NUCLEAR ROCKET ENGINE AFTERHEAT REMOVAL

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Abstract

An analysis of the open cycle technique for the removal of afterheat from a nuclear rocket engine is presented because of its application to early space vehicles.

The Way-Wigner equation for the generation of beta and gamma particles is used with an expression for the attenuation of delayed neutrons for afterheat prediction. Coolant flow for afterheat removal is determined as a function of system temperature rise and is established for typical nuclear rocket operating times.

It is concluded that when engine system temperatures during shutdown are low, coolant losses charged to afterheat removal will have a significant effect upon payload.

Introduction

Heat is generated in a nuclear rocket engine during shutdown due to the decay of fission products. This heat must be removed in a manner which prevents engine system damage if later restart is required or if recovery for examination or reuse is to be attempted. A technique for adequately removing afterheat is analyzed in this paper and payload penalties which will be encountered due to afterheat removal are evaluated. The analysis is directed toward flight applications because of current interest in this topic; however, the technique is applicable to ground-based systems as well.

Nomenclature

\[ \begin{align*}
A & \quad \text{Wetted area} \\
c & \quad \text{Average specific heat of "heat sink"}
\end{align*} \]

in. \(^2\)

b/\(\text{lb} - ^\circ\text{F}\)

121
**Rocket Reactor Model**

A schematic representation of the engine system used for this analysis is presented in Fig. 1. For simplicity, pumps, shields, piping, and control devices have been omitted. The coolant flow is depicted as passing through a regeneratively cooled nozzle, a reflector, a pressure shell, and then through the reactor core. It is obvious that as the afterheat is generated, those items nearest the heat source will absorb most of the afterheat.

**Afterheat Generation**

The decay products are composed of delayed neutrons, lasting for a few seconds, and beta and gamma rays. The Way-Wigner afterheat equation has been used to determine beta and gamma decay power as a function of operating time, \( t_o \), and shutdown time, \( t_s \):
Fig. 1. Typical Nuclear Rocket Engine.
\[
\frac{P_s}{P_0} = 6.6 \times 10^{-2} \left[ t_s^{-0.2} - (t_o + t_s)^{-0.2} \right] \quad (1)
\]

Eq. 2 represents the delayed neutron contribution as a function of shutdown reactivity and delayed neutron fraction (1):

\[
\frac{P_s}{P_0} = \frac{D \gamma t_s}{1 - D} \quad (2)
\]

The total afterheat power is obtained by combining Eqs. 1 and 2. With the assumption that shutdown reactivity is $7$, Fig. 2 presents the total afterheat power. As will be noted, the delayed neutron power becomes negligible after about 100 seconds shutdown time and may be neglected thereafter. Operating times of 300 and 1000 seconds shown in the figure are typical of nuclear rocket engine operation.

The total afterheat is obtained from integration of Eqs. 1 and 2:

\[
\frac{Q_T}{P_0} = \int_0^\infty \left\{ 6.6 \times 10^{-2} \left[ t_s^{-0.2} - (t_o + t_s)^{-0.2} \right] + \frac{D \gamma t_s}{1 - D} \right\} dt_s \quad (3)
\]

By again assuming a step change in reactivity of $7$, the solution of Eq. 3 is obtained in terms of operating time:

\[
\frac{Q_T}{P_0} = 8.25 t_o^{0.8} + 1.271 \quad (4)
\]

Eq. 4 is shown graphically in Fig. 3. Note that for an operating time of 300 seconds, the total afterheat is 9 seconds which is 3% of the energy generated during operation.

**Selection of Cycle**

The scheduling of afterheat removal is primarily a system requirement. For purposes of classification, the removal methods are grouped as follows:

1. Open cycle
2. Closed cycle
3. Combination open and closed cycle
Fig. 2. Reactor Power During Shutdown.
Fig. 3. Potential Afterheat at Reactor Shutdown.
In the open cycle, coolant* is expelled through the engine system at a predetermined rate until the remaining heat generated can be absorbed or disposed of by the system. One of the disadvantages of the open cycle is that coolant flows of from 5 - 20% of the total propellant flow may be required. Another disadvantage of the open cycle is the large variation in coolant flow rate which may be as high as $10^{-3}$ or $10^{-6}$ of that required for full power operation. One solution to this problem is the intermediate storage of the generated heat in the system itself with periodic removal while operating the pump at its minimum flow rate. The main advantages of the open cycle are its relative simplicity and light weight because existing system components are utilized.

