Calculations of the Radiobiologic Risk Factors in Nuclear-Powered Space Vehicles

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THE engineering fundamentals, potentialities and problems associated with the application of nuclear energy to rocket propulsion have been reported.[3,4,8,11,24,26,27] Work on nuclear rocket propulsion has been underway at the Los Alamos Scientific Laboratory for a number of years under the code name *Project Rover*.[25] An inherent advantage of nuclear propulsion is the unlimited energy supply of a reactor that can be used to heat a low molecular-weight propellant like hydrogen to much higher exhaust velocities than are possible in chemical rockets operating at the same temperature. The higher exhaust velocities lead directly to superior rocket performance. The nuclear rocket is considered as indispensable for extra-terrestrial voyages, and appears ideally suited for use as a reusable satellite-booster, moon-ferry or interplanetary vehicle capable of carrying very large payloads at a nominal cost.[11]

A recent nuclear-rocket timetable[1] revealed the following:

1946—First nuclear rocket proposal; scheme shelved
1955—Decision to sponsor study program
1957—Four programs acknowledged:
  Rover—nuclear rocket
  Pluto—nuclear ramjet
  Snap—auxiliary nuclear power for satellites
  Ionic Propulsion—advanced propulsion system
1958—First test of nuclear rocket reactor
1959-60—Choose reactor for first nuclear rocket
1965-70—First nuclear rocket flight

The problems[14] and risks[15] associated with man in space include the obvious variations in acceleration, weightlessness, changes in the closed ecological system, possible decompressions,[16] meteoroidal collisions,[31] extra-terrestrial radiation (cosmic and Van Allen's radiation belt),[29] temperature variations and psychologic factors. A recent evaluation[15] of long duration space operations revealed that, "it is not the hostile space environment *per se*, but the overall reliability of space vehicular system, especially the complex sealed cabin system, which will determine the success and safety of orbital, lunar, and planetary operations." Of all the risk factors involved in space flight, exposure to ionizing radiations has perhaps received the most attention. The use of a nuclear reactor for propulsion will increase the radiation hazard to which the spacemen will be exposed.

It is true that the earth is surrounded by at least one dangerous radiation belt and Van Allen[29] believes dose rates of 100 r per hour may exist above the equator. But this does not mean that such radiation will add significantly to

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the exposure of a crew on an interplanetary flight in a nuclear-powered space ship since the Army's *Pioneer III* indicates that relatively low dose polar exits probably exist. If we assume that, as additional satellite data become available, it will be possible to plot optimal trajectories and velocities for minimum time in the radiation belt(s), then the prime radiation source for the astronauts will be the nuclear reactor.

The rapid development in reactor technology could make construction of a nuclear powered space vehicle possible in about ten years. Therefore, it is not premature to study the human factors involved in the design of such vehicles. Human factors involve the difficult task of predicting human requirements, capabilities and functions long before a system has been firmly laid down. Human factor specialists, as members of the advance design team, are continuously confronted with decisions for which they have inadequate information. The forecasting of human requirements for nuclear space ships is no exception. Ideally, the radiobiologist desires a minimum radiation dose, because any exposure to ionizing radiation, no matter how small, will result in some damage to the individual. The design engineer, on the other hand, desires a minimum of shielding because of weight and cost considerations.

This study was conducted to obtain order of magnitude figures required to evaluate the biological risk factors involved in future nuclear powered space flight. The utilization of such data can help the design team to avoid pitfalls and unjustifiable compromises at the expense of the human occupants in the initial design of an optimal nuclear space system. Although the object should always be to minimize any exposure to radiation, concessions by the radiobiologist may be necessary to make certain missions feasible. Therefore, the question is, How much shielding is necessary for acceptable protection of the crew? The answer to this question depends on many factors.

What is involved is not an elimination of all the risks involved in manned space flight, for that is impossible, but rather an evaluation of the factors, so that the balance tips in favor of the benefits gained from manned space ventures in nuclear powered vehicles.

The problem is to calculate human risk in direct and scattered radiations at various separation distances from the reactor and at different power outputs, without shielding, and with varying amounts of shielding weights. These calculations have been made and can be utilized by design teams to arrive at an optimal nuclear space ship design.

BIOLOGICAL ASPECTS OF IONIZING RADIATION

Ionizing radiations accompanying the use of nuclear power can penetrate matter and the human body is no exception. The passage of ionizing radiations through the body is not sensed even though lethal doses are absorbed. The principal means of energy dissipation by an ionizing radiation in its passage through matter is the ejection of electrons from atoms through which it passes. An atom so ionized is left positively charged, that is, an ion. When an atom is ionized, the molecule of which it is a part almost certainly undergoes chemical change.[20] It is the chemical change resulting from the ionization which causes the biological effect. The damage to living tissue has been summarized as follows:[12] "The damage to irradiated tissue is fundamentally the same regardless of the type of ionizing radiation. The number of ions produced and their distribution within the cells determines the extent of the damage. Radiation doses even in the lethal range cause ionization of only a small fraction of the total number of molecules in a cell. If these affected molecules are important to the life of the cell, for example, are those composing enzymes, genes, and chromosomes, involvement of even a few may lead to the death of the cell."

TABLE I. CLINICAL COURSE IN MAN FOLLOWING VARIOUS ACUTE WHOLE-BODY DOSAGES OF IONIZING RADIATION

Dose	Not Hospitalized			Hospitalized		
	Trivial	Light	Moderate	Serious	Grave	Lethal
600r						100%
500r					6%	94%
400r				3%	58%	39%
300r			6%	68%	26%	
200r	1%	33%	64%	2%		
100r	98%	2%				

In general, the rapidly proliferating tissues (for example, blood-forming tissues and the intestinal and germinal epithelium) are usually the most radiosensitive, while nervous tissue and muscle are relatively radio-resistant. The illness produced by exposure to radiation of the entire body or a large part of the body is termed acute radiation syndrome. The symptoms depend primarily upon the dose and the exposed organs.[6,10,12]

Medical evidence of human ability to sustain acute or short-term exposure to whole-body radiation appears to be reasonably clear.[5,6,10,12,20,21,23,30] Our present knowledge and appreciation of the pathologic effects of radiation in man comes from experimental work on animals, as well as from the available human data which include:

1. Results of excessive exposure to x-rays and radium in the early days.
2. Results of more moderate exposures to different forms of radiation, as experienced by cyclotron workers.
3. Results of introduction of naturally occurring radio-elements into the body, notably radium.
4. Effects of exposure at Hiroshima and Nagasaki.
5. Observations on populations irradiated by fallout.
6. Additional observations from clinical radiotherapy; use of artificial isotopes in therapy; a very limited number of accidents in atomic energy work, and certain statistical surveys of large groups.

In an excellent study, Gerstner[10] made a comparative analysis of human data of nuclear accidents, Japanese bomb casualties, and radiotherapy patients to obtain the clinical picture of the acute radiation syndrome. The pertinent information in Gerstner's report is summarized in Table I, and in the following general statements:

Dose range 0 to 50 r: Sub-threshold for the acute radiation syndrome and presents no medical problem in emergency situations.

