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THE EFFECT OF STEAM DENSITY ON REACTIVITY IN THREE
STEAM COOLED FAST BREEDER REACTORS

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ABSTRACT

The effect of changes in steam density on reactivity has been calculated for three steam cooled breeder reactors of 3600, 2500, and 1200 psi operating pressure. When flooded at end of life the systems show reactivity increases of 4%, 1%, and 16% for the high, intermediate, and low-pressure systems. When voided at beginning of life the systems show increases in reactivity of .5%, 2% and .9% for the high, intermediate, and low-pressure systems. When voided at end of life the intermediate, and low-pressure systems show increases in reactivity of 1.9% and .7% respectively and the high-pressure system shows a decrease in reactivity of 3.8%.

Keywords: Reactivity, steam coolant, density, reactors, and safety.

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THE EFFECT OF STEAM DENSITY ON REACTIVITY IN THREE STEAM COOLED FAST BREEDER REACTORS

F. G. Welfare

1. INTRODUCTION

When a reactor is operated with a coolant contained under high pressure, detailed consideration must be given to the possibility that a rupture in the system could result in loss of the coolant. When, as in the case in the steam cooled reactors, the system contains large quantities of water which could be pumped into the core by procedural errors, detailed consideration must be given to the possibility that the system may be subjected to increased steam density or flooded with water.

Mechanical safeguards may be incorporated into the system to prevent voiding or flooding or to control the maximum speed with which they can occur. Complete information about voided and flooded characteristics is still necessary in order to justify the safeguards economically and to consider the safety of the system under various combinations of failing safeguards.

An accident which results in increased reactivity may be handled by the shutdown system if the control rods have sufficient worth and if the shutdown system can respond fast enough and with adequate dependability. However, all of the reactivity changes reported here are those which would apply if the control rods remained in their operating positions while the change in coolant density took place. This is admittedly an extreme condition which can probably be relaxed by a combined analysis of the time over which a density change can occur, the response time of the control systems, and the reactivity effect of a density change. The extreme assumptions used here are felt to be a useful foundation for more explicit considerations.

2. REACTOR SYSTEMS CONSIDERED

Three steamed cooled fast breeders were considered in the evaluation of the steam cooled concept¹. These are referred to in the present work by a fundamental characteristic — their pressure. The low-pressure² and high-pressure³ designs were by the Babcock and Wilcox company and the intermediate-pressure⁴ design was by the Karlsruhe Nuclear Research Center.

All of the systems are fueled by oxide pins arranged in hexagonal bundles. The intermediate and low-pressure systems have cylindrical cores while the high-pressure design has an annular core. In all of the designs the active core region was surrounded by a blanket of fertile material. Design details of the reactors are shown in Table I.

In the evaluation, all of the systems were assumed to be operated on a recycle mode. Start up was on plutonium of a composition expected to be available from pressurized water converter systems. The intermediate and low-pressure systems were soon operating primarily on plutonium bred within the systems but the high-pressure system continued to require the addition of fissile material in order to maintain criticality.

3. CALCULATION OF DENSITY EFFECTS

The effect on reactivity of changing steam density was calculated as follows. The code ASSAULT⁵, a two-dimensional multigroup code, was used to calculate an effective multiplication factor for each density. These multiplication factors were then compared in order to determine the effect of the change.

Cross sections were obtained by averaging over the neutron spectra corresponding to each system and each steam density situation. The code GAM II⁶ was used for this purpose. In situations where thermal cross sections were required the code THERMOS⁷ was used. At normal and reduced steam densities the low and intermediate-pressure systems used six fast groups and the high-pressure system used eight fast groups and one thermal group. For calculations at steam densities greater than normal a thermal group was added to the low and intermediate-pressure systems.

Table I

Properties of the Steam-Cooled Fast Breeder Reactors in this Study

	Low Pressure	Intermediate Pressure	Super- Critical
System Pressure, psi	1200	2500	3600
Net Electric Power, Mw	1000	1000	1000
Thermal Power, Mw	2900	2519	2326
Thermal Efficiency, %	34.5	39.7	42.2
Core Geometry	Cylindrical	Cylindrical	Annular
Core Height, ft	2.42	4.95	4.75
Core Radius, ft	5.88	4.31	Inside 2.36 Outside 3.93
Core Volume, liters	7434	8190	4160
Axial Blanket Thickness, ft	1.5	1.18	1.5
Radial Blanket Thickness, ft	1.2	1.25	Inside 1.56 Outside 1.42
Core Volume Fractions:			
Fuel	0.54	0.47	0.42
Structure	0.13	0.20	0.18
Coolant	0.33	0.33	0.40
Fuel Material	UO ₂ -PuO ₂	UO ₂ -PuO ₂	UO ₂ -PuO ₂
Core Fuel Density, % of Theoretical	85	87	85
Fertile Fuel Density, % of Theoretical	90	87	90
Core Clad Material	Inconel 625	Inconel 625	19-9DL SS
Fertile Clad Material	348 SS	Inconel 800	19-9DL SS
Core Fuel Pin o.d., in.	0.35	0.276	0.23
Core Clad Thickness, in.	0.012	0.015	0.010
Number of Pins Per Core Assembly	391	469	504
Avg. Blanket Steam Density, lb/ft ³	1.92	7.07	11.8
Avg. Core Steam Density, lb/ft ³	1.92	4.11	6.62
Avg. Core Fuel Temperature, °K	1644	1673	1693
Avg. Blanket Fuel Temperature, °K	1089	773	800
Core Heavy Metal Inventory, kg	33,012	31,800	14,492
Blanket Heavy Metal Inventory, kg	55,761	52,756	45,473
Fertile Pin o.d., in.	0.475	0.492	0.455
Fertile Pin Clad Thickness, in.	0.016	0.022	0.015
Number of Pins per Fertile Assembly	211	169	162
Number of Fertile Assemblies	126	120	198

