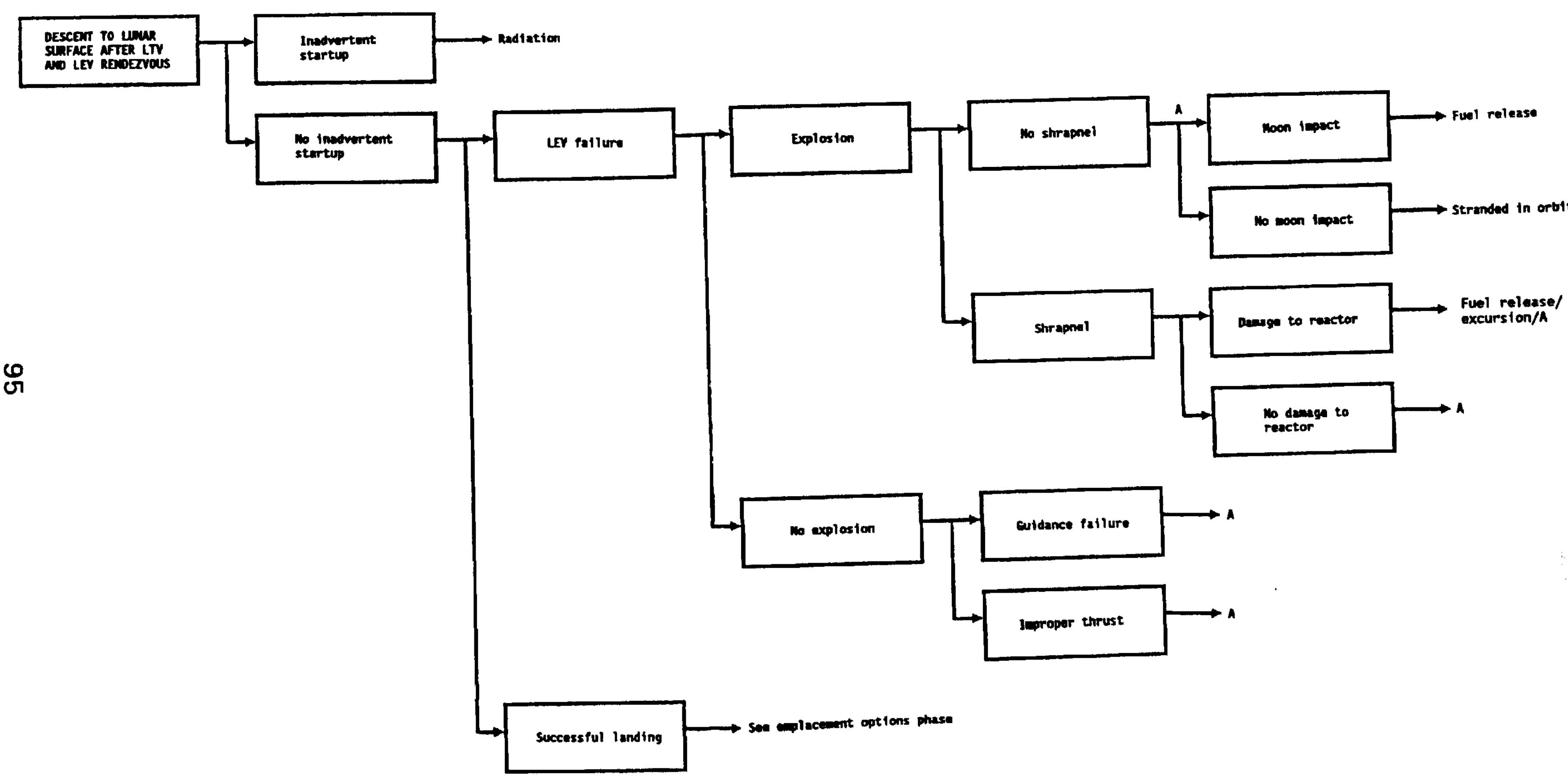

Figure 6-14 Simplified Event Tree for the Lunar Mission Phase Descent to Lunar Surface (After LTV and LEV Rendezvous)

Table 6-9
Emplacement Phase Accidents and Resulting Reactor Environments

Accident	Reactor Environment
Collision	Impact
Drop reactor	Impact
Control failure	Excursion
Inadvertent reactor startup	Inadequate heat sink

site. The possibility of an excursion was included since a reactor design may allow removal of criticality-prevention devices subsequent to arrival on the lunar surface which were designed for high speed impacts, see Figure 6-15. These same types of accidents may occur at the emplacement site as the reactor is lifted from a lunar surface transport cart and lowered into an excavation or inside a berm enclosure. The power system may require some assembly. Subsequent to the assembly of the nuclear reactor power system, a series of tests will be performed. Even with no assembly, startup testing will be required. A reactor control failure during startup and testing may result in an excursion.

A nuclear power system which turnkey would not be susceptible to most of the accidents shown in Table 6-9 and Figure 6-15.

Operation and Maintenance

During normal operation, system failures and external events can lead to unsafe reactor operating conditions. Depending upon the probability of the failure or the event, a reactor may be designed to accommodate the consequences of the failure or event. Design basis events were identified in the SP-100 program. Accidents related to the failure of the safety functions designed to accommodate these events were included in this study. Also included as accidents were events leading to unsafe conditions to astronauts but not necessarily to a failed power system. Examples would be an inadvertent startup of the reactor during maintenance procedures or an astronaut inadvertently contacting live power cables. These failures and external events are listed as accidents in Table 6-10. It should be recognized that at this time minimal astronaut involvement with the power system is preferred. A turnkey power system which only requires cable hookup will eliminate any safety concerns with respect to maintenance or repair.

Loss of the primary coolant loop fluid or just the loss of flow of the primary coolant wil cause the power system to be unable to remove heat as it

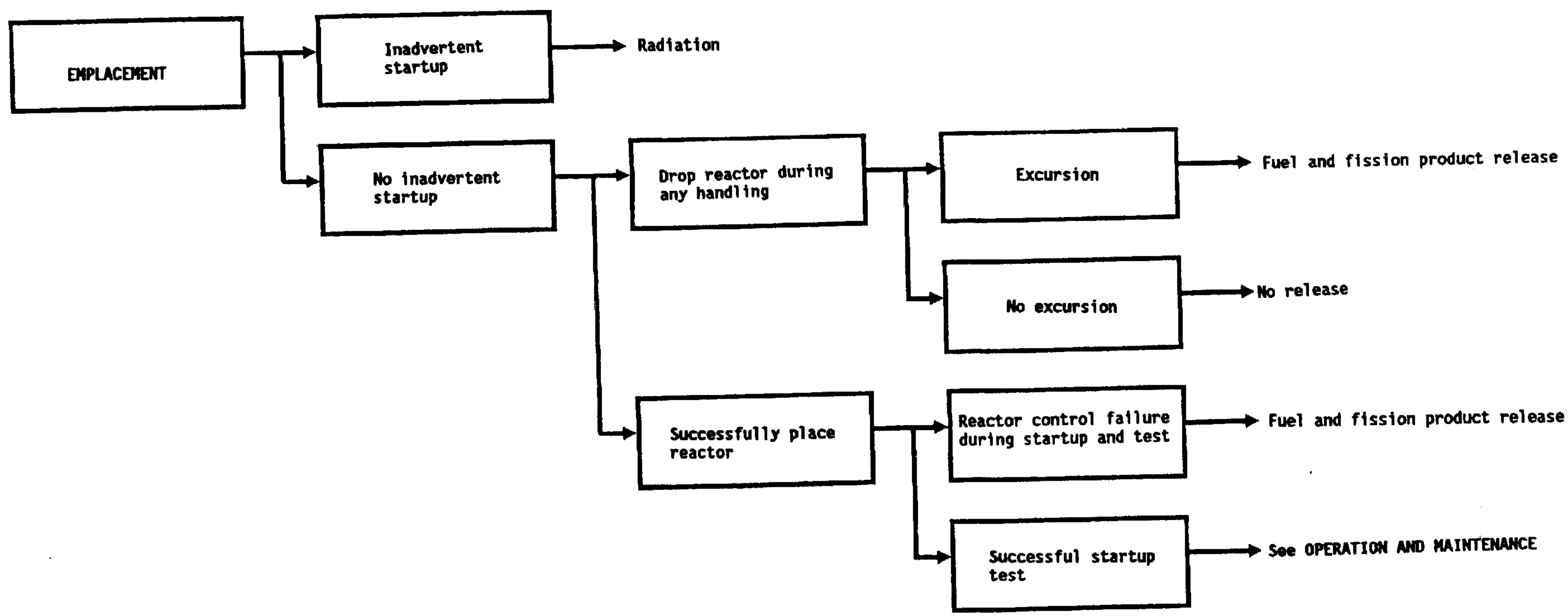

Figure 6-15 Simplified Event Tree for the Lunar Mission Phase Emplacement

Table 6-10
Lunar Mission Operation and Maintenance Phase Accidents and Resulting Reactor Environments
(Sheet 1 of 2)

Accident	Reactor Environment
Loss of coolant	Inadequate heat rejection path
Loss of flow	Inadequate heat rejection path
Loss of power conversion subsystem	Inadequate heat rejection path
Loss of heat sink	Inadequate heat rejection path
Loss of load	Inadequate heat removal path
Reactor I&C failures or sufficiently degraded state	Excursion or shutdown
Reactor safety subsystem failures including environmental effects	Excursion or shutdown
Reactor safety subsystem sufficiently degraded state	Excursion or shutdown
Exceed fuel temperature limits	Degraded operation lifetime
Inadvertent startup during maintenance	Shutdown[1]
Loss of uninterruptible power (e.g., battery)	Unable to monitor after shutdown
Fuel pin failure	Fission product release
Loss of communications with habitat/space station/earth	Uncontrolled by external command

Table 6-10
Lunar Mission Operation and Maintenance Phase Accidents and Resulting Reactor Environments
(Sheet 2 of 2)

Accident	Reactor Environment
Excessive positive reactivity insertion	Excursion
Unplanned negative reactivity insertion	Power-down or shutdown
Loss of power to buses	Uncontrolled
Astronaut contact with power cables	N/A
Meteor impact	Impact

1. During maintenance the reactor will be shutdown, but the potential exists for astronaut exposure to harmful radiation fields.

is generated in the reactor core. If the power conversion subsystem or the heat rejection subsystem fails to function, a scram condition will exist and decay heat will have to be removed. A loss of load would also result in a scram condition.

Failures in the reactor instrumentation and control and in the safety subsystems may result in inadvertent positive or negative reactivity insertions depending upon system design. Failures can also lead to the inability of the system to determine that the system is operating in an unsafe condition. Degradation of the instrumentation and control subsystem and the safety subsystems can also result in unsafe operation.

Exceeding fuel temperature limits during operation may not result in a hazardous condition at the moment of the event. However, reactor internal component degradation may be sufficient to effect component and system lifetimes. System design may no longer be adequate to meet predicted performance levels and lifetimes.

Astronauts may have to perform maintenance activities on the nuclear power system to meet reliability requirements. Hence, the potential exists for astronauts to be exposed to unsafe levels of radiation due to inadvertent operation of the reactor should these maintenance tasks require shutdown. A highly reliable system would require not maintenance and thus, eliminate this concern.

After a shutdown command, a power supply will be required to monitor the status of the reactor and remove decay heat. A loss of this independent power supply may lead to reactor core disruption due to excessive temperatures. It will certainly lead to the inability of the astronauts to determine the condition of the reactor. A shutdown command could fail to shutdown the reactor but trip the power conversion subsystem to the shutdown mode. Without power to monitor the status, this condition would not be identified.

Fuel pin failure would result in the release of fission products into the primary coolant. The deposition of the fission products in the primary loop could lead to astronaut radiation overexposure during maintenance operations at the power production site.

Loss of communication with the reactor will prevent control of the reactor by external commands.

Excessive positive reactivity insertions will lead to a reactor excursion and the destruction of the core. An unplanned negative reactivity insertion will result in a loss of power and possibly shutdown. These events may occur as a result of system degradation.

Loss of power to buses will result in loss of safety function and possibly, an uncontrolled reactor.

A meteoroid impact may result in an unsafe impact environment. Meteors typically impact at speeds from 1 km/sec to 72 km/sec (Ref. V-3). Damage to the reactor may range from small punctures of a coolant loop to complete destruction of the power system with subsequent dispersal of the reactor core materials.

The above accidents have been lumped together into the five accidents shown in Figure 6-16. Most of the above accidents will result in hazardous conditions should reactor control or decay heat removal fail. Fuel cladding failure as shown in Figure 6-16 represents fuel pin failure during normal operation and not as a result of reactor control failure or a loss of coolant accident. Also shown in the figure is the consequences to the habitat of a failure of the reactor, loss of power to the habitat. Primary power to the habitat will be lost whenever the nuclear power system is shut down.

<u>Disposal</u>

Three alternate fuel disposal schemes have been identified: 1) disposal in place on the moon, 2) disposal on the moon away from the power production area, and 3) insertion into a parabolic escape orbit. Potential accidents for these options have been separated and are listed in tabular form.

The disposal in place option would have the reactor shut down and left in place in the power production area. Potential accidents for this disposal strategy are listed in Table 6-11. Failure of the reactor to shutdown at end of life will result in reactor operation with unpredictable performance. The reliability and effectiveness of safety systems and functions would be unknown. Failure of the reactor system to provide for permanent shutdown may

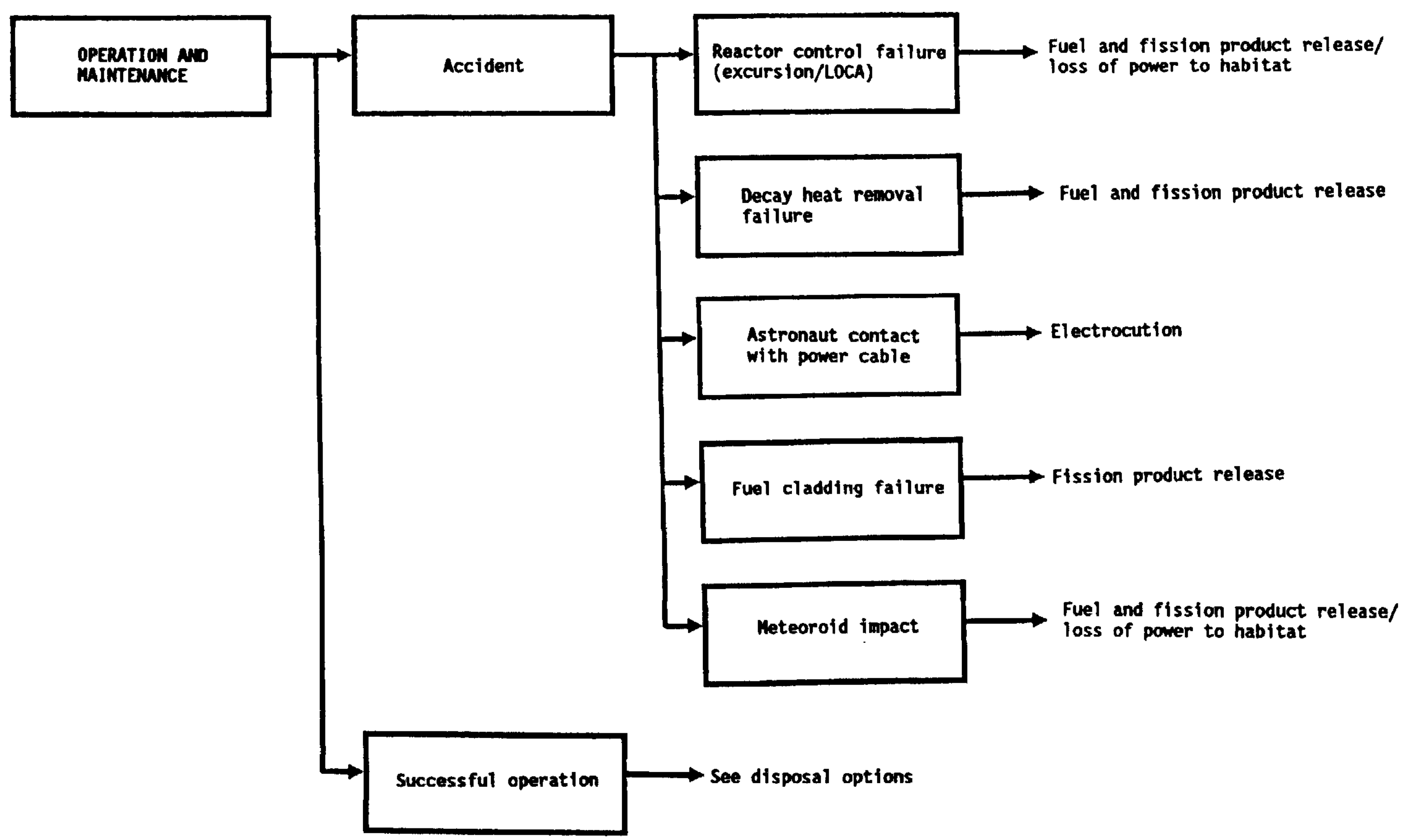

Figure 6-16 Simplified Event Tree for the Lunar Mission Phase Operation and Maintenance

Table 6-11
Disposal In Place Phase Accidents and Resulting Hazards

Accident	Hazard
Failure to shutdown permanently at end of life	Radiation to astronaut
Loss of decay heat removal	Release of fission products
Unrestricted access to site	Radiation to astronaut
Containment failure	Contamination of regolith
Micrometeor impact	Fission product release

allow an extended period of cycles of low power reactor operation as the fission products buildup and decay. This could result in radiation exposure during disposal operations, see Figure 6-17. Subsequent to shutdown, decay heat must be removed until the heat generation level has sufficiently decayed to the point where loss of a decay heat removal system will not lead to breach of cladding and the release of fission products.

Depending upon the emplacement scheme, the reactor may present a radiation hazard. An emplacement scheme which uses distance for shielding (e.g., an unshielded reactor in a crater) may require distance for shielding of the disposed reactor. Unrestricted access to the reactor may result in radiation overexposure to an astronaut.

The reactor will be exposed to the lunar environment for a significantly long period of time. Containment may be breached by material failure due to interaction with the lunar environment or due to meteor impact. Fission products may be released.

Disposal on the moon away from the power production area may potentially experience the accidents listed in Table 6-12. The accidents and resulting hazards are the same as for the disposal in place option with the exception of transportation accidents. The reactor may be dropped during handling and the transport cart may roll over. These accidents will involve low speed impacts which may lead to fission product release depending upon the condition of the reactor, see Figure 6-18.

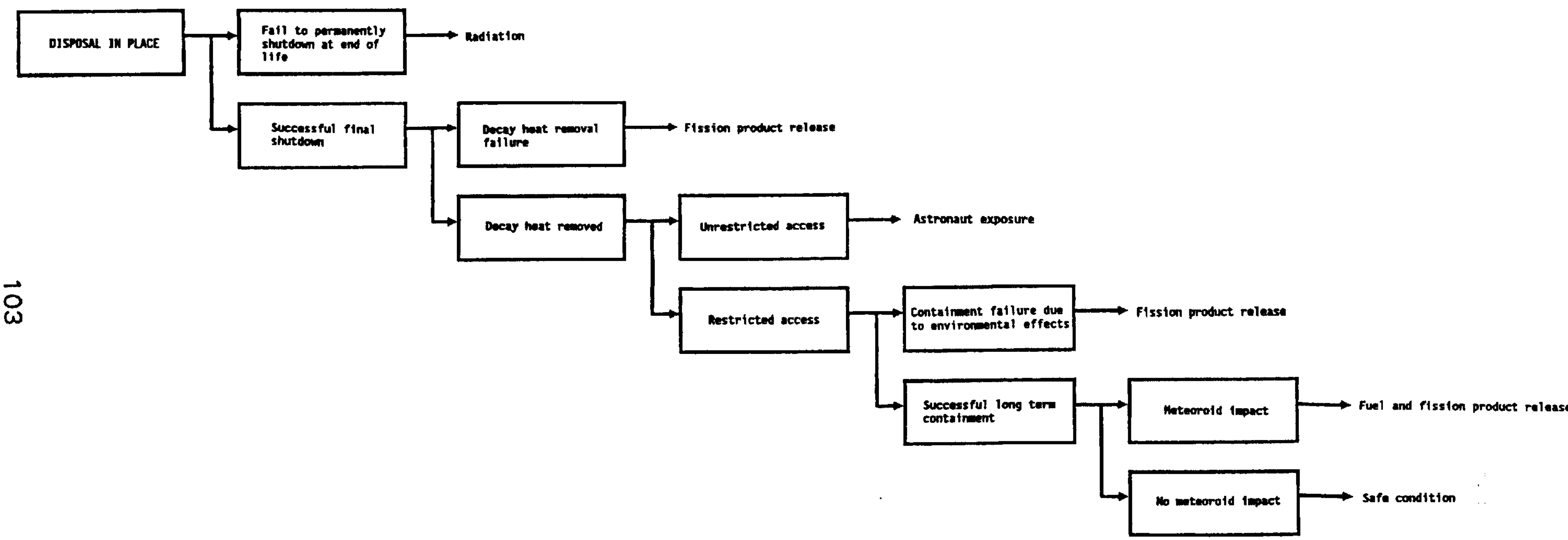

Figure 6-17 Simplified Event Tree for the Lunar Mission Phase Disposal In Place

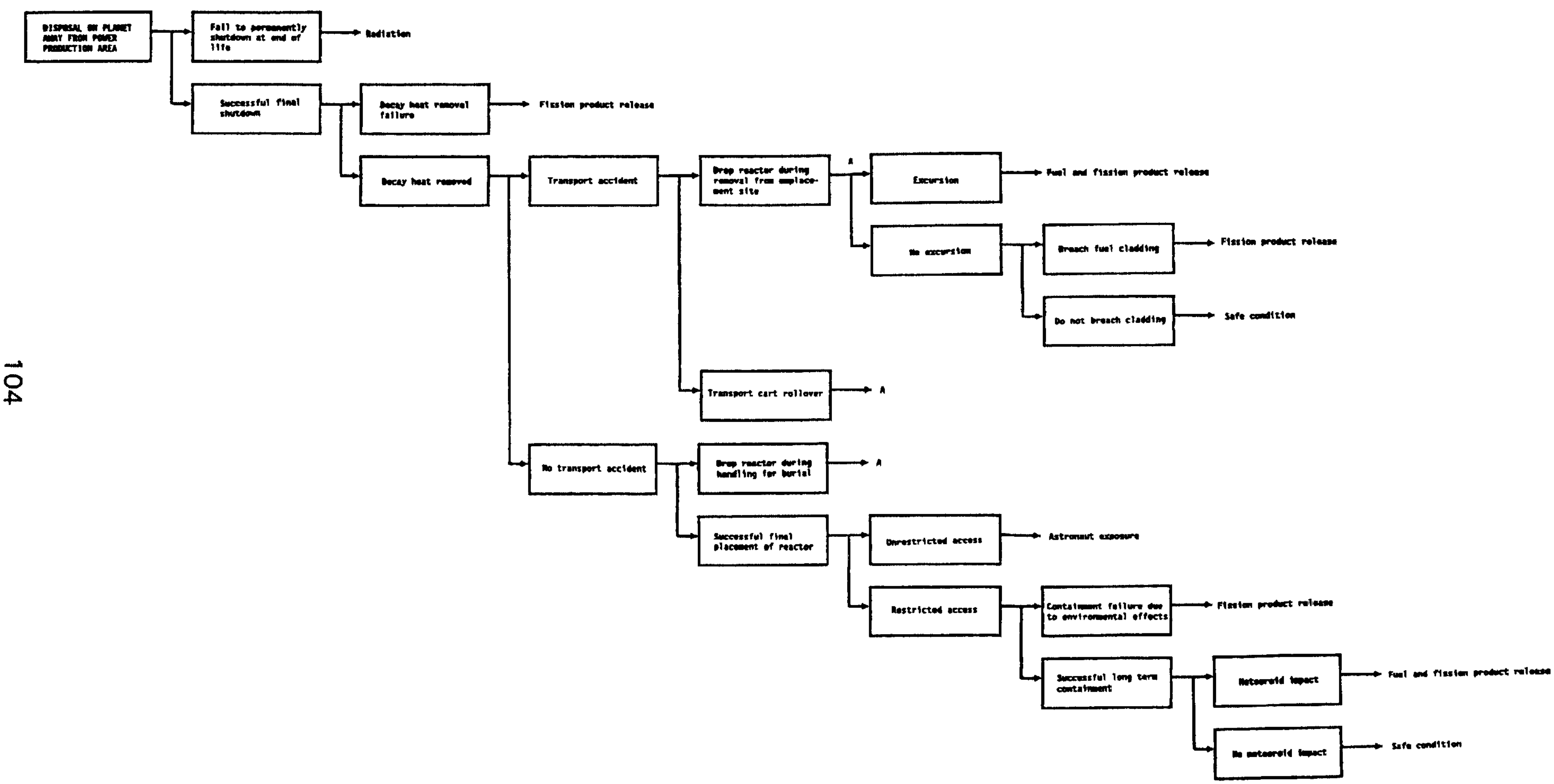

Figure 6-18 Simplified Event Tree for the Lunar Mission Phase Disposal Away From Power Production Area

Table 6-12
Disposal Away From Power Production Area Phase Accidents and Resulting Hazards

Accident	Hazard
Failure to shutdown permanently at end of life	Radiation to astronaut
Loss of decay heat removal	Release of fission products
Drop reactor	Release of fission products
Transport cart rollover	Release of fission products
Unrestricted access to site	Radiation to astronaut
Containment failure	Contamination of regolith
Meteor impact	Fission product release

Disposal by means of insertion into a parabolic escape trajectory would involve launching the reactor by lunar excursion vehicle. Representative accidents are listed in Tables 6-13 and 6-14. In addition to the accidents common to the previous disposal strategies, accidents involving the lunar excursion vehicle will be possible. Potential accidents associated with the separation of the reactor with booster from the lunar excursion vehicle are introduced. The booster will add to the lunar excursion vehicle accidents and consequences. These additional accidents and consequences are lumped with the lunar excursion vehicle failure and consequences because the booster was assumed to be a similar LO_2 and LH_2 propulsion system. Failure of the lunar excursion vehicle and the disposal booster to separate may lead to the decision to land the lunar excursion vehicle for repair or replacement. A return to the lunar surface would introduce the possibility of lunar excursion vehicle failures and reactor impact during descent. A condensed version of the previous accident and environment table format has been used due to the large number of possible accidents and environments.

The simplified event tree for the option to dispose by parabolic trajectory is shown in Figure 6-19. Contrary to previous event trees, an explosion of the lunar excursion vehicle at launch from the surface of the

Table 6-13
Disposal by Parabolic Trajectory Phase Accidents and Resulting Hazards

Accident	Hazard
Failure to shutdown permanently at end of life	Radiation to astronaut
Loss of decay heat removal	Release of fission products
Drop reactor	Release of fission products
Transport cart rollover	Release of fission products

Table 6-14
Disposal by Parabolic Trajectory Phase Accidents and Resulting Reactor Environments

Accident	Reactor Environment
Lunar excursion vehicle failure	Impact Projectiles Explosion
Collision after separation	Impact Explosion Projectiles
Disposal booster failure	Projectiles Stranded in orbit Impact Explosion

moon was assumed to lead to fission product release regardless of whether a reactor excursion occurred or not since the reactor had operated for its lifetime. The consequences of impacting the surface of the moon after LEV failure would depend on the altitude at the moment of LEV failure. As such, allowance was made for an impact without damage to the reactor.

