Accuracy of Fuel Motion Measurements Using In-Core Detectors*

by

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An initial assessment has been made as to how accurately fuel motion can be measured with in-core detectors. A portion of this assessment has involved the calculation of the response of various detectors to fuel motion and the development of a formalism for correlating uncertainties in a neutron flux measurement to uncertainties in the fuel motion.

Initially, four idealized configurations were studied in one dimension. These configurations consisted of

1. A single fuel-pin test using ACPR
2. A seven fuel-pin test using ACPR
3. A full subassembly (271 pin) test using a Class I ANL-type SAREF
4. A full subassembly plus six partial subassemblies (~ 1000 pin) test using a Class III GE-type SAREF

It was assumed that melt would occur symmetrically at the center of the test fuel and that fuel would therefore disappear from the center of the geometry. For each case a series of calculations was performed in which detector responses were determined at several radial locations for the unperturbed core and for the core with various fractions of the fuel replaced with Na. This fuel loss was assumed to occur essentially instantaneously such that the power level in the remaining portion of the test fuel remained unchanged from that of the initial unperturbed condition.

Three types of detectors have been considered for the purpose of comparison:

1. An isotropic detector with a flat energy response
2. A 2π detector with a flat energy response, the active hemisphere being directed radially inward
3. An isotropic detector with a U^{238} fission cross section response

These responses are believed to be reasonable for representing a possible range of application for in-core detection.

Figure 1 shows the ratio of the detector response in the perturbed configuration to that in the unperturbed configuration, ϕ/ψ, vs the fraction of total test fuel mass which has disappeared, $\Delta m/m$, for the 1-pin experiment on the ACPR. Only isotropic U^{238} and flat-response detectors are shown. Radial positions vary from 0.56 to 4.5 cm from the center of the test pin. A steep negative slope indicates a sensitive response to fuel motion. Thus the detectors closest to the pin are the most sensitive to fuel motion. In addition, the U^{238} response detector is more sensitive to fuel motion than the flat response detector. This is due to the energy discrimination afforded by the U^{238} fission threshold. Note that at 20 percent fuel motion (i.e., 20 percent of the volume of the fuel in the pin has vaporized or otherwise disappeared from the calculation) the most sensitive detector signal has fallen about 6 percent below its unperturbed level.

Figure 2 shows the analogous results from the seven-pin ACPR experiment. Again, isotropic U^{238}-fission and flat-response detectors are assumed, and again the U^{238} detector is seen to be superior. Radial locations from 0.464 to 4.5 cm are shown, the 0.464 cm location being between the central pin and the surrounding six pins. Note that for the most sensitive detector in this 7-pin case, a 20 percent fuel loss results in a signal decrease slightly in excess of 10 percent.

For both of these hypothetical ACPR experiments it is apparent that all detectors shown will see a relatively high background neutron flux from the driver core. This is inherent in a test such as this since the test fuel mass is necessarily small compared with the driver core, and its signal correspondingly so. Such a disparity between the signal and background can be minimized by placing the detectors close to the test fuel and by tailoring the experimental configuration in some way so as to shield the detector from the driver core. No attempt was made in the calculations performed here to minimize the background inside the test region and it is believed the present results can be improved without great expense.

The corresponding curves for a 2π flat-response detector have not been processed in time for this presentation. It is expected that such detectors will have responses similar to the isotropic U^{238} response shown here. Optimization of in-core detector schemes for use in an ACPR experiment of the present type will require additional studies on candidate detectors and on the tailoring of the geometry to reduce the background.

Figure 3 shows detector response curves for the full subassembly test in the Class I SAREF. Detector radial locations vary from 0.5 to 9.9 cm; i.e., from points deep within the pin matrix to points several cm outside the test hex. The value of placing detectors inside the fuel pin matrix is apparent from this figure. At 20 percent fuel loss the 0.5 cm U^{238} detector signal falls by over 30 percent while the signal for a U^{238} detector located outside the test hex falls by less than 3 percent at the same fuel loss. A 2π flat response detector located outside the test hex shows a signal decrease of about 4 percent under the same conditions.