Dose range 51 to 100 r: Will cause trivial and transitory clinical changes posing no medical problem. According to present knowledge, these mild acute affects are followed by complete recovery and return to normal life.

Dose range 101 to 150 r: Conclusions parallel those given for the previous dose range.

Dose range 151 to 200 r: The acute radiation syndrome becomes noticeable in the majority of the exposed, and reaches clinical significance in a few highly radio-sensitive persons. Approximately 200 r will be the clinical tolerance or threshold dose and beyond this an appreciable number of the exposed can be expected to develop significant complications requiring hospitalization and intensive medical treatment. Present knowledge leads to the conclusion that in this dose range, complete recovery will follow after the patient passes through the acute radiation syndrome, even in its more severe form.

Dose range 200 to 400 r: Clinical course predominantly serious or grave, depending on individual susceptibility, with all exposed persons requiring hospitalization and intensive medical treatment. Properly instigated treatment promises a favorable outcome and, most likely, recovery to a normal and vigorous life.

Dose range 401 to 600 r: Clinical course predominantly grave, with best present indications that 450 r will be lethal to 50 per cent, and about 600 r will be lethal to 100 per cent of the exposed persons.

Each person receives, on the average, a total accumulated dose from natural background radiations of about 4.3 r over a thirty-year period. This may be as high as 5.5 r in some places in the United States because at high altitude the cosmic ray component increases. Some persons receive no radiation from medical x-rays; others may get a great deal. On the average, a total accumulated dose to the gonads is about 3 r of x-radiation during a thirty-year period.[21] Combining these radiations the average person gets a little over 7 r in the thirty-year periods.

The consequences of chronic lifetime exposure to ionizing radiation are not so clear. There is evidence, however, that long term damage can be assessed largely in terms of decreased life-span. As will be seen later, the use of nuclear powered space ships involves very short periods of reactor operation, and thereby primarily involves acute, rather than chronic effects of radiation. Future use of reactors as secondary-nuclear-auxiliary-power (SNAP), and possibly in ion propulsion engines, may involve chronic exposures. Groups like the one under Pickering[23] have devoted many years to the study of the biological and medical aspects of ionizing radiation associated with nuclear weapons, devices, and the aircraft nuclear propulsion program (ANP). Their research efforts will continue to give us a better understanding of the chronic and acute radiation effects in man. All the radiobiologic data collected to date will have a direct bearing on the design of nuclear reactors for use in space.

Available data indicate that sublethal irradiation of the whole body causes premature death primarily by accelerating the actual biological aging process.[5] In general, for given dose rates, the survival time is inversely related to the amount of radiation energy absorbed. The shortening of life is generally greater if a given total dose is absorbed in a short period of time, that is, an acute radiation exposure. As an example, workers exposed to the maximum permissible AEC dose rate of 0.3 r per week (15 r per year), would receive a dose of 450 r in thirty years and presumably show no visible signs of damage. However, the same dose of 450 r received as whole-body acute radiation would probably be fatal to 50 per cent of the exposed persons.

Any radiation is genetically undesirable, because radiation induces harmful mutations. Present available data leads to the conclusion that the genetic harm is proportional to the total dose, that is, the total accumulated dose to the reproductive cells from the conception of the parent to the conception of the child.[21] The overall study of the mutation generating effect of ionizing radiation in man has been hindered by lack of many important facts concerning human genetics. Knowledge is needed about the number of existing mutations carried by mankind, mutation rates, the structure of human populations, the rate of elimination or dissemination of mutant genes in human populations, and about those factors, including radiation, which affect human genetics.[2]

How great an increase in mutation rate is tolerable to the human race? Even if an accurate prediction could be made, the decision of what is a "tolerable" dose is to a large extent a moral and philosophic problem.

A gene can be mutated, permanently altered, by certain agents; heat, some chemicals and radiation. The change is presumably an alteration in the complicated chemical nature of the gene. The prime problem in estimating the genetic effects of ionizing radiation, is the determination of the "doubling dose," that is, the dose required to double the spontaneous rate of mutation. The best biological judgment indicates that the values of the "doubling dose" are almost surely more than 5 r and less than 150 r and recently several experienced geneticists have estimated a narrower range of 30 r to 80 r.[21] A mutated gene is duplicated in each subsequent cell division and if in an ordinary body cell, it is merely passed along to other body cells. The mutant gene, under these circumstances, is not passed on to progeny, and the effect is limited to the person in whom the mutation occurred.

It is obvious that the foregoing genetic considerations do not apply if the irradiated individual does not have offspring after the period of exposure. This so significantly decreases the genetic hazard that it should be a factor in nuclear space ship crew selection. The crews in the early exploratory flights will probably be highly trained mature persons over thirty-five years of age with completed families. Inasmuch as the genetic concern involves the general public, even if a small number of irradiated astronauts decided to have additional offspring after their return to earth, the mutagenic effects would be very diluted. However, if this is ever considered a problem, it should be possible to set up "semen-banks" for departing astronauts, so that if they decide to have additional progeny, they will carry the parental hereditary characteristics which exist-ed before the possible exposure to the reactor and cosmic radiations.

The committee on genetic effects of atomic radiation of the National Academy of Science[21] recommends (1) "that individual persons not receive more than a total accumulated dose to the reproductive cells of 50 roentgen up to age thirty years (by which age, on the average, over half of the children will have been born), and not more than 50 roentgen additional up to age forty (by which time about nine-tenths of their children will have been born)," and (2) "that every effort be made to assign to tasks involving higher radiation exposures individuals who, for age or other reasons, are unlikely thereafter to have additional offspring."

There have been many attempts to modify the deleterious effects of ionizing radiation by prophylaxis and treatment. One of the authors had some degree of success with hypoxia,[17], carbon monoxide,[18] and altitude acclimatization.[19] Others have tried reducing compounds, that is, cysteine, cysteamine, glutathione, antibiotics, blood transfusion, hypothermia, and hibernation. Present animal experimentation indicate that the reduction of prompt and delayed radiation effects is not hopeless. Protective drugs like AET (S,2-Aminoethylisothiuronium Br HBr) and isologous bone marrow (IBM) have great promise.[2] AET drastically reduces the biological effects of radiation in animals. This chemical seems to localize in bone marrow and blood forming organs, exerting its protective influence there. At the last International Congress of Radiation Research meeting, David G. Doherty of Oak Ridge National Laboratory, stated, "If results on mice can be extrapolated with any confidence, a one gram pill of AET should cut in half the damage to a person's system from a radiation dose as high as 400 roentgen." Despite this encouraging news, it may be some time before the drug can be used with confidence in humans. Therefore, the panacea for protection against ionizing radiation is still structural shielding.

Shielding of any part of the body reduces damage to the entire organism. This is also a fruitful area of research. To date, it has not been demonstrated that a small shield, protecting a part of the body, is more effective than a shield of equal weight covering the entire body. Therefore, we shall consider only whole-body shielding in the following radiation dose and shield weight calculations.

