JUN 19 1961

TID-12988

MASTER

RADIATION SAFETY IN THE DEVELOPMENT AND USE
OF NUCLEAR ENERGY FOR ROCKET PROPULSION

By

Wright H. Langham

Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission

A. Makes any warranty or representation, expressed or implied with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights, or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

SUMMARY

Past preoccupation of the public and the press with the potential hazards of world-wide radioactive fallout from nuclear weapon tests may lead, in the near future, to concern over the potential radiation hazards of nuclear rocket propulsion.

Three prototype nuclear propulsion reactors have been tested already by the Los Alamos Scientific Laboratory. Although future reactors will create formidable radiation safety problems, they will be small compared to those of even nominal nuclear weapons. A nuclear propulsion reactor capable of five million pounds of thrust will have an energy output equal only to a 7-kiloton nuclear weapon.

A vigorous safety program is being conducted concurrently with engineering development such that adequate assurance of safety will be possible by the time flyable reactors are available. Intensive studies, involving both measurements and theoretical predictions, carried on since the inception of the reactor program, have enabled delineation of the problem areas and resulted in reasonably sound predictions of the potential radiation hazards of testing and flying a minimal performance system capable of producing 1000 MW of power for an operating cycle of 5 minutes.

The reactor, although containing more U^{235} than an atomic bomb, could not produce a significant nuclear explosion under the most drastic accident conditions. At most, the energy release would be only about

3 per cent of the maximum power rating of the reactor. Prompt neutron and gamma radiation during operation, although delivering a lethal dose in less than one-tenth of a second at a distance of 20 feet, will not deliver significant exposure to test and launch crews at a distance of 1 mile. Accidental release of accumulated fission products during static testing, launch pad failure, or early mission abort would be confined largely to the controlled area of the launching or testing site. Such an accident would produce considerable contamination of the facilities, and extensive decontamination operations would be necessary before permanent reoccupancy. This, however, could be accomplished without undue risk by proper planning and the use of remote control and shielded handling equipment. Impact outside the controlled area of an operated reactor, either as a result of late mission failure or re-entry from orbit, could produce a potential radiation hazard to the public domain as well as an international political incident of considerable magnitude. Means of dealing with this particular problem area need further study. Choice of seacoast-, ocean-, and island-based launching sites, controlled re-entry and impact, and reactor burn-up or fission product boil-off in space are possibilities. General biospheric contamination from nuclear rocket operations is an insignificant problem compared to that created by nuclear weapon tests. Radiation problems of manned nuclear rockets are prodigious but amenable to solution.

INTRODUCTION

During the past decade, preoccupation and concern of the public and the press with the potential hazards of world-wide fallout from nuclear weapon tests have, in many cases, resulted in somewhat negativistic thinking toward anything involving radiation and radioactivity. This, of course, includes development and use of nuclear energy regardless of purpose.

The intent of this paper is to encourage positive thinking regarding development and use of nuclear energy in an area for which it has a vast potential -- the propulsion of rockets for space exploration.

Man's progress through the ages can be measured in terms of his ingenuity in harnessing sources of energy to perform work. Solar energy undoubtedly played a role in his very development. With time he progressed from the use of chemical energy of his own body to the use of fire, beasts of burden, electricity, and now to the use of energy derived from atomic fission and hopefully, in the future, that from nuclear fusion. As his dreams and accomplishments have become greater and greater, so have his needs for more concentrated sources of energy. Now that he stands on the threshold of space conquest, the use of nuclear energy for this purpose is the next logical step. Inherent in development and use of each new source of energy has been a certain probability of risk to the user. The cave man undoubtedly suffered inadvertent disasters with the use of fire; beasts of burden have been known to kill their masters; and we are well acquainted with

the risks inherent in the use of electricity and other forms of power providing support for our present society.

Regardless of the source of energy, it is not possible to eliminate all probability of risk other than to eliminate its use entirely. Only by foregoing the probability of gain are we able to forego the probability of risk. Careful and progressive consideration, however, of the potential hazards involved can result in a lower probability of risk and a greater net gain. Inherent in the release of nuclear energy is a unique potential hazard -- that of ionizing radiation which in sufficient doses can produce deleterious effects in man and materials.

