INL/MIS-19-56719-Revision-0

Fuel Motion Monitoring During Transient Testing at TREAT - A Talk for University of Illinois

January 2019

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Idaho Falls, Idaho 83415

http://www.inl.gov

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Fuel Motion Monitoring During Transient Testing at TREAT

David Chichester
Directorate Fellow
Idaho National Laboratory

December 2019

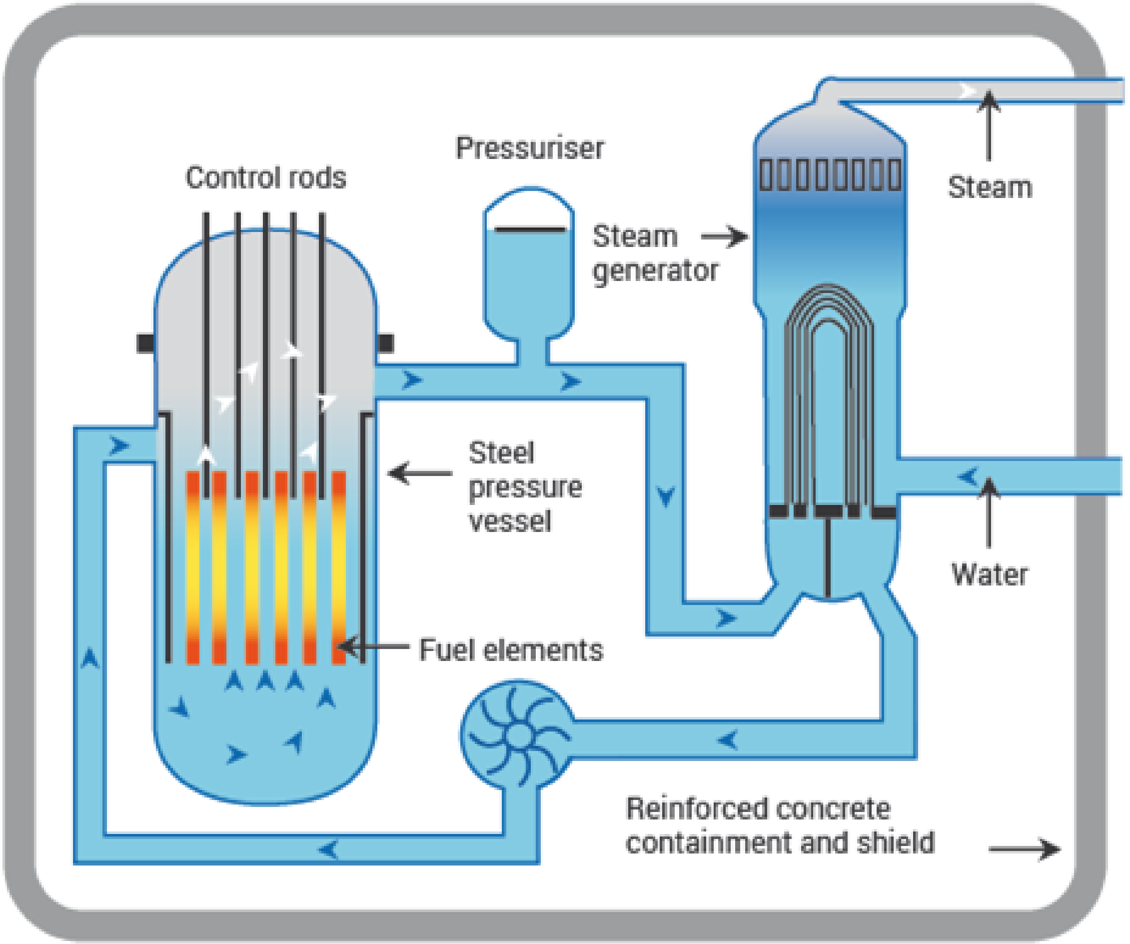
Introduction

- Introduction of transient accidents and fuel-failure mechanisms
- Overview of fuel failure, and transient testing research and development
- Discussion of TREAT and how experiments are performed
- Discussion of the TREAT fast-neutron hodoscope and its fast-neutron detectors
- Discussion of some data from recent tests at TREAT
- Summary

TREAT Transient #1022

Nuclear Safety – Defense in Depth

- Containment of core materials is the ultimate objective of reactor systems - *defense in depth*
    1) **Fuel cladding**
    2) Reactor vessel
    3) Containment building
- Fuel-cladding failure is a complex phenomenon, some aspects can be studied in the laboratory but not all
- There are few places in the world where in-core test-to-failure experiments can be performed with irradiated nuclear fuel



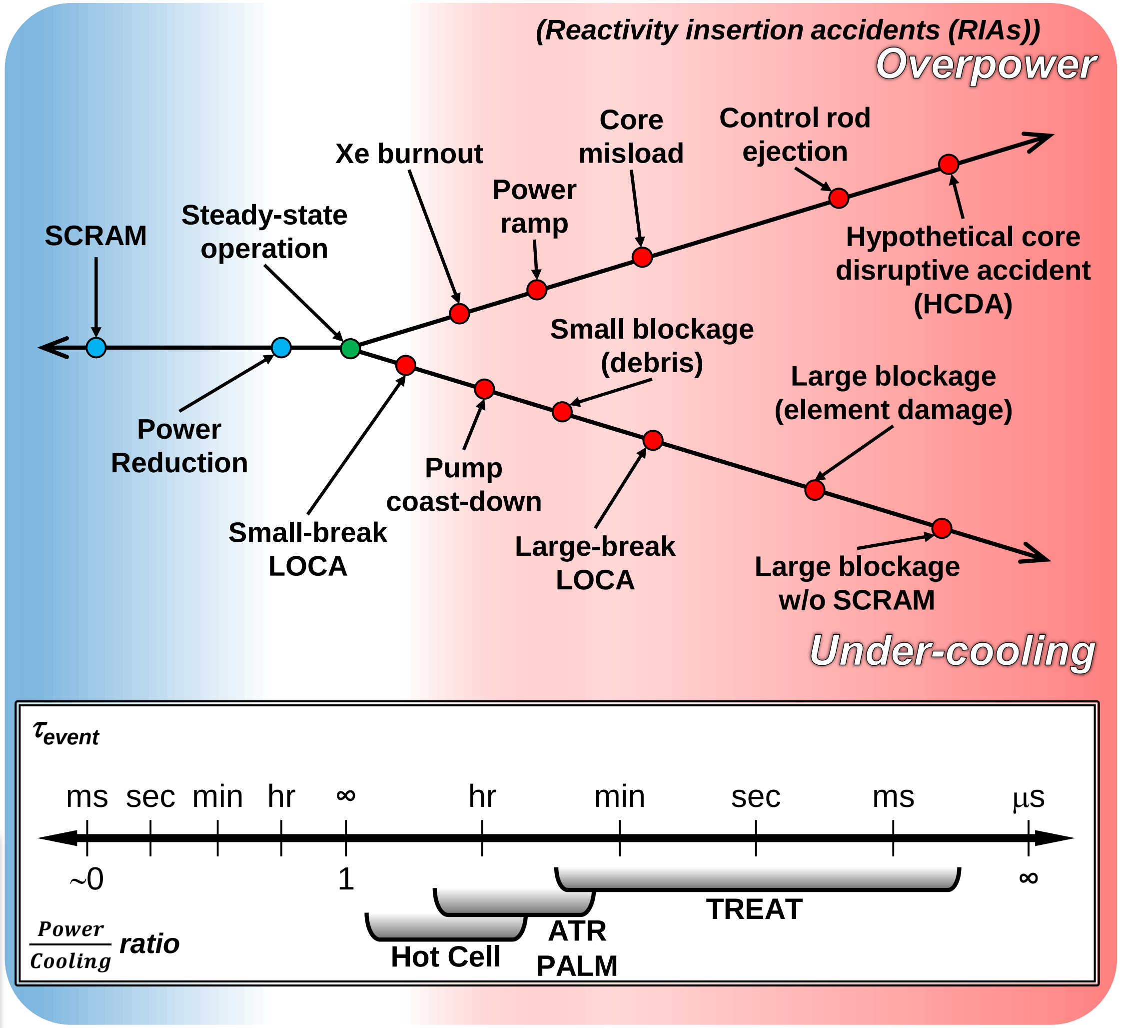
Light water reactor layout

www.world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/nuclear-power-reactors.aspx

Transient Testing of Nuclear Fuel Systems

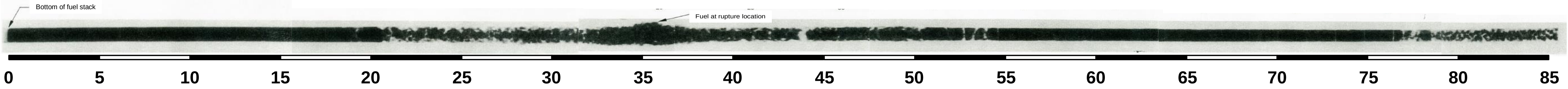
"Transient testing" is the study of fuel and fuel-system behavior under power-cooling mismatch conditions

- Conduct the experimental activities required to describe how fuel systems respond to transients (both operational and off-normal)
- Reactor design criteria
  - Prevent damage to pressure boundary
  - Maintain coolable geometry
- Compliance demonstrated by accounting for:
  - Threshold for fuel fragmentation
  - Energy deposited during fuel-coolant interactions
  - Threshold for fuel failure and associated fission product release fraction



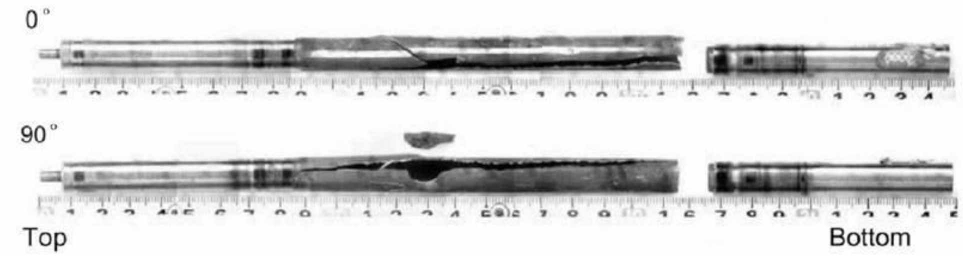
Transient testing is performed to provide this data

How Does Fuel Fail in a Transient?



Neutron radiography of a failed fuel rod, showing internal rubbleization

- The fuel rapidly heats up
  - Cracking → rubbleization → melting
  - Fission gasses rapidly released from the fuel matrix cause a pressure pulse
  - Fission products rapidly diffusing into the cladding form eutectics
- The cladding is breached
  - Mechanical stress & thermal conductivity degrade clad
  - Pellet–cladding mechanical interaction (PCMI)
  - Pellet–cladding chemical interaction (PCMI)
  - Gas-pressure leads to burst cladding
- Fuel debris enters the coolant region
  - Loss of local cooling accelerates damage evolution
  - Debris transport induces damage elsewhere
- High-temperatures lead to clad (Zr) - steam catalysis and hydrogen production



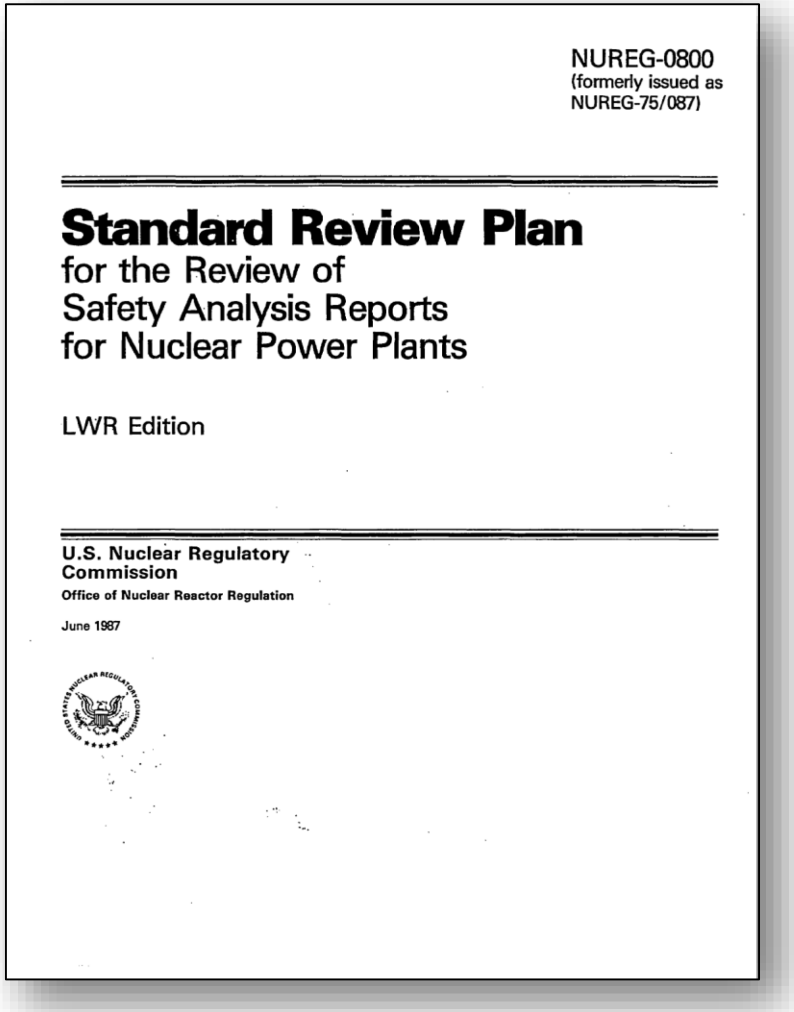
Photograph of breached cladding

Why Test Transient Fuel Behavior? – Regulatory Standpoint

- NUREG-0800 requires:

1) the fuel system is not damaged as a result of normal operation and anticipated operational occurrences;
2) fuel system damage is never so severe as to prevent control rod insertion when it is required;
3) the number of fuel rod failures is not underestimated for postulated accidents; and
4) coolability is always maintained.

- Licensing of a fuel system requires identification of all degradation mechanisms and failure modes and definition of failure thresholds corresponding to each degradation mechanism.



NUREG-0800
(formerly issued as
NUREG-75/087)

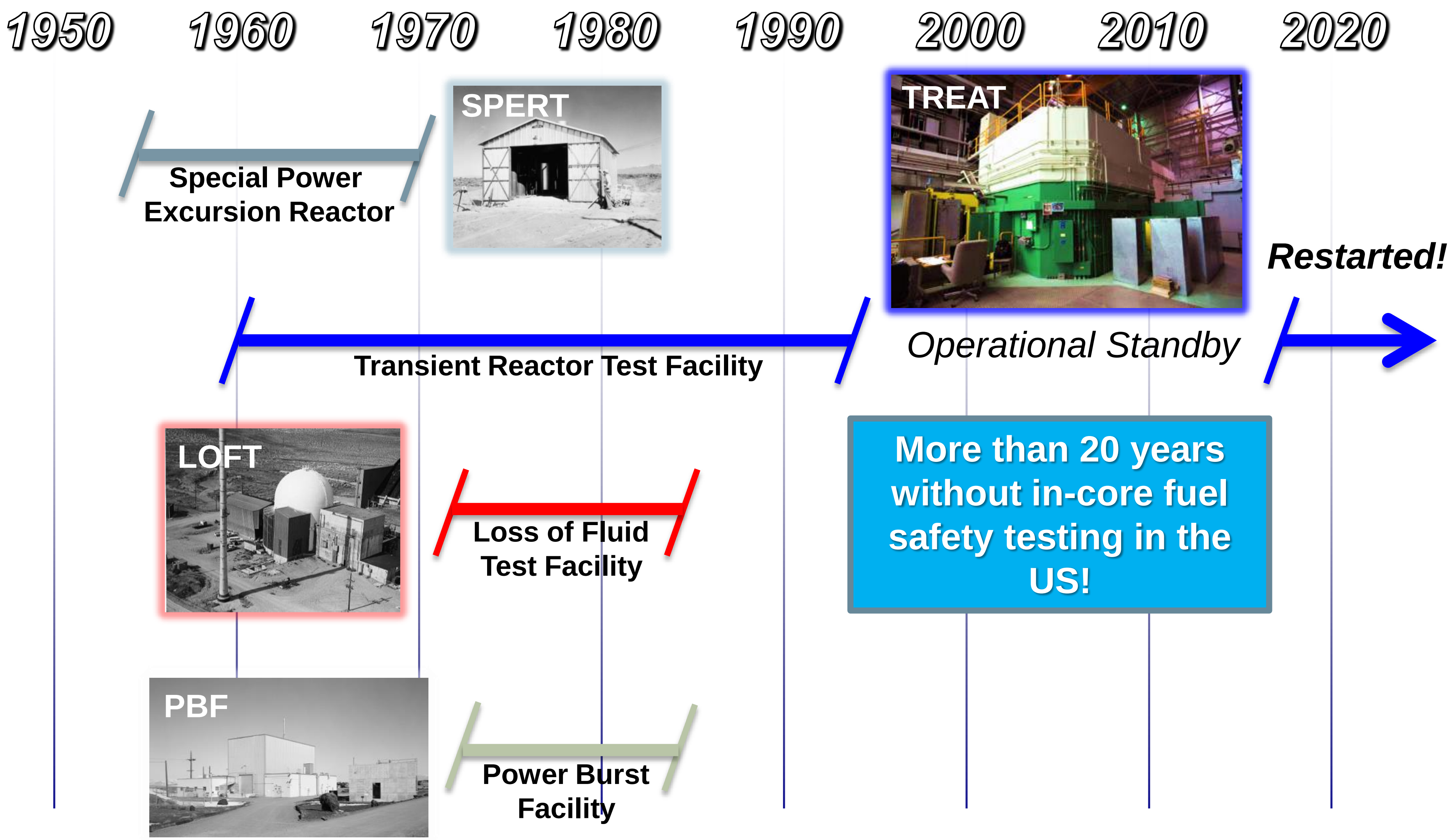
Standard Review Plan
for the Review of
Safety Analysis Reports
for Nuclear Power Plants

LWR Edition

U.S. Nuclear Regulatory
Commission
Office of Nuclear Reactor Regulation

June 1987

U.S. History of Fuel Safety Testing – National Reactor Testing Station



Special Power Excursion Reactor

Transient Reactor Test Facility

Operational Standby

Restarted!