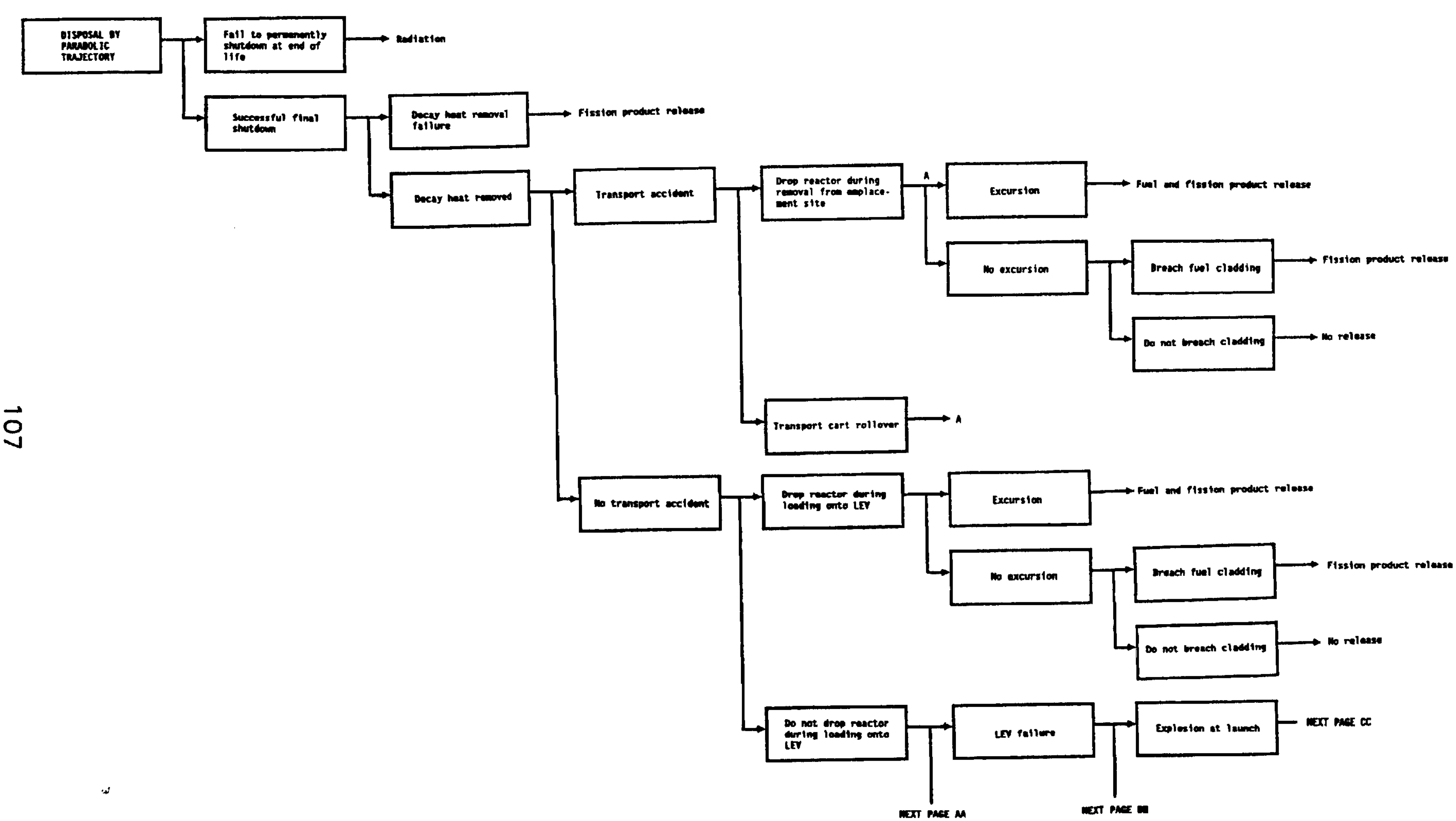

Figure 6-19 Simplified Event Tree for the Lunar Mission Phase Disposal by Parabolic Trajectory

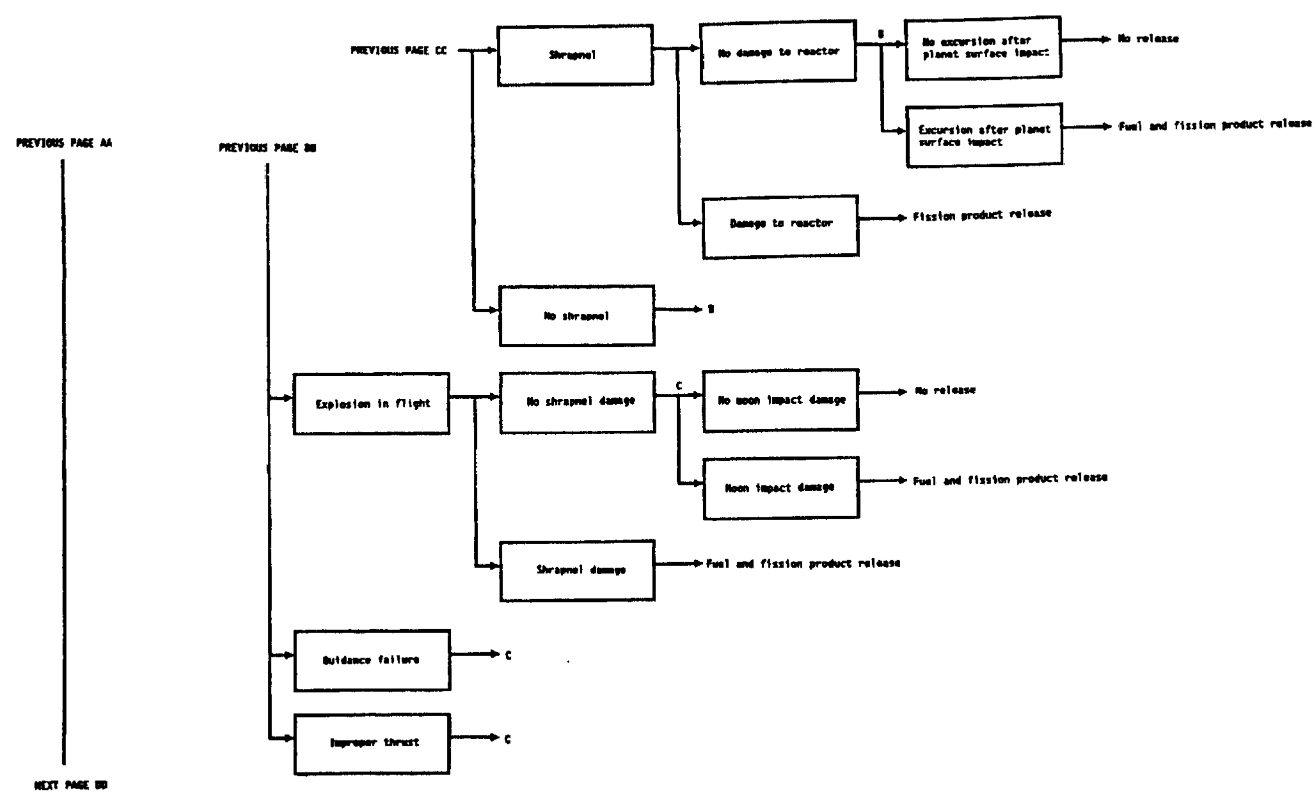

Figure 6-19 Simplified Event Tree for the Lunar Mission Phase Disposal by Parabolic Trajectory (cont.)

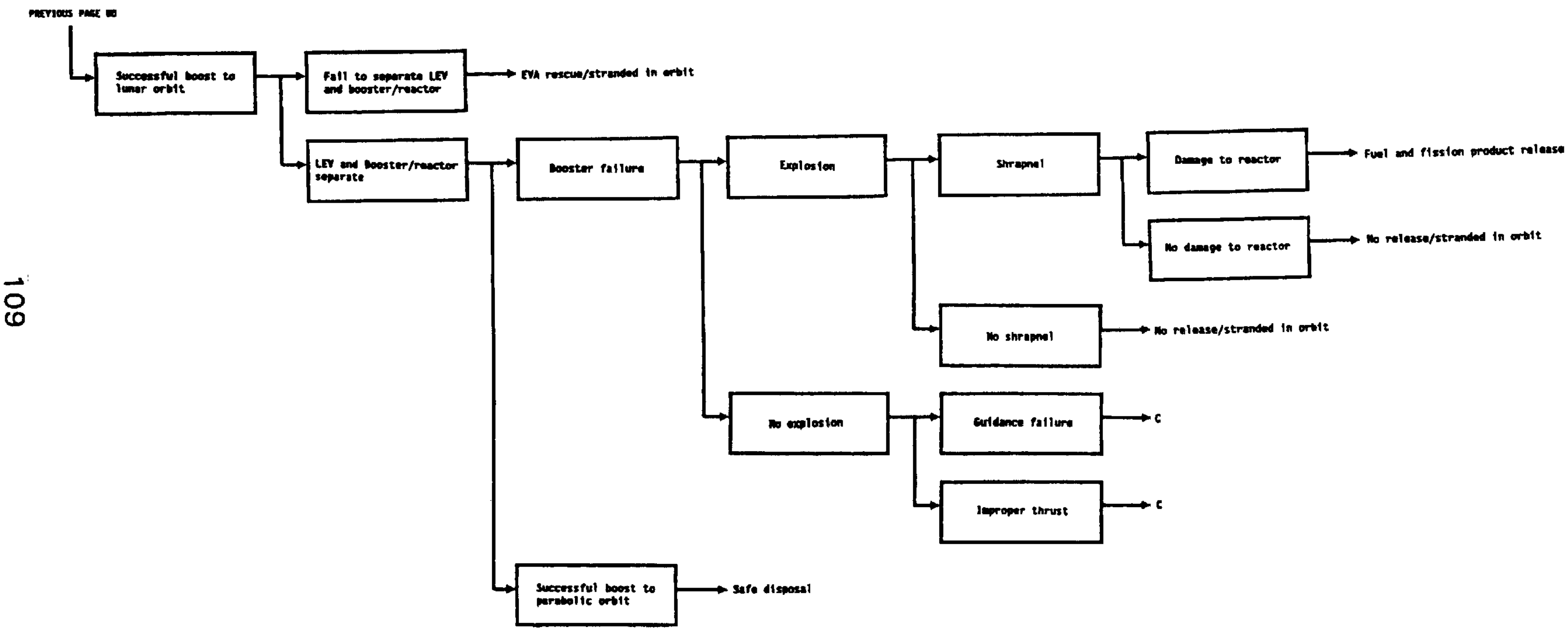

Figure 6-19 Simplified Event Tree for the Lunar Mission Phase Disposal by Parabolic Trajectory (cont.)

6.2 MARTIAN OUTPOST

Pre-launch

For the purposes of this study, the accidents and nuclear power system environments for this phase of the martian mission has been assumed to be the same as the corresponding lunar mission phase, see section 6.1. For purposes of brevity, the simplified event tree constructed for this mission phase has not been included. The reader may use the corresponding simplified event tree for the lunar mission. The same step has been taken for other Mars mission phases where the lunar and Mars simplified event trees are indistinguishable.

Launch to Low Earth Orbit

For the purposes of this study, the accidents and reactor environments for this phase of the martian mission has been assumed to be the same as the corresponding lunar mission phase for an expendable launch vehicle, see section 6.1. The corresponding simplified event tree is shown in Figure 6-20.

Low Earth Orbit Space Vehicle Assembly

For the purposes of this study, the accidents and reactor environments for this phase of the martian mission has been assumed to be the same as the corresponding lunar mission phase for an expendable launch vehicle, see section 6.1. The corresponding simplified event trees are shown in Figures 6-21, 6-22, 6-23 and 6-24. A direct launch to Mars was assumed only with chemical rocket propulsion since launch from earth with a nuclear rocket propulsion system appears to be unacceptable to the general public.

Trans-Mars Orbit Insertion

For the purposes of this study, the accidents and reactor environments for this phase of the martian mission has been assumed to be the same as the corresponding lunar mission phase for a LO_2 and LH_2 fueled expendable launch vehicle (ALS), see section 6.1. The corresponding simplified event tree for a LO_2/LH_2 propelled transfer vehicle is shown in Figure 6-25.

Nuclear thermal propulsion will likely involve the use of liquid hydrogen as a propellant. Failures of the nuclear thermal booster did not include an explosion of the system since there will be no oxygen available in the vicinity of the liquid hydrogen. As such, the simplified event tree in Figure 6-26 for nuclear thermal propulsion is the same as for chemical propulsion with the exception of no explosion of the nuclear propulsion system. Failures were limited to guidance failure and improper thrust. Due to the short time the nuclear booster would be thrusting, on the order of tens of minutes, guidance failures and incorrect thrust levels have been assumed to result in similar circumstances.

The use of nuclear electric propulsion may eliminate some of the potential accidents and resulting environments found with chemical and nuclear thermal boosters. Guidance failures and improper thrust levels are treated

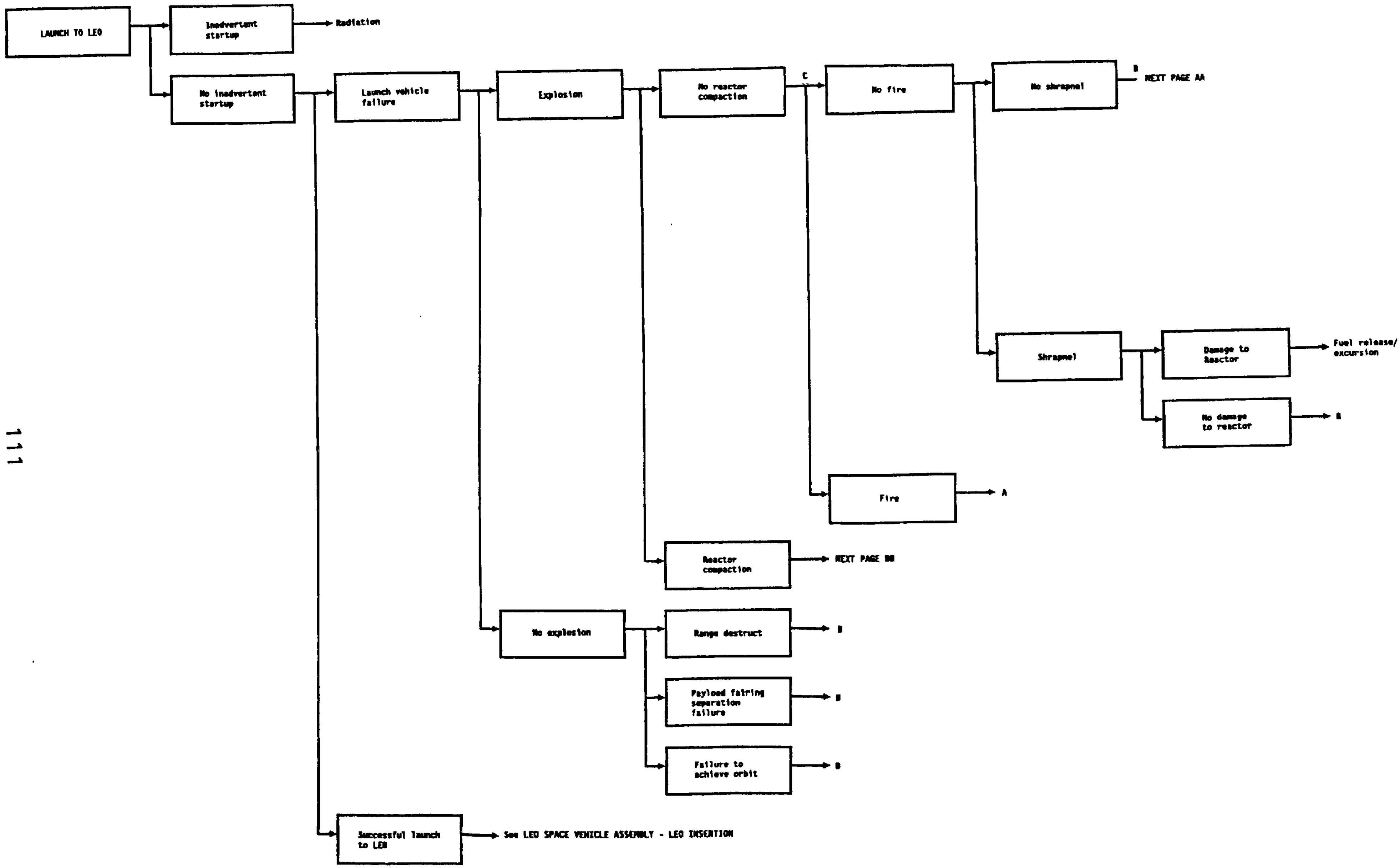

Figure 6-20 Simplified Event Tree for the Mars Mission Phase Launch to Low Earth Orbit

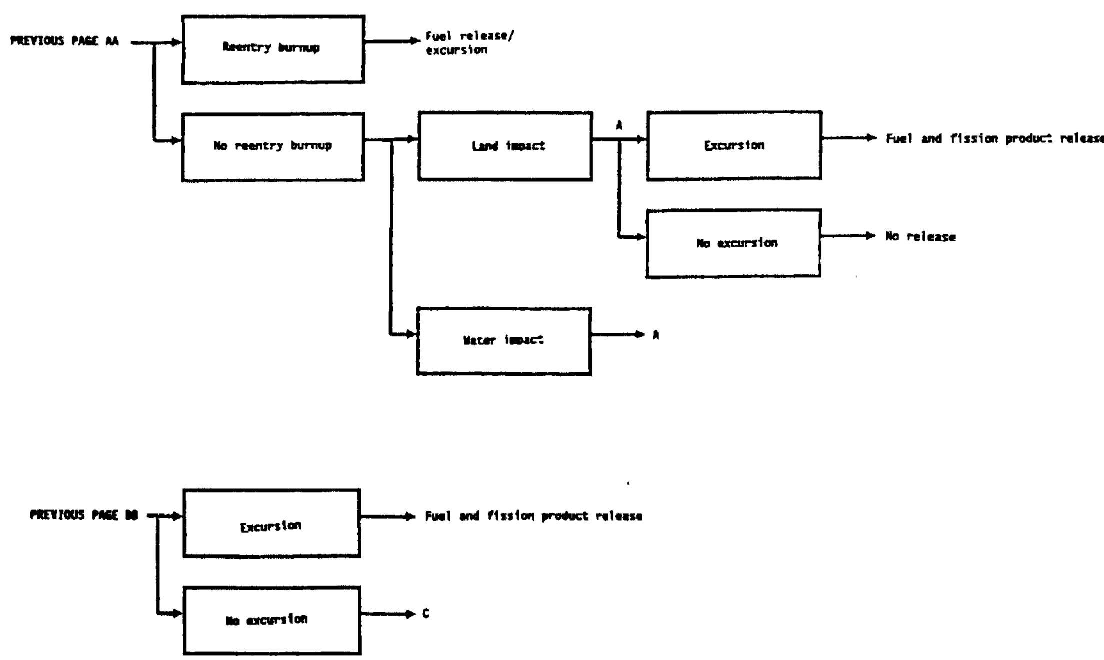

Figure 6-20 Simplified Event Tree for the Mars Mission Phase Launch to Low Earth Orbit (cont.)

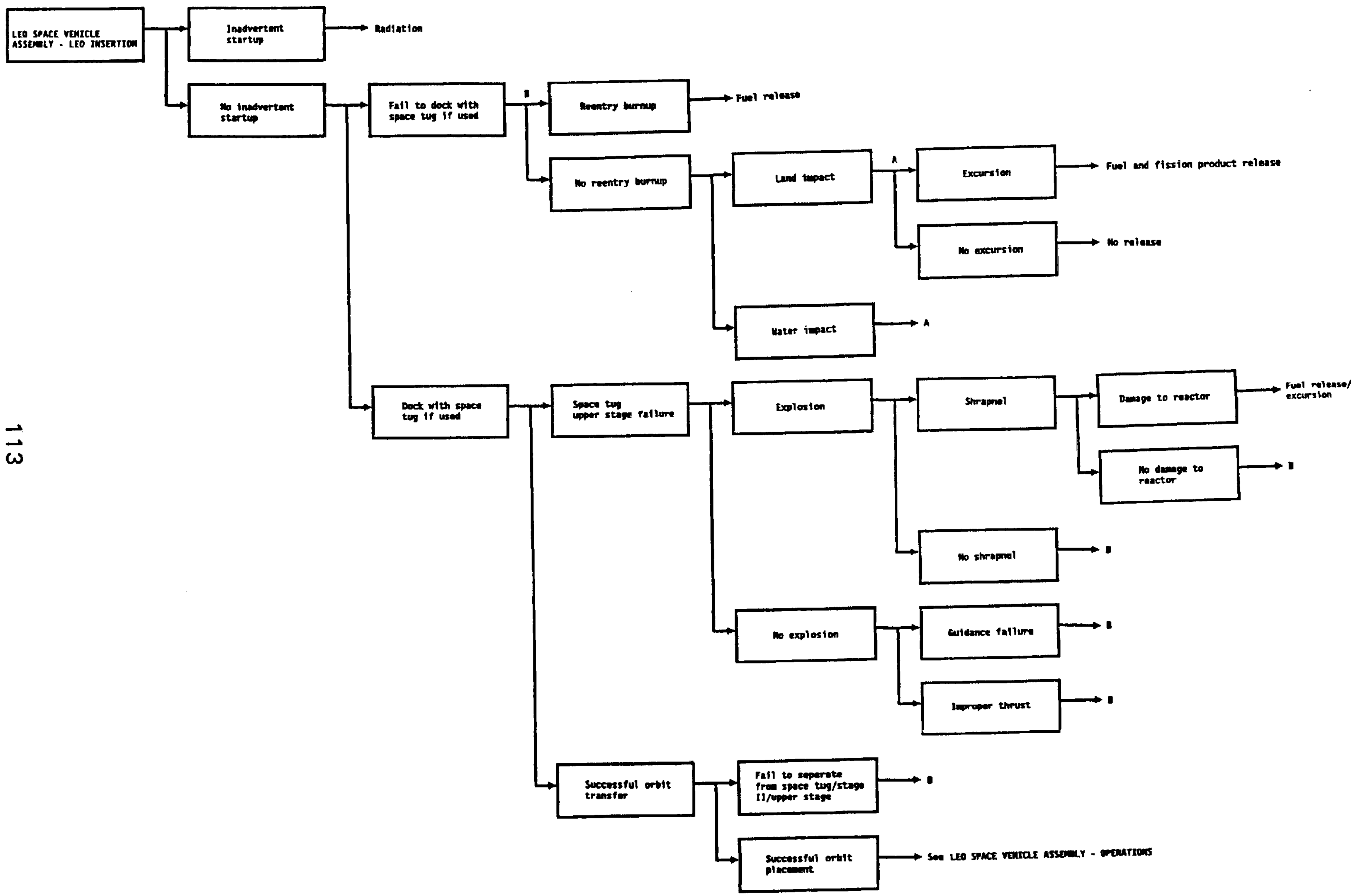

Figure 6-21 Simplified Event Tree for the Mars Mission Phase Low Earth Orbit Space Vehicle Assembly - LEO Insertion

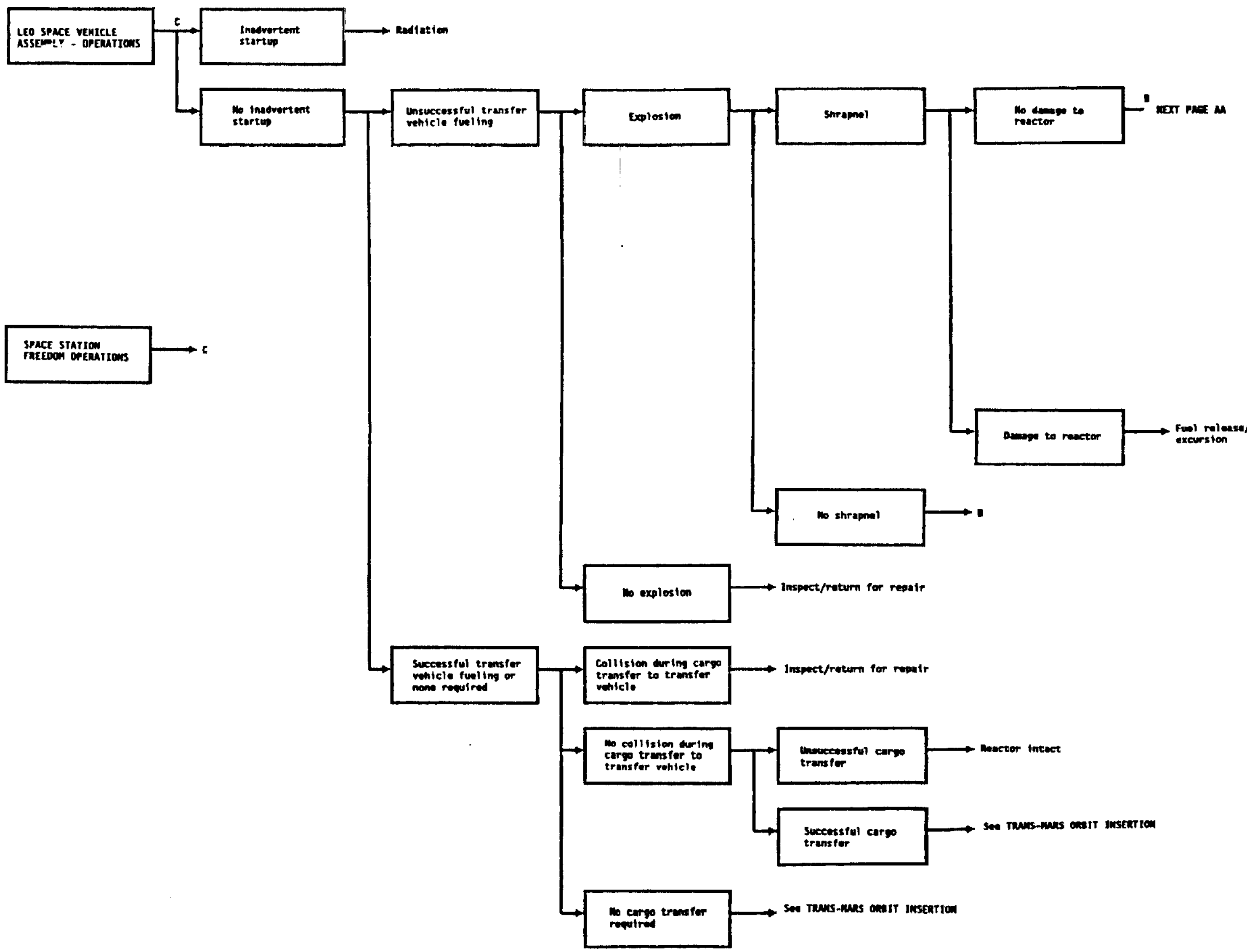

Figure 6-22 Simplified Event Tree for the Mars Mission Phase Low Earth Orbit Space Vehicle Assembly - Operations

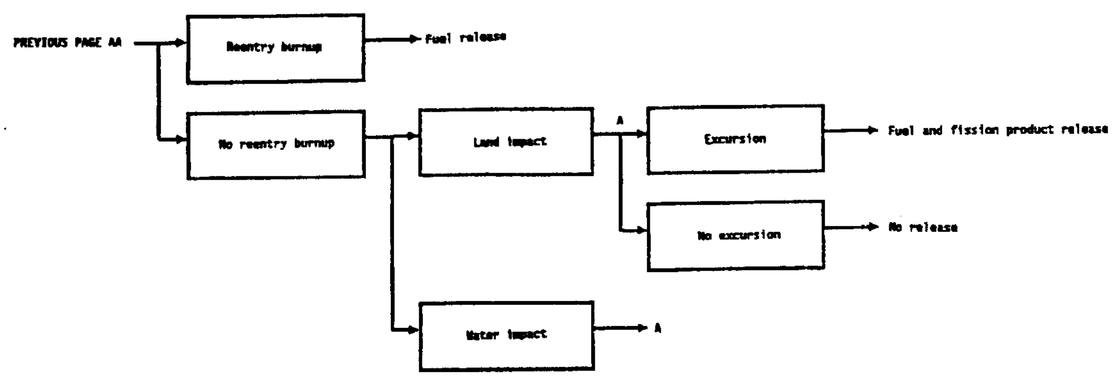

Figure 6-22 Simplified Event Tree for the Mars Mission Phase Low Earth Orbit Space Vehicle Assembly - Operations (cont.)

