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DYNAMIC ANALYSIS OF AN OPEN-CYCLE GAS-CORE NUCLEAR ROCKET

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • APRIL 1973

1. Report No. NASA TM X-2784	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle DYNAMIC ANALYSIS OF AN OPEN-CYCLE GAS-CORE NUCLEAR ROCKET		5. Report Date April 1973
		6. Performing Organization Code
7. Author(s) George E. Turney and Arthur W. Kieffer		8. Performing Organization Report No. E-7266
		10. Work Unit No. 503-04
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Reactivity and flow rate disturbances were used to investigate the transient response of a conceptual open-cycle gas-core nuclear rocket engine. The disturbances were made with the system initially operating at its steady-state design point. Results of the study show that the feedbacks associated with the propellant density and propellant temperature have a dominant effect on the response of the system. Furthermore, there appears to be a rather limited range of values of these propellant feedback coefficients for which the gas-core nuclear rocket has a stable response. The system was rather insensitive to a fuel flow rate disturbance, whereas a similar disturbance in the propellant flow rate caused large changes in reactor power. For most reactivity and flow rate disturbances, the response showed oscillations of various intensity.

17. Key Words (Suggested by Author(s)) Open-cycle gas-core; Nuclear rocket; Transient operation; Analytic study		18. Distribution Statement Unclassified - unlimited	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 29	22. Price* $3.00

* For sale by the National Technical Information Service, Springfield, Virginia 22151

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SUMMARY

An analytic investigation was made into the transient operating characteristics of the open-cycle gas-core nuclear rocket engine. The engine is being considered for high-specific-impulse applications (3000 to 5000 sec). The gas-core reactor under consideration has a gaseous fuel cloud inside the core. Hydrogen propellant, which evelopes the fuel cloud, is continually injected into the core, heated, and ejected to produce thrust.

Results of this study show that the feedbacks associated with the propellant temperature have a dominant effect on the response of the system. Furthermore, there appears to be a rather limited range of values of these propellant feedback coefficients for which the gas-core nuclear rocket has a stable response. The most stable response occurred when the reactivity coefficients were at their reference values (most probable values).

The system was rather insensitive to a fuel flow rate disturbance, whereas a similar disturbance in the propellant flow rate caused large changes in reactor power. For most reactivity and flow rate disturbances, the response showed oscillations of various intensity.

INTRODUCTION

The gaseous core nuclear rocket is a high-temperature advanced propulsion system for space applications. This conceptual propulsion system has the potential for achieving both a relatively high thrust (10^4 to 10^6 N) and a high specific impulse (3000 to 5000 sec). In this respect, the gas-core nuclear rocket has a distinct advantage over the solid-core nuclear rocket, which can operate with a maximum specific impulse of 800 to 900 seconds, and also over chemical rockets, which can achieve a specific impulse of 350 to 500 seconds.

Two conceptual gas-core reactor designs are currently under consideration. One is an "open cycle" design and the other is a "closed cycle" design. In the open-cycle engine design, the fissioning uranium plasma is surrounded by flowing hydrogen propellant. Both the fuel and propellant are contained in a common pressure vessel and there is no physical boundary separating the fuel and propellant. In the closed-cycle or "nuclear light-bulb" engine design, the fissioning fuel is physically separated from the flowing hydrogen propellant by a thin wall which is transparent to thermal radiation.

For both of these conceptual designs, the mode of heat transfer from fuel to propellant is thermal radiation. However, with the open cycle, a fraction of uranium plasma is carried away by the flowing propellant and exhausted from the system. To compensate for this loss, fuel must be added continuously to the system to maintain a critical fuel mass.

At the Lewis Research Center, interest has been focused primarily on the open-cycle gas-core engine concept. One of the reference gas-core engines currently under study has a cavity diameter of 3.05 meters (10 ft) and a design power level of 5900 megawatts. A preliminary design study of this reference gas-core engine was made and is reported in reference 1.

To date, most of the work done on this gas-core engine concept has been related to the operation of this engine at steady-state design conditions. However, to gain a more complete understanding of the overall operation of the gas-core engine, an examination of the non-steady-state (or transient) operation is necessary. For this purpose, a study was made to examine the dynamic behavior of the open-cycle gas-core engine. (A similar study is reported in ref. 2.) The specific objectives of this study were (1) to determine the transient response of the gas-core engine to step changes (forced perturbations) in reactivity, propellant flow rate, and fuel flow rate; and (2) to investigate the effects of variations in the dominant reactivity feedbacks on the response and stability of the gas-core engine system.

The study described in this report was made by using a high-speed digital computer. The results of this study, along with a description of the system equations and the dynamic model used to represent the 5900-megawatt reference gas-core engine, are presented.

SYSTEM DESCRIPTION

A simplified diagram of the conceptual open-cycle gas-core engine is shown in figure 1. The central cavity in this engine is surrounded by a spherical shell of beryllium oxide which serves as the moderator-reflector material. The inside wall of the cavity is made of a thin layer of slotted or porous material, such as graphite, through which propellant is introduced into the cavity. The flowing propellant inside the cavity is heated to a high temperature (near 2×10^4 K) by thermal radiation from the fissioning

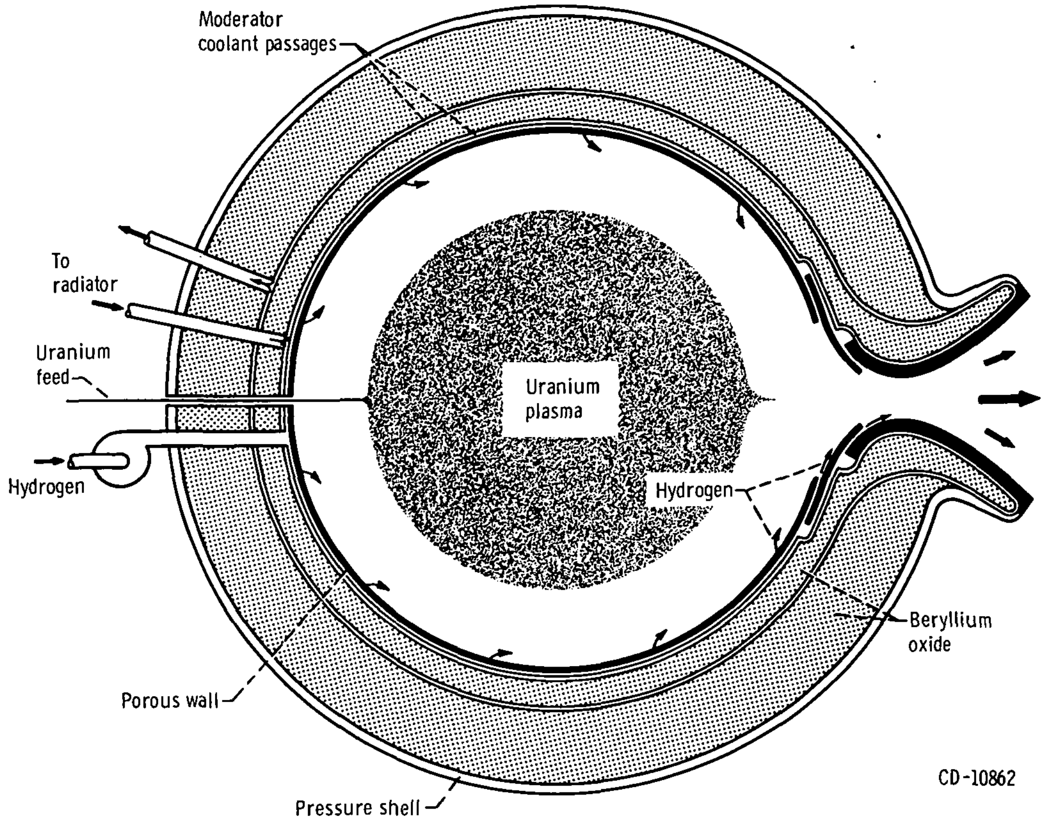

Figure 1. - Porous-wall gas-core engine.

uranium plasma. The high-temperature propellant is exhausted through a nozzle to produce thrust.

At temperatures below about 6000 K, the opacity of the hydrogen propellant is relatively low. Consequently, pure hydrogen is a rather poor attenuator of thermal radiation below this temperature. To improve the opacity of the hydrogen propellant, a small amount of seed material such as tungsten dust (about 5 wt. %) must be injected into the cavity with the hydrogen.

