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EVALUATION OF SNAP
REACTOR DISPOSAL TECHNIQUES

AEC Research and Development Report

ATOMICS INTERNATIONAL

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By

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I. INTRODUCTION

The safe use of SNAP reactor systems is predicated on the degree to which the system accommodates and provides adequate solutions for the following two potential radiological problems.

- 1) Fission products generated under accident conditions, and
- 2) Fission products generated during normal operation

These are the only potential radiological problem areas associated with SNAP reactor utilizations, since criticality is a prerequisite to the generation of fission products and their associated radiological safety problems.

Other studies in the Nuclear Safety program are directed towards solution of the first problem area. This report directs its attention to the second problem area concerning satisfactory disposal of the fission products generated during the mission. It is therefore the objective of this study to identify and provide a logical method for selecting the best means of disposing of fission products generated during normal operational space reactor systems.

In order to properly scope the magnitude of the disposal problem, it is necessary to study the quantity of fission products generated. This magnitude depends upon the reactor power level and the duration of reactor operation. These quantities determine the ultimate concentration of fission products which must be disposed of, and is shown in Figure 1. In considering techniques for such disposal, the significant variables include reactor power level, orbital parameters, and ballistic coefficient. The orbit altitude and the ballistic coefficient determine the satellite lifetime, hence, the time available for decay of the fission products prior to atmospheric reentry. The relationship between orbit lifetime and orbit altitude for two typical ballistic coefficients is shown in Figure 2. It can be seen that, for most space missions above 450 nautical miles (n. mi), the reactor system will remain in orbit for greater than 300 yr. If a reliable technique is employed to terminate reactor operation, then it can be seen from Figure 1 that reactors at altitudes greater than 450 n. mi will contain little or no fission product inventory when they reenter. If the reactor is in a subcritical configuration following reentry and water impact, or if the

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Figure 1. Dose Rate at 1 ft From Reactor, No Self-Shielding

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Figure 2. Satellite Orbit Lifetime

reactor is designed to be intrinsically subcritical in water, then any mission at altitudes greater than 450 n. mi is obviously safe, and can present no hazard to the general population. Hence, this class of reactor mission (which may represent the largest potential use) presents no safety problems and will not be discussed further.

Only the space reactor systems which can be classified as near-earth orbit missions with high power levels require disposal schemes. The most likely application for reactors under these conditions is the manned space station; however, some high-power short-duration unmanned applications may also require near-earth orbits. The emphasis for this study will be the low earth orbit manned space station.

Under these conditions, the range of orbit conditions requiring disposal can be defined by the appropriate orbital criteria. For continuous manned operation in orbits about the earth, the limit is found to be a rather narrow range of altitudes. The radiation belt places an upper limit to the altitude which can be used for these near-earth orbits. An upper altitude of about 330 n. mi for a circular orbit will approximate the lower edges of the radiation belt. This value is chosen as the upper limit for near-earth manned space stations. It is possible to design a space station which will have an elliptic orbit and spend more time at higher altitudes; but for our considerations a circular orbit is adequate.

For a lower altitude, it is assumed that any space station which will utilize nuclear power will be in an orbit of greater than two months duration. For shorter orbits, the main advantage of nuclear systems (long life) is not utilized. Although some nuclear missions may develop for shorter lifetimes, they will not be emphasized in this study.

These two limits, the radiation belt and the orbit duration, produce a band in which near-earth manned space stations can be considered. This band ranges from a lower level of from 180 to 200 mi to an upper level of from 320 to 340 mi. It is within this band, shown in Figure 2, that all major near-earth manned space stations will fall.

Inclusion of unmanned reactor systems raises the operation orbit altitude for disposal investigation to about 450 n. mi. This limit is imposed by the time

for orbit decay from these altitudes. Operation at altitudes greater than 450 n. mi results in orbit lifetimes (Figure 2) greater than 300 yr for ballistic coefficients of typical reactor systems. Based upon this criterion, the altitude band used for reactor disposal investigations lies between 200 and 450 n. mi altitude.

II. SUMMARY

Active and passive reactor disposal modes have been evaluated to establish their relative merits and conditions of best application. The active disposal modes included deorbit for ocean disposal, intact earth impact and recovery, orbit enhancement, and earth escape. Random reentry was also considered as a disposal mode in the event of active disposal failure and as a primary passive mode.

Quantitative evaluation of the selected disposal modes resulted in establishment of the reliability of the intended event, the probability of hazard, weight penalties, effect on the reactor system configuration, and the state-of-the-art attainability of systems required to facilitate the event. Probability fault trees were constructed for each disposal mode with a differentiation for reactor design criteria; reentry ablation, or containment. These fault trees were based on the derived reliabilities of the various disposal systems and relations for earth land mass (26%) and the regions of this area where reactor impact will result in disassembly (68%).

The random reentry of a reactor at some future date dependent upon its mission orbital parameters and aerodynamic properties was evaluated as both a primary disposal mode and as a backup in the event of active disposal failure. The reentry ablation design results in a factor-of-100 improvement in safety for the random reentry cases evaluated; and also applies as a backup for all active disposal methods except reactor recovery.

The ocean disposal method for a spent reactor uses a propulsion system to transfer the reactor from its mission orbit to a trajectory impacting in a deep ocean area. The accuracy of the maneuver is not stringent, and results in a nominal increase in reactor system weight (18 to 20%). The system reliability is relatively high (0.943), based on a solid main propulsion system with 1 yr of space storage. Ocean disposal of a reactor designed for atmospheric ablation, primarily as a backup in the event of deboost failure, is the most preferable of the active disposal methods. This is related to the significant reduction in potential hazard for nominal weight penalty (20%) and use of off-the-shelf disposal components with minimum perturbations to present reactor system designs.

Intact reentry and recovery of a reactor for disposal is an extension of ocean disposal with a significant degree of sophistication required. Very accurate guidance, control, and large propulsion systems are required. These factors, and the increased probabilities of a fuel handling accident, since reentry ablation violates the basic intact disposal criterion, reduces the attractiveness of this method.

Reactor disposal through propulsion boost to a higher orbit, or reactor separation when the combination of reactor ballistic coefficient and orbit parameters, results in a sufficiently long satellite lifetime for fission product decay. The reactor separation scheme was found to be very attractive due to a combination of very high reliability, low weight penalties, and effect on the reactor system. This method of reactor separation cannot be universally adapted to all orbit altitudes, and can be used only above a circular altitude of greater than about 350 n. mi, for a reactor ballistic coefficient of 100 psf. This combination of altitude and ballistic coefficient provides the minimum satellite decay for fission product decay. Propulsive boost requires the use of a supplemental system package capable of performing the required orbit transfer.

Propulsion of the spent reactor out of the earth's ecological system is attractive from the standpoint of complete hazard removal. However, propulsion systems capable of performing this maneuver impart very large weight penalties (93 to 95%), with extensive reactor system perturbations, and are not presently available without development programs. Also, the probabilities of hazard for reactors designed for either reentry ablation or intact impact, while less than for random reentry, are respectively higher than the other active disposal methods. The combination of these factors places earth escape as the least desirable of the active disposal methods evaluated.

Disposal evaluations for future specified space missions using reactor power sources should be based on a figure of merit derived by the techniques outlined in this study.

III. DISPOSAL MODES

The disposal techniques for enhancement of SNAP reactor safety at conclusion of useful reactor life in a low Earth orbit are described in this section. During the past few years, many potential techniques have been proposed and discussed for safe disposal of the reactor's fission products. All of these techniques make use of boost, deboost, or reentry burnup in various combinations to successfully prevent contact between the general public and the reactor fission product inventory. The methods adopted for this disposal study are an extension of those discussed in Reference 1, where an analysis of resultant general population hazard has been made. The evaluation and comparison of the disposal schemes with respect to effects on system configuration, hazard, reliability, availability and weight penalty are presented in the next section of the report.