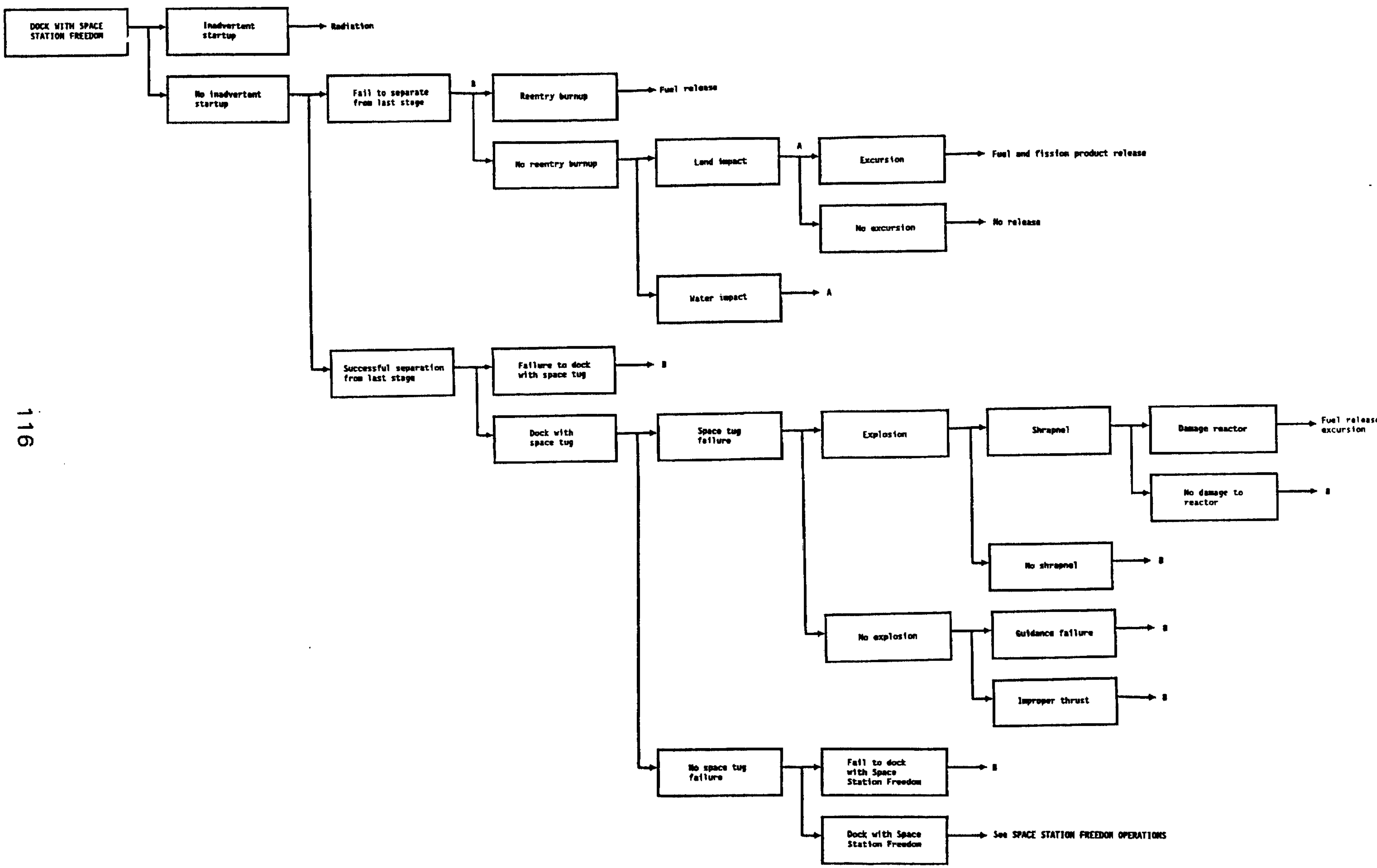

Figure 6-23 Simplified Event Tree for the Mars Mission Phase Dock With Space Station Freedom

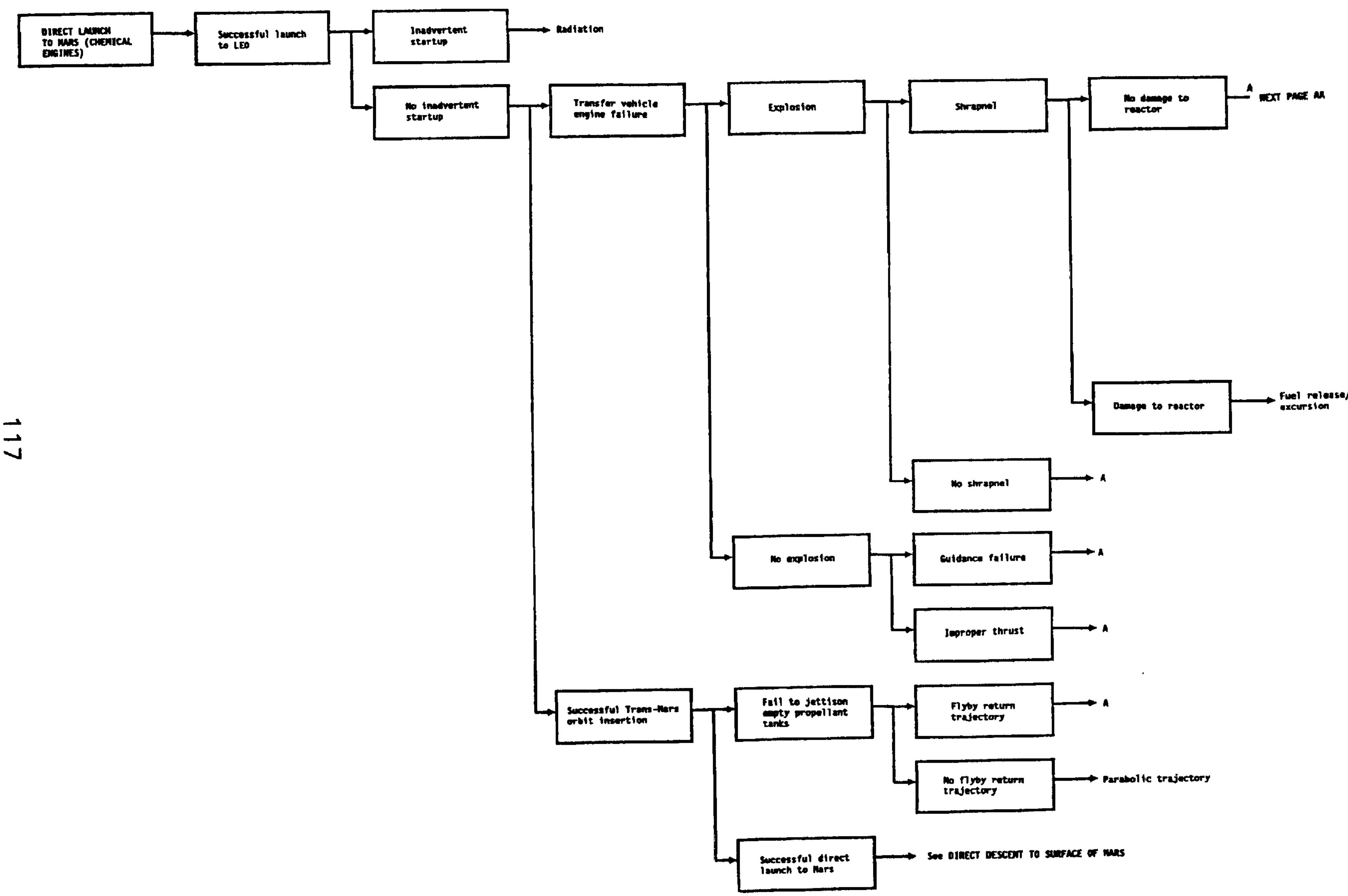

Figure 6-24 Simplified Event Tree for the Mars Mission Phase Direct Launch To Mars

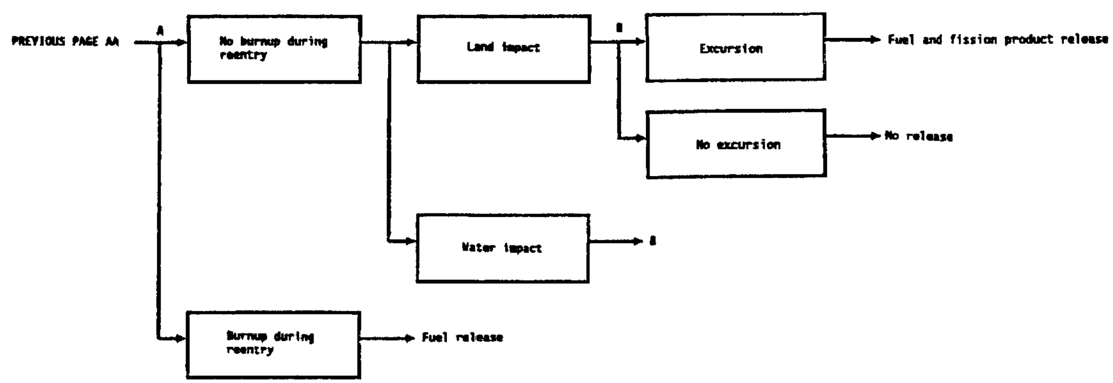

Figure 6-24 Simplified Event Tree for the Mars Mission Phase Direct Launch to Mars (cont.)

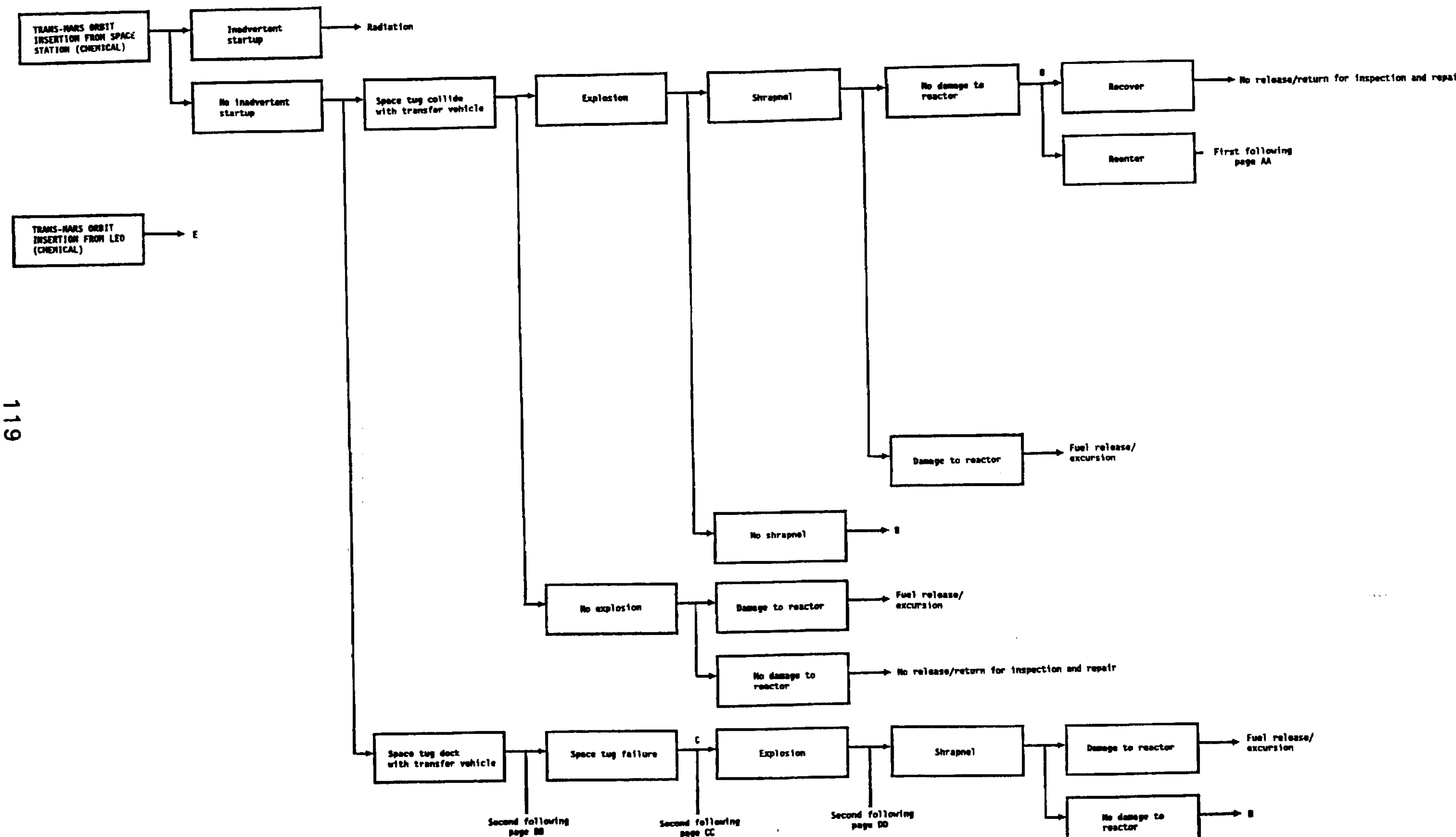

Figure 6-25 Simplified Event Tree for the Mars Mission Phase Trans-Mars Orbit Insertion (By Chemical Rocket)

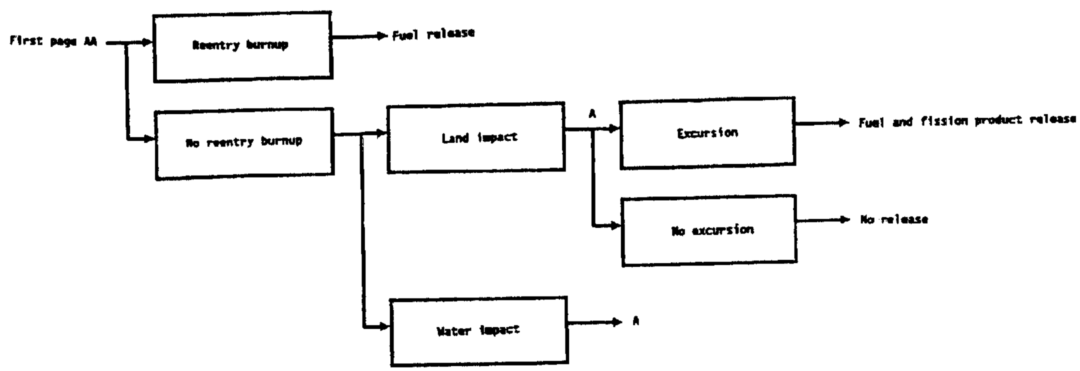

Figure 6-25 Simplified Event Tree for the Mars Mission Phase Trans-Mars Orbit Insertion (By Chemical Rocket) (cont.)

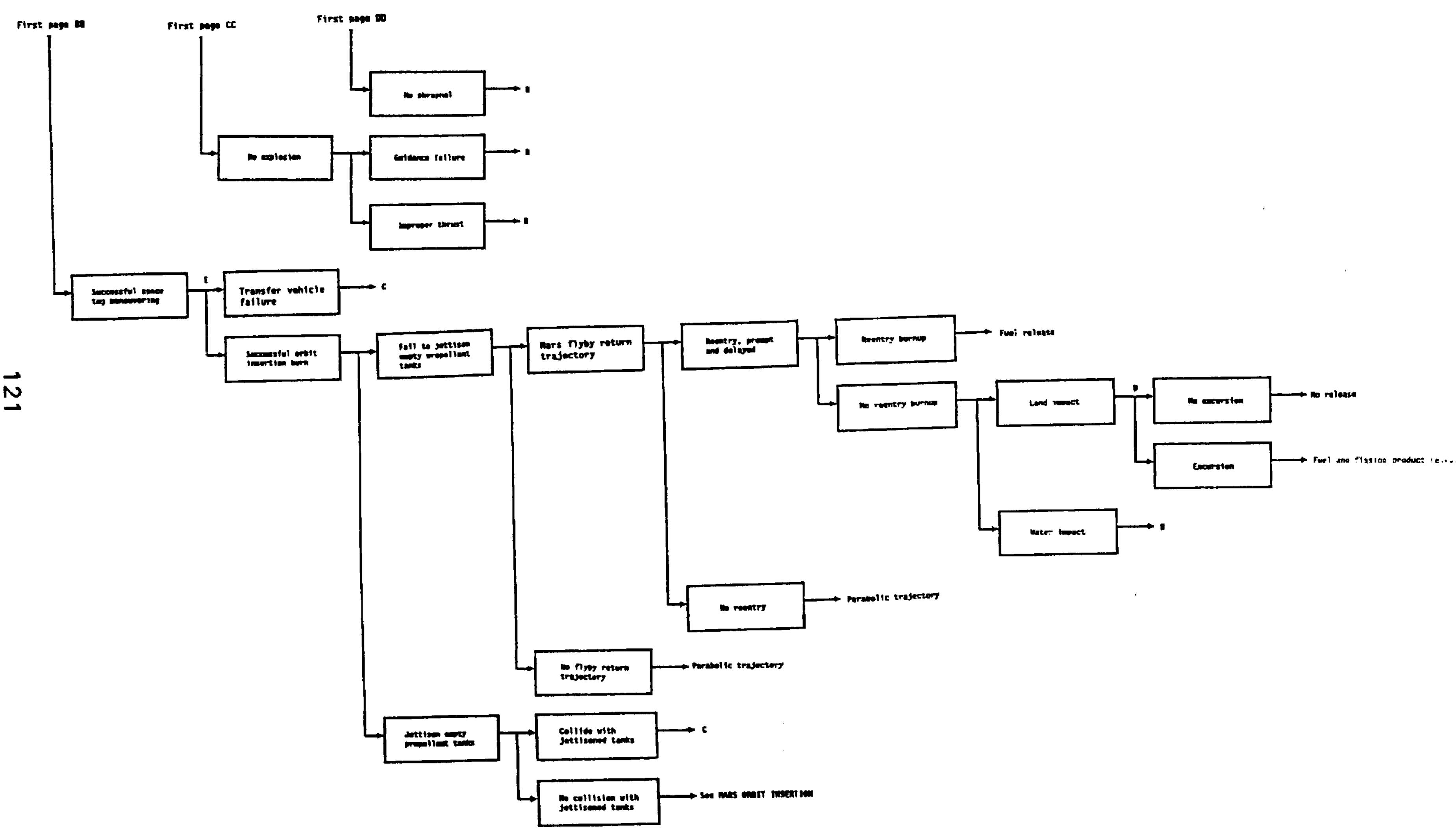

Figure 6-25 Simplified Event Tree for the Mars Mission Phase Trans-Mars Orbit Insertion (By Chemical Rocket) (cont.)

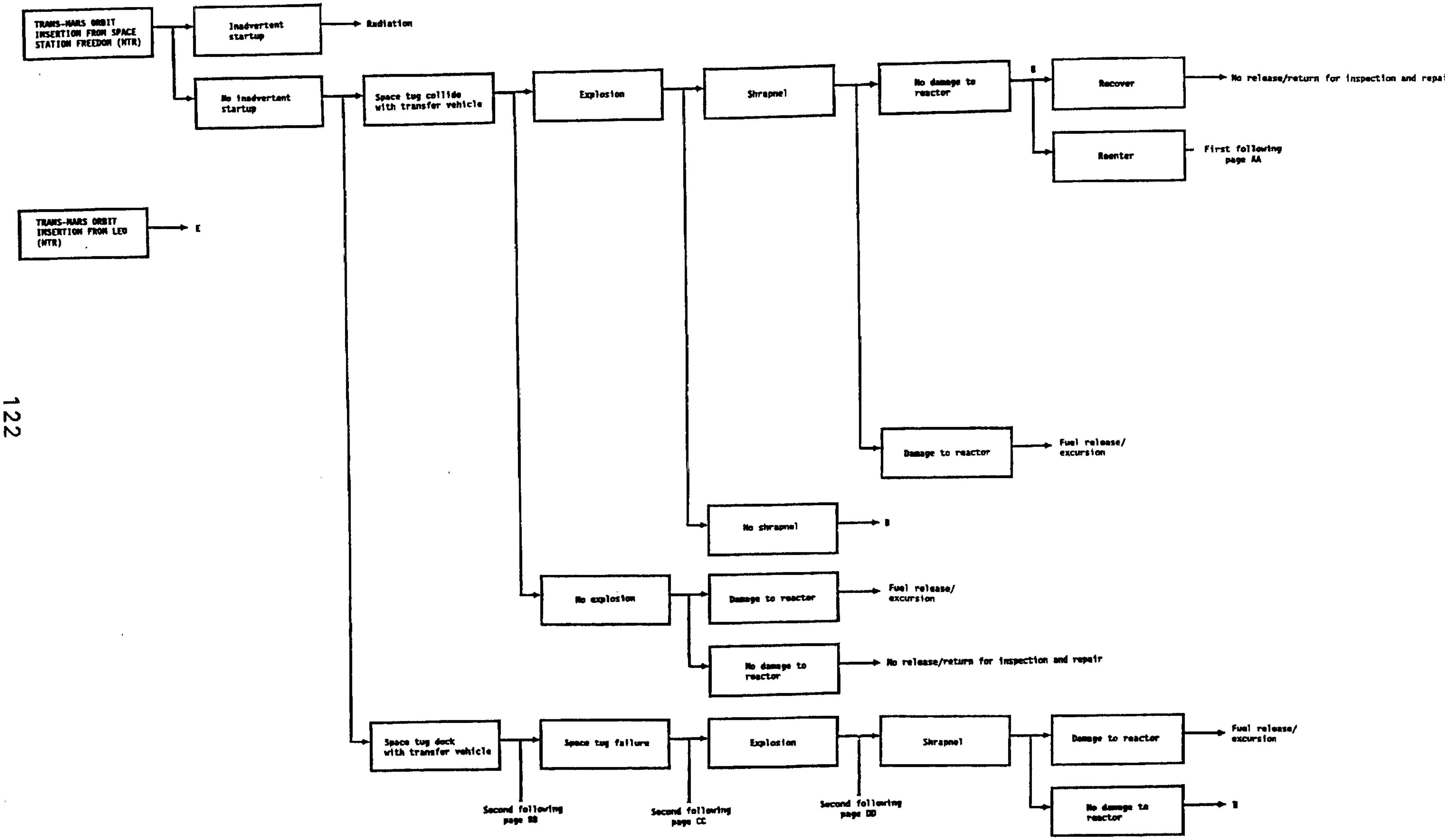

Figure 6-26 Simplified Event Tree for the Mars Mission Phase Trans-Mars Orbit Insertion (By Nuclear Thermal Rocket)

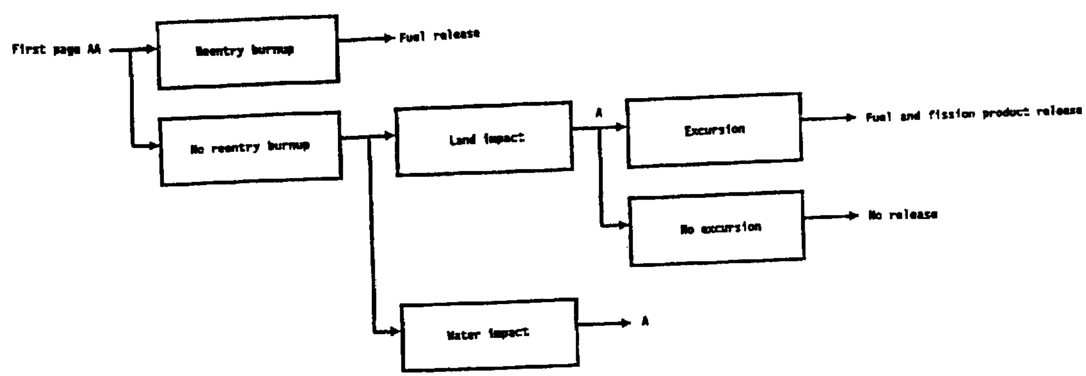

Figure 6-26 Simplified Event Tree for the Mars Mission Phase Trans-Mars Orbit Insertion (By Nuclear Thermal Rocket) (cont.)

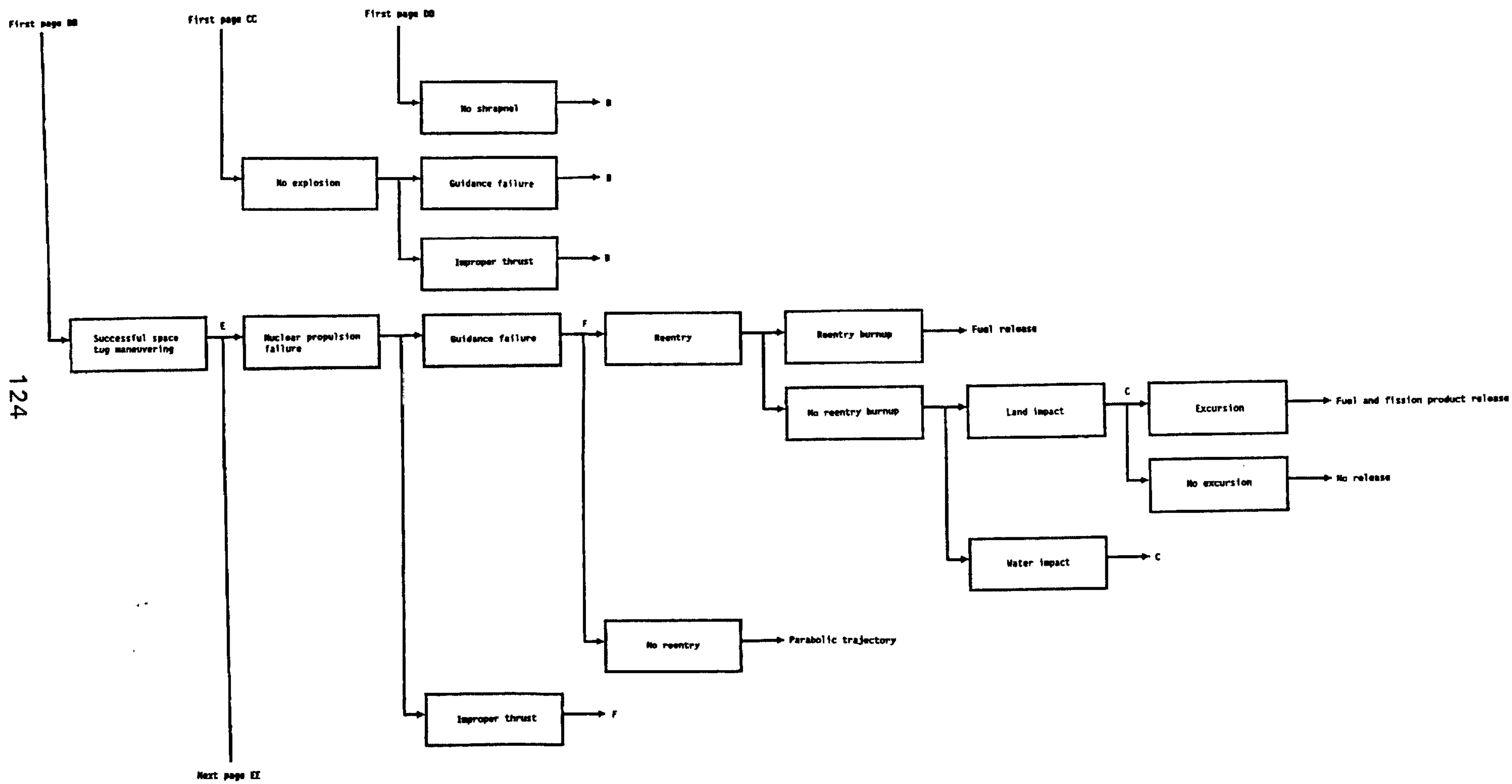

Figure 6-26 Simplified Event Tree for the Mars Mission Phase Trans-Mars Orbit Insertion (By Nuclear Thermal Rocket) (cont.)

