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Heat Removal System for Shutdown in Nuclear Thermal Rockets and Advanced Concepts

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PACS numbers:

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Nomenclature

A_c = cross-sectional area of heat exchanger

A_s = surface area for radiative heat transfer

A_0 = a constant

A_1 = a constant

a = acceleration

c_p = coolant specific heat capacity

f_c = coolant volume fraction in the core

f_h = hydrogen volume fraction in the core

g = planetary gravity

I_{sp} = specific impulse

M_o = total mass of the vehicle

m_c = mass of HRS coolant inside the core

m_r = mass of HRS coolant outside the core

m_{hrs} = total mass of the HRS

m_t = total HRS coolant mass

$\dot{m}$ = propellant mass flow rate before shutdown

$\dot{m}_d$ = propellant mass flow rate after shutdown

n = n times the gravity of the planet or moon

P_d = delayed power generation

P_o = reactor power before shutdown

ΔP = pressure drop over the core

p = pressure

Δp = pressure drop over heat exchanger

R = heat exchanger outer radius

R_o = rocket radius

r = radial coordinate

T = temperature of propellant

T_c = outlet temperature of coolant

$\overline{T_c}$ = average temperature of coolant

T_d = thrust after shutdown

T_f = fuel temperature

T_i = inlet temperature of coolant

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T_o = thrust before shutdown

ΔT = difference between outlet and inlet coolant temperature

t = time elapsed since shutdown

t_o = time at power before shutdown

V = average coolant velocity

V_{core} = volume of the core

ΔV = change of vehicle velocity

v_e = exhaust velocity of propellant

β = fraction delayed neutrons

γ = heat decay fraction of the nominal power, $\frac{P_d}{P_o}$

δ = gap thickness

ϵ = emissivity

μ = viscosity

ρ_c = coolant density

σ = Stefan-Boltzmann constant

I. INTRODUCTION

It is well-known that a nuclear thermal rocket (NTR) cannot be abruptly shut down. After a power manoeuver, the reactor has contaminated itself with fission products and the decay heat released must be removed by maintaining an adequate flow of hydrogen through its passages.

The objective of this work was to derive a first estimate of how much hydrogen will be needed to prevent the core from overheating after shutdown, and, from this, be able to assess the advantages of using a dedicated decay heat removal system to reduce or eliminate the amount of hydrogen needed to prevent the core from overheating after shutdown. Furthermore, the use of such a heat removal system could be needed by certain special nuclear thermal propulsion concepts, such as the fission fragment rocket [1] or the more recently proposed pulsed nuclear thermal rocket [2], where significant amplification of specific impulse, I_{sp}, as well as thrust can be obtained by the direct use of fission fragments or by pulsing the nuclear core, respectively.

II. HYDROGEN NEEDED TO PREVENT THE CORE OVERHEATING AFTER A MANEUVER

Many semi-empirical formulations for decay heat after shutdown in a nuclear reactor are available, but in view of the uncertainties in the context considered here and for preliminary estimate purposes, the simplest expression, due to Way and Wigner [3], known as the Wigner-Way formula, which is valid from 10 seconds to 100 days after shutdown, seems appropriate:

$$P_d(t) = 0.0622 P_o \left[t^{-\frac{1}{5}} - (t_o + t)^{-\frac{1}{5}} \right] \tag{1}$$

where P_d is the power generation due to beta particles and gamma rays, P_o is the reactor power before shutdown, t_o is the time, in seconds, of operation at this power before shutdown, and t is elapsed time since shutdown, in seconds.

From this relationship, we can assess the hydrogen needed for "aftercooling" of the nuclear-rocket engine after shutdown. To begin with, we need to calculate the total decay heat power after shutdown, which, according to Eq. (1), depends on the power P_o and time t_o used during the previous maneuver (with the nuclear-rocket engine operating at nominal power). There are two important cases to consider, as follows.