The Los Alamos Scientific Laboratory has already conducted three nuclear propulsion reactor tests -- Kiwi-A, Kiwi-A Prime, and Kiwi-A Three (Fig. 1). Like their namesake, the New Zealand flightless bird, these reactors were not capable even of lifting their own weight. The purpose of these tests, however, was to prove reactor concepts and to provide information for future design and fabrication. Formidable as the engineering problems may be, they will be solved by progressive stages, and reactors will evolve from flightless Kiwis to those capable of minimal flight performance and eventually to systems capable of millions of pounds of thrust -- adequate for placing man on the planets of his solar system and returning him to earth.

During these tests, careful studies were made of the neutron and gamma radiation source strengths and fission product release of the

Fig. 1. A test of a prototype nuclear rocket propulsion reactor conducted at the Nevada Test Site by the Los Alamos Scientific Laboratory.

001 007

LOS ALAMOS
PHOTO LABORATORY

NEG.
NO. 601069

PLEASE RE-ORDER
BY ABOVE NUMBER

reactors. These and other pertinent studies will be carried out during all phases of the reactor development and testing program, and by the time flyable systems are developed the radiation problems will be sufficiently understood to permit their use with adequate assurance of safety.

RADIATION PROBLEMS OF A MINIMAL FLYABLE SYSTEM

From information already available, it has been possible for Los Alamos scientists and others to outline the areas of concern and to predict with reasonable assurance the magnitude of the potential radiation hazards expected from a minimal performance flyable reactor. For this purpose, let us assume that a reactor of about 1000 MW power is used to heat hydrogen propellant for a period of about 5 minutes. The energy release in this operating cycle would be 300,000 (3×10^5) megawatt-seconds requiring 10^{22} nuclear fissions and would be equivalent to a 0.07-kiloton nuclear bomb if released instantaneously. Such a rocket would deliver about 50,000 pounds of thrust, which would project it about 2000 miles or, if used as a second-stage atop a missile of the Atlas or Titan class, would propel itself into a high orbit around the earth. Although it would be classed as a minimum performance system, it would not be a "Kiwi" and would be a big step in nuclear-powered rocket propulsion.

Areas of Concern

The potential radiation problems of testing and launching nuclear rocket systems include the possibility of direct neutron and gamma ray exposure of operating personnel from normal operation or in the event of a criticality accident. Involved also is the possibility of delayed radiation exposure of operating personnel and the general population as a result of fission product release during normal operation, launch pad failure, or purposeful or accidental in-flight system destruction. Reactor impact could involve both immediate and delayed radiation exposures of launch personnel or the general population. Consideration should be given also to occupancy of a contaminated launch or impact area and to general biospheric contamination from fallout. It is not possible to consider all of these points here. The following discussion is confined, therefore, to a brief general consideration of a few of the more pertinent points as they apply to the minimal performance reactor.

Possibilities of a Criticality Accident.--Usually one of the first questions asked is whether such propulsion reactors could create a nuclear explosion comparable to an atomic bomb. Any circumstance which can enhance the neutron economy of a reactor in a sufficiently drastic way may lead to a power excursion. If the energy liberated in an excursion can be safely assimilated within the reactor, it will be nondestructive; if the energy release is too large, serious functional damage or even partial destruction of the reactor may result. Excursions could conceivably occur in a propulsion reactor in

several ways. These include a gross malfunction in the control rods (such as their sudden, complete, and irreversible withdrawal), sudden compression of a reactor with the simultaneous filling of voids (cooling passages) and assumption of a more favorable shape (an extremely improbable happening), the filling of system voids with an effective moderator material (such as water or liquid hydrogen), or the addition of a means of reflecting escaping neutrons back into the core (possibly by immersion in water).

Such "upper limit" accident yields have been calculated for a variety of conditions. The results show that partial core vaporization (perhaps as much as 15 per cent) might occur with some spread of the volatilized fission products. Loss of the core material would, however, "quench" the nuclear reaction, making it impossible for an explosion resembling an atomic bomb to occur. At most, the energy release would be only about 3 per cent of the maximum power output of the reactor, and most of this energy would be used up in heating the reactor and volatilizing some of the core. There would not be a high order explosion.

