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PRELIMINARY REVIEW OF POTENTIAL BIOLOGICAL HAZARDS FROM DEPOSITION OF NUCLEAR ROCKET DEBRIS IN THE EARTH BIOSPHERE.

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PRELIMINARY REVIEW OF POTENTIAL BIOLOGICAL HAZARDS FROM DEPOSITION OF NUCLEAR ROCKET DEBRIS IN THE EARTH BIOSPHERE

ABSTRACT

Assuming preorbital startup of a nuclear rocket and failure to make an acceptable orbit, a likely operational response is to fragment the reactor and other components by means of an ordnance destruct system. The potential biological hazards from deposition of radioactive debris depend upon many factors; chiefly, reactor operating history, particle size, atmospheric residence time, and deposition density on the earth. Reactor debris particles ranging in size from one centimeter diameter down to respirable sizes have been considered with respect to the biological effects resulting from inhalation, ingestion, external radiation from a ground deposit and beta irradiation of the skin in contact with such particles. Although the data are not adequate for precise assessment of potential hazard, a preliminary review of available information has shown that the most significant consideration is the intense beta radiation at the surface of small, highly radioactive, insoluble particles --- of the order of 10^7 rad/hour at the surface of a one centimeter diameter particle at the estimated time of deposition.

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1.0 INTRODUCTION

1.1 Statement of Problem

The nuclear reactor is one of the major competing sources of power in the development of United States space capabilities. Indeed, there is reason to believe that, by the late 1960's, nuclear rocket propulsion will provide a significant step forward in the exploration and exploitation of near and intermediate space. It is likely that in early testing, the vehicle will be lifted off by chemical boosters and subsequently switched to nuclear propulsion for the assigned mission.

After a power run, the reactor core will contain a significant inventory of fission products; thus presenting a potential radiation hazard whether the nuclear stage remains in orbit for some time or is brought down in a controlled recovery operation. One of the possible ways to reduce the intensity of the radiation source is to fragment and disperse the reactor core by means of an ordnance destruct system. Present thinking also favors use of ordnance destruct as a basic response to an operational abort. If this route is to be followed, it is essential that core design, operational techniques and destruct system efficiency all be considered with respect to the potential hazards associated with deposition of nuclear rocket debris in the biosphere. Hence, the questions: what are the radiological health problems to be expected from such debris; and, is it possible to establish an acceptable maximum particle size for destruct system specifications.

1.2 Scope

For the purpose of this preliminary analysis, many important physical parameters were specified in a grossly simplified way.[1]

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Detailed examination of other pertinent physical data has shown that, in its present form, the available information is not adequate to permit a satisfactory evaluation of the biological effects of reactor particles surviving atmospheric reentry. However, a limiting case may be defined within the framework of the source term, transport and deposition data given below.

Reactor debris particles ranging in size from one centimeter diameter down to respirable sizes have been considered with respect to the biological effects resulting from inhalation, ingestion, external radiation from a ground deposit and beta irradiation of skin in contact with such particles.

2.0 SOURCE TERM

2.1 Operating Conditions

Power level.....10^3 Mw

Operating time.....300 seconds

Total Volume of Core.....6×10^5 cc

Fuel Material.....UC_2 - graphite

Specific Gravity.....2.0 gm/cc

2.2 Operating Sequence

2.2.1 Orbital or sub-orbital nuclear startup.

2.2.2 Operate for 5 minutes (10^{22} fissions).

2.2.3 Reactor shutdown.

2.2.4 "Short" boil-off period.

2.2.5 Destruct (some fragments as large as 1 cm diameter).

2.2.6 Assume 30 minutes residence time (fall time) for the debris in the atmosphere.

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2.3 Fission Product Inventory

A viable computer program has not been available for calculating fission product inventories, correcting isotopic concentrations for boil-off, ablation losses or other such phenomena, and calculating effective energies for the debris reaching the earth. Many reports include inventory data but list only those isotopes that have been assumed to be the most "significant" ones based upon consideration of internal dose. The only data available giving a detailed breakdown of more than a few selected isotopes as a function of time after reactor shutdown were obtained from WANL.[2] However, these data are based upon operating conditions grossly different from the ones specified for this preliminary study. Furthermore, the WANL calculations do not take into account after-heat boil-off (see 2.2.4), they are given for only a few specified times, and they do not extend for a long enough period post shutdown to be useful for evaluating potential biological hazards.