Recent flow experiments have shown that with an appropriately shaped porous wall and with proper injection of propellant, a nearly stagnant central region can be maintained within the cavity. Although some uranium is carried out of the cavity with the propellant, it is expected that the rate of fuel loss will be of the order of 1/200 of the propellant flow rate.

In the 5900-megawatt reference gas-core engine, about 22 kilograms of uranium-235 are required inside the cavity to make the system critical. With an average uranium plasma temperature of about 60 000 K and a cavity pressure of 400 atmospheres, the central fuel cloud occupies approximately 30 percent of the reference cavity volume.

A significant fraction of the fission energy released in the gas-core cavity (about

5 to 8 percent) is deposited as thermal energy in the moderator-reflector material. This thermal energy is created by the interactions of neutrons and high-energy gammas with these materials. In this study we assumed that 6 percent of the reactor power was deposited in the moderator-reflector material. To remove this heat, coolant channels which contain flowing helium gas under high pressure are spaced throughout the moderator. The heat is transferred from the moderator to the flowing helium and rejected to space by a waste-heat radiator. A preliminary design of a helium flow system for removing heat from the moderator and a waste-heat radiator for rejecting this heat are described in reference 1. Figure 2 is a simplified schematic of the heat rejection system.

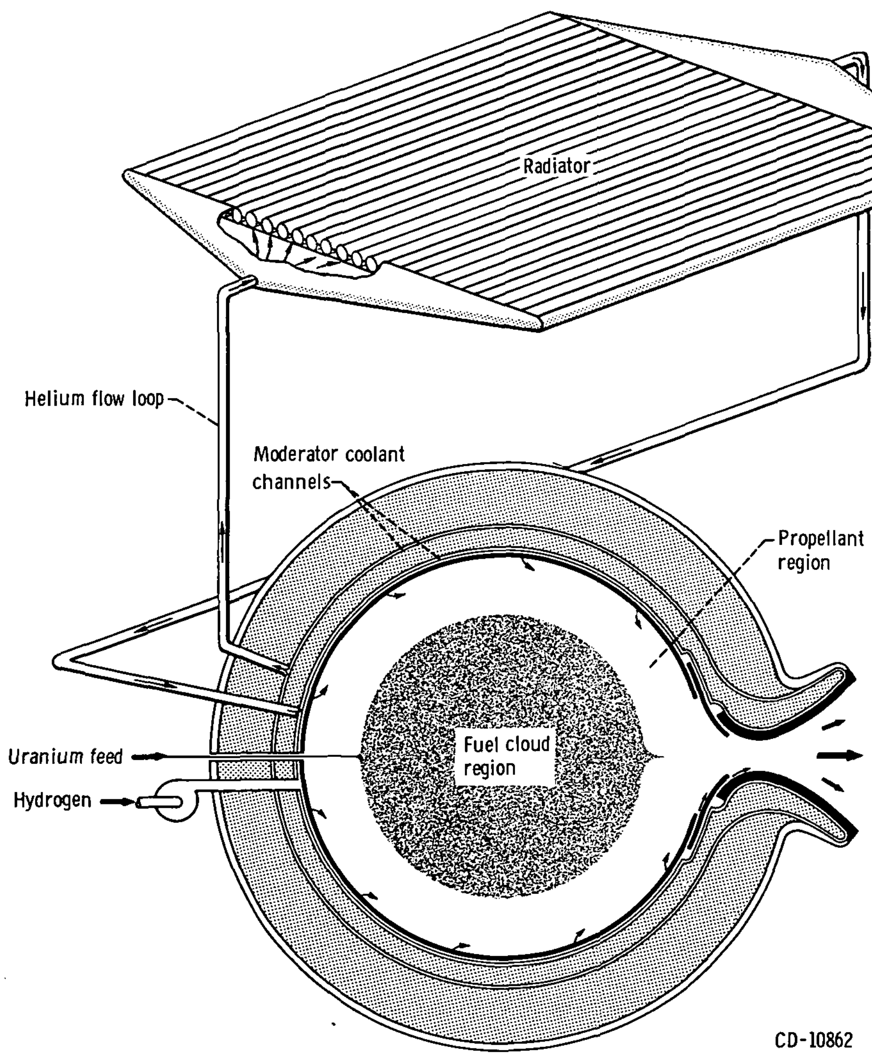

Figure 2. - Simplified schematic of single-loop system for removing heat from moderator of gas-core engine.

The design point operating conditions for the reference gas-core engine system are as follows:

Reactor power, MW	5900
Approximate engine thrust, N	196 000
Approximate specific impulse, sec	4400
Propellant mass flow rate, kg/sec	4.54
Fuel mass flow rate, kg/sec	0.023
Diameter of fuel cloud, m	2.04
Mass of fuel inside cavity, kg	21.5
Mass of hydrogen inside cavity, kg	3.15
Cavity pressure, atm	400
Cavity diameter, m	3.05
Average temperature of fuel, K	59 400
Average temperature of propellant, K	15 750
Average moderator temperature, K	1390

ANALYSIS

To investigate the transient behavior of the 5900-megawatt reference gas-core engine system, mathematical models were formulated to represent the gas-core engine and its associated heat rejection system. In this section we describe these models and also the dynamic equations which relate to the time-dependent behavior of the system.

The dynamic analysis of the gas-core engine system was made by using the Continuous System Modeling Program (CSMP). This digital simulation program is described in reference 3. Briefly, the procedure used in this analysis was to describe the time-dependent behavior of the variables in the gas-core engine with a system of equations. These equations were then set up on the CSMP and solved simultaneously in a continuous fashion to produce a time-dependent description of the system behavior.

The basic assumptions used in this study and related to the gas-core engine operation are the following:

(1) The core cavity and the fuel cloud inside the cavity are spherical in shape.

(2) The fuel cloud remains in the center of the cavity during steady-state and transient operation; that is, the fuel cloud and cavity are concentric.

(3) A single lump model was used to represent the fissioning fuel cloud; and the temperature of the entire fuel cloud was assumed to be uniform.

(4) A single lump model was used to describe the state of the propellant inside the cavity.

(5) The average temperature assigned to the propellant inside the cavity is a function of the average of the enthalpies of the incoming and outgoing hydrogen propellant.

(6) The reference temperatures assigned to the hydrogen and fuel entering the cavity are 555 and 2780 K, respectively.

Gas Core Equations

Core power. - The rate of neutron density change of the gas-core reactor was obtained from the kinetics equation with six groups of delayed neutron precursors or

$$\frac{dn}{dt} = \left(\frac{\delta k - \beta}{l^*}\right)n + \sum_{i=1}^{6} \lambda_i C_i \tag{1}$$

where

$$\beta = \sum_{i=1}^{6} \beta_i$$

(All symbols are defined in the appendix.)

The rate of change in precursor concentration in the cavity is determined from the conservation relation (ref. 4),

$$\begin{pmatrix}\text{Rate of change}\\ \text{in concentration}\\ \text{of } i^{th} \text{ group of}\\ \text{precursors}\end{pmatrix} = \begin{pmatrix}\text{Rate of production}\\ \text{of } i^{th} \text{ group of}\\ \text{precursors}\end{pmatrix} - \begin{pmatrix}\text{Rate of removal}\\ \text{of } i^{th} \text{ group by}\\ \text{decay}\end{pmatrix} - \begin{pmatrix}\text{Rate of removal}\\ \text{of } i^{th} \text{ group by}\\ \text{outflow}\end{pmatrix}$$

Or, in equation form,

$$\frac{dC_i}{dt} = \frac{\beta_i}{l^*} n - \lambda_i C_i - \lambda_{loss} C_i \tag{2}$$

The decay constants and yield fractions of the six delayed neutron groups and the prompt neutron generation time are listed in table I. The coefficient λ_{loss} is defined as the

TABLE I. - DECAY CONSTANTS AND YIELD FRACTIONS OF DELAYED NEUTRON PRECURSORS AND PROMPT NEUTRON GENERATION TIME[a] FOR FISSION OF U^{235} IN 5900-MEGAWATT REFERENCE GAS-CORE ENGINE

