AEROSPACE NUCLEAR SAFETY

SC-DC-67-1900
July 1967
CONF-670714--6

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PRESENTED AT THE SECOND INTERNATIONAL SYMPOSIUM ON NUCLEONICS IN AEROSPACE AT COLUMBUS, OHIO ON 12 JULY 1967

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ABSTRACT

Our future in space will be governed largely by the amount of power we can carry there for our use. One of the most promising sources of power is from the decay of radioactive isotopes. Although power levels are not high (that is, generally below 1000 watts electrical), the reliability and long life of these systems are indeed attractive. The challenge of the future is to increase the specific power of these systems, and at the same time to increase the overall safety. This paper discusses the problem concerned with increasing aerospace nuclear system safety.

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Introduction

Our future in space will be governed largely by the amount of power we can carry there for our use. One of the most promising sources of power is from the decay of radioactive isotopes. Although power levels are not high (that is, generally below 1000 watts electrical), the reliability, long life, and light weight of these systems are indeed attractive. Present technology achieves about 1 watt per pound with a life of over 5 years. Figure 1 is a summary of information gathered from a number of government and commercial users showing the number of systems of various power levels which are being forecast for use through 1973. With an average of seven flights per year over this period, it is obvious that care must be taken to assure that no accident will occur which will result in a radiological hazard.

Anyone designing a nuclear power supply or anyone wishing to employ a nuclear power supply in a space mission has a moral obligation to provide a system approach which has been designed to provide a maximum of safety. Failure to follow proper safety design approaches could have serious consequences and could endanger the lives of many people in the world's population.

Space Power Organization

In the United States, the development of all nuclear power supplies for use in space is under the direction of the Atomic Energy Commission. In a 1965 reorganization, the AEC established a Space Electric Power Office (SEPO) to direct the development of all SNAP (Systems for Nuclear Auxiliary Power) power units. This new organization and the Space Nuclear Propulsion Office (SNPO) both report to Milton Klein, who heads the Space Nuclear Systems division (SNS). Figure 2 shows the organization as it now exists.

	YEARS						
POWER RANGE $W_{(e)}$	'67	'68	'69	'70	'71	'72	'73
10-30		2	9	4			
30-100	1	2		2	3	2	3
100-300		2	1	1	3	2	3
300-1000					3		5
>1000					1	1	
TOTAL NUMBER	1	6	10	7	10	5	11
CUMULATIVE TOTAL	1	7	17	24	34	39	50

