

A Distributed Fiber Optic Sensor Network for Online 3-D Temperature and Neutron Fluence Mapping in a VHTR Environment

Reactor Concepts RD&D

Dr. Pavel Tsvetkov

Texas A&M University

In collaboration with:

General Atomics

Idaho National Laboratory

Luna Innovations

Suibel Schuppner, Federal POC

Abderrafi Ougouag, Technical POC

Final Report

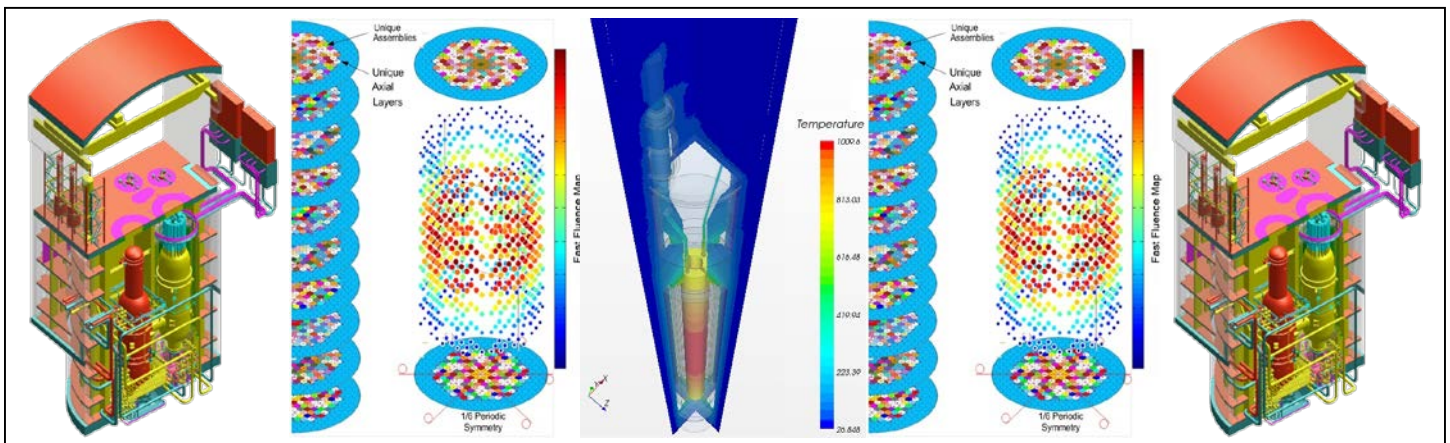
A DISTRIBUTED FIBER OPTIC SENSOR NETWORK FOR ONLINE 3D TEMPERATURE AND NEUTRON FLUENCE MAPPING IN A VHTR ENVIRONMENT

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Texas A&M University, Department of Nuclear Engineering

Tel 979-845-7078
Fax 979-845-6443

337 Zachry Engineering Center,
MS3133, College Station, TX, 77843

<http://engineering.tamu.edu/nuclear>
tsvetkov@tamu.edu



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Recipient: Texas A&M University
College Station, Texas, 77843

Contract: 00090311

Project: 09-808

Principal Investigator: Pavel Tsvetkov, 979-845-7078,
tsvetkov@tamu.edu

Co-Principal Investigator: Shannon Bragg-Sitton, sitton@tamu.edu
Shannon.Bragg-Sitton@inl.gov

Collaborators: Bryan Dickerson, dickersonb@lunainnovations.com
Joseph French, frenchj@lunainnovations.com
Donald McEachern, Donald.McEachern@ga.com
(project advisor)
Abderrafi Ougouag, Abderrafi.Ougouag@inl.gov
(project advisor)

TPOCs: Abderrafi Ougouag, 208-526-7659,
Abderrafi.Ougouag@inl.gov

Federal POC: Suibel Schuppner, 301-903-1652
SUIBEL.SCHUPPNER@nuclear.energy.gov

The work enables development of a highly reliable, distributed fiber optic temperature and fluence sensor network operable under high temperature/neutron fluence conditions and located throughout the reactor core (axial and transverse dimensions). The project scope encompasses fabrication of the sensor hardware, test article design and fabrication to support in-core testing, sensor hardware demonstration at the Texas A&M University TRIGA research reactor, 3D modeling of the NGNP/VHTR configuration and scaling from the TRIGA test environment to the anticipated VHTR operating conditions. The corresponding temperature/neutron field map reconstruction and optimization of in-core detector positioning to minimize uncertainties are also be performed. The advantages of real-time in-core monitoring are illustrated





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A Distributed Fiber Optic Sensor Network for Online 3-D Temperature and Neutron Fluence Mapping in a VHTR Environment

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Contact: Dr. Pavel V. Tsvetkov, Associate Professor, Department of Nuclear Engineering, Texas A&M University, MS3133 TAMU, 337 Zachry Engineering Center, College Station, TX, 77843-3133, tsvetkov@tamu.edu, 979-845-7078, fax: 979-845-6443





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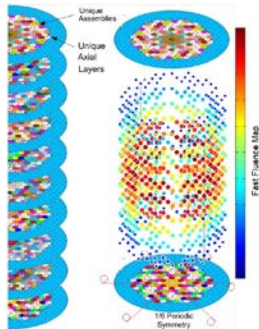
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1. Abstract

