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ADVANCES IN CLAD BLOCKAGE DETECTION*

By

C. L. Fink, A. De Volpi and G. Stanford

Reactor Analysis and Safety Division
Argonne National Laboratory
Argonne, Illinois 60439

ABSTRACT

The use of high energy (> 6 MeV) capture gamma rays as a means of detecting steel movement in a transient test has been investigated. Experimental results for steady state reactor operation indicate that this method is capable of providing a reasonably unique signature of steel. In addition, the signal-to-background ratio of an R-series 7-pin test capsule was measure to be approximately 0.6 for 1 cm^3 of steel. It is estimated that this value will permit a time-resolved steel detection capability of $\sim$0.2 cm^3. Implementation of this method to the 122-cm hodoscope required a minimum of modifications, and preliminary results using this array support a steel detection capability at least to the level of blockage formation.

INTRODUCTION

During destructive tests performed on fuel pins at TREAT, steel motion can play a significant role in the subsequent course of an accident sequence. In particular, steel blockages due to clad and structure materials can prevent cooling of fuel within a test section and impede dispersal of fuel out of the core region. Consequently, the time history of steel movement is important in understanding the accident sequence of a transient and in the calibration of accident codes used in the prediction of more complicated accidents.

One major problem in the implementation of a steel motion capability is the difficulty in developing a detection method that provides a clear distinction between steel and fuel. A second problem, which also makes steel detection difficult, is the separation of the steel motion within the test section from the large constant background of steel structural components which surround the test section. At present, the most promising method for overcoming these problems consists of using the high energy (>6 MeV) capture gamma rays produced in steel. Since most of the gamma rays from the components of steel (iron, nickel, chromium) occur above 6 MeV and since the gamma rays from the fuel are concentrated at lower energies, this method appears capable of providing a distinguishing signature between steel and fuel. In addition, background gamma rays produced in the reactor core are expected to have

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an energy distribution similar to that of fuel and therefore, even if these gamma rays are scattered by the fuel, they will not contribute to a masking of the "steel" response.

The material presented in this paper deals primarily with the detection of steel motion by the use of capture gamma rays. Data taken within a reactor environment are presented on the steel-to-fuel response as well as on the signal-to-background ratio for a typical test capsule. In addition, a brief description of a gamma detection array for the new 122-cm hodoscope is briefly described together with a discussion of some of the preliminary transient results obtained.

MEASUREMENT OF THE STEEL-TO-FUEL RATIO

The data presented in Ref. 1 show that the steel-to-fuel ratio can be made greater than one. Because of the limited data available at the time, it was decided to perform a new series of measurements of this ratio using the 122-cm hodoscope. The central column of the hodoscope was scanned across a test section composed of a steel tube (2.54 cm in diameter by 0.159 cm thick) and a single R-series test pin (14% enriched UO_2 with an estimated calibration factor of 7 W/g-MW [TREAT]). Scan data were simultaneously collected using both the fast neutron detectors and a 1.27 by 2.54 cm NAI(Tℓ) detector.

The results of these scans are shown in Figs. 1 and 2 for two different gamma ray thresholds. The solid points represent the experimental data while the open circles were obtained by reflecting the experimental points from the lower gauge readings about the center of the steel tube. The difference between the reflected and experimental points corresponds to the fuel and clad contribution, and this contribution is shown at the bottom of the figures. The observed position of the fuel and clad from the gamma ray scans is in good agreement with the position of the fuel pin as given by the fast neutron scans. The division between the fuel and clad was calculated from the measured steel response at the center of the tube and is based on the assumption that the clad-to-steel response at this point is given by the ratio of the clad and steel tube thickness.

The data presented in Figs. 1 and 2 clearly show the steel response rapidly exceeding the fuel signal as the gamma ray threshold energy increases. Experimental data on the steel-to-fuel response as a function of energy are shown in Fig. 3. The test section was the same as that used in the measurements presented in Figs. 1 and 2 but the size of the NaI crystal was changed to 1.91 by 2.54 cm. In addition, the gamma ray beam was incident on the crystal in a direction perpendicular to the symmetry axis of the crystal. For convenience, the data has been normalized to a source volume of 1 cm^3 and a TREAT power of 1 MW. Figure 3 also contains a theoretical prediction[2] of the fuel and steel count rate based on the gamma ray yield of constituent elements at thermal energies.