Loss of Fluid Test Facility

Power Burst Facility

More than 20 years without in-core fuel safety testing in the US!

The Transient Reactor Test (TREAT) Facility

The Transient Reactor Test (TREAT) Facility

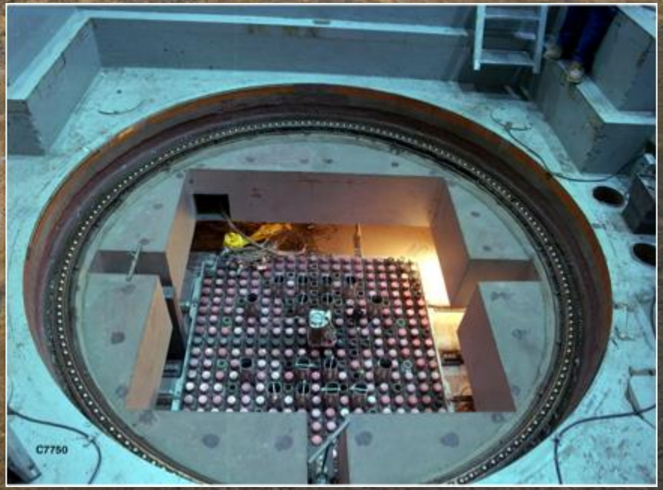
Unique design delivers the nuclear environment required to meet fuel safety research needs

19 GW Peak Transient Power (with 100 kW Steady-state power option)

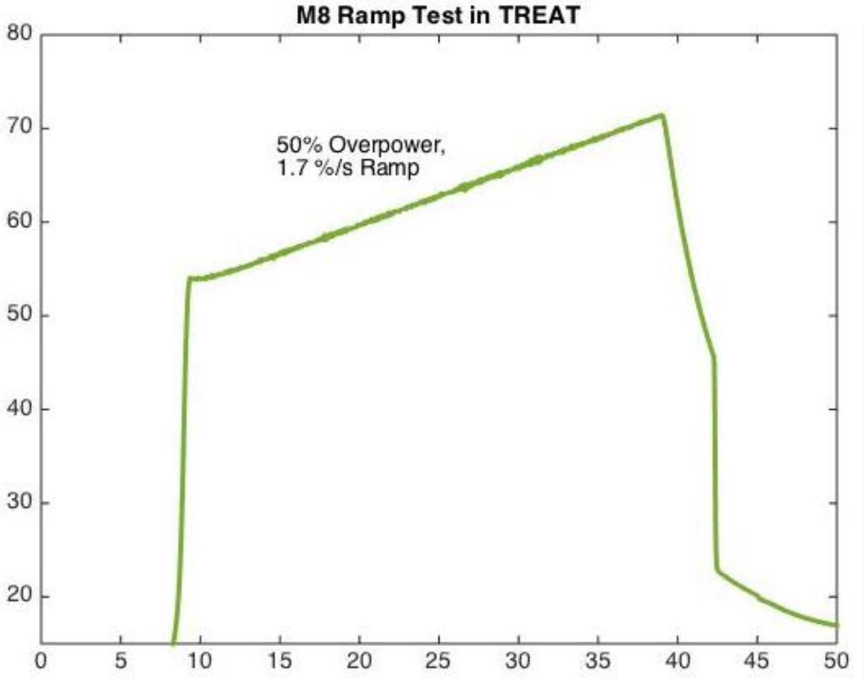
Fuel assemblies: 10 cm × 10 cm (19 × 19 array); 0.2 wt.% HEU oxide in graphite

Core: (1.9 m × 1.9 m) × 1.2-m height

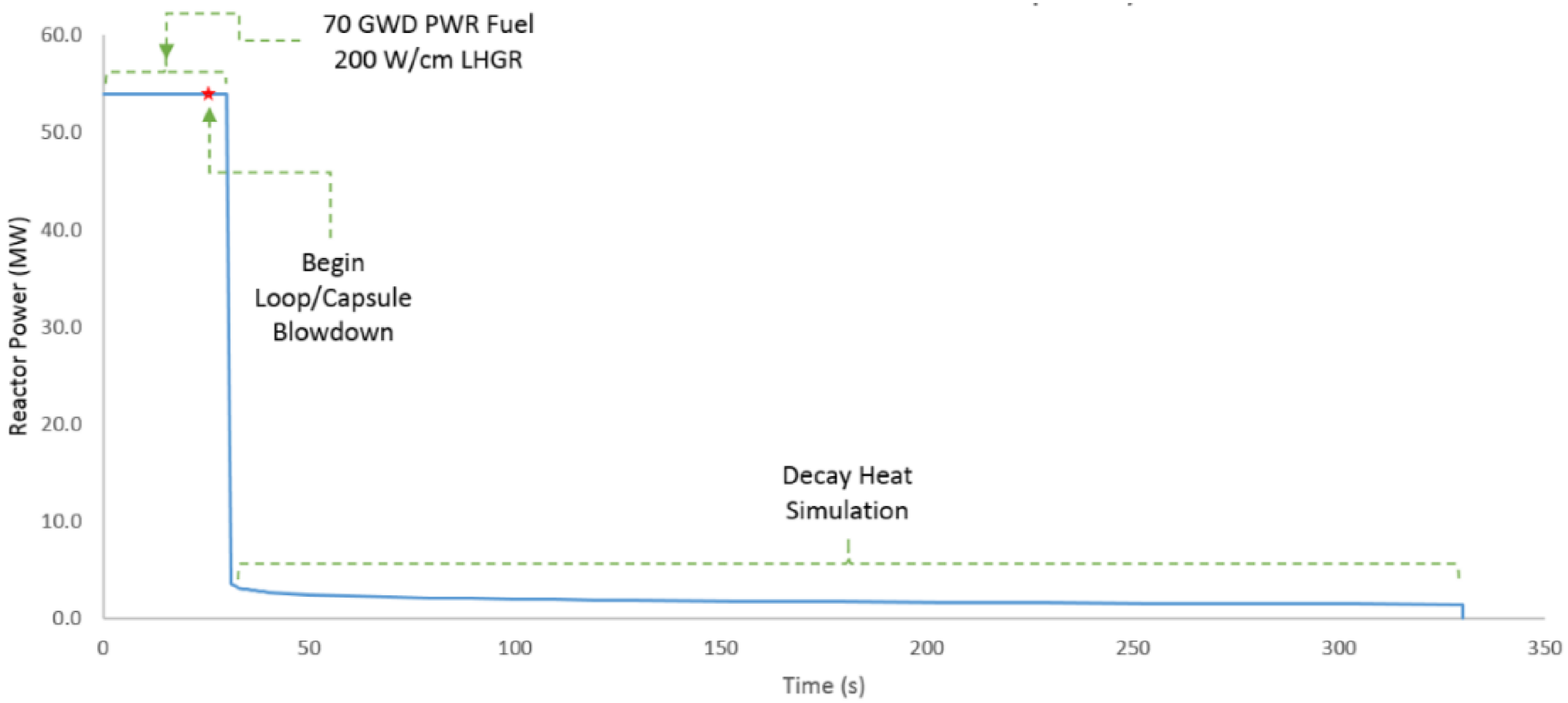
Instantaneous, large negative temperature coefficient (self protecting driver core)