Advanced instrumentation capable of operating in high-temperature/high-radiation environments is required to fully map the temperature and neutron fluence distributions in the proposed very high-temperature reactor (VHTR) cores. This project will develop a highly reliable, distributed fiber optic temperature and fluence sensor network operable under high-temperature/high-neutron fluence conditions and located throughout the reactor core. The project scope encompasses fabrication of the sensor hardware, test article design and fabrication to support in-core testing, sensor hardware demonstration at a university TRIGA research reactor, 3D modeling in a VHTR configuration, and scaling from the TRIGA test environment to the anticipated VHTR operating conditions. The project will also perform corresponding temperature/neutron field map reconstruction techniques and optimization of in-core detector positioning to minimize uncertainties. The proposed in-core monitoring is expected to reliably perform under extreme conditions that allow on-demand positioning in the reactor vessel. This results in direct in-core monitoring in prismatic core configurations and an opportunity to position detectors at innermost outer reflector locations or inside the central graphite column of the pebble bed system.

Online temperature and fluence mapping provides real-time assessment of reactor performance, benchmarks simulation and analysis codes used in core design and modeling, and allows optimization of operating margins. Existing instrumentation either fails prematurely due to combined effects of high temperatures and radiation and cannot perform reliably for the entire 18-month refueling cycle, or does not provide sufficient real-time information. The current near-term VHTR design has a projected coolant outlet temperature ranging from 750°C to 950°C, with nominal fuel temperatures ranging from 700°C to a maximum of 1,250°C. These conditions, combined with the high-radiation environment, create extremely harsh operational conditions that pose tremendous challenges for in-core monitoring system design. These challenges are currently mitigated by providing out-of-core monitoring capabilities and applying corresponding reconstruction techniques to determine temperature and neutron fluence rate profiles across the reactor core. These techniques cannot predict local phenomena due to significant uncertainties and, hence, result in higher safety margins.

Original project number designator: 09-241.

Original PI: S. Bragg-Sitton, Texas A&M University.

Collaborators: T. Bertch - General Atomics, B. Dickerson - Luna Innovations, R. Fielder - Luna Innovations, D. McEachern - General Atomics, A. Ougouag - Idaho National Laboratory, A. Sang - Luna Innovations, P. Tsvetkov - Texas A&M University.



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2.Executive Summary

2.1. Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

2.1.1. Introduction

Robust sensing technologies allowing for 3D in-core performance monitoring in real time are of paramount importance for already established LWRs to enhance their reliability and availability per year, and therefore, to further facilitate their economic competitiveness via predictive assessment of the in-core conditions. This is even more so the case for emerging advanced reactor technologies, such as Next Generation Nuclear Plants (NGNPs), Very High Temperature Reactors (VHTRs). The NGNP/VHTR will be a full-sized demonstration of the Generation IV VHTR for a range of potential applications from electricity to process heat.[1] The novel VHTRs are characterized by very hostile in-core conditions of high temperatures and hardened neutron spectra, in which traditional sensors may operate reliably only for a limited amount of time failing prematurely due to combined effects of high temperatures and radiation.[2,3] In existing prototypes, like HTTR, this challenge is mitigated by providing out-of-core monitoring capabilities together with reconstruction of in-core values as well as by allowing for sensor insertion/withdrawal on demand thus extending their useful lifetime.[4]

In the present project, the 3-year effort is focused on enabling development efforts to yield a highly reliable, distributed fiber optic temperature and fluence sensor network operable under high temperature/neutron fluence conditions and located throughout the reactor core (axial and transverse dimensions).[5] The project scope encompasses fabrication of the sensor hardware, test article design and fabrication to support in-core testing, sensor hardware demonstration at the Texas A&M University TRIGA (Training, Research, Isotope Production, General Atomics) Mark I 1MW research reactor, 3D modeling of the NGNP/VHTR configuration and scaling of the results from the TRIGA test environment to the anticipated VHTR operating conditions. The corresponding temperature/neutron field map reconstruction techniques and optimization of in-core detector positioning to minimize uncertainties and enhance sensing reliability are also performed. The project is funded by the DOE Nuclear Energy University Program.

This paper discusses the project efforts and outcomes, hardware, and gained operational experience. Notably, advanced in-core test assembly has been developed and deployed for experimental confirmation of fiberoptics sensor performance characteristics in VHTRs via emulation of VHTR in-core conditions in TRIGA reactor cores.[5,6]

2.1.2. High Temperature Furnace

Emulation of the VHTR conditions in the TRIGA requires three criteria to be met: spectrum, temperature, and environment. The sensor test assembly is required to be irradiated to a fluence of 2×10^{19} n/cm² and operate at 1000oC. A high temperature test furnace has been designed, manufactured and deployed in the TRIGA core to achieve this objective. The developed furnace design originates from the General Atomics furnace developed in the 1970s for high temperature reactor (HTR) fuel testing in TRIGA reactors.[6]

Figure 1 shows the overall layout of the high temperature test assembly (left) and the experimental setup in the TRIGA pool (right) during acceptance testing procedures confirming its operational readiness prior to installing in the allocated position within the TRIGA core and commencing the experimental program. This furnace assembly is a successful culmination of several years of design, construction and testing efforts within the project. The furnace was designed and fabricated with the guidance of analytical and numerical tools, the STAR-CCM+ package, in particular.

