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JUSTIFICATION AND SPECIFICATION
FOR AN FTR OSCILLATOR

James R. Sheff

August 1970

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By

James R. Sheff^(a)

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ABSTRACT

The justification is provided for a reactivity oscillator in the Fast Test Reactor (FTR). As a basis for this choice, arguments are given substantiating the need for experimental confirmation of the stability of the reactor. Confirmation of the stability requires measurement of the reactor transfer function including feedback effects. The oscillator method is chosen from those transfer function measuring techniques available.

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I. INTRODUCTION

This report reviews the study and the conclusions of an investigation into the need for the measurement of the reactor transfer function of the Fast Test Reactor (FTR). The investigation also included definition of how often the measurement should be made and a study of the methods available for measuring such transfer functions. The methods are evaluated and the oscillator method was selected as the method most appropriate.

II. SUMMARY

The questions of whether, when, and how the reactor transfer function should be measured are investigated and answered for the FTR. The transfer function, it is concluded, must be measured in order to:

- Determine experimentally if the system is stable,
- Confirm the model describing the important characteristics of the system,
- Measure experimentally several important dynamic coefficients of the system, and
- Confirm the planned correct operation of the control system.

This report recommends that the transfer function be measured by the oscillator method. Other methods reviewed and discussed included transient perturbation (rod drop), pseudo-random perturbation, and periodic but nonsinusoidal perturbation.

A reactivity oscillator may be used for purposes other than feedback transfer function measurements. Recommended

ancillary uses for FTR include; (a) measurement of reactivity near the critical point, (b) measurement of the total delayed neutron fraction, (c) measurement of the components of the delayed neutron fraction, and (d) as a diagnostic aid to fuel testers.

As an aid to those responsible for the generation of specific design and requirement documentation, a list of suggested functional requirements and their current justification has been assembled in Section IX.

III. CONCLUSIONS

It is concluded that the reactor transfer should be measured under a variety of operating conditions at initial start-up and at infrequent intervals thereafter. The subsequent measurements will most probably be made at times when major core changes are made. The transfer function measurement must be made many times with many combinations of parameters descriptive of reactor operating states. Such parameters would include power level, sodium flow, various pump options, and automatic control system options. The frequency range over which data should be taken should be 0.001 to 10 cps.

The principal method of measurement should be via sinusoidal reactivity oscillations, using a specially-built oscillating rod. Data analysis should be done digitally. Provisions must be made for minimal on-line analysis to confirm data quality.

IV. SHOULD TRANSFER FUNCTION MEASUREMENTS BE MADE?

Before discussing how or when to make transfer function measurements, the question of whether such measurements should be made at all deserves some serious comment. It is equally important, however, that this comment should be the result of a sincere attempt to answer this question rather than just a listing of reasons for doing what everyone else does, or what someone merely feels would be "nice" to do.

With the above thought in mind, what can be expected to result from a transfer function measurement? Generally the useful results obtainable are:

- An experimental determination to learn if the system is stable, and if so, in what region,
- A confirmation of the model which is used to describe the dynamic characteristics of the system,
- An experimental measurement of several system dynamic coefficients,
- A confirmation of the planned control system behavior:
- To support the fuel testing through determination of quantities of interest concerning either the test bed or the test itself.

The first item is the most important and will be discussed after the last four items have been treated. The last three results then represent a system measurement presumably to get some estimate of parameters to confirm models or to adjust them via inclusion of experimentally obtained data. From the point of view of the model builder or analyst, such measurements do not fall under the goal of the FIR ~~per se~~ but they could be included in the category of LMFBR support. However, time for this should presumably have a lower priority with respect to the prime FIR goals. For the operating staff, the measurements would be useful if the reactor's dynamic model including or excluding experimentally determined coefficients was required as part of the operation strategy. With the exception of virtually static feedback information, this is not probable unless and until such time that an automatic transient-following-monitor for the power is incorporated into an anomaly detection system of the reactor. It is more probable, however, that such systems, e.g., the reactivity decrement summing device will operate only when the system is in an

essentially static state. This is not to say that feedback information will not be required for such systems, but that it can be obtained to an adequate degree via other means.

