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TRIBUTION

GENERATION OF BWR POINT KINETICS REACTIVITY FUNCTIONS

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PLANT TRANSIENT ANALYSIS GROUP

SEPTEMBER 1982

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ABSTRACT

Reactivity as a function of void fraction, fuel temperature and boron concentration has been determined at two points in the second cycle of a typical BWR/3 (Quad Cities 1). These functions are applicable to the analysis of ATWS events - in particular they are useful for determining when the reactor will be shut down due to the addition of soluble boron. The reactivity functions may be applied with caution to other plants at similar initial operating conditions i.e. at close to full power and full flow and with a low control rod density.

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CONTENTS

INTRODUCTION

This project is motivated by the need to provide the Nuclear Regulatory Commission (NRC), Division of Systems Integration the capability to perform calculations of anticipated transients without scram (ATWS) in order to assess the adequacy of emergency procedures being developed by the BWR Owners Group. Since such ATWS calculations will most likely be done with a code in which the neutron kinetics is modeled with a lumped parameter (or point) model, it is imperative to have a reactivity function which can be used in the power (i.e. neutron kinetics) calculation.

The specific objectives of this project are to determine a reactivity function for Cycle 2 conditions for a BWR/3 and then to assess its uncertainty and applicability to the analysis of other BWR designs and other operating conditions.

The rationale for working with a BWR/3 is twofold. First, NRC is sponsoring the development of a BWR/3 plant model for use with TRAC-BD1 (for other than ATWS applications) and will be supporting a similar effort for RELAP5. Secondly, most of the data needed to generate a reactivity function is already available at BNL for the Quad Cities 1 (BWR/3) reactor.

The reactivity during an ATWS event will change due principally to changes in the void fraction, fuel temperature and boron concentration. The effect of changes in water temperature is small and can be neglected. Control rods do not insert during an ATWS event and, therefore, their movement need not be accounted for in the reactivity function. The reactivity effect of void, boron, or fuel temperature depends on local effects. Hence two different distributions of void that give the same average void fraction may give different reactivity contributions. (The same is true for fuel temperature and boron.) This makes it difficult for a point kinetics model to adequately predict core behavior for an ATWS event.

What is frequently done in order to obviate this problem is to define a reactivity function and a (time-independent) weighting function for different axial regions of the core. The calculated variable (e.g. void fraction) for each axial region is then used to determine the region reactivity contribution which is then weighted to obtain the core reactivity for use in calculating power. The weighting function is frequently taken as the initial power distribution. Since the weighting function should more properly be taken as the time dependent power distribution (which is generally unknown) and since it is difficult to uniquely define the region-wise reactivity function we have taken a different approach.

The effect of time dependent spatial weighting and averaging of reactivity is taken account of by deriving the reactivity of the system with a steady state spatial calculation at the conditions expected during an ATWS event. The three-dimensional steady state core simulator SIMULATE is used to calculate the multiplication constant k_{eff} at a sufficient number of state points so that a least-squares-fit to an analytical reactivity function can be made.

The success of this method is predicated on knowing the conditions expected during the transient and on the fact that the error incurred in using a static model to calculate a dynamic situation is sufficiently small. The general conditions expected in terms of power level, flow rate, inlet subcooling and pressure can be predicted well enough for the purposes of this work. The error introduced by assuming quasi-steady state conditions will affect the accuracy of predicting small changes in reactivity. However, it is long term changes in reactivity that are of most interest in the ATWS analysis planned, i.e. it is of more interest to know the total amount of reactivity that boron must supply to keep the system subcritical than it is to know the instantaneous change in reactivity due to a small change in void fraction or fuel temperature. Consequently, the errors introduced in this quasi-static approach should be acceptable.

In the next section the features of the computer codes used in this analysis are summarized. The section on results then discusses the state point calculations and the resulting reactivity function. An assessment of the error in this function is also given as is a discussion of the relationship of these results to the calculation of reactivity coefficients. The section concludes by addressing the general applicability of the results to other operating conditions and plants. The last section summarizes the conclusions of this study. In the Appendix the definitions needed to interpret the reactivity function for RELAP5 and TRAC-BD1 are given.

CALCULATIONAL MODEL

The principal computer codes used in this study were the core analysis code SIMULATE [1] and the fuel bundle analysis code CASMO [2]. SIMULATE is a coupled neutronic and thermal hydraulic steady state and core depletion code. The three dimensional neutronics model uses Børresen's method for solving the so-called "1-1/2 group" nodal diffusion equations. The core-reflector interface is treated with albedo parameters. The thermal-hydraulics model is based on user supplied correlations for fuel temperature and flow distribution (obtained at BNL from auxiliary calculations with the THERM-B code) and built-in correlations for void fraction (including subcooled boiling).

