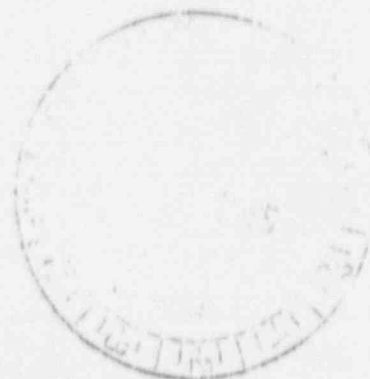


Aug/64

THE SAXTON CHEMICAL SHIM EXPERIMENT

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Editors

J. Weisman

S. Bartnoff

Contributors

S. Bartnoff

W. D. Fletcher

M. J. Bell

F. J. Frank

P. Cohen

A. J. Impink

R. W. Colombo

G. R. Taylor

T. L. Erion

J. Weisman

August, 1964

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Abstract

An extensive program to demonstrate the feasibility of operation with chemical shim control has been conducted at the Saxton reactor. Boric acid remained in the core continuously from May 23, 1963, to January 20, 1964. After a brief period of non-borated operation, chemical shim operation resumed on March 6 and continued until April 20 when the reactor was shutdown temporarily for replacement of experimental fuel rods. Total average core burnup was then 6330 MWD/MTU, of which 4521 MWD/MTU was incurred during chemical shim operation. Peak burnup was 15,600 MWD/MTU.

The experimental data obtained do not indicate any significant boron accumulation on the core surface at power or any decrease in core lifetime under normal operating conditions. The data also indicate that alkali addition for pH control is satisfactory in both pure water and the chemical shim solution; moreover, the expected hot channel factors were achieved.

The future program will test the behavior of defected Zircaloy rods, provide a technique for detecting heavy crud deposits if they are present, and evaluate the feasibility of chemical shim operation with bulk boiling in some channels.

The Saxton Chemical Shim Experiment

I. Introduction

The Saxton nuclear power facility is a closed-cycle pressurized water reactor plant having a nominal output of 20 megawatts (thermal). The principal characteristics of the core are summarized in Table 1. The primary purposes of the plant are to produce engineering information from planned experiments and to test new methods of reactor operation with potential applications to power plants. The experimental program is being carried out jointly by the Westinghouse Atomic Power Division (WAPD) and the Saxton Nuclear Experimental Corporation (SNEC), a subsidiary of General Public Utilities Corporation.

The first phase of the experimental program at the Saxton reactor is being devoted to investigation of "chemical shim control" using boric acid. The adjustment of moderator properties by addition of a soluble neutron poison for control of reactivity with lifetime leads to significant economic advantages when applied to closed cycle water reactors. Use of "chemical shim control" not only reduces the number of control rods and control rod drives but allows full advantage to be taken of the lower hot channel factors achievable with non-uniform radial fuel enrichment.* In view of these advantages, the large Westinghouse reactor plants now being designed will use chemical shim control.

* P. Cohen and H. Graves, Nucleonics 22, No. 5, 75 (May 1964)

Table 1

Principal Characteristics
of the Saxton Reactor Core

Core Description

Average core diameter (cold)	28.07 inches
Actual core length (cold)	36.6 inches
Number of fuel assemblies	21
UO ₂ in the core	2256 lbs (measured)
Uranium enrichment	5.69%

Fuel Rods

Pellet diameter (cold)	.357 in
Fuel tube O.D.	.391 in
Total number of rods	1676

Control Rods

Number of movable rods	6
Control rod shape	Offset cruciform

Thermal and Hydraulic Design Data

Total coolant flow	2.8×10^6 lbs/hr
Nominal operating pressure	2000 psi
Average coolant temperature	530°F

II. Program Summary (J. Weisman)

A. Objectives

The basic objectives of the Saxton chemical shim control program have been the accumulation of reactor operating experience to demonstrate the feasibility of the concept and the determination that no operating problems exist. The major concern in the operation of a chemical shim plant was the possibility that boron might accumulate in some manner on the core surface and subsequently be released rapidly. A secondary concern was that boron accumulation might occur in an irreversible manner (that is, not to be reduced as the boron concentration is reduced) and hence lead to a significant reduction in core lifetime.

Extensive out-of-pile tests have disclosed only two mechanisms by which significant boron accumulation could occur. The first possibility was indicated by the study of solutions during nucleate boiling on the surface of electrically heated rods. By means of a sodium tracer, it was determined that, under nucleate boiling conditions in the presence of heavy crud deposits, a significant concentration of the sodium occurred on the surface of the rod. The accumulation disappeared rapidly when boiling on the surface of the rods was terminated. This concentration effect was observed only in the presence of crud deposits far heavier than those expected in normal reactor operation.* If such a concentration effect had been

* WCAP-3771 "Radiotracer Studies of Hideout at High Temperature & Pressure" (June 63) L. Picone, D. Whyte, and G. R. Taylor.

obtained in the reactor with boric acid, this would have been observed as a reactivity loss; in particular as an abrupt change in power coefficient at the onset of nucleate boiling. Such a reactivity loss would have been reversed once the power was reduced below the level at which nucleate boiling occurred.

It has been observed that crud levels in the water of pressurized water reactors are reduced when the main coolant is maintained at an alkaline pH. Since boric acid is essentially un-ionized at operating conditions, the benefits of high pH can be obtained by addition of very small amounts of alkali to the borated coolant. Under nucleate boiling conditions, it is conceivable that deposition of alkali borate salts could occur on the surface of the fuel rods. There is out-of-pile evidence that if this were to occur with a lithium additive, re-solution of the salt might not occur. The problem of metaborate precipitation was one of those carefully studied during the experiment.

A third mechanism, one of simple "exchange absorption" of borate by the corrosion product deposits on the surfaces of the fuel, is also known. The extent of boron accumulation on the core is dependent on the coolant boric acid concentration and the amount of crud on the core. However, the small quantities of borate which can be absorbed make the process insignificant from a reactivity standpoint.

B. Experimental Program

Three major techniques have been used to demonstrate the absence of boron accumulation. The first of these has been the careful comparison of the predisted core reactivity with that observed. Any boron accumulation on core surfaces would have been observed as a decrease in reactivity beyond that expected. Particular attention was paid to the transition from nucleate boiling to non-nucleate boiling conditions.

The second technique was concerned with the demonstration that alkali metaborate precipitation did not occur. Careful follow of the alkali to boron ratio was maintained for periods during the test. The absence of a change in this ratio demonstrates the absence of metaborate precipitation.

The third technique used was that of hot cell examination of a test subassembly after appreciable chemical shim operation. The surfaces of the fuel rods were scraped and the deposits removed, weighed, and analyzed. The reactivity worth of this deposit was then estimated.

Prior to chemical shim operation, an extensive series of low power physics tests was conducted. These were followed by a period of rodded operation at power. The tests provided the information required to conduct the reactivity follow during chemical shim.

Chemical shim operation at Saxton began on May 27, 1963. After operation at 15 and 20 MWt, the reactor was brought to 23.5 MWt which is 3.5 MWt above the level for which the plant is rated under rodded operation. Boric acid remained in the core continuously until January 20, 1964, although power operation terminated on November 22. During this period, the reactor operated under a variety of conditions and an average burnup of 3440 MW days/tonne was accumulated during this period. (Total average burnup at the end of the period was 4735 MW days/tonne.) A test subassembly was then removed for examination. A brief period of non-borated operation began on January 30 in order to provide additional information on the effect of burnup on reactivity in an unborated core. Chemical shim operation resumed on March 6 and continued until April 20. Total average core burnup was then 6330 MWD/tonne, of which 4521 MWD/tonne was incurred during chemical shim operation.

C. Results

The test program has successfully demonstrated the feasibility of chemical shim control. No significant operating problems have been encountered. Under normal operating conditions, the data indicate that:

- 1) There is no significant accumulation of boron-containing material on the core surfaces during plant operation. Deviations from reactivity predictions were well within the estimated error and no deleterious trends could be observed.

- 2) There is no decrease in core lifetime because of chemical shim operation. Examination of the central subassembly showed no significant accumulation of high cross section materials on the fuel surfaces.
- 3) pH control of the coolant can be accomplished successfully. Chemistry studies indicated no problem with alkali stability in the coolant.
- 4) For the Saxton reactor, the expected hot channel factors were in reasonable agreement with calculations.
- 5) Chemical shim, under normal conditions, causes no hazardous situation to arise to affect plant operation.

III. Experimental Program Description (T. L. Erion - J. Weisman)

A. Reactivity Follow Ground Rules

The safeguards report for the chemical shim experiment considered the possibility that a boron-containing material could be dislodged from the fuel surfaces and rapidly removed from the reactor core. Since definitive operating data showing that this would not occur were not then available, it was decided that reactor operation would be conducted in a manner which would limit any possible release to a harmless value. It was conservatively postulated that a release of material from the core might take place over half the coolant transit time through the core. Based on this assumption, the magnitude of the reactivity release which could be tolerated under various operation conditions was computed. A limitation was then imposed that power operation would continue only so long as the unexpected reactivity loss which could be associated with any poison material on the core surfaces allowing for experimental uncertainties was below the appropriate limit.

In order to evaluate the extent of possible accumulation of poison material on the core, the predicted core reactivity was carefully compared with that observed. To accomplish the required reactivity accounting, initial conditions were established and the control rod positions measured. The initial point chosen was the hot, borated, zero power condition prior to operation with boric acid at power. The reactivity changes caused by

departures from the initial conditions are calculated using previously established values of the coefficients for power, temperature, pressure, boron concentration, control rods, pH, and the time dependent reactivity worths of uranium, plutonium, samarium, xenon, and other fission products. The predicted reactivity changes are used to compute the predicted positions as a function of time for the single controlling rod in the core.

As experimental data were obtained, the observed control rod positions were corrected to account for differences between the base conditions of temperature, power level, boron concentration, pressure, and pH used in making predictions and the actual conditions at the time of the observations. The discrepancy between predicted position of the control rod and observed position as corrected was taken by the operator as a measure of "unexplained" reactivity. Any boron accumulation would appear as an unexplained reactivity loss.

In determining the allowable unexplained reactivity loss, an estimate was made of the uncertainty in the reactivity prediction, caused by uncertainty in the reactivity parameters used, and the uncertainty associated with the actual measurement. The statistically combined uncertainties were then subtracted from the reactivity release value which the transient studies had previously shown to be safe. The difference remaining, which was about 1/2 the computed allowance, was taken as the maximum allowable unexplained loss. This quantity varied between 0.3 and 0.4% $\Delta k/k$ during the test.

Upon completion of a given portion of the experiment, a core reactivity prediction was made based on the actual power conditions during and prior to the run. The experimentally observed rod position, boron concentrations, coolant temperatures, and power were then used to compute the observed reactivity. The difference between the observed and calculated reactivity is that which is reported in subsequent sections of this report as the final value of the unexplained reactivity at the given time in life. These numbers differ slightly from those used by the operator in that they take into account a) the reactivity variation of xenon and other isotopes induced by the power oscillation about the nominal power level, b) the variation in effective flux seen by the various nuclides with changes in rod position and burnup, and c) the small difference between unexplained reactivity expressed in terms of predicted and observed reactivity changes and that in terms of predicted and observed rod positions.

B. Test Program

1. Pre-Chemical Shim Operation

In order to provide a firm basis for subsequent chemical shim reactivity follow, a careful program of tests was carried out prior to chemical shim operation. The first phase of the program consisted of low power physics measurements. These included measurements of control rod worth, boron, and flow worth at ambient and operating

temperatures. Temperature and pressure coefficients were measured over a wide range of boron concentrations. The measurements covered a variety of conditions and were far more comprehensive than would have been required had an experimental program not been planned.

After completion of the low power physics program, the reactor was brought to full power in a step-wise manner. Transient responses and power distributions were measured at each successive power level. After conducting the transient tests at full power of 20 MWt, the reactor was run at this full power for two 21-day periods. This provided the information required to check the computations used for predicting reactivity changes caused by fuel burnup during chemical shim operation.

At the conclusion of the burnup studies, the reactor was shut down cold in order to insert three test subassemblies. A nine rod subassembly containing five thin-walled stainless steel clad fuel rods and four Zircaloy clad rods was inserted in the central test position. Four of the stainless fuel rods were removable, i.e., they could be removed from the subassembly without destruction of the can. All rods contained fuel which produced power at the normal reactor power density level. The purpose of this subassembly was to allow crud buildup measurements to be made readily, furnish a comparison of Zircaloy and

stainless steel clad behavior in a chemical shim environment, and to test the performance of elastically collapsed cladding.

A second subassembly containing five thin-walled stainless-steel rods and four Zircaloy elements was inserted in a peripheral position. This subassembly was identical to the first subassembly except that the stainless steel rods were enriched to a slightly greater extent. It was planned to move this assembly subsequently to the central position. At that time, the "spiked" rods would produce ≈ 10 KW/ft.

A third subassembly containing a 1/2 in. I. D. thimble was inserted in another peripheral test position. This thimble was used for a small oscillating absorber. It was expected that comparison of the absorber position oscillations with the flux oscillations so produced could be used for the determination of reactivity transfer coefficients. Unfortunately, the absorber jammed shortly after the reactor went to power and the desired information was not obtained.

2. Step-Wise Approach to Power with Chemical Shim

With the reactor at 520°F, 2100 psi, and zero-power, the coolant was borated to a level of approximately 1200 ppm B. The boron level was such that, when the critical control rod position was established, all rods except one were withdrawn from the core. The critical rod position was carefully measured.

operation at 20 MWt, the plant was brought to 22 MWt. After remaining at this power level for a day, during which time core flux maps were taken to demonstrate that predicted hot channel factors were not exceeded, the plant was taken to 23.5 MWt on June 22.

Operation at the elevated power level of 23.5 MWt was especially significant. Under these conditions, calculations predicted that a substantial fraction, approximately 16% of the core surface area, was in the nucleate boiling region. This was verified by the results of core noise analysis.* It will be recalled that it had been thought that significant reversible boron accumulation might be possible under such nucleate boiling conditions. The reactivity follow observation showed no significant change in unexplained reactivity during the continued operation at 23.5 MWt.

4. Examination of pH Effects

It has been observed in other closed-cycle water reactors, Yankee and BR-3, that changes in the main coolant pH caused observable changes in core reactivity. Although this phenomenon is not well understood, theories have been advanced that the reactivity changes may be related to possible pH induced changes in the quantity, nature, thermal conductivity properties and/or

* This work was partially supported under AEC Contract AT(30-1)-3269

distribution of the crud on the fuel surfaces. In order to investigate this effect under chemical shim conditions, several experiments were conducted where the alkali in the coolant was removed by demineralization and subsequently replaced.

The first of these tests was conducted under chemical shim conditions at a power level of 23.5 MW. In later parts of the program, tests were conducted under non-nucleate boiling conditions and, during a later phase of the program, under unborated conditions. The conditions under which tests were conducted were:

- 1) chemical shim - 23.5 MWt-530°F, 2000 psi -
substantial
nucleate boiling
- 2) chemical shim - 15 MWt, 520°F, 2100 psi -
no nucleate
boiling
- 3) chemical shim - 0 MWt, 520°F, 2000 psi -
no power
generation
- 4) unborated coolant - 20 MWt, 520°F, 2000 psi -
some nucleate
boiling

5. Extended Operation Under Chemical Shim

Upon completion of the pH test at 23.5 MWt, operation continued at this power level until July 10, when it was reduced to 20 MWt. The reactor was then shut down on July 15 for scheduled maintenance. After completion of the maintenance, the reactor was operated at 20 and 15 MWt through August and early September. During the 15 MWt operation, the previously mentioned pH test under non-nucleate boiling conditions was

performed. Operation at 23.5 MWt resumed September 12. With the exception of a brief shutdown from September 30 to October 3, the reactor remained at that level until November 19.

During the extended operation under nucleate boiling conditions (at 23.5 MWt) careful attention was paid to the change in reactivity with lifetime.

No significant change in the unexplained reactivity was observed under these conditions of boiling. This is considered strong evidence that buildup of poison on the core surface did not occur as a result of boiling.

6. Test Assembly Insertion and Low Power Physics Measurements

In the shutdown following the extended operation, the test subassemblies inserted prior to chemical shim were removed. The rod oscillator assembly containing the jammed oscillator was replaced by a unit containing a redesigned oscillator. The new subassembly also contained 8 hollow tubes into which direct reading nuclear detectors could be inserted.