Unfortunately, the accurate measurement of the parameters relevant to feedback is frequently quite difficult for several reasons. The major reason is that unless the feedback is very strong, its measurement is essentially second order to the zero power measurement. Thus, a 1% error in the basic zero power measurement can be magnified to 20+% in the feedback. In published feedback transfer function data, the tendency is noted to have too many parameters determined by too few data taken over too narrow a frequency band.

The need for an experimental check of the reactor's stability is the crux of the issue. Usually one can readily say that a careful study of the system's stability has been performed with the finest models available, including extensive parameter sensitivity studies. As a result, if no sensitivity towards instability is noted, then, perhaps, the conclusion should be that no experimental stability check is needed. The error of this logic can best be illustrated by showing the EBR-I (Mark II fuel) Transfer Function both before (calculated)⁽¹⁾ and after (experimental)⁽²⁾ the core's incipient instability was discovered. The resonance was sufficiently large that it completely reversed the expected trend.

The range of frequencies spanned by Figure 2, is indicated on Figure 1. The frequencies of Figure 1 and 2 are related by $\omega = 2\pi f$ where the units are radians/sec for ω and cps for f .

It is not valid to argue that the cause of resonance effect has been adequately explained and that it can now be designed out of reactors. This particular resonance effect can be a big problem in small reactors but it is less significant in large

FIGURE 1. Calculations of the EBR-I Transfer Function Prior to Operation.

FIGURE 2. Measured Transfer Function of EBR-I Mark-II Fuel.

reactors. The key point is not what the unknown effect was, but that it was unknown and unaccounted for in the calculations. The only meaningful argument for not making oscillator measurements must be based upon past statistics. Thus, an estimate must be made of the probability of an unknown effect arising as determined from previous reactor designs. It is questionable if enough fast reactors have been built to make a valid argument that an unknown undesirable effect will not arise. This is especially true since it has already occurred in the case of the EBR-I.

As an aftermath of the EBR-I fuel-melting problem, it is not at all clear that the effect is well understood. Even though the accidental melting of EBR-I, Mark II fuel was caused by inadequate and perhaps too casual planning and conduct of the experimental test, there was a feeling in the aftermath that the instability, known to exist, combined with the melting incident, could have disastrous effects upon the development of fast reactors.

In summarizing, the reasons for making transfer function measurements must rest primarily upon the need for making an experimental determination of the reactor's stability within at least the domain of usual or potential operation. There is sufficient reason based upon this justification alone to make such measurements a requirement.

V. METHODS OF MEASUREMENT

The fundamental quantity to be measured is the transfer function. This section reviews the methods available for transfer function measurements.

The basic information needed concerns the dynamic response of the reactor. Such information can be obtained from monitoring almost any sort of significant dynamic change either directly in the time domain or in the frequency domain via some sort of frequency analysis. Some techniques which have been successfully used on thermal systems have apparently not yet even been tried on fast reactors, and although they have very good potential, they will not be seriously considered for FTR use. The only reason for their exclusion is that they are not included in the state-of-the-art for fast reactors. An example of such a method is to employ random or pseudo-random rod motion followed by frequency domain noise analysis of the input and output signals.

The most popular alternative approach to an oscillator in fast reactors seems to be time analysis of the transient produced by some sort of relatively fast (usually negative) reactivity insertion. In EBR-II,⁽³⁾ the procedure has been to drop a special stainless steel rod (worth = 44) from the core and then record the power decrease on magnetic tape. The rod drop time is about 1/4 sec. The recovery of reactivity via feedback amounts to 0.54 after one sec and 1.0¢ after 10 sec. Noise causes errors of $\pm 0.15\%$ which makes a high degree of resolution difficult. In EBR-II such data have been compared with oscillator data and were eventually used to estimate the magnitude of hypothetical bowing of the oscillator rod at low frequencies in order to resolve discrepancies at least in part.

