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POST-SHUTDOWN TEMPERATURE OF A BURIED REACTOR SYSTEM FOR A LUNAR-BASED POWER PLANT

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SUMMARY

Delayed neutron fissions, fission product decay, and induced radioactivity are sources of energy which affect the temperature of a reactor after shutdown. A study of the afterheat from these sources was made on a lithium cooled fast reactor system for a lunar based power plant which is assumed to be buried beneath the lunar surface.

A large amount of tantalum alloy T-111 is used in the core structure and pressure vessel of this reactor. This results in an unusually high energy contribution from induced activity because of the production of the long-lived isotope Ta^{182}. Contributions from the other sources follow normal energy decay patterns of other reactors after shutdown.

Considering all the significant sources of afterheat, a heat transfer analysis was done to determine the post-shutdown temperature characteristics of the reactor system, assuming passive cooling only (no active heat removal systems in operation, such as cooling jackets or heat exchangers). For all operating times considered (1, 10, 100, or 1000 days) the temperature rises slowly, rising less than 170° K in the first 10 minutes after shutdown. The system temperature reaches a peak in about 2 hours after shutdown in the case of one day of reactor operation. The temperature does not peak until about 24 hours after shutdown in the case of 1000 days of reactor operation.

The temperature peaks which would occur with only passive cooling are too high to be tolerated in all cases of reactor operating time. Therefore auxiliary cooling is necessary to prevent the system from overheating. However, because the rate of rise in system temperature is low in the first several minutes following shutdown of the reactor, it is not critical that the maximum required auxiliary cooling rate be established immediately at shutdown. The maximum cooling rate must be established before system temperature reaches the maximum tolerable level. The auxiliary cooling can gradually be reduced and eventually be terminated as the after heat of the reactor decays.

Auxiliary heating is required if the system is to be prevented from cooling down to the freezing point of the lithium coolant when the operating times of the reactor have been as short as one or two days. Auxiliary heating to prevent solidification of lithium will also be required after longer periods of reactor operation if the shutdown period is very long.

INTRODUCTION

Large manned lunar bases may be considered for the purpose of scientific exploration of the moon. Several types of power plants are being considered for these bases. A compact lithium cooled fast spectrum reactor has been proposed as the heat source for power plants in the range of 500 kWe.

This study was undertaken to determine the heat generation rate of the reactor after shutdown and the effect of the afterheat on the reactor system temperature when heat is rejected by passive means only. Maximum use of passive cooling minimizes auxiliary equipment weight and auxiliary power requirements. However, auxiliary cooling must be used when passive cooling allows the reactor system to overheat. Overheating can cause damage to the system which will prevent further operation of the power plant. Auxiliary heating is required if solidification of the lithium is to be avoided. The expansion that occurs on remelting frozen lithium may also cause damage to the system.

SYSTEM DESCRIPTION

A schematic diagram of the proposed reactor heat source system buried beneath the lunar surface is shown in figure 1.

The heat source in this system is a compact fast spectrum nuclear reactor which is to operate normally at 2.17 MWt. The lithium reactor coolant during normal operation exits at a temperature of 1220° K. A diagram of the reactor is shown in figure 2. Preliminary design studies established the reactor component materials to be:

(1) Uranium nitride fuel

(2) Tantalum alloy (T-111) fuel cladding, fuel element support structure, pressure vessel, and piping

(3) Molybdenum alloy reflector.

The proposed system shown schematically in figure 1 consists of two liquid metal loops (primary loop and intermediate loop). Liquid lithium coolant is pumped continuously through the reactor and heat exchanger of the primary loop by two (for reliability through redundancy) electromagnetic pumps. The heat removed from the reactor is transferred from the primary loop to the intermediate loop through a liquid-metal-to-liquid-metal heat exchanger. An electromagnetic pump provides the pumping power to circulate liquid lithium through the intermediate loop. The heat absorbed in the intermediate loop is transferred to the power conversion loop through another heat exchanger.

To limit the dose rate to about 1 mrem/hr at the location of the power conversion equipment, the reactor was assumed to be buried 10.1 meters below the surface. This depth was the result of a preliminary shielding calculation based on an assumed lunar material composition and a density of 1 gram per cubic centimeter. Various estimates of subsurface lunar material densities are generally greater than 1 gram per cubic centimeter and range up to 1.5 gram per cubic centimeter. Therefore the density value used is considered conservative. The primary loop itself is a potential source of radioactivity due to possible contamination by fission products. Therefore all primary loop components were kept at least 4.57 meters below the surface to limit the possible dose rate at the surface.

The entire system (including pipes, pumps, reactor, and heat exchangers) is enclosed in a thin stainless steel jacket to keep the hot refractory materials from contacting the lunar soil. There is a vacuum gap with an average width of 0.635 centimeter between the system and the jacket.

ANALYSIS OF ENERGY RELEASED IN THE REACTOR FOLLOWING SHUTDOWN

Delayed Neutron Fissions

The energy from delayed neutron fissions after shutdown was calculated by using the equation for variation of flux with a step change in reactivity (ref. 1, p. 238)

$$\frac{P_{t_{as}}}{P_o} = \left[\frac{\beta}{\beta - \rho} \exp\left(\frac{\lambda \rho t_{as}}{\beta - \rho}\right)\right] - \left[\frac{\rho}{\beta - \rho} \exp \frac{(\beta - \rho) t_{as}}{l}\right] \qquad (1)$$

β delayed neutron fraction = 0.0068

l neutron generation time ≈0.04 μsec

The values used for β and l are typical for very fast-spectrum reactors using reflector materials which contain elements having high atomic numbers.

The value of ρ, the step change in reactivity at shutdown, is designed to be about 0.04. The value of λ, the average decay constant of delayed neutrons, is 0.080 second^{-1} (from ref. 1, p. 240) and t_{as} is the time after reactor shutdown. Substitution of these values in the equation shows that the second term is negligible beginning at times much less than 1 second after shutdown. Thus, only the first term was used. The exponent in this term after a short period of time is a function of the longest lived source of delayed neutrons which has a half life of 55.6 seconds. As a result the reactor will have a period of -80 seconds shortly after shutdown. The ratio of shutdown power to operating power (or flow) then becomes

$$\frac{P_{t_{as}}}{P_o} = 0.146\ e^{-t_{as}/80} \tag{2}$$

The reactor power initially slopes to 14.6 percent of its operating value and then decays on an 80 second period.

