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RADIATION ENVIRONMENT OF REACTORS FOR
NUCLEAR ROCKET PROPULSION*

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ABSTRACT

Results of systems studies on nuclear rocket propulsion show that reactors for this purpose are likely to have very high power levels, very high power densities, and thin shields. The integrated dose from such radiation sources will be comparable to any now confronting the ANP Program, but the dose rates will be orders higher. These problems will be discussed as they relate to some reactors under consideration at LASL.

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INTRODUCTION

The material in this report was prepared for presentation to people involved in the study of Radiation Effects. As such it is intended to reproduce and emphasize some features which define and characterize this realm of interest. It is not a complete survey of the field and represents neither the scope of the laboratory's effort nor the variety of information available from systems studies. The information given is used to estimate the order of magnitude of the total radiation and dosage rates to be expected from propulsion reactors capable of interesting missions. These radiation problems are very severe. An early awareness of their magnitude, leading to the accumulation of pertinent data and experience well before the necessity for its application, might permit a considerable reduction in the time required for their solution. It is hoped that this paper will stimulate work in this area.

FORMULATION OF THE PROBLEM

The reactor type considered here employs the direct cycle heat exchanger concept, which is the most conventional and practical design concept to date. Several advanced concepts have been explored which might permit higher temperatures or higher energy absorption per pound of fuel with smaller power plants, lower pressure drops, etc., but such systems are not discussed because they only present an aggravated radiation problem.

The potential area of application of nuclear propulsion may be explained in terms of the "rocket equation," which is

$$V + V_{\text{losses}} = I_{\text{sp}} g \ln M$$

where V is burnout velocity, V_{losses} contains drag and gravity losses, I_{sp} is effective average specific impulse (pounds of thrust per pound of fuel burned per second), g is a dimensional constant (32 ft/sec²) and M is the ratio of launch mass to system mass at burnout. The left side of this equation is fairly well determined by the nature of the flight path (satellite, ICBM, etc.), so in most cases only I_{sp} and M are in the designer's hands. The specific impulse of a propellant is proportional to the square root of the ratio of its absolute temperature to its mean molecular weight.

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The operating temperatures of chemical and nuclear systems are comparable, but the mean molecular weights of the exhaust of a nuclear engine can be somewhat smaller than those of a chemical engine. In the usual chemical system, the oxidizer atoms participating in the combustion process are necessarily heavy and produce even heavier product molecules, whereas nuclear systems can heat and even dissociate a monopropellant (hydrogen, NH_3 , JP_4 ...). The molecular weight ranges are ~ 18 -30 for chemical systems and ~ 2 -8 for nuclear systems. Thus the I_{sp} capability of an advanced nuclear system is about twice that of an advanced chemical system and theoretically permits a gain for any mission by a factor 8-9 in burnout weight for fixed launch weight. However, the question of developing a package which actually achieves the theoretical mass ratio is a slightly different one and depends upon such things as propellant density, missile structural design, and engine design. In the nuclear system, the reactors which one must consider are -- at minimum size and weight -- still large compared to a small chemical system. Thus their area of application is restricted to the larger systems such as those employed when high burnout velocities, high payloads, or both are required. Fortunately, the more exacting the mission, the greater are the premiums offered by high specific impulse. It therefore seems reasonable that nuclear systems may be of greatest interest for super-ICBM, satellite, or more demanding missions.

Because of the large thrusts required for "interesting" missions, the reactor heat powers required are of the orders 1000-20,000 megawatts. Reactor operating times for these missions range from 300-400 seconds. The fuel region specific powers may range from 90-250 MW/ft³. Though high performance could partially be used to relieve the problem, reactor weight is always important because of its exponential influence in the rocket equation. One needs maximum thrust per pound of reactor, which implies a system with minimum shielding. Ducting of propellant, of course, insures negligible shielding in at least one direction.