The SIMULATE input model for Cycle 2 of Quad Cities 1 was developed at BNL [3] in order "to provide the base for wide ranging technical assistance to the USNRC." The model was used to calculate power, exposure, void fraction, exposure-weighted void fraction and fuel temperature (among other quantities) in each of 24 axial nodes in the 724 bundles in the core. This was done for 16 exposure intervals from the beginning-of-cycle core-average exposure of 6.61 MWD/kg to the end-of-cycle core-average exposure of 12.0 MWD/kg.

The model was validated via the comparison of calculated power distributions with data from the TIP instrumentation [4]. The root-mean-square relative difference between the calculated and measured data at 24 axial locations for 41 TIP traces varied between 11 and 14% for the 11 exposure

points at which TIP data were available. The calculated exposure-interval-weighted effective multiplication constant, k_{eff}, for Cycle 2 was 1.006 ± .003 where the uncertainty is the root-mean-square deviation for the 16 exposure points. These results were considered to be satisfactory considering the uncertainties in the TIP data and in the parameters which define the operating state over an exposure interval such as control rod configuration, power level, inlet subcooling, core flow rate and pressure. (The uncertainty in the reactor parameters comes from the fact that they are averages over the exposure interval.) This level of confidence is necessary in order to determine reactivity effects, however, it would be desirable to have other data (e.g. a measured power coefficient, or information from a transient) in order to further support the use of this model for determining the reactivity effect of core variables such as void fraction and fuel temperature.

The two-group cross sections which are needed for the SIMULATE model are obtained using the multigroup two-dimensional transport theory code CASMO. The input model for CASMO explicitly represents the fuel rods, channel box, water gap and control blades. The code calculates fuel depletion and fission product buildup. Gadolinia burnup is characterized in CASMO with data obtained at BNL with the auxiliary code MICBURN. For each bundle type approximately 135 state point calculations are done so that the cross sections which are used in SIMULATE can be a function of exposure, exposure-weighted void fraction, void fraction, fuel temperature and the presence of control blades. The effect of soluble boron was not present in the original Quad Cities 1 model and hence the necessary cross sections were generated as part of the present effort [5].

RESULTS

SIMULATE State Point Calculations

Two operating points during Cycle 2 were selected for study; one at end-of-cycle (EOC2) and one at beginning of cycle (BOC2). The intent was to have the two points as different as possible in terms of exposure and control rod configuration. However, it was also of interest to have the reactor conditions as stable as possible prior to the operating point chosen and to have the power as high as possible. Operation at BOC2 and EOC2 was not at full power. The two points selected were, therefore, a compromise. The BOC2 point chosen was State Point 19 (the numerical value refers to Reference 4) at an exposure point representing 11% into the cycle; the EOC2 point chosen was State Point 25 at 79% into the cycle. The control fractions (total notches inserted over total notches possible) were 0.282 and 0.079 for State Point 19 and 25, respectively. In both cases the initial power was 86% of rated (2511 MW) power.

SIMULATE was used to calculate the effective multiplication constant k_{eff} at each operating point and at several state points which might be expected during an ATWS event. The conditions at each of these state points are

given in Tables I and II for the BOC2 and EOC2 operating points respectively. Given in the tables are the power level, inlet flow rate, inlet subcooling and boron concentration which must be specified in the SIMULATE input model. The order of the entries is in decreasing power level. Also given in the tables are the resulting core-average void fraction and reactivity ρ ($=\ln (k_{eff}/ k^{o}_{eff})$ where the superscript zero represents the operating point). The core-average fuel temperature (K) which is also of interest is not listed but can easily be constructed from the core power P* (as a fraction of rated power) using the correlation that SIMULATE uses locally to determine fuel temperature: $\bar{T}_f = 560 + 362P^*$.

In order to assure that the fuel temperature variation extended from an overpower situation down to shutdown conditions, cases were run at 120% of rated power down to decay heat levels corresponding to 5% of rated power. The inlet flow rate was varied according to what would be expected after a recirculation pump trip i.e. a reduction to natural circulation. The power vs flow operating map [6] was used to determine appropriate conditions under "normal" natural circulation conditions.