RADIATIONS AND SHIELDING CALCULATIONS

At present, an analysis of the nuclear radiations attendant to the operation of a nuclear rocket propulsion system must necessarily be based upon assumptions. The assumptions used herein are:

1. That 0.6 percent of the reactor power is dissipated by radiations leaving the reactor.
2. Of these radiations, the gamma flux in Mev/cm^2 sec. is ten times the fast neutron flux in neutrons/cm^2 sec.
3. The thermal neutron flux is equal to the fast neutron flux.
4. The gamma flux is divided into energy groups of 0.5, 2.0 and 5.0 Mev in order to simulate the fission spectrum.
5. The fast neutron flux is taken to be 2.0 Mev, but as will be seen later, the mag-

nitude of this value is not important in this analysis.

6. All radiations leave the reactor isotropically.
7. The reactor operating time is assumed as 300 sec., however, the length of this time will not have a great influence on the shield weight in this study.

Each of these assumptions has been analyzed to some extent, and none appear to yield a large source of error.

Calculations have been conducted on the basis of the above assumptions. A thin layer of B^{10} is taken to surround the reactor to essentially convert the thermal neutrons to 0.5 Mev gammas. These are then added to the gamma spectrum. This procedure essentially eliminates the need for consideration of the n, γ, reaction in nitrogen. Figure 1 indicates the dose rate at various separation distances for variable reactor power as produced by the direct radiations. Neutron flux to dose rate conversion is taken as given by Snyder and Neufeld.[28] In computing thrust, hydrogen is the assumed propellant with an assumed specific impulse of 865 seconds.

Scattering calculations were made on gamma rays considering all space to have the same air density as that associated with the altitude of the rocket at any particular time. Both energy and directional properties of the gammas were retained during the scattering process by the use of the Klein-Nishina scattering theory. Thus, the angular and energy dependence of the gamma radiation arriving at the receiver is known. Due to the high shield-

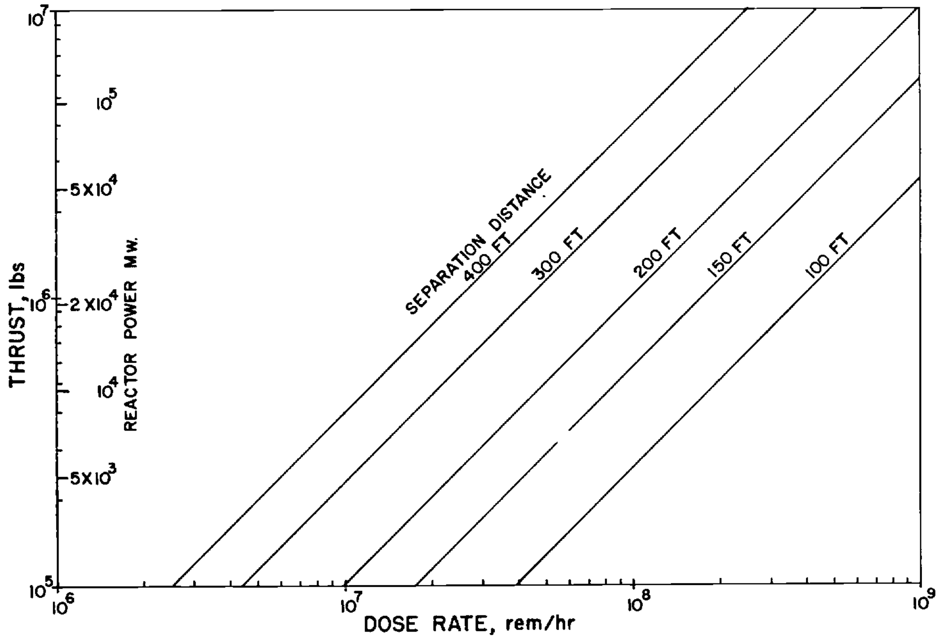

FIGURE I

Fig. 1. Dose rate in crew compartment from unshielded direct radiations during reactor operation.

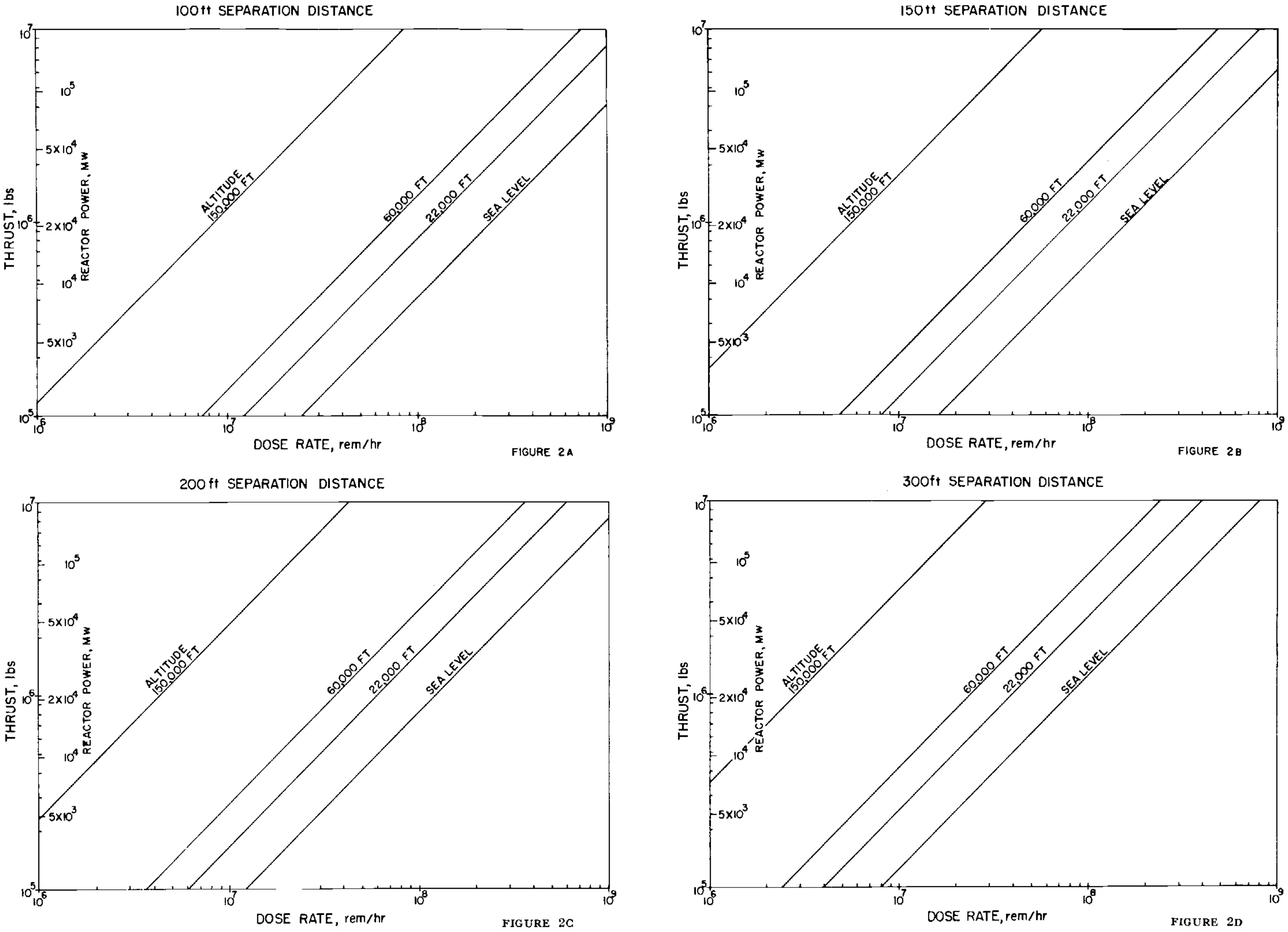

FIGURE 2A

FIGURE 2B

FIGURE 2C

FIGURE 2D

Fig. 2. Dose rate in crew compartment from unshielded scattered radiations for various separation distances.

