ANALYTICAL STUDY OF THE DYNAMIC BEHAVIOR OF THE SELF-CONTROLLED MARVIKEN BOILING HEAVY-WATER REACTOR

KEYWORDS: *reactors, heavy water, boiling water, Marviken, BHWR, dynamics*

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The quantitative influence of the void and Doppler coefficients on the dynamics of the Boiling Heavy-Water Reactor (BHWR) under different operating conditions has been examined extensively. Owing to the difficulty of calculating these coefficients exactly and their great influence on the dynamic behavior of the self-controlled reactor, these parameters have been studied over a wide range. The studies also improve understanding of the transient behavior of the BHWR concept. It has been found that undamped oscillations can arise with special combinations of the reactivity coefficients. In the nonlinear dynamic model used, the void reactivity contribution comes from the changes of the exit void and the subcooling. The oscillations induced by the reactivity feedbacks have different dampings and frequencies of ≈ 0.003 or ≈ 0.03 cps, depending on the sign and the magnitude of the void reactivity coefficients.

The transient neutron flux responses to step reactivity perturbations that have the first peak (limited by the fuel Doppler coefficient) as the largest overshoot or that are strongly damped oscillations lie in a well definable area in the exit void and subcooling reactivity coefficient coordinate system. Disturbances introduced by reactivity variation and main steam-valve opening are discussed. The transient responses calculated were those of the neutron flux, reactivity, pressure, moderator temperature, exit void, average void, subcooling, and temperatures of the boiler and superheater fuel.

INTRODUCTION

In the Marviken Boiling Heavy-Water Reactor[1,2] the water leaving the condensor is heated in the feed-water heaters before entering the moderator, where it is, in turn, heated by radiation and thermalization effects and by the heat transferred from the boiler and superheater channels. Above the moderator tank, the feedwater is mixed with the saturated water from the boiler channels. After mixing, the water flows down by natural circulation through the downcomer into the boiler channels. The saturated steam leaves the steam drum through the superheater channels. The main steam valve is kept fully open at normal operation. Below full power and pressure, different auxiliary systems affect the dynamics of the plant.

Analytical studies were performed with a nonlinear analog computer model of the plant and with digital computer programs for steady-state calculations.[3] Here, only the dynamic behavior of the reactor system at full power and pressure will be discussed. The transient response to different perturbations of the self-controlled reactor is important when judging the performance of the system. With the actual disturbances and time intervals, xenon poisoning has a considerable amplifying effect on the transient. The xenon reactivity contribution was, therefore, included in the model.

The void reactivity coefficients are some of the most important but most poorly known parameters. Because of this and the great influence of even the Doppler reactivity coefficient on the dynamic behavior of the self-controlled reactor, these parameters were studied over a wide range. All other parameters were fixed at their normal values, averaged for the whole reactor. With these mean values of the natural-circulation loop,

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no hydrodynamic oscillations occurred during the analytical transient studies of this single-channel model.

The void distribution varies during the transient. The stationary vertical void distribution has been calculated for different conditions around the initial state. On the basis of these calculations, the dynamic changes of the distribution were approximated with a linear function that related the changes of the exit void, average void, and subcooling. This supposition permits the exit and average void to change in opposite directions. This occurs, for example, for changes of the neutron flux. In this case, the water flow at the boiling channel inlets varies little with moderate power changes at the actual operating point of the natural-circulation loop. If the power is suddenly increased, there follows an increase of the steam production and the exit void and a decrease of the saturated water flow from the boiler channel outlet which is mixed with the moderator flow. Later on, the subcooling will increase because of this and because of the increase of the saturation temperature and feed-water flow, causing the initially increased average void to decrease. This reduction is obtained because exit void changes are very moderate. This, in turn, is because the operating point is on the flat part of the void vs steam quality curve and the increasing pressure tends to reduce the void volume. The effect of pressure variation strongly influences the changes in the void distribution.

The void reactivity contribution, which is distributed over the core, can also be approximately referred to the variation of some specific parameters such as exit void, average void, subcooling, or boiling boundary. In the present studies, the void reactivity contribution has been represented by only two variables, proportional to the changes of the exit void and the subcooling, respectively. The respective coefficients are called exit void and subcooling reactivity coefficients.

THE ANALYTICAL MODEL

The studies were performed with a nonlinear model developed some years ago. The dynamic part of the analytical model has been suited to use fully the available AE analog computer capacity. The model contains about 120 operational amplifiers of which about 20 are used as integrators, and a number of nonlinear elements such as servo and quarter square multipliers and diode function generators. The use of such a big model requires many numerical calculations, and it was necessary to develop digital computer programs for the calculation of initial values of all the variables, numerous proportionality coefficients, and potentiometer and function generator settings and test values.

Because of limited capacity of the analog computer, space dependence was neglected except for axial space dependence of the void variation, which was considered in a quasi-stationary manner.

The model contains the following parts of the system:

1) neutron kinetics
2) thermodynamics and hydrodynamics of the moderator
3) thermodynamics and hydrodynamics of the downcomer
4) thermodynamics and hydrodynamics of the boiler channels and steam drum
5) thermodynamics and hydrodynamics of the superheater channels
6) thermodynamics and hydrodynamics of the external system.