In an ATWS event the operator might allow the water level in the downcomer to fall below the level at which emergency core cooling systems (ECCS) e.g. high pressure coolant injection and reactor core isolation cooling, would ordinarily be actuated. In these situations the natural circulation rate would be less than "normal" keeping the void fraction reasonably high and, therefore, the system subcritical. With reduced (or no) feedwater and ECCS water the inlet subcooling would also be reduced. The low power state points given in Tables I and II were determined in order to reflect these conditions. Inlet flow drops to only 10% of rated flow (108 Mlb/hr) and inlet subcooling to 5.2 BTU/lb. Hence, at these low power conditions the void fraction is actually greater than it was at the operating point.

For both BOC2 and EOC2, state point calculations were done with increasing amount of soluble boron representing the latter stages (in terms of power generation) of the ATWS event. In addition, as boron concentration increased it was assummed that ECCS water would have increased so that flow and inlet subcooling would increase.

The calculations at EOC2 included several state points where the pressure was elevated by 100 psi. A typical ATWS scenario has relief valves opening and closing and the time-average pressure can, therefore, be 100 psi above the operating value. Although this does change the void fraction it is not expected to have a significant effect on the reactivity function and hence was not considered for BOC2 (which was actually analyzed after the EOC2 cases were completed).

The conditions chosen for the SIMULATE state point calculations yielded deviations from criticality considered acceptably small in most cases. With the exception of the cases at high (400 ppm) boron concentration the reactivity was within 0.02 of the initial operating point.

Table 1 State point calculations at BOC2[a]

Case Number	Power % Rated	Inlet Flow % Rated	Inlet Subcooling BTU/lb	Boron Concentration ppm	Core-Average Void Fraction	Reactivity
1	120	100	24.0	0	.348	- .00951
2[b]	86	82	24.0	0	.293	0.0
3	60	40	24.0	0	.391	- .00865
4	40	30	24.0	0	.344	- .00112
5	20	25	24.0	0	.169	.02160
6	20	15	10.3	0	.383	- .00283
7	10	10	10.3	0	.315	.00641
8	10	10	5.2	0	.336	.00427
9	10	10	10.3	100	.296	- .00852
10	10	10	10.3	200	.274	- .02280
11	5	10	10.3	300	.132	- .02380
12	5	20	10.3	400	.047	- .03260

a Core-average exposure, 7.22 MWD/kg; control density, 0.282; pressure, 1034 psia.
b Operating conditions

Table II State point calculations at EOC2[a]

Case Number	Power % Rated	Inlet Flow % Rated	Inlet Subcooling BTU/lb	Boron Concentration ppm	Core-Average Void Fraction	Reactivity
1	120	100	20.6	0	.359	- .01303
2[b]	86	91	20.6	0	.260	0.0
3	60	30	20.6	0	.474	- .01924
4[c]	60	30	10.3	0	.451	- .01557
5	40	30	20.6	0	.357	- .00492
6	20	25	20.6	0	.165	.01739
7[c]	20	25	20.6	0	.156	.01974
8[c]	20	25	10.3	0	.199	.01469
9	20	15	10.3	0	.379	- .00407
10	10	10	5.2	0	.319	.00388
11	10	10	10.3	100	.268	- .00939
12	10	10	10.3	200	.240	- .02368
13	10	25	20.6	300	.047	- .01867
14	5	25	20.6	400	.008	- .03125

a Core-average exposure, 10.83 MWD/kg; control density, 0.079.
b Operating conditions.
c These cases are at 1107 psia; all others are at 1007 psia.

The range of spatial distributions for these cases is demonstrated by Figure 1 which gives the axial (i.e. radially averaged) power distribution for five cases at EOC2. The different spatial weighting represented by these curves of various core perturbations (void, fuel temperature and boron) are incorporated into a single reactivity function as shown in the next subsection.

Reactivity Function

The state point calculations were used to obtain a reactivity function which depends on core-average void fraction α, fuel temperature T_f and boron concentration B. The particular form chosen,

$$\rho = a_1 + a_2\alpha + a_3\alpha^2 + a_4 T_f^{\frac{1}{2}} + a_5 B + a_6 B\alpha, \qquad (1)$$

is based on BNL's experience with BWR calculations and is consistent with the cross section modeling in SIMULATE.

In SIMULATE cross sections are a function of void fraction that is determined by values at three void fractions i.e. essentially a quadratic function. The fuel temperature effect is proportional to the square root of T_f. If a term, for example, containing the product αT_f appeared in Equation (1) it would be inconsistent with the cross section model in SIMULATE (even though it might have a non-zero coefficient due solely to spatial effects and the fitting process) and, therefore, is not considered. The macroscopic cross section for boron is proportional to boron mass and a function of void fraction.[5] Since boron concentration and void fraction are usually the calculated quantities in a transient code, boron mass (which is a function of α and B) is not used explicitly.