Figure 1. Anticipated isotope generator flight schedule

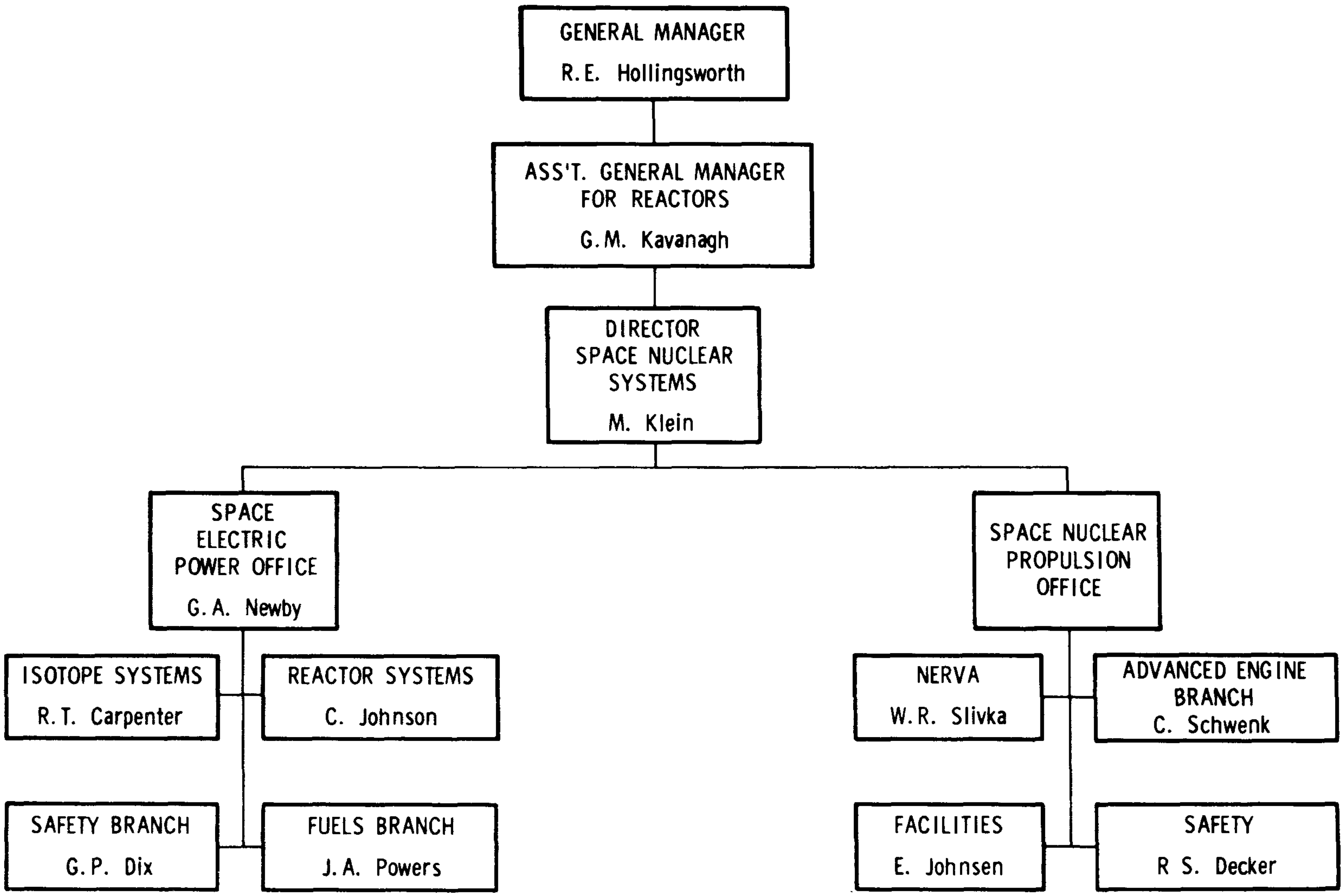

Figure 2. AEC organization as related to space nuclear systems

SEPO consists of four branches. The Isotope Systems Branch is responsible for the development of all isotope power supplies for use in space. This work is handled through contracts with private industry. The Reactor Systems Branch bears a similar responsibility in the field of reactor power supplies. Both branches are responsible for the development of power supplies whose use will not subject the world's population to any significant risk of injury. This responsibility is in turn passed on to the manufacturer of the power supply who must prepare the system safety analysis. The development of the isotope fuel forms used in each of the systems is the responsibility of the Fuels and Materials Branch, who must work closely with the Isotope Systems Branch in each development program.

The Safety Branch in SEPO is responsible for assuring by close liaison with the Isotope Power Branch during development and by independent review that safety has in fact been achieved in the design and use of the system. This branch is also responsible for the coordination of safety reviews by other branches of the AEC and other Government agencies. These reviews form the basis for the AEC's approval which is required for each flight.

Documentation Requirements

SEPO has prepared a guide, "Safety Documentation Requirements for Space Nuclear Power Systems," for its contractors. These guidelines define the necessary documentation, and specify when it is needed and by whom and to whom it is submitted. A summary of the documentation requirements is shown in Figure 3.

While these documentation requirements have been prepared specifically for electric power systems, they may also be applied with minor modification to other space nuclear systems, such as thrusters, heat sources, instrumentation, and other small sources of various types. The depth of detail of the documentation depends on the nature of the radiation source associated with each system.