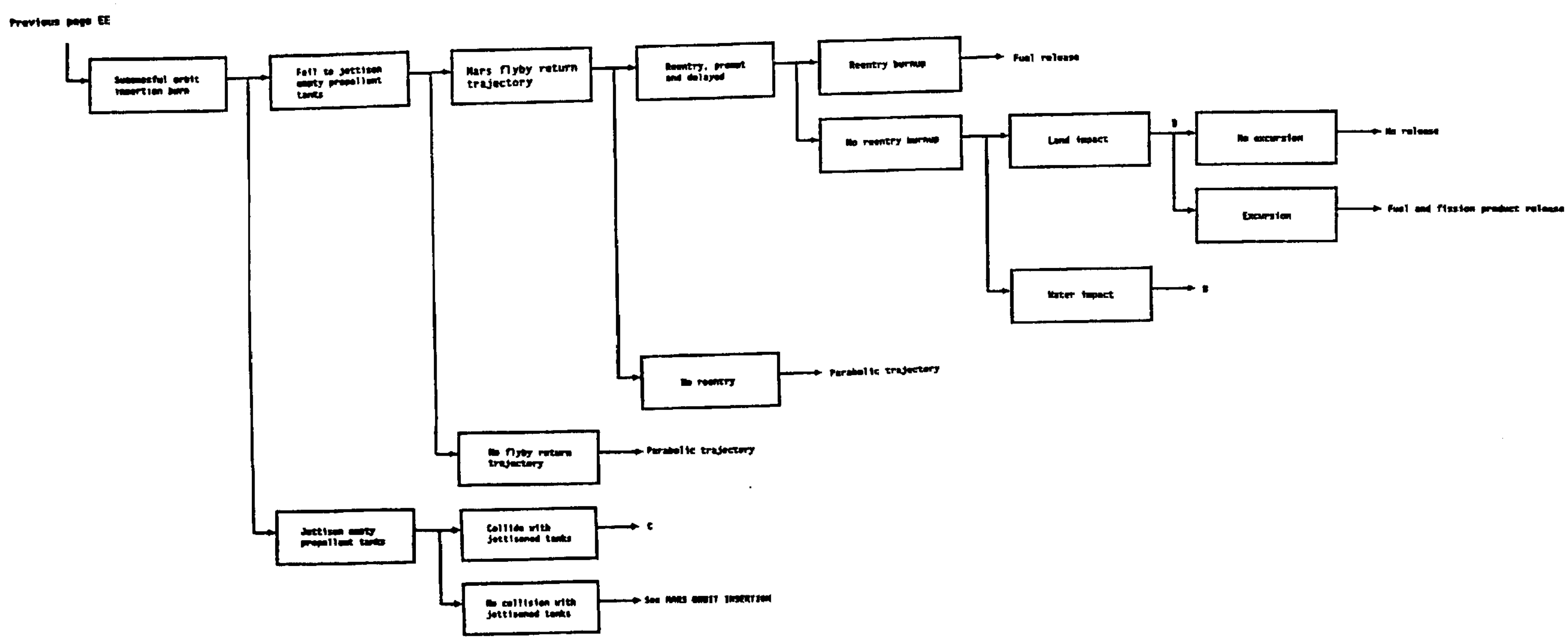

Figure 6-26 Simplified Event Tree for the Mars Mission Phase Trans-Mars Orbit Insertion (By Nuclear Thermal Rocket) (cont.)

differently. The low thrust and long burn times required more readily allow remedial action in the event of a failure, see Figure 6-27. It will however, introduce the potential for impact on the moon during the lunar flyby assumed for this study.

<u>Mars Orbit Insertion</u>

Potential accidents for this phase of a mission to Mars are listed in Table 6-15. The aerobrakes and the requirement that the Mars transfer and

Table 6-15
Mars Orbit Insertion Phase Accidents and Resulting Reactor Environments

Accident	Reactor Environment
Failure to separate	Reentry
Guidance failure	Impact
Aerobrake failure	Impact
Collision of transfer and excursion vehicles	Impact Projectiles Explosion
Failure of transfer and excursion vehicles to rendezvous	Stranded in orbit
Inadvertent reactor startup	Inadequate heat rejection path

excursion vehicles separate prior to orbit insertion increase the possibility for accidents over that of lunar orbit insertion. The simplified event tree for this mission phase where orbit insertion is by aerobrake is shown in Figure 6-28.

The accident failure to separate was assumed to lead to earth reentry due to the return-to-earth flyby trajectory nature of potential trans-Mars orbits. Since the design of the excursion vehicle aerobrake is not defined, the possibility exists that the excursion vehicle aerobrake would not be sufficient for earth orbit insertion and could result in uncontrolled reentry.

Orbit insertion guidance and aerobrake structural failures could result in the excursion vehicle impacting the surface of Mars The atmosphere of Mars is very thin compared to that of earth (see Appendix) and thus will not

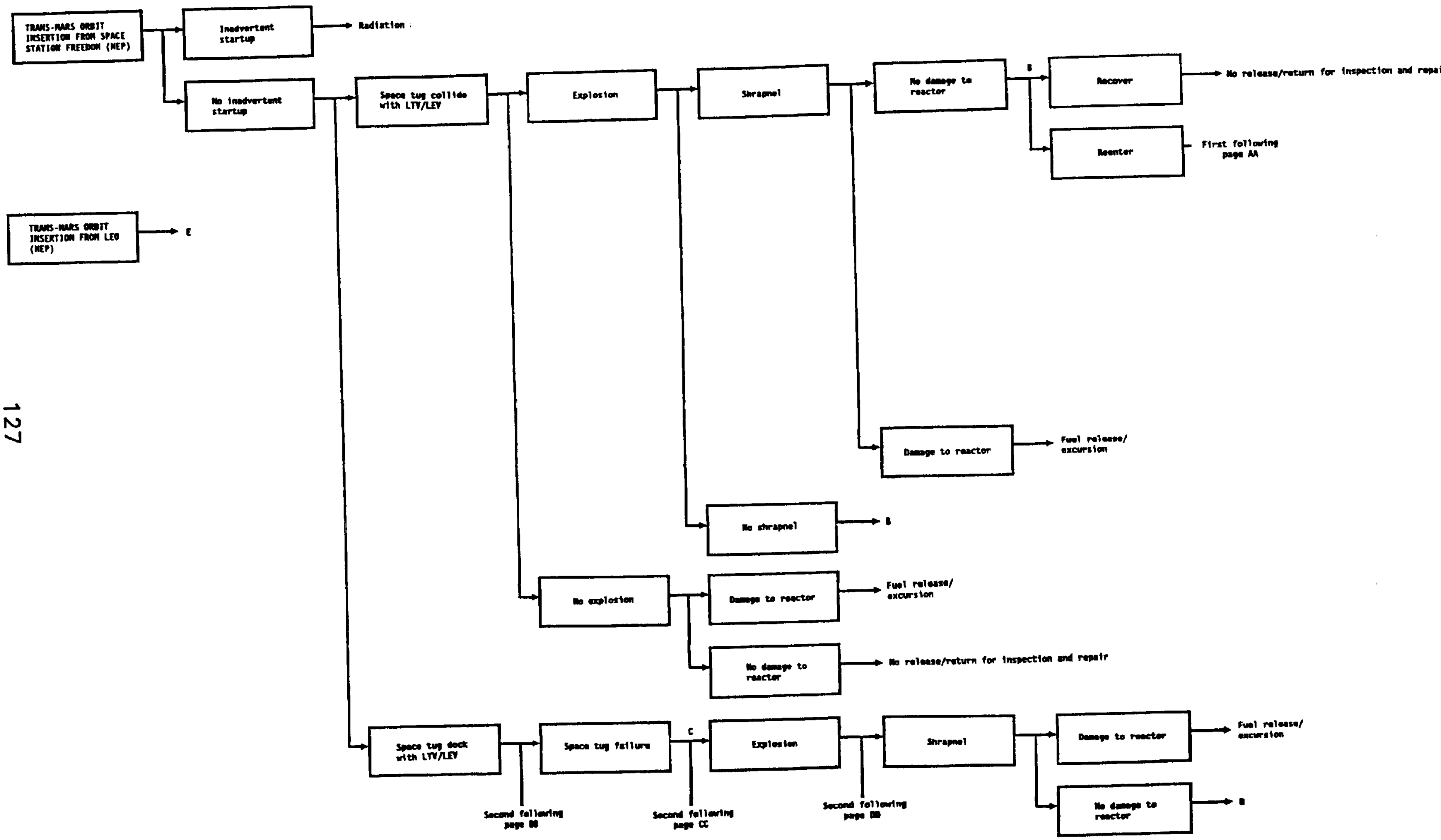

Figure 6-27 Simplified Event Tree for the Mars Mission Phase Trans-Mars Orbit Insertion (By Nuclear Electric Propulsion)

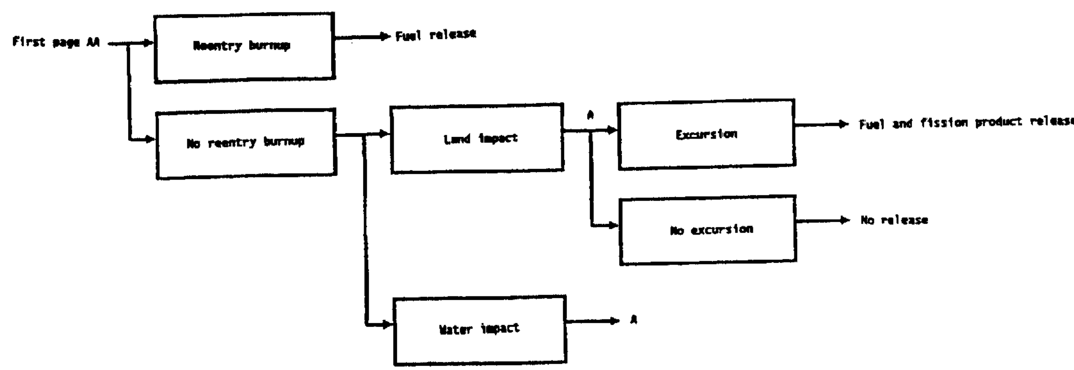

Figure 6-27 Simplified Event Tree for the Mars Mission Phase Trans-Mars Orbit Insertion (By Nuclear Electric Propulsion) (cont.)

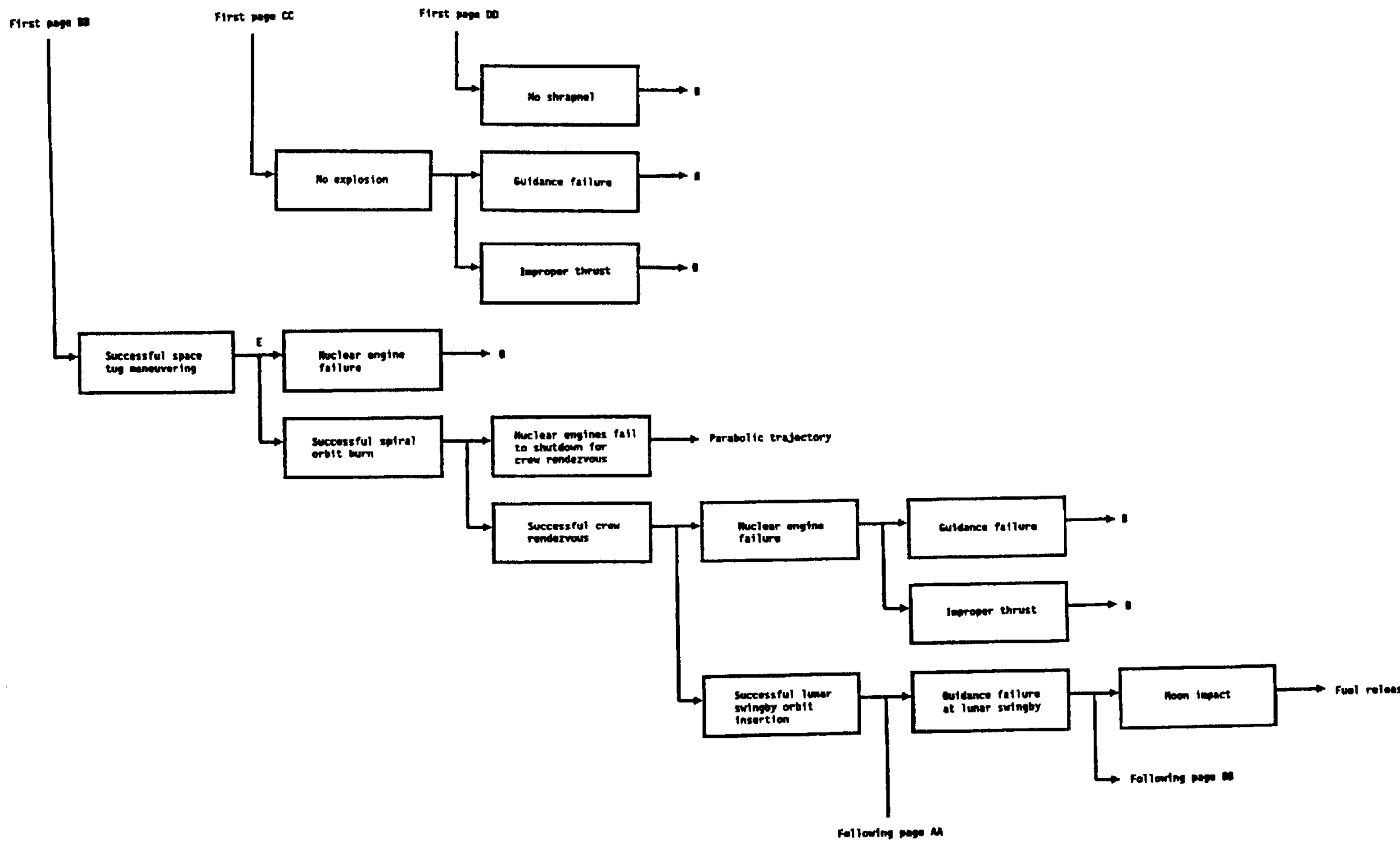

Figure 6-27 Simplified Event Tree for the Mars Mission Phase Trans-Mars Orbit Insertion (By Nuclear Electric Propulsion) (cont.)

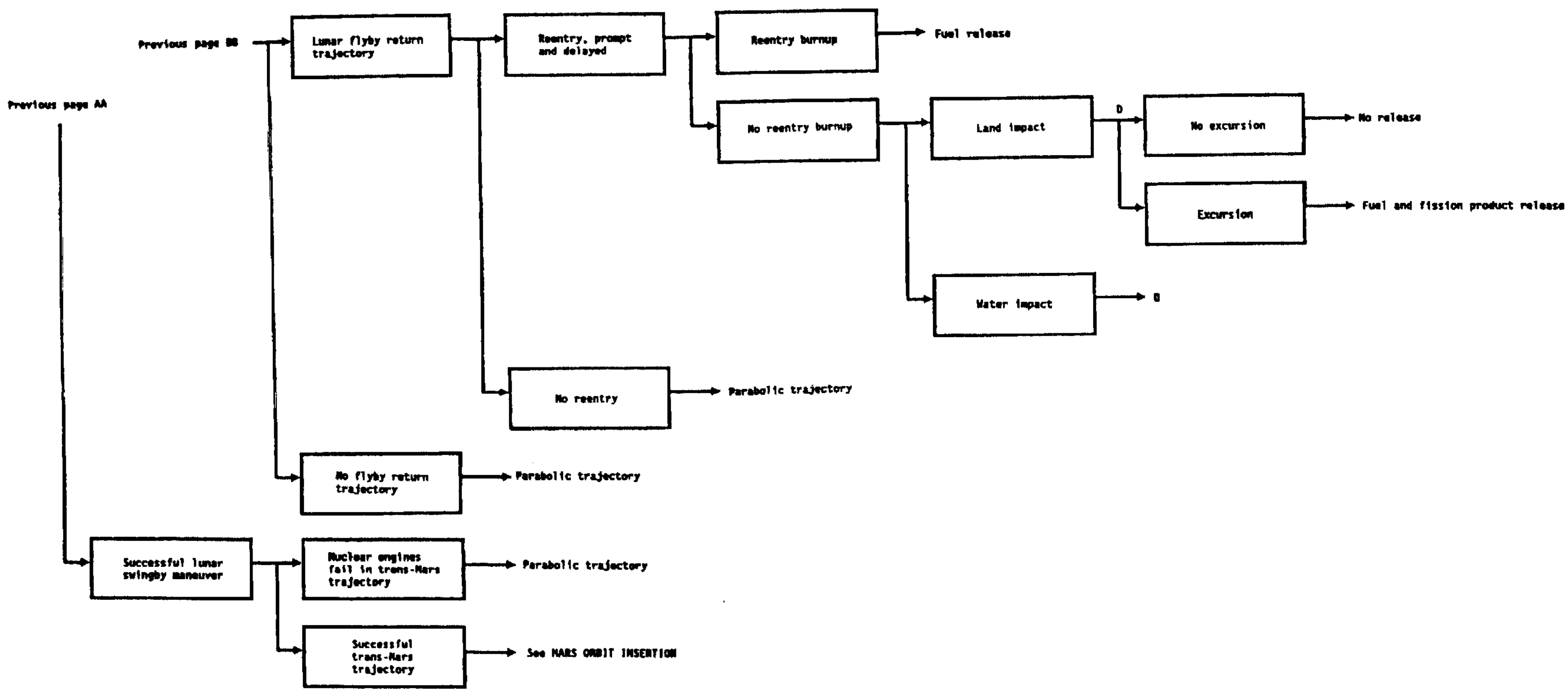

Figure 6-27 Simplified Event Tree for the Mars Mission Phase Trans-Mars Orbit Insertion (By Nuclear Electric Propulsion) (cont.)

provide a similar reentry drag environment. An impact on the surface of Mars may result in the complete destruction of the reactor.

A collision of the transfer and excursion vehicles during the rendezvous maneuver may result in reactor impact with structural components of the vehicles and other cargo and, possibly, an explosion. Propellant tanks may rupture during the collision yielding a projectile field. A damaged reactor may release fuel and possibly undergo an excursion. The fuel and fission products would be released in orbit and on the surface of Mars if the reactor was to subsequently impact the planet.

A failure to rendezvous has not been listed as a safety-related accident. The excursion vehicle could be left in orbit until the next piloted transfer vehicle arrives or it could be sent to the martian surface as in an unmanned cargo flight. In either case, the reactor would be stored in a safe configuration.

An inadvertent reactor startup is possible with the reactor heat rejection system not deployed. As stated previously, a radiation hazard would be created for the flight crew. A fission product inventory would be created which may present a hazard to astronauts during emplacement of the reactor on the surface of Mars.

Mars orbit insertion by nuclear propulsion, thermal or electric, would not be subject to the potential accidents caused by use of the aerobrake maneuver and the subsequent rendezvous, see Figure 6-29. Failures of the nuclear propulsion systems have been limited to guidance and thrust failures since an explosive source is missing. Resultant trajectories will lead to earth reentry if no thrusting occurs and the trans-Mars orbit has a return leg which intersects the earth, surface impact on Mars, and parabolic orbits.

A direct descent to the surface of Mars would have the potential for the accidents shown in Figure 6-30. Failures consist primarily of the inability of the transfer and excursion vehicles to separate and the insufficient performance of the descent (excursion) vehicle. If a single transportation vehicle is used, separation failure would be precluded. If the transfer and excursion vehicles did not separate, the transportation vehicles and payload may return to earth on a flyby trajectory. An explosion of the descent vehicle may lead to fuel release and possibly an excursion with the remaining fuel and fission products released upon impact with the surface of Mars.

During this mission phase the excursion and transfer vehicles would rendezvous if such a transport system was used. The simplified event tree for this rendezvous is shown in Figure 6-31. The assumption was made that the excursion vehicle would be fueled with LO_2 and LH_2. Impact on the surface of Mars after an explosion in orbit was assumed not possible since the atmosphere of Mars is too thin to adequately slow down the reactor. The potential reactor configurations after an accident are a safely stowed reactor stranded in orbit, a damaged reactor releasing fuel and possibly fission products, and a reactor operating inadvertently. The stranded, damaged reactor would contaminate the orbit. An operating reactor may be a hazard to the flight

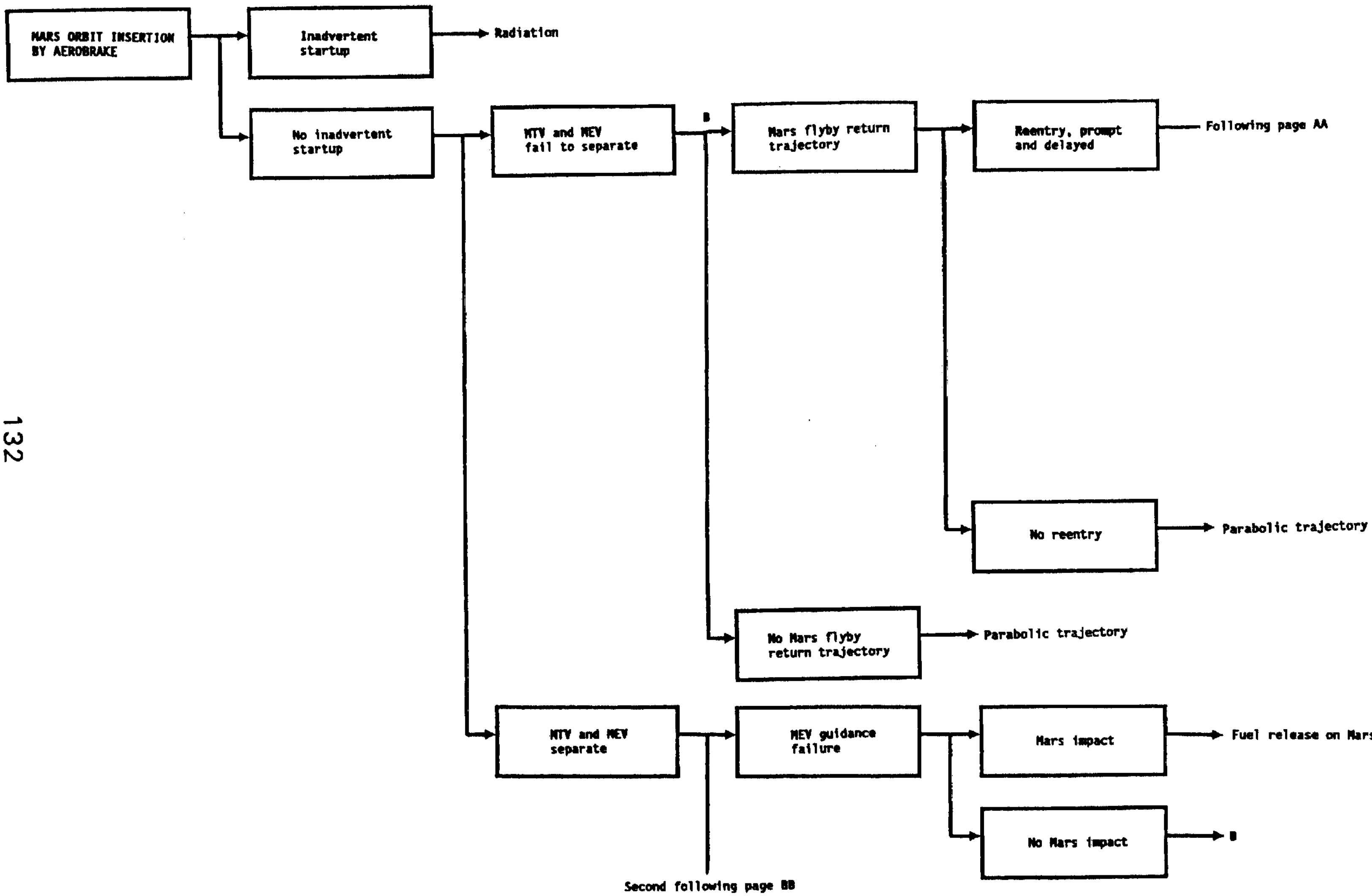

Figure 6-28 Simplified Event Tree for the Mars Mission Phase Mars Orbit Insertion By Aerobrake

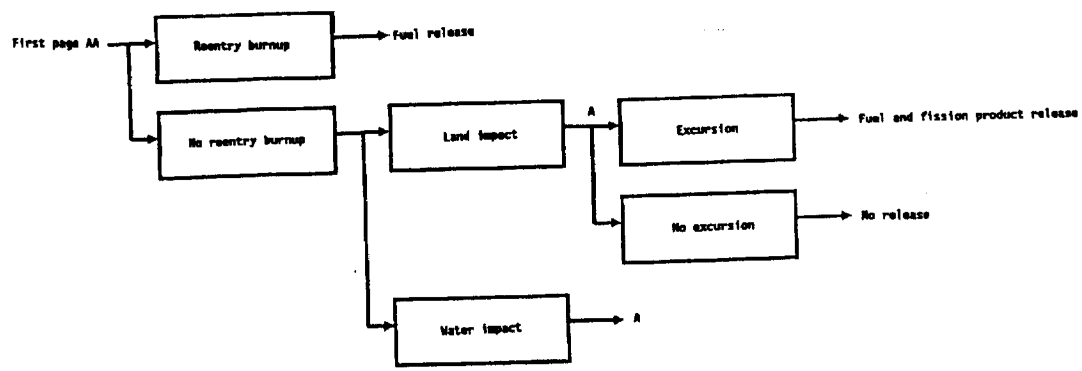

Figure 6-28 Simplified Event Tree for the Mars Mission Phase Mars Orbit Insertion By Aerobrake (cont.)

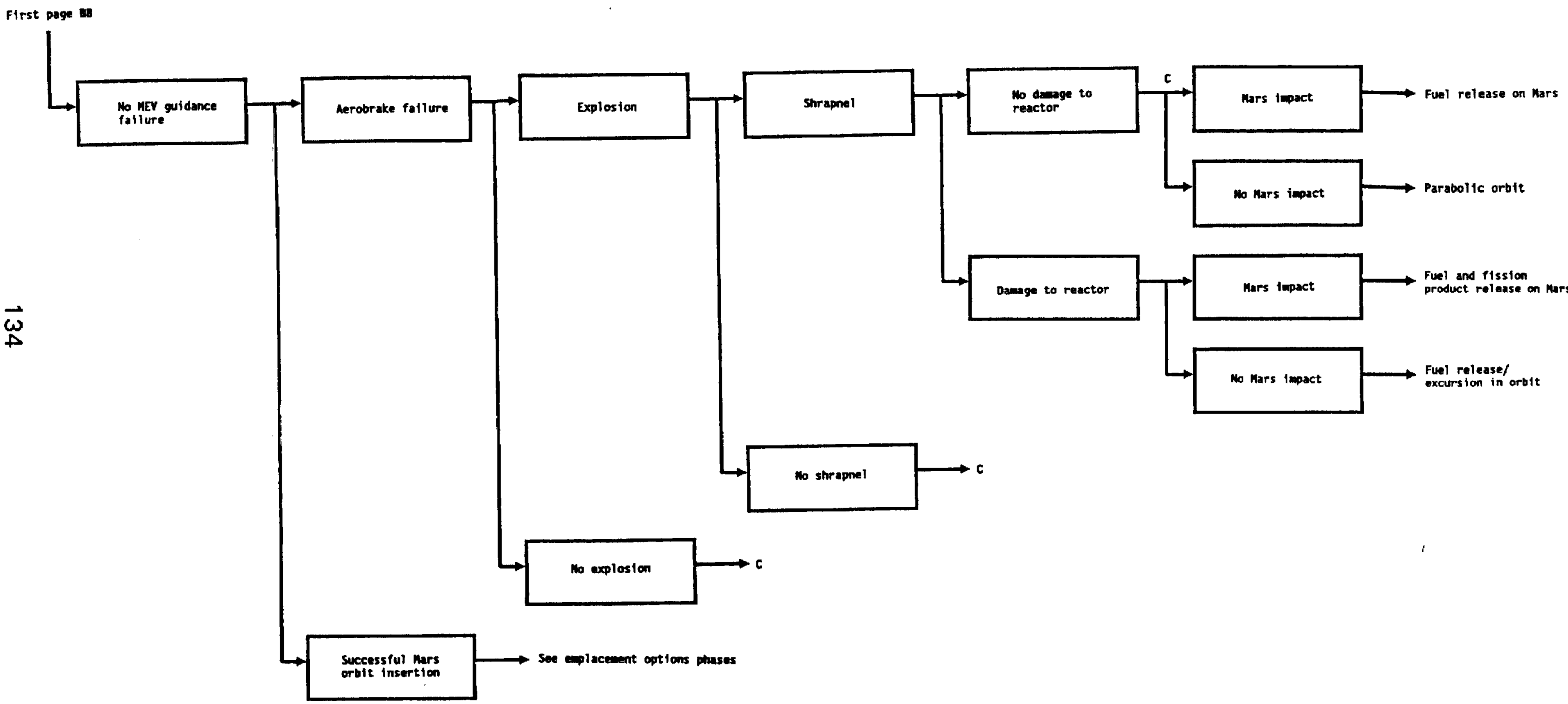

Figure 6-28 Simplified Event Tree for the Mars Mission Phase Mars Orbit Insertion By Aerobrake (cont.)