The data which have been used in making the radiation hazard estimates for this preliminary study are listed in Table 1. They were derived from early Los Alamos[3] estimates of gross fission product inventory. Admittedly, these are only order of magnitude estimates of fission product inventory, and the radiation hazard evaluations presented in this report can be no more reliable than the basic data.

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Table 1

Fission Product Inventory (Curies at Shutdown)

Isotope	Martin (MND-2517)	Westinghouse (A.B. Rothman and G. L. Grandy)	Los Alamos (LA-2409)
Sr^{89}	-	2.177×10^{3}	6.61×10^{1}
Sr^{90}	4.8	5.655	4.2
Y^{90}	-	1.858×10^{-3}	1.23×10^{-3}
Nb^{97}	3.05×10^{3}	6.348×10^{4}	-
Ru^{105}	8.61×10^{3}	8.31×10^{6}	-
Rh^{105m}	5.74×10^{3}	8.007×10^{5}	-
I^{131}	5.92×10^{1}	2.138×10^{1}	4.98×10^{1}
Xe^{133}	-	1.242×10^{1}	2.61×10^{-1}
I^{135}	3.26×10^{5}	4.992×10^{5}	2.98×10^{5}
Xe^{135}	-	2.387×10^{3}	1.72×10^{3}
I^{137}	4.28×10^{7}	5.72×10^{7}	-
Cs^{137}	4.26	3.756	3.72
Ba^{140}	7.71×10^{3}	1.138×10^{4}	7.0×10^{3}
Ce^{143}	7.65×10^{3}	9.046×10^{3}	-
Ce^{144}	4.75×10^{2}	4.917×10^{2}	-
Nd^{149}	3.49×10^{5}	3.067×10^{5}	-
	4.35×10^{7}	6.721×10^{7} 6.21×10^{8} (161 other isotopes) 6.88×10^{8} (total for 177 isotopes)	3.2194×10^{5}
All isotopes $\approx 1.5 \times 10^{9}$			1.35×10^{9}
		at 10 min.	1.53×10^{8}
		at 30 min.	6.1×10^{7}
		at 2 days	4.06×10^{5}
		at 100 days	5.1×10^{3}

[redacted]

2.4 Depletion of Primary Source

On the basis of KIWI tests, it is estimated that fission product loss during reactor operation amounts to about five per cent of the gross inventory. In the absence of information concerning the relative loss rates of each element this figure has not been used; instead, the gross fission product inventory has been used as give in the Los Alamos report[3] (2.3, Table 1).

Sattizhan and Bryant[4] calculated the reduction in fission product inventory attributable to reactor after-heat boil-off. Table 2 gives the estimated per cent remaining of the amount that would have been retained in the core without boil-off at 10 minutes, 2 days, and 100 days.

Table 2

Per Cent of Total Activity

Unheated			Heated		
Time after irradiation			Time after irradiation		
10 min.	2 days	100 days	10 min.	2 days	100 days
96	97	100	22	36	24

The retention factors (Table 2) were applied to inventory estimates derived from the Los Alamos data (Table 1) and plotted logarithmically to permit estimates of fission product inventory after boil-off at times other than the above.

3.0 ATMOSPHERIC TRANSPORT

3.1 Ablation Losses

Further reduction in the quantity of radioactivity per particle of the rocket reactor debris can be expected as a result of aerothermodynamic heating of the reactor fragments during their reentry into

the atmosphere. For order of magnitude estimates of this loss, it may be assumed that one centimeter diameter particles are not significantly affected (possibly < 20 % loss), 0.1 cm diameter particles may lose 80 per cent or more of their original mass and 0.01 cm diameter particles would be completely consumed, not contributing to early time fallout.