The coefficients a_1 to a_6 in Equation (1) were obtained by a least squares fit of ρ to the data in Tables I and II. The results along with the boron requirement for subcriticality are given in Table III for both BOC2 and EOC2. The boron requirement which is one of the key parameters for an ATWS calculation is defined as the minimum boron concentration B_{min} needed for subcriticality[a] at the point in time when there are no voids and the fission rate is essentially zero. From Equation (1)

$$B_{min} = \left[a_2\alpha_o + a_3\alpha_o^2 + a_4\left(T_{f0}^{\frac{1}{2}} - T_{f1}^{\frac{1}{2}}\right)\right] / a_5 \qquad (2)$$

where the subscript zero refers to the initial operating point and the subscript 1 refers to the (essentially) zero power temperature.

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a. Actually the reactor is just critical with B_{min}, but a slight increase would make it subcritical.

FIGURE 1.
AXIAL POWER DISTRIBUTION
EOC2 STATE POINTS

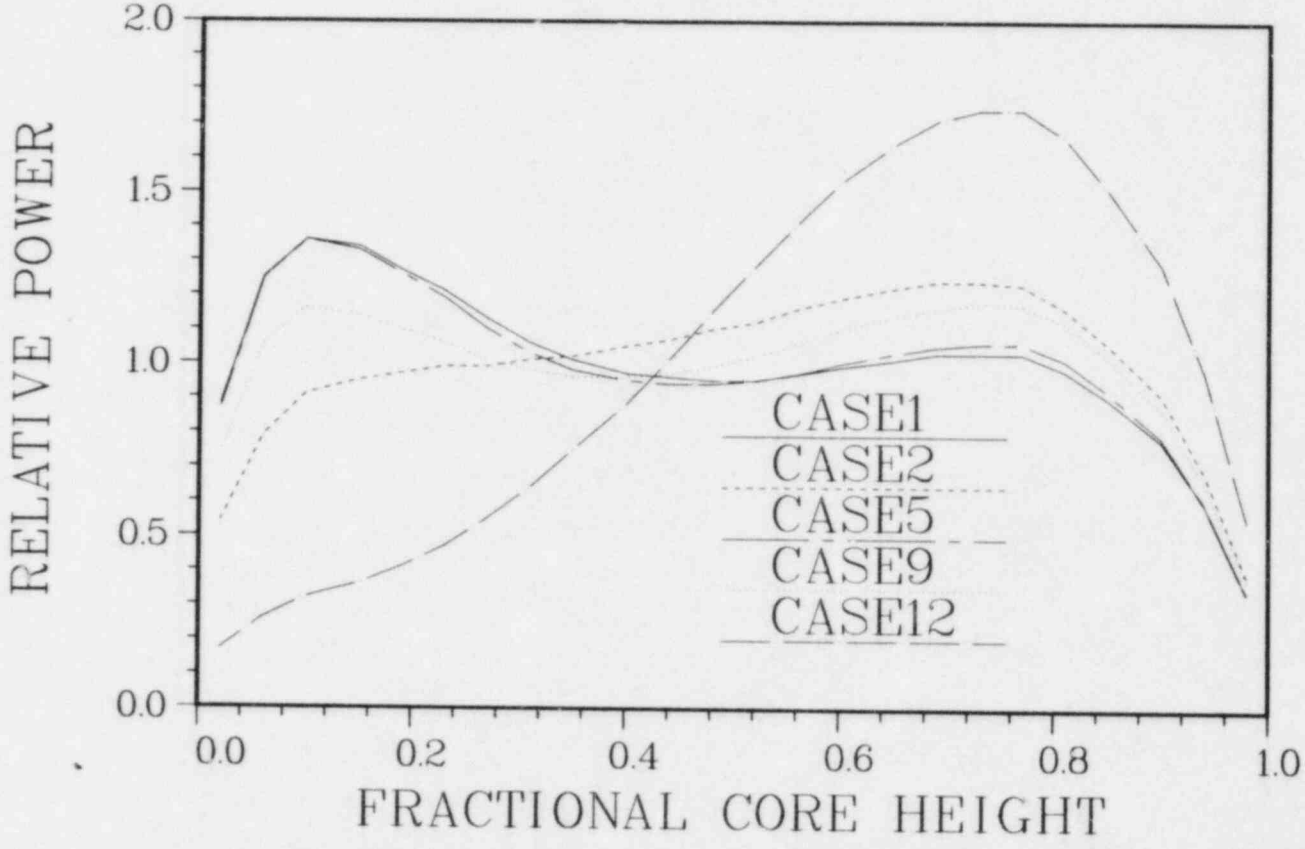

Table III Reactivity parameters and boron requirement

$$\rho = a_1 + a_2\alpha + a_3\alpha^2 + a_4 T_f^{\frac{1}{2}} + a_5 B + a_6 B\alpha$$