The spectrum of disposal modes has been categorized into five general areas which include random reentry, ocean impact, intact Earth landing with recovery, orbit enhancement, and Earth escape. Random reentry is considered a passive mode, while the others are active disposal modes. An active disposal mode failure will result in an alternate disposal mode depending on both the maneuver attempted and the type of failure associated with the primary disposal mode. A schematic of these alternatives is shown in Figure 3 for the active disposal modes. All active modes have some probability of degenerating into a random reentry upon a system failure. Therefore, this method is discussed first.

A. RANDOM REENTRY

A random reentry dispersal or impact occurs in the absence or failure of a disposal system. In the event that this should occur, the probability of impact within a given latitude interval is equal to the fraction of satellite track within that interval.⁽²⁾ This means that impact point probability for a polar orbit is equivalent for each elemental area on the surface of the Earth. Therefore, the probability of a random reentry from polar orbit in the ocean, or unpopulated region is about 0.9⁽¹⁾ The inherent design of the reactor and system dictates the final fate of the reactor upon reentry. The reentry flight mode orientation

Figure 3. Disposal Methods

and the degree of ablation resistance material will determine what occurs to the reactor assembly during this period. The spectrum ranges from intact containment at impact to complete ablation and dispersion. Both of these cases are described in the following paragraphs.

1. Ablation and Disassembly

In this case, the desired conditions are for the reactor to have been shut down in a sufficiently long-lived orbit for fission product decay. During this period of time, satellite decay occurs due to the dissipation of the satellite's potential energy by drag forces. The terminal phase of this flight results in a trajectory where aerodynamic heating ablates and disassembles the reactor vessel with subsequent exposure and ablation of the fuel rods. The event concludes with the small particles of the fuel dispersed in the atmosphere.

2. Intact Reentry

The criterion for accomplishing this event is to guarantee reactor vessel survival through the reentry heating pulse. This inherent capability could be built into the system through a design including ablation protective material, or a reactor-shield configuration that is aerodynamically stable shield-first. The hazards associated with this event are criticality and fuel handling accidents.

B. DEORBIT FOR OCEAN DISPOSAL

The ocean disposal of a SNAP reactor system is desirable from a safety standpoint since the probability of population exposure is markedly reduced from the random reentry case. The accomplishment of the reentry maneuver is predicated upon a propulsive change in orbital velocity such that a reentry trajectory terminating in the deep ocean results. The exactness of the control and propulsion systems need only be sufficient to guarantee deep ocean impact.

The reactor design alternatives (Figure 3) are the same as in the random reentry case; namely, containment through impact, with subsequent deep ocean burial or ablation and dispersal placing the resultant fallout debris immediately into the depths of the ocean. The advantage to containment and burial are the marked reduction in the probability of atmospheric contamination; however, in the event of deboost failure and if the reentry mode reverts to the previously described case of random reentry, the probability of a fuel handling accident will be increased if intact reentry is used.

C. INTACT EARTH IMPACT AND RECOVERY

This disposal mode deboosts the reactor into a reentry trajectory where impact occurs at a predetermined land recovery target area. This technique is an extension of the intact ocean burial case where a reactor capable of surviving the aerodynamic reentry heating pulse is deboosted into the deep ocean. The accomplishment of the sequence of events from orbit to recovery set criteria which involves the following: a very accurate guidance and control system for deboost alignment, large reliable propulsion system, and a configuration with orientation stability and well-known aerodynamic parameters.

Malfunction during activation of this type of disposal would result in a random reentry where the intact reactor will survive the aerodynamic heating pulse. The hazards posed by this event could be either criticality or the fuel handling accident.

D. ORBIT ENHANCEMENT

Reactor applications are likely on manned flight where orbital altitudes lie between 200 and 400 n. mi. These short lived orbits, less than 50 yr., require the use of a reactor disposal system to enhance the aspect of reentry safety. The method considered to accomplish disposal is to boost the spent reactor into a long lived orbit where sufficient time exists for the fission products to decay. Therefore, at a subsequent time when atmospheric reentry occurs all hazard can be removed by the ablation and dispersion of the reactor. The design sophistication of the boost system depends upon the intended mission. The most efficient application of a velocity change to enhance orbital lifetime is the double firing of the rocket system to produce a Hohmann transfer from the near-earth orbit to the storage orbit. It is also possible to consider the use of a single velocity increase to produce an elliptic orbit with the desired lifetime.

The failure of the boost system results in a random reentry (Figure 3) at an earlier time than that required for fission product decay. The types of boost failure that are considered include short orbits resulting from propulsion misalignment and failure to ignite either the first or second burn in a Hohmann transfer maneuver. These short orbit failure modes result in a possible atmospheric contamination hazard due to the design criterion for reentry burnup. Proceeding one step further in possible failure modes results in a reactor which for some reason does not burn up. This case results in the possibilities of criticality and fuel handling accidents.

E. EARTH ESCAPE

This method solves the safety problem by inserting the reactor into a parabolic Earth escape orbit. The obvious advantage of this method is complete removal of all associated hazards from the Earth's ecological system. The primary drawback inherent with this disposal technique lies in the very large

propulsion system requirement. This requirement is due to the change in orbit velocity by values in excess of 10,000 fps to achieve the escape maneuver.

The hazards associated with the failure of an escape maneuver are related to the finite probabilities that exist for an occurrence of all preceding disposal modes, except land recovery. The escape maneuver would be activated at a point in the orbit such that a propulsion misalignment resulting in deboost would result in an ocean impact. The hazards associated with this event would be the same as those discussed for the case where ocean disposal is the primary mode. The alternative to immediate ocean impact would be orbit augmentation to lifetimes dependent upon the propulsive change in orbit perigee altitude and orbit eccentricity. This would result in a random reentry at the conclusion of satellite decay. These possibilities are shown graphically in Figure 3.

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IV. COMPARISON PARAMETERS FOR DISPOSAL MODE EVALUATION

The criteria selected for evaluating reactor disposal techniques, and discussed in this section, were developed to facilitate quantitative analyses and comparison of the various conceptual disposal modes. Evaluation terms were grouped into the following categories: reliability, radiological hazard, weight penalty, and system requirements associated with development and performance. Criteria set down for each of the evaluation parameters are described in the following paragraphs.

A. RELIABILITY

The overall system reliability was divided into the aspects of the probabilities associated with fault tree analyses; disposal guidance, control, and propulsion systems; reactor system operation due to modifications or added components; and the inherent reactor ablation characteristics. The reliability of the guidance, control, and propulsion systems investigated for disposal use was based on the results presented in the study ⁽³⁾ conducted by Space Division of NAA. These results include the related effects of guidance, control, propulsion systems, and the orbit storage factors. The reactor ablation characteristics during hypersonic flight in the atmosphere were selected as the basis for determining reliability of atmospheric dispersal or containment.

B. HAZARD

Radiological hazards associated with each disposal technique must relate the magnitudes for each of the possible occurrences on the probability trees. The spectrum of hazards for the range of disposal techniques is from zero for Earth escape to a finite value for an intact reactor which survives reentry heating and locates at an unknown random location. The intermediate possibilities include partial reentry ablation of the reactor where intact fuel elements are released, but do not ablate, and complete reactor ablation where the fuel is reduced to minute particles with world-wide dispersion (atmosphere disposal).

The intact reactor hazard is based on the dose rate of a SNAP-8 reactor (600 kw) given in Figure 4. This dose rate is based on time after shutdown for a nominal expected space mission where the operating lifetime is expected

Figure 4. Dose Rate at 1 ft
From a 600-kwt
Reactor, No
Self-Shielding

to be in excess of one year. The threshold criterion of damage, or demarcation between low and high doses, was taken at 25 rem/hr. This was the value used in previous analyses described in References 1 and 4. Based on this total dose rate of 25 rem/hr, it is evident from Figure 4 that orbit lifetimes on the order of hundreds of years are required for fission product decay after reactor shutdown.