1) Neutron kinetics is treated as a single energy group comprising four delayed groups. The contributions to the reactivity balance by the mean values of the following variables are considered: boiler and superheater fuel temperature; exit void; subcooling; moderator temperature; and xenon poisoning.

2) The heat balance of the moderator is simulated by a first-degree time lag. The changes in moderator temperature are calculated as the arithmetical mean value of the changes in inlet and exit temperatures.

3) The mixing of the moderator flow with the flow of water from the boiler channels is supposed to be complete in the volume above the moderator tank. Changes in the water level are taken into consideration. The transport delays caused by the downcomer and the volume below the moderator tank are simulated as two separate first-degree time lags in cascade.

4) The dynamic heat balance of the boiler fuel is described by a first-degree differential equation involving the mean temperature. The changes in the heat transferred from the fuel to the cooling medium are proportional to the changes in the difference between the mean temperature of the fuel and the saturation temperature in the model. The changes in the heat-transfer boiler channel and moderator are supposed to be proportional to the changes in the difference between the saturation temperature and the moderator mean temperature.

The general thermodynamical and hydrodynamical equations were simplified to calculate the relationships between the actual inlet and exit values. In this simplification, the total water and steam content of all the boiler channels is considered as a mass and heat storage. A linear function derived from calculated steady-state changes combines the changes of the exit void, average void, and subcooling. An empirical relationship is used between the saturation pressure, exit void, and exit steam quality. The pressure-drop components of the natural-circulation loop are calculated as follows: The single-phase frictional pressure drop in the downcomer and nonboiling part of the channels is set proportional to the square of the total mass flow. The two-phase frictional pressure drop in the boiler channels (including the risers) is calculated according to the fog flow model and by using channel exit values. As the changes in the acceleration pressure drop are much less than the pressure drops noted above, calculation is strongly simplified. The inertial pressure drop is supposed to be a linear function of the first derivatives of the inlet and exit mass flows.

The steam drum is handled as a single mass storage.

5) The equations of the superheater channels are included in the model but will not be discussed here because of their small influence on the total dynamics.

6) The external system simulation contains equations for the steam turbine, preheater, and control of feed water flow.

EFFECT OF VOID AND FUEL-TEMPERATURE COEFFICIENTS ON DYNAMIC BEHAVIOR

The on-off type control system of the Marviken reactor is planned to be nonactive in a range of about ± 5% neutron flux deviation from the reference level determined by the difference between the saturation pressure and its reference value. Within these limits, the plant is operated as a self-controlled reactor. The control rods are worked with a stepwise movement. The reactivity perturbation chosen for the calculations was a +25 pcm step, which is about the same magnitude as the expected reactivity change from one step movement of a control rod. The fuel Doppler coefficient was in turn -3, -4.5, or -6 pcm per percent change of power. The exit void reactivity coefficient was varied from -30 to +30 pcm per percent. In Fig. 1, the transients of the neutron flux are clearly arranged in a coordinate system with the exit void reactivity coefficients on the horizontal axis and the subcooling reactivity coefficients on the vertical axis.

Owing to the chosen void reactivity representation and the assumed linear function joining together the changes of exit void, average void, and subcooling, there is a ratio between the exit void and subcooling reactivity coefficients for which the void reactivity is proportional to the changes of the average void. Only under this condition can a reactivity coefficient referred exclusively to the changes of the average void be given. The heavy line along which the relationship is valid passes through the origin and is marked with the average void reactivity coefficient in Fig. 2. For other ratios of the exit void and subcooling reactivity coefficients, void reactivity variation is not proportional to the changes of the average void during the transient.

Under the special restrictions given below, one can define an average void reactivity coefficient, even with exit void and subcooling reactivity coefficients other than those discussed above.

During a short time interval at the beginning of the transient caused by a reactivity perturbation, the subcooling remains constant and therefore influences neither the void distribution nor the void reactivity contribution in the model. However, under such conditions, the void reactivity contribution can be referred exclusively to the changes of the average void. In Figs. 1 and 2, intermittent lines correspond to the average void reactivity coefficient at the beginning of the transients caused by a reactivity perturbation.

Also during quasi-stationary conditions, e.g., some minutes after the step perturbation in cases where the response is neither oscillatory nor strongly increasing, an average void reactivity coefficient can be defined instead of the two used. This reactivity coefficient as well as the dynamic behavior of the reactor depends on whether or not the pressure is kept constant during the transients.

With slow variations at constant steam-valve opening (i.e., at variable pressure), the average void reactivity coefficient is constant along the chain dotted lines. These lines, valid for constant steam-valve opening and derived from the slowly decaying part of the transient responses, are approximately equidistant straight lines in the area where they are drawn. If the pressure is kept constant by controlling the steam valve, the average void reactivity coefficient at slow changes, usually called void coefficient, is constant along the chain double-dotted lines.