Obviously the interpin U^{238} detector offers interesting possibilities for measuring fuel motion in large-scale tests. Conversely, in this full subassembly configuration, any detection system viewing the test core from the outside suffers from a severe lack of sensitivity to fuel motion.

Figure 4 shows a similar set of detector response curves for the Class III SAREF with a full test subassembly and six partial subassemblies. In this figure $\Delta m/m$ refers to the fraction of fuel lost from the central test hex only; no fuel loss is considered from the partial subassemblies.

As before, the interpin U^{238} detectors show far more sensitivity to fuel motion than do the others considered. The most sensitive detector shows about a 28 percent drop in signal for 20 percent fuel motion, which is very close to the result obtained for the Class I SAREF.

Having examined in-core detectors in one dimension, and having found somewhat favorable results, a series of two-dimensional calculations was undertaken to provide additional information. The two-dimensional analysis considered only the Class III SAREF with full test subassembly and six partial subassemblies in the test region. The unperturbed case and two perturbed configurations were examined. Normalization between configurations was based on the assumption that the power level in the test core remained unchanged.

Unlike the one-dimensional calculations, the two-dimensional studies require the use of an a priori model of the fuel motion. Without presuming to judge the merits of one model over another, a model which might be described as the "toothpaste tube" model was used for the present study. That is, the fuel was assumed to melt and vaporize at the center of the core, the vapor pressure rupturing the clad at the top of the active fuel region and forcing the molten fuel to squirt out at that point. Thus fuel is rapidly transported from the center to the top of the core and is distributed there within the coolant channels in some manner. For present purposes, fuel was assumed to be forced out of the inner seven layers of pins, to fill the coolant channels in the lower part of the upper axial blanket first and then begin filling the upper part of the test core and the top of the upper axial blanket, depending on the amount of fuel being moved.

Detector responses to such fuel motion are included in Figure 5 which shows vertical transits at three different radii for U^{238} detectors when about 6.5 percent of the fuel mass of the central hex has moved. The initial and final fuel configurations assumed are shown diagramatically on the left; the detector responses are shown on the right. The maximum relative response occurs in the upper blanket region where the fuel is deposited. The meaning of the double peak in the detector responses in this region is unclear. It may not be physical but rather be the result of a numerical problem in the calculation.

Figure 6 shows the same data when about 12 percent of the core mass has moved. Again the largest proportional response occurs in the axial blanket with the most sensitive response being given by the detector located closest to the core axis. The profile of the displaced fuel is followed in general by the detectors; however, all sharp edges on the fuel density are blurred over, giving a greatly smoothed profile. One may conclude that pinpointing the location of the fuel motion and its density profile based on measurements such as these will be a difficult task; however, an axial resolution of about ±5 cm and a radial resolution of about ±0.5 cm should be possible.

These two-dimensional data can be put into a form similar to the one-dimensional results presented earlier. This has been done in Figure 7 in which the detector response vs $\Delta m/m$ is shown for various interpin detector locations. The abscissa here goes only to 12 percent but at this level the response of the most sensitive detector in the depletion region has dropped by about 40 percent from the unperturbed case. Correspondingly, the response of the most sensitive detector in the fuel deposition region has increased by about a factor of 5. Therefore the tentative conclusion that in-core detection of fuel motion is a potentially viable scheme for multiple subassembly tests is supported by preliminary two-dimensional studies.

An approximate formalism has been developed for correlating detector response with fuel motion. It can be shown that a linear detector located at the center of the fuel depletion region in the two-dimensional model considered here, and measuring the neutron flux to an accuracy of ±10 percent, should be able to detect fuel losses on the order of 2 percent of the total central hex mass. At fuel-motion levels of 10 percent such a detector should be able to measure the motion quantitatively roughly to within a factor of 2. If n(independent) measurements of the flux in the vicinity of the fuel motion are correlated by an unfolding technique such as that described in the previous talk, this error should decrease as $1/\sqrt{n}$; i.e., 100 detectors should reduce the uncertainty in the measured mass of moving fuel from a factor of two to about ±20 percent. Larger fractional fuel motion should be measureable to correspondingly greater precision.