The subassembly in the core periphery which contained Zircaloy and thin clad stainless fuel rods was removed from the core, examined with the periscope, and placed in the fuel storage rack. The periscopic examination of this assembly indicated it to be essentially free of crud deposits. This unit was replaced by one of the normal subassemblies which had been in the core at the startup.

The central subassembly, containing Zircaloy and thin clad stainless rods, was also examined periscopically. These fuel rods

showed what appeared to be a thin deposit of reddish-brown crud over a portion of the rod. The deposit covered the greatest area in the high flux region. It was estimated that only about 10-15% of the rod surface area had any deposit. After this visual examination, the assembly was placed in a shipping container and brought to the Westinghouse Waltz Mill site. After appropriate cooling, the unit was moved from the shipping cask to the hot cells. There the subassembly was dismantled and the fuel rods carefully examined. The examination included measurement of the area of the deposits, scraping selected portions of the rod to determine the total weight of the deposit, and chemical analysis of the deposit.

The central subassembly was replaced by a new test unit. This unit contained five Zircaloy clad fuel rods and two stainless steel clad rods. In addition, it had two rods which simulated absorber rods of the rod cluster control (RCC) scheme. These RCC rods were contained within a guide thimble separated from the rod by a narrow annulus. The rods contained depleted uranium so that the heat generation of absorber material could be simulated. The purpose of this assembly was to determine whether, under static conditions, crud buildup in a reactor would cause a significant increase in the force required to withdraw the rod from the guide tube. A special fixture was provided so that the withdrawal forces could be measured after the assembly was removed from the reactor.

Critical positions were carefully determined before and after the subassembly insertion. Following the critical measurements, the previously mentioned pH test at zero power was performed.

7. Non-Borated Operation

On completion of the shutdown work, the reactor was brought to temperature and deborated. Careful reactivity follow was maintained during the final stages of the deboration, which was accomplished by ion exchange. After the boric acid had been essentially all removed, 75 ppm of boron were added to the system. Core reactivity was again followed. If there had been a reversible deposit of boron on the core surfaces, the change in reactivity during that dilution, caused both by removal of boron from the main coolant and by the release of boron from the core surface, would have been greater than that during the second dilution, when only removal of boron from the main coolant was involved. No such effect was observed.

The reactor was then brought to power and rod oscillator experiments were conducted at both 15 and 20 MWt. The results of these tests were subsequently compared with the results of similar tests under chemical shim conditions.

The transfer functions determined by these tests showed no evidence of any power reversible boron hideout at the test conditions.*

*WCAP-2627 "Saxton Kinetic Experiments" V. Rajagopal (June 1964). This work was partially supported under AEC Contract AT(30-1)-3269.

At the conclusion of the oscillator tests, the pH test with an unborated coolant was conducted. When the alkali was restored, lithium was added instead of potassium. Operation at 20 MWt continued for approximately 10 additional days. This period was used to provide a recheck of the burnup rates under conditions where they could not be obscured by chemical shim effects.

8. Renewed Chemical Shim Operation - Lithium Stability Tests

Prior to these tests, the hot cell examination of the subassembly which had been in the central core position was completed. From the information so obtained, it was possible to estimate the reactivity worth of the deposit on the core surfaces. Conservative calculations indicated this to have a reactivity worth of no more than $.01\% \Delta k/k$. It was therefore concluded that there was no significant neutron absorbing deposit on the core at the end of the non-borated operation. Accordingly, the hot borated critical measured at the beginning of the renewed chemical operation was taken as a new base point. To this point was assigned a minimal value of unexplained reactivity loss corresponding to a conservative calculation of the worth of the crud deposit. Subsequent reactivity computations are all referred to this new base point.

The reactor was brought to 23.5 MWt with intermediate operation 15 and 20 MWt for rod oscillator measurements. No change in the unexplained reactivity was observed as the power was increased from 15 to 23.5 MWt.

This period, March 6 through 30 of 1964, while the reactor operated with 560 - 660 ppm of boron in the coolant, was also used to demonstrate the stability of LiOH as a pH control agent. During this period, the lithium level was of the order of 0.4 - 0.5 ppm. The lithium concentration gradually increased because of the $B^{10} (n, \alpha) Li^7$ reaction. The lithium growth in the coolant followed predictions based on data obtained during May and June of 1963. If metaborate precipitation had occurred, a change in the growth rate should have been observed.

The lithium concentration in the coolant was then increased to approximately 1.7 ppm. This level was maintained from April 1 to April 7 while careful chemical surveillance was maintained. Again the lithium growth in the coolant followed predictions.

Plant operation continued until April 20 at which time an extensive shutdown for the replacement of a number of experimental subassemblies was begun.

IV. Results of the Reactivity Follow Program
A. J. Impink, R. W. Colombo, F. J. Frank

A. Calculation Procedures

1. Reactivity Parameters

Throughout the chemical shim program at Saxton, an attempt has been made to predict and to follow reactivity changes in the reactor as closely as possible. To this end a rather comprehensive set of reactor physics measurements was carried out, both at zero power and at full design power, before operations at power with boron in the main coolant were undertaken. Analysis of data obtained during the preliminary experimental program yielded values of the reactivity kinetics coefficients of temperature, pressure, and power. The reactivity worths of xenon and of control rods and boron in solution also were obtained. A later series of measurements, carried out during chemical shim operation and subsequently verified during rod-controlled, zero-boron operation, established the value of the reactivity coefficient of moderator alkalinity level.

In constructing the reactivity balance during chemical shim operation, primary emphasis was placed on these experimentally determined reactivity coefficient values, as opposed to values obtained by analytical predictions, for several reasons. The general premise was established that measured values more faithfully represent the net result, in terms of reactivity,

of changes in the physical characteristics of the system that do values extracted from studies based on idealized analytical models of the system. Of greater influence in favoring the experimental values was the recognition that deviations from predicted behavior could be detected only through measurements made during operations. If systematic errors are to be avoided in comparing predictions with measurements, the predictions would need to be based on data obtained in the same manner as the data in which subsequent evaluations of behavior were to be based.

Wherever practical, the experimental data were compared with the results of previous theoretical studies to insure that the reactivity coefficients derived were realistic. It was observed, in general, that the experimental best values agreed reasonably well with theoretical predictions.

The one reactivity effect that could not be measured adequately and therefore had to be based on theoretical calculations was that caused by burnup. Although experimental data were used during the earliest part of the program, as soon as burnup contributed a significant component to the reactivity balance, use was made of an analytical, multi-dimensional burnup model. The model depended on experimentally measured flux distributions to predict reactivity changes resulting from long-term burnup and from spatial transient effects. Burnup

rate measurements were made periodically both prior to and during chemical shim operations. Comparison of the theoretical predictions with the results of these measurements under specified conditions permitted verification of the model.

2. Computational Techniques

The Saxton reactivity balance was based on the so-called "differential" model. The method allows detection of anomalous reactivity behavior by comparing measured and predicted reactivity changes over a series of successive short time intervals. By way of contrast, the alternate "integral" model relates all reactivity changes directly to a base point which may be rather remote in time. Although the two methods may seem to differ significantly, the only fundamental difference is in the method of establishing the reactivity equivalent of control rod motion at various power levels.

A predicted change in reactivity embodying the sum of the reactivity equivalents of all changes in core conditions (temperature, pressure, power level, boron and xenon concentrations, pH level, and burnup) is compared with the reactivity equivalent of the observed control rod motion required to compensate for the change. The difference between the predicted change in reactivity and the measured change is then, by definition, an incremental change in unexplained reactivity. The total unexplained reactivity at any time is the aggregate of all incremental changes

in unexplained reactivity which have occurred in successive time intervals since the reference starting point. In particular, boron deposit on core surfaces, which is not accounted for in the reactivity balance, would be indicated by an unexplained reactivity loss. Since unexplained reactivity is expressed in terms of a readily observed physical parameter, e.g. control rod position, it is possible for reactor operations personnel to be aware at all times of the status of the reactor with respect to shutdown restrictions.

A gradual increase in the degree of sophistication of the reactivity balance calculations took place during the initial phase of chemical shim operation. During the initial power operations the balance calculations were carried out entirely by hand at the site, both by WAPD reactor physics personnel and by SNEC operations personnel. During this period a rather simple version of the burnup calculation, based largely on earlier experimental results, was in use. As operations progressed and burnup became more significant a more detailed theoretical method was adopted for burnup reactivity evaluation.

Finally, when the basic models had been shown to be adequate for maintaining a close reactivity balance, an IBM 7094 computer code (SCOOP) was prepared to expedite carrying out the prediction and follow calculations. Incorporated in the code was a refinement of the burnup calculation technique which gave a better

representation of spatial effects. Otherwise the code reproduced the computations which earlier had been carried out by hand. Provision was made for direct communication between the Saxton site and the East Pittsburgh computer installations so that WAPD personnel at the site could obtain prediction and follow information directly and speedily.

The repeated analysis of earlier data incorporating improved computation procedures and particularly the refinement of the burrow calculation has resulted in a series of progressively more detailed evaluations of the behavior of unexplained reactivity during the first phase of chemical shim operation at Saxton. Minor improvement of methods and elimination of known deficiencies still continue.

The results of the reactivity follow presented below are those obtained from the most recent analysis of the experimental data. At the time that these calculations were made, several deficiencies in the SCOOP code and its library had been identified but had not yet been eliminated. The actual data plotted represent computer output corrected by hand calculations to compensate for systematic errors introduced by the then current version of the code.

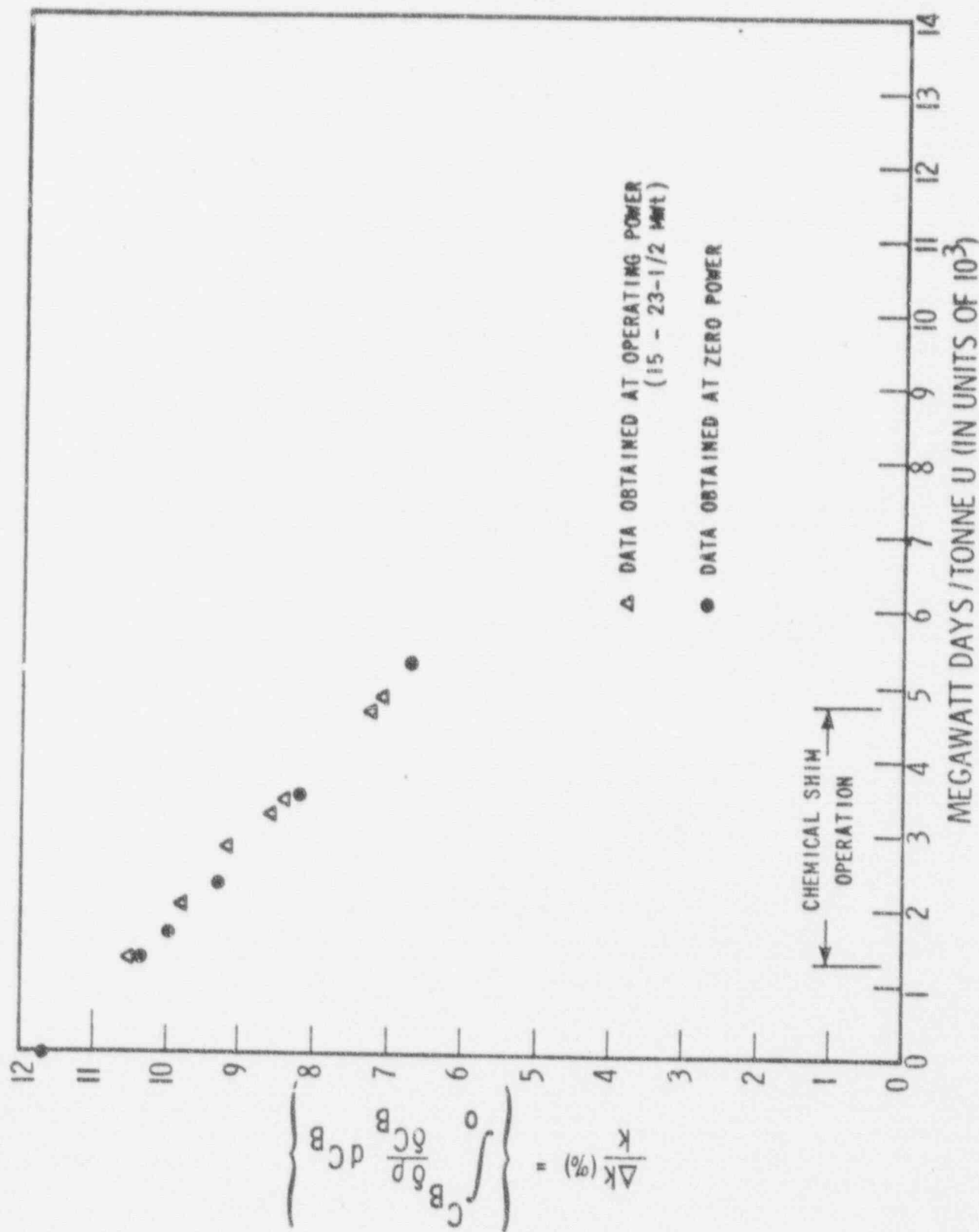
B. Follow Results

1. Observed Reactivity Behavior

The reactivity behavior during chemical shim operations

at Saxton may be analyzed both macroscopically and microscopically. Macroscopically, one may consider the long term variation of core reactivity as a function of burnup under otherwise constant conditions. Figure 1 shows the excess reactivity available in the core at various stages of burnup over a period extending from beginning of life to well after the first phase of chemical shim operation. In this case the remaining excess reactivity was calculated from the results of a series of periodic boron concentration measurements made at successive stages of burnup when a prescribed set of physical conditions had been established in the core. For comparison, the equivalent of the maximum allowable unexplained loss in reactivity is also shown. It is apparent that no significant change in core reactivity was observed either at the start or at the termination of the first phase of chemical shim operation.