The Dounreay Reactor, after its extensive series of oscillator measurements extending over a year or more, has adopted a rod-drop method⁽⁴⁾ for the routine measurements required by their safety clearance to demonstrate an adequately fast negative component in the overall reactivity coefficient. A natural boron rod (worth = 10¢) is dropped into the core and the resulting transient measured. The drop time is 0.5 sec,

and this is just barely fast enough to resolve the 0.5 sec time constant of the fast feedback. A single slower lumped time constant of 20 sec is also obtained.

It is thought that for FTR this method should be kept in mind only for potential later use as was done in Dounreay. The reasons for this are as follows:

- It is a newer technique in terms of actual experimental application and is less well developed.
- Although all of the information in a fairly long oscillator measurement is theoretically in a single suitably chosen transient, its experimental recovery from a single transient is in general not possible. If the transient must be repeated many times, time spent for such a measurement will rapidly equal the oscillator measurement.
- The pulse must be kept small if nonlinear effects are to be avoided (presumably they could be handled with sophisticated analysis) and if the temperature coefficients in question are sufficiently rapidly varying functions of temperature
- A special rod rather than one of the reactor's rods usually must be used. Usually, it must produce as nearly as possible a step change in reactivity. The EBR-II concept of dropping the rod out seems more desirable than dropping it in as is done at Dounreay, but in most reactors, this choice is not open to the experimenter.
- At some time after the initial start-up measurement, if a much lower accuracy can be tolerated, then a single rod drop measurement would seem to offer very clear advantages over an oscillator.

Examples of both step positive perturbations (≈ 1.54) and nonlinear data analysis are available for thermal reactors.⁽⁵⁾ The nonlinear data analysis was shown to be unnecessary as would be expected for the perturbation used.

A sequence of three different trapezoidal shaped reactivity perturbations generated by ramp insertion and subsequent withdrawal have been successfully used for transfer function measurement in Fermi.⁽⁶⁾ In Fermi, one of the regulating rods was used to generate the pulses. This feature in itself was directly responsible for most of the advantages and disadvantages claimed for the method itself. Use of a suitably controlled reactor regulating rod in a manner compatible with any of the other schemes suggested here or elsewhere would yield the same advantages and disadvantages. In particular, (1) no complex system need be built and (2) no special core lattice position is required. Unfortunately the maximum frequency obtainable is dictated by the maximum speed that the rod can move and this is invariably made slow. In the Fermi oscillator, usable frequencies were restricted to less than 0.15 cps which is too slow by a factor of 10 to catch the fast-response feedback effects which should be present. Depending upon the reactor's control system logic, it may be impossible to do automatic control measurements while using a regulating rod for perturbations. Some of the other advantages claimed for this method along with comments are given below. The first is that the frequency-variable coverage of the spectrum is more complete, a feature which results principally from the off-line data analyses as well as the possible acceptance of poorer accuracy for any particular frequency. Secondly, a time saving in data accumulation is claimed, and this is true in many cases for all broad banded input methods. Unfortunately, there is always a reduction in the signal-to-noise ratio and, hence, less accuracy. The problem is that only a fairly restricted perturbation is allowed, and by using a very narrow frequency-band perturbation, a higher signal-to-noise ratio will result. This allows quite short measurements at various frequencies for a given accuracy. If a very wide band signal is used

subject to the same restriction upon total perturbation, then it is true that only one measurement need be made to obtain many frequencies via later off-line analysis. However, the signal-to-noise ratio will be poorer requiring the measuring time to be longer if the same accuracy is to be achieved. The latter in some cases may even prove to be impossible. The point is that careful analysis of each proposed system must be made before it can be determined if a broad band method is better than a narrow band method.

Similar measurements also have been done upon EBR-II; apparently principally during periods in which the oscillator was not working because of extensive rubbing problems. The data apparently were never analyzed except in a superficial manner.

In summary, the advantages obtained by use of a regulating rod are not worth the penalty paid in frequency restrictions. The potential shortening of data-taking time may exist in certain circumstances, but where it does, one of several other broad band perturbation methods seems even more desirable. An example is the pseudo random method mentioned above. The uniform or closer coverage of the frequency range is desirable and is available via suitable planning in all other methods, and in particular, it would be a desirable feature of oscillator measurements.

