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THREE DIMENSIONAL FLUX CONTROL

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THREE DIMENSIONAL FLUX CONTROL

G. F. OWSLEY

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HW-58409
Page 2

THREE DIMENSIONAL FLUX CONTROL

INTRODUCTION

Recent correlations of slug rupture data have indicated that the failure rate increases markedly with specific slug power. After the fact flux traverses have shown that a large share of the ruptures have occurred in conjunction with flux peaks significantly higher than normally expected. If more complete in-core flux information were available, it is expected that a major portion of the ruptures could be shown as having been caused by abnormally high flux peaks. However, at present there is neither means for continuously monitoring flux distribution nor an operating control system which can be used for effectively controlling the flux distribution in the longitudinal as well as the radial direction. It appears feasible to undertake a program at this time having the specific objective of controlling and lowering the maximum to average slug power in the Hanford Reactors. There is every reason to believe that a marked decrease in the rupture rate would result from such a course of action.

The purpose of this document is to systematically examine the justification for longitudinal flux control*, the apparent obstacles and limitations to efficient control, and a feasible course of action designed to fulfill the desired flux distribution objectives. It is hoped that this report will stimulate criticisms and suggestions concerning the flux control problem and objectives.

SUMMARY AND RECOMMENDATIONS

The incentive for longitudinal flattening arises primarily from the dependence of fuel element ruptures on specific power. After the fact flux traverses have shown that specific powers up to 30 per cent⁽¹⁾ higher than would be expected with the normal sinusoidal distribution have been experienced. Secondary but significant incentives are higher conversion ratios and better knowledge and stability of reactivity parameters and control rod worth. A conversion ratio increase of up to 1 percent may be possible.

The ultimate objective is to operate routinely with a stable flux distribution flattened in all directions through the use of fringe enrichment to an economic optimum. The three basic problems are 1) determining the optimum sized flattened zone, 2) achieving the desired distribution, and 3) maintaining this distribution in the presence of the total and local reactivity transients tending to upset this balance. Achieving a satisfactory solution to this latter problem is probably the biggest obstacle to effective three dimensional flattening.

The successful application of three dimensional flux control at the Hanford Reactors is dependent on improvement in the following areas.

1. Longitudinal flux monitoring.

The current in-core monitoring program has the objective of providing adequate three dimensional flux distribution information.

*The longitudinal flux distribution refers to the flux (more exactly, specific power) profile parallel to the process tubes.

(1) Private communication - R. R. Bloomstrand.

2. Supplementary control.

The horizontal rod system by itself is inadequate for more than radial flux distribution control. Supplemental control is required. Application of the poison spline and column displacement systems will aid significantly. It is hoped that full development of these two techniques will be adequate.

3. Longitudinal extension of flattened zone.

Use of enrichment in the front and rear of process tubes will extend the flattened zone longitudinally. A calculational method should be developed to optimize the enrichment use.*

4. Total control.

Longitudinal fringe enrichment will be permitted only if a means of supplementary disaster control can be applied which will guarantee compliance with the present criterion. The poison spline system may provide a satisfactory solution.

5. Handling enriched material.

Considerable down time is required for handling irradiated enriched material to prevent inadvertent assembly of a critical mass in the discharge basin. Unless a more efficient means for handling enriched material safely is developed much of the gain from fringe enrichment will be precluded.

It is believed that personnel skill and reliability will be key factors in assuring the success of three dimensional control. The complexities of this type of operation may require considerable operator training plus competent technical direction and planning on a more continuous basis than has been necessary in the past.

Primarily because of the relatively longer length of the NPR design it is believed that the longitudinal flux control problem will be more limiting there than at the existing reactors. Thus, solution of this problem at the existing reactors will be particularly applicable to NPR design and operation.

DISCUSSION

1. Background

Control techniques designed to balance the radial flux distribution were initiated in about 1950 to permit maximum power levels when limited by specific tube power considerations. For several years significant technical effort was required for training operators, developing and securing adequate monitoring devices, solving increasingly complex control problems resulting from power level raises, and assuring on a continuous basis that proper operating procedures were followed. However, operating experience and process improvements have reduced the control of the reactors to a relatively well established set of rules which the operators can follow. Improvements in control mechanisms and instrumentation have aided. Among the more important are:

*A longitudinal extension of the flattened zone at the K Reactors could be achieved by controlling with the central control rods. This is not possible now because of the cycling problem.