The microscopic behavior of the unexplained reactivity is shown in Figure 2. In this figure core conditions (boron concentration, pH level, power level, and control rod position) are plotted as functions of calendar time. The interval begins with the start of power operations with boron in the main coolant in May 1963 and continues to the shutdown and termination of the first part of the chemical shim test in November 1963. Superimposed on the history of changes in core

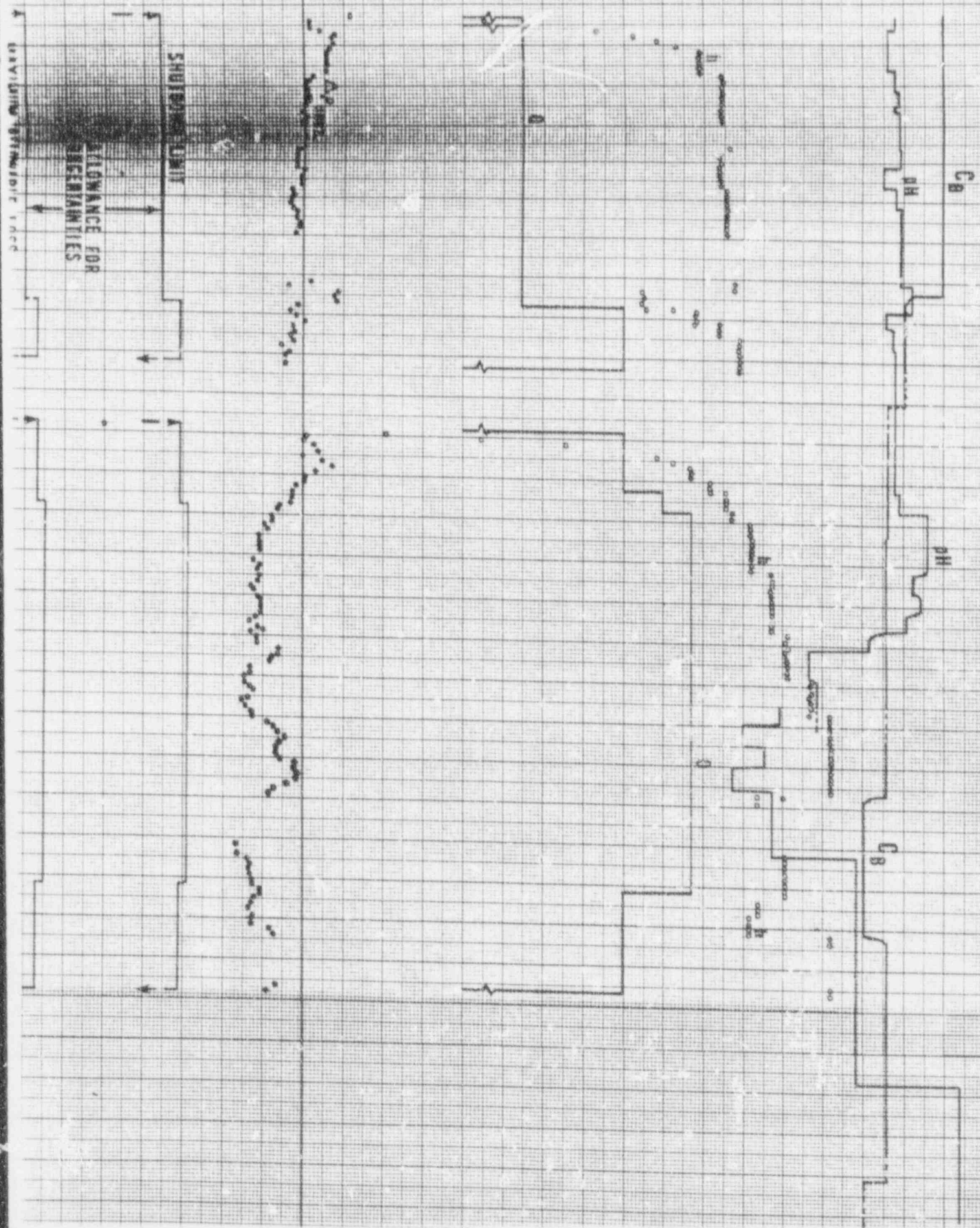


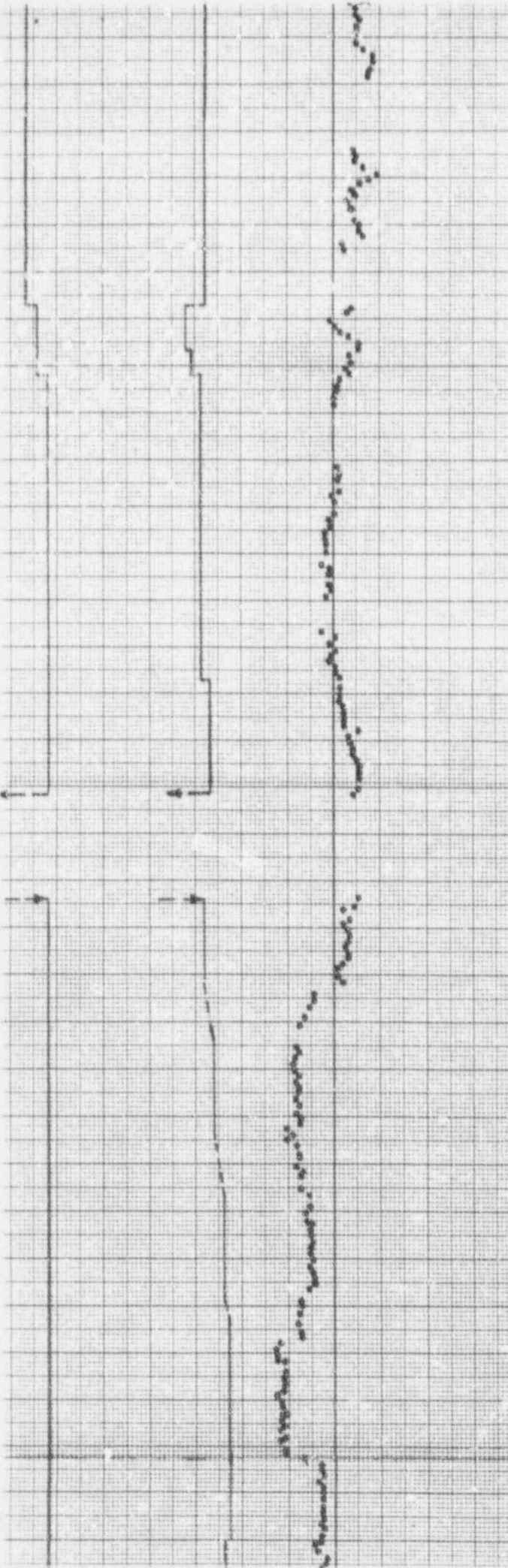
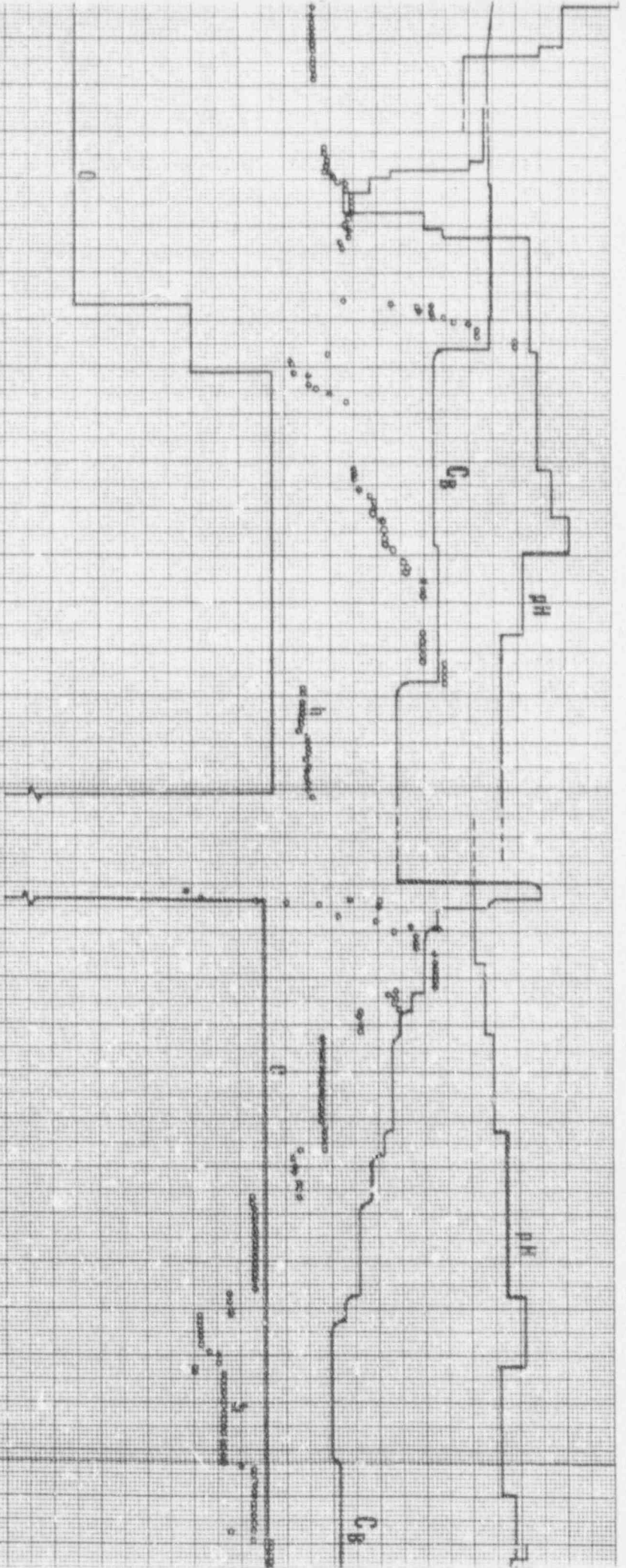
SAXTON DEPLETION
FIG. 1

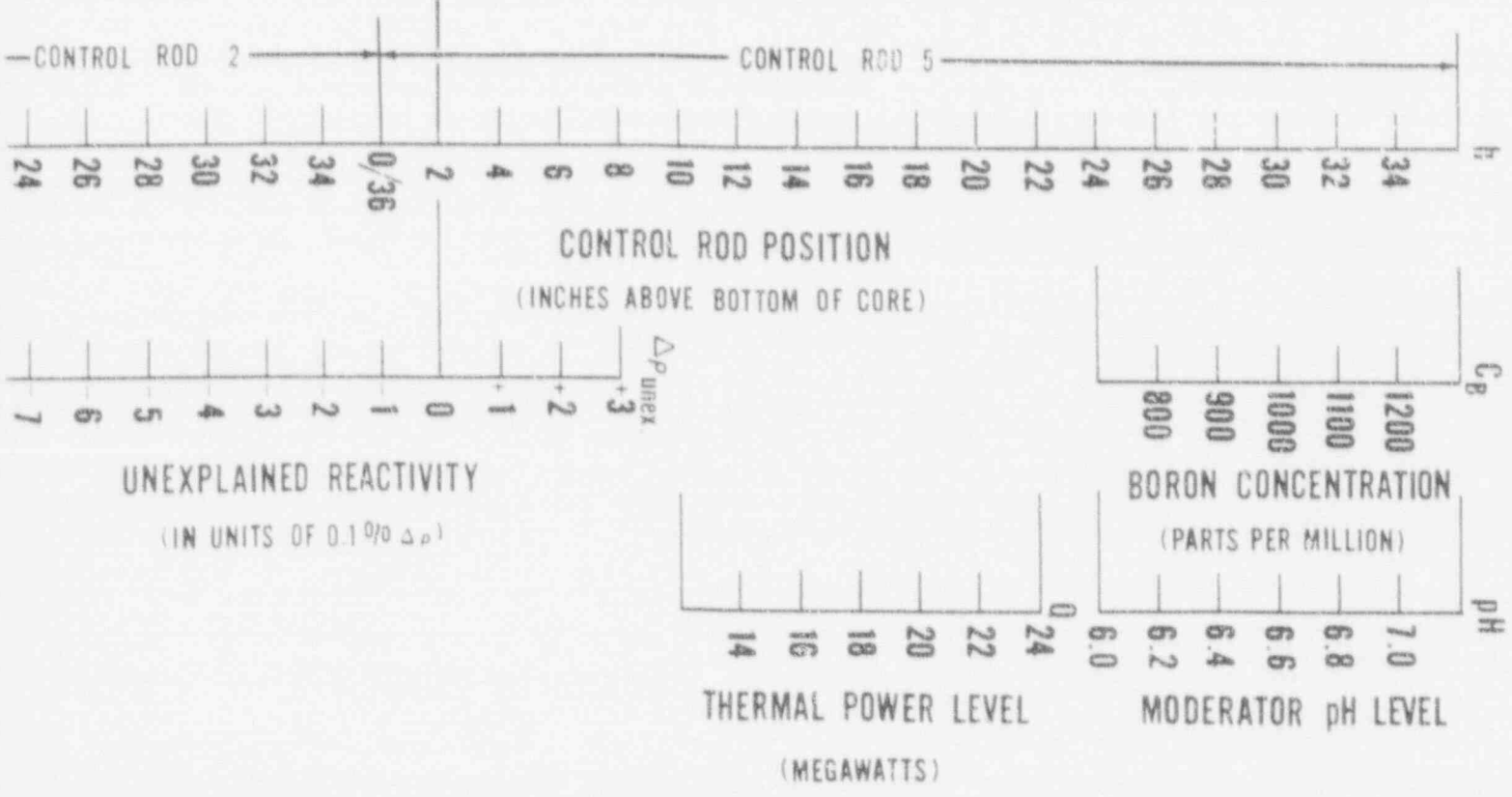
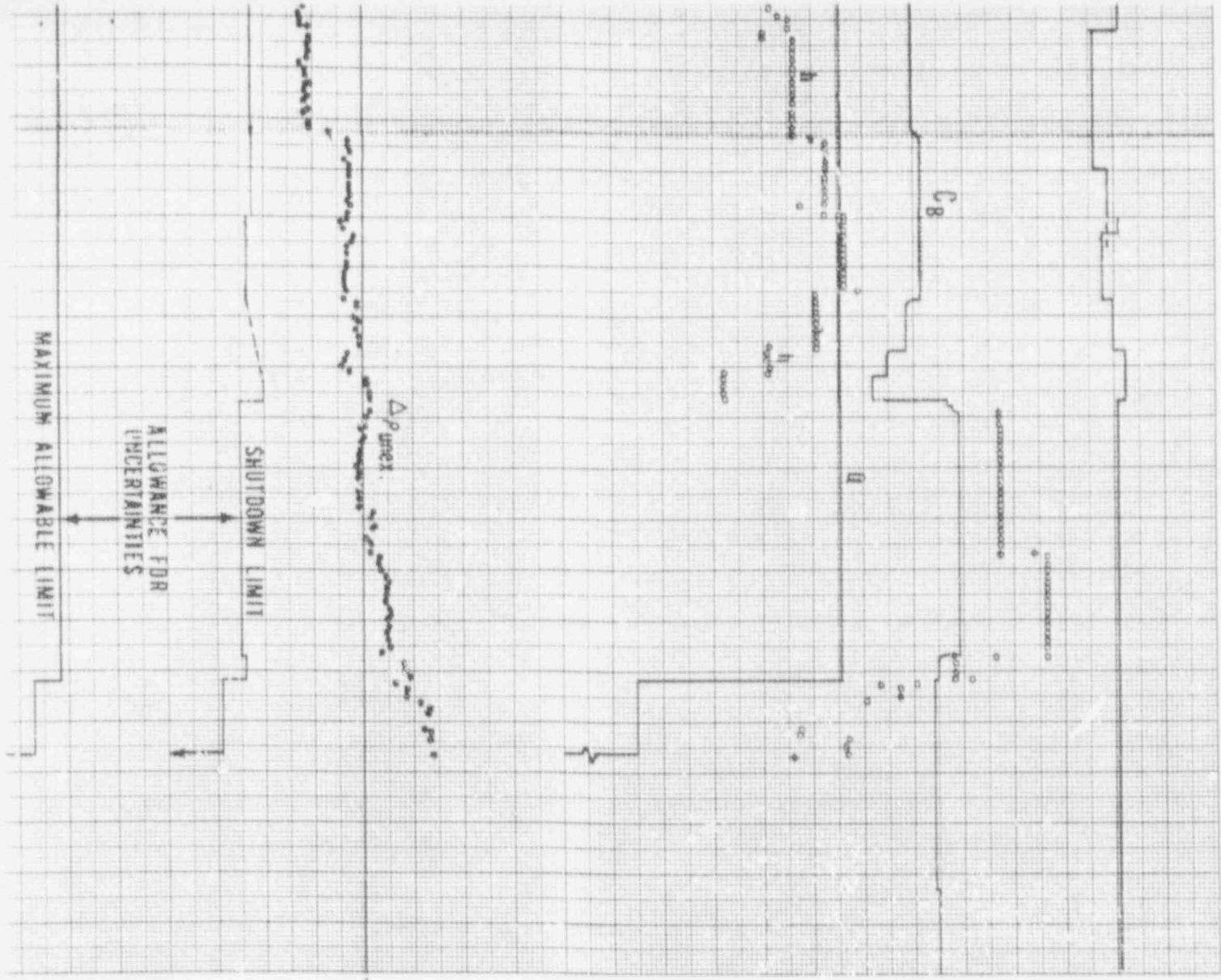
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CONTROL ROD 2

CONTROL ROD 5







conditions is the corresponding history of the variations in unexplained reactivity, again defined as the accumulated difference between predicted and measured reactivity changes. Included also are the maximum allowable and shutdown limits imposed on unexplained reactivity loss. The shutdown limit, which is the controlling factor during power operations, is defined as the maximum allowable unexplained loss in reactivity reduced by the estimated maximum combined uncertainties in the reactivity equivalents of the core parameters and represents the maximum reactivity loss permitted during operation.

Examination of the detailed behavior of unexplained reactivity as plotted in Figure 2 shows that the unexplained reactivity tends to fluctuate within a band width of about 0.2% and that superimposed on the fluctuations are two periods of relatively rapid loss of about 0.1% in reactivity in late June and early October, respectively. Although it has not been positively demonstrated, it is strongly suspected that the small fluctuations are, in general, systematic in nature and arise as a consequence of the method used to synthesize spatial effects in calculating burnup. It has been noted that there is a strong correlation between the fluctuations and the corresponding central rod position with respect to a series of prescribed reference positions.