Direct Radiation from Full-Scale Static Testing.--A nuclear reactor operating at 1000 MW would produce very high prompt neutron and gamma radiation doses. In fact, if a man stood within 20 feet of such a reactor during operation and without any radiation shielding, he would receive a lethal dose in less than one-tenth of a second.

Radiation dose, however, drops off very fast with distance from the source and, as shown in Fig. 2, to protect operating personnel during a full-scale static test of a 1000 MW reactor, it is necessary only that they be approximately 1 mile away. At this distance, their exposure would be only about 60 mrad, which is below the maximum permissible exposure for 1 week.

After shut-down, the reactor will continue to give off gamma radiation and will be a significant radiation hazard for many days. This phenomenon, however, is very well understood. The decrease of radiation dose rate as a function of time after shut-down is well known, and safe remote control handling and inspecting procedures are already worked out. A large controlled exclusion radius around the reactor obviously is required for a considerable time after normal operation, or it must be moved into a shielded area.

Accidents Involving Fission Product Escape.--If the existing knowledge of total activity resulting from a reactor operation could be supplemented with accurate description of its space and time distribution, all post shut-down radiation problems (approach to reactor, contamination, fallout, etc.) could be clearly defined and rigorously evaluated before a test. Lacking this information, these problems can be and have been explored for the maximum hazardous conditions imaginable.

If full-scale static testing is needed at the launch site, the

Fig. 2. Prompt radiation dose from a nuclear propulsion reactor during a 3×10^5 MW-sec operating cycle.

STATIC TESTS AT NTS

(NORMAL FULLSCALE OPERATION -- 3×10^5 MW-SEC)

PROMPT GAMMA AND NEUTRON RADIATION

31 013

LOS ALAMOS
PHOTO LABORATORY

NEG.
NO. 603235

PLEASE RE-ORDER
BY ABOVE NUMBER

greatest radiation hazard from it which one can contemplate would result from a maximum criticality excursion occurring at the end of a full power cycle with complete destruction of the missile and release of 100 per cent of the fission products into a cloud passing directly over occupied areas. Estimates of the total dose for such a case have been made and are shown in Fig. 3. Including the effects of the operating reactor, internal and external exposure during cloud passage, and exposure from fallout, the total doses to personnel would be about 4, 2.8, 1.3 rads, and 0.14 rad at distances of 100 yards (inside a 5-foot concrete bunker), and at 1 mile, 2 miles, and 10 miles, respectively.

These doses would be negligible at all upwind distances beyond 1 mile, so one would normally choose meteorological conditions such that the prevailing winds move across the test site away from the control point and significant population groups in the public domain, making sure no personnel were located at short range in the downwind direction. During actual launch of a rocket, the same features would be desirable, though not mandatory, along any path overflowed by the rocket. These features suggest that island or seacoast launching sites affording ocean overflight should be given first consideration. Several existing conventional launching sites near populated areas may be compatible with these conditions, depending on details of the local meteorology and oceanography.

Fig. 3. Radiation dose as a function of distance from a destructive accident involving a maximum criticality excursion at the end of a 3×10^5 MW-sec operating cycle.

ROCKET SYSTEM CAPTIVE TESTS

(MAXIMUM CREDIBLE ACCIDENT AT END OF FULLSCALE OPERATION)

TOTAL RADIATION DOSE - PROMPT, RESIDUAL AND DURING CLOUD PASS

LOS ALAMOS
PHOTO LABORATORY

NEG.
NO. 603455

PLEASE RE-ORDER
BY ABOVE NUMBER

Impact and Re-entry of an Operated Reactor.--One of the most serious potential problems is that created by uncontrolled impact of a nuclear rocket motor after it has been operated long enough to have accumulated a large fraction of its full complement of fission products. Because of the rate of decay of these fission products, it will remain a dangerous radiation source for many months or even years. The reactor may impact within the controlled launching area as a result of early mission abort or launch pad failure, it may impact at great distance from point of launch as a result of late failure, or it may re-enter the earth's atmosphere from orbit and impact anywhere on the earth's surface.

