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PROPULSION REACTOR TEMPERATURE CONTROL
WITH THE INTERNAL POWER LOOP ELIMINATED*

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ABSTRACT

Incremental changes of either temperature or the mass of hydrogen in Rover and NERVA reactors generate natural feedback reactivity which makes the reactor self-stabilizing. An increase in reactivity generated by either rod position or flow rate increases will raise power. This will increase core and gas temperature which decrease reactivity. Thus the system will come to a new balance at slightly higher power and temperatures when the natural reactivity decrease just offsets the increase from rod position or flow rate changes. At 1000 megawatts power and 70 lbs/sec flow rate, the static incremental gains from control rod position and flow rate to average core temperature are $\frac{68^{\circ}\text{R}}{^{\circ}\text{C}}$ and $\frac{31^{\circ}\text{R}}{\text{lbs/sec}}$ respectively. The natural reactivity loop also tends to cancel the non-linear effects of the reactivity-to-power gain dependency on power level, and the core heat exchanger bandwidth dependency on flow rate. Advantage has been taken of these core characteristics in developing a new temperature control system which does not have the internal power control loop common to earlier propulsion reactors. The change has resulted in considerably improved temperature control system stability and reliability.

A natural progression of development steps in nuclear rocket engine controls has led to the use of a temperature control system with an inner logarithmic power control loop. This scheme generally has been satisfactory,

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but two major improvements can be realized by eliminating the inner power control loop. First, the natural hydrogen and temperature reactivities permit the development of a temperature control system with appreciably better dynamic characteristics than can be realized with an internal power loop. Secondly, reliability will be improved because the power controller and the nuclear instrumentation will no longer be in the control system during hot tests. Power control and nuclear instrumentation will still be used for low power tests and for power scrams.

A block diagram of the new temperature control system is shown in Fig. 1. The temperature error voltage is operated on by the temperature controller, which drives twelve rotary control drums in the beryllium reflector. Each drum has a segment of boral which faces the core when the drums are at 0°. As the drums are rotated "out" toward 180°, the boral rotates away from the core, making it more reactive. The controller drives the drums as required to bring the measured temperature into agreement with the temperature demand. When the system is used to control core exit gas temperature, the average of three thermocouples is used as the measured temperature. When the system is used to control core material temperature, ten thermocouples are used in the averaging circuit to develop the measured temperature. A rejection circuit is used to reject thermocouples which differ from the average by more than a pre-set amount. The linearized transfer function for core material thermocouples is

$$G_7(s) = \frac{0.0303}{\frac{s}{6.28} + 1} \quad \text{volts/°R.}$$

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The temperature controller can be used in two ways. They are:

1. Allowing the controller to have the capability of moving the drums the full 0 - 180° span.
2. Having a control drum program to produce the calculated drum motion for the run profile. This implies that the controller would normally operate

around zero volts, and it can be clamped as a safety precaution to limit its capability to increase temperature.

It is the opinion of the authors that method 1 is superior for a flyable system, but the development of an automatic startup system going directly to control on temperature is required to use it. Method 2 is being used for Phoebus reactors because the controller clamps make it possible to manually close the temperature loop at ambient reactor temperature without having the temperature controller run the drums out. This is required for the present method of setting up the initial conditions for hot reactor runs.

The transfer function of the temperature controller which will be used during the Phoebus-1B tests is

$$G_1(s) = \frac{0.8s + 1}{s} \quad \text{volts/volt.}$$

The linearized transfer function of the electro-hydraulic control drum actuator is

$$\frac{\delta\theta}{\delta\theta_D} = 1.8 \frac{22}{22 + s + 0.0175s^2 + 1.34(10)^{-4}s^3 + 4(10)^{-7}s^4} \quad \text{degrees/volt.}$$

The drum reactivity worth is approximately

$$\frac{\delta(\delta K_D)}{\delta\theta} = 0.062 \sin \theta \quad \$/\text{degree.}$$

The control drum position does not normally vary from 90° by more than a few degrees. For most linearized controls analysis work, the worth can be treated as a constant 0.062\$/degree, and

$$G_2(s) = \frac{2.46}{22 + s + 0.0175s^2 + 1.34(10)^{-4}s^3 + 4(10)^{-7}s^4} \quad \$/\text{volt.}$$

The inherent stability of the natural reactivity in the core is the key to success for temperature control without an internal power control loop. If reactivity is increased by moving the drums out, temperature increases and hydrogen density decreases. These effects produce negative temperature and hydrogen reactivity changes which tend to stabilize the system at a new, slightly higher operating temperature. The same reasoning will show that a small increase in flow rate at a constant position of the drums will also produce a small rise in reactor temperature. Static values for such changes around full power were measured during the Kiwi-B-4E test. The direct measurements were

$$\left. \frac{\Delta \bar{T}}{\Delta \theta} \right|_{\dot{W}} = \frac{68^\circ \text{R}}{^\circ \theta} \quad \text{and} \quad (1)$$

$$\left. \frac{\Delta \theta}{\Delta \dot{W}} \right|_{\bar{T}} = - \frac{0.46^\circ \theta}{1 \text{ lb/sec}} \quad (2)$$

where $\bar{T}$ = average core material temperature. Multiplying equations (1) and (2),

$$\left. \frac{\Delta \bar{T}}{\Delta \dot{W}} \right|_{\theta} = \frac{31^\circ \text{R}}{1 \text{ lb/sec}}$$

