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ATOMICS INTERNATIONAL

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NAA-SR-MEMO 1705

This document contains 13 pages

This is copy 2 of 12 series A

Issued to San Francisco

[redacted]

A 10358

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Series A
Issue Date: 8/21/56

FEASIBILITY STUDY OF PLUTO TEST FACILITY

by M. F. Huntsinger and J. A. Brinkman

I. Problem Outline

A. Description of Device

Feasibility calculations for a nuclear ramjet ground test facility have been performed assuming the general configuration given in AI-1563. The following parameter values were initially assumed:

1. Reactor core is right circular cylinder 6' diameter x 4' long with 50% void.
2. Reactor thermal power is 100 Mw.
3. Core thermal neutron flux is 2×10^{14} nv.
4. Air flow through reactor is 250 lbs/sec at Mach 0.6 and 0.223 atmospheres absolute pressure.
5. Air temperature in reactor is 3000° F.

B. Problems Investigated

A ground test facility for this device differs from those for chemically fueled devices principally because of the radiation and toxicity hazards associated with the device and its exhaust. The following hazards were investigated:

1. Toxicity of diffused fission products in exhaust.
2. Toxicity of eroded fuel and fission products in exhaust.
3. $Argon^{41}$ and C^{14} production in air stream inside reactor.
4. Effects of fuel element melting.
5. Radiological safety.

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II. Diffusion of Fission Products from Fuel Elements

A. Assumptions and Approximations

At about 3300° F diffusion of fission products from the carrier - UO_2 sintered compact is assumed to follow the approximate expression:

$$R = 1 - \frac{n}{n_o} = \frac{4}{\pi^{3/2}} \sqrt{\frac{t-t'}{\tau}} \qquad (1)$$

where:

$$\tau = \frac{L^2}{2D}$$

L = thickness of plate-type fuel element

D = effective average diffusion coefficient of fission products. (D will be assumed to be equal to 10^{-7} cm^2/sec for all fission products, yielding a value of 6.5 hrs for τ if L is taken as 0.060").

R = fraction of originally produced material which has diffused out.

n = number of molecules remaining in fuel

n_o = number of molecules produced in fuel at t

t' = time that n_o molecules were produced in fuel

t = time

Equation (1) is valid only for $t-t' \leq \tau/2$ and so is limited. However, for test runs up to 2 or 3 hours duration, its use is valid, since τ is of the order of 6 hrs. Because almost all of the fission products are above their free-state melting points, it is assumed that essentially all will diffuse out. Diffusion through the carrier is assumed to be the rate-limiting process. The carrier is assumed to be at a temperature of 0.75 to 0.80 of its melting point, as will be the case if the carrier is BeO. Diffusion coefficients for various materials in typical

ceramics at temperatures corresponding to about 3/4 of their melting temperatures are generally within a factor of 10 of the value $D = 10^{-7}$ cm^2/sec. It is felt, therefore, that use of this value will give R-values correct to within a factor of 3, since D enters only as $D^{1/2}$ in Eq. (1).

The activity of fission products produced in a reactor in an interval t' to t' + dt' is given by

$$A = PK \left[t-t'\right]^{-1.2} dt' \qquad (2)$$

where A and K are in arbitrary units, and P is the reactor power.

The fraction of the fission products escaping from the fuel surface per second is obtained by differentiating (1):

$$\frac{dR}{dt} = \frac{2}{\pi^{3/2} \gamma^{1/2}} (t-t')^{-1/2} \qquad (3)$$

Combining this with equation (2) yeilds the rate of activity release into the gas stream due to an incremental irradiation time:

$$dR_{A_d} = \frac{2\,PK}{\pi^{2/3} \gamma^{1/2}} \frac{dt'}{(t-t')^{1/2} (t-t')^{1.2}} \qquad (4)$$

R_A = curies/second released to exhaust.