The whole class of measurements using a large number of repeated periodic reactivity pulses or basically oscillator measurements can be combined into two groups depending upon the types of analysis equipment required. The first of these contains all broad-frequency-banded perturbations and requires frequency analysis equipment for data reduction. Examples are periodic pulses of triangular, square, or trapezoidal shapes. Experiments in this group apparently have not been performed

upon fast reactors, but a long sequence of periodic triangular or trapezoidal perturbations is more desirable than analysis of a single trapezoidal pulse as has been described above.

The other group is essentially the classical oscillator experiment and is characterized by an attempt to make the input signal sinusoidal and of a discrete frequency. Thus, the method of analysis of the resulting data is reduced to obtaining only an amplitude and phase of the sinusoidal input. This is the preferred method for FTR application. A sinusoidal reactivity perturbation is obtained by making the rod either go up-or-down in an undulating manner or to rotate. Only the latter has been utilized extensively in past fast reactor measurements. Its major disadvantage is the difficulty with which the amount of peak-to-peak reactivity can be made to vary. The worth can be changed by changing the rod, varying the vertical location of the rod, and varying the surrounding environment of the rod. The first and last methods are inconvenient at best. The undulating motion has not been tried seriously in a fast reactor, but will be used in SEFOR. SEFOR picked such a rod for the very reason already suggested; ease with which the perturbation amplitude can be adjusted.

It is not clear whether the undulation motion will be more or less prone to misalignment and bowing problems, but such problems have been an obvious and, currently perhaps, a more subtle hindrance to oscillator measurements at low frequencies.

VI. PLANNED USES FOR AN FTR OSCILLATOR

An oscillator is a valuable tool and can ultimately contribute much to the overall FTR experimental program. This applies equally to the experimenter who is oriented to either fuel tests or operations. However, only those

well-founded and justified uses are discussed here. A low-frequency reactivity oscillator has two basic uses which are reactivity measurements below, but near criticality, and measurements of the dynamic feedback effects. As a bonus, the reactivity measurement yields the effective delayed neutron fraction. This is a measure of the important safety margin between a delayed and a prompt critical reactor. And lastly, the individual delayed neutron parameters can be subjected to an integral test via comparison with results from the zero power oscillator test. Potential future uses of the oscillator include diagnostic and probe oriented tests. The oscillator is utilized as a viewing window in these tests. Oscillator tests usually are possible without interference with the objectives of reactor operation. The advantages of non-interference are obvious.

The use of a general purpose variable frequency oscillator for routine reactivity measurements is not feasible and does not seem to be particularly desirable. Several reasons for this stand will be detailed below. Reactivity measurements by use of the oscillator should be made, however, as a check upon the oscillator itself and other reactivity devices. They should be made in the startup tests. The oscillator would be a useful backup for other reactivity meters. What reasons could exist for not using the oscillator as a general purpose meter? The restriction that such usage imposes first of all is that the oscillator must be capable of being installed and operated during the refueling operation. This is because subcritical reactivities are very important during refueling periods. Such operation might be most easily obtainable by making the oscillator loadable into a closed loop, but this will not be the most desirable location from the point of view of measurements of at-power feedback. Secondly, a special poison element would be required in order to gain sufficient worth to make meaningful measurements. The rod might even be difficult to fabricate.

A special purpose unit would probably be essential if such a method is to be the principal means of reactivity measurement. It could probably be made smaller, operate at a more optimum frequency, and perhaps even be located so that its insertion and removal could be automatic. Thus, the general unit should be restricted to initial and special-test reactivity measurements.

The total delayed neutron fraction and the check of contributions to the delayed neutron fraction will be done since this information results from the zero-power oscillator measurements. The zero power measurements are a necessary part of the at-power feedback effects data reduction. The problem of time spent upon the measurements is critically important since the FTR is to be a "production" device rather than a research test device.

Above all, the time which should be spent depends upon whether the tests are showing the existence or lack of hazardous conditions. Secondary to this then is the concurrence or lack of concurrence of the data to the predictions. It seems desirable to currently assume a lack of hazardous conditions and a general concurrence with the predictions. Deviations from this state of affairs will produce the need for longer testing. The length of time allotted to a test also can be varied based upon whether it can be scheduled at the same time other tests are in progress, but this effect cannot be considered quantitatively here. This should be done when the appropriate information is available.

