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NUCLEAR AEROSPACE SAFETY PROBLEMS
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RFS-192
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MASTER

This subject in its broadest sense implies all safety problems which have arisen in the conquest of space which are of a nuclear origin. This presumably includes radiation problems associated with manned flight in space created by such natural phenomenon as (1) heavy primary cosmic radiation, (2) geomagnetically trapped corpuscular radiations surrounding the earth and other astronomical bodies, (3) solar flare radiation, (4) or radiations inherent in nuclear auxiliary power systems, or finally, (5) problems created by the use of nuclear propulsion systems.

I will only make a very few brief remarks on most of these areas and then concentrate most of my time on the subject of safety problems created by nuclear propulsion systems, in particular nuclear rocket propulsion.

1. Space Radiation

Deleterious effects of ionizing radiations on man and materials necessitate its consideration in manned space conquest. Experiments have indicated that biological effects of ionizing radiations increase at least up to a point with increasing ionization density or linear energy transfer of the radiation to tissue.

(a) Primary Cosmic Radiation

The primary cosmic rays incident at the top of the earth's atmosphere is composed of 79 percent in number of protons, 20% alpha particles, .78% carbon, nitrogen, and oxygen nuclei and .22% of nuclei with atomic number greater than 10. The energy of these particles may vary from 10^9 to 10^{18} electron volts per particle. The dose rate from this mixture is about 12 millirads per day and twice this at greater distances from the

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earth. The localized cell damage by such highly energetic particles is complete in the track core and results in death of the cells. These tracks are few and far between, however, so that unless the track traverses an area where a few cells are vital (regions of hypothalamus) or the replacement potential of tissues is limited (lens of eye) the potential hazard is probably well within the limits of an acceptable calculated risk. Experiments employing microbeams and accelerated heavy ions are underway to assist in establishing the biological significance of the heavy primaries.

(b) Secondary Cosmic Radiation

At sea level about 30% (30 millirad/year) of the average natural background radiation dose sustained by the population comes from secondary cosmic rays. This radiation comes from the primary radiation and consists of ~80% mesons constituting the secondary hard component, and 20% electrons constituting the soft component and .05% primary protons. The intensity of this radiation increases rapidly with altitude as a consequence of decreased air absorption and increases also with increasing geomagnetic latitude (up to 55%) as a consequence of the earth's magnetic field. Radiation intensities within the operating range of commercial jet aircraft (12 km) are not of any biological significance. At the altitude of maximum intensity (~24 km) the total ionization dose rate is only about 15 millirad/day. Continuous exposure for a year would result in an approximate integrated dose of 5 rad. This just equals the maximum permissible yearly dose rate recommended by the International Commission on Radiological Protection for lifetime employment in the nuclear energy field.

2. Geomagnetically Trapped Geomagnetic Radiations

In 1938 Van Allen and his colleagues discovered the presence of high energy radiation above the atmosphere of intensity greatly exceeding the cosmic rays. The radiation consists largely of protons and electrons trapped in the geomagnetic field. The particles spiral around the geomagnetic lines of force and oscillate between the poles as well as drift around the geomagnetic axis producing a ring current.

There are two concentric zones or belts symmetrical about the geomagnetic axis.

(a) Inner Radiation Belt

The inner belt consists of hard protons of maximum energy at least 700 mev and softer electrons of maximum energy 0.8 mev. The electron spectrum seems to resemble a degraded beta ray spectrum of maximum energy 0.8 mev. These properties support the hypothesis that the majority of the particles of this Van Allen belt originate from the decay of outward moving fast neutrons generated at the top of the atmosphere by cosmic ray interactions.

The free neutron undergoes radioactive decay as expressed by the formula $n = p^+ + e^- + \bar{\nu}$, with a half-life of about 12 minutes and the maximum energy of the electrons of 0.78 mev. Although the injection rate of these particles into the geomagnetic field is extremely low, they remain trapped for times long enough to account for the observed intensities.

The inner belt begins at about 1000 km altitude and extends from about 20°N to 20°S with respect to the magnetic equator. The intensity appears to double about every 100 km and reaches a maximum at about 3000 km. The maximum dose rate has been estimated to be about 100 rads/hour and is primarily due to the hard proton

component. This belt is quite stable in time. This inner belt is fortunately above the altitude at which early manned expeditions are made. In later missions by proper trajectory and speed any radiation hazard can be avoided or sufficiently reduced to make it no serious problem.

(b) Solar Radiation Belt

The outer Van Allen belt is quite different and distinct from the inner one. It is much greater in extent than the inner belt. It consists mainly of soft electrons of energies up to a few hundred kev and is quite variable in time, particularly during solar flares. Flashes of electrons of energies over 200 kev of the order of $10^8/\text{cm}^2\text{-sec}$ have been observed. This corresponds to a surface dose of the order of 10^4 rads/hour.