Delay group	Decay constant, λ_i, sec^{-1}	Yield fraction, β_i
1	3.880	0.0002432
2	1.400	.0013632
3	.311	.0012032
4	.116	.0026048
5	.0319	.0008192
6	.0128	.0001664
	Total	0.0064

[a]Prompt neutron generation time, $l^* = 4\times10^{-3}$ sec.

reciprocal of the fuel (precursor) residence time in the cavity; that is,

$$\lambda_{loss} = \frac{1}{\text{Fuel residence time}} = \frac{\dot{W}_F}{M_F} \tag{3}$$

The relation between neutron density and power is as follows:

$$\dot{Q} = KM_F n$$

where K is a proportionality constant or

$$n = \frac{\dot{Q}}{KM_F} \tag{4}$$

Substituting equation (4) into equations (1) and (2) and defining

$$D_i = KC_i$$

we have, after some algebraic manipulation

$$\frac{d(\dot{Q}/M_F)}{dt} = \frac{\delta k - \beta}{l^*}\left(\frac{\dot{Q}}{M_F}\right) + \sum_{i=1}^{6} \lambda_i D_i \tag{5}$$

and

$$\frac{dD_i}{dt} = \frac{\beta_i}{l^*}\left(\frac{\dot{Q}}{M_F}\right) - (\lambda_i + \lambda_{loss})D_i \tag{6}$$

From the following relation we then obtain the cavity power

$$\dot{Q} = M_F\left(\frac{\dot{Q}}{M_F}\right) \tag{7}$$

Reactivity. - Six independent feedback effects were considered in this dynamic study. The variables in this system which contribute to the overall feedback mechanism are (1) fuel temperature, (2) moderator temperature, (3) propellant temperature, (4) fuel volume, (5) propellant density, and (6) fuel mass. A block diagram of the gas-core reactor with these six feedback loops is depicted in figure 3. The reactivity feedback coefficients for this system were calculated by the procedure described in reference 5. The numerical values obtained for these coefficients and used in this study are listed in table II.

The coefficients in table II were calculated at or near the design point operating conditions for this reference system. But, because of the assumptions and procedure used in the calculations, some uncertainty exists in the actual values of these coefficients. In addition, some of the coefficients can be considered constant only over a small region about the design point. This is particularly true of the propellant temperature coefficient, which varies significantly with the temperature of the propellant. Nevertheless, until experimental verification is obtained, the values given in table II should be considered as reasonable estimates of the feedback coefficients at this time. In the remainder of this report we refer to the values in table II as the "reference" feedback coefficients for this system.

Mass-volume relations for fuel and propellant. - The rate of change in fuel mass inside the cavity is given by the conservation equation

$$\frac{dM_F}{dt} = \dot{W}_{F, in} - \dot{W}_{F, out} \tag{8}$$

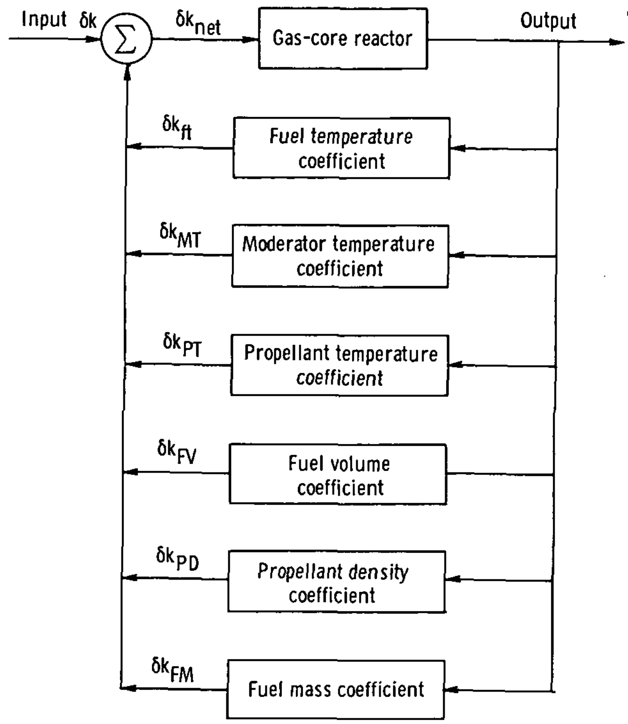

Figure 3. - Block diagram of gas-core reactor with feedbacks.

TABLE II. - CALCULATED REACTIVITY FEEDBACK COEFFICIENTS FOR 5900-MEGAWATT REFERENCE GAS-CORE REACTOR

System variable	Equation for feedback coefficient
Fuel temperature	$\delta k_{FT} = +0.00119(\Delta T/T)_F$
Moderator temperature	$\delta k_{MT} = -0.020(\Delta T/T)_{MOD}$
Propellant temperature	$\delta k_{PT} = -0.3148(\Delta T/T)_P$
Fuel volume	$\delta k_{FV} = +0.070(\Delta V/V)_F$
Propellant density	$\delta k_{PD} = -0.190(\Delta \rho/\rho)_P$
Fuel mass	$\delta k_{FM} = +0.290(\Delta M/M)_F$

Similarly, the conservation equation for propellant mass inside the cavity is

$$\frac{dM_P}{dt} = \dot{W}_{P, in} - \dot{W}_{P, out} \tag{9}$$

The flow rates of fuel and propellant entering the cavity were maintained constant at their design values. But the total flow rate out of the cavity is limited by the choked flow conditions at the exhaust nozzle. Since most of the gas which leaves the core consists of propellant, the mixed mean temperature of fuel and propellant leaving the cavity is approximately equal to the propellant exit temperature. Thus, we can write

$$\dot{W}_{F, out} + \dot{W}_{P, out} = \frac{kP}{\sqrt{T_{P, out}}} \tag{10}$$

A correlation has been proposed by Ragsdale (ref. 6) which relates the ratio of propellant to fuel flow rates out of the cavity to the volume fraction of fuel in the cavity. Ragsdale's correlation is

$$\frac{\dot{W}_{F, out}}{\dot{W}_{P, out}} \propto \left(\frac{V_F}{V_C}\right)^3 \tag{11}$$

The data used to develop this correlation were obtained from gas-core fluid flow experiments described in references 7 and 8.

The propellant density can be obtained from the following relation:

$$\rho_P = \frac{M_P}{V_P} \tag{12}$$

The fuel density was obtained from an equation of state for the uranium plasma (ref. 6); the equation is

$$\rho_F = \frac{3.4\times10^6 \, P}{T_F^{1.77}} \tag{13}$$

A common pressure was assumed in the propellant and fuel regions of the cavity. Consequently, the cavity pressure was obtained from the state equation of the hydrogen.

A curve fit to the data of Patch (ref. 9) gives the following:

$$P = 2.53\times10^{-4}\,\rho_P T_P^{1.6} \tag{14}$$

The respective volumes of fuel and propellant in the cavity are given by the equations

$$V_F = \frac{M_F}{\rho_F} \tag{15}$$

$$V_P = V_C - V_F \tag{16}$$

where the cavity volume V_C is 14.8 cubic meters.