FISSION PRODUCTS

The energy from fission product decay depends on the length of time the reactor is at power before shutdown and the time after shutdown. Several correlations of fission product decay heat are available. The equation by K. Shure and D. J. Derdziak (ref. 2) was used herein.

The correlations of fission product decay energy found in the literature are for thermal fission in U^{235}. However, the fission products will change with the energy of the neutrons causing fission. Equations or correlations were not available for decay of fission products for fast reactors so those for thermal reactors were used. It is not expected that the fission product decay heat released will be much different in the two cases. Long and short lived isotopes are distributed over the whole range of fission products so that the slight shifts in distribution that would occur in a fast reactor would not cause a significant error for this calculation.

INDUCED RADIOACTIVITY

Induced radioactivity is produced by parasitic absorption of neutrons by any material of the reactor including the fuel, flow tubes, pressure vessel, reflector, and coolant. Parasitic absorption includes all the absorbed neutrons which do not produce fission. This neutron induced activity like fission product activity is a function of both irradiation time (t_{ir}) and decay time (t_{as}). The power for each radioactive isotope (i) produced is (ref. 3, p. 7-14)

$$P_{t_{as}} = N_P \sigma \varphi E_i \left(1 - e^{-\lambda_i t_{ir}}\right) e^{-\lambda_i t_{as}} \tag{3}$$

The reactor was assumed to be divided into 3 structural sections (core, reflector, and pressure vessel) and the neutron flux into three energy groups. Absorption cross sections for the three energy groups were obtained from a neutron activation code developed at Lewis Research Center.* Tables I, II, and III list material weights, neutron fluxes, and cross sections.

*The neutron activation code was developed by Suzanne T. Weinstein, Radiation Effects Section, Direct Energy Conversion Division, Lewis Research Center.

ANALYSIS OF SYSTEM TEMPERATURE CHARACTERISTICS

If the system is allowed to cool passively after the reactor is shutdown, the system temperature variation with time will depend on the following factors:

(1) The initial temperature (the average steady state operating temperature of the reactor coolant)

(2) The rate at which energy is being absorbed by the system

(3) The heat capacity of the system

(4) The ability of the system to reject or retain heat. This in turn depends on the temperatures, geometry, and thermal properties of both the system and its environment.

HEAT TRANSFER MODEL

In establishing the heat transfer model of the system, it was assumed that the primary and intermediate loops were coupled thermally so that the afterheat is uniformly distributed in the system. The heat is then radiated across the narrow vacuum gap to the jacket which surrounds the system. The entire surface of this jacket is used as a heat transfer surface from which heat is conducted into the lunar soil.

Based on an engineering design study, sizes and spacing of system components were estimated. The total surface area available for heat transfer was calculated for the system, including the reactor, all piping, heat exchangers, pumps, etc. The dimensions of an equivalent cylinder with the same total length and surface area as the whole system were calculated. This equivalent cylinder has a total length of 30.5 meters and a diameter of 9.75 centimeters. Since the 30.5 meters of the system piping are distributed in an approximately uniform manner within a vertical span of

10.1 meters (the burial depth of the reactor), the system was approximated by three identical 10.1 meter long vertically buried cylinders. Because the three cylinders are identical, only one will be considered in the model along with one third of the total heat. The jacket around the system acts as a thermal radiation shield and is represented by a thin cylindrical shell which is concentric with the equivalent cylinder from which it is separated by a 0.635 centimeter vacuum gap. A sketch of the heat transfer model is shown in figure 3.

The following conditions were assumed and approximations made:

(1) The heat capacity of the material within the volume of the 9.75 centimeter diameter cylinder is considered to be the same as that of lithium, because a very large portion of the total volume of the system is filled with lithium.

(2) The system is passively cooled, that is, no heat is being removed from the system by either the power conversion loop or an auxiliary cooling loop.

(3) All of the heat being generated by the reactor is absorbed in the system.

(4) The temperature gradients within the system are small and will be ignored.

This last condition should be approached because of the excellent thermal conductivity of liquid lithium. Furthermore, the electromagnetic pumps are assumed to operate, thereby distributing the heat around the system. Even when the system is operating at full power, the maximum difference in temperature in the system (between reactor outlet and turbine inlet) is only about 66.5° K. Therefore, with only shutdown power available and with no heat load on the system, the temperature gradients should be small even with greatly reduced fluid flows.

(5) Temperature gradients in the stainless steel jacket are also small enough to ignore.

(6) The thermal conductivity of lunar soil was selected at 0.346 watts per meter per ^{o}K. Thermal conductivities available for lunar material ranged from 6.9×10^{-3} watts per meter per ^{o}K for high porosity dust to 2.25 watts per meter per ^{o}K for solid rock (ref. 4, p. 7-9). It was reasoned that the material surrounding the system would probably be crushed rock, therefore the value of thermal conductivity assumed is much closer to the value for rock than the value for dust. The assumed value is very close to the value of thermal conductivity of dry earth sand.

(7) No discontinuities in lunar soil surrounding the system were assumed. Such changes as those resulting from excavating and refilling are difficult to predict.

(8) It is assumed that changes in system temperature occur slowly enough so that the problem can be treated as a series of steady state problems with average temperatures and heat fluxes.

(9) The variation with time of the lunar soil temperature just below the surface is small and was considered constant at 230^{o} K. This assumption is in accordance with information resulting from calculations made under the assumption that the lunar material is basaltic rock covered with a 1 centimeter thick layer of dust. Under these conditions the temperature only 0.76 meter below the surface is 230^{o} K and varies by only $\pm 12^{o}$ K during the period of one lunation (ref. 4, p. 7-18).

