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ON THE EFFECTS OF COOLDOWN REQUIREMENTS

UPON MISSION APPLICATIONS FOR NUCLEAR ROCKETS*

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ABSTRACT

When considering mission applications for nuclear rockets, one encounters the problem of the delayed energy produced by fission product decay after the full power operation phase. If restarts are not planned for the engine, the problem can be ignored because each engine is jettisoned at the end of its operation. However, if restarts are considered, at least two aspects of the cooldown problem must be examined. First, the program necessary for safe reactor cooldown and propellant requirements for this and second, the feasibility of producing useful thrust during this cooldown. Studies have been made of the cooldown requirements as a function of operating times for mission applications at the NERVA-2 power level and their effects on the specific impulse and vehicle weight. These calculations include realistic limits upon exit gas temperatures imposed by reactor design considerations. The effects upon I_{sp} were studied using as a parameter the fraction of cooldown propellant assumed to produce thrust. The results indicate I_{sp} degradation of 2 to 15 seconds and vehicle weight increases of 6,000 to 40,000 lbs over the range considered.

INTRODUCTION

In mission applications of nuclear rocket engines at the Phoebus II reactor power level (5,000 MW), the post-shutdown energy produced by the delayed neutrons and by the radioactive decay of the fission products represents a non-negligible

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fraction of the total energy release. Fig. 1 shows the magnitude and time history of this delayed energy, calculated as described below, for 5,000 MW-1800 sec operation. It can be seen that the immediate post-shutdown power level is about 30% of full power and that the energy is released over periods of time measured in days.

If no restarts are planned for the reactor engine, as is the case for the current mission applications,¹ this aspect of reactor operation can be ignored in the mission analysis because the engine is jettisoned immediately at the end of its full power operation and only the energy and thrust produced during the controlled full power phase needs to be considered. However, the safe shutdown of such an engine for subsequent operation during a mission requires detailed information about this energy release to provide a cooldown program consistent with the reactor requirements. Hence, in any mission application involving restarts of the engine, the effects of this delayed energy release upon the mission, direct and implied, must be taken into account.

There are two direct effects to be considered; the additional weight of the cooldown propellant and increased tank weight to accommodate it, and the degradation of the specific impulse caused by the reduced temperature at which this cooldown propellant must be used to provide an acceptable reactor shutdown.

The implied effects arise from the complications of carrying along throughout a considerable fraction of the mission time a rather large radioactive source (the decaying reactor core) which can influence other aspects of the mission, e.g., extravehicular activities of the astronauts for manned missions, and scientific experiments. It is the purpose of this paper to give quantitative estimates of the direct effects of this aspect of reactor operation upon mission applications which include restarts and to indicate the nature of the implied effects.

COOLDOWN REQUIREMENTS

To calculate the energy release rate from the fission product decay, a

Way-Wigner relation was used.² This relation gives the energy release rate from the fission products per fission, $P_{\beta\gamma}$, as a function of time after the fission as:

$$P_{\beta\gamma}(t) = \frac{3.9}{t^{1.2}} \quad \text{MeV/sec} \quad (1)$$

t = time after fission in seconds

The constant 3.9 was determined by a fit to the data of Perkins and King³ for the time range considered (10 to 10^6 sec).

The reactor operation phase was taken as a step function as shown in Fig. 2. If equation (1) is integrated over the fission production time t_0 to t_s , the fission product decay power at a time t is given by

$$P_{\beta\gamma}(t) = \int_{t_0}^{t_s} P_{OAK} \frac{3.9 du}{(t-u)^{1.2}} = 0.103 P_0 \left[(t-t_s)^{-0.2} - (t-t_0)^{-0.2} \right] \text{MW} \quad (2)$$

$t > t_s + 1$

$P_{\beta\gamma}$ $\equiv$ power from fission product decay - MW

P_0 $\equiv$ engine design power level - MW

t_0 $\equiv$ time of initiation of full power operation - seconds

t_s $\equiv$ time of reactor shutdown - seconds

A $\equiv$ conversion factor, megawatts to fissions/sec = 3.3×10^{16} fissions/sec/MW

K $\equiv$ conversion factor, MeV/sec to megawatts $\equiv 1.6 \times 10^{-19}$ MW/MeV/sec

The restriction, $t > t_s + 1$, arises because of the singularity at $t = 0$ in Eq. (1); for times shorter than 1 sec after shutdown, the power was taken to be constant and equal to the power at $t_s + 1$ sec. Clearly, for runs of times much greater than 1 sec this does not lead to significant error in the power or power integrals.