To summarize: accurate in-core detection of fuel motion in experiments involving a large number of pins appears at this state of the analysis to offer an improvement in sensitivity of fuel-motion detection compared with systems viewing the core from outside the test chamber, and thus to be viable from a theoretical point of view. The desirable attributes for such a detection scheme are:

1. High-energy response detectors
2. Detectors located within the fuel pin matrix at axial locations along the full length of the core, including the axial blankets
3. Additional detectors, possibly 2π, located outside the fuel assembly to correlate gross fuel motion particularly in case of loss of signal from interpin detectors following fuel melt.

Specific details of the candidate detectors will be presented in the next paper.

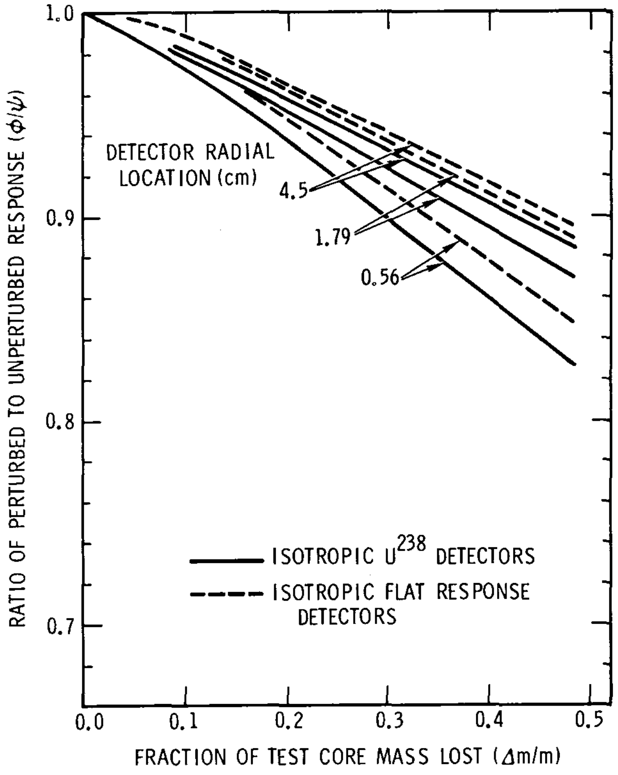
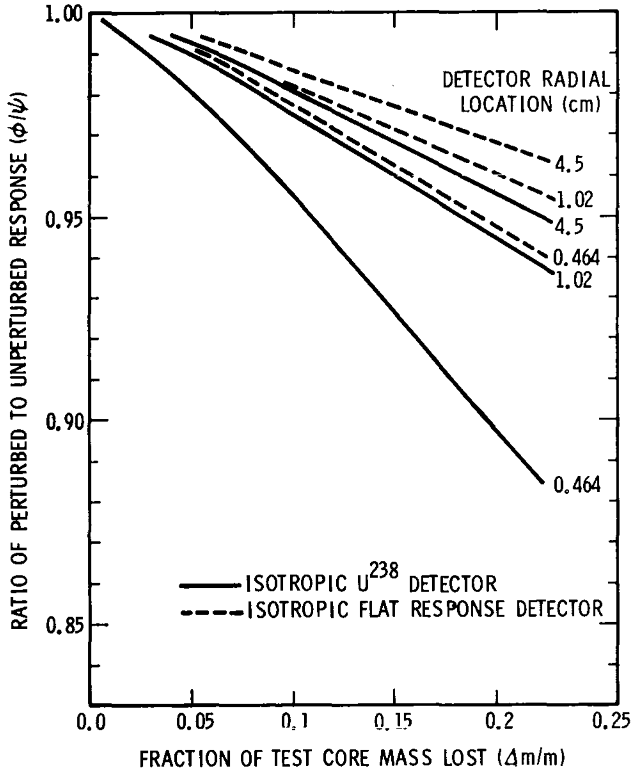