Transient Profiles at TREAT

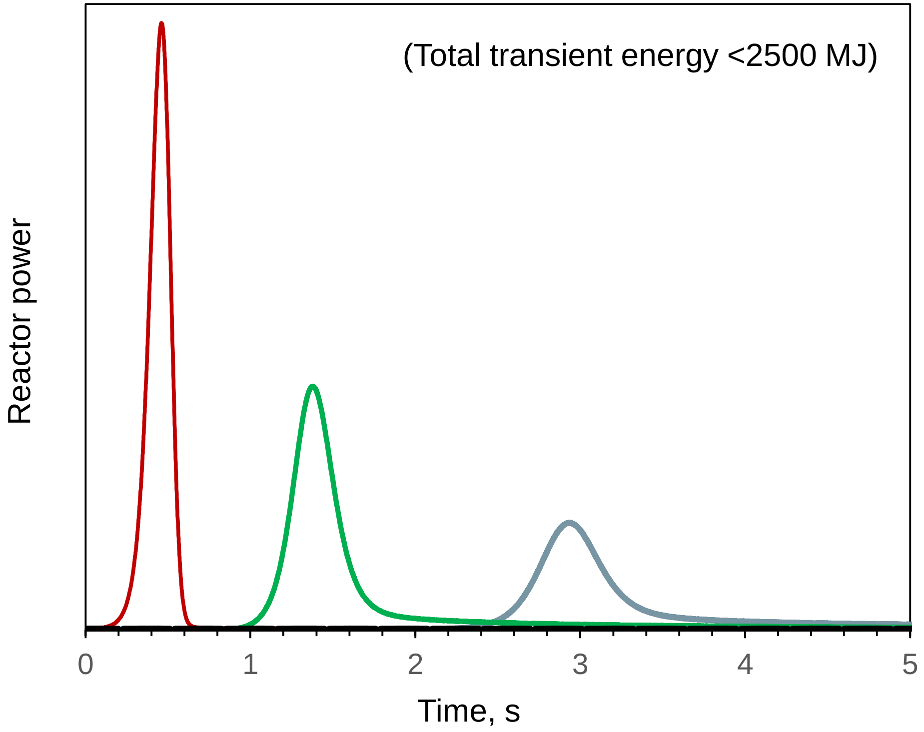


Power ramp

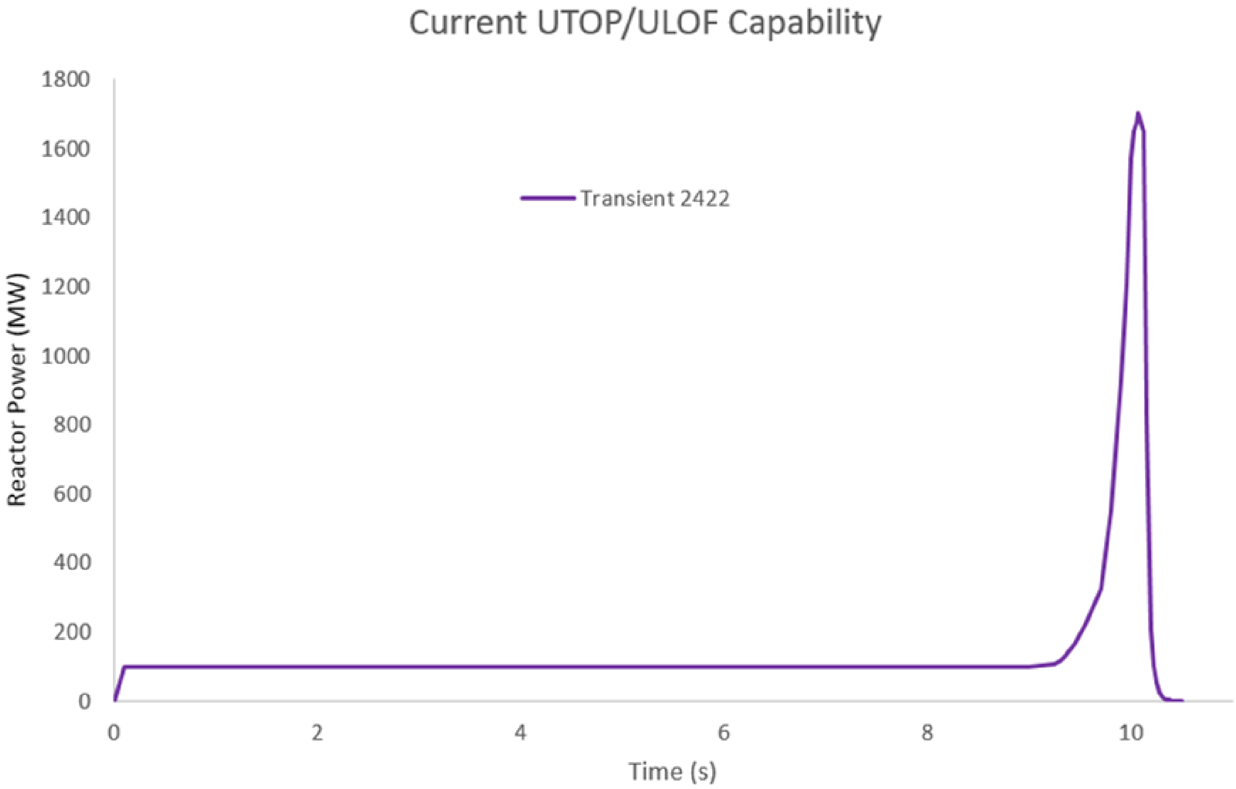


Loss of coolant accident (LOCA) profile

Transient Profiles at TREAT

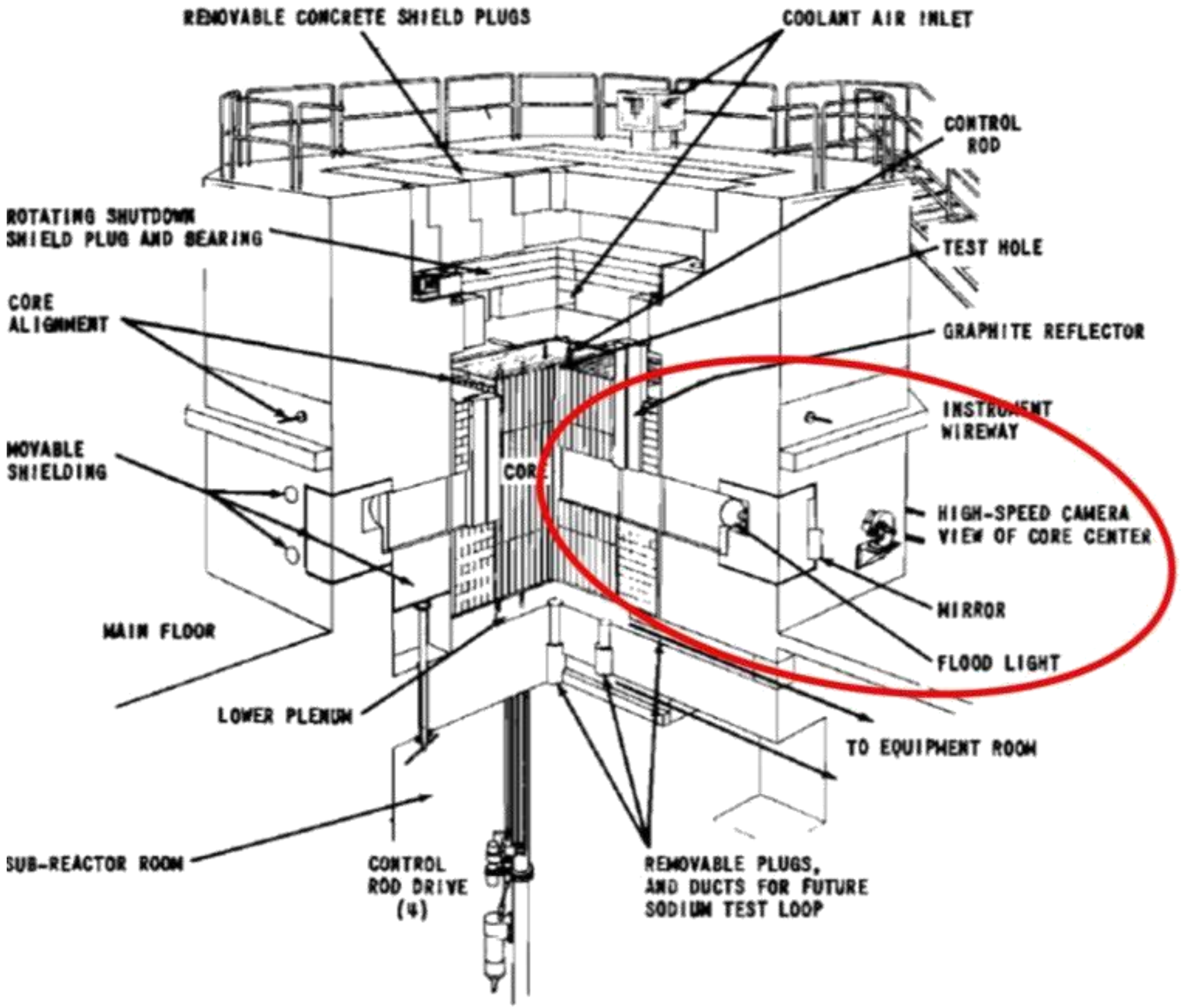


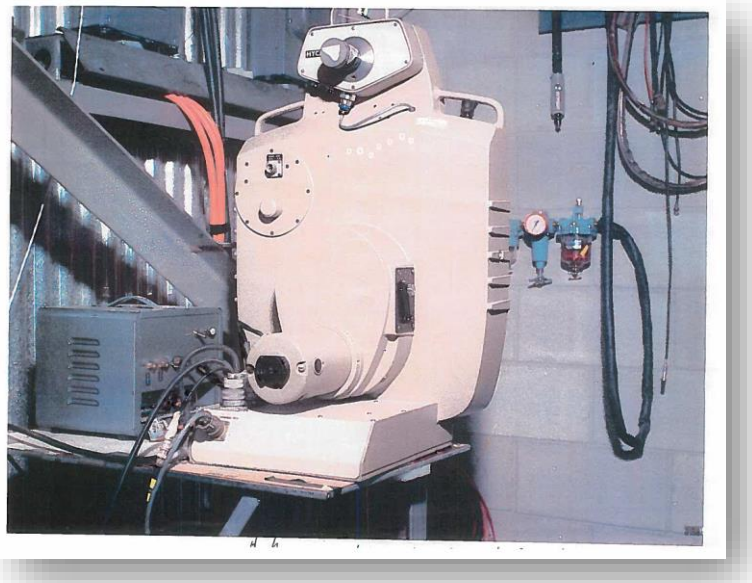
Pulses



Complex profiles

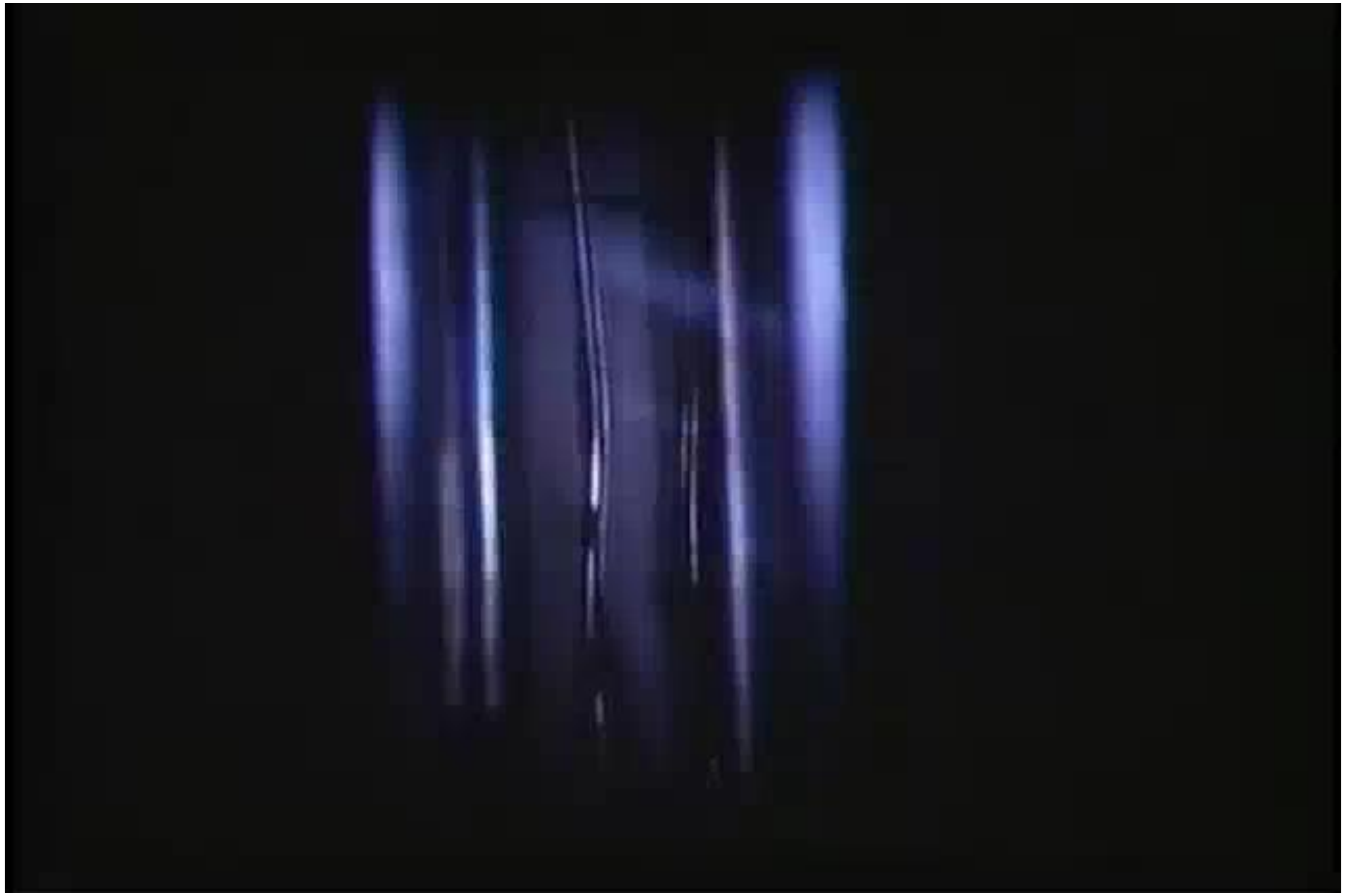
Early Fuel Motion Imagery at TREAT





High-speed camera used in early TREAT tests

A Single Fuel Rod in Air During a High-Power Transient



VIDEO_TS-0-01 (4 m 30 s)

A Single Fuel Rod in Water (LWR Reactivity Insertion Accident, RIA)

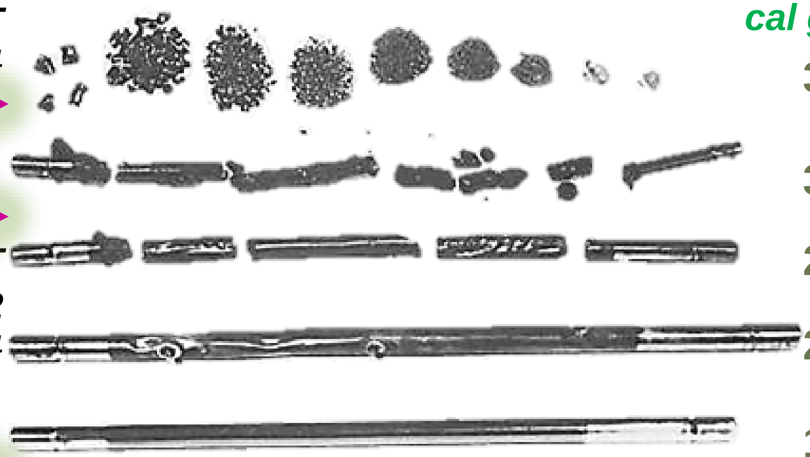
Historical visualization experiments conducted at TREAT to establish LWR fuel failure modes (early 1960's)

CEN-224T
450 cal g^{-1}

CEN-231T
368 cal g^{-1}

CEN-222T
shot 2
305 cal g^{-1}

CEN-222T
shot 1
165 cal g^{-1}



Energy deposition cal g^{-1} UO_2

378

338

287

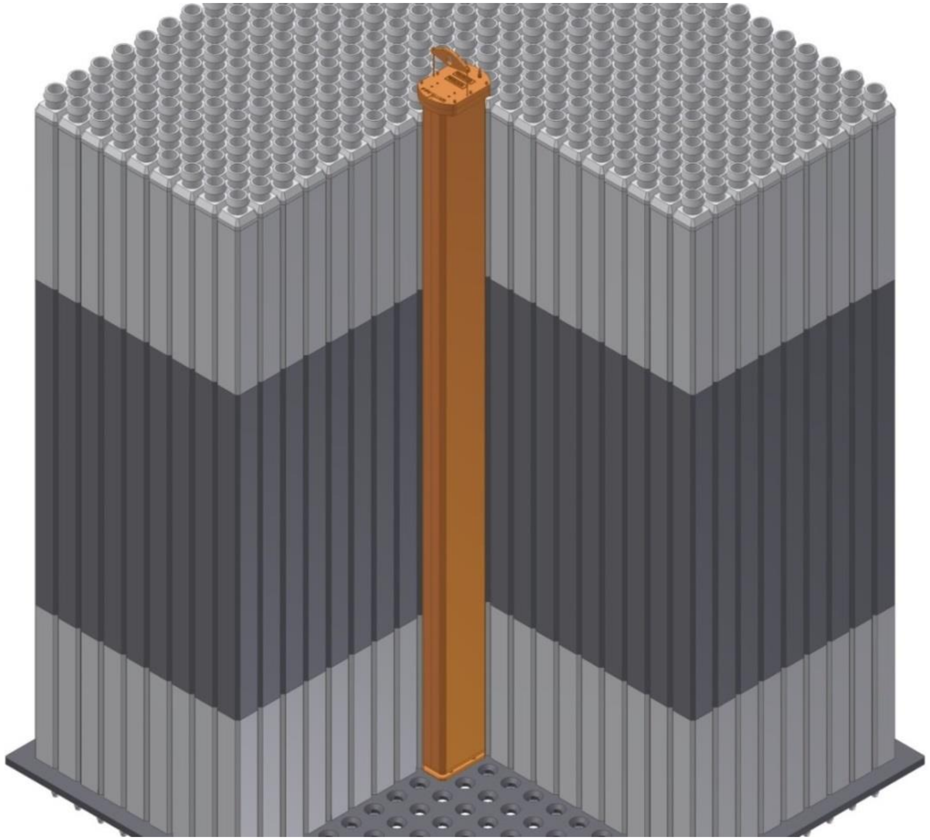
240

168

Fuel subjected to different levels of energy deposition

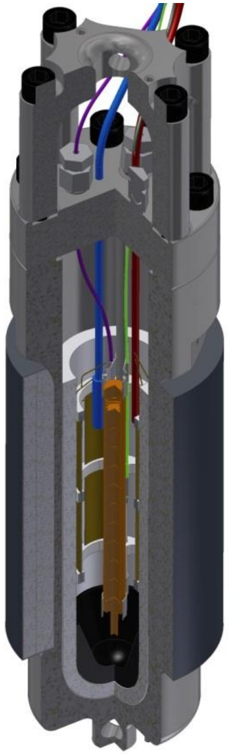
Transient Experiments at TREAT Today

- Testing is done using drop-in capsules that hold fuel specimens and serve as containment for the experiments
- Static environment devices
  - Pre-pressurized to 16 MPa
  - Electrically pre-heated up to 300 ºC
  - Dry inert gas, steam, or liquid sodium
- Flowing loop devices
  - Custom-developed for water
  - Induction pump for liquid sodium



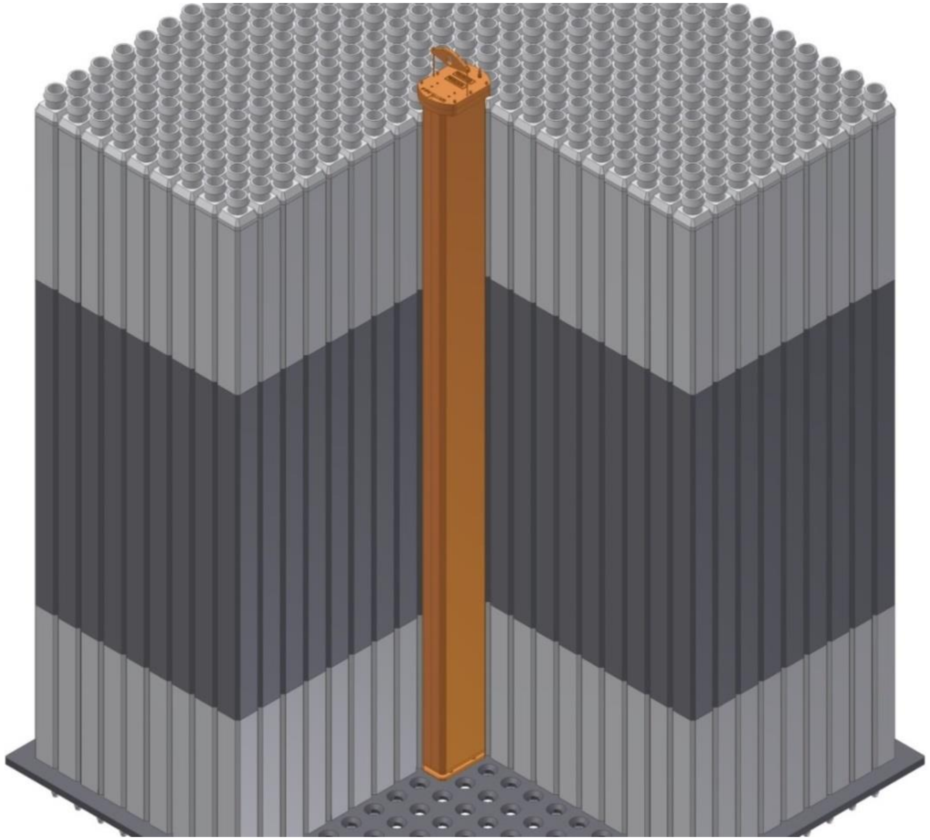
Three-dimensional rendering of the TREAT core, illustrating the fuel elements (grey) and the transient test device (orange)

Transient Experiments at TREAT Today – Static Capsule



Individual fuel-rod test capsule

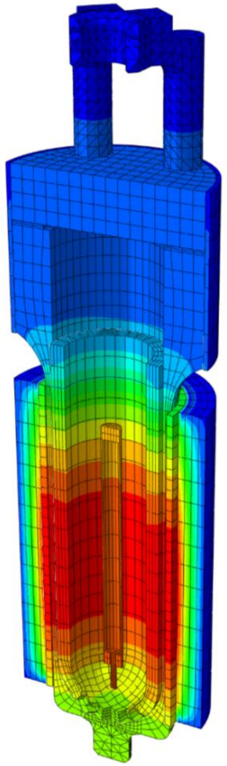
Leak-tight secondary enclosure



Three-dimensional rendering of the TREAT core, illustrating the fuel elements (grey) and the transient test device (orange)

Transient Experiments at TREAT Today – Static Capsule

A super crucible!



Individual fuel-rod test capsule

Leak-tight secondary enclosure

Insertion of a test rig into the TREAT reactor

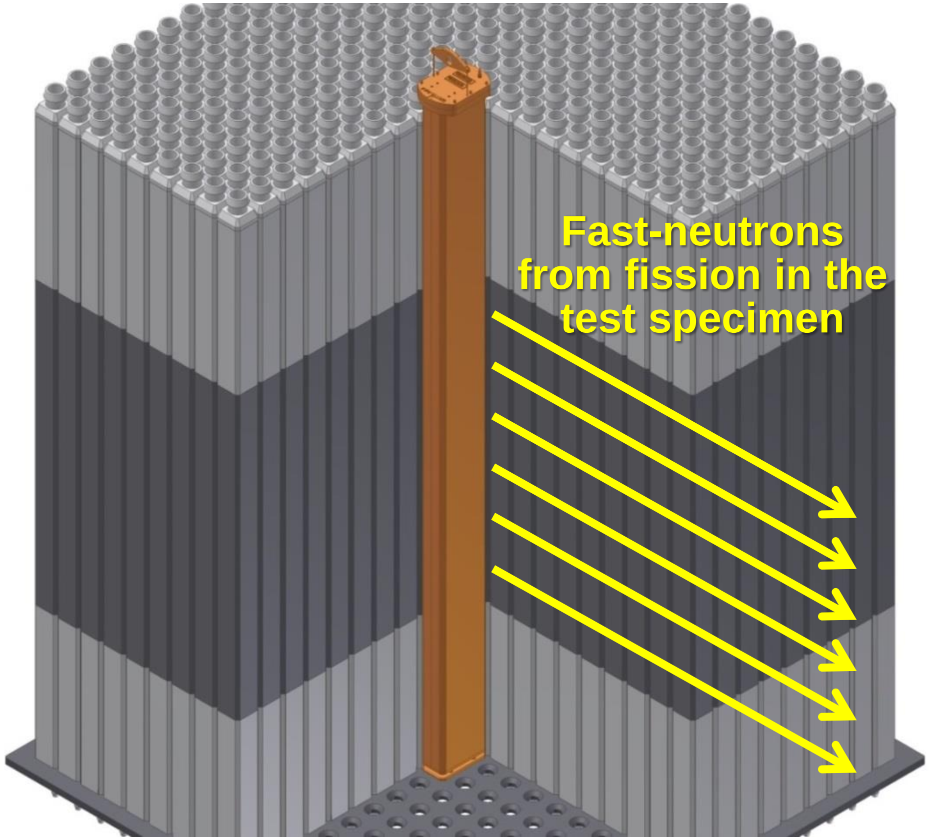
Capsule Design

'SETH' test capsule with crucible liners

Monitoring Fuel Motion During Experiments at TREAT

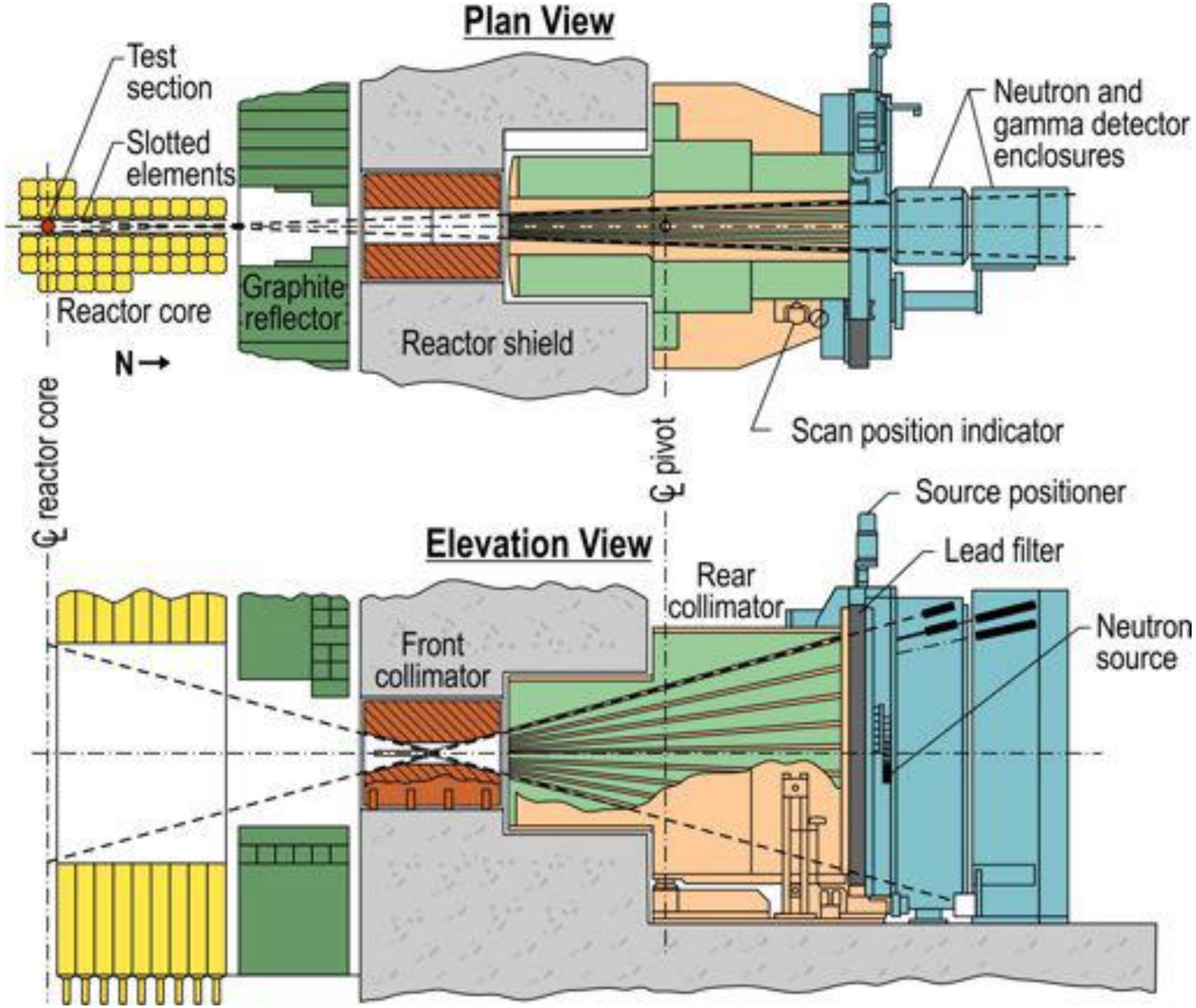
Transient Experiments at TREAT – Fuel Motion Monitoring

