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In-situ Material-motion Diagnostics and Fuel Radiography in Experimental Reactors*

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IN-SITU MATERIAL-MOTION DIAGNOSTICS AND FUEL RADIOGRAPHY WITH EXPERIMENTAL REACTORS[*]

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ABSTRACT

Material-motion monitoring has become a routine part of in-pile transient reactor-safety experiments. Diagnostic systems, such as the fast-neutron hodoscope, were developed for the purpose of providing direct time-resolved data on pre-failure fuel motion, cladding-breach time and location, and post-failure fuel relocation. Hodoscopes for this purpose have been installed at TREAT and CABRI; other types of imaging systems that have been tested are a coded-aperture at ACRR and a pinhole at TREAT. Diagnostic systems that use penetrating radiation emitted from the test section can non-invasively monitor fuel without damage to the measuring instrument during the experiment. In addition, they can provide pre-test and post-test radiographic images of test sections installed in the reactor. Studies have been made of applications of hodoscopes to other experimental reactors, including PBF, FARET, STF, ETR, EBR-II, SAREF-STF, and DMT.

INTRODUCTION

The direct time-resolved measurement of material-motion is an important objective for nuclear-reactor-safety experiments. Because experimental reactors provide the most prototypical test conditions, fuel-motion diagnostic systems have been installed at available transient-reactor facilities, and studies have been made of possible application to less-adaptable or new reactors.

In order to obtain crucial time-dependent data or to optimize experiment information, safety experiments that proceed beyond operational limits can be monitored in real time to assess changes in fuel, coolant, or cladding integrity. In practical terms, indestructible diagnostic systems have been developed that non-invasively provide time-resolved fuel-motion data during the course of brief transient experiments. In addition, these systems can provide in-situ time-integrated radiography of the pre- and post-test fuel distribution. A clear, narrow passage through the core is necessary for ex-core detection of in-pile test phenomena, as shown in Fig. 1 for TREAT.

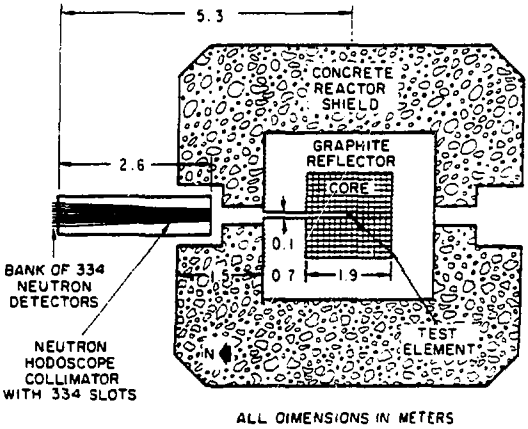

Fig. 1. Schematic arrangement of test fuel and hodoscope at TREAT

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[*] Work performed under the auspices of the U.S. Department of Energy.

Because of the broad scope of largely unpublished work conducted in these investigations, the description of these studies will be abbreviated in order to allow room for a unique collection of illustrations and references that would suffice for future investigations.

TREAT

Development of the fast-neutron hodoscope[1] fuel-motion-monitoring system started in 1963, early after TREAT was built, taking advantage of the reactor's flexibility for experimental facilities (Fig. 2). A more advanced version of the hodoscope has evolved[2], and further expansion is planned in conjunction with the TREAT upgrade. TREAT tests are now performed on assemblies up to seven pins contained in special test vehicles (Fig. 3).