	BOC2 (State point 19)	EOC2 (State point 25)
a_1	.0826	.0806
a_2	- .0996	- .1100
a_3	- .0268	.0100
$a_4 \times 10^3$	-1.72	-1.78
$a_5 \times 10^4$	-1.73	-1.70
$a_6 \times 10^4$	-0.11	-0.27
B_{min}, ppm	241	225

The error in the results given in Table III is difficult to assess. The fitted function has an rms deviation from the SIMULATE reactivity points of 0.0002 and 0.0005 for BOC2 and EOC2 respectively. The corresponding numbers for the maximum deviation are 0.0004 and 0.0008. Hence, the least squares fitting procedure does not produce a significant error.

Two other sources of error are the uncertainty in the state points chosen to represent the accident conditions and the basic uncertainty in the SIMULATE calculated multiplication constant, k_{eff}. Since the error in k_{eff} is expected to be mostly a systematic error the error in reactivity should be small and the major source of uncertainty is any inconsistency between the state points used and those which would actually be encountered.

In order to demonstrate this, reactivity functions were generated from subsets of the cases given in Tables I and II. The results are given in Table IV. The first subset chosen for BOC2 eliminated the case with the highest boron concentration (Case 12, Table I) since this case was the furthest from criticality (ρ = -.03). The results did not change significantly. The second subset also eliminated the zero-boron case which was furthest from criticality (Case 5, Table I). This had no effect on the fuel temperature coefficient but significantly affected the other coefficients. Elimination of Case 5 removed the case with the low void fraction (α = .169) If operator procedures are indeed such that the void fraction can always be maintained at close to its initial value during the early stages (before boron injection) of an ATWS event then perhaps this subset is more realistic than the base calculation.

However, note that the void coefficient $\left.\frac{d\rho}{d\alpha}\right|_{B=0} = a_2 + 2a_3\alpha$ is identical for all

three BOC2 calculations at $\alpha \approx 0.35$ and B_{min} only changes by 10%. The important integral efforts, therefore, do not vary as much as the individual coefficients in Equation (1).

The first subset calculation for EOC2 was (as above for BOC2) without the 400 ppm boron concentration situation (Case 14, Table II) which had the largest deviation from criticality (ρ = -.03). Again there was an insignificant change in the coefficients. The next subset chosen eliminated zero-boron cases (3,4,6,7 Table II) with the largest deviation from criticality ($|\rho|$=0.016 to 0.020). For this subset the results also did not change significantly. The next subset eliminated the case (13, Table II) at 300 ppm. The least squares fit for the boron coefficients a_5 and a_6 then was determined by only two state points (B=100, 200 ppm) and B_{min} changes significantly by 50 ppm. Since B_{min} is outside the range of boron concentrations used in the least squares fit it is recommended that this subset not be considered.

The result of the analysis of Table IV is that the reactivity parameters given in Table III can be used to give reasonably accurate results for the boron requirement and the fuel temperature and void reactivity coefficients during an ATWS event provided that the conditions calculated for the ATWS event are within the range of conditions (Table I and II) used to generate these functions. Since this involves a bit of engineering judgement it is recommended than any ATWS analysis with these results be repeated with coefficients adjusted to achieve large void and fuel temperature reactivity coefficients coupled with a small boron reactivity worth and then the ATWS analysis should be repeated with small reactivity coefficients to assure that the first results are conservative.

Reactivity Coefficients

The fuel bundle void coefficient ($\left(\frac{d\rho}{d\alpha}\right|_{B=0}$) for a BWR in general becomes stronger (more negative) with increasing exposure and when control blades are present. Going from BOC2 to EOC2 there are, therefore, two opposing trends. From the results given in Table III the reactor void coefficient ($a_2 + 2\,a_3\alpha$) is more negative at EOC2 for $\alpha \lesssim .14$ whereas for higher void fractions it is less negative at EOC2. If one considers the uncertainty in these results one can conclude that the void coefficient is essentially the same at these two operating points. This is not unexpected because of the two opposing trends. Note that the core-average exposure at the BOC2 operating point is 7.2 MWD/kg and at the EOC2 point is 10.8 MWD/kg. The control fractions at BOC2 and EOC2 are 0.282 and 0.079, respectively.