The two relatively rapid losses of reactivity occurred

during operations at about 23 MWt under generally stable conditions. Close chemistry follow both prior to and immediately after each of these periods showed no evidence of abnormal conditions in the system. Nor does any model as yet hypothesized for a possible mechanism for accumulation of boron on the core surface offer an explanation for the reactivity loss in terms of boron deposition. Since similar behavior of reactivity was observed in the Yankee reactor when operating at power without boron in the main coolant*, it is believed that the abnormal behavior during these two periods may be the result of changes in the physical characteristics of the fuel (possibly pellet cracking, for example) coupled with attendant changes in the flux and xenon distributions. It is noteworthy that the reactivity lost in both cases appears to have been fully recovered during succeeding weeks. Although neither the fluctuations nor the relatively rapid losses in reactivity appear to bear any relation to boron hideout, these perturbations did tend to blur the details of the reactivity follow.

2. Analysis of the Observed Reactivity Behavior

Several different hypotheses have been advanced to describe how boron deposition might occur. The hypotheses differ both

*WCAP 6050, "Analysis of the Reactivity Characteristic of Yankee Core I" C. G. Poncelet, pp 11-14, 17

in their internal physio-chemical mechanism and in the external physical conditions under which deposition could be expected to occur. The respective models predict that if there is an unexplained change in reactivity caused by boron accumulation, it should be evident during:

- a. the initial rise to power at the inception of chemical shim power operation.
- b. long term steady state operation at power.
- c. the transition from nucleate boiling conditions in the core to fully subcooled conditions.

Comments and observations on operations under each of these three conditions follow.

The Initial Power Rise

Initial operation of power with a significant quantity of boron in the main coolant began on May 27, 1963. Expected reactivity changes during the rise to power and the ensuing transient period were those caused by the power defect and by changes in number densities of fission product nuclides, particularly xenon-135, in the core. During this initial period externally controlled core conditions (pressure, temperature, boron concentration, pH level, and, after the power rise, power level) were held constant. Reactivity changes were compensated for by control rod motion.

The relevant model for boron deposition indicated that boron could be expected to deposit either concurrently with, or soon after, the initial rise to power. Indication that deposition had taken place would be an unexplained loss of reactivity. Examination of the results obtained from the reactivity follow reveals that a slight gain in reactivity occurred. More detailed calculations than those carried out by the SCOOP code indicates that this gain is associated with spatial redistributions of fission products and of plutonium nuclide concentrations.

Extended Operations

A second hypothesized boron deposition mechanism postulates that deposition might take place over extended periods of operation at rates dependent both on the main coolant boron concentration and on the extent of nucleate boiling in the core. In the absence of superimposed experimental perturbations, reactivity prediction calculations need take into account only burnup effects (including temporal transients) and the compensating control rod motion. Boron accumulation, were it occurring as hypothesized, would appear as a gradual unexplained loss of reactivity in the reactivity follow calculations. In principle, a change in reactivity induced by boron accumulation would be indistinguishable from an apparent change in reactivity arising from an error in the burnup calculations and, indeed, could

readily be masked by an error in the calculated burnup, provided, of course, that the loss of reactivity caused by burnup is linear with energy production.

Actually the experimental program pursued during the first phase of chemical shim operation exposed the reactor to a variety of operating conditions. Periodic shutdowns, and startups after varying times at zero power, led to temporal transients in both the observed and the calculated burnup rates caused by production and burnout of plutonium and samarium. Operations were carried out at power levels both with and without nucleate boiling in the core. Boron concentration in the main coolant varied over a broad range from 1200 ppm to 600 ppm and was successively decreased and increased as dictated by experiments and operations in progress. Each of these perturbations in burnup rate, power level, and boron concentration should have had a unique effect on the apparent rate of change of unexplained reactivity.

Close analysis of the detailed reactivity follow during the periods of extended operation under a variety of conditions shows no significant correlation of the rate of change of unexplained reactivity with any of the suspected parameters. As noted above, the changes that are observed show a rather good correlation with control rod position as is expected on theoretical grounds.

Power Reversible Boron Deposition

It has been observed in out of pile tests that nucleate boiling on a heat transfer surface tends to increase deposition on the surface of some materials from concentrated solutions in the coolant. The postulated mechanism for this effect predicts that when a core in which a significant amount of boron deposition has occurred is taken from the nucleate boiling regime of operation to the fully subcooled regime, in which all boiling is suppressed, an observable gain in reactivity should take place. This gain should occur as the boron initially concentrated on the core surfaces is released and swept out of the core. The reactivity gain would appear as a change in unexplained reactivity either simultaneous with or shortly following the power reversal.

An experiment to test this hypothesis was conducted prior to the late November shutdown in an attempt to observe the postulated reactivity gain. Detailed follow results indicate that there was no detectable change in unexplained reactivity that could be associated with the power reversal itself, nor was there any delayed change in unexplained reactivity during the subsequent xenon transient. There is some uncertainty in the latter observation because of a fluctuation in unexplained reactivity which began about a day before the power reversal as a result of a change in central rod position with respect

to the reference position and persisted through the remainder of the test period.

C. Conclusions

Experience extending over approximately six months of operation at power with up to 1200 ppm boron in the main coolant at Saxton indicates that:

1. At no point in the Saxton operation did the amount of unexplained reactivity possibly attributable to boron deposition exceed the operational shutdown limit. Furthermore, in a variety of tests no evidence was found of boron accumulation exceeding in reactivity equivalent the minimum amount detectable with the methods currently in use.
2. The reactivity follow procedures currently available and in use at Saxton are capable of detecting unexplained changes in reactivity of the order of 0.1% in reactivity or less where these occur over short or intermediate periods of time.
3. Over long periods of time, during which complex burnup effects may become significant, long term unexplained changes in reactivity may be less readily detected. In this case the decreased degree of confidence in the validity of the reactivity follow results is reflected in an increased allowance for uncertainties. These uncertainties are applied to the maximum allowable unexplained loss in reactivity in determining the operational shut-

down limit for unexplained reactivity loss.

4. It is feasible at Saxton to maintain a detailed reactivity follow over extended periods of time encompassing many, if not all, of the operational maneuvers likely to be experienced in a conventional pressurized water power reactor.

V. Chemical Surveillance Program *
W. D. Fletcher, G. R. Taylor

The surveillance program at Saxton has two principal objectives. These are: 1.) to improve the state of knowledge regarding the effects of chemical shim on pressurized water reactor integrity and general operation, and 2.) to demonstrate by chemical means that use of chemical shim causes no hazardous situation to arise which could affect continuous plant operation. To fulfill these two objectives, an intensive chemistry program was conducted. The most significant contributions made from this to the overall Saxton program were found to be from the following areas of study:

1. Chemical shim solution stability at reactor operating conditions.
2. The pH effect on core reactivity.
3. The tests for possible hideout of poison in the reactor core.
4. Examination of crud deposits (loosely adherent corrosion products) from the core.
5. The assessment of the effects of the chemical shim solution on plant materials of construction.

A summary of the results of the chemical surveillance program is given below.

A. Coolant Technology

Numerous prior studies at WAPD and other installations formed the basis for choosing the water chemistry for the Saxton primary coolant, for both before and during chemical shim operation. The

* This work was partially supported under AEC contract AT(30-1)-3269.

selection of this chemistry was deemed the most satisfactory for long term plant operation, and one that was believed to be completely stable at reactor operating conditions.

1. Control Chemistry

Prior to chemical shim, the Saxton primary coolant contained additives of potassium hydroxide at a nominal concentration of $\sim 10^{-4}$ molal (up to 3.8 ppm potassium) and dissolved hydrogen at 25-35 cc (STP)/kg coolant. These, respectively, were maintained in the coolant to reduce the transport of radioactive corrosion products throughout the system, and to prevent net radiolytic decomposition of the water. With chemical shim operation, boric acid was added to the coolant to the extent of 1200 ppm boron, while potassium hydroxide and hydrogen concentrations were maintained the same. With continued operation, boric acid was progressively removed from the coolant, as required to compensate for core depletion.

2. Chemical Properties

Work at WAPD prior to chemical shim operation at Saxton showed that properties of the boric acid solution at normal temperature (70°F) are somewhat different from those of conventional reactor coolants. Mostly, the solution pH and conductivity of the chemical shim solution, as measured at room temperature, are significantly different from that of pure water containing alkali. This is illustrated in Figure 3,

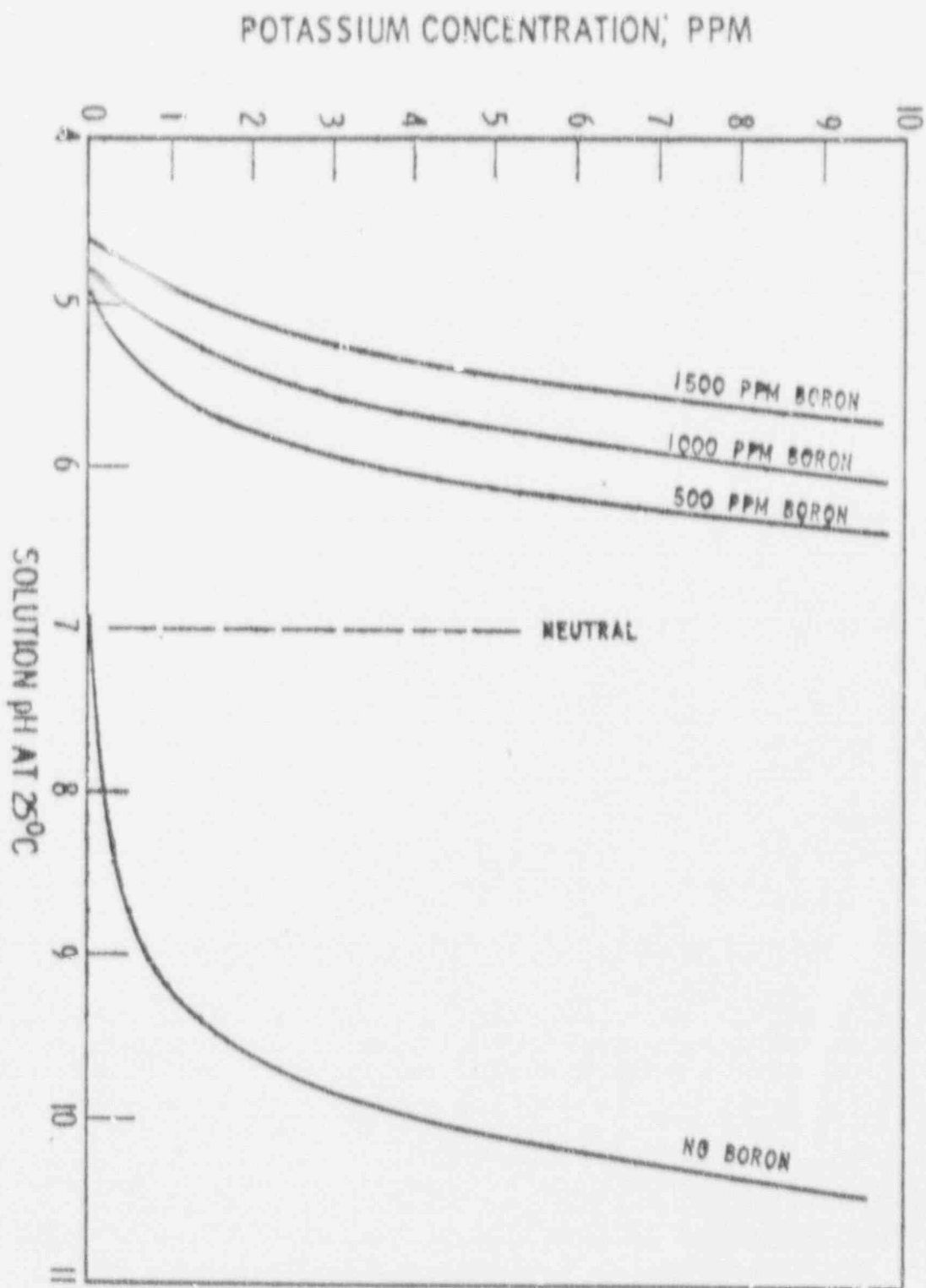


Figure 3 Variation of Solution pH at 25°C with Alkali and Boric Acid

which shows the variation of solution pH at room temperature with boric acid and potassium hydroxide concentrations. In contrast to the solution properties at room temperature, and probably more important, are the solution properties at reactor coolant temperature. In this case, at a solution temperature of about 530°F, the average coolant temperature at Saxton, it has been determined by calculation that the solution pH is controlled mostly by its alkali hydroxide content, and influenced little by the presence of boric acid. This is illustrated in Figure 4, which shows the variation of high temperature pH with boric acid and potassium hydroxide concentrations. The net result of using boric acid with alkali hydroxide, therefore, is to maintain approximately the same environment for primary system materials at the elevated temperature.

As will be described later in this report, the solution pH at elevated temperatures has been a valuable tool for interpretation of the pH effect on core reactivity.

B. Operational Chemistry

The demonstration of successful reactor operation with chemical shim has required very close surveillance of coolant chemistry during initial power runs as well as during special physics or chemistry tests. This was accomplished by on-site analysis of the coolant by WAPD personnel at the time of interest, followed by transfer of samples to WAPD for further analysis. The results of these

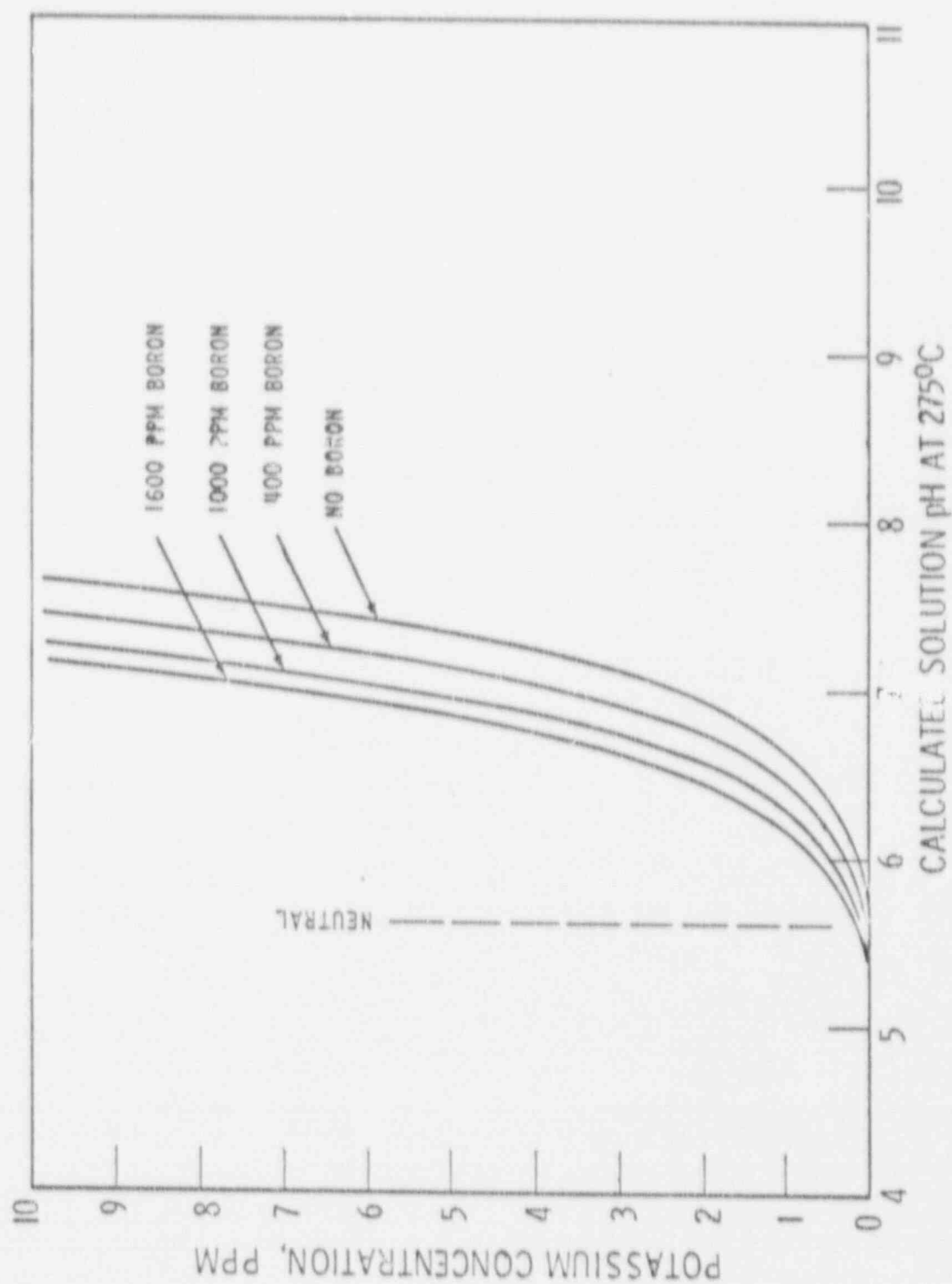


Figure 4 Variation of Solution pH at 275°C with Alkali and Boric Acid

analyses are summarized below

1. Stability of the Chemical Shim Solution

Chemical shim operation began on May 27, 1963, at a power level of 15 Mwt, followed over the next few weeks by a programmed rise in power to 23.5 Mwt. During this period, the coolant contained from 1050 to 1200 ppm boron as boric acid and about 3 ppm potassium as the hydroxide. Very careful analysis of the coolant during this and subsequent periods of power operation showed no unexplained variation in either boron or potassium. This was found to be the case regardless of whether or not local boiling existed on the core surfaces. (About 16 percent of the core surface is estimated to be at nucleate boiling conditions at a power level of 23.5 Mwt.) It is recognized that one part per million change of boron in the coolant could, if deposited uniformly on the reactor core, account for approximately 0.4 percent change in reactivity, so that consistent boron analyses to ± 1 ppm, in themselves, do not prove the absence of boron accumulation. The coolant analyses, however, coupled with core physics measurements, do present a convincing argument against such accumulation. Moreover, it is reasoned that if salt deposition were to be induced by nucleate boiling on core surfaces such that deposits of potassium borate formed, an equivalent of one part per million boron from the coolant would be accompanied by four parts per million potassium. This is a very

sensitive indication of salt deposition since potassium analyses are reliable to ± 0.1 ppm. With no unexplained variation in the potassium evident, within analytical precision, it may be confidently assumed that either no potassium borates were formed at Saxton conditions or that any formed were immediately re-dissolved in the coolant.