Equation (2), however, is valid only for t-t' > 10 sec. If the activity is measured at a time Δt after escape from the fuel element, the equation may be written as an integration over the reactor running time:

$$R_{a_d} = \frac{2\,PK}{\pi^{2/3} \gamma^{1/2}} \int_0^{t-\Delta t} \frac{(t-t')^{-1.2}}{(t-\Delta t-t')^{1/2}} dt' \qquad (5)$$

If Δt is taken as the time-of-passage of a fission product from the reactor to an exhaust point (at the top of a stack, for example) such that $\Delta t \ll t-t'$, the integral may be evaluated easily. Using appropriate P and K values for a 100 Mw reactor, the activity released by diffusion is then:

$$R_{A_d} = 9 \times 10^5 \left[(\Delta t)^{-0.7} - (t)^{-0.7} \right] \text{ curies/sec} \quad (6)$$

where t and Δt are to be measured in seconds.

Table I lists the activity release rates as a function of running time and Δt.

Table I

Exhaust Activity Release Rates Due to Diffusion

Δt (sec) \ t	1 min curies/sec	10 min curies/sec	1 hour curies/sec	Asymptotic Limit curies/sec
10	1.3×10^5	1.7×10^5	1.8×10^5	1.8×10^5
30	3.2×10^4	7.3×10^4	8.0×10^4	8.3×10^4
60		4.1×10^4	4.8×10^4	5.1×10^4
150		1.7×10^4	2.4×10^4	2.7×10^4
600			0.73×10^4	1.02×10^4

III. Erosion of Fission Products:

Eroded fission product release rates may be approximated by assuming the fission products are freed as they would exist during the running time independent of other effects. Erosion is assumed to take place in a linear manner with time and a value of erosion rate, C, corresponding to 3% fuel element mass loss during 10 hours, was used. Equation (2) may be used to obtain contributions to the eroded

activity during incremental running times:

$$dR_{A_e} = CPK \ (t-t')^{-1.2} dt' \qquad (7)$$

Again measuring the activity after a delay time Δt, the total activity erosion rate is given by integration from start-up to $t-\Delta t$:

$$R_{A_e} = \frac{CPK}{.2} \left[(\Delta t)^{-.2} - (t)^{-.2} \right] \qquad (8)$$

where $C = .833 \times 10^{-6}$ sec^{-1}.

Using numerical values as in (6):

$$R_{A_e} = 1140 \left[(\Delta t)^{-.2} - (t)^{-.2} \right] \text{ curies/sec} \qquad (9)$$

Table II lists the erosion activity in the exhaust stream.

Table II

Eroded Activity Release Rates

Δt sec \ t	1 min curies/sec	10 min curies/sec	1 hour curies/sec	10 hours curies/sec
10	210	406	497	580
60		210	301	382
120		161	252	337
300		51.7	143	225
600			90.5	177

IV. Erosion of Fuel Carrier

Erosion rates identical to those used under III., above, give the exaust fuel carrier content as 7.5 grams/sec assuming the carrier is BeO.

V. Induced Activity in Air Stream

The two important nuclear reactions in air-cooled reactors are the A^{40} (n, γ) A^{41} reaction and the N^{14} (n,p) C^{14} reaction. The activity release rates under the above conditions are:

A^{41} (t 1/2 = 1.82 hrs): .106 curies/sec
C^{14} (t 1/2 = 5,580 years): 20 μ curies/sec.

VI. Reactor Malfunction

The most likely serious reactor malfunction appears to be the development of a "hot spot" in the coolant channels with resultant melting of a portion of the fuel material and release of the included fission products. Converting the reactor power to heat units, the heat production rate is 2.7 cal/sec/gm of BeO. If the reactor configuration is such that there are many coolant channels, one of which becomes obstructed, the heat available for fuel melting will be the product of the heat production rate times the mass of the uncooled fuel. If one channel in a total of 4000 were inoperative, about 6×10^3 cal/sec would melt 20 gm/sec of the fuel. The release of fission products accompanying this event may be obtained from equation (2) assuming a short time duration:

$$R_{A_c} = 150 \left[(\Delta t)^{-.2} - (t)^{-.2}\right] \frac{\text{Curies}}{\text{gram melted}} \qquad (10)$$

Where: Δt is again the time of flight of the material to the point of interest and t is the measurement time since start-up.