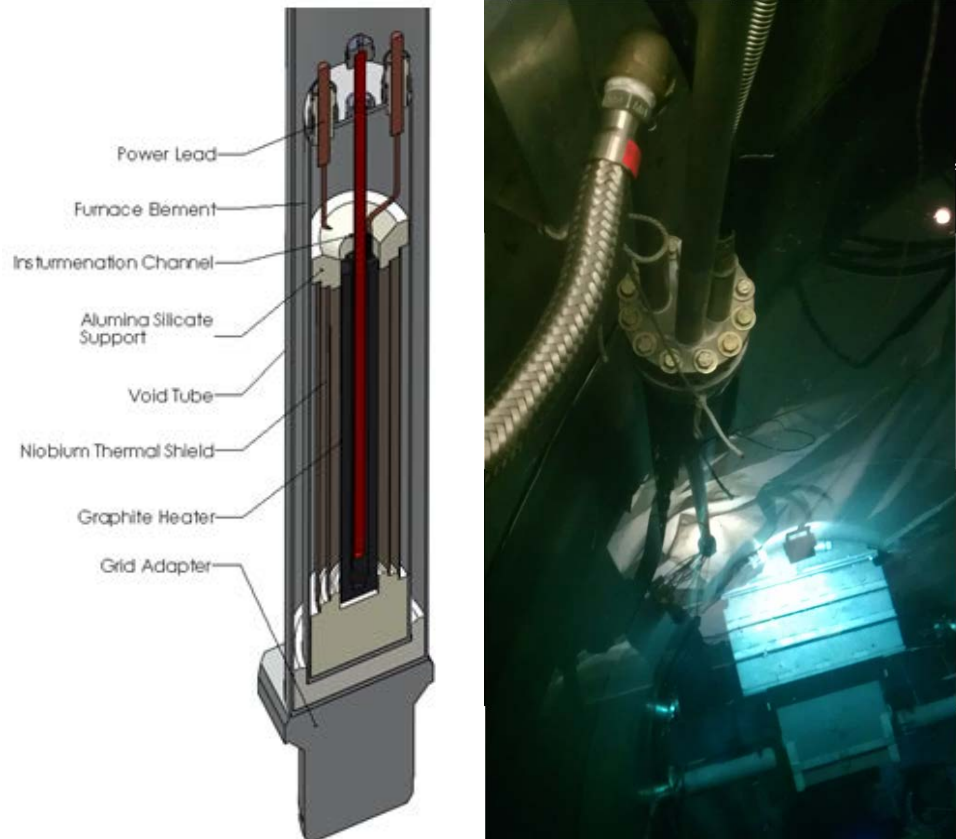


Fig. 1. High temperature test assembly design (left) and the experimental setup during the TRIGA in-pool acceptance testing (right).

The high temperature furnace is capable of an automatic startup triggered by a user input followed by a swap to a PID controller. Fig. 2 shows the transition during the startup to the PID controller. The transition limits the temperature gradient from exceeding 0.2 °C/s and prevents temperature overshoot to less than a degree. The PID controller was optimized at the acceptance testing stage of the experimental program and further improved following operation in the reactor environment.

During operation, the reactor undergoes various transients of known power. These are normally to accommodate sample movements or experiments and vary between 100 kW and 1 MW. With the PID controller active, the furnace temperature is maintained.

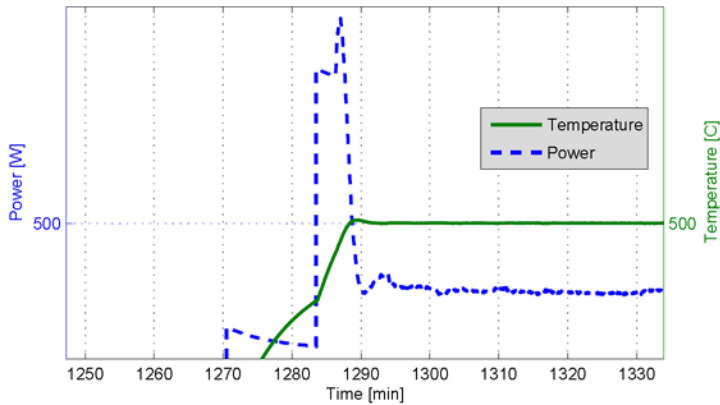


Fig. 2. Automatic swap to PID controller via LabView.

Figure 3 shows the operation of the high temperature furnace throughout a day, completely unattended where the depression in power between 500 and 1000 minutes corresponds to the reactor operation at 1MW.

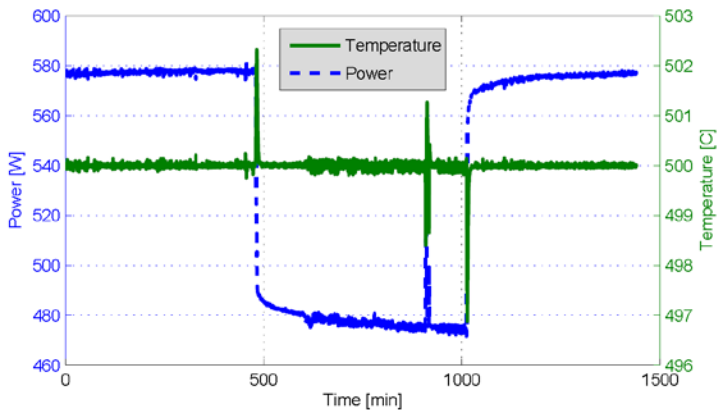


Fig. 3. Full day operation of the high temperature furnace showing ohmic power and temperature.