A. Case I: In-space Orbital Maneuver

Let us first consider an in-space orbital maneuver and neglect the gravitational acceleration of planetary or moon bodies. The maneuver consists of a change of velocity ΔV. If the acceleration a is assumed constant during the maneuver, then it is given by

$$a = \frac{\dot{m} v_e}{M_o} \tag{2}$$

where $\dot{m}$ is the mass flow rate of the propellant (hydrogen) during the maneuver, v_e is the exhaust velocity of the propellant, and M_o is the total mass of the vehicle, which is assumed constant, i.e. the mass of propellant ejected during the maneuver is assumed to be negligible compared to M_o.

The time t_o needed for such a maneuver is given by $a t_o = \Delta V$, which results in the following relationship:

$$t_o = \frac{\Delta V M_o}{\dot{m} v_e} \tag{3}$$

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Noting that the thrust, T_o, is given by $T_o = \dot{m}v_e$, then t_o may be rewritten as

$$t_o = \frac{\Delta V M_o}{T_o} \tag{4}$$

The rate at which kinetic energy is being put into the jet, which equals the reactor power, is given by

$$P_o = \frac{1}{2}\dot{m}v_e^2 \tag{5}$$

or

$$P_o = \frac{1}{2}T_o v_e \tag{6}$$

Inserting Eqs. (6) and (4) into Eq. (1) yields

$$P_d(t) = 0.0311 T_o v_e \left[t^{-\frac{1}{5}} - \left(\frac{\Delta V M_o}{T_o} + t \right)^{-\frac{1}{5}} \right] \tag{7}$$

This decay heat power must be removed by exhausting additional propellant to prevent the core overheating. Therefore, according to Eq. (5), the mass flow rate of propellant needed during decay heat removal after shutdown, $\dot{m}_d$, is given by

$$\dot{m}_d(t) = \frac{2P_d(t)}{v_e^2} \tag{8}$$

which combined with Eq. (7) yields

$$\dot{m}_d(t) = 0.0622 \frac{T_o}{v_e} \left[t^{-\frac{1}{5}} - \left(\frac{\Delta V M_o}{T_o} + t \right)^{-\frac{1}{5}} \right] \tag{9}$$

By integration of Eq. (9) one obtains the total mass of propellant $m_d(t)$ needed for cooling the reactor over a period of time t after a shutdown:

$$m_d(t) = 0.0622 \frac{T_o}{v_e} \int_{t_{\min}}^{t} \left[t^{-\frac{1}{5}} - \left(\frac{\Delta V M_o}{T_o} + t \right)^{-\frac{1}{5}} \right] dt \tag{10}$$

where $t_{\min}$ is 10 seconds, the lower limit of the range of validity of the Wigner-Way formula (Eq. (1)), and t is also in seconds and must be less than 8.64×10^6 seconds (100 days), the upper limit of the range of validity of the Wigner-Way formula. In practice, t will be the time at which the

power falls to a level where other means of heat removal (conduction and radiation) are sufficient to cool the core. Performing this integral, we obtain

$$m_d(t) = 0.0778 \frac{T_o}{v_e} \left[\left(\frac{\Delta V M_o}{T_o} + 10 \right)^{\frac{4}{5}} - 10^{\frac{4}{5}} + t^{\frac{4}{5}} - \left(\frac{\Delta V M_o}{T_o} + t \right)^{\frac{4}{5}} \right] \tag{11}$$

Of course, the core will also need to be cooled over the first 10 seconds following shutdown. Eq. (11) therefore represents a slight underestimate of the amount of propellant required.

B. Case II: Lift-off or Landing on a Planet or Moon

An interesting case to consider is during lift-off, or landing on a planet or moon, where high thrust is essential and a NTR is more attractive than other options. For this case, let us consider that our rocket with initial mass M_o and propellant exhaust velocity v_e is working with a total acceleration, say, ng, i.e. n times the gravitational acceleration of the given planet g, where n is in the range 2–5. The thrust is given by

$$T_o = M_o ng \tag{12}$$

and then Eq. (11) becomes

$$\frac{m_d(t)}{M_o} = 0.0778 \frac{ng}{v_e} \left[\left(\frac{\Delta V}{ng} + 10 \right)^{\frac{4}{5}} - 10^{\frac{4}{5}} + t^{\frac{4}{5}} - \left(\frac{\Delta V}{ng} + t \right)^{\frac{4}{5}} \right] \tag{13}$$

This hydrogen will continue generating thrust at a decreasing rate, and contributing to the final velocity of the space vehicle, and this must be taken into account in the calculations.

