RECEIVED BY TSC

62-721663-1

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

ABSTRACT

Nuclear Safety in Nuclear Power and
Propulsion Devices for Space*

by

G. A. Graves

Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico 87544, U. S. A.

The use of nuclear devices in space systems may introduce them to a wide variety of abnormal or extreme conditions in the event of system malfunctions. Undesirable circumstances which could be encountered include explosion, fire, reentry, impact, and contact with land or water. But it does not follow that exposure to diverse and hostile environments need produce an event of nuclear consequence-- i.e., one leading to significant fuel dispersal, criticality, or radiation exposure. Nuclear space systems can be studied on the ground and their nuclear safety characteristics verified or enhanced before their employment in space. Extensive research in this area has been carried on for many years in the United States and has led to the development of various means and policies through which safety is promoted or assured. These include special features in design, proscriptions on modes of operational use, and counter-measures directed at protecting against specific eventualities. Some examples of these approaches and of the research supporting them are given, and illustrative applications to isotope and reactor power supplies and to propulsion reactors are shown.

MASTER

*Work performed under the auspices of the U. S. Atomic Energy Commission

DISTRIBUTION

U.S. AEC OFFICIAL

U.S. AEC OFFICIAL

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

1. INTRODUCTION

It is appropriate at a meeting concerned with the use of nuclear power and propulsion devices in space to mention some of the steps taken to assure safety in that use. Yet this subject is too extensive to permit any comprehensive coverage in a single paper. The best one can hope for is to present some idea of the nature of the problems involved, of the approaches taken to deal with them, of the testing by which the soundness of those approaches is continuously being explored, and of the results of operational experience.

To supplement the account in this paper, the reader is urged to consult the references. They are by no means comprehensive, but they can introduce their readers to space nuclear safety and point them to further sources.

2. GENERAL CONSIDERATIONS

Nuclear safety as used here simply means those steps taken to assure that neither operating personnel nor the general public are unduly exposed to nuclear radiation or radioactive materials through use of space nuclear systems. It includes the precautions taken to mitigate the consequences of any such exposure that might occur. (Facility protection is also a factor in nuclear safety planning, but will not be considered here.)

Nuclear safety for a space system is not an end which can be pursued without regard to other considerations (Fig. 1). It must not cause undue penalties in weight, reliability, or development expense. The user of a space nuclear power supply measures performance in terms of watts per kilogram of total system weight. Heat source weight, safety system weight, and power convertor weight make up that total; no one part can become disproportionately large without jeopardizing system acceptance. A nuclear safety system tending to compromise the overall reliability of a spacecraft or space mission by undue complexity or undue reaction sensitivity is not likely to be tolerated. Safety development costs may be

a substantial part of system costs and also figure in user acceptance. Safety must be attained, but its pursuit has constraints.

Safety is integral to the system. It must be considered from the inception of a project, and it is in its details specific to each project (even though it has some universal elements among many projects). It cannot be legislated, or accomplished by rules laid down from afar, for each space system is unique in terms of the nuclear units it needs and can accept and is unique in the environments and potential hazards to which its nuclear units may be exposed. Thus safety has to be considered and incorporated into every stage of a project, from system design, research and development, and hardware procurement, through installation and use. It must be accepted as a responsibility of everyone involved in these activities - by the nuclear system contractor, by the AEC/NASA project office and by the mission and user project offices. It cannot be left to external safety reviewers. Such persons render judgements when the work is completed; they do not and cannot build safety into that which they review.

To the extent possible, standardization of space nuclear system safety approaches is desirable. Development of safety criteria for newly emerging systems; standardization of safety documentation; standardization of analytical, experimental, and computational techniques; formalization of safety review procedures; development of systematic contingency planning; and establishment of routine operational safety procedures are all important goals whose attainment can greatly expedite the transition between the sporadic use of a few prototype systems and the routine use of many space nuclear systems.

But standardization in approach to safety questions is feasible only to the extent that consistent elements underlie the safety issues for separate systems. Standardization should never become so sought after or acceptable that it is allowed to disguise real differences between systems or conceal the uniqueness of particular problems. Nor should it be allowed to lead to complacency, for safety research and safety technology

should advance with the needs and potentialities of the times. Evolution in ideas and approaches should occur. New concepts, techniques, and devices should be created. New methods should be proposed and tried. Adaptation is important: The abilities to track, deorbit, locate and recover conventional spacecraft apply equally to nuclear spacecraft; improvements in these abilities - if understood and accepted into nuclear safety planning - may provide new possibilities and alternatives for safe use.

3. POTENTIAL SAFETY PROBLEMS

Both radioisotope and reactor systems offer a variety of potential safety problems. Some are intrinsic, deriving from the nature of the systems themselves, while others are extrinsic, arising as possible consequences of individual or sequential external occurrences unrelated to the presence of a nuclear system.

Intrinsic problems associated with radioisotopic power systems might include excessive gas buildup (from α decay), excessive heat, material diffusion, change in form or stability, chemical reaction, radiation damage, and the like (Fig. 2). Radioisotopic systems liberate heat at a rate determined only by their initial charge of material and its subsequent decay. Source-associated problems are present throughout the system's life. The utter insensitivity of radioactive decay to external events partially decouples radioisotopic sources from such events, though the presence of internal heat may modify their responses.

In general, few safety-related intrinsic operating problems actually arise in radioisotopic sources. Their character and persistence helps make them recognizable and ground detectable. They can be effectively countered by good design, backed by normal quality assurance and reliability controls.