Considering the simplicity of the theoretical model and the difficulty in obtaining the experimental data, the agreement between theory and experiment is reasonable. The largest uncertainty in the model is

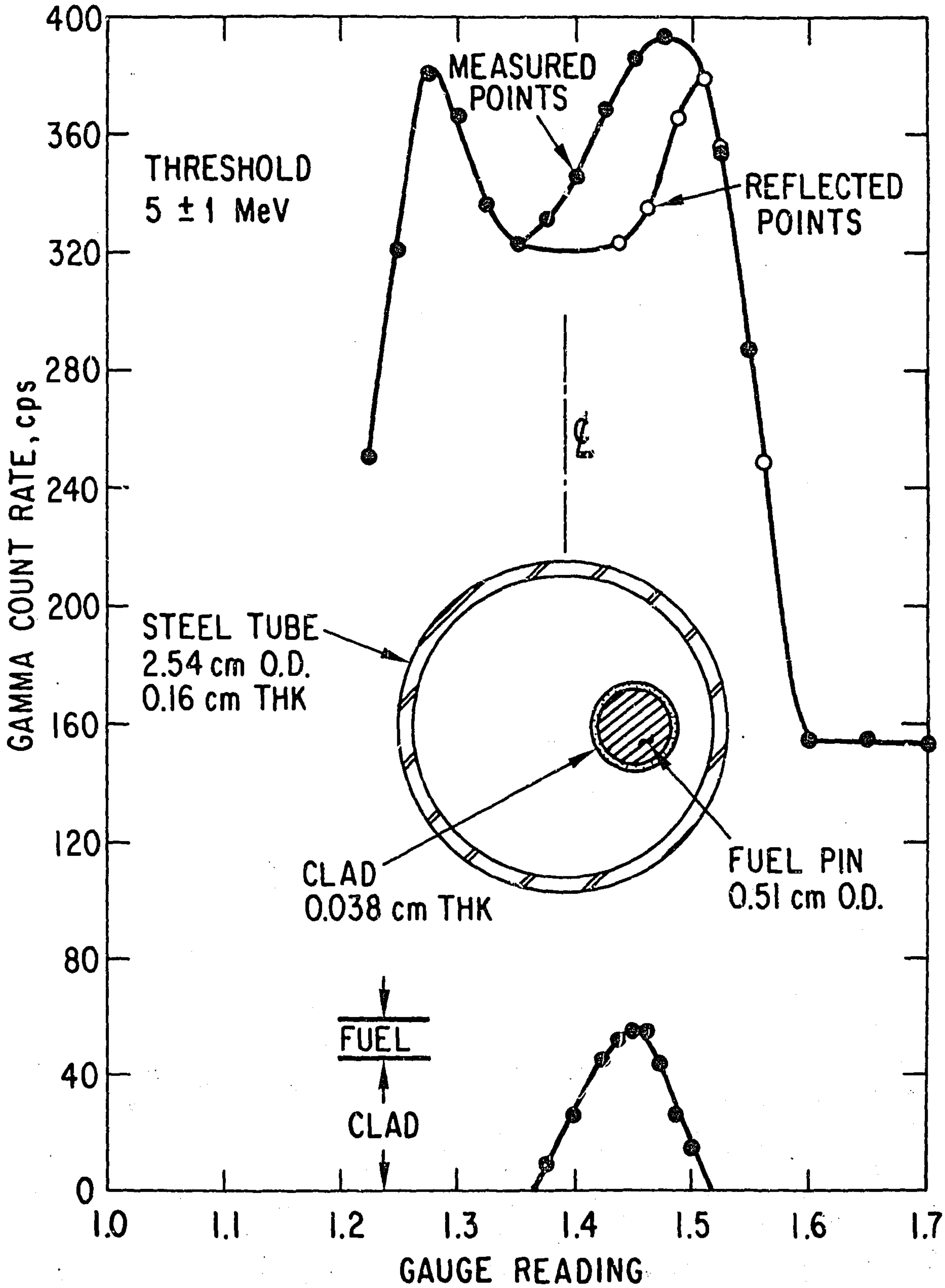


Fig. 1. Gamma Ray Scan of Steel Test Section for a Gamma Ray Threshold of 5 MeV.