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HW-58409
Page 4

a) Control mechanisms.

More poisonous and relatively trouble free horizontal rods, half rods, the poison column control facility.

b) Instrumentation.

The flexowriter tube outlet temperature recorder and the multi-point tube outlet temperature deviation recorder.

Despite the developments in radial control the longitudinal flux distribution has been almost completely ignored. This deficiency stems from three primary reasons: 1) the incentive for longitudinal control has not previously been large or at least has not been defined; 2) no method exists currently for efficiently monitoring the longitudinal flux distribution continuously; and 3) existing control systems are not suited for this type of control. However, recent observations have shown that flux peaks as much as 30 percent higher than normally expected have occurred, probably quite frequently. Some rupture experience appears to correspond to this peaking. Thus, there is now a definite incentive for longitudinal flattening. Consequently, mechanisms are currently being developed to continuously monitor the in-core flux distribution and to control the reactors longitudinally.

2. Incentives

A rigorous quantitative analysis of the justification for longitudinal control has not been performed and is probably not possible at this time. However, it is possible to examine the benefits to be gained on a qualitative and semi-quantitative basis. It is believed that such an approach gives a reasonable concept of the gains which are possible from controlling the specific slug powers.

a) Ruptures.

Two of the reactor variables that control fuel element rupture rates are specific slug power and slug surface temperature.* It follows, therefore, that changes in flux distribution -- which necessarily affect the magnitude of both these factors -- will significantly affect the rupture rate. This conclusion is borne out by plant rupture experience.

A comparison of solid fuel element rupture rates have shown that for a given tube power, tube outlet water temperature, and exposure the side hot-spot rupture rate at C Reactor was about five times greater than at the old reactors.⁽²⁾ Examination of available weasel data covering the period of time during which the difference in rupture rate was experienced, revealed two significant differences between C Reactor flux distribution and the composite older reactor distributions. First, flux peaking was of a larger magnitude at C Reactor; and second, the peak powered slugs were generally downstream of center at C Reactor,

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*Concluded from proven effect of the tube power, and tube outlet temperature on ruptures. (HW-55377).

(2) HW-55377, "Analyses and Correlation of HAP0 Rupture Experience with Natural Uranium Material", R. R. Bloomstrand and W. I. Neef.

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HW-58409
Page 5

and upstream of center at the older reactors. At a given tube power, this results both in relatively higher specific powers and higher slug surface temperatures for the C Reactor case.

The correlations in reference (2) showed that tube power, tube outlet temperature, and exposure all affect the side hot-spot rupture rate. By assuming that these relationships hold on a slug-by-slug basis expressed in terms of slug power, slug surface temperature, and slug residence time, calculations have been performed to quantitatively estimate the effect of changes in flux distribution on the rupture potential. The net difference in rupture potential between the composite average flux distributions of the C Reactor and the older reactors is about a factor of four. It is concluded, therefore, that the observed difference in fuel element performance between the C Reactor and the older reactors was largely due to differences in front-to-rear flux distribution.

The question arises as to what magnitude of dollar savings can be expected from controlling the longitudinal flux distribution. The answer requires a rather exact knowledge of the current flux profile and how the magnitude and shape of the distribution may be altered by efficient control. The following should give an idea of the savings which should be possible.

The plant production loss due to ruptures can be conservatively placed at about \$360,000 per month. This is based on a rupture frequency of one rupture per month per reactor and assumes a rupture results in one full day of production loss. Figure I is a plot of relative rupture potential as a function of relative central peaking. Inspection shows that a relatively small change in peaking can have a large effect on the rupture potential.

