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A BRIEF DESCRIPTION OF THE ROVER TYPE REACTOR,
ITS INHERENT SAFETY PROBLEMS AND TEST PROGRAMS

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I. INTRODUCTION

As you have heard in other papers, the general Rover program has associated with it three principal phases and pieces of hardware. These programs are known as Kiwi¹⁾, NERVA²⁾, and RIFT³⁾. The Los Alamos Scientific Laboratory has been closely associated since its inception with the design and development of the basic reactor configuration called Kiwi. As the name implies, this part of the program was never supposed to produce a flyable device. The engineering of this reactor into a flyable engine is being carried out by the Aerojet-Westinghouse industrial team in the NERVA program in a series of engine tests known as NRX. The fully designed engine will then be integrated into the complete flight vehicle stage by the Lockheed Missile and Space Company in the Rover in Flight Test designated as the RIFT program.

The previous speaker has confined his remarks to the overall vehicle problems as seen by personnel responsible for the

- 1) Kiwi - Flightless New Zealand Bird
- 2) NERVA - Nuclear Engine for Rocket Vehicle Application
- 3) RIFT - Reactor in Flight Tests

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successful launch of the RIFT vehicle. I will give you a brief description of the Rover type reactor and inherent safety problems and describe a few of the test programs.

2. REACTOR DESCRIPTION

Reactors designed for space applications fall into two general categories.

1) Those intended to provide electrical power for equipment or propulsion.

2) Those intended for propulsion by means of a direct cycle heat exchanger. The Rover program has been associated with this latter type of reactor.

In this presentation I will give you a schematic look at the reactor itself and then a brief survey of the general effort in progress which is particularly concerned with the reactor proper. The interior reactor description, as you can see from the first figure, is quite schematic since details of the reactor design and its performance are still considered classified.

The previous Kiwi series of reactor tests have been carried out at the Nuclear Rocket Development Center in Nevada to proof test a number of possible core designs. The Kiwi B-4 and NRX series of hot tests, planned for early next year, represents the most promising design.

Approximately 50,000 pounds of thrust per 1000 megawatts of reactor power is expected from this basic design.

The principal Kiwi B-4 reactor components are:

- 1) Numerous graphite uranium bearing fuel elements with multiple coolant passages,
- 2) An external composite reflector,
- 3) A series of control rods within the reflector region,
- 4) A pressure vessel, and
- 5) A nozzle for proper gas expansion.

The critical mass is several hundred kilograms of U^{235} .

Liquid hydrogen serves both as a coolant and propellant. The propellant enters the system by flowing through the nozzle shell for regenerative cooling. It then flows through the coolant passages in the reflector surrounding the core and along the inner surfaces of the pressure vessel. Vaporization takes place in this zone. The flow from the reflector assemblies is directed along the pressure vessel dome and through a plenum chamber which distributes the coolant through the multiple passages in the fuel elements. The thermal power of the reactor is absorbed in this region. The propellant is then discharged at very high temperature and velocity through the nozzle.

More details can be shown of the exterior view of the reactor as you can see in Figure 2. In this picture Kiwi B-4A is in the disassembly building after operation. One can see the control rod actuator rods extending through the pressure vessel.

Figure 3 shows the reactor on the test stand at the Nevada

KIWI-B4-A

NG2477

Reactor Test Site. The control rod actuators can be seen in the room under the reactor. The method of introducing the liquid hydrogen into the nozzle is also clearly visible.

3. SAFETY PROBLEMS ASSOCIATED WITH ROVER FLIGHT SAFETY

There are two principal areas where the use of nuclear rockets has required additional safety analysis.

a) The determination of the magnitude, the probability and the consequences of nuclear incidents on or near the launch pad and the means of preventing such potential accidents.

b) The disposal after reactor operation of the highly radioactive core in a manner which does not expose the general public to undue hazards.

4. TEST PROGRAMS

An extensive safety program is now in progress to cope with these problems. This is sponsored by the joint AEC/NASA Space Nuclear Propulsion Office. A Rover Flight Safety Panel has been appointed by this office to act as an advisory group. Membership includes the principal government and industrial participants in the Rover program.

Overall safety work now in progress includes detailed studies and experiments to determine such items as

- 1) Safe reactor assembly and transport to the Cape.
- 2) Reactor checkout and mating to the engine.
- 3) Assembly of the nuclear stage to the overall vehicle.

- 4) Trajectory studies for optimum safety.
- 5) Anticriticality and poison systems for the safe handling and launch of the reactor.
- 6) Destruct and disposal schemes to eliminate any hazard to the general public after reactor operation.
- 7) A study of the overall radiation problems associated with the use of nuclear rockets.
- 8) The magnitude and consequences of the principal type of potential nuclear accidents.

Let us now look at each of the general cases mentioned in the preceding section starting with the launch pad area.

5. ANALYSIS OF LAUNCH PAD ACCIDENTS

A number of different accidents are conceivable during the vehicle assembly at the launch pad. An extensive analytical program has been in progress at Los Alamos to evaluate the magnitude of the more probable or larger potential nuclear incidents. You will hear more about this work in the following paper.