C. WEIGHT PENALTY

Disposal system weight penalties result from the respective aspects dependent upon the selection of primary and backup disposal techniques for a given mission application. These include reentry ablation enhancement by structural design for ablation and possible aerodynamic stabilization appendices to enhance the aerodynamic heating magnitude through preferred orientation. The deboost and boost methods require guidance, control, and propulsive systems. The impulsive propulsion systems capable of performing any of the disposal maneuvers were studied by the Space Division of NAA. The definition of propulsion system capabilities for disposal applications determined in this

study is presented in Reference 3. These systems are composed of the following main propulsion/reaction control system combinations: liquid bipropellant/liquid bipropellant, solid propellant/cold gas, liquid monopropellant/liquid monopropellant, catalytically heated cold gas/catalytically heated cold gas, and cold gas/cold gas. However, the disposal payload weights in the 3000-lb range for a SNAP-8 reactor-shield configuration and the large velocity changes required by some maneuvers eliminated cold gas and catalytically heated cold gas main propulsion systems. Propulsion system weight penalties were prepared for the SNAP-8 power level system. The weight penalty factors are presented in Figure 5 for the reactor shield and separated reactor disposal configurations. The disposal propulsion systems increase by appreciable factors from the nominal 1000 fps delta V required to deboost to the 10,000 fps required to achieve an earth escape maneuver.

D. SYSTEM DEVELOPMENT AND PERFORMANCE PARAMETER

Adaptation of a particular disposal mode, whether it be the inherent passive reentry ablation and dispersion method or an active propulsion orientated system, require reactor system redesign. In the event that a disposal system is not currently state-of-the-art, consideration must be given to expenditure of dollars, manpower, and lead time for the procurement and integration on an operational reactor system. In addition, overall system reliability and the cost effectiveness to attain required reliabilities must be evaluated. The first step in the evaluation is to determine a present status category. These were grouped into the following: (1) Off-the-shelf disposal system with proven reliability and no integration required; (2) Available disposal system components that require integration and determination of compatibility with the reactor system; (3) Minor redesign of reactor and/or disposal system components to satisfy mission safety requirements; (4) Extensive redesign, test, and evaluation of reactor and disposal system; (5) Conceptually feasible design; however, the attainment of flight hardware would require extensive development, test, and evaluation to accomplish the specified application requirements. Present hardware and space system capabilities are given in the Space Planners Guide ⁽⁵⁾.

Figure 5. Disposal Propulsion System Weight Requirements
(Main Propulsion/Reaction Control System)

V. DISPOSAL MODE EVALUATIONS

The quantitative analyses of the selected disposal modes were derived to provide a means of evaluating the Aerospace Nuclear Safety for any proposed mission, manned or unmanned.

A. RANDOM REENTRY

The random reentry mode could be the primary reactor disposal mode, an example of this is the SNAP 10A⁽⁴⁾ or as a backup to active disposal modes. The reactor design, including safety criteria, dictates whether the reactor will ablate and disperse or contain the fuel elements to impact. Therefore, these two possibilities were evaluated according to the criteria established for the study. The fault tree evaluation of reactors designed for reentry ablation with subsequent dispersion and for containment is given in Figure 6.

1. Reliability

The high reliabilities associated with the random reentry cases are based on analyses, tests, and the inherent nondegradation nature of these systems. If ablation and dispersal do not occur with a reactor designed for reentry burnup, finite probabilities exist for intact impact in the ocean (0.74 out of 1.00), and for land impact where disassembly results in a fuel handling accident. The probabilities of these events are shown on Figure 6 and indicate the probability of a fuel handling accident to be 1.77×10^{-3} per flight. If the intact reactor core survives impact, the assumption must be made that enough water will be eventually encountered to cause criticality. This underscores the need for a mechanism for ensuring water subcriticality.

The reliability of success for atmospheric containment was taken as 0.99. This is considered to be the maximum creditable value considering the present state of the art. Besides, an increase would not have any appreciable effect on the occurrence of the fuel handling accident determined to have a probable occurrence of 0.175 (Figure 6). This event follows a land impact on surfaces hard enough to result in a disassembly.

a) DESIGN FOR ABLATION AND BURNUP

b) DESIGN FOR INTACT IMPACT

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Figure 6. Random Reentry, Reactor Ablation, and Intact Impact Reactor Designs

2. Hazard Evaluation

The probabilities of success for a reactor designed for atmospheric ablation or containment are high (0.99), due to inherent design features which can be built into a reactor system. The containment design fuel handling hazard, or overexposure index, is about two decades higher than that of the system designed for ablation. The magnitude of this hazard for a zero-order approximation is proportional to the dose rate one foot from a fuel element an hour after impact. This quantity, illustrated in Figure 4, clearly shows the need for shutdown, and the value of an end-of-life shutdown device.

This fuel handling hazard has been demonstrated to be a prime safety consideration⁽¹⁾ however, the danger resulting from atmospheric contamination must also be considered. This has been done in Reference 6 where results show that hazard to the general public is very small; and when compared with the atmospheric contamination due to weapons testing; the level of radioactivity is minute. Another hazard occurrence considered is related to a criticality occurring on land due to the influx of water around a reactor which survives impact. This could be precluded by an intrinsic subcriticality design.

The combined hazard occurrence probabilities for fuel handling and exposure to a land criticality are 2.6×10^{-3} and 0.257 for reactors designed for reentry burnup and intact impact, respectively.

3. Weight Penalty

Weight penalties were based on the required modifications or additions to a SNAP-8 configuration to satisfy inherent passive ablative or containment criteria during reentry. The present SNAP-8 design results in atmospheric containment. This was demonstrated by the Reactor Ablation Disintegration Experiment (RADE)⁽⁷⁾. The containment reliability of 0.99 could be achieved through modifications requiring less than 100 lb (about 3% weight penalty). This method results in a system modification where the reactor-shield becomes a free reentry body at high altitudes and is aerodynamically stable in a shield-forward position through maximum aerodynamic heating.

Reentry ablation of a SNAP-8 reactor requires redesign of the reactor vessel and grid plates to enhance the ablation characteristics of the system, and

release of the fuel elements to expose them to the reentry heat flux for a period adequate to ensure ablation. The weight penalty, for the ablative system is related to reactor ablation enhancement. In addition to reactor vessel redesign, two alternate concepts are available for accomplishing this objective. First, an inherent device sensitive to low levels of aerodynamic heat that melts and separates the reactor vessel from the remaining system. The free reactor would then be free to tumble and receive aerodynamic heating around its total periphery with subsequent fuel element release. An alternate concept stabilizes the reactor shield in a reactor-forward position by an aerodynamic skirt aft of the shield. This results in higher (large ballistic coefficient due to mass of shield) and concentrated aerodynamic heating of the reactor. The added weight to perform these concepts is relatively low, and is estimated not to exceed 150 lb (5% weight penalty). The ablation process for the SNAP 10A zirconium-hydride fuel elements ⁽⁸⁾ has shown that this fuel form ablates with high probability if released from the core configuration at appropriately high altitudes. The smaller diameter SNAP 8 fuel elements have been shown to ablate with greater probability than the SNAP 10A elements. This is typical of higher-power reactors.

4. System Development and Performance Parameters

The design requirements for systems inherently capable of ablating to an extent where fuel elements are released or, conversely, maintaining structural integrity to impact are both definitely state-of-the-art. However, the adoption of either concept requires development tests, evaluation, and verification of principle. The intact criterion is more easily satisfied than ablation, since the reactor system would not require additional reactor system qualification tests. This is related to the structural redesign required to enhance reactor ablation during reentry. The effects on the configuration in the case of redesign to promote SNAP 8 reactor ablation result primarily in the areas of reactor vessel, head, and grid plates. This is primarily a structures problem where composite, light-weight construction would be appropriate. These structural requirements to enhance reentry ablation result in minor reactor system perturbations.

From the standpoint of system development, effect on the reactor system configuration, and degradation of performance the intact impact system is

preferred. This is primarily related to reactor redesign to promote reentry ablation and the extensive test programs that would be required to qualify the reactor operation and verify the ablation characteristics.

B. DEORBIT FOR OCEAN DISPOSAL

Controlled deorbit of the reactor, with or without its associated power conversion system, has been suggested for control of the potential hazard. Ocean disposal of SNAP reactors designed to satisfy criteria for reentry ablation and containment has been evaluated. The probabilities associated with the various possibilities are given in the fault trees in Figure 7.

