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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

The postshutdown cooling requirements were calculated for the tungsten water-moderated reactor concept. The reactor was assumed to have operated at full power for 1 hour. An amount equivalent to 5.25 percent of the hydrogen used during the operation at full power is required to remove the energy generated after shutdown.

The postshutdown cooling schedule requires continuous hydrogen flow for the first 1000 seconds followed by 23 pulsed cooling periods. The last hydrogen pulse occurs at 6.1 days after shutdown. The pulse flow rate is 0.3 pound per second (0.136 kg/sec) and the duration of the pulses range from 4250 seconds early in the schedule to 1300 seconds at later times.

INTRODUCTION

The concept of a nuclear rocket-engine system based on the use of a tungsten water-moderated reactor (TWMR) was originated at the Lewis Research Center. The TWMR is a thermal reactor that uses water as the moderator, uranium dioxide as the fuel, and tungsten enriched in tungsten 184 as the fuel-element structural material. As is common to all nuclear rocket-engine systems, hydrogen is used as the propellant to maximize specific impulse. The reactor (see fig. 1) consists of a tank containing a number of pressure tubes that are attached to tube sheets at the inlet and outlet ends of the reactor. The pressure tubes contain the fuel elements. The space inside the tank between the tubes is filled with water, which serves both as the neutron moderator and as a coolant

*Summer Faculty Fellow, 1966.

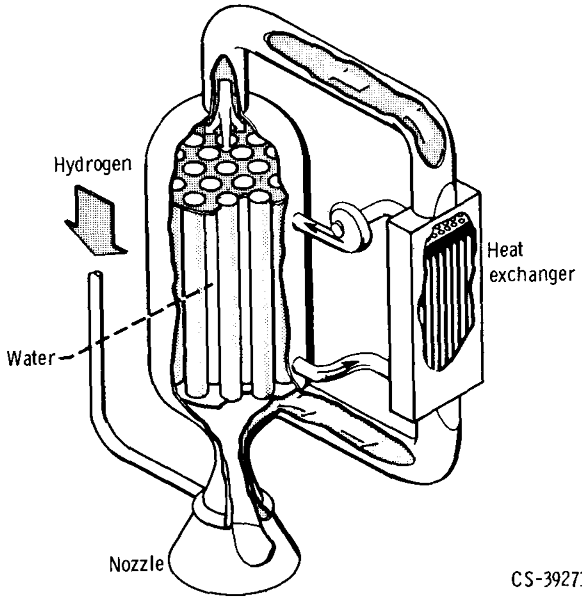


Figure 1. - Tungsten water-moderated reactor concept.

for the structure. Heat is generated in the water by neutrons and gamma rays and is also transferred to the water by heat leakage from the hot fuel elements, each of which is located in a pressure tube. The removal of heat is provided by pumping the water through the core and a heat exchanger in a closed loop. The water is regeneratively cooled in the heat exchanger by the hydrogen propellant, which flows from a supply tank through the nozzle and heat exchanger into the core. As the hydrogen flows through the core pressure tubes and through the fuel elements, it is heated to a high temperature and is expanded out the nozzle to produce thrust.

The potential advantages of the concept lie in the following areas: The use of tungsten provides a high-temperature material with good thermal shock resistance, tensile and compressive strength, thermal conductivity, and resistance to corrosion by the hydrogen propellant. The properties of tungsten also permit the fabrication of fuel elements with very thin cross sections for good heat transfer. The use of water as the moderator provides a good coolant for the pressure vessel and structural members and reduces core size and weight over that obtained for most moderator materials. In this concept, the fuel element assemblies are structurally independent of each other and thus permit individual development of these assemblies.

A program was undertaken at Lewis to investigate the engineering feasibility and performance of the TWMR nuclear rocket system. The results of these investigations are reported in references 1 to 7. This report gives the results of an analysis of aftercooling requirements performed as part of the TWMR program.

Nuclear rocket-engine systems that require restart capability must include provisions for cooling the reactor core and structure during postshutdown intervals. The energy that must be removed is deposited by delayed neutrons, beta particles, and gamma rays that are emitted from fission and activation products generated during reactor operation. Delayed neutron emission rapidly decreases to a negligible level. On the other hand, significant beta and gamma emission persists for a relatively long period of time after shutdown.

Aftercooling of the core and structure must be provided until either the engine is restarted or until the internal heat-generation rate decreases to a level that can be removed by thermal radiation to space without exceeding any component temperature limit.

SYSTEM OPERATING ASSUMPTIONS

A number of system operating assumptions were made for this analysis:

1. The bulk water temperature level must stay within the limits of 525° and 700° R (292° and 389° K). These limits are established to avoid freezing in the heat exchanger, on one hand, and remaining below the temperature at which the strength of the aluminum pressure tube begins to decrease rapidly (about 760° R or 422° K), on the other.

2. The fuel temperature is limited to the 5000° R (~2800° K) design temperature. This temperature limit was based on the strength capability of the fueled tungsten.

3. It was assumed that the hydrogen is gaseous when it enters the heat exchanger.

4. It was assumed that the water flow rate is continuous during the entire postshutdown period. A minimum water flow rate of 100 pounds per second (45.4 kg/sec) or about 10 percent of design flow was assumed. This flow rate ensures turbulent flow in the core and heat exchanger. It was further assumed that an auxiliary power system would supply the pumping power for this minimum flow rate.

5. Prior to shutdown it was assumed the reactor operated at the design power of 1540 megawatts for 1 hour. This operating time is of the order of the operating time required for a manned Mars mission for reactors of this design power.

ENERGY DEPOSITION IN FUEL

The kinetic energy of the fission fragments and energy from the absorption of beta and gamma emissions result in the heat generation in the fuel elements during reactor operation. The kinetic energy release is proportional to the fission rate in the fuel.