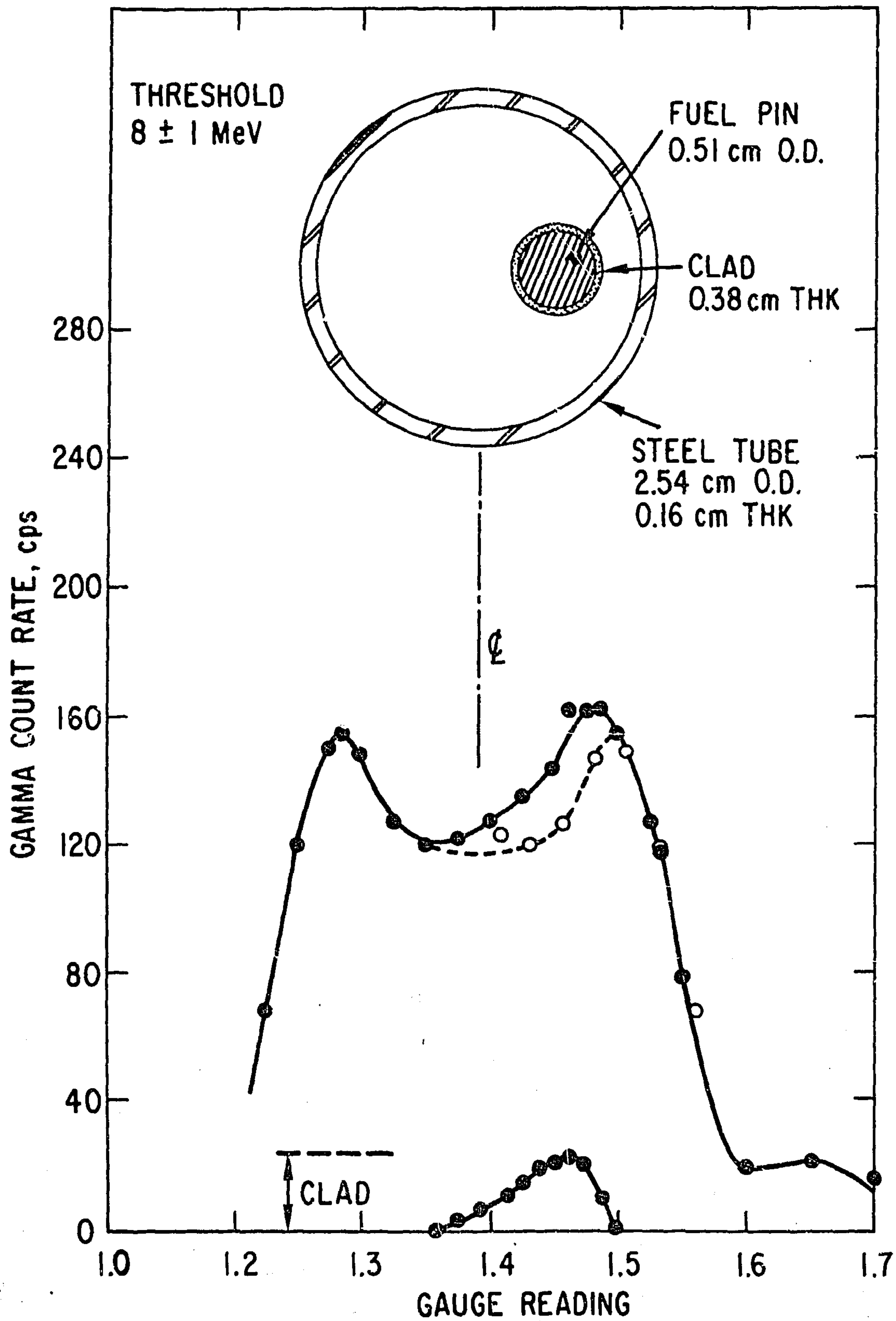


Fig. 2. Gamma Ray Scan of Steel Test Section for a Gamma Ray Threshold of 8 MeV.