HEAT TRANSFER EQUATIONS

With the assumptions listed above and the geometry shown in figure 3, the heat transfer model can be described as a vertically buried cylindrical heat source of uniform temperature transferring heat to the lunar soil in the presence of an isothermal plane located parallel to and just below the lunar surface. An equation that describes the heat flux under these conditions is (ref. 5, p. 83)

$$Q_{cond} = \frac{2\pi L(T_2 - T_3)(K_m)}{\ln \frac{4L}{D_s}} \tag{4}$$

The heat radiated from the system to the jacket is calculated using the equation for radiation heat transfer between walls of concentric cylinders (ref. 6, p. 405)

$$Q_{rad} = \frac{\sigma A_1 \quad T_1^4 - T_2^4}{\frac{1}{\epsilon_1} + \frac{A_1}{A_2}\left(\frac{1}{\epsilon_2} - 1\right)} \tag{5}$$

For a finite interval of time (Δt_{as}) a change in temperature (T_1) of (ΔT_1) will take place. An average value for (T_1) of $\left[T_o + (\Delta T_1/2)\right]$ will be used for the interval. Also because of the change in (T_1) there will be a change in the heat stored in the system ($K_3 \ \Delta T_1$). This change in stored heat will either add or subtract from the available heat during the time interval, depending on whether the temperature is rising or falling. Allowing for these conditions and for the fact that $Q_{rad} = Q_{cond}$ the total heat loss per unit length during the time interval (Δt_{as}) may be expressed as:

$$Q \ \Delta t_{as} = K_2 \left\{ \left[T_o + \frac{\Delta T_1}{2}\right]^4 - \left[K_4 - K_5 \left(\frac{\Delta T_1}{\Delta t_{as}}\right) + C\right]^4 \right\} \Delta t_{as} + K_3 \ \Delta T_1 \tag{6}$$

With known heat production rate (Q) at known time after shutdown (t_{as}) the change in system temperature (ΔT_1) can be determined for a selected time interval (Δt_{as}) using equation (6). The temperature at the end of the interval is ($T_o + \Delta T_1$).

RESULTS AND DISCUSSION

Energy Released After Shutdown

The equations for delayed neutron and induced activity and the correlation for fission product decay power were incorporated into a computer program* and runs made for several reactor operating times.

The shutdown power versus decay time is shown in figure 4 and tabulated in table IV. The results listed in the table show the contribution to shutdown power from each source as well as the total power for each operating time considered. Decay times covered included times from 10 seconds up to one year. Reactor operating times considered were 1, 10, 100, and 1000 days. The life of the proposed reactor is 50,000 hours or approximately 2000 days. Power generation after shutdown at the end of life is very close to that after 1000 days of operation, therefore, results for more than 1000 days of reactor operation were not included.

It also can be seen in table IV that the power from induced radioactivity builds up to a significant amount even after only 1 day of operation. It is at a level comparable to the fission product power for most of the first year of shutdown time. This normally neglected source of power is significant in this proposed high temperature fast reactor because of the long lived isotope Ta^{182} produced from the large amount of tantalum alloy T111 used in the core and pressure vessel.

As would be expected, the longer the operating time of the reactor, the higher the power will be at any given time after shutdown. The rate of decrease in power after shutdown is greatest for short

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*The program was written for the IBM 360. "Reactor Power Generation After Shutdown - Lunar Based Power Plant" by John Peoples, Dynamics and Control Branch, Nuclear Systems Division, Lewis Research Center.

operating times. For longer operating times, where tantalum activity and long lived fission products become more significant, the rate of decrease in power after shutdown is lower.

Figure 5 shows the total energy release or integrated power after shutdown. These curves are useful in shutdown and accident heat transfer analysis.

System Temperature After Shutdown

The results of the heat transfer calculations are shown in graphic form in figure 6. The curves for all four cases of reactor operating time considered have basically the same characteristics. The temperature begins to rise slowly after shutdown, rising only about 170^{0} K in the first 10 minutes. Following the first 10 minutes after shutdown of the reactor, the time versus temperature characteristics of the reactor system for the four cases of operating time considered begin to diverge. The temperature rises more quickly and for a longer period of time before reaching a peak for longer periods of reactor operation. The system temperature reaches a peak in about 2 hours after shutdown in the case of one day of reactor operation and does not peak until about 24 hours after shutdown in the case of 1000 days of reactor operation.

The decline in temperature which follows the peak is slower for longer periods of reactor operation. The approximate periods of time after shutdown required for the system to cool back down to the normal operating temperature are: 9 hours for 1 day of reactor operation, 1 day for 10 days of reactor operation, $5\frac{1}{2}$ days for 100 days of reactor operation, and 72 days for 1000 days of reactor operation.

Auxiliary Cooling and Heating

To prevent the system from overheating, auxiliary cooling is required following shutdown of the reactor in all cases of reactor operating time. However, due to the fact that the system temperature rise is slow during the first several minutes following reactor shutdown without auxiliary cooling, and presuming that a slight increase in system temperature is tolerable, it is not critical to have the peak auxiliary cooling rate established immediately after reactor shutdown. The peak auxiliary cooling rate must be established before the maximum tolerable temperature is reached. The auxiliary cooling rate may be reduced to conserve auxiliary power and to preserve the heat stored in the system in order to keep the reactor coolant molten for a longer period of time in cases where it may be critical to do so. Finally the auxiliary cooling may be terminated once the heat generation rate has decayed to where passive cooling can again keep the system temperature at a tolerable level.

In cases of reactor operating times of more than a few days, it appears that keeping the lithium coolant above the freezing point will not be a problem. However, after only one day of reactor operation, the system will remain above the freezing point of the lithium coolant for about 7 earth days. Stored energy for heating will then be required in order to prevent the system coolant from solidifying.

SUMMARY OF RESULTS

1. The main sources of energy contributing to shutdown power are fission product decay and neutron induced activity of the tantalum in the reactor core and pressure vessel.

2. The delayed neutron contribution to shutdown power is negligible within 500 seconds after shutdown.

3. The rate of temperature increase during the first several minutes after shutdown with no auxiliary cooling is low, making it unnecessary to establish the peak auxiliary cooling rate immediately after reactor shutdown.

4. In all cases of reactor operating time, auxiliary cooling is required to prevent the system from overheating. Auxiliary cooling can be terminated when shutdown power has decayed enough so that passive cooling can reject heat at a high enough rate to prevent overheating.

5. Auxiliary heating will probably be required to prevent the coolant from solidifying if the reactor has operated for only a short time (on the order of one day).