Unoperated reactor systems possess no internal heat and introduce no problems of intrinsic type before startup. But during normal operation they require coolant, and even after operation they may possess a substantial though rapidly decreasing decay heat source. A reactor's

intrinsic need is to properly tie heat generation and heat removal together. This problem is addressed by seeking to prevent inadvertent control rod (or control reflector) motion, thus avoiding undesired reactor startups or excursions, and by seeking to provide an adequate and assured supply of operational and postshutdown cooling. Restrictions on control rod motion can be imposed readily up to the chosen startup time. Potential "runaways" are addressed thereafter by multiple failsafe means of reactor shutdown, or "scrams." Unintended new heat generation is therefore unlikely. But sustained cooling from external supplies cannot always be assured, so in practice it is necessary to consider the temperature increases potentially derivable from postulated runaways or cooling supply failures. If such increases are serious, countermeasures - steps for preventing them or coping with them - must be adopted. For example, one would consider providing redundant cooling if doing so would reduce risk of loss of reactor structural integrity and system or mission failure.

In general, the intrinsic problems of reactor systems are also of such a nature that they need concern us little here. They are not likely to result in enough kinetic energy generation to cause reactor disassembly and premature return of material from space, so it is only necessary that control rod motion and (therefore) startup be proscribed until attainment of a long-lived orbit. Postoperational decay will then assure that reactors offer no significant terrestrial consequence. (Any criticality engendered on return from space would produce new fission products, and must be avoided, but means are available for doing this.)

Both types of nuclear systems may be subjected to extrinsic, (externally-induced) circumstances or events affecting their integrity (Fig. 3). These have variable probabilities of occurrence in time and space and their consequences may also vary depending on when and where they arise. They may arise in ground handling, pre-launch, launch, early or late ascent, orbital operation, or as a result of reentry or impact. A partial list of pertinent events or circumstances includes fire, vibration, acceleration, shock, pressure, fragment (or projectile) impact, tumbling and spin, reentry heating, ablation, and impact. These have further

differentiations of importance. A fire's temperature and duration may depend on whether the fuel feeding it is of solid or liquid form and on exactly which solid or liquid, on its quantity, on the degree of fuel-oxidizer mixing obtained in an accident, and even on the place of accident occurrence. The blast over-pressures or projectile motion that result from an explosion have similar strong dependence on configuration, fuel type, and mix; a consequence is that these problems rarely scale with fuel quantity or vehicle size. Impact may be on water or land, and on hard or soft surfaces, with variable outcomes for containment integrity, corrosion environment, subsequent fuel dissolution, dispersion, re-suspension, etc.

It is important to remember that these individually-significant external events may come in sequence. For example, there could be shock or missile effects from explosion at high altitude, followed by reentry heating, then impact.

Nuclear reactors and radioisotope systems intended for space applications have to be examined in relation to these single hazards and sequences of hazards. Responses differ for the two systems. Reactors may gain reactivity through compaction (as from explosion or impact) or through immersion in water or hydrocarbon fuels. A reactor's ability to be critical though it has internal voids or only has a (nuclearly) finite reflector, can give it a susceptibility to external events that radioisotopic systems do not possess.

4. PHILOSOPHY OF APPROACH

Good safety policy requires attention to all potential problems, whether arising internally or externally, but it is usually the latter which pose the most difficulty and concern. The conditions accompanying externally induced accidents or malfunctions are highly imprecise and difficult to specify and their effects are ambiguous in consequence. How then is this problem to be handled?

It has already been hinted that few ideas addressed to a single aspect of a system, such as safety, can be translated into hardware in the

dynamic and weight-limited environment of a space vehicle without compromising some other aspect of performance. An "optimally"performing" and "perfectly safe" system will never be flown! What must be done in the case of a real system which one might like to fly - one offering adequate performance and promising safety - is to somehow determine what might happen to it under normal or accident conditions when flown and then to assess on a probabilistic basis what those happenings could mean and decide whether there is sufficient safety in the consequences. One goal is to establish that the nuclear system can suitably sustain not merely the most probable accidents but also all accidents of low probability which have severe potential consequences for any local or general population. Only if it can do this is it satisfactory.

The philosophy that seems best suited to this goal (Fig. 4), while undergoing continuous reexamination and some evolution in time, calls for a combination of the rigorous hardware development and testing methods of the terrestrial nuclear power industry with the probabilistic and contingency approach of aerospace operations.

Let us suppose that hardware offering improved safety is proposed and appears feasible. The design is first thoroughly analyzed with respect to its normal behavior and performance and analyzed with respect to its response under postulated accident conditions. It is finally subjected, in the development phase, to a series of rigorous and severe tests in simulated accident environments. It must confirm its expectations by performing satisfactorily in all these and meet normal reliability and quality assurance specifications before being accepted as a new candidate design.

But to this valuable, stringent, and formalistic approach of terrestrial nuclear systems, further insights must be added. Not all potential accidents, accident environments, nor conceptual accident sequences can be simulated. To estimate their likely effects, the elements of probability analysis must be invoked. One must ask: What is the chance of this

occurring or going wrong, what is the probability that this first event will be accompanied with or followed by this or that further occurrence, what then the probability of third occurrences, etc? If these chances can be expressed for all conceptual possibilities - for every chain of events, the "probability tree" so formed would give a complete representation of the likelihood and potential severity of all conceivable happenings.

The result will be known no better than the individual probabilities are known or expressable, so it is important that these probabilities be tied to realism to the closest extent possible. This is not as difficult as might at first be supposed. One may be able to use experienced probabilities for abort before a certain time or altitude, to use real probabilities for occurrence of pad fires, for destruct, for tracking error, location of impact points, recovery of source, and so forth. Any probability - real or assumed - should be reevaluated and updated as knowledge or experience changes. Conservatism in favor of safety is important, too, but one should know when, where, and how he is employing it.