The high temperature furnace operation has been smooth and stable. It is expected to maintain operational integrity throughout the experimental program of the project and in follow-on experimental efforts with minimal maintenance. The process of installation and data acquisition has occurred without major problems. The automatic PID controller works well with the parameters that were set manually.

2.1.3. Fiberoptics vs. STAR-CCM+ Predictions

Figure 4 illustrates a comparison of the thermal distribution from fiber optic measurements to the spatial gradient from the STAR-CCM+ simulation. The largest discrepancies are at the axial ends of the graphite since there are significant assumptions on the contact resistances with the alumina supports. This will affect the heat transfer from the ends. It was assumed, in the

modeling, that there would be about 20% contact (only allowed 20% of the mesh volume to transfer heat between surfaces).

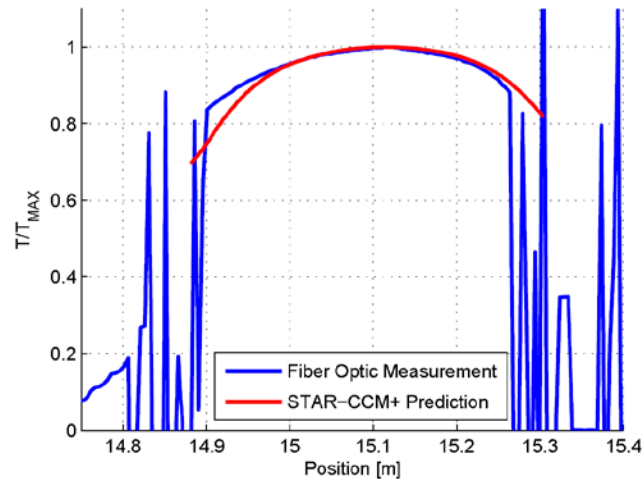


Fig. 4. Normalized temperature distributions from fiberoptics measurements and the STAR-CCM+ model.

It has been observed that fiberoptics measurements are severely affected by vibrations due to natural circulation cooling of the reactor while operating. The affected regions are typically at the fiber end (15.25+ meters) and at the feedthrough into the furnace (14.8 – 14.9 meters). It does appear that the vibration induced noise affects the measurement only locally and that the rest of the measurement is not impacted. The shape of the temperature distributions do closely match with the peak being predicted within a centimeter. As expected, the temperature gradients near the edges of the graphite heating element (the end of the STAR-CCM+ data plot corresponds with the end of the graphite heater) are steeper.

During operation of the furnace at an average temperature of 500oC, the fiberoptics measures an average temperature of 720.2oC; compared to the thermocouple readings this poses a challenge for the fiberoptics. The observed differences appear to be due to internal fiberoptics material effects and their interpretation by the fiberoptics data acquisition and processing software package.

At the present state of the question, there appear to be significant dependencies of the fiberoptics sensing on the software data package performance, especially on calibration and built-in material effects models. These dependencies jeopardize contemporary uses of fiberoptics-based sensing architecture. However, these observations do not exclude future potential applications as software packages mature.

2.1.4. Fiberoptics Lifetime Measurements

twelve fiberoptics sensors were available for irradiation within the fiber optic instrumentation probe. This probe contains four of each of the temperature, gamma, and neutron detecting sensors, of which three fibers had failed prior to arrival of the probe at Texas A&M University. An average fluence of 1.0×10^{19} n/cm² was reached for each fiberoptics sensor type during the

available operational time. The results of this irradiation are summarized in Table 1. Two fibers failed to initial thermal stressing and the two remaining gamma fibers failed as a result of the irradiation, as shown in see Fig. 5.

Table 1. Fiberoptics 3-month-irradiation survivability

Fiberoptics Sensor Type	Final Condition	Comment
Gamma 1	Failed – DOA*	
Temperature 2	Failed	Failed immediately at startup.
Neutron 3	Survived	
Gamma 4	Failed – DOA*	
Temperature 5	Survived	
Neutron 6	Failed – DOA*	
Gamma 7	Failed	Failed at 4.5×10^{18} n/cm ² fluence.
Temperature 8	Survived	
Neutron 9	Survived	
Gamma 10	Failed	Failed at 5.8×10^{18} n/cm ² fluence.
Temperature 11	Failed	Failed immediately at startup.
Neutron 12	Survived	

DOA – dead on arrival.

It is likely that the failures of gamma-sensing fibers were resulting from material swelling. Both fibers failed with the same characteristics of increased return loss at point between support ferrule interfaces within the instrument probe. This assertion has not been physically confirmed in the present analysis.

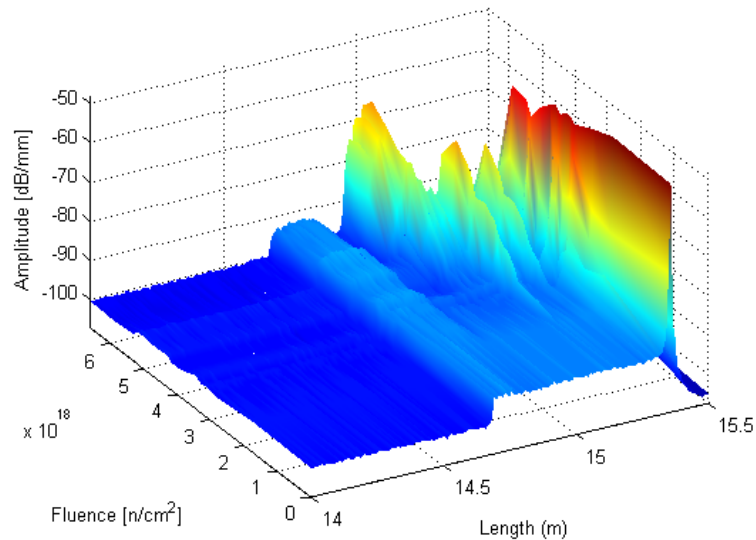


Fig. 5. Gamma fiber return loss over probe length during irradiation.