Gas-core energy transfer. - Consider a control volume which surrounds the fissioning uranium fuel cloud. Then an energy balance on the fuel cloud can be written as follows:

$$\begin{pmatrix}\text{Rate of change in}\\ \text{thermal energy of}\\ \text{fuel cloud}\end{pmatrix} = \begin{pmatrix}\text{Rate of fission}\\ \text{energy release}\\ \text{in fuel cloud}\end{pmatrix} + \begin{pmatrix}\text{Rate of energy added}\\ \text{to fuel cloud by in-}\\ \text{coming fuel}\end{pmatrix}$$

$$- \begin{pmatrix}\text{Rate of energy re-}\\ \text{moved from fuel}\\ \text{cloud by outgoing fuel}\end{pmatrix} - \begin{pmatrix}\text{Rate of energy}\\ \text{transferred from}\\ \text{fuel to propellant}\end{pmatrix}$$

$$- \begin{pmatrix}\text{Rate of energy}\\ \text{transferred from}\\ \text{fuel to moderator}\end{pmatrix}$$

The second and third terms on the right side of this expression are relatively insignificant and can be safely neglected. Thus, the approximate energy balance equation for the fuel cloud in terms of the system variables is

$$M_F \left(C_p\right)_F \frac{dT_F}{dt} = \dot{Q} - \dot{Q}_P - \dot{Q}_{MOD} \tag{17}$$

The rate of heat transfer from fuel to propellant was determined from the relation (ref. 6)

$$\dot{Q}_P = 1.29\times10^8 \frac{D_F}{P}\left(\frac{T_F}{14\,000}\right)^{6.25} \tag{18}$$

The rate of energy transfer to the moderator (resulting from neutron and gamma interactions) was assumed to be a constant 6 percent of the reactor power; thus,

$$\dot{Q}_{MOD} = 0.06\ \dot{Q} \tag{19}$$

A similar energy balance on the hydrogen propellant inside the cavity is

$$\begin{pmatrix}\text{Rate of change in}\\ \text{thermal energy}\\ \text{of propellant}\end{pmatrix} = \begin{pmatrix}\text{Rate of energy}\\ \text{transferred from}\\ \text{fuel to propellant}\end{pmatrix} + \begin{pmatrix}\text{Rate of energy added}\\ \text{to propellant region}\\ \text{by inflowing propellant}\end{pmatrix} - \begin{pmatrix}\text{Rate of energy removed}\\ \text{from propellant region}\\ \text{by outflowing propellant}\end{pmatrix}$$

Or, written in terms of the system variables,

$$M_P \frac{d\overline{H}_P}{dt} = \dot{Q}_P + \dot{W}_{P,in}H_{P,in} - \dot{W}_{P,out}H_{P,out} \tag{20}$$

As stated before in this section, the average enthalpy of the propellant inside the cavity was assumed to be equal to the arithmetic mean of the inlet and outlet propellant enthalpies. That is,

$$\overline{H}_P = \frac{H_{P,in} + H_{P,out}}{2} \tag{21}$$

And the average propellant temperature inside the cavity was determined from the arithmetic mean propellant enthalpy

$$T_P = f(\overline{H}_P) \tag{22}$$

Moderator Heat Rejection System

As stated before in this section, we assumed that 6 percent of the reactor power was deposited in the moderator in the form of heat. Based on this heat load, a waste-heat rejection system was sized for this system.

In reference 1, a preliminary design is presented of a single-loop helium-coolant heat rejection system for the 5900-megawatt reference system. This heat rejection system has four radiators, each consisting of 113 TZM tubes (tube o. d. = 3.81 cm; tube i.d. = 2.54 cm) with a length of 40.5 meters. The tubes in this radiator design are arranged in a parallel, coplanar configuration with central connecting fins. The radiator system described in reference 1 is capable of rejecting 420 megawatts with an average design radiator temperature of 1310 K.

For the reference system described in this report, only 6 percent of the design power, or about 350 megawatts, is deposited in the moderator. Because of the smaller heat load, a proportionally smaller radiation size is required. Thus, in this study, we used a radiator system configuration similar to that described in reference 1, but with a proportionally smaller number of tubes in each of the four radiators. Some of the characteristics of the radiator system used in this study are

Radiator coolant	Helium
Number of radiator segments	4
Average radiator temperature, K	1310
Radiator tube material	TZM
Number of tubes per radiator segment	94
Tube o. d., cm	3.81
Tube i. d., cm	2.54
Radiator length, m	40.5
Total effective radiator surface area (4 segments), m^2	3934
Total radiator planform area (4 segments), m^2	1967
Total radiator system weight, kg	154 060
Assumed surface emissivity	0.90
Central fin effectiveness	0.60
Fin width, cm	4.45

These data were obtained by proportionally scaling the preliminary design data for the heat rejection system described in reference 1.

In the analytic model of the heat rejection system, the heat transfer in the moderator was treated as one section, while a two-section model was used for the radiator. The radiator sections were proportioned such that each section rejects approximately an equal amount of heat. The following equations were used for the model of the heat rejection system:

Moderator:

$$\frac{dT_{MOD}}{dt} = \frac{1}{C_{MOD}M_{MOD}}\left[\dot{Q}_{MOD} - h_{MOD}A_{MOD}\left(T_{MOD} - \frac{T_{RI} + T_{RO}}{2}\right)\right]$$

Coolant in moderator:

$$\frac{d\left[(T_{RI} + T_{RO})/2\right]}{dt} = \frac{1}{\left(M_{He}\right)_{MOD}\left(C_p\right)_{He}}\left[h_{MOD}A_{MOD}\left(T_{MOD} - \frac{T_{RI} + T_{RO}}{2}\right) - \dot{W}_{He}\left(C_p\right)_{He}(T_{RI} - T_{RO})\right]$$

Coolant in radiator (section 1):

$$\frac{d\left[(T_{RI} + T_{1-2})/2\right]}{dt} = \frac{1}{\left(M_{He}\right)_1\left(C_p\right)_{He}}\left[\dot{W}_{He}\left(C_p\right)_{He}(T_{RI} - T_{1-2}) - h_R A_{R1}\left(\frac{T_{RI} + T_{1-2}}{2} - T_{R1}\right)\right]$$

Coolant in radiator (section 2):

$$\frac{d\left[(T_{1-2} + T_{RO})/2\right]}{dt} = \frac{1}{\left(M_{He}\right)_2\left(C_p\right)_{He}}\left[\dot{W}_{He}\left(C_p\right)_{He}(T_{1-2} - T_{RO}) - h_R A_{R1}\left(\frac{T_{1-2} + T_{RO}}{2} - T_{R2}\right)\right]$$

Radiator (section 1):

$$\frac{dT_{R1}}{dt} = \frac{1}{M_{R1}\left(C_p\right)_R}\left[h_R A_{R1}\left(\frac{T_{RI} + T_{1-2}}{2} - T_{R1}\right) - \sigma\epsilon E A_{EFF1} T_{R1}^4\right]$$

Radiator (section 2):

$$\frac{dT_{R2}}{dt} = \frac{1}{M_{R2}\left(C_p\right)_R}\left[h_R A_{R2}\left(\frac{T_{1-2} + T_{RO}}{2} - T_{R2}\right) - \sigma\epsilon E A_{EFF2} T_{R2}^4\right]$$

RESULTS AND DISCUSSION

The system dynamics were investigated for 0.1 percent step changes in reactivity (approx. 15¢) and 10 percent step changes in the flow rate of the propellant and the fuel. The system was assumed to be operating at its design point prior to each disturbance. The reactivity disturbances were made for various reactivity feedback coefficients. A cavity pressure of 10 percent above the design operating point is regarded as a stress limit on the cavity structure.

Step Changes in Reactivity

A reactivity insertion initiates several main changes inside the cavity. For example, a positive reactivity insertion immediately increases reactor power. The increased power then increases the fuel temperature. The propellant temperature also rises because more radiant heat is received from the fuel. Since both fuel and propellant are gases, the cavity pressure changes with temperature and therefore increases. During this time the boundary between the fuel and propellant expands or contracts such that the pressure of both gases remains equal. The outgoing flow rates may also change because they are influenced by the temperature and pressure in the cavity (inlet flow rate maintained constant). These foregoing interactions become continually modified through the various reactivity feedbacks listed in table II. The combined action of these feedbacks is critical to the stability of the reactor. By independently varying the reactivity coefficients, the sensitivity of the individual feedbacks and their effect on the system response can be evaluated. In this section, we describe the response of the system to step changes in reactivity for various propellant reactivity feedback coefficient values.

Reactivity feedback coefficients at reference. - The system dynamics for reactivity disturbances were first examined by inserting a 0.1 percent step of positive reactivity at time zero with all reactivity feedback coefficients at their reference value. Figure 4 shows the effect of this disturbance on reactor power. The disturbance causes the reactor power to oscillate at a frequency of approximately 0.6 hertz. The power peaks, after about 0.2 second, at about 103 percent of design. The oscillations to some extent are caused by the large reactivity feedbacks of this reactor. The reactivity feedbacks, which are both positive and negative, have a total effect which is negative and which opposes a change in reactor power. The reaction time (lag) of the various reactivity feedbacks also influences the oscillations. Because the oscillations are damped and the reactivity feedback is negative, the reactor power approaches a steady-state value of 101 percent of design after about 9 seconds.