APPENDIX - SYMBOLS

A_1 surface area of a unit length of the system as represented in the heat transfer model

A_2 surface area of a unit length of the thermal radiation shield as represented in the heat transfer model

C constant temperature T_3

D_s diameter of the thermal radiation shield as represented in the heat transfer model

E_i energy released by the i^{th} fission product upon decay

K_m thermal conductivity of lunar subsurface material

K_1 $\dfrac{\ln(4L/D_s)}{2\pi K}$

K_2 $\dfrac{\delta A_1}{\dfrac{1}{\epsilon_1} + \dfrac{A_1}{A_2}\left(\dfrac{1}{\epsilon_2} - 1\right)}$

K_3 $\rho V C_P$ (C_P of lithium) + (ρ of lithium)

K_4 QK_1

K_5 K_1K_3

L vertical distance between the bottom of the heat transfer model and the isothermal surface

l neutron generation time

N_P total atoms of isotope (p)

P_o steady state reactor operating power

$P_{t_{as}}$ reactor power level at time, t_{as}, after shutdown

Q average heat flux during the time interval (Δt_{as})

T_o system temperature at the beginning of the time interval (Δt_{as})

T_1 system temperature

T_2 temperature of the thermal radiation shield

T_3 temperature of the isothermal layer near the lunar surface

t_{as} time after reactor shutdown

t_{ir} irradiation time

V volume of one unit length of the equivalent cylinder of the heat transfer model

β delayed neutron fraction

δ activation cross section (in induced activation calculations)

ϵ_1 emissivity of external surface of the system

ϵ_2 emissivity of the internal surface of the thermal radiation shield

λ average decay constant for delayed neutrons

ρ step change in reactivity ($\Delta K/K$, where $K = 1$)

σ Stefan-Boltzman constant (in heat transfer calculations)

φ neutron flux

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4. Niedz, F. J.: Survey of the Physical and Environmental Parameters of the Moon. Rep. 4810, General Electric Co. (NASA CR-55064), Feb. 1963.

5. Kreith, Frank: Principles of Heat Transfer. International Textbook Co., 1958.

6. Eckert, E. R. G.; and Drake, Robert M., Jr.: Heat and Mass Transfer. Second ed., McGraw-Hill Book Co., Inc., 1959.

TABLE I. - REACTOR REGIONS, MATERIALS,

AND EARTH WEIGHTS

Location	Material	Material weight, kg	Element	Element weight, kg
Core	Fuel (UN)	190.2	U	178.8
			N	11.41
	T-111	152.3	Ta	136.3
			W	12.2
			Hf	3.8
	Coolant	4.76	Li	4.76
	Tungsten	11.44	W	11.44
Reflector	Mo	458.08	Mo	458.08
	Coolant	1.59	Li	1.59
	T-111	144.37	Ta	129.2
			W	11.6
			Hf	3.5
Pressure Vessel	T-111	71.73	Ta	64.24
			W	5.7
			H_f	1.72

TABLE II. - NEUTRON FLUXES BY GROUP AND REGION (NEUTRON/CM^2-SEC)

Location	Group I (14.9 MeV to 0.82 MeV)	Group II (0.82 MeV to 5.53 keV)	Group III (5.53 keV to 0.40 eV)
Core	3.15×10^{13}	6.98×10^{13}	2.17×10^{11}
Reflector	5.83×10^{12}	3.08×10^{13}	3.19×10^{11}
Pressure vessel	8.94×10^{11}	7.69×10^{12}	5.33×10^{11}

TABLE III. - ACTIVATION CROSS SECTIONS

IN SQUARE CENTIMETER PER GRAM

Isotope (reaction)	Group 1	Group 2	Group 3
$U^{235}(n,\gamma)$	1×10^{-6}	1.6×10^{-5}	3.5×10^{-4}
$U^{238}(n,\gamma)$	1.4×10^{-4}	8.6×10^{-4}	6.4×10^{-3}
$Ta^{181}(n,\gamma)$	1.2×10^{-5}	2.5×10^{-3}	8.2×10^{-2}
$Ta^{181}(n, 2n)$	4.5×10^{-6}	--------	--------
$W^{184}(n,\gamma)$	8.0×10^{-7}	2.1×10^{-4}	1.3×10^{-3}
$W^{186}(n,\gamma)$	1.6×10^{-2}	1.4×10^{-4}	1.6×10^{-3}
$Hf^{179}(n,\gamma)$	4.6×10^{-7}	5.4×10^{-6}	1.8×10^{-2}
$Hf^{180}(n,\gamma)$	7.6×10^{-6}	2.0×10^{-4}	3.1×10^{-3}
$Mo^{97}(n, p)$	1.7×10^{-5}	--------	--------
$Mo^{98}(n,\gamma)$	6.7×10^{-6}	2.8×10^{-4}	6.3×10^{-3}
$Mo^{100}(n,\gamma)$	5.1×10^{-8}	2.2×10^{-5}	3.4×10^{-5}

TABLE IV. - REACTOR DECAY POWER (IN MEGAWATTS BASED ON 2.17 MW OPERATING POWER)

Reactor operating time, days	Reactor decay time	Delayed neutron fissions	Fission products	Neutron induced radio-activity	Total
1	10 sec	0.28	9.1×10^{-2}	----------	0.371
	100 sec	.091	5.1×10^{-2}	----------	.142
	500 sec	6×10^{-4}	3.72×10^{-2}	4×10^{-4}	3.82×10^{-2}
	1 hr	--------	1.66×10^{-2}	3×10^{-4}	1.69×10^{-2}
	1 day	--------	2.01×10^{-3}	1.8×10^{-4}	2.19×10^{-3}
	1 week	--------	2.41×10^{-4}	8.1×10^{-5}	3.2×10^{-4}
10	10 sec	0.28	9.36×10^{-2}	1.27×10^{-3}	3.74×10^{-1}
	100 sec	.091	5.81×10^{-2}	1.26×10^{-3}	1.50×10^{-1}
	500 sec	6×10^{-4}	4.26×10^{-2}	1.23×10^{-3}	4.44×10^{-2}
	1 hr	--------	2.18×10^{-2}	1.12×10^{-3}	2.29×10^{-2}
	1 day	--------	5.55×10^{-3}	9.67×10^{-4}	6.52×10^{-3}
	1 week	--------	1.44×10^{-3}	7.29×10^{-4}	2.17×10^{-3}
	1 month	--------	3.36×10^{-4}	5.98×10^{-4}	9.35×10^{-4}
100	10 sec	0.28	1.00×10^{-1}	6.12×10^{-3}	3.85×10^{-1}
	100 sec	.091	6.30×10^{-2}	6.11×10^{-3}	1.59×10^{-1}
	500 sec	6.1×10^{-4}	4.54×10^{-2}	6.08×10^{-3}	5.21×10^{-2}
	1 hr	--------	2.47×10^{-2}	5.97×10^{-3}	3.06×10^{-2}
	1 day	--------	8.22×10^{-3}	5.78×10^{-3}	1.40×10^{-2}
	1 week	--------	3.49×10^{-3}	5.36×10^{-3}	8.85×10^{-3}
	1 month	--------	1.46×10^{-3}	4.62×10^{-3}	6.09×10^{-3}
	1 year	--------	1.40×10^{-4}	6.09×10^{-4}	7.49×10^{-4}
1000	10 sec	0.28	1.03×10^{-1}	1.28×10^{-2}	3.95×10^{-1}
	100 sec	.091	6.61×10^{-2}	1.28×10^{-2}	1.69×10^{-1}
	500 sec	6.1×10^{-4}	4.69×10^{-2}	1.27×10^{-2}	6.02×10^{-2}
	1 hr	--------	2.61×10^{-2}	1.26×10^{-2}	3.87×10^{-2}
	1 day	--------	9.67×10^{-3}	1.24×10^{-2}	2.20×10^{-2}
	1 week	--------	4.90×10^{-3}	1.17×10^{-2}	1.66×10^{-2}
	1 month	--------	2.72×10^{-3}	1.017×10^{-2}	1.29×10^{-2}
	1 year	--------	6.59×10^{-4}	1.34×10^{-3}	2.00×10^{-3}

