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EFFECT OF REACTOR COOLANT RADIOACTIVITY UPON CONFIGURATION FEASIBILITY FOR A NUCLEAR ELECTRIC PROPULSION VEHICLE

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SUMMARY

A preliminary shielding analysis was carried out for a conceptual nuclear electric propulsion vehicle designed to transport payloads from low earth orbit to synchronous orbit. The vehicle employed a thermionic nuclear reactor operating at a power level of 1575 kilowatts and generated 120 kilowatts of electricity for a round-trip mission time of 2000 hours. Propulsion was via axially directed ion engines employing 3300 pounds of mercury as a propellant. Allowable radiation constraints for the sensitive power conditioning electronics components during the round trip were 1×10^{11} neutrons/cm^2 ($E > 0.1$ MeV) and 1×10^5 rad, for the neutrons and gammas, respectively. The vehicle configuration permitted a reactor shadow shield geometry with LiH as the neutron shield and the mercury propellant for gamma shielding. However, a large fraction of the radioactive NaK reactor coolant was unshielded and in close proximity to the power conditioning electronics. An estimate of the radioactivity of the NaK coolant was made and its unshielded dose rate to the power conditioning equipment calculated. It was found that the activated NaK contributed about three-fourths of the gamma dose constraint. (This did not include any fission products that might leak into the coolant.) The NaK dose was considered a sufficiently high fraction of the allowable gamma dose to necessitate modifications in configuration to make this axial thrust concept feasible.

INTRODUCTION

Application of nuclear thermionic space power propulsion systems both for unmanned interplanetary and geocentric orbit missions is being studied by NASA. One of these missions involves transporting payloads from low earth orbit to synchronous orbit. Vehicles with axially directed thrusters are under consideration for this mission. A schematic of such a vehicle employing a 120 kilowatt-electric power system (1575 kW reactor thermal power) currently being considered, is shown in figure 1. This vehicle is referred to in this report as the Nuclear Electric Propulsion (NEP) tug (ref. 1). From the figure it can be seen that the reactor is located at one end of the vehicle with the scientific payload at the other. The reactor is an in-core thermionic device designed to convert fission heat directly into low-voltage direct current electricity within the reactor. It is cooled by NaK, a sodium-potassium liquid metal, which becomes radioactive when exposed to the high neutron flux field of the reactor. The low voltage direct current electricity is carried by cables in the support boom to the power conditioning equipment where it is converted to high voltage direct current electricity. The high voltage direct current is then fed to the ion engines and used to accelerate a propellant, in this case mercury, which produces thrust to propel the vehicle. Each round-trip mission has a duration of 2000 hours, after which it is planned to refuel the vehicle and use it again for a maximum of 10 missions.

Since the power conditioning equipment as well as the scientific payload will contain radiation sensitive electronics, a radiation shield is necessary to meet the radiation constraints for this equipment of 1×10^{12} neutron/cm^2 ($E > 0.1$ MeV) integrated neutron flux, and 1×10^{6}-rad gamma dose over the entire vehicle operating lifetime, or one-tenth of these values for each 2000-hour mission. The reactor is shielded by a LiH neutron shield layer together with the mercury propellant. These are arranged in a shadow