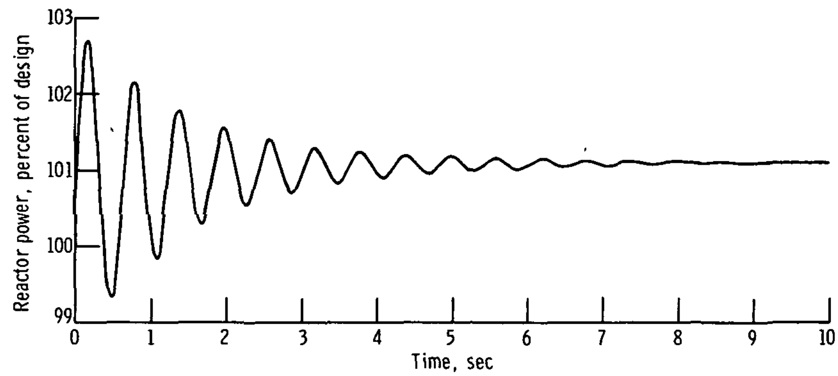

Figure 4. - Reactor power response following 0.1 percent step increase in reactivity at time zero, where all feedback coefficients are reference values.

Time plots of the fuel temperature, the propellant temperature, and the cavity pressure are given in figures 5, 6, and 7, respectively. Each variable follows reactor power according to expectation. A slight phase lag in the temperature and pressure transients is caused by the thermal capacitance of each gas. The propellant temperature shows additional lag because the heat from the reactor must pass through the fuel before it can reach the propellant. These lags are then passed on to the reactivity feedbacks.

System transients were also obtained for a 0.1 percent step of negative reactivity with all reactivity coefficients at their reference value. The results had oscillations which were similar to those for the positive step insertion except that the oscillations started in the opposite direction with the power initially decreasing. The power reached a steady state of 97 percent of design.

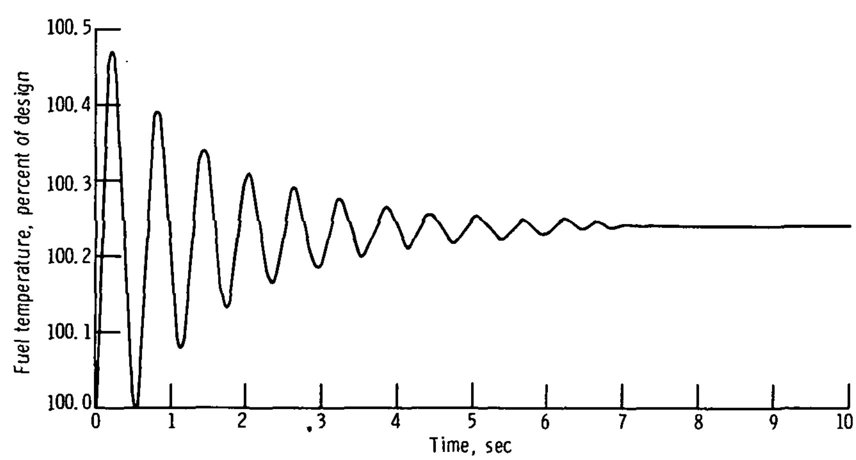

Figure 5. - Fuel temperature response following 0.1 percent step increase in reactivity at time zero, where all feedback coefficients are reference values.

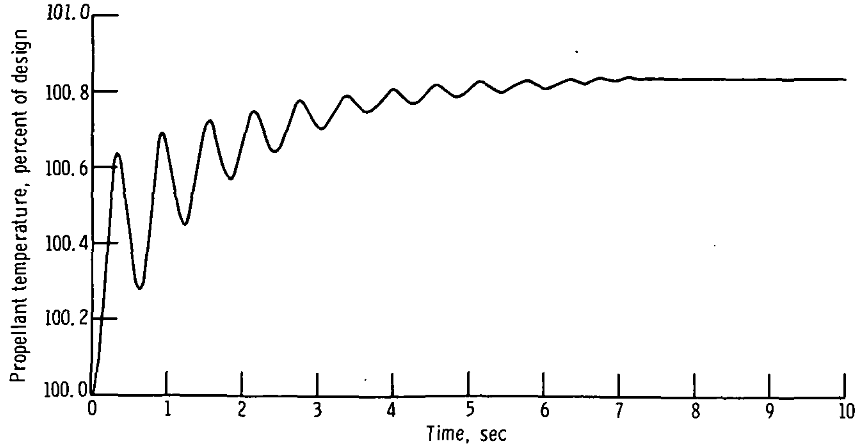

Figure 6. - Propellant temperature response following 0.1 percent step increase in reactivity at time zero, where all feedback coefficients are reference values.

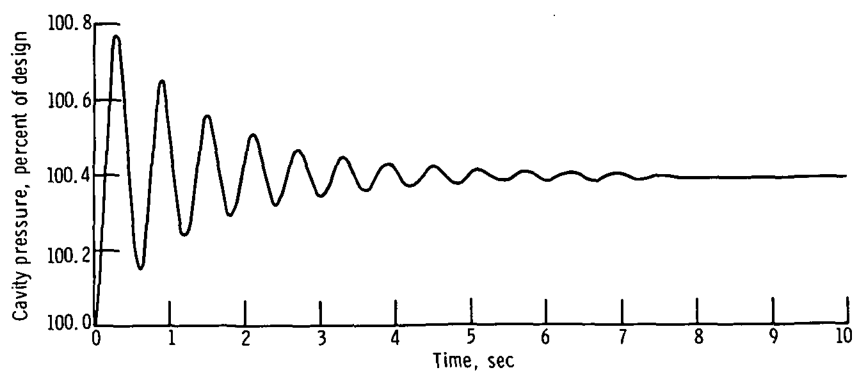

Figure 7. - Cavity pressure response following 0.1 percent step increase in reactivity at time zero, where all feedback coefficients are reference values.

Propellant feedback coefficients other than reference. - Uncertainty in the calculated values of the various reactivity feedback coefficients prompted an investigation into the effect of the more important ones. The calculated, or reference, values of the propellant temperature and propellant density coefficients were changed to 1/2 times and to 2 times their original values. A positive reactivity step of 0.1 percent was again inserted for each case and a comparison was made.

The first set of transients were obtained with the propellant density feedback coefficient at one-half of its reference value. The reactor power response is shown in figure 8. The reactivity step was inserted at time zero. The power response is oscillatory and differs from the reference case by showing diverging oscillations. The fuel temperature, propellant temperature, and cavity pressure showed similar oscillations; the results are shown in figures 9 to 11.

The same type of disturbance was again made with the reactivity feedback at twice

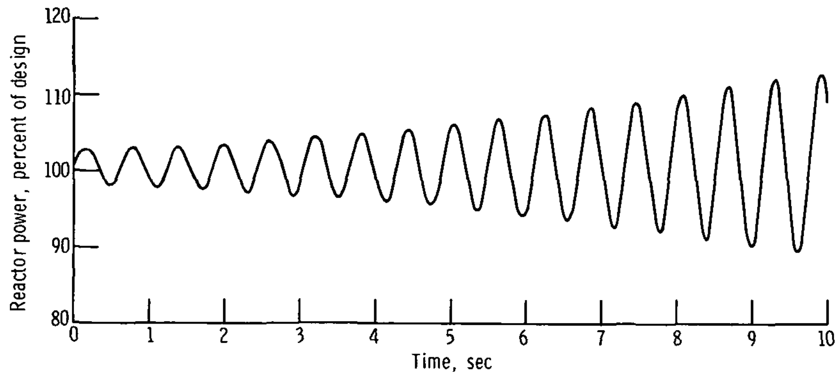

Figure 8. - Reactor power response following 0.1 percent step increase in reactivity at time zero, where propellant density feedback coefficient equals one-half reference value.

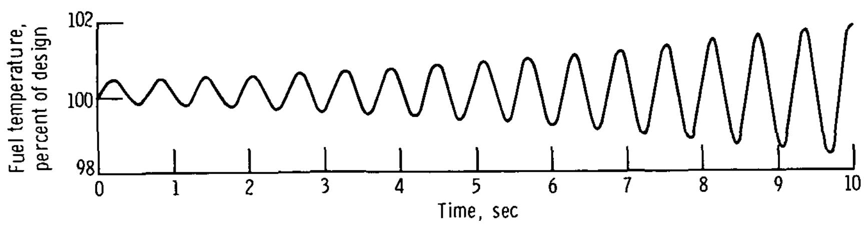

Figure 9. - Fuel temperature response following 0.1 percent step increase in reactivity at time zero, where propellant density feedback coefficient equals one-half reference value.