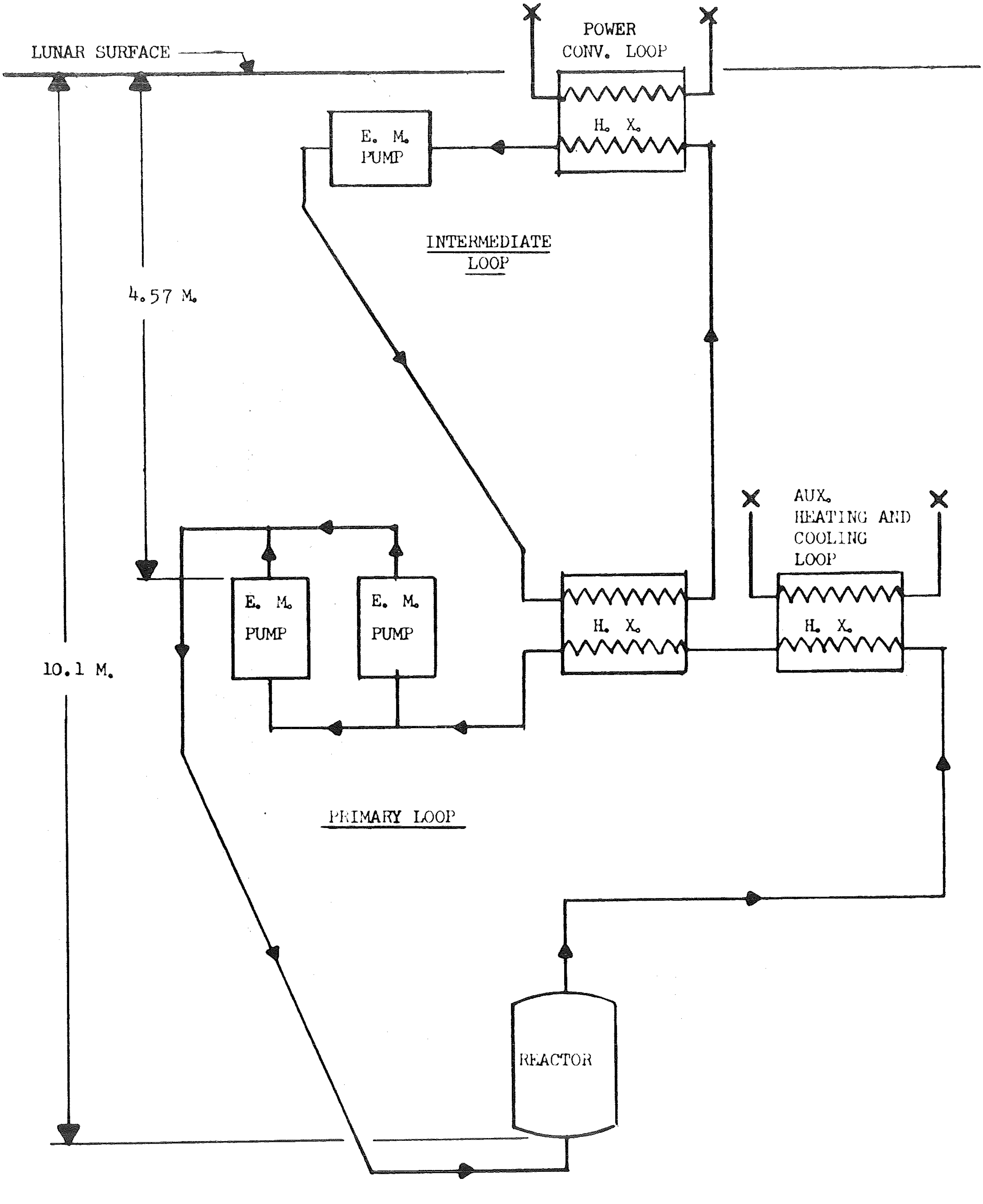

FIG. 1 REACTOR HEAT SOURCE SYSTEM SCHEMATIC

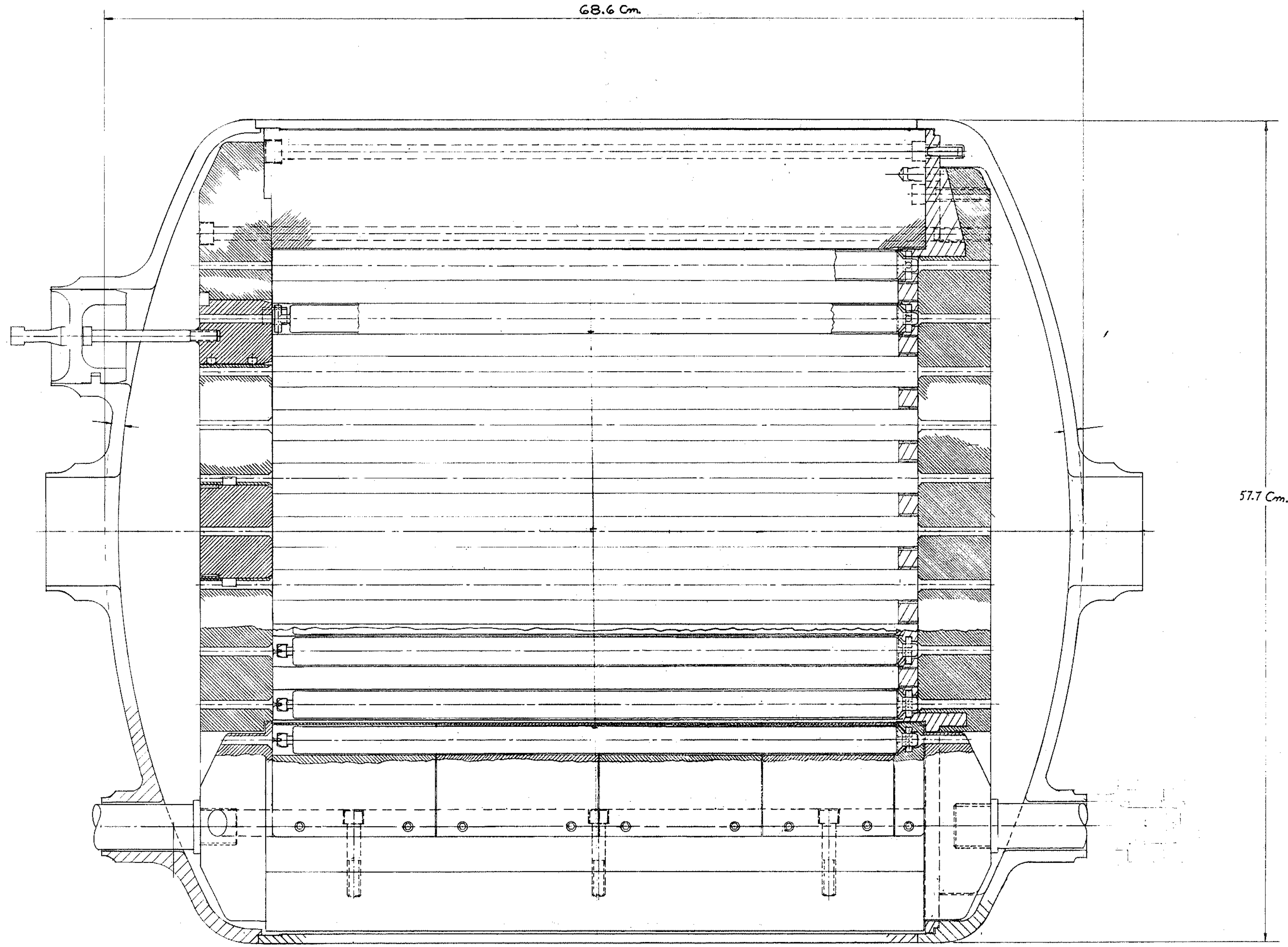

FIG. 2 COMPACT FAST SPECTRUM REACTOR