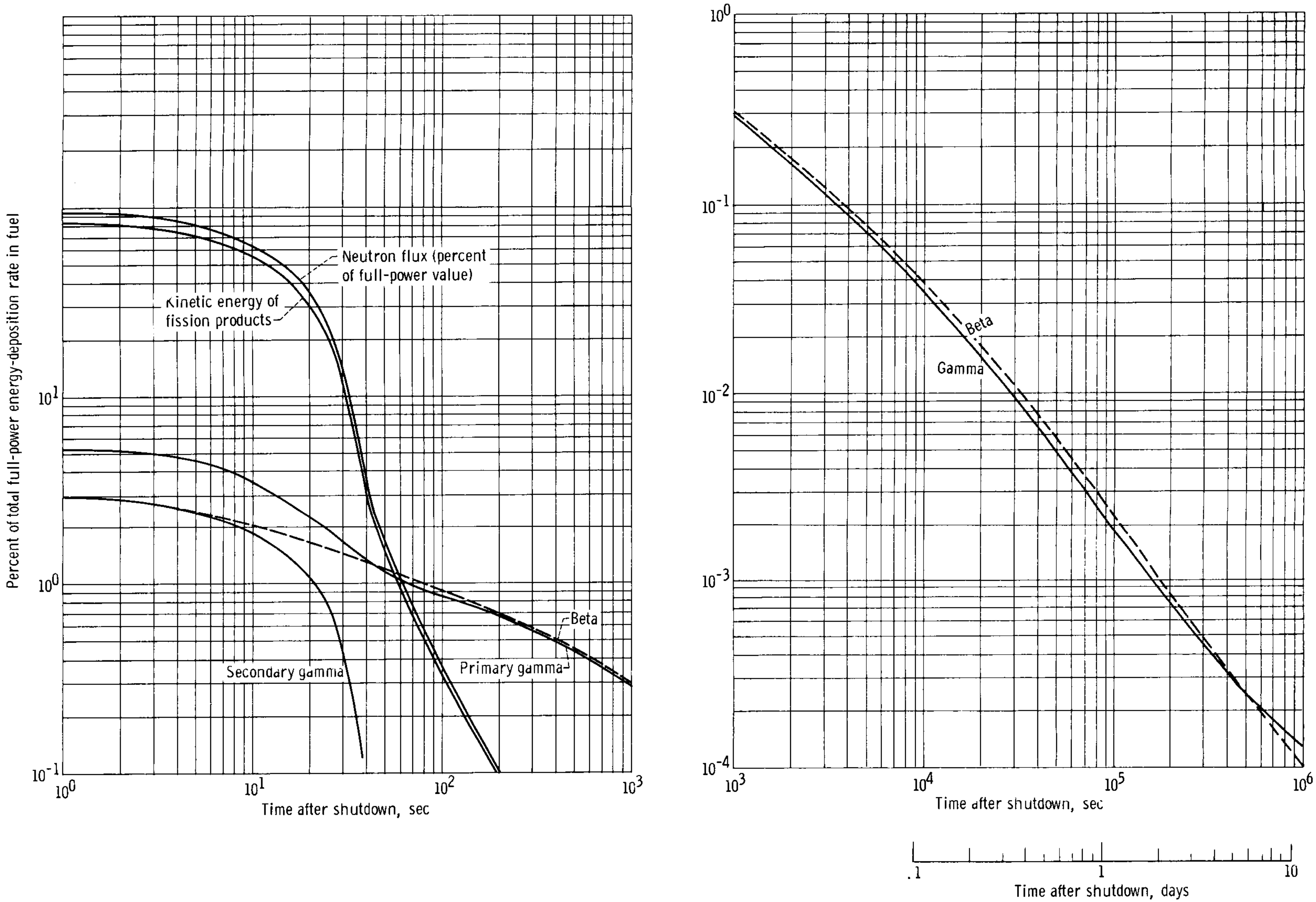
Beta particles originate from the decay of fission products and also from the decay of activation products generated by neutron capture in core materials. Gamma rays originate from the decay of fission products (primary gammas), from inelastic scattering and radiative capture of neutrons (secondary gammas), and from the decay of activation products. Both beta and gamma emissions from fission product decay persist for a long period of time after reactor shutdown. These two energy sources make it necessary to provide long-term aftercooling.

A shutdown schedule for the TWMR is presented in reference 8. For this study, the fission rate and secondary-gamma production rate during the shutdown transient are assumed proportional to the flux levels reported in reference 8. The heat-generation rate in the fuel resulting from the energy sources described above is shown in figure 2. Calculations have shown that beta- and gamma-energy deposition from activation products are negligible; hence, these energy sources have not been included in this analysis. Figure 3 shows the total energy-deposition rate in the fuel as a function of time after the initiation of reactor shutdown and represents the sum of the individual contributions shown in figure 2. In constructing these figures, a reactor operating time of 1 hour and a design power of 1540 megawatts was assumed.

The data detailing beta activity after shutdown were taken from reference 9. Primary- and secondary-gamma contributions were calculated at full power using the digital computer program ATHENA (ref. 10), which uses Monte Carlo techniques to determine radiation transport and heating. These detailed full-power calculations were used to determine the energy-deposition rates after shutdown. For the case of primary gammas, the energy-deposition rates after shutdown were assumed proportional to the source intensity:

$$\dot{Q}_t = \dot{Q}_{100\%} \times \frac{I_t}{I_{100\%}}$$

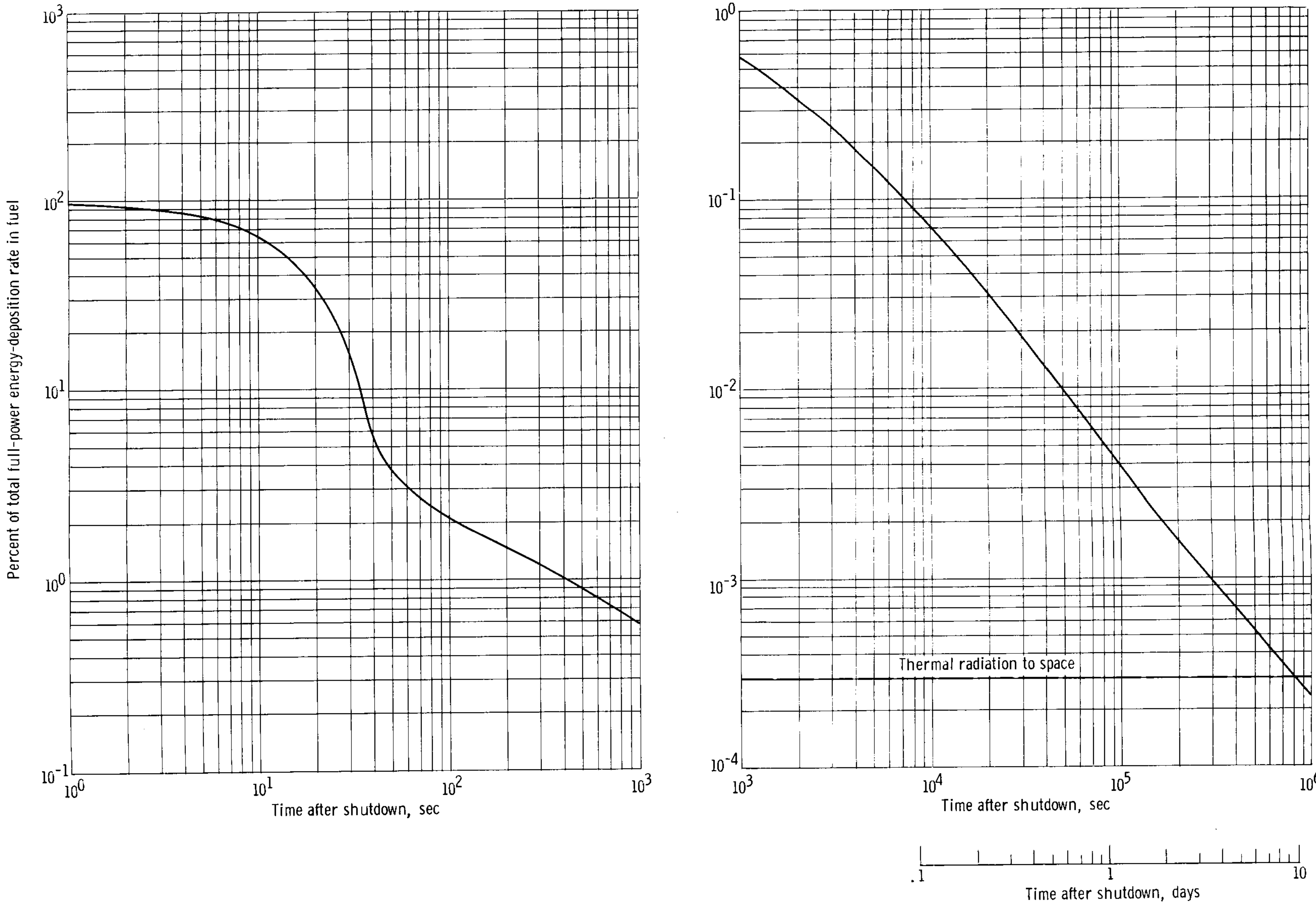
where $\dot{Q}_t$ is the energy-deposition rate at time t after shutdown, $\dot{Q}_{100\%}$ is the energy-deposition rate at full power, I_t is the primary-gamma source intensity at time t after shutdown, and $I_{100\%}$ is the primary-gamma source intensity at full power. Similarly, the secondary-gamma energy-deposition rates after shutdown were assumed proportional to the neutron flux level (which decays rapidly). The values of the primary-gamma source intensity for the first 9 hours after shutdown were taken from reference 11. For later times, the data from reference 9 was used after it was normalized to the data of reference 11 at 9 hours after shutdown. The primary and secondary gamma spectrum was assumed constant for these calculations.



(a) 1 to 1000 seconds after shutdown.

(b) 1000 to 1 000 000 seconds after shutdown.

Figure 2. - Energy deposition in fuel.



(a) 1 to 1000 seconds after shutdown.

(b) 1000 to 1 000 000 seconds after shutdown.

Figure 3. - Total energy-deposition rate in fuel.

ENERGY DEPOSITION IN WATER

Energy deposited in the water results from neutrons slowing down, gamma energy deposition from primary and secondary gammas both generated directly in the water and also in the water cooled structural members, and thermal leakage from the hot fuel elements. The thermal leakage consists of conduction and radiation from the fuel-element support tube across a gap containing stagnant hydrogen to the aluminum pressure tube during periods of hydrogen flow (see fig. 4). When hydrogen flow is terminated, the

