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CONSIDERATIONS FOR CLOSED-LOOP BRAYTON POWER CYCLE FOR NUCLEAR THERMAL ROCKET WITH DECAY HEAT

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A nuclear thermal rocket (NTR) is an example of a broader class of nuclear thermal propulsion (NTP) technologies. In future years, the nuclear thermal rocket will be a viable option for Mars and deep-space missions because of its high specific impulse (Isp) and efficient power conversion systems. One issue associated with NTP is cooling the reactor during post-thrust operations while in transit. One solution would be to incorporate a Brayton power cycle into the engine. The benefits of this are two-fold. Firstly, incorporating a power cycle would provide power to the habitat module without the need for solar panels (which become much less viable the farther out into space a spacecraft travels). Secondly, the Brayton cycle would act as a coolant system for the nuclear reactor during post-thrust operations and would eliminate the need to power down the reactor completely. Nuclear decay heat from the reactor could provide power for a time, but once the energy from decay heat drops below the energy needed to run the power cycle, the nuclear reactor can provide the additional energy needed to keep thermal power input into the cycle constant. This paper aims to investigate the benefits of incorporating a Brayton power cycle into the nuclear thermal rocket as well as model the reactor power input needed during this post-thrust transitional period.

I. INTRODUCTION

Nuclear thermal propulsion is an advanced propulsion system that offers increased efficiency and shorter travel times. In order to optimize the effectiveness of this technology, the nuclear reactor could also be used to provide thermal power to a power cycle to provide energy to the habitat module.

I.A. Nuclear Thermal Propulsion

Nuclear thermal propulsion is not a new technology. Nuclear thermal rocket tests were common in the 1960s and 1970s. This testing (primarily occurring in the Nevada desert) almost produced a flight-ready nuclear thermal rocket before budget cuts in early 1972 ended the program.[1] Considering that NTRs were so advanced decades ago and given modern technology and renewed interest in nuclear propulsion, major upgrades could be made to past NTP technologies to improve their effectiveness in space. For example, conceptual crewed missions to Mars still use solar panels, even those that use NTP as the main propulsion technology. The reasoning is understandable, though, since the current focus of NTP is to prove it to be a viable propulsion technology. However, once this viability is proven, NTRs can be used for much more. Crewed and non-crewed missions to Mars and other deep-space destinations will require significantly more power than many current missions do because of the need for astronauts and/or robots to perform more science.

Nuclear fission is a great power source for terrestrial application but even more so for deep-space applications. In the places where solar power is weak, the wind does not blow, and fossil fuels lack energy density, nuclear power thrives. For these reasons, nuclear power is the most viable power source for missions beyond Mars that require large amounts of power.

Many missions—especially crewed missions—will require power not only upon reaching the destination but also during transit. For these missions, NTRs are the ideal propulsion technology because of its ability to provide power to the crew during transit. Currently, NTR designs do not incorporate the nuclear core in generating electricity; however, later generations of this technology likely will.[2] With power demands in the kilowatts and tens of kilowatts, a nuclear fission core can provide the power a spacecraft needs with relative ease.

I.B. Power Conversion

Incorporating a power cycle within the NTR's engine system has a two-fold benefit. Firstly, running a fluid through the tie tubes of the reactor core will act as a coolant during non-thrust operations. Secondly, incorporating a power cycle into the system allows for power to be produced without solar arrays.

Solar energy is dependent on the solar flux available at a given distance from the Sun, which greatly limits the amount of solar energy available for deep-space missions. Solar flux S is proportional to the inverse square of distance r from the sun as shown in Eq. (1):

$$S \propto 1/r^2 \tag{1}$$

This relationship shows that the viability of solar power drops drastically the further out into the solar system a spacecraft travels. This drop would require colossal solar arrays for the spacecraft, adding extra mass to the spacecraft. Integrating a power cycle into the system would eliminate this problem as the power output of a nuclear reactor is not dependent on distance from the Sun but rather can be manipulated to the power level desired. This advantage of a power cycle becomes increasingly significant the further out into space the spacecraft travels as the mass addition to the spacecraft would depend only on the desired power level. However, within the proximity of Earth, a power cycle would lose much of its benefit as the Sun's solar energy flux is high enough that the mass per kilowatt of energy produced by solar arrays would be less than that of nuclear energy. Calculation can be done to show that nuclear energy becomes more mass efficient somewhere between Earth and Mars, but this distance is subject to change as solar array technology becomes more sophisticated. It is apparent, however, that for deep-space missions, nuclear energy is more mass efficient than solar energy and will continue to be.