2.1.5. In-Core Sensor Positioning and Data Processing

A 3D whole-core exact-geometry model of a VHTR hexagonal-block configuration with a detailed component representation has been developed and implemented for calculations with MCNP/MCNPX and Serpent. The model is based on the NGNP pre-conceptual design features.[1]

The modeling approach allows for development and applications of in-core 3D performance map reconstruction techniques accounting for novel direct 3D in-core measurement approaches for extreme environments of HTRs such as would be eventually offered by fiberoptics sensing once this instrumentation technology matures to the level of reactor applications. Figure 6 summarizes six considered potential sensor arrangements within the VHTR including active core and reflector regions.

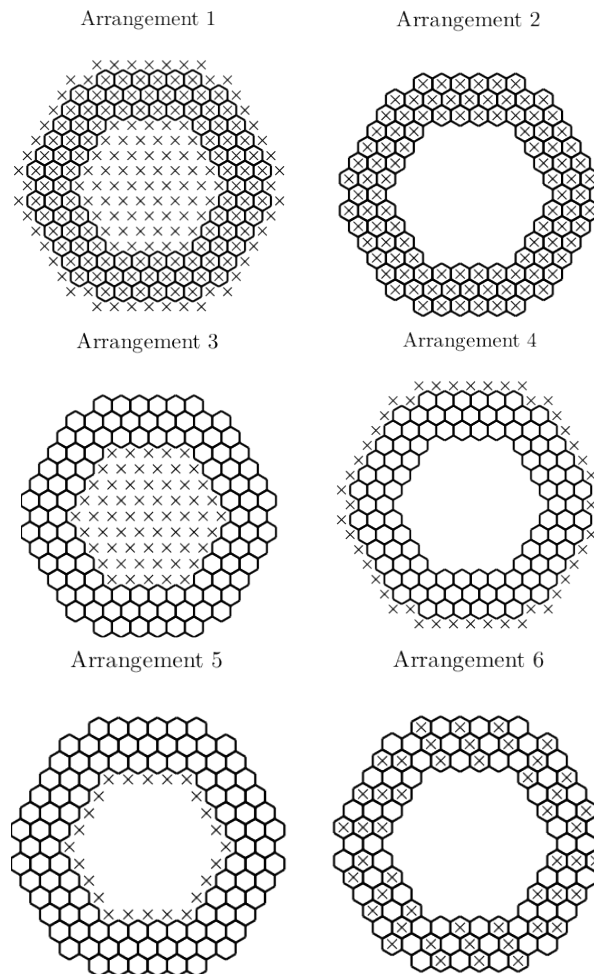


Fig. 6. Sensor arrangements within a VHTR, instrumented blocks are marked with “X”.

Figure 7 shows the average reconstruction relative errors for each of the arrangements depicted in Fig. 6. It is interesting to note that while arrangement 1 contains the most sensors, it does not always perform the best.

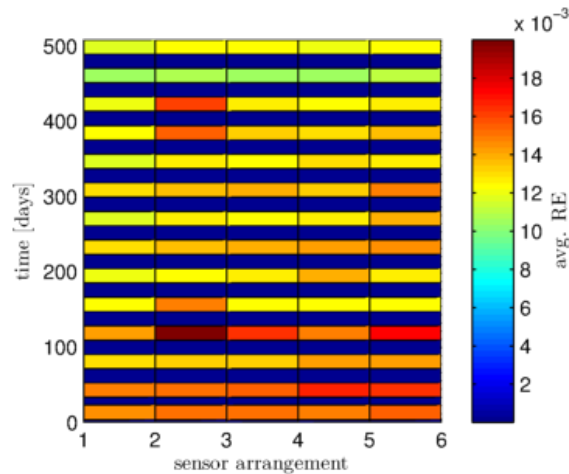


Fig. 7. Average reconstruction relative errors (avg. RE) for six sensor arrangement configurations.

2.1.6. Conclusions

This report presented the results and observations obtained in the course of the 3-year program. The gained practical experience with fiberoptics sensors and computational evaluations of distributed sensing networks for reactor in-core applications indicate potential opportunities for future applications, especially in the environments which would be either physically hostile or geometrically challenging for traditional sensing technologies. Furthermore, as indicated above, distributed sensing allows gathering more robust data during reactor operation which is essential not only for predictive safety monitoring but also for competitive reliability and economics. The project was focused on NGNP/VHTR environments but the analyzed fiberoptics sensing and 3D in-core monitoring via distributed sensing are of paramount value for LWRs, emerging SMRs and all advanced nuclear reactors.