1. Reliability

The success of the deorbit maneuver is determined by the reliability of the deboost package. This requires that guidance, control, and propulsion subsystems perform in the desired manner. The value of 0.943 was selected for this system, based on data from Reference 3 for a solid main propulsion and cold gas reaction control system combination having been in space storage for a 1-yr period. This reliability is for a system using present state-of-the-art redundant components. This reliability would degrade to about 0.76 for a space storage of 5 yr.

The disposal area is extremely large, in that any deep ocean area satisfies the impact position criteria. Therefore, the definition of orbit parameters and retrofiring commands are not stringent, an accuracy within one sigma being acceptable. The deboost sequence is the straightforward procedure outlined below. The orbiting payload would be monitored by the numerous tracking stations within the SPADATS (Space Detection and Tracking System) network, and an ephemeris determined by the NORD (North American Air Defense) central processing center at Colorado Springs. This would enable a prediction of the state vector (position and velocity) to be made and the appropriate constants, based on these ephemeral data, entered into the on-board autopilot programmer via the command link. In spite of the recent advances in tracking techniques within the SPADATS, only moderate quality of the predicted position and velocity may be expected, hence, it would be most desirable to acquire and track the payload package within several orbital periods prior to the actual time of intended abort.

a) DESIGN FOR ABLATION AND BURNUP

b) DESIGN FOR INTACT IMPACT

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Figure 7. Controlled Reentry into Deep Ocean, Reentry Ablation, and Intact Impact Reactor Designs.

Once the orbital parameters have been established, the on-board Guidance and Control System will be activated by a command link. The reactor package must then be oriented for retrorocket firing. This will be accomplished by the rise of a horizon scanner and a star tracker. The horizon scanner will align the body-roll axis to the local vertical. A roll-search maneuver will then be executed to acquire a precalculated stellar pattern by the star tracker. The gyros will then be uncaged, a programmed initial attitude corresponding to the injection point will be attained, and the vehicle will continue in orbit to the precalculated injection position where ignition will occur either on command or upon a preprogrammed timing signal. In the event that the control sequence can only be completed to the alignment with the local vertical, the maneuver can still be successfully completed through a system logic that places the propulsion system alignment angle at 90° . The control system must have this fault-tree sequence in its program; also a larger propulsion system is required.

The guidance, control, and propulsion sequence given above is essentially for an unmanned situation. The reliability of disposal performance may be greatly enhanced for manned applications. With respect to the control and guidance systems, the manned space station could contain this electronic equipment, and could control by TM the functions on the reactor package. The space station provides continuous reactor package tracking capability, and can provide monitoring and command functions throughout the sequence. In the deboost case, the space station can track the reactor package to impact and pinpoint the exact disposal location.

Overall reliability of 0.934 for successfully deboosting the reactor into an ocean reentry trajectory was determined based on propulsion system and ablative, or intact impact, reliabilities (Figure 7). The remainder of the fault-tree sequences shown in Figure 7 are concerned with probabilities for failures and types of hazards that could be expected. These are based on known water-to-land ratios and the best known percentage value of land where reactor disassembly will occur on impact.

2. Hazard

The evaluation of hazards associated with this disposal maneuver shows considerable reduction over the random reentry cases. The probabilities of a

fuel handling hazard for the ablative and intact impact reactor designs are 10^{-4} and 10^{-2} , respectively. The effect of using ocean disposal results in more than an order of magnitude reduction in the hazard associated with a random reentry. The combined hazard occurrence probabilities for fuel handling and exposure to a land criticality are 1.47×10^{-5} and 1.47×10^{-2} for reactors designed for reentry burnup and intact impact, respectively. In addition, ablative system atmospheric release over land masses has been reduced from a probability of about 0.26 for the random reentry case to 5.6×10^{-2} for the ocean deboost maneuver. The probability of hazard occurrence for the intact impact design remains 100 times that expected for the reentry ablative system, as in the random reentry cases.

3. Weight Penalty

Guidance, control, and propulsion components result in added system weight. The guidance and control equipment to perform this operation is estimated to weigh between 35 and 50 lb. The command system weight will be between 15 to 30 lb, with power requirements (i.e., batteries, etc) of between 10 and 20 lb. Total weight of this equipment will therefore vary from an estimated 60 lb for reactors under 200 lb to 100 lb for systems over 200 lb (SNAP 8).

Retrovelocity increments necessary to perform the deboost operation must be determined to estimate the propulsion system weight. Impact accuracy is not paramount in ocean disposal; however, it is desirable to consider the optimum deboost situation. For any combination of orbit altitude, deboost velocity increment, and reentry body ballistic coefficient, an optimum propulsion alignment angle exists for minimum range. This relationship is given in Figure 8, and a more detailed explanation and derivation appear in Appendix A.

A propulsion alignment angle of 90° was considered in addition to the optimum case. This was done to determine the increased propulsion required to enhance system reliability. A comparison of deboost velocity and range requirements for the optimum and 90° propulsion alignment cases is presented in Figure 9. The minimum velocity requirements of 1000 fps, or less, for the optimum case are not feasible for deboost with a constant 90° propulsion alignment angle.

Figure 8. Minimum Reentry Range
Propulsion Alignment
Angle Relationships

Figure 9. Reentry Range for
Optimum and 90-Degree
Propulsion Alignment
Angles

A velocity of 2500 fps (Figure 9) is required in the 100 to 400 n. mi altitude range to achieve deboost when propulsion is fired at 90° to the satellite velocity vector. The disposal weight penalties for the reentry ablation and intact impact reactor systems are presented in Table 1 for optimum and 90° propulsion alignment deboost cases. The use of a simplified guidance and control system requires an added 10% weight penalty (Table 1) when compared with the optimum firing angle case.

TABLE 1
DISPOSAL WEIGHT PENALTIES REQUIRED
FOR OCEAN DISPOSAL

DEBOOST PROPULSION	DISPOSAL SYSTEM WEIGHT PER CENT OF REACTOR SYSTEM	
	REENTRY ABLATION AND DISPERSION REACTOR DESIGN	INTACT IMPACT REACTOR DESIGN
V = 1000 fps (optimum propulsion alignment angle)	14	12
V = 2500 fps (90° propulsion alignment angle — simplified case)	24	22

4. System Development and Performance Parameters

In addition to the required configuration modifications to enhance ablation or containment guidance, control, and propulsion system components must be integrated into the overall reactor system. The components required for guidance, control, and propulsion are all off-the-shelf packages with proven reliability^(3, 5). Performance testing of the integrated disposal and reactor systems would be required to verify reliability and overall operation compatibility. The disposal system is independent of the reactor ablation, or intact impact, reentry criteria. Hence, the development and performance evaluations depend on combining existing hardware into an optimum configuration with respect to the physical geometric constraints of the SNAP system.

C. INTACT EARTH IMPACT AND RECOVERY

The second active disposal method considered for deboost schemes is to accurately place the reactor in a known location and proceed to locate, recover and then dispose of the reactor, using standard waste-disposal techniques. The major constraint imposed on this technique is the impact area accuracy requirement. Only a containment type of reactor design was evaluated due to the recovery criterion, since reentry burnup designs are not compatible with the recovery philosophy. Disposal event probabilities are given in Figure 10 in fault-tree form for reactor recovery after deboost from space.

Figure 10. Controlled Reentry, Intact Impact on Land, and Recovery (Design for Intact Impact)

1. Reliability

This disposal mode would be considered a success at the point where reactor recovery is accomplished. This requires that guidance, control, propulsion, and recovery systems function properly. The logic of the fault tree (Figure 10) indicates that the system would function with a recovery reliability of 0.915. Propulsion and guidance systems similar to those of the ocean disposal were employed for this maneuver. This system, with a larger velocity capability, has a reliability of 0.943⁽³⁾ at the end of 1 yr of space storage; and forms the initial branching on the fault tree. The deboost velocity is 3000 fps due to the impact accuracy requirements. Also, the maneuver is altitude-limited to orbit altitudes of 275 n. mi or less. In the event of failure, 0.057, the reentry mode reverts to the random intact case. The reliability of containment was selected at the 0.99 value used throughout the study.