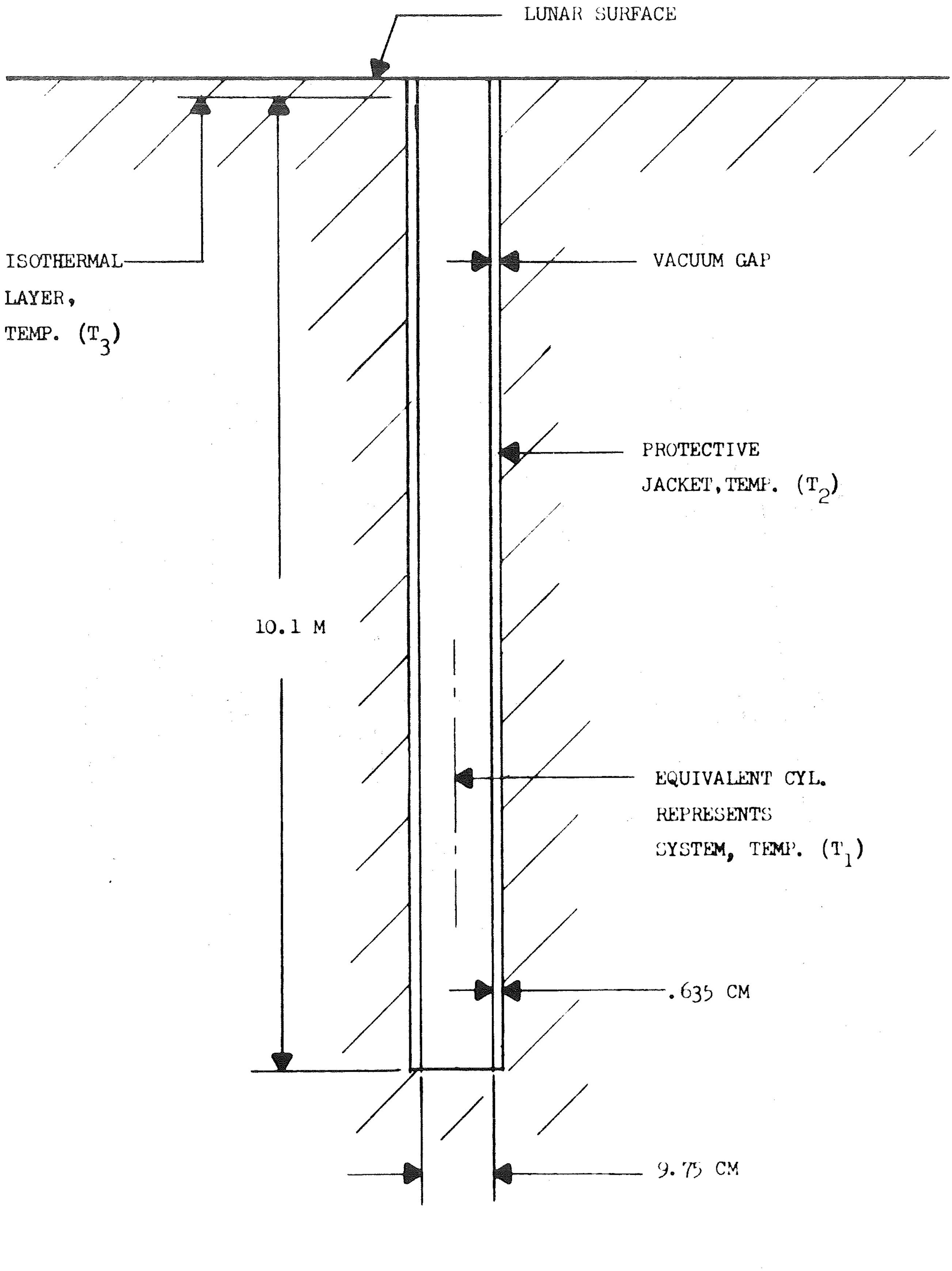

FIG. 3 HEAT TRANSFER MODEL FOR BURIED REACTOR

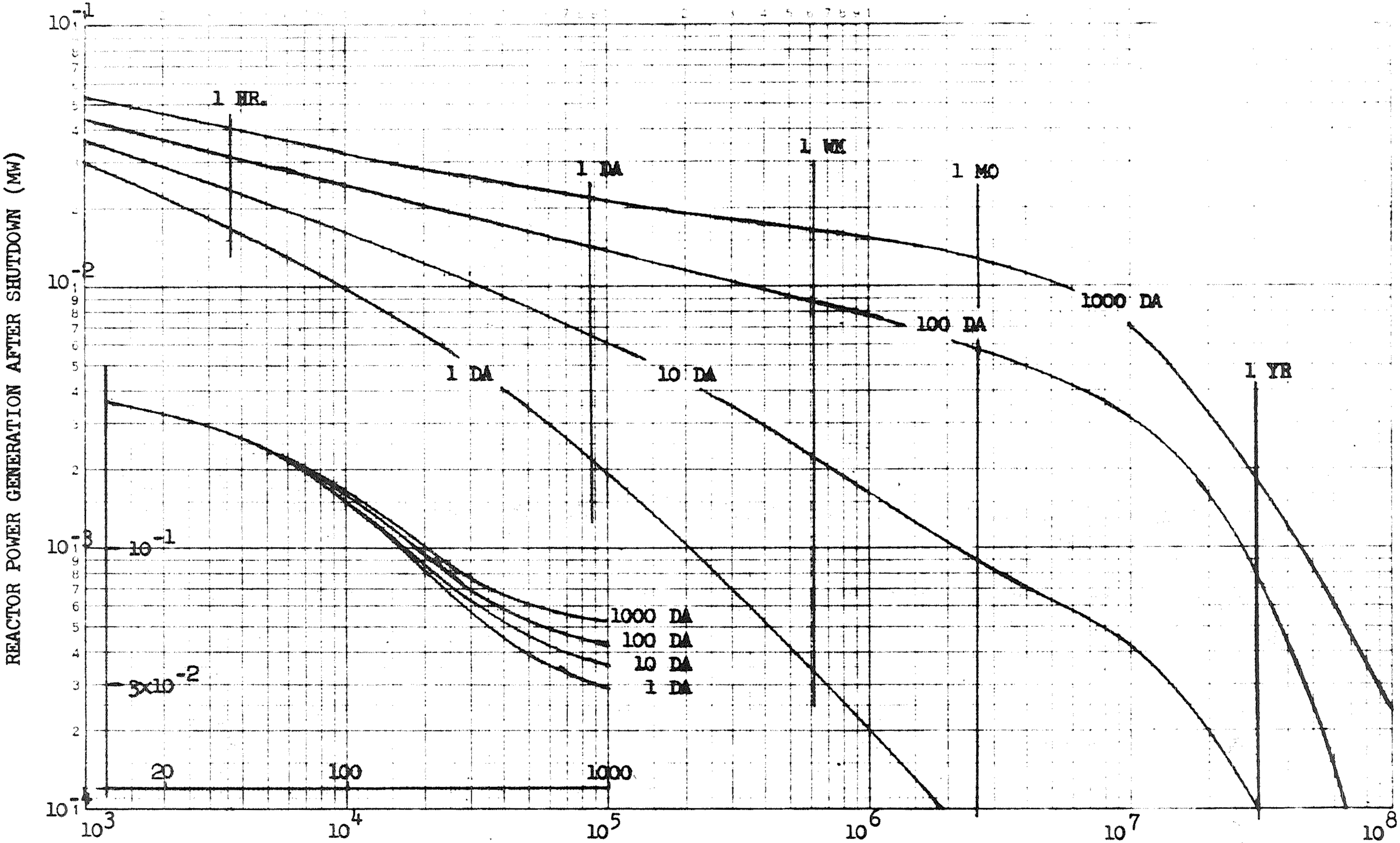

FIG. 4 REACTOR POWER AS A