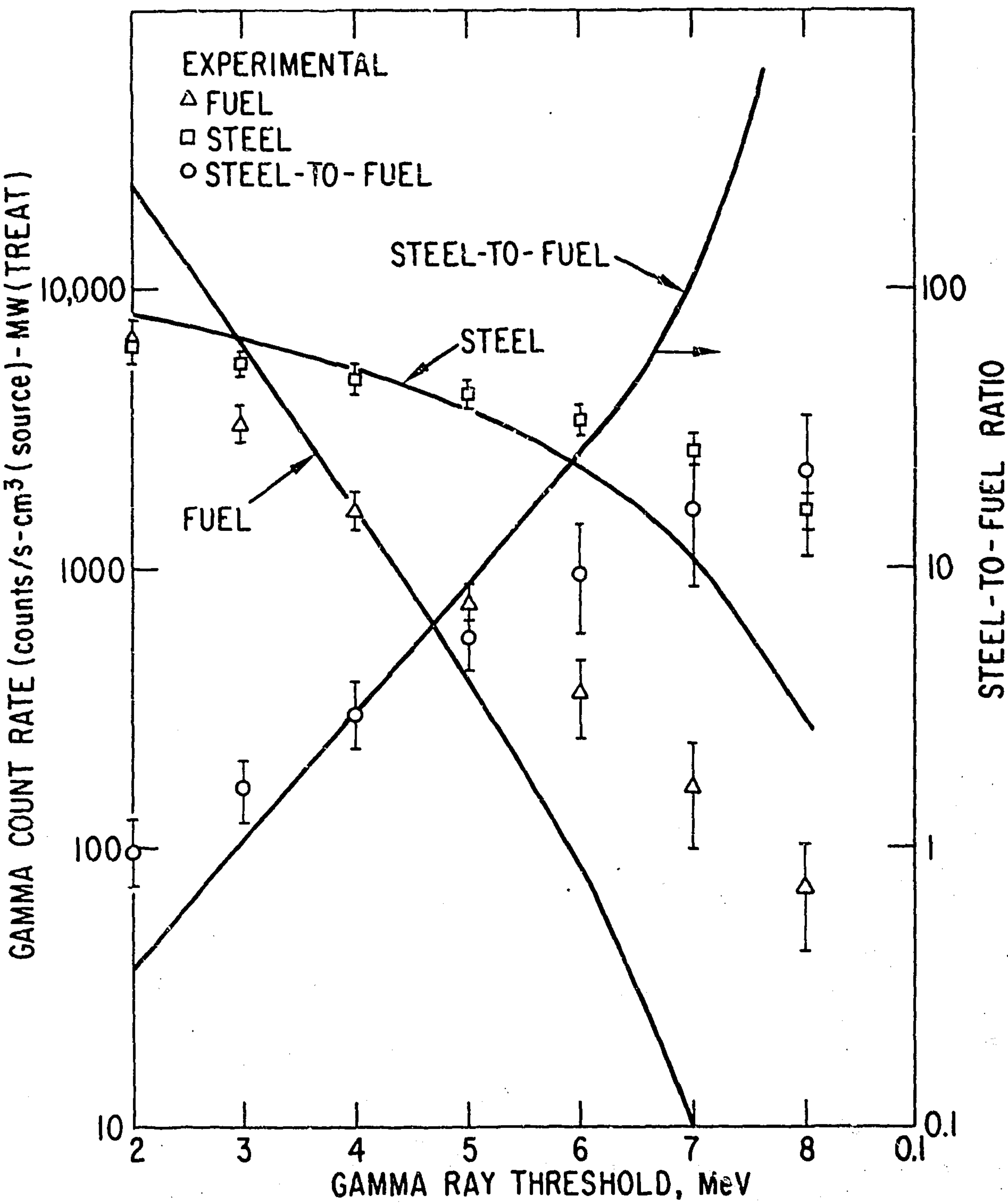


Fig. 3. Calculated and Measured Gamma Ray Count Rates for Steel, Fuel and the Steel-to-Fuel Ratio as a Function of the Gamma Ray Threshold Energy.

in the gamma ray efficiency of small NaI detectors at high threshold energies. In particular, variations in the assumed pulse height distribution of monoenergetic gamma rays in the crystal can change the calculated results by a factor of 2 to 4.

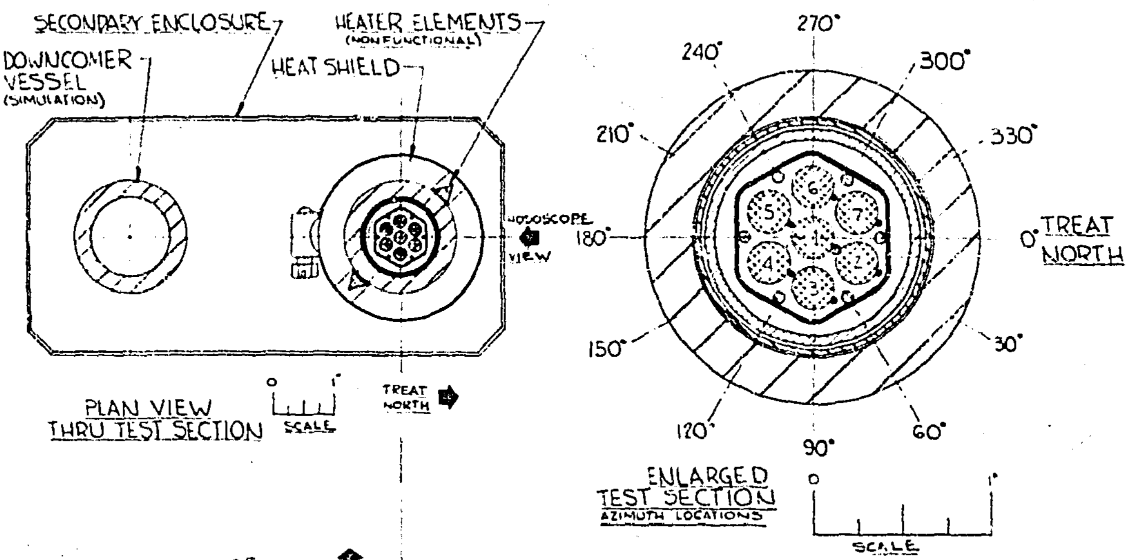
The calculations and data of Fig. 3 demonstrate that the steel response dominates the fuel response as the gamma ray threshold increases. Also the slow decrease in the steel response allows the use of high threshold energies without a significant reduction in the measured count rate. Using an 8 MeV bias as a typical value, results in a steel-to-fuel ratio of approximately 20 for a 14% enriched R-series fuel pin. As the enrichment of the fuel pin increases, this ratio will decrease, but even in the case of a 65% enriched pin, the expected steel-to-fuel ratio will still have a minimum value of 4. The value of the steel-to-fuel ratio sets a lower limit on the minimum amount of steel movement which can be directly detected when there is significant fuel motion. Since the neutron detectors are sensitive only to fuel motion, however, this lower limit can be extended by analytic treatment of the data.