Referring to Fig. 1, if we let

$$\frac{\delta(\delta K_{FB})}{\delta P} = G_4(s) + G_5(s)$$

$$= G_8(s), \text{ then}$$

$$\frac{\delta P}{\delta(\delta K_D)} = \frac{G_3(s)}{1 + G_3(s)G_8(s)} \quad (3)$$

If $G_3(S)G_8(S) \gg 1$, equation (3) becomes

$$\frac{\delta P}{\delta(\delta K_D)} = \frac{1}{G_8(S)} \quad (4)$$

In equation (4) the neutron kinetics transfer function, $G_3(S)$, has been cancelled. This removes the usual gain dependency on power level and the gain and phase dependency on period from the control system. In addition, the basic poles in $G_6(S)$ and $G_8(S)$ are the same because both functions are determined primarily by the core heat exchanger. Since $G_8(S)$ is in the denominator of $\delta P/\delta(\delta K_D)$, the $G_8(S)$ poles become zeros in $\delta P/\delta(\delta K_D)$. These zeros tend to cancel the poles in $G_6(S)$, thus making the temperature control system characteristics less susceptible to the heat exchanger time constant dependency on flow rate.

The improvement in dynamic characteristics of the new system is illustrated in Fig. 2. This figure shows what happens to the open loop gains of temperature control systems with and without internal power control as the reactor operating level is lowered. The reference case is applicable to both systems at the Phoebus-1B full power hold (1500 Mw and 95 lbs/sec). The remaining two curves show the open loop gain of each system at the shutdown hold (80 Mw and 20 lbs/sec). The most important characteristic shown in Fig. 2 is the large difference in gain between the two systems. The closed loop bandwidth of the system with internal power control has dropped to approximately 0.01 to 0.02 cps, which is too slow to be of any practical use. The new system closed loop bandwidth is approximately 0.18 cps, which is still fast enough to be useful in operating the reactor.

The temperature control system in the NRX/EST reactor was operated with and without the internal log power loop. Measured transfer function data for both modes of operation are shown in Fig. 3.

Open loop transfer functions of the Phoebus-1B temperature control system are shown in Fig. 4. Analog computer data are shown for the intermediate hold (625 Mw and 60 lbs/sec), the full power hold (1500 Mw and

95 lbs/sec), and the shutdown hold (80 Mw and 20 lbs/sec).

The greatest uncertainty in the analysis of the new temperature control system is in the calculation of temperature reactivity. This uncertainty could lead to some deviation between predicted and observed system characteristics. Calculated and measured temperature reactivity data are shown in Fig. 5. The calculations were done with the HEX 2 digital code. Inputs to the code were measured data for power, flow rate, and control drum position from the Kiwi-B-4E hot run. The code calculates reactor temperatures and pressures, and hydrogen, control drum, and total reactivities as a function of time. All outstanding reactivity is then defined as temperature reactivity, and an attempt is made to correlate this reactivity with the average core temperature. The steady-state data, which includes the Phoebus-1A data and the Kiwi-B-4E data at the end of the first hold and during the second and third holds, should be reasonably accurate. The startup and shutdown data are more subject to error because the core was not in thermal equilibrium. The reactivity changes between the holds were verified by direct measurements. The change from hold 1 to hold 2 was a temperature change at constant flow rate. The change from hold 2 to hold 3 was a flow rate change at constant temperature. Thus, the measured control drum position changes as the operating conditions were changed from hold to hold gave a direct measure of temperature and hydrogen reactivity changes.

The first planned use of the new temperature control scheme was for the restart of Phoebus-1A in June, 1965, but the restart was not done. The system was used successfully to control core exit gas temperature during an NRE-EST experiment in March of this year. Present plans are to use it for core material temperature control on all future hot tests of Phoebus reactors.

T_D = TEMP. DEMAND, VOLTS
 T_m = TEMP. MEASURED, VOLTS
 T_E = TEMP. ERROR, VOLTS
 Θ = DRUM POSITION DEMAND, VOLTS
 δk_D = CONTROL DRUM REACTIVITY, \$
 δk_{FB} = CORR. FEEDBACK REACTIVITY, \$

δk_H = HYDROGEN REACTIVITY, \$
 δk_T = TEMP. REACTIVITY, \$
 δk_{T0} = TOTAL REACTIVITY, \$
 P = REACTOR POWER, KW
 T = CONTROLLED TEMP., °R
 $\dot{W}$ = HYDROGEN FLOW RATE, LB/SEC

FIG. 1, SIMPLIFIED BLOCK DIAGRAM, TEMPERATURE CONTROL SYSTEM