The effect of steam density was calculated at the beginning of the start up cycle (BOL) and at the end of the equilibrium cycle (EOL). In the case of the high-pressure system the atomic densities used at the end of life were the result of a complete fission product description used in a two dimensional burnup calculation. In the case of the intermediate and low-pressure systems the fission products were not important enough during the normal burnup to warrant their explicit use. The atomic densities used at the end of life for these systems were derived by running a zero dimensional depletion calculation and adding the fission product concentrations to the fuel nuclide concentrations obtained in the 2 dimensional depletion.

4. RESULTS AND DISCUSSION

The results of the coolant density analysis are summarized in Table II. These results show that the low and intermediate-pressure systems are normally operated at or very near their point of minimum reactivity. Either an increase or a decrease in steam density will result in an increase in reactivity for these systems.

The intermediate-pressure system shows a maximum change of about 2% in reactivity. This is, of course, a very significant reactivity effect but it is of a size which can be overcome by insertion of shutdown rods. Therefore, in this reactor, increases in reactivity due to changes in steam density can be overcome by the shutdown system if the system operates faster than the density change takes place and if the system operates with adequate reliability.

For loss of coolant the low-pressure system has a maximum increase in reactivity of about 1%. This too can be handled by the shutdown system and requires only that the system react with adequate speed and reliability. Flooding of the low-pressure system at beginning of life results in an increase in reactivity of about 16% and at end of life in an increase of about 7%. The first of these is larger than the control rod worth and the second is about equal to the control rod worth. Therefore, the system must be so designed that (a) flooding

Table II
Reactivity Effects of Various Steam Conditions^a

Steam Density ^b	High Pressure	Intermediate Pressure	Low ^c Pressure
Normal Steam Density			
Beginning of Start-up Cycle			
0.0	1.00503	1.02095	1.00943
.05		1.01370	
.5	.99536		
.90		1.00223	
1.0	1.00000	1.00000	1.00000
2.0			1.00031
Flooded			1.16637
Steam Density	High Pressure	Intermediate Pressure	Low Pressure
Normal Steam Density			
End of Equilibrium Cycle			
0	.96156	1.01880	1.00734
.5	.97954	1.00229	1.00172
.95	.99815		
1.0	1.00000	1.00000	1.00000
2.0	1.02700		1.00097
4.0			1.00728
5.0	1.04670		
7.0		1.00754	1.01993
10.0			1.03027
15.0			1.04208
20.0			1.06152
Flooded	1.04381	1.01145	1.06913

^aThe quantity tabulated is the ratio of k effective at non-normal steam density to k effective at normal steam density.

^bThe ratios shown apply to the core steam densities. The blanket steam densities were changed by the same factor until the density of water was reached. After this point the blanket densities were held constant and the core densities were increased toward the flooded conditions.

^cThe steam density analysis of the low-pressure system was performed under contract by the Nuclear Technology Corporation of White Plains, New York.

cannot occur, (b) the worth of the control system is increased or, (c) a neutron poison is kept in the system water.

The reactivity of the high-pressure system as a function of steam density is quite different from that of the other systems. In the high-pressure system a change in steam density can result in either an increase or a decrease in reactivity depending on the time at which the change takes place and on the magnitude and direction of the density change. Figure 1 shows a plot of the reactivity data for the high-pressure system. At BOL a decrease in steam density results in an initial decrease in reactivity and then in an increase after a reactivity minimum is passed. At EOL decreasing the steam density results in a decrease in reactivity and increasing the density results in an increase in reactivity until a maximum is passed. The decrease following the maximum is very slight.

Several additional calculations have been run in an effort to better understand the somewhat unexpected results in the high-pressure system. The first of these was a series of perturbation calculations. These were run using the same cross section data and procedures as described for the basic calculations. The code EXTERMINATOR-II⁸ was used. This code will calculate the effect of unit variation in nuclide density on the various components of the system reactivity. Table III shows a summary of some of the perturbation results. The totals shown in this table are the slopes of the reactivity versus steam density curves at the point being considered. The figures in Table III are positive if a change in steam density results in a change in reactivity of the same algebraic sign as the density change. The figures are negative if a change in steam density results in a change of opposite sign in reactivity.