II. DESIGN CONSIDERATIONS

It is necessary to have an overview of the Brayton cycle to be used. Although a physical model has not yet been produced, the following assumptions and considerations will be helpful in considering the materials and components of the cycle as well as the thermal power input to the cycle.

II.A. Brayton Cycle

There have been several proposed designs for a dual-mode nuclear thermal engine, including both static and dynamic power conversion systems. The Brayton, Stirling, and Rankine cycles are dynamic conversion systems and are thought to be superior to thermoelectric and thermionic systems—both static conversion systems—due to their high efficiency, low mass, long life, and high durability.[3] The design currently being looked at most closely is a closed-loop Brayton cycle, which could be used for science missions requiring around one kilowatt-electric of power or could be scaled upwards of around ten kilowatts-electric of power for manned missions to Mars. Energy from the decay heat of the reactor after thrust mode in addition to energy from the reactor running in low-power mode would be used to give a constant heat input into the cycle. Hot hydrogen would be run through the tie tubes to be heated up by the decay heat and the reactor. This hydrogen would then be fed into a heat exchanger to heat up a helium-xenon gas mixture running through a second loop, the Brayton cycle. A helium-xenon mixture was chosen because helium's low molecular weight is favorable for heat transfer while xenon's higher molecular weight favors increased turbomachinery performance.[4] A standard Brayton cycle is expected, consisting of a turbine, radiator, compressor, and heat exchanger. A regenerative heat component could also be added to the cycle to improve efficiency, but a trade study would need to be performed to determine if the added efficiency to the cycle would translate to a less massive system.

The most problematic component of such a cycle is the radiator, easily the most massive component of the system. The large amount of heat needed to be radiated contributes to the mass of the component, which needs to be carefully designed to lower area and, subsequently, mass.[5] One viable option is to replace the zirconium hydride tie tubes with a beryllium oxide moderator. Zirconium hydride has a much lower melting point than beryllium oxide's melting point of around 2700 Kelvin.[6] This increased melting point would allow for the cycle to be run at a higher temperature, which is advantageous for radiator mass as shown in Eq. (2).

$$P = e\sigma A T^4 \tag{2}$$

The Stefan-Boltzmann Law shows that power dissipation P increases proportionately with the fourth-power of temperature T. Additionally, the area A of radiation is indirectly proportional to the fourth-power of temperature, meaning that even doubling the radiator temperature for a given power output decreases the radiator area by a factor of sixteen. This is, of course, neglecting other effects raising the cycle temperature could have on the cycle, including the performance and size of turbomachinery components. It does seem sure, though, that raising the cycle temperature decreases the area and, subsequently, the mass of the radiator. This does, however, have a negative impact on the efficiency of the cycle. But with the power cycle requiring the reactor running at almost one ten-thousandth of the power level required during thrust, the negative impact on cycle efficiency can likely be negated given the decrease in mass of the spacecraft since such little fuel is being used for the power cycle relative to fuel consumption during thrust mode. Additionally, the tradeoff between cycle efficiency and mass reduction can be optimized by using the nozzle as a radiator. If the temperature can be raised enough to isolate radiator area to the nozzle alone, then optimal efficiency and mass savings will be reached.

II.B. Decay Heat Model

The majority of the heat emanated from the reactor is the decay heat, which is a product of fission fragments that eventually decay by gamma or beta emission. Another small amount of heat will be produced from fissions in the reactor that will keep the fuel above its ductile to brittle transitional temperature, which ensures that the fuel is structurally sound. The extra heat would then be dissipated through LH_2 rejection through the core, or it can be dissipated through the addition of radiator area on the spacecraft. Neither of these options are extremely mass efficient, which makes them expensive. While adding a power cycle onto an existing NTR is not a low mass operation either, it acts as a mass efficient means to produce large amounts of energy on the spacecraft with marginal introduction of complexity.