The decreasing thrust is calculated as $T_d(t) = \dot{m}_d(t) v_e$, which, using Eq. (9), can be expressed as

$$T_d(t) = 0.0622 T_o \left[t^{-\frac{1}{5}} - \left(\frac{\Delta V M_o}{T_o} + t \right)^{-\frac{1}{5}} \right] \tag{14}$$

and for the lift-off maneuver becomes

$$T_d(t) = 0.0622 M_o ng \left[t^{-\frac{1}{5}} - \left(\frac{\Delta V}{ng} + t \right)^{-\frac{1}{5}} \right] \tag{15}$$
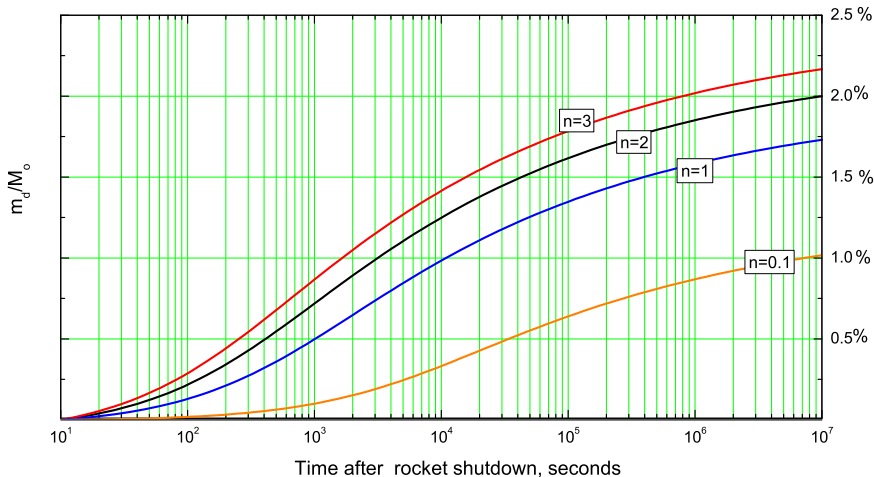
FIG. 1: Propellant required for cooling the nuclear rocket after a LEO maneuver.

C. Discussion

To obtain some idea of the shape of the curve predicted by Eq. (13), let us consider a Mars Design Reference Mission. In this, a large launch vehicle of ~100 tonnes is placed in low Earth orbit (LEO) ($\Delta V = 9.3$ km/s). Also, let us take the maximum exhaust velocity for a solid NTR to be 9 km/s or thereabouts. The resulting curves are shown in Fig. 1 using several values of acceleration.

As can be seen from this figure, the propellant mass as a percentage of the mass of the vehicle is independent of the mass of the vehicle and only depends on the acceleration and ΔV. The hydrogen needed to prevent the core from overheating is about 2% of the total vehicle mass. The specified mass of the NERVA NTR when full was more than 178,000 kg. 2% of this is 3560 kg.

III. FEASIBILITY OF USING A DEDICATED HEAT REMOVAL SYSTEM

It is interesting to assess the advantages of using a dedicated residual heat removal system (HRS) to reduce or eliminate the amount of hydrogen needed to prevent the core overheating after shutdown. The advantages of using a HRS must primarily be weighed against the additional space-craft mass incurred as a result of incorporating this auxiliary cooling system into the vehicle. In this section, we perform some calculations on the mass requirements of the system. Although these are admittedly very simplified calculations, nevertheless, they will allow us to gain an important insight into the mass of the system.

The additional HRS mass can be estimated using the fact that the total mass of the HRS will primarily depend on two factors, namely: (a) the inventory of coolant mass used, and (b) the mass of the pumping equipment. Let us examine these two factors separately.