2. Hazard

The potential hazard to the population is greater for the recovery maneuver than for ocean disposal. This can be seen from the probability of 0.023 for a fuel handling accident (Figure 10) in the intact recovery method. This increase in the radiological hazard is related to the maneuver taking place over land for a reactor designed to contain the fuel through reentry heating. The probability of atmospheric contamination is small, due to the intact reactor design requirement. The total probability of atmospheric release is 0.010.

3. Weight Penalty

The weight requirements of components to successfully complete the reentry maneuver include guidance, control, propulsion, and recovery systems. The weight requirement for guidance and control systems is about 100 lb for the SNAP 8 system. This is essentially the same system used in the ocean disposal system. The primary difference between the ocean disposal and impact recovery techniques is the accuracy with which the reactor must be deorbited. In the first case, the CEP (circular error probable) can be large, since the target is the vast ocean. For these considerations it is assumed that a CEP down-range of 100 mi coupled with a cross-range of 10 mi is more than adequate. This results in a dispersion area of 1000 mi² for the ocean disposal mode. For the second case, recovery following impact, a CEP down-range

of 10 mi with cross-range of 5 mi is probably necessary to limit the search area to 50 mi². This area is reasonable for search, but it should be remembered that the resulting search operation of over 50 mi² is a major undertaking. The radioactivity of the hunted object should lighten the otherwise formidable search task.

The recovery criterion of this technique required a detailed evaluation of all possible errors at, and during, the programmed deboost sequence. These include orbit position and velocity uncertainties, deboost thrust vector misalignment, propulsion cutoff timing errors, and reentry body aerodynamic uncertainties. These factors were correlated to obtain the required deboost velocity increment to successfully complete the deboost maneuver.

The ephemeral data can be expected to be good to values of 15 fps down-range and 5 fps cross-range. The alignment error is of the order of 1°, and for this system should produce negligible range error by proper selection of firing angle. The thrust cut-off error is taken as 1/3% of the total velocity increment and the timing error of 2 sec. It has been calculated that the timing error of 2 sec will produce a down-range error of 8.2 mi and is the relative constant for all orbits under consideration, since it is a function of the circular orbital velocity. The velocity error, due to ephemeral data and thrust cut-off, produces errors which are a function of the total retrovelocity increment. Using these parameters, a study of down-range dispersion as a function of orbital altitude and retrovelocity was conducted. The results are shown in Figure 11. The cross-range dispersion which is a function of ephemeral data and alignment error was calculated. It was found that the error in cross-range velocity due to ephemeral data (5 fps) was not important in the analysis compared with the error in alignment. From the standpoint of recovery, it is the impact area which determines the degree of difficulty associated with the potential recovery operation. This can be approximated by multiplying the cross-range and down-range errors, as shown in Figure 12. The final phase of the reentry trajectory takes place in the sensible atmosphere where the reentry body aerodynamic characteristics must be considered. Therefore, the impact dispersion due to ballistic parameter uncertainty was determined. The results are given

Figure 11. Error Analysis of Reactor Deorbit

in Figure 13 in the form of a nomograph. The example shown in Figure 13 is for a maneuver which uses a 2000 fps deboost velocity applied at the optimum propulsion alignment angle. The impact dispersion will be about 16 n. mi for a nominal ballistic coefficient of 50 psf known to plus or minus 50%. This 50% value of uncertainty is probably high, and a representative value of 10% is felt to be appropriate for the study.

The deboost velocity requirements for the recovery disposal technique are presented in Figure 14 along with requirements for ocean disposal where optimum and 90° propulsion alignment angles are employed. The deboost velocity requirements for intact reactor recovery become exceedingly large for orbit altitudes above 275 n. mi (Figure 14), and this altitude was selected as the upper limit for the maneuver. The weight penalty for reactor recovery was therefore based on a deboost velocity increment of 3000 fps and results in a 27% system weight increase for guidance, control, propulsion, and recovery systems.

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Figure 12. Expected Disposal Area From a Deboosted Reactor

4. System Development and Performance Parameters

The effects of adding the required disposal components for deboost to a SNAP reactor system are essentially the same as in the ocean disposal method. The one significant addition are the recovery system components. Each of

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Figure 13. Impact Dispersion Resulting From Ballistic Parameter Uncertainty

Figure 14. Velocity Requirements for Intact Recovery and Ocean Disposal

these sub-systems are presently available with proven reliability (References 3 and 5). The development time and evaluations are related to verification of reactor and recovery system survival through reentry heating to intact impact. The major reliability requirement of the system is proof of successful recovery. This aspect is directly related to overall accuracy and reliability of deboost guidance, propulsion and aerodynamic parameters of the reentry body. The attainment of this system with proven reliability is therefore significantly more difficult than for deboost into the vast ocean for disposal.

D. ORBIT AUGMENTATION

The disposal option discussed in this section is related to orbit lifetime augmentation to provide time for fission product decay. This objective can be accomplished through propulsion boost to a higher orbit, or reactor separation when the combination of reactor ballistic coefficient and orbit parameters results in a sufficiently long satellite lifetime. The situations where separation can be used as an orbit lifetime augmentation are given in Figure 15 where orbit altitudes and ballistic coefficients required for a 50 yr satellite lifetime are given. A typical ballistic coefficient for a reactor is 100 psf (compared with

Figure 15. Circular Orbit Satellite Lifetime

20 psf for a manned space station) which results in a minimum altitude for orbit augmentation of about 335 n. mi (Figure 15). The use of propulsive boost for orbit augmentation is therefore required at lower orbit altitudes. The probabilities of events following reactor separation or propulsive boost for orbit augmentation are given in Figures 16 and 17, respectively. These orbit augmentation methods were evaluated in the following subsections. This was done due to their distinct operational differences.

1. Orbit Augmentation Through Reactor Separation

a. Reliability

The basic event to initiate the maneuver is simply separation of the reactor from the power conversion system and space craft. This separation event has been determined to occur at a 0.9999 reliability⁽³⁾. This value forms the basis for preparing the fault trees given on Figure 16.

b. Hazard

The potential hazard for this disposal technique is extremely low. This is primarily due to the high probability of maintaining the reactor out of public

Figure 16. Reactor Satellite Lifetime Augmentation Through Reactor Separation, Reentry Ablation, and Intact Impact Reactor Designs

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contact during the period required for fission product decay. For situations of this type, the separation and shutdown of the reactor (with its ballistic coefficient of about 100) from the reentering space station would reduce the hazard level by a factor of from 1.1×10^{-2} to 2.2×10^{-4} . It is important to note, however, that whereas an operating reactor whose operation is terminated by reentry contains a larger hazard potential over a shutdown and separated reactor, it does not follow that the act of separation always produces a large reduction in potential hazard. In addition to the fact that shutdown produces an important reduction in hazard level, the benefits from increasing the orbital lifetime by a factor of 5 (in this reference case) by separation are a function of the orbital altitude of the space station. This is shown in Figure 18, where the ratio of hazard potential for the separated reactor to that for the unseparated reactor is plotted as a function of orbital altitude. It is seen that in the range of manned space station applications a hazard reduction of less than a factor of ten is effected. For altitudes greater than 400 mi the effect of separation becomes more important.

Hazard comparison based on the fuel handling accident favors the ablation system, due to its inherent ability to disperse the fuel. Probabilities of a fuel handling accident for the reactors designed for reentry ablation and containment are 1.8×10^{-7} and 1.8×10^{-5} (Figure 16), respectively.

c. Weight Penalty

An advantage to this disposal method is its simplicity and very low requirement for supplemental hardware. The weight penalties for the manned application are essentially the same as for random reentry. These weight allowances are 5 and 3% for reactors designed to satisfy ablation or intact impact, respectively. The unmanned application would require the addition of electrical and communication equipment (about 5%). The disposal system weight penalties for manned and unmanned applications are summarized in Table 2.

d. System Development and Performance Parameters

The basic perturbations on the reactor system configuration are required to satisfy the reentry burnup or intact impact criteria. The effect of adding a separation device on the reactor configuration would be very minor. The electronic, communication, and separation devices are off-the-shelf items which require only integration and demonstration testing.