II.B.1 Propellant Heat Dissipation

In conjunction with the six-group point kinetics time differencing approximation, the decay heat is modeled as prescribed by Emrich with the use of Eq. (3).[7] The thermal power of the decay heat is expressed as an integral over the time that fissions are taking place during full-power operation as shown in Eq. (3).

$$P_D(\mathrm{t}) = 0.0132\ \mathrm{P}_t \int_{t_o}^{t_f} (t-T)^{-1.2}\ \mathrm{dT} \tag{3}$$

Integrating from time t_0 to the burn time t_b of the thrust where t-t_b can be exchanged for τ, the time after the burn has ended, resulting in Eq. (4).

$$P_D(\mathrm{t}) = 0.066\ \mathrm{P}_t[\tau^{-0.2} - (\tau + t_b)^{-0.2}] \tag{4}$$

The thermal power due to neutronic fission in the reactor is given by the rate of fission multiplied by the amount of energy per fission as shown in Eq. (5).

$$P_f(\tau) = \mathrm{N}(\tau)\Sigma_f vQc \tag{5}$$

The total thermal power is then given by the following in Eq. (6) and Eq. (7).

$$\mathrm{P}(\tau) = P_f(\tau) + P_D(\tau) \tag{6}$$

$$\mathrm{P}(\tau) = \mathrm{N}(\tau)\Sigma_f vQc + 0.066\ \mathrm{P}_t[\tau^{-0.2} - (\tau + t_b)^{-0.2}] \tag{7}$$

The total energy produced in the reactor from the initial to final time is given by Eq. (8).

$$\Delta\mathrm{E}(\tau) = \int_{t_o}^{t_f} (\mathrm{N}(\tau)\Sigma_f vQc + 0.066\ \mathrm{P}_t[\tau^{-0.2} - (\tau + t_b)^{-0.2}])d\tau \tag{8}$$

This result can be solved numerically since the neutron population must also be numerically solved. The initial time is set to 30 seconds because of the common thought of producing thrust with the LH_2 for the first 30 seconds after burn. This can then be used to solve for the amount of propellant needed to cool the reactor after shutdown in Eq. (9) and Eq. (10).

$$\Delta E = m\, c_p \Delta T \tag{9}$$

$$m = \frac{\Delta E}{c_p \Delta T} \tag{10}$$

For the case without a power cycle, the decay heat is let to run to a time after burn of roughly 20,000 seconds. The total energy is solved for numerically, giving an approximation for the mass of propellant needed.

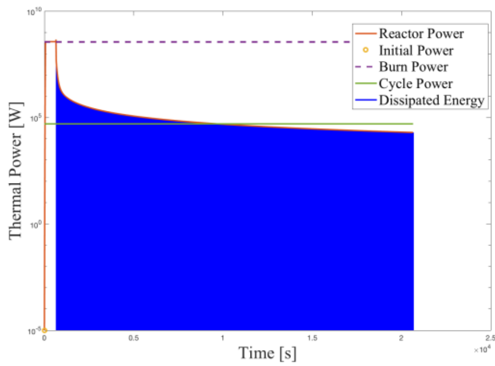

Fig. 1. Dissipated energy without power cycle. Mass of LH_2 rejected equals 713 kilograms.

For the case with a power cycle as shown in Fig. 2., the decay heat is let to run to a time at which the power generated is equal to the desired power input of the thermal cycle. This would be the point at which the cycle can productively use the decay heat and be turned on to generate electricity.

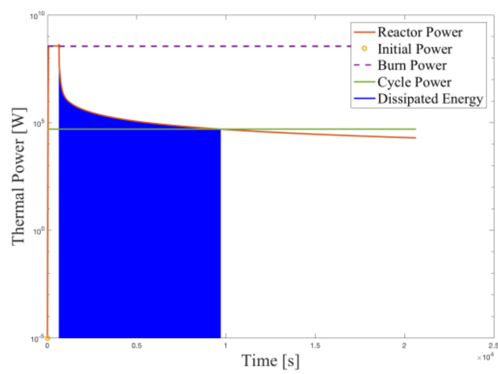

Fig. 2. Dissipated energy with power cycle. Mass of LH_2 rejected equals 614 kilograms.

II.B.2. Analysis

The longer the propellant is needed for heat rejection, the more total propellant is used. Including a power cycle reduces this amount of LH_2 from 713 kilograms to 614 kilograms, a 14% decrease. For cycles running on higher power levels, this difference can become even more significant. For a 500 kW_t cycle power necessity, the LH_2 used reduces to around 400 kilograms, a 44% decrease. It is unlikely that a spacecraft in the near future will require that much power input, but it is likely that within the next several decades, a kilowatt or tens of kilowatts of thermal power could be needed.

These marginal decreases in propellant mass required to cool the core post-thrust will not introduce large increases in efficiency. They will instead mitigate the relatively large increase in mass that will be necessary for the inclusion of a nuclear thermal to electric power conversion system that will likely be heavier than an equivalent solar panel array. Again, as the power requirements of the mission increase, the greater efficiencies nuclear power systems achieve.