3.2 Atmospheric Residence Times

Significant fractions of the gross fission product inventory may be eliminated from the core material during operation, depletion by means of after-heat boil-off, reentry ablation and additional boil-off by diffusion during descent. In addition, the amount of radioactivity remaining in a piece of the reactor core also will decrease rapidly as a function of time for radioactive decay. The effective decay time can be taken to be the time required for a fragment to fall to earth.

Assuming smooth spherical particles of density 2.0 grams/cc, it may be estimated[5] that those of one centimeter diameter will reach the ground in about 30 minutes, 0.1 cm diameter pieces require two hours to fall, and 0.01 cm diameter particles will not deposit in less than about 100 days. Odd shaped, rough surfaced fragments, such as may be expected from an explosive destruct, generally require more time to fall than do smooth spherical particles because of increased aerodynamic drag.

The more conservative figure of 30 minutes atmospheric residence time was specified for the purpose of this preliminary study.

4.0 DEPOSITION IN BIOSPHERE

4.1 Fission Product Inventory as Deposited

[redacted]

4.1.1 Curies per Particle

Table 3

Gross Fission Product Inventory
(Curies per 1 cm diameter particle*)

Time since shutdown	30 min	2 days	100 days
No boil-off or ablation	53.1	0.354	0.00445
With boil-off (no ablation)	13.9	0.127	0.00106
With boil-off and ablation**	11.1	0.102	0.00085
(0.1 cm)	(2.8×10^{-3})	(25×10^{-6})	(21×10^{-9})

*Except for case of ablation, curies decrease by a factor of 10^3 for every factor of 10 reduction in fragment diameter.

**Assume 20 per cent loss for 1 cm and 80 per cent loss for 0.1 cm diameter particles.

4.1.2 β - γ Energies

In contrast to most power reactors, the nuclear rocket propulsion reactor is characterized by high power levels and short operating times. Its relative inventory of radioactive elements should be similar to that resulting from firing a fission weapon. Consequently, the vast amount of published data on weapons tests fallout may be used for making order of magnitude estimates of dose rate from rocket reactor debris.

Sondhaus[6] and Dunning[7] have published calculated average maximum energies for fission product β and γ radiation as a function of time after fission. As a rule of thumb, the effective β-energy is taken to be one-third of the maximum β-energy. Estimated β and γ energies are listed for 30 minutes, 2 days and 100 days in Table 4 (Graph 1, Dunning[7]).

[redacted]

[redacted]

Table 4

Estimated β and γ Energies[7]
After Shutdown

Time After Shutdown	30 min	2 days	100 days
γ-energy (Mev)	1.3	0.6	0.6
E_β Max β energy (Mev)	3.3	1.20	1.03
$\bar{E}_\beta$ Effective β energy (Mev)	1.1	0.40	0.34

4.2 Surface Distribution

Relative hazard is related in a non-trivial way to the probability of an individual contacting one or more reactor particles. Thus, for example, if a small particle is capable of producing essentially the same end effect as a large one (i.e., if the main difference is the required exposure time), then the smaller may be the less desirable because the probability of human contact will be greater.

Based upon apparently conservative assumptions, Decker[8] concludes that the upper limit of surface deposition density amounts to a single particle one centimeter diameter per square kilometer (or one 0.1 cm diameter particle per 1,000 square meters; or one 0.01 cm diameter particle per square meter).

4.3 Weathering - Leaching

Natural decomposition of nuclear rocket debris is another potential effect that has a general bearing on the evaluation of biological hazards. The relationship of weathering to radiation safety depends upon the particular hazard in question; thus, as leaching continues, the β-γ radiation field may decrease because portions of the source material will penetrate into the ground surface where the added

[redacted]

shielding will absorb some of the emitted energy. On the other hand, leaching of soluble components of the fission products is a step toward the assimilation of these radionuclides into man's food chains and water supplies.