- A key measurement at TREAT is monitoring the movement and relocation of fuel
- Method: fast-neutron hodoscope
  1. A row of fuel elements is left empty between the fuel and the outside
  2. A fast-neutron collimator with hundreds of small slits is placed external to the core, each viewing a small area of the test vehicle
  3. Fast neutron detectors are placed at the outside surface of the collimator
  4. Fission is induced in the fuel sample by the reactor during the transient
  5. Fission-neutrons from the test specimen leak from the core, through the slits, and are measured in the detectors



Three-dimensional rendering of the TREAT core, illustrating the fuel elements (grey) and the transient test device (orange)

TREAT Fast-Neutron Hodoscope

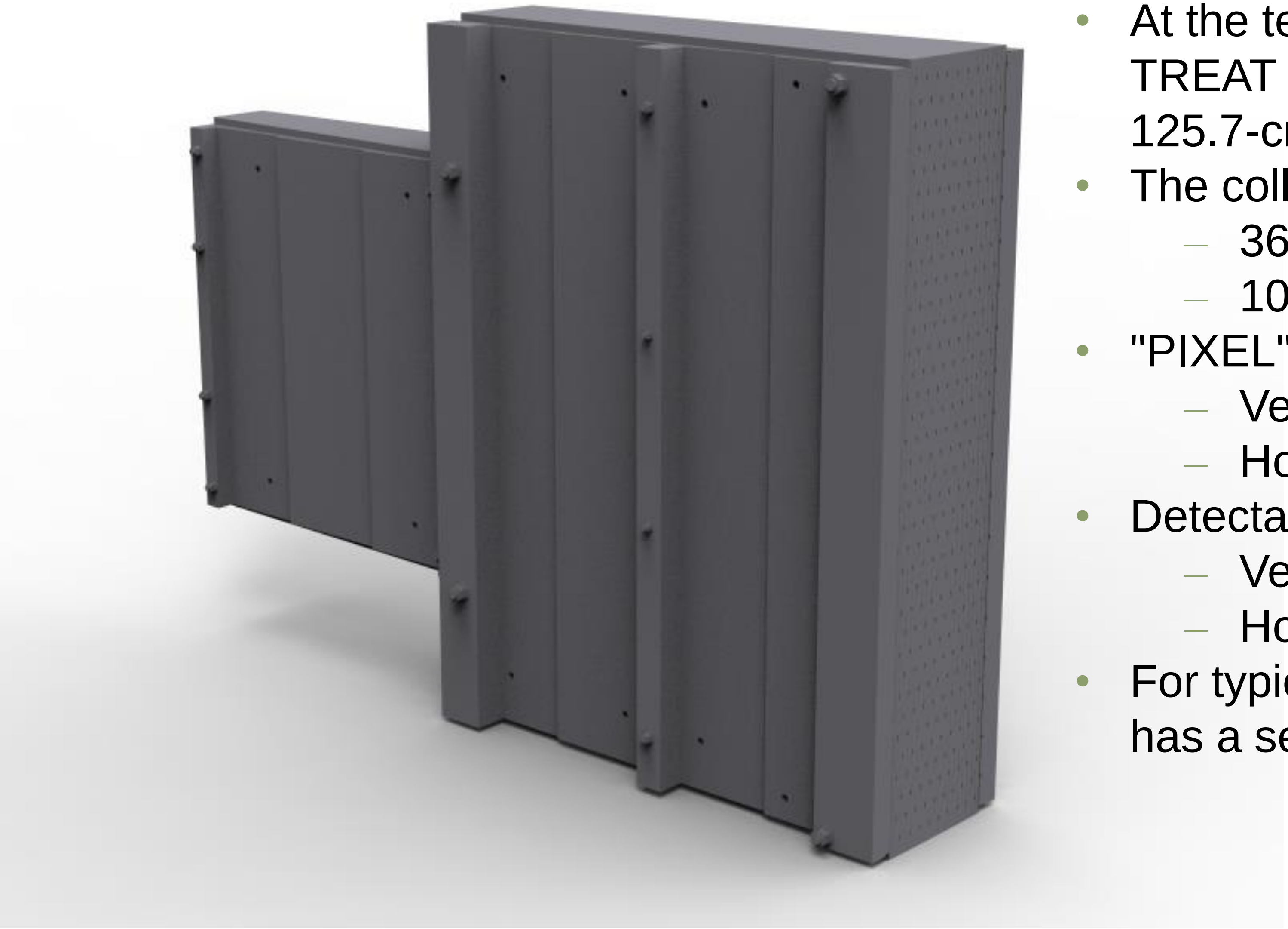


TREAT Fast-Neutron Hodoscope

View of the Hodoscope system from the side

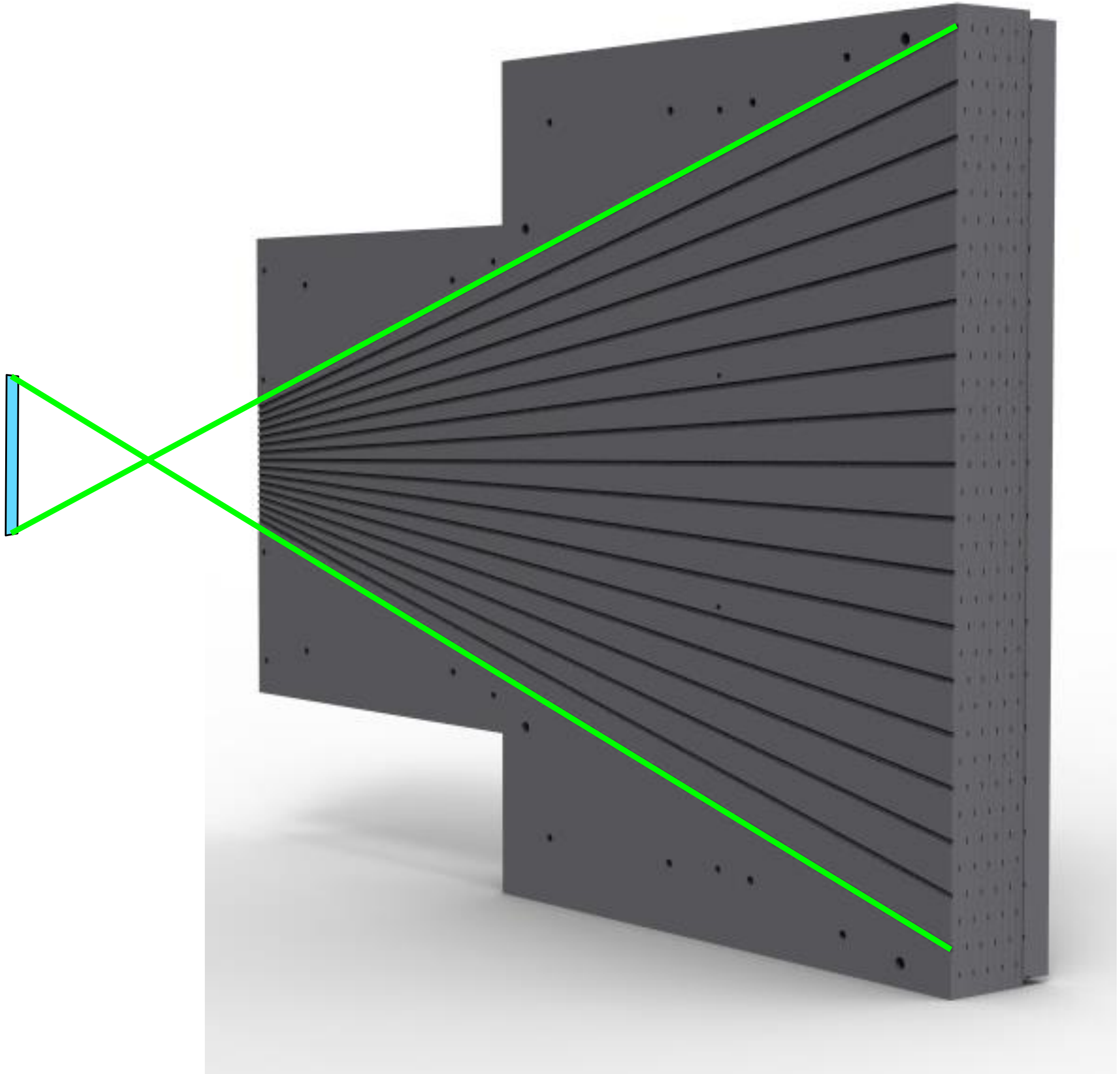
View of the Hodoscope system from the rear, with the detector panel open

Collimator



- At the test-item location (the center of the TREAT reactor), the system has a field of view 125.7-cm tall by 6.9-cm wide area
- The collimator has 360 pixels
  - 36 vertical pixels
  - 10 horizontal pixels
- "PIXEL" sizes:
  - Vertical = 34.5 mm
  - Horizontal = 9.4 mm
- Detectable motion
  - Vertical = 6 mm
  - Horizontal = 0.2 mm
- For typical experiment fuel loadings, each pixel has a sensitivity of ~0.1 g of fuel

Collimator



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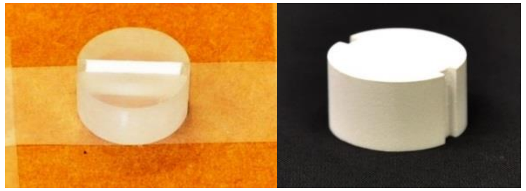
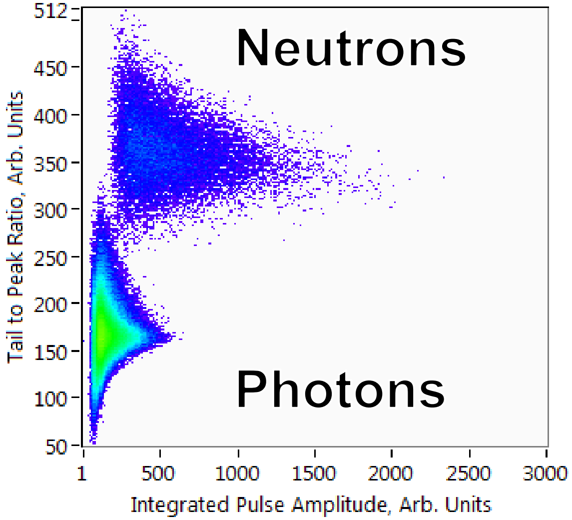
Hodoscope Detectors



PRS button before and after painting

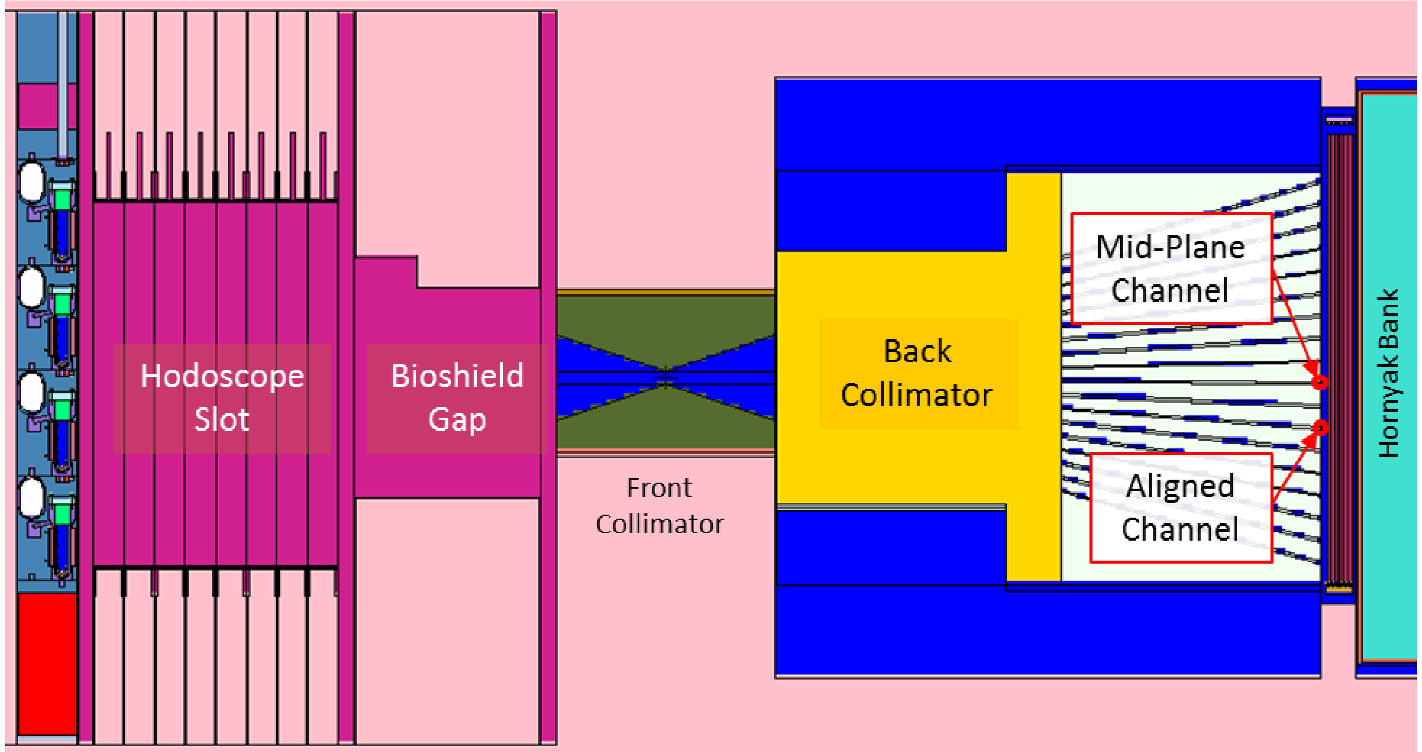


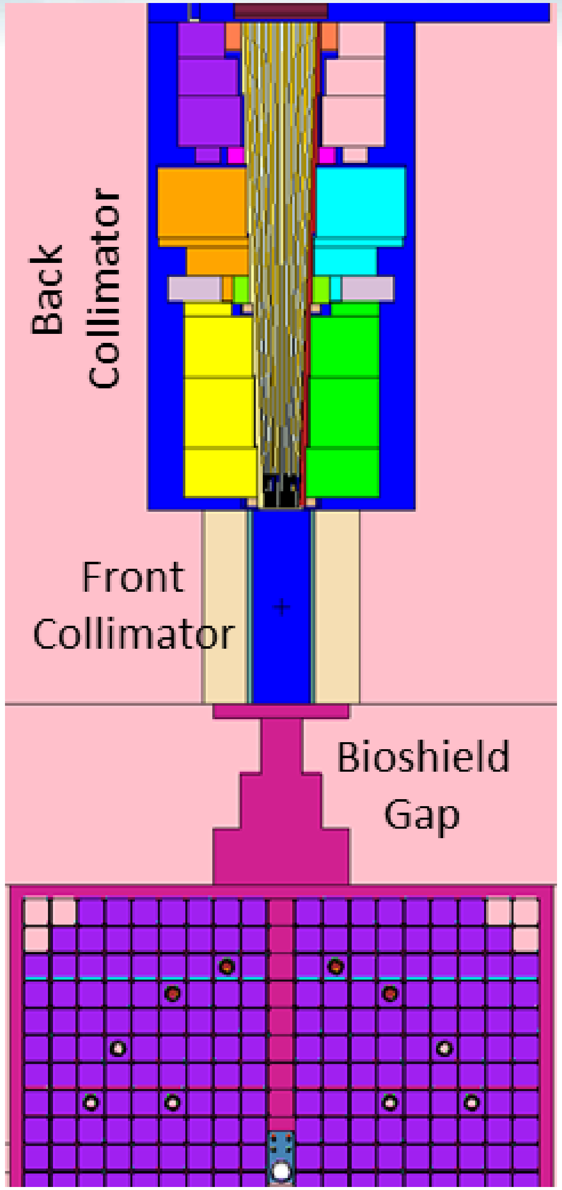
Typical example of PRS particle pulse-shape discrimination