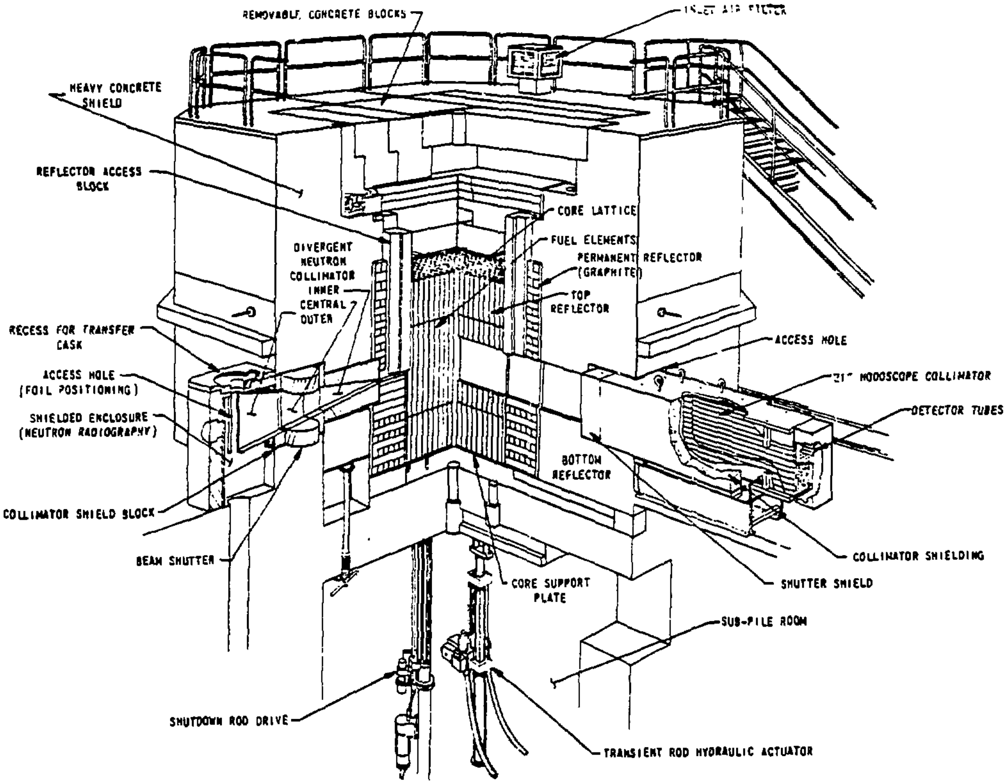


Fig. 2. Cutaway of TREAT reactor showing 0.5-m hodoscope at TREAT

The hodoscope (Figs. 4 and 5) can measure pre-failure internal fuel-pin motion, determine time and elevation of cladding breach, and measure post-failure fuel-motion under a wide range of prototypical experiment conditions. To date, nearly all directly observed quantitative in-pile fast-reactor dynamic data regarding fuel relocation, velocity, timing, and reactivity worth has been obtained from hodoscopes. The data is applied to experiment and reactor design, accident-code analysis and confirmation, and licensing.

The TREAT hodoscope has been able to resolve motion involving as little as 50 mg of fuel in prototypical tests. Time resolution as short as 1 ms can be achieved, subject to statistical limits, over a wide range of reactor power levels. Figure 6 provides an example of the multi-parameter data from a transient.

The diagnostic equipment that has been installed for fuel-motion measurements has been used for other purposes. The hodoscope can detect large movements or accumulations of steel or inconel during transients. It also provides post-test digital radiographic data of fissile and structural material distribution within test sections, before they are physically disturbed by removal from the reactor or by disassembly.