The Reference Design portion of the safety documentation establishes a currently valid and consistent description of the system, its application, and operation. The Accident Model portion identifies the possible malfunctions leading to potential nuclear safety problems and treats the probabilistics associated with each potential accident. The Safety Analysis portion presents an evaluation of the nuclear safety aspects of the system. These documentation requirements represent the initial step toward standardizing the procedural aspects of space nuclear safety.

1. WHO SUBMITS DOCUMENTATION?

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

2. WHAT DOCUMENTS ARE SUBMITTED?

REFERENCE DESIGN ACCIDENT MODEL SAFETY ANALYSIS	} SAFETY DOCUMENTATION

3. WHEN IS THE SAFETY DOCUMENTATION SUBMITTED?

THREE TIMES* IN THE LIFE OF A PROGRAM, AS PRELIMINARY, INTERIM, AND FINAL SAFETY DOCUMENTATION.

FIRST SUBMISSION - ONE MONTH AFTER COMPLETION OF CONCEPTUAL DESIGN OF SNAP.
SECOND SUBMISSION - FOUR MONTHS PRIOR TO DELIVERY OF SNAP TO USER.
THIRD SUBMISSION - SIX MONTHS PRIOR TO FLIGHT.

4. 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.

*TIMES INDICATED ARE OPTIMUM AND APPLICABLE IF PROGRAM SCHEDULE PERMITS.

Figure 3. Safety documentation requirements for space nuclear systems

Safety Analysis

The preliminary safety analysis is particularly important. It will generally be in this document that the more important potential hazards are identified. A safety test program can be then formulated which will provide the basis for the subsequent safety evaluations.

A safety analysis is performed by systematically examining the potential hazards that exist as a consequence of an attempted launch. Figure 4 is a simplified multiple path array which can be used to illustrate the technique. The first row shows three possible consequences of an attempted launch. The sum of the probabilities in this row is 1.0 or in other words the launch attempt must result in passing into one of the blocks. A particular mission may require more blocks than shown here, particularly if different hazards result from the many different aborts that may occur. This is no problem; the only requirement is that the sum of the probabilities for this row must total 1.0. From each block in the first row we may potentially pass into any block in the second row. Again, more than three blocks may be required. As before, the only requirement is that the sum of the probabilities in this row, from each block in row one, must again be 1.0. Using this simplified chart, we can see there are nine different paths which arrive at the third row where we must now decide which form the resulting exposure may take. Having selected the exposure mode, we arrive at the fourth row where we evaluate the hazard. At this point we select the severity of exposure of interest and then calculate the number of people given this exposure and the probability of exposure. The term "Severity of Exposure" is used to denote levels of injury which may vary from fatality to slight injury or exposure to more than a given dose level. A very important thing to recognize is that any path may produce some hazard, even the successful flight.

Figure 5 is shown to illustrate the complexity of an actual flight. This example has over 900 different paths between launch and the ultimate injury. A properly executed safety analysis will examine every important path.

When all important paths have been evaluated then a mathematical summation is made to determine the expected number of people to receive the injury of interest. Figure 6 shows the formula for obtaining this result. Summations will generally be required for a number of different levels of injury. Where an exact definition of injury is not available, it may be appropriate to select a level of exposure consisting of, for example, inhalation of one or more particles of a given size range.