The fuel bundle void reactivity coefficient for the bundles in Cycle 2 of Quad Cities 1 at a burnup of 10 MWD/kg without control blade or boron is $\sim$-0.059 (see Cases 2-6, Table V) from 0 to 40% void fraction and $\sim$-0.11 from 40 to 70% void fraction. These numbers are of course for an infinite array. The effect

of leakage is to make the void coefficient ~10-15% more negative.[7] From the results for the reactor void coefficient given in Table III and from other studies as well [7] it is seen that the effect of spatial weighting can result in a void coefficient ~30% more negative than the fuel bundle coefficient.

The reactor fuel temperature reactivity coefficient $\frac{d\rho}{dT_f^{1/2}} = a_4$ is also more negative than the infinite bundle coefficient. The latter is -1.2×10^{-3} and -1.4×10^{-3} $K^{-1/2}$ at 0 and 40% void fraction for a Quad Cities 1 fuel bundle at 10 MWD/kg. The fuel temperature coefficient from Table III is -1.7×10^{-3} $K^{-1/2}$.

Values of void reactivity coefficients for Quad Cities 1 obtained by General Electric [6] are -0.14 at operating conditions and -0.10 with no voids. Although these are close to the present results no conclusions can be drawn since it is not stated under what conditions the GE numbers have been generated. The same is true for the fuel temperature coefficient which is reported [6] as -1.2×10^{-5} $°F^{-1}$ or $\sim -1.3 \times 10^{-3}$ $K^{-1/2}$.

The boron reactivity coefficient with no voids is $\left.\frac{d\rho}{dB}\right|_{\alpha=0} = a_5 = -1.7 \times 10^{-4}$ ppm^{-1}. At end-of-cycle when the effective delayed neutron fraction is 0.00546 this is equivalent to ~50¢ per pound of boron in the core (inchannel and bypass regions).

Application to Other Plants and Operating Conditions

The applicability of the Cycle 2 BWR/3 reactivity function to other cycles and other reactors was ascertained by doing calculations of fuel bundle reactivity coefficients and by considering GE results for bundle and core reactivity coefficients.

Fuel bundle calculations for the void and boron reactivity coefficients for 8 bundle designs are listed in Table V. The coefficients were generated with CASMO at a single exposure (10 MWD/kg) and the void coefficient was calculated using the infinite lattice multiplication constant at two void fractions (0 and 0.4). Hence the results do not have general applicability and are presented to study the effect of bundle design only. Since fuel temperature is a little less important than void or boron no results are presented for its reactivity coefficient. Table V also lists some of the principal features of each bundle. Cases 2-6 are the bundles found in Cycle 2 of Quad Cities 1. The 7x7 arrays listed are also typical of the initial loading of BWR/4s. The low enrichment bundle (Case 1) is also found in BWR/4s. Two of the 8x8 arrays (Cases 7 and 8) are typical reload bundles for BWR/3s and BWR/4s. They were chosen for this calculation because their high U-235 and gadolinia content and the presence of water holes differentiates them from the other 8x8 array to the extent possible. An attempt was made to include specific BWR/6 fuel bundles in the table, however,

Table IV Reactivity parameters under different conditions

	BOC2			EOC2			
	Base	Without Case 12	Without Cases 5,12	Base	Without Case 14	Without Cases 3,4 6,7,14	Without Cases 13,14
a_1	.083	.083	.074	.081	.080	.081	.080
a_2	- .100	- .101	- .054	- .11	- .11	- .11	- .11
a_3	- .027	- .024	- .092	.010	.005	.011	.004
$a_4 \times 10^3$	-1.7	-1.7	-1.7	-1.8	-1.8	-1.8	-1.8
$a_5 \times 10^4$	-1.7	-1.7	-1.5	-1.7	-1.7	-1.7	-1.4
$a_6 \times 10^4$	.1	.1	- .5	- .2	- .5	- .4	-1.6
B_{min}, ppm	241	243	220	225	227	228	274

Table V Fuel bundle reactivity coefficients[a]