Picking a measuring time upon the basis of the feedback effects measurements, leads to the conclusion that the zero power measurements should be the best of the data set because they are used with all other sets. However, since the data is treated in an additive sense, there is no benefit obtainable from zero power data having an accuracy better than about ten times that of the high power data.

The measurement of the feedback function requires first a measurement of the zero power transfer function, G . The transfer function is the system response when the oscillator is operated at various frequencies, and the term zero power implies not only that the power level should be low but also that the pumps are off. Then a transfer function measurement, H , is made at the state for which the feedback function, F , is desired. Those states of obvious interest are both zero power and high power with various modes of sodium flow and with and without the automatic control system. The quantities F , G , and H , are related as follows

$$H = \frac{G}{1 + FG} \quad (1)$$

or
$$F = \frac{1}{H} - \frac{1}{G} \quad (2)$$

All three quantities are complex functions and thus involve both real and imaginary parts. Figures 3 to 6 show examples of these functions for the FTR. The magnitude and phase of both the feedback, H , and the zero power, G , transfer functions are shown in Figures 3 and 4. Changes in the Doppler coefficient produce substantial effects as shown in Figures 5 and 6. A ten-fold reduction is seen to produce almost the same effect as a zero Doppler coefficient. The curves of magnitude presented are all similar to Figure 1 and show no tendency toward the resonance phenomenon seen in Figure 2. The question of reactor stability versus instability is the principal reason for transfer function measurement, but it is usually not easily determined from the data such as shown in Figures 3 to 6.

The basic concept of stability versus instability is easily understood through Equation (1). For any frequency, if $FG = -1$, the denominator equals zero and H is infinite. The system is unstable. Thus the values of FG as a function of frequency are important to the question of stability and are shown in Figure 7. In such a phase plane plot, the magnitude is the

FIGURE 3. Magnitude of the FTR Zero Power and Feedback Transfer Functions.

FIGURE 4. Phase of the FIR Zero Power and Feedback Transfer Functions.

FIGURE 5. Magnitude of the Feedback Transfer Function as the Doppler Coefficient Varies.

FIGURE 6. Phase of the Feedback Transfer Function as the Doppler Coefficient Varies.

FIGURE 7. Phase Plane Plot of the FG Product

distance from the origin and the phase angle is the angle measured from the positive real axis to the vector through the point in question. Alternatively, the abscissa is the real part of FG and the ordinate is the imaginary part. The scales have been made logarithmic which requires them to be discontinuous along the axes. The curves are seen to be nowhere near the -1 point, but this is not sufficient to guarantee a stable system. Why this is so is discussed further in Section VII. However, the curves are asymptotically to the right of the imaginary axis for ω approaching zero, and they go to the origin without crossing the negative real axis as ω approaches infinity. These latter facts do guarantee stability.

The time spent upon each feedback measurement should depend upon whether the state of the reactor operation is a normally acceptable operating state. For example, the measurement at full power and full normal flow could be done quite well because the measurement will not interfere with the test irradiations in the reactor. If it proves possible to have variable reactivity capabilities, then, for these usual operation cases, a small perturbation with a longer measuring time would minimize interference with operations.

The answer to the question of how often should the transfer function be measured depends strongly upon what is found. But measurements will probably only be necessary during initial operation and after any major core changes. The actual state of the reactor can and should be monitored via an anomaly detection system utilizing the digital control system. In this way, the digital computer can make most decisions automatically as to the desirability of an oscillator test.

The Dounreay Fast Reactor has both an oscillator and a rod drop device, and the latter is quite capable of satisfying the measurements required by the routine safety controls.

VII. EXAMPLES OF FAST REACTOR FEEDBACK EFFECTS

Some measured results of fast reactor feedback will be presented to illustrate the types of behavior thus far encountered. The emphasis will be placed upon a comparison of various observed effects rather than upon the details of particular cases. The feedback function, F , will be the quantity compared. It is given by Equation (2), page 14, and is a complex function having a real and imaginary part. The experimental feedback functions, F , are shown in Figure 8 for several fast reactors. The ordinate and abscissa are the imaginary and real parts of F . Also shown is the theoretical prediction for FTR.