- Experiments at TREAT are one-of-a-kind events, very-high reliability is required for measurements
- Today's Hodoscope uses proton recoil scintillator (PRS) detectors – ZnS/epoxy matrix sandwiched between Lucite hemi-cylinders
- During a test data is recorded for each detector every 0.001 seconds
- Maximum instantaneous data rate is roughly 400,000 events s^{-1}

Simulation and Modeling

- End-to-end radiation transport model for the test device using MCNP6
  - Variance reduction: discarding neutrons below 0.1 MeV
  - Variance reduction: using angular source biasing





FMMS Data Visualization and Control Room User Interface

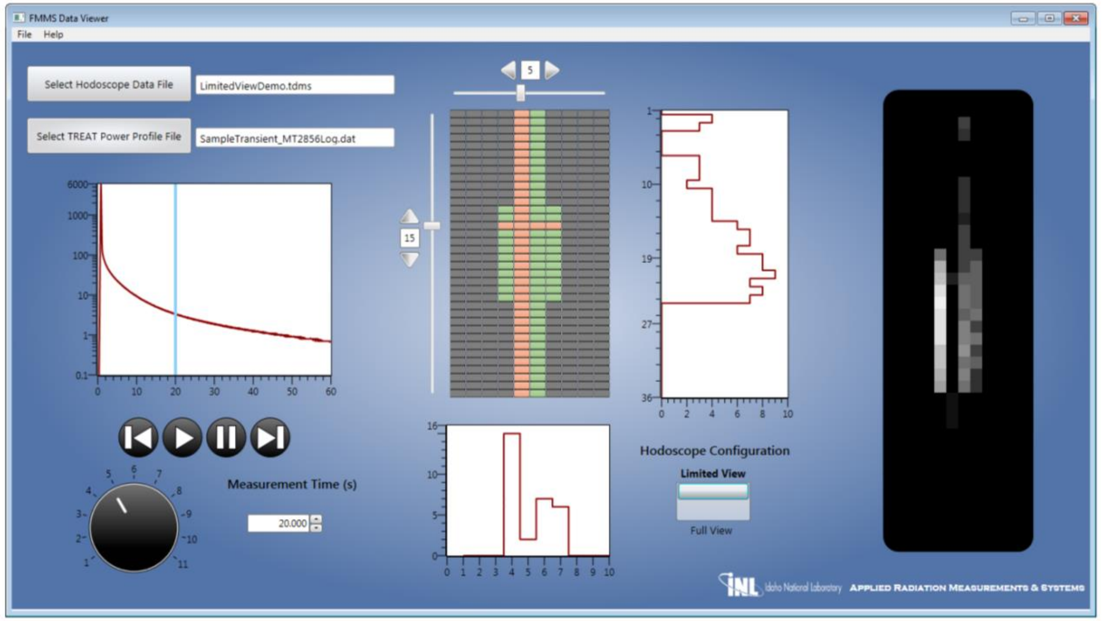
- Data analysis and visualization software prototype was developed; analysis will use transient information to convert event counts in the PRS detectors to mass values, using an advanced adaptation of the power coupling factor called the mass coupling factor (MCF, to be experimentally determined)
- Time-dependent analysis, allowing for 2-D time-stepped transient evaluations

Individual column/row viewers

Transient information

Playback controls

2D visualization

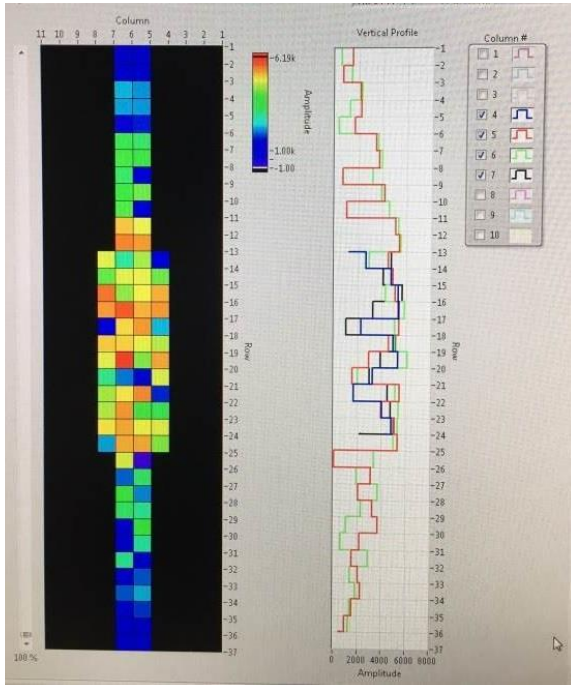


Select Hodoscope Data File: LimitedViewDemo.tdms

Select TREAT Power Profile File: SampleTransient_MT2856Log.dat

Measurement Time (s): 20.000

Data visualization GUI



Control room GUI

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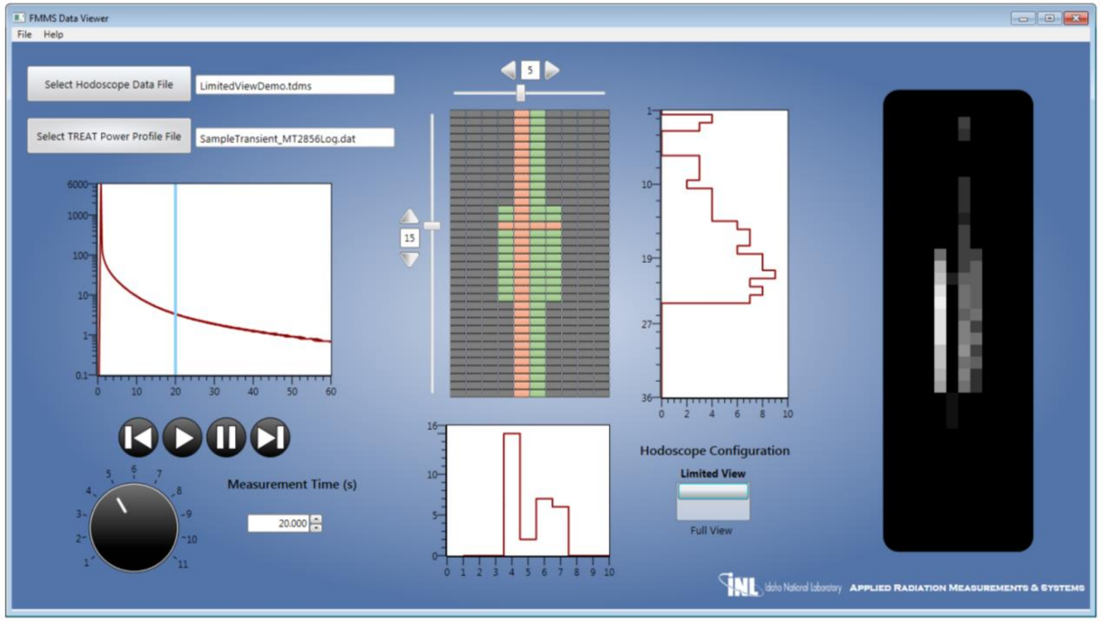


LimitedViewDemo.tdms

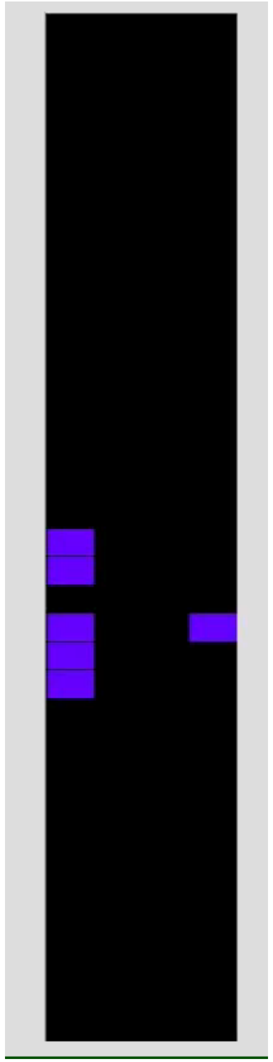
SampleTransient_MT2856Log.dat

20.000

2D visualization

"RAW" hodoscope pictogram data from T2886 (290 ms pulse)

Data visualization GUI

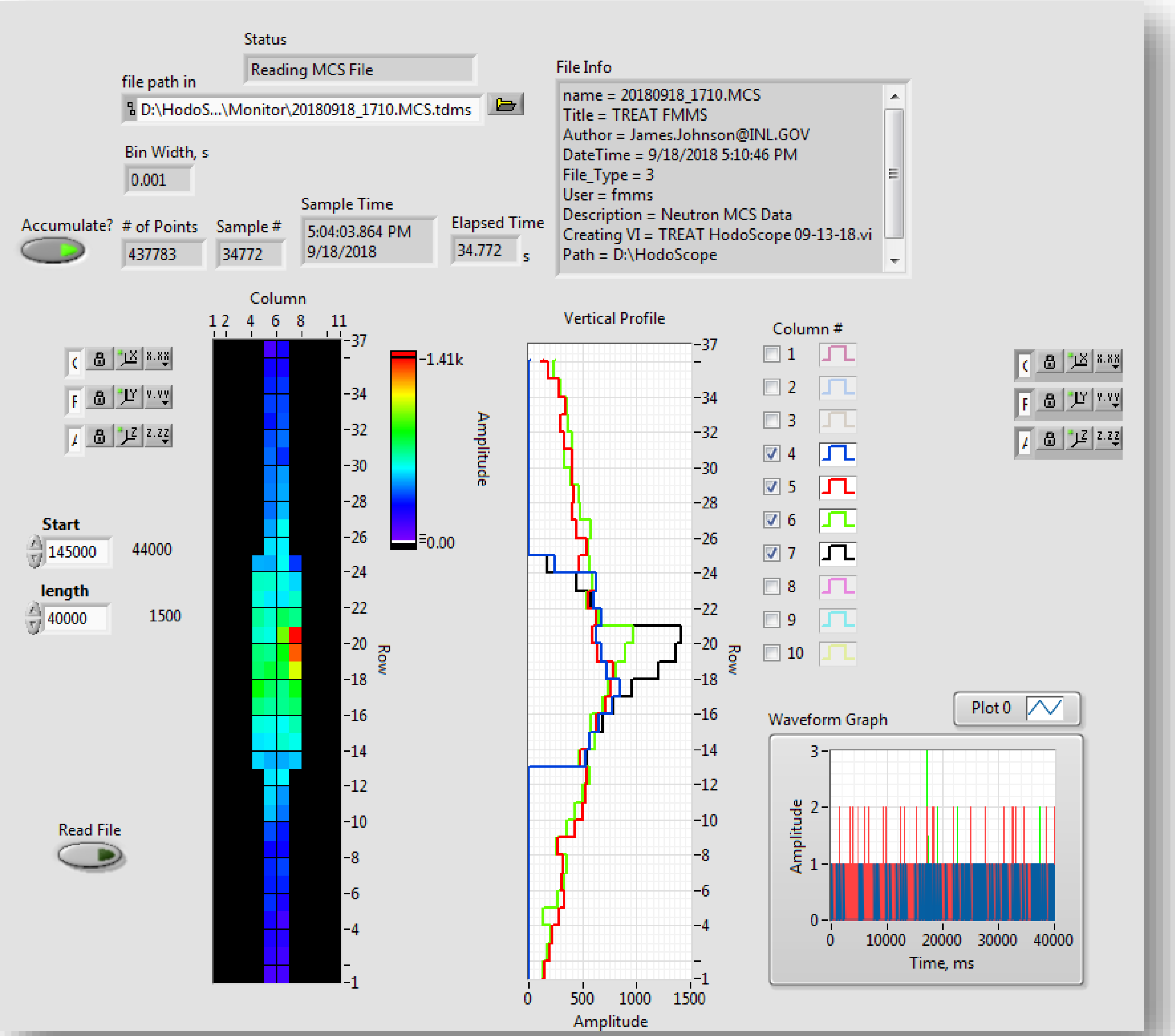


Control room GUI

Our First Data with Fuel in the Test Device (September 18, 2018)

Transient 2913

- We found that the Hodoscope was not centered on the fuel in the capsule; we later rotated the FMMS platform, this moved the fuel rod from column 7 to column 5 in the image
- This low-power transient (nominal 101.3 ± 1.8 MJ) produced sufficient in-pin fissions to generate a fast-neutron signal measurable by the system



Status: Reading MCS File

file path in: D:\HodoS...\Monitor\20180918_1710.MCS.tdms

Bin Width, s: 0.001

Accumulate?

# of Points: 437783

Sample #: 34772

Sample Time: 5:04:03.864 PM 9/18/2018

Elapsed Time: 34.772 s

File Info

name = 20180918_1710.MCS
Title = TREAT FMMS
Author = James.Johnson@INL.GOV
DateTime = 9/18/2018 5:10:46 PM
File_Type = 3
User = fmms
Description = Neutron MCS Data
Creating VI = TREAT HodoScope 09-13-18.vi
Path = D:\HodoScope