Equation (10) would not apply to a reactor run-away due to the fission rate excursion. Fission products released for this occurance would depend on temperature coefficients of reactivity; a general expression for the released activity is given by:

$$Q = 1.85 \times 10^6 E_r \quad t^{-1.2} \text{ Curies} \qquad (11)$$

where E_r is the excursion energy release in megawatt-seconds. In the absence of a catastrophis explosion, these effects are not much larger than the diffusion effect.

VII. Facility Design Recommendations

A. Permissible Dosage Limits

A design principle for installations which will involve exposure of employees to radiological hazards is that routine exposures determined by the design itself must be kept below 10% of the permissible dose. This is obviously necessary in order to provide for non-routine work involving additional exposure.

Permissible radiation exposures caused by an installation, which occur beyond the confines and control of the installation, are 10% of those permissible for controlled areas.

The permissible exposure rate for the general population is within an order of magnitude of the background rate.

In this facility design, the principle routine radiation hazard control problem is apparently the fission products in the exhaust stream. Permissible exposures to this gas stream must be calculated from the following effects:

1. "Submersion" beta and gamma dose (from surrounding air)
2. Lung dose (from inhaled air)
3. Integrated dose due to biological uptake of long-lived material
4. Effects of "rain-out" and "fall-out" of active material on and off the test site.

Before the actual design of the facility is undertaken, complete investigations of the above effects must be made for each proposed design on an individual isotope basis.

For this preliminary feasibility study, only effect (1), above, has been investigated. Although effect (2) may be of equal importance, (1) is at least indicative. Assuming one test run per day, the maximum exposure must be 6 mrem per run to persons at

the test site. Because the radiation energy absorbed per unit mass by the body is approximately the same as that absorbed by air, and assuming an average beta energy of 0.4 Mev/disintegration and gamma energy of 0.7 Mev/disintegration, a maximum permissible air concentration (MPC) for the exhausted fission products may be calculated:

$$(MPC)_A = \frac{1.82 \times 10^{-2}}{T} \text{ curies/meter}^3 \qquad (12)$$

where T is the running time/day in hours.

B. Calculated Dosages

1. The reactor exhaust air stream is about 88.5 M^3/sec at STP. The activity content of this air under the conditions of Table I, is about 10^5 times the permissible after 1 hours run with a Δt of 10 seconds. Because of the large exhaust volume, immediate dilution with fresh air by this factor is impractical. A preliminary investigation reveals that both increasing Δt and upper atmosphere meteorological dilution is required to produce ground concentrations as low as (12) indicates.

2. Trapping the diffused and eroded activity appears to be the only alternative to elevated atmospheric release. Although high-efficiency filter media good to sub-micron particle sizes are available, the fission product isotopes of Br, I, Kr and Xe cannot be trapped unless the exhaust air is cooled to near liquid air temperatures. These isotopes are unfortunately important contributors to total fission product activity.

3. The BeO permissible air concentration used for occupational exposure is 0.1 gm/m^3. The exhaust air at STP will contain about 10^5 times this concentration under the assumptions of Table II.

4. A^{41} and C^{14} production, while appreciable, are small compared to the expected fission product activities.

5. Because it is presumably non-routine, fuel element failure would not account for appreciable exposure compared to the routinely released fission products.

6. Reactor runaway may be assumed to have consequences similar to that event for other reactors of similar fuel content. As for other reactors, a complete investigation of runaway likelihood and consequences for the particular configuration is required prior to site selection.