On-site impact following early thrust failure (after 90 seconds of operation) has been considered, and the radiation dose rates as a function of time after impact of the intact reactor are shown in Fig. 4. At a distance of 10 meters (about 30 feet), the radiation dose rate is still 1 r/hr after 3 months. However, since impact in this case would be in a controlled area, the reactor could be moved by remote control or shielded handling equipment into a previously prepared shielding facility somewhere in the vicinity of the launching site. The situation would be somewhat more difficult if the reactor broke up on impact and spread its fission products over the launching site. Figure 5 shows the radiation dose rates in the contaminated area as a function of time after impact, assuming the fission products from a 90-second operation were spread over areas of 0.1 and 1 square mile. Obviously, the areas could not be reoccupied for

Fig. 4. Radiation dose rate at 10 meters from an intact 1000 MW reactor that impacted after 90 seconds of operation.

RADIATION DOSE RATE AS A FUNCTION OF TIME AFTER IMPACT

(REACTOR INTACT. 100 PERCENT RETENTION OF FISSION PRODUCTS.)

READING AT DISTANCE OF 10 METERS. 90 SEC REACTOR OPERATION.

W.G. Tansley

LOS ALAMOS
PHOTO LABORATORY

NEG.
NO. 603234

PLEASE RE-ORDER
BY ABOVE NUMBER

Fig. 5. Radiation dose rate from surface contamination, assuming even distribution of the fission products from a 90-second operating cycle over areas of 0.1 and 1 square mile.

RADIATION DOSE RATE AS A FUNCTION OF TIME AFTER IMPACT

(REACTOR DESTROYED WITH 100 PERCENT OF FISSION PRODUCTS SPREAD
UNIFORMLY OVER 0.1 AND 1.0 MI²)

90 SEC REACTOR OPERATION.

LOS ALAMOS
PHOTO LABORATORY

NEG.
NO. 604341

PLEASE RE-ORDER
BY ABOVE NUMBER

several days unless decontamination measures were taken. However, since impact is in a controlled area, this could be accomplished without undue risk.

Offsite ground impact of an intact or ruptured reactor as a result of late mission failure poses a serious potential problem, since it would occur in an uncontrolled area and no facilities and equipment would be readily available to cope with the situation. For this reason, development of ocean or seacoast launching sites providing a test range over great spans of the ocean should be seriously contemplated. Not only are there few people in the ocean wastes, but there are natural mixing and diffusing mechanisms in the water, which would dilute and disperse the radioactivity very rapidly. Even if all the fission products from 3×10^5 MW-sec of operation were liberated and retained within the surface 20 meters of water, it has been estimated that the radioactivity level in the contaminated zone would remain above that acceptable as a continuous source of drinking water for a period of only 2 to 3 days, and dilution would be sufficiently rapid that occupants of a ship passing through the area almost immediately after impact would receive practically no radiation exposure. If the reactor sank below the thermocline (depth about 100 meters) before breaking up, there would be practically no return of radioactivity to the surface.

Shallow water impact is not as desirable as deep water impact. Escaped fission products in solution would be more concentrated, because

of the shallower depth, and longer times would be required for the radioactivity to decay to normal tolerance levels. Shallow water impact might also make a short-term seacoast contamination problem if the off-shore currents did not flow away from the land masses; this possibility can be appraised only in light of data on the oceanography near possible launching areas.

The shielding effect of water is so great that ~ 15 feet covering a reactor containing all the fission products formed in a 120-second, 1000-MW cycle would barely be detectable at the surface (Fig. 6). Conversely, water shallow enough to permit radiation detection at the surface above an intact reactor is probably also shallow enough to permit monitoring and restriction of the potentially dangerous area until the reactor is recovered.

If a nuclear propulsion reactor that had been operated in orbit re-entered the earth's atmosphere and impacted on its surface, the potential hazard created would depend on the length of time the system had remained in orbit after shut-down. Figure 7 shows the radiation source strength of a reactor as a function of time after a 3×10^5 MW-sec operating cycle. Even after 10 years, the radiation dose rate at 10 meters distance is still about 0.1 r/hr. Since re-entry and impact would be uncontrolled, the reactor may fall anywhere, thereby creating a potential hazard to the public domain as well as a potential international political incident of considerable magnitude.

Means of dealing with this particular problem area are not presently available, and further studies will be necessary. Promising

Fig. 6. Effectiveness of water depth as a radiation shield for a reactor impacting offshore after operating at 1000 MW for 120 seconds.