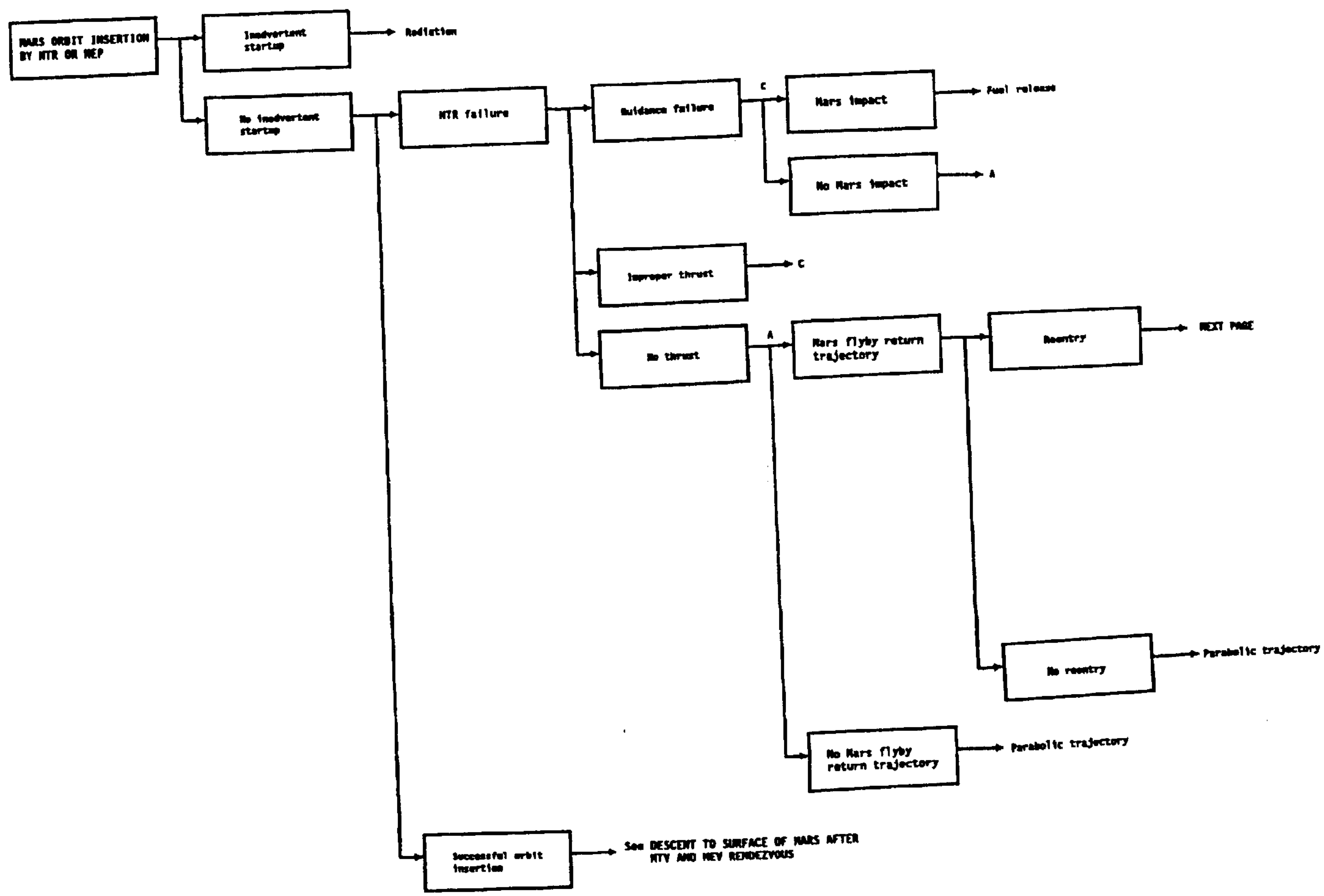

Figure 6-29 Simplified Event Tree for the Mars Mission Phase Mars Orbit Insertion By Nuclear Propulsion

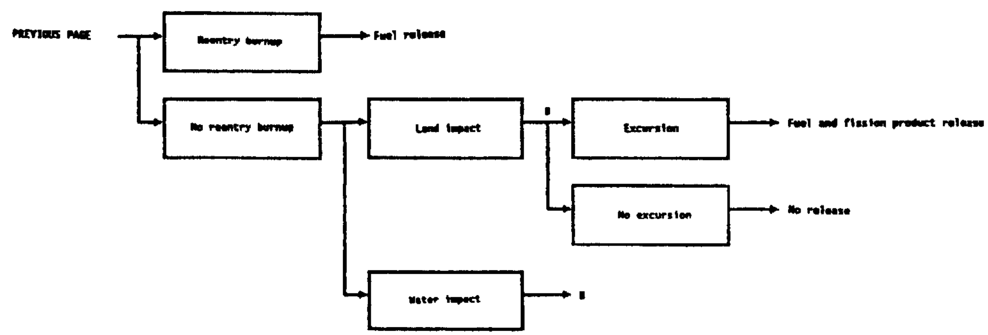

Figure 6-29 Simplified Event Tree for the Mars Mission Phase Mars Orbit Insertion By Nuclear Propulsion (cont.)

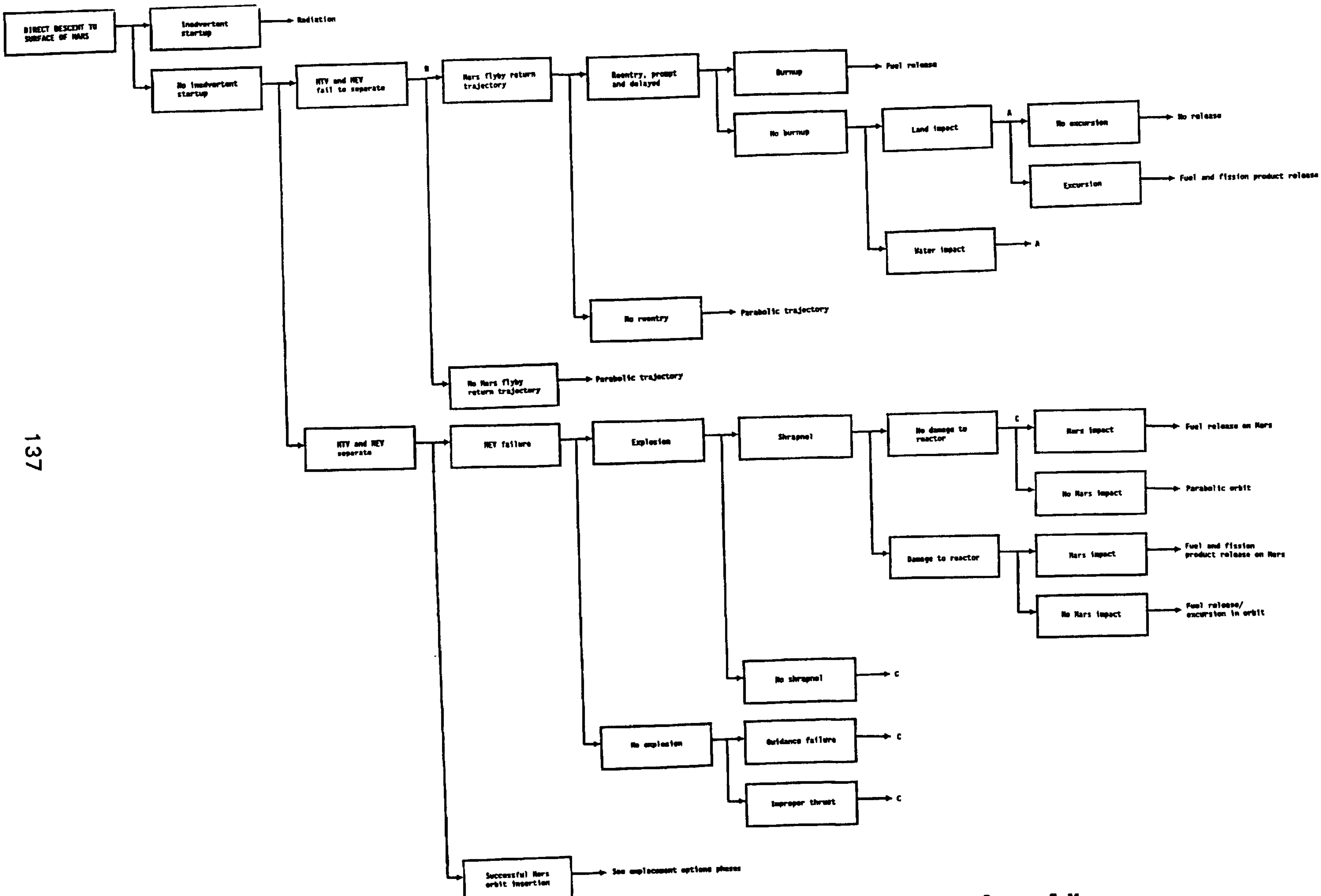

Figure 6-30 Simplified Event Tree for the Mars Mission Phase Direct Descent to Surface of Mars

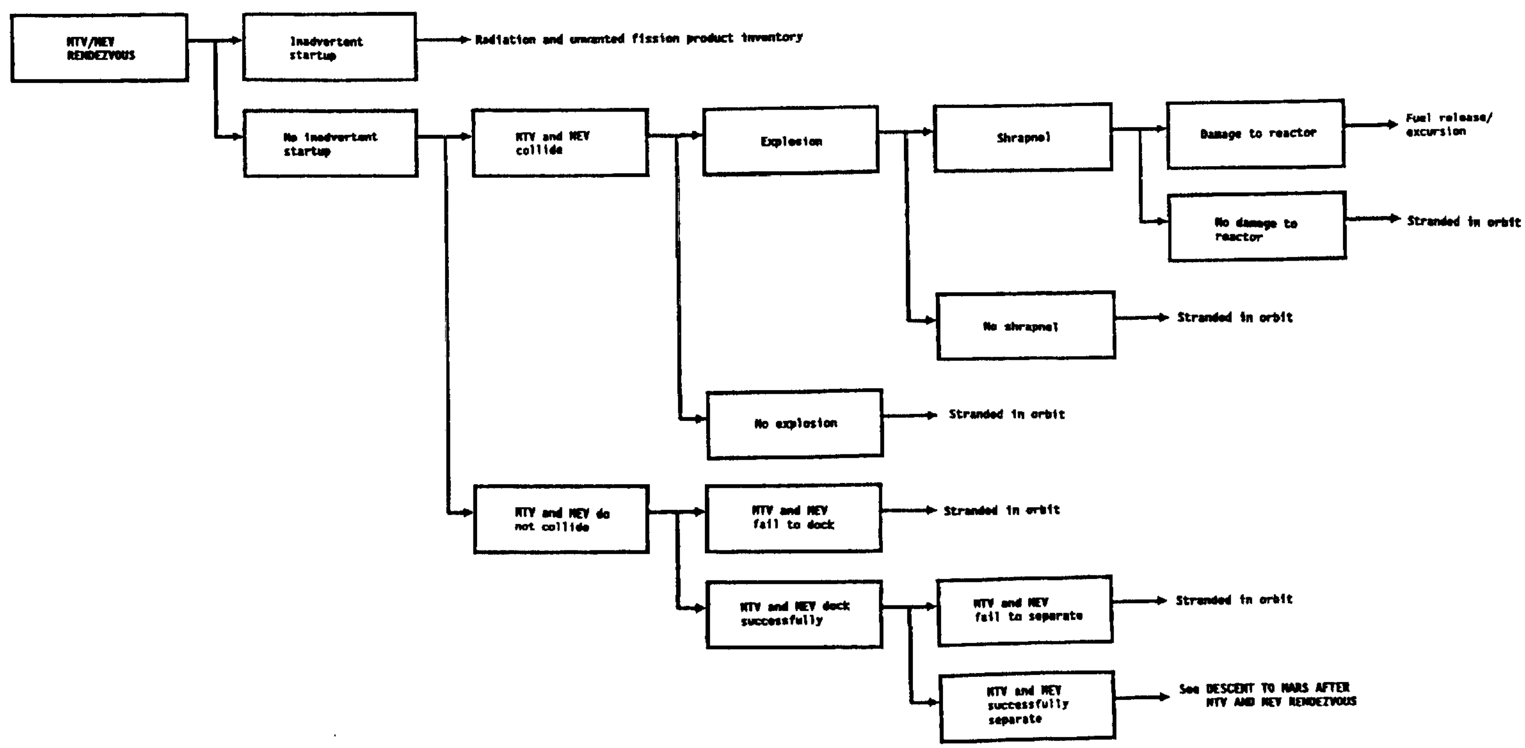

Figure 6-31 Simplified Event Tree for the Mars Mission Phase Mars Orbit Insertion By Aerobrake (MTV/MEV Rendezvous)

crew if the startup occurs when the excursion and transfer vehicles are attached and after crew transfer to the excursion vehicle. No such problem would occur for a cargo flight. An option on a cargo flight would be to boost the excursion vehicle into an escape trajectory.

Descent to Surface of Mars

After a successful separation of the Mars transfer and excursion vehicles, a guidance error may cause the excursion vehicle to impact the surface of Mars, see Table 6-16. Propellant tank ruptures during these

Table 6-16
Descent to Surface of Mars Phase Accidents and Resulting Reactor Environments

Accident	Reactor Environment
Guidance failure	Impact
Aerobrake failure	Impact
Descent engine failure	Impact Explosion Projectiles
Inadvertent reactor startup	Inadequate heat rejection path

accidents may provide a source of projectiles. A damaged reactor may lead to fuel release and possibly, a nuclear excursion. The simplified event tree for this mission phase is shown in Figure 6-32. A failure of the guidance system to initiate descent would strand the reactor in orbit.

A failure of the aerobrake during descent will likely cause the excursion vehicle to tumble out of control. The vehicle may break up. The reactor may or may not detach from the excursion vehicle. The end result would be impact on the surface of Mars at high speed. The reactor would also impact the martian surface should the descent engines fail, e.g., loss of thrust, guidance error, and failure to ignite. The transition between aerobrake descent and ignition of the descent engines can result in impact on the martian surface should the aerobrake fail to properly jettison. In any case, surface impact may lead to complete reactor destruction.

An inadvertent reactor startup is possible with the reactor heat rejection system not deployed. Possible resultant events include the generation of a hazardous radiation field for the flight crew, the generation of fission products which may pose a hazard during emplacement, and fuel release.

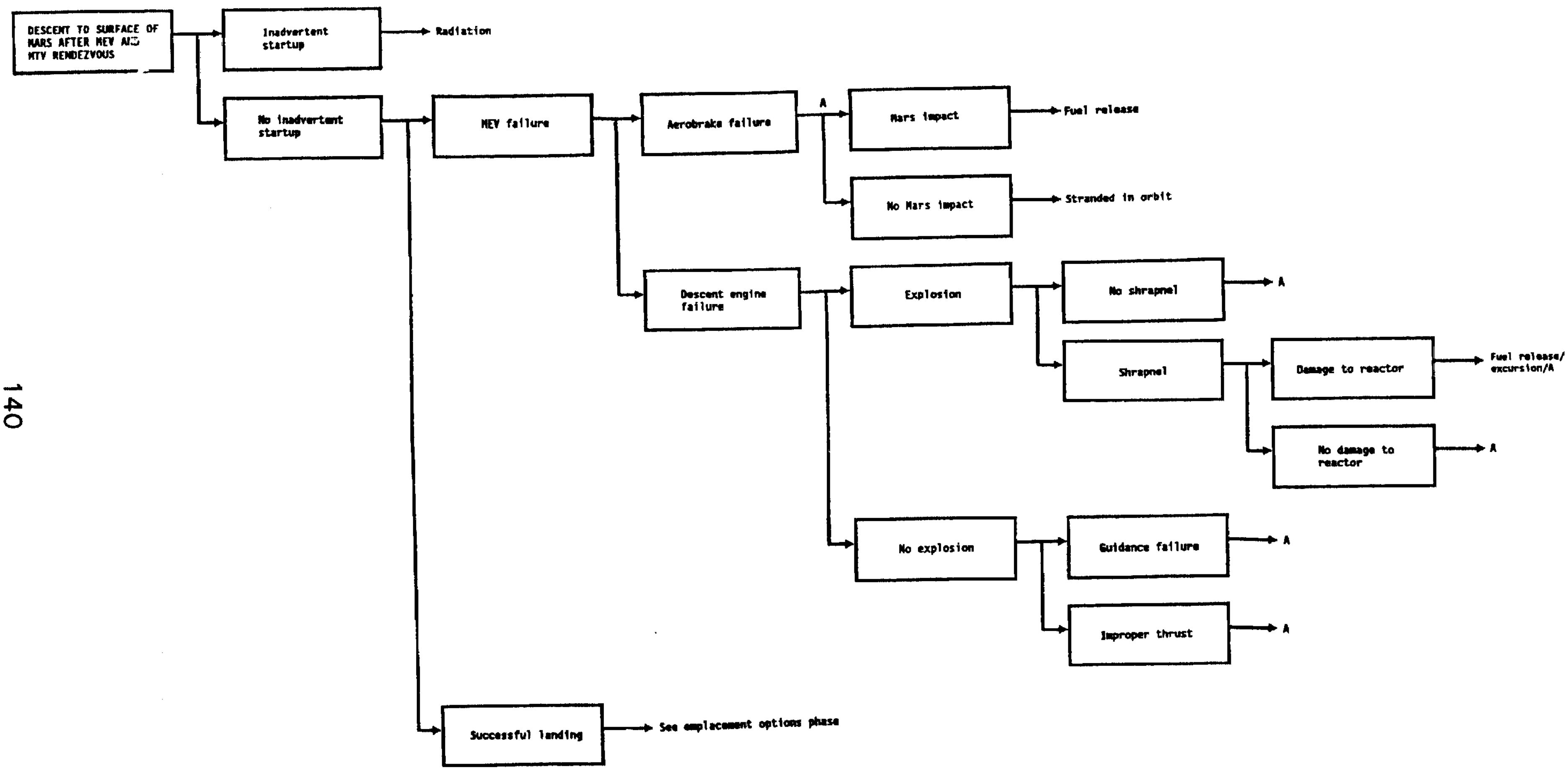

Figure 6-32 Simplified Event Tree for the Mars Mission Phase Descent to Surface of Mars After MEV and MTV Rendezvous

Emplacement

For the purposes of this study, the accidents and reactor environments for this phase of the Mars mission has been assumed to be the same as the corresponding lunar mission phase, see section 6.1, except for the effects of the martian atmosphere and soil.

Operation and Maintenance

For the purposes of this study, the accidents and reactor environments for this phase of the Mars mission has been assumed to be the same as the corresponding lunar mission phase, see section 6.1, except for the effects of the martian atmosphere and soil. The corresponding simplified event tree is shown in Figure 6-33. Note the addition of the effects of the atmosphere to the list of accidents.

Disposal

For the purposes of this study, the accidents and reactor environments for this phase of the Mars mission has been assumed to be the same as the corresponding lunar mission phase, see section 6.1, except for the effects of the martian atmosphere and soil. Figure 6-34 contains the simplified event tree for this mission phase option.

6.3 SUMMARY

A preliminary identification of safety issues can now be performed. Events and nuclear power system responses to events defined in the event trees which have the potential to leave the reactor in an unsafe configuration are safety issues. An example would be the environment of Mars. During the Operation and Maintenance and disposal phases of a mission to Mars, the fuel and fission product barriers, reactor vessel and fuel pin cladding, could be breached by the constituents of the martian environment leading to the release of fuel and fission products. The identification is preliminary because the event trees and accident environments are characterized qualitatively. The next iteration on this assessment process would be the evaluation of data available to describe accident environments and the generation of data for occurrence probabilities. Should reactor response be shown to leave the reactor in a safe condition or the occurrence probability be sufficiently small to produce very small contribution to the overall mission risk, the safety issue would be eliminated. The potential accidents and reactor responses identified in this chapter may not necessarily lead to a safety issue which must impact design. A risk assessment is required to put these potential accidents and hazards in perspective, including non-nuclear and space environment risks.

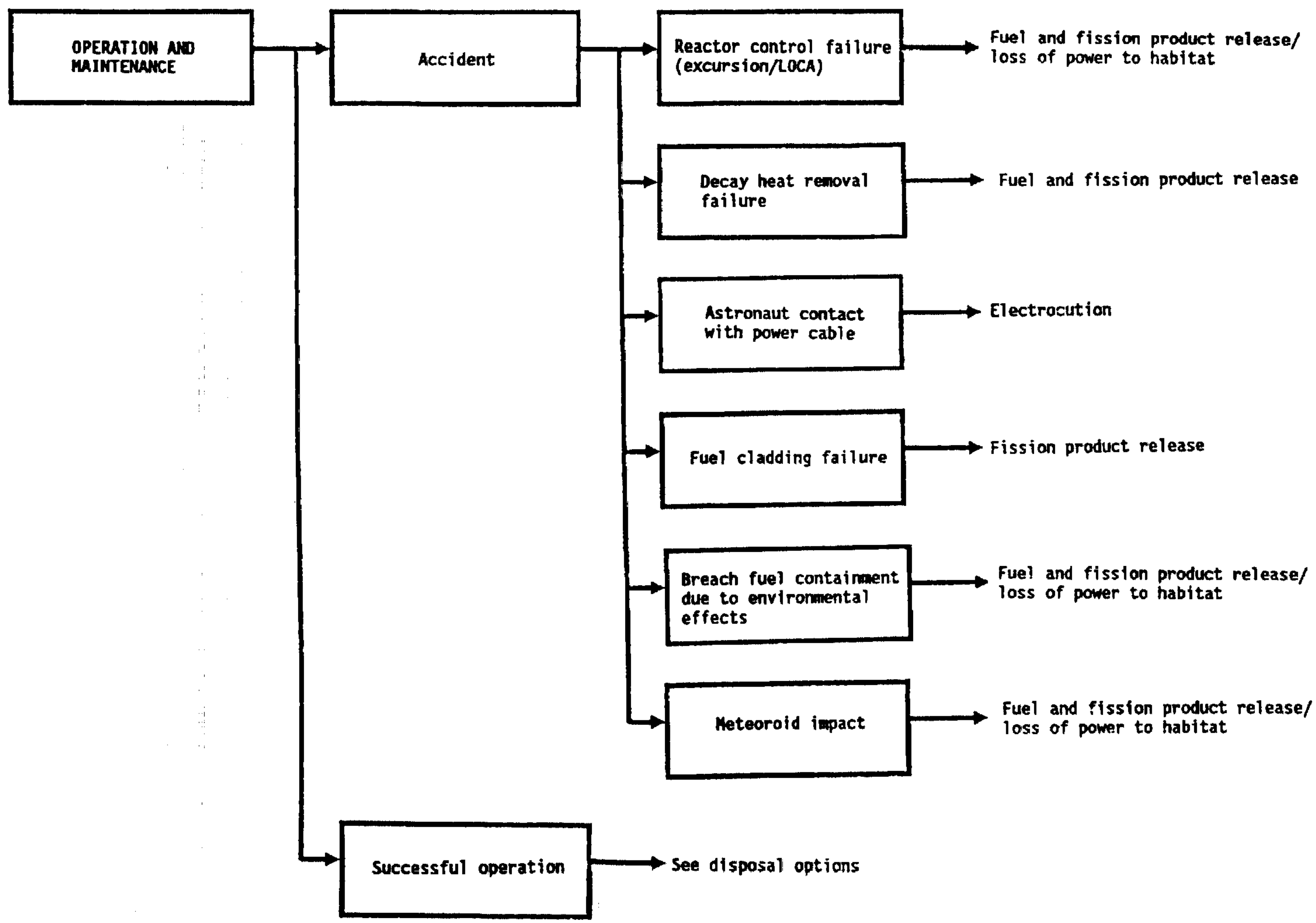

Figure 6-33 Simplified Event Tree for the Mars Mission Phase Operation and Maintenance

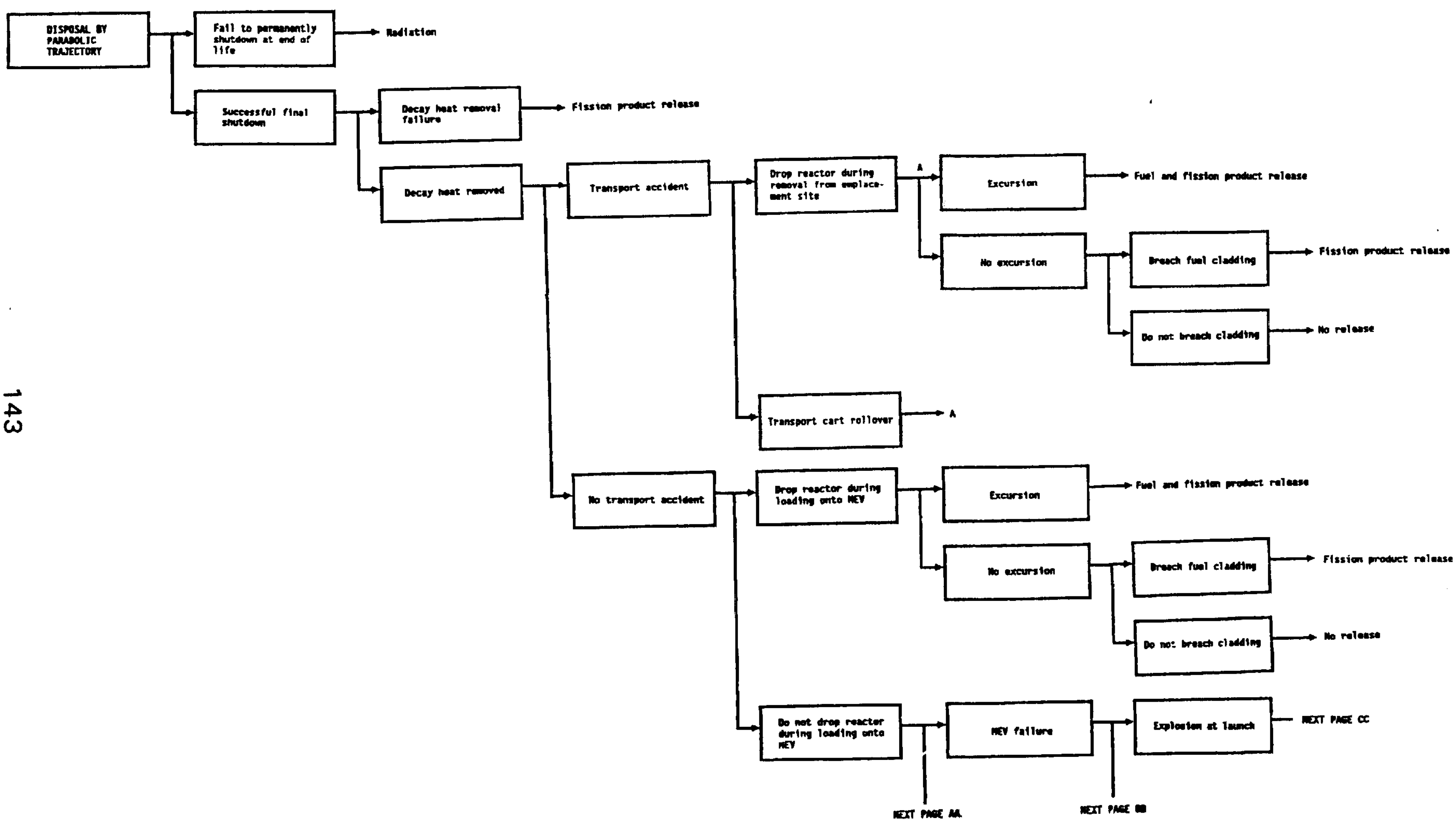

Figure 6-34 Simplified Event Tree for the Mars Mission Phase Disposal by Parabolic Trajectory

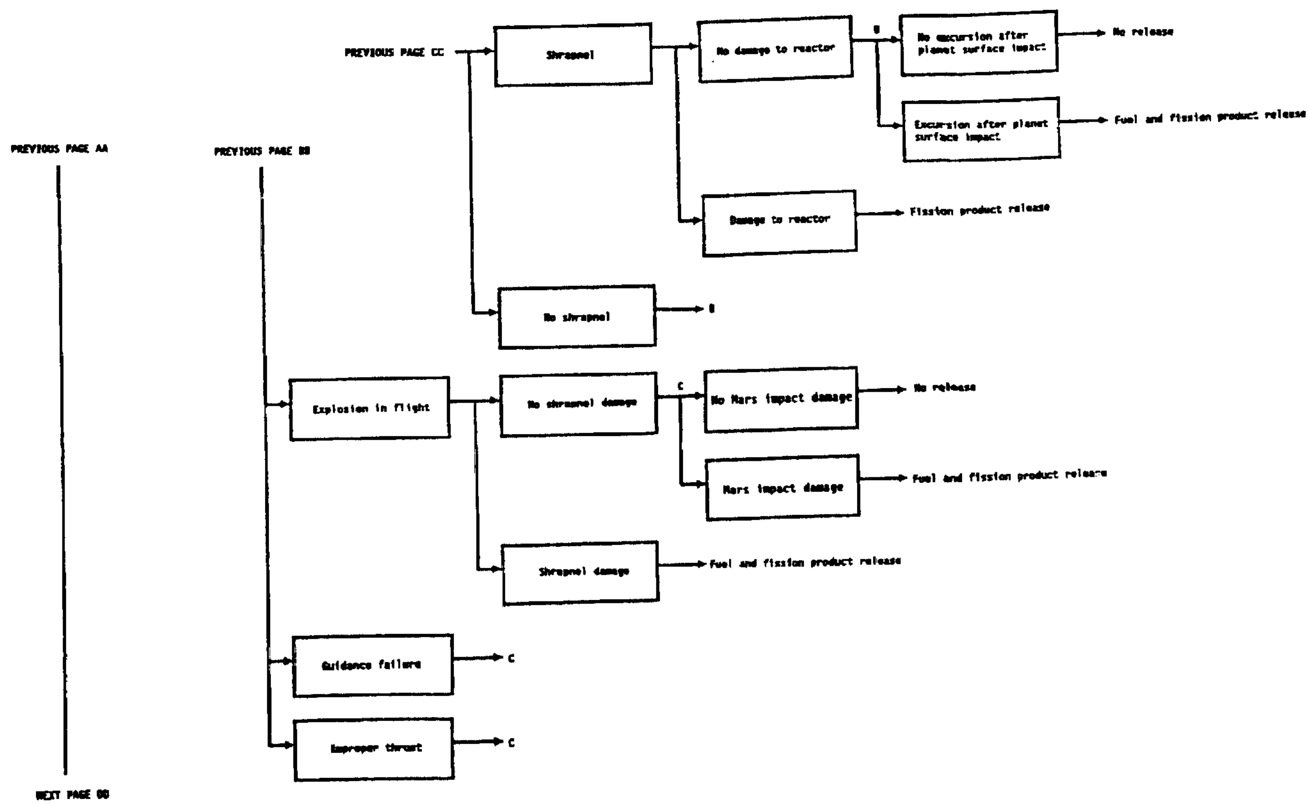

Figure 6-34 Simplified Event Tree for the Mars Mission Phase Disposal by Parabolic Trajectory (cont.)