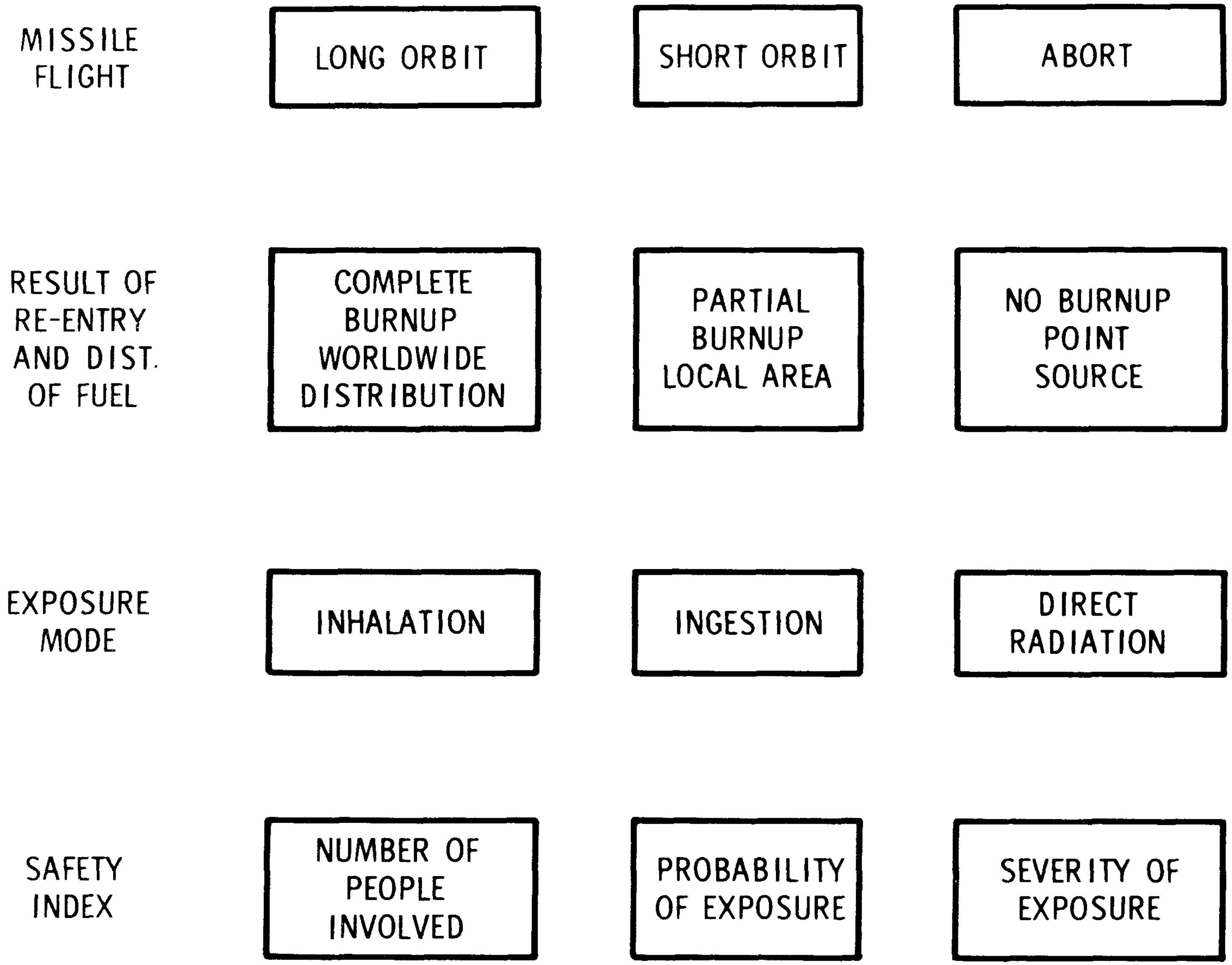

Figure 4. Aerospace safety analysis plan--mission fate

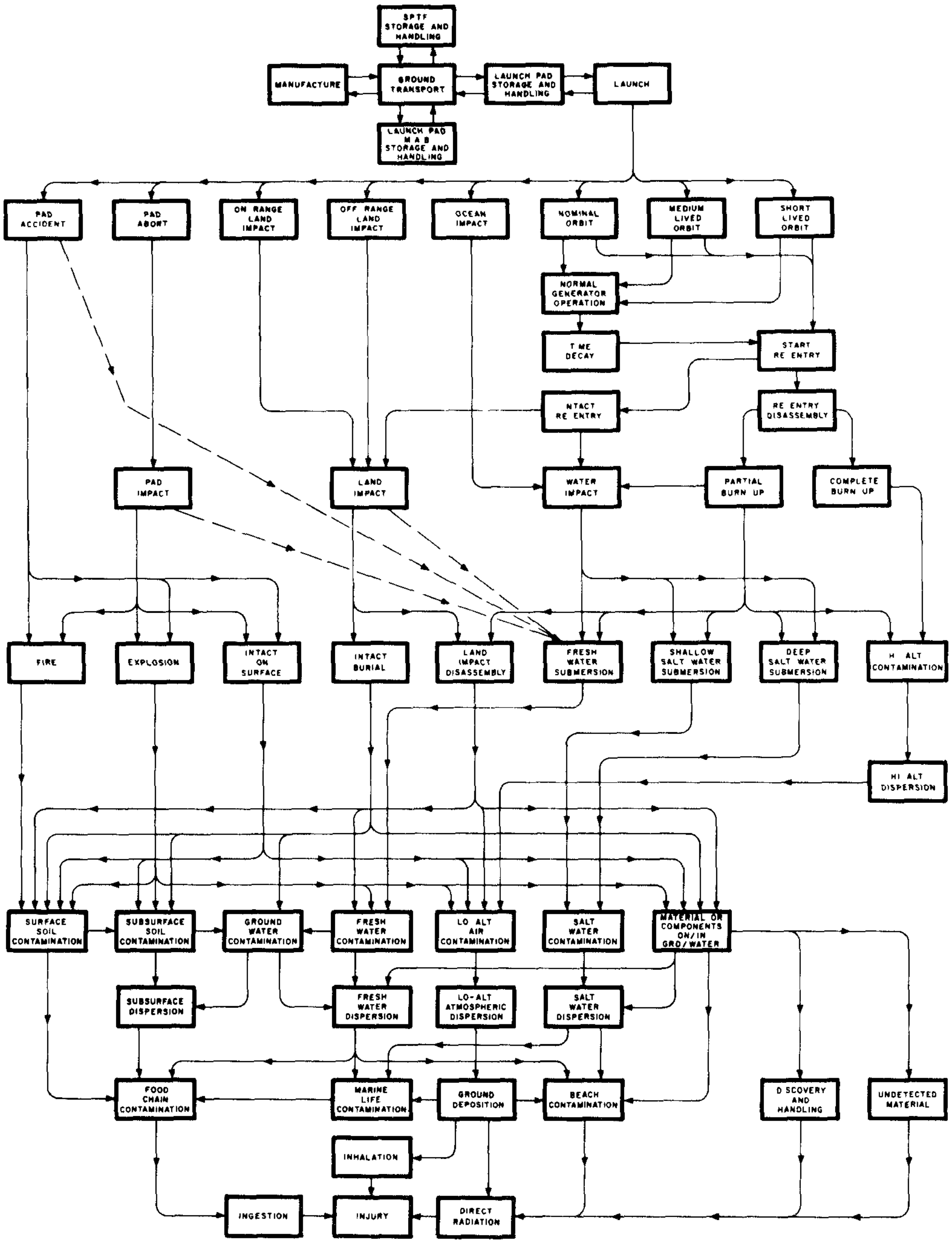

Figure 5. Isotope generator hazards flow chart

METHOD OF CALCULATING EXPOSURE

$$\sum_{i=1}^{n} N_i P_i \leqq x$$

N_i = the number of people exposed to a given dose d or more on the ith path

P_i = the probability of N_i people being exposed to d or more on the ith path

n = the number of possible hazard paths

x = the expected number of people exposed to d or more as a result of the flight

Figure 6. Method of calculating exposure

In any event, one is now in a position to judge the acceptability of a flight. If the expected number of injuries is at a low enough level, considering the importance of the flight and other factors, then the flight may be considered acceptable. If the number is higher than desired, the same technique may be applied to a different mission profile, generator design approach, or fuel to see if the expected number of injuries can be reduced to an acceptable level.