Bundle description					Void Coefficient[b]	Boron Coefficient, ppm^{-1}
Core	Array	Enrichment	Gadolinia[c]	Water Holes	$x\text{-}1.0\times10^2$	$x(-1.0\times10^4)$
1	7x7	1.10	-	-	3.92	2.23
2	7x7	2.12	3%(2),0.5%(1)	-	5.88	1.86
3	7x7	2.12	3.0%(2)	-	5.89	1.85
4	7x7	2.30	2.5%(3)	-	5.86	1.85
5	7x7	2.71[d]	3.0%(5)	-	6.36	1.64
6	8x8	2.50	1.5%(4)	-	5.79	1.82
7	8x8	2.65	3.0%(6)	2	4.89	1.85
8	8x8	2.89	3.0%(7)	2	5.14	1.79

a At 10 MWD/kg
b Defined from 0-40% void fraction
c Rod w/o (no. of rods)
d Contains mixed oxide fuel

the necessary design information is not available from the usual sources available to BNL. The higher enrichment 8x8 cases (7 and 8) are expected to approximate a BWR/6 bundle.

The void and boron reactivity coefficients in Table V are all quite similar except for two special lattices which are somewhat out of the mainstream. Case 1 is a very low enrichment bundle and Case 5 contains mixed-oxide fuel. It is notable that in general the reactivity coefficients do not change significantly in going from a 7x7 to an 8x8 lattice, or by changing U-235 enrichment or gadolinia loading. This conclusion, however, is not supported by GE.[8] Their results show that for a given exposure, the void coefficient (calculated as above, using 0 and 40% void fractions) for different reload cases can vary by a factor of two. Other sources of information for GE plants [9] report a single core void coefficient that changes by a factor of two (from -.09 to -.20) in going from a 251" design BWR/6 to a 238" design BWR/6. This is relevant provided we can assume that the differences are due to bundle design.

Three other factors which are important in determining void coefficients are exposure, void fraction (both instantanous and historical) and the presence of control blades. These are factors that depend more on the operating state of the reactor rather than on the specific design of the fuel bundles in that reactor. The exposure dependence can be significant, e.g., for Case 2 in Table V the void coefficient went from 0.042 to 0.063 in going from 0 to 20 MWD/kg. The void coefficient can increase (become more negative) by a factor of 2-3 in going from 0 to 70% void fraction.[10] The presence of a control blade also increases the void coefficient - by as much as a factor of four.[11] The net effect of all of these variable is a complex function of the operating state i.e., it will depend on control rod configuration, exposure distribution, inlet flow rate, etc.

The results in the present study at two operating points were not very different (cf Table III). Nevertheless, the above evidence suggests that these might be significant changes if other operating points more widely separated were chosen. Furthermore, calculations of GE [8] for core void reactivity coefficients at different exposures and (presumably) different control rod densities (but fixed void fraction) indicate that the coefficient may vary by a factor of two.

It is, therefore, recommended that additional reactivity functions be generated at other operating points for other plants in order to have more accurate reactivity functions available and to quantify the range of the coefficients in Equation (1). Failing this it is recommended that the present reactivity function be applied to other plants at similar conditions with caution. These results should not be applied at beginning-of-life in which the exposure and control rod pattern might be greatly different than the conditions used in the present study or to cores with a large fraction of mixed-oxide or other experimental fuel. As a means of exercising caution, safety calculations should

include parametric studies with the coefficients in the reactivity function varied in order to assure that the most conservative situation is being considered.

SUMMARY

Two reactivity functions have been derived for Cycle 2 of the Quad Cities 1 BWR/3. The reactivity is a function of void fraction, α, fuel temperature, T_f (K) and boron concentration, B (ppm). It is applicable to the analysis of ATWS events with a code which uses a point neutron kinetics model. The function for BOC2 (core-average exposure E of 7.2 MWD/kg) is

$$\rho = 0.0826 - 0.0996\alpha - 0.0268\alpha^2 - 1.72 \times 10^{-3} T_f^{\frac{1}{2}} - 1.73 \times 10^{-4} B - 0.11 \times 10^{-4} B\alpha \quad (3)$$

and for EOC2 (E = 10.8 MWD/kg) is

$$\rho = 0.0806 - 0.110\alpha + 0.0100\alpha^2 - 1.78 \times 10^{-3} T_f^{\frac{1}{2}} - 1.70 \times 10^{-4} B - 0.27 \times 10^{-4} B\alpha \quad (4)$$

These functions were generated by fitting the reactivity obtained from static calculations at reactor state points expected during an ATWS event. As a by-product of generating these functions it is found that the minimum amount of boron needed to shut down the reactor to a hot zero power condition will be approximately 240 ppm for the BOC2 condition and approximately 225 ppm for the EOC2 condition.