Although fundamental feasibility and potential applications for fiberoptics sensors have been established, the technology is, by far, is not ready for near-term practical in-core implementations. The noted challenges include excessive dependencies of sensing system performance characteristics on vibrations due to thermo-mechanical core characteristics, resulting noise effects, internal fiberoptics material effects and their interpretation by the fiberoptics data acquisition and processing, and overall inherent dependencies of fiberoptics sensing technologies on accompanying software components to recover and interpret measured performance characteristics, and frequent calibration needs for the system to operate meaningfully. These observations strongly suggest the need for further research efforts to systematically resolve these challenges, thus allowing taking a full advantage of the existing fiberoptics and distributed sensing capabilities for next generation in-core instrumentation solutions for current LWRs as well as SMRs and advanced reactor systems.

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2.2. 3D Mapping and Reconstruction for In-Core Monitoring in Advanced Reactors

2.2.1. Introduction

Advanced sensor networks and data processing algorithms are needed for future generation nuclear reactors and energy systems. In many cases, detector systems designed for current generation LWRs cannot survive in advanced reactors. Reactor safety margins for these advanced systems must account for uncertainties in reactor operating conditions.

Accurate on-line reconstruction approaches would significantly reduce the uncertainties present in predictive capabilities for core-wide distributions thus enhancing system reliability and availability per year, and therefore, facilitating economic competitiveness via predictive assessments of the in-core conditions.

This paper is focused on reconstruction techniques for the very high temperature reactor (VHTR), one of several next-generation designs supported by the Generation IV International Forum (GIF).[1]

The novel VHTRs are characterized by very hostile in-core conditions of high temperatures and hardened neutron spectra, in which traditional sensors may operate reliably only for a limited amount of time failing prematurely due to combined effects of high temperatures and radiation.[2,3]

In existing prototypes, like HTTR, this challenge is mitigated by providing out-of-core monitoring capabilities together with reconstruction of in-core values as well as by allowing for sensor insertion/withdrawal on demand thus extending their useful lifetime.[4]

The goal of the ongoing effort is to develop an advanced 3D in-core mapping and reconstruction via distributed sensor networks.

2.2.2. High-Fidelity Reactor Model

A 3D whole-core exact-geometry model of a VHTR hexagonal-block configuration with a detailed component representation has been developed and implemented for calculations with MCNP/MCNPX and Serpent. The model is based on the NGNP pre-conceptual design features.[1] The modeling approach allows for development and applications of in-core 3D performance map reconstruction techniques accounting for novel direct 3D in-core measurement approaches for extreme environments of HTRs.

Earlier benchmark studies validated applicability of the modeling approach to correctly represent design features and performance characteristics of HTRs.[5,6] Figure 1 illustrates details of this model. The model color scheme demonstrates the ability to quantify physics characteristics while varying properties per block. It allows for tracking environments in fuel and coolant channels.

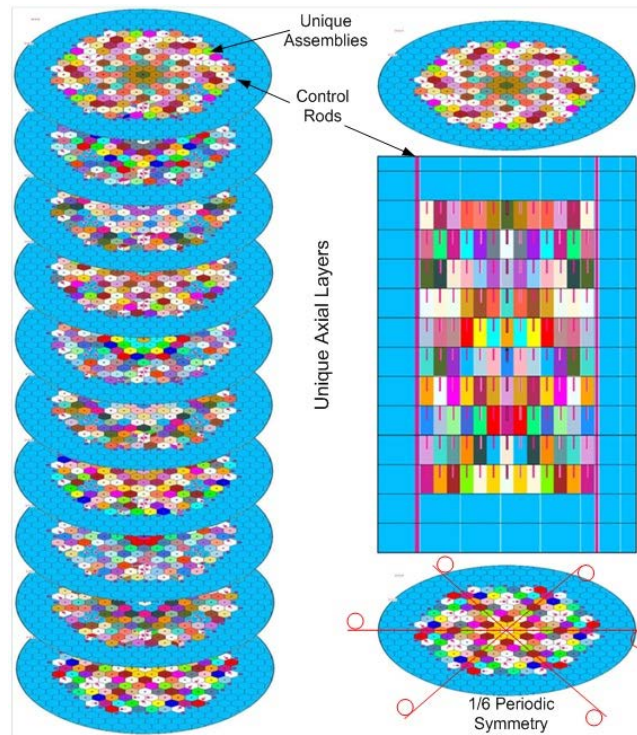


Fig. 1. High fidelity whole-core VHTR model.

2.2.3. Performance Analysis

This work is particularly concerned with the location in the core where neutron flux was at a maximum. The location of the hot spot is a complex function of time.

Figure 2 shows how the neutron flux hot spot moved up and down the core as a function of time. This complex behavior shows the need for a robust sensor network capable of providing sufficient information to reconstruct the in-core flux distribution. The corresponding Fig. 3 shows the flux distributions in the reactor at several different times during operation.

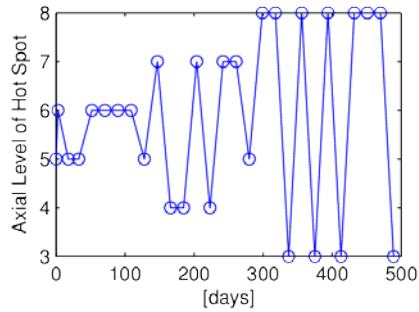


Fig. 2. Axial fluctuations of neutron flux hot spots as a function of time during reactor operation at full power.