If, for example, the peaking is currently 10 per cent above cosine, a reduction to 5 per cent above cosine will reduce the rupture potential by one-third. The practical effect is either (1) the reactor operates at the same level and goal exposure with one-third less rupture loss, or (2) the rupture loss is held constant but power and/or goal exposure are increased. In either event the magnitude of the "savings" is large - of the order of \$100,000 per month.

b) Conversion Ratio.

The over-all conversion ratio of a column of uranium can be improved by flattening the flux distribution. This effectively equalizes the relative exposures of slugs in the column thus increasing the conversion ratio for a constant column exposure. For example the following table demonstrates the change in conversion ratio with flatness for an average discharge exposure of 800 MWD/Ton.

Relative Tube Conversion Ratios as a Function of Flattening⁽³⁾⁽⁴⁾

<u>Distribution Ratio of Peak Exposure to Average</u>	<u>Relative Conversion Ratio gr/gr</u>	<u>Relative Pu Produced Unit Heat Production</u>
1.44 (cosine reference)	1.0000	1.0000
1.00 (Flat)	1.0021	1.0189
1.83 (Peaked)	0.9968	0.9711
1.20 (Probable Flattening Limit)	1.0011	1.0102

A difference of one per cent in the relative amount of plutonium produced per MWD is equal in value to that much production increase.

Further, a more detailed knowledge of the front to rear flux distribution will reduce the random uncertainties in conversion ratio and product quality which exist in current theoretical formulations.

c) Other.

The reactivity prediction for various materials, control rods, temperature coefficients and xenon could be more accurate if the related effect on the longitudinal flux distribution could be more accurately measured and if the distribution were maintained relatively constant.

Graphite growth and contraction could be expected to be less severe if fringe and central powers were brought closer together. Of course, this is not necessarily so at the graphite overbored K Reactors.

3. Problems

a) Flux Monitoring.

The first requirement for longitudinal control is continuous knowledge of the flux distribution. At present no method exists for continuously monitoring the actual in-core flux level. Slug traverses are performed periodically to determine the history, and in reactors where a relatively large number of graphite thermocouples exist these are used for flux determination to some extent. Both these techniques are too slow to be of significant value for determining continuous control action.

(3) Build-up and burnout constants supplied by W. E. Niemuth.

(4) Flux shapes taken from HW-56522, "Slug Factors for Various Flux Distributions," D. E. Goins and D. E. Clarke.

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HW-58409

Page 7

Recently an intensive program was initiated for developing and installing an in-core flux monitoring system. The most attractive approach appears to be duplication of the wire traverse and in-core gamma chamber systems currently in use at Savannah River. Development work is planned on chambers before definitely selecting any one type. However, the wire system should be satisfactory for Hanford without further costly and time consuming development.

The wire system consists of a mechanism for inserting a wire into a process tube during operation and then monitoring the activity along its length after it is withdrawn. A suitable read-out system is included. Present plans call for reserving five process channels at each reactor for the wire system.

The chamber system for continuous monitoring will require some development and testing effort to assure adequate dependability and reliability of the chambers. One attractive candidate appears to be the gamma sensitive ion chamber currently in use at Savannah River. The chambers would probably be installed, five chambers per channel, in the five process tubes used with the wire system.

It is believed that the dual system is well justified. The 25 chambers will give continuous indication which can be used by the operator to control by. The wire system will give a detailed profile of the flux distribution, front to rear, and will be necessary to calibrate the chambers.

Completion of the dual system at all reactors within the next two years should be possible if it is decided not to adhere to the normal project action procedure.

b) Reactivity Control.

Controlling with horizontal rods exclusively has two distinct control disadvantages. First, the rods are too strong reactivity-wise to make fine adjustments in flux distribution. Essentially, the reactors have sufficient reactivity to operate with 5 to 9 control rods in the lattice, the tips of each rod representing a point of control. The rods are positioned so that these tips are well located to provide course control of the radial flux distribution. However, only the tips fulfill the flexibility requirement - the major portion of the rods inserted, and therefore of the reactivity invested in control contribute only in a clumsy fashion to control of cycling tendencies.

The second disadvantage of operation with the horizontal rods is that their movement transverse to the process tubes is not suited for front to rear reactivity compensation to prevent cycling. This deficiency becomes serious with increased longitudinal flattening. Currently the K Reactors are purposely operating with an anti-flattened longitudinal flux profile because uncontrollable cycling has been experienced with a more flattened distribution.

