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AEROSPACE NUCLEAR SAFETY
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MASTER

In 1958 the United States placed its first satellite in an earth orbit. The signals from this satellite were heard for about two weeks, the limit of the battery supplied power. Since then the United States has put forth a major effort in space. Satellites weighing many tons have been orbited which have required electrical power plants producing as much as several thousand watts. It became apparent early in the space program that the operation of electrical payloads in space for extended periods of time would dictate that some form of solar or nuclear energy would ultimately be required.

The Atomic Energy Commission, in the early 1950's studied a number of nuclear energy power source concepts from the viewpoint of establishing their feasibility for use in future spacecraft. Both reactors and radioisotope generators were considered. Although ground-based reactors are inherently large and heavy and require massive shielding, it appeared possible that smaller compact versions could be designed for space use. Likewise, the high specific power available from several of the radioisotope materials made it probable that reasonable power levels could be obtained from isotope power sources.

The first space atomic power source was demonstrated in 1959. Called the SNAP-3, this isotopic generator used Polonium-210 as a fuel, weighed four pounds and produced in excess of $2\frac{1}{2}$ watts of power for 90 days. The total power available from this four pound unit was equivalent to nearly one ton of nickel cadmium batteries. In 1961 a version of the SNAP-3 generator fueled with Plutonium-238 was used to power a portion of two navigational satellite systems. One of these nuclear powered systems is still operating. The condition of the other is unknown since it ceased transmitting after eight months of operation, apparently due to an electronic failure.

Starting in 1963, larger plutonium fueled isotope power supplies were flown on three navigational satellites. These power supplies were designed to develop 25 watts for five years. Two of these are still in orbit while a third was destroyed as a result of a failure of the missile to place the satellite in orbit.

In 1965 the first reactor power supply, designated SNAP-10A, was placed in orbit around the earth. This unit produced in excess of 500 watts of electrical power for a period of 43 days. The reactor was then apparently shutdown by an onboard sensor which malfunctioned. Until shutdown, the power supply performance exceeded expectations.

These systems are members of a family of atomic power supplies designed for use in space. Figure 1 shows the different systems under development. The left side of the chart shows the higher powered systems which are reactors and include units to produce heat as well as those to produce electricity. The right side of the chart shows the lower powered systems, again divided between those to produce heat and those to produce electricity. Figure 2 gives the characterization of the various systems including weight, fuel, and power level.

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There is some hazard associated with the use of radioactive materials as an energy source. This is also true of other useful energy sources, like steam or gasoline. The public has learned to accept certain safety precautions in order to benefit from these more common energy sources, and a similar pattern will evolve with radioactive materials.

The ability of any nation to successfully pursue the exploration of space is most certainly governed by the amount of electrical energy which can be delivered by space power supplies. Figure 3 shows a spectrum of power levels versus lifetime for various space systems. The higher levels of power can be met only by use of reactors. Clearly, there is no competition with atomic energy in this area. In the high intermediate levels, solar dynamic systems, isotope dynamic systems, or reactor systems, all using rotating machinery for energy conversion, can meet the power levels. The low intermediate power levels can be handled by either solar static or isotope static systems.

Considering the broad spectrum of capability, nuclear energy will certainly prove to be indispensable in space. Safety probably represents the greatest deterrent to the extensive use of nuclear power in space thus far. Safety is not something that just happens. It must be carefully thought out and positive steps taken to achieve it.

The next chart, Figure 4, is shown to present in the form of a multiple path array, a simplified version of the overall aerospace nuclear safety problem. Given a launch, the chart shows that the flight can result in one of three things. Either the missile achieves a successful orbit, or a short orbit, or it aborts. By definition, all possible eventualities of an attempted launch can be made to fit into one of the blocks. The sum of the probabilities in any row is one. The number of blocks in this row can be as many as desired as long as the sum of probabilities totals one. The second row shows what can happen as a result of reentry. Again, every eventuality is covered in this row. The third row shows the form the resulting exposure may take. The final row is a safety index which consists of three items to be evaluated; the number of people involved, the probability of exposure, the severity of exposure. More will be said later about this safety index. The chart is used to illustrate a systematic method of analysis which will cover all the possible consequences of a flight. There are 27 different paths through this array of blocks which must be considered and for which a safety index should be evaluated. For an actual system, the number of paths will be more than represented by this array. Some systems can involve several thousand separate paths depending on the number of rows and columns necessary to describe the mission. It is important to note that the probability of exposure is never zero along any path so that some evaluation will always be necessary. For example, a power supply designed to reenter intact has some finite possibility of burning up and it may in fact develop that the greatest potential hazard exists along this undesired path.

When the important critical paths are isolated, then attention can be given to these areas to reduce the potential hazard by reducing the number of people involved, the severity of the exposure, or the probability of occurrence (the three items in the safety index.)

The primary approach to the safe use of isotope power in space has been the selection of ~~low~~ altitudes that have a long lifetime relative to the half-

life of the isotope. Ten half-lives will reduce the isotope inventory by a factor of 1000. However, in attempting a launch, there is some probability that a short orbit or an abort will occur. Usually the more hazardous situations can arise along one of these paths. If the short orbit path, because of its random reentry characteristic, proves to be the most critical, the designer may be able to reduce the probability of incurring a short orbit by selecting a ballistic ascent into orbit rather than a Hohmann transfer. Although a reduction in missile performance is incurred, the probability of being in the short orbit may be reduced by a factor of 100 or more. Or, as an alternative, the designer may choose to reduce the random character of a short orbit reentry by including a command deorbit system with the atomic power supply to achieve reentry where desired. Gains in safety, by a factor of 10 to 100 are possible with this approach. These are only two of many possible ways of improving the safety picture. The designer is limited only by his own ingenuity in developing safer systems. In some instances the situation may arise where a switch in design approach is necessary. A careful analysis may show that an intact design involving a given fuel form is safer than a burnup design or the reverse may be true.