A.   Coolant Mass Inventory

Let us consider the schematic shown in Fig. 2 for the calculation of the total mass of coolant needed. In this, for the sake of generality, a flat circular design is selected as the most simple heat exchanger for radiative heat removal. Coolant is entering the core with a temperature T_i and, after being heated in the core by an amount ΔT, is exiting at an outlet temperature

$$T_c = T_i + \Delta T \tag{16}$$

To a good approximation $T_c \simeq T_f$, where T_f is the fuel temperature, and thus $\Delta T \simeq T_f - T_i$.

The total coolant mass inventory in the HRS can be divided into two contributions, namely: the coolant in the core, m_c, and the coolant circulating outside the core (i.e. in the exchanger), m_r. Thus, the total coolant mass inventory m_t is given by

$$m_t = m_c + m_r \tag{17}$$

To calculate the coolant inventory outside the core, we proceed as follows.

First, let us calculate the pressure drop in the exchanger depicted in Fig. 2. For the one-dimensional viscous flow in cylindrical co-ordinates, the momentum equation yields [4]:

$$\frac{dp}{dr} = \frac{12\mu V}{\delta^2} \tag{18}$$

where p is pressure, r the radial coordinate, μ the coolant viscosity, V the average velocity of the coolant inside the exchanger, and δ the gap thickness, as depicted in Fig. 2.

However, by continuity:

$$\dot{m}_c = \rho_c V A_c = \rho_c V 2\pi r \delta \tag{19}$$

where $\dot{m}_c$, ρ_c and A_c are the coolant mass flow rate, density and heat exchanger local cross-sectional area, respectively.
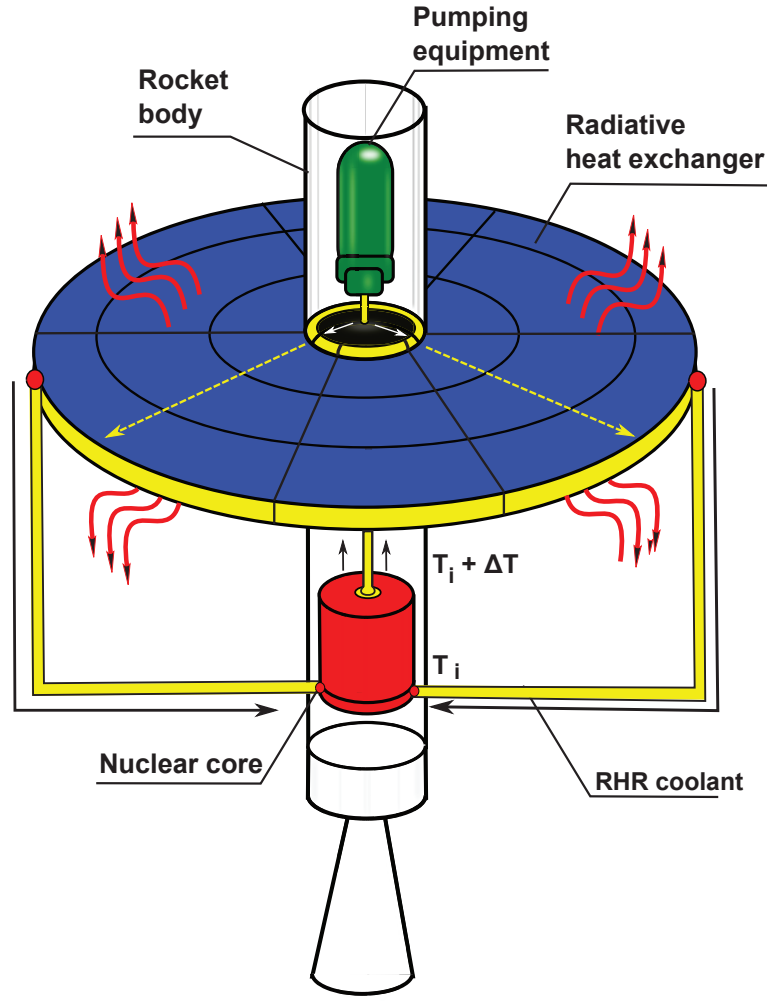
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FIG. 2: Schematic of HRS coolant exchanger for the pressure drop calculation.