For purposes of illustration (only) one might make the following assessment of the probability of a system impacting from short orbit (an orbit less than one year) on land in a rural area with some attendant fuel release:

$$P_1 P_2 P_3 P_4 P_5 P_6 = P_{\text{release}} \quad \text{where}$$

$$P_1 = \text{Probability of short orbit} = 1.7 \times 10^{-3}$$

$$\quad \quad \quad (\text{improper injection in long orbit})$$

$$P_2 = \text{Probability of land impact} = \text{land}/(\text{land plus water}) = 2.6 \times 10^{-1}$$

$$P_3 = \text{Probability of rural impact} = 8.6 \times 10^{-1}$$

$$P_4 = \text{Probability of non-burial} = 6 \times 10^{-1}$$

$$P_5 = \text{Probability of hard surface} = 10^{-2}$$

$$P_6 = \text{Probability of capsule failure} = 5 \times 10^{-1}$$

$$\quad \quad \quad (\text{on hard surface, etc.})$$

So $P_{\text{for some fuel release}} = 1.1 \times 10^{-6}$ for this particular kind of event.

One would have to go further and estimate the nature of this fuel release, via other probabilities, before making a conclusion about the likely consequences of this single event. For example, available impact test data might show that little fuel would be released from the subject fuel capsule even on hard impact, that little of that might be in respirable "fines", that only a few percent of fines produced by impacting a non-yielding surface might be raised to a height adequate for atmospheric dispersion, etc. Quantification of these factors would permit an estimate of the quantity and distribution of potentially respirable source. That in turn could be applied to a population probability distribution in order to finally derive the chance, and the nature of the chance, that some individuals would be affected by this one type of event. The procedure then would be repeated for all events, both more and less probable and more and less hazardous, whereupon a proper feeling for the overall risk attendant to the operation would become known. A decision to proceed or not could then be made, based on what that risk was and its relation to mission need.

It is clear that such an analysis, though difficult, has many virtues. It can reveal important but possibly neglected events. It can highlight weaknesses in design. It can suggest fruitful areas for improvement, i.e., it can help put the effort where the safety payoff will be large. And it provides an intelligent and rational approach which gets away from the impossible dream that "absolutely everything must be always safe under every circumstance."

In the latter respect it is akin to what we already do in everyday life. We all have some feeling, albeit often intuitive, of the probabilities of unfortunate events - i.e., of the chance we will be in an airplane crash, of the chance we will be hit by a car upon crossing a street, of the chance we will slip on the ice and break our leg, and so forth. We subconsciously weigh those probabilities and their consequences against our needs and desires as we decide whether or not to take an airplane trip, whether to dart through traffic or wait, whether to walk or take the streetcar. And the important thing is not that our knowledge

and judgement in such matters need be perfect; it is important only that it be sufficiently good.

There is one more item basic to the philosophy of a sound space nuclear safety program. That is contingency planning. Intensive reliability analyses and tests minimize the frequency of aborts, but they do occur. A whole spectrum of range safety practices and contingency must be ready to deal with them. Familiar range countermeasures include vehicle destruct plans, alternate flight plans, and personnel exclusion areas to minimize the consequences of potential aborts. But further contingency plans should also be developed, employing the conservative assumption that an abort will occur and that well-calculated post-abort actions will minimize its consequences. The aim should be to consider in advance the steps needed to combat any possible malfunction and to assure that the needed personnel and equipment will be on hand with preplanned action if it occurs.

An illustration of this is provided by the Apollo 13 mission. When there was a rather violent fuel cell oxygen tank failure on the service module, the Apollo 13 mission aborted in translunar flight. Yet the astronauts returned safely to earth using the life support and propulsion system of the lunar module in a linked command, service, and lunar module configuration which afforded them a "lifeboat" until just before reentry. The nuclear fuel capsule, which they carried loaded in a Graphite Lunar Module Fuel Cask (GLFC) especially designed for abort reentry survival, separated from the lunar module on reentry and impacted in the Tonga Trench whose great depth made it preferable to other otherwise equally safe areas. The survival of the astronauts, and the intact reentry and placement of the fuel at a pre-planned disposal site, are both tributes to good basic design and to the contingency approach. This approach, restated, is to ask "Even though you think it isn't going to happen, what can you do and what should you do if it does?" Affirmative planning should be done, including mobilization for action warranted by the answers to those questions.

LAST PAGE OFFICIAL

LAST PAGE OFFICIAL

5. EVOLUTION IN EXPERIENCE AND DESIGN

The review papers at this Symposium by G. A. Newby and D. S. Gabriel on the United States nuclear power and propulsion programs have pointed out that a variety of isotopic and reactor power systems are under study or development and that systems of both kinds have been employed in space. To date, there has been but one reactor system launched, while about fifteen radioisotopic power systems have been used, of which some employed multiple heat sources. The radioisotopic systems are the more thoroughly developed, so this discussion will mainly concern them. All employed to date have power supplies by converting the decay heat of plutonium-238 to electricity by use of Pb-Te thermoelectrics.

The first of the isotopic Space Nuclear Auxiliary Power, or SNAP, systems to be launched in space were the 2.7 and 25 (electrical) watt SNAP-3's and SNAP-9's. The use was on Transit navigational satellites. The fuel was plutonium metal (^{238}Pu), encased in an assembly which could contain it during severe ground accidents or early flight mishaps but assured of releasing it during reentry in the event the launch system did not achieve an earth orbit. This approach was partly suggested by the low melting point (600°C) and high oxidation rate of the fuel. The attraction in this form of disposal was the long residence time and large dilution factor resulting from oxidation, vaporization, and dispersal at high altitudes.

After numerous ground tests verified adequate containment with respect to ground accidents, two SNAP-3's were launched in 1961. They are still in orbit and their orbit lifetimes will exceed 1000 years. The thermoelectric generator on one still functions to provide some power.