The outer belt has an ill-defined inner boundary beginning at about 12,000 km above the magnetic equator and passes through a maximum at about 15,000 km and then decreases far out into outer space. It extends about 30° geomagnetic North to 30° South.

Leakage of electrons from the low altitude horns of this belt probably are associated with auroral radiation. This is especially true when solar flares disturb the earth's magnetic field.

Although a dose rate of 10^4 rad/hour appears alarming it does not pose as serious a problem as the inner belt since the soft electrons are easy to shield against.

3. Solar Flare Radiation

Solar flares are connected with rapidly varying sun spot magnetic fields. High energy protons arrive at high altitudes 1 to 2 hours after onset of the visual phase and may persist for days with energies ranging into the Bev

range. Intensities may increase orders of magnitude above cosmic ray levels.

Low energy protons and electrons arrive about 1 day after onset at which time magnetic disturbances are noted on earth.

The flares strongly affect the outer Van Allen belt. At first the population of the outer belt decreases sharply accompanied by magnetic storms and auroral displays on earth. The decrease persists about 12 hours with fast and intense fluctuations in time scales of minutes. This is followed by a slow rise in intensity to several times the initial value.

The radiation dose rate from the proton component of solar flares can reach significant proportions during common solar disturbances. The dose rates for protons above a 25 Mev energy have been estimated to be 35 rad/hour.

Very large flares which have been observed a half a dozen times during the last 20 years pose a rather dangerous situation since intensities can be an order of magnitude greater than for average flare. Manned space flight must take these into account on a calculated risk basis.

II. Space Vehicle Nuclear Power Plants

Every useful space vehicle has some electric power requirements. On-board type of power is required for control guidance, instrumentation, tracking, and range safety. Power requirements for such supplies may vary from a few watts to 100 kilowatts.

Another category of electric power is also required to test advanced types of propulsion systems now under study. These include arc jets, plasma jets, and ion engines. Power requirements for such systems will run into the megawatts.

The most practical system over this entire range of power requirements appears to be some form of nuclear energy. Power generators making use of fission products or artificial radioactive isotopes have already demonstrated their reliability for low on-board power requirements. Small compact nuclear reactor systems are now under development for higher on-board power systems.

This type of power system has been designated SNAP (Space Nuclear Auxiliary Power). Examples of isotope power generators are SNAP-9A and SNAP-11, 25 watt isotope generators using the energy from α particles emitted by plutonium 238 and cerium 242 to power transit navigational satellites and for surveyor soft lunar landings, respectively. Another type will use the energy from β particles emitted by strontium titanate. Although the largest isotopic power unit now in use has a power level of 5 watts, present state of the art permits immediate construction of a 25 watt unit. The practical limit for isotopic power is about 300 watts.

Examples of SNAP type nuclear reactor power units are SNAP-8 system which will produce 30 - 60 kilowatts for use on the Saturn. A SNAP-10A 500 watt reactor unit is under development as well as the SNAP-50 300 - 1000 KW range device. These reactor systems are small liquid metal cooled devices using sodium, potassium or lithium as the heat exchange medium.

The space radiation hazards associated with all of these small power generating units is minimized by completely shielding the devices and sealing them in strong containment shells. Launch pad problems are thus pretty well eliminated. The remaining problem is their ultimate disposal. Great effort is going into a program to assure that none of the active material will return to earth, but will be dispersed in the upper atmosphere by vaporization.

III. Space Vehicle Nuclear Propulsion

Let us now look at the principle subject of my talk which is related to the safety problems associated with the use of nuclear propulsion systems of the heat exchange type.

In the summer of 1960 considerable attention became focused on the need for more extensive work on the hazards involved when using nuclear rockets in space.

This was brought to a head by a meeting of the Aerospace Nuclear Safety Board, a report from Lee Adams on the Nuclear Safety Aspects of the Rover Program, and the successful Hail A series of tests.

Specific safety requirements to which nuclear rockets must conform were not established then or are yet available. General ground rules that were used in the engine contract bidding have been used as a guide line.

1. For all normal ground and flight operations exposure of rockets and the general public shall not exceed the levels specified in the Federal Protection Guides.
2. Nuclear rocket engines shall not be operated in flight in a manner which would permit the reactor, or large fragments thereof, to reenter and impact on the earth's land masses.
3. Unplanned controlled disposal of radioactive material into space, the upper atmosphere, and the deep ocean areas is permissible.

In order to cope with potential safety problems in the use of nuclear rockets in space, a program was initiated by the AEC in the fall of 1960.

A Rover Flight Safety Panel was established by the AEC to (1) advise and assist in the assessment of possible hazards, (2) critically review current safety programs, and (3) develop and recommend plans for continuing safety research and development programs.