DECLASSIFIED

HW-58409
Page 8

It is believed that two supplementary control devices currently being developed and installed on the reactors will compensate for the deficiencies of the horizontal control rod system.

The poison spline system offers the opportunity for inserting a relatively weak poison in any process tube during operation using the form of a thin metal strip which can be inserted under the metal charge. Its principle advantages for control are readily apparent: "hot spots" in any portion of the reactor can be reached without depressing or distorting the flux in other areas, and the capacity of the total operating control system can be extended almost indefinitely. Mechanical, material, and radiation problems still must be solved before the system is completely operational and the expected gains can be realized. However, there is assurance that all these problems will be solved within the next year. Although splines are thought of as flexible poison they do not have the versatility of a control which can be moved to any position by remote operation. Spline insertion and removal requires manual work which is relatively slow. Thus, although splines are excellent for the fixed placement of poison for periods of several hours or more, they are not suited for constant shifting to prevent flux cycling. Fortunately, it should normally be possible to position the splines and rods to achieve an optimum flux distribution and then use the rods to prevent flux level shifting. This has proven to be a satisfactory approach at D Reactor where splines are currently in use.

The control of increased tendencies for longitudinal flux cycling is a different matter. Calculations and experience have shown that a flatter front to rear flux distribution will definitely decrease the longitudinal distribution stability. Although the combination of splines and horizontal control rods may permit limited longitudinal control, a means for compensating with continuously available reactivity adjustments which affect longitudinal distribution without significantly affecting the radial distribution will be desirable, and very probably necessary, before optimum front-to-rear flux distributions can be maintained. Essentially the equivalent of a control rod system operating parallel to the process tubes is required.

This need has been foreseen and the column displacement facility is being developed for precisely this purpose. The column displacement facility is capable of shifting a column of uranium or poison back and forth in a process tube by remote operation from the control room. One such assembly is being tested at the KW Reactor at present. Results to date have been satisfactory.

The reactivity investment and production space loss for these devices would probably be slight since the most attractive type of operation would be the shifting of a slightly shortened natural uranium column of I & E geometry. This movement should very effectively control longitudinal flux shifting tendencies without upsetting the radial distribution or significantly altering the total reactivity maintained in the control rods.

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HW-58409

Page 9

It is hoped that a full reactor prototype of the displacement facility will be installed on at least one K Reactor in this fiscal year. Successful coordination of rods, splines, and column displacement at the K Reactors should permit return to the "inboard" horizontal rod configuration, and, if other problems discussed in this report are satisfactorily solved, optimum longitudinal flattening with front to rear enrichment.

c) Total reactivity control - nuclear safety.

A third limitation to increased reactor flattening is the restriction imposed by the total nuclear safety control criterion which effectively requires that the control system have sufficient capacity to maintain the dry reactor sub-critical as long as the coolant channels are useful. Unfortunately, the vertical channels into which the vertical controls (ball 3-X primarily) are inserted are too closely confined to the central portion of the reactor to be fully effective in the fringe enriched reactor. To satisfy this criterion the extent of radial flattening by enrichment is currently limited in all except the C and H Reactors. Further, longitudinal enrichment is not permitted at any reactor at present.

With a particular type of fuel element and loading scheme there is little that can be done to decrease the amount of reactivity poison which must be put into the reactor to maintain subcriticality upon water loss, but considerable improvements can be made in the placement of supplemental poisons in the wet reactor so that the vertical safety system will cause a greater reactivity decrease when inserted.