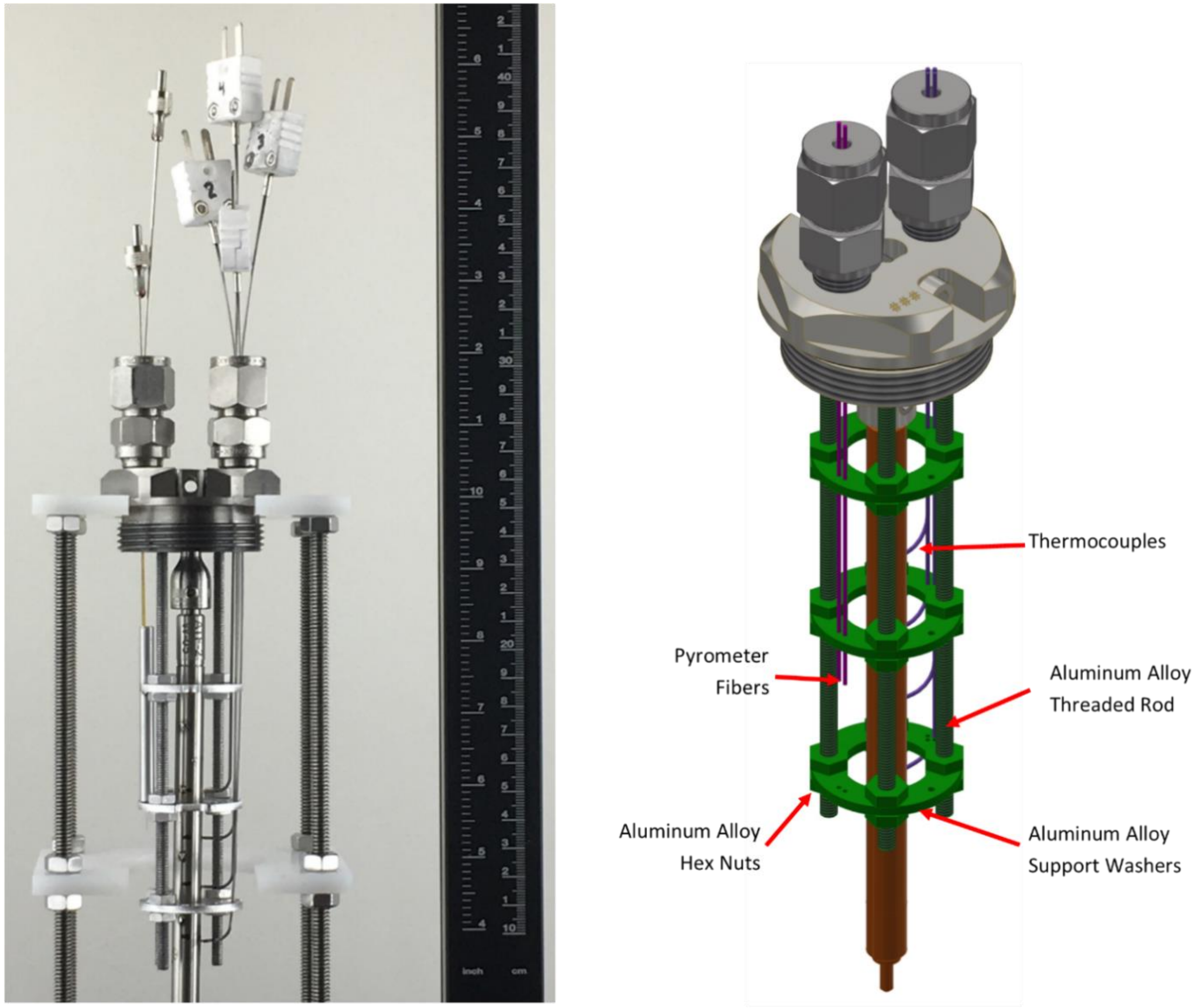
Start: 145000 44000

length: 40000 1500

Column #
☐ 1
☐ 2
☐ 3
☑ 4
☑ 5
☑ 6
☑ 7
☐ 8
☐ 9
☐ 10

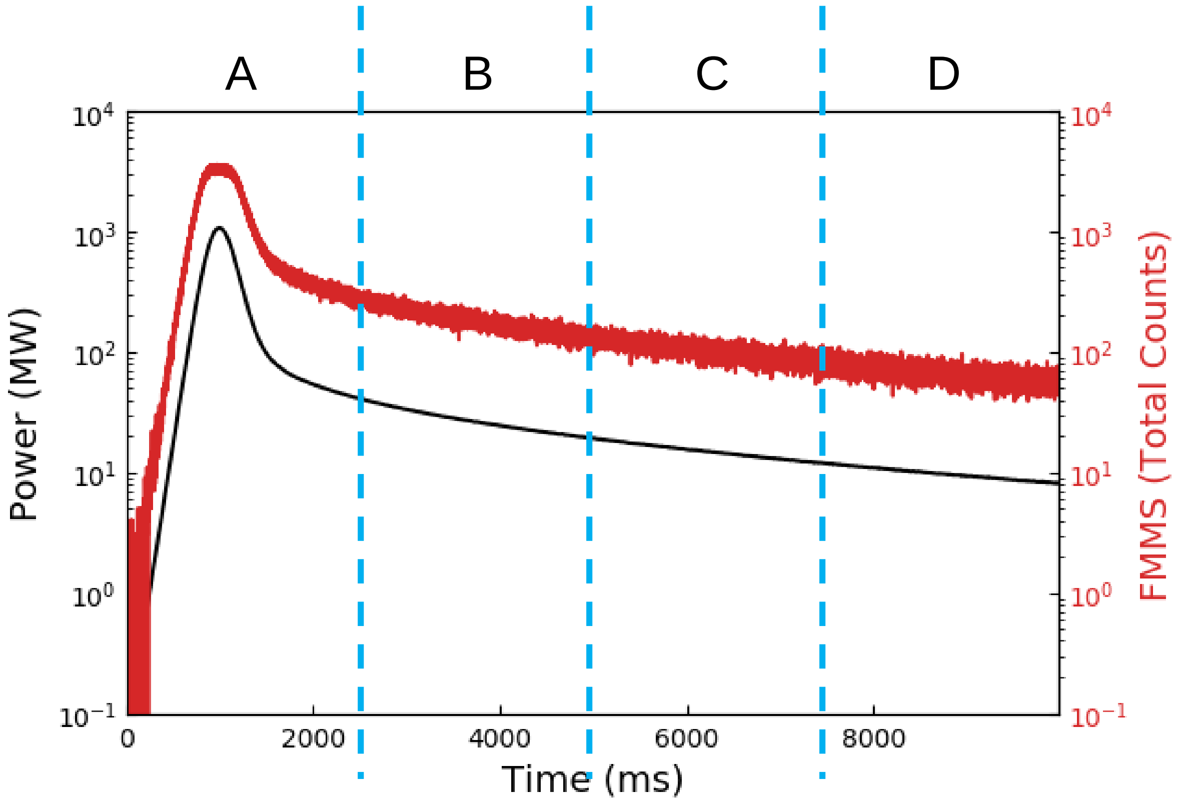
SETH-E – First Case of Fuel Movement

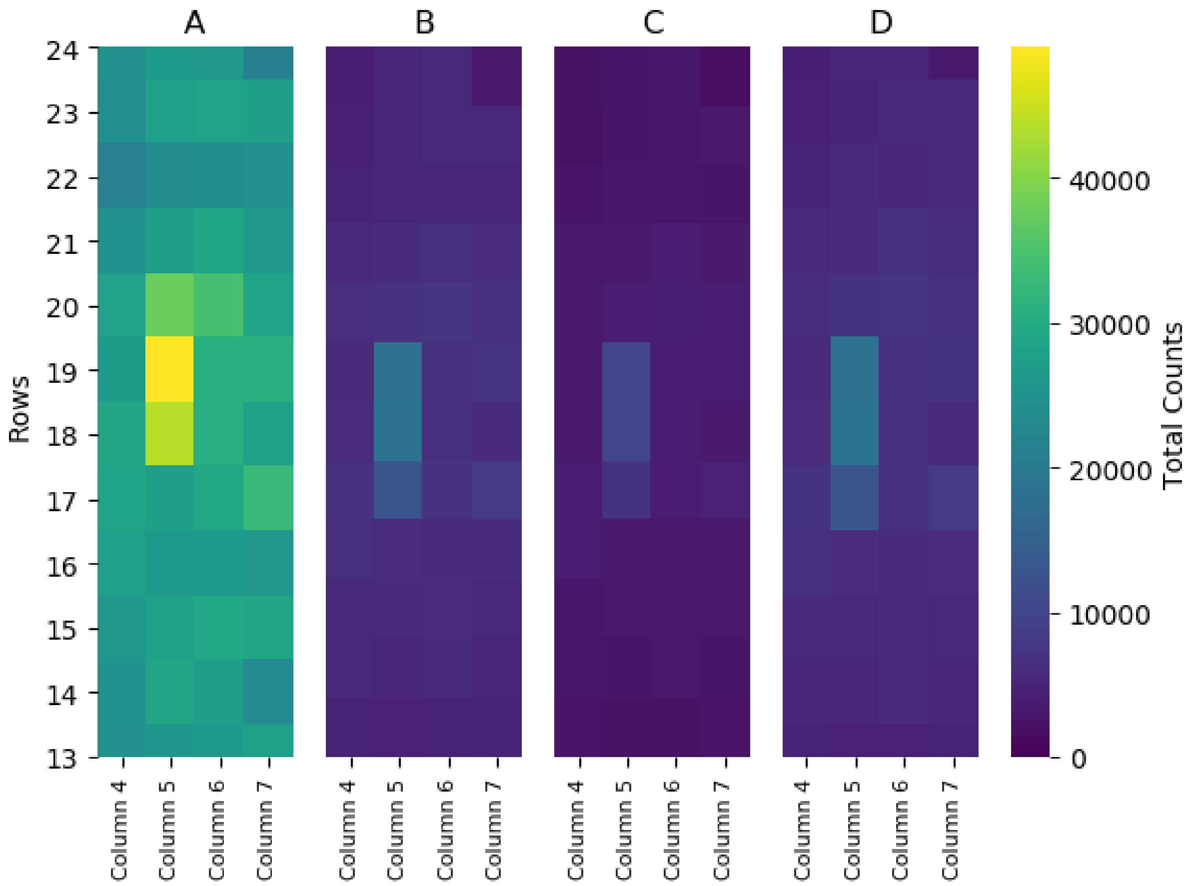
- Separate Effects Test Holder (SETH)
  - Used in TREAT experiment-program commissioning tests in 2018
  - Supports a 10-pellet rodlet of 4.9% enriched, commercially-produced, fresh UO_2 pellets
  - Pellet stack length = 10.16 cm
  - Zr alloy cladding with typical PWR radial dimensions
- SETH-E was subjected to a 1.69% Δk/k reactivity addition, resulting in approximately 500 MJ total reactor energy
  - Energy chosen to approach clad melting temperature
  - Cladding deformation occurred followed by downward motion
  - Peak cladding temperatures was measured at 2113 C

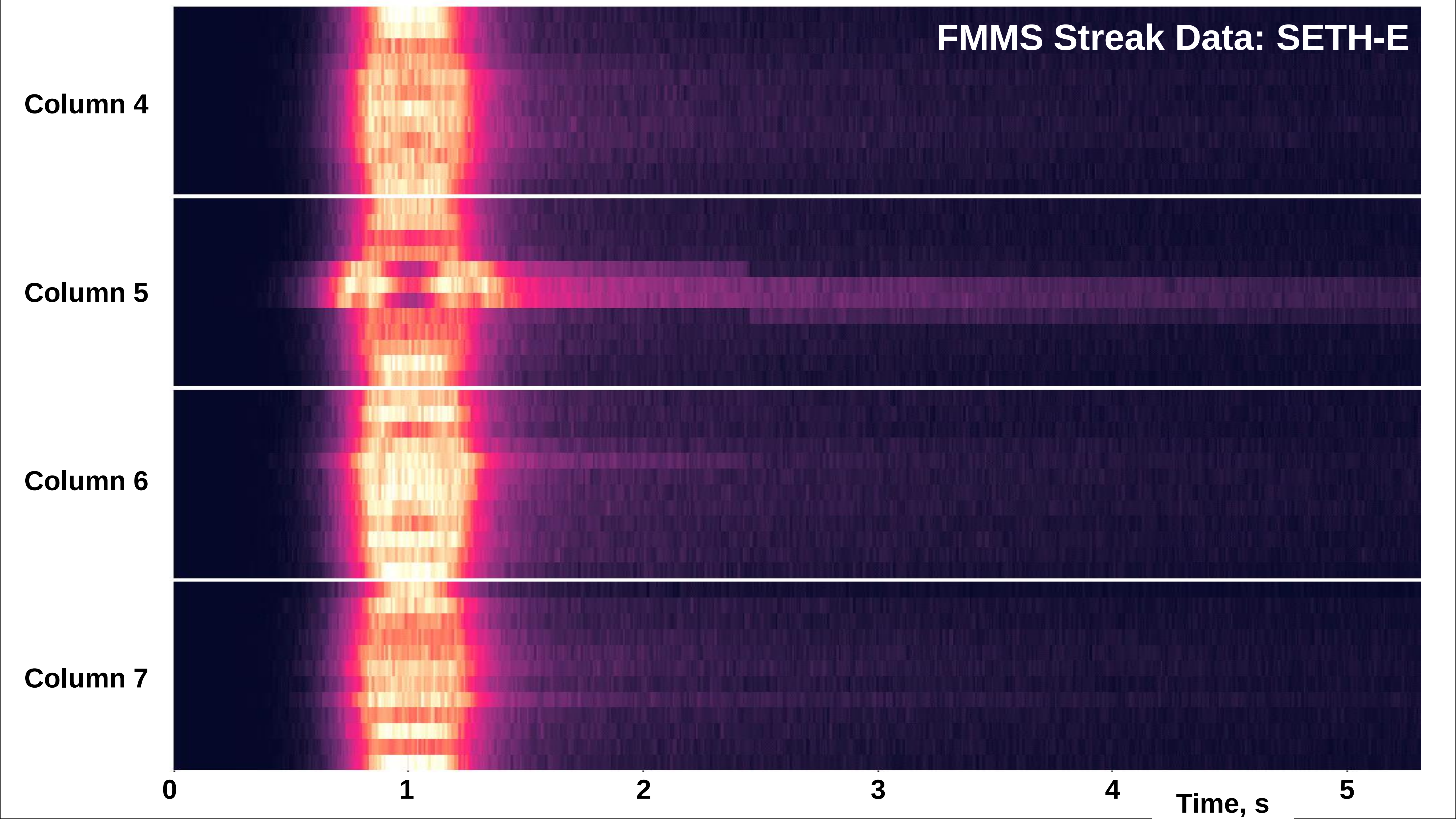


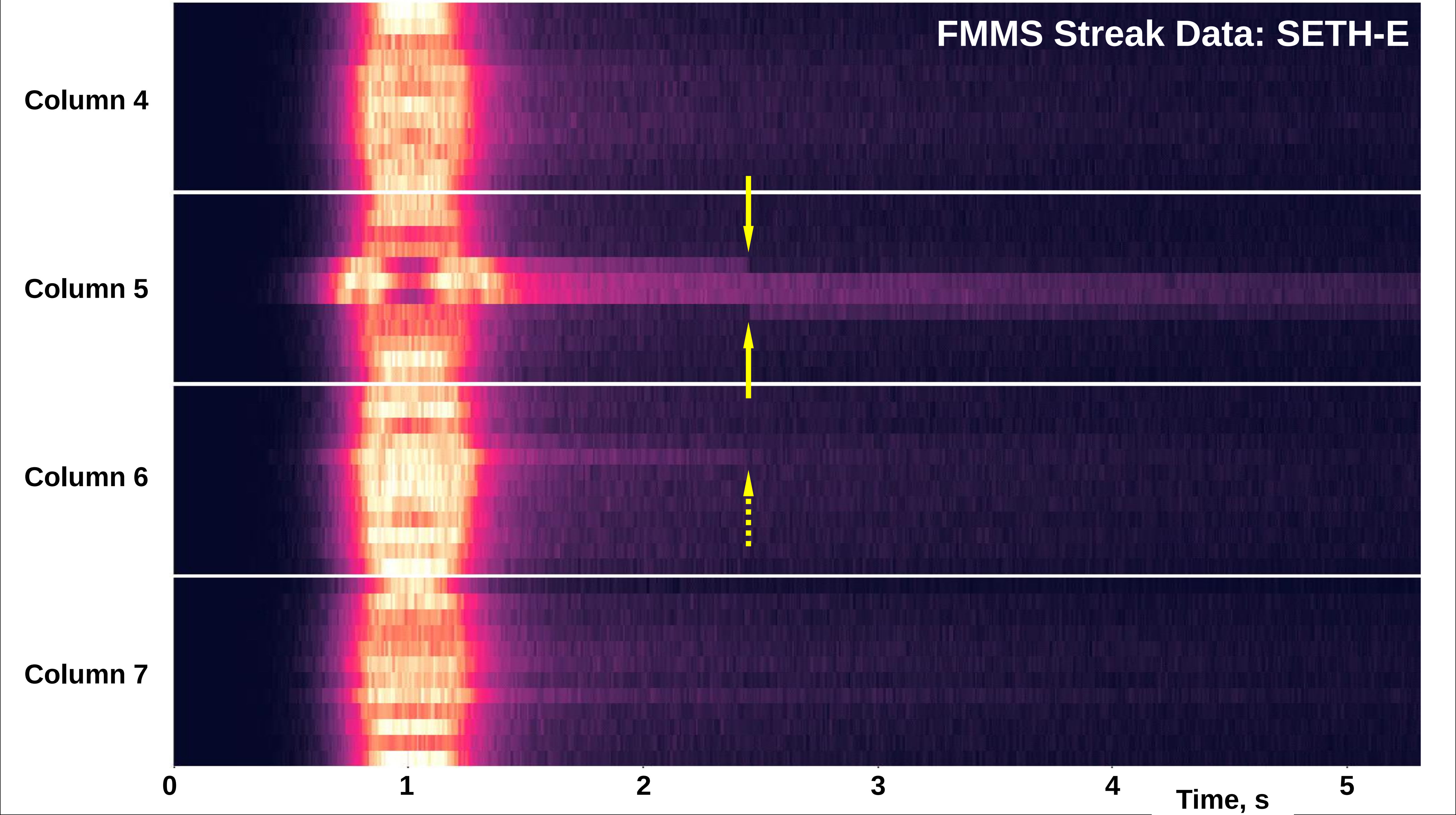
SETH experiment rig photo and visualization

SETH-E: First Case of Fuel Movement, Data (T2924)