The average void reactivity coefficients valid at the beginning of the transients caused by a reactivity perturbation have the same sign in Fig. 2 as the exit void reactivity coefficients. The average void reactivity coefficients valid at quasi-stationary conditions and constant steam-valve opening are negative above and positive below a line going through the origin with a slope corresponding to an exit void and subcooling reac-

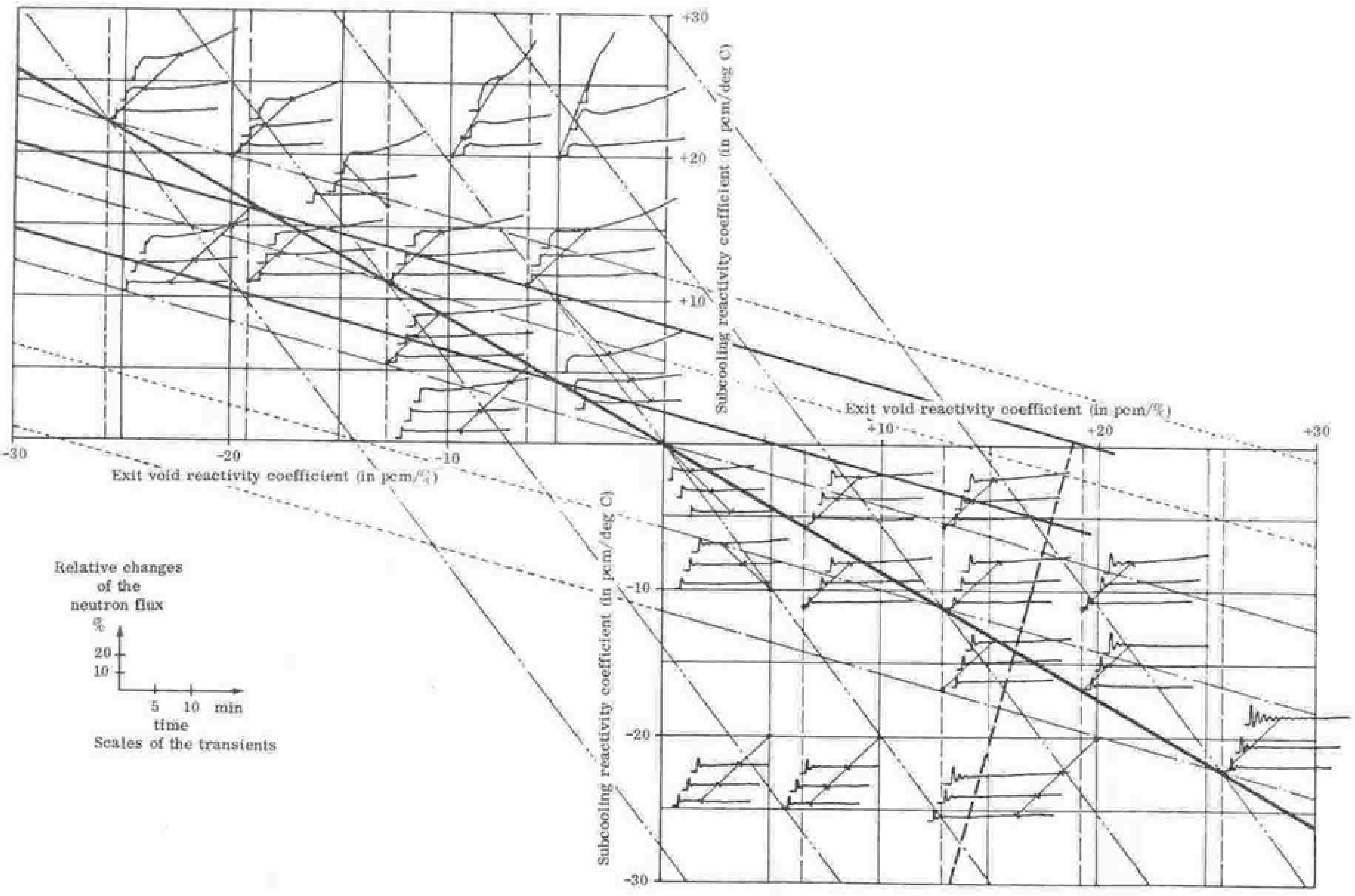

Fig. 1. Transient responses of the neutron flux at various void and Doppler coefficients and +25 pcm step disturbances of the reactivity. The responses are arranged in the exit void and subcooling reactivity coefficient coordinate system. Lines for different average void coefficients and a stability region are also shown. The response curves are shown in groups of three. In each group the upper curve is for a Doppler coefficient of -3 pcm/percent, the middle one for a Doppler coefficient of -4.5 pcm/percent, and the lowest one for a Doppler coefficient of -6 pcm/percent.