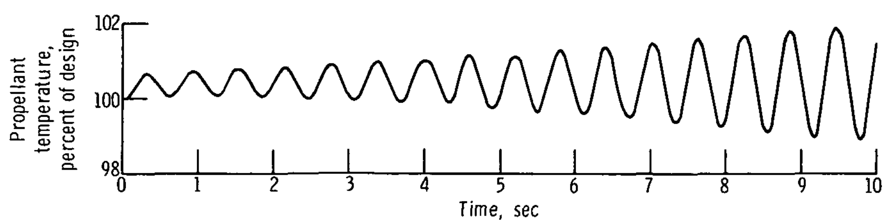

Figure 10. - Propellant temperature response following 0.1 percent step increase in reactivity at time zero, where propellant density feedback coefficient equals one-half reference value.

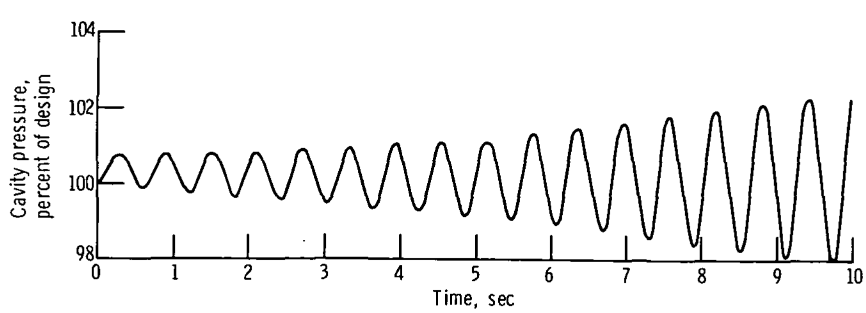

Figure 11. - Cavity pressure response following 0.1 percent step increase in reactivity at time zero, where propellant density feedback coefficient equals one-half reference value.

its reference value. For this case the power increases very quickly to more than 180 percent of design in the first 10 seconds, as shown in figure 12. The increased power produces a cavity pressure which exceeds the cavity design limit of approximately 110 percent. The cavity pressure, fuel temperature, and propellant temperature are shown in figure 13.

System transients were also obtained for different propellant temperature coefficients. The disturbance was again a positive 0.1 percent reactivity step with all other feedback coefficients at their reference value. Figure 14 shows the reactor power transients for a propellant temperature coefficient at 1/2 times the reference value. The power response shows an increase to nearly twice its design value at the end of 10 seconds. The response of the fuel temperature, the propellant temperature, and the cavity pressure is shown in figure 15.

Figure 16 shows the power transient for the same reactivity step disturbance but with the propellant temperature coefficient at 2 times the reference value. This case is extremely oscillatory and unstable. Similarly large oscillations take place in the fuel temperature, the propellant temperature, and the cavity pressure; the respective results are shown in figures 17 to 19.

The response for most values of the propellant reactivity coefficient was undesirable. Whenever the reactivity coefficients were not at reference, the response was either unstable or the transients exceeded design limitations. The large reactivity feedbacks of this system with their respective time lags are analogous to the destabilizing influence of a controller with a predominant integral action of high gain.

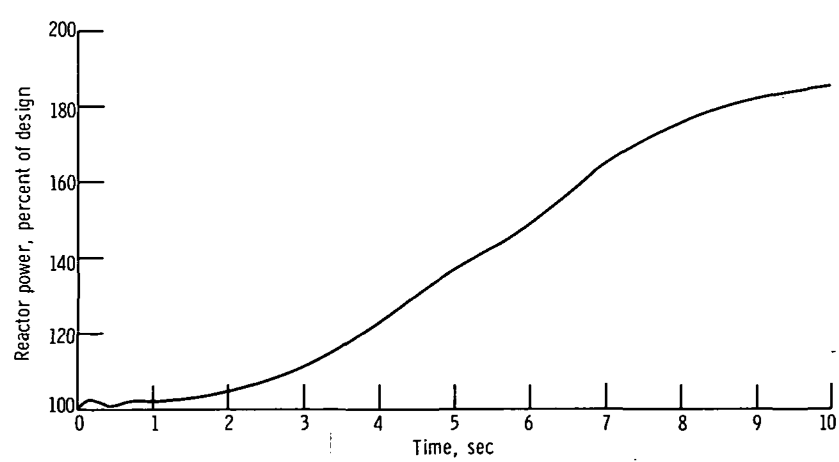

Figure 12. - Reactor power response following 0.1 percent step increase in reactivity at time zero, where propellant density feedback coefficient equals twice reference value.

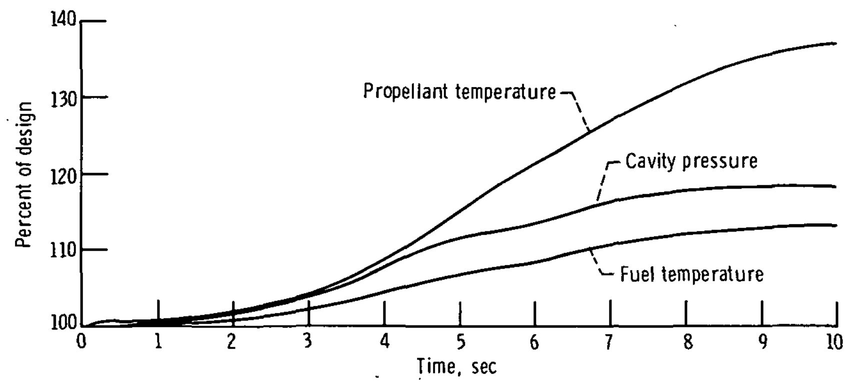

Figure 13. - Response of fuel temperature, propellant temperature, and reactor power to 0.1 percent positive reactivity step at time zero, where propellant density of feedback coefficient equals twice reference value.

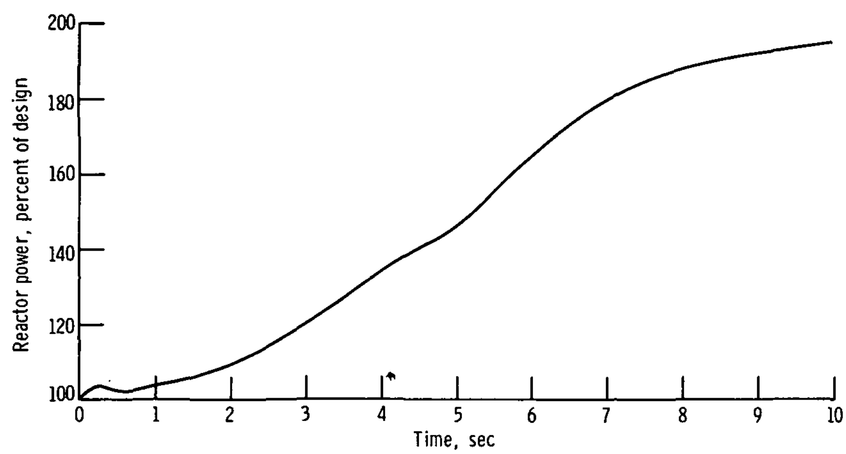

Figure 14. - Reactor power response following 0.1 percent step increase in reactivity, where propellant temperature feedback coefficient equals one-half reference value.