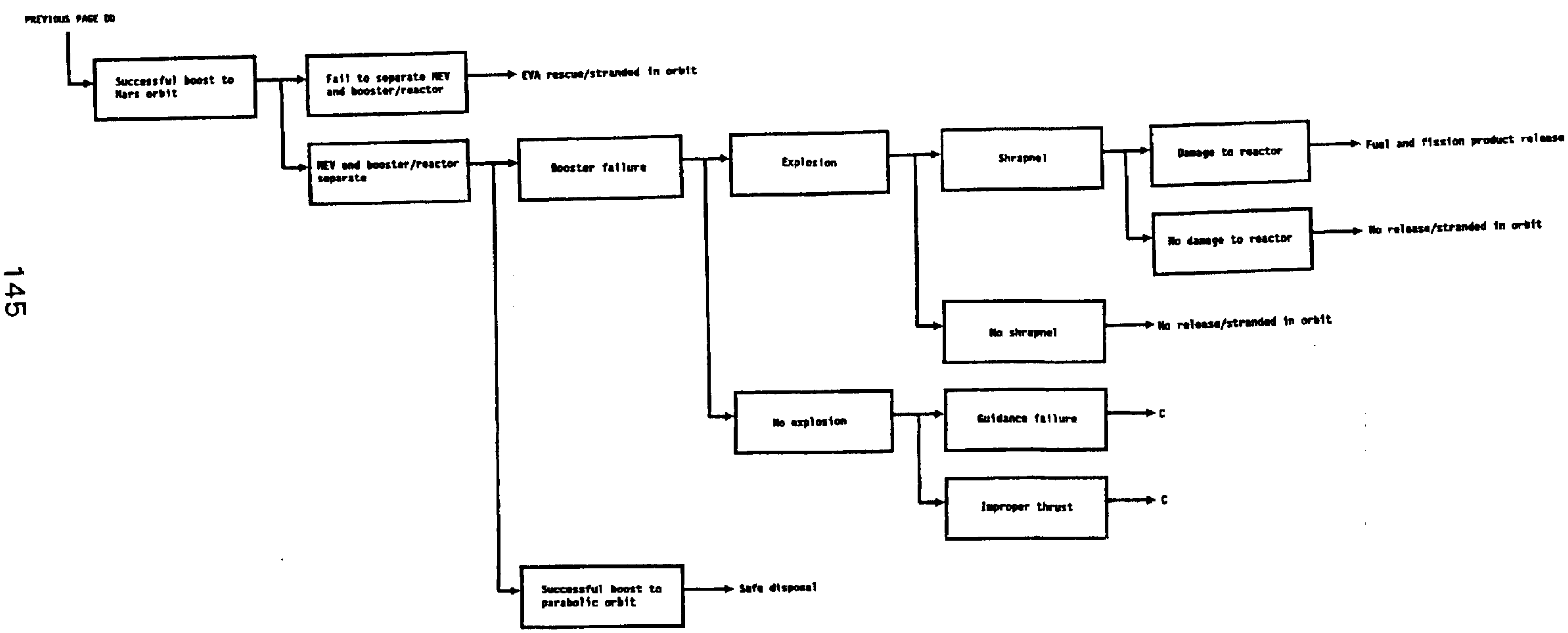

Figure 6-34 Simplified Event Tree for the Mars Mission Phase Disposal by Parabolic Trajectory (cont.)

7.0 SAFETY ISSUES

A summary of the safety issues identified in the SP-100 program is found in Table 7-1. These safety issues are relevant to missions to the moon and Mars with the possible exception of space debris in low earth orbit. The amount of time spent in low earth orbit will be significantly less than for proposed SP-100 missions. Whether this will result in an insignificant space debris risk must be determined. An examination of the simplified event trees developed in evaluating potential accident scenarios in the preceding chapter reveals that these safety issues are common to the Space Exploration Initiative missions. These issues have been clearly defined in the SP-100 safety program (Refs. V-4 and V-5) and will not be discussed here.

Table 7-1
Compilation of SP-100 Program Safety Issues

Hazard to launch vehicle
Criticality in launch vehicle explosion environments
Criticality in water and/or soil
Criticality after reentry and secondary impacts
Toxicity from dispersal of released hazardous materials
Reentry dispersal of fuel and fission products
Space debris penetration of primary coolant boundary
Inadvertent startup and reactivity insertion
Shutdown capability at any time
Fission product release during normal operation
Reactor power control
Loss of coolant, flow, and heat sink
Loss of load
Final shutdown
Decay heat removal
Loss of communication
Loss of safety function

Safety issues which have been identified in addition to those mentioned above for the SP-100 program are listed in Table 7-2. The list order does not reflect the results of any estimation of the hazard level. Each of these

Table 7-2
Safety Issues Derived From Missions to the Moon and Mars

Criticality after transfer and excursion vehicle explosions
High voltage power cables*
Loss of power to habitat*
Radiation emitted during operation and maintenance (if any)
Mars environment
High speed impact on the moon and Mars
Return flyby trajectories
Disposal after operation on planet
Outpost contamination from released fission products
Reactor stranded in orbit

* Not normally considered a nuclear safety issue

safety issues was identified as a result of the analyses reported in chapter 6. The following discussion presents the safety issues identified as a result of the preliminary hazards analysis, the results of which were presented in the preceding chapter.

Criticality is a safety concern following explosions. Projectiles produced in an explosion in the vacuum of space present a similar potential for reactor damage as for shrapnel generated by launch vehicles. The magnitude of the shrapnel environment from explosions of the transfer and excursion vehicles is unknown due to the absence of detailed designs. However, a significant amount of LH_2 and LO_2 will be aboard the transport vehicles. If propellant tanks with common bulkheads are used, failure of the bulkhead separating the propellants would result in a confined-by-missile explosion. Tank rupture due to excessive tank pressure during propellant transfer from transfer vehicle to reusable excursion vehicle, if used, may also produce a hazardous source of projectiles. A reactor excursion would produce a radiation field hazardous to a flight crew or Space Station Freedom astronauts. It would likely damage the reactor sufficiently that an occurrence in low earth orbit or on a trajectory that will allow a return to earth after a mission abort prior to moon or Mars orbit insertion may be hazardous to the population of earth.

Power cables on the surface of the moon and Mars will present a safety hazard to the astronauts. Contact may result in electrocution. Additionally, power may be loss to the habitat(s). Any loss of power to the habitat(s) is life threatening without some means to provide emergency backup power. Life support systems and thermal management will require power to maintain conditions conducive to the survival of the astronauts. Short term solutions such as EMUs may be used, but long term solutions will require power or the base will have to be abandoned. An emergency power system may be required to maintain the excursion vehicle in a launch ready condition for subsequent base abandonment.

The radiation field external to a reactor produced during operation will be a hazard to astronauts on the surface of the planet. Some method of shielding will be required, whether it be separation distance or physical barrier or some combination of the two. Shielding studies have been performed to attempt to determine the optimum configuration. However, astronaut dose limit requirements have not been properly defined. Both exposure period and dose plane location have been subject to considerable variability. Astronaut movement and time spent at a location have not been factored into shielding studies in sufficient detail. Astronauts will be involved in many activities which have the potential to expose them to reactor generated radiation fields, e.g., occupation of the habitat, activities about the habitat area, and maintenance in the vicinity of the power production area. Also, additional sources of man-made radiation such as mobile radioisotope power sources have not been factored into reactor shielding studies. Finally, dose limits which have previously been defined have been prescribed for different periods of time. A shield design based upon a 30 day mission will be inadequate for long term missions such as the 600 day Mars preparatory mission. The shield should be designed for the longest expected mission to avoid the need for any retrofit action.

Shielding of the reactor to provide protection to the astronauts introduces a safety concern from Table 7-1 which had been solved previously in the SP-100 program. Reactor control for SP-100 is by external reflectors. The relatively large neutron leakage of a compact reactor in space allows for this simple, efficient control method. The placement of shielding material close around the reactor will, however, diminish the worth of the reflectors surrounding the reactor. Neutron scattering from the shielding material back into the reactor may render the reference flight system reflector control design inadequate.

The Mars environment is highly corrosive to refractory materials (see Appendix A). Containment of fuel and fission products must be maintained.

Missions to the moon and Mars have the potential for high speed surface impact as noted in chapter 6. Impact will be at high speed due to the lack of any atmosphere sufficient to reduce velocity by drag forces. Planetary approach velocities which may reach several km/sec, see Figure 7-1. Earth impact speeds have been estimated at 269 m/sec for the SP-100 (Ref. V-4). This is an order or magnitude smaller than typical Mars approach speeds. Additionally, the lack of an atmosphere on the moon and the low density of the atmosphere on Mars will not provide the vehicle breakup common to reentry on earth.

Once the transport vehicle has been successfully inserted into the trans-lunar or trans-Mars orbits, risk to the general population does not reduce to zero. In the interests of providing the safest mission profile for flight crews, missions will likely have transfer vehicle flight trajectories which will allow planet flyby and return to earth should a mission be aborted. The reactor may be returned to low earth orbit. The issue of the capability of the returning spacecraft to safely achieve low earth orbit with cargo attached has not been investigated. The transfer vehicle propulsion system may not be designed for full cargo return.

Fuel and fission product containment will be an important safety consideration during planet surface operation and as a factor in the choice of disposal strategy. Depending upon the amount and type of astronaut activity in the vicinity of the power production area on the moon, surface contamination due to a breach of fission product containment may result in contamination of the habitat. An astronaut traversing a contaminated area may carry radioactive particles back to the habitat on his EMU. The Mars environment adds a new dimension to these safety issues. The surface winds will entrain fission products and disperse them. Additionally, the harsh environment of Mars will necessitate substantially greater fuel and fission containment barrier requirements over that required for the moon.

To avoid overlooking a possible safety issue, the circumstance where a reactor is stranded in orbit has been noted. A reactor may be stranded in orbit around the earth, the moon or Mars. If a reactor stranded in low earth orbit cannot be recovered, reentry will occur. This is an obvious hazard to the general population. SP-100 has overcome this hazard by not operating the reactor until it is in the operating orbit and by designing the reactor to impact earth intact after the inadvertent reentry. A reactor stranded in orbit around the moon or Mars will not pose a threat to the general population, but may pose a threat to subsequent flight crews. The potential will exist for an inadvertent rendezvous and collision since the reactor will likely be in an orbit used for subsequent missions to the same planetary outpost. A collision may result in damage to the reactor which is sufficient to produce a nuclear excursion. The resulting radiation field would be hazardous to surviving astronauts.

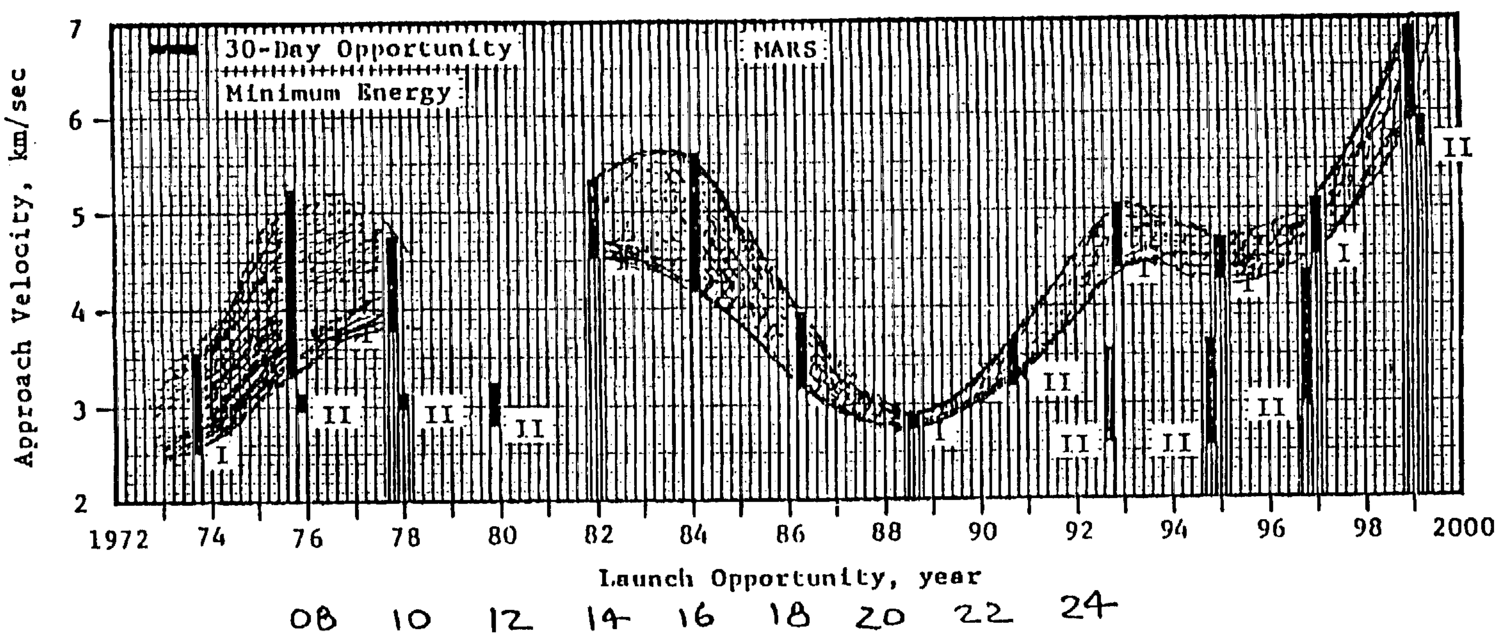

Figure 7-1 Mars Approach Velocity as a Function of Launch Opportunity (Ref. VII-1)

8.0 SAFETY ISSUE RESOLUTION

8.1 SP-100 PROGRAM SAFETY ISSUE RESOLUTION

Resolution approaches taken in the SP-100 program are listed in Table 8-1 by safety issue. No further comments will be presented since this program has a well established safety program (Refs. V-4 and V-5) which has documented this information in many sources.

Table 8-1
SP-100 Program Safety Issue Resolution Approaches
(Sheet 1 of 6)

Safety Issue	Resolution
Hazard to launch vehicle	Primary coolant lithium solid at launch Insignificant fission product inventory at launch Latches and locks on reflectors, safety rods, gas separators, TEM pumps, power converters, and radiator panels Encryption and decryption startup command sequence Monitor inhibits while in payload bay Category 1 hazardous functions identified and inhibited Category 2 hazardous functions to be identified in flight program Reflector and safety rod drives without power during launch Fracture control program to be implemented for beryllium Automatic shutdown springs used to keep reflectors and safety rods in safe shutdown positions while the reactor is in the launch vehicle The design is required to meet stress corrosion cracking requirements
Criticality in launch vehicle explosion environments	Latches and locks on safety rods to restrict rod movement relative to fuel Core subcritical with full compaction Honeycomb core structure Weak link in actuator mechanism at shield to maintain safety rod integrity and alignment High temperature materials PWC-11(2741K)

Table 8-1
SP-100 Program Safety Issue Resolution Approaches
(Sheet 2 of 6)

Safety Issue	Resolution
Criticality in water and/or soil	Rhenium poison provides thermal neutron absorption Latches and locks on safety rods to restrict rod movement relative to fuel Adequate negative reactivity in safety rods to ensure subcritical configuration Reentry heat shield provides predictable water entry orientation Honeycomb core structure and reactor vessel prevents fuel spreading Weak link in actuator mechanism at shield to maintain safety rod integrity and alignment
Criticality after reentry and secondary impacts	Latches and locks on safety rods to restrict rod movement relative to fuel during reentry and impact Adequate negative reactivity in safety rods to ensure subcritical configuration Honeycomb core structure prevents fuel pin spreading on impact Reentry shield assures impact orientation and temperature control Reentry shield protects against oxidation during reentry Small amount of core buckling and crushing helps prevent safety rods dislodging from core during impact and burial Honeycomb supported by fuel pins prevents disruption of core by solid rocket booster fragments
Toxicity from dispersal of released hazardous materials	Lithium coolant solid at launch High temperature materials used UN(3123K), BeO(2803K),PWC-11(2741K) Fracture control program for beryllium
Reentry dispersal of fuel and fission products	Reentry shield protects against heat fluxes, oxidation and aerodynamic loads Insignificant fission product inventory at at launch Bonded fuel cladding Fission gas plenum for each fuel pin High temperature materials PWC-11(2741K) and carbon-carbon (reentry shield)

Table 8-1
SP-100 Program Safety Issue Resolution Approaches
(Sheet 3 of 6)

Safety Issue	Resolution
Space debris penetration of primary coolant boundary	Primary coolant lithium solid prior to startup Auxiliary coolant loop to remove decay heat in event primary heat transport loop is inadequate Beryllium shield over primary coolant loop piping where exposed to debris Damage assessment per NASA SP-8042 (Ref. VIII-1)
Inadvertent startup and reactivity insertion	Latches and locks on safety rods and reflectors Two independent means (safety rods and reflectors) to maintain subcriticality Rods locked in core prior to startup Reflectors locked out prior to startup Actuators not powered prior to startup, no power to clutches, and no power to energize brakes Command required to operate actuators Three independent inhibits, one of which precludes startup by RF energy Shutdown springs load safety rods and reflectors to least reactive positions Controller software to meet NSTS fault tolerance requirements Control elements (reflectors and rods) are moved away from and out of the core individually and incrementally in a pre-programmed manner to prevent a rapid reactivity insertion Encryption and decryption devices and command sequence Inadvertent startup inhibits monitored
Shutdown capability	Two independent means of shutdown (safety rods and reflectors) Redundancy in safety rods and reflectors
Fission product release during normal operation	Bonded fuel cladding Gas plenum within each fuel pin

Table 8-1
SP-100 Program Safety Issue Resolution Approaches
(Sheet 4 of 6)

Safety Issue	Resolution
Reactor power control	Negative void, temperature, and power reactivity feedback coefficients Two independent shutdown means (safety rods and reflectors) Redundancy in safety rods and reflectors Control elements (safety rods and reflectors) moved individually and incrementally, maximum reactivity insertion limited to 1.5%/minute power increase Redundant sensors for temperature, pressure and primary coolant flow Redundant temperature sensors per primary coolant loop Diverse thermocouples and Johnson noise sensors Design basis accidents studied to identify operating conditions requiring shutdown or power reduction Safety rod position limit switches to confirm location Reflector continuous position indicators Control system diagnostics to detect malfunction to change control sequencing Control system diagnostics prior to shutdown to reduce likelihood of spurious scram Control system diagnostics after shutdown to determine if autonomous restart appropriate, battery power will monitor safety systems up to 1.5 hour after shutdown Shutdown springs move safety rods and reflectors to shutdown position upon loss of power to the actuators

Table 8-1
SP-100 Program Safety Issue Resolution Approaches
(Sheet 5 of 6)

Safety Issue	Resolution
Loss of coolant, flow, and heat sink	Auxiliary coolant loop removes decay heat in the event the primary heat transport loop is inadequate Design basis accidents requiring shutdown Two independent means of shutdown with redundancy High temperature materials PWC-11(2741K), UN(3123K) Beryllium shield over primary coolant loop piping where exposed to space debris TEM pumps used for passive, automatic decay heat removal Redundant reactor outlet temperature sensors per primary coolant loop Diverse thermocouples and Johnson noise sensors Redundant system pressure sensors initiate shutdown upon loss of pressure Diverse methods of decay heat removal with primary coolant loop and auxiliary coolant loop Redundancy with multiple primary and secondary coolant loops in primary heat transport system Primary heat transport coolant leaks detected by pressure sensors Auxiliary coolant loop leaks detected by pressure differential
Loss of load	Parasitic shunt Design basis event requiring power reduction at shunt failure
Final shutdown	Two independent and diverse methods of shutdown (safety rods and reflectors) Redundancy in safety rods and reflectors Automatic at end-of-mission Uses independent clock with shutdown time preset at launch and not resettable Clock powered by critical loads bus Single fault tolerant Battery power for restart limited to a few hours Irreversibly interrupt power supply to reflector and safety rod clutches

Table 8-1
SP-100 Program Safety Issue Resolution Approaches
(Sheet 6 of 6)

Safety Issue	Resolution
Decay heat removal	Diverse methods of decay heat removal with primary coolant loop and auxiliary coolant loop Redundancy with multiple primary and secondary coolant loops in primary heat transport system
Loss of communication	Design basis event requiring shutdown after time limit exceeded
Loss of safety function	Design basis event requiring shutdown

8.2 RECOMMENDED NEW SAFETY ISSUE RESOLUTIONS

The following discussion is restricted to resolution approaches identified for mission phases and aspects of mission phases not previously covered by low earth orbit operation applications of reactors in previous safety assessments, especially the SP-100 safety program. The safety issues addressed are those in Table 7-2.

Criticality After Vehicle Explosions

An explosion in space is always a possibility when using chemical propulsion (Ref. VIII-2). An explosion of significance requires propellant and oxidizer to mix and pool. Propellant and oxidizer tanks must rupture together and the time and means to mix and pool must be provided. Furthermore, an ignition source is required. This simultaneous rupturing could occur due to collisions between orbiting vehicles, collisions between the vehicle and the space station structure, or projectiles emanating from an exploding rocket engine.

Not all tank ruptures will lead to an explosion; as mentioned previously, mixing, pooling, and an ignition source are required. Due to the lack of design data, the possibility exists that the LH_2 and LO_2 may be configured in the excursion and transfer vehicle tanks in the same manner as in a Centaur, i.e., LH_2 and LO_2 in a tank separated by a common bulkhead. A projectile from an exploded rocket engine could impact one compartment of the tank causing a collapse of the common bulkhead resulting in the mixing and pooling necessary to allow an explosion. The explosion fragments may provide the ignition source. Even with ignition, the mixture may only burn vigorously. The Centaur confined-by-missile mode of explosion from the 1985

Galileo and Ulysses Final Safety Analysis Report (Ref. VIII-3) is an example. Should the LH_2 and LO_2 be contained in separate tanks, an explosion of consequence is unlikely, since the means to mix and pool are missing and an external source of oxygen (e.g., the atmosphere) is also missing. The threat from Space Shuttle external tank explosions was considered nil after 150,000 ft for this reason (Ref. V-2).

Projectiles, fragments and shrapnel, will be produced due to explosions of rocket engines and propellant tank ruptures. Not all tank ruptures, however, will result in projectiles. The majority of the pressurized tanks in the Shuttle Orbiter are made of titanium (Ti-6Al-4V). These tanks typically fail due to overpressure by splitting open and relieving pressure. They do not fragment, but generally split apart in hemispheres. Projectile fields will also be attenuated by intervening structure. Projectile environments will be heavily dependent upon the materials and structures used in the transfer and excursion vehicles.

The SP-100 is being designed to remain subcritical during launch accidents by providing sufficient negative reactivity and the structural capability to retain this negative reactivity. Neutron absorber rods will be locked into place inside the reactor core at launch to be removed only upon the startup command. These rods have been designed to keep the reactor core subcritical under all postulated reactor configurations resulting from explosions, projectiles, fragments, and shrapnel. Hydrocode analyses by General Electric (Ref. I-1) have been performed to verify the rods will remain in the reactor core during the explosion environments resulting from failures of the space shuttle. Nuclear reactor accommodation of the explosion environments possible during any phase of the moon and Mars missions is not known at this time due to the lack of sufficient design detail of the launch, transfer, and excursion vehicles. The use of an expendable launch vehicle may eliminate solid rocket motor casing fragments as a safety concern since the reactor should be located above any fragment field generated in an explosion of the launch vehicle.

<u>Radiation Emitted During Operation and Maintenance</u>

Radiation exposure control during operation and maintenance will involve shielding, distance, and time wherever practical. The particular radiation exposure limits for astronauts has not been clearly defined.

The National Council on Radiation Protection has published guidelines in NCRP Report No. 98 (Ref. IV-1). These guidelines are listed in Tables 8-2 and 8-3. Annual dose is limited to 50 rem with a 30 day limit of 25 rem. The career dose limit is dependent upon sex and first-mission age of the astronaut. These career limits are based upon a lifetime excess risk of cancer mortality of 3 percent.

Radiation exposure controls for astronauts need to include the effects of all sources of natural and man-made radiation, both stationary and mobile. Past shielding studies for stationary (Refs. IV-3 and IV-4) and mobile (Ref. VIII-4) systems have ignored the presence of sources of man-made radiation in

Table 8-2
National Council on Radiation Protection Guidelines for Exposure of Spaceflight Crewmembers to All Sources of Radiation (Ref. IV-2)

Time Period	Blood Forming Organs (mSv)
30 days	250
Annual	500
Career	See Table 8-3

Table 8-3
National Council on Radiation Protection Guidelines for Career Wholebody Dose-Equivalent Limits Based on a Lifetime Excess Risk of Cancer Mortality of 3 percent (Ref. IV-2)

Age (years)	Female (Sv)	Male (Sv)
25	1.0	1.5
35	1.75	2.5
45	2.5	3.2
55	3.0	4.0

addition to the reactor. This is primarily due to the lack of information on the complimentary surface power system. An allocation of exposure to natural and man-made radiation is required. An analysis must be performed of potential astronaut activity on the surface of the moon and Mars to characterize the potential for exposure of the astronauts to man-made radiation sources. Time and distance estimates are required. From this characterization, an optimum dose limit allocation between mobile and stationary man-made radiation sources can be made.

The characterization of astronaut activities for the purpose of dose limit allocations must include all potential missions. A dose limit based upon a 30 day astronaut stay will result in astronaut overexposure during the 600 day lunar mission dress rehearsal for the missions to Mars. Dose limits should be based upon the longest potential astronaut stay expected during the lifetime of the nuclear reactor surface power system.

Dose limits have not been suggested based upon a realistic and complete set of dose plane locations. Dose limits for man-made radiation emanating from surface nuclear reactors have been proposed for the habitat area at various distances from the power production area (e.g., 1 km and 5 km), at arbitrary distances, and at the innermost point of the radiator panels. Shielding requirements for lunar surface operations of mobile DIPS units have been investigated and the results reported in Reference VIII-4 where separation distance and exposure time control were used for an unpressurized manned/robotic rover. No allowance was made for man-made radiation from surface nuclear reactors and exposure limits were based upon balances estimated as shown in Table 8-4.