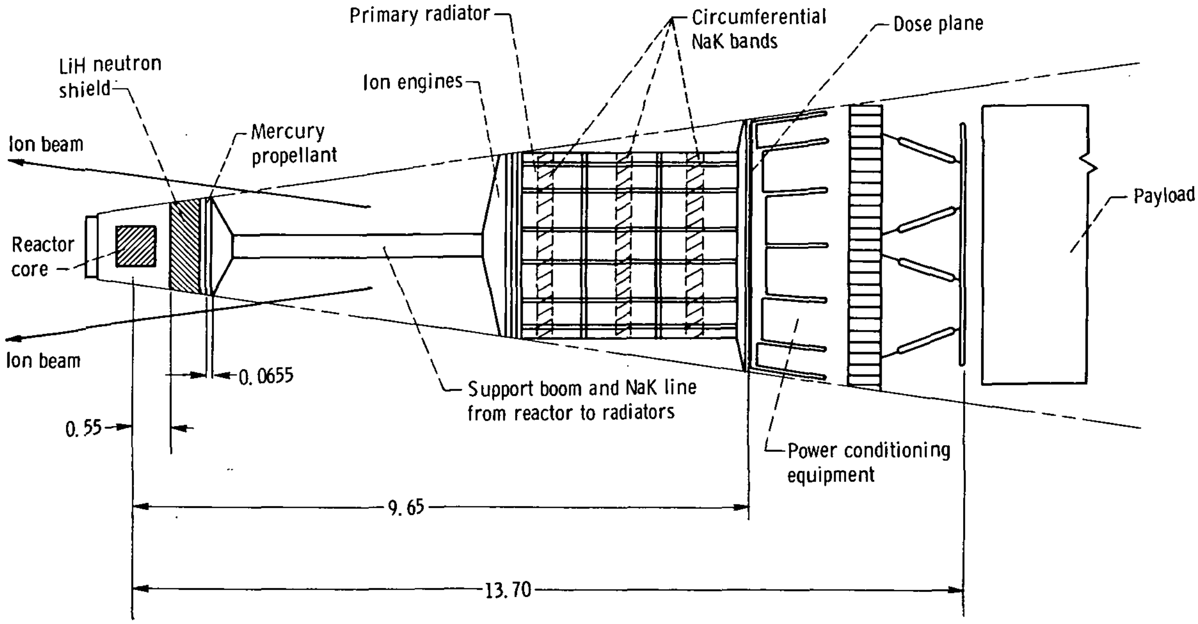

Figure 1. - Schematic of 120-kilowatt-electric Nuclear Electric Propulsion (NEP) tug. (All dimensions in m unless indicated otherwise.)

shield geometry of about a 9^{o} half-cone angle which is sufficient to shadow the entire vehicle configuration. The NaK coolant lines are located in grooves cut into the periphery of the LiH shield, but run on the outside of the mercury propellant tank. The electric lines run along the outside of both shields. The primary radiator and lines leading from the reactor to the radiator and return, all containing radioactive NaK coolant, are unshielded and in close proximity to the sensitive power condition electronics. It is of primary importance to determine the amount of radioactivity in the NaK coolant and to estimate its dose contribution to the equipment, since, if the dose contribution is a major fraction of the radiation constraint, a major change in vehicle configuration could be required.

The purpose of this report is to explore the importance of the NaK activity and to determine its impact upon the feasibility of the vehicle configuration based upon the aforementioned radiation constraint values. Calculations were carried out to estimate the activity of the NaK and its dose contribution. The calculations and results are described next.

ESTIMATE OF NaK COOLANT ACTIVITY AND ITS CONTRIBUTION TO THE GAMMA DOSE

The NaK reactor coolant becomes radioactive as a result of exposure to the high neutron field when passing through the reactor. The thermionic reactor and shadow shield are shown in figure 2. The core is surrounded by both radial and axial BeO reflectors. The NaK coolant is found in those regions enclosed within the niobium pressure vessel shown in the figure. This includes the core, upper and lower axial reflectors, and inlet and outlet plenum chambers. Only the Na^{24} activity was computed in calculating the NaK coolant activity. The contribution from the K^{42} source was neglected since this contributes a negligible amount to the dose compared with the Na^{24} source.

The total saturated Na^{24} activity in the coolant loop was calculated as follows. An existing DOT code (ref. 2) two-dimensional transport criticality calculation of the reactor (made at NASA Lewis by Wendell Mayo) was used to calculate the Na^{24} capture rate throughout the core and axial BeO reflector. The calculation was a 32 by 25 spatial mesh cell, 20 energy group, P_1S_4, performed in r-z geometry.

A significant amount of NaK exists in the plenum chambers; however, the 2-D criticality calculation did not extend past the BeO reflector. To obtain an estimate of the NaK capture rate in the plenum, a 1-D spherical geometry ANISN code (ref. 3) calculation was made to estimate the shape of the capture rate distribution in the plenum.