When the SNAP-9 systems were designed, at approximately ten times the power of the SNAP-3's, the basic safety approach was similar. Internally, however, the ten-fold-larger inventory of plutonium metal fuel was subdivided and inserted into six capsules, each assured of reentry burnup, yet each capable of surviving severe surface launch abort environments. The last one launched in this series, in April 1964, did abort and the

fuel burned up as predicted and was diluted in the earth's atmosphere to insignificant ground concentrations. Values still being measured in 1969 were well within the pre-launch analyses performed by the safety community (Ref. 3).

New fuel forms with higher melting temperature suggested the possibility of effecting the intact return of fuel for possible retrieval, re-processing and re-use in future programs. With these fuels, and with the addition of a graphite heat shield, it was possible to produce a heat source which would survive reentry if it failed to achieve orbit. Such a heat source was incorporated into the SNAP-19 nuclear generators which were to power the Nimbus weather satellites. The fuel was $^{238}\text{PuO}_2$ microspheres of approximately 50-250 microns diameter. Besides their high temperature properties, these microspheres satisfied other criteria. They were too large to be inhaled (as produced), too small to be a significant external hazard, and so stable and inert chemically as to present small ingestion hazard. (The size range for respirable particles is about 0.3 - 2.6 microns.) The only significant hazard lay in the possible inhalation of "fines", fuel particles highly degraded in size, say down to a few microns. These beads were encapsulated within a shell of Haynes 25, an alloy chosen for various advantageous properties, including superior and tested resistance to seawater corrosion. This capsule was surrounded by a graphite ablator to form the "Intact Reentry Heat Source" (IRHS) and matched to the hexagonal interior shape of the thermoelectric generator unit.

The first launch vehicle carrying this system had to be destroyed in May 1968 by the Western Test Range safety officer at 100,000 feet altitude because of erratic flight. It carried two SNAP-19 generators. The system impact point was placed by radar and onboard telemetry as being in the Santa Barbara channel about three miles north of San Miguel Island, where the water depth was about 100 meters. Previous analysis and testing which had been done left little doubt that the two fuel capsules were intact. The capsules had survived test circumstances more difficult than

those of impact. The generator casing materials, capsule materials, and fuel had all been tested in the ocean and the low dissolution of the fuel was known. Though safety was considered assured, the contingency plan, calling for establishment of precautionary air and water monitoring, was executed as part of the pre-planned emergency response and maintained until the abort conditions were fully clarified. NASA, AEC, and DOD then proceeded to institute joint recovery actions as part of this plan. There was little urgency in this, but the fuel was an economic asset, post-mortem information on the actual abort performance of the heat sources was desired, and the challenge afforded by this unique opportunity needed to be met. The recovery story is a rather fascinating one, involving side-looking sonar and remote television, heavy seas, prolonged delays or halts, use of a small manned submersible (which located and photographed the capsules), and even use of a diver in full diving apparatus to accompany the capsules to the surface in recovery to insure they were not lost. Recovery was accomplished nearly six months after the abort. Subsequent examination showed that the capsules had experienced no deleterious effects from the destruct action, impact, or residence on the ocean bottom, and the graphite ablators surrounding the capsules were intact (Fig. 5.)

Plutonium microspheres fuel the SNAP-27 generators of the Apollo Lunar Surface Experiments Packages (ALSEPs) - though other even more advanced fuel forms have appeared - because the requirements for Apollo were fixed earlier. Four of these generators have been successfully placed on the lunar surface through the Apollo 12, 14, 15, and 16 missions. The fuel on Apollo 13 was impacted intact within its reentry cask into the depths of the Pacific Ocean.

Conceptual accident conditions for the multistage SATURN V vehicle, with its loading of 5,800,000 pounds of propellants, cover a very large spectrum of possibilities. Their interaction with the Apollo payload and its SNAP-27 fuel cask, under the worst possible yield conditions, can be severe. To resist them, the fuel cask has been successfully tested in a shock overpressure field of 650 psi (representing a 30% yield of the

SATURN V S-IV B third stage immediately below the fuel cask) and the cask has been subjected to fragments having velocities up to 3200 feet per second. The effects of SATURN V fireball and afterfire were also examined, and it was concluded that the fuel cask would survive these when protected by its graphite ablator and/or the secondary beryllium heat shield it contained.

Nevertheless, it was possible to postulate some unique and rather ill-defined but formidable accident environments which could potentially degrade exposed microspheres. These were known to be conditions of very low occurrence probability, requiring for example the simultaneous release of microspheres into a fireball at the time of fireball initiation, with the fireball itself being of a size attainable only by the catastrophic launch pad abort of the entire vehicle. But the possibility in principle on such conditions meant that safety policies based on "containment" should be reviewed and that they might need modification or clarification.

The policy answer to that review, as of today, is usually expressed by the word "immobilization". The concept is aimed directly at the fundamental safety problems of fuel inhalation and widespread ground contamination. The intent is to interdict the formation, release, dispersion and human inhalation of respirable (< 3 microns) particles of ^{238}Pu during and after an accident involving a nuclear power supply. This intent is of course satisfied by "containment" in its classical sense. However, this is probably not realistically achievable over the wide spectrum of potential abort environments which can be postulated. Perfect containment over the active life of the fuel (for ^{238}Pu the half-life is ~ 87 years) would not only require that a pressure-tight vessel, free of minor cracks, survive the most severe abort environments but it should also experience no consequential degradation for decades thereafter. Rather than thinking purely in terms of containment then, one should think in terms of aims. The aims of safety are generally satisfied if ^{238}Pu release rates can be controlled so that the total amount of ^{238}Pu aerosols entering the environment is kept below permissible levels at any time during and after an

accident. Immobilization seeks to achieve this by making beneficial collective use of the properties of the fuel form, the heat source materials, and the environment itself. It does not interfere with the policy of returning errant heat sources to radiological control whenever possible, but demands that the fuel be biologically inert should this not be possible.