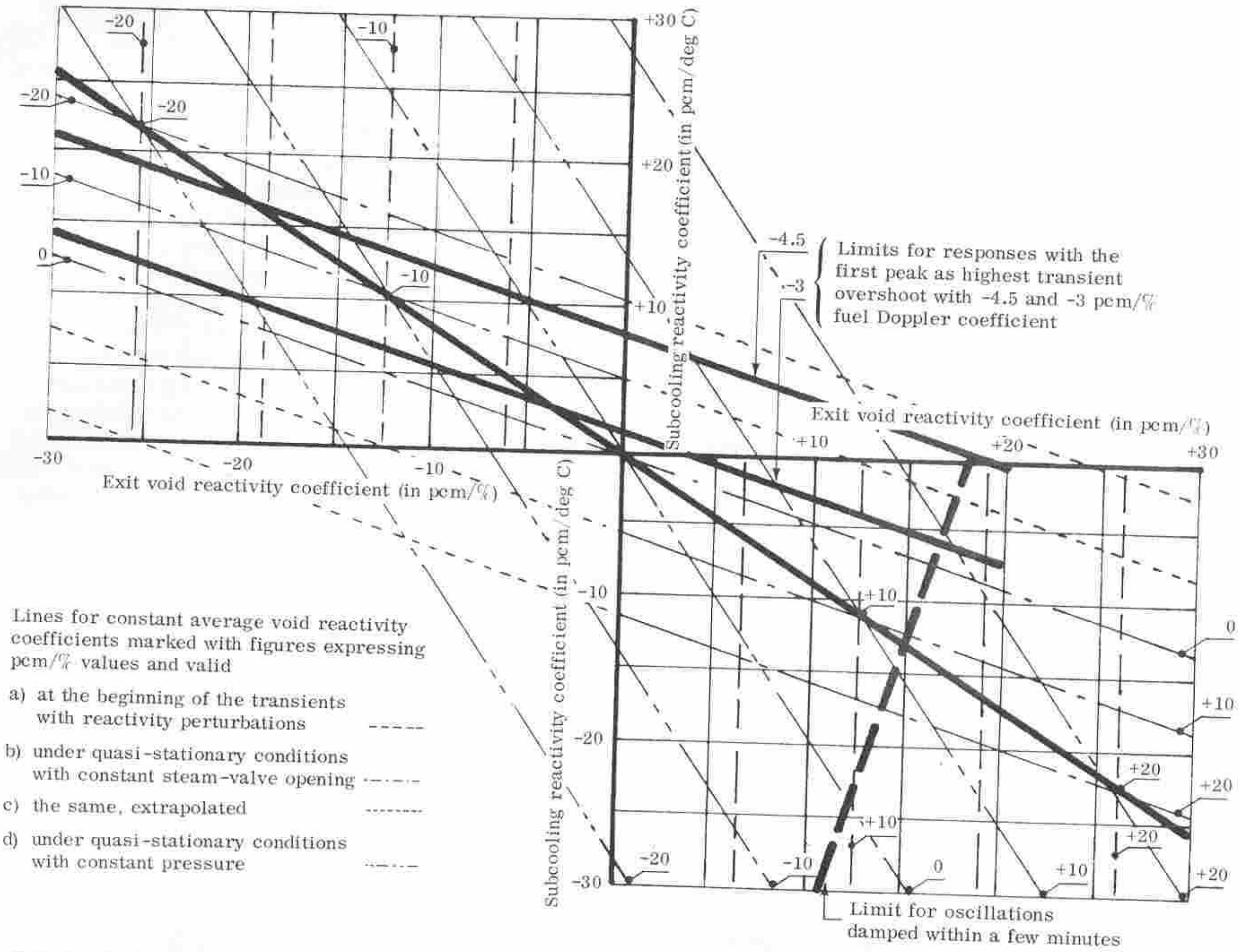

Fig. 2. Reference system for Fig. 1. Different average void coefficients and a stability region are also shown.

tivity coefficient ratio of about -2.5 (pcm/%)/(pcm/deg C). The average void reactivity coefficients valid at quasi-stationary conditions and constant pressure are positive to the right and negative to the left of a line going through the origin with a slope corresponding to an exit void and subcooling reactivity coefficient ratio of about -0.5 (pcm/%)/(pcm/deg C).

One can define an area in this coordinate system in which the first peak of the response of the neutron flux is the highest overshoot. In this area the combined reactivity feedback coming from the changes of the exit void, the subcooling, the xenon poisoning, and the temperature of the fuel and moderator is so strongly damped that the above condition is fulfilled; that is, the first peak is the highest overshoot.

The upper limits of this area are lines with a slope of about -2.5 (pcm/%)/(pcm/deg C) and crossing the vertical axis at about +8 and +2 pcm/deg C for -4.5 and -3 pcm/percent fuel-temperature coefficients, respectively. The right-hand border is approximated by a line perpendicular to the upper limits and crossing the horizontal axis at about +20 pcm/percent. This line excludes cases with responses that are not damped within a few minutes. The lower and left borders have not been defined in this study. As can be seen, one has to go away from this area quite a bit to get strongly diverging transient responses.

It is obvious that the average void coefficients during quasi-stationary conditions at constant steam-valve opening or constant pressure have both positive and negative values in the second and fourth quadrants. The above-discussed orientations of the lines for constant average void reactivity coefficients and the limitations of the stability area are, of course, valid only for the data used.

It can be seen from Fig. 1 that, with negative exit void and positive subcooling reactivity coefficients, the transient overshoots increase for increasing absolute values of the subcooling reactivity coefficient and decrease for increasing absolute values of the exit void reactivity coefficient. For the opposite sign combination, the contrary is valid. This tendency is naturally more evident with small Doppler fuel coefficients. The xenon poisoning also has an amplifying effect.