FUNCTION OF TIME AFTER SHUTDOWN FOR VARIOUS REACTOR OPERATING TIMES

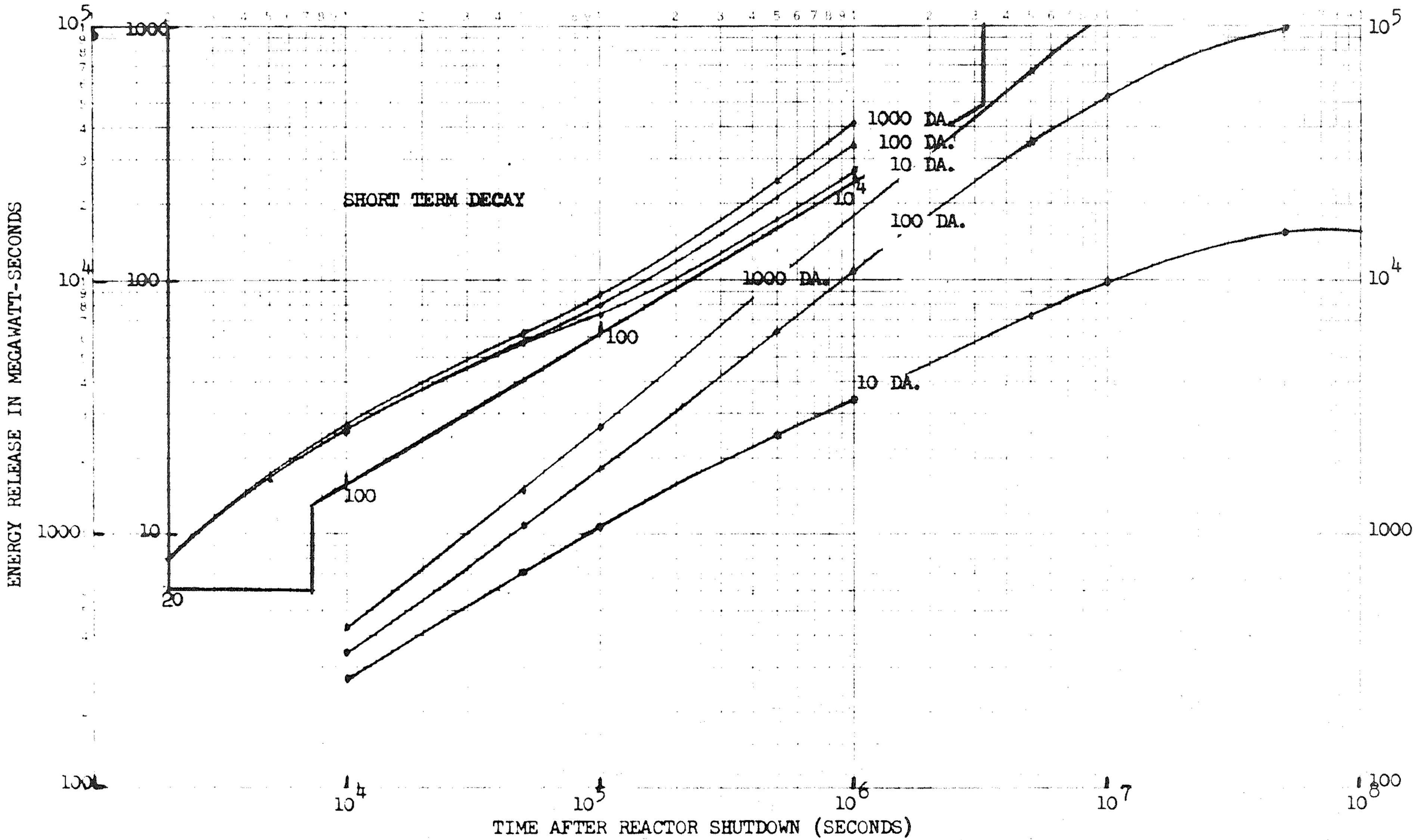

FIG. 5 TOTAL ENERGY RELEASE (INTEGRATED POWER) AS A