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Figure 18. Effect of Reactor Separation for Satellite Lifetime Augmentation on Hazard Level

2. Orbit Augmentation Through Propulsion

a. Reliability

Success of the orbit transfer maneuver is dependent upon reliability of the guidance, control, and propulsion systems. This overall reliability has been determined to be $0.857^{(3)}$ for a liquid monopropellant main propulsion and

liquid monopropellant reaction control system including a 1 yr storage factor and redundant components. This type of propulsion was selected based on the second burn restart requirement of the orbit transfer maneuver. The propulsion system reliability established the fault-tree success branch in Figure 17.

TABLE 2
DISPOSAL WEIGHT PENALTIES REQUIRED FOR ORBIT
AUGMENTATION BY REACTOR SEPARATION

TYPE OF APPLICATION	DISPOSAL SYSTEM WT % OF REACTOR SYSTEM	
	REENTRY ABLATION AND DISPERSION REACTOR DESIGN	INTACT IMPACT REACTOR DESIGN
Manned	5	3
Unmanned	10	8

Accomplishment of a preprogrammed sequence of guidance, control, and propulsion is essential for an unmanned application. The reliability of disposal performance may be greatly enhanced for manned applications where the space station can perform initial electronic control functions for the reactor disposal package. After separation, and the first burn, the space station could provide continuous tracking and command of the reactor. The space station will be located slightly ahead and below the reactor package when the second burn is required. It can therefore reorient the reactor package for the second burn, and monitor its performance.

Consideration of the preferential location for activating the boost sequence was evaluated in terms of overall maneuver reliability. The preferred activation location in the orbit is where a random propulsion firing places the impact point of any reentry trajectory in the ocean. The angle of uncertainty is defined as the segment of propulsion alignment angles in which random reentry occurs

Figure 19. Magnitude of Angular Segment in Random Propulsion Firing Where Neither Immediate Reentry nor a 50-yr-Lifetime Orbit Results

beyond one orbit but in less than 50 yr. This angle of uncertainty, presented in Figure 19, is based on results of the parametric survey described in Appendix A. The combination of a control-only malfunction, and the percent of cases where ocean impact occurs, defines the probability of ocean impact. Low altitude orbits were used where reactor separation for lifetime augmentation is not feasible. The remaining branch on the fault-tree in Figure 17 relates the probabilities of hazards for random reentry.

b. Hazard

The primary consideration for hazard in this study was the fuel handling accident. The probabilities of occurrence were evaluated to be 2.3×10^{-4} and 2.3×10^{-2} for the ablative and containment reactor designs, respectively. In addition to these probabilities, it is illustrative to examine the reduction of hazard as related to initial orbit conditions and boost. The most efficient application of a velocity change to enhance orbital lifetime is the double firing of the rocket system to produce a Hohmann transfer from the near-Earth orbit to the storage orbit. It is also possible to consider the use of a single velocity

increase to produce an elliptic orbit with the desired lifetime. Velocity requirements for these two variations, the double and the single impulse, are shown in Figure 20. The ballistic coefficient of the orbiting reactor system plays an important part in determining the velocity increment needed to perform the storage operation. It is evident that larger ballistic coefficients favor orbital storage systems, and that systems of ballistic coefficients around 100 can be boosted to 50-yr orbits from very low near-earth orbits (170 mi) with only a small (560 fps) velocity increment. The velocity requirements for the single- and double-impulse maneuvers were calculated by the procedure described in Appendix A. These velocities were based on orbit altitudes required for a 50-yr satellite lifetime consistent with ballistic coefficient. The satellite lifetimes were based on calculations performed by the procedure given by Billick⁽⁹⁾. An example of the effect of boost velocity on the hazard level is given in Figure 21. Hazard level was plotted as a function of boost velocity for altitudes of 100 and 200 n.mi. For an increase in boost velocity from 440 to 750 fps at an altitude of 200 n.mi., a reduction of four orders of magnitude in hazard will be accomplished. It therefore is not advantageous to be stingy with propellant for this scheme.

c. Weight Penalty

Additional system weight required to successfully accomplish the orbit transfer maneuver results from guidance, control, and rocket system components. The velocity requirements to achieve a 50-yr orbit are given in Figure 20 as a function of ballistic parameter and reactor operation (initial with respect to disposal altitude. Velocities are presented for the single impulse maneuver and the bitangential transfer. The former applies to all the propulsion impulse at once to give an elliptical orbit, while the latter divides the propulsion into two steps to achieve a higher circular orbit. The amount of propulsion required to achieve equivalent satellite lifetimes is always greater for the single impulse than for the bitangential maneuver (Figure 20). This phenomenon is related to the exponential decrease in drag with altitude; therefore, an apogee altitude considerably higher than the bitangential circular altitude is required to give the same mean value of satellite drag. These maneuvers are described in greater depth in Appendix A.

Figure 20. Orbit Augmentation Velocity Requirements to Achieve 50-yr Lifetime

A liquid monopropellant main propulsion and liquid monopropellant reaction control system was selected for the bitangential maneuver. This system combination was selected from the possible propulsion systems⁽³⁾ for application to double impulse, or restart capability and reliability. The total velocity requirements to accomplish a bitangential orbit transfer for 50-yr or greater lifetimes is less than 1000 fps in all cases (Figure 20). Therefore, the weight penalties for disposal of a reactor based on atmospheric ablation with release or containment were determined to be 18 and 16% respectively. This is the combination of propulsion, guidance, and control systems.

d. System Development and Performance Parameters

The disposal system components are all state-of-the-art; most of which have been used in space on an operational basis. Modification of the basic SNAP configuration would include integration of the disposal systems and reactor redesign to satisfy the selected reentry mode; ablation, or intact impact. The integration, testing, and evaluation of the disposal system is independent of reentry mode.

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Figure 21. Hazard Level Reduction by Boosting to Higher Orbit

E. EARTH ESCAPE

Complete removal of the reactor from the earth's ecological system is a logical extension of the orbit augmentation disposal technique. The probabilities for the spectrum of events following an attempted impulsive escape boost for both ablative and containment reactor designs are presented in Figure 22.

1. Reliability

Success of the proposed escape maneuver is like other propulsive techniques and is dependent on the reliability of the guidance, control, and rocket system components. The overall reliability of the propulsion system (solid main propellant with cold gas reaction control system) has been determined at 0.849⁽³⁾. This reliability established the base for developing the earth escape disposal fault-trees (Figure 22).

The preferred location for boost activation lies at a point in the orbit where a random propulsion, control failure, places the locus of impact points in ocean regions. In addition to ocean impact, orbit augmentation and random reentry can occur for other segments of propulsion alignment angles. Random reentry also occurs from a system failure resulting in no rocket ignition. The construction of the fault-tree branches related to system failures in Figure 22 are based on these possibilities. Ocean impact and orbit augmentation events were based on the following: control system reliability⁽³⁾ and the mean percent of propulsion alignment angles (Appendix A) where ocean impact (25%) and orbit augmentation (64%) occur.

2. Hazard

The probability of a fuel handling accident for the earth escape maneuver is 9.6×10^{-4} and 2.5×10^{-2} for reactors designed for reentry ablation and containment, respectively. These probabilities are less than those calculated for the passive random reentry technique; however, the reduction is not commensurate with the amount of propulsion required.

3. Weight Penalty

The additional weight required to accomplish the maneuver is primarily a function of the rocket fuel required to augment the reactor satellite velocity

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Figure 22. Propulsive Boost to Earth Escape, Reentry Ablation, and Intact Impact Reactor Designs

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by about 10,000 fps. The system weight penalties based on a solid main propulsion and cold gas reaction control system are related primarily to propulsion (Figure 5). The values for reactors designed for atmospheric ablation and containment are 95 and 93% respectively.