New fuel forms have been evolved to aid the immobilization goals. One step in this evolution was developed at the Los Alamos Scientific Laboratory. It was to use $^{238}\text{PuO}_2$ feed material, mix it with 10% ThO_2 to enhance thermal and chemical stability above that of microspheres, and prepare this into solid solution particles deliberately pre-sized above the respirable range. These particles were coated with molybdenum, hot-pressed into a disc as shown in Figure 6, and the disc was coated with molybdenum by vapor deposition.

Several of the significant safety attributes of this fuel form have been set down by Dix (Ref. 4). "By virtue of its shape, reentry heating is minimized, and its conductivity is greater than PuO_2 , which lowers reentry surface temperatures. It is more resistant to the impulsive loads of high velocity impact and more energy is required to degrade it into respirable particles. Its surface area is smaller than an equivalent thermal inventory of microspheres, which yields considerably less vaporization into a SATURN-type fireball. Finally, the pre-sized solid solution particles immobilize the ^{238}Pu more effectively and the refractory cermet matrix and disc coating has to yield to the rigors of the abort spectrum before the particles can be exposed and degraded to evolve any respirable ^{238}Pu ".

Fuel discs of this general type, but without ThO_2 , have been used recently in SNAP-19 generators aboard the Transit (navigation) and Pioneer (Jupiter flyby) spacecraft. A similar SNAP-19 RTG configuration, for the Viking (Mars lander) spacecraft is shown in Fig. 7. The fuel capsule (cf. Fig. 8) employs a Ta-10W liner between the fuel discs and the T-111 refractory alloy strength member, which is covered with a Pt-20 Rh clad. Each part has a purpose: The liner aids in the task of encapsulating

fuel discs, the strength member offers high thermal stability and superior impact strength at high temperatures (it is to deform under impact and retain the fuel), and the clad provides oxidation protection for the strength member.

The heat source assembly consists of the fuel capsule together with the material which adapts it to the generator and protects it in abort situations. Principal parts of the Transit RTG heat source (Fig. 9), outside the fuel capsule, are its graphite "heat shield", the pyrographite "thermal barrier" body and sleeves, and an inconel can. In reentry, the graphite acts as an ablator while the pyrographite inhibits the influx of heat to the fuel capsule. The graphite ablator is protected against oxidation during ground operations by the inconel.

New radioisotope heat sources are evolving toward assemblages of special design, containing individual small units of fuel capable of operating at higher temperature, and providing their own reentry and impact protection. This is illustrated in Fig. 10. Each of the 24 fuel spheres in this Helipak assembly is contained in its own iridium shell and protected by a wound graphite impact shell. The fuel is pure plutonium dioxide ceramic. Each sphere develops about 100 watts of thermal power. Impact testing of these plutonium dioxide fueled spheres at about 280 feet per second against granite has begun at Los Alamos. This fuel form offers promise and may be developable into an efficient generator meeting the immobilization criterion. Other concepts for distributing the fuel into modular survivable reentry bodies are also being explored.

This account of fuel development illustrates the constant interplay that goes on between design objectives, safety needs, test results, and flight experience. It reminds us again that safety does cost, that safety considerations are inseparable from system considerations, that standardized approaches assist in comparison and evaluation, and that evolution in approach is logical and necessary.

6. OTHER TESTS AND OTHER SOURCES

We have looked briefly at changes in radioisotopic heat sources in response to program needs, safety considerations, analytical and ground test results, and flight experience. Each of these areas has broad implications - testing for example - and we could extend the discussion to other sources.

Analysis and testing embrace many activities. This is seen by looking at Fig. 11, which was compiled a few years back to point out areas in which standardization of approach appeared useful. (The benefits to be gained by having systematic and standardized means of making comparisons are that work at different laboratories or under different test conditions can be meaningfully correlated, the program guidance latent in the work becomes more readily apparent, and the number of tests and analyses required for a given level of understanding can be reduced.) In each of the roughly 30 different areas on this list, and in others as well, research is being done or has been done. It is intended to do such research to appropriate degree for every nuclear system of concern whether that is a small source or a reactor.

Small sources, which may be used for thrusters, for heat for life support or thermal control, or for gages, detectors, dial illuminators, density meters, calibrators, etc. have been launched in considerable number. Though the safety problems they pose are usually small, they are treated with respect. It is noteworthy that a small ^{241}Am source on the Nimbus B satellite was also recovered from the Santa Barbara channel and returned to radiological control along with SNAP-19s.

Testing on a large nuclear system goes on in all areas listed in Fig. 11, often in sequence. The Pioneer program gives examples. Pioneer heat sources, in Comparative Impact Tests, were heated to proper temperature and impacted at various orientations against granite blocks just to study the source vulnerability to this one variable. In Launch Abort Sequential Tests, the test paths followed by the various heat sources were all

LAST NUC OFFICIAL

LAST NUC OFFICIAL

sequenced and different - for example an overpressure impact test might be followed by a fragmentation impact test and then by a liquid propellant fire test and a solid propellant direct contact fire test, for all one unit, while another unit might go from a fragmentation impact test to a solid propellant fire proximity test and then to a liquid propellant fire test. The various sources, even if degraded, moved through their test sequence without repair, so as to provide a realistic history. Reentry Impact Sequential Tests were also performed - e.g. vibration, simulated reentry heating (by a plasma arc), and impact were varied in conditions and intensity - e.g., some units had different degrees of preheat, impact could be by airdrop on ground or by rocket sled against granite. An Aero-physics Test Program looked at effects of heat source orientation and gas stream mach number on drag coefficients, heat source ablation, and heating distributions. The fuel itself was often simulated in these tests by substituting ThO_2 for PuO_2 . This was only a minor perturbation and the tests were made as realistic as possible in all other respects, including proper preheat. The apparatus employed was wide-ranging.

