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Control of ZrH Reactor Reactivity Perturbations During
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ABSTRACT

See Page 2

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ABSTRACT

Scheduled and inadvertant vehicle maneuvers in manned and unmanned space missions may result in reactivity perturbations to the ZrH reactor due to fuel and control drum motion from acceleration forces. Potential power and outlet coolant temperature excursions could result in interruptions of PCS power generation, or excessive coolant temperatures if uncontrolled.

It may be possible to eliminate reactivity perturbations by suitably loading the fuel segments so they cannot "rattle" within the cladding and designing a control system with "zero" backlash. The feasibility of these design features has not yet been evaluated.

This analysis compares potential uncontrolled reactor transients with allowable transients for uninterrupted electrical power generation from a Brayton system, and presents a control scheme to limit transient reactor outlet temperatures to 1250°F for a system designed to operate at a nominal 1200°F reactor outlet.

Potential uncontrolled transients could result in a reactor outlet temperature swing of $\pm 77^{\circ}\text{F}$ about a nominal 1200°F and a reactor power swing of +92 Kwt and -67 Kwt about a nominal 130 Kwt for the Brayton System.

I. INTRODUCTION

Manned and unmanned space vehicle design requirements may include maneuvering for gravity field orientation, orbit changes, docking, etc. Such maneuvers will impose acceleration and deceleration forces on station components that can result in mechanical displacements relative to the station structure of components not rigidly attached to the structure. These components could be characterized as capable of "rattling" during station maneuvers. In the current stage of the flight ZrH reactor design, the fuel segments are free to rattle in the cladding, and the control drums may rattle on their mountings. This rattling will probably be reflected in small reactor power and temperature changes due to the resulting reactor geometry (reactivity) changes.

During launch, the vibration suppressor (collar button) imposes a load on the fuel segments which restricts their motion. During startup, however, the cladding expands more than the fuel and after the reaction reaches full power, the load is removed and the fuel segments are free to rattle. The fuel swelling space or gap between fuel and cladding at the beginning of core life can permit lateral or centrifugal acceleration forces to move the fuel against the cladding wall. A 12 mil diametral gap between the fuel and cladding could result in an average 6 mil radial motion of the fuel. A radial fuel movement of 6 mils has been estimated to produce a 6% reactivity change⁽¹⁾ which would produce a noticeable power transient. Free-play or backlash in the gearing between control drums and control drum motors can also permit lateral or rotational acceleration forces to rotate the drums through the backlash to produce reactivity changes and noticeable power transients. The extent of such backlash movement cannot be estimated as of this writing due to lack of a detailed drum system design, but could be expected to result in reactivity changes on the order of those estimated for fuel movement. Some control on the degree of drum backlash that must be sustained is possible through use of special gear designs, so that this source of power perturbations during station maneuvering should be minimized. The fuel elements as a source of perturbations, on the other hand, do not appear to be readily amenable to design modifications to avoid rattling prior to fuel swelling, so that other means for coping with this condition may be required.

To assess the potential effect of vehicle maneuvers on reactor performance, the combination of fuel and control drum movement from acceleration forces has been assumed to introduce a combined 10% reactivity step disturbance to the reactor reactivity balance, and the system response to this disturbance was computed for the Brayton power generation system shown schematically on Figure 1 assuming constant electrical power generation is maintained from the power conversion system.

To counteract the probable positive reactivity perturbations produced by station maneuvers, augmented control reactivity backing up the control action provided by the reactor outlet temperature controller may be necessary. This might consist of a limited setback action of the control drums to rapidly eliminate the excess reactivity introduced by the station maneuver but limited to a short time interval to avoid an overly subcritical reactivity balance. The action amounts to a large gain in control reactivity for a short period when large (~10%) positive reactivity perturbations occur.

II. RESULTS

A. Inherent System Response

The inherent system response to a range of positive and negative step reactivity perturbations is summarized on Figure 2 for the 295 element ZrH reactor operated at 130 Kwt with a helium-xenon gas Brayton Cycle Power Conversion System (PCS). The curves shown present the peak change in reactor power (ΔP), average coolant temperature (ΔT_{xb}) in the intermediate heat exchanger and Brayton boiler, and reactor outlet coolant temperature (ΔT_{ro}) for the first cycle of the damped system response to the step reactivity input. The assumption that these perturbations will be generated as steps is considered to be conservative in terms of input time as maneuver acceleration forces are not normally applied instantaneously. The step input assumption was made, however, to obtain maximum system transients for a given reactivity input, because acceleration forces though not applied instantaneously may build up quite rapidly during maneuvers, and because it was the most simple form of reactivity input in the computer code used for the system simulation.

ZRH REF. REACTOR - BRAYTON CYCLE PCU SYSTEM

REACTOR

INX

BNX

PCU

RADIATOR

T = TEMP. - °F
(w/w0) = FLOW RATIO
(w0 = RATED FLOW)

EMP = ELECTROMAGNETIC PUMP
CWP = CENTRIFUGAL PUMP
[Symbol] = TRANSPORT DELAY / PIPE & THERMAL TIME CONSTANT - SEC.