There are a number of other points about Figure 8 worth mentioning aside from the obvious feature that they are all quite different. Inspection of the frequencies, shown on the ends of the curves, shows that they all rotate clockwise from low to high frequency. The two curves least like the others are FIR and EBR-I. A large Doppler coefficient is the cause for FIR being different and the Mark II fuel loading of EBR-I produced an almost unstable reactor. The curve for Dounreay also shows a slight tendency towards instability.

The concept of instability is easily understood by observing the quantity, FG . However, it is not a simple matter to determine instability from curves of F . Curves of F have been presented here because this is the usual form available in the literature. Some features of instability can be seen in the graphs by following the reasoning given below.

FIGURE 8. Feedback Functions For Several Reactors.

As has already been noted, the reactor will be unstable if FG becomes equal to minus one. H , as given by Equation (1), page 14, becomes infinite. Also, since F is proportional to the power to at least the first order, a negative real axis crossing of the product FG can be made to intersect the -1 point by increasing the power. Hence the concern becomes whether the FG product even crosses the negative real axis. As can be seen in Figure 4, G varies from pure negative imaginary, -90 degrees, to pure positive real, zero degrees, as the frequency spans the range from 0.001 to 10 cps. Thus, usually the product FG will cross the negative real axis for some point along that part of the F curve in the third quadrant. That is in the region where F has negative real and imaginary parts. This is because the effect of multiplying G times F will be a clockwise rotation of all points of F by angles between 0 and 90 degrees.

When the negative real axis crossings occur as in Figure 8 for EBR-1 and Dounreay, it is an indication that the reactor will be unstable at some higher reactor power. It then becomes important to know if this higher power is obtainable by the operating reactor, and if so, does the F curve still have the same basic shape? The latter question arises because the curves of F result from a linearization of a non-linear process about a particular power level. The linearization may produce a significantly different result at a much higher power level. In many cases, a large almost undamped oscillatory behavior, characterized by some resonance frequency, can result even before an unstable power level is reached.

In Figure 8, the large loop in the third and fourth quadrants is the measured feedback in the EBR-I Mark II fuel loading which has such an oscillatory instability. The resonance frequency was roughly 0.04 cps, and it did vary with power level and other operating parameters as would be expected. This frequency is seen to be in agreement with those in Figure 8

near the negative real axis crossing. The magnitude of the $\mathbf{KG}$ product at this crossing was about 0.7 when the reactor power was 370 kW and the sodium flow was 108 gal/min.

The feedback of the Dounreay Reactor also has a contribution in the third quadrant. The frequency is again about 0.34 cps, but the magnitude is smaller by a factor of about 20 as shown in Figure 8. This very slight tendency toward instability only exists for certain operating conditions in Dounreay. This particular Dounreay measurement is for "old" fuel and a small amplitude oscillator perturbation. It is not surprising to find a different result for new and old fuels, but the strong dependence of the old fuel result upon perturbation size was very surprising.

VIII. FTR EQUIPMENT REQUIREMENTS

A reactivity oscillator is recommended for the transfer function measurements in FTR. The perturbation should be sinusoidal and should be produced by either a rotating rod containing an off-axis poison element or an undulating rod. The data analysis should be digital which requires at least an analog-to-digital converter and a magnetic tape recorder. Preliminary data analysis must be done on-line which means equipment must be available for this purpose. The analysis requirements can be met by the digital data handling system if sufficient priority for its use is available. The alternatives to the digital data handling system are a small digital computer or an analog computer. Both are small enough to be rack-mounted. The digital approach is the best.

The variability of reactivity worth is an extremely valuable feature. Thus if a rotating rod can be made with this variable feature, then this would be the recommended approach. If not, then the undulating approach would be most desirable. SEFOR, the first fast reactor to adopt the

undulating approach, will provide valuable information about the advantages and disadvantages of this approach. Variability was a key point in the SEFOR selection of this approach. The oscillating rod should be located interchangeably in either a control rod location or a test loop location. The control rod location will interfere less with experiments, but the test location will be more desirable during initial startup.