ing capability of the fuel for a nuclear rocket, only those radiations leaving the source and incident to the receiver at angles greater than 15° to the source-receiver centerline were included in the calculations. Single scattering theory was used throughout this analysis.

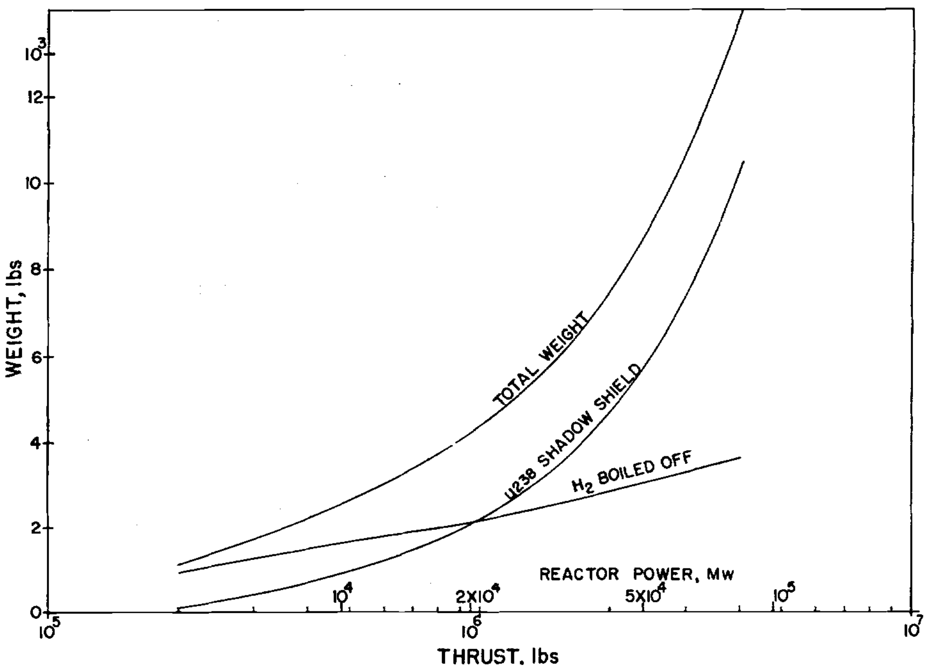

Fig. 3. Shadow shield weight optimization.

The analysis of fast neutron scattering assumed elastic, isotropic scattering of the neutrons, again maintaining angular and energy cognizance over the neutrons. The results of these analyses are indicated in Figure 2, which illustrates the reactor power, altitude, and separation distance dependence of the scattered radiation dose rate.

Inasmuch as hydrogen is the assumed propellant, considerable radiation absorption will take place in the propellant tanks. The radiation will be sufficiently high, that a shadow shield should be provided above the reactor to prevent excessive boil off of propellant. An optimization has been conducted to find the shadow shield which will give the minimum total weight of shadow shield plus boiled off hydrogen as a function of reactor power. The optimized values are indicated in Figure 3.

In determining the shield requirements for a manned nuclear vehicle, a minimum volume compartment for three persons was chosen. Figure 4 shows the compartment which meassures 3x6x7 feet. This compartment need only act as shielded quarters during propulsion phases in planetary atmospheres. If anthropometric requirements dictate, this shielded compartment (well) can be used as sleeping quarters. This well is assumed to be surrounded on the sides and base by three to six feet of hydrogen, which will be used as reactor after-coolant after propulsion termination. This hydrogen provides some amount of attenuation; however, it mainly acts to thermalize the incident neutrons which are absorbed in a B^{10} layer about the outside of the compartment shield. The isotropically released gammas from the neutron absorption are added to the incident gamma flux. This total gamma flux is then attenuated by a shield. Mercury is the assumed shield material here due to its unique property of being in the liquid state at room temperatures and having shielding properties almost equal to lead. Insulation would be required between the liquid hydrogen and the mercury. The shielding is sculptured so as to minimize the shield weight for a given dose rate. It should be noted that in a practical situation, extreme care would be taken to protect the flight and ground personnel from acute mercurialism which is often fatal. Acute mercury poisoning results in damage to the kidneys and chronic mercury poisoning damages the nervous system. Although maximum allowable concentration of mercury in air is 0.1 mg/cu. meter, hermetic sealing of the space cabin should virtually eliminate any possibility of cabin contamination.

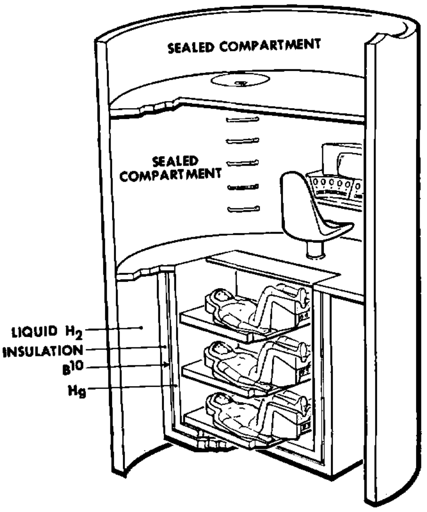

Fig. 4. Schema of shielded well in passenger compartment.

Large propellant supplies are required for nuclear propelled vehicles. This propellant will appreciably attenuate the direct radiations during all but the final portion of the propulsion time when the propellant level is low. Calculations have been made on the direct radiation dose rate as a function of time, using shadow shield, propellant, after-coolant, B^{10}, and mercury attenuation. Integration of the dose rate over the burn time yields the results given in Figure 5 (integrated dose as a function of reactor power, mercury shield weight, and separation distance). The B^{10} weight is in all cases negligible. The integrated direct dose varies inversely as the separation distance squared.