Complex tests or test series like these are planned, conducted, analyzed and reviewed for any system to which they are appropriate, extending even to reactors. Reactor configurations realistic in all major respects, except for special engineering to provide very high rates of reactivity insertion, have been deliberately tested to destruction in the SNAPTRAN tests and the KIWI Transient Nuclear Test. The aim was to test the validity of codes predicting excursion size from reactivity insertion parameters under extreme conditions, even beyond those representing "worst" accidents. The results showed the theory to give a good representation of behaviour in such cases and in fact to be a bit on the conservative side. The knowledge gained in reactor transient tests such as these is valuable because it serves to normalize the codes under extreme conditions and it lends confidence to their use in other circumstances.

7. COUNTERMEASURES

The conducting of such reactor excursion tests does not mean that comparable accidents are expected to occur. It appears possible to guard against them quite effectively. Orifice jets can mechanically limit hydraulic flows - wherever such flows are used for control, "poison wires" can be inserted and retained in reactor cores until startup to prevent excursions from immersion as a result of launch accidents, reflector or reactor parts can be jettisoned and reactor disassembly can be effected either thermally or explosively to prevent criticality on reentry.

Countermeasures of various kinds have been mentioned throughout this paper. Others exist. Auxiliary thrust systems can sometimes be used to raise or lower payload velocities, possibly providing the necessary margin to establish a "safe" orbit or to de-orbit instead if that is desired. Flight trajectory shaping can be used to change potential impact points as a function of mission operating times. The list of possibilities and points of application is long. Careful attention to contingency planning should suggest the approaches which are best.

8. DOCUMENTATION AND REVIEW

It would be almost impossible to form any assurance of the safety a complex nuclear space system without some account which fully sets out what its nature is, what has previously been considered and done concerning it, what its accident environment and problems may be and what these imply for its safety. If the documentation of these matters is complete and reasonable, its consideration can reveal the safety problems of the system at an early date. A three step documentation and review process commencing at the conceptual phase has been used to meet this need (Fig. 12). The general purpose of this process is to:

1. Assure that the AEC, The Mission Project Office and System Contractors have discharged their nuclear safety responsibilities in the design, development, and use of

the system by demonstrating that safety requirements have been met, or exceeded.

2. Provide reviewers with a basis for performing an independent assessment of the system to see if it meets applicable nuclear safety criteria.
3. Provide the supporting documentation necessary to seek and obtain interagency flight approval.

The content and input requirements of these safety documents were usually reviewed with the systems contractor prior to contract negotiations and actions he is to take on receipt of safety evaluations have been outlined. The direct line responsibility has resided with the project offices. When large nuclear systems are involved, the review ultimately feeds into an Interagency Safety Evaluation Panel, (Fig. 13), composed of members and advisors drawn from the AEC, NASA, and the DOD. Each of these three panel agencies submits a report and recommendations through its agency head to the National Aeronautics and Space Council for its consideration and judgement. They in turn may submit the matter to the President for his approval.

9. SUMMARY AND CONCLUSION

There is no way of assuring perfect safety for any human activity, including that of operating nuclear power and propulsion devices in space. But there are some ways of addressing safety questions which elucidate the problems more clearly than others, and ways of proceeding which combat the risk more fully than others. It is suggested that the approach outlined here has those merits. It seeks to incorporate safety into the system from its inception, to explicitly identify and quantify the risks, to adopt measures reducing those risks, and to provide a program of analysis, test, and review which assures that those risks are adequately countered before decisions to launch are made.

This approach has been successful in practice. There is reason to believe it will be successful in the future, for, though the safety problems

INCHIO 231 1541

INCHIO 231 1541

to be addressed are formidable, there is no suggestion that they are intractable. Thus with continuing careful attention to these problems, the beneficial use of nuclear systems in space should steadily advance. With the advantages in flexibility, power, and performance which nuclear systems bring, this should rapidly and safely improve on the use of "Space for World Development".

IASI AEC OFFICIAL

IASI AEC OFFICIAL

REFERENCES

1. G. A. Newby, "U. S. Space Electric Power Program," this Symposium.
2. D. S. Gabriel, "Nuclear Propulsion in the United States," this Symposium.
3. T. J. Dobry, "A Safety Review and Future Considerations for Space Radioisotope Power Systems," paper presented to American Nuclear Society, San Francisco, November 1969. (Abstracts of such ANS papers may be found in the ANS Transactions for the meeting.)
4. G. P. Dix, "Nuclear Safety of Space Nuclear Power Systems," Aerospace Nuclear Applications Proceedings, American Nuclear Society (ANS Topical Meeting, Huntsville, Alabama, April 1970).

The following were not specifically cited but are very useful:

5. G. P. Dix, "Advances in the Safety of Space Nuclear Power Systems," Paper at 2nd International Symposium on Power from Radioisotopes, Madrid, Spain, June 1972.
6. G. P. Dix, "Future Considerations in Space Nuclear Safety," Paper at American Nuclear Society Meeting, June 21, 1966.
7. R. T. Carpenter, "Status of U. S. Radioisotopic Space Power Systems," Isotopes and Radiation Technology, Vol. 9, No. 3, p. 330-344 (Spring 1972).
8. R. T. Carpenter, "Space Nuclear Power Systems, p. 13, Proceedings of the National Symposium on Natural and Manmade Radiation in Space, V(NASA TMX-2440), Las Vegas, Nevada, March 1971, E. A. Warman, Editor.
9. R. I. Weiner, D. W. Pyatt, and M. D. Starr, "Navy Transit RTG Safety and Test Integration from Users Viewpoint," p. 540-546, 7th Inter-society Energy Conversion Engineering Conference Proceedings, San Diego, California, Sept. 1972. (Proceedings available from American Chemical Society, Washington, D. C.)