The major nuclear requirement for location of the oscillator is that a reactivity gradient exist so that the reactivity will be a function of the poison position. The rod then must be undulated or rotated with variable speed in one of several possible manners.

The specifications for the design depend heavily upon the reference reactor and the trade offs imposed and difficulties encountered in the design. For this reason, the specification of rod worth will be done in some detail and the tools necessary for repeating the procedure will be included. The choice of the flux perturbation size with respect to the total flux, requires compromise. It should be kept small to avoid non-linear effects in the measurement and it should be made large to allow easier, better, and faster measurements. The nominal value will be picked at $\delta n/n = 0.1$ for the zero-power transfer function measurement. The necessary perturbation in δk as a function of frequency is shown in Figure 9. The peak-to-peak δk to obtain the desired perturbation varies by a factor of 10. Thus, there is an incentive to build into the system a capability for changing its worth at least once during a measurement scan. If this is impossible, then the capability of changes before installation or via the mode of installation would be desirable. Adjustment during operating is in general quite difficult to do with a rotating rod, and is fairly easy to accomplish with the undulating motion.

FIGURE 9. Peak to Peak Reactivity Necessary for 10% Perturb as a Function of Frequency

Fermi's oscillator had two rods; the first built had a worth of 64, but it was found that it could not be used at high powers. The second one, built for high-power operation, had only a 2¢ worth. Each was used independently, and no attempt made to change from one to the other during a measurement. The optimum low frequency δk increases with power in a reactor with negative feedback. This is the converse of the actual Fermi rod worths.

FIR reactivity gradients as a function of radial and axial position in a two-fuel-zoned core are shown in Figures 10 and 11. At the position of maximum core gradient a value of 30 m¢/g-cm is available. There is available 75 m¢/g for a rod having an off-center peak-to-peak ^{10}B motion of 2.5 cm. Hence, 27 g of ^{10}B would be required to get a 2¢ peak-to-peak reactivity change. This value, however, is based upon a peak value in the axial direction. The average value is about 1/2 of the peak or then 54 g would be required. In the Fermi oscillator, the 2¢ rod actually required 110 g.

IX. FUNCTIONAL REQUIREMENTS AND THEIR JUSTIFICATION

The basic functional requirements for the oscillator design and their justification are listed below. This particular list is probably not all inclusive and is not meant to be a final compilation. It is instead a list based upon the needs as the author currently views them. Each requirement as listed will be followed by an indented justification.

- A. The frequency of oscillation shall be continuously variable within the range of 0.001 to 10 cps.
 - The high frequency limit, 10 cps, is required in order that both the full extent of significance feedback effects upon the transfer function and also a small portion of the asymptotic convergence back to the zero power transfer function can be measured. The latter provides an

FIGURE 10. Radial Reactivity Gradient Along Core Midplane.

FIGURE 11. Axial Reactivity Gradient Along Core Center of FTR

independent check upon the absolute equipment calibration. The low-frequency limit must be and is set on the basis of what is state-of-the-art as there will be feedback effects at lower frequencies. They are less significant, however, in that at very low frequency, marginal stability and/or even instability can be controlled via the control system. Frequencies as low as 0.0005 cps were measured at Dounreay.(7)

- B. Any frequency selected within the operating range shall be stable within +2% on a per cycle basis.
- Adequate definition of the transfer function required overall accuracy of oscillator frequencies in the order of $\pm 3\%$. This error reflects itself into 1.5% error in the amplitude of a single measurement. This must be then multiplied by 1.5 because the result represents a subtraction of two measurements or $2-1/4\%$, and then multiplied by a frequency dependent factor based upon how much the two measurements differ. The net effect is an error which will range from 5% at low frequencies to $>100\%$ at the upper limit of usable feedback information. In the frequency regions of prime importance it will be of the order of 20%. This requirement can be relaxed somewhat in the range of 0.001 to 0.005 cps if it proves difficult to meet. This has been the case in both Fermi and EBR-II. Through digital data reduction techniques, value judgments about data quality can be made and invalid data may be either corrected or eliminated with only potential losses in results of accuracy and/or measuring time.
- C. Measurement of the frequency selected shall be within $\pm 1\%$.
- The measurement should be more accurate than the adjustment as a usual matter of course, and secondly if digital data processing is used, data showing errors greater than

1% can be selectively dropped and hence through data analysis some improvement over equipment limitations can be gained.