The total energy released as a function of time during cooldown is given by the integral of Eq. (2):

$$E_{\beta\gamma}(t) = \int_{t_s+1}^t P_{\beta\gamma}(u) du + P_{\beta\gamma}(t_s + 1)$$

$$= 0.129P_0 \left[(t - t_s)^{0.8} + (t_s - t_0 + 1)^{0.8} - (t - t_0)^{0.8} \right] - 0.103 \left[(t_s - t_0 + 1)^{-0.2} \right] \quad (3)$$

$E_{\beta\gamma} \equiv$ integrated power or total energy released to time t - Mw-sec

The above analytic approximations for power and energy were compared with more exact empirical data⁴ and the power was found to agree within approximately $\pm 20\%$ over the time interval considered (100 to 1,000,000 sec). Comparison of the energy or power integral, however, showed better agreement, being within 8% over the same range. Because the integral or total energy determines the cooldown weight requirements, it is felt that the use of the simple approximation is justified in the present analysis.

In addition to the fission product decay energy, the fission power produced by delayed neutrons must also be removed. This delayed power will be a function of the detailed reactor shutdown profile and hence will vary. For this analysis, a constant shutdown reactivity of -3.5 was assumed and the resulting fission rate from delayed neutrons was calculated by solving the reactor kinetics equation using six delayed neutron groups.

To calculate the coolant required for removal of this total energy, the assumption was made that exit gas temperatures during cooldown would not exceed 1000°R . This limitation is consistent with current analysis of off-design performance for the Phoebus II reactor and arose from structural cooling considerations.⁵ The time for termination of cooldown was taken as the time for which $P_{\beta\gamma} = 10$ kW. This is based on experimental data from past tests of Kiwi and Phoebus reactors^{6, 7} which indicate that conductive and convective cooling will maintain the core at a reasonable temperature at 10 kW and hence for a space vehicle a system could be devised to remove the residual energy at this power level. The quantity of interest for the present argument is the integral value rather than the flow rate and thus details of the cooldown profile,

whether it consists of pulses or continuously varying flow rate, do not enter so long as all the energy is removed at an average exit temperature of 2000°R until the residual power is 10 kW.

Thus, the weight of liquid hydrogen used for cooldown can be calculated directly from an energy balance:

$$W = \int_{t_s}^{t_{10kW}} \dot{w} dt = \frac{E_{\beta\gamma}(t_{10kW})}{\Delta h \cdot j} \quad (4)$$

$W \equiv$ weight of liquid hydrogen - lbs

$t_{10kW} \equiv$ time at which $P_{\beta\gamma} = 10$ kW-sec

$\Delta h \equiv$ enthalpy change of hydrogen between 40°R and 2000°R = 6.935×10^3 Btu/lb

$j \equiv$ conversion factor, Btu to MW-sec = 1.054×10^{-3} MW-sec/Btu

Fig. 3 shows values of W as a function of engine operating time at 5000 MW and Table 1 lists the time to reach 10 kW as a function of operating time:

TABLE I

Operating time (seconds)	Time to 10 kW (seconds)
300	2.5×10^5
600	3.98×10^5
1,000	6.3×10^5
3,000	1.59×10^6
6,000	3.1×10^6
10,000	3.9×10^6

EFFECTS UPON MISSION APPLICATIONS

It is clear that the cooldown propellant can be used to produce useful thrust albeit at lower specific impulse. The nature of the availability of the thrust is indicated in Fig. 4 where thrust versus time is plotted for a 5000 MW-1800 sec operation. This figure shows the maximum available thrust from cooldown. It can be seen that the thrust is well-defined in time and magnitude and hence its usefulness is limited. In maneuvers such as escape from orbit it may be possible to use all of the coolant to produce useful thrust whereas for mid-course

correction maneuvers and capture into an orbit, none of it may be available.

The effects upon the mission can be considered as consisting of a weight penalty and a specific impulse penalty.

Weight Penalty

Considering the fraction of the thrust-producing coolant as a parameter, α , the weight of non-thrust producing coolant plus additional stage weight can be plotted versus operating time as is shown in Fig. 5. This weight represents a direct weight penalty per engine for restart capability. With α ranging from 0 to 1, the additional stage weight was calculated using a tank mass fraction (ratio of usable propellant to stage weight) estimate of 0.8 (Ref. 1). For reference, the estimate of 34,000 lb for the engine weight (Ref. 1) is shown on the plot. It can be seen that for operating times of 1800 sec and an α of 0.1 the engine weight equals the non-thrust-producing coolant and stage weight, which suggests, if this consideration is taken alone, a trade-off between carrying additional engines in lieu of cooldown weights rather than re-starting the engine.