Figure 1. Detector Response to Fuel Motion in a One-Pin ACPR Experiment

Figure 2. Detector Response to Fuel Motion in a 7-Pin ACPR Experiment



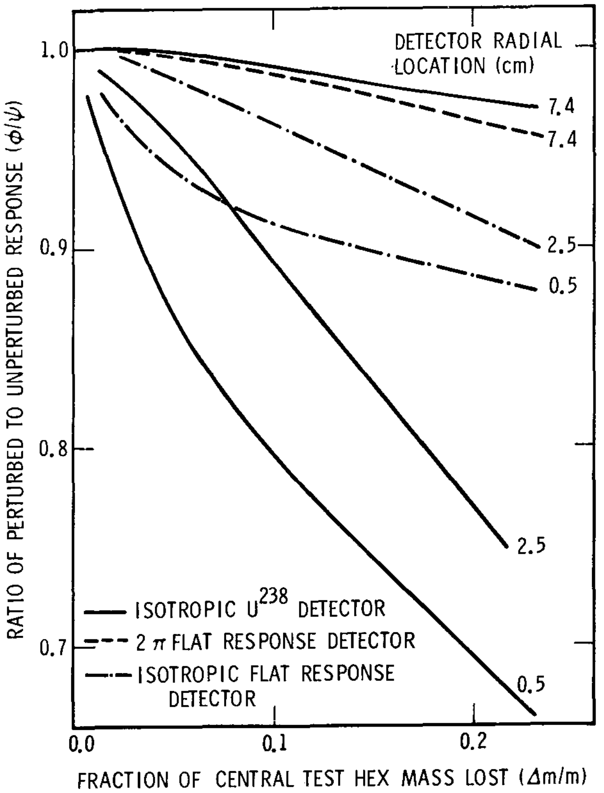


Figure 3. Detector Response to Fuel Motion in a Class I SAREF Reactor

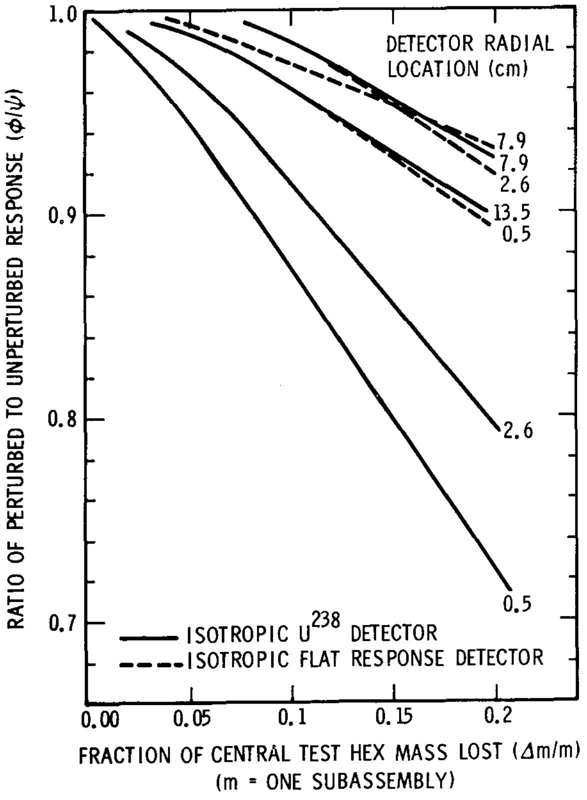


Figure 4. Detector Response to Fuel Motion in a Class III SAREF Reactor