Nothing is known about the natural weathering of rocket reactor debris. Likewise, there is no information available concerning leaching of reactor fragments in fresh water. Furthermore, it is unlikely that UC_2 pellets weather in the same way that has been observed for weapons test fallout[9, 10]; the glassy pellets related to near-in fallout from a ground shot, release less than one per cent of their total gross β-activity; Sr^{90} is leached in varying degrees ranging from trace amounts (glassy particles) to 86 per cent (electrodialysis on samples from a balloon shot).

Strontium$^{89 + 90}$ are of considerable importance with regard to long-term contamination of the food chain. However, they contribute only a very small amount to the β-γ dose rate. Hence, if nothing is leached out except strontium, the result is an increase in potential internal exposures, but with no appreciable reduction in the β-γ radiation dose rate.

5.0 RADIATION HAZARD TO MAN

5.1 Inhalation

5.1.1 Lung retention as a function of particle size

The probability of a given particle passing through the nose and upper respiratory tract and subsequently being deposited in the lung, is strongly affected by the "aerodynamic equivalent" size of the particle[11, 12, 13]. This equivalent size depends upon many factors;

the shape of a particle, its linear dimensions and its effective density are major controlling parameters. Other important factors include the number concentration of particles per unit volume, and physico-chemical characteristics such as electrostatic charge and hygroscopicity. For the purpose of this study all particles are assumed to be spherical and of specific gravity 2.0 grams per cubic centimeter. Other particle characteristics are assumed to be negligible with respect to inhalation.

It appears doubtful that reactor debris particles larger than about 40 microns in diameter can penetrate through the nasal passages.[14,15,16] Particles of about 10 microns have a small but finite probability of reaching and being deposited in the upper respiratory tract. Intermediate sized particles (3 - 10 μ diameter) that reach the lung are deposited with high efficiency upon the ciliated mucous epithelium lining the air passageways. Optimum size for retention in the respiratory acini is on the order of one μ (0.0001 cm) diameter.

5.1.2 Solubility in Lung Fluids

The question of solubility of particulates in the lung is a very difficult one to approach by any means. Since the chemical nature of the substance lining the respiratory alveoli is not well understood,[17] the choice of a suitable simulant for lung fluids is open to considerable doubt. Animal studies have been reported in which water soluble thorium sulfate behaves as if it were "insoluble" in the lung[18] and water insoluble silver iodide appears to be highly "soluble" in the lung.[19] Thus, it seems that water is definitely ruled out as an in vitro solvent. Until much more is known about the solvent properties

[redacted]

of lung fluids, the only available approach is to choose the most likely simulant and to obtain as much correlated human and animal data as possible.

The author[20] has reported on six cases of human exposure to uranium compounds by inhalation. In these cases (2 each exposed to U_3O_8, $UO_2(NO_3)_2 \cdot 6H_2O$, and UO_2F_2), the ratio of the initial lung burden to the initial urinary uranium excretion rate is roughly in inverse proportion to the rates of solubility of the compounds in body fluids. This observation is not surprising. "Of all the various pathways by which an inhaled aerosol may reach the bloodstream and subsequently be detected in the urine, the one that might be expected to control the urinary excretion rate immediately following an acute inhalation is removal by solution in lung fluids."[20]

On April 26, 1960 at ORNL there was an accidental release of graphite dust (0.05 to 8 μ diameter) containing certain fission products in and on the graphite particles. Several persons inhaled the dust and subsequently were counted in a whole body counter to determine the amounts of radionuclides inhaled. Urine samples indicated that only strontium (Sr^{89+90}) was being excreted. <u>In vivo</u> gamma-ray spectrometry gave adequate sensitivity to measure all of the significant radioisotopes except for those of strontium, but, if the strontium could be assumed to be leaving the graphite particle at the same rate as other nuclides, an estimate of the strontium body burden could be obtained.