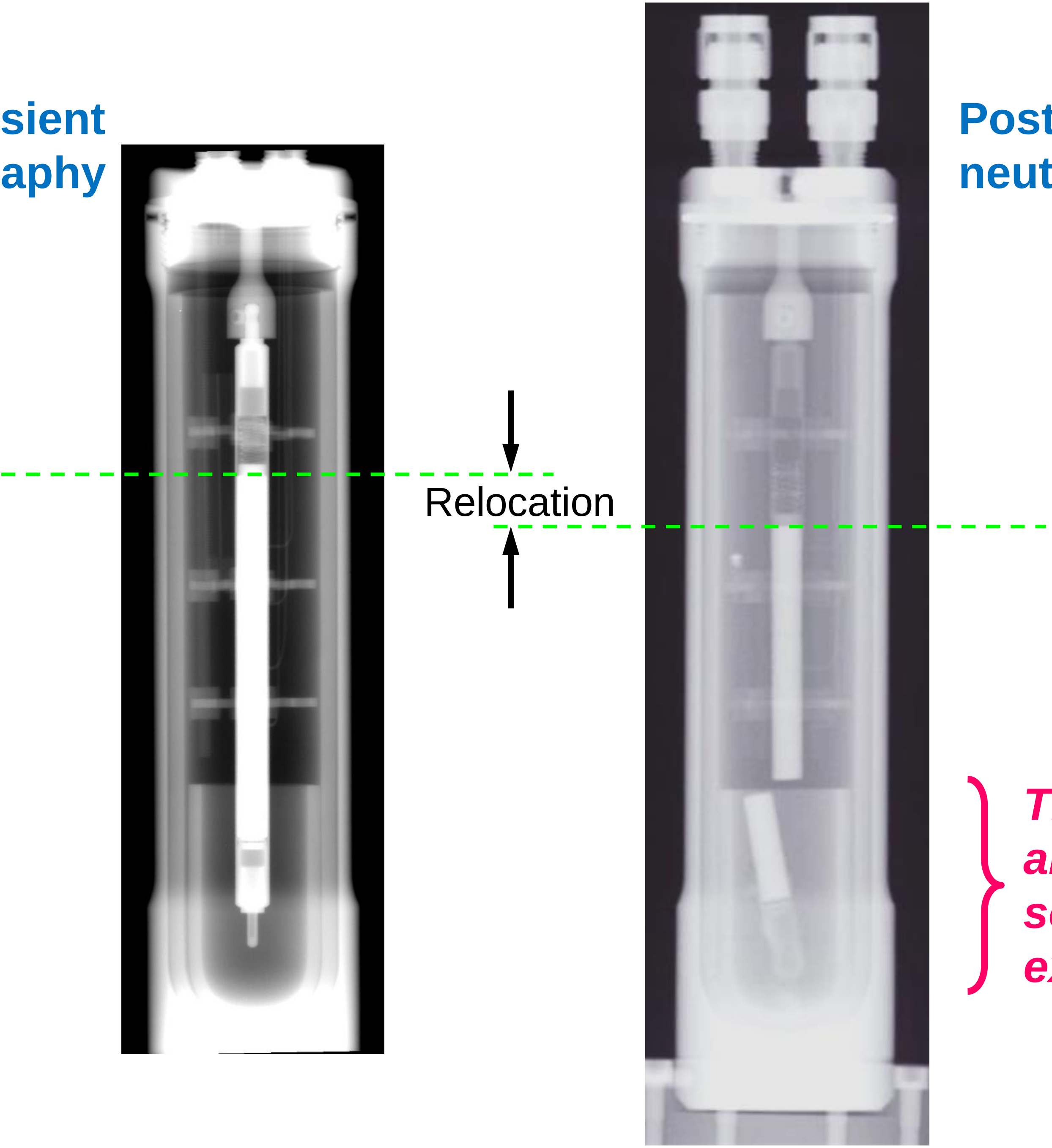

FMMS Streak Data: SETH-E
Column 4
Column 5
Column 6
Column 7
0
1
2
3
4
5
Time, s


FMMS Streak Data: SETH-E
Column 4
Column 5
Column 6
Column 7
0
1
2
3
4
5
Time, s

SETH-E Radiography

Pre-transient x-ray radiography

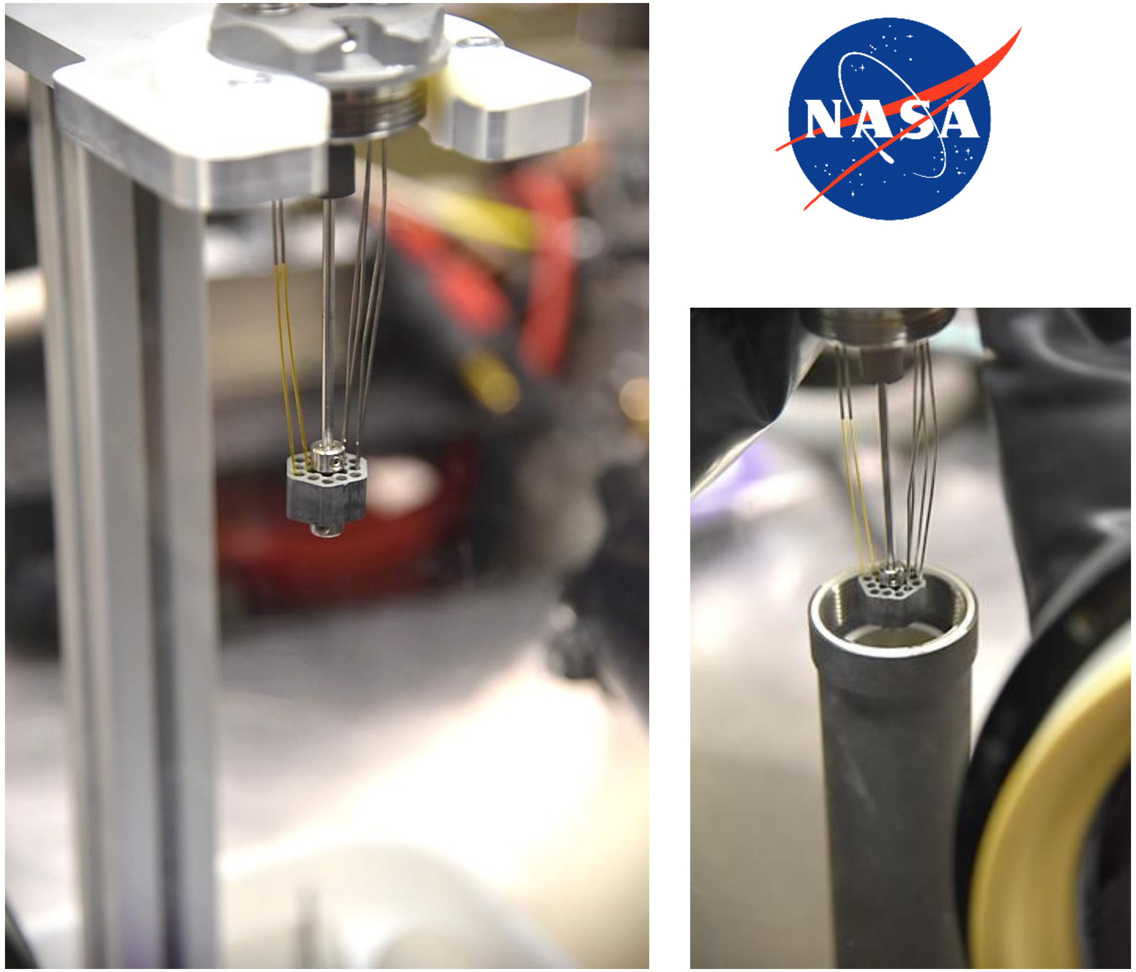
Post-transient neutron radiography



The fuel rod cracked and broke a part sometime after the experiment was over

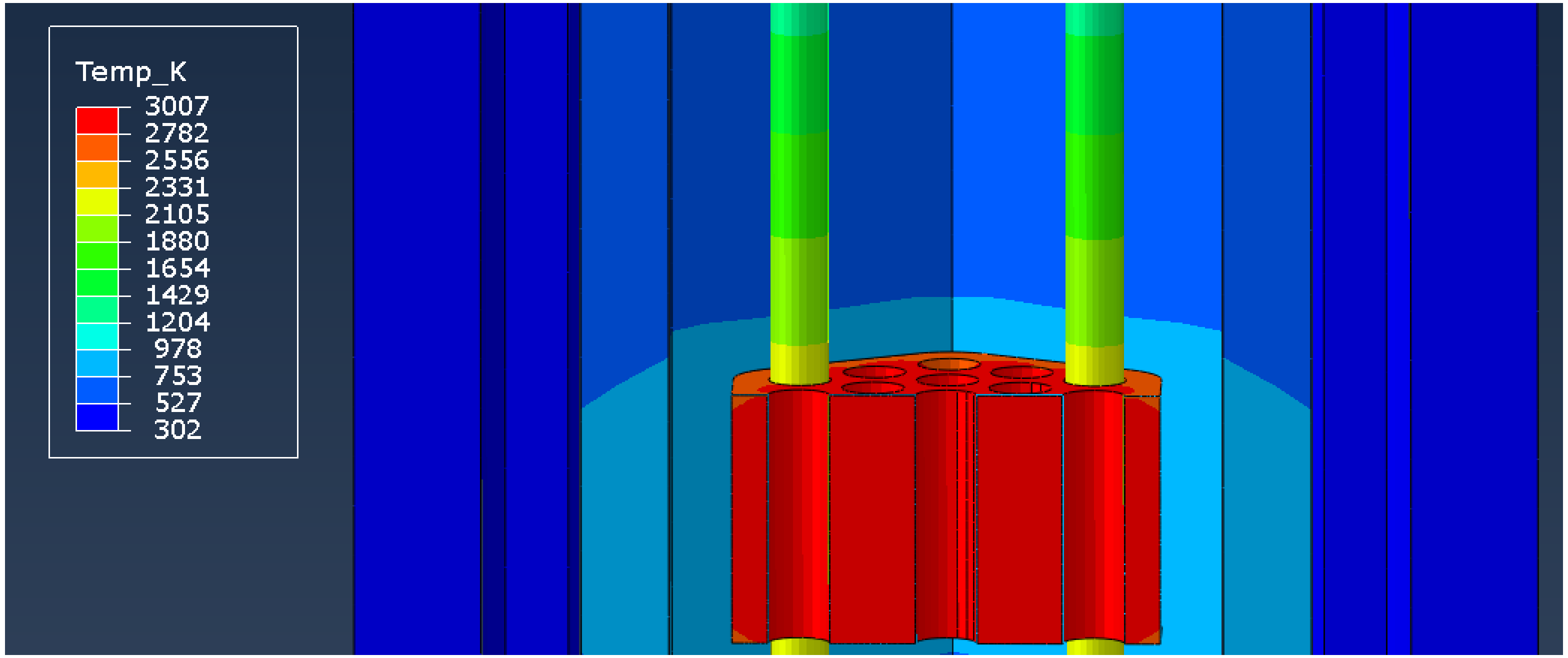
SIRIUS – Space Nuclear Thermal Propulsion Fuel Testing

- A SETH capsule was used to perform multiple transient tests of a conceptual nuclear thermal propulsion (NTP) fuel
- Goal to determine if new candidate fuels can endure the extreme heat and heating rates that would exist in a nuclear thermal rocket
- The fuel sample was made using spark plasma sintering, an advanced manufacturing method that rapidly fuses mixtures of metal and ceramic powders
  - Hexagonal, 19-hole Mo-W cermet
  - Uranium-235 enrichment at 21%
  - Heating rate ~95 Kelvin s^{-1} (similar to NERVA program)
  - Peak temperature ~2600-2850 K for 60 s
  - Six separate test cycles



SIRIUS-1 experiment during assembly

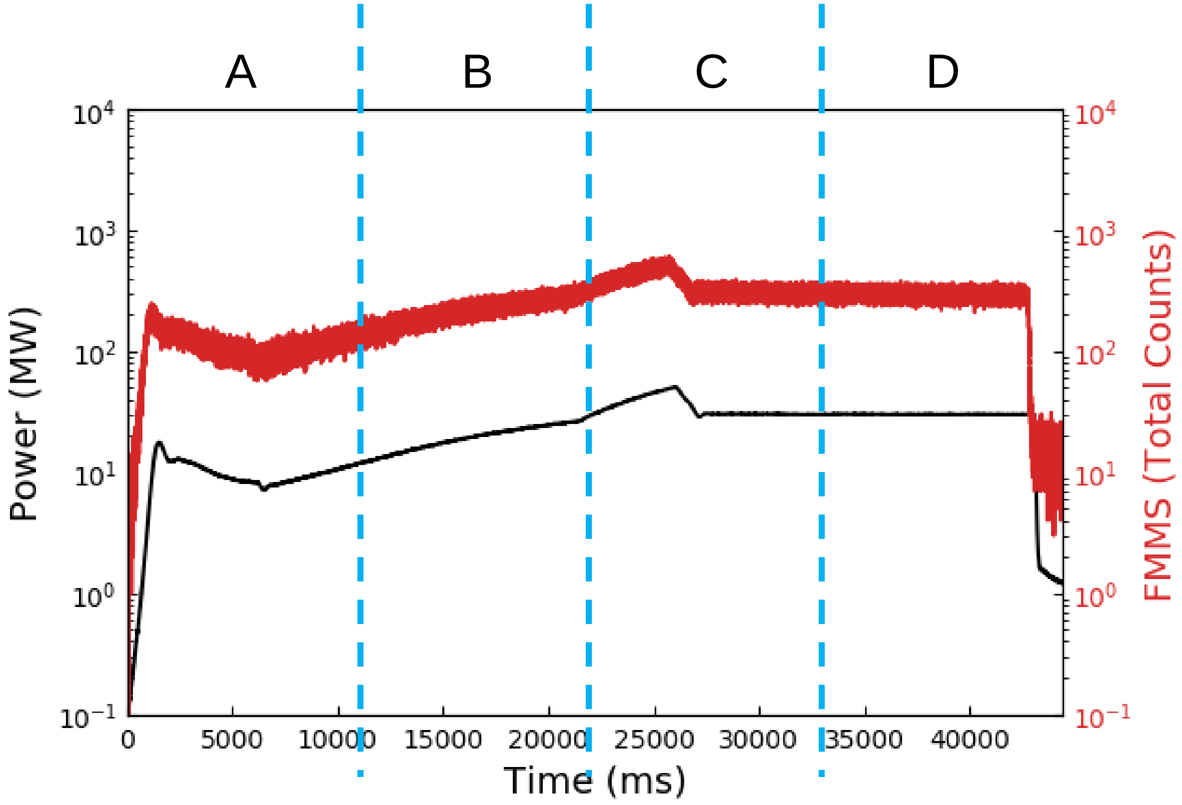
SIRIUS-1 Thermal Modeling

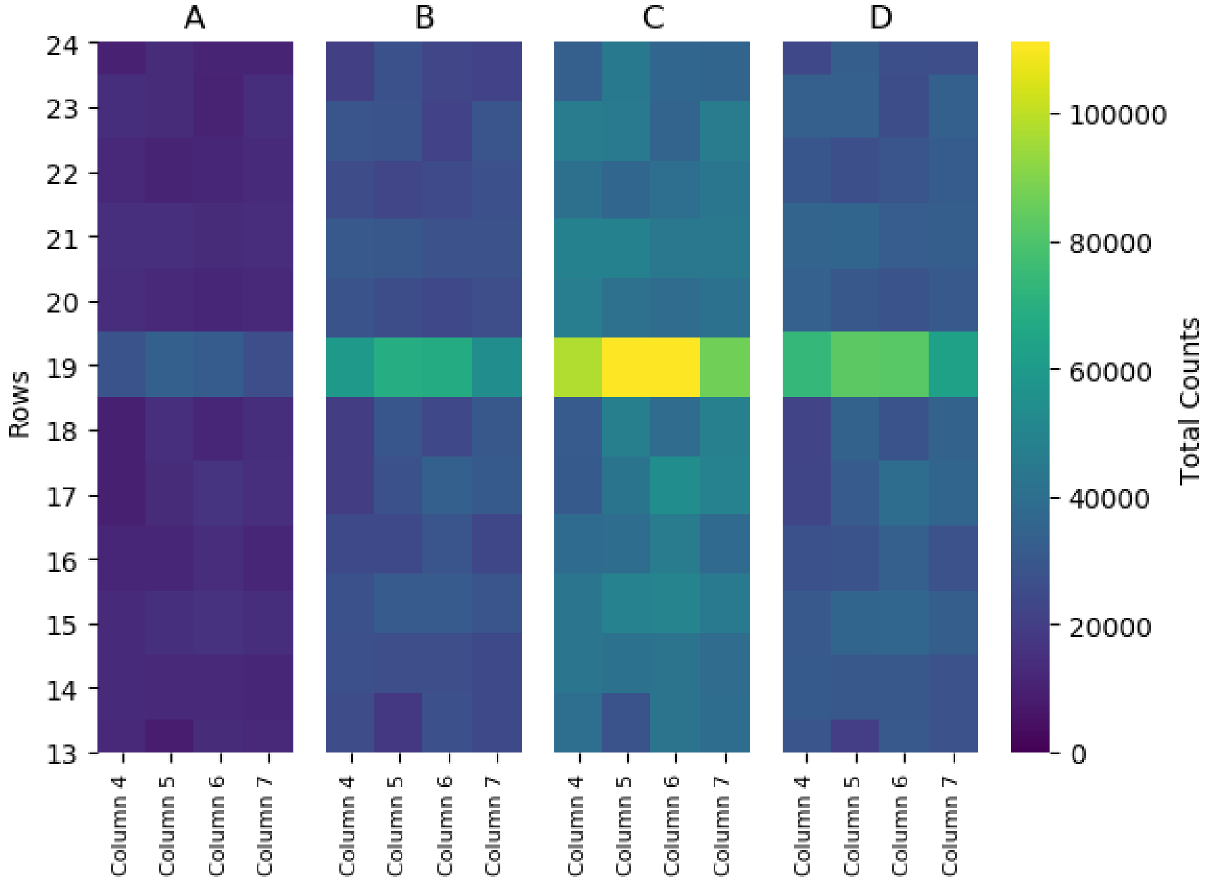


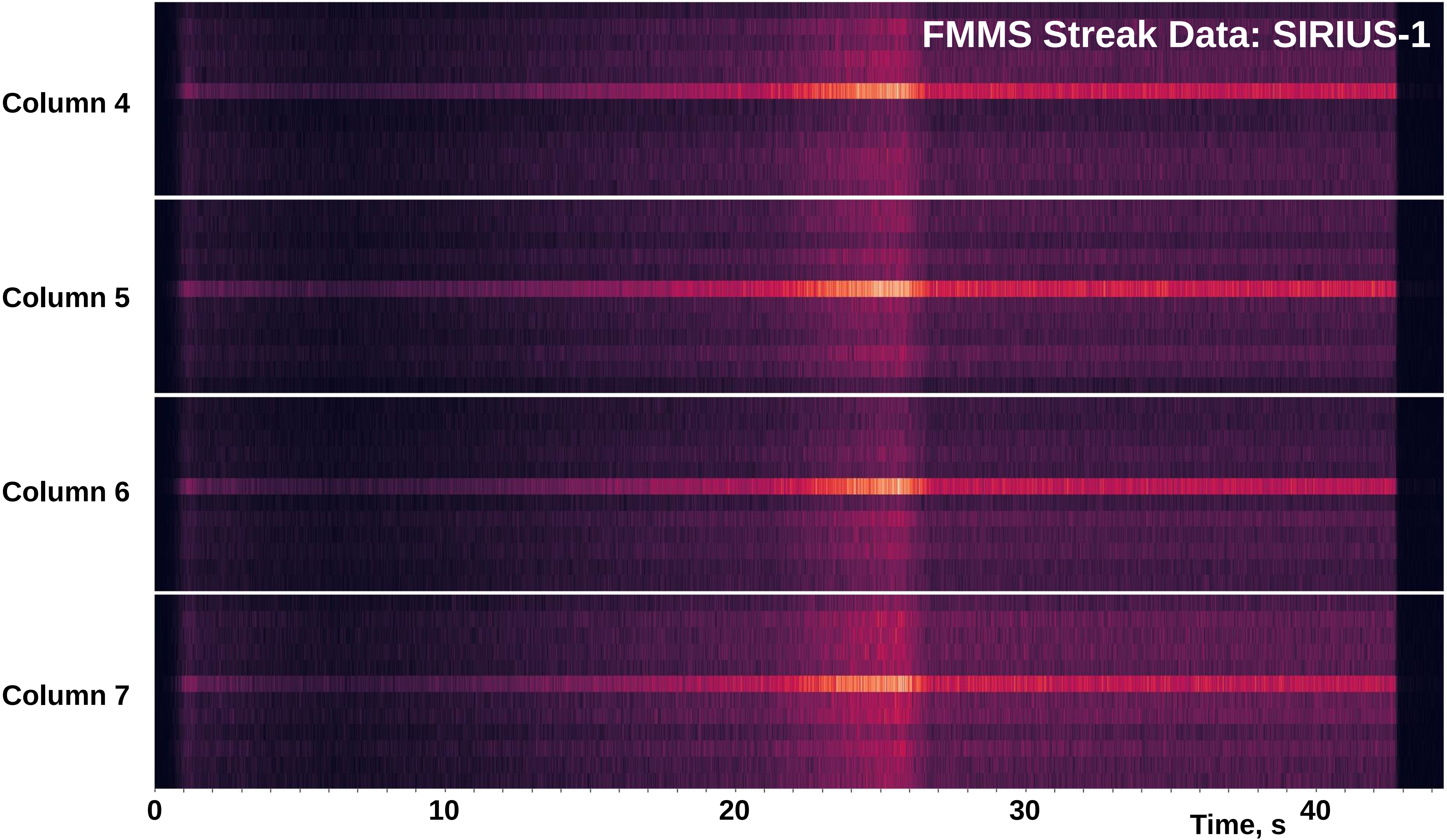
A combination of MCNP, STARCCM+ and ABAQUS codes were used to perform preliminary design of the SIRIUS-1 capsule. This image shows predicted temperature distribution in the fuel zone during the isothermal hold.