For the ratio of (-0.5 pcm/%)/(pcm/deg C) for the exit void and subcooling reactivity coefficients, further studies were performed to find the onset of undamped oscillations. The exit void and subcooling reactivity coefficients were varied from -20/+40 to +20/-40 (pcm/%)/(pcm/deg C), and the fuel Doppler coefficient from 0 to -6 pcm/percent. The effect of the xenon poisoning was ignored.

In Fig. 3, the transient responses of the neutron flux are arranged according to the void and fuel reactivity coefficients. One can observe that with the above ratio of void-to-subcooling reactivity coefficients, increasing positive values of the exit void coefficient result in oscillations with a period of more than half a minute. For the opposite sign combination, increasing absolute values of the coefficients result in oscillations with a period of about five minutes. As expected, more negative fuel Doppler coefficients give more stable conditions.

EFFECT OF A STEP PERTURBATION OF THE REACTIVITY AND STEAM-VALVE OPENING

In Figs. 4 and 5, the transient responses of the neutron flux, reactivity, saturation pressure, moderator mean temperature, exit void, average void, subcooling, and boiler and superheater fuel mean temperatures are recorded for different perturbations and void coefficients. There are four different combinations of the exit void and subcooling reactivity coefficients. The first of these combinations lies outside the stability area defined in Figs. 1 and 2, the second combination lies on the boundary of the area, and the remaining two combinations lie inside the area. The figures record all the variables with reactivity contributions in the model except xenon poisoning.

The responses to a reactivity step of +25 pcm can be studied in Fig. 4. In correspondence with Figs. 1, 2, and 3, the +/- sign combination for the exit void and subcooling reactivity coefficients gives a more stable system than the opposite one. As previously discussed, at the very beginning of the transients, the exit and average void deviate in the same direction, while later on, the average void changes into the opposite direction. This

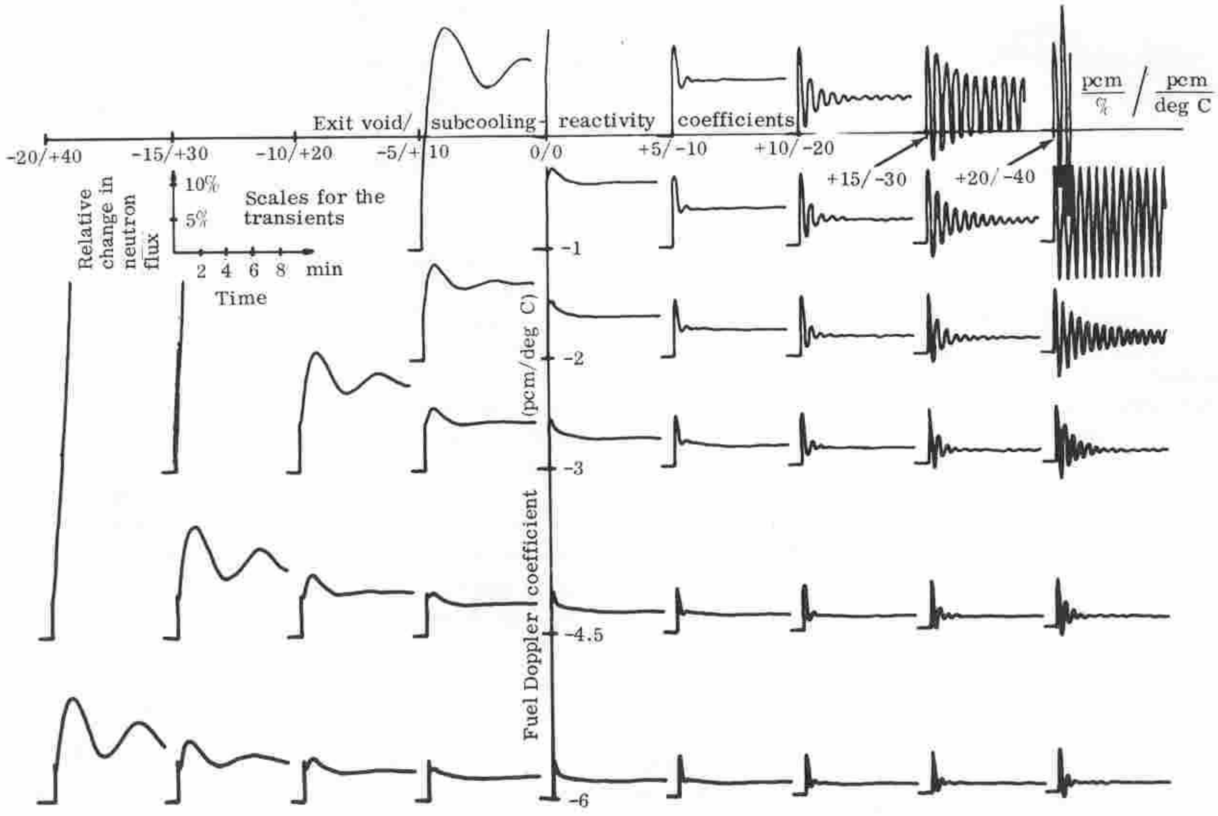

Fig. 3. Stability chart showing the neutron flux response at +25 pcm step perturbation, with different Doppler and void reactivity coefficients using constant ratio between the exit void and subcooling reactivity coefficients.