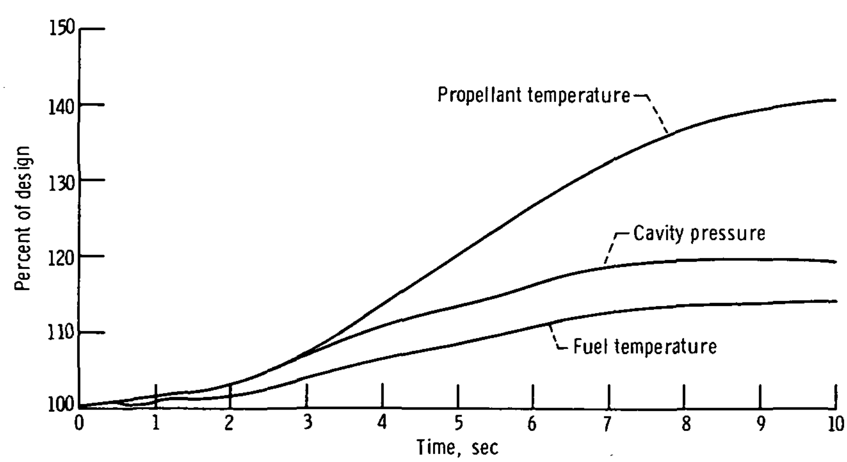

Figure 15. - Response of fuel temperature, propellant temperature, and reactor power to 0.1 percent positive reactivity step at time zero, where propellant temperature feedback coefficient equals one-half reference value.

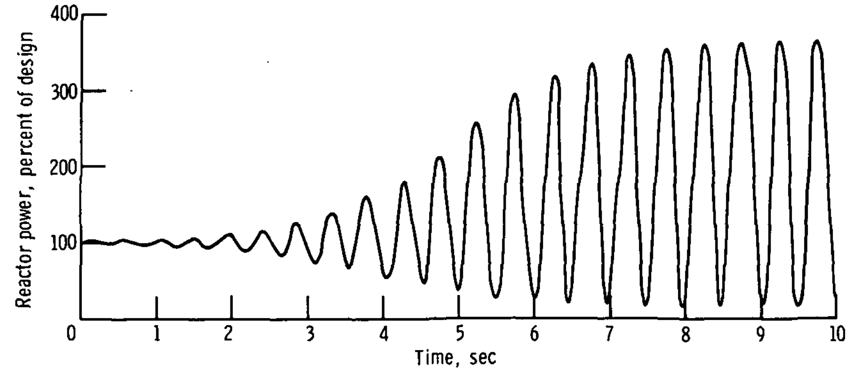

Figure 16. - Reactor power response following 0.1 percent step increase in reactivity at time zero, where propellant temperature feedback coefficient equals twice reference value.

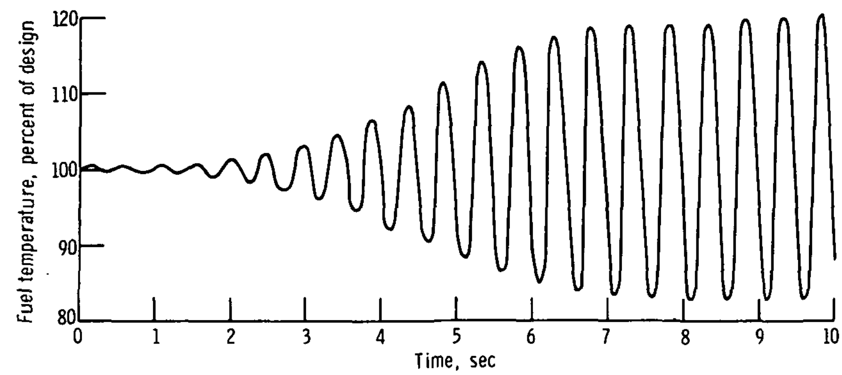

Figure 17. - Fuel temperature response following 0.1 percent step increase in reactivity at time zero, where propellant temperature feedback coefficient equals twice reference value.

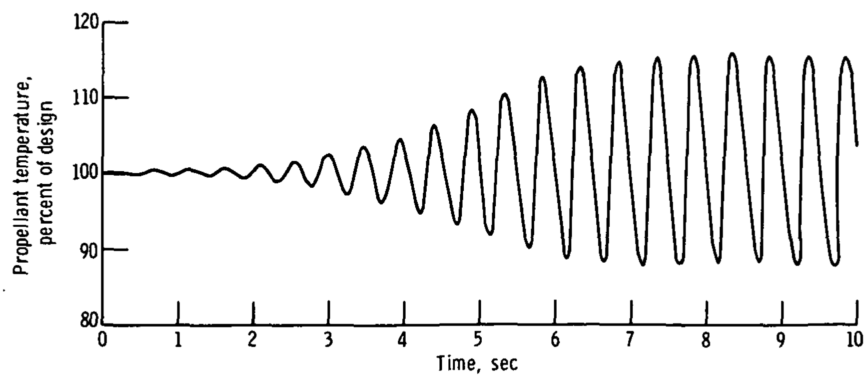

Figure 18. - Propellant temperature response following 0.1 percent step increase in reactivity at time zero, where propellant temperature feedback coefficient equals twice reference value.

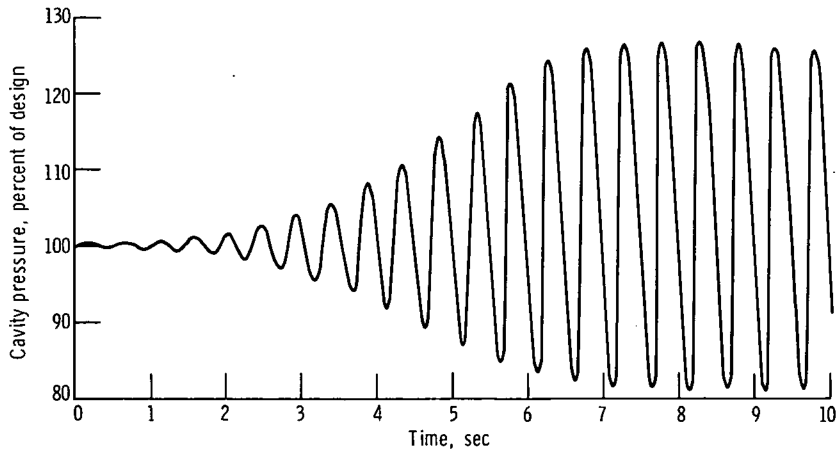

Figure 19. - Cavity pressure response following 0.1 percent step increase in reactivity, where propellant temperature feedback coefficient equals twice reference value.

Step Changes in Propellant Flow Rate

A change in propellant flow rate directly affects the propellant density and temperature. The propellant temperature in the cavity is affected because the propellant entering the cavity is relatively cold; the propellant density is affected because a changed flow rate tends to alter the propellant mass in the cavity. The 10 percent change which was made in the incoming flow rate amounted to 0.455 kilogram per second. This represents a large disturbance on the 3.15 kilograms of propellant residing in the cavity. The propellant density feedback had the most predominant effect on reactor power. This feedback can make the reactor unstable because it is positive, even though its coefficient in table II has a negative sign.

The first propellant flow rate disturbance is presented for a 10 percent step increase in flow rate. The increased flow rate increases the cavity pressure and the propellant density. The propellant density feedback then causes the power to decrease. The decreased power further increases the propellant density. Thus, interactions between power and density are reinforcing and can force a shutdown. The results are shown in figure 20, which is a composite plot of the more significant changes brought about by the disturbance made at time zero. The power appears to move toward shutdown. The fuel temperature is also reduced by the reduced reactor power. The lower temperature then lowers the cavity pressure.

The predominance of the propellant reactivity feedbacks during this flow rate disturbance is shown in figure 21. The propellant temperature feedback is positive and opposite from the propellant density feedback. The propellant density feedback is the largest of the two; at the end of 10 seconds it shows a reactivity change of approximately -0.35 percent, or -50¢. The other reactivity feedbacks are small in compari-

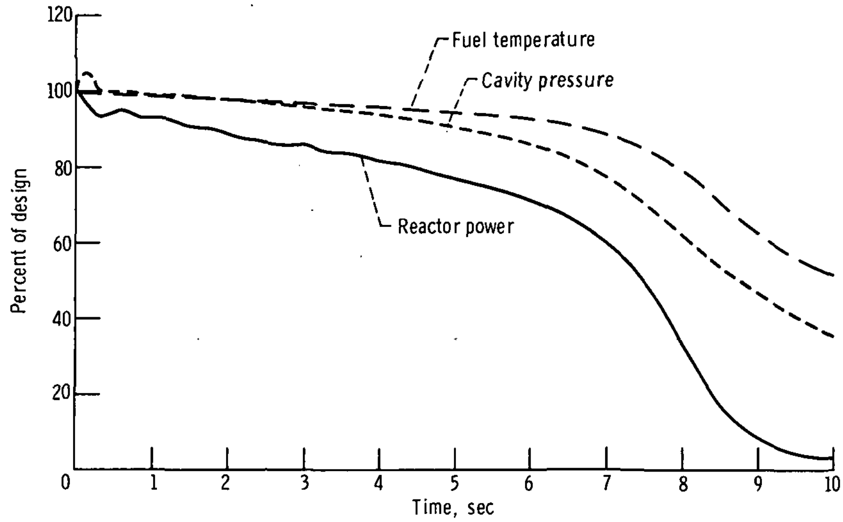

Figure 20. - Response of fuel temperature, pressure, and reactor power to 10 percent step increase in propellant inlet flow rate at time zero, where all feedback coefficients are reference values.