The high chemical propulsion weight penalties could be drastically reduced through the singular use of a low-thrust electric propulsion system or a combination with chemical propulsion. The former concept would use a small propulsive system that could convert a portion of the remaining reactor power generation capability into thrust. Therefore, escape velocity could be achieved by gradual acceleration into an outward spiral orbit from the Earth. A very reliable attitude control system is required; however, the need for a rocket propulsion system is eliminated. The alternate concept is an inherently stable system where the thrust is applied in an outward radial direction on a gravity gradient stabilized platform. After initiation of the event, the outward orbit spiral of the reactor system will continue until the gravity gradient approaches a possible instability threshold. At this point, a relatively small chemical rocket would complete the escape maneuver.

4. System Development and Performance Parameters

Modification to a SNAP reactor system would require a major redesign to accomodate the extremely large propulsion system needed to accomplish the escape maneuver. This requirement overshadows all other considerations for determining the effect on the reactor system. Propulsion systems capable of producing sufficient thrust to augment the reactor system satellite velocity by 10,000 fps are available. However, these are upper stages of launch vehicles (i. e., the Scout, Agena, Centaur, etc), and would require modification for this boost application. The development, test, and evaluations required for this concept constitute a major program in itself. Therefore, the rating for this conceptually feasible but extremely expensive mode of disposal is quite low when compared with the other active disposal modes presented.

VI. CONCLUSIONS

The basic Aerospace Safety Nuclear criteria for the disposal of reactors used in either manned or unmanned applications are essentially the same. At the present time, these criteria is simply to minimize the potential hazard to the general public. The primary differences in manned and unmanned missions lie in orbit altitude range and power levels. For manned stations, limits associated with the radiation belt and the orbit duration produce an altitude band ranging from a lower level of from 180 to 200 n. mi. to an upper level of from 320 to 340 n. mi. The upper altitude limit does not apply for unmanned applications.

Power level requirements for reactors used in manned applications are expected to be on the order of SNAP 8 (35 kwe), or higher. Unmanned power requirements for reactor systems may be in the 10-kwe range.

The merits of the selected disposal modes for the spectrum of reactor applications in space have been evaluated in this study. The reliability of successfully removing all land-hazard occurrences is summarized in Table 3 for the various disposal modes. Based on this reliability, propulsive deboost for ocean disposal attained the highest probability for successfully removing land hazards for all the disposal modes considered. The reliabilities are enhanced by the use of a reactor design that is intrinsically subcritical in water. This effect is also shown in Table 3. Comparison of disposal mode reliabilities was extended to include atmospheric contamination through the release of fission products. The reliabilities for successful removal of all land-hazard occurrences and atmospheric contamination are presented in Table 4 for the various disposal modes. The highest reliability for satisfying these criteria is through orbit enhancement by reactor separation. However, this is not universally applicable due to orbit altitude restraints; and ocean disposal of a reactor designed for intact impact attained the highest reliability for universal application. These reliabilities for intact impact ocean disposal of a basic reactor and one with an intrinsic subcriticality device are 0.97533 and 0.98003, respectively. It can be noted from Tables 3 and 4 that the active disposal modes result in a large improvement in the hazard reliability over the random reentry case.

TABLE 3
DISPOSAL MODE RELIABILITIES FOR SUCCESSFUL
REMOVAL OF ALL LAND HAZARD OCCURRENCES

REACTOR DESIGN CRITERIA DISPOSAL MODE	REENTRY ABLATION AND DISPERSION	INTACT IMPACT
Passive Random Reentry	0.99740 (0.99823)*	0.7430 (0.8250)*
Deorbit for Ocean Disposal	0.99985 (0.99990)	0.98530 (0.99000)
Intact Earth Impact and Recovery	- -	0.96630 (0.97700)
Orbit Enhancement by Reactor Separation (When Applicable)	0.99917 (0.99999)	0.91797 (0.99998)
Orbit Enhancement By Impulsive Boost	0.99895 (0.99977)	0.89500 (0.97700)
Earth Escape	0.99858 (0.99903)	0.96275 (0.97500)

*Intrinsic Subcritical Reactor Design

The probabilities of radiological hazard occurrences on land are presented in Figure 23 for the disposal modes evaluated in this study. This hazard comparison graphically illustrates the reduction in potential hazards due to active disposal methods. The use of any active disposal mode reduces the hazard by at least an order of magnitude. The need for intrinsic subcriticality, particularly for orbit augmentation and whenever intact impact is specified, is clearly evident from Figure 23.

TABLE 4
DISPOSAL MODE RELIABILITIES FOR SUCCESSFUL REMOVAL
OF ALL LAND HAZARD AND ATMOSPHERIC
CONTAMINATION OCCURRENCES

REACTOR DESIGN CRITERIA DISPOSAL MODE	REENTRY ABLATION AND DISPERSION	INTACT IMPACT
Passive Random Reentry	0.00740 (0.00823)*	0.733 (0.815)*
Deorbit for Ocean Disposal	0.00982 (0.00987)	0.97533 (0.98003)
Intact Earth Impact and Recovery	- -	0.95633 (0.96703)
Orbit Enhancement by Reactor Separation (when applicable)	0.99907 (0.99990)	0.91797 (0.99998)
Orbit Enhancement by Impulsive Boost	0.85795 (0.85877)	0.89359 (0.97559)
Earth Escape	0.85128 (0.85173)	0.94868 (0.96093)

*Intrinsic Subcritical Reactor Design

On the whole, reentry ablation reactor design hazard probabilities are lower than for the intact impact design. This is primarily due to the theoretical ability to remove the fuel handling hazard. Therefore, it is appropriate to comment on the zirconium-hydride reactor where fuel separation from the reactor is the largest present problem in utilization of reentry burnup for disposal. In near-Earth orbits, reentry burnup can be enhanced by the use of chemical or nuclear destruct systems which perform the function of reactor

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Figure 23. Disposal Mode Hazard Comparison

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disassembly and early exposure of the fuel to the reentry environment. It is evident that a highly reliable reactor disassembly system, coupled with reentry ablation of the fuel, can provide an adequate disposal system for zirconium-hydride reactors.

A comparison of added system weight to accomplish the various disposal modes is given in Figure 24. These weight penalties are primarily a function of the propulsion systems required to deboost or boost the reactor out of the operational orbit. The deboost and propulsive orbit augmentation methods require added system weight which can be justified, considering the degree of safety enhancement. These weight penalties are based on the total reactor system. For example, the disposal system weight for orbit augmentation (atmospheric containment and intact impact) of a 3000-lb reactor system would be about 330 lb. The earth escape maneuver impulsive velocity change appears to be ruled out on added system weight alone. This disposal mode requires virtual doubling of the reactor system weight placed in orbit.

The results indicate that ocean disposal for a reentry ablative reactor is the most preferable of the active disposal modes. This is based on a high reliability of success (Table 3), the greatest reduction in potential radiological land hazards, a moderate weight penalty for deboost propulsion, and state-of-the-art availability for the required deboost components. Earth escape disposal appears to be the least desirable of the disposal modes. This is related to the extensive weight penalty and perturbations to the reactor system.

The disposal study evaluations and results are based on theoretical and empirical correlations in existence at the time of writing (1967). There is every indication that the basic values will be valid into the 1970's, based on projections given in Reference 5.

Disposal evaluation for a specified mission (orbit parameters, power level, etc) in the future should expand on this study. The selection of the most advantageous disposal method could then be evaluated based on a cost effectiveness analysis for hazard alleviation. This type of analysis would place a dollar value on the degree of potential hazard associated with each disposal mode. The basis for compiling the figure of merit would then include the amount of design and qualification for respective systems to achieve equal scales of reliability: and costs for development, test, evaluation, production, facilities, and operations.