II.B.3. Reactivity Control

For a thermal to electric power conversion system, a constant power source is necessary. To achieve this constant supply given decreasing decay heat, the reactivity is solved for as a function of time to introduce more fission power as time goes on.[8] This will then make up for the difference between the cycle power and decay heat. To produce the decay heat model—including power from fission—it was necessary to approximate the point kinetics equations, Eq. (11) and Eq. (12).

$$\frac{dN}{dt}(t) = \frac{\rho(t) - \beta}{\Lambda} N(t) + \sum_i \lambda_i C_i(t) \qquad (11)$$

$$\frac{dC_i}{dt}(t) = \frac{\beta_i}{\Lambda} N(t) - \lambda_i C_i(t) \qquad (12)$$

To have steady-state power, Eq. (7) is differentiated with respect to time and set to zero.

$$\dot{P}(\tau) = \dot{N}(\tau) Q c \Sigma_f v - 0.0132 P_t [\tau^{-1.2} - (\tau + t_b)^{-1.2}] \qquad (13)$$

Eq. (11) is then substituted for $\dot{N}(\tau)$ and reactivity is solved for.

$$\rho(\tau) = \frac{\Lambda}{N(\tau)} \left[\frac{0.0132 P_t [\tau^{-1.2} - (\tau + t_b)^{-1.2}]}{Q c \Sigma_f v} - \sum_i \lambda_i C_i(\tau) \right] + \beta \qquad (14)$$

II.B.4. Further Analysis

The major assumptions in Eq. (14) are (1) no decay heat from fissions after the burn time (including after the neutron population increases again), (2) the power during burn is constant, (3) the decay heat follow that given in Eq. (3), and (4) all constants $(\Lambda, Q, v, \Sigma_f, \lambda_i, and\ \beta)$ are correct and constant with time. From these assumptions, the results in Fig. 3., Fig. 4., and Fig. 5. are found.

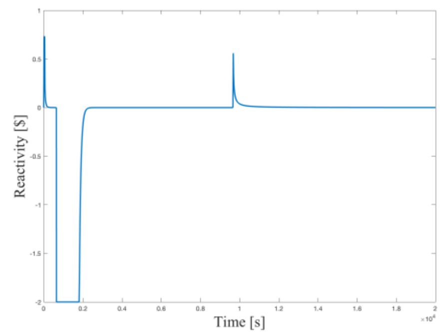

Fig. 3. Reactivity control from low power to burn power to cycle power. The discontinuity near 10,000 seconds is where Eq. (14) is implemented to maintain desired power.

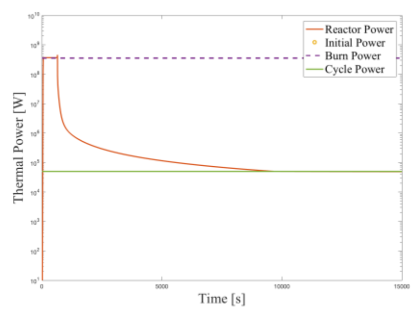

Fig. 4. Thermal power of reactor following reactivity control.

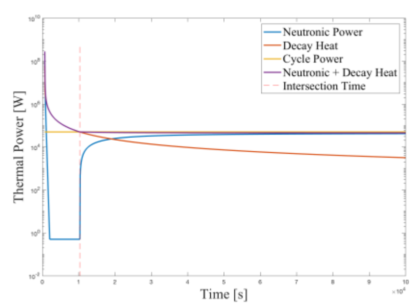

Fig. 5. Neutron and decay products' power response to derived reactivity control.

Fig. 5. shows that the total power level remains constant at the desired cycle power for an indefinite amount of time after cycle power is reached. As the

power from fission approaches the desired cycle power, the reactor can be treated normally, as if there was no decay heat of comparable magnitude.

III. CONCLUSIONS

The inclusion of a power cycle would bring benefits to the future class of NTRs proposed for deep-space missions. The mass savings from nuclear power as opposed to solar allow the spacecraft to carry more propellant or more materials for science. Additionally, raising the temperature of the power cycle could lead to additional mass savings as the need for large radiators would be reduced. The required power input from the reactor for this cycle is increased as decay heat decreases which can be modeled. Future work could include producing a physical model of a potential Brayton cycle to study its parameters as well as the radiator mass needed to cool it in an airless environment.

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