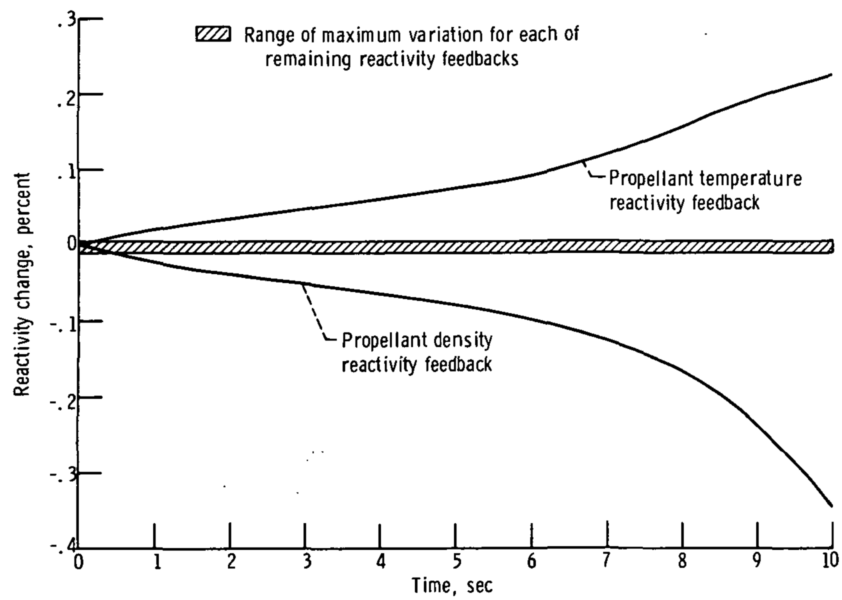

Figure 21. - Reactivity feedback change following 10 percent step increase in propellant inlet flow.

son. The variation of each remains within a region which is designated by slanted lines in figure 21. The relative strength of the propellant feedbacks was also evident in the other runs.

The second propellant flow rate disturbance was a 10 percent step decrease in the incoming flow rate. Figure 22 shows the results for reactor power, cavity pressure, and fuel temperature for a 10 percent step decrease of propellant flow rate. As in the previous case, the propellant density again predominates. Its reactivity contribution is positive and caused the power to rise. The power rise is limited, however, because the density changes less at the higher power levels and the propellant temperature feedback then becomes predominant and causes the power to level off.

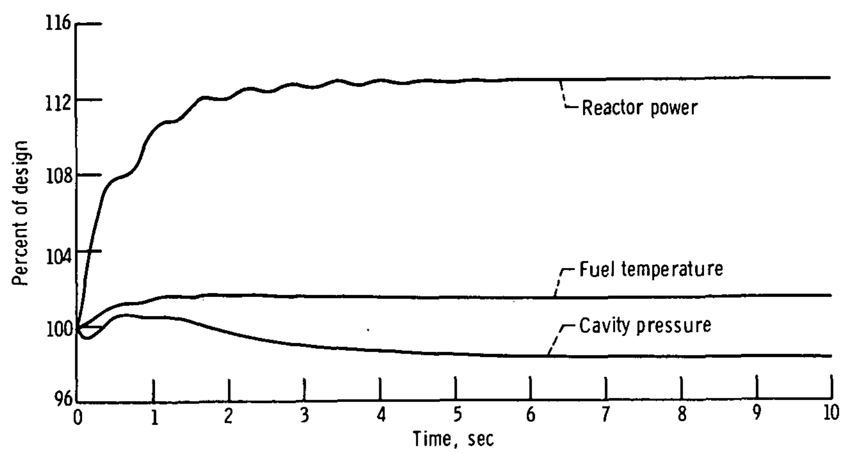

Figure 22. - Response of fuel temperature, pressure, and reactor power to 10 percent step decrease in propellant inlet flow rate at time zero, where all feedback coefficients are reference values.

Step Changes in Fuel Flow Rate

The results for the fuel flow rate disturbance were not significant because the 10 percent disturbance amounted to a change in flow rate of only 0.0002 kilogram per second. Relative to the 21.5 kilograms of fuel residing in the cavity, such a change represents a very small disturbance to the system. During the first 10 seconds the power excursions were less than 5 percent.

SUMMARY OF RESULTS

The transients characteristics of the gas-core reactor were investigated for step

TABLE III. - SUMMARY OF SYSTEM RESPONSE CHARACTERISTICS

Input disturbance	Reactivity feedback coefficients	Type of system response
+0.1 Percent reactivity step	Reference value	Oscillatory
-0.1 Percent reactivity step	Reference value	Oscillatory
+0.1 Percent reactivity step	Propellant density equals one-half reference value	Oscillatory; appears unstable
	Propellant density equals twice reference value	Damped; exceeds design limit
	Propellant temperature equals one-half reference value	Damped; exceeds design limit
	Propellant temperature equals twice reference value	Oscillatory; appears unstable
10 Percent increase in propellant flow	Reference value	Damped; reactor shuts down
10 Percent step increase in propellant flow	Reference value	Damped

disturbances of reactivity and flow rate disturbances of the fuel and the propellant. The disturbances were introduced at the design operating point. Table III summarizes the response characteristics of the various cases.

The more significant results obtained from this investigation are the following:

1. The stability of the reactor depends greatly on its reactivity feedbacks. The reactivity feedback from the propellant was determined to be the most predominant. Results for the various propellant feedback coefficients that were investigated showed that the system response depended largely on the value of these coefficients. Satisfactory responses were limited to a few cases. In most cases the response was oscillatory and ranged from damped oscillations to unstable oscillations.

2. A 10 percent step decrease in propellant flow rate increased reactor power by more than 12 percent.

3. A 10 percent step increase in propellant flow rate drastically reduced the power from 100 percent to less than 5 percent of design in 10 seconds.

4. A 10 percent increase in fuel flow rate had no significant effect.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 22, 1973,
503-04.

APPENDIX - SYMBOLS

A	heat-transfer area, m^2
C_i	i^{th} group of delayed neutron precursor concentration, neutrons/m^3
C_{MOD}	moderator heat capacity, J/(kg)(K)
C_p	heat capacity, J/(kg)(K)
D	diameter, m
D_i	power generated by i^{th} group of delayed neutron precursors, W/kg
E	fin effectiveness
H	enthalpy, J
$\overline{H}$	average enthalpy, J
h	heat-transfer coefficient, W/(sec)(m^2)(K)
K	proportionality constant
k	choked nozzle flow constant, (kg)($K^{0.5}$)/(atm)(sec)
l^*	prompt neutron generation time, sec
M	mass, kg
n	neutron density, neutrons/m^3
P	pressure, atm
$\dot{Q}$	reactor power, W
$\dot{Q}_P$	heat transferred from fuel to propellant, W
$\dot{Q}_{MOD}$	reactor power lost to moderator, W
T	temperature, K
t	time, sec
V	volume, m^3
$\dot{W}$	flow rate, kg/sec
β_i	fraction of delayed fission neutrons belonging to i^{th} group
δk	reactivity
ϵ	emissivity
λ_i	decay constant of delayed neutron
λ_{loss}	reciprocal of fuel residence time, sec^{-1}

ρ	density, kg/m^3
σ	Stefan-Boltzmann constant, $W/(m^2)(K^4)$

Subscripts:

C	cavity
EFF	effective
F	fuel
He	fluid in heat rejection system (helium)
P	propellant
R	radiator
RI	radiator inlet
RO	radiator outlet
1	radiator section 1
2	radiator section 2
1-2	radiator location between sections 1 and 2

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