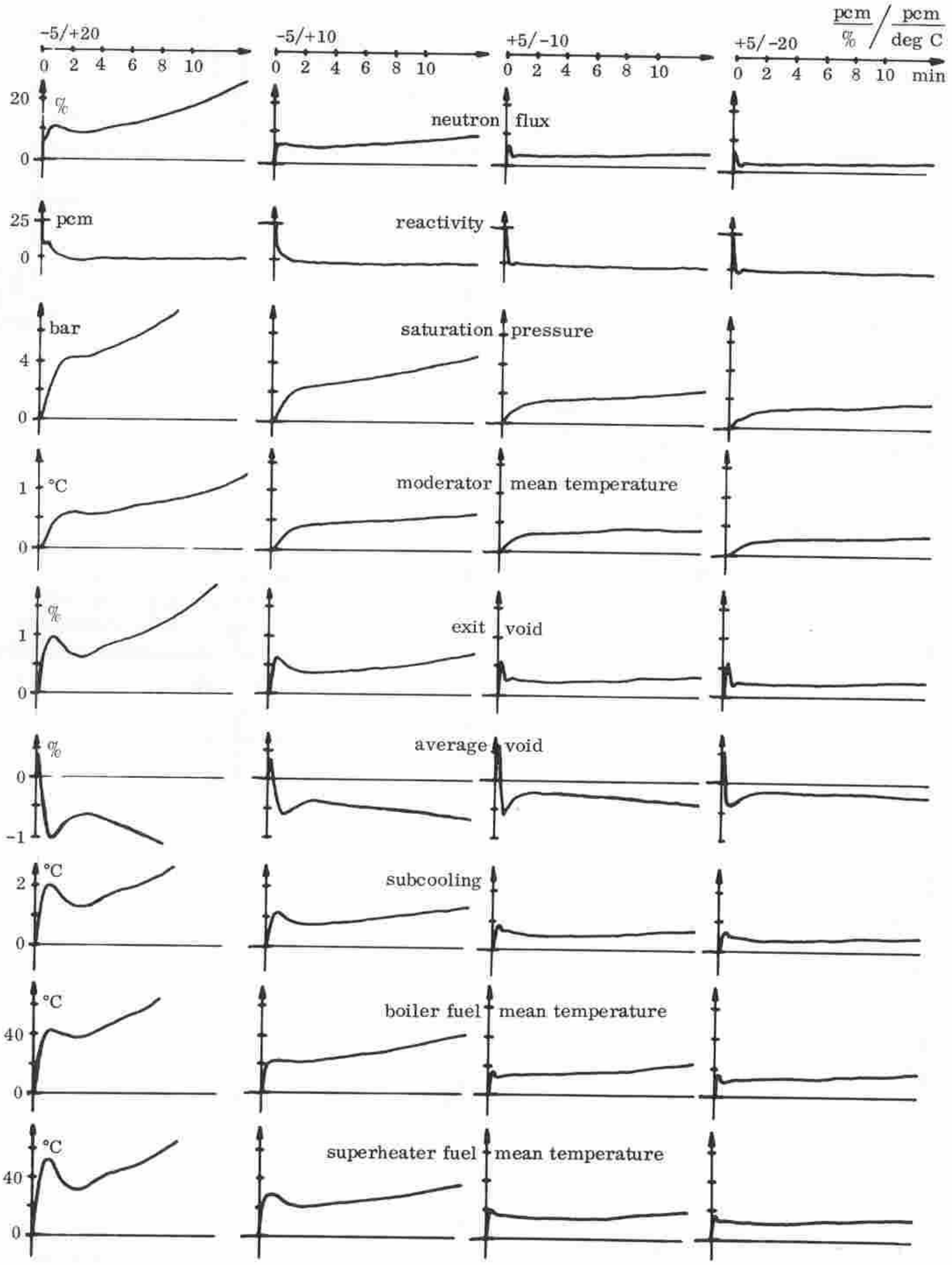

Fig. 4. The response of the neutron flux, reactivity, saturation pressure, moderator temperature, exit void, average void, subcooling, and boiler and superheater fuel temperatures at different exit void and subcooling reactivity coefficients to +25 pcm reactivity perturbation. $\alpha_{fuel} = -4.5$ pcm/percent.

tendency is so strong that the final changes of the exit and average void have different signs. This behavior of the exit and average void can be explained by the increase of the subcooling.