Initial results indicate that some of these may have an appreciable nuclear yield. Serious consideration has therefore been given to the use of a complete reactor poison system which will remove the possibility of a nuclear incident. You will hear more details of such a system in a later paper.

A survey of the many possible causes for nuclear excursions on or near the launch pad has lead to the following general

types for more detailed analysis.

- A. Dry excursions (not involving water or propellants)
 - 1. Inadvertent control rod motion
 - 2. Land impact of the reactor
- B. Wet excursions (propellants or water immersion)
 - 1. Core flooding by water or propellant
 - 2. Core implosion from a booster propellant explosion

The principal causes for dry type excursions are 1) inadvertent control rod motion, and 2) collapse of the core into a more favorable geometry due to impact on the launch pad.

The reactor response to control rod motion is in general well understood from the design and testing of the reactor. The probability for accidental rod motion can be reduced to a very low value by proper design and prescribed handling procedures.

It is more difficult to determine the consequences of a core impact. Two scale experiments have just been completed to assist in the evaluation of such accidents since the yield will depend on the rate of density increase in the core region. One experiment consisted of dropping a 1/3 scale core 75 ft onto a steel slab; another simulated a 300 ft drop by impacting the core following a rocket sled acceleration.

Figure 4 illustrates the sled set up used by the Sandia Corporation to produce a 140 ft/sec impact velocity.

Figure 5 shows a composite view of the scale reactor at the moment of impact and about 1 millisecond later when the compression was at a maximum.

Density as a function of time is determined by a number of simultaneous gamma ray transmission measurements together with high speed photography of the change in core geometry during impact. No density increase was observed in the 75 ft drop test while the 300 ft equivalent drop indicated a definite density increase of five percent or less. Estimates of the nuclear yield based on these recent measurements will be given in the following paper.

Let us now consider the wet type of nuclear incidents. The principal causes are 1) flooding of the core by water or propellant, and 2) core implosion produced by a booster propellant explosion.

The probability of core flooding either from the handling of the engine in the vicinity of the large amounts of hydrogenous materials existing at the launch area or from booster failure is appreciable. The detonation of large amounts of LH_2 , LO_2 , and RP-1 can result in large overpressures. This type of incident appears to provide the largest potential yield with estimates in the range of 10^{21} to 10^{22} fissions. The use of a poison system mentioned above will prevent this type of nuclear excursion on the launch pad.

Since predictions as to the size of accidents can never be any better than the assumptions which must be made in the calculations, it is of importance to obtain experimental information where possible as a check. A number of experiments are in progress at the LASL to determine the magnitude of a nuclear incident produced by water entering the core.

Calculations and measurements were made to determine if it might be possible for a nuclear engine to continue operation for extended times if it were subjected to gradual accidental water or fuel flooding. These included measurements of the heat transfer properties between water and uranium-graphite fuel material at elevated temperatures as well as estimates of fuel life for water immersion at temperatures from 500°C to over 2000°C. Heat transfer rates between fuel and water were found to vary by over a factor of 17 in this temperature range. The fuel material was surprisingly resistant to attack by water until very high temperatures were reached. On the other hand estimates indicate that only very low power levels can be tolerated without reaching excessive temperatures since cooling can only take place by conduction from the external surfaces of the reactor to the water. These results make it appear extremely unlikely reactivity conditions could ever be such that a reactor could operate in a 'chugging' or semi-stable condition and thus build up an appreciable fission product inventory. The most probable result is an almost

instantaneous nuclear incident which fragments the core and prevents further operation. If immediate destruction does not occur the reactor will tend to build up extreme internal temperatures due to poor heat conduction out of the core resulting in destruction by rapid erosion, vaporization, and melting of reactor components.

The accurate prediction of the fission yield and kinetic energy release of wet type excursion is difficult. The reactivity coefficient as a function of temperature is not known under transient conditions; one does not have a good knowledge of the equation of state for graphite in the important region from the point of vaporization to beyond the triple point ($\sim 4000^{\circ}\text{K}$ at 100 atmospheres); and the detailed behavior of the uranium-graphite fuel under rapid transient conditions is not well known.

A number of experiments are planned to aid calculations in such accident estimates. In particular, a full scale reactor excursion will be carried out at NRDS in Nevada in about one year.

This experiment is aimed at obtaining a number of important parameters which will assist in understanding excursions in a nuclear rocket engine. Since the wet type excursion is expected to produce the largest yield and the disposal of the reactor in the ocean is permissible during the RIFT program it appears desirable to obtain first hand information for this

type of nuclear incident. It is therefore planned to place the reactor immediately above a large water basin and deliberately inject water into the coolant channels under well known conditions.

The experiment is aimed at releasing about 10^{21} fissions with a possible kinetic energy release of a few hundred pounds of HE equivalent.

Data from this test, known as "SWET" for Simulated Water Entry Test, should provide the following type of information.