The situation and general solution can be explained as follows: The reactivity control in the wet reactor is normally located in the center as are the safety controls. This results in severe shadowing of the two systems so that the reactivity poisoning increase following a safety system drop is restricted. This central placement of the operating reactivity controls (horizontal rods, poison columns) is necessary at full power level to secure an optimum flux distribution; however, when the total control requirement is restrictive the reactor is either at zero or at a low power level (just prior to and subsequent to cold start-ups). The obvious solution is to locate the normal poison outside the safety control region during start-up periods. (The poison spline system is well suited for this procedure since the poison can be inserted wherever it will be most effective and removed without seriously disrupting the operation.) The principle problems are reliable knowledge of reactivity effects with this procedure, assurance that the necessary restrictive poison loading procedures will be followed, and reliability and speed of the spline insertion and withdrawal system. It is believed that a modified flattening pattern during start-up periods utilizing the spline system will permit three dimensional flattening with fringe enrichment. A calculational method to compute the reactivity status with satisfactory accuracy for complex loadings of poison and enrichment may be feasible with the IBM 709 computer.

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HW-58409

Page 10

Another potential aid to total control is the inclusion of resonance neutron absorbers in the ball 3-X system to increase the strength. This possibility is currently being investigated.

d) Longitudinal enrichment -- economic optimization.

No composite computation model has been developed which will permit a systematic determination of an optimum flux distribution in all dimensions which considers the effects and costs of fringe enrichment as well as the benefits from improved flattening. Attempts to date have been restricted to some limited portion of the optimization and thus suffer in accuracy because directly related factors are treated as constants rather than as variables.

Availability of the IBM 709 computer and improved quantitative relationships, particularly between reactivity distribution, flux distribution, specific power, rupture potential, and conversion efficiency, should make formulation of an adequate optimization program practical. Initial progress has been made by Process Technology personnel using the 550 computer.

e) Enrichment handling.

Because of the possibility of achieving a critical mass in water with the normal enriched material now used, severe handling restrictions for irradiated enrichment have been imposed which significantly increase reactor shutdown time. Schemes which increase the number of tubes charged with enriched fuel elements will result in a corresponding increase in shutdown time. As a further point it should not be overlooked that handling increased amounts of enriched material will increase the probability of serious reactor loading errors.

Various schemes have been proposed for reducing the downtime resulting from E metal discharge. The most attractive appears to be discharging directly into boron or cadmium lined buckets in which the volume is too small to assemble a critical mass of any material used in the reactor. It appears that with full use of this technique and adequate procedures designed to prevent inadvertant grouping of a critical mass, enriched and natural uranium can be discharged together without time consuming special pick-ups.

4. Conclusions

- a) It is believed that the foregoing analysis is a fairly complete statement of the major problems and that the suggested solutions should be feasible, reasonably straightforward and adequate. However, it is to be expected that unforeseen problems will arise before a nearly optimum and stable three-dimensional flux distribution is achieved. These problems should be surmountable at an acceptable cost. Technical or financial limitations could restrict the final effectiveness of three-dimensional control; however, this possibility should not stop the required development effort at this time. The possible gains in rupture reduction certainly warrant some risk.

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HW-58409

Page 11

- b) People with considerable ability and experience will be required to properly plan loadings and control for a reactor where longitudinal as well as radial flux distribution is to be optimized. Improper use of enrichment and the controls could negate any gains expected from longitudinal flattening. First, training will be necessary to develop competent operators for properly using the various devices at their disposal for flux control. It is believed that with adequate training, operators can be expected to perform the routine and straightforward control operations. However, the non-routine situations in which considerable skill and understanding is required will probably be frequent. An experienced technical man may be necessary to direct the operation at such time to realize full benefits from three dimensional control. Thus increased off shift technical coverage could be required.
- c) For the existing reactors three-dimensional control should yield considerable gains but certainly is not necessary to justify operating the reactors. However, at the NPR there is a very good possibility that the longitudinal as well as the radial flux distribution must be controlled to make operation practical. This is primarily because of the relatively large tube length at the NPR and the potentially more severe temperature coefficients of reactivity. Before longitudinal control is possible at the NPR the same monitoring and supplementary control problems outlined in this report will probably have to be solved. Thus, development of efficient three dimensional control for the old reactors will have significant value toward making the NPR operational.

ACKNOWLEDGEMENT

The author wishes to acknowledge the very significant contribution of R. R. Bloomstrand who wrote the portion of this report discussing the observed influence of the longitudinal flux distribution on the rupture rate.

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FIGURE I

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