A "TYPICAL" REACTOR PROPOSAL

General Design Features. The proposal to be discussed here represents a single area of study in the application of nuclear energy to the propulsion problem. Whether a demonstration of the technical feasibility of an engine will utilize a system like the one shown, a metallic-fueled system,

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or still another type remains to be seen. Space will not be devoted to these alternate proposals, to laboratory policies, or to development problems (like high-temperature materials, heat-transfer and stress analysis, propellants, controls, instrumentation, neutronics, etc.). Though the test reactor shown here may never be built, it underwent sufficient design study to provide "typical" data on radiation levels. Figure 1 shows the schematic. Propellant cools the Be reflector before passing thru the enriched-uranium-loaded graphite fuel plates for heat exchange. The pertinent data on power, weight, etc. are shown in the figure. The average power density in the fuel region would be $\sim 120 \text{ MW/ft}^3$. The reactor would be critical with $\sim 40 \text{ kg}$ of U^{235} .

Operating Radiation Levels. From data upon the fission density and reactor flux spectrum at each point in space (as obtained by S_n calculations upon this material composition) it was found that the maximum internal flux would be $\sim 4 \times 10^{16} \text{ n/cm}^2\text{-sec}$ at the design power. The average energy of a neutron of this internal flux is $\sim 500 \text{ kev}$. (This quantity should not be confused with the average energy of the neutrons producing fission, which is $\sim 1 \text{ ev}$.) The reactor permits about one neutron to escape the pressure shell per fission, with a mean energy of $\sim 300 \text{ kev}$. About 15% of the leakage neutrons have roughly a fission spectrum energy distribution, while the remainder are close to thermal energies. The leakage is fairly isotropic because the point of maximum fission power is well away from the exposed end. The internal neutron dose rate is $\sim 10^9 \text{ rem/second}$ in this system, and at two meters from the center of the reactor core (with isotropy), the neutron dose rate from the $\sim 1.8 \times 10^{14} \text{ n/cm}^2\text{-sec}$ is about $3.5 \times 10^6 \text{ rem/sec}$ or $\sim 1300 \text{ rem/sec}$ per megawatt.

The energy distribution of gamma rays leaking from the reactor and the internal gamma ray energy deposition were found from Monte Carlo calculations. Here, 10,000 gamma rays were liberated with the proper initial energy distribution in each of the six axial fuel sections and followed in space and energy thru the material, note being taken of their local energy depositions until they either reached a photoelectric "cutoff" or escaped the reactor pressure shell. The input gamma spectrum was based largely upon the data of Gamble, et al.; the mean energy was $\sim 1.05 \text{ mev}$. Normalization of the results for the total power and the expected axial power distribution (with about 14 mev allowed

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per fission for the total contribution from prompt, delayed, and capture gammas) gave a net leakage from the reactor which was almost exactly one curie per watt of power, or roughly one gamma per fission. This is the maximum value, and is not attained until after about five minutes operation; just after startup, the source strength is only 70% as great. The mean energy of the leakage gammas was ~ 0.85 mev. The leakage was reasonably isotropic, but higher fluxes came through the end away from the nozzle because of the forward peaking of the fission power. Considered as an isotropic emitter of 2700 megacuries bare source strength, the dosage rate at two meters from the center of the reactor core is $\sim 8.5 \times 10^4$ rep/sec or ~ 30 rep/sec per megawatt. The factor (~ 40) between this and the neutron dose occurs because the neutrons deliver about four times as much energy per gram of tissue and have relatively 10 times the biological effectiveness of the gamma rays on a per particle basis. At this distance, the total integrated dosage during the 8.0×10^5 MW-sec of proposed operation for this reactor is thus $\sim 1.3 \times 10^8$ rep. About 18 MW of power is carried from the reactor by neutrons and gammas, with the latter bearing up to three-fourths of the total. The internal gamma dosages and dose rates exceed the two meter value by more than a factor 100, though it is hard to pin this figure down. The gamma source alone deposits as much as $8+$ MW/ft³ into the fuel volume (1.5 times as much in the plates since the fuel volume is $\sim 1/3$ void). The internal gamma power deposition over a geometry representing a somewhat idealized version of this reactor (i.e., materials have been made homogeneous by volume averaging and dimensions have been slightly modified) is shown in Fig. 2.