- 1) A check on the predicted yield and on the assumptions made in the calculations. This will permit a greater reliance on calculational predictions for other possible nuclear transients.

- 2) A detailed study of the dispersion of fission products in the air and water. The fission product dispersal is highly dependent on the cloud rise and this experiment will determine the type of cloud rise to be expected from an excursion at low altitude over water.

- 3) The kind of missile damage and the cleanup requirements which an excursion requires.

- 4) Data for post-operational disposal by a nuclear transient.

The upper limit of a water impact incident depends on how fast water can be introduced into the core. This can be determined by measurements now in progress on the break up of the

fuel elements and collapse of the nozzle as a function of water impact velocity.

6. POST-OPERATIONAL REACTOR DISPOSAL

A second major safety problem is the satisfactory disposal of the nuclear engine after successful operation or in case of some malfunction after start up. A nuclear incident due to reentry prior to reactor start up can always be avoided by the use of an explosive system which will break the reactor up into pieces that will not go critical upon water immersion, i.e., an anticriticality destruct system. REON* Division of Aerojet General is working on such a system.

The problem becomes somewhat more difficult if the reactor has operated and built up an appreciable fission product inventory which may be in the range of $10^6 - 10^7$ curies. In the present RIFT program, which uses a ballistic trajectory over a controlled deep water area, reactor disposal in one piece is permissible under the present ground rules. It is thought to be highly desirable, however, to test disposal techniques, which would be required on any nuclear space mission, during the RIFT program. A number of disposal systems have been thought of to take care of such a situation. These are listed below.

- 1) The use of an auxiliary chemical propulsion system

* Rocket Engine Operations - Nuclear

to place the nuclear rocket in orbit in case of failure.

- 2) Start the nuclear rocket only after achieving orbit.
- 3) Chemical attack on core materials.
- 4) Chemical explosives for reactor fragmentation.
- 5) Nuclear explosion for reactor fragmentation.

Marshall Space Flight Center and the Lockheed Missile and Space Company have investigated the feasibility of methods 1 and 2. Both are possible, but will result in a considerable loss in payload.

Chemical explosives for reactor fragmentation have shown some promise in work performed at LASL, Aerojet and the Aberdeen Proving Grounds. It appears difficult, however, to achieve complete fragmentation. Objections to this disposal scheme are that 1) some fragments appear to remain with volumes of several cubic centimeters, and 2) the weight of the necessary projectiles and launchers is large.

The use of chemical additives to weaken or disintegrate the core materials have shown some promise. In particular, this approach in conjunction with one of the other schemes may enable more complete fragmentation or enhance the burnup of the fragments on reentry.

The fifth scheme is under active investigation at the LASL. Calculations and in-pile experiments have been carried out which indicate that some types of Rover fuel can be

fragmented into very small pieces by a rapid deliberate nuclear transient. Experiments resulting in fuel fragmentation have been performed both by rapid electrical heating as well as in the Argonne Laboratories' TREAT Reactor Facility. These experiments as well as the calculations have shown that fragmentation is quite dependent on the detailed fuel composition as well as the speed of the nuclear transient.

Additional in-pile fuel experiments for testing the Nuclear Destruct Concept are planned in the near future in reactors being tested to destruction in the SPERT and STEP programs being carried out by the Phillips Petroleum Company at Arco, Idaho.

This concept for reactor disposal appears to have several possible advantages since calculations indicate that a hydrogenous projectile can produce a very rapid nuclear transient.

- 1) The launching mechanism may be lighter and simpler and the projectile is less sensitive to radiation damage.
- 2) The fragmentation promises to be much more complete based on present in-pile tests.
- 3) Residual activity of the fragments should be lower. Since the uranium particles and their immediate surroundings are heated to the highest temperature, most of the fission products should be vaporized and escape in space or be deposited on the surface of fragments where they can be lost by ablative processes during reentry.

Experiments directed toward understanding the direct radiation hazard from the escape of fission products under a variety of normal and accidental reactor conditions have been performed at the LASL. Such experiments include the leaching rates of fission products from fuel samples under a variety of water immersion conditions, the escape of fission products from the fuel under normal full power operating conditions, and the escape of fission products from the fuel under abnormal situations of extreme reactor temperature and rapid transient conditions.

The Naval Radiological Defense Laboratory is performing more detailed work on the release of fission products into water. The Nuclear Utilities Services is under contract with the Space Nuclear Propulsion Office to conduct an evaluation of the overall environmental safety aspects of nuclear flight operations at Cape Canaveral. One item under study in this contract is the problem of returning reactor fragments after disposal in space. In particular, the size requirements which will satisfy all public health and safety requirements is under detailed investigation.

7. CONCLUSIONS

At the present time it appears that there are no insurmountable safety problems created by the application of

nuclear power for rocket propulsion. The use of a poison system in the reactor core during all assembly and launch procedures will completely remove all safety worries in handling a reactor on or near the launch pad. Such a system now appears quite feasible.

Post-operational disposal has been attacked in a number of ways with the promise that one or several schemes in conjunction will satisfy all safety requirements.