2. Changes in Chemistry Incurred with Chemical Shim

Numerous samples have been collected from the Saxton primary system since initial power operation for the purpose of noting any significant changes in their elemental or radiochemical content upon operating with chemical shim. Primary coolant samples have consisted mostly of solutions, crud-filtered from the coolant solution, and gases, dissolved in the coolant. Analyses have shown the following:

a. Chemical Impurities

Solutions - Essentially no significant changes in

solution impurities have been evident with the change to partially neutralized, boric acid coolant chemistry. The exception to this has been, as expected, the ingrowth of lithium from the $B^{10} (n,\alpha) Li^7$ nuclear reaction. Measurements on the rate of lithium increase in the Saxton coolant during chemical shim operation can be accurately predicted by the expression*

* Weisman, J. Editor, WCAP-2548, Saxton Quarterly Progress Report for the Period Ending September 30, 1963, January 6, 1964, p. 15.

$$\frac{d Li}{dt} = 10^{-3} C_B P_t$$

where

$d Li/dt$ = change in parts per billion of Li
in coolant/day

C_B = total boron concentration in coolant, ppm

P_t = reactor power level, MWt

Crud-Filtered from Coolant Solutions - The crud level or concentration of insoluble impurities in the Saxton coolant has been found to remain fairly constant at ~50 parts per billion during normal power operation. On shutdown, or following a thermal or hydraulic change in the system, the crud level has been noted to rise temporarily to 250 ppb. Analysis of typical crud samples for before and during chemical shim operation are given in Tables 2 and 3.

It can readily be noted that both chromium and manganese contents of the crud have increased with the change to chemical shim operation. Each of these elements has increased by a factor of two to five, while the other elements have changed little or not at all. This increase is best shown by comparing element ratios in typical crud

Table 2

TYPICAL ANALYSIS OF CRUD FROM SAXTON PRIMARY COOLANT
CORROSION PRODUCTS

ELEMENT	BEFORE CHEM SHIM AFTER > 2500 HOURS AT 530 ⁰ F WITH KOH	DURING CHEM SHIM AFTER 3000 HOURS AT 530 ⁰ F WITH KOH & H ₃ BO ₃
<u>PERCENT</u>		
Fe	17.5	26.4
Cr	2.4	13.4
Ni	6.2	4.5
Mn	0.6	1.2
Mo	0.3	0.8
Co	< 0.1	0.2

Table 3

TYPICAL ANALYSIS OF CRUD FROM SAXTON PRIMARY COOLANT

TRAMP ELEMENTS

ELEMENT	BEFORE CHEM SHIM AFTER >2500 HOURS AT 530°F WITH KOH	DURING CHEM SHIM AFTER 3000 HOURS AT 530°F WITH KOH & H ₃ BO ₃
PARTS PER MILLION		
Ag	400	300
Al	14,000	15,000
B	200	1,000
Ca	6,500	3,700
Cu	1,600	2,100
Mg	11,000	11,000
Pb	11,000	9,000
Si	50,000	65,000
ppb CRUD IN COOLANT	83	47

samples (Table 4) with corresponding ratios in AISI304 or 316 stainless steel. From this comparison, it appears that with boric acid, the transport corrosion products more nearly agree in composition with that expected for uniform corrosion of the base metal.

Other elements in the Saxton crud, shown in Table 3, are mostly tramp contaminants such as silicon and aluminum, which arises from the effusion of jack-sparks from the coal-fired boilers of the old power plant on the site.

The presence of boron in the crud sample removed from boric acid solution during chemical shim is not unexpected. The amount of boron in the crud due to absorption alone, however, is difficult to ascertain, since the analysis shows the absorbed boron plus any boric acid occluded as solution in the sample. A concentration of 1000 ppm boron in the crud is not considered excessive.

Gases - Dissolved in the Coolant - Dissolved hydrogen is maintained in the coolant by a hydrogen overpressure in the purification surge tank. There has been some difficulty in adjusting the hydrogen to lie between the narrow limits of 25-35 cc (STP)/kg because of the various operational sequences relating to pressurizer and surge tank levels. This, however, is an operations problem and is not affected by the

Table 4

COMPARISON OF SAXTON CRUD COMPOSITION WITH STAINLESS STEEL

WEIGHT RATIO	AISI 304 OR 316 STAINLESS STEEL	CRUD ANALYSIS PRE-CHEM SHIM	CRUD ANALYSIS DURING CHEM SHIM
Fe/Cr	4	14	3
Fe/Ni	7	3	5
Fe/Mn	35	130	21
Cr/Ni	2	0.2	2

presence of chemical shim.

Dissolved oxygen was routinely analyzed for each day, and there was no noticeable change in the values upon operating with chemical shim. Occasionally, the pressurizer liquid would show up to 0.1 ppm oxygen, and the primary coolant up to 0.05 ppm, but for the most part the oxygen was at, or below, the limit of detection of 0.005 ppm.

b. Purification by Ion Exchange

The purification demineralizer, which contained K-OH cycle, mixed-bed resin, was used frequently during power runs prior to chemical shim. Since adding boric acid to the coolant, however, there have been only brief periods of demineralizer operation, due mostly to rigid requirements of various physics measurements on the core. To conduct a satisfactory physics program, all operations involving temperature or chemistry changes were held to the minimum. For this reason, only limited data is yet available as to demineralizer efficiency of the K-borate form resin. The data obtained thus far is reported in Table 5, in terms of the decontamination factor, DF, the ratio of bed inlet to bed outlet activities.

The DF for radio-iodine is expected to be very high

Table 5

EFFICIENCY OF ION EXCHANGE PURIFICATION AT SAXTON

NUCLIDE	PRE CHEM SHIM K-OH FORM RESIN	DURING CHEM SHIM K-BORATE FORM RESIN
	DECONTAMINATION FACTOR (INLET/OUTLET)*	
I-133	9×10^4	1×10^2
I-131	4×10^4	
Co-58	2×10^3	9×10^3
Co-60	3×10^3	1×10^3
Cs-137	10	7
K-42	2	
Xe-133	0.68	
Xe-135	0.73	
* AT 10 GPM COOLANT FLOW \approx 3 GPM/FT ²		

with the K-OH form resin, owing to the favorable equilibria of OH form anion resin for iodide and to decay of iodide in the bed.* In the borate form, the exchange for iodide is not as favorable, yet a DF of 130, shown in Table 5, is quite adequate to maintain a low level of iodine activity in the coolant. The fractional DF for xenon shows that more xenon is in the bed effluent, than in the influent, due to decay of iodine precursors in the bed. The low DF for K-42 is expected since the resin is in the potassium form. Any difference between inlet and outlet activities of K-42 can be attributed to isotopic exchange with natural potassium in the bed. The exchange of cesium with a potassium-form cation resin should not be too favorable, as indicated by a DF of ~7 in Table 4. Earlier work by Simon and co-workers has also shown that equilibria are not favorable for cesium exchange with potassium form resins.** Since cesium activity growth in the coolant is slow, and requires long operating times to attain significant amounts, this nuclide will undoubtedly be controlled through normal coolant feed and bleed processes.

* WCAP-3716, "Ion Exchange in Boric Acid Solutions with Radioactive Decay", W. D. Fletcher, November, 1962.

**WAPD-CDA(AD)-528, "The Performance of Base-Form Ion Exchangers for pH Control and Removal of Fission Products from Pressurized Water Reactors", G. P. Simon et al, April, 1959.

c. Radiochemical Impurities

Radio-nuclides of both fission products and corrosion products are found in the Saxton primary coolant. These are usually analyzed for at WAPD by radiochemical separation and gamma spectrometry. Samples collected before and during chemical shim operation have shown, in general, only minor differences. The exception to this has been apparent in the Cr-51 content of the crud filtered from the coolant. As would be expected, the increase in elemental chromium in the crud with chemical shim has also increased the Cr-51 activity of the samples. Other than this, no significant changes in corrosion product activities are noticeable.

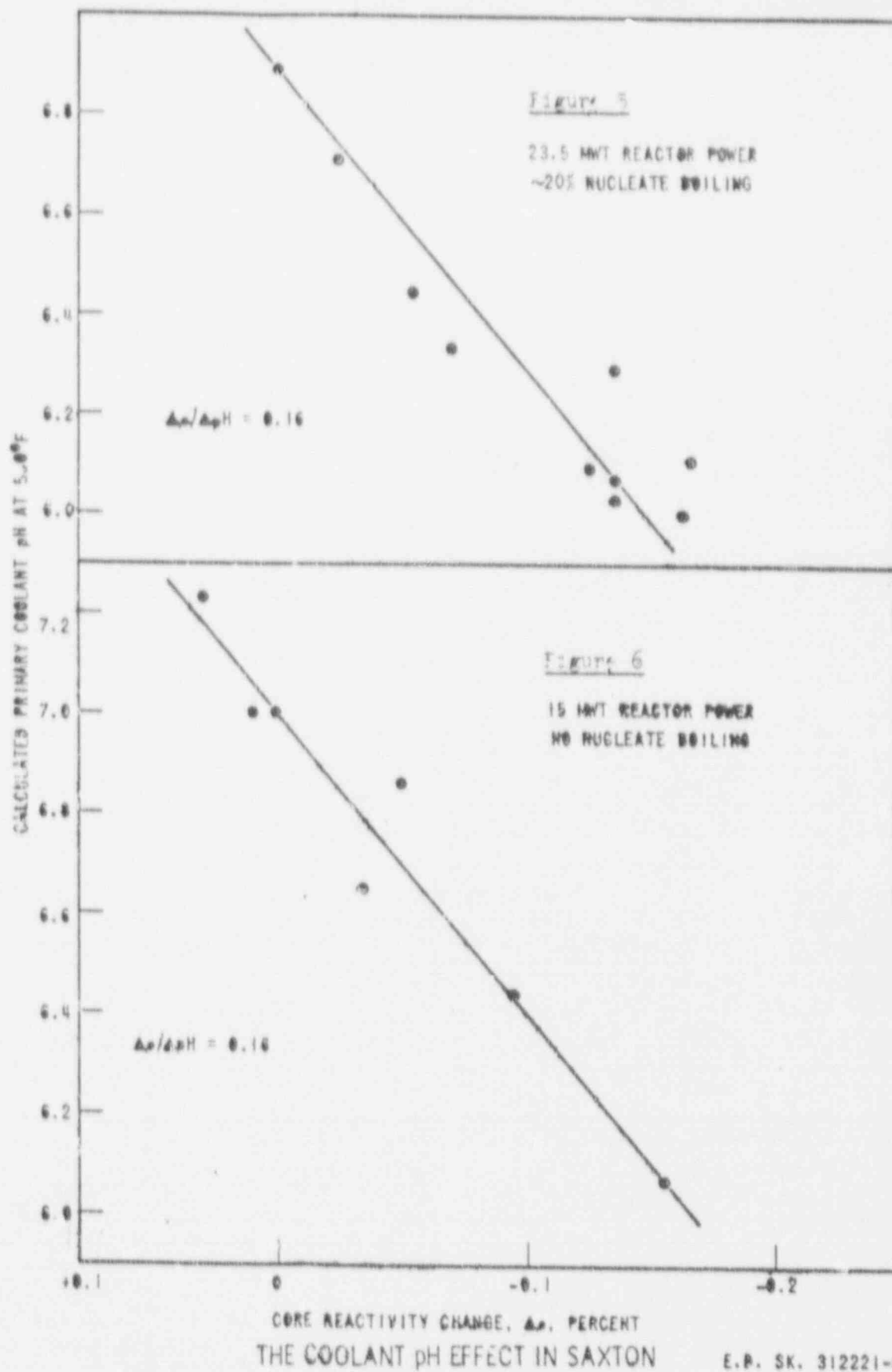
Fission products in the Saxton coolant are believed to result from one or more defective fuel tubes in the reactor core. It is estimated that fuel generating approximately 0.02% of the total power is contributing fission products to this coolant. This would constitute 0.4 average fuel tubes. From this defect, fission products I-131, I-133, Xe-133 and Xe-135 predominate. There is also some Cs-137 and Kr-88, but in minor amounts. There was no noticeable increase in the amounts of fission products, or the computed fuel-affected, after operating with chemical shim for ~3000 hours at 530°F.

C. Special Tests

A number of tests of a chemical nature have been performed at Saxton in keeping with the two principal objectives of the chemical surveillance program. These are described in the following:

1. The pH Effect on Reactivity

One of the most interesting observations made at Saxton is the apparent relationship between coolant pH and core reactivity. Based on observations made from tests first performed at the Yankee Atomic Electric plant, as summarized in the Yankee monthly operational reports, a series of experiments were designed and carried out at Saxton to learn more about the pH effect. In the Saxton tests, and while the reactor was at full power of 23.5 Mwt with chemical shim, alkali metals potassium and lithium were removed from the coolant by cation exchange. As the alkali metal concentration was lowered, core reactivity decreased accordingly, until ion exchange was stopped. Potassium was next added to the coolant, and within a period of about twelve hours, the reactivity lost during alkali removal was recovered. The data have been correlated in terms of solution pH at the elevated temperature of 530°F from the curves presented as Figure 4, for 1000 ppm boron solutions. The result for reactivity change with pH is given in Figure 5. It was found that the data correlated reasonably well to give a slope for $\Delta\rho/\Delta \text{pH}$ of 0.16 percent reactivity per pH unit.



A similar pH test was performed at 15 Mwt to determine if there would be any difference at conditions where no local boiling existed on the core surfaces, as was the case at 23.5 Mwt. Again, potassium and lithium concentrations were altered, either by potassium addition or by ion exchange, and, as before, a reactivity change was encountered. The data were computed in terms of solution pH at the elevated temperature, and the result is shown in Figure 6. The slope of this line agrees with data collected at 23.5 Mwt, again giving a $\Delta\rho/\Delta \text{pH}$ of 0.16 percent reactivity per pH unit. The coolant boron concentration during this test was 1050 ppm.

A third pH test was performed while the reactor was just critical with no power. The coolant alkali was almost completely removed. Then, after 24 hours, the alkali was restored by addition of potassium hydroxide. Critical measurements taken throughout the entire sequence of alkali adjustment showed no change in core reactivity within an estimated error of ± 0.01 percent. This test was conducted with less than 10 ppm boron in the coolant.