FIGURE 1

REF 24H KECOTZ-BRYNTHI PCS RESPONSE
TO STEP REACTIVITY INSERTIONS

BHX - BRANTON CYCLE BOILER

B. Allowable Coolant Temperature Transients

The permissible primary or secondary loop coolant temperature transients that can be tolerated without compromise of the power generating capability for four PCS's are listed on Table I below with an indication of the nature of the power generation failure occurring when these limits are exceeded.

TABLE I
PCS Allowable Coolant Temperature Transients (2)

Nominal Design Characteristics	Thermoelectric	Hg Rankine	Organic Rankine	Brayton
Net Power, Kwe	25	51	25	25
Reactor T _{out} , °F	1200	1200	850	1200
NaK ΔT, °F	135	170	75-100	75-100
NaK Flow, lbs/sec	16.7	16	9-6.7	7.5-5.6
Thermal Power, Kwt	550	600	150	125
Allowable Primary NaK Temperature Oscillation	+200°F	+100°F	+200°F - 50°F	+200°F
Failure or Degradation Mode	Thermal Stress Effects on Module	(+100) Too large a decrease in turbine flow due to early pinch point & high ΔP in boiler. (-100) Boiler carry over to turbine due to late boiling and insufficient super-heat	(+200) Decrease in turbine flow due to high boiler ΔP. (-50) Choking of turbine diffuser causing loss of ΔP across turbine	Thermal stresses in HX's, Cooler & Recuperator (+200) Over-power speed control (-200) Loss of Power and self sustaining speed

Comparison of the results summarized on Figure 2 and Table 1 shows that reactivity inputs up to 10¢ in either direction can be sustained in all the candidate systems without disrupting electrical power output except for the organic system. A negative reactivity input greater than -7¢ when using an Organic Rankine cycle may result in turbine choking.

Data shown on Figure 2 were based on no automatic controller action following the reactivity input. The typical reactor outlet temperature controller used in these systems would provide some corrective action in addition to the inherent feedback control, so that the Organic Rankine system with automatic control action included could be expected to show a tolerance for step reactivity disturbances greater than the -7¢ obtained with inherent feedback control alone.

From the results, it would be concluded that perturbations to the power systems from station maneuvering may not require special precautions, preparation, or control action to prevent power interruption from the PCS in any of the four candidate systems.

C. Reactor Outlet Coolant - High Temperature Limit

With the potential for temperature and power transients as shown on Figure 2, the control requirements and transient behavior of the reactor was investigated assuming the maximum reactor outlet temperature is limited to 1250°F. The uncontrolled response of the system to a +10¢ reactivity step produces a reactor outlet coolant temperature excursion shown on Figure 3 that exceeds 1250°F for an interval of 350 seconds with a transient peak of 1277°F.

Normal control action will be designed to cope with considerably smaller and slower reactivity perturbations, so that typical control action will not be capable of controlling reactor outlet coolant temperatures for such reactivity disturbances. From Figure 3, it is seen that reactor power rise would have to be arrested before 60 seconds following the step input, so that reactor subcriticality would be required before 60 seconds from the combination of inherent reactivity feedback effects and automatic control action. The reactivity balance for the system transient without control action is shown on Figure 4, indicating an excess reactivity of 4¢ remaining from the step input at 60 seconds in the transient. Assuming controller

FIGURE 3. Reactor coolant temperatures for uncontrolled system response to a +10% reactivity input step.

REF ZRH-BRAYTON PCS +100 REACT STEP

FIGURE 4. Reactor reactivity balance for uncontrolled system response to a +10% reactivity input step.

action initiated simultaneously with the step input perturbation, a control reactivity rate of 4% /min would provide a just critical reactor at 60 seconds. In practice, instrumentation, and control circuitry response, time for the controlled parameter to reach control activation levels (~ 20 seconds in this system), and time for coolant temperature peaking following power peaking would reduce time for control action in this case from 60 seconds to about 30 seconds, or less. A control rate on the order of 8 to 10% /min would be required for such disturbances which would make reactor outlet temperature control impractical within a reasonable deadband range.

A control scheme considered for limiting positive reactor outlet temperature excursions within 1250°F is outlined functionally on Figure 5. Normal control action over a nominal 20°F deadband (10 to 30°F with TC uncertainty) is backed up for positive temperature transients (above 1200°F - nominal operating temperature) by a limited setback action which activates control drum movement at the setback rate for a fixed time interval. The setback reactivity rate assumed for this study was 20% /sec., so that a $\frac{1}{2}$ second setback action would provide the reactivity necessary to cancel the input perturbations.