SHALLOW WATER IMPACT AFTER 120 SEC OPERATION

(RADIATION ATTENUATION AS A FUNCTION OF
WATER DEPTH)

REACTOR INTACT. 100 PERCENT RETENTION OF FISSION PRODUCTS.

LOS ALAMOS
PHOTO LABORATORY

NEG.
NO. 603230

PLEASE RE-ORDER
BY ABOVE NUMBER

Fig. 7. Radiation source strength of a reactor as a function of time after having undergone a 3×10^5 MW-sec operating cycle.

RE-ENTRY FROM ORBIT AFTER 300 SEC OPERATION

(RADIATION SOURCE STRENGTH AS A FUNCTION OF
TIME AFTER SHUTDOWN)

LOS ALAMOS
PHOTO LABORATORY

NEG.
NO. 604340

PLEASE RE-ORDER
BY ABOVE NUMBER

areas of investigation would appear to be a study of the possibility of reactor burn-up or fission product boil-off in space; a study of the possibility of dispersal of the reactor in space with investigation of burn-up of the reactor fragments on re-entry; and a study of the possibility of controlled impact on return from space.

General Fallout Contamination.--The possibility of destroying nuclear reactors in the upper atmosphere and space to prevent their re-entry and impact naturally leads to the question of general radioactive fallout contamination as has occurred from nuclear weapon testing.

Release of fission products from nuclear rocket systems, whether during static testing or actual flight, may result in both local and long-range fallout. The magnitude of this problem can be evaluated rather satisfactorily, however, on the basis of experience with fallout from nuclear weapon testing. The minimal performance nuclear reactor is equivalent in energy release and fission product production to a fission weapon with a 0.07-kiloton yield. A nuclear rocket as large or larger than the largest chemical rockets planned (5 to 6×10^6 pounds of thrust) would be equivalent only to a 7-kiloton nuclear weapon -- small indeed compared to weapons that have been tested within the continental United States. Assuming complete release of fission products into the upper troposphere and lower stratosphere, 250 1000-MW reactors could be tested before the fallout contamination would equal that produced by a single nominal 20-kiloton bomb. Furthermore,

in actual flights, a single-stage nuclear rocket, if fired successfully, would spend only about 100 seconds of its operating time below the equatorial tropopause, where the return time of fission products will be relatively short. Fission products released above the tropopause will have a progressively longer return time with increasing altitude of release, and above a few hundred thousand feet the return time may be in excess of 100 years. A graphic representation of local and world-wide contamination from nuclear rockets is presented in Fig. 8.

The long-lived fission products Sr^{90} and Cs^{137} are the ones primarily responsible for the problem of general or world-wide fallout. Nuclear weapon tests to date have resulted in approximately 90,000 kiloton equivalents of fission energy release, which has produced about 9 and 16 MC (million curies) of Sr^{90} and Cs^{137} , respectively. Approximately two-thirds of the total is or soon will be deposited over the earth's surface as potential biospheric contamination. These materials are decaying at the rate of approximately 2 per cent per year (half-life ~ 28 years). Strontium⁹⁰ and Cs¹³⁷ biospheric contamination is decreasing, therefore, at rates of approximately 1.2×10^5 and 2.2×10^5 curies per year, respectively. Since the standard 1000-MW reactor operating for 300 seconds produces ~ 12 curies of Sr^{90} and ~ 14 curies of Cs^{137} , 10,000 such tests in which the reactors were disintegrated in the upper troposphere and lower stratosphere could be conducted per year without increasing the present biospheric level.

Fig. 8. Tropospheric and stratospheric fallout from nuclear rocket operations.

TROPOSPHERIC AND WORLD WIDE FALLOUT

5×10^4 LBS. THRUST $\Rightarrow$ 0.07 KT FISSION

5×10^6 LBS. THRUST $\Rightarrow$ 7.0 KT

WEAPONS TESTS TO DATE $\Rightarrow$ 90,000 KT

LOS ALAMOS
PHOTO LABORATORY

NEG.
NO. 603233

PLEASE RE-ORDER
BY ABOVE NUMBER

The magnitude of the hazard of local offsite fallout may be ascertained from the radiation exposures of the general population in the vicinity of the Nevada Test Site. The average exposure of the 1,000,000 persons living nearest the test site has been at the rate of about 0.5 r per 30 years. Fission products from approximately 1000 kilotons of fission energy release have been discharged into the local environment from aboveground detonations. This is equivalent to approximately 140 kilotons per year. About 50 per cent of the contamination is believed to have fallen out in the general vicinity of the test site, and about 50 per cent has been distributed as longer range tropospheric fallout. Assuming that fission product release from a reactor operation results in essentially the same general contamination conditions, 2000 full-scale tests or launchings (in which 100 per cent of the fission products were released) could be conducted per year for 7 years before the average radiation dose received by residents immediately offsite would be equal to that experienced by the residents of our Western states as a result of Nevada weapon tests.