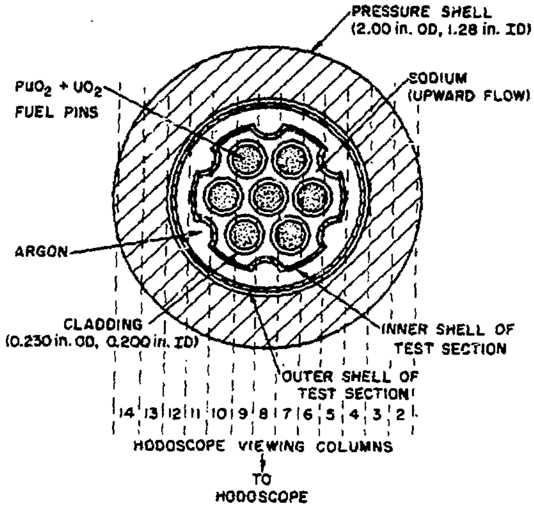


Fig. 3. Cross-section of typical 7-pin subassembly at TREAT

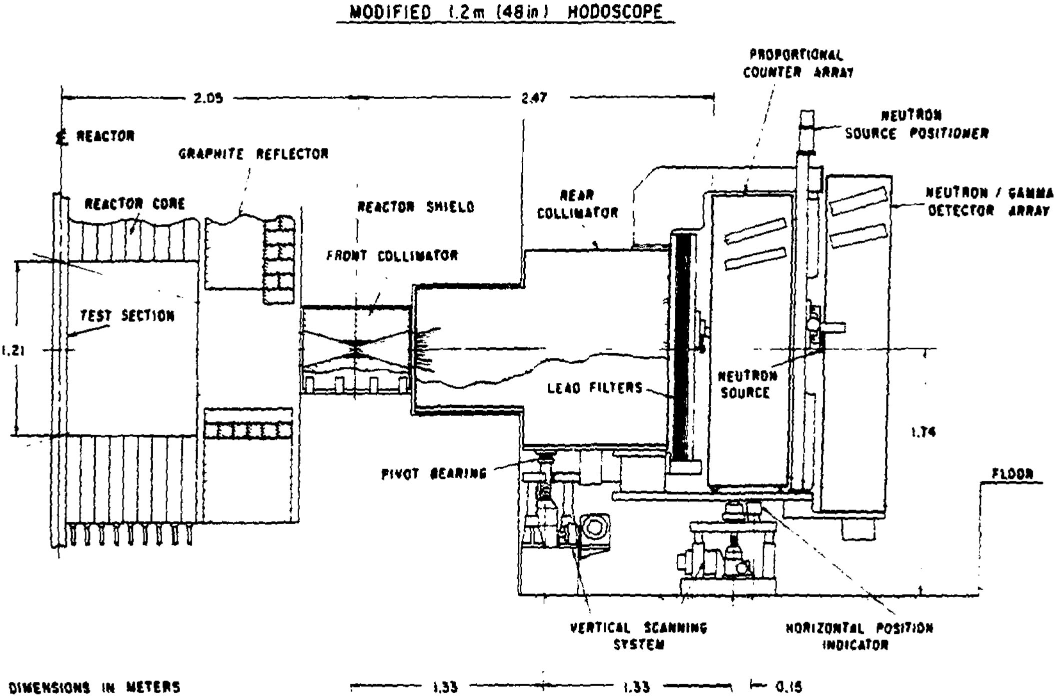


Fig. 4. Drawing of Modified 1.2-m hodoscope at TREAT

Fig. 5. Photograph of modified 1.2-m hodoscope at TREAT

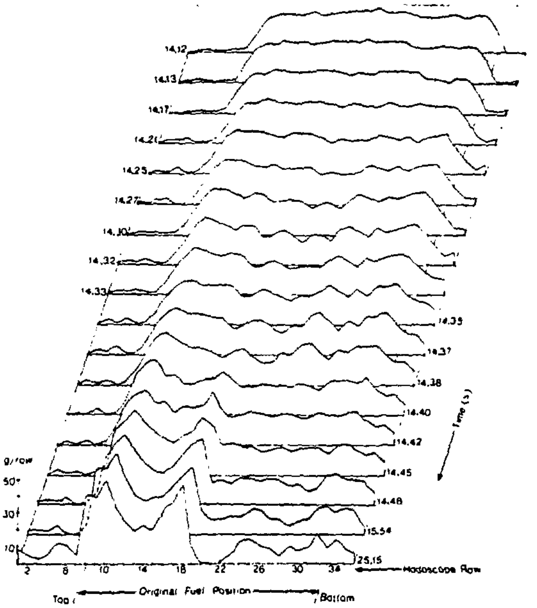


Fig. 6. Hodoscope multiparameter data for fuel position, mass, and time during TREAT transient L8

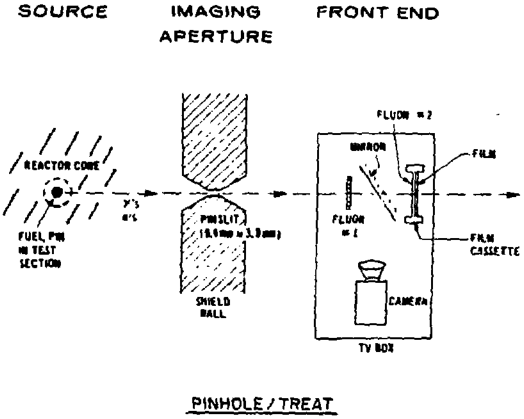


Fig. 7. Pinhole fuel-motion diagnostic imaging device tested at TREAT

Pinhole-imaging System

Alternative devices for fuel-motion measurement have undergone tests at TREAT. Over the past five years, Los Alamos National Laboratory has developed two types of pinhole-imaging systems. Proof-of-principle was established for a stacked pinhole array (Fig. 7) in transient and steady-state tests. Both programs have been phased out.

TREAT Upgrade

The TREAT reactor is being upgraded to allow transient tests with 37-pin bundles in an advanced TREAT loop (ATL -- see Fig. 8). In order to cover the wider field of view, the hodoscope is to be expanded. At the same time, design of a higher resolution central zone (Fig. 9) is being undertaken in order to accommodate single-pin and phenomenological tests with the same collimator.

To improve and expedite pre- and post-test in-situ radiography, the ATL would be rotatable in core, thereby permitting hodoscope fast-neutron scanning tomography prior to removal of the test section. As the ATL is withdrawn from the reactor after an experiment, a gamma-ray collimated scanning system is planned to allow tomography of the full length of the loop, including the plena.

APPLICATIONS AT OTHER EXPERIMENTAL REACTORS

Fuel-motion diagnostic systems have been used at other experimental reactors. A full-scale hodoscope system is operational in the CABRI reactor at Cadarache, France. A four-channel hodoscope system[3] was developed by Los Alamos National Laboratory and used for diagnostic evaluation at PARKA. Many studies have been made of possible application to other reactors.[4]

