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ARTICLE

Expansion of the Fast Neutron Hodoscope at TREAT to Support Fuel Safety Experiments

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In 2024 the Fuel Motion Monitoring System (FMMS), or Hodoscope, at the Transient Reactor Test Facility, was expanded from 96 viewing channels to 192 viewing channels, effectively doubling the FMMS field of view. This increase in capability will allow the FMMS to support larger scale fuel tests, encompassing height-of-core test devices, test devices with multi-pin fuel assemblies, and test devices with recirculating coolant flow. Work supporting the expansion included refurbishing 96 additional proton recoil scintillator (PRS) detectors, doubling the data acquisition system (DAS) installed architecture, improving time synchronization in the DAS, and new research to measure the PRS detector energy-dependent, fast-neutron detection efficiency. In addition, laboratory activities have produced an improved benchtop testing capability for assessing the DAS, time synchronization, and external start triggering, along with an updated capability to scan PRS detectors to develop a laboratory baseline normalization prior to deployment to the Transient Reactor Test Facility.

KEYWORDS: TREAT, Hodoscope, fast neutron, transient fuel safety

I. Introduction

Despite continued advances in the capability of computational tools for predicting multiphysics phenomena contributing to transient fuel system performance, experimental studies remain the standard for assessing fuel survivability during off-normal conditions. At Idaho National Laboratory (INL) the Transient Reactor Test Facility (TREAT) is used for experimental studies of reactor fuels and fuel-system performance under accident scenarios. This is a graphite-moderated, air-cooled reactor which uses highly-enriched uranium-dioxide dispersed through a graphite and carbon matrix. It accepts a diverse and growing number of test devices capable of emulating a variety of environments including air, water, and sodium, under both reactivity insertion accident (RIA) and loss-of-coolant accident (LOCA) transient scenarios.[1,2]

The TREAT Reactor was refurbished and returned to operational status in 2017, after a multi-decade closure.[3] A part of this refurbishment was a partial restoration of the TREAT Fuel Motion Monitoring System (FMMS), or "Hodoscope".[4] This refurbishment involved restoring 96 channels of fast-neutron proton recoil scintillator (PRS) detectors and developing an all-new, all-digital high-speed data acquisition system.[5,6] The hodoscope incorporates a large, multi-slit, steel collimator that provides line-of-sight views towards the center of the core forming a total field-of-view (FOV) 66-mm in width and 1,242 mm in height, with 10 vertical columns and 36 horizontal rows (**Fig. 1**). (Each viewing slot covers an area roughly 6.6-mm wide by 34.5 mm tall.[7]) Behind this collimator is a detector support cabinet capable of holding 360 PRS detector assemblies. The initial 96-channel PRS array developed during the TREAT restart effort was capable of monitoring and imaging fuel movement in small fuel rodlet experiments, with test specimens generally less than 10 mm in width and less than 200 mm in height. Over the next five years, new experiments are being planned for TREAT that will require a larger FOV for the Hodoscope. To address this upcoming need, a 2024 development effort took place at INL to develop and deploy a second set of 96 channels of PRS detectors for the TREAT FMMS.[8]

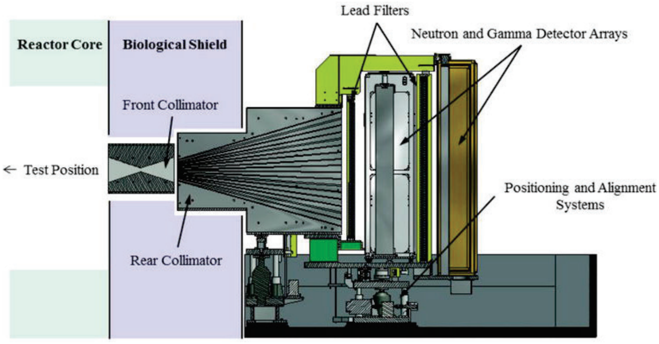

Fig. 1 Cross-sectional illustration of the FMMS components

II. Expansion Activities

Several different tasks took place as a part of the 2024 FMMS expansion to 192 channels, including addressing the new heat load on the system, doubling the data acquisition capability, and synchronizing the time for all digital components.