Some of the most interesting material on this subject appears in Contractor publications. These and similar documents of limited distributions were not cited because they are hard to acquire. Internationally available material should include the Proceedings volumes referenced under Numbers 8 and 4 (both very good general sources), the annual IECEC Proceedings (1972 may be obtained from ACS, the 1970 issue from ANS.) The AEC's Understanding the Atom booklets entitled: Nuclear Reactors for Space Power by W. R. Corliss, Power from Radioisotopes, by W. R. Corliss and R. L. Mead, Nuclear Propulsion for Space, by W. R. Corliss and F. S. Schwenk, Snap Nuclear Space Reactors, by W. R. Corliss, are pertinent and readable, and have short bibliographies. These booklets are available from USAEC, P. O. Box 62, Oak Ridge, Tennessee, 37830.

14-00000

14-00000

LIST OF FIGURES

Fig. 1 - Some General Safety Considerations	#729943
Fig. 2 - Intrinsic Potential Problem Areas	#729944
Fig. 3 - Extrinsic Potential Problem Areas	#729941
Fig. 4 - Elements Basic to a Sound Space Nuclear Safety Philosophy	#729942
Fig. 5 - SNAP-19 Heat Sources on Ocean Bottom	30 S-275
Fig. 6 - LASL CMB-11 Fuel Disc	#701909
Fig. 7 - SNAP-19 RTG - Viking A & B	71 S-467
Fig. 8 - SNAP-19/Pioneer Heat Source	#729946
Fig. 9 - Transit Heat Source Design	#729940
Fig. 10 - Helipak Assembly	R-12 S-70
Fig. 11 - Standardization of Analytical Experimental and Computational Studies	#729978
Fig. 12 - Safety Documentation Requirements for Space Nuclear Systems	#729979
Fig. 13 - Proposed Overall Space Nuclear Safety Review	#729980

SOME GENERAL SAFETY CONSIDERATIONS

* SAFETY HAS COSTS AND CONSTRAINTS

WEIGHT
SYSTEM RELIABILITY
\$/WATT IN ORBIT

* SAFETY IS INTEGRAL TO THE SYSTEM

SOME PARTS SYSTEM-UNIQUE
BELONGS IN EVERY SYSTEM DEVELOPMENT PHASE - beginning to end
RESPONSIBILITY OF EVERYONE - contractor, project office, user

* STANDARDIZED SAFETY APPROACHES ARE USEFUL

SAFETY CRITERIA
DOCUMENTATION
ANALYTICAL, TEST, COMPUTATIONAL TECHNIQUES
REVIEW PROCEDURES
CONTINGENCY PLANNING
OPERATIONAL SAFETY PROCEDURES

* SAFETY RESEARCH AND TECHNOLOGY MUST ADVANCE

NEW IDEAS, DEVICES, TECHNIQUES FOR SYSTEM SAFETY
ADAPT OTHER NEW SPACE TECHNOLOGY TO SYSTEM SAFETY
EVOLVE NEW CONCEPTS FROM NEW KNOWLEDGE

INTRINSIC POTENTIAL PROBLEM AREAS

* ISOTOPE SYSTEMS

- GAS BUILDUP
- EXCESSIVE HEAT
- DIFFUSION
- CHEMICAL REACTION
- RADIATION DAMAGE

* REACTOR SYSTEMS

- UNSCHEDULED CRITICALITY
- POWER EXCURSION
- COOLANT FAILURE
- RADIATION DAMAGE

EXTRINSIC POTENTIAL PROBLEM AREAS

* INDIVIDUAL EVENTS

FIRE - Time and Temperature Variable

EXPLOSION - Shock, Overpressure, and Projectile Production Variable

VIBRATION, ACCELERATION, TUMBLING OR SPIN

RE-ENTRY - Shock, Ablation,

IMPACT ON LAND OR WATER - Immersion, Burial, Compaction, Corrosion,
Oxidation, Dissolution, Dispersion
Re-suspension, Fixation

* SEQUENTIAL EVENTS

VARIOUS COMBINATIONS OF INDIVIDUAL EVENTS ABOVE

ELEMENTS BASIC TO A SOUND SPACE NUCLEAR SAFETY PHILOSOPHY

* QUALITY HARDWARE DESIGN AND DEVELOPMENT

ANALYZE BEHAVIOUR UNDER NORMAL AND ABNORMAL CONDITIONS
ANALYZE BEHAVIOUR UNDER POTENTIAL ACCIDENT CONDITIONS
TEST AT DESIGN AND OFF-DESIGN CONDITIONS
TEST AT SIMULATED ACCIDENT CONDITIONS
ADHERE TO RELIABILITY AND QUALITY CONTROL MEASURES

* PROBABILISTIC ANALYSIS

FIND PROBABILITY OF SEPARATE EVENTS
FIND PROBABILITY OF SEQUENCED EVENTS
ASSESS PROBABLE CONSEQUENCES OF EACH SEQUENCED EVENT
DESCRIBE SIZE AND NATURE OF RISK FROM ALL EVENTS
DETERMINE IF SPECIFIC COUNTERMEASURES OR CHANGES NEEDED - if so, change and repeat process.
MAKE BENEFIT-RISK JUDGEMENT

* CONTINGENCY PLANNING

ASSUME EACH POSSIBLE EVENT WILL OCCUR
ASSESS ACTIONS NEEDED IN LIGHT OF PROBABLE CONSEQUENCE FROM OCCURRENCE
PREPARE AND IMPLEMENT COMPLETE CONTINGENCY PLAN

FIG. 5

SNAP-19 HEAT SOURCES
ON OCEAN BOTTOM

CMB-II

1 in.

2 in.