The coolant mass flow rate is given by the overall energy balance condition for heat removal:

$$\dot{m}_c = \frac{P_d}{c_p \Delta T} \qquad (20)$$

where c_p is the coolant specific heat capacity, and ΔT is, as defined above, the difference between

the core inlet and outlet coolant temperatures. Thus, the coolant velocity varies with radius according to

$$V = \frac{P_d}{2\pi r \delta \rho_c c_p \Delta T} \tag{21}$$

For the sake of generality, it is convenient to express the decay power P_d as a function of the nominal power P_o before shutdown:

$$P_d = \gamma P_o \tag{22}$$

Then Eq. (20) can be expressed as

$$\dot{m}_c = \frac{\gamma P_o}{c_p \Delta T} \tag{23}$$

In this way, we can calculate the coolant mass requirement for a HRS working at nominal power, i.e. $\gamma = 1$ (e.g. for a fission fragment rocket [1] or a pulsed NTR [2]), or only for decay heat removal after shutdown, for propellant saving purposes, as discussed in previous sections. In the latter case $\gamma \simeq 0.06$ or 6% of the nominal power immediately after shutdown.

Combining Eqs. (21) and (22):

$$V = \frac{\gamma P_o}{2\pi r \delta \rho_c c_p \Delta T} \tag{24}$$

Eq. (18) then becomes

$$\frac{dp}{dr} = \frac{6\mu\gamma P_o}{\pi r \delta^3 \rho_c c_p \Delta T} \tag{25}$$

This equation, integrated between the internal radius of the exchanger (which in our simple model is the radius of the rocket) $r = R_o$ and the external radius $r = R$, yields the required pressure difference to sustain the flow:

$$\Delta p = \frac{6\mu\gamma P_o}{\pi \delta^3 \rho_c c_p \Delta T} \ln\left(\frac{R}{R_o}\right) \tag{26}$$

Noting that $R \gg \delta$, the available heat transfer surface area is given by

$$A_s \simeq 2\pi \left(R^2 - R_o^2\right) \tag{27}$$

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with the factor of 2 taking into account the fact that there are two available surfaces (upper and lower). Using this relationship to substitute for R in Eq. (26), and then solving for the gap thickness of the heat exchanger yields:

$$\delta = \left[\frac{3\mu\gamma P_o}{\pi\rho_c c_p \Delta T \Delta p} \ln \left\{ \frac{A_s}{2\pi R_o^2} + 1 \right\} \right]^{\frac{1}{3}} \tag{28}$$

The total mass of coolant circulating within the exchanger is calculated as $m_r = \frac{1}{2}\rho_c A_s \delta$, which, using Eq. (28), results in:

$$m_r = \frac{\rho_c A_s}{2} \left[\frac{3\mu\gamma P_o}{\pi\rho_c c_p \Delta T \Delta p} \ln \left\{ \frac{A_s}{2\pi R_o^2} + 1 \right\} \right]^{\frac{1}{3}} \tag{29}$$

Energy balance requires that the energy produced per unit time in the core must be radiated into space by the HRS. The local coolant temperature within the heat exchanger is, to a good approximation, the temperature at which the HRS is initially radiating into space. Therefore

$$\gamma P_o = \epsilon\sigma \left(\overline{T_c}^4 - T_\nu^4 \right) A_s \tag{30}$$

where ϵ is the HRS emissivity, σ is the Stefan-Boltzmann constant, $\overline{T_c}$ is the appropriate average value of the coolant temperature, A_s is, as before, the radiative heat transfer area of the vehicle, and T_ν is the local radiation temperature, which is just a few degrees Kelvin far from the Sun, and thus, to a good approximation, T_ν^4 can be neglected in comparison to $\overline{T_c}^4$.