These considerations indicate that world-wide contamination from nuclear rocket propulsion programs is not a serious problem. The principal problem is a local one confined to operating personnel and to population groups in the general vicinity of testing, launching, or impact sites.

MANNED NUCLEAR ROCKET SYSTEMS

Manned nuclear rocket systems are certainly an attractive dream of the future. The nuclear space ship is considered by many as indispensable for manned interplanetary travel and colonization of the moon. Unfortunately, neutron and gamma ray leakage from the nuclear reactor itself will add to the radiation problems of space conquest. Systems capable of delivering adequate performance will be prodigious radiation sources, necessitating careful shielding of flight crews. Fortunately, considerable distance between crew and reactor will be possible, and rocket fuel and other supplies can be used effectively as shielding material (Fig. 9). The problem is also simpler once outside the atmosphere, where shadow shielding can be employed effectively. There is the possibility also that doses from space ambient radiations (solar flare protons, cosmic rays, Van Allen or magnetically trapped radiations in the vicinity of planets) will require shielding of flight crews anyway; therefore, requiring nuclear energy to propel the heavily shielded craft and resulting in less net addition of weight to protect from the prompt radiation of the nuclear reactor.

Presently established radiation protection standards are predicated on the assumption that a person will be potentially exposed throughout his working life-time and that his employment in pursuits involving radiation will not subject him to any greater probability of risk than any other industrial occupation. Over the past 10 to

Fig. 9. Possibilities of crew shielding in a manned nuclear rocket.

20 years, the National and International Commissions on Radiological Protection have revised the basic standards downward, which has resulted in increased anxiety over the hazards of radiation exposure. This downward trend has not been the result of positive evidence of damage resulting from the use of the earlier values, but is the result of a number of factors. First, there is a general feeling that genetic, life shortening, and leukemogenic effects of radiation may not be threshold phenomena. If this be true, then any exposure (no matter how small) will carry a small but finite probability of risk. It is prudent, therefore, to prescribe basic standards of protection that are as low as is compatible with the job to be done. Second, improvements in radiation protection techniques have made it possible to work with lower basic protection standards without seriously decreasing the benefits gained from the use of radiation and radioactive materials. Third, the large-scale development of the nuclear energy industry has increased greatly the number of people potentially exposed to radiation. If the harmful effects of radiation are statistical in nature, the probability someone will be injured will increase with the number of people exposed. This again makes it prudent to lower the basic standards if the lowering does not significantly limit the benefits to be gained.

Acceptance of radiation risk (whether from space ambient radiation or use of nuclear propulsion devices) in space exploration should

be considered in context with the magnitude of the potential gain. The space program should set up its own basic radiation protection standards. Because of the inherent weight requirement of shielding and its interaction with the rest of the space system, radiation exposure limitations should be set realistically. Limitations that are too conservative will impose major engineering penalties, which may result in greater over-all risk to the astronaut. As space technology and engineering improve and more and more people are exposed, the basic standards can be lowered in keeping with the magnitude of other inherent risks.

ACKNOWLEDGMENTS

It should be pointed out that few of the basic data and concepts given above depend on conjecture or unsubstantiated conditions. From the beginning of the Los Alamos Scientific Laboratory's program in nuclear propulsion reactors, intensive measurements and theoretical predictions of the potential hazards created by such devices have been pursued with sufficient vigor that safety considerations are keeping pace with engineering development. Many have contributed to the ideas set forth in this paper, especially Messrs. G. A. Graves, W. R. Stratton, P. S. Harris, R. Reider, E. C. Anderson, and M. A. Van Dilla, all of this Laboratory. Their contributions are gratefully acknowledged.