O'Brien, R. C., et al., "The SIRIUS-1 Nuclear Thermal Propulsion Fuels Transient Test Series in the Idaho National Laboratory TREAT Reactor," Nuclear and Emerging Technologies for Space, American Nuclear Society Topical Meeting Richland, WA, February 25 – February 28, 2019, available online at http://anstd.ans.org/

SIRIUS-1: NTP Fuel Testing, Data (T2952)






FMMS Streak Data: SIRIUS-1
Column 4
Column 5
Column 6
Column 7
0
10
20
30
40
Time, s

Summary

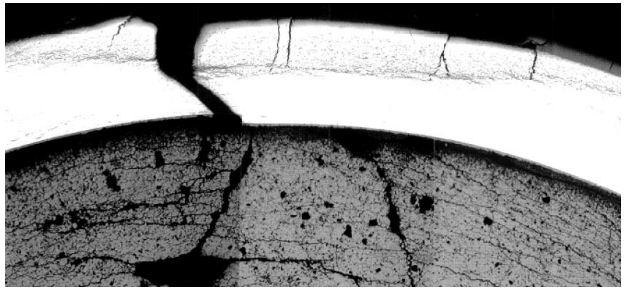
- The resumption of transient testing at TREAT restores our ability to perform engineering-scale fuel safety testing in the US
- Experiments are now underway at TREAT that perform baseline performance measurements of LWR fuel, these are leading to tests of new, accident-tolerant fuel (ATF) systems
- Flexible test devices have been developed and qualified, allowing research teams to propose experiments without developing their own capsules
- Fuel motion monitoring with the Hodoscope provides real-time insight into fuel-system performance and accident progression
- Visitors are Welcome!

TREAT goes critical, Nov. 14, 2017

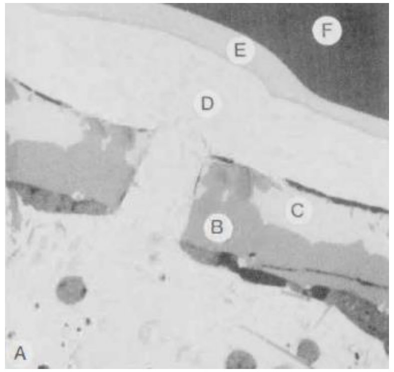
Idaho National Laboratory

Fuel Failure Before a Transient

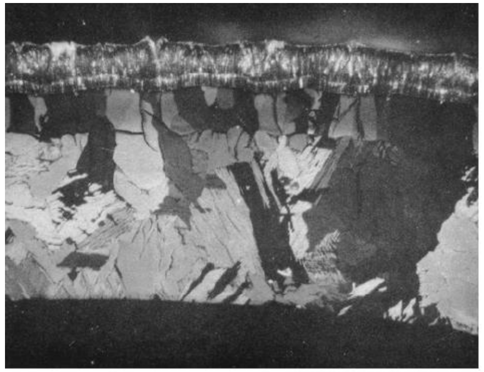
- Fuel damage mechanisms (initial damage → release of FP)
  - Fuel- (pellet-) cladding mechanical interaction (FCMI/PCMI)
  - Fuel-cladding chemical interaction (FCCI)
  - Cladding pressurization
  - Fuel swelling & relocation
- In-pin axial fuel motion
- Fuel melting
- Fission gas migration & release
- Solid fission product migration



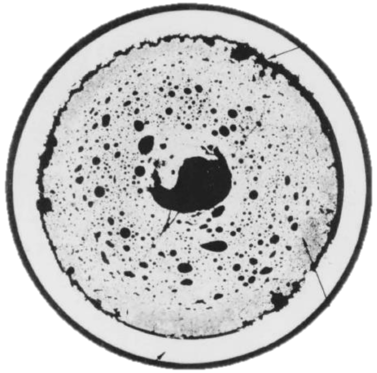
Cladding failure at hydride blister, NEA-6847



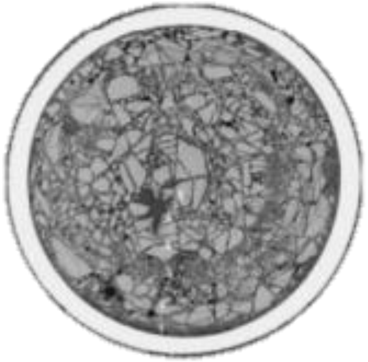
FCCI in TREAT test M5 (metal-SFR), ANL-IFR-124



Cladding oxidized at LOCA conditions, NEA-6846



Result for TREAT test M7 (metal-SFR), ANL-IFR-124



LOCA fragmentation, NEA/CSNI/R(2016)16

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[1] *NEA/OECD, "Nuclear Fuel Behaviour Under Reactivity-Initiated Accident (RIA) Conditions" NEA-6847 (2010).*

[2] *NEA/OECD, "Nuclear Fuel Behaviour in Loss-of-coolant Accident (LOCA) Conditions," (2009).*

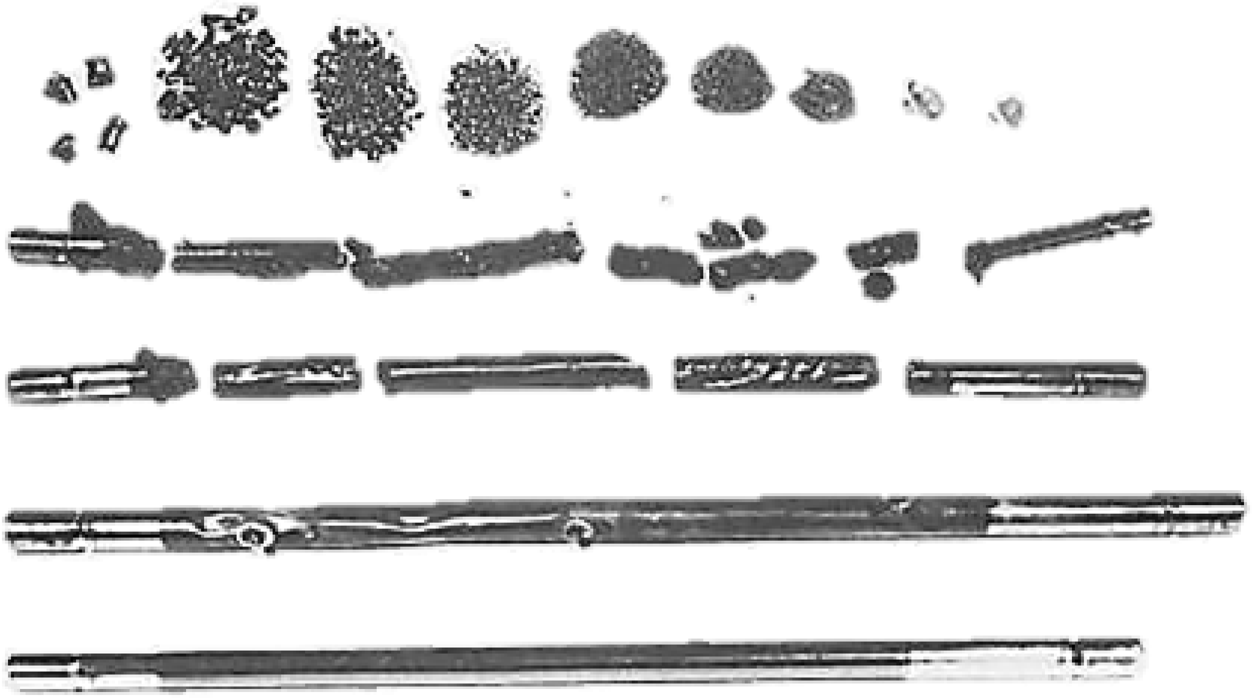
[4] *NEA/OECD, "Report on Fuel Fragmentation, Relocation, Dispersal," NEA/CSNI/R(2016)16.*

[3] *Bauer, T., et al., "First Overpower Tests of Metallic IFR Fuel in TREAT," ANL-IFR-124 (1989)*

Why Test Transient Fuel Behavior?

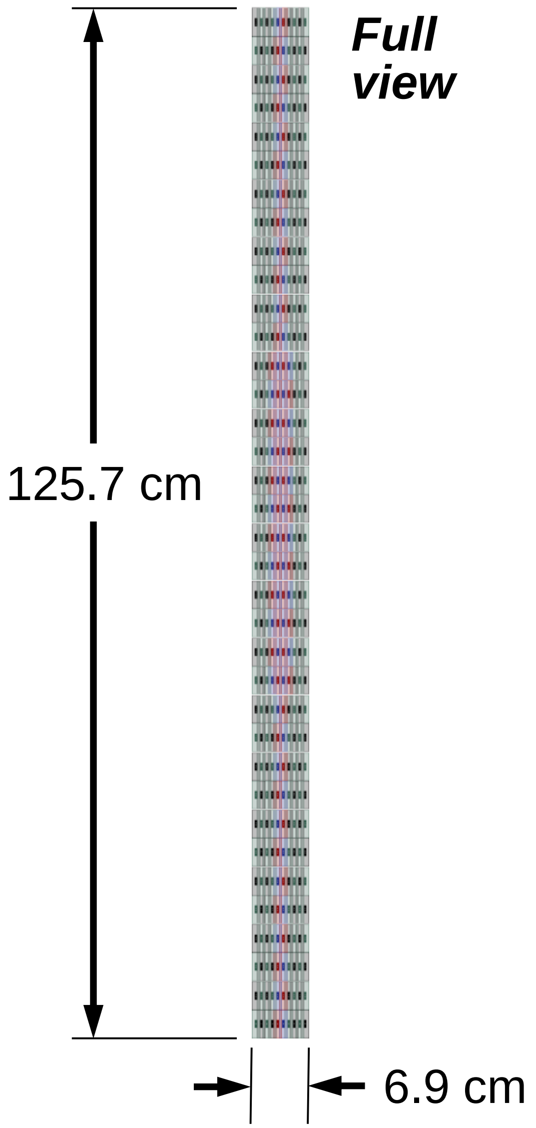
- Performance and containment of core materials
  - Design and qualify new fuel systems and reactor designs
  - Establish and demonstrate fuel safety criteria for fuel
    - Derive, demonstrate, show margin
    - Develop understanding of fuel damage mechanisms
  - Develop and validate predictive tools

Energy Deposition, cal g^{-1} UO_2

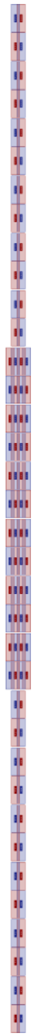


Fuel subjected to different levels of energy deposition

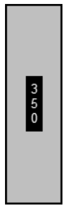
Field of View and Pixels



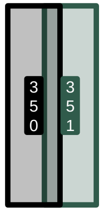
Full view



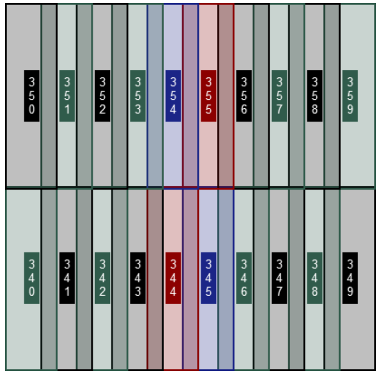
Limited view



- Collimator channels have a full view of 0.254 cm x 0.94 cm area (0.24 cm^2)
- Each channel has a 0.94 cm x 3.45 cm penumbral area (3.24 cm^2)

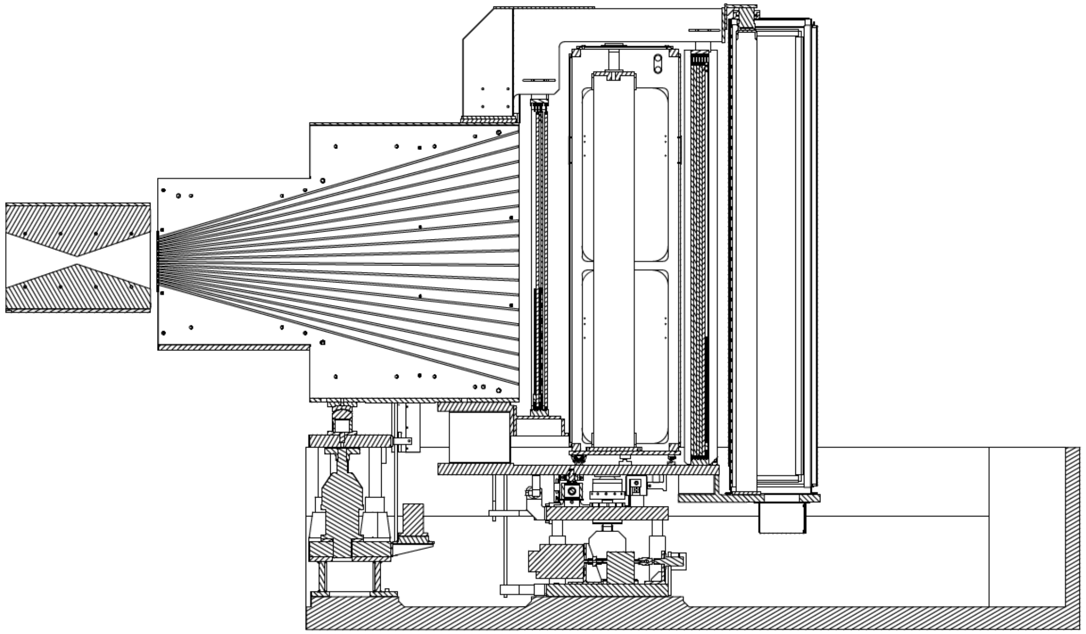


Penumbra overlap in the horizontal direction…

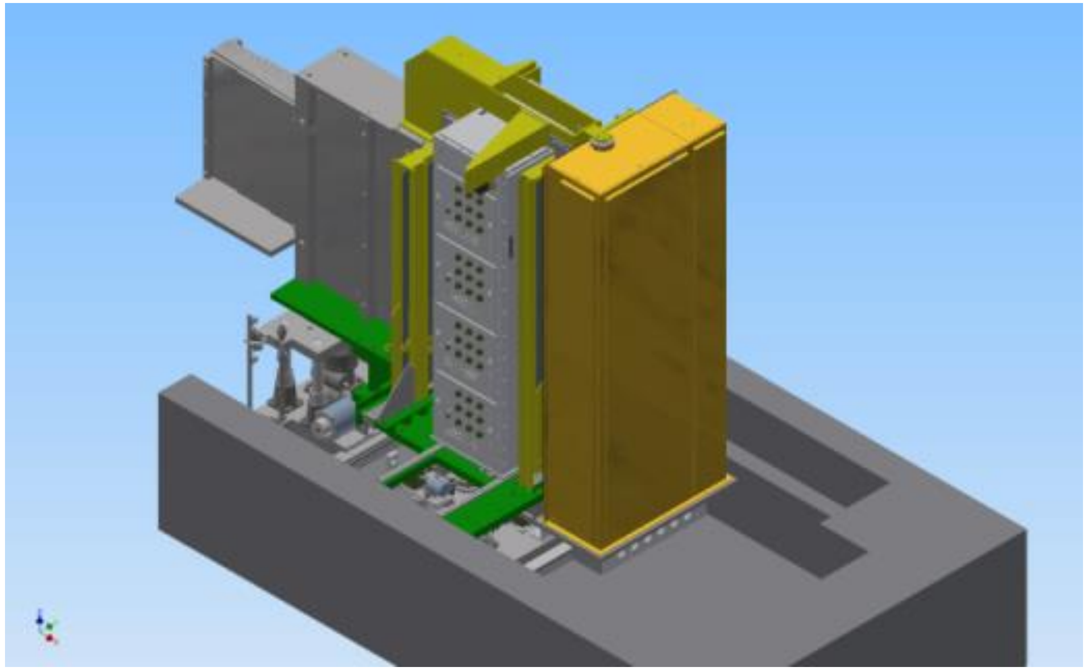


…but not in the vertical.

TREAT Fast-Neutron Hodoscope



2-D cross-section line drawing of the Hodoscope



Perspective 3-D view of the Hodoscope, from the northeast