It is desirable to maximize the gain in temperature in the coolant in order to increase the rate of radiative heat transfer to empty space. Taking into account the fact that this temperature must be less than or equal to the temperature of the fuel, T_f, i.e. $\overline{T_c} < T_c \le T_f$, and that, as discussed, $\Delta T \simeq T_f - T_i$, and assuming that $\epsilon = 1$, which is a valid approximation if working with high temperatures, Eq. (30) may be rewritten as

$$A_s = \frac{\gamma P_o}{\sigma \overline{T_c}^4} \tag{31}$$

which, when inserted into Eq. (29), gives

$$m_r = \frac{\rho_c \gamma P_o}{2\sigma \overline{T_c}^4} \left[\frac{3\mu\gamma P_o}{\pi\rho_c c_p \Delta T \Delta p} \ln \left\{ \frac{\gamma P_o}{2\pi\sigma \overline{T_c}^4 R_o^2} + 1 \right\} \right]^{\frac{1}{3}} \tag{32}$$

Finally, we need an estimate of the mass of coolant inside the core, m_c. This can be approxi-

mately inferred by the following reasoning.

The volume of coolant inside the core will be a fraction of the total volume of the core, V_{core}. Denoting this fraction f_c, then we have

$$m_c = f_c \, \rho_c V_{\text{core}} \tag{33}$$

If the propellant (hydrogen) channels are also used as coolant channels for the HRS after shutdown, then f_c will equal the fraction of propellant (hydrogen) used in the core, f_h. Even if it is necessary to use dedicated coolant channels, e.g. as in the pulsed NTR concept [2], f_h could be taken as an upper limit for f_c for the HRS. Thus, if the assumption that $f_c \leq f_h$ is accepted as reasonable, Eq. (33) becomes

$$m_c \leq f_h \, \rho_c V_{\text{core}} \tag{34}$$

The volume fraction of hydrogen in an NTR is mostly determined by neutronic considerations. Because the hydrogen used as the propellant is also used as a moderator, a specific volume ratio between the volume of hydrogen V_h (as moderator) and the volume of fuel V_f is needed in order to thermalize neutrons. This ratio is $\frac{V_h}{V_f} \simeq 1.5$ or thereabouts, meaning that $f_h \simeq 0.6$.

Thus, Eq. (17) can be rewritten as

$$m_t \simeq f_h \, \rho_c V_{\text{core}} + \frac{\rho_c \gamma P_o}{2\sigma \overline{T}_c^4} \left[\frac{3\mu\gamma P_o}{\pi \rho_c c_p \Delta T \Delta p} \ln \left\{ \frac{\gamma P_o}{2\pi\sigma \overline{T}_c^4 R_o^2} + 1 \right\} \right]^{\frac{1}{3}} \tag{35}$$

B. Pumping Equipment Mass

The second factor to be considered is the mass of the pumping equipment, m_p, which includes the pump, piping and valves associated with the pump and turbine-drive system. For an NTR, this mass can be estimated by the following functional relationship [5]:

$$m_p = A_1 \frac{\dot{m}_c}{\rho_c} \Delta P^{\frac{2}{3}} + A_0 \tag{36}$$

where $\dot{m}_c$ is the coolant mass flow rate, ρ_c the coolant density, ΔP the pressure drop over the core, A_1 a constant of value $A_1 = 0.049 \text{ kg-s m}^{-3} \text{Pa}^{-\frac{2}{3}}$, and A_0 a constant of value $A_0 = 50$ kg included to take into account the reality that a pump-turbine system for nearly zero flow rate will still have a finite mass.

The coolant mass flow rate $\dot{m}_c$ is calculated using Eq. (23), which, when inserted into Eq. (36), gives

$$m_p = A_1 \frac{\gamma P_o}{c_p \rho_c \Delta T} \Delta P^{\frac{2}{3}} + A_0 \tag{37}$$

The total mass of the HRS including the coolant, m_{hrs}, is given by

$$m_{\mathrm{hrs}} = m_t + m_p \tag{38}$$

which, using Eqs. (37) and (35), yields

$$m_{\mathrm{hrs}} \simeq f_h\, \rho_c V_{\mathrm{core}} + \frac{\rho_c \gamma P_o}{2\sigma \overline{T}_c^4} \left[\frac{3\mu\gamma P_o}{\pi \rho_c c_p \Delta T \Delta p} \ln\left\{ \frac{\gamma P_o}{2\pi\sigma \overline{T}_c^4 R_o^2} + 1 \right\} \right]^{\frac{1}{3}} + A_1 \frac{\gamma P_o}{c_p \rho_c \Delta T} \Delta P^{\frac{2}{3}} + A_0 \tag{39}$$