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1. Heat Load

During the seven years of operations prior to the expansion, the initial 96-channel array Data Acquisition System (DAS) electronics demonstrated high operational temperatures. Electronics operating at elevated temperatures can contribute noise to the PRS signals and cause reliability issues. Although the manufacturer of the DAS electronics does not specifically identify a maximum operational temperature, they do indicate that elevated temperatures lead to accelerated deterioration. This behavior has also been observed by FMMS engineers who have continually monitored hardware temperatures over the years and found a typical operational temperature of 68 °C.

For the expansion the engineering team identified that for optimal operation the hardware temperature should not exceed 54 °C. To address this a TRIPP-LITE cooler (EATON, Woodridge, Ill., USA) was incorporated into the newly designed expansion chassis. The cooler was installed into the bottom of the rack such that cold air could be drawn in circulated by the system's internal fans. To further optimize the cooling of the chassis, various system component position configurations were tested. The wire mesh doors on the front and back of the cabinet were found to play a significant role, allowing the cool air to leak out before being distributed by the system's fans. Plexiglas covers were installed over these mesh door panels to prevent the cool air from escaping the system, forcing it to flow over the electronic circuitry. A photograph of the cabinet and the cooler is shown in **Fig. 2**.

Fig. 2 TRIPP-LITE cooler, shown on the left side, installed into the DAS cabinet

2. New PRS Assemblies - Lab Testing

Following procedures developed for the refurbishment of the original 96 PRS detector assemblies, 96 additional PRS detector assemblies were developed and tested.[4-6] This work included the following sub tasks.

(1) Crude Voltage Bias Determination

A voltage bias scan was performed to find the gain-response curve for each detector. This allowed the detectors to be set at a voltage that was appropriate to produce a specific count rate. The bias scan used five ^{252}Cf sources approximately 20 inches away and at the center of the test stand that produced a cumulative emission rate of ~5.2×10^6 neutrons per second. The scan took ~12 hours, with a dwell time of 60 minutes for every 25-volt step over the bias range of -900 to -600 volts.

(2) Laboratory Baseline Normalization

Using the same assembly of five ^{252}Cf sources (**Fig. 3**), an X-Y translation stage was used to position the sources in front of each detector. The voltage bias was then fine-tuned, to adjust the gain of each detector. A proportional-integral-derivative (PID) controller was used to adjust the bias voltage until the count rate was within ±5%. The mean count rate for all 96 detectors was 29.9 counts per second with a standard deviation of 0.57.

Fig. 3 Detector count rate measurement setup using five neutron sources.

(3) Relative Efficiency Determination

The neutron time-of-flight (nToF) method is a technique employed to ascertain the speed of neutrons, which in turn allows for the determination of their energy. In this process, the known (Watt) energy distribution of neutrons emitted from ^{252}Cf is used as a benchmark. By comparing this well-characterized distribution with the neutron energy distribution that is measured experimentally, it is possible to deduce the relative neutron efficiency of a detector. The nTOF method was used to measure the relative energy-dependent neutron detection efficiency of a subset of PRS detectors, using a stilbene organic scintillator as a "start" detector which triggered the start of a clock. The clock was then stopped when an event was detected in any of the PRS detectors; an example nToF spectrum is shown in **Fig. 4**; the relative neutron efficiency results are shown in **Fig. 5**. Pulse shape discrimination (PSD) was also employed to ensure correct differentiation between gamma rays and neutrons.