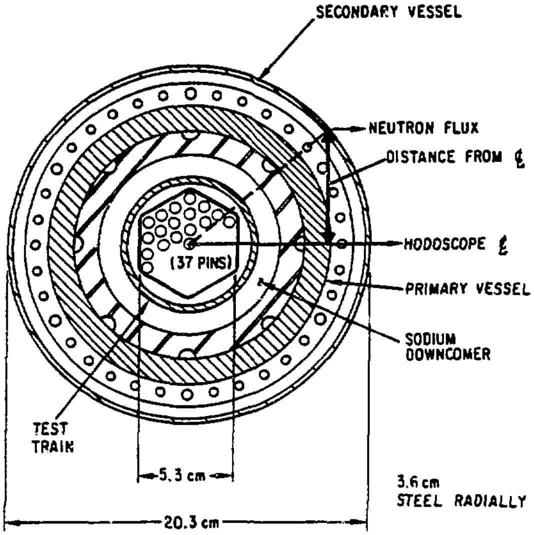


Fig. 8. Cross-section of planned 37-pin subassembly for TREAT-upgrade

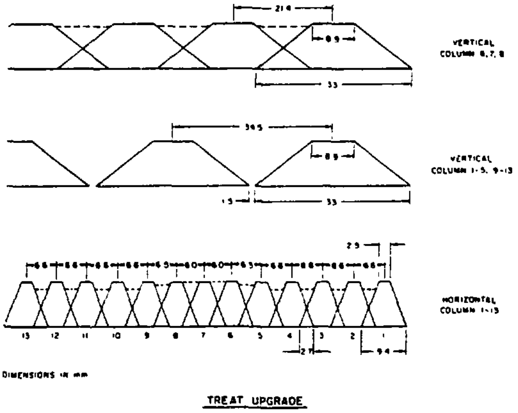


Fig. 9. Expanded collimator with high-resolution central zone planned for TREAT Upgrade -- (a) resolution functions

The hodoscope that has been designed and operated for the CABRI reactor[3] is part of a multinational project. As shown in Fig. 10, the 150-channel collimator was fitted into the reactor, and water was displaced from the viewing slot. It is designed for single-pin experiments.

A coded-aperture fuel-motion diagnostic device (CAIS -- see Fig. 11) has been fabricated and installed within the Sandia ACRR tank.[3] Although specific fuel motion results have not been published, their projected assessment of capabilities approaches that experienced by hodoscopes. During an initial Sandia design assessment, an out-of-tank hodoscope was considered.

In-core Detection Devices

Fuel-motion monitoring systems that are mounted out of core are indestructible and have high resolution. However, if the reactor is not suited for a viewing slot, small neutron or gamma detectors can be placed within the core or even within the test section, although those within the test section are subject to early failure. In-core fuel-motion monitors have been tested at ETR as part of the SLSF program and at ACRR for supplementary use there and at CABRI. If sufficient reliability were to be demonstrated, these detectors might provide qualitative material relocation information not otherwise attainable.

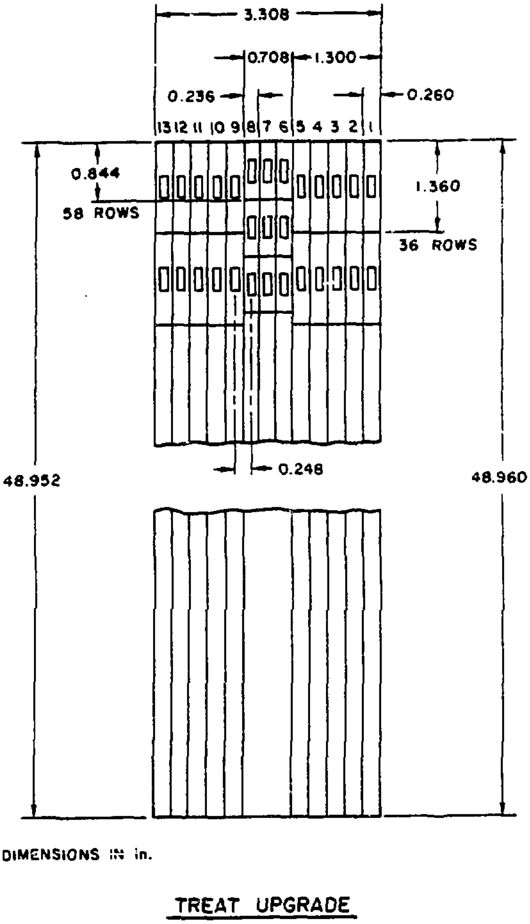


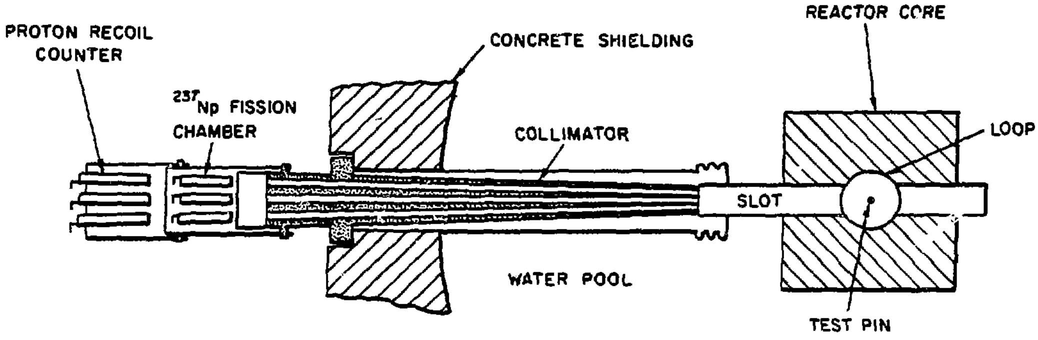
Fig. 9. (b) collimator pattern planned for TREAT Upgrade

STUDIES FOR APPLICATION TO OTHER REACTORS

For both the light-water and sodium-cooled reactor safety programs, design studies have been made of applications of fuel-motion diagnostic systems, particularly the hodoscope because of its proven track record. Both LANL and Sandia have proposed the use of accelerator sources[3] with various imagingsystems.

In the case of the Power Burst Facility (PBF), a removable section was built into the reactor biological shield to provide for retrofit. Although no use has not been made of this bricked-in wall, studies have been made on two occasions of possible installation of a hodoscope (Fig. 12).

FARET[5] was to be provided with a hodoscope collimator situated in the reflector zone (Fig. 13). A key feature of the design was the preservation of reactor integrity by keeping the collimator and detector system within the reactorvessel.

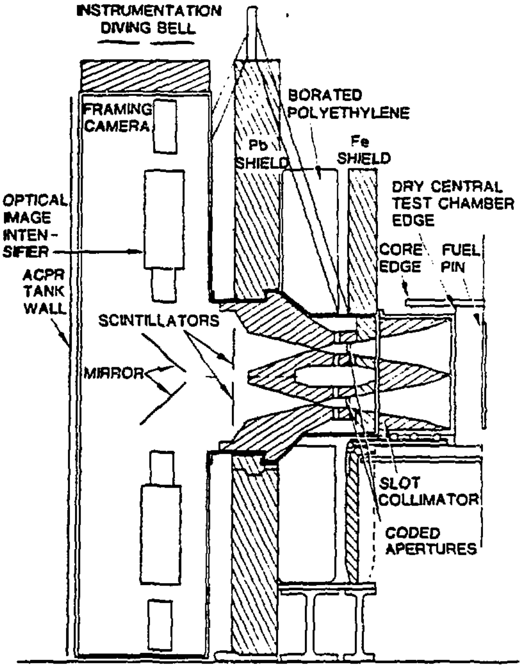


CABRI

Fig. 10. Top view of hodoscope operational at CABRI/Cadarache

In a study that commenced in 1968, a hodoscope was considered as an integral device for monitoring fuel motion in a test facility being evaluated for LMFBR safety studies.[6] Whole-core involvement was anticipated, resulting in massive fuel motion; one scenario is presented in Fig. 14.

As part of a later study of safety-research experimental facilties (SAREF),[4] a proposed Safety Test Facility would have included two (Fig. 15) or three high-resolution hodoscope viewing slots, the latter to provide three-dimensional results necessitated by the large test bundles and multiple assemblies.



CAIS/ACRR

Fig. 11. ACRR coded-aperture diagnostic device

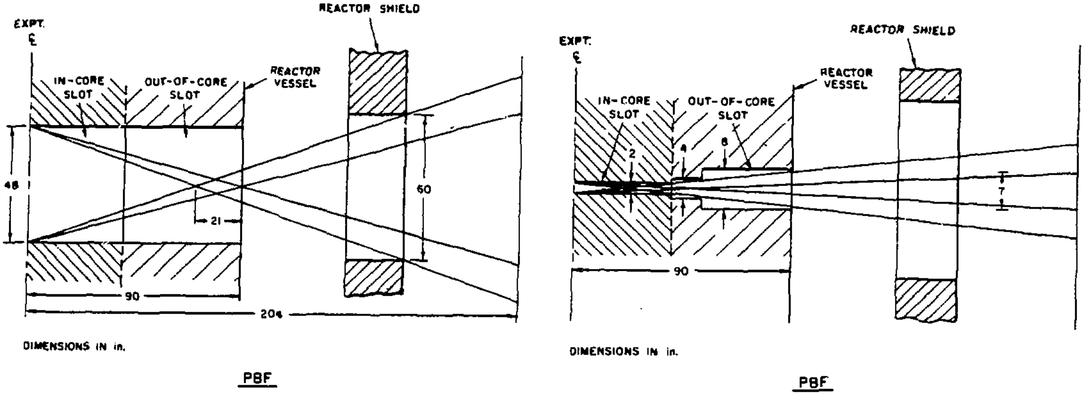


Fig. 12. Proposed PBF hodoscope optics -- (a) side view; (b) top view

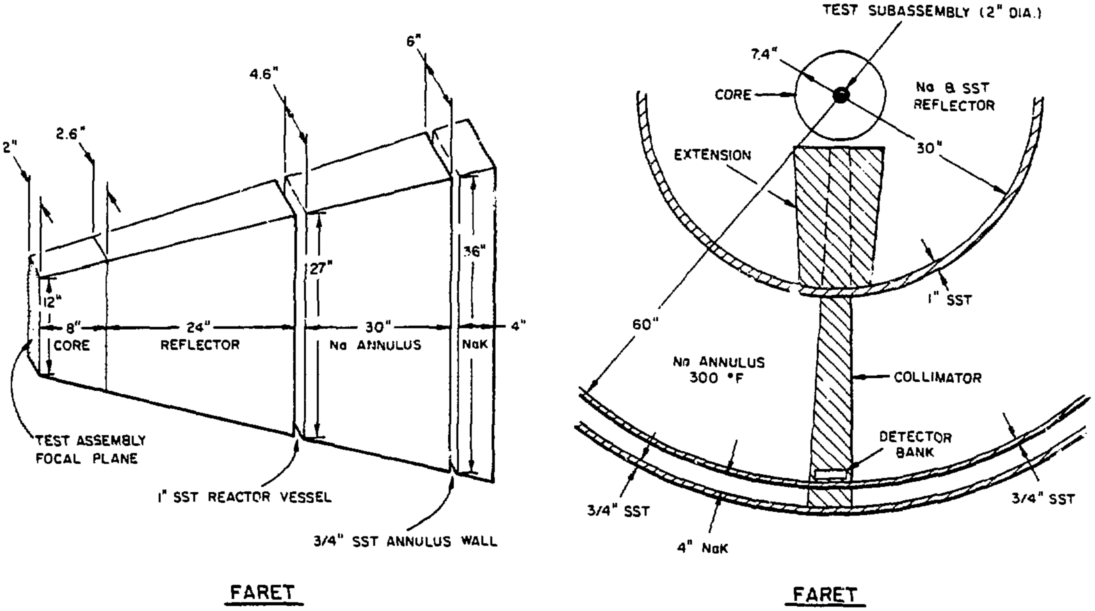


Fig. 13. Collimator proposed for in-vessel hodoscope in FARET -- (a) cutaway view of collimator sections in reactor vessel; (b) plan view of collimator and detector arrangement

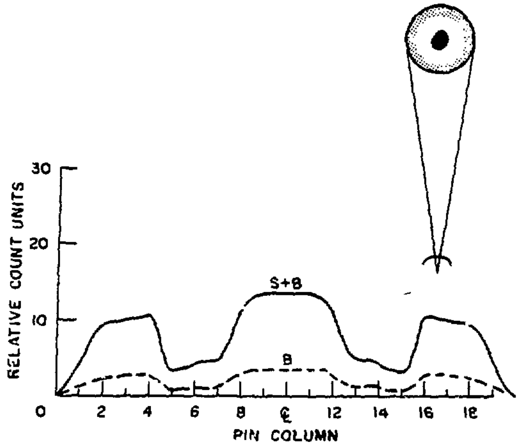
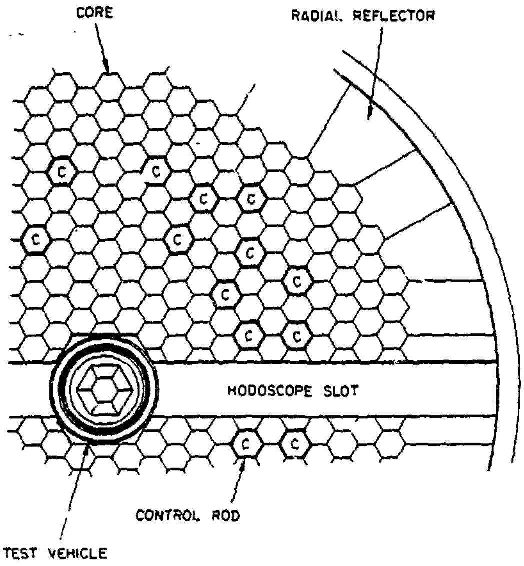


Fig. 14. Anticipated response to hodoscope for destruction of a full subassembly in early STF design

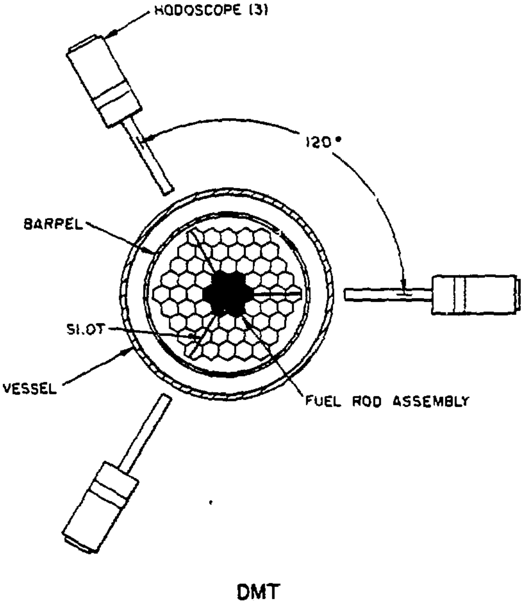
A three-angle viewing-slot design (Fig. 16) was recommended for the special-purpose Dispersal Mechanism Test facility. High resolution was not required for this type of test, and the large object size and the amount of intervening material would have made better resolution infeasible. For these reasons, a three-collimator coarse-resolution hodoscope system that would withstand the destructive nature of the test was anticipated. The apparatus would detect major fuel movement during the transient and would monitor residual spontaneous neutron and gamma activity from the post-test fuel distribution.

A coarse-resolution hodoscope was also considered for in-core use with EBR-II. In this design (Fig. 17), the essential collimating principles of the hodoscope would have been preserved, accepting a loss in resolution in order to avoid compromising the integrity of the reactor vessel or causing a major reactor redesign.



SAREF

Fig. 15. SAREF core configuration plan with viewing slots for hodoscopes



DMT

Fig. 16. Hodoscope arrangement designed for DMT

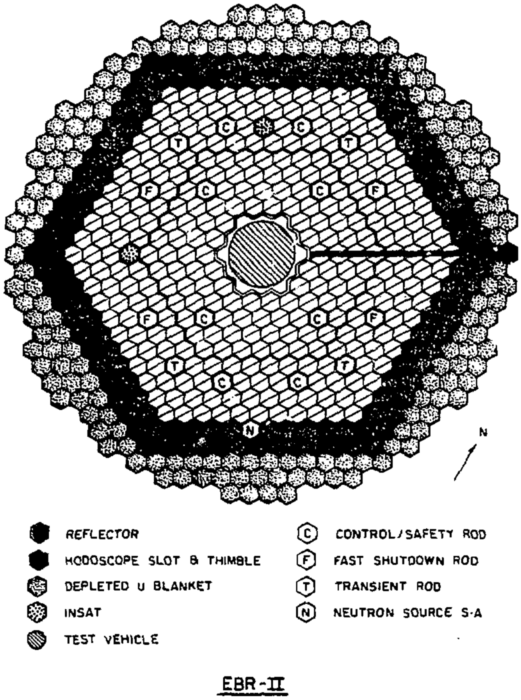


Fig. 17. Core layout for EBR-II modified to accept a coarse-resolution hodoscope

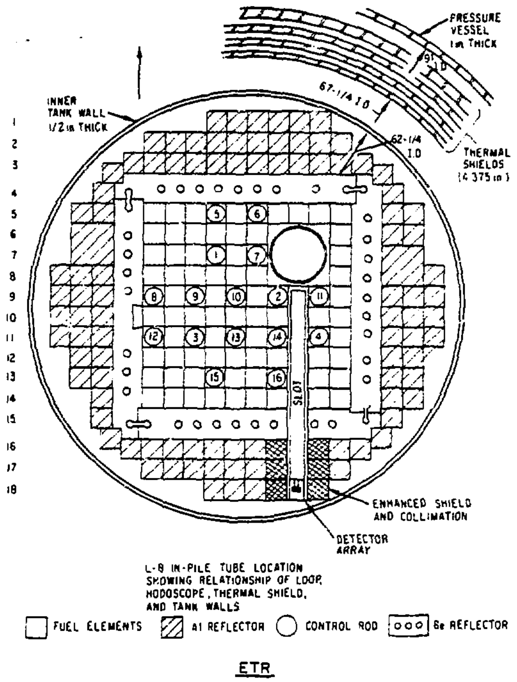


Fig. 18. Coarse-resolution hodoscope layout proposed for ETR

Two approaches were studied for ETR. One was a less-expensive coarse-resolution hodoscope fitted into the core and reflector region (Fig. 18). The other was an advanced and detailed design that was rendered for a high-resolution hodoscope. This required core and shielding modifications while retaining integrity of several vessels (Fig. 19).

POSSIBLE FUTURE APPLICATIONS

Although most of these tests and programs so far described have involved LMFBR safety studies, the diagnostic techniques can be applied more widely. They can be used for gas-cooled reactor experiments, such as some that had been anticipated for both ETR and TREAT, and they can be applied to water-reactor studies, including those conducted in PBF and TREAT. The reactor or the test-object coolant is not a significant determinant of hodoscope sensitivity. Hodoscope collimating principles are also likely to be useful in any fusion reactor or hybrid testing facility.

Although all applications to date have involved experimental reactors, future use with operational facilities is conceptually feasible. In particular, ex-vessel monitoring of LMFBRs might be possible with a coarse-resolution hodoscope system that was built into the reactor biological shield. Not only would such a system aid in providing operational-safety information before and during operation, but it would give a picture of fuel location in a degraded core. Some consideration had been given to fuel-status monitoring before and during TMI-2 core disassembly, using fast-neutron active and passive interrogation techniques.

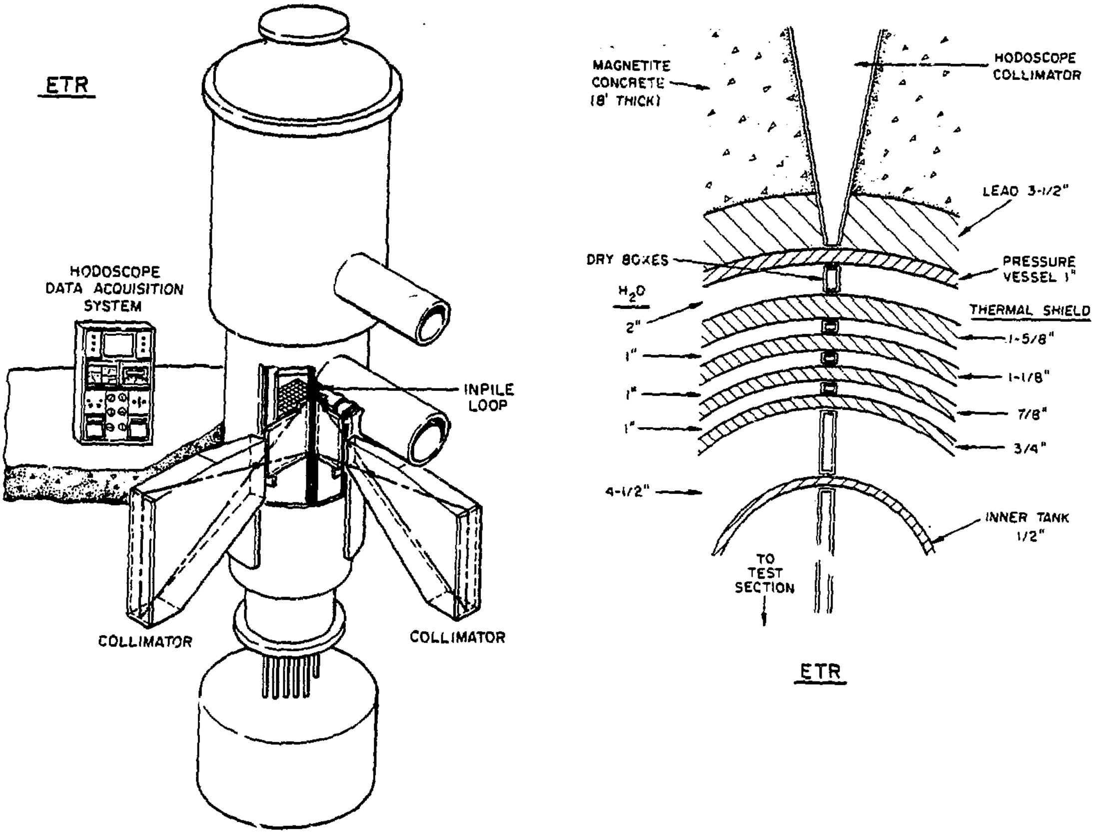


Fig. 19. High-resolution hodoscope proposed for ETR -- (a) isometric view; (b) layout within reactor vessel and shield

CONCLUSIONS

As a result of extensive experience in design and operation of hodoscope systems, material-motion surveillance applications in other experimental reactors can be assessed with high confidence.

The most important determinant is probably design flexibility to simplify installation -- TREAT being an example of a reactor with good flexibility for post-construction implementation of fuel-motion diagnostic systems. ETR, EBR-II, TMI-2, and FARET are cases of reactors built or designed before consideration was given to diagnostics of this type, while PBF, DMT, TREAT-Upgrade, and both STFs had hodoscopes incorporated in their original concept. Prior consideration would not only improve the fuel resolution potential, but it would also decrease the total cost of the diagnostic system.

Material-motion diagnostics in reactors provides capabilities for fuel and steel measurement during transient or steady-state operations. The same apparatus may be used effectively for fuel radiography using neutrons or gammas from test vehicles that are minimally disturbed after an experiment.

Although alternative methods of monitoring have been developed, they have yet to surpass hodoscope performance in quantification of the fuel motion. One reason for this is that the alternatives rely on induced gamma rays, which do not have the same distinctive directional attributes as fast neutrons. Accelerator sources have special problems caused by the need for a full transmission slot in the reactor; in-core detectors are relatively insensitive and have ambiguous response; and in-test detectors are subject to destruction when construction materials melt. If an external slot cannot be provided, a coarse-resolution hodoscope appears to be a better compromise.

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