A fourth pH test of reactivity was conducted while the plant was at 20 Mwt, and with a primary coolant boron concentration of about 7 ppm. For this test, potassium was reduced from 3.18 to 0.1 ppm by ion exchange. Approximately 36 hours after the start of ion exchange, a maximum loss in reactivity

of ~ 0.17 percent $\Delta\rho$ was observed. Alkali was restored in the coolant by the addition of $\text{LiOH} \cdot \text{H}_2\text{O}$, to the extent of 0.7 ppm, and the reactivity previously lost was regained in about 10 hours. The average pH coefficient of reactivity was measured to be ~ 0.13 percent $\Delta\rho/\Delta \text{pH}$. The kinetics of this test are shown in Figure 7. Very careful analysis of the coolant showed no unexplained variation in boron concentration within the analytical precision of ± 0.1 ppm. These tests have shown the pH effect on reactivity to be a valid parameter to be considered in the operation of Saxton, as well perhaps in other nuclear reactors. Since boric acid was present in the coolant in gross quantities (~ 1000 ppm B) during the first two tests, it could not be stated unequivocally that boron absorption on core surfaces was not responsible for the reactivity behavior observed with a change in pH. In this respect, the core surfaces would have to function as an ion exchanger, wherein borate would exchange with hydroxyl ion, giving rise to increased or decreased reactivity. However, during the last pH test at 20 Mwt, with 7 ppm boron in the coolant, very careful solution analysis showed no variation in boron within ± 0.1 ppm. To account for the observed reactivity swings, approximately 0.4 ppm boron would either appear or disappear from the coolant if ion exchange on core surfaces were occurring. Moreover, the kinetics of the pH effect would tend to contradict the process of ion exchange of any substance

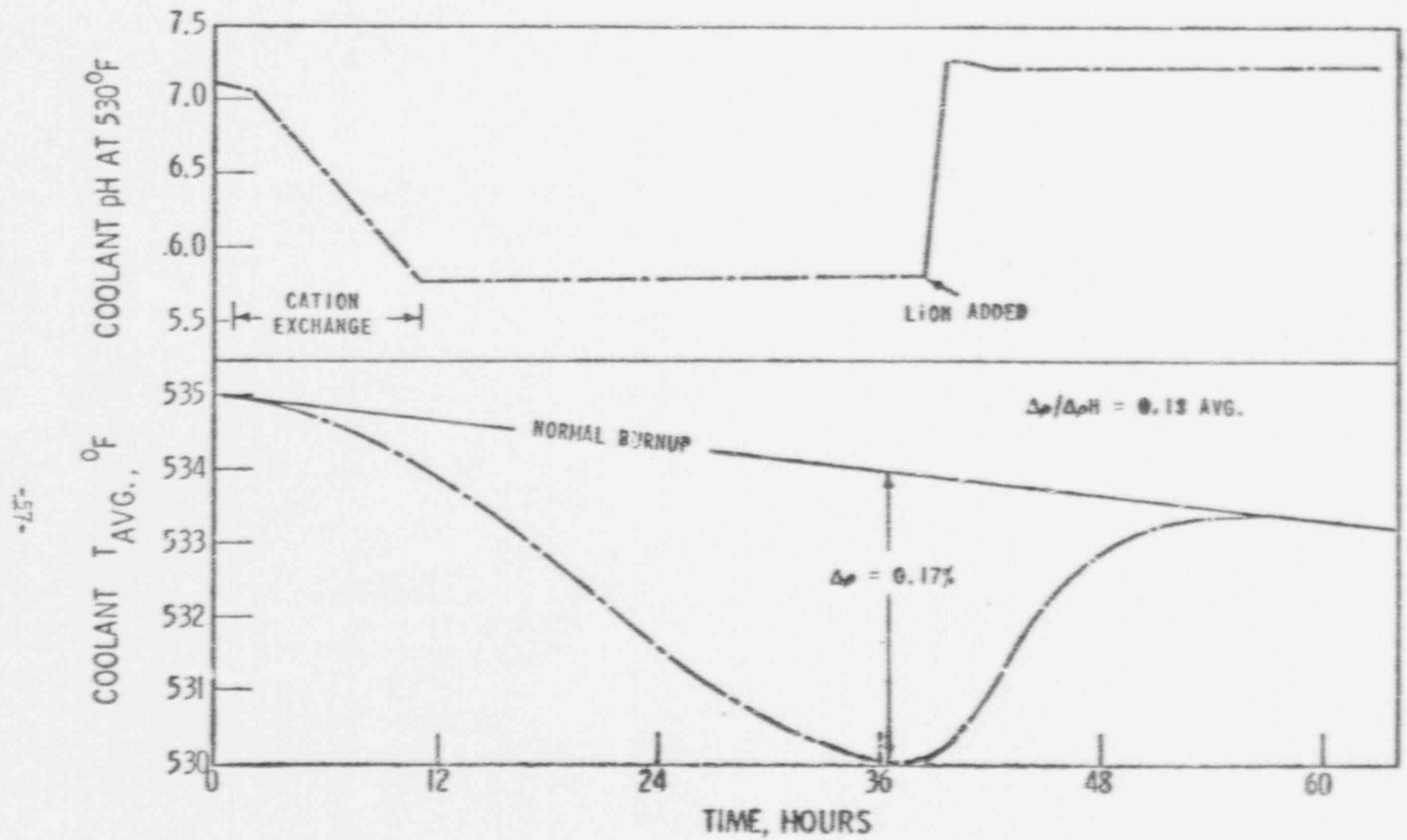


Figure 7 Change of Reactivity with Coolant pH at Sixten - 20 MWt - No Burn

on the core surfaces. The time required to attain the full swing in reactivity caused by a step change in pH is of the order of 10 to 20 hours. It would seem that ion-exchange processes, even those limited by diffusional mechanisms, would occur much more rapidly than this, since the reaction zone is at elevated temperatures. At present there is an hypothesis that the changes in reactivity are possibly caused by a change in heat transfer properties of the core surfaces. This would result from a slow reorientation of the crud deposit structure with the change in solution pH. At high pH, the crud is believed to be a dense crystalline material with good heat transfer properties. At low pH, the crud is a voluminous mass of material having poorer heat transfer properties, causing increased fuel temperature which, through the Doppler effect, lowers the reactivity. A change in crud structure with alteration of pH is not too unreasonable an assumption. Observations have been made of decreasing liquid pressure drops through flow test sections with the addition of alkali to the high temperature water.* By analogy, the voluminous crud in the test section reorients to a dense deposit, lessening restrictions to flow. Quantitative verification of this hypothesis is not possible because of lack of suitable heat transfer data for crud deposits as a function of pH. Calculated values for the temperature

* Picone, L. F., "In-Pile Test of Chemical Shim", WCAP-3729, June 1963. To be released.

change in the fuel, required to account for observed reactivity effects caused by Doppler, have been higher than seem plausible. On the other hand, the absence of a pH effect at zero reactor power shows the effect to be power dependent. Before the pH effect is satisfactorily explained by the heat-transfer consideration or any other mechanism, additional studies must be made. Tests are currently planned at Saxton to explore this phenomenon further.

2. Nucleate to Non-nucleate Boiling Test

The continued use of boric acid solutions for shim control in a power reactor is dependent on complete solution stability at all conditions of operation. This requirement dictates that no significant amounts of boron be deposited in the system by any mechanism that could be rapidly reversed. Such mechanisms have been evaluated at Saxton considering deposition of boron on the fuel rod surfaces as boric acid or as borate salts. If boron were to deposit on core surfaces, a thermal or hydraulic transient could conceivably release a sufficient amount of the deposit to result in an undesirable reactivity insertion.

The postulated mechanisms for boron deposition are based on laboratory studies of adsorption and of salt deposition with boiling. In the adsorption* studies, it has been found that

*Fletcher, W. D., Krieg, A., and Cohen, P., "The Behavior of Austenitic Stainless Steel Corrosion Products in High Temperature Boric Acid Solutions", WCAP-1689 Rev., May, 1961.

borates can be reversibly adsorbed by corrosion product oxides in amounts proportional to the solution boric acid concentration.

In the radiotracer studies*, it was shown that with sufficiently thick porous deposits on a heated surface, as for example, fuel elements heavily fouled with crud, salts from solution can precipitate in the deposit during nucleate boiling.

With sufficient crud deposits on the core surfaces, therefore, both of these mechanisms (if valid) could lead to significant quantities of boron accumulation.

To demonstrate the stability of boric acid solution at reactor operating conditions and to determine if these conditions would lead to deposition on core surfaces, precise chemical inventory measurements were made at the start of chemical shim operation. During the initial phase of operation at 20 Mwt with 1200 ppm of boron and 3.8 ppm of potassium in the coolant, analyses indicated no change in either constituent during two weeks of these conditions, except for slight changes because of solution make-up additions.

*Picone, L. F. "Radiotracer Studies of Hideout at High Temperature and Pressure", WCAP-3731, June 1963.

Upon increasing the power to 23.5 Mwt, which resulted in nucleate boiling on about 16 percent of the core surfaces, the boron and potassium concentration again remained unchanged with continued operation. Following about three months operation at 23.5 Mwt, the reactor power was reduced to 15 Mwt, changing from conditions of nucleate to non-nucleate boiling. Analyses of boron, potassium, and lithium showed no increase in concentration, and there was no change in core reactivity which could be attributed to the reduction in power.

It is concluded from these tests that no boron or alkali deposition, within the accuracy of the analyses, is evident during conditions of either nucleate or non-nucleate boiling. This is further substantiated by physics measurements of core reactivity described elsewhere in this report.

3. Lithium Stability Test

Since the start of chemical shim operation at Saxton, it has become increasingly evident that the use of potassium as the alkali for pH control is not altogether necessary. If lithium were selected as the alkali, it would be compatible with that lithium produced by the $B^{10} (n,\alpha) Li^7$ reaction, and result in a coolant with only one, instead of two, different alkali additives. Because of the possibility that with boric acid lithium could lead to metaborate salts which have retrograde

solubility, there has been, in the past, some reluctance to use lithium with boric acid. It was considered possible that these salts might deposit on heated surfaces, particularly under nucleate boiling conditions, and once formed the lithium metaborate might not redissolve but remain in place.

To explore the use of lithium hydroxide in the chemical shim solution, a test was performed at Saxton in which the reactor power was increased from 15 to 23.5 Mwt while the coolant contained 560 to 660 ppm boron and 0.45 ppm lithium as the hydroxide. After 24 days at 15 Mwt, the power was increased to 20 Mwt, and then, after 3 days, the power was further increased to 23.5 Mwt, where 16 percent of the core surface was at conditions for nucleate boiling. Throughout the entire sequence, coolant chemistry was carefully monitored. Lithium analyses of the coolant were compared with the calculated rate of increase expected at each power level and boron concentration. At no time during the test was there any indication of unusual concentration changes for either boron or lithium. After three days at 23.5 Mwt the very careful chemistry follow was terminated; no lithium metaborate deposition was evident at these conditions.

During the first week of April, the reactor was operated at 23.5 Mwt with 1.7 - 1.8 ppm of Li in the coolant. Again the experimentally observed rate of Li buildup agreed closely with that expected, thus indicating there was no metaborate precipitation.

D. Crud Examinations* (L. F. Picone)

One of the most important observations made at Saxton, in substantiation of the indicated minimal deposition of boron on core surfaces, was examination of the fuel rods of an experimental fuel assembly. Following the reactor shutdown on November 22, 1963, the central 3 x 3 subassembly was removed from the core and transferred to the W Post-Irradiation Facility (WPIF) for detailed examination in the hot cells. This assembly had been placed in the core during the February, 1963 shutdown and had, therefore, been in service throughout the entire chemical shim test. It has accrued more than 3000 equivalent full power hours of chemical shim service and, since it was located in the core-center, had been at conditions of nucleate boiling at a reactor power of 23.5 Mwt.

The 3 x 3 assembly contained both stainless steel clad and Zircaloy clad fuel rods that could be removed from the assembly. These rods were examined very carefully in the hot cell, and the crud deposit (that which was loosely adherent to the cladding surface) was removed by scraping. This material was weighed and

*This work was partially supported under AEC contract AT(30-1)-3269.

analyzed for its chemical and radiochemical content. A summary of the results of sampling and examination of the crud deposits is as follows:

1. The stainless steel clad fuel rod had an average crud surface concentration of 70 mg/dm^2 (3 rods sampled) on the areas where crud appeared.
2. The Zircaloy clad fuel rod had a crud surface concentration of 58 mg/dm^2 (1 rod sampled) on the areas where crud appeared.
3. The maximum thickness of a section of corrosion product deposit on the stainless steel fuel rod was 1.5 mils. This value was obtained from the metallographic examination. The deposit thickness varied around the rod circumference from the 1.5 mil value to essentially zero.
4. Chemical analyses indicate that the amounts of neutron poison associated with the observed amounts of deposited crud could constitute only a small reactivity loss in the Saxton core.
5. The most significant deposition on the fuel rods occurred from about 14 inches to 23 inches from the tops of the rods.

The surface concentrations of the corrosion products deposits as determined from the weights of material scraped from the rods are reported in Table 6. These values include only that material which is deposited from the coolant on the fuel rod surface and is more or less transient (deposit). No values are available to date

on the concentration of the tight corrosion products which are essentially oxides grown in place (film).

Table 7 reports the chemical analysis of the corrosion product deposits. The composition of the Saxton deposit is significantly different from that of deposits obtained from other reactor systems and in-pile loop tests; i.e., PW² Core I Blanket Bundle, Yankee Core I, APD-in-pile loop test. The Saxton deposit is significantly enriched in chromium and manganese as compared with the other reactor deposits. No explanation can be given at present for this difference in chemical composition.

TABLE 6

Crud Deposit Surface Concentrations of Saxton Fuel Rod

Rod Number	Surface Crud Concentrations	Thickness of Deposit (1)	Total Crud on Rod Surface (2)	Total Rod *Area Crudded (3)
	mg/dm ²	(mils)	mg	dm ²
22 (SS)	83	.210	28	.340
13 (SS)	74	.167	35	.468
14 (SS)	53	.134	18	.333
103 (Zr)	58	.146	20	.350
				*Nominal rod area <u>3</u> dm ²

TABLE 7

Chemical Composition of Saxton Fuel Rod Deposits

Element	Chemical Composition (% of Oxide Sample)			
	Rod 22	Rod 13	Rod 103	Rod 14
Fe*	35.24	37.88	47.17	32.94
Ni*	7.01	8.26	10.14	6.49
Cr*	11.91	11.33	8.73	9.18
Co	.0625	.0975	.0950	.0950
Mn*	8.8	11.1	11.0	7.6
Zn	.163	.143	.142	.094
Ag	< .001	.025	.035	.002
In	.1700	.1350	.1150	.6000
Cd	.1500	.1425	.1700	.1170
B	.0615	.0725	.0168	.0950
Al	~ 1.0	~ 1.0	~ 1.0	~ 1.0
Ca	.0675	.140	.0550	~ 1.5
Cu	~ .10	~ .1	~ .10	~ .1
K	< .02	< .02	< .02	< .08
Li	.0240	.0297	.0170	.0687
Mg	~ 3.0	~ 3.0	~ 3.0	~ 3.0
Na	.0140	.0065	~ .0065	.0220
Nb	.0142	.0120	.0117	.0079
Pb	~ .43	~ .38	~ .26	.28
Si	~ 1.5	~ 1.3	~ 1.1	~ 1.5
Sn	~ .37	~ .32	~ .29	~ .21
Ti	~ .55	~ .50	~ .45	~ .30
V	.0340	.0245	.0260	.0122
Zr	.0222	.0212	.0645	.0118

* Results \pm 20% relative, all others \pm 30 to 50% relative.

- (1) Assumes that the deposit is essentially magnetite having a porosity of 0.70.
- (2) Based on the assumption that all deposits on the rod are of the same concentration as the sampled area.
- (3) It is estimated that the probably error is + 10% to - 50%.