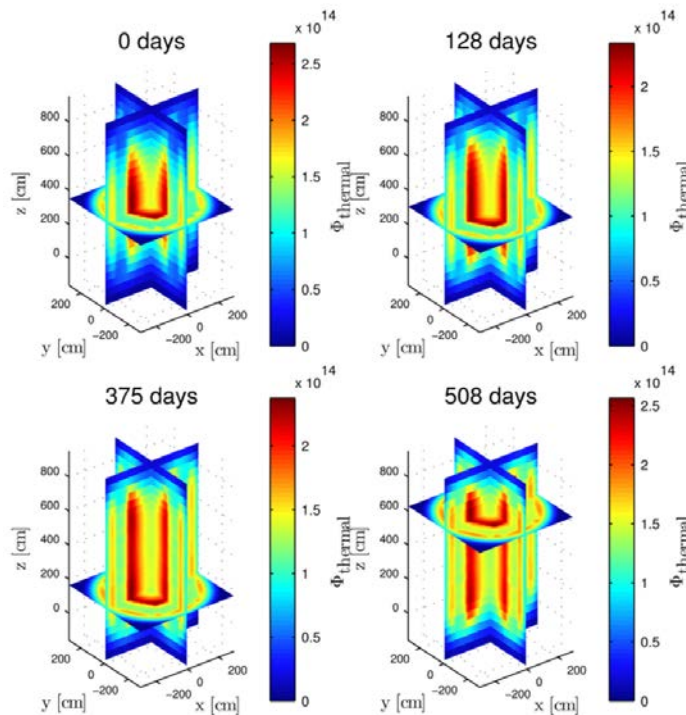


Fig. 3. Snapshots of the neutron flux distributions at several times during reactor operation at full power.

2.2.4. Reconstruction Approach

The conceptually simplest flux reconstruction methods are those based on pure interpolation. An algorithm that could linearly interpolate on an unstructured grid was used in order to accommodate any possible sensor configuration.

Using this method, a tetrahedral mesh is constructed whose vertices correspond to locations where the neutron flux is measured by a sensor. Mathematical techniques were then used to

linearly interpolate the neutron flux across the reactor core. The single-block sensor arrangement used to test the interpolation-based reconstruction algorithms is shown in Fig. 4.

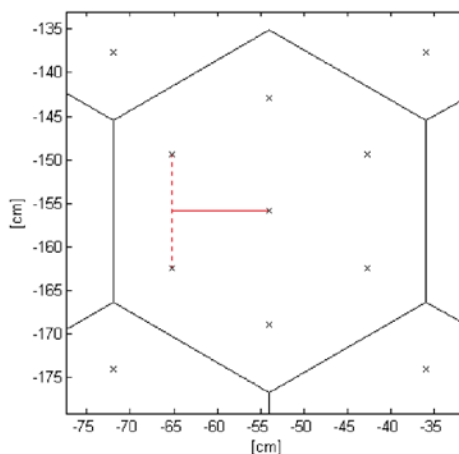


Fig. 4. Sensor layout used within a single block structure.

Figure 5 summarizes six considered potential sensor arrangements within the VHTR including active core and reflector regions.

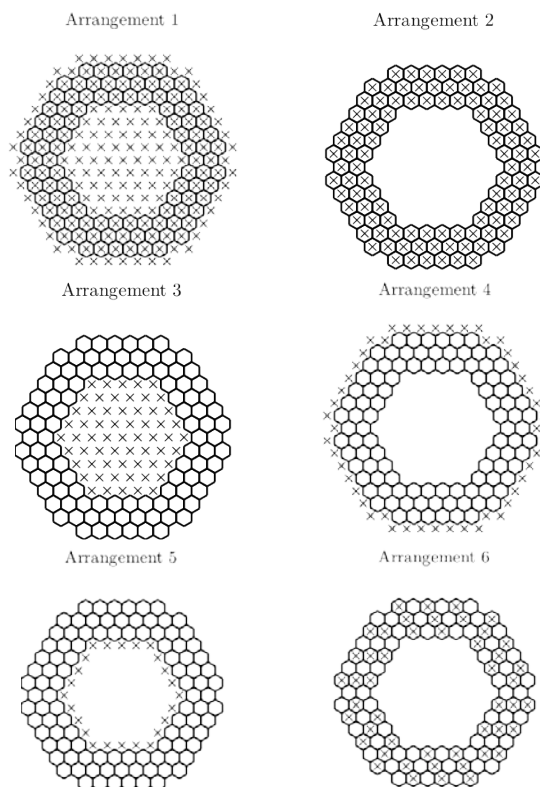


Fig. 5. Sensor arrangements within a VHTR, instrumented blocks are marked with “X”.

The proper orthogonal decomposition (POD) is a data analysis tool that can be used to create low-dimensional representations of high-dimensional data. POD has been used in a variety of fields including image compression, signal processing, turbulence analysis, and design optimization. In this work we focused on its use with time-series data. Given an ensemble of time-series data, POD can be used to create spatial modes, sometimes called empirical eigenfunctions, that can be used to reconstruct the data.

The POD-based method performs well, and better than the interpolation-based method, in the reconstruction relative error and percent error in true hotspot magnitudes. Figure 6 shows a detailed view of the algorithm's performance in predicting the z coordinate of the hotspot. Except for a few spikes, the error is modest for lower levels of noise, but degrades to unacceptable levels as the noise amount increases.