FUNCTION OF TIME AFTER SHUTDOWN FOR VARIOUS REACTOR OPERATING TIMES

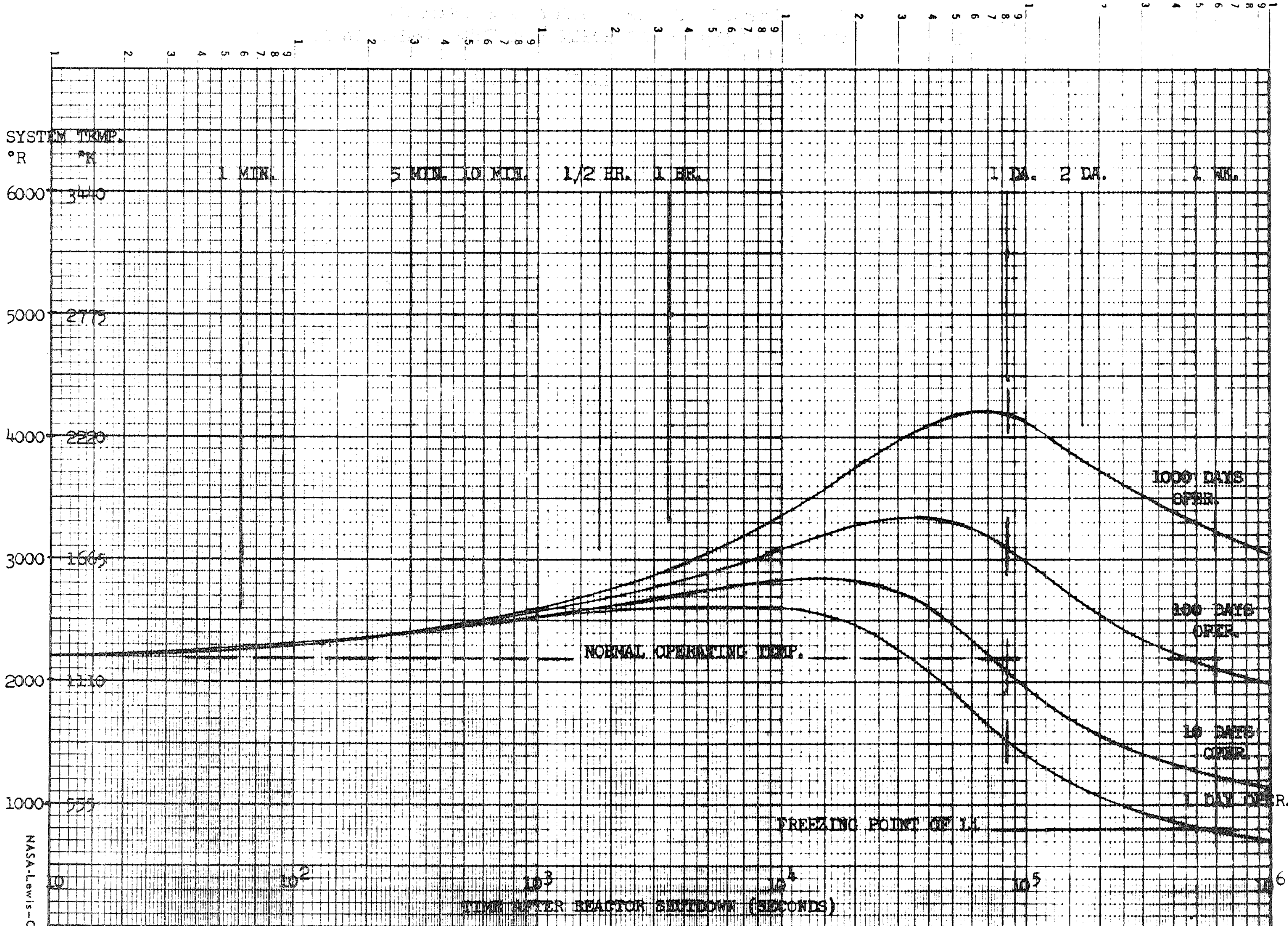

FIG. 6 REACTOR SYSTEM TEMP. VS. TIME AFTER SHUTDOWN