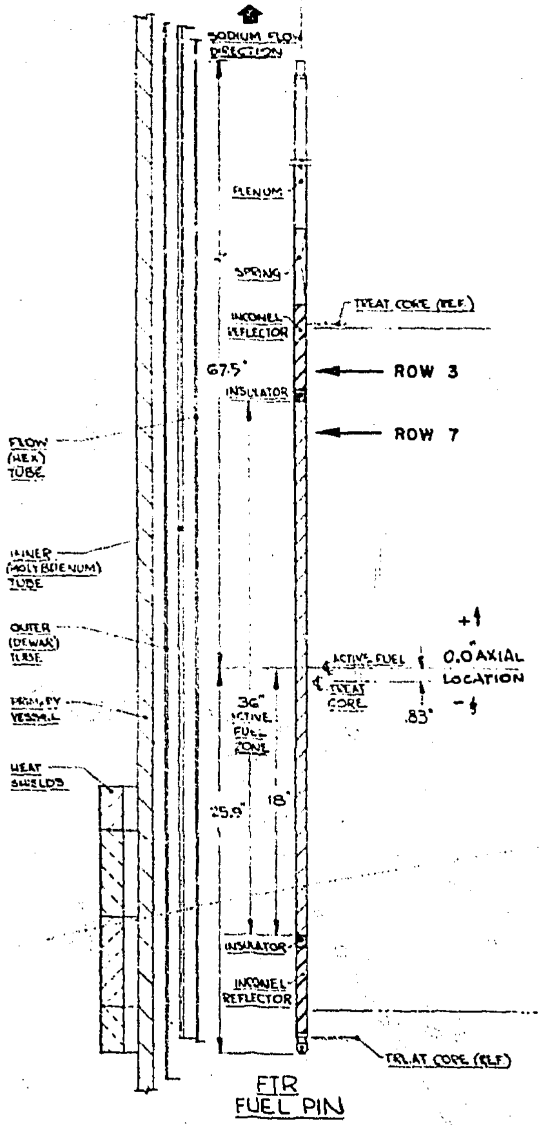
SIGNAL-TO-BACKGROUND RATIO

One of the most important physical parameters in determining the detectability of steel motion in an actual transient situation is the signal-to-background (S/B) ratio. Because of statistical limitations on the number of counts collected, the S/B ratio sets a limit on the time interval over which data must be collected in order to be statistically certain that a given volume of steel has moved. Also from a practical point of view, a small S/B ratio may result in small spurious effects masking steel motion. Examples of such effects are: drifts in the electronic gain of the detection device with time or reactor power, variations in the calibration factor within the test section as fuel motion begins, and possible spatial changes in the background due to variations in the flux within the core of the reactor.

A series of measurements were made of the S/B ratio of the R-series test capsule when positioned inside the TREAT reactor. The S/B ratio was measured by performing a gamma ray scan of the test loop for two different axial positions of the 7-pin fuel assembly. The two positions corresponded to a location in which the fuel pins contained UO_2 fuel pellets and a location in which the UO_2 fuel pellets had been replaced by Inconel reflector rods. A schematic of the R-series test loop and the positions of the axial scans are shown in Fig. 4. The positioning of the loop in the reactor was such that both the primary containment vessel as well as the downcomer vessel were in the hodoscope line of sight. The total wall thickness of these two tubes was 2.8 cm.

The results of the scans are shown in Fig. 5. The reactor power was 80 KW and the data was collected using the gamma detection array described in a subsequent section of this paper. It is estimated that a single hodoscope channel subtends approximately 1 cm^3 of material from the 7 test pins when centered on the test section. Thus, the results from row 3 indicate that under these conditions the S/B ratio for 1 cm^3 of steel is 0.6 ± 0.2. Note that the background includes both fuel and steel contributions.