Specific Impulse Penalty

Use of a fraction of the cooldown hydrogen as a propellant leads to a degradation of specific impulse for any given maneuver which can be calculated:

$$\bar{I}_{sp} \equiv \frac{\text{Impulse}}{\text{lb}} = \frac{W_o \times I_{sp_o} + \alpha W_{cd} I_{sp_c}}{W_o + \alpha W_{cd}}$$

$I_{sp} \equiv$ average specific impulse

$I_{sp_o} \equiv$ design specific impulse = 800 sec

$I_{sp_c} \equiv$ cooldown specific impulse = 533 sec

$W_o \equiv$ propellant used at 800 sec

$W_{cd} \equiv$ cooldown propellant

In this analysis, the design specific impulse was taken as 800 sec and it was assumed that this scaled as the square root of chamber temperature although it is recognized that other factors such as chamber pressure and nozzle expansion ratio enter.

Fig. 6 shows I_{sp} plotted versus operating time with α as a parameter. It can be seen that for α between 0 and 1, operating times of 1800 sec, I_{sp} degradation is from 2-1/2 sec to 13-1/2 sec.

While it is clear that the sensitivity of the mission application to variations in specific impulse, or the so-called exchange factors calculated for the Mars mission in Ref. 1 cannot be applied to other missions inasmuch as they represent partial derivatives of a particular function evaluated at a specific value of the function, they can nevertheless be used to obtain an estimate of the effects for similar missions. Exchange factors calculated in Ref. 1 indicate that a change of 15 sec of specific impulse leads to a change in initial total weight of the vehicle of 3.5 percent which is about 70,000 lbs for this mission.

CONCLUSIONS

It has been shown that a restart requirement for a nuclear engine mission application can lead to direct initial vehicle weight penalties comparable to the initial engine weight and through specific impulse degradation, equivalent weight penalties exceeding the engine weight depending upon the mission and upon how successful one is in using the cooldown fraction to produce thrust. These are the direct effects.

Additionally, it is shown that the cooldown thrust is well-defined in time and magnitude and hence its usefulness is limited. Indeed, for some precise maneuvers a non-thrust producing cooldown mechanism would be required to prevent perturbations to the trajectory.

Finally, one should consider the implications of carrying along the large radioactive source which the cooled-down reactor represents. The radiation fields produced by this source would exist outside the shadow shield for considerable periods of time and would limit extravehicular activities and could influence scientific experiments.

Reactor restart requirements exist for ground test development programs to

maximize the amount of data per reactor. Even here, it should be pointed out, that such a requirement can introduce problems which may never be faced in a non-restartable mission application, e.g., the separation of thermal recycle effects upon the operation of the reactor from other effects.

REFERENCES

1. "Mission Oriented Advanced Nuclear System Parameters Study" Final Report Volume I, TRW Space Technology Laboratories, Redondo Beach, Calif. 8423-6005-RU000, March, 1965.
2. K. Way and E. P. Wigner, Phys. Rev. 73, 1318 (1948).
3. J. F. Perkins and R. W. King, "Energy Release from the Decay of Fission Products", Nuclear Science and Engineering 3, 726-746 (1958).
4. D. M. Peterson, G. A. Graves and R. Seale, "Tables and Curves from N-3 Post Shutdown Radiation Study", Los Alamos Scientific Laboratory (To be published as LA-2902).
5. J. Hedstrom, Reactor Design Group, Los Alamos Scientific Laboratory, Private communication.
6. "Preliminary Report, Kiwi B-4E-301" LA-3185-MS, Los Alamos Scientific Laboratory, November, 1964.
7. "Preliminary Report, Kiwi B-4D-202 Full Power Run" LA-3120-MS, Los Alamos Scientific Laboratory, August 1964.

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Fig. 1 Total delayed energy and energy release rate versus time after shutdown - 5000 MW - 1800 sec operation.

Fig. 2 Power profile assumed for 5000 MW NERVA II engine cooldown studies.

Fig. 3. Cooldown propellant weight plus additional stage weight (excluding engine weight) vs. operating time for 5000 MW NERVA II engine. Exit temperature of 2000°R assumed.

Fig. 4. Maximum thrust from cooldown propellant versus time after shutdown for 5000 MW 1800 sec. operation.

Fig. 5. Weight of cooldown propellant plus additional stage weight (excluding engine weight) vs. operating time for 5000 MW NERVA II engine, with the thrust producing fraction, α , as the parameter. The estimated weight of the engine is shown.

Fig. 6. Average specific impulse vs. operating time with α , the thrust producing fraction of the cooldown propellant, as a parameter. Exit temperature during cooldown is assumed to be 2000°R .