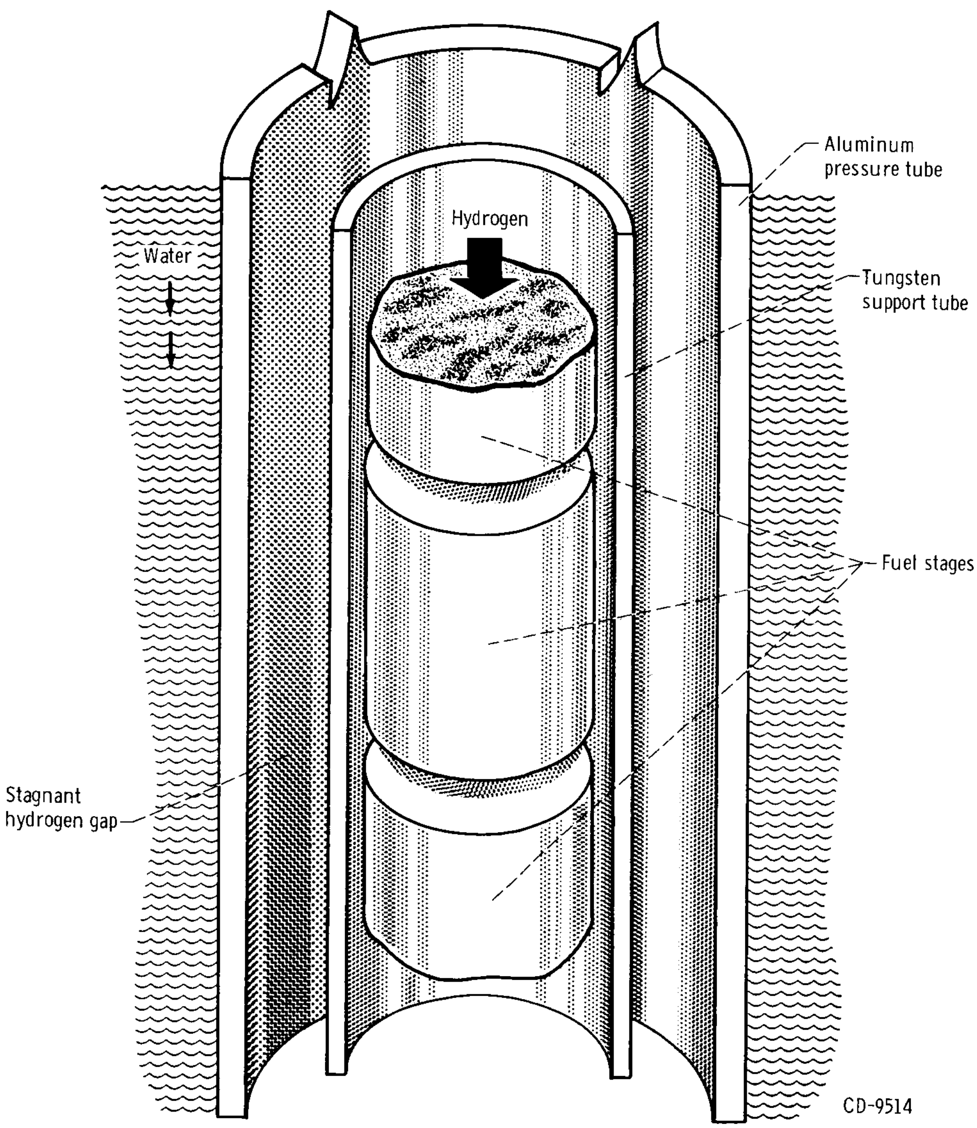


Figure 4. - Fuel assembly section.

hydrogen in the stagnant hydrogen gap is vented to space; hence, thermal radiation is the only heat-transfer mode from the support tube to the pressure tube during periods of no hydrogen flow.

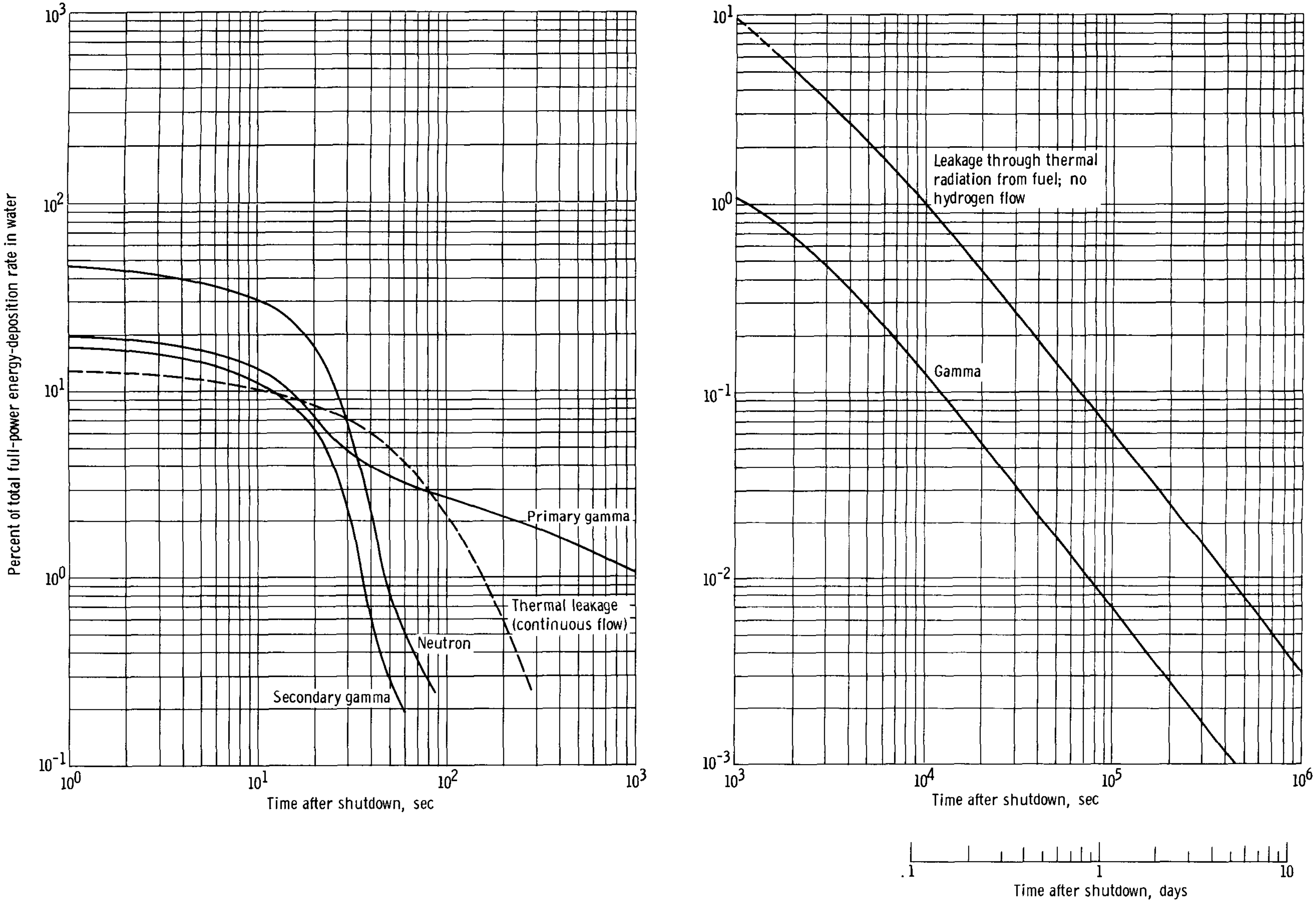
The total energy-deposition rate in the water at full power is 50 522 Btu per second (5.34×10^7 J/sec) or about 3.5 percent of the energy generated by the fuel elements. The breakdown of the energy deposition in the water at full power is as follows:

	Percent of Total
Neutron	48
Primary gamma	21
Secondary gamma	18
Thermal leakage	13

The time variation of these energy sources after shutdown is shown in figure 5. As shown in figure 5(a), the thermal leakage decreases to a negligible level during the continual flow phase. This decrease in leakage results from the fuel assemblies and support-tube temperature decreasing to a level not much higher than the aluminum pressure tube temperature. Thus, the driving force for heat transfer is small. When continuous flow is terminated, the temperature of the fuel assemblies increases and the thermal leakage to the water again becomes significant.

Similarly, the fuel assemblies cool down during periods of pulsed flow. The assumption was made that the thermal leakage during these flow periods is also negligible. After each flow pulse is terminated, the temperature of the fuel assemblies increases and the thermal leakage becomes significant. Figures 5(b) and (c) show the thermal leakage from the hot fuel assemblies during periods of no flow. Thermal leakage is shown as a continuous curve over the entire pulsed flow phase for convenience of presentation. Actually, the thermal leakage rates are discontinuous during periods of hydrogen flow. Figure 6 shows the total energy deposition rate after shutdown and represents the sum of the individual contributions shown in figure 5.

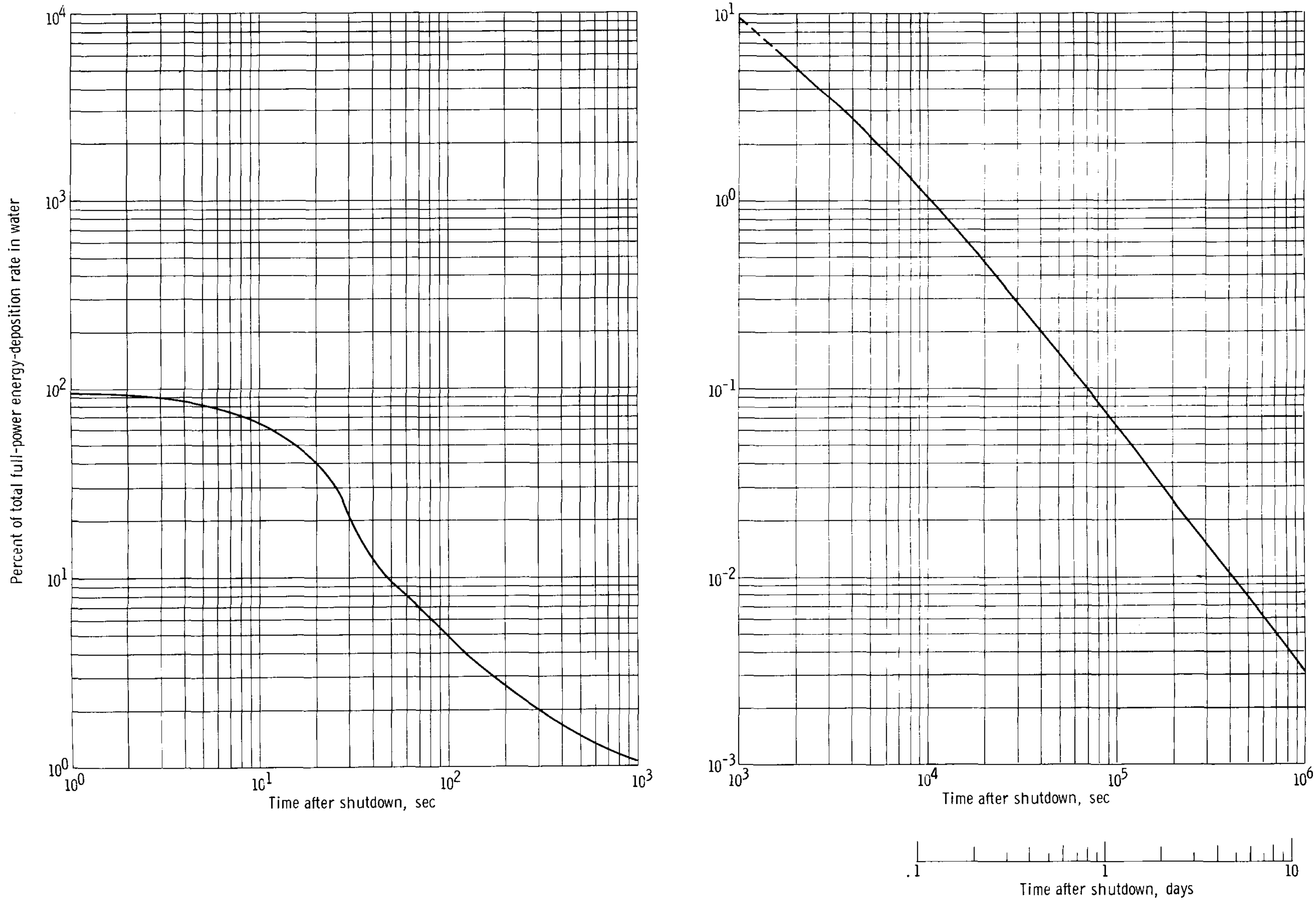
The neutron and secondary-gamma energy-deposition rates after shutdown were assumed proportional to the flux level shown in reference 8. The primary- and secondary-gamma energy-deposition rates at full power were calculated using the computer program ATHENA. These full-power values were used to determine the postshutdown values in a manner similar to that discussed in ENERGY DEPOSITION IN FUEL.