To obtain an estimate of the mass of the HRS predicted by Eq. (39), we assume some typical values of the parameters: For a nuclear core of radius 0.25 m and length 0.75 m (somewhat similar to a NERVA nuclear core), the resulting core volume is $V_{\mathrm{core}} \simeq 0.15$ m^3; with $f_h = 0.6$ (as discussed above); $\sigma = 5.670 \times 10^{-8}$ W m^{-2} K^{-4}; $T_f \simeq 3000$ K, which is close to the maximum melting temperature of some nuclear fuels investigated; a rocket radius $R_o = 3$ m; a maximum permissible coolant core and heat exchanger pressure drop of 1.0 MPa [6]; $A_1 = 0.049$ kg-s m^{-3} Pa$^{-\frac{2}{3}}$ and $A_0 = 50$ kg [5]. Choosing lithium as the most suitable coolant for space applications [2, 7], we have $\rho_c = 400$ kg m^{-3}, $c_p = 4169$ J kg^{-1} K^{-1} and $\mu = 0.14 \times 10^{-3}$ kg m^{-1} s^{-1}; and we take the coolant inlet temperature T_i to be the melting temperature of lithium, i.e. $T_i \simeq 500$ K.

Finally, the coolant temperature falls as it circulates in the HRS and heat is radiated into space. However, for a HRS with a very small gap thickness, i.e. $\delta \to 0$ (which is desirable in order to minimize the inventory of coolant inside the exchanger), each radial element of coolant circulating inside the exchanger will store a very small amount of sensible heat per unit radial length (dr). If the initial temperature of the coolant is high enough, which is the case if $T_c \simeq T_f \simeq 3000$ K, then the coolant temperature would reduce rapidly. So, if it is allowable to assume that $\overline{T}_c \simeq \frac{T_f}{2}$, the resulting relationship between HRS mass and power is as shown in Fig. 3.

Noting that the power immediately after shutdown P_d is about 6% of the reactor power before shutdown according to Eq. (1), then, for a Phoebus-2A-like reactor, which delivered over 4000 MW of thermal energy within the NERVA/Rover programme, for $\gamma = 0.06$, $P_d = 240$ MW, and thus Fig. 3 shows that the required HRS mass would be ~200 kg. Although the value calculated is,
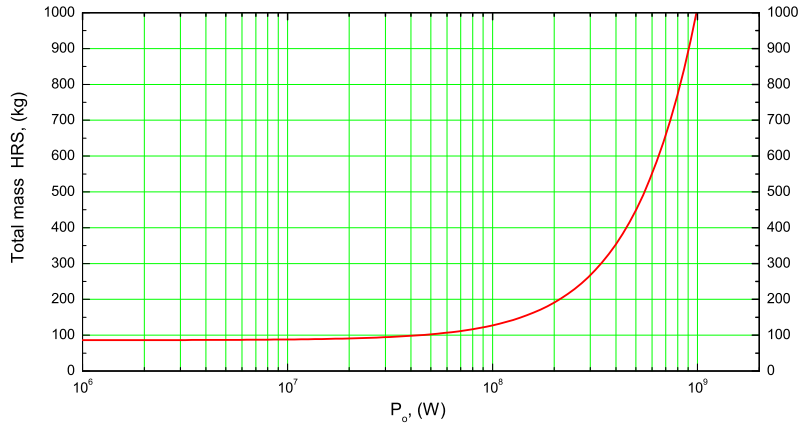
FIG. 3: HRS mass as a function of power calculated using Eq. (39).

admittedly, a very rough estimation, in which some factors contributing to the mass of the system, such as the structure of the heat exchanger, the thickness of its walls, etc. have not been considered, nevertheless this allows us to gain some insight into realistic values for HRS mass. To stay on the safe side, let us assume the true mass of the HRS is double this figure, i.e. ∼400 kg. This is just 11% of the mass of hydrogen (propellant) estimated to be required for NTR cooling purposes in subsection II C. It seems as if a dedicated HRS is certainly worth considering.