The closed cycle has the obvious advantage in that coolant is not expended. On the other hand, it requires the use of a radiator which becomes very heavy as power dissipation requirements increase. Another problem associated with the closed cycle is the conversion from an "open cycle" during power operation to a closed system for cooldown. The provision for closing the nozzle and diverting the coolant is by no means a simple problem. It is probable that some form of nozzle plug would be required to effect the closure. An advantage of the closed cycle is that it provides a heat source for the production of auxiliary power. If required, the reactor could continue to operate at a low power level after thrust termination with the radiator used as a heat rejection device.

An appropriate combination of open and closed cycle has been proposed to take advantage of the best features of each. During the initial cooldown when generated heat is large, the open cycle is contemplated. After the initial cooling period, when shutdown power is smaller, the system would be closed and the remaining afterheat dissipated through a radiator. Each method has its own merits. Selection of a technique will depend upon specific system requirements.

In this paper, the open cycle has been chosen as the method for afterheat removal because of its simplicity and adaptability to early vehicles.

Afterheat Removal

To analyze the afterheat removal technique, it is necessary to establish the heat transfer requirements. A simplified heat transfer model has been assumed to avoid the dif-

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*The term "coolant" is used rather than "propellant" because it is possible they will not be the same fluid.
ficulty of solving the complex set of differential equations of transient conduction and convection. The model assumes a constant area channel surrounded by the mass to be cooled. The differential equations assumed for the model are:

$$\frac{\partial T}{\partial A} = \frac{h}{wcp} (T_w - T)$$  \hspace{1cm} (5)

$$\frac{\partial T_w}{\partial A} = 0$$  \hspace{1cm} (6)

$$\frac{dQ}{dt} = wc_p (T_2 - T_1) = -mc \frac{dT_w}{dt}$$  \hspace{1cm} (7)

The heat transfer effectiveness is defined as:

$$\eta = \frac{T_2 - T_1}{T_w - T_1}$$  \hspace{1cm} (8)

By combining Eqs. 7 and 8, an expression is obtained with gas discharge temperature, $T_2$, eliminated:

$$\frac{dT_w}{dt} = -(T_w - T_1) \frac{wc_p \eta}{mc}$$  \hspace{1cm} (9)

If $T_1$, $wc$, $\eta$, and $mc$ are assumed constant and independent of time, the solution of Equation 9 is defined in terms of initial and final wall temperatures:

$$T_{wf} = T_{wo} - (T_{wo} - T_1)(1 - e^{-\frac{mc}{twcp\eta}})$$  \hspace{1cm} (10)

By assuming values for maximum and minimum wall temperatures, inlet coolant temperature, and system heat capacity per degree, $mc$, Equation 10 is solved for total coolant mass, $tw$, during the cooldown period. If the mass flow rate is specified, the time required for a cooldown period may then be calculated.

The minimum coolant requirement may be defined as that which results in maximum coolant specific impulse. Ideally, this means maintaining as high a coolant discharge temperature as possible while dissipating power at the generated rate. Practically, this method is not feasible because of the large variations in required coolant flow rate.
If the coolant flow rate is established at the minimum allowable value upon shutdown, then the coolant discharge temperature will decrease with time because the rate of afterheat generation decreases with time. Constant coolant flow rate, although an uncomplicated method, results in very large coolant flow requirements, e.g. possibly three to four times that required for the mission.

In this analysis, a minimum coolant flow rate of 10% of design flow was selected to assure turbulent flow within the reactor. At lower rates, laminar flow would be established in the reactor, causing problems of flow maldistribution and excessive local core temperatures.

An alternate approach to a single cooling period is to allow the engine system itself to act as an intermediate heat sink with energy being removed by a periodic coolant flow. In the Afterheat Removal Schedule shown in Fig. 4, arrows indicate the introduction of coolant. Eq. 10 may then be separately applied to each cooldown period, the number of periods being determined by dividing the total afterheat by the energy to be removed per cycle. In this equation, the product mc may be replaced by total afterheat, $Q_T$, divided by $(T_{W0} - T_{Wf})$ and total coolant flow obtained rather than coolant flow per cooldown cycle.