(a) 1 to 1000 seconds after shutdown.

(b) 1000 to 1 000 000 seconds after shutdown.

Figure 5. - Energy deposition in water.



(a) 1 to 1000 seconds after shutdown; continuous hydrogen flow.

(b) 1000 to 1 000 000 seconds after shutdown; pulsed flow.

Figure 6. - Total energy-deposition rate in water.

ENERGY REMOVAL

During power operation of the reactor, hydrogen removes the energy generated in the fuel assemblies and also the energy generated in and transferred to the water. The engine system was designed so that the temperature limits of both the critical water-cooled components and the fuel elements are approached but not exceeded during normal operation. During the first 1000 seconds of postshutdown operation, the fuel element temperature is limiting.

After 1000 seconds of postshutdown operation, however, the pressure-tube temperature limit dictates the energy removal requirements and thus determines the hydrogen flow schedule. During this period, calculations show that radiative heat transfer from the fuel is sufficient to keep the fuel elements below the maximum surface temperature limit; hence, convective cooling is not required after 1000 seconds. The results of these calculations are presented on figure 7, which shows the calculated maximum fuel temperatures as a function of power for the case when there is no hydrogen flow. These calculations were based on radiative heat transfer from the fuel assemblies to the pressure tube with convective heat transfer to the water. The calculations show that, at powers less than 0.58 percent, (1000 seconds after shutdown, see fig. 3), the fuel temperature will not exceed 5000° R (~ 2800° K); hence, convective cooling of the fuel elements is not required at lower power levels. However, cooling of the water is required at lower powers.

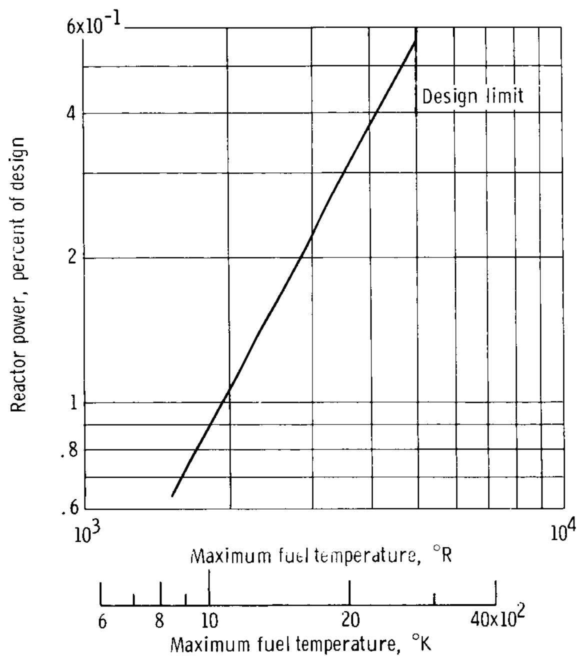


Figure 7. - Maximum fuel temperature at low power with no hydrogen flow.

All hydrogen coolant flow can cease when the energy radiated to space equals the energy generated in the reactor. The energy that can be radiated to space is 3×10^{-4} percent of full power as shown in appendix A. The heat-generation rate decays to this value 800 000 seconds (about 9 days) after shutdown as shown on figure 3.

POSTSHUTDOWN COOLING SCHEDULE

Continuous Flow Phase

Continuous hydrogen flow is required for the first 1000 seconds after shutdown. The flow rate is proportional to the power generated in the fuel from shutdown until the power decreases to about 25 percent of full power. At lower power levels, the relative hydrogen flow must be greater than the relative power to ensure turbulent flow in the core as shown in figure 8. Turbulent flow is desired in all flow passages at low power levels to avoid unstable flow conditions that may result in laminar flow in some of the channels and turbulent flow in other channels and that cause high fuel temperatures in the channels

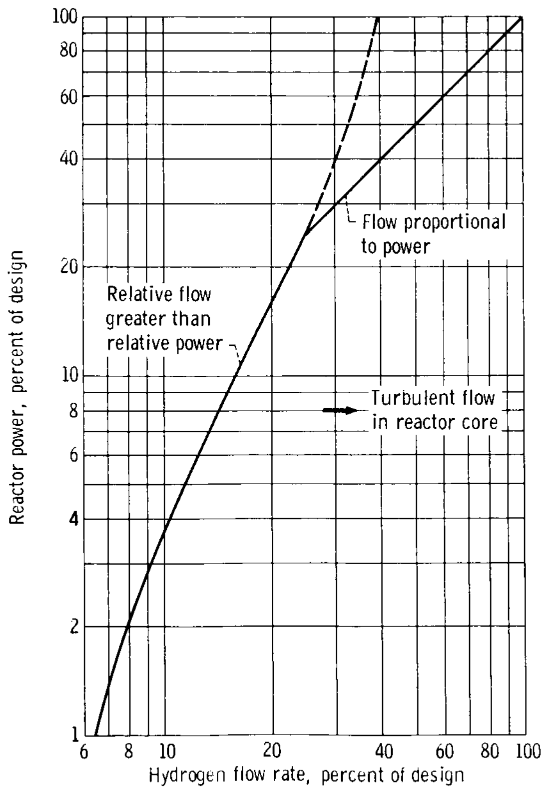


Figure 8. - Flow required for turbulent flow in fuel as function of power level.

with laminar or reduced flow rates. The water flow rate during the first 1000 seconds after shutdown is assumed to be proportional to the hydrogen flow rate.