- D. The reactivity function shall be sinusoidal with an amplitude that is variable from 1¢ to 5¢, (24 to 10¢ peak-to-peak) when it is located in an open loop test position.
- The reactivity must be variable so that the effect upon the experiment of such variation can be measured. It must be sinusoidal because the data reduction methods assume this to be the case. Circular rotation at a uniform speed of an absorbing material may be deemed adequate to meet this requirement.
- E. The amplitude selected within this range shall be stable within $\pm 1\%$.
- The reasons are the same as Item B, and the requirement of $\pm 1\%$ yields errors in the result on the order of 16% in the frequency region of prime importance.
- F. The design of the oscillator mechanism shall allow a life expectancy of the reactivity element of one year under full power conditions of the FIR with an oscillator operating period of 200 hr during that year.
- The calibration of a new reactivity element is a time-consuming operation. (If done manually it may require a week or so.) Although the actual operating period of the oscillator may be short (relative to the cycle of operation of the reactor), continued deterioration of the reactivity element during this period of reactor operation must be limited in such a manner that total life of the reactivity element is one full year.
- G. The oscillator mechanical hardware shall be physically compatible with both the reactivity control positions and the contact instrumented test positions.

The actual location of the oscillator within the core will depend upon the availability of positions. The FTR configuration allows the installation of through-the-head components at the reactivity control positions and test positions. In order to ensure the availability of space for the oscillator, it must be compatible with either of these positions.

- H. Provisions must be made to indicate the static position of the reactivity element at eight equally spaced positions in its normal travel. These eight positions shall be accurate to within 1/2% exclusive of backlash. Dynamic positions shall be indicated at least once per cycle within 1/2%. The sensor shall be compatible with the recording instrumentation used to determine the transfer function.
- The position of the reactivity element when the oscillator is static is required to calibrate the worth values of the oscillator. Traces of the position of the reactivity element with respect to time are also required during operation of the oscillator in order to confirm the transfer function of the FTR.
- I. Equal capability shall be provided for forward and reverse rotation of the drive mechanism.
- The capability of the drive mechanism to rotate in either direction is required to establish the operational characteristics of the mechanism. Backlash is one of the major characteristics necessary in order to calibrate the mechanism.
- J. Each component of the oscillator mechanism shall be capable of operation in all environments of the FTR from zero to full power operation.

- To adequately assess the power feedback characteristics the oscillator must operate and the transfer function must be determined at several power levels of the FTR.
- K. The system, exclusive of the reactivity element, shall be designed for an operating lifetime of 4000 hr at full power conditions.
- It is estimated that the oscillator mechanism will be used at the rate of four times per year with a recalibration required once a year. The 4000 hr of operational life will suffice for approximately seven years of total operational life.

X. CONCLUSIONS

The stability of the FTR should be confirmed by experiment during startup. The theory of fast reactor stability is not sufficiently well developed to guarantee a priori prediction of a stable system.

A reactivity oscillator and the oscillation method most nearly meets the FTR requirement to utilize state-of-the-art techniques. If for some reason, measurements become a routine requirement, then less-time consuming but perhaps less accurate techniques should be investigated. An adjustable reactivity worth of the perturbation is an important feature hence very serious consideration should be given to using an undulating rod instead of a rotating one if such an adjustment proves difficult for the rotating type. For this reason, the SEFOR work -- the first recent attempt to use an undulating rod -- should be watched closely.

The most desirable locations for the oscillator rod (in the order of preference) are a normal control rod position, a special position probably identical to the control rod position, or an open loop position. The processing of the data can best be done digitally, and on-line data processing should be done to confirm data quality.

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