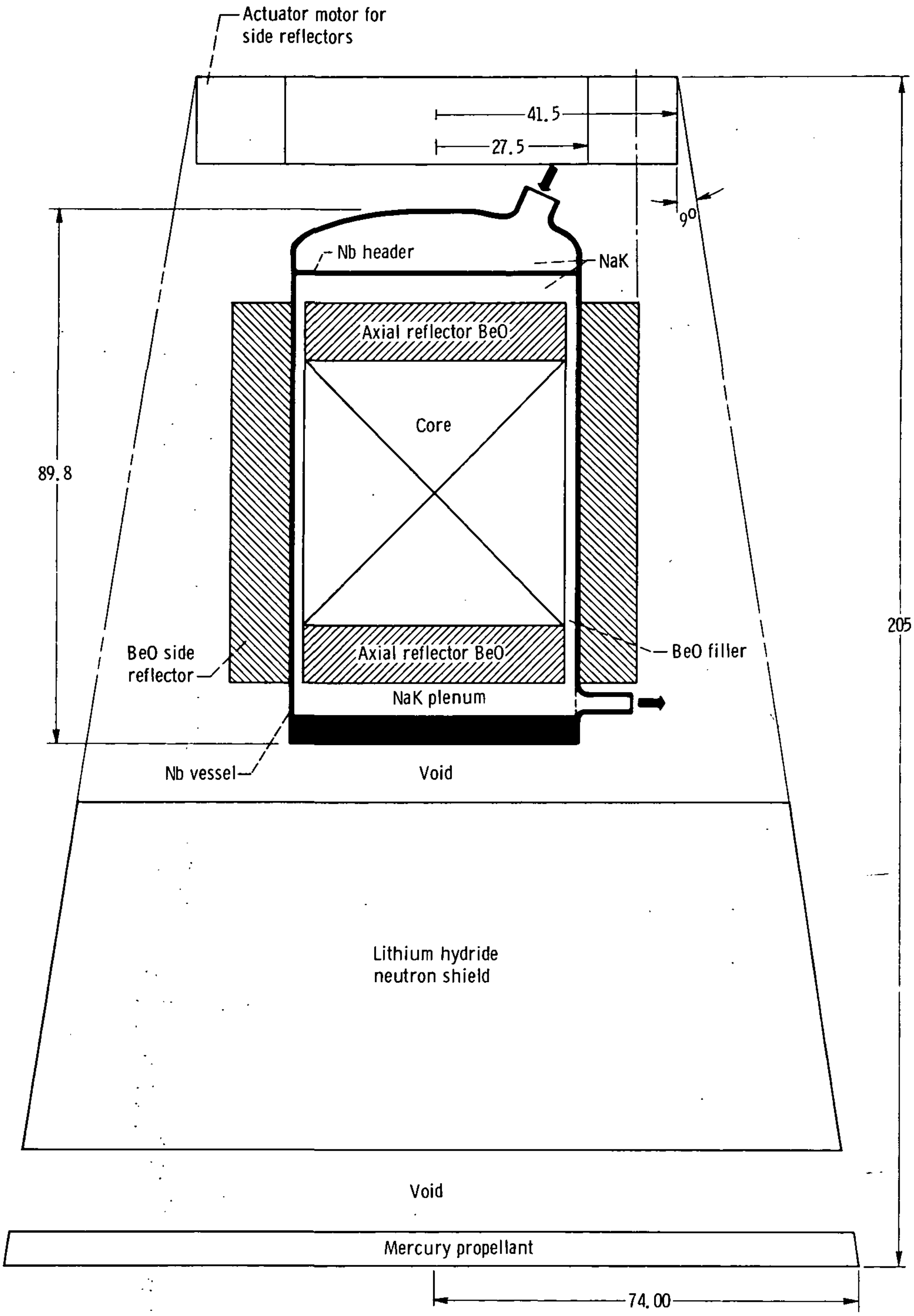

Figure 2. - Reactor-shield geometry. (All dimensions in cm unless indicated otherwise.)

The 1-D results were then matched to the 2-D values at the reflector-plenum interface and appropriately scaled throughout the rest of the plenum. A plot of the resulting relative axial capture rates through the core, axial BeO reflector, and NaK plenum is shown in figure 3. The figure shows that the sodium capture rate in the core is low compared with that in the axial BeO reflector. This is due primarily to the softening of the neutron spectrum in the BeO reflector and the fact that the sodium capture cross section is much higher for low energy neutrons. A summary of the sodium capture rates in various regions of the reactor is shown in table I. The total capture rate for the entire reactor (with two plenum chambers) is 7.95×10^{-5} captures/second per source neutron/second. The table indicates that sodium captures in the core, axial reflectors, and plenum chambers are about equal in magnitude. For a power level of 1575 kilowatts, the total saturated Na^{24} activity in the entire coolant loop is 9.92×10^{12} disintegrations per second (268 Ci). The amount of NaK in the coolant loop and its distribution which are required for the dose calculations is shown in table II.