LASL

U.S. ATOMIC ENERGY COMMISSION SNAP 19 RTG - VIKING A&B

TELEDYNE
ISOTOPES

FIG. 7

SNAP 19 / PIONEER HEAT SOURCE

FIG. 8

Transit Heat Source Design

FIG. 9

FIG. 10

STANDARDIZATION OF ANALYTICAL, EXPERIMENTAL
AND COMPUTATIONAL STUDIES

* ANALYTICAL AND EXPERIMENTAL

- AERODYNAMIC (FLOW REGIMES, STABILITY, FORCE AND MOMENT)
- AEROTHERMODYNAMIC (HEATING, HEAT TRANSFER, MELTING, ABLATION)
- AEROTHERMOCHEMICAL (MASS REMOVAL, REACTION KINETICS, DIFFUSION)
- MECHANICAL (IMPACT, EARTH MEDIA, SHOCK, FRAGMENTATION)
- THERMAL (FIREBALL REACTIONS, EARTH BURIAL, OVERHEATING)
- CHEMICAL (CORROSION, SOLUBILITY)
- RADIOLOGICAL (HUMAN CONTACT, DOSE)
- RADIOBIOLOGICAL (INTERNAL, EXTERNAL EFFECT)
- PROBABILISTIC (FAILURE MODES, SEVERITY, HUMAN EXPOSURE)

* COMPUTATIONAL

- REENTRY (TRAJECTORY, ORBITAL LIFETIME, HEATING, ABLATION CODES)
- SOURCE TERM (INVENTORY, FALLOUT CODES)
- PROBABILISTICS (CODES TREATING SYSTEM FAILURES, DOSE, & DOSE
PROBABILITY)

SAFETY DOCUMENTATION REQUIREMENTS FOR SPACE NUCLEAR SYSTEMS

* WHO SUBMITS DOCUMENTATION?

THE USER SYSTEM PROJECT OFFICE, SUPPORTED BY THE AEC SYSTEM PROJECT OFFICE.

* WHAT DOCUMENTS ARE SUBMITTED?

REFERENCE DESIGN	}	SAFETY DOCUMENTATION
ACCIDENT MODEL		
SAFETY ANALYSIS		

* WHEN IS THE SAFETY DOCUMENTATION SUBMITTED?

THREE (3) TIMES IN THE LIFE OF A PROGRAM, AS PRELIMINARY, INTERIM, AND FINAL SAFETY DOCUMENTATION. ON AN OPTIMAL SCHEDULE:

<u>FIRST SUBMISSION</u>	- ONE (1) MONTH AFTER COMPLETION OF CONCEPTUAL DESIGN OF SNAP.
<u>SECOND SUBMISSION</u>	- FOUR (4) MONTHS PRIOR TO DELIVERY OF SNAP TO USER.
<u>THIRD SUBMISSION</u>	- SIX (6) MONTHS PRIOR TO FLIGHT.

* TO WHOM IS IT SUBMITTED?

TO THE COGNIZANT USER AND AEC HEADQUARTERS PROJECT OFFICE MANAGERS AND DIRECTOR OF REGULATION WHO REFER IT TO THEIR SAFETY STAFFS FOR REVIEW.

PROPOSED OVERALL SPACE NUCLEAR SAFETY REVIEW PROCEDURE

*Includes Safety Evaluation by Safety Staffs of Project Offices.

REFERENCES

1. G. A. Newby, "U. S. Space Electric Power Program," this Symposium.
2. D. S. Gabriel, "Nuclear Propulsion in the United States," this Symposium.
3. T. J. Dobry, "A Safety Review and Future Considerations for Space Radioisotope Power Systems," paper presented to American Nuclear Society, San Francisco, November 1969. (Abstracts of such ANS papers may be found in the ANS Transactions for the meeting.)
4. G. P. Dix, "Nuclear Safety of Space Nuclear Power Systems," Aerospace Nuclear Applications Proceedings, American Nuclear Society (ANS Topical Meeting, Huntsville, Alabama, April 1970).

The following were not specifically cited but are very useful:

5. G. P. Dix, "Advances in the Safety of Space Nuclear Power Systems," Paper at 2nd International Symposium on Power from Radioisotopes, Madrid, Spain, June 1972.
6. G. P. Dix, "Future Considerations in Space Nuclear Safety," Paper at American Nuclear Society Meeting, June 21, 1966.
7. R. T. Carpenter, "Status of U. S. Radioisotopic Space Power Systems," Isotopes and Radiation Technology, Vol. 9, No. 3, p. 330-344 (Spring 1972).
8. R. T. Carpenter, "Space Nuclear Power Systems, p. 13, Proceedings of the National Symposium on Natural and Manmade Radiation in Space, V(NASA TMX-2440), Las Vegas, Nevada, March 1971, E. A. Warman, Editor.
9. R. I. Weiner, D. W. Pyatt, and M. D. Starr, "Navy Transit RTG Safety and Test Integration from Users Viewpoint," p. 540-546, 7th Inter-society Energy Conversion Engineering Conference Proceedings, San Diego, California, Sept. 1972. (Proceedings available from American Chemical Society, Washington, D. C.)

Some of the most interesting material on this subject appears in Contractor publications. These and similar documents of limited distributions were not cited because they are hard to acquire. Internationally available material should include the Proceedings volumes referenced under Numbers 8 and 4 (both very good general sources), the annual IECEC Proceedings (1972 may be obtained from ACS, the 1970 issue from ANS.) The AEC's Understanding the Atom booklets entitled: Nuclear Reactors for Space Power by W. R. Corliss, Power from Radioisotopes, by W. R. Corliss and R. L. Mead, Nuclear Propulsion for Space, by W. R. Corliss and F. S. Schwenk, Snap Nuclear Space Reactors, by W. R. Corliss, are pertinent and readable, and have short bibliographies. These booklets are available from USAEC, P. O. Box 62, Oak Ridge, Tennessee, 37830.

LAST AEC OFFICIAL

LAST AEC OFFICIAL