The responses to a step change from 100% to 90% of the main steam-valve opening are shown in Fig. 5. The cases with acceptable exit void and subcooling reactivity coefficients from the point of view of inherent stability as defined in Fig. 2 have a good load-following character, while other void coefficients give an initial power overshoot in the wrong direction for the self-controlled reactor. It

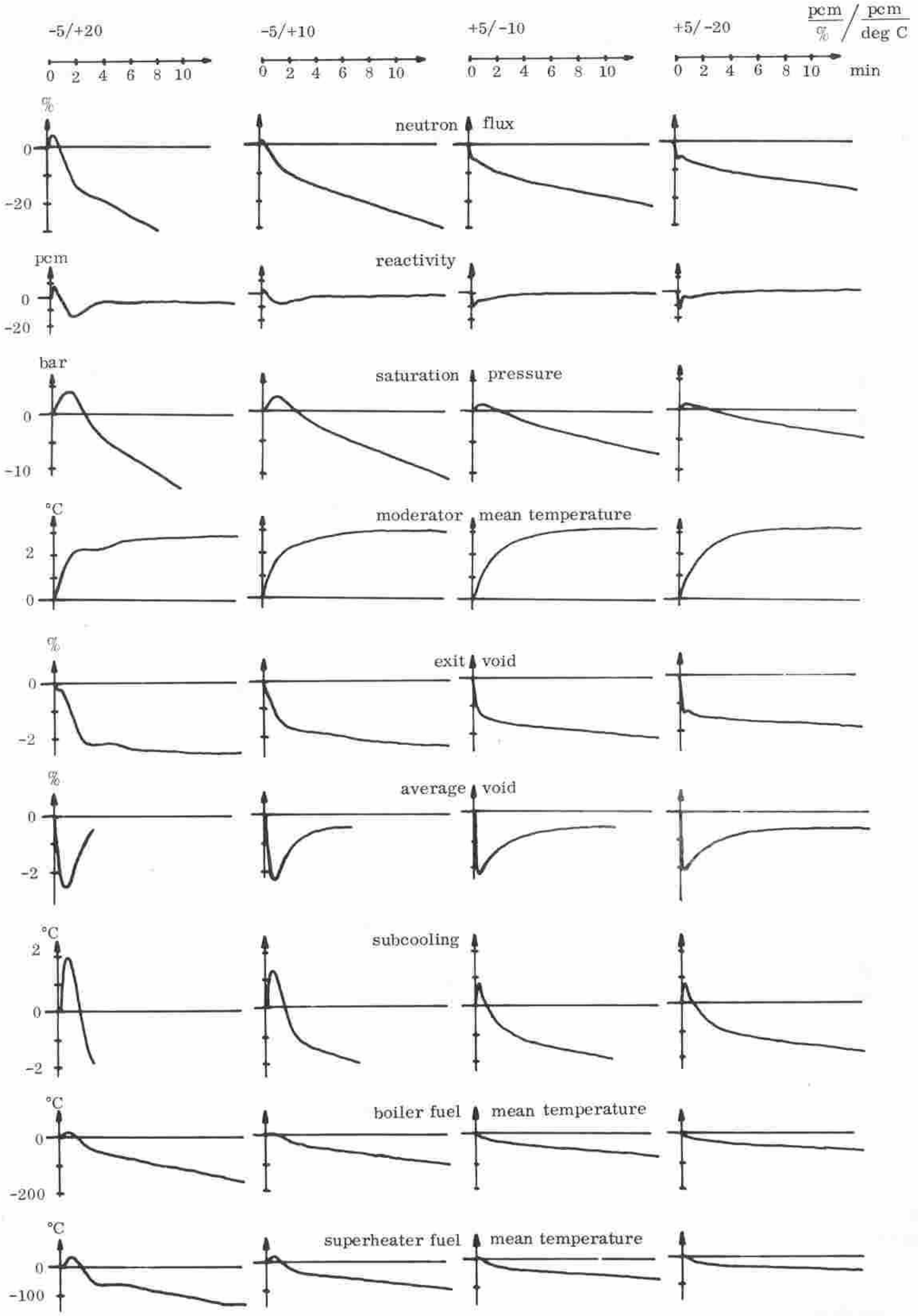

Fig. 5. The response of the neutron flux, reactivity, saturation pressure, moderator temperature, exit void, average void, subcooling, and boiler and superheater fuel temperatures at different exit void and subcooling reactivity coefficients to a step reduction of the main steam-valve opening (100% → 90% effectively). $\alpha_{\text{fuel}} = -4.5$ pcm/percent.

is also true that the sensitivity of the system to changes in the steam-valve opening increases when going away from the stability area.

Reisch and Spanne[3] detailed studies about the effect of the power and pressure level, the moderator temperature coefficient, and other disturbances of the system. The nonlinear character of the system is quite clear in this reference.

CONCLUSIONS

When considering results given in the paper, one should have in mind that the data used are not well known, and complicated processes with distributed parameters were simulated in a simplified manner.