The uncertainty in these results is difficult to assess. It is influenced by the applicability of the state points used to the ATWS event of interest, by the error incurred in representing a dynamic situation by a static one and by the error in the static calculation. Hence it is recommended that when these reactivity functions are applied to a BWR/3 at operating conditions similar to those encountered during Cycle 2, the calculations should be repeated with coefficients adjusted by a moderate amount to achieve a more conservative situation.

It is also difficult to determine the general applicability of these results to other conditions and other plants. It is, therefore, recommended that additional reactivity functions be generated for these other situations. Without these additional calculations the present results can be applied to other plants at similar operating conditions but a series of calculations should be done with varying coefficient to determine a more conservative situation. The present results should not be applied to cores with dramatically different conditions, e.g. at beginning-of-life, or at a low power, low void fraction, high control rod density initial condition.

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APPENDIX

Use of the Reactivity Function in Specific Codes

The BWR transient codes used at BNL for NRC work that utilize point kinetics are RELAP5/MOD1 and TRAC-BD1 Version 12. In RELAP5 the formula for reactivity is [12]

$$r(t) = r_o + r_B = \sum_i^{n_s} r_{si}(t) + \sum_i^{n_\rho} \left\{ W_{\rho i} R_\rho \left[\frac{\rho_i(t)}{\rho_i(o)} \right] + \alpha_{wi}\, T_{wi}(t) \right\}$$

$$+ \sum_i^{n_F} \left\{ W_{Fi} R_F \left[T_F(t) \right] + \alpha_{Fi} T_{Fi}(t) \right\} \qquad \text{(A1)}$$

The input needed to define the variables in Equation (A1) in terms of the reactivity function given by Equation (1) is defined below. Note that there is no boron term in Equation (A1) - a deficiency that is to be rectified in MOD1.5.

$r_o = 0.0$

r_B - calculated by the code such that $r(0) = r_o$

$r_{si}(t)$ - not entered since there is no control rod motion

$W_{\rho i} = W_{Fi} = 1.0$; spatial weighting is accounted for in the a_i, i=1.6

$R_\rho \left[\frac{\rho_i(t)}{\rho_i(o)} \right]$ - a function of the form

$$R_\rho(x) = \frac{1}{\beta} \left\{ - \frac{\rho_o}{\rho_f - \rho_g} \left[a_2 + \frac{2\rho_f a_3}{\rho_f - \rho_g} \right] x + \left(\frac{\rho_o}{\rho_f - \rho_g} \right)^2 a_3 x^2 \right\}$$

where ρ_f and ρ_g are saturation densities of liquid and vapor and

$$\rho_o = (1-\alpha_o)\, \rho_f + \alpha_o \rho_g$$

where α_o is the initial void fraction for a particular reactivity function (e.g. $\alpha_o = 0.293$ or $\alpha_o = 0.260$ for Table III)

α_{wi} - not used since moderator temperature change is not significant

$R_F \left[T_F(t) \right]$ - a function of the form $R_f(x) = \left(\frac{a_4}{\beta} \right) x^{1/2}$

α_{Fi} - not used

(Note that by defining R_ρ as a function of $\frac{\rho_i(t)}{\rho_i(o)}$ rather than as a function of $\rho_i(t)$ as implied in Equation(1) we incur an error of only ~1% in R_ρ.)

In TRAC-BD1 the formula for reactivity is [13]

$$(\Delta k/k)_{FB} = \sum \{ C_{DUP,i} \left[\sqrt{T_{F,i}^{n+1}} - \sqrt{T_{F,i}^{n}} \right] W_{TF,i} + C_{TM,i} \left[T_{M,i}^{n+1} - T_{m,i}^{n} \right] W_{TM,i}$$

$$+ C_{VD,i} \left[\alpha_i^{n+1} - \alpha_i^{n} \right] W_{VD,i} + C_{B,i} \left[\rho_{B,i}^{n+1} - \rho_{B,i}^{n} \right] W_{B,i} \qquad (A2)$$

The input neded to define the variables in Equation (A2) in terms of the reactivity function given by Equation (1) is defined below.

$$W_{TF,i} = W_{TM,i} = W_{VD,i} = W_{B,i} = 1.0$$

$$C_{DOP,i} = a_4$$

$$C_{TM,i} = 0.0$$

$$C_{VD,i} = a_2 + 2a_3\alpha_o$$

$$C_{B,i} = \left[a_5 + \frac{\rho_f a_6}{\rho_f - \rho_g} \right] + \frac{a_6}{\rho_f - \rho_g} \rho_W$$

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