MONITOR WIRE LOCATIONS

INNER WIRES OUTSIDE SURFACE OF HEX FLOWTUBE							OUTER WIRES OUTSIDE SURFACE OF PRIMARY VESSEL						
I.D. NO.	AXIAL LOC. (IN)	AZIMUTH LOC. (DEG)	RBCAL -1	-2	-3	-4	I.D. NO.	AXIAL LOC. (IN)	AZIMUTH LOC. (DEG)	RBCAL -1	-2	-3	-4
-1	0	0	x	x	x	x	-41	0	0	x	x	x	x
-2	0	30					-42	0	30	x			
-3	0	60	x	x	x	x	-43	0	60	x	x	x	x
-4	0	90					-44	0	90	x			
-5	0	120	x	x	x	x	-45	0	120	x	x	x	x
-6	0	150					-46	0	150	x			
-7	0	180	x	x	x	x	-47	0	180	x	x	x	x
-8	0	210					-48	0	210	x			
-9	0	240	x	x	x	x	-49	0	240	x	x	x	x
-10	0	270					-50	0	270	x			
-11	0	300	x	x	x	x	-51	0	300	x	x	x	x
-12	0	330					-52	0	330	x			
-13	20	120	x				-53	20	120	x	x	x	x
-14	18	"	x				-54	18	"	x	x	x	x
-15	16	"	x				-55	16	"	x	x	x	x
-16	14	"	x				-56	14	"	x	x	x	x
-17	12	"	x				-57	12	"	x	x	x	x
-18	10	"	x				-58	10	"	x	x	x	x
-19	8	"	x				-59	8	"	x	x	x	x
-20	6	"	x				-60	6	"	x	x	x	x
-21	4	"	x				-61	4	"	x	x	x	x
-22	2	"	x				-62	2	"	x	x	x	x
-23	-2	"	x				-63	-2	"	x	x	x	x
-24	-4	"	x				-64	-4	"	x	x	x	x
-25	-6	"	x				-65	-6	"	x	x	x	x
-26	-8	"	x				-66	-8	"	x	x	x	x
-27	-10	"	x				-67	-10	"	x	x	x	x
-28	-12	"	x				-68	-12	"	x	x	x	x
-29	-14	"	x				-69	-14	"	x	x	x	x
-30	-16	"	x				-70	-16	"	x	x	x	x
-31	-18	"	x				-71	-18	"	x	x	x	x
-32	-20	"	x				-72	-20	"	x	x	x	x