The most important conclusions concern the allowable maximum absolute values of the coefficients for the chosen void reactivity representation from the aspect of the dynamic behavior of the system. Applying step reactivity perturbations, one finds that the transient neutron flux responses that have their first peak (limited by the fuel Doppler coefficient) as the largest overshoot or that are strongly damped oscillations, lie in a well-defined area in the exit void and subcooling reactivity coefficient coordinate system. The boundaries of this area can be used as stability limits. The borders of the stability area depend on the used-fuel Doppler coefficient. Figure 1 shows that in the region of the void coefficient studied, the upper limits for -4.5 and -3.0 pcm/percent fuel Doppler coefficients are straight parallel lines going above the line passing through the origin with a slope corresponding to the exit void and subcooling reactivity coefficient ratio of about (-2.5 pcm/%)/(pcm/deg C). The limits for -4.5 pcm/percent fuel Doppler coefficient coincides with the line for -15 pcm/percent average void reactivity coefficient under quasi-stationary conditions and constant steam-valve opening, while the -3 pcm/percent Doppler coefficient limit coincides approximately with the -5 pcm/% average void reactivity coefficient line. The right-hand border of the area is a line perpendicular to the upper limits going through the point on the abscissa corresponding to about +20 pcm/percent exit void reactivity coefficient. This last line excludes cases with responses that are not damped within a few minutes. This stability region decreases with decreasing power and pressure level. The average void coefficient valid under quasi-stationary conditions and constant pressure, usually called the void coefficient, can be either positive or negative in this area.

It is obvious that the void reactivity feedback that was used, composed of contributions proportional to the changes in the exit void and subcooling, is more adequate than a void reactivity feedback proportional only to the changes in the average void.

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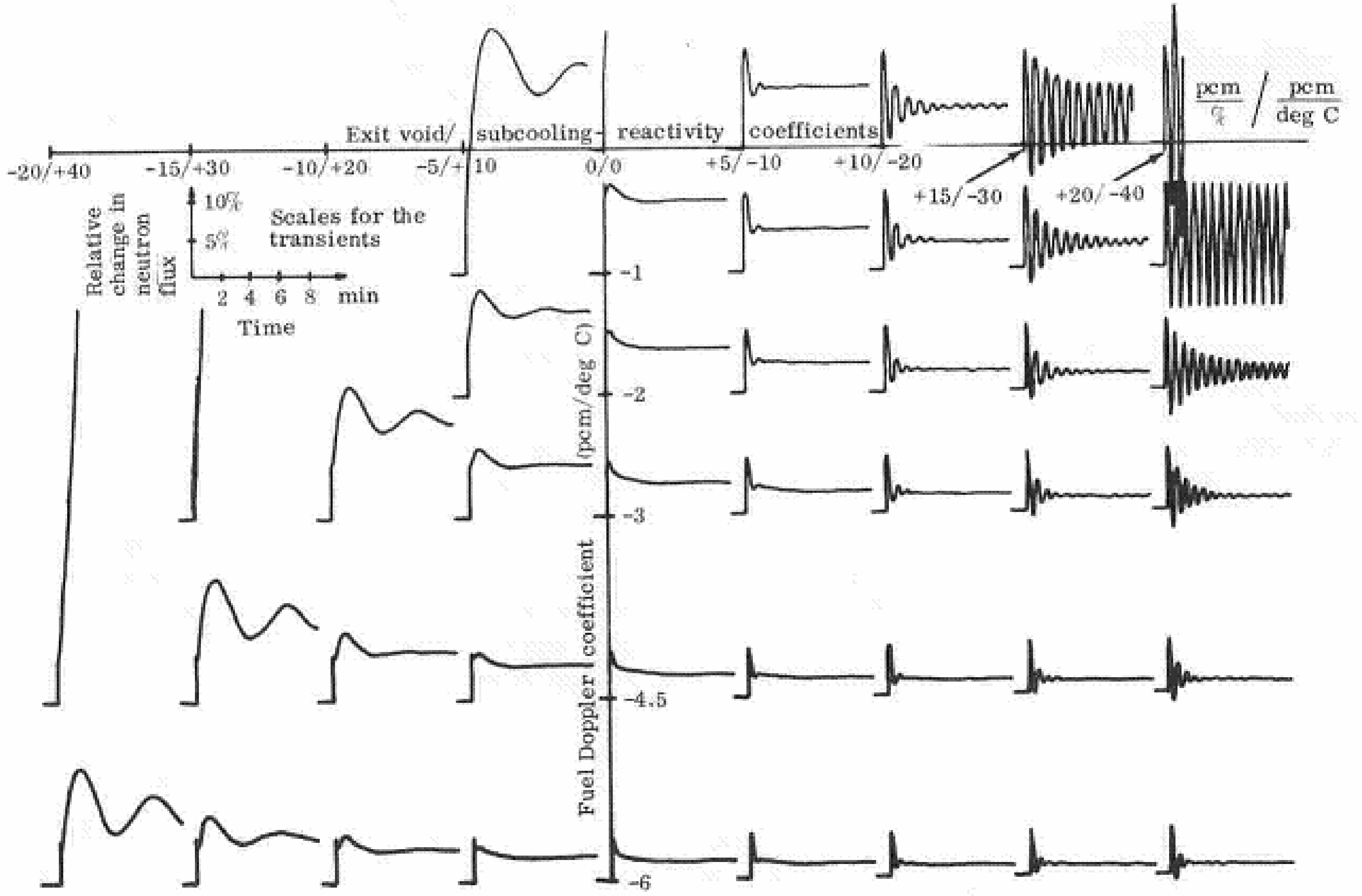

Fig. 3. Stability chart showing the neutron flux response at +25 pcm step perturbation, with different Doppler and void reactivity coefficients using constant ratio between the exit void and subcooling reactivity coefficients.