To determine the capability of such a system to limit the reactor outlet temperature excursion within 1250°F for a $+10\%$ reactivity input step, the control scheme outlined on Figure 5 was added to the system computer simulation used previously, and system response with the normal and augmented control action included was computed. Reactor outlet temperature during normal system operation would be within the control deadband defined by the nominal setpoint levels and measuring thermocouple uncertainties. With the selected 20°F deadband, and the assumed $\pm 5^{\circ}\text{F}$ uncertainty in thermocouple accuracy, reactor outlet temperature could be within the range of 1185°F to 1215°F at the time a station maneuver occurs. Time to reach control system setpoints for a $+10\%$ reactivity input will be slightly different in each case, so that both initial conditions were considered.

Results for the high initial outlet temperature condition are shown on Figure 6. Outlet temperature was assumed to be 1210°F as shown on Figure 6 with normal control action activated at 1215°F to prevent activation of control action simultaneous with the input disturbance. A five second time delay was assumed for the combination of thermocouple time constant and

FIGURE 5

R.A.H. REACTOR COOLANT OUTLET HIGH TEMP. PROTECTION CONTROL

REACTOR COOLANT OUTLET TEMP. °F

1200
1180
1160
1140
1120
1100
1080
1060
1040
1020
1000
980
960
940
920
900
880
860
840
820
800
780
760
740
720
700
680
660
640
620
600
580
560
540
520
500
480
460
440
420
400
380
360
340
320
300
280
260
240
220
200
180
160
140
120
100
80
60
40
20
0

FULL SETBACK
 $\dot{P} = 200^\circ\text{F}/\text{SEC TO}$
DIAGN. FUEL OUT

MAX. ALLOWABLE TEMP. TRANS OR STEADY STATE

LIMITED SETBACK
 $\dot{P} = 200^\circ\text{F}/\text{SEC TO } 10^\circ\text{F}$

CONV. DEAD BIND.
($\pm 10^\circ\text{F}$)

HIGH CONTROL LEVEL

TC = THERMOCOUPLE UNCERTAINTY - $\pm 5^\circ\text{F}$

FIGURE 6. Reactor coolant temperatures for controlled system response to a +10% reactivity input step - High initial temp.

control drum activation delay. Normal control action was activated at 19 seconds followed closely by the limited setback action (1230°F) at 34 seconds. Peak transient outlet temperature is 1240°F occurring 50 seconds after the step perturbation so that the temperature rise is limited to 30°F as a result of the rapid control action. The reactor transient reactivity balance is shown on Figure 7.

Results for the low initial outlet temperature are shown in Figure 8 in which it was assumed that outlet temperature was at the lowest value possible (1185°F) without normal control action. Normal control action at the high end of the deadband was initiated at 41 seconds and limited setback at 64 seconds for the $+10\%$ perturbation. Peak outlet transient temperature is 1235°F occurring 70 seconds after the step input giving a transient temperature rise of 50°F , or 20°F greater than with the high initial temperature condition as a result of the 30 second increase in time to reach the limited setback trip level. The transient reactivity balance for this excursion is shown on Figure 9.

From Figures 7 and 9, the influence of outlet temperature at the time of station maneuvering on the resulting power system excursion can be seen. The longer time interval to reach control system trip levels permits more inherent feedback reactivity to develop before limited setback reactivity is actuated. As a result, setback action for the low initial condition results in a peak subcriticality of 6.3% , compared to 4.0% for the high initial condition. The reactor power transients generated by these reactivity transients are reflected in the reactor outlet coolant temperature dips shown on Figures 6 and 8. The high initial temperature case on Figure 6 shows a dip to 1190°F for a drop of 50°F from the transient peak, or 20°F from the initial level. In the low initial temperature case on Figure 8, the outlet temperature dip is to 1164°F for a drop of 71°F from the transient peak, or 21°F from the initial level indicating a negligible sensitivity to initial temperature for the temperature dip generated by the assumed control action.

References

1. H. Rodd, personal communication 8/70.
2. R. B. Harty, personal communication, 8/70

FIGURE 7. Reactor reactivity balance for controlled system response to a +10% reactivity input step - High Initial temp.

REF-ZRH BRAYTON PCS-CONTROL FOR +100 STEP-LO

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FIGURE 8. Reactor coolant temperatures for controlled system response to a +10% reactivity input step - Low initial temp.

FIGURE 9. Reactor reactivity balance for controlled system response to a +10c reactivity input step - Low initial temp.

III. CONCLUSION

From the results obtained in this brief analysis, it is tentatively concluded that appreciable ($\sim 10\%$) and abrupt reactivity perturbations generated by space station maneuvering can be controlled to minimize system power and temperature transients by modifications to the proposed control system. The modification used in this analysis represents only one approach to the problem. The most attractive approach will require detailed consideration of system modification costs, weight penalties, reliability, and failure mode effects.

Flight reactor control system analysis will define the reactivity perturbations which can be sustained within the control deadband, and depending on the rate as well as the magnitude of the reactivity perturbation many of the maneuvering perturbations should be controllable by an outlet temperature control system. The assumption of step input disturbances used in this analysis may prove pessimistic upon further consideration of station maneuvering characteristics.

In view of the general nature and brevity of this investigation the conclusions indicated above are necessarily tentative and will require review and analysis for a specific system application. Of basic importance in such an analysis is the interaction with the power conversion system.