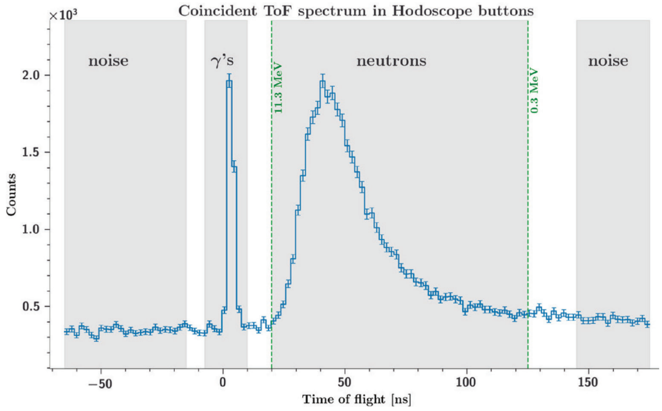

Fig. 4 Example nTOF spectrum for a PRS detector

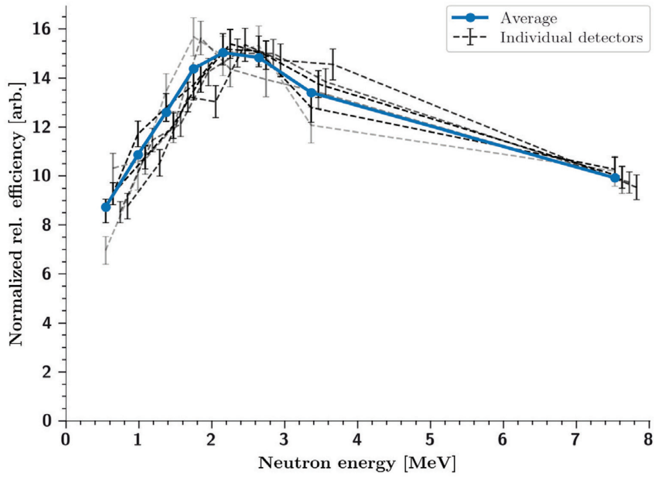

Fig. 5 Relative neutron efficiency for the evaluated detectors

3. Expanded FMMS Equipment Installation at TREAT

Installation of the FMMS expansion equipment took place the first week of June, 2024. The process started with opening the FMMS cabinet and having radiological control technicians perform a survey for contamination. No contamination was found, allowing for the removal of all the original 96 detector assemblies. Concurrently, the placement of new, 30.5-m signal and voltages cables was conducted.

Discovery of various levels of detector uncoupling in laboratory testing of a subset of the original, 7-year-old PRS assemblies prompted the need to inspect all of the originally-installed detector assemblies for anomalies such as separation between the scintillator and waveguide, cracks, and dried optical gel. After these inspections, and repairs when needed, cleaning and recoupling of all the PRS buttons and photomultipliers was completed, including applying new optical gel. The PSD performance for all 192 detectors PSD was evaluated once more.

The newly-recoupled detectors were inserted in their corresponding positions in the FMMS detector cabinet. New signal and high-voltage cables were connected to all 192 detectors. After all the detectors were installed and connected to the FMMS DAS, a performance verification scan was conducted to ensure that no high-voltage or signal cables were crossed during the installation process. A plutonium-beryllium (PuBe) radioisotope neutron source was used to scan the detector cabinet face in 10-mm increments with a dwell time of 60 s at each position, totaling over 200 hours. An additional scan was completed to verify the set parameters for each detector, i.e., detector voltage, location, PSD map and detector number, were saved to the configuration correctly. This scan was completed with the same procedure as the previous normalization, but for a much longer dwell time of 1200 seconds for each PRS assembly, with the source positioned directly in front of each detector. When the verification scan was completed, the detectors had a mean count rate of 53.60 counts per second and a standard deviation of 2.27.

4. System Testing

An operational test was performed with the TREAT reactor held at a constant 80 kW to enable the verification of detector performance. The center-peaked power distribution along the core axis was observed, as expected (**Fig. 6**).

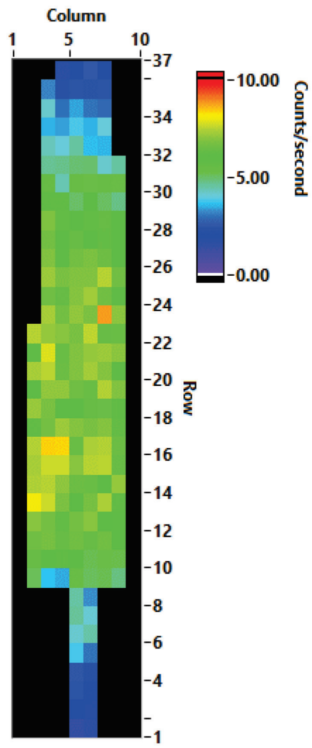

Fig. 6 Expanded FMMS baseline response to TREAT at 80 kW

As seen in the figure, the detector loading into the system was asymmetric and covered the two central columns (5 and 6) top to bottom, with other columns having less coverage. This was chosen to ensure full FOV coverage of test devices that are planned for use within TREAT over the next several years. The FMMS and its detectors performed as expected and none of the high-voltage values or lower-level discriminators required adjustment following this test.