Figure 6 indicates the shield weights required to give various integrated doses from scattered radiation for various separation distances and variable reactor power. A typical earth atmospheric exit trajectory has been assumed which, when integrated over density, yields approximately thirty seconds equivalence of exposure at sea level density. For a given shield weight, the integrated scattered dose varies directly as the reactor power

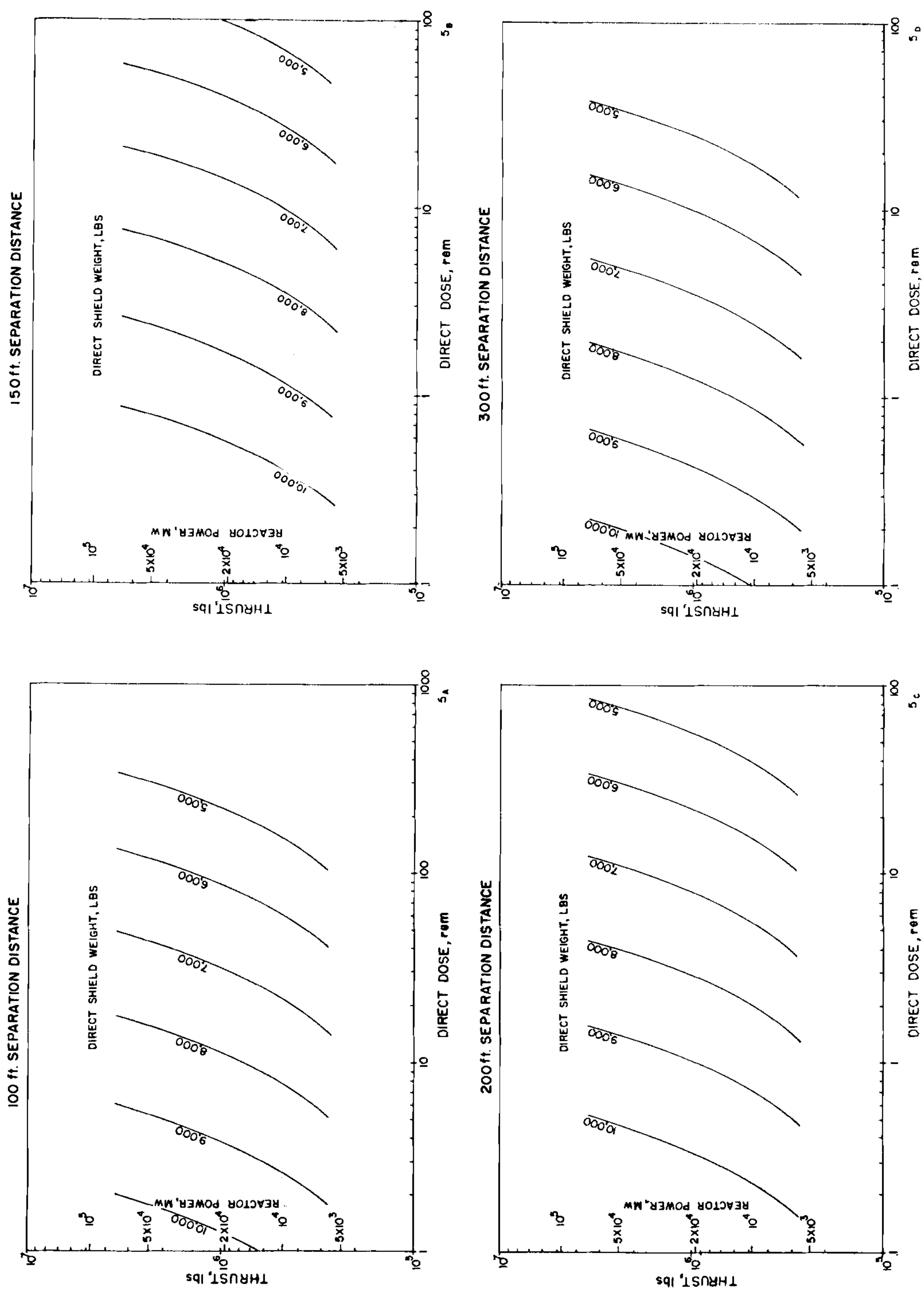

Fig. 5. Integrated direct dose in crew compartment as a function of thrust and shield weight (Hg) for various lengths using optimum shadow shield.

and the integrated density and inversely as the separation distance.

We can use the earth equivalent atmospheric scatter dose calculations for launchings from the surface of Mars, since the integrated scatter dose leaving Mars will probably be lower than the one for the earth. The Martian atmosphere is believed to be principally nitrogen.[7] Argon is also probably present.[9,13] In 1948 Kuiper discovered CO_2 spectrographically and estimated there is twice as much CO_2 per unit area on Mars as on earth. However, later calculations indicate that there is about 10 times as much of the gas on Mars as on earth. The surface pressure on Mars is probably 50 to 100 millibars, while the terrestrial sea level pressure is slightly more than 1,000 millibars. "Gravity on Mars is only 0.37 of ours, so the mass of the atmosphere per unit area is evidently between 1/8 and 1/3 of our own.[13] Although the Martian atmosphere is considerably less dense than ours, the density gradient is much lower owing to the flatness of the gravitational field of Mars so that the air rises to greater heights."[9]

The total equivalent atmosphere (uniform density under a uniform pressure of 760 mm. Hg) of the earth is only 9 km (5½ miles), while the equivalent atmosphere of Venus is probably at least 12 km.[9] If surface landings are attempted on Venus, the subsequent nuclear launching of the vehicle would probably give integrated atmospheric scatter doses a little higher than those calculated for the earth.

The time of applicability of the scatter and direct shields does not coincide. For this reason, our liquid mercury shield may be easily moved from position of scatter shield to that of direct shield. Figures 5 and 6 indicate that the shield required to hold the scattered radiation doses to reasonable levels more than adequately shields the direct radiations. If this procedure of a dual purpose shield material does not prove to be sufficiently attractive, weight can be saved on single purpose immovable shields by using U^{238}. The shield weights are reduced to about 70 per cent of their value for mercury if uranium is used.

Preliminary analysis indicates the possibility of utilizing the basic requirements of oxygen, food, water and CO_2 absorber to sustain the crew in the sealed cabin as shielding material. Without recovery, recycling or regeneration of any kind, the average man metabolizing 3,000 KCal per day requires a minimum of about 12.2 pounds per day of O_2, food, water and CO_2 absorber. In a basal state, metabolizing about 1,760 KCal per day, the average man will require 7.3 pounds per day. This means that a three-man crew on an earth-mars-earth trip of approximately 1,000 days would require at least 21,900 pounds, and probably not more than 36,600 pounds of O_2, food, water, and CO_2 absorber, depending on their metabolic activity. Conservation of material is possible, so that with about an 80-pound water purification and recycling system per man, assuming availability of power, we could reduce the 12.2 pound per man per 3,000 KCal/day requirement to 7.3 pounds, or a total of 22,140 pounds for a crew of three, which includes 240 pounds for the three water systems. In addition, if we regenerate