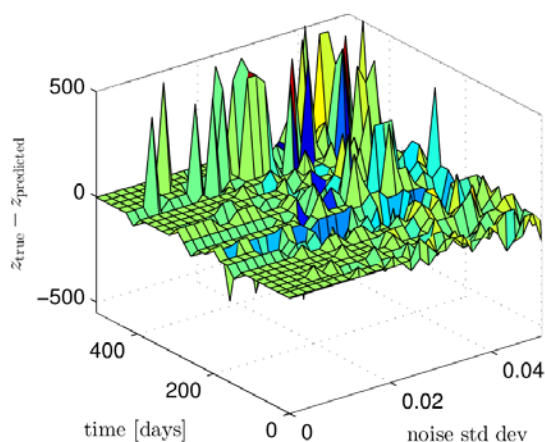


Fig. 6. Error in z coordinate of POD algorithm's predicted hotspot location when signal is noisy.

Sensor failure was modeled by deterministically failing the closest sensors to the core-wide hot spot. The reconstruction algorithm was run testing the effects of failing up to five sensors for each sensor arrangement. All cases used all modes from the POD basis generated from the odd-numbered snapshots. Sensor failure has the largest effect on arrangements 4 and 5; however, these two arrangements had the fewest sensors to begin with.

2.2.5. Conclusions

This paper presented the results and observations obtained in the course of the 3-year program. The computational evaluations of distributed sensing networks for reactor in-core applications indicate potential opportunities for future applications.

The project was focused on NGNP/VHTR environments but the analyzed sensing and 3D in-core monitoring via distributed sensing are of paramount value for LWRs, emerging SMRs and all advanced nuclear reactors.

The interpolation-based algorithm is conceptually straightforward and performs well provided enough sensors are placed in the core. It is doubtful that it would be economically feasible to remove fuel pins from the core just to insert more sensors.

The POD-based reconstruction method is recommended over the interpolation-based method because it yields more accurate reconstructions with fewer sensors. The POD-based method was able to reconstruct the in-core flux with 24 sensors more accurately than the interpolation-based algorithm could with 211 sensors. The POD method was also better at handling signal noise and sensor failure.

The chief disadvantage of the POD-based method is that its behavior is not as predictable as the interpolation-based method. The snapshots fed into the algorithm must span the operating conditions experienced by the reactor.

2.2.6. References

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3. Introduction

Generation IV very high temperature reactors (VHTR) constitute one of the near-term advanced reactor design groups that have a potential for early deployment. The VHTR designs stem from historical high temperature gas-cooled reactors which have been in operation since the 1950s.

Generation IV VHTRs offer a broad spectrum of potential applications ranging from electricity generation to industrial heat applications to nuclear waste management. The next generation nuclear plant (NGNP) will be a full-sized demonstration VHTR targeting industrial heat applications and electricity.[1]

However, the current near-term VHTRs have projected helium outlet temperatures ranging from 750°C to 950°C, with nominal fuel temperatures being as high as 1250°C.[1] These high temperatures expected in VHTRs, combined with the high radiation environment, create extremely harsh operating conditions for in-core monitoring systems, limiting accessibility of the core and longevity of the instruments. This challenge is currently mitigated by providing out-of-core monitoring capabilities together with reconstruction of in-core values.

Advanced instrumentation capable of operating in high temperature/radiation environments can be used to fully map the temperature and neutron fluence distributions in advanced reactor cores. Online, distributed measurements provide real-time assessment of reactor performance and can be used to benchmark simulation and analysis codes.

However, the harsh operational conditions pose tremendous challenges for in-core monitoring system design. A distributed fiber optic temperature and fluence sensor network operable under extreme conditions and which may be located throughout a reactor core (axial and transverse dimensions) is currently being developed.

Online direct 3D in-core temperature and fluence mapping via a distributed sensor network provides real-time assessments of reactor performance characteristics facilitating safe and reliable operation of VHTRs with optimized operational margins and potentially minimal needs for operator/maintenance interventions.

This report discusses the ongoing effort to develop an advanced 3D in-core mapping via a distributed sensor network that would be capable of reliable performance in high temperature/high radiation environments for prolonged periods comparable at least to the fuel loading lifecycles. The project is funded by the DOE Nuclear Energy University Program and is focused on testing of a distributed fiber optic sensor network for online 3D temperature and neutron fluence mapping in the VHTR in-core environment.[2]

Supported by a DOE Nuclear Energy University Programs award, the project scope encompasses fabrication of sensor hardware, test article design and fabrication to support in-core testing, sensor hardware demonstration at the Texas A&M University (TAMU) TRIGA research reactor, 3D modeling of the NGNP/VHTR configuration and scaling from the TRIGA test environment to the anticipated VHTR operating conditions. A test configuration that allows for simultaneous exposure of the fiber optic sensors to high temperature and high radiation fields has been designed, and fabrication is currently under way.

The high temperature test device is adapted from in-core furnace equipment licensed for use in TRIGA research reactor facilities in the early 1970s (Nuclear Regulatory Commission licenses

R-38 and R-67). Device irradiations and post-test analysis will be performed at the TRIGA facility. Although the TRIGA environment can vary significantly from that expected in the proposed VHTR and other advanced reactor designs, the flexibility of operation, ease of startup, and sample accessibility make it ideal for initial component testing.

3.1. Objective

The proposed work will enable development of a highly reliable, distributed fiber optic temperature and fluence sensor network operable under high temperature/neutron fluence conditions and located throughout the reactor core (axial and transverse dimensions).

The project scope encompasses fabrication of the sensor hardware, test article design and fabrication to support in-core testing, sensor hardware demonstration at a university TRIGA research reactor (URR) facility, 3D modeling of the NGNP/VHTR configuration and scaling from the TRