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Time-Resolved and Time-Integrated Radiography of Fast Reactor Fuel Elements*

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ABSTRACT

The fast-reactor safety program has some unusual requirements in radiography. Applications may be divided into two areas: time-resolved or time-integrated radiography. The fast-neutron hodoscope has supplied all recent time-resolved cineradiographic in-pile fuel-motion data, and various x-ray and photographic techniques have been used for out-of-pile experiments. Thick containers and the large number of radioactive fuel pins involved in safety research have been responsible for some nonconventional applications of time-integrated radiography of stationary objects. Hodoscopes record fuel-motion during transient experiments at the TREAT reactor in the United States and CABRI in France. During these power transients, fuel elements are nondestructively and destructively irradiated within containment vessels positioned at the center of the reactors. Because of the particularly hostile environment (high ambient radiation background and thick-walled containers), fast neutrons from fission are used as the detected radiation. The operational parameters of the hodoscope system are characterized by time resolution of 1 ms, space resolution in the order of 1 mm, mass resolution of about 0.1 g -- for reactor transients that last from 0.3 to 30 s. The data accumulated during a transient is stored on digital magnetic media and analyzed after the experiment. The hodoscope may also be used for in-situ time-integrated fast-neutron and gamma-ray radiography. Other special techniques have been under development for out-of-pile nondestructive radiography of fuel element subassemblies, including fast-neutron and gamma-ray tomographic methods.

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FUEL-MOTION DIAGNOSTICS

The safety of nuclear reactors is dependent in part upon the inherent and engineered design of fuel elements that, if they fail, will not add substantial uncontrollable reactivity to the core. Extensive static and dynamic testing of fuel elements has taken place at many laboratories throughout the world. In particular, in-reactor transient tests of fuel pins have been conducted routinely at the United States Department of Energy reactor TREAT in Idaho since 1958 [1].

The fast-neutron hodoscope is a diagnostic instrument developed for the purpose of monitoring the motion of fuel during reactor safety experiments. Such experiments consist essentially of placing one or more fuel pins in a container or coolant loop that is centered in the TREAT core. The fuel is then subjected to a reactor burst of neutrons and gamma rays that induce fissions in the fuel. The fuel being tested, which is placed at the center of the reactor core, emits fission and capture radiation caused by a burst of reactor neutrons; the emitted radiation can travel unimpeded through an opening in the core to the fuel-motion diagnostic instrumentation that is installed in the biological shield. In recent years tests have focused on nuclear fuel for fast reactors.

In order to accommodate fuel-motion diagnostic systems, clear visual access to the center of core was provided in the reactor facility design. The hodoscope is mounted outside the core (as shown in Fig. 1), aimed towards the test section at the center. Each test section (for example, Fig. 2) is enclosed in multiple barriers which prevent radiation leakage. Tests performed to date have had up to seven fuel pins.

The reactor burst can be programmed through four decades of power for a time duration ranging from 0.1 to 100 s. The energy input to the test fuel can easily be sufficient to destroy its integrity, resulting in clad failure and extensive fuel relocation.

The instrumentation task is defined by the experimental conditions. The fuel element or elements for in-pile experiments are normally placed in a thick-walled (1 to 3 cm) steel vessel or loop. The diagnostic instrumentation must be located out of the reactor core in order to survive the burst and avoid undue background effects. Because of the brief duration of the transient, the recorded data is not analyzed until after the transient.

Experiment objectives include measurement of the amount of fuel disturbed by the fission burst, the time and location of displacement, and the velocity of fuel. In a typical transient the cladding around the fuel often fails and some of the fuel melts. Mass resolution should be in the order of a few tenths of a gram, time resolution of a millisecond or so, and spatial resolution in the range of a millimeter, more or less.

A relatively unique aspect of in-pile fuel-motion cineradiography is the need for quantitative data; although qualitative phenomenological observation and visualization of processes is of importance, the precise and accurate determination of fuel mass movement is the dominant objective [2]. Achievement of the combined resolution in space, time, and areal density that is needed places demands upon the design and operation of the instrumentation system that are not encountered in other forms of diagnostics.

The hodoscope performs these objectives by measuring high energy fission neutrons originating in the induced fission process within the fuel. The major constituents of the hodoscope system are subsystems for collimation, detection, signal processing, data recording, and analysis.

Other instrumentation is used for measurement of thermal-hydraulic conditions (flow, pressure, temperature), and the physical remains of an experiment are examined afterwards by penetrating radiography and destructive disassembly.

DESCRIPTION OF APPARATUS

The hodoscope collimator subsystem basically consists of a stack of tapered steel plates with 360 milled tapered slots. The steel plates (Fig. 3) are encased in concrete for shielding. A pivot system allows lateral translation of the collimator. Neutrons that originate in line of sight of a collimator slot opening are able to pass freely through the collimator.

A rectangular area 1.2 m high and 6.7 cm wide at the center of the reactor is viewed directly by the collimator, which is located about 3 m from the fuel being tested, as depicted in Fig. 4. A photograph of one of two hodoscope collimator systems is shown in Fig. 5.

Fast-neutron detectors are attached at the end of each slot. These detectors are relatively efficient for fission neutrons, while being highly insensitive to gamma rays. The detectors also have a wide dynamic range, having low noise level and capability to achieve high count rates.

Electronic scalers assigned to each channel collect counts for the duration of each counting interval until the data is transferred to a dedicated high-speed magnetic disk for permanent recording.

Analysis of the data requires data processing, image reconstruction, and some interpretation. Normalization must take place for instantaneous power level and for nonuniform efficiency of detectors. Corrections are applied for instrumental effects, such as deadtime and nonlinear response. Background is subtracted, based on calibration experiments and curve fitting. Compensation for inherent effects such as self-shielding and axial neutron flux gradient must be undertaken in order to quantify the fuel-mass displacement results.

The experimental data is routinely reconstructed into various image reconstructions of the original events. Because applications of hodoscope data require precise knowledge of the fuel mass involved in each displacement episode, much of the ensuing processing and analysis is devoted to quantification of the data. Consequently, the results which are presented below are selected to show a sample of the techniques of illustration and quantification. Such results are usually embodied in a series of internal reports that describe all aspects of the data treatment; eventually reports that contain a summary of data accumulated and analyzed are published by the experimenter.

Each detector in the hodoscope array responds to changes in fission density, which is directly related to fuel density and power level. Figure 6 contains graphs of the power-normalized axial component plotted as a function of time into the transient. Changes that take place when statistical significance becomes adequate are indicated by changes in the normalized count ratio. Several methods of power normalization are available, including the use of detectors focused on parts of the array that are unlikely to see fuel motion. Figure 6 is a way of presenting the large amount of data in a manner that can be compared to nuclear-reactor accident-analysis codes.

The data from all detectors may be displayed in ways that give access to an integrated view of the course of fuel motion. Figure 7 contains intensity-modulated renditions (hodographs), in which grey level density equates directly to higher fuel mass. The fuel pin is seen to undergo two-dimensional snaking that corresponds to a helical spiral in three dimensions.

In reactor safety studies, the axial component of fuel motion is frequently the property of main interest. In that case, the results of a symbolic hodograph may be summed across rows to produce a set of row-average column results, as shown in Fig. 8 The axial fuel motion trend for that experiment can be clearly seen in a quantitative manner. In these plots only changes from the reference fuel condition have been plotted, so that grey areas represent no change, dark areas are net gains, and light areas are losses of fuel.

Finally, movies can be made to convey the dynamic aspects of the experimental results. We have done this in a number of cases.

Key capabilities of the TREAT hodoscope are summarized in Tables I and II. The segmentation of the design into a large number of channels is a key factor that gives the hodoscope the simultaneous capability of tolerating large count rates, having a wide dynamic range, and discriminating against background. Each detection channel is capable of handling close to 10^6 c/s, and the selection of detectors and their operating mode permits an optimum choice to be made in terms of signal and background.

TABLE I

Hodoscope Capabilities (1.2 m collimator)

Maximum Viewing HEIGHT	1.2 m
Maximum Viewing WIDTH	7 cm
Maximum CHANNEL CAPACITY	360
Interchannel HORIZONTAL spacing	7 mm
Interchannel VERTICAL spacing	34 mm
Detectable HORIZONTAL MOTION	0.2 mm (minimum)
Detectable VERTICAL MOTION	6 mm
1-pin MASS-DISPLACEMENT RESOLUTION	0.05 g/channel (minimum)
7-pin MASS-DISPLACEMENT RESOLUTION	0.35 g/channel (minimum)
Data-collection INTERVALS	0.1 ms (minimum)
Data-interval CAPACITY	8000 intervals (maximum)
Minimum TREAT power	10 kW
Maximum TREAT power	20,000 MW
Dynamic-power RANGE	10,000

Two transient reactors in the United States (TREAT and ACRR) and one in France (CABRI) are uniquely arranged to accept high-resolution fuel-motion diagnostic instrumentation. A hodoscope that incorporates several improvements in design and instrumentation has been installed and operated since about 1978 in the CABRI reactor at Cadarache under an multi-national program. The CABRI hodoscope, though developed along the same principles as the TREAT hodoscope, has several significantly different features. It achieves more precise static location of fuel by careful design, machining, and detector selection. Published results have shown it has met design goals for high accuracy in measurement of axial fuel motion. A four-channel hodoscope was built into the PARKA facility at Los Alamos laboratory in order to measure resolution for 37- and 91-pin subassemblies.

Three types of ex-core diagnostics systems alternative to the hodoscope have reached some degree of experimental verification: flash x-ray, pinhole, and coded-aperture. There are two variations of the flash x-ray system. One depends on passing a beam of high energy x-rays (up to 20 MeV) through the test section; it requires, accordingly, a full-slot through the core. However, there are many experiments in which the reactivity loss of an additional half-slot cannot be tolerated. Flash x-ray systems have produced excellent tramsmission images of test fuel with thick surroundings, but such machines operating with a repetition rate of at least 1000 pulses/s have not been demonstrated with the beam current and reliability required. Also, high-energy x-rays cannot be used to directly distinguish between fuel and steel.

The other type of flash x-ray system encodes the beam in order to yield superior modulation, a wider field of view, and overcome the broad source and poor resolution associated with intense sources. Either a coded source or coded beam may be used.

A passive coded-aperture system for emmitted gamma radiation has been under development for over five years at Sandia Laboratories. A modified fresnel zone plate is used to modulate the radiation produced in the fuel pin at the Annular Core Research Reactor. Initial proof tests under combined transient conditions indicated a poor signal-to-background ratio. Redesign of the system has resulted in a delay in reporting fuel motion data.

A pinhole system has been developed at Los Alamos National Laboratory for application to TREAT. The design was based on security-classified results of successful pinhole application in imaging nuclear-weapons explosions during underground testing. This system has reached an advanced stage of development in application to TREAT, resulting in three direct comparative tests with the hodoscope. Some quantitative data on fuel motion external to the pin was measured by the pinhole in test PINEX-2, but internal fuel-pin motion was not detectable. In the three-pin AX-1 experiment, a non-redundant pinhole array was unable to detect any of the fuel motion that occurred.

As a result of several years of evaluation and testing, certain improvements have reached the stage of design, fabrication, and impending installation at TREAT. The most significant improvement will be the addition of an array of methane-filled high-pressure proportional counters, patterned on work at CABRI. The detectors have undergone extensive steady-state and transient proof tests. Compared to the Hornyak buttons, the proportional counters should provide a more linear response at high power.

Some points of comparison and interest may be drawn with respect to other forms of cineradiography. The instrumentation demands of in-pile diagnostics are more severe than applications in out-of-pile reactor experiments, which, lacking competing background, can make use of pulsed or continuous low-energy X-ray sources of sufficient penetration. Relatively straightforward detection and image recording systems may be used out-of-pile.

SCANNING AND RADIOGRAPHY

Hodoscope detectors respond to fuel movement across the viewing region of any detection channel. Because of this, the hodoscope is optimized for dynamic effects, in contrast to other imaging systems which are optimized to record static images. Hodoscope fuel movement optimization has been frequently underrated; moreover, hodoscope capability to resolve motion in increments that are much smaller than the interdetector pixel separation has often not been appreciated.

Because relative motion is the critical effect that induces signal changes that are measured by the hodoscope, it does not matter whether the fuel moves past the viewing pixel of a collimator channel or whether the pixel is scanned past stationary fuel. Because of this equivalence, it is possible under low-power steady-state reactor conditions to measure and verify the theoretical capabilities of the hodoscope; it is not necessary to drive the fuel to destruction for this purpose. With a fuel sample loaded in the test region of the core and with the TREAT reactor brought up to 80 kW, a power level not likely to induce damage to the fuel, the hodoscope collimator is scanned across the object plane to produce a full profile of the source in about a half hour. In addition to aiding diagnostic development, this procedure has been routinely practiced for alignment of the collimator before a transient and for test-fuel characterization after an experiment. The result may be reconstructed into an image that corresponds to a fast-neutron radiograph, as shown in Fig. 9, which compares the post-test distribution of fissile material with the pretest intact distribution.

Hodoscope in-situ fast-neutron scanning utilizes existing facilities. In this mode the hodoscope scans both vertically and horizontally to increase its effective spatial resolution for stationary objects. This takes advantage of the equivalence of relative motion between the collimator and the fuel object. Thus the results may be interpreted directly in terms of fuel-motion spatial resolution.

The test section may be rotated to provide three-dimensional tomography. Implementation of this feature is planned for an upgraded TREAT reactor. In addition to fuel distribution, it may be possible to simultaneously sort out steel relocation using the gamma-ray hodoscope system.

The application of deconvolution techniques to hodoscope scan data is illustrated in Fig. 10. Here, for the single pin PINEX-3 experiment, the 0.8 mm central void is identifiable after deconvolution.

A related development being planned is that of fuel-pin plenum radiography. If fuel is ejected during a transient from the original fuel zone, it will disperse into the upper and lower plena, which are outside the 1.2 m field of view of the hodoscope. The first logical opportunity for post-transient radiographing of the plena is while the test section is being withdrawn from the core of the TREAT reactor. Detectors can be positioned so as to detect decay gamma rays emitted from the entire test section after the experiment. Tomographic images may be obtained by providing relative rotation. A hodoscope-type scanning system appears most promising.

SUMMARY OF CAPABILITIES

Because each detection channel can be optimized for selective response to fast neutrons, which are the most faithful and penetrating radiation signature of fuel, and because each channel can handle large count rates, the segmented design of the multichannel hodoscope has a high performance capability. This largely accounts for the good signal-to-background ratio and wide dynamic range of the hodoscope. Despite the object of interest being surrounded by two or more centimeters of steel, mass resolution can be approximately 0.1 g. Spatial resolution, dominated by design and by statics, is less than 1 mm for horizontal fuel displacement. Data collection intervals less than 1 ms may be used, although simultaneous time resolution may be larger because of the reciprocal statistical relationship to other resolution parameters. Recording duration adequate for all transients has been accomplished by the use of magnetic disk and tape recording. A high degree of redundancy may be built in to provide the needed readiness and reliability that has been experienced in association with the unique fast-reactor-safety fuel destruction experiments.

By a combination of instrument design, normalization of data, calibration, and data validation, it has been possible to reliably achieve in-pile fuel-motion detection with adequate sensitivity in time, displacement, velocity, and mass resolution. The foundations in hardware and software now exist for advancements in application and for coping with future experiments that contain more fuel pins and have thicker test-vehicle walls. To do so requires an understanding of underlying principles, a convenient means of recovering data, programmed methods of data processing, experience in data analysis, and sufficient recognition of sources of error. Comparison with alternative diagnostic devices indicates the strengths and weaknesses of each. Certain features of hodoscope instrumentation and operating principle are relevant to other forms of cineradiography.

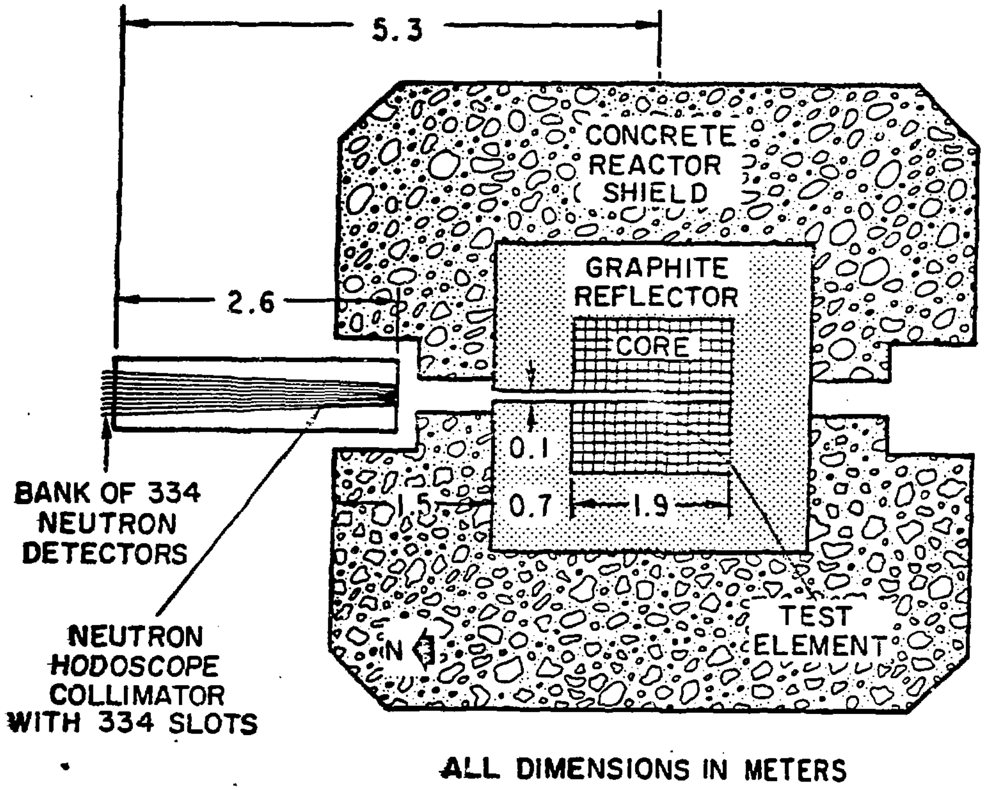
Acknowledgment

Development, operation, and support of the hodoscope system has benefitted from the efforts of many people at Argonne.

References

1. A. De Volpi, "Survey of Cineradiographic Techniques Applied to Nuclear Reactor Safety Experiments," 1st European Conf. on Cineradiography, Paris (1981).

2. A. De Volpi, et al., "Fast-neutron Hodoscope at TREAT: Methods for Quantitative Determination of Fuel Dispersal," Nucl. Tech. (to be published).



ARRANGEMENT OF HODOSCOPE ON NORTH FACE OF TREAT REACTOR VIEWING TEST ELEMENT THROUGH SLOTTED ELEMENTS.

Fig. 1. Layout at TREAT

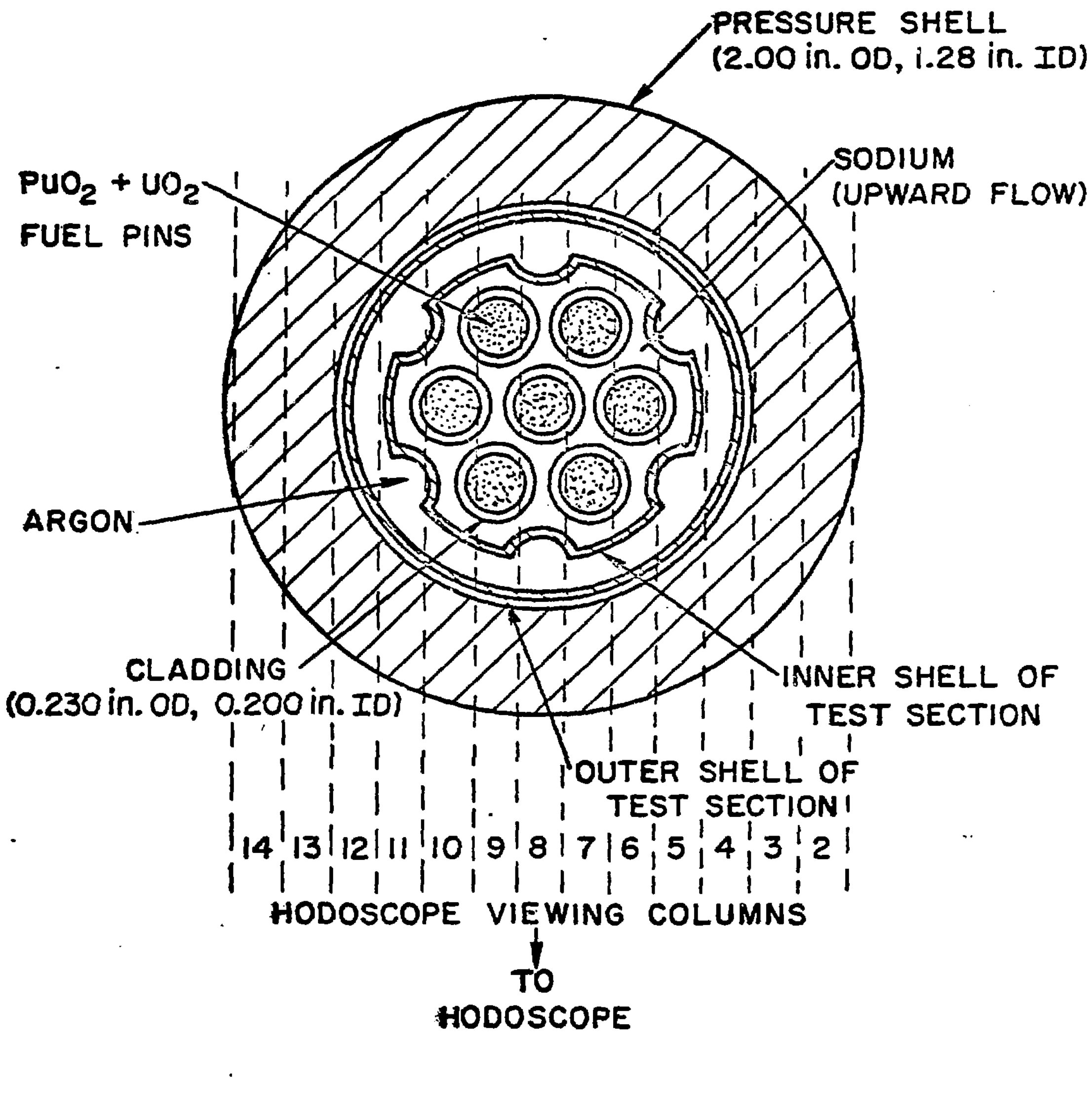


Fig. 2. Cross-section of test container

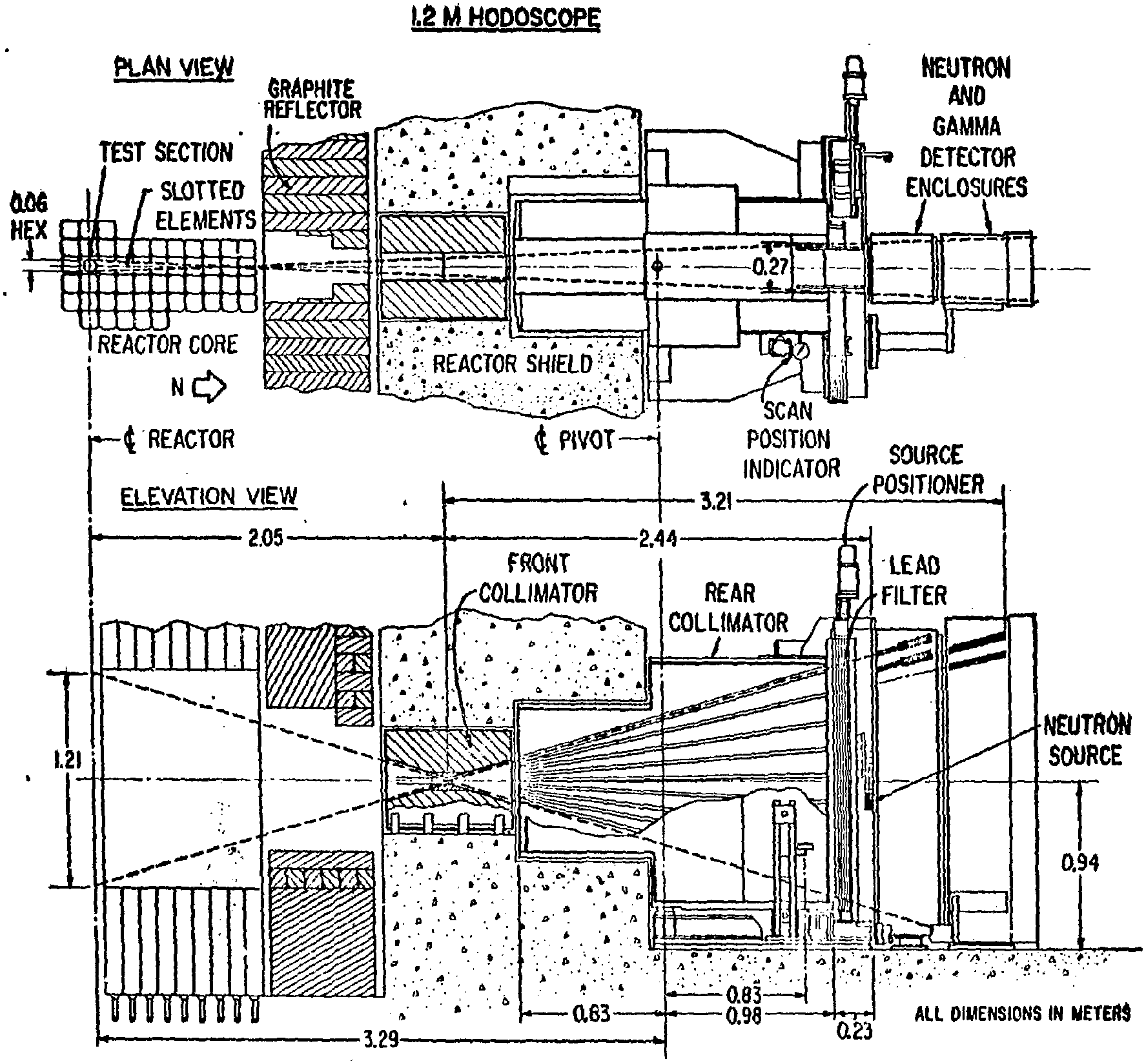


Fig. 3. Schematic diagram of hodoscope

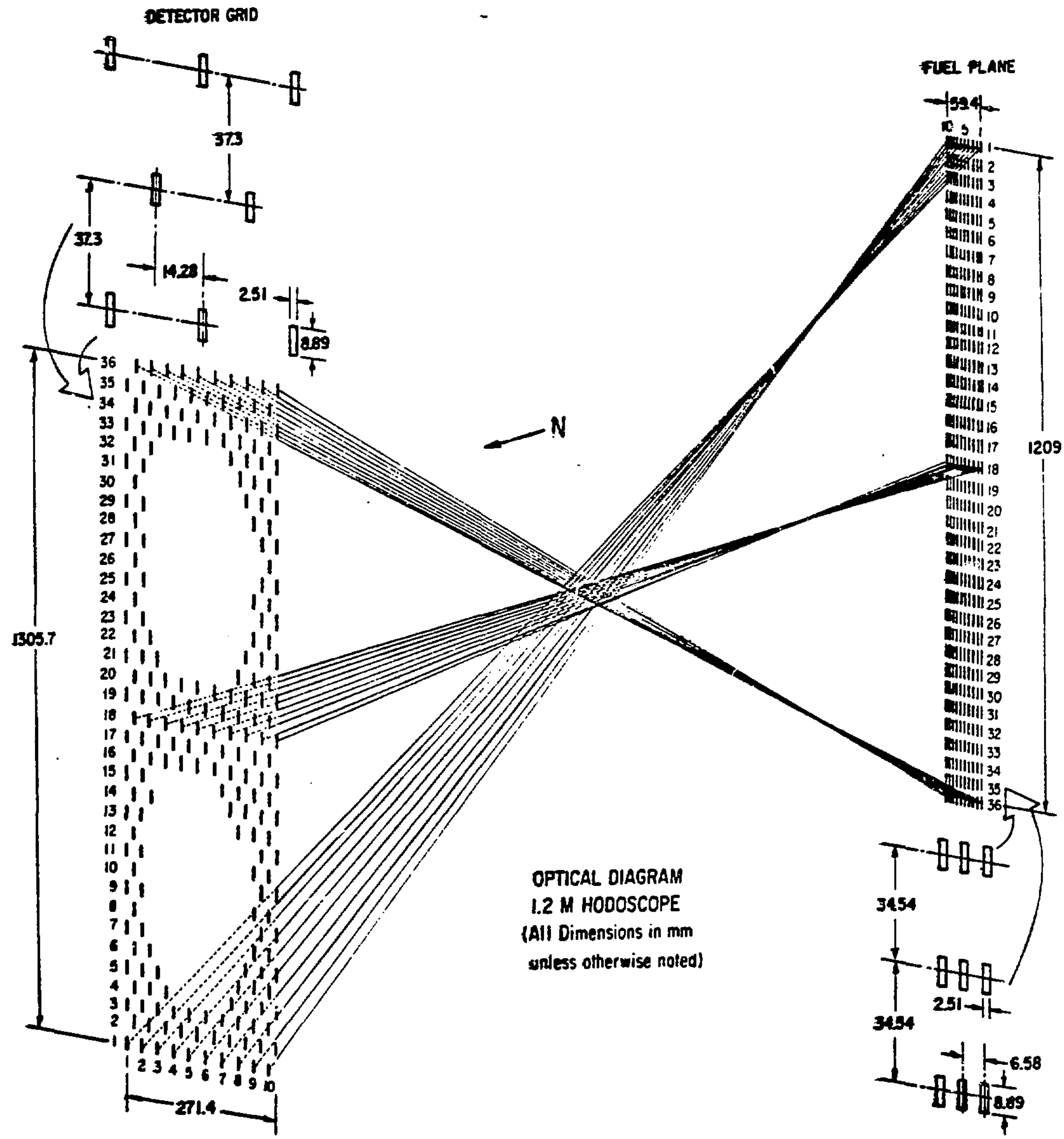


Fig. 4. Hodoscope collimator ray projections

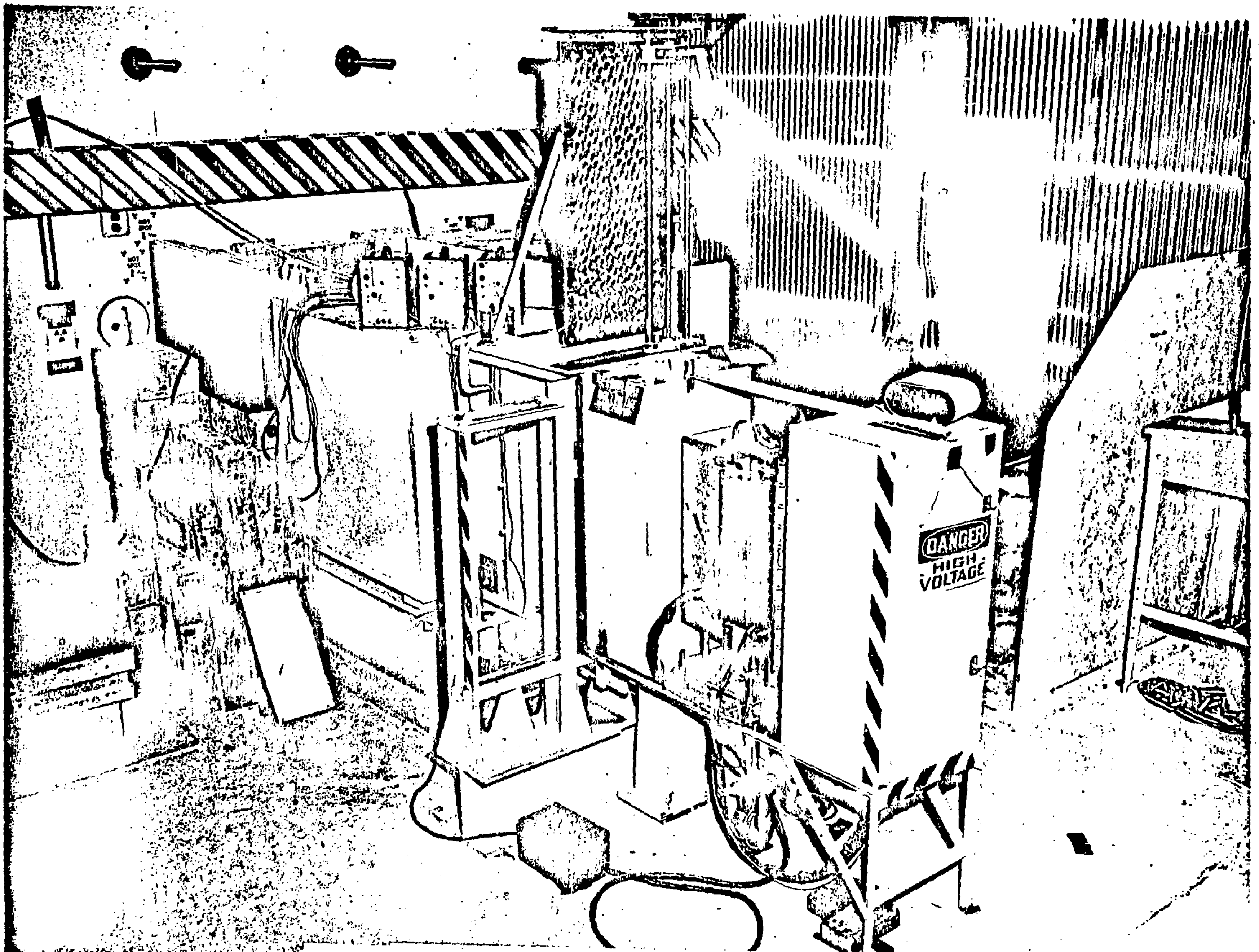


Fig. 5. Photograph of hodoscope installed at TREAT

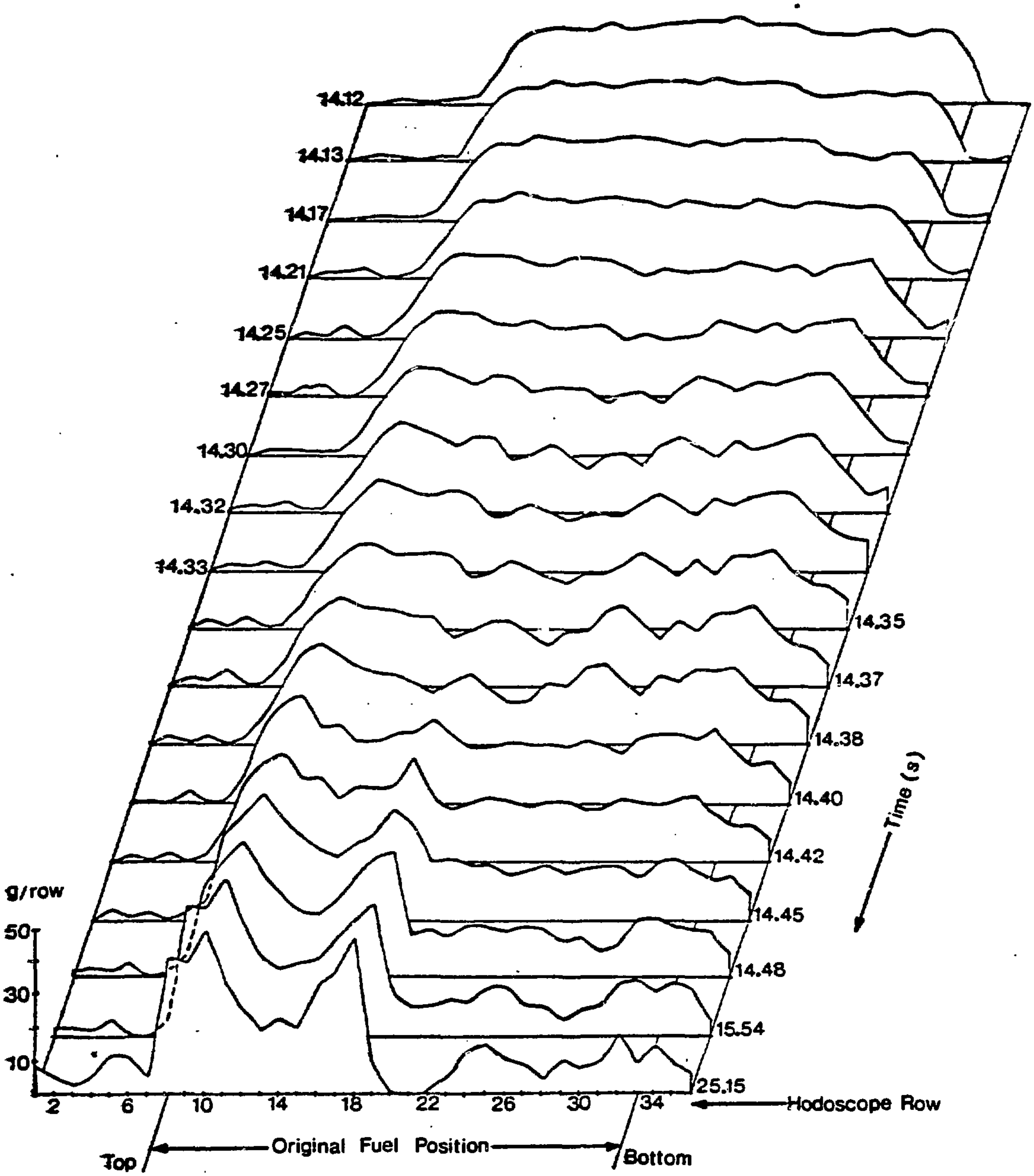


Fig. 6. Multiparameter plot of fuel motion (Experiment L7)

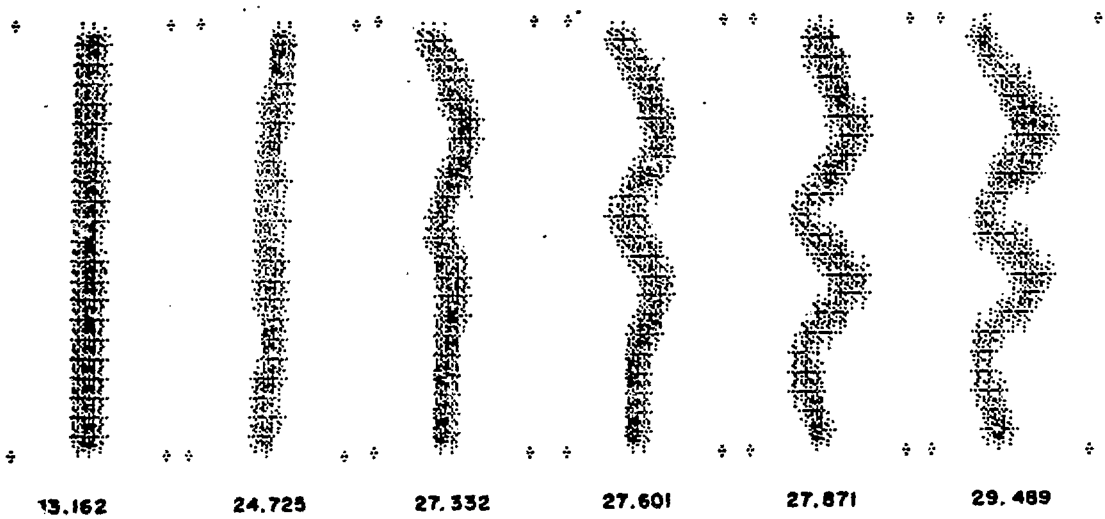


Fig. 7. Intensity-modulated hodographs
(Experiment R3)

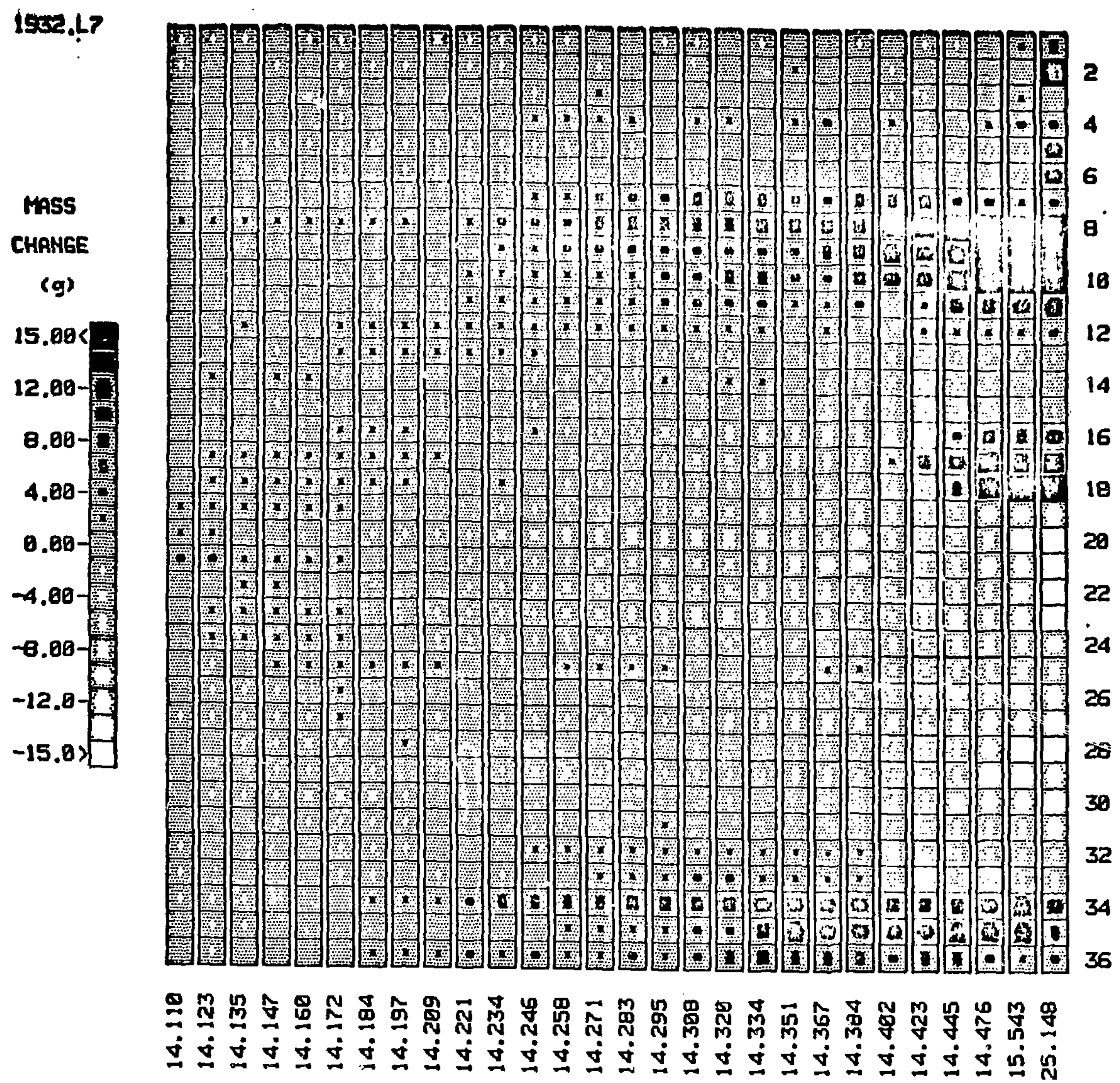


Fig. 8. Axial component of fuel motion (Experiment L7)

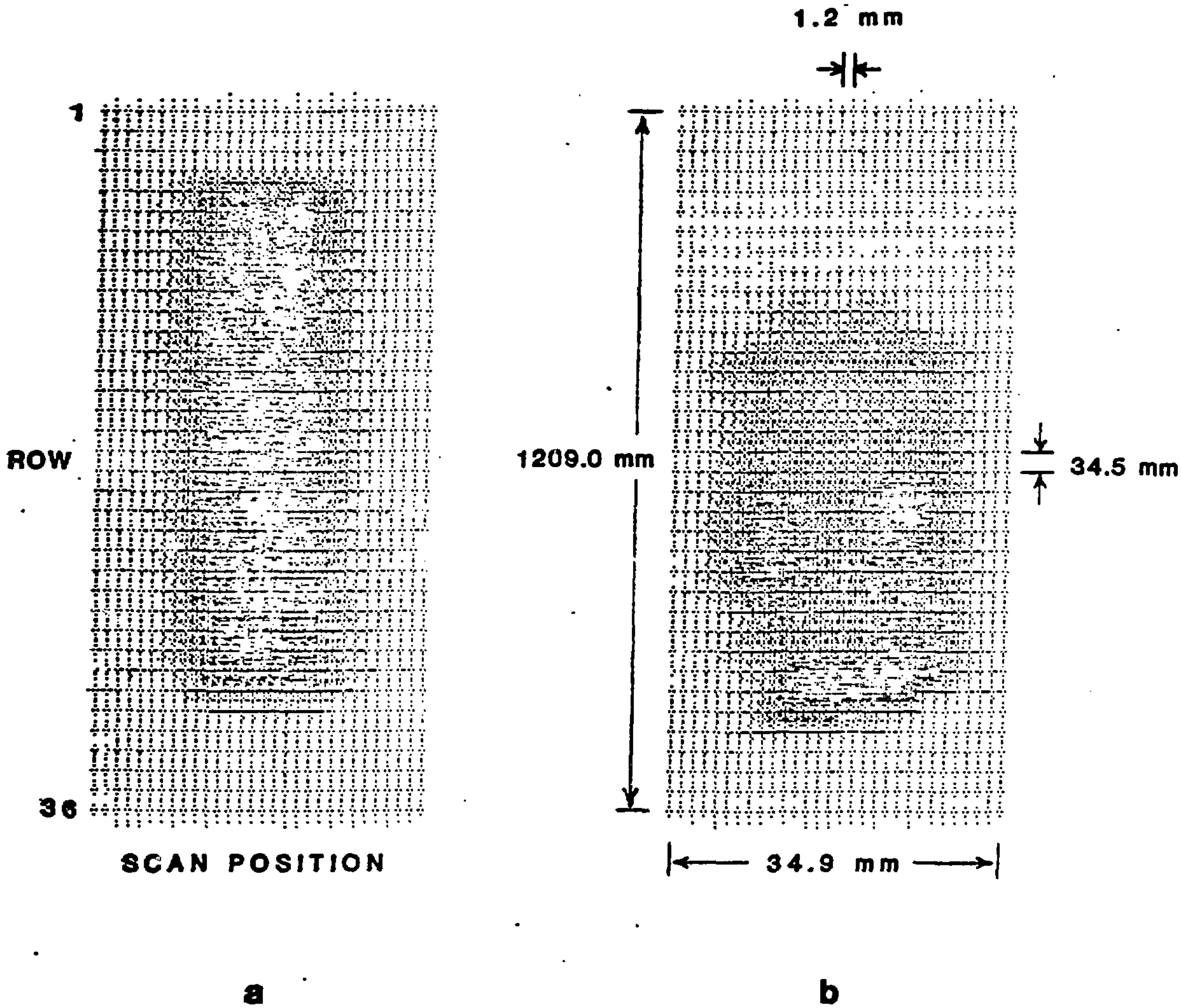


Fig. 9. Digital reconstruction of fast-neutron radiographs (Experiment R8)

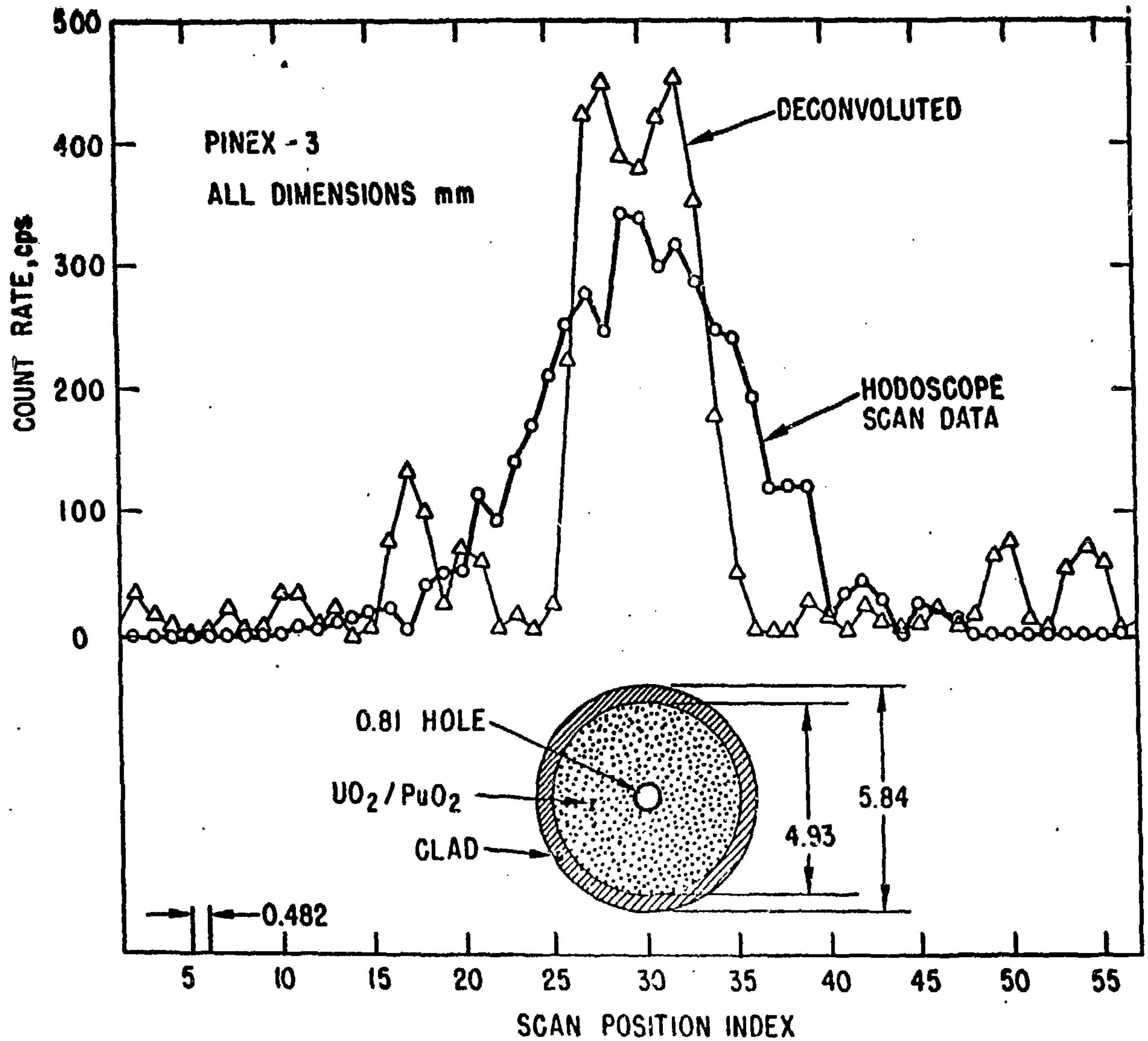


Fig. 10. Scan data deconvoluted to reveal central void in single pin (PINEX-3)