> "A solubility test was conducted to determine the rate of dissolution of the various materials in blood serum which was used to approximate the composition of lung fluids. A dust sample was immersed in blood serum contained in a semipermeable membrane bag which was suspended in a larger quantity of serum. The serum

[redacted]

was kept at body temperature during the test and at intervals a mixture of 5% CO_2 and air was bubbled through the serum to facilitate mixing. Small aliquots of serum were taken from the outer container at intervals out to 18 hours. The strontium was by far the most readily soluble of the radioactive materials. Strontium accounted for only 13.5% of the beta-activity in the original sample, whereas, within 18 hours strontium accounts for over 94% of the beta-activity in solution. After the first hour, the rate of movement of strontium into the serum phase was essentially constant at 1.48% per hour. It is interesting to note that this rate corresponds to a half-life of 1.95 days. This may be compared with the 2-day half-life for transport of strontium from lung to blood which was estimated from urine data." [21]

The above results generally agree with the information on weathering of weapons test fallout (section 4.3). Except for strontium$^{89 + 90}$, which apparently is very soluble in the conditions of interest, only insignificant quantities of the other fission products are leached out of the graphite matrix. However, nuclear rocket reactor fragments may behave in an entirely different manner; consequently, solubility tests should be made. Pending solubility test data, the following tentative assumptions will be made regarding fission products in reactor core particles: (1) assume strontium to be completely and rapidly dissolved, and (2) assume that the β-γ radioactivity is not depleted by leaching.

5.1.3 Lymph Nodes

Considerable evidence has been accumulated to show that the hilar lymph nodes and other lymphoid tissue accumulate appreciable quantities of poorly soluble particulate matter initially deposited in the lung.[19, 20, 22] While the localized concentration in the lymphoid tissue can reach very high values compared to the average concentration in the lung, still the absolute amount of material translocated to the lymphatic system is generally quite small with respect to the quantities

deposited in the lung. Furthermore, it is likely that particles that are stored in peribronchiolar lymphoid tissue or are being moved slowly along lymphatic channels, will add to the radiation dose received by the bronchiolar epithelium. In addition, because of the relatively rapid decay of the fission product mixture at early times, the considerable time delay in translocation of particles from lung to the lymph nodes, effectively reduces the amount of energy delivered to lymphatic tissue. Thus, with respect to fragments from the core of a nuclear rocket reactor, despite the possibility that from 1 to 10 per cent of the initial lung deposit may reach the lymphatic system, nevertheless, the lung parenchyma and the bronchiolar tissues are likely to receive the highest radiation dose.

5.1.4 Internal Radiation Dose following Inhalation

(a) "Soluble" Fission Products

By comparison with other solubility data (sections 4.3 and 5.1.2), it is assumed tentatively that all strontium, but only strontium, is leached rapidly out of the reactor core fragments by lung fluids.

The largest size particle likely to reach the alveolar spaces of the lung is probably less than 10 microns diameter. During the period 30 minutes to 100 days post shutdown, single 10 micron particles would contain, at most, 1.7 pc Sr^{89} and 0.001 pc Sr^{90} without considering loss due to boil-off or ablation. Assuming the optimum size particle for lung retention to be one micron diameter, under the worst condition (no boil-off; no ablation; particles deposited in lung two days after shutdown), an integrated exposure of approximately

10^{13} particles-seconds per cubic meter (1 μ diameter) is required to produce one rem to the bone based on Sr^{89} (0.312 rem/μc inhaled[23]).

Although better information concerning boil-off, ablation loss, meteorological dispersion and solubility may alter the picture, for the present gross review, it appears that internal dose related to inhaled soluble components is not a controlling factor.

(b) "Insoluble" Fission Products

By observation of Table 7 (section 5.4) it is seen that a 10 micron diameter particle can deliver approximately 900 rad/hour to tissue in contact with the particle at 2 days after shutdown. Although the atmospheric residence time for 100 μ diameter particles is on the order of or greater than 100 days, if some larger particle should be broken into 10 μ particles at a low altitude it might be possible to deposit a 10 μ or a 20 μ diameter particle in the upper respiratory tract.

The effective half-life for elimination of 10 to 20 μ particulates from the upper respiratory tract probably ranges from about 1 to 3 days (0.7 days for graphite particles[21]). This range is equivalent to an average retention time (half-life divided by 0.693) of from 1 to 4 days. If a 20 μ particle (no boil-off) were inhaled and retained on day 2, the average β-dose rate to the bronchiolar epithelium near the particle would be greater than 3,500 rad/hour (average retention time 4 days). For a 10 μ particle (with boil-off) the average β-dose rate would be a factor of about 20 less (average retention time 1 day).

