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ABSTRACT

The significance of steam voids and control rods on the Doppler feedback in a gadolinia shimmed BWR is demonstrated. The importance of bypass voids when determining void feedback is also shown. Calculations were done using a point model, i.e., feedback was expressed in terms of reactivity coefficients which were determined for individual four-bundle configurations and then appropriately combined to yield reactor results. For overpower transients the inclusion of the void effect will make the Doppler feedback stronger. The effect of control rods is to reduce Doppler feedback. For overpressurization transients the inclusion of the effect of bypass void will increase the reactivity due to void collapse.

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Introduction

Calculating the Doppler and void reactivity feedback in a boiling water reactor (BWR) is important in many safety analyses as well as in core performance evaluations. For rapid overpower transients, such as the design-basis rod-drop accident, the power excursion is sensitive to the Doppler feedback which is the primary quenching mechanism. For overpressurization transients, such as a turbine trip event, core responses are sensitive to the void feedback which is the driving mechanism (1,2,3). The present paper demonstrates the importance of certain factors which affect the calculation of the feedback and which are not always taken into account by reactor analysts. Specifically, we are interested in the effect of in-channel voids and control rods on Doppler feedback and the effect of voids in the bypass region on the overall void feedback.

To quantify these effects, it is useful to think of the reactivity as a function of fuel temperature (T_f), in-channel void fraction (α_I) and bypass region void fraction (α_B). If the reactivity is expanded in a second order Taylor series, nine separate components (terms) will result. We find that we can neglect the second order terms: $\frac{\partial^2\rho}{\partial T_f^2}$, $\frac{\partial^2\rho}{\partial \alpha_B^2}$, $\frac{\partial^2\rho}{\partial T_f \partial \alpha_B}$, and $\frac{\partial^2\rho}{\partial \alpha_I \partial \alpha_B}$. The reactivity feedback can then be written as

$$\Delta\rho = \Delta\rho_D + \Delta\rho_\alpha \qquad (1)$$

where we define the Doppler feedback as

$$\Delta\rho_D \equiv \frac{\partial\rho}{\partial T_f}\,\Delta T_f + \frac{\partial^2\rho}{\partial\alpha_I \partial T_f}\,(\Delta\alpha_I)\,(\Delta T_f) \qquad (2)$$

and the void feedback as

$$\Delta\rho_\alpha \equiv \frac{\partial\rho}{\partial\alpha_I}\,\Delta\alpha_I + \frac{1}{2}\,\frac{\partial^2\rho}{\partial\alpha_I^2}\,(\Delta\alpha_I)^2 + \frac{\partial\rho}{\partial\alpha_B}\,\Delta\alpha_B \qquad (3)$$

Of particular interest in this paper is the last term in Eq. (2) and Eq. (3).

Calculational Model

The reactor model used in the study was the BWR/4 design of General Electric at hot full power conditions. The core is composed of an array of supercells consisting of three fuel bundles with a high average enrichment (2.5 w/o) and one bundle with a low average enrichment (1.1 w/o). Each bundle is enclosed by a Zircaloy channel. Between the bundles is the bypass region which may contain a control blade. There are five different types of these supercells in the core, each having a different gadolinia loading in its high enrichment bundles.

Reactivity coefficients were calculated using a "point" (or infinite lattice) model, i.e., the feedback was calculated from individual supercell calculations rather than from a full reactor calculation (4,5). For the Doppler calculations the Doppler coefficients for all supercell types are appropriately summed by volume and k_∞ weighting to obtain the results for both uncontrolled and controlled situations. For the void calculations only a single supercell type was considered in order to simplify lengthy calculations. For either feedback effect the core reactivity coefficients are obtained by using effective controlled and uncontrolled fractions to weight the corresponding supercell results. The effective control fraction is that which makes the core multiplication factor equal to unity.

The reactivity, ρ, for individual supercells is obtained from calculations of the effective multiplication factor, k, ($\rho = \ln k$) which in turn is a function of the infinite multiplication factor, k_∞, the migration area, M^2, and the geometric buckling B^2:

$$k = \frac{k_\infty}{1+M^2B^2}$$

With k calculated as a function of void fraction and fuel temperature, the individual supercell reactivity coefficients can be determined.