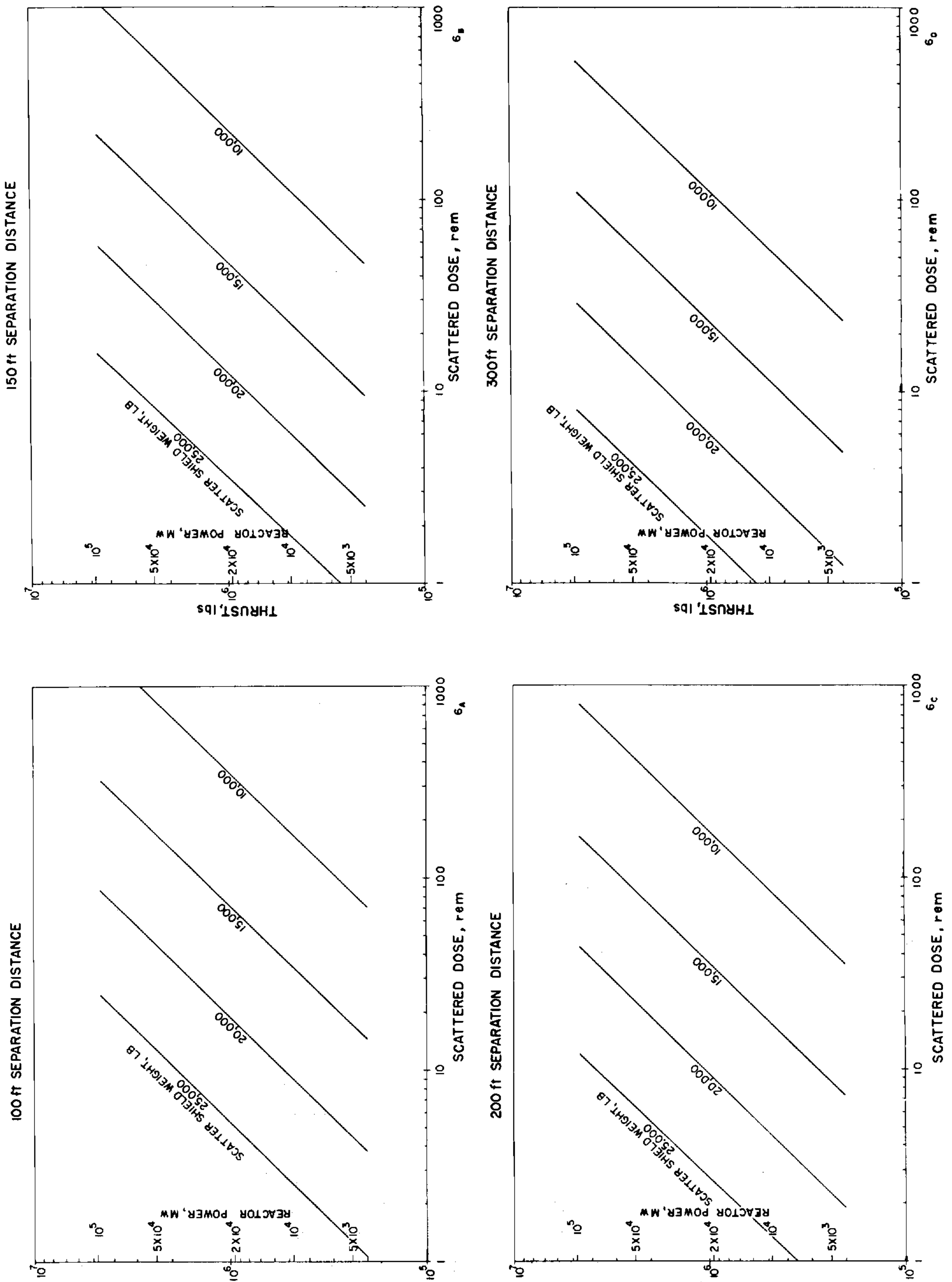

Fig. 6. Integrated scattered dose in crew compartment as a function of thrust and shield weight (Hg) for various distances (equivalent sea level time=30 sec.).

the CO_2 system (that is, CaOH about a 50 pound system), the daily requirement per average man is reduced to 4.7 pounds, or 14,490 pounds for the crew of three.

The ultimate in economy would be a balanced closed system—a miniature replica of the earth itself. Theoretically, a biologic organism like the unicellar algae could maintain the sealed cabin in a balanced state, by absorbing CO_2, giving off oxygen, and being used by man as food. An aesthetic problem may arise in an algal system, since human excreta would be fed to the little organisms, which they would metabolize, and allegedly the algae would be fit for human consumption and nourishment. Although this vital research has been encouraged, inasmuch as we require an understanding of the fundamental mechanisms involved, progress has not been so rapid as to insure the development of a light weight reliable system within the next several years that would maintain the physical and mental efficiency of a crew for 1,000 days on nothing but a harvested algal diet, regardless of how balanced the diet may be chemically. The value of an algal or equivalent biological system will come with the setting up of lunar and planetary bases in addition to long duration space flights.

Because nuclear space ships will have large payload capabilities, it would be wise to utilize the necessary O_2, food, water, and CO_2 absorber, as a crew shield. As mentioned above, depending on the system used, this weight could be 14,490 to 36,600 pounds. Although these low atomic number materials are not as effective as mercury, lead or uranium shields of equal weight, they could be used to reduce the actual dead weight radiation shield, since they are part of the useful payload. This subject will be covered in detail in a subsequent report.

RESIDUAL RADIATION

Nuclear power has an unwanted by-product in quantities of radioactive fission product which could constitute a radiation hazard. However, on the basis of analyses conducted to date the residual radiation in our nuclear space ship is not considered to add significantly to the overall dose if the direct radiation shield is left intact.

A nuclear power plant has another unusual aspect in that at shut-down, the power level in the reactor does not drop immediately to zero. The reactor contains a sufficient accumulation of short-lived fission products that it will evolve appreciable quantities of heat for some time after shut-down. In our case, the hydrogen after-coolant used in dissipating this heat will continue to give the nuclear space ship small amounts of thrust. After reactor shut-down the crew will experience a decrease of G in a short period of time, but a true state of weightlessness may not exist for some time. This unusual condition resulting from the use of an after-coolant in nuclear propulsion, may have a definite advantage in the spatial and cabin orientation of the crew immediately following the nuclear part(s) of the flight. It might have some physiologic and psychologic advantages, since the crew would have a little time to adapt themselves to the effects of the decreasing gravity.

EARTH-MARS-EARTH MISSIONS

We will use two flight missions A and B to illustrate the radiation doses and shield weights involved in a round trip Martian voyage. Until some exploratory landings on Mars have been made, we cannot assume the utilization of any naturally occurring elements for fuel, shielding, or the basic requirements for man's survival. Therefore we will consider our nuclear space ships to be fully loaded on earth for the complete round trip.

Mission A involves a nuclear powered launch from the surface of the earth, through the earth's atmosphere; the orbiting of Mars; and a nuclear powered return to earth with a non-nuclear landing.

Mission B is essentially the same as Mission A, except it involves a non-nuclear landing on Mars and a nuclear take-off through the Martian atmosphere. For the purposes of this study, we are considering the Martian atmosphere as equivalent to that of the earth, although in reality, the scatter doses will probably be less.

To illustrate the variation in dose and shield weight, we have chosen a reactor power output of 2.1×10^4 MW, or 10^6 pounds thrust at an assumed specific impulse of 865 seconds for the hydrogen propellant. Figure 7 can be used to obtain numerous examples at this power output by varying crew-reactor separation distances and shield weights to obtain integrated scatter and direct radiation doses at the crew compartment. In the following examples, we assume the direct shield comes from the scatter shield and therefore, the total take-off shield weight will be the scatter shield plus the optimized uranium reactor shield and the hydrogen boil-off weight.

Mission A Example 1.—At a 100-foot crew-reactor separation distance, (Fig. 7a) with a 25,000 pound mercury scatter shield, an integrated dose of 5.2 rem would be received on exit through the earth's atmosphere. As soon as the vehicle is out of the earth's atmosphere, with reactor power still on, 15,000 pounds of this shield could be dropped overboard. The remaining 10,000 pounds of mercury would serve as the direct shield, which is required for the nuclear power phase on the return trip from the Mars orbit. On the initial nuclear take-off from the earth, the hydrogen fuel keeps the direct dose from reactor operation and residual radiation at an insignificant amount. On the return to earth with the use of nuclear power and the consumption of the hydrogen fuel, an integrated dose of 1.3 rem would be received with the 10,000 direct shield in place. The crew would receive a total of about 6.5 rem from nuclear operation on this mission.

Example 2.—At the 100-foot crew-reactor separation distance (Figure 7a) the initial take-off scatter shield weight could be reduced by 10,000 pounds, that is, to 15,000 pounds take-off weight, if an acute dose of 71 rem scatter radiation is permitted on exit through the earth's atmosphere. We can drop 5,000 pounds and save 10,000 pounds of mercury for the direct shield needed for the nuclear part of the return flight, then the crew would be exposed to an additional 1.3 rem.

Example 3.—At a 300-foot crew-reactor separation distance (Fig. 7d) and a take-off scatter shield weight of 25,000 pounds, the crew would receive about 1.8 rem on exit through the earth's atmosphere; at this time all but 10,000 pounds of the shield could be dropped overboard. On the nuclear phase of the return from Mars orbit, the crew would receive an additional 0.15 rem, or a total of less than 2 rem from the reactor for the whole trip.

Example 4.—Under the same separation distance of 300 feet as in Example 3, the initial take-off scatter shield weight could be reduced from 25,000 pounds to 10,000

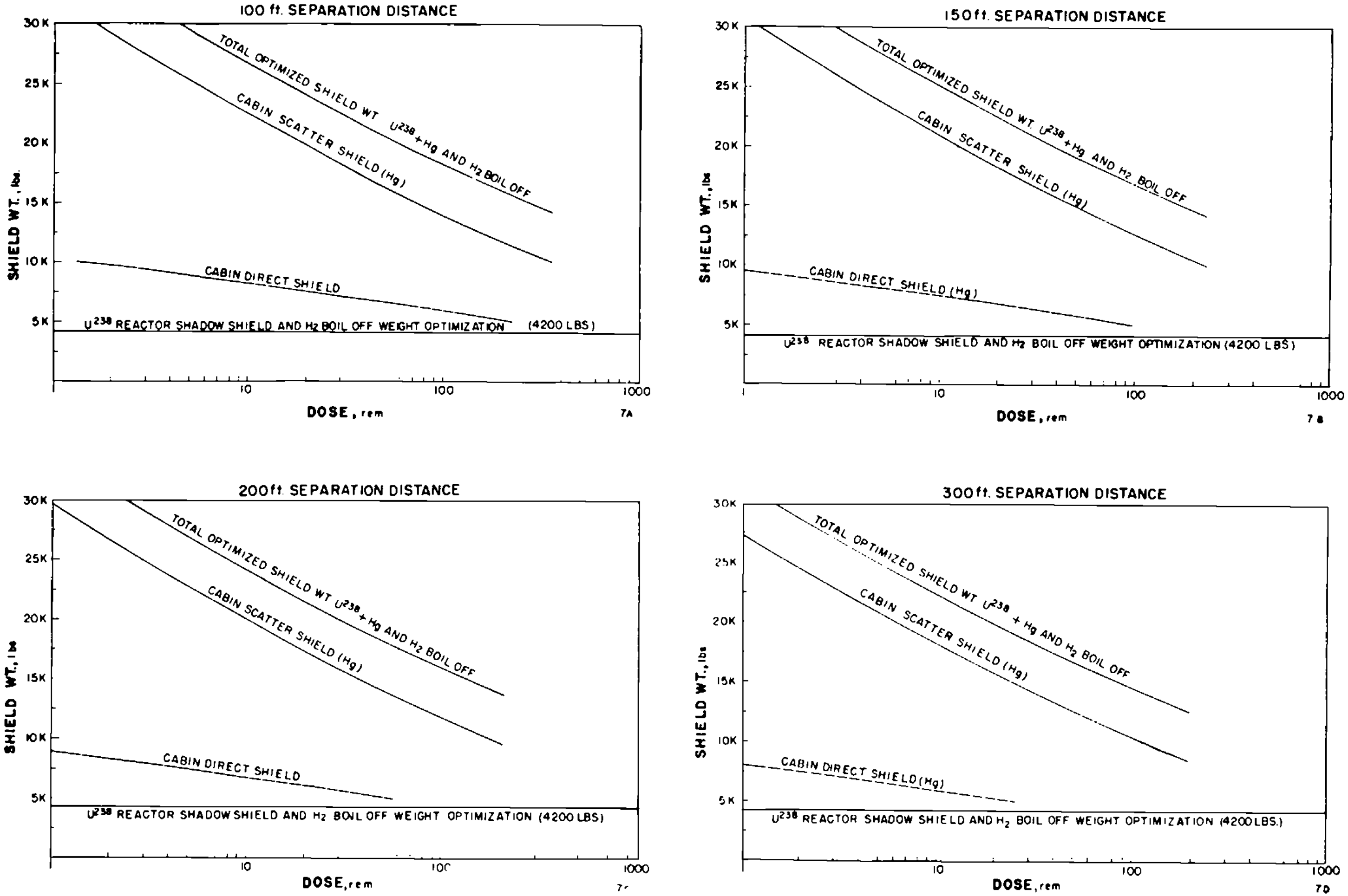

Fig. 7. Integrated scatter and direct doses in crew compartment as a function of shield weights for various separation distances and a reactor power of 21,000 MW, or 10^6 pounds thrust at Isp of 865 sec. for H_2. NOTE: shifting the mercury scatter shield to become the direct shield optimizes total shield weight and decreases direct dose.