Table 8-4
Radiation Exposure to Astronauts on Moon (Ref. VIII-4)

Sources of Radiation	Mission Length (days)[1]				
	30	90	180	365	600
Natural sources					
1. Earth-moon-earth	4.3	4.3	4.3	4.3	4.3
2. Lunar surface	1.0	3.2	6.6	13.3	22.0
3. Solar particle event (10 gm/cm^2 shield)	1.2	1.2	1.2	2.4	4.0
Total dose	6.5	8.7	12.1	20.0	30.3
NCRP-98 guidelines	25.0	50.0	50.0	50.0	100.0
Dose balance (rem/mission)	18.5	41.3	37.9	30.0	69.7

[1]Mission length includes 4 days for round trip to moon.

Proper sizing and comparison of shielding alternatives will require the allocation of dose limits at prescribed locations. Various astronaut activities will require them to perform duties at the habitat area, at the launch/landing site, at the soil processing plant, and at locations away from the outpost which will require travel outside the protection of the habitat on surface rovers. A shadow shield to protect the astronauts at the habitat may not provide any protection at other locations. A total dose limit must be recognized as the summation of the doses acquired from the various locations astronauts will be performing their duties. Also, dose limits should be separated into nominal and emergency limits. A nominal limit should reflect the diversity of duties required of each individual astronaut, not necessarily the worst case exposure compiled from all astronaut duties. Emergency limits should be set to reflect the availability of an excursion vehicle for outpost abandonment in addition to the consequences to the astronauts of power system failure.

Mars Environment

In addition to the CO_2 atmosphere, the martian soil has been found to contain oxidants, see Appendix A. The martian soil is periodically entrained and suspended in the atmosphere by surface winds. Also, H_2SO_4 and HCl aerosols are believed to be present in the wind blown dust. Reactor materials will be required to withstand the CO_2 atmosphere and these oxidants and acids during operation and for long term storage if final disposal is on the surface of Mars.

The Reference Flight System SP-100 uses refractory metals due to the high temperatures required for operation within design constraints of mass and payload envelope. These materials are not compatible with long term operation and disposal on the surface of Mars. This problem is well known and has been identified previously (Ref. IV-3). Current efforts to investigate environmental effects on SP-100 refractory materials is limited to low earth orbit conditions, e.g., meteoroids, debris, atomic oxygen, and plasma (Ref. VIII-5). Research is required for material compatibility with the martian environment. Coatings such as silicide for refractory metals need to be investigated for long term reliability. Reactor designs using alternate materials, such as stainless steel, which operate at lower temperatures and are compatible with the martian environment need to be considered. Isolation of the refractory materials from the martian environment should be investigated as a potential solution. The refractory metals could be encased in a vessel which supports a vacuum or inert atmosphere between the outside vessel and the inner refractory materials, e.g., encase the primary coolant loop piping in a stainless steel tubing with a vacuum between them.

High Speed Impact on the Moon and Mars

Both high and low speed impacts are possible during a flight to the moon or Mars. Low speed impacts involve such diverse accidents as dropping the reactor on the lunar and martian surfaces; planet surface transportation cart rollover; handling accidents at planet orbit rendezvous and on the surface of the planet; and low speed collisions during orbital maneuvers in low earth orbit. High speed impacts are possible during a flight to the moon or Mars. High speed impacts on the lunar and Mars surfaces may occur during moon/Mars orbit insertion and descent to the surface. They may also occur during launch from the earth and upon return to the earth should the space vehicle fail to orbit the moon or Mars and return to the earth. The issue of a return to earth without orbiting the moon or Mars is discussed below under the safety issue of return flyby trajectories. An additional possibility for lunar surface impact may occur if nuclear electric propulsion is used and the trans-lunar orbit requires a gravity assist flyby of the moon.

Impact speeds may be as high as planet approach velocities, 2 to 7 km/s (7 to 23 kft/s) for Mars (Figure 7-1), since the moon has no atmosphere and Mars has too little atmosphere to adequately slow down the spacecraft. The reactor is unlikely to survive such an impact on the moon or Mars. The SP-100 reactor is being designed to survive a 269 m/s impact on pavement grade concrete. The risk to the mission from this type of accident will have to be estimated taking into account flight path angle, incoming velocity, and the aerobrakes. Guidance system failures should be the dominate risk contributor. Highly reliable transfer vehicle guidance systems will minimize risk. The reactor must be designed to survive earth reentry so that the risk to the general population is insignificant.

The nuclear power system will not be operated until it is emplaced on the surface of the moon or Mars. This will minimize the radioactivity inventory.

An environmental hazard would be meteoroid impact. An impact analysis needs to be performed to determine the minimum meteor mass required as a function of velocity to penetrate the fuel cladding. With this mass, the risk can be estimated from this high speed impact source for comparison with other mission risks to determine the need for any extra precautions.

Return Flyby Trajectories

Flights to the moon and Mars are likely to use trans-lunar and trans-mars trajectories which will allow return to earth should the space vehicle propulsion system fail to function for orbit insertion. This type of trajectory would be failsafe. If a failure in the propulsion system used for orbit insertion around the moon or Mars is detected during the trans-lunar or trans-Mars trajectory phase of the mission or the system fails to operate when commanded, a return flyby trajectory would allow the space vehicle to return to earth with little or no additional thrusting for retrieval of astronauts and cargo. The propulsion system may be either chemical or nuclear. The term return flyby trajectory has been used to denote a trajectory from the earth to the moon or Mars which would not require a significant thrust at the moon or Mars to insert the space vehicle into a trajectory which will return the space vehicle to the earth. The returning space vehicle would contain the original cargo, including the surface power system reactor. The potential exists for the returning space vehicle to reenter the earth's atmosphere should the propulsion system failure preclude an earth avoidance maneuver. Reactor earth reentry survival in a subcritical configuration will have to be guaranteed so that the risk to the general population is insignificant.

The preferred resolution to reduce the risk to the general population to an insignificant level would be ejection of the nuclear reactor at some time in the return flyby trajectory when such an action poses very little threat to the general population. This would be the most likely means of reducing the threat since a return flyby trajectory would probably call for ejection of the cargo and unused propellant since transfer vehicles do not appear to be designed for insertion into low earth orbit with such a large mass. It is not clear that the propulsion system for the SEI space vehicles would be capable of earth orbit insertion with the full cargo. The return trajectory should have a perigee altitude of at least 1000 km in case ejection of the reactor fails. If ejection of the reactor is not possible, the transfer vehicles would have to be designed to accommodate this mission abort scenario. The transfer vehicle would have to be designed so that the aerobrake, or the attached excursion vehicle, could safely insert the spacecraft into orbit about the earth. The particular flight maneuvers associated with earth orbit insertion should be chosen to minimize risk to the general population. Because the reactor will not be operated until it is emplaced on the surface of the moon or Mars, mission risk will not be aggravated by a fission product inventory. The safety issue of a nuclear propulsion system as part of this returning space vehicle was not addressed since it was outside the scope of this task.

Disposal After Operation on Planet

The problem of safe disposal of the used nuclear reactor core is a complex issue. The problem involves fuel and fission product containment, radiation exposure and diversion.

Three disposal schemes have been proposed: 1) storage in place, 2) storage away from the power production area, and 3) insertion into a parabolic trajectory. Of the three, disposal by insertion into a parabolic trajectory will involve launching the used reactor core from the surface of the moon and Mars. Disposal by parabolic trajectory from the moon and Mars has the potential for accidents during launch from the planet surface and boost from orbit around the planet. These accidents may leave the planet surface or the orbit contaminated. An unplanned retrieval from orbit will create circumstances for additional accidents and significant radiation exposure to astronauts if their presence is required.

Disposal by launching the used reactor core to a nuclear safe orbit about the moon or Mars (not one of the preferred disposal schemes) would result in the used reactor presenting a hazard for future flights. Boost to a nuclear safe orbit from low earth operating orbits has always been desirable in other missions, e.g., SP-100 and Multimegawatt, since it minimizes the risk to the public and the cost of disposal. As previously mentioned, launches from the moon and Mars will involve the potential for contamination of the planet surface after a launch accident.

Lunar and Mars surface disposal, i.e., storage in place or away from the power production area, eliminates the hazards associated with schemes that require launching from the planet surface for disposal. However, the environmental safety concerns become important for long periods of time. Storage by these means will require fission product containment for hundreds of years. During long storage times, provisions must be made to restrict access to the storage areas to avoid overexposure to the radiation. These provisions must be viable for the time required to either allow for radioactive decay to reduce the radiation hazard to acceptable levels or until a safer method of disposal can be found. Markers may have to be employed to prevent losing track of the disposal site over hundreds of years.

Any method of surface storage of the used nuclear reactor fuel would be dependent upon the need to remove the used core from the power production area for such purposes as reusing portions of the existing power system versus the ability to safely remove the used core without overexposing the astronauts or contaminating the environment while removing the spent fuel. This issue has been considered should the decision be made in the future to require the removal of the reactor from the vicinity of the base. A commitment to permanent human occupation of the lunar surface may require removal of the used reactors from the base area to avoid clustering these radioactive sources around the base. Spent fuel removal could be accomplished by means of robots to prevent astronaut exposure. Should the use of robots to remove the fuel fail, remedial efforts may be required; these should minimize astronaut exposure. Spent reactor fuel stored on Mars would be required to withstand the martian environment for many years. A risk assessment must be performed to assist in determining which disposal scheme is best. The disposal strategy must have minimum astronaut interaction and adequate long term safe storage with minimum risk.

Outpost Contamination

Accidents on the surface of the moon and Mars may result in the release of fission products. Contamination of the surface may result in contamination of the habitats. Astronauts may walk through a contaminated area and carry the fission products to the habitat on the extravehicular mobility unit. Containment of the fission products on the surface of Mars will be further complicated by the martian winds. A reactor containment/guard vessel is recommended.

Reactor Stranded in Orbit

The Space Exploration Initiative mission profiles will increase the number of potential accidents in low earth orbit which may lead to inadvertent reentry above that for previous SP-100 mission profiles. However, most of the new accidents will not introduce any new reentry environment that has not been identified in the SP-100 program. Those accidents which strand an undamaged reactor in earth orbit may result in the reactor entering the atmosphere under conditions for which the SP-100 reactor is currently being designed. A damaged reactor, however, has the potential to release fuel during inadvertent reentry and earth impact (Ref. VIII-1). A risk assessment (Ref. VIII-1) has been performed of potential SP-100 missions involving the inadvertent reentry of a damaged reactor. The risk was found to be low. A new reactor would have to be analyzed and tested as the SP-100 has been, and as a flight qualified SP-100 would have to be.

A reactor stranded in orbit about the moon or Mars will not pose a risk to the population of the earth. However, it may pose a hazard to future flights which require insertion into the same orbit to descend to the outpost. The hazard associated with an intact reactor orbiting about the moon or Mars may be insignificant or easily resolved by tracking. A damaged reactor which is part of a debris field resulting from an accident may pose a hazard of significance. A reactor which has undergone an excursion may add a radioactive element to the hazard. The risk to a mission of a reactor stranded in orbit about the moon or Mars is expected to be low because transfer vehicle designs will maximize the chances for astronaut survival and this design philosophy will reduce the probability for a reactor stranded in orbit. An analysis needs to be performed to validate that the risk to a mission of a nuclear reactor, damaged or not, stranded in orbit about the moon or Mars is low.

Although the following safety issues are not usually considered nuclear system safety issues, they have been included for completeness. Astronaut contact with the high voltage power cables and the loss of power to the habitat life support systems threaten the lives of the astronauts. As part of the total power system design, including power distribution and backup for critical life support systems, these issues are discussed below.

High Voltage Power Cables

One option for the distribution of power from the nuclear reactor to the various areas of the outpost is cable placed above ground. Whether this cable is placed on the surface or suspended above the surface, it will be a safety hazard to the astronauts. Either physical barriers or proximity warning systems should be used to protect the astronauts. Possible methods to protect the astronauts would be suspending the cable high enough to allow any vehicle to pass safely below, posting warning signs and beacons along the length of the cable, developing a warning system installed in EMUs which would alert the astronaut to the presence of the cables, and restricting access to areas in the outpost by physical barriers and the establishment of pathways to be used within the outpost area. There is likely a very large number of solutions to this safety hazard, a combination of some of which will provide safe working conditions without a significant mass penalty.

Loss of Power to Habitat

This issue is not normally considered a nuclear safety issue. It has been included here because it does have an impact on the safety of the astronauts. The following discussion will have some application to any central power system used on the moon and Mars.

In all cases where the nuclear reactor is shutdown due to a failure and in some cases where power is reduced, the habitat will not have sufficient power to maintain life support systems. It is the responsibility of the power system designer to prevent a power system response which will place the astronauts in a life threatening situation. An uninterruptible power source must be provided which will maintain minimum life support capabilities.

Habitat power requirements in the case of nuclear reactor shutdown or power-down will be time dependent based upon the response of the habitat life support systems to a loss of power. Power requirements immediately after loss of power may be very small, only that needed to provide lighting and energy to open and close airlocks so that astronauts will be able to exit the habitat to obtain other sources of power that are available to replace the nuclear reactor until it is repaired or the outpost is abandoned. An analysis must be performed to identify the power needs of systems after a nuclear reactor power system shutdown or power reduction.

The solution to this safety hazard will require the mix of stationary and mobile surface power systems be coordinated. Safety requirements will certainly demand all systems meet specific availability goals. These goals may result in a set of mobile power source units always located at the outpost within specified distances from the habitat. Photovoltaic power sources may supplant mobile power sources during the lunar day.

A reliability, availability, and maintainability (RAM) analysis is required of all surface power systems (including extravehicular mobility units) with respect to meeting the life support requirements of the astronauts. These life support requirements would include maintenance of the excursion vehicle to provide the astronauts the option to abandon the outpost. The goals of the RAM analysis must be consistent with the purpose of the outpost and the restrictions placed upon any emergency options due to the remoteness of the outpost from earth and the harsh environment in which the outpost exists.

Reactors designed for low earth orbit applications are typically required to meet reliability goals. Reliability goals are used for systems which are not repairable. The nuclear reactor power system for the moon and Mars may have some degree of repairability. Also, the availability of power to the astronauts is most important. As such, it would seem that an availability goal is more appropriate. A nuclear power system should be designed with an availability goal(s) for power to sustain life support systems and other vital power consumers as a part of a total power management and distribution system of stationary and mobile power sources. A RAM analysis is advised.

8.3 SP-100 RESOLUTIONS REVISITED

The missions postulated for the SP-100 Reference Flight System have been in orbit about the earth without the presence of astronauts. The use of an SP-100 as a power source on the surface of the moon and Mars requires the reactor power system to be man-rated and be subject to a new set of potential accident environments and operating conditions. This section contains a discussion of the results of a cursory examination of the safety issue resolution approaches and design features used in the SP-100 Reference Flight System in light of the new missions.

Launch Aborts

Larger launch vehicles have been proposed for the lunar and Mars missions. When sufficient design details are forth coming, data characterizing the environments resulting from launch vehicle failures will have to be generated and compiled in the same manner as has been done for the Space Shuttle (Ref. VIII-6) and the Titan IV (Ref. VIII-7). These new environments and failure rates will then be used to design the nuclear reactor to survive these environments as has been done for the Galileo spacecraft (Ref. V-2) and will be accomplished for the SP-100.

Diversion

The safety issue of diversion has been previously covered in the SP-100 program. Additional potential diversion conditions would result from inadvertent reentries due to unsuccessful flights to the moon and Mars where the nuclear reactor would return to earth on safe return flyby trajectories. As discussed above concerning return flyby trajectories, this safety issue could be solved by ejection of the reactor into space away from the earth.

Decay Heat Removal

The SP-100 Reference Flight System uses the primary coolant loop and the auxiliary coolant loop systems to remove decay heat from the reactor core after shutdown. The auxiliary coolant loop system consists of bayonet tubes inside the reactor core in which coolant is pumped by TEM pumps to a radiator where the heat is rejected to space. The primary coolant loops also use TEM pumps. These systems have been designed for operation in zero-g space.

A steady state analysis (Ref. VIII-8) was performed to determine the feasibility of designing a primary heat transport loop with the capability of removing reactor decay heat by natural convection. The study was based upon a 2.36 MW_t SP-100 reactor operating on the lunar surface with either a Brayton or a Stirling power conversion subsystem. The reactor-to-Stirling heat exchanger was assumed to have properties similar to that of the Brayton heat exchanger. Two flat linear induction pumps were assumed in series in the single loop. Figures 8-1 and 8-2 illustrate the temperature differences developed across the reactor as a function pipe height and diameter. Figure 8-1 presents results of the analysis at one second after shutdown and Figure 8-2 presents similar results for 50 seconds after shutdown. Temperature differences were on the order of 100 C to 200 C for a configuration of 6 m from reactor to heat exchanger with 8 cm diameter pipe. Thus, excessive temperatures would not occur if the reactor design used natural convection in the primary coolant loop should the secondary heat transfer loop fail to provide a heat sink. A transient analysis is required to confirm that reactor temperatures are not excessive.

A potential method to accommodate a loss of coolant accident is containment of the primary coolant loop inside a guard vessel. When the primary loop fails, the escaping coolant would be contained within the guard vessel. The guard vessel would be designed so that the captured coolant would cover the reactor and decay heat would be rejected by heat pipes or radiator attached to the guard vessel wall or by direct radiation. A cursory steady state thermal analysis was performed to determine the temperature drop from the reactor to the guard vessel for a lunar application. The break in the primary loop was assumed to have occurred so that the coolant levels inside the guard vessel and inside the reactor primary loop were the same. The resulting temperature drop was on the order of 950 to 1000 °F. Only conduction heat transfer was assumed since analysis had indicated that natural convection heat transfer was doubtful. However, the analysis indicated that it is possible to remove the decay heat by boiling. Provided the pressure inside the guard vessel can be kept close to the martian atmospheric pressure,

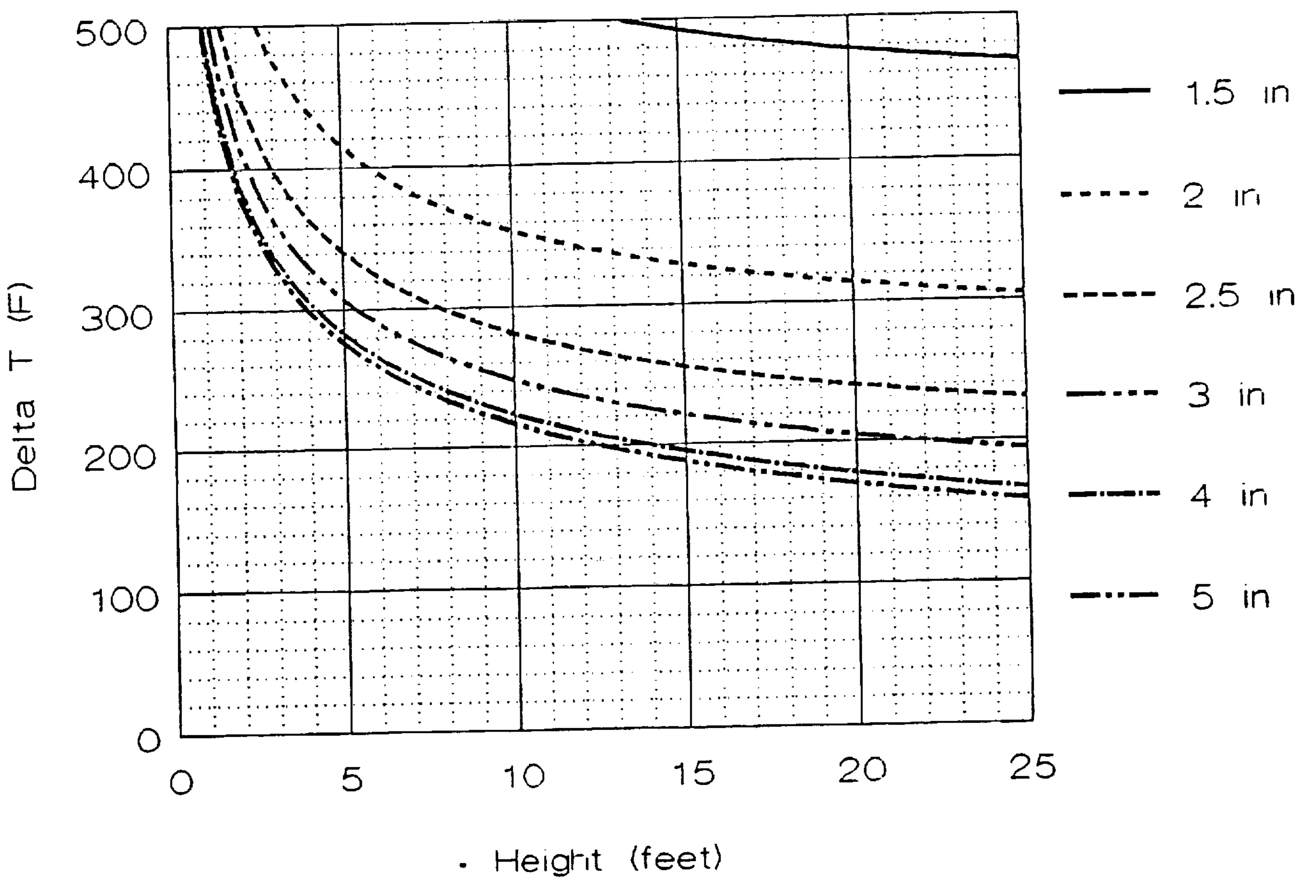

Figure 8-1 Thermal Driving Head at 6.57% of Full Power for SP-100 as a Function of Height and Pipe Diameter (Ref. VIII-8).

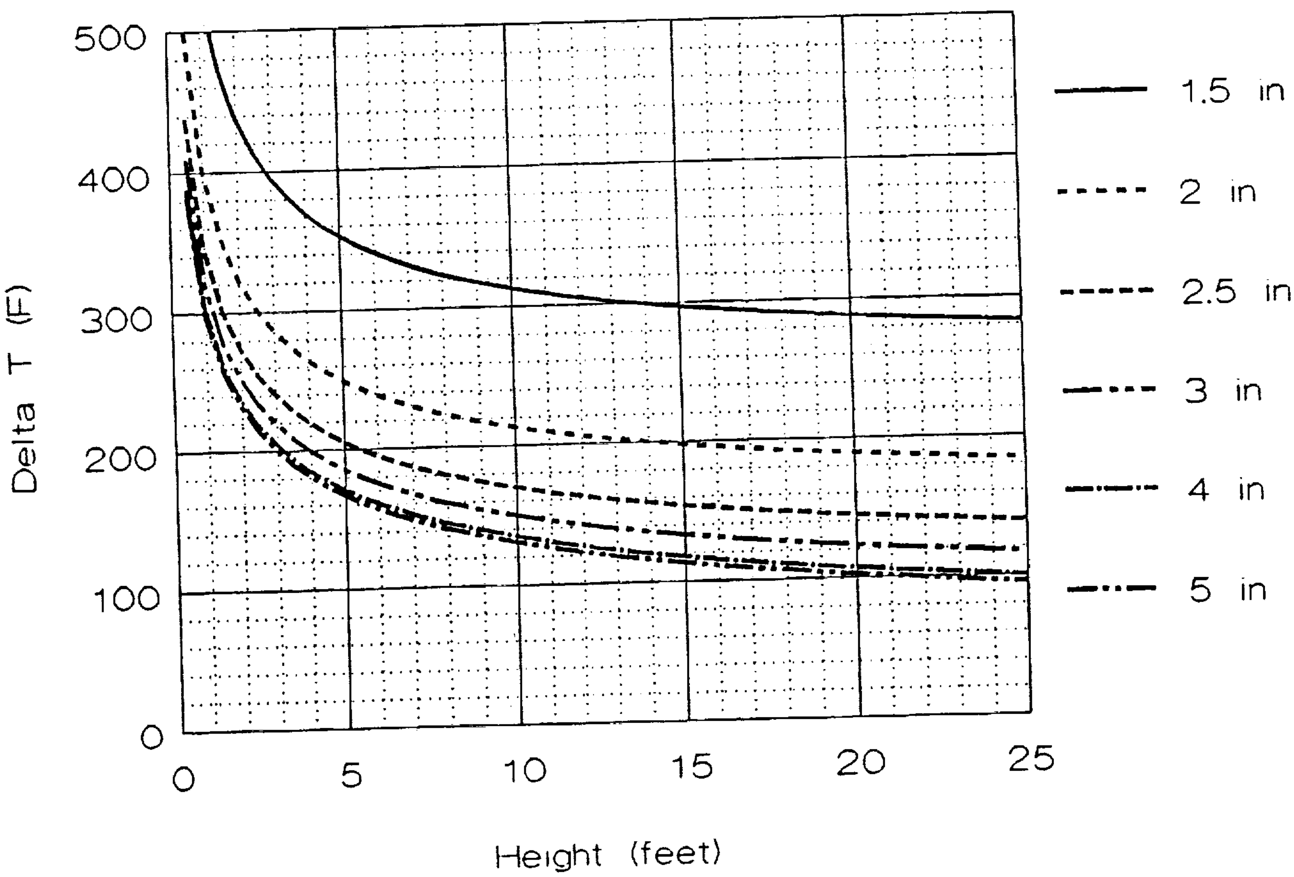

Figure 8-2 Thermal Driving Head at 3% of Full Power for SP-100 as a Function of Height and Pipe Diameter (Ref. VIII-8).

the lithium saturation temperature of 1156 K (corresponding to maximum atmospheric pressure) would be well below the normal operating temperature of the reactor. A transient analysis is required to estimate peak fuel cladding temperatures to verify this method of accommodating a loss of coolant accident. Should this method be found adequate, an auxiliary coolant loop system such as used on SP-100 would not be used.

Gas Management

To remove the threat of uncovering the reactor core due to gas formation inside the primary coolant, a gas separator/accumulator has been used for SP-100. This should be eliminated in favor of a conventional expansion tank similar to those used for terrestrial reactors. This will take advantage of the effects of gravity and yield a more reliable system.

Reactor Control

Reactor control with BeO reflectors may not be adequate for a man-rated reactor. Leakage out the reactor may be significantly reduced by a man-rated shield in close proximity to the reactor. Poison backed reflectors may be required to reduce the backscattering produced by the shield. An analysis with benchmark testing is required.

Currently, the possibility of astronauts performing maintenance or repair activities is remote. As such, consideration should not be given to a reactor design which allows for replacement and maintenance of reflectors, safety rods, and reflector and rod drive mechanisms.

Power to monitor reactor status and restart the reactor after shutdown for the SP-100 reactor is provided by battery for a very short period of time, on the order of a few hours. This may not be sufficient for reactor applications on the moon and Mars if system diagnosis is to be performed and some repair work is to also be performed. A much longer period of time will be required for diagnosis and repair in addition to startup. To minimize the chances for astronaut overexposure during repair activities after shutdown, an uninterruptible power supply to the nuclear power system monitoring and safety systems should be provided. This power supply may consist of batteries for the short period of time required to locate and move a mobile power source to the reactor site. A RAM analysis would determine power source requirements based upon the mean-times-to-diagnosis and -repair the reactor failures. A nuclear reactor power system without the possibility of repair would eliminate this safety issue. However, the ability to monitor a failed system until a safe shutdown has been accomplished would be wise.

The conventional approach to regulating the electric load demand for an unattended space nuclear power system is to employ a shunt resistor between the power system and the load. This method requires the reactor operate at full thermal power at all times. The difference between the power output of the power system and the load is rejected into space as heat. Unnecessary fuel burnup results if the load demand is lower than the power produced. However, the shunt is required if the integrated power system is not inherently load following. A study (Ref. VIII-9) of the integrated SP-100 thermoelectric converter power system has shown that the power system may not be load following at all demand levels. For any region where the power system would not be load following, a shunt regulator could be employed. There have been studies suggesting the use of active feedback controllers (Refs. VIII-10 and VIII-11). The design of such control systems are in the conceptual stage. A dynamic power conversion system designed to be load following is suggested to eliminate this problem.

Inadvertent Startup

Inadvertent startup of the reactor is currently prevented by locking safety rods inside the reactor core and reflectors in the least reactive position. To move these rods and reflectors, a coded command sequence is required to power the rod and reflector actuators. For SEI applications, inadvertent startup should be prevented by using a key lock mechanism which requires an astronaut or robot to initiate startup. This mechanism could be similar to those used on the SNAP and SP-100 programs at launch.