C. Facility Selection vs. Reactor Behavior

1. The design conception suggested under B (2), above is obviously expensive but obtains the best hazard control.

2. After B (2), the most likely design would involve stack disposal of the reactor exhaust. Because of the high temperature and exhaust velocities available, an effective "release height" due to upward rise of the exhaust gases should be realized according to an equation by Bryant and Davidson:

$$\Delta h = d \left(\frac{V_s}{u}\right)^{1.4} \left(1 + \frac{\Delta T}{T_s}\right) \qquad (13)$$

Δh = height of rise in meters above stack
d = stack diameter in meters
V_s = exit velocity, M/sec
T_s = ambient air temperature
ΔT = temperature excess of stack gas
u = wind velocity, M/s

This equation is an approximation which has not been varified for heights above several hundred feet and takes no account of atmospheric temperature gradients. The equation yields a Δh of 2000 ft. for a stack exit velocity of 200 mph, stack gas temperature of 1000° F, a

stack diameter of 7.6 feet, and a wind velocity of 17 mph. These parameters were chosen only from the point of view of practicality for both the installation and the equation validity.

3. Under various meteorological conditions, ground concentrations for released contaminants have been related to release heights by Sutton, Holland, and others.

Application of these equations has been made assuming a set of meteorological conditions found at the National Reactor Testing Station near Arco, Idaho. This involves a lapse condition (which has 52.7% occurance), with the diffusion parameters:

C_y = .28 (crosswind virtual diffusion coefficient)
C_z = .21 (vertical virtual diffusion coefficient)
n = .20 (stability parameter)
u = 7 meters/sec (wind velocity)

From a continuous point source the maximum ground concentration is given by

$$X_{max} = \frac{2Q}{e\pi u h^2} \frac{C_z}{C_y} \qquad (14)$$

Where Q is the release rate corrected for radioactive decay and h is the release height. The distance from the origin to the point of maximum ground concentration is given in meters by:

$$d_{max} = \left[\frac{h^2}{C^2}\right]^{\frac{1}{2-n}} \qquad (15)$$

where C is a combined diffusion parameter.

To apply these equations to the test facility, Q must be calculated by equation (5) where $d_{max} = u \Delta t$. Since this yields a large Δt, integration of (5) must

be carried out exactly. This yields the series

$$R_{A_d} = Q = \frac{2\,PK}{\pi^{3/2}\gamma^{1/2}}\, t^{-0.7}\,(1-\frac{\Delta t}{t})^{1/2}\left[2+\frac{2^3(1.2)}{3!}(1-\frac{\Delta t}{t})+\right.$$

$$\left.\frac{2^5 2!(1.2)(2.2)}{5!}(1-\frac{\Delta t}{t})^2+\frac{2^7 3!(1.2)(2.2)(3.2)}{7!}(1-\frac{\Delta t}{t})^3+\cdots\right] \quad \ldots(16)$$

which may be numerically evaluated when $t > \Delta t$, or when the reactor operating time approximates the "drift" time.

For the above conditions, d_{max} is 9.5 Km and X_{max} is 0.74×10^{-3} c/m^3 and 0.5 μg/m^3 of BeO after the reactor has run for one hour.

4. It would appear from these rough approximations that the direct stack disposal method may be employed under correct meteorological conditions. Because the erosion products may not be small particulates, the test area would be subject to heavy particle fall-out. For this reason and because of the BeO problem, erosion must be reduced as much as possible.

It must be emphasized that the above calculations are extremely crude approximations. This is largely due to the meteorological variables, and therefore, before ground test facility designs of this nature are begun, a not inconsiderable meteorological investigation must be undertaken.

VIII. Summary

Of the hazard sources, eroded BeO and the radioactivity of the diffused fission products appear to far outweigh all others. One hour after initial start-up, the exhaust gases (after a delay time of 10 seconds) would contain a concentration of BeO and fission products which is a factor of 10^5 greater than that permissible for either.

Stack disposal to the atmosphere appears to be the most feasible means of handling this gas. A crude computation indicates that under favorable meteorological conditions, such disposal could prevent the radioactivity at ground level from exceeding tolerance levels, although the effects of fall-out were not considered. On the other hand, a loss of 1% of the volume of BeO in the reactor during a 10 hour run leads to a ground contamination which is of the same order of magnitude as tolerance limits for BeO.

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