In switching from a burnup approach to an intact approach, one is confronted with the very difficult problem of trying to compare the acceptability of a low probability of exposing a small number of people to a high level of hazard, with a higher probability of exposing a large number of people to a low level of hazard.

I will devote the remainder of my talk to the presentation of some thoughts on this subject that may eventually form a basis for criteria which can be used to make such judgments. Earlier, you will recall, I indicated that the terminal evaluation of the array of the multiple path chart is a safety index involving the number of people exposed, the probability of exposure, and severity of exposure. What is needed to form the basis for an approach to this problem is a naturally occurring hazard that is readily acceptable to the world's population, but at the same time has the potential from a single incident of involving a large segment of people. Typhoons, hurricanes, tsunamis, or earthquakes, seem at first to fit the criteria; however, even though they often involve a number of people they certainly could not be classified as "acceptable" since no one would agree to an operation which had any probability of causing casualties at the rate of any of these natural accidents. Nature has provided one form of hazard that does seem to fit the requirements. This is the hazard associated with the entry of meteorites.

Figure 5 is a set of curves relating to iron meteorites showing their size, frequency of arrival, and resulting lethal area. It can be seen, for example, that five meteorites weighing ten tons each enter the earth's atmosphere each year. Picking another size, it can be seen that a meteorite weighing 100,000 tons can be expected to strike the earth at a rate of about 5×10^{-4} per year or one every 2000 years. The well known crater in Arizona was made by a meteorite of this size. The resulting crater was 1.2 km in diameter. It has been estimated that all life within a diameter of 10 km was destroyed as a result of this impact. The newspapers recently noted that an asteroid named Ictharus will pass within $4\frac{1}{2}$ million miles of the earth in the summer of 1968. This asteroid, which revisits the earth every 19 years is about one mile across and will weigh in the vicinity of 10 billion tons. The chart shows that the crater from this meteorite, should it ever strike the earth,

would be perhaps 100 km in diameter while the lethal area would cover a diameter in the range of 1000 km. There are two craters in Africa that are 25 and 40 km in diameter, providing evidence that large meteorites do strike the earth. A book on the subject of meteorites states that evidence indicates the earth has been bombarded throughout geological time by meteorites and there is no reason to believe it will not continue. It is noteworthy that a ton of meteoritic material traveling at meteorite velocities represents the kinetic energy of 10 tons of high explosive.

From these curves, and the population distribution on the earth, the curve shown in Figure 6 was derived. It shows the relation between the number of people that could be killed from a given size meteorite striking the earth and the probability of that event happening. It shows, for example, that the probability of one death per year is about one in 300 while the probability of as many as eight million people being killed is about one in one billion. In spite of the fact that about ten meteorites strike the surface of the earth each day, there apparently has never been a death attributed to a meteorite. An individual's personal hazard is remote, being about one chance in 10^{-11} of being struck in any given year.

Again, referring to the last row of the multiple path chart, the three items suggested for consideration in the safety index were the number of people involved, the probability of exposure, and severity of exposure. As can be seen, Figure 6 provides a form of a safety index guide for the most severe possible exposure from a naturally occurring hazard. It seems reasonable to assume that this could also prove to be a quite acceptable guideline for a man-made hazard. It should be possible to draw other curves on this chart which can represent other levels of exposure (severe injury, slight injury, 100 rem, 25 rem, maximum permissible body burden, etc.) If the curves for other levels of exposure can be added, the chart could form a basis for safety design as well as evaluation.

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FIGURE 1

SNAP, POODLE AND ROVER DATA

<u>SNAP</u>	<u>WEIGHT (lbs)</u>	<u>APPROXIMATE SIZE O. D. x HEIGHT(in.)</u>	<u>FUEL</u>	<u>POWER OUTPUT</u>	<u>LIFE/MISSION TIME</u>
2	1470	----	U-235	3 KWe	1 YEAR
3	4	5 x 6	Po-210/Pu-238	3 We	90 DAYS
8	1500-4500	30 x 50	U-235	30/60 KWe	1 YEAR
9A	27	20 x 10	Pu-238	25 We	5 YEARS
10A	1000	60 x 120	U-235	500 We	1 YEAR
11	30	20 x 12	Cm-242	25 We	90 DAYS
17	30	10 x 36	Sr-90	25-30 We	5 YEARS
19	30	20 x 11	Pu-238	30 We	5 YEARS
23	900	25 x 25	Sr-90	60 We	5 YEARS
27	30	17 x 18	Pu-238	50 We	5 YEARS
POODLE	30	4 x 17	Po-210	5 KW	----
ROVER/ NERVA	8500	52 x 96	UC ₂	1000MWT	----

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FIGURE 2

FIGURE 3

MISSILE FLIGHT	LONG ORBIT	SHORT ORBIT	ABORT
RESULT OF RE-ENTRY AND DIST. OF FUEL	COMPLETE BURNUP WORLDWIDE DISTRIBUTION	PARTIAL BURNUP LOCAL AREA	NO BURNUP POINT SOURCE
EXPOSURE MODE	INHALATION	INGESTION	DIRECT RADIATION
SAFETY INDEX	NUMBER OF PEOPLE INVOLVED	PROBABILITY OF EXPOSURE	SEVERITY OF EXPOSURE

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FIGURE 4

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FIGURE 5

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FIGURE 6