Pulsed Flow Phase

After the first 1000 seconds, a pulsed hydrogen flow schedule can provide the required cooling to remove the heat from the water. The calculated pulse schedule is shown in table I. There are a total of 23 pulsed flow periods required ranging from 1300

TABLE I. - HYDROGEN FLOW SCHEDULE DURING PULSED FLOW PHASE

Time at which flow is terminated, sec after shutdowns	Duration of no-flow period, sec (a)	Time at which flow is initiated, sec after shutdown	Flow pulse duration, sec (b)
[c]1 000	300	1 300	4250
5 550	450	6 000	1750
7 750	750	8 500	1550
10 050	1 000	11 050	1475
12 525	1 300	13 825	1300
15 125	1 625	16 750	↓
18 050	2 100	20 150	
21 450	2 650	24 100	
25 400	3 400	28 800	
30 100	4 500	34 600	
35 900	4 900	40 800	
42 100	6 100	48 200	
49 500	7 500	57 200	
58 500	9 800	68 300	
69 600	12 000	81 600	
82 900	15 300	98 200	
99 500	19 200	118 700	
120 000	25 300	145 300	
146 600	31 000	177 600	
178 900	43 300	222 200	
223 500	60 700	284 700	
286 000	88 900	374 400	
375 700	150 000	525 700	↓

[a]Length of time for water to increase its temperature from 525° to 700° R (292° to 389° K). Total heat transferred to water through thermal leakage from hot fuel assembly is 483 000 Btu (5.1×10^{8} J) for each no hydrogen flow period.

[b]Flow rate, 0.3 lb/sec (0.136 kg/sec).

[c]Time at which the continuous flow phase is terminated.

seconds to 4250 seconds. The last pulse terminates at 527 000 seconds (6.1 days) after shutdown with the water temperature at 525° R (292° K). The main storage tank pressure provides the driving force for the hydrogen flow during the pulse flow phase. At the end of 800 000 seconds, when the energy radiated to space is equal to the internal generation rate, the water temperature reaches a temperature of 700° R (389° K). In calculating the pulsed flow schedule, it was assumed that, for each pulse, the hydrogen flow would be initiated when the water temperature reaches 700° R (389° K) and terminated when the temperature decreases to 525° R (292° K). In addition to cooling the water, the hydrogen causes a temperature decrease in the fuel assemblies and piping and structural components in the hydrogen flow path. During periods of no hydrogen flow, it was assumed that one-half of the energy generated in the fuel is transferred to the water and the other half remains as sensible heat in the fuel assemblies and structural members (see appendix B).

Heat Exchanger Operation

It is assumed in this analysis that turbulent hydrogen flow through the heat exchanger is desired to avoid the possibility of laminar flow instability. Turbulent hydrogen flow can be maintained at a flow rate as low as 0.3 pound per second (0.136 kg/sec) or 0.32 percent of design flow.

The operating characteristics of the heat exchanger are such that it operates more efficiently at lower hydrogen flow rates. Figure 9 shows that the energy removal per pound (or kg) of hydrogen decreases with increasing flow rate. Thus, for most efficient

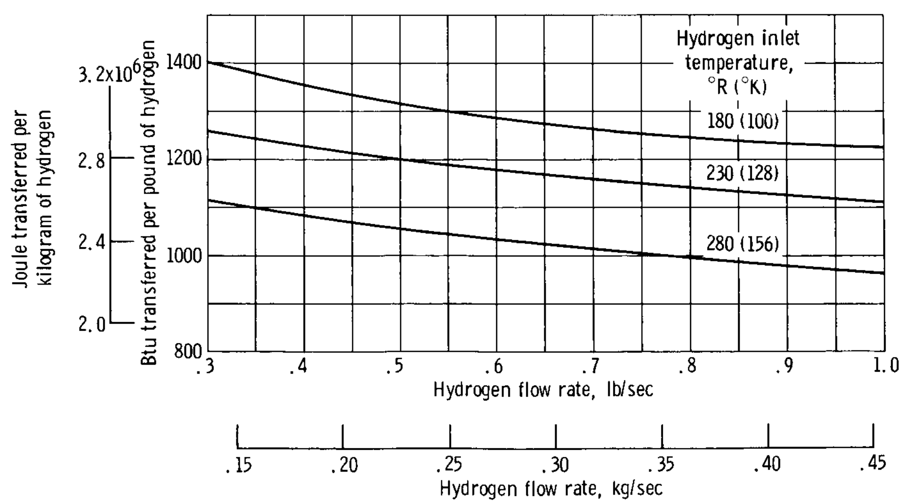


Figure 9. - Variation of heat exchanger effectiveness with flow rate and inlet temperature.

operation, the flow rate during pulse periods should be maintained as low as possible (e.g., 0.3 lb/sec or 0.136 kg/sec). A water flow rate of 100 pounds per second (45.5 kg/sec) was assumed during the entire pulsed flow phase. A heat exchanger hydrogen-inlet temperature of 230° R (128° K) was used in the analysis of the pulse flow requirement.

Total Postshutdown Hydrogen Flow

The flow rate during the first 1000 seconds is shown on figure 10. Integrating the continuous flow rate and the pulsed flow periods results in a total hydrogen coolant requirement equivalent to 5.25 percent of the total hydrogen used during the hour of full-power operation.

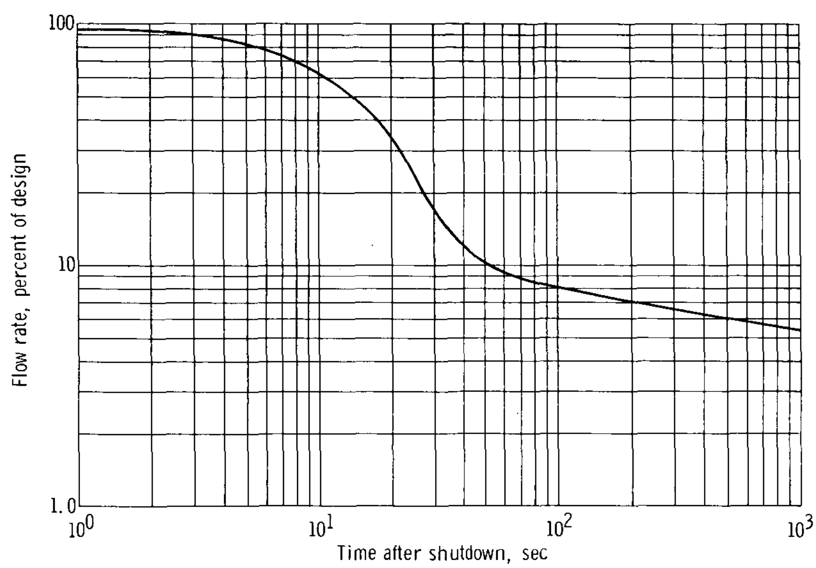


Figure 10. - Hydrogen flow rate 1 to 1000 seconds after shutdown. 100 Percent flow, 92.7 lb/sec (42.1 kg/sec).