TABLE II. SUMMARY OF EXAMPLES OF MISSIONS FROM EARTH TO MARS AND BACK

Mission	Reactor-Crew Distance (Feet)	Reactor Operation In Atmosphere		Earth to Mars				Mars to Earth				Total Mission Dose (REM)
				Scatter		Direct		Scatter		Direct		
		Earth	Mars	Dose (REM)	Shield Lb. Hg	Dose (REM)	Shield H_2	Dose (REM)	Shield Lb. Hg	Dose (REM)	Shield Lb. Hg	
Earth—Mars Orbit—Earth	100	Yes	No	5.2	25K	Nil	—	0	0	1.3	10K	6.5
	100	Yes	No	71	15K	Nil	—	0	0	1.3	10K	72
	300	Yes	No	1.8	25K	Nil	—	0	0	0.15	10K	2.0
	300	Yes	No	110	10K	Nil	—	0	0	0.15	10K	110
Earth—Mars Landing—Earth	100	Yes	Yes	5.2	25K	Nil	—	5.2	25K	1.3	10K	12
	100	Yes	Yes	5.2	25K	Nil	—	71	15K	Nil	15K	76
	300	Yes	Yes	1.8	25K	Nil	—	24	15K	Nil	15K	26
	300	Yes	Yes	6.2	20K	Nil	—	110	10K	0.15	10K	117

Reactor power—21,000 MW; Specific impulse—865 seconds; Propellant—H_2.

pounds, if the crew were permitted to receive a one time acute dose of about 110 rem on exit through the earth's atmosphere. The 10,000 pounds of mercury as the direct shield would reduce the direct exposure to about 0.15 rem.

Mission B Examples.—The nuclear take-offs through earth and Martian atmospheres increases the scatter radiation dose received by the crew, as the following examples indicate:

Example 5.—At a 100-foot crew-reactor separation distance (Fig. 7a), and a 25,000 pound scatter shield, the crew would be exposed to 5.2 rem on exit through the earth's atmosphere. The 25,000 pounds of scatter shield would remain in place for the trip to Mars, so that on nuclear exit through the Martian atmosphere, the crew would receive an additional 5.2 rem (probably less). If the 25,000 pounds of scatter shield were used for the direct shield, an insignificant amount of direct radiation would be received by the crew. If, after exit through the Martian atmosphere, there was an advantage in dropping 15,000 pounds of shielding, the remaining 10,000 pounds would permit a direct exposure of only 1.3 rem. This flight then, could be accomplished for a total dose of less than 12 rem.

Example 6.—At a separation distance of 100 feet, and a scatter shield of 25,000 pounds, the crew would receive a scatter dose of 5.2 rem on exit through the earth's atmosphere. As soon as the vehicle was out of the earth's atmosphere, 10,000 pounds of the scatter shield could be dropped. The nuclear take-off through the Martian atmosphere would be accomplished with 15,000 pounds of scatter shield. The crew would be expected to receive a scatter dose of about 71 rem (actually less), and with the 15,000 pounds becoming the direct shield, the direct radiation would be insignificant. The total dose for this trip would be about 75 rem.

Example 7.—At a separation distance of 300 feet, and a 25,000 pound scatter shield, the crew would receive a scatter dose of 1.8 rem on passing through the earth's atmosphere. If we dropped 10,000 pounds, and kept 15,000 pounds of shielding material, then on the nuclear take-off through the Martian atmosphere, the crew would receive 24 rem. Since the direct dose would be very small, the crew would receive about 26 rem from the reactor for the whole trip.

Example 8.—At the 300-foot crew-reactor separation distance and an initial take-off scatter shield of 20,000 pounds, the crew would receive an earth atmosphere scatter dose of 6.2 rem. If 10,000 pounds of this shield were dropped after passing through the earth's atmosphere, the remaining 10,000 pounds scatter shield would permit a Martian atmospheric scatter dose of about 110 rem. The direct dose would be only 0.15 rem, hence, the total dose received by the crew for this trip would be about 117 rem.

For convenience the examples presented above are summarized in Table II.

The data presented in this study permit the calculation of scores of varied missions, by trading crew dose received for a saving in shield weight and the reverse lowering of the dose by increasing the shield weight. Analyses to date indicate that the scatter radiation poses the major problem in nuclear flight and a range of shield weights and doses exist which should make manned nuclear powered flights practical.

It should be noted that in the practical situation mercury would not be dumped freely into the earth's atmosphere. In missions where an advantage could be gained from dropping a certain amount of the scatter shield after exit through the atmosphere, mercury and the containers or an equivalent amount of lead could be jettisoned.

SUMMARY AND CONCLUSIONS

Although many assumptions were made in arriving at the numerical values presented in this study, the analytical form and the general order of magnitude of the results should not be altered thereby. Certainly the gradual accretion of knowledge in the field will permit future refinements of these calculations. This study reveals the following salient points:

1. Manned nuclear powered flight is feasible.

2. The nuclear reactor is considered the prime radiation source. Since polar exits probably exist, it should be possible to plot trajectories and velocity profiles for minimum time in Van Allen's radiation belt(s). If shields are maintained in place while exiting through the radiation belt(s), the dose received from the belt(s) will be small relative to the scattered and direct radiation doses. Interplanetary cosmic radiations and possible radiation bands around the moon and nearby planets still require study.

3. The calculations in this study can be utilized by design teams to arrive at an optimal nuclear space ship design which will not unduly compromise the crew or the vehicle.

4. The problem in calculating human risks involves obtaining the direct and scatter (acute rather than chronic) radiation doses for given mission profiles at various crew-reactor separation distances for different reactor shields and powers. The problem of RBE for incident neutrons has been simplified by the use of the H_2-B^{10} combination to convert the neutrons to gammas.

5. The largest dose will come from the atmospheric scatter radiation if the

reactor is used during atmospheric exit and propellant and other material are used as direct radiation shields. Operation of the reactor in planetary atmospheres (earth, Mars, and Venus) will require scatter shielding for the crew. The times of applicability of the scatter and direct shields do not coincide, so that a possible dual purpose shield like mercury (which has attenuating properties almost equal to lead) is recommended and used in the calculations. Since the direct shield comes from the scatter shield, the total take-off weight of the shield is that of the scatter shield. If the ship does not take off on nuclear power through an atmosphere, the shield weight reverts to the weight of the direct shield.

6. Residual radiation after reactor shutdown is not expected to add significantly to the total dose, if the direct shield is left intact.

7. Designers will have latitude in chosing a particular material or combinations of materials for the direct and scatter shields. U^{238} would save about 30 percent over mercury and 20 percent over lead. The thousands of pounds of payload, like oxygen, food, water, and equipment, could be used to reduce the total shield weight. The attenuating properties of these low atomic number materials would not be as effective as the mercury. A subsequent study will cover this point in detail.

8. Several examples are given for a 21,000 MW reactor power which indicate Martian orbital and landing missions may be accomplished for shield weight combinations between 10,000 and 25,000 pounds for total integrated acute dose between 2 and 117 rem.

9. Efforts have been initiated to cover shielding for reactors of lower powers such as may be used in ionic propulsion systems and auxiliary power plants and will be covered in a subsequent report.

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Medical Departments For Airlines — A Necessity

A few of the 80 airlines of the world have good medical departments, but less than one-fifth of the scheduled airlines have formal medical organizations. The report that each month, for a five-month period in 1957, a pilot on active duty died while in the cockpit will emphasize the importance of continuing medical supervision, as well as of the value of having a co-pilot. One of the pressing problems in this area relates to the changing age distribution of airline pilots. With many of these men now entering age groups beyond 45 and 50, many problems of health and safety may be anticipated.—Ross A. McFarland: Health and Safety in Transportation, *Public Health Reports,* August, 1958.