Based on the chemical composition of the crud given in Table 7, it may be shown that a uniform core deposit of 470 mg/dm^2 of this material would be required for 0.3 percent loss in reactivity. As given in Table 6, only a small fraction of the total area of the fuel rods was covered, and in this area the maximum deposit was $\sim 80 \text{ mg/dm}^2$. Since examination of a peripheral assembly, during the November 22 shutdown, showed no deposits of crud, it would be overly conservative to assume a uniform core deposit of 80 mg/dm^2 . The actual crud deposit over the entire rod (having $\sim 3 \text{ dm}^2$ area) is about 8 mg/dm^2 . If it is assumed this is equivalent to 16 mg/dm^2 , because of the crud being located in the high worth area of the core, this leads to a maximum of 0.01 percent $\Delta k/k$ worth of the crud deposit. This, of course, is essentially the same as no loss in reactivity that could be attributed to irreversible deposition of poison material in the crud.

F. Conclusions

The foregoing summary presents conclusive evidence that from the plant chemistry viewpoint, operation of a pressurized water reactor with chemical shim is completely satisfactory and that no real problems of safety or plant operations are evident. The Saxton program has fulfilled the objectives of the Chemical Surveillance

Program in that, 1.) the knowledge of effects of chemical shim operation on plant integrity and general operation has been improved, and 2.) that chemical shim operation under normal conditions causes no hazardous situation to arise to affect plant operation.

VI. Flux Distribution Studies
F. J. Frank

A. Summary

The three-dimensional power distribution and nuclear hot channel factors in the Saxton core under chem shim operation were determined using the measured flux wire activations in conjunction with analytical two-dimensional (x,y) power distributions as determined by the PDQ code.

The following conclusions can be made regarding the results:

1. All hot channel factors were below the design limit.
2. There is good agreement between the power distribution determined by thermocouple data and that determined by flux wire data. The root mean squared difference ranged from 4.7% to 7.4% for the cases studied.
3. The power distribution as determined by thermal data is more uniform than that determined by flux wire data.
4. The fuel assembly grids located at 4 positions along the length of the assembly cause a decrease in the axial hot channel factor because of flux depression.

Three quantities are used to describe the power distribution in the core. First, the axial peaking factor F_z which is defined as the ratio of the peak axial power to average axial power along any channel. Second, the hot channel factor $F_{\Delta H}$ which is defined as the maximum to average enthalpy rise of the coolant in a flow

channel. And finally, the hot channel factor F_Q which is defined as the ratio of maximum power density at a particular point to the average power density.

A summary of the nuclear hot channel factors $F_{\Delta H}$ and F_Q is given in Table 8. These values include an added 10% uncertainty factor. The hot channel factor F_Q is determined by the product of the axial peaking factor F_Z and the hot channel factor $F_{\Delta H}$. The hot channel factor $F_{\Delta H}$ represents the average of four fuel rods (plus 10%) which are located at each corner of the assemblies noted in Table 6.

B. Comparison of Expected and Observed Results

The design hot channel factors allowable during 23.5 MWt chem shim operation were originally reported in the Nuclear Design and the Hazards Report as a nuclear $F_{\Delta H}$ of 2.03 (2.47 including engineering factor) and a nuclear F_Q of 2.79 (2.92 including engineering factor). The calculated nuclear factor F_Q did not have the usual 10% margin below the design value. It was hoped that measurements might yield this margin. This however did not happen.

In the estimation of the design value for 23.5 MWt, consideration was not given to the fuel follower rods and the heat generated outside of the fuel pellets. A re-evaluation of the design hot channel factor F_Q was performed by the Thermal and Hydraulics Group. With 90 fueled follower rods fully inserted into the core, 2.7% heat

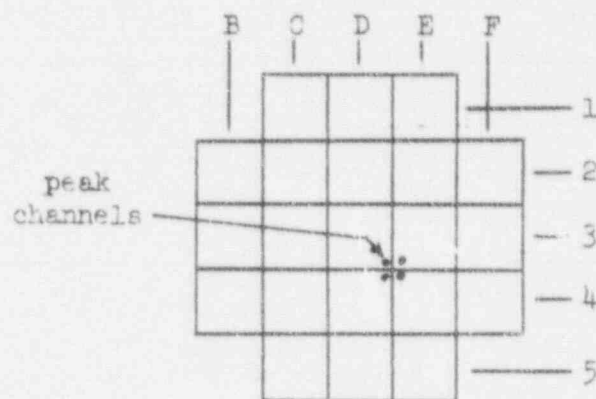
TABLE 8

Nuclear Hot Channel Factors

Chem Shim Operation

Height of					Location	
<u>Rod 5</u>	<u>Power</u>	<u>C_B</u>	<u>F_{ΔH}</u>	<u>F_Q</u>	<u>Corner of Assy.</u>	<u>Run No.</u>
18.39	23 MW	700	1.90	2.78	D3,E3,D4,E4	308.7.8
20.12	23.19	685	1.88	2.69	"	308.7.10
21.22	23.25	717	1.97	2.81	"	308.7.9
21.72	20	1107	2.00	2.98	"	308.3.2
21.74	14.6	1200	1.97	2.96	"	308.1.8
22.34	23	783	2.03*	3.01*	"	308.7.5
23.17	14.5	1200	1.98	2.95	"	308.1.10
24.36	23	1060	1.91	2.90	"	308.3.7
26.07	23.5	1004	1.98	2.77	"	308.3.8
26.72	23	873	1.93	2.71	"	308.7.2
23.5 MW Design Value			2.03	3.03		

* Only 4 wires irradiated

Saxton
Assembly Locations

generated outside of the fuel pellets, and a peak heat rate of 14.1 kw/ft, the maximum permissible nuclear F_Q can be increased to 3.03 (3.17 including engineering factor). Thus, as Table 6 indicates, the measured hot channel factors having had a 10% uncertainty added to them are still below the revised design limits.

A comparison of hot channel factors which occurred during rodded operation with those which occurred during chem shim operation shows the latter values to be higher. The nuclear hot channel factors observed during rodded operation were of the order of 1.76 and 2.68 for $F_{\Delta H}$ and $F_{U.C.}$ respectively. The higher values observed during chem shim are due to the uniform fuel loading in the Saxton core. Proper chem shim design required non-uniform fuel loading in order to achieve a uniform power distribution. Boration of the core then permits an optimum rod configuration which minimizes the distortion of power and consequent higher hot channel factors caused by the rods. However, control rods are beneficial in flattening the power distribution in a uniformly loaded core. Thus the programmed rod configuration in the Saxton core results in a more uniform power distribution and consequently lower hot channel factors than that experienced under the borated conditions.

A summary of the power distributions determined by flux wire data and that determined by thermal data is shown in Figure 8.

Run	308.1.8	5-29-63
Run	308.1.10	6-5-63*
Run	308.3.2	6-12-63
Run	308.3.7	6-24-63
Run	308.7.2	10-8-63
Run	308.7.8	10-22-63
Run	308.7.9	10-31-63

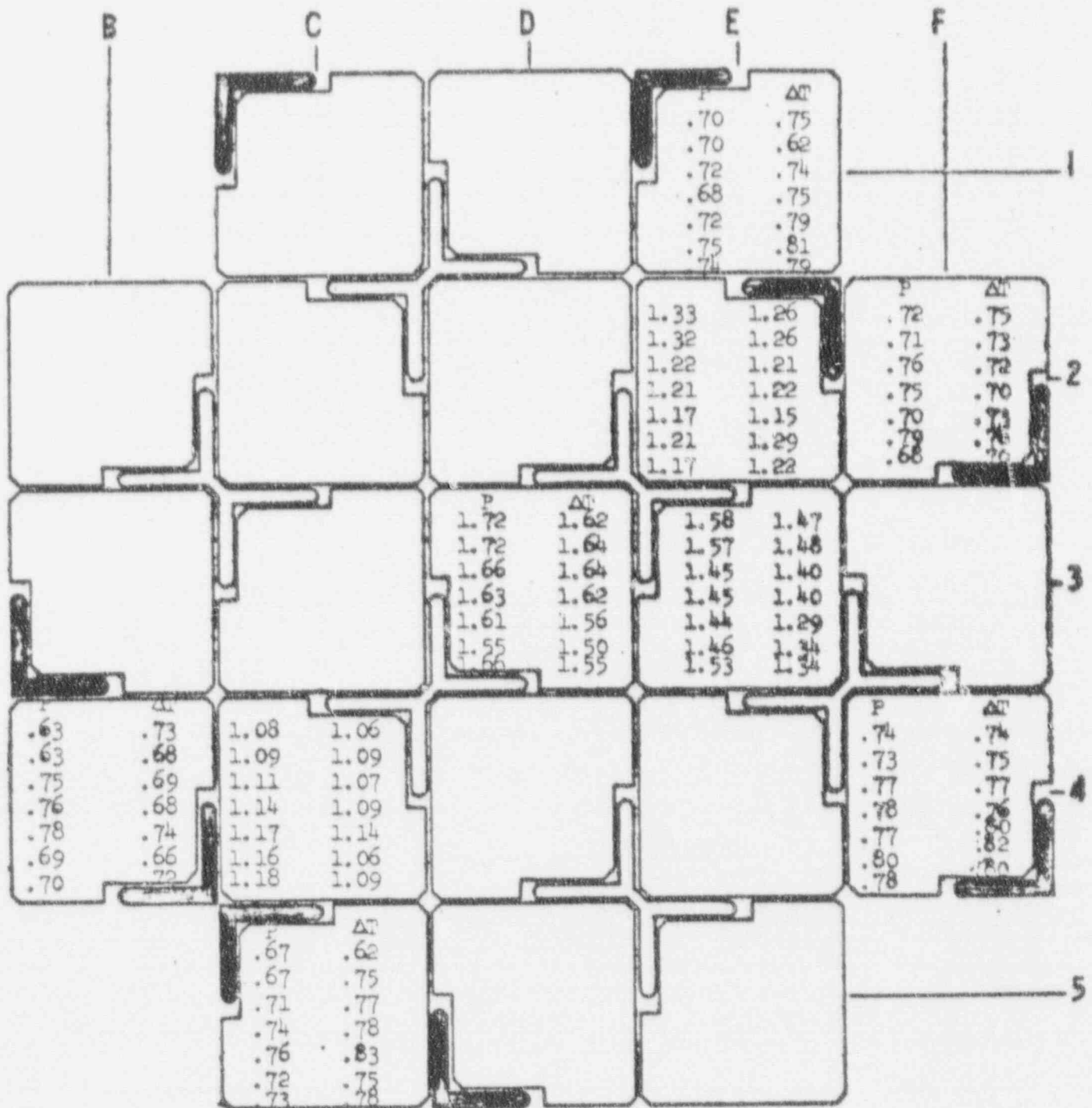


Figure 8 Comparison of Thermal and Nuclear Power Distribution
Chem Shim Operation

The nuclear distributions were determined using the flux wire activations in conjunction with analytical two-dimensional (x,y) power distributions as calculated by the PDQ code. The PDQ calculations were based on the 20 MWt, 1000 ppm boron, no xenon, no depletion condition.

A measure of agreement between the nuclear power distribution and the thermal power distribution is obtained by calculating the root mean squared difference, where the difference quality is defined as:

$$\sigma = \left[\frac{1}{N} \sum_{i=1}^N \left(\frac{P_i - T_i}{P_i} \right)^2 \right]^{1/2}$$

where:

P_i = the normalized nuclear power in assembly i

T_i = the normalized thermal power in assembly i

A summary of the root mean squared difference for the various tests is shown in Table 9.

TABLE 9

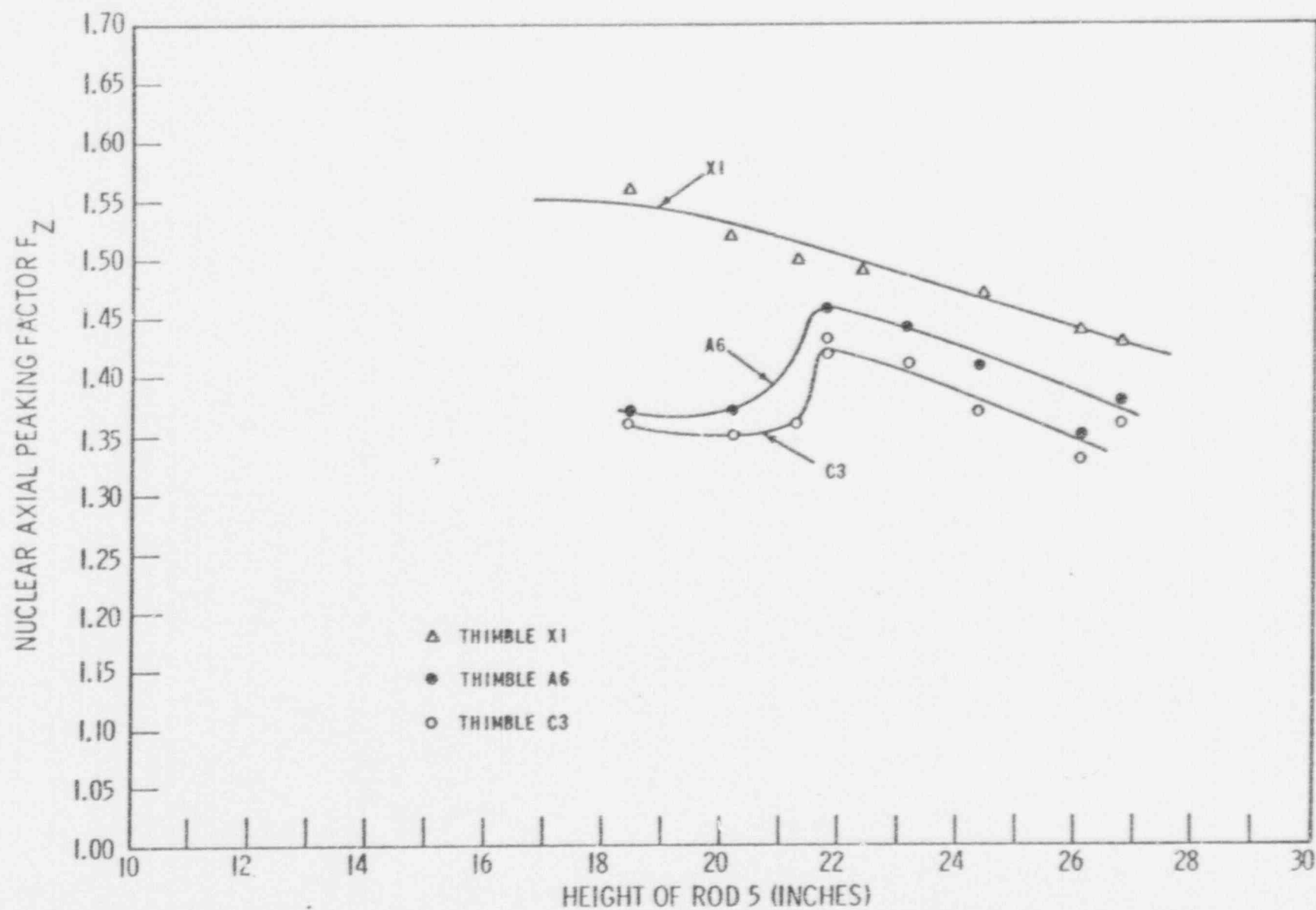
Summary of Root Mean Squared Differences

<u>Run No.</u>	<u>Date</u>	<u>Height of Rod 5</u>	<u>Power (MWt)</u>	<u>Boron (ppm)</u>	<u>c%</u>
308.7.8	10/22/63	18.39	23	700	5.94
308.7.9	10/31/63	21.22	23.25	717	6.59
308.7.2	10/8/63	26.72	23	873	6.61
308.3.7	6/24/63	24.36	23	1060	6.05
308.3.2	6/12/63	21.72	20	1107	4.69
308.1.8	5/29/63	21.74	14.6	1200	7.37
308.1.10	6/5/63	23.17	14.5	1200	6.89

The variation of the axial peaking factor F_2 with the movement of rod 5 is shown for three thimbles in Figure 9. The variation of the nuclear hot channel factors F_Q and $F_{\Delta H}$ is shown in Figures 10 and 11, respectively.

The results show a dip in the value of the axial peaking factors for thimbles A6 and C3 when rod 5 is inserted beyond approximately 21.5 inches. The peaking factor for thimble X1 does not experience a dip. Since the thimbles A6 and X1 were nearest the hot channel and therefore represent the best estimate of the power distribution at that point, the hot channel factors F_Q and $F_{\Delta H}$ also experience a decrease.