The results shown in Table III support the results obtained by direct calculation of the various steam conditions. The direct calculation for the BOL case, as shown in Figure 1, displays a minimum reactivity as the steam density is reduced from normal. The existence of this minimum is implied by the change in sign of the slope as derived from the perturbation calculation.

Fig. 1. k_{eff} vs Steam Density High Pressure System.

Table III
Results of Perturbation Calculations
 $\Delta k/k$ Per Percent Change* in Steam Density

Steam Location	EOL-NORMAL				BOL-NORMAL				BOL-.5 NORMAL			
	$\frac{\Delta k}{k} \sigma_a$	$\frac{\Delta k}{k} D$	$\frac{\Delta k}{k} \text{ spectrum}$	Total	$\frac{\Delta k}{k} \sigma_a$	$\frac{\Delta k}{k} D$	$\frac{\Delta k}{k} \text{ spectrum}$	Total	$\frac{\Delta k}{k} \sigma_a$	$\frac{\Delta k}{k} D$	$\frac{\Delta k}{k} \text{ spectrum}$	Total
Inner Blanket	-.000001	+.000081	+.000015	+.000095	-.0000010	+.000080	-.000097	-.000018	-.000000	+.000049	-.000092	-.000043
Outer Blanket	-.000002	+.000042	-.000006	+.000034	-.0000005	+.000018	-.000022	-.000005	-.000000	+.000016	-.000027	-.000011
Core	-.000003	+.000082	+.000172	+.000251	-.0000028	+.000118	-.000012	+.000103	-.000001	+.000069	-.000061	+.000007
Total	-.000006	+.000205	+.000181	+.000380	-.0000040	+.000216	-.000131	+.000080	-.000001	+.000134	-.000180	-.000047

*The density changes are percent changes from the conditions specified.
In terms of the change in mass per unit volume, a percent change in the .5 normal case results in half of the density difference corresponding to a percent change in the normal density cases.

Perhaps the most interesting information resulting from the perturbation calculation is the effect of the changes in spectrum on the reactivities. At BOL the spectrum effect is negative (a decrease in steam density results in increased reactivity) but at end of life this effect is reversed. Plots were made of the adjoint flux at BOL and EOL for radial and axial traverses through the system. These plots show that low energy neutrons are of much greater importance at EOL than at BOL. At BOL the blanket regions contain little or no fissile material (the exact amount of plutonium in the blanket at BOL depends upon the refueling scheme being used) so that the thermal neutrons are of little importance there. At EOL the blanket contains fissile plutonium and about 25% of the fissions are occurring in the blankets. Under these conditions removal of the steam and the attendant spectral hardening have an important effect.

A series of transport calculations was also run for the EOL high-pressure system. These were run using ANISN⁶ which is a discrete ordinates transport code. The calculations were run for a radial traverse through the reactor near the middle of the core. Cross sections used were developed by use of GAM-II and THERMOS. An automated procedure exists for punching of cross sections in the format needed for ANISN.

In the transport calculations the normal steam case was calculated and the vertical buckling was adjusted to give a value near critical. This value of buckling was then used in calculations at reduced steam density. The results of these calculations are shown in Table IV. These results also show a reduced reactivity under loss of steam at EOL in the high-pressure system. These results show the diffusion approximation to agree qualitatively with transport theory even in the rather extreme geometry of the high-pressure system.

The procedure used for broad group averaging of the cross sections in this work is a compromise dictated by data processing limitations. The cross sections were spectrum averaged for two regions — the core and the radial blanket. A fission spectrum was assumed for the neutrons introduced into both regions, but in reality the neutrons introduced into the blanket region would be predominately leakage from the core. The core cross sections

Table IV
Results of Transport Calculations

Steam Density	$K_{\text{effective}}$ at Reduced Density
	$K_{\text{effective}}$ at Normal Density
Normal	1.000
.5 Normal	.982
Void	.969

were used only in the core but the structure and coolant cross sections from the blanket were used in other regions as needed. Some of these other regions were very different from the blanket resulting in an additional difference between the spectra used in the group averaging and the spectra used in the reactivity calculation. A possible source of error is thus built into the procedure. The accurate solution of this problem will require development of procedure for either accurate calculation of spectra in blanket and structure regions or the ability to use a group structure sufficiently fine that the spectra are of secondary importance.

CONCLUSIONS

The effect of changes in steam density on reactivity in a steam cooled reactor is a complex phenomenon depending on the steam pressure, the steam volume fraction, and the exposure of the fuel. For this reason, with the present state of information on the subject, each proposed reactor and fuel cycle must be individually evaluated. For the systems considered here the effect of voiding ranges from a 3.9% decrease in the high-pressure system to a 2% increase in the intermediate-pressure systems. The effect of flooding ranges up to a 16% increase in reactivity in the low-pressure system.

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