CONCLUDING REMARKS

The cooling of the TWMR after the 1-hour operation at the design power of 1540 megawatts can be accomplished by continuous cooling for the first 1000 seconds after shutdown followed by an intermittent pulsed cooling schedule. Cooling of the fuel elements controls the flow schedule for the first 1000 seconds after shutdown; thereafter, cooling of the water is the controlling factor. The last cooling pulse occurs at 6.1 days after shutdown. After the first 1000 seconds, a water flow rate of 100 pounds per second (45.5 kg/sec) is required during the entire aftercooling phase. An amount equivalent to 5.25 percent of the hydrogen expended during full-power operation is required to provide the aftercooling.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 18, 1967,
122-28-02-04-22.

APPENDIX A

RADIATION TO SPACE FROM THE PRESSURE VESSEL

The following equation describes the radiation from the pressure vessel.

$$q = 2\pi r L \epsilon \sigma \left(T^4_{source} - T^4_{sink}\right)$$

where q is the energy radiated, r is the radius of the pressure vessel, L is the length of the pressure vessel, ϵ is the emissivity, σ is the Stefan-Boltzmann constant, T_{source} is the absolute temperature of the pressure vessel, and T_{sink} is the absolute temperature of the sink. The following values are representative of the TWMR:

Radius of pressure vessel, r, ft; m	2.065; 0.63
Length of pressure vessel, L, ft; m	4.57; 1.39
Emissivity, ϵ	0.9
Stefan-Boltzmann constant, σ, Btu/(sec)(ft^2)(^{o}R^4); W/(m^2)(^{o}K^4)	4.75×10^{-13}; 5.67×10^{-8}
Absolute temperature of pressure vessel, T_{source}, ^{o}R; ^{o}K	660; 367
Absolute temperature of sink, T_{sink}, ^{o}R; ^{o}K	400; 222

The energy radiated from the reactor vessel is 4.2 Btu per second (4.43×10^3 J/sec) or about 3×10^{-4} percent of full power. Therefore, where the total energy generated in the core has dropped below 3×10^{-4} percent of the full-power value, no additional hydrogen flow is required.

APPENDIX B

DISTRIBUTION OF ENERGY GENERATED IN FUEL ASSEMBLIES DURING PERIODS OF NO HYDROGEN FLOW

During the pulsed flow phase, not only does the hydrogen coolant remove energy from the water in the heat exchanger, but also it removes energy from the fuel assemblies, piping, upper headers, and other structure. During periods of no hydrogen flow, the energy deposited in the fuel assemblies by the beta particles and gamma rays causes an increase in the temperature of the fuel assemblies and, through several heat-transfer modes, causes an increase in the temperature of the water and structural components.

The length of time between hydrogen pulses is dictated by the time required to raise the temperature of the 2760 pounds (1255 kg) of water from 525° R to 700° R (292° K to 389° K). The energy deposited in the water results from internal heat generation by gamma rays and from thermal radiation from the hot fuel assemblies to the pressure tubes with subsequent convective heat transfer to the water. The thermal radiation is dependent on the temperature history of the fuel assemblies which, in turn, is dependent on the distribution of the energy generated in the fuel. The distribution of the energy generated in the fuel assemblies during periods of no hydrogen flow can be estimated as follows:

(1) Water temperature: The energy required to raise the water temperature from 525° to 700° R (292° to 389° K) is about 483 000 Btu (5.1×10^{8} J). For this estimate, it is assumed that the gamma energy deposition in the water (which is about an order of magnitude less than the thermal leakage) is negligible and is not included.

(2) Sensible heat of fuel: For an average temperature change of 2000° R (1110° K) in the fuel assembly, the energy required for the 121 fuel assemblies is 237 000 Btu (2.5×10^{8} J). For this estimate, a mass of 28 pounds (12.7 kg) for a fuel assembly (including tungsten, uranium dioxide, and stainless-steel components) and a heat capacity of 0.035 Btu per pound per $^{\circ}$R (1.46×10^{2} J/(kg)($^{\circ}$K)) are assumed.

(3) Sensible heat of piping, upper headers, and other structures: Although it is not known how much energy is deposited in these components, a reasonable assumption is that they absorb an amount of energy equivalent to that absorbed by the fuel (237 000 Btu or 2.5×10^{8} J). Hence, of the total energy generated in the fuel during the time that the temperature of the water is increasing from 525° to 700° R (292° to 389° K), about half is deposited in the water. The length of time between pulses increases with time after shutdown because of the decreasing rate of energy deposition as shown in table I.

It is recognized that the assumptions in items 2 and 3 may be questionable. If the assumptions are too high, more energy would be transferred to the water with the result that additional hydrogen coolant would be required. However, the effect upon the total postshutdown cooling requirement is small. For example, let it be assumed that the energy absorbed in the fuel, piping, and upper headers is each as much as 25 percent too high. Then the amount of hydrogen required to cool the water during the pulsed flow phase would be 20 percent greater (the hydrogen requirement during the continual flow phase is not affected by these assumptions). Because 58 percent of the total aftercooling flow is expended during the pulse flow phase, about 12 percent more total aftercooling flow would be required (a total amount equivalent to 5.9 percent of the hydrogen expended during full-power operation instead of 5.25 percent).

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