MONITOR WIRE IDENTIFICATION:
RBCAL-1-5 (TYPICAL)
WIRE NUMBER
TEST NUMBER

Fig. 4 Cross Sectional View of the R-Series Test Capsule

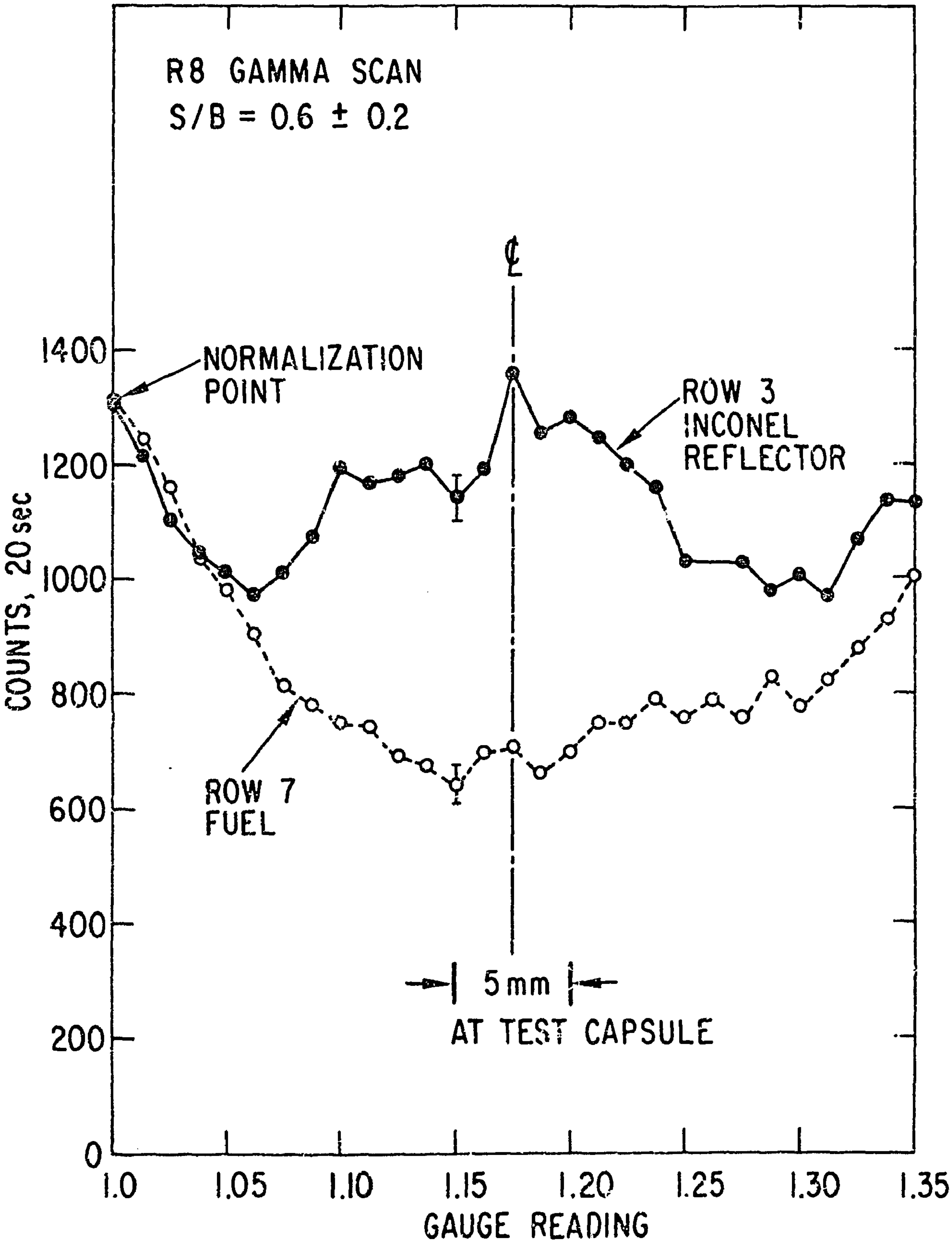


Fig. 5. Gamma Ray Scan of the R8 Test Capsule at a Reactor Power of 80 kW.

Since this value is approximately a factor of 2 larger than would have been predicted using the thickness of the relative materials, there is a considerable reduction in the steel background due to flux and gamma ray attenuation in the surrounding steel structure.

Another interesting feature of Fig. 5 is the insensitivity of the gamma ray detector in row 7 to the fuel present at this position. This result adds confirmation to the steel-to-fuel ratio results presented in the previous section.

It is interesting to estimate the maximum amount of steel motion, which can be time-resolved, by using experimental results from the fast neutron detectors. The minimum S/B ratio for the Hornyak buttons has been determined to be approximately 0.12 for a 7-pin test assembly. This corresponds to approximately 0.5 g of fuel. If the assumption is made that steel detectors have the same minimum S/B, then the smallest amount of steel which we would expect to detect is approximately 0.2 cm^3 per channel. For reference, the volume of clad subtended by a single hodoscope channel, when centered on a single fuel pin, is 0.1 cm^3.

It should be noted that this discussion is based on statistical considerations and does not attempt to take into account other spurious effects which might tend to increase this minimum volume.

A GAMMA DETECTION ARRAY

Since a large steel-to-fuel ratio was achieved in a steady state reactor environment, it was possible to proceed to a transient test. Because of a limit on the number of data channels which could be handled by the present recording system, the number of gamma channels was restricted to 108. This is not a significant limitation, since this number of channels permits coverage over the three central hodoscope columns. These three columns in turn provide a complete coverage of the fuel test section in a 7-pin test although penetration of the flow tube at the extreme lateral edges is not covered. The interface problems of this array with that of the fast neutron array were reduced by using the same electronic boards, power supplies and photomultiplier tubes for the gamma and neutron detectors. Because of positioning and calibration problems, the gamma array was placed between the hodoscope collimator and the Hornyak button detector enclosure. A picture of the array, before the enclosure covers were installed, is shown in Fig. 6. Since there is only a limited space in this region, it was necessary to have the gamma ray beam incident on the crystal in a direction perpendicular to the crystal's symmetry axis. The crystal dimensions were chosen as 1.91 x 2.54 cm in order to provide a complete coverage of the collimator channel and in order to fit directly onto the 1.91 cm photomultiplier tube. The entire assembly is encased in 1.3 cm of lead which in turn is covered with cadmium. Fabrication and installation of the gamma detection array required approximately three months and the array was first used for transient R8.