C.   HRS for Fission Fragment and Pulsed NTR Concepts

There are at least two known nuclear rockets concepts which demand the use of a dedicated HRS for heat removal when working at nominal power. One of these is the fission fragment rocket [1] and the other the pulsed NTR [2]. In the former, due to isotropic emission, the fission fragments not terminating inside the propellant deposit energy inside the reactor walls, and thus cooling the walls coated with fissioning fuel is crucial [8]. In the latter, if the pulsed NTR is intended for specific impulse (I_{sp}) magnification, then all the fission fragment energy is unwanted and must be removed by an auxiliary system.

For both concepts, if we assume a nominal power on the order of 1 GW, then, according to Fig. 3, the HRS mass requirements should be ∼1 ton. To be on the safe side, we can assume a mass an order of magnitude larger than the calculated figure, i.e. ∼10 tons. Although this might seem a prohibitively large figure, it must be borne in mind that, for these concepts, the magnification in I_{sp} can be 2–3 times or even more (depending of the reduction in radiative losses inside the core). With such I_{sp} magnification factors and because of the strong dependence of the propellant mass

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needed on I_{sp}, the reduction in the mass of propellant required to, say, lift 100 tons of payload into LEO will be ∼100 tons.

D. Delayed Neutrons Flux After Shutdown

In the preceding sections, only the heat generated after shutdown from the radioactive decay of fission products was considered and the fission heat from delayed neutrons was neglected. This is a valid approximation after a few minutes, because the heat generated from fission products reduces much more slowly than the fission heat from delayed neutrons. However, the delayed neutrons resulting from fission occurring before shutdown continue to be released and have an important effect on the neutron flux and heat generation rate immediately after the reactor is shut down [9], and must therefore be considered in the calculation of the mass requirements for a HRS.

If, as before, P_o is the reactor power before shutdown, then the power at time t after the insertion of negative reactivity due to fission heat from delayed neutrons $P_n(t)$ is given by [9]

$$\frac{P_n(t)}{P_o} \simeq \frac{\beta}{\beta - \rho} \exp\left(\frac{-t}{80\,(\mathrm{s})}\right)$$ (40)

where β is the fraction of delayed neutrons, and ρ the negative reactivity inserted.

This expression gives an idea of the variation of fission heat power after shutdown by the rapid insertion of control rods, producing a large negative step change in reactivity. For instance, assuming $\rho = -0.1$, which is about as large a value as can be realized in a reactor [9], and noting that β is 0.0065 for uranium-235, the resulting power ratio will initially be about 0.06, i.e. the fission heat power will be 6% of the steady-state, pre-shutdown, value.

This figure is very similar to the power from the decay of fission fragments immediately after shutdown. Thus, to be on the safe side, by doubling the value of the delayed power P_d used in Eq. (39), we will approximately double the estimated mass requirements for our HRS, i.e. ∼800 kg, rather than ∼400 kg. Even so, a dedicated HRS is still worth serious consideration based on the estimates presented here.

IV. CONCLUSIONS

An estimate of the propellant needed for shutdown aftercooling in nuclear thermal reactors and the feasibility of using a dedicated heat removal system was analyzed. Some interesting conclusions are drawn by this study as follows:

(a) Up to a 2% of the total mass of the spacecraft in hydrogen will be wasted in a LEO manoeuver after shutdown of the nuclear core. This non-negligible hydrogen mass overcomes by far the unavoidable hydrogen boil-off losses.

(b) By using a dedicated heat removal system, this sacrificed hydrogen could be saved and used more properly for propulsion.

(c) Mass requirements of a dedicated heat removal system when it is weighed against the propellant saving gained makes a very attractive option.

(c) The attractiveness of a dedicated heat removal system in NTRs is even higher if used in advanced nuclear rocket concepts as the fission fragment rocket or pulsed NTRs, where the gain in propellant would be not just by aftercooling saving but also from the magnification in I_{sp}

Acknowledgments

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