Examples of Improved Safety

I would next like to address myself to examples of design changes which can significantly enhance safety. The first example concerns changes to the mission profile. The most efficient way to obtain a high orbit is to fly the mission using an intermediate transfer orbit. In this case, the booster and first burn of the second stage are used to place the system in an elliptical orbit with an 80- or 90-mile perigee and apogee at the desired orbit altitude. The second stage then is shut down and the system allowed to coast to apogee where restart and a short burn will circularize the orbit at the desired altitude. With this type of mission profile, failure of the second stage to restart will leave the spacecraft in the elliptical orbit with a lifetime of only a few months. The probability of this failure is estimated to be around 3 in 100. If this type failure is contributing to a large number of expected injuries, then the mission profile may be altered to significantly reduce the probability of a short orbit. The change consists of elimination of the intermediate orbit. In the new flight profile, the missile is flown along a ballistic flight path with a maximum altitude corresponding to the desired orbital altitude. As before, restart and burn at this altitude will place the spacecraft in the desired orbit; however, failure to restart will result in ballistic reentry of the spacecraft in a prescribed area (rather than random orbital decay reentry). This change can decrease the probability of a short orbit from 3 in 100 to about 1 in 1000, a decrease in the expected number of injuries from this source by a factor of 33.

If burnup or partial burnup from failure to achieve the desired long-lived orbit is contributing the major portion of the expected injuries, then a change in design so the generator can survive reentry can reduce the probability of burnup or partial burnup by a factor between 1 in 100 and 1 in 1000. Of course the intact design brings forth a new set of safety problems which must also be analyzed, namely, the hazard of an intact generator randomly reentering and impacting somewhere on land.

If this latter problem, namely, the random land impact, proves troublesome, a design approach might be followed which would use controlled deorbit to enhance safety by reentering the power supply so it impacts in the ocean rather than on land. Admittedly these systems can be costly and heavy; however, if the Pacific Ocean is the target, it is likely that timer-operated fail-safe deorbit schemes using inflatable drag devices could prove workable.

The previous examples have considered changes to the mission profile or to the power generator. Changes to the fuel form can also be effective. In the case of polonium-210, a very volatile fuel form, significant reductions in expected injuries can result if the fuel is chemically or mechanically tied up so that rupture of the fuel container will release only a small fraction of the fuel.

In addition, significant safety advantages exist with the use of some of the other isotope decay fuels. For example, a nominally 100-watt electrical generator using about 1-1/2 megacuries of krypton-85 could be built at about 0.75 watt per pound of generator weight. With such a system, the probability of injury from an accident to anyone in the general population is much less than 10^{-6}.

Conclusions

The safety of nuclear power supplies is steadily increasing. More advanced designs and more sophisticated methods of analysis are producing significantly better systems than were available only a few years ago. However, tomorrow's systems must be even better. Industry, with the help of the AEC, must accept this challenge and set design goals that will yield absolutely safe nuclear power systems. We must never have an accident which has serious consequences, for to do so will set back the space power program many years.

With respect to safety, I think two statements from the International Commission on Radiological Protection (ICRP) are well worth noting:

> Relative to future expansion of nuclear energy--"It is of the utmost importance in this connection to make sure that nothing is done now that may prove to be a serious hazard later, which cannot be corrected at all or will be very expensive to correct...

"Even when individual exposures are sufficiently low so that the risk to the individual is acceptably small, the sum of these risks, as represented by the total burden arising from the somatic and genetic doses in any population under consideration, may justify the effort required to achieve further limitation of exposure."

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