The k_∞ and M^2 needed for each supercell type for both controlled and uncontrolled situations were calculated with the TW0TRAN-II code (6) using an S_4 approximation, transport corrected isotropic scattering, reflecting boundary conditions and eight (five thermal) energy groups. In this calculation the fuel rod was homogenized with its associated water; all other regions were explicitly represented. The eight group cross sections were obtained from unit cell calculations with the integral transport theory code HAMMER (7). This code uses an 84 group library based on ENDF/B-IV. Temperature dependent resonance effects are considered for both the uranium and gadolinium isotopes.

Doppler Feedback Results

The Doppler coefficient $\left(\frac{\partial\rho}{\partial T_f}\right)$ was calculated as a function of fuel temperature for three uniform in-channel void fractions using an effective control fraction which makes the reactor critical. The results are given in Fig. 1. The effect of voids is seen to be significant throughout the temperature range of interest. The coefficient can therefore be either overestimated or underestimated if a fixed void fraction is used. The curves also show how the Doppler effect starts to saturate with increasing fuel temperature.

Because of this dependence on void, it is necessary for the Doppler feedback $\Delta\rho_D$ to be a function of both α_I and T_f. If Eq. (2) is applied, then the cross term must be calculated. Table I summarizes the importance of the cross term $\frac{\partial^2\rho}{\partial\alpha_I\partial T_f}$ relative to the conventional Doppler reactivity coefficient $\frac{\partial\rho}{\partial T_f}$. The data are shown separately for fully uncontrolled and controlled cores. The cross term needs to be multiplied by $\Delta\alpha_I$ to be compared directly with $\frac{\partial\rho}{\partial T_f}$; nevertheless, it is clear from the table that the effect of including the cross term is to make the Doppler reactivity feedback more negative when $\Delta\alpha_I$ is positive as in an overpower transient.

Table I also shows significant differences between the controlled and uncontrolled results with the controlled coefficients being less negative. At full power conditions at beginning-of-cycle and especially at end-of-cycle the control density is low and the uncontrolled coefficient accounts for most of the Doppler feedback. At zero power, the control density is high and the Doppler coefficient will be overestimated if the controlled coefficients are neglected.

Void Feedback Results

The in-channel void coefficient was calculated as a function of critical void fraction (the α_I at which k =1) with the bypass void fraction as a parameter. The results for $\left(\frac{\partial\rho}{\partial\alpha_I}\right)_{\alpha_B}$ are given in Fig. 2. The graph shows that the presence of bypass void makes the in-channel void coefficient more negative. For instance at 0.40 critical void fraction the coefficient becomes 8% and 13% more negative for bypass void fractions of 0.10 and 0.20, respectively.

The void coefficient shown in Fig. 2 does not take into account the effect of a change in bypass voids which may occur during a transient. The void feedback $\Delta\rho_\alpha$ should be a function of both α_I and α_B. If Eq. (3) is applied then the last term, $\frac{\partial\rho}{\partial\alpha_B}\Delta\alpha_B$, must be calculated. Table II provides results for both partial void coefficients $\left(\frac{\partial\rho}{\partial\alpha_I}\right)_{\alpha_B}$ and $\left(\frac{\partial\rho}{\partial\alpha_B}\right)_{\alpha_I}$. The results are for both fully controlled and fully uncontrolled cores. Even at small bypass void fractions the partial bypass void coefficient is significant relative to the partial in-channel void coefficient. To obtain the relative effect on the total void feedback, the relationship between $\Delta\alpha_I$ and $\Delta\alpha_B$ would have to be known. For most transients $\Delta\alpha_B$ is expected to have the same sign as $\Delta\alpha_I$ but be smaller in magnitude.

For the hypothetical situation where α_I and α_B are equal, the relative magnitudes of the coefficients reflect the importance of different regions of the supercell independent of varying void. To demonstrate this, note that the ratio of partial bypass void coefficient to partial in-channel void coefficient at 20% void is 0.19 and 0.20 for controlled and uncontrolled supercells, respectively. The ratio of bypass volume to in-channel volume is 0.23 and 0.18 for the same two cases, respectively. In addition to the volume fraction, the presence of control blades and the loading of peripheral fuel rods are important in determining the relative magnitude of the coefficients.

Table I also shows how the coefficients increase in the presence of control blades. This is due to the importance of the increased absorption in the control blades. Note, however, that for a given void condition the effect of bypass voids relative to the effect of in-channel voids is smaller in the presence of the blades due to the smaller bypass volume. The data also show that the void coefficient increases with increasing void fraction. This is true for both partial coefficients and is true for either fixed α_I or α_B. It is the same trend as is seen in Fig. 2 and reflects the increasing importance of a given amount of water as the total amount of water decreases.