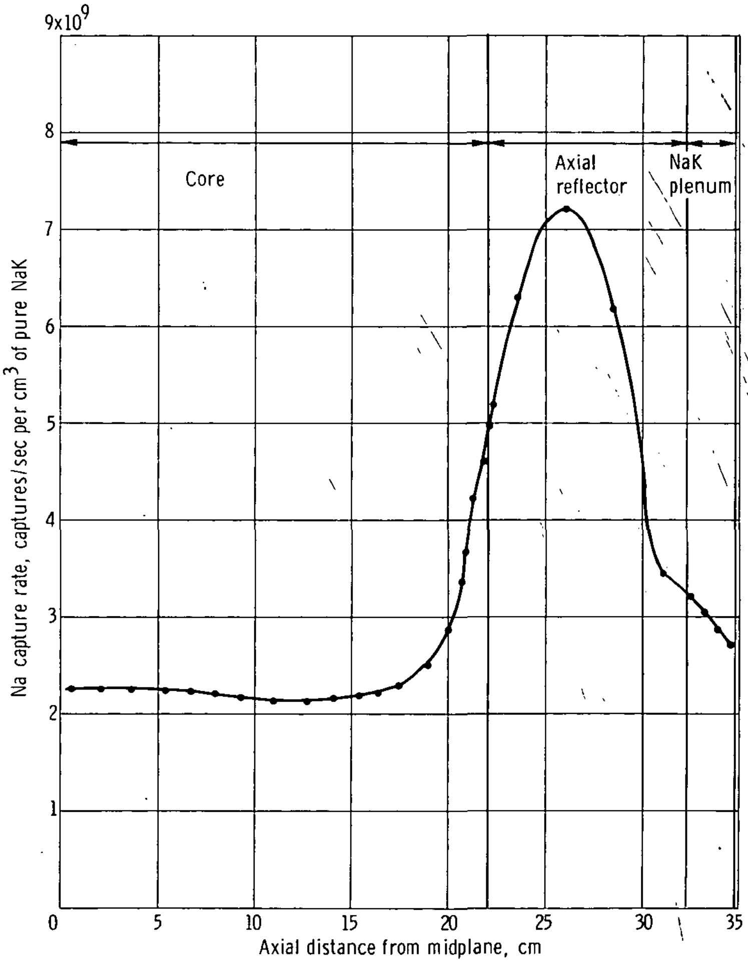

Figure 3. - Sodium capture rate along axis of reactor.

TABLE I. - SODIUM CAPTURE RATES IN

VARIOUS REACTOR REGIONS

Reactor region	Na capture rate, captures/sec per source neutron/sec
Core	2.25×10^{-5}
Filler region	1.16
Axial BeO reflectors	2.18
Plenum chambers	2.36

TABLE II. - DISTRIBUTION OF NaK AND Na^{24}

ACTIVITY IN COOLANT LOOP

Location	Mass inventory, kg	Na^{24} activity	
		dis/sec	Ci
Reactor	24	1.30×10^{12}	35
Radiator	57	3.03	82
Reactor piping to radiator and return	105	5.59	151
Total	186	9.92×10^{12}	268

A QAD Code (ref. 4) line-of-sight point kernel calculation was made to calculate the unshielded dose rates from radioactive Na^{24} at a set of nine detectors located in the power conditioning region. The simplified geometry used for this calculation is shown in figure 4. The NaK pipe was assumed to be uniformly filled with NaK, with a source of 5.59×10^{12} disintegrations per second (151 Ci) of Na^{24}. The radiator source of 3.03×10^{12} disintegrations per second (82 Ci) was almost all distributed in the three circumferential bands, each 30 centimeters wide and equally spaced, as shown in figure 4. No self-shielding for any material was assumed. Two regions of thermal insulation shielding were calculated to have a mass per unit area of 0.6 gram per square centimeter each. This is negligible for radiation shielding purposes. The dose contribution from the NaK in the reactor was small since it was shielded by the shadow shield and located much further from the dose plane. The dose rates are shown in table III. From this table it is seen that the average dose rate at the plane closest to the radiator is about 36 rad per hour, with about three-fourths of this coming from the radiator. At a plane 0.61 meter (2 ft) further away, the dose rate decreases to about 25 rad per hour. At a plane 1.22 meters (4 ft) from the radiator the dose rate is about 18 rad per hour. For a mission operating time of 2000 hours, the integrated unshielded dose from the