On the basis of available data, it seems very unlikely that respirable size particles could reach ground level in less than a year (reduces dose rate by a factor of about 1000). However, the potential hazard does not appear to be negligible, even for atmospheric residence times greater than a year. More information is needed with respect to dose rate as a function of time and particle size, and more data is needed concerning atmospheric residence times and possible particle concentrations at ground level.

There appears to be no obviously severe hazard associated with the inhalation of nuclear rocket reactor debris, providing that the likelihood of inhaling a single 10 or 20 μ particle is small for times less than about a year, and that inhalation of several such particles by the same person is unlikely even beyond a year. If inhalation of such particles does constitute a significant hazard, the most likely problem will arise from irradiation of the lung parenchymal and bronchiolar tissue and will probably not be related to lymph node deposition or the translocation of "soluble" components to bone, etc.

5.2 Ingestion

As in all of the considerations of this report, the probability of ingesting more than one particle is unknown. If one assumes that the largest single particle likely to be ingested is one millimeter diameter (along with food), it may be estimated[7] that such a particle (no boil-off) could produce about 30 rad to the adult lower larger intestine if ingested within one to four hours after reactor shutdown. If ingestion occurs at about two days, the associated dose would be about 10 rad per one millimeter particle (if ingested at 100 days

would produce about 0.2 rad). If such size particles deposit on fresh growing foods, to be effective, action must be taken within a few days to restrict consumption of the raw (i.e., unprocessed and non-stored) foods.

Until better data is available on fresh-water leaching of fission products from reactor debris, no assessment can be made of this mode of ingestion. However, it does not seem likely that ingestion via fresh-water supplies will present a significant problem.

5.3 External Radiation from a Ground Deposit

5.3.1 Uniform Deposit

Assuming a uniform distribution of the fission product activity over a flat plane, and taking the deposition concentration to be as noted in section 4.2, the amount of radioactivity per square meter is given in Table 5. Dose rates at one meter were calculated using a β-dose rate to γ-dose rate ratio of 3.45:1.[24]

Table 5

Estimated Dose Rate (mrad.hour) at 1 meter above Contaminated Plane (Equivalent to one 0.01 cm diameter particle per square meter)

Time since shutdown	30 min	2 days	100 days
Without boil-off	1.4 (mrad/hr)	< 0.01	< 0.0002
With boil-off	0.4	< 0.004	-

Despite the many gross approximations that were used to obtain the estimated maximum dose rates at one meter, the results indicate that radiation from a uniformly deposited area source is not likely to present a significant hazard.

[redacted]

5.3.2 Single Particles

Using the γ-ray energies (E) listed in Table 4, an estimate of the γ-dose rate at one foot, from a point source containing "C" curies of radioactivity (γ curies $\approx$ 1/2 β curies),[24] may be obtained from the approximation formula,

$$D = 6\ CE \text{ rad/hour at 1 foot}$$

The total dose rate ($\beta + \gamma$) from a point source is approximately 150 times the γ-dose rate.[24]

Table 6

Estimated Dose Rate at 1 Foot from a Single Particle (1 cm diameter)* rad/hr

Time since shutdown	30 min	2 days	100 days
No boil-off or ablation	31,000 rad/hr	96	1.2
With boil-off (no ablation)	8,100	35	0.3
With boil-off and ablation	6,400	28	0.2

*For 0.1 cm diameter particles all estimates are a factor of 10^3 lower except for ablation for which the estimates are 1.6, 0.007 and 0.00006 for the times 30 minutes, 2 days and 100 days.