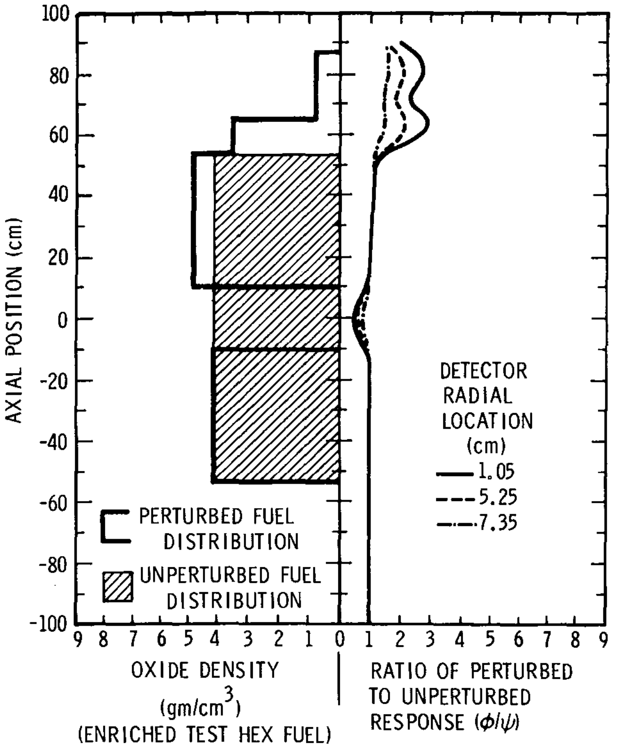


Figure 5. Detector Response to 6.48% Fuel Motion (Central Hex) in a Class III SAREF Reactor

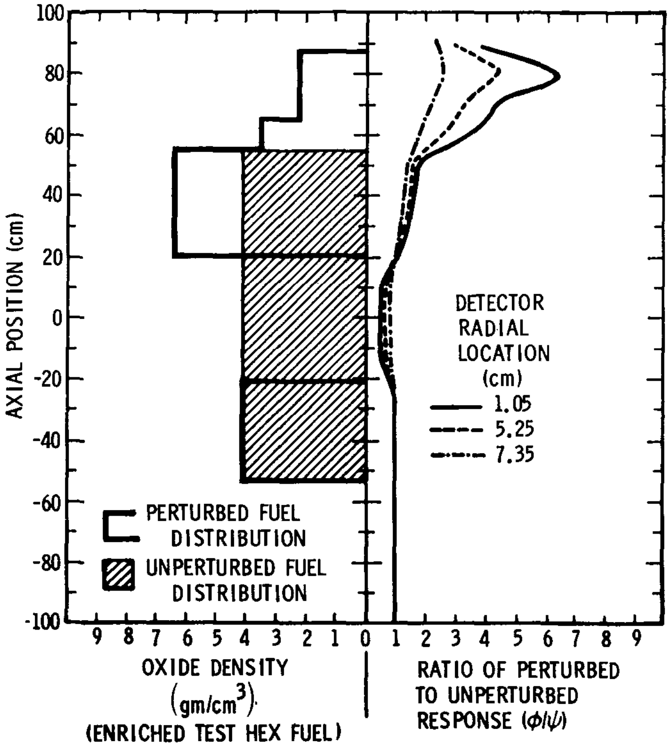


Figure 6. Detector Response to 12.25% Fuel Motion in a Class III SAREF Reactor

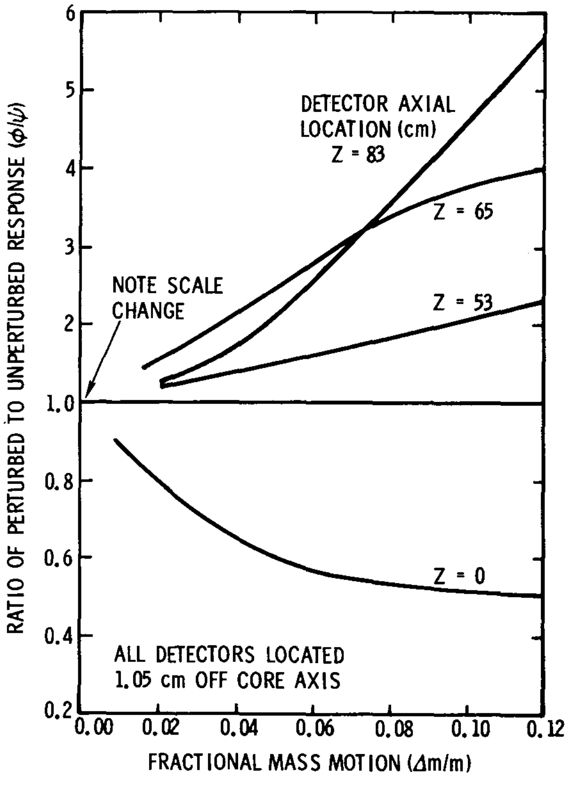


Figure 7. Detector Response to Fuel Motion in a Two-Dimensional Class III SAREF Reactor