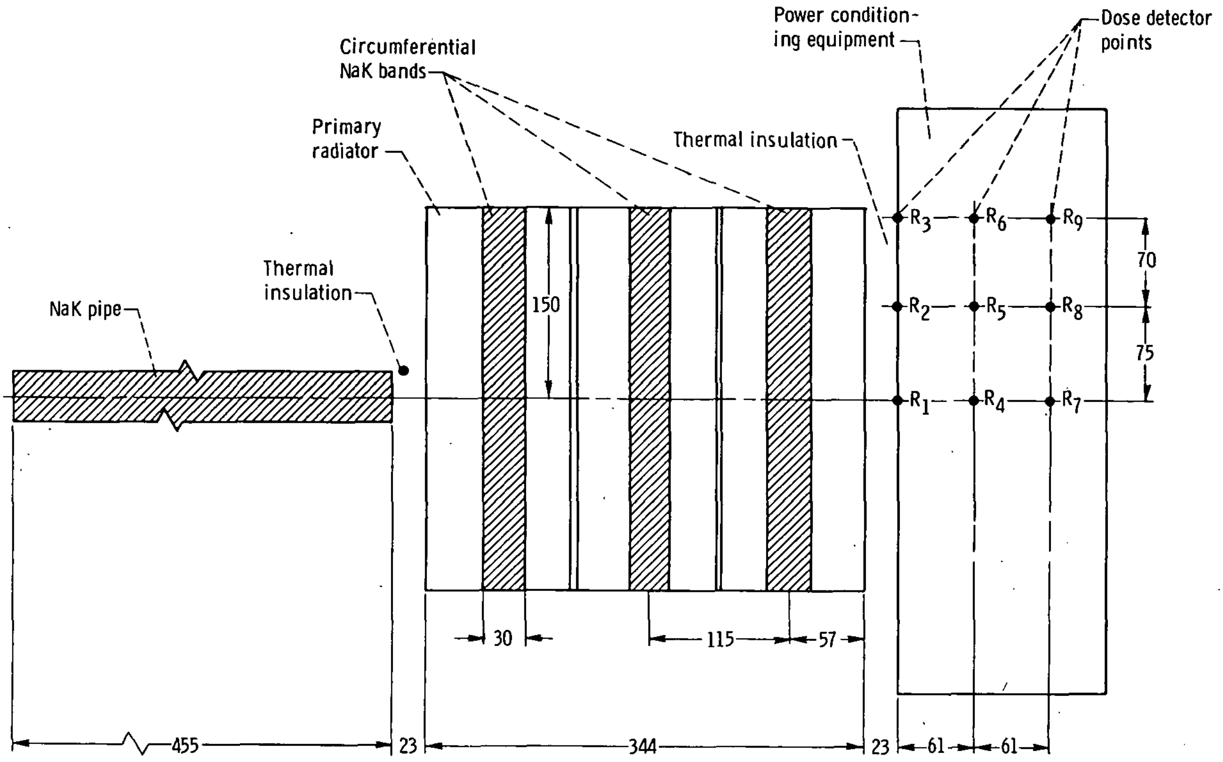

Figure 4. - Geometry used to calculate doses from radioactive NaK coolant. (All dimensions in cm unless indicated otherwise.)

TABLE III. - UNSHIELDED Na^{24} DOSE RATES

Receiver	Receiver coordinates, cm		Dose rate from pipe, rad/hr	Dose rate from radiator, rad/hr	Total dose rate, rad/hr
	r	z			
1	0	845	7.7	28.1	35.8
2	75	845	7.6	29.4	37.0
3	145	845	7.2	28.8	36.0
4	0	906	6.3	19.4	25.7
5	75	906	6.2	19.2	25.4
6	145	906	5.9	17.5	23.4
7	0	967	5.2	13.5	18.7
8	75	967	5.1	13.2	18.3
9	145	967	5.0	12.0	17.0

NaK to the closest part of the power conditioning electronics is 7.4×10^4 rad or about three-fourths of the allowable value of 1×10^5 rad.

The actual dose from the NaK is probably higher than this, however, since the dose estimate does not take into account any fission products that might leak into the coolant. Thus, the dose estimate is somewhat optimistic and there is a clear indication that the present vehicle configuration is marginal in its ability to meet the gamma radiation dose constraint without a significant revision.

CONCLUSIONS

For the given radiation dose constraints and reactor power level, the dose from the radioactive NaK is the most important contributor to the gamma dose for this particular configuration. The present vehicle configuration is considered marginal in its ability to meet the allowed radiation constraint values and must undergo modifications to make this axial thruster concept feasible. In any event, the NaK activity must be taken into account in future vehicle configuration feasibility studies.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 10, 1973,
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