The design of a BWR attempts to minimize the amount of boiling of the coolant in the bypass region. A recent study (8) indicates that boiling is to be expected with 8% being a typical value for the void fraction in the bypass region. In some BWRs bypass holes which are designed to increase the flow in the bypass region have had to be plugged to alleviate a vibration problem. This would tend to increase the amount of bypass coolant boiling and hence the importance of the partial bypass void coefficient.

Conclusions

The effect of voids on the Doppler feedback is to make the total Doppler feedback stronger. For some transients, such as the overpower transient due to a rod drop accident, neglect of the effect is conservative. Accident analysis codes that utilize a point kinetics model should include the cross term $\frac{\partial^2 \rho}{\partial \alpha_I \partial T_f}$ if the Doppler reactivity is calculated by Eq. (2) or should include a void dependence if the Doppler reactivity is input in tabular form, i.e., $\Delta\rho_D = \Delta\rho_D (T_f, \alpha_I)$.

The effect of control blades is to make the Doppler feedback less negative. This means that neglecting the effect is nonconservative in overpower transients. The effect is mitigated by the absence of control blades at full power and by the fact that in certain transients, such as the rod drop accident, the major contribution to Doppler feedback will occur in the unrodded portion of the core where the power increase is localized.

The effect of bypass voids on the void feedback is to increase the void reactivity feedback. In overpressurization transients, such as a turbine trip, the severity of the power excursion is determined by the increase in reactivity caused by the collapse of voids. Hence, not taking into account the bypass void is nonconservative for these transients. The bypass void can be accounted for either using a coefficient as defined by Eq. (3) or by providing for the inclusion of an α_B dependence if $\Delta\rho_\alpha$ is input in tabular form. The magnitude of the effect depends on the amount of in-channel and bypass void, the bypass volume, and the fuel bundle nuclear design.

The analysis described herein has been based on a point model and the concept of reactivity. If transient calculations are being done with a spatial model then the same conclusions hold but they apply to the cross sections rather than the reactivity. Cross sections depend on void and fuel temperature. If they are being represented with feedback coefficients then by analogy with Eq. (1) we must have:

$$\Delta\Sigma = \frac{\partial\Sigma}{\partial T_f}\,\Delta T_f + \frac{\partial^2\Sigma}{\partial\alpha_I\,\partial T_f}\,(\Delta\alpha_I)(\Delta T_f) + \frac{\partial\Sigma}{\partial\alpha_I}\,\Delta\alpha_I + \frac{1}{2}\,\frac{\partial^2\Sigma}{\partial\alpha_I^{\,2}}\,(\Delta\alpha_I)^2 + \frac{\partial\Sigma}{\partial\alpha_B}\,\Delta\alpha_B \qquad (4)$$

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Table I

Doppler Reactivity Coefficients*

Voids (%)	T_f (^oC)	Uncontrolled $\frac{\partial\rho}{\partial T_f}$	Uncontrolled $\frac{\partial^2\rho}{\partial\alpha_I\partial T_f}$	Controlled $\frac{\partial\rho}{\partial T_f}$	Controlled $\frac{\partial^2\rho}{\partial\alpha_I\partial T_f}$
0	286	-2.56	-1.51	-2.09	-0.51
	1000	-1.37	-0.81	-1.12	-0.27
	2000	-0.97	-0.55	-0.79	-0.18
	3000	-0.79	-0.41	-0.65	-0.12
40	286	-3.08	-1.05	-2.26	-0.34
	1000	-1.64	-0.56	-1.21	-0.18
	2000	-1.16	-0.42	-0.86	-0.14
	3000	-0.95	-0.38	-0.70	-0.14
60	285	-3.26	-0.81	-2.32	-0.26
	1000	-1.74	-0.44	-1.24	-0.14
	2000	-1.24	-0.35	-0.88	-0.13
	3000	-1.02	-0.36	-0.73	-0.16

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*In units of 10^{-5} Δk/k/°C.