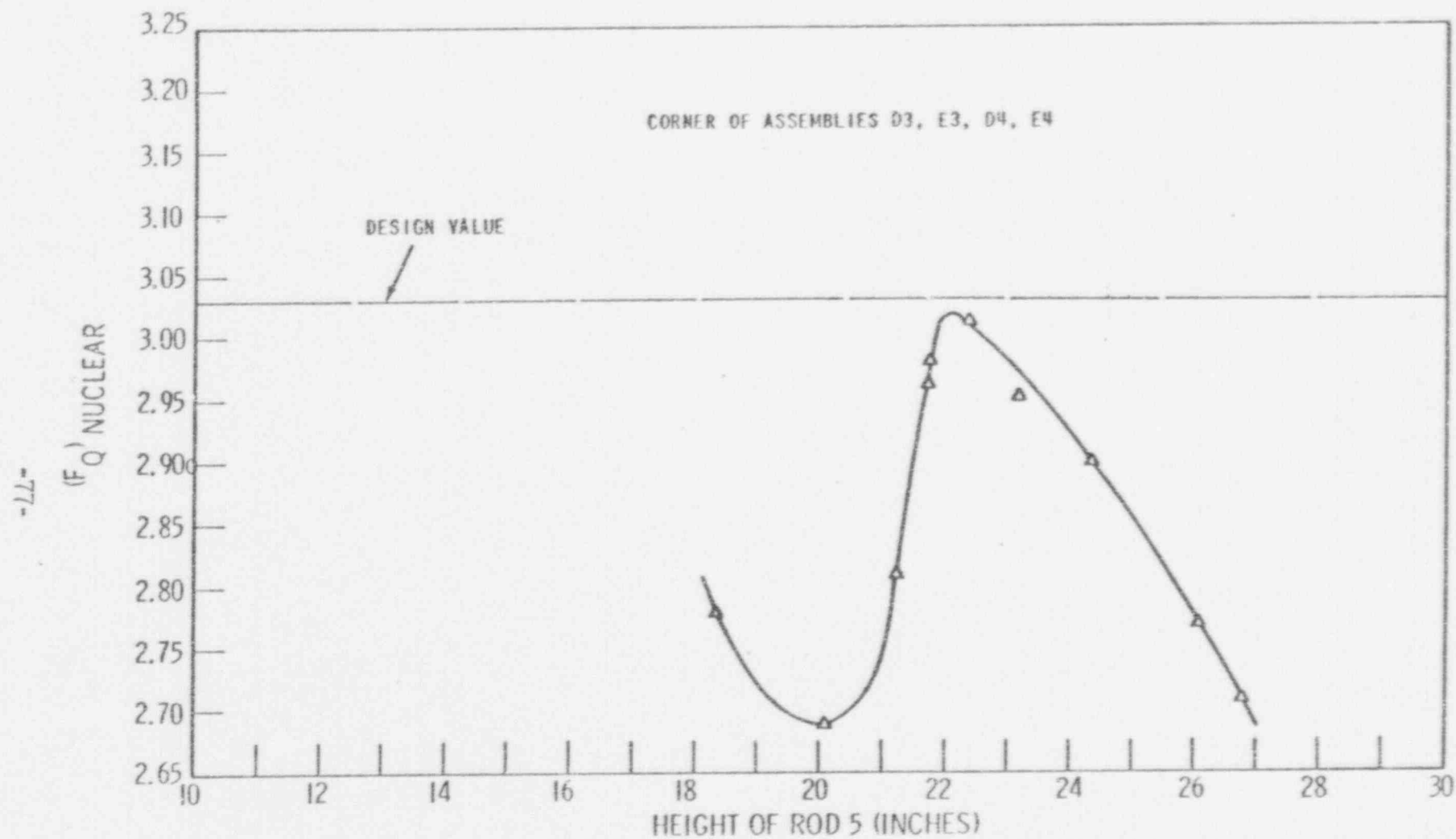
These effects can be explained by considering the variation



NUCLEAR AXIAL PEAKING FACTOR vs WITHDRAWAL OF ROD 5, CHEM SHIM OPERATION

FIG. 9

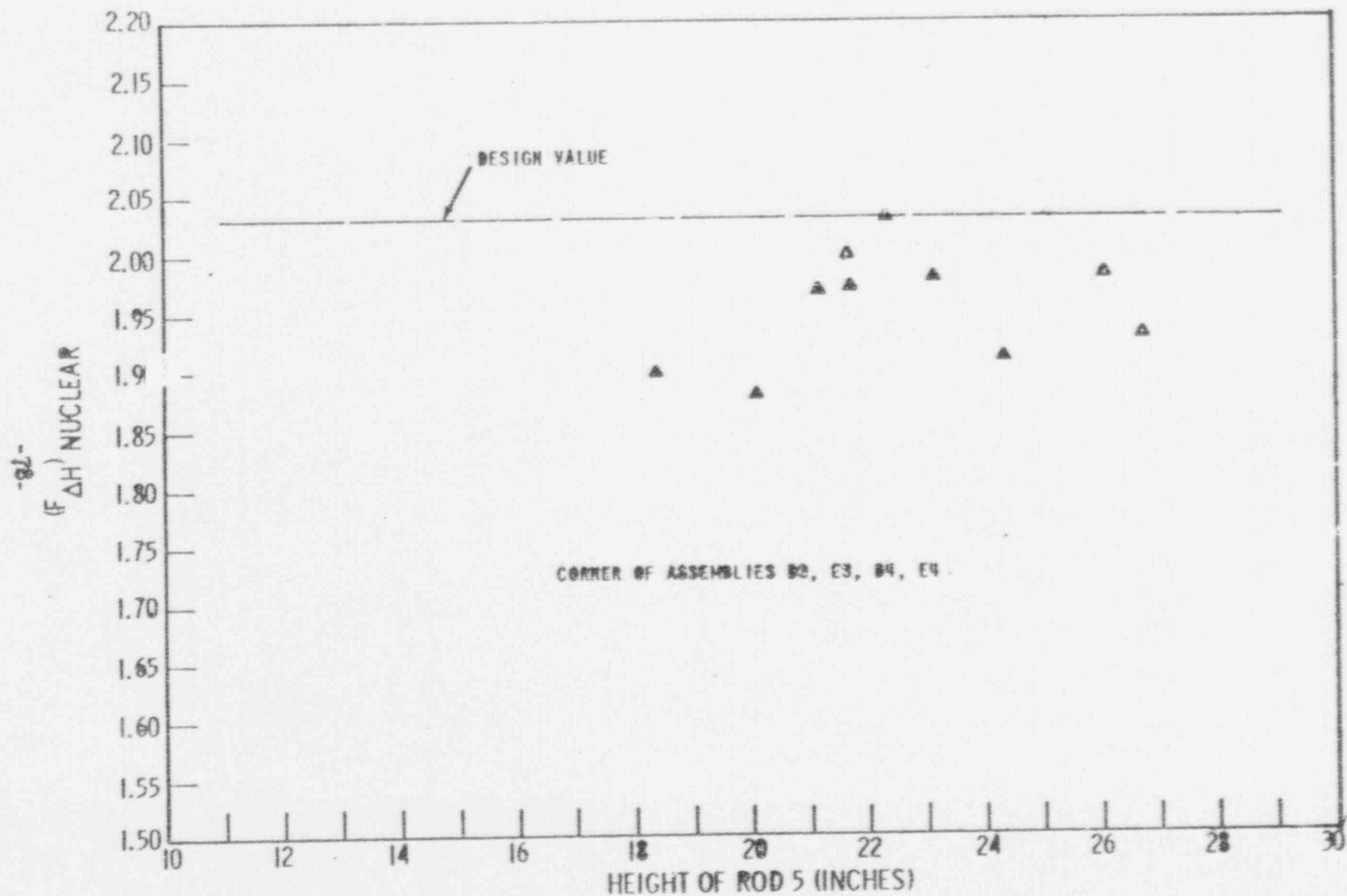
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NUCLEAR HOT CHANNEL FACTOR F_Q vs WITHDRAWAL OF ROD 5, CHEM SHIM OPERATION

FIG. 10

E. D. SK. 322159-B



NUCLEAR HOT CHANNEL FACTOR $F_{\Delta H}$ vs WITHDRAWAL OF ROD 5, CHEM SHIM OPERATION

FIG. 11

E. D. SK. 322158-B

of the axial power distribution (F_z) for thimbles A6 and X1 as rod 5 is inserted. In general, as rod 5 is inserted, the power peaking becomes more pronounced and the position of the peak moves toward the bottom of the core. These effects are most noticeable in those thimbles nearest the banked rod (as in thimble X1) as the peak of the flux distribution approaches the absorbing spacer grids with insertion of rod 5, the flattening of the top of the flux distribution becomes more prominent. This effect is observable for the flux distribution of thimble A6. The peak of the flux distribution measured in thimble X1 is near the spacer grid for all the measured rod heights. Thus, while the peak is depressed, the dip in the axial factor does not occur.

The depletion distribution of the Saxton core at the April 20, 1964 shutdown and for subassemblies then present is shown in Table 10. The distribution was determined using the SADAR (Saxton Data Reduction) code. The average core depletion was a total of 6330 MWD/MTU (134,040 Mwhrs) of which 4521 MWD/MTU (95,736 Mwhrs) was incurred during chem shim operation. Peak burnup was 15,600 MWD/MTU.

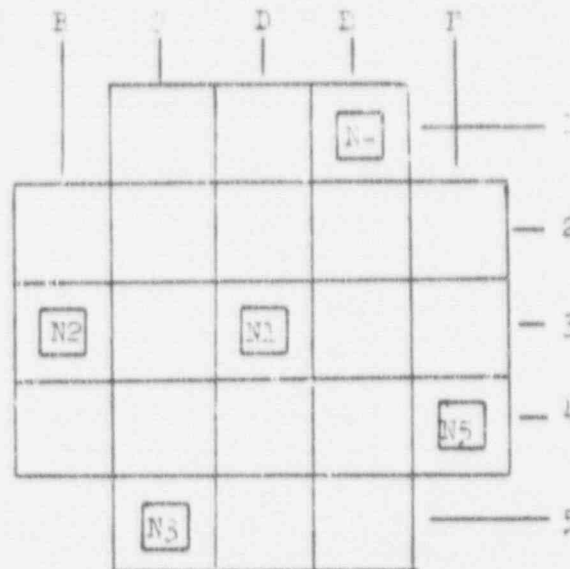


TABLE 10

Core Depletion as of April 20, 1964

Assembly	MW hrs	MWD/MTU
C1	4731.8	4625
D1	5020.3	5528
E1	3074.0	4324
B2	4615.4	5012
C2	7118.4	7730
D2	1456.9	8141
E2	7235.5	7072
F2	4759.7	4595
B3	5106.9	5707
C3	7011.1	7832
D3	7005.8	8979
E3	7173.8	8560
F3	5201.0	5727
B4	4959.7	4828
C4	6295.4	6932
D4	7200.0	8043
E4	1012.3	7680
F4	4398.6	5137
C5	4375.7	4888
D5	5549.5	5424
E5	4229.5	4593
N1	460.42	4000
N2 (No fuel)	0	0
N3	194.73	2052
N4	157.26	1537
N5	118.26	1077

VII. Conclusions and Future Studies
S. Bartnoff, J. Weisman

A. Conclusions

It is believed that the Saxton program has demonstrated the feasibility of chemical shim operation under normal conditions.

For normal conditions, the experimental data indicate:

- 1) No significant accumulation of boron containing material on core surfaces during plant operation.
- 2) No decrease in core lifetime because of chemical shim conditions.
- 3) Alkali addition to enable operation at a high pH is satisfactory.
- 4) The Saxton hot channel factors meet predictions during chemical shim operation.

The first conclusion, lack of boron accumulation during operation, has been the most difficult to demonstrate. However, it is believed that the careful reactivity follow conducted during this experiment has provided a conclusive demonstration. During the chemical shim test period the predicted reactivity has essentially remained within $0.2\% \Delta k/k$ of that predicted. A variation in unexplained reactivity of this magnitude must be expected considering the uncertainties in the prediction.

As noted in Section IV, examination of the reactivity follow results of Figure 2 indicate that when the reactor power was first increased to 23.5 MWt, there was a small increase in the unexplained

reactivity loss. Although the magnitude of this loss is well within the expected errors, its occurrence at this time requires careful consideration. This small loss does not correspond to a power reversible deposit since a number of such power changes were made and no trend was observed. Examination of the core central subassembly after chemical shim showed that the reactivity worth of core crud remained very small after chemical shim operation. Hence, the approach to 23.5 MWt after non-borated operation essentially duplicated the first rise to 23.5 MWt under chemical shim. This second rise to 23.5 MWt showed no change in unexplained reactivity in going from 15 to 23.5 MWt. This is believed further to justify the conclusion that the original rise from 20 to 23.5 MW was not accompanied by a boron deposition.

The fact that chemical shim operation leads to no decrease in core lifetime was demonstrated by the results of the hot cell examination of the central subassembly. Even with the conservative assumption that the entire core surface was coated to the same degree as the assembly, the reactivity worth of the deposit was negligible.

The chemical surveillance program has shown that small quantities of potassium or lithium may be used for obtaining the benefits of high pH operation. Careful study has shown no hint of difficulty at the alkali levels required.

Hot channel factors, computed from flux wire irradiations and thermal-hydraulic data, were highly satisfactory. Even after allowing for the possible uncertainties, the predicted values were not exceeded.

B. Future Studies

Although it is believed that the major question of chemical shim feasibility has been answered, work remains to be done in a few areas, i.e.:

1. Oscillator Studies

Because of the jamming of the first oscillator, completion of this program has been delayed. The preliminary data have shown no evidence of power reversible boron hideout.* The program will be continued during the remaining portion of the experiment.

2. Artificial Crud Tests

The tests which have been run to date have shown chemical shim to be satisfactory under normal reactor operating conditions. It is desirable also to investigate operation under certain abnormal conditions; in particular, operation with high crud deposits on core surfaces. As previously mentioned, out-of-pile tests indicate the possibility of a power reversible boron accumulation. It would be very useful to have a technique which would allow a reactor operator to determine whether

*WCAP-2627 "Saxton Kinetic Experiments". V. Rajagopal, (June, 1964)

such a situation existed. This can be done by simply cutting back on reactor power or changing reactor temperature and pressure to suppress nucleate boiling. This would eliminate any reversible deposition (if any were present) and show up as reactivity gain. The absence of this gain would assure the reactor operator that this high crud situation does not exist.

The nucleate boiling - non-nucleate boiling transition test has been carried out at Saxton. As expected, since the crud level was low, significant reactivity changes were not observed. Under normal operating conditions, it is not believed feasible to accumulate the crud levels required to achieve a significant reactivity change. In order to demonstrate this technique, it is planned to inject synthetic crud into the main coolant system. Out-of-pile tests have demonstrated that such material tends to deposit preferentially on heated surfaces. Hence, it should be possible to build up an appreciable deposit on the core surfaces. The nucleate to non-nucleate boiling transition under these circumstances should yield a significant change.

3. Tests of Defected Zircaloy Clad Rods

Incomplete information is available on the behavior of defected Zircaloy clad rods in a chemical shim environment. Since Zircaloy is proposed for use in some large chemical shim controlled plants, it is desirable to obtain additional information. Accordingly, tests of purposely defected Zircaloy rods have been scheduled for the next portion of the program.

4. Boiling Studies

The present tests have been limited to nucleate boiling conditions. No steam has been present at the exit of any of the channels. Operation at higher exit temperatures with chemical shim control deserves study since it would lead to higher pressure steam and more efficient energy conversion. The effect of bulk boiling on possible boron deposition mechanisms is unknown. A test program to evaluate chemical shim and bulk boiling at the exit of the hot channels is being planned.

Acknowledgment

The success of the Saxton Chemical Shim Program was largely made possible by the efforts of the SNEC and Westinghouse personnel at the Saxton site. We should like to acknowledge the cooperation of W. H. Layman, Manager of SNEC, H. J. Williams, Saxton Plant Superintendent, D. E. Hetrick, I. Finfrock, D. Howard, J. Roth and R. W. Swift of the SNEC staff. The efforts of the Westinghouse engineers at Saxton, T. L. Erion and R. W. Colombo, ably assisted by E. A. Hooper and S. L. Pekar, are gratefully acknowledged.

The program relied heavily on many people at a Westinghouse APD. The efforts of the personnel of Chemical Development, Plant Development, and Reactor Development who participated in this program are also acknowledged.