In recapitulation, expressing dosage in the physical unit rep rather than the biological one of rem, we find that dose rates of ~ 160 rep and ~ 6 rep per second per megawatt should prevail in tissue-like substances exposed at 2 m and 10 m, respectively. The interesting powers lie between 1000 and 20,000 MW, and the operating times are ~ 300 -400 seconds, so the extremes of energy release range from $\sim 0.3 \times 10^6$ to $\sim 8.0 \times 10^6$ MW-sec, with 10^6 MW-sec probably providing a good median example. For such a case one might expect an integrated dosage of $\sim 1.6 \times 10^8$ rep at 2 meters and 6×10^6 rep at 10 meters.

Problem Areas. The problem areas are fairly obvious in light of the above facts. The accumulation of radiation effects data with the highest attainable dose rates is

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particularly desirable. High integrated dosages are also important. Ways to combat the heat problem will be needed and the development of radiation insensitive and radiation resistant transducers, instrumentation, and electronics should be encouraged. Considerable radiation will scatter past propellant tanks into the nose cone of such a rocket while it is in the atmosphere. Data upon the amount and spectra to be expected for such radiation are needed as well as information upon electromagnetic propagation through the local region of strong ionization. The sooner data and experience can be accumulated in these and other pertinent areas, the sooner the development of higher performance missiles may be possible.

INTEGRAL TESTING

Though they have extremely high powers, it must not be felt that these propulsion reactors are accompanied by a new order of energy release or radioactive fallout hazard. For example, let us take 10^6 MW-sec as a typical value of energy release, which is within a factor of ten in either direction from all presently projected cases. In this instance, less total fissions are involved than would result from operating a 15 MW reactor for one day; only one-fourth as many fission fragments are produced as would result from the testing of a 1.0 kiloton (high-explosive equivalent) atomic weapon. This may also be contrasted with $\sim 10^8$ MW-sec for an ANP mission. Superior shielding in the latter case results in roughly comparable integrated exposures in the neighborhood of both reactors; however, the rocket propulsion reactor dose rates will be orders higher.

In spite of the above statements, the unusual features of these reactors (unshielded, ducted, uncontained, high leakage fluxes, etc.) dictate their developmental operation and testing away from populated places. An area at the Nevada Test Site has been selected for this purpose. Figure 3 shows the proposed layout. Projected facilities include a control area from which the reactors will be operated remotely, a test cell area and adjacent propellant tank farm about two miles from the control building, and a maintenance-assembly-disassembly (MAD) building forming the third point of a triangle. A remotely-controlled prime mover on railroad tracks can transfer a hot reactor from the test cell into a concrete disassembly vault where it can be taken apart by manipulators and special tools. This

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vault should be capable of handling a reactor within two weeks which was operated for 1.5×10^7 MW-sec. Flexibility and safety were dominant considerations in deciding this arrangement of facilities. Large power devices can be tested with negligible dose at the control rooms, no personnel hazard should result from disruptive or even explosive failure of a reactor, operations in the three areas can be conducted nearly independently, and there is room for such expansion as may be needed with continuing development. Figure 4 shows the initial test cell and propellant tank farm area.

The first reactor tests will be made on a device labelled KIWI-A, which is a highly-reflected, highly-moderated system with a smaller fuel region than the reactor previously shown and the "low" total power of 100 MW. Figure 5 shows a KIWI-A schematic. These first tests should provide information on temperature coefficients of reactivity over a large temperature range, heat transfer coefficients, transient response, propellant possibilities, and leakage flux detail, as well as providing a good deal of valuable experience in reactor instrumentation, operation, and disassembly. Figure 6 shows an artist's sketch of KIWI-A in testing position.

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Fig. 1. A "typical" propulsion reactor proposal.

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Fig. 2. Internal gamma power deposition in MW/ft³ for 2700 MW reactor proposal.

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Fig. 3. Proposed layout of Nevada Test Facilities.

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TEST AREA NO. 1
NTS PROJECT 400
U.S. ATOMIC ENERGY COMMISSION

BURNS & McDONNELL ENGINEERING CO.
Engineers-Architects-Consultants
Kansas City, Missouri

Fig. 4. Initial test cell and propellant tank farm area.

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Fig. 5. KIWI-A reactor schematic.

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Fig. 6. Artist's sketch of KIWI-A in test position.

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