At the Laboratory a Rover Flight Safety Office and Committee were established to coordinate existing effort in this area and promote experiments which would aid in solving potential Flight Safety problems. In general, the Laboratory effort has been confined to problems associated with the core itself rather than the entire vehicle.

An early decision that all initial applications involving nuclear rockets would be confined to upper rocket stages has helped to reduce associated safety problems. There are two principle areas where work is required.

1. A determination of the magnitude and probability of a nuclear incident on or near the launch pad and means of preventing such accidents, and
2. The disposal of the highly radioactive core after operation in a manner which does not expose the general public to undue hazards.

I will describe some of the work in these two areas, beginning with the launch pad area.

1. Launch Pad Problems

Two general types of launch pad accidents appear possible.

(1) Dry excursions not involving water or propellants. The main causes are inadvertent control rod motion or impact and collapse of the reactor into a more favorable geometry.

(2) Wet excursions involving hydrogenous liquids. The principle causes are flooding of the core by water or propellant, or a core implosion from a propellant explosion. A series of experiments on fuel life and heat transfer rates as a function of temperature appears to make it highly improbable that a reactor can continue to operate in a semi-stable state while partially submerged in water. It will either blow itself up immediately

or operate at a very high temperature where core life would be short. Calculational estimates have been made or are in progress on all of the principle types of accidents.

If one places various types of accidents in order of increasing size, they seem to be arranged in the following order. (1) Accidental control rod motion, (2) impact on the pad, (3) booster propellant explosion, (4) external water reflection, (5) rapid penetration of water into the coolant channels of the core.

These range in yields from 10^{19} fissions to better than 10^{21} fissions. Rapid water insertion appears to be by far the worst kind of accident with possible explosive yields of a few hundred pound of HE equivalent.

In order to get a single point check with theory and get a better understanding of the fission product dispersal due to a major incident a full scale simulated water injection experiment known as SWET is planned for next year at NEDS.

A second full scale nuclear transient test is also presently planned to gain a better understanding and check with theory of the transient response of a Rover reactor. The normal Nevada testing has always had as its primary objective the development of a satisfactory reactor as far as temperature and time of operation for rocket use is concerned. Little opportunity is available for accident type transient experimentation.

A number of new machine codes have been developed to cope with the Rover accident calculations. The principle calculational uncertainties arise from (1) a lack of knowledge of equation of state of graphite, (2) a lack of knowledge of the energy or temperature coefficient of

reactivity which should be used under transient conditions and the unknown behavior of the fuel itself during a fast transient.

In order to obtain a better estimate of the type of incident due to the impact of a reactor on the launch pad, several 1/3 scale drop tests are planned for the near future. These will seek to determine the average core density as a function of time by means of fast photography and gamma ray transmission measurements. Due to the potential magnitude of some of the possible launch pad incidents serious consideration is now being given to poisoning the reactor 100% until after take-off. This implies that the reactor cannot go critical under any conditions. Calculations are now in progress here to determine an optimum poison arrangement.

Work is in progress at all Kivi tests to gain information on the fission product release and dispersal during normal tests. At present particular emphasis is placed on iodine. Extensive coverage of this nature will be undertaken at the SHET experiment.

Measurements on the leaching of fission products by sea water have been made at the Laboratory. These are now being continued at NREL to determine selective uptake by marine life.

2. Safe Disposal

One of the most difficult Flight Safety problems is to determine a means for disposing of the large residual radioactivity existing in the core after full time operation. The nature of nuclear fission is such as to make it reasonable to assume that potential radiation hazards of nuclear reactors scale in relation to the total energy produced. As a reference example, consider a 1000 MW

reactor operating for 3 minutes. The energy release involved in this case would be about 10^{12} fissions or 3×10^4 MW-sec. An one hour after operation there is a source strength of about 100 curies per MW-sec. In the reference example this means disposal of some 10^6 curies.

A number of possible disposal methods have been tested or are under study at Los Alamos.

LRL initiated work which tested the feasibility of using chemical explosives for core fragmentation. Some forty-five 1/3 and 1/10 scale shots were fired to test scaling laws, and determine the effect of a number of parameters such as graphite properties, core geometry, explosive weight and metal parts on the fragment size.

The general conclusions based on fragment size distributions were that a full scale central explosive of 1000 lb would result in some fragments with a centimeter or so diameter which probably are unacceptable. Full scale tests are now in progress at Arecibo and Aberdeen to verify these conclusions.