Table II

Partial Void Reactivity Coefficients*

Void, %		Uncontrolled		Controlled	
α_I	α_B	$\left(\frac{\partial\rho}{\partial\alpha_B}\right)_{\alpha_I}$	$\left(\frac{\partial\rho}{\partial\alpha_I}\right)_{\alpha_B}$	$\left(\frac{\partial\rho}{\partial\alpha_B}\right)_{\alpha_I}$	$\left(\frac{\partial\rho}{\partial\alpha_I}\right)_{\alpha_B}$
20	0	-0.08	-3.82	-3.96	-21.66
	5	-0.10	-4.03	-4.14	-21.92
	10	-0.38	-4.42	-4.33	-22.37
	20	-0.92	-4.84	-4.70	-23.18
40	0	-1.56	-7.69	-5.98	-31.56
	5	-1.84	-8.24	-6.25	-32.25
	10	-2.13	-8.84	-6.54	-33.00
	20	-2.69	-10.19	-7.10	-34.52
60	0	-4.04	-11.74	-9.73	-43.39
	5	-4.73	-12.66	-10.07	-44.66
	10	-5.43	-13.49	-10.41	-45.82
	20	-6.84	-15.88	-11.11	-48.30

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*In units of 10^{-4} Δk/k/% Voids.

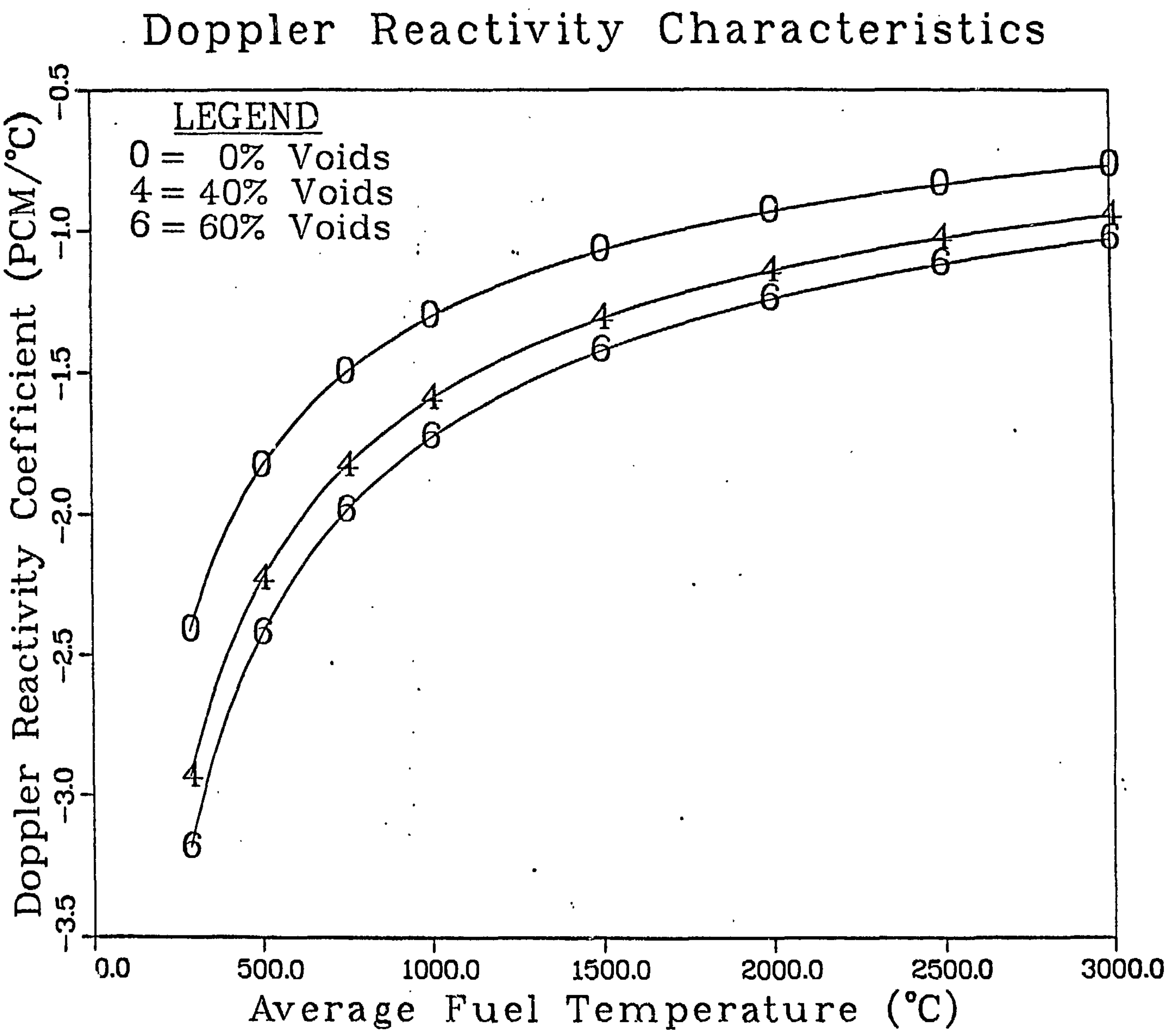

Fig. 1 EFFECT OF VOID ON THE DOPPLER COEFFICIENT

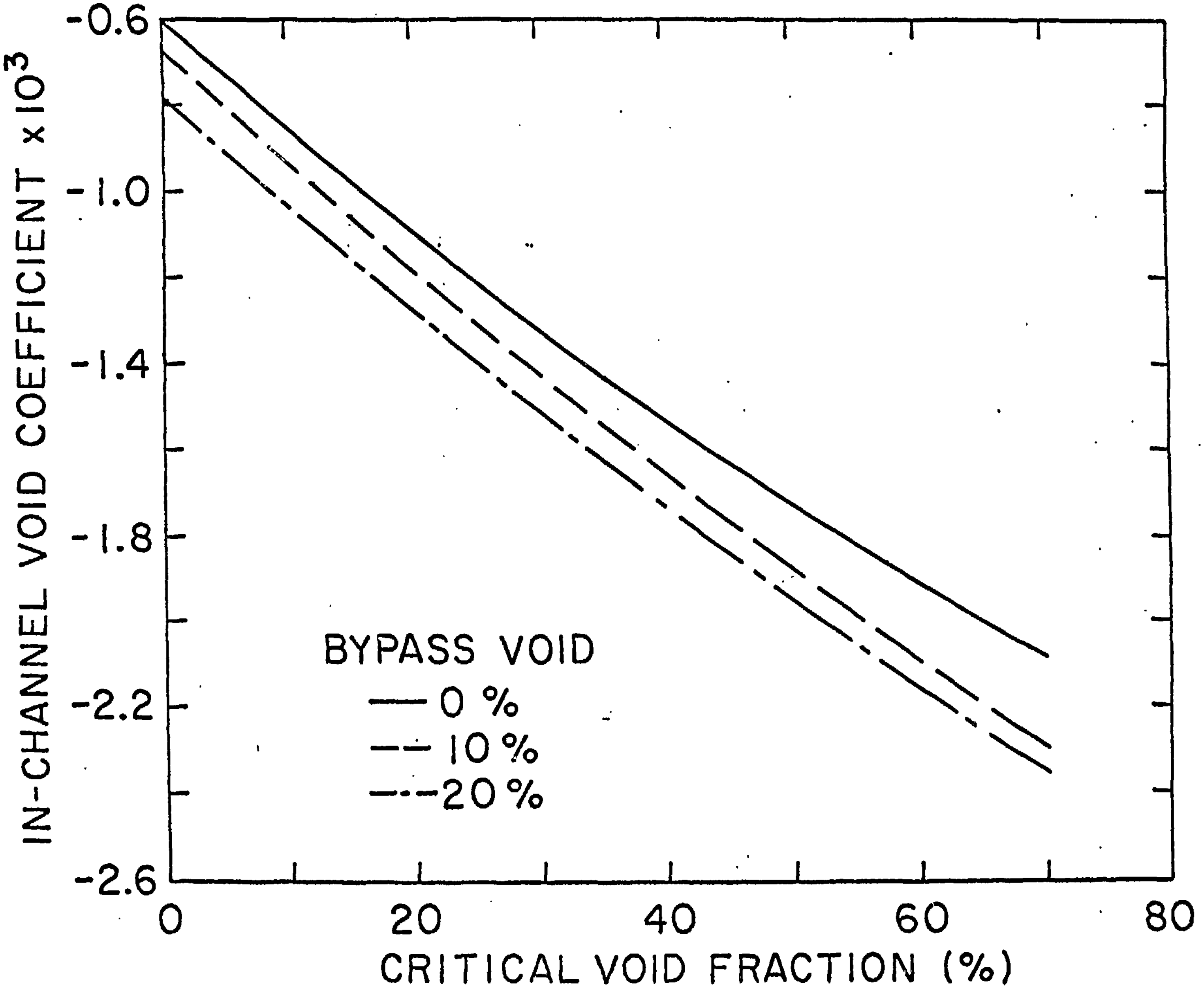

Fig. 2 PARTIAL IN-CHANNEL VOID COEFFICIENT