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Figure 24. SNAP 8 Reactor Disposal Mode Weight Penalty Comparison

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APPENDIX A

DERIVATION OF ORBIT MODIFICATION EQUATIONS

Orbit maneuvers required for the study consisted of immediate deboost and reentry, orbit augmentation for extended satellite lifetime, and the orbit parameters resulting from propulsion at any arbitrary in-plane alignment angle. The equations for these situations have been derived for impulsive velocity change at any point in the trace of a satellite orbit. This orbit sets the initial conditions to determine the satellite speed and flight angle at the selected point for the intended maneuver. The derivation is based on a mathematical model with a spherical earth and an inverse-square force field. In this case the energy of the satellite is expressed by the Vis-viva equation below:

$$\left(\frac{ds}{k_s dt}\right)^2 = \mu \left(\frac{2}{r} - \frac{1}{a}\right) \quad . . . (1)$$

The satellite orbit parameter and the impulsive velocity change provide the required data to calculate the initial conditions of the transfer orbit. The velocity vector applied to the system is shown in Figure 25 with respect to the propulsion alignment angle. For a deboost case, the available velocity change due to propulsion and the orbit parameters of velocity and altitude specify an optimum propulsion alignment angle for minimum range. Range is specified either in degrees of earth arc or nautical miles of ground track. Range angle is shown in Figure 26 as the angular distance from the orbit modification maneuver (Point A, Figure 26) to entry into the sensible atmosphere (Point B), ν atm range, and ground impact (Point C), ν impact range. Calculation of the optimum propulsion alignment angle, β_{opt} , is performed by numerical differentiation of angular range with respect to propulsion alignment angle to obtain a minimum solution. Angular range was determined by taking the difference of the true anomalies at the desired locations. The expression used for the true anomaly was obtained by rearranging terms in the orbit equation to give the following expression.

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Figure 25. Orbital Parameters and Propulsion Alignment Angles of Reactor System

$$\nu = \cos^{-1} \left[\frac{a(1-e^2)}{er} - \frac{1}{e} \right] \quad \dots (2)$$

The terminal phase of the flight in the sensible atmosphere was correlated to curves of trajectory output obtained from digital computer runs. The input to these trajectory correlations requires knowledge of flight velocity, flight angle, and altitude position. The velocity, V_{sen} , and flight angle, γ_{sen} , were determined from energy (Equation 1) and conservation of angular momentum, respectively. The expression defining the flight angle was expressed in the following manner.

$$\gamma_{sen} = \cos^{-1} \left[\frac{r V \cos \gamma}{V_{sen} r_{sen}} \right] \quad \dots (3)$$

For an initially circular orbit, the greatest increase in satellite lifetime for a given amount of propulsion is secured by a bitangential Hohmann transfer. The

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Figure 26. Deboost Trajectory Geometry (A-2)

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Figure 27. Bitangential Boost Parameters

velocity increments are applied at a propulsion alignment angle of 180° at both the active points in the maneuver. A schematic of this maneuver is shown in Figure 27 where the propulsion events occur at the perigee and apogee of the transfer orbit. These are Points A and B, respectively, in Figure 27. The amount of velocity supplied by propulsion to achieve a specified altitude, and satellite lifetime, is the sum of the two impulses. This characteristic velocity was obtained by relating orbit energy parameters to obtain the change in velocity at each point of application. The velocity to transfer into the elliptical orbit is the following.

$$\Delta V_1 = V_1 - V_{c_1} = V_{c_o} \sqrt{\frac{2 r_o}{r_1} - \frac{2 r_o}{r_1 + r_2}} - V_{c_o} \sqrt{\frac{r_o}{r_1}} \quad \dots (4a)$$

This equation can be simplified by substituting $\rho = r_2/r_1$ and rearranging to obtain

$$\Delta V_1 = V_{c_1} \left(\sqrt{\frac{2\rho}{1+\rho}} - 1 \right) \quad \dots (4b)$$

The velocity required to circularize the transfer ellipse is derived in a similar manner to that above to obtain:

$$\Delta V_2 = \frac{V_{c_1}}{\sqrt{\rho}} \left[1 - \sqrt{\frac{2}{1+\rho}} \right] \quad \dots (5)$$

The total velocity change is simply the algebraic sum of Equations (4b) and (5). In the event that only one impulse occurs, the final orbit would be defined by Equation (4b).

The third possibility that exists is for a propulsion activation at an arbitrary propulsion alignment angle. This will impart a velocity vector to the system that may deboost, or augment the satellite. This event was analyzed

by determining the orbit parameters resulting from any arbitrary event. The calculation procedure begins with determining the resultant orbit velocity, flight angle, and orbit energy parameter after the propulsive impulse. At this point, the perigee altitude is determined and examined for the possibility of earth impact. Should this occur, the range is determined by the method outlined above where true anomalies are computed for the initial and terminal points in the reentry trajectory. Satellite lifetime is calculated for the other alternative where the orbit is modified to new parameters. This requires calculation of the orbit eccentricity which was determined by solution of the following expression,

$$e = \left[1 - \frac{r^2 V^2 \cos^2 \gamma}{V_c^2 a} \right]^{1/2} \quad \dots (6)$$

The techniques outlined in this appendix provide the basis for solution of the various orbit modification possibilities. The computational methods were programmed in Fortran for the IBM System 360. The program was used to evaluate requirements for boost, deboost, and the sensitivities of propulsion velocity and alignment errors. For the most part, these are described in the main text; however, a parametric study to determine the types of orbit modification that could be expected from a random in-plane propulsion firing was performed. The parameters investigated encompassed the range or orbit altitudes and velocity changes for both deboost and boost. Orbit lifetime, range to impact, and the angular segment of propulsion alignment angle where random reentry occurs are presented on Figures 28 through 36. The combinations of initial orbit altitudes (200, 300, and 400 n mi) and velocity changes (1000, 2000, and 5000 fps) are presented on Figures 28 through 36 in the combination shown in Table 5. It can be seen that an increased velocity change for a given altitude results in a greater probability of both orbit augmentation and immediate reentry. It is also apparent, as you would expect, that higher initial orbits result in greater probability of orbit augmentation and decrease in the probability of immediate reentry for a given velocity increment.

TABLE 5
FIGURE LOCATIONS DESCRIBING EVENTS FOLLOWING
ORBIT MODIFICATION THROUGH PROPULSION
AT ARBITRARY ALIGNMENT ANGLES

INITIAL ALTITUDE N. MI	Velocity Change, fps		
	1000	2000	5000
200	Figure 28	Figure 29	Figure 30
300	Figure 31	Figure 32	Figure 33
400	Figure 34	Figure 35	Figure 36

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Figure 28. Events Following 1000-ft/sec In-Plane Velocity Change in Initially 200-n. mi Circular Orbit

Figure 29. Events Following 2000-ft/sec In-Plane Velocity Change in Initially 200-n. mi Circular Orbit

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Figure 30. Events Following 5000-ft/sec In-Plane Velocity Change in Initially 200-n. mi Circular Orbit

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Figure 31. Events Following 1000-ft/sec In-Plane Velocity Change in Initially 300-n. mi Circular Orbit

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Figure 32. Events Following 2000-ft/sec In-Plane Velocity Change in Initially 300-n. mi Circular Orbit

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Figure 33. Events Following 5000-ft/sec In-Plane Velocity Change in Initially 300-n. mi Circular Orbit

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Figure 34. Events Following 1000-ft/sec In-Plane Velocity Change in Initially 400-n. mi Circular Orbit

Figure 35. Events Following 2000-ft/sec In-Plane Velocity Change in Initially 400-n. mi Circular Orbit

Figure 36. Events Following 5000-ft/sec In-Plane Velocity Change in Initially 400-n. mi Circular Orbit

APPENDIX B

NOMENCLATURE

a	semimajor axis of an elliptical orbit
Bc	ballistic coefficient
e	orbit eccentricity
r	radius vector
t	time
V	velocity vector
β	propulsion alignment angle
γ	flight angle
μ	gravitational parameter of the earth
ν	true anomaly of orbit position

SUBSCRIPTS

C	circular orbit conditions
O	reference conditions corresponding to circular orbit at the earth's radius
opt	optimum conditions
sen	flight parameters at entry into the sensible atmosphere