Fig. 5 illustrates system temperature and coolant flow during the shutdown cycle. It should be noted that maximum temperature during the initial cooldown (immediately following power operation) is greater than the maximum system temperature after initial cooldown because of system temperature limitations without coolant. Further, the point where the system can dissipate the remaining afterheat may be a matter of hours after initial shutdown.

Fig. 6 presents total coolant flow per unit operating power as a function of maximum system temperature during cooldown for a typical engine system. It is significant to note that as system temperature increases, the amount of coolant required for cooldown decreases. The total afterheat coolant flow for a typical engine system may range from 5 - 30% of the total flow during operation.

**Effect on Performance**

Although the analysis presented is approximate in many respects, reasonable estimates of shutdown performance can be obtained for integration with the overall vehicle performance.

The final step in the afterheat removal analysis is the determination of the effect on vehicle performance. The average specific impulse for cooldown has been obtained by
Fig. 4. Typical Afterheat Removal Schedule.
Fig. 5. Typical Afterheat Removal Sequence.
Fig. 6. Total Coolant Flow During Cooldown.
determining the coolant discharge temperature as a function of time (Eq. 7), using coolant temperature to obtain specific impulse, and integrating specific impulse over the cooldown period. Fig. 7 presents the coolant total impulse during shutdown as a function of maximum system temperature. The curve shows that total impulse increases with decreasing temperature even though specific impulse decreases with decreasing temperature. Present estimates indicate that the total impulse during shutdown range from 2 - 17% of the operational requirement.

Since operational temperature and specific impulse are higher than during afterheat removal, it is desirable to determine the coolant weight penalty for afterheat removal for integration with vehicle performance. By first finding the afterheat total impulse, the total flow during operation that would give the same total impulse during cooldown is found. The coolant weight penalty is then obtained from the difference between the hypothetical and actual flows.

To illustrate this point, the following example has been prepared. The following values are assumed for the engine:

- Operating time: 300 sec
- Maximum system temperature during cooldown: 2000° R
- Operating power: 5000 mw
- Design flow rate: 300 lb/sec
- Design specific impulse: 900 sec
- Hydrogen as coolant and propellant
- Propellant mass fraction: 0.6
- Payload mass fraction: 0.2

It is interesting to note that the assumed engine and vehicle parameters result in a mission velocity of about 27,000 fps. Such a vehicle would be capable of a 65 day, minimum energy transfer of a probe from low Earth orbit to the vicinity of Mars; or a 33 hour flight from a low Earth orbit to a Lunar orbit.

The shutdown coolant flow per unit operating power is obtained from Fig. 6 as 1.2. The total coolant for the shutdown period is:

\[ W_{T_{\text{coolant}}} = 1.2 \times 5000 = 6000 \text{ lb} \]

The total impulse per unit operating power during shutdown is obtained from Figure 7 as \(0.5 \times 10^3\). Total impulse for cooldown is:

\[ I_{T_{\text{coolant}}} = 0.5 \times 10^3 \times 5000 = 2.5 \times 10^6 \text{ lb-sec} \]

The propellant flow that gives the same total coolant impulse is obtained by dividing the total coolant impulse by...
Fig. 7. Total Impulse During Cooldown.
the design specific impulse:

\[ tw = \frac{2.5 \times 10^6}{900} = 2,780 \text{ lb} \]

The difference between coolant flow during shutdown and the comparable propellant flow that gives the same total coolant impulse is defined as "excess coolant:"

\[ W = 6000 - 2780 = 3220 \text{ lb} \]

Propellant flow is the product of design flow and operating time:

\[ W_{\text{propellant}} = 300 \times 300 = 9 \times 10^4 \text{ lb} \]

Assuming a propellant mass fraction of 0.6 and a payload fraction of 0.2, the payload is then calculated:

\[ W_{\text{payload}} = 9 \times 10^4 \times \frac{0.2}{0.6} = 30,000 \text{ lb} \]

Since the excess coolant has not been accounted for, it can be assumed that it is part of the payload. It should be noted that the excess coolant is approximately 11% of the payload.

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References