End of Life Shutdown

End-of-life shutdown is a safety issue because a nuclear reactor that fails to shutdown may preclude access to the power production site to emplace a replacement reactor or to remove the reactor for disposal away from the power production area. Final shutdown should be accomplished by a clock mechanism which will activate at a preset time set prior to operation. This preset time must not be resettable. The clock mechanism must be single fault tolerant. It must operate independently of the reactor operating mode or the power conversion subsystem operation. It must also irreversibly interrupt the power supply to the reactor control drives, both safety rods and reflectors.

Availability

Reactors designed for low earth orbit applications are typically required to meet reliability goals. Because reliability and safety are so closely related, some discussion is necessary concerning reliability goals and their applicability to planet surface reactor power systems for manned missions. Reliability goals are used for systems which are not repairable. The nuclear reactor power system for the moon and Mars may have some degree of repairability. Also, the availability of power to the astronauts is most important. As such, it would seem that an availability goal is more appropriate. A nuclear power system should be designed with an availability goal(s) for power to sustain life support systems and other vital power consumers as a part of a total power management and distribution system of stationary and mobile power sources.

9.0 REFERENCES

I-1 "SP-100 Reference Flight System System Design Review." General Electric. May 1988.

III-1 Cohen, Aaron. "Report of the 90-Day Study on Human Exploration of the Moon and Mars (Advance Copy)," NASA, November 1989.

III-2 Weaver, D. "Lunar Evolution Case Study," MASE, July 1989.

III-3 McDaniel, G. Inhouse ETO, Presented at the Human Exploration Initiative Status Review Meeting, NASA, George C. Marshall Space Flight Center, February 28, 1990.

III-4 "Lunar/Mars Outpost: Interim Review #1," Martin Marietta, December 14, 1989.

III-5 Cothran, B., and J. McGhee. "Space Transfer Concepts and Analysis for Exploration Missions." The Boeing Company. NASA Contract NAS8-37857, Presented at the Nuclear Propulsion Workshop, Pasadena, CA, June 19-22, 1990.

III-6 Sumrall, P. "MTV/MEV Overview," Presented at the Human Exploration Initiative Status Review Meeting, NASA, George C. Marshall Space Flight Center, February 28, 1990.

IV-1 "Guidance on Radiation Received in Space Activities." U. S. NCRP. Report No. 98, July 1989.

IV-2 Bloomfield, H. S. "Overview of NASA Radiation Exposure Limit Guidelines for Spaceflight Crewmembers," NASA LeRC, presented at the 36th annual meeting of the American Astronautical Society, Los Angeles, CA, November 3, 1989.

IV-3 Bloomfield, H. S. "Small Reactor Power Systems for Manned Planetary Surface Bases." NASA LeRC. Technical Memorandum 100223, December, 1987.

IV-4 Mason, L. S., H. S. Bloomfield, and D. C. Hainley. "SP-100 Power System Conceptual Design for Lunar Base Applications." NASA LeRC. Technical Memorandum 102090, January 1989.

V-1 O'Handley, Douglas. "Exploration Back to the Moon, to Mars, to the Stars," presented at the 36th annual meeting of the American Astronautical Society, Los Angeles, CA, November 3, 1989.

V-2 "Final Safety Analysis Report for the Galileo Mission." U. S. DOE. Contract Number DE-AC01-79ET32043, December 1988.

V-3 "DIPS Conceptual Design Safety Assessment," Rockwell International, Rocketdyne Division. Report DIPS-0029-00, DOE Contract No. DE-AC01-88NE32129, 1988.

V-4 "SP-100 Reference Flight System, System Design Review." General Electric. May 1988.

V-5 "SP-100 Program Industry Briefing." General Electric. July 1990.

VI-1 "Meteoroid Damage Assessment." NASA. Report SP-8042, May 1970.

VII-1 "Exploration Back to the Moon, to Mars, to the Stars." Rockwell International, Satellite Systems Division, 1989.

VIII-1 Bartram, B. W., and A. Weitzberg. "Radiological Risk Analysis of Potential SP-100 Space Mission Scenarios." NUS Corp. Report No. 5125, U. S. DOE Contract DE-AC01-88NE32135, August 1988.

VIII-2 Buden, D. "Mars Mission Safety", Aerospace America, June 1989.

VIII-3 "Final Safety Analysis Report for the Galileo Mission and the Ulysses Mission." U. S. DOE. GESP 7200, DOE Contract DE-AC01-79ET32043, October 1985.

VIII-4 Keshishian, V. "DIPS Radiation Shielding," Rockwell International, Rocketdyne Division, Report EID-00087, March 1990.

VIII-5 Ferguson, D. C., and J. M. Winter. "The SP-100 GES and CSTI High Capacity Power Space Environmental Effects Program." Proceedings of the Seventh Symposium on Space Nuclear Power Systems, Albuquerque, NM, January 7-10, 1990.

VIII-6 "Space Shuttle Data for Planetary Mission Radioisotope Thermoelectric Generator (RTG) Safety Analysis." NASA. Report NSTS 08116 (Rev. B), September 1988.

VIII-7 "Titan IV Radioisotope Thermoelectric Generator (RTG) Safety Databook." NASA LeRC, March 1989.

VIII-8 Johnson, G. A. Internal Letter to R. B. Harty, "SP-100 Lunar Surface Natural Circulation Decay Heat Removal," Rockwell International, Rocketdyne Division, August 6, 1990.

VIII-9 El-Genk, M. S., J. T. Seo, and J. J. Buksa. "Load-Following and Reliability Studies of an Integrated SP-100 System." J. Propulsion, Vol. 4(2), March-April 1988.

VIII-10 Metzger, J. D., M. S. El-Genk, and A. G. Parlos. "Application of a Model-Reference Adaptive Controller to Ensure Load-Following of an SP-100 Type Space-Nuclear Power System." Proceedings of the Seventh Symposium on Space Nuclear Power Systems Albuquerque, NM, January 7-10, 1990.

VIII-11 Parlos, A. G., and S. K. Menon. "Design of a Nonlinear Controller For Rapid Power Level Changes in Nuclear Systems." Proceedings of the Seventh Symposium on Space Nuclear Power Systems, Albuquerque, NM, January 7-10, 1990

APPENDIX A
LUNAR AND MARTIAN ENVIRONMENTS

To accomplish a safety issue identification, it is necessary to predict power system response to the environments to which it will be exposed. This section contains a brief summary of the lunar and martian environments. The information presented was taken from References A-1 and A-2.

Moon

The atmospheric density measured during the Apollo program indicated a surface nighttime value of 2×10^5 molecules/cm^3, approximately sixteen orders of magnitude less than earth standard. Lunar atmosphere composition is listed in Table 1.

Table 1
Lunar Atmosphere (Ref. A-1)

Gas	Concentration (molecules/cm^3) Day	Night
H_2	$< 6 \times 10^3$	$< 4 \times 10^4$
He	2×10^3	4×10^4
Ne	-	$< 10^5$
Ar	-	$< 3 \times 10^3$

The surface of the moon has two major regions, maria with vast plains of basaltic lava flows and the highlands. The surface of the moon is strongly fragmented. This mantle, the regolith, consists of shocked fragments of rocks, minerals, and glass spherules formed by meteor impact. The maria regolith varies from 3 to 16 meters thick and the highlands have a regolith depth of at least 10 meters. The typical composition of the regolith is shown in Table 2 with a few physical properties listed in Table 3.

Meteor impact rate per cm^2 is believed to be between 1.1 and 50 craters per million years for craters greater than 500 μm. The micrometeoroid flux for the lunar surface has been estimated to be modeled by the following:

$$\text{Log } N = -14.64 - 1.584 \text{ Log } m - 0.063 (\text{Log } m)^2, \quad 10^{-12} \text{ gm} \leq m \leq 10^{-6} \text{ gm}$$

and

$$\text{Log } N = -14.671 - 1.213 \text{ Log } m, \quad 10^{-6} \text{ gm} \leq m \leq 1 \text{ gm}.$$

Table 2
Regolith Chemistry (Ref. A-1)

Compound	Weight %
SiO_2	44.5
Al_2O_3	26.0
TiO_2	0.39
FeO	5.77
MgO	8.06
CaO	14.9
Na_2O	0.25
Cr_2O_3	0.06

Table 3
Lunar Regolith Physical Properties (Ref. A-1)

Parameter	Nominal Value
Thermal Conductivity (cal/sec-cm-K)	$1 - 2.8 \times 10^{-5}$
Thermal Inertia (cm^2-$sec^{1/2}$K/cal)	400 - 1000
Specific Heat (cal/gm-K)	0.20
Emissivity	0.9 - 1.0

It has been postulated that meteoroid impacts will result in the ejection of lunar material up to an altitude of 30 km. An average annual individual cumulative lunar ejecta flux-mass distribution over three ranges of the ejecta velocity, V_{ej}, is described by

$$\text{Log } N_{ej} = -10.79 - 1.2 \text{ Log } m, \quad 0 \le V_{ej} \le 0.1 \text{ km/sec},$$

$$\text{Log } N_{ej} = -11.88 - 1.2 \text{ Log } m, \quad 0.1 \le V_{ej} \le 0.25 \text{ km/sec},$$

and

$$\text{Log } N_{ej} = -13.41 - 1.2 \text{ Log } m, \quad 0.25 \le V_{ej} \le 1.0 \text{ km/sec},$$

where

N_{ej} = number of ejecta particles of mass m or greater per m^2-sec,

m = particle mass (gm),

V_{ej} = particle velocity (km/sec).

Figure 1 shows a model of the lunar surface temperature as a function of thermal inertia. A thermal inertia value of 800 cm^2-$sec^{1/2}$-K/cal appears to best fit data taken at the lunar equator.

Mars

Key physical properties of Mars are listed in Table 4. The composition of the martian atmosphere is mostly carbon dioxide as shown in Table 5. Wind

Table 4
Key Physical Properties of Mars (Ref. A-2)

Surface Temperature (K)	130-300
Insolation; Average Surface at Equator (kW/m^2)	0.18
Surface Pressure (mbar)	6-15
Water Vapor (μbar)	0.13
Surface Wind Speed (m/sec)	2-7

Table 5
Martian Atmosphere (Ref. A-2)

Gas	Mole Percent
CO_2	95.3
N_2	2.7
Ar	1.6
O_2	0.13
H_2O	0.03
CO	0.07
Ne	2.5 ppm
Kr	0.3 ppm
Xe	0.08 ppm
O_3	0.03 ppm

driven dust layers are only centimeters or less thick. Data have indicated wind speeds up to 30 m/sec at the surface. Atmospheric dust is characterized in Table 6. The martian atmosphere is believed to be saturated with water

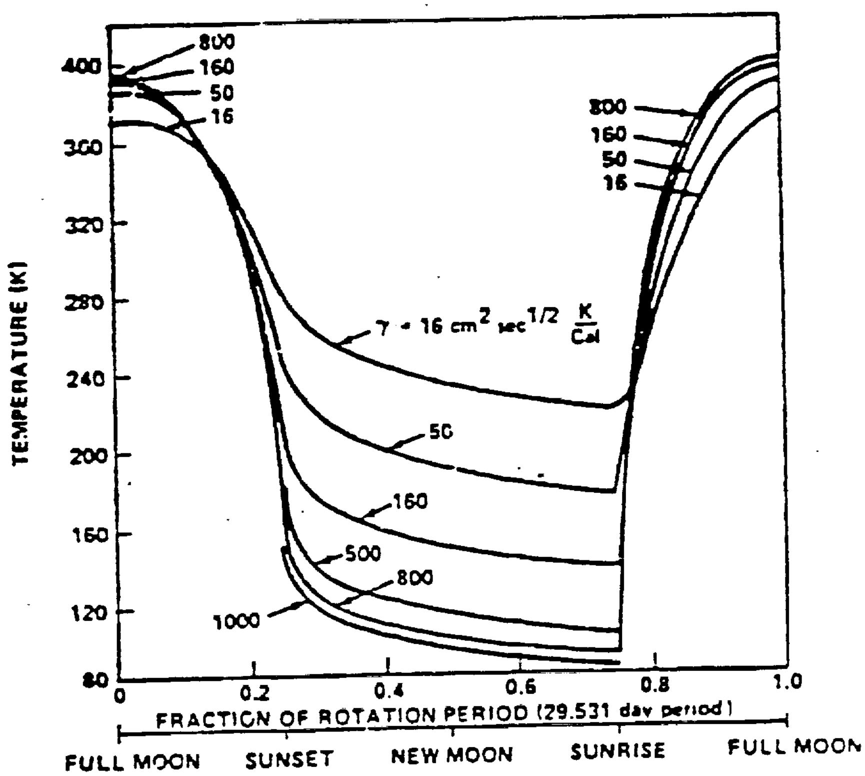

Figure 1 Lunar Equatorial Temperature as a Function of Time and Thermal Inertia (Ref. A-1).

vapor at night. Frost was found at the Viking landing sites.

Table 6
Martian Atmospheric Dust (Ref. A-2)

Dust Concentration	10 ppm
Dust Column Loading (during storm)	0.001 gm/cm^2
Air Column Loading	20 gm/cm^2
Mean Dust Particle Size	2.5 μm

Models for the martian atmosphere are shown in Figures 2 and 3. Mean low and high pressures are plotted in Figure 2. The density model couples the cool temperature model with the low pressure model and the warm temperature model with the high pressure model. The cool, low pressure model would best represent the atmosphere in late northern summer at a latitude of 45 degrees. The warm, high pressure model represents early southern summer at a latitude of 25 degrees. Figure 4 shows the surface daily mean pressure as a function of time over one martian year (687 days) at the two Viking landing sites. The scale labeled L_s represents the aerocentric longitude of the Sun. Pressures and deviations are in millibar. Diurnal temperatures observed at the two Viking landing sites over a period of one sol (24.46 hr) varied from 180 K to 240 K.

Estimates have been made of the soil composition of the martian surface and are shown in Table 7. The sum of the compounds does not equal 1.0 due to

Table 7
Composition of Martian Soil (Ref. A-2)

Compound	Weight %
SiO_2	44.7
Al_2O_3	5.7
Fe_2O_3	18.2
MgO	8.3
CaO	5.6
K_2O	<0.3
TiO	0.9
SO_3	7.7
Cl	0.7

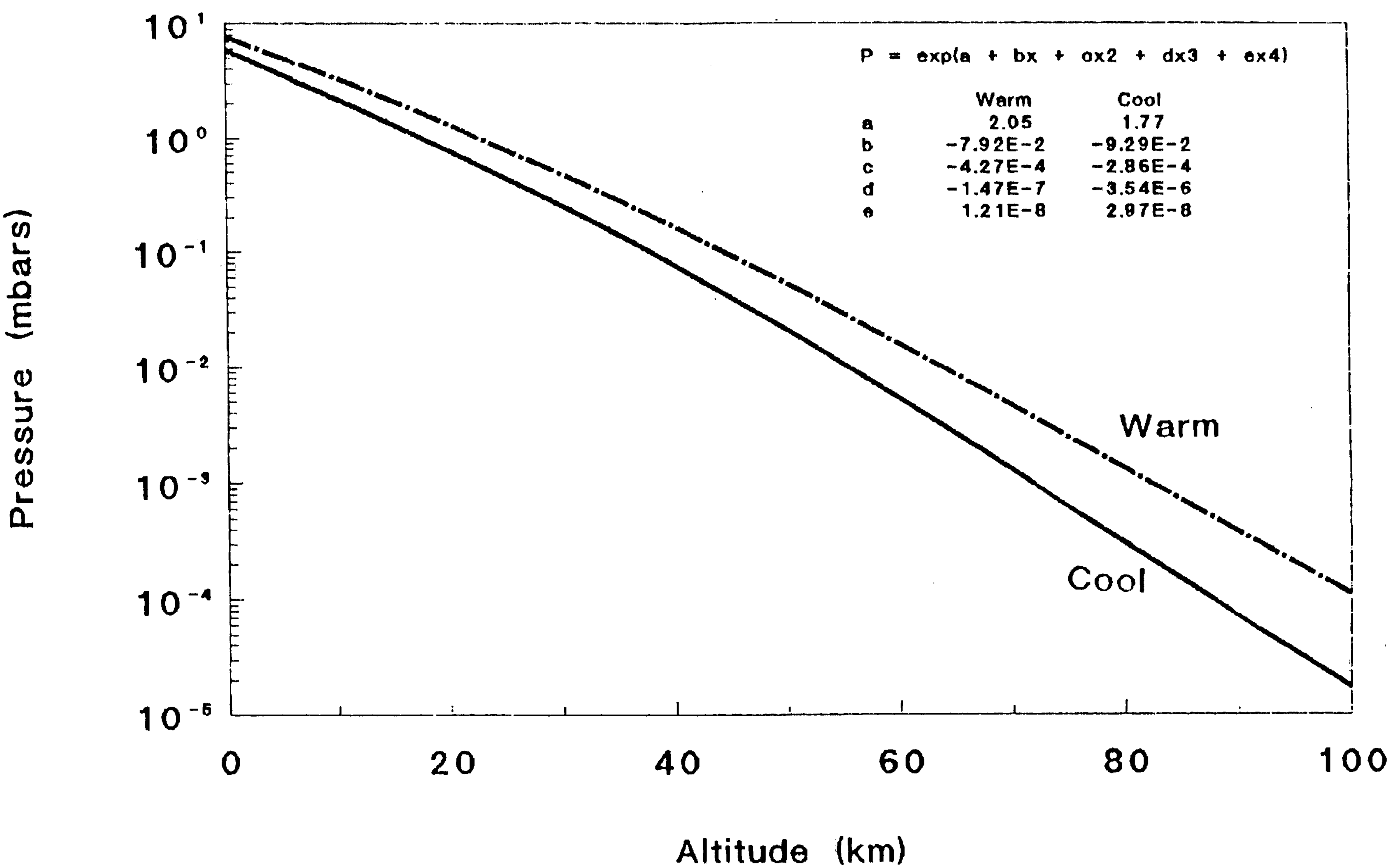

Figure 2 Martian Atmospheric Pressure (Ref. A-2).

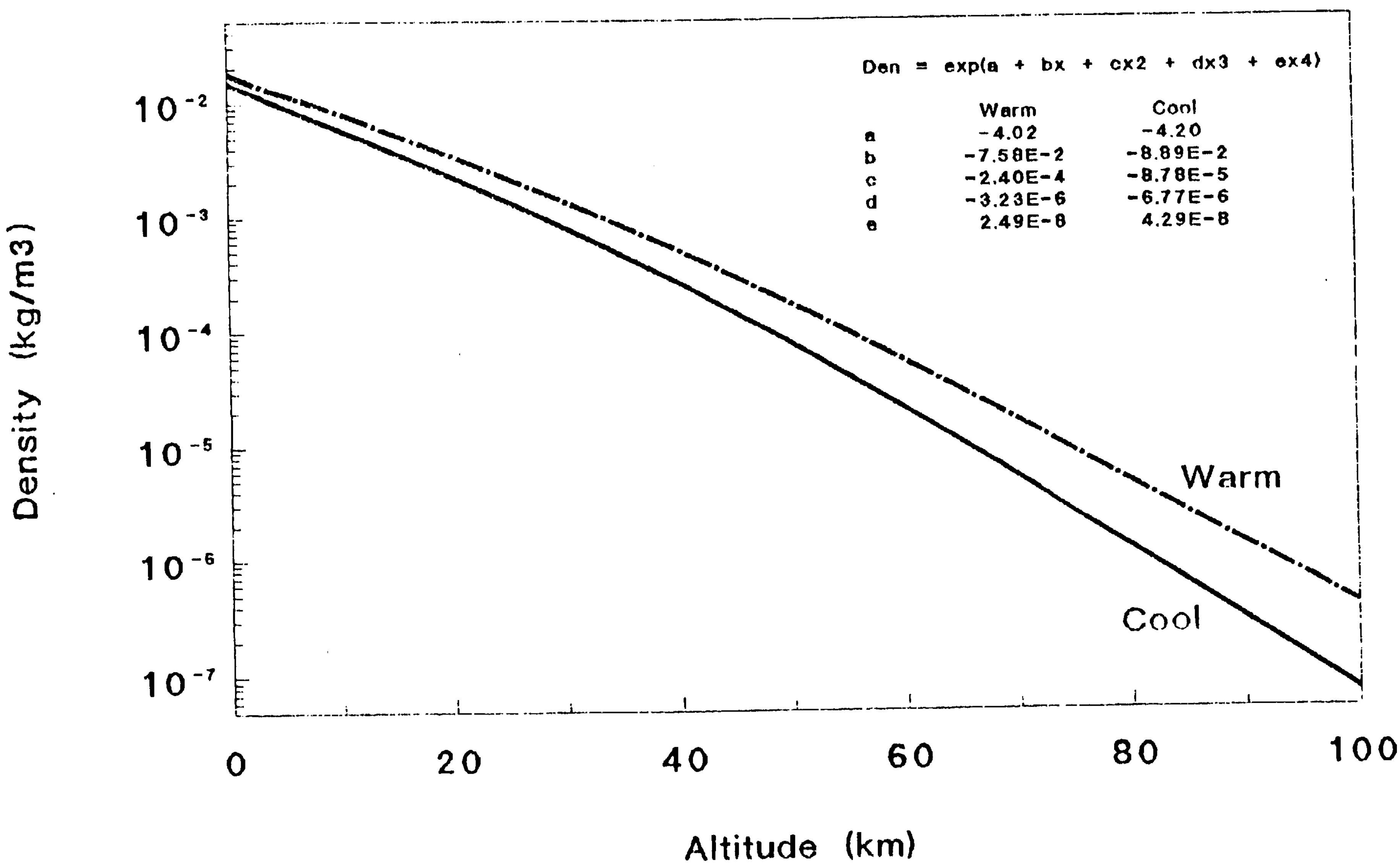

Figure 3 Martian Atmospheric Density (Ref. A-2).

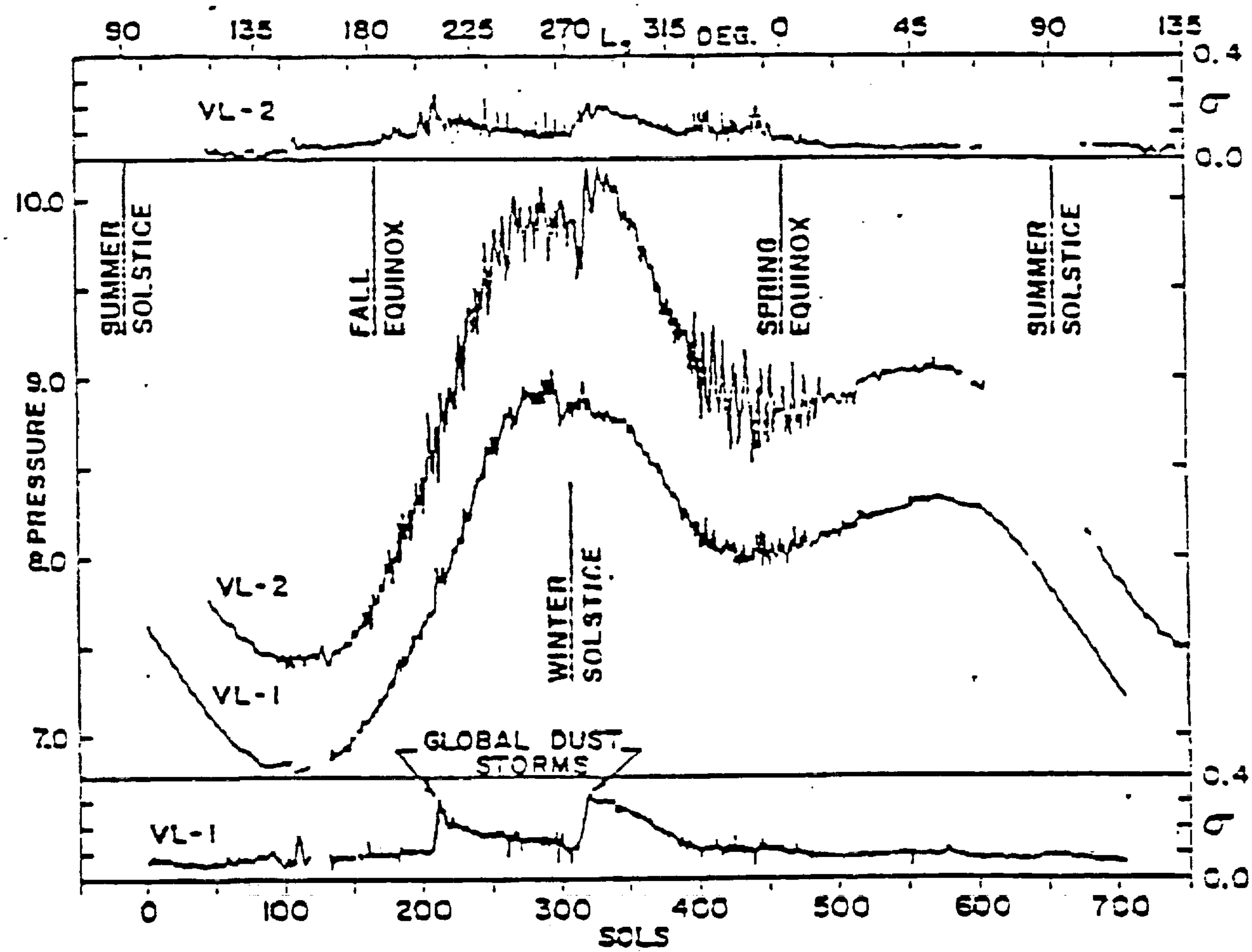

Figure 4 Martian Surface Pressure Variation Over One Martian Year (Ref. A-2).

the inability of the Viking 1 lander to detect elements with atomic numbers less than 12 (phosphorus). Mechanical properties are shown in Table 8.

Table 8
Mechanical Properties of Martian Soil (Ref. A-2)

Parameter	Nominal Value
Thermal Conductivity (cal/sec-cm-K)	$2 - 20 \times 10^{-5}$
Thermal Inertia (cm^2-$sec^{1/2}$-K/cal)	100 - 600
Specific Heat (cal/gm-K)	0.15 - 0.19
Emissivity	0.9 - 0.98
Albedo	0.2 - 0.4
Bulk Density (gm/cm^3)	1 - 1.8
Penetration Resistance ($N/cm^2/cm$)	0.01 - 0.1
Adhesion (N/cm^3)	$10^{-4} - 10^{-3}$
Density (gm/cm^3)	3.933

Surface materials contain absorbed water (1%) and carbon dioxide (50 - 100 ppm). Liquid water cannot exist on the martian surface. Evidence points to a permafrost layer varying from 1 km at the equator to several kilometers at the poles. Within 40 degrees of the equator the ground is dehydrated to a depth of at least one meter.

Oxidants have been found in the martian soil. Experiments on the Viking landers indicated that oxidizing compounds such as peroxides and superoxides are present in the martian soil which is periodically suspended in the atmosphere by the wind. Additionally, the presence of H_2SO_4 and HCl aerosols in the wind blown dust have been indicated.

REFERENCES

A-1 Johnson, G. "Lunar Surface Environmental Data," Engineering Product Document No. EID-00081, Rockwell International, Rocketdyne Division, January 1990.

A-2 Johnson, G. "Martian Surface Environmental Data," Engineering Product Document No. EID-00082, Rockwell International, Rocketdyne Division, January 1990.

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15. Supplementary Notes

16. Abstract

This report presents the results of a study to identify potential hazards arising from nuclear reactor power systems for use on the lunar and martian surfaces, related safety issues, and resolutions of such issues by system design changes, operating procedures, and other means. All safety aspects of nuclear reactor power systems from prelaunch ground handling to eventual disposal were examined consistent with the level of detail for SP-100 reactor design at the 1988 System Design Review and for launch vehicle and space transport vehicle designs and mission descriptions as defined in the 90-day SEI study. Information from previous aerospace nuclear safety studies was used where appropriate.

Safety requirements for the SP-100 space nuclear reactor system were compiled. Mission profiles were defined with emphasis on activities after low earth orbit insertion. Accident scenarios were then qualitatively defined for each mission phase. Safety issues were identified for all mission phases with the aid of simplified event trees. Safety issue resolution approaches of the SP-100 program were compiled. Resolution approaches for those safety issues not covered by the SP-100 program were identified. Additionally, the resolution approaches of the SP-100 program were examined in light of the moon and Mars missions.

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