A second destruct mechanism examined at LRL was the feasibility of using a chemical additive. Experiments on direct oxidation of the fuel did not look hopeful and furthermore a large mass of oxygen would be required. The use of BF_3 , on the other hand, looked highly promising as far as speed and particle size is concerned. Unfortunately, the reaction is most effective at 100°C or below and essentially stops at 400°C . Since aftercooling requirements exist anyway, this may not be too serious a requirement. Work at Westinghouse on other materials has not uncovered any other promising post operational additives.

A third disposal scheme is to make use of a rapid nuclear transient as a fragmentation scheme. A nuclear

destrust mechanism requires the creation and use of a rapid release of energy through the fission process. The ability to release sufficient energy may be inherent in the system or provided by an auxiliary device.

Los Alamos has examined what appears to be the principle means for providing such a mechanism.

A. Nuclear Emulsion - core destruction through the use of a separate nuclear explosive.

1. A large weapon type device to completely vaporize the core. Such a device might be placed at a large distance above the fuel tank or behind a substantial shield to reduce radiation levels.

2. A small size device exploded within or next to the reactor in order to flood the reactor core with a fast neutron burst and explosive shock. Such a device would have to be placed behind a radiation shield and lowered next to the reactor after decay of the delayed neutrons.

B. Self-Destruction - production of a fast nuclear transient within the core itself.

1. Transient induced by rapid control rod motion.

2. Transient produced by a projectile containing moderator only or moderator plus fissionable material.

The interesting feature of the Nuclear Destrust Concept is that it appears to provide a dual mechanism for core disposal. Localized hot spots can be produced by the heating of the uranium particles which produce sufficient stresses and vapor pressure to fragment the fuel which is then dispersed by the quickly following shock wave or explosion.

A number of different types of uranium bearing graphite fuels are under study to determine the effect of uranium

oxide and uranium particle size on the fuel fragmentation and size distribution.

Calculations indicate that in some cases fragmentation is highly dependent on the nuclear transient period since conduction to the graphite matrix can effect peak uranium temperatures.

Experiments have been carried out on the Argonne TRAMP Reactor Facility which can provide sufficient energy to fuel samples to vaporize 15 or 20% of the fuel material. It has been found that the presence of uranium oxide assists fragmentation by producing localized pressures from the rapid production of CO in the conversion of uranium oxide to uranium carbide. Very small uranium particles containing no oxide could not be fragmented in this facility whose fastest period is 40 milliseconds.

Particle size effects will be studied in other faster nuclear burst facilities. Several reactor destruct experiments are planned during the next year. An oxide type core reactor will be subjected to a 1.8 millisecond period in about October and is expected to produce an energy deposition in Rover type fuel samples sufficient to give fragmentation. A few months later a SMAR-type device will be flooded with water. This is expected to give a period of less than a millisecond with sufficient flux to fragment Rover fuel. Our own SNET experiment will provide a period of less than a millisecond. Plans are also in progress to incorporate fuel samples in any suitable future underground weapons test if any further tests should be planned.

Calculations are in progress on the feasibility of shooting a slug of uranium, hydrogenous material, or

beryllium into the core to induce a more powerful transient than can be produced by control rod motion alone.

The following table illustrates the types of transients that are obtainable from using a projectile containing moderating and moderating plus fissionable materials. A full scale test may be required to demonstrate the effectiveness of this disposal method.

A strong nuclear transient hopefully has the ability to produce sufficiently small fragments which will either burn up on reentry, or are sufficiently small as to pose no public health problem and thus provide a satisfactory disposal other than removal to outer space.

There are other less desirable ways of reducing the reentry problem. The nuclear reactor might not be started until a stable orbit is achieved through longer chemical boosting. Ultimate disposal might be planned for outer space only through the use of special chemical booster rockets. Either of these methods, however, would require a sacrifice in payload and not making use of the full capabilities of the nuclear system.

TABLE I

<u>Mod. (rad., cm.) Condition</u>		<u>Total Fissions (X10²¹)</u>	<u>Period Milliseconds</u>	<u>kex(\$)</u>	<u>Minimum Fissions/gm (X10¹⁴)</u>
CH ₂ (4cm) + .67 kg U ²³⁵ , Be ² to 6.35 cm		5.0	.067	16.91	7.5
Be (6.35cm) + 1 kg U ²³⁵		~1.24	.119	8.15	2.8
Be (6.35cm)		~1.04	.20	7.46	1.5
CH ₂ (5cm)	No U ²³⁵	.71	1376	5.67	1.1
	0.4 kg	3.7	.128	14.54	5.5
	1.0 kg	6.7	.071	18.88	9.5
	2.0 kg	8.5	.048	21.09	11.8
Be (5cm)	No U ²³⁵	.285	.366	2.83	0.48
	0.4 kg	.41	.333	3.89	0.68
	1.0 kg	.43	.30	4.05	0.72
	2.0 kg	.49	.267	4.39	0.82