PRELIMINARY TRANSIENT RESULTS

While a detailed analysis of the gamma detection array results for

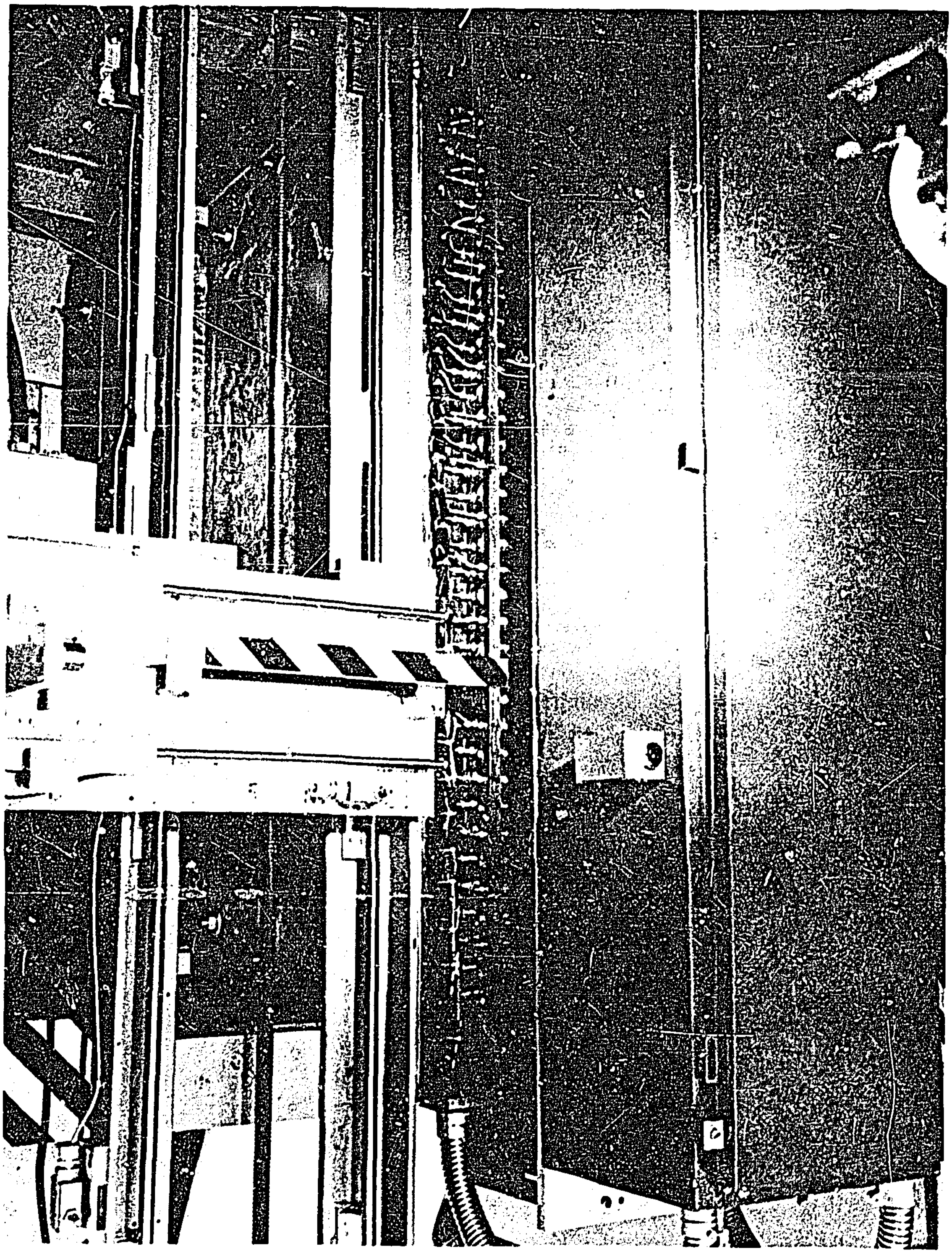


Fig. 6 Photograph of the Gamma Detection Array for the 122-cm Hodoscope before the Back and Side Enclosures were Installed.

transient test R8 has not been completed, certain general observations can be made. The most important observation is that steel motion was detected in R8 and that the gamma ray detectors do not appear to be unduly sensitive to fuel motion. There were systematic effects, however, which tended to mask the steel motion. Most of these effects occurred as slow variations in the detector response as a function of time. While some of these variations may have been due to electronic gain changes, the majority appear to be due to variations in the background emitted by the structure material surrounding the test section. These variations can be corrected analytically but they do complicate the unraveling of steel motion.

SUMMARY

Experimental results described in this paper have shown that high energy capture gamma rays are capable of providing a reasonably unique signature for steel placed in a typical test capsule. The results also indicate that the signal-to-background ratio of an R-series 7-pin test assembly is approximately 0.6 for 1 cm^3 of steel and that this value is expected to allow a time-resolved steel capability of 0.2 cm^3. Implementation of this technique to the present hodoscope required a minimum of modifications. Finally, preliminary results have been obtained which appear to support a transient steel detection capability at least to the level of blockage formation.

REFERENCES

1. A. De Volpi, C. L. Fink and R. R. Stewart, "Monitoring Clad Blockages," Information Exchange Conference on Reactor Fuel- and Clad-Motion Diagnostics, Nov. (1975).

2. S. T. Cheng, "Steel and Fuel Gamma Ray Response Rates," Resident Summer Associate Report, (Summer, 1976).

Advances in Clad Detection

ADDENDUM 1

An additional problem in the analysis of steel movement under transient conditions is caused by changes in the flux depression due to fuel when significant axial motion of fuel occurs. In particular it has been observed that as fuel slumped axially in R8, the increase in flux in the steel containment vessel at the voided elevation produced a fictitious movement of steel into this axial region. This effect would be expected to be largest for the R-series test train since there was no thermal filtering and thus flux depression effects may be larger than when neutron filtering is used. Further investigation will be necessary before a quantitative decision can be made on the observation of steel blockages when significant axial motion of fuel occurs. The results from preliminary analyses of R8 do indicate, however, that steel blockage detection is possible before significant axial motion of fuel begins.

Since the movement of fuel is directly monitored by the neutron detectors, in principle it would be possible to apply a model-dependent correction which relates neutron flux (and hence the specific rate of neutron capture in the steel) to the measured data.