An example of the FMMS spatial imaging of fuel during a transient is shown Fig. 7. In this test an unirradiated test rodlet representing a pressurized-water-reactor (PWR) fuel rod was held within a newly designed transient water irradiation system for TREAT (TWIST) test device.[9] The fuel length was 25 cm and the enrichment was 3.2 wt.% ^{235}U. The FMMS control platform was rotated in order to center the rodlet along one column of the hodoscope collimator. The up-down pivot of the collimator was not adjusted; as seen in the image, the top and bottom of the rodlet each partially-subtended an image pixel, leading to a reduced signal in those PRS assemblies. The data in this image represent a 1-ms time slice during this transient.

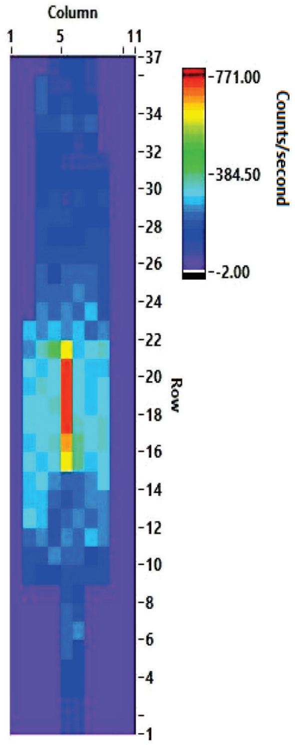

Fig. 7 Example FMMS 1-ms image frame for a 25-mm long PWR rodlet under a transient irradiation.

III. Conclusion

The expansion of the FMMS is needed to support upcoming experiments focused on longer fuel pins, complex geometries and multi-pin assemblies, and flowing-coolant test loops. An example of these experiments is a new sodium coolant test loop which will closely mimic the piping layout and flowing molten sodium characteristics of a proposed sodium fast reactor. The FMMS will enable monitoring and tracking of fuel fragmentation, relocation, and dispersal (FFRD) throughout these planned experiments. This type of fuel tracking was demonstrated by the FMMS during its first incarnation, prior to the TREAT shutdown in 1992. As suggested by Fig. 7, the value of real-time fuel motion data that will be generated by the new FMMS will be a useful aid to INL's transient fuel safety research and development program in the years to come. This fuel movement, which will be recorded with 1-ms timing accuracy, will provide key insights into understanding how current fuels, and new fuels under development for advanced reactor systems, survives and fails, under the extreme conditions of reactivity insertion accidents and loss-of-coolant accidents.

Acknowledgment

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References

1) D. C. Crawford, et al., "Experimental Capabilities of the Transient Reactor Test (TREAT) Facility," Report ANL/RE/CP-96981, Argonne National Laboratory-West, Idaho Falls, Idaho (1998).
2) D. Okrent, et al., "The Reactor Kinetics of the Transient Reactor Test (TREAT) Facility," Report ANL-6174, Argonne National Laboratory, Argonne, Ill. (1960).
3) D. Wachs, et al., "The Transient Reactor Test (TREAT) Facility: A New Era in Fuel Safety Research," *NEA News* No. 36.1 (2018).
4) D. L. Chichester, et al., "The TREAT Fast-Neutron Hodoscope and Plans for Restoring it to Operation," Report INL-CON-15-34260, Idaho National Laboratory, Idaho Falls, Idaho (2015).
5) J. D. Hix, et al., "Evaluation, Refurbishment, and Characterization of Fast Neutron Scintillators for the TREAT Fuel Motion Monitoring System," *IEEE Nucl. Sci. Symp. Conf. Rec.*, Atlanta, Georgia, Oct. 21-28 (2017).
6) S. M. Watson, et al., "A Multi-Purpose Test Station to Characterize Fast Neutron Detectors for the Transient Reactor Test Facility (TREAT) Fuel Motion Monitoring System," *IEEE Nucl. Sci. Symp. Conf. Rec.*, Atlanta, Georgia, Oct. 21-28 (2017).
7) "TREAT Hodoscope Operating Manual," Spec. No. R0206-1002-SA-00, Argonne Nat. Lab., Argonne, Ill. (1979), p. 33.
8) D. Chichester, et al., "Expansion of the Fuel Motion Monitoring System," Report INL-RPT-24-80554, Idaho National Laboratory, Idaho Falls, Idaho (2024).
8) C. Jensen, et al., "Combined TREAT-LOC and SATS LOCA Experiment Plan," Report INL-RPT-22-69915, Idaho National Laboratory, Idaho Falls, Idaho (2022).