5.4 β-Dose Rate to Skin

Probabilities of human contact with single fragments of the reactor core, as well as specific sites of retention are not well known. However, on the basis of experience with humans contaminated by fallout from weapons tests[25] and from experimentation[26, 27] it may be expected that particles will be retained for appreciable periods of time on exposed skin, and for much longer periods of time where the skin is covered with hair or loosely woven clothing. A rough estimate of β-dose rate expected at the surface of a one centimeter diameter

[redacted]

[redacted]

sphere indicates that dose rates on the order of 10^7 rad/hour may be expected at 30 minutes after shutdown. Owing to the complexities of β-ray absorption and scattering, it is not possible to calculate the dose rate reliably from the source strength, even if the source contains only one isotope.[28] However, approximations of the dose rate at the surface of a spherical β-particle source (Table 7) may be derived by methods described by Hine and Brownell.[28]

The maximum permissible dose rate for occupationally exposed persons is approximately 0.6 rad/week to the skin. The British Medical Research Council has adopted the value 900 rad as an extreme emergency β-ray tolerance. A level of 3,000 to 5,000 rep has been quoted as necessary to influence the field combat effectiveness of fighting men.[29] Skin injury from fallout material in direct contact with the skin can be significant when the dose exceeds approximately 1,000 rad.[30] Although the surface dose necessary to produce recognizable transepidermal injury varies greatly with the energy of the β-ray source (1500 rep for 1.53 Mev β compared to 20,000 for a 0.17 Mev β), the estimated dose to the basal layer of the epidermis to produce such effects is remarkably constant (1400 ± 300 rep).[31] In view of the reported effects produced by β irradiation of human skin, it would seem inadvisable to suggest an acceptable dose greater than that quoted by the British Medical Research Council (900 rad).

6.0 CONCLUSION

In practically no case is the available information adequate for producing a satisfactory assessment of potential biological hazards resulting from the deposition of nuclear rocket debris in the earth

[redacted]

Table 7

Estimated Dose Rate at the Surface of a Spherical β-Particle Source

Diameter of Particle	Time Since Shutdown	Ratio of Dose Rate at Center of Sphere (radius b) to that in an infinite volume[28] $\frac{D(o,b)}{D_\beta}$	Ratio Surface Dose Rate to that at Center[28] $\frac{D(b,b)}{D(o,b)}$	Dose Rate at Surface of Particle (rad/hour) Without boil-off	With boil-off
1.00 cm	At 30 min	0.93	0.42	50,000,000	10,000,000
	2 days	0.9999	0.47	100,000	50,000
	100 days	0.9999	0.48	1,000	400
0.1 cm	At 30 min	0.13	0.50	8,000,000	2,000,000
	2 days	0.54	0.46	70,000	30,000
	100 days	0.64	0.45	900	200
0.01 cm	At 30 min	0.013	0.50	800,000	200,000
	2 days	0.133	0.50	20,000	7,000
	100 days	0.161	0.50	300	60
0.002 cm	At 30 min	0.0026	0.50	200,000	40,000
	2 days	0.0299	0.50	4,000	1,000
	100 days	0.0358	0.50	40	10
0.001 cm	At 30 min	0.0013	0.50	80,000	20,000
	2 days	0.0171	0.50	1,000	900
	100 days	0.0201	0.50	30	7

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biosphere. The very gross estimates of dose rates produced by this review indicate that the problem is a very important one and that certain implications of potential hazard should be examined in much more detail than has been the case to date. While the biological data are not as perfectly clear as one would like, this is one of the very few cases in which the biological information is, in most respects, much better than the physical data pertaining to the problem. Additional research effort is needed in the following areas:

(1) Calculations of fission product inventory as a function of time, losses during operation, boil-off losses, and ablation losses. This should include all fission products and induced activities for all anticipated combinations of power levels, boil-off times, and efficiencies of destruct systems.

(2) Recalculate β-dose rate on the basis of individual isotope inventory data.

(3) Experimental studies of β-dose rates at the surface of simulated reactor fragments containing known amounts of selected individual isotopes.

(4) Experimental studies relating to the leaching of individual fission products from reactor fragments in fresh-water and in a simulant of lung fluids.

(5) Since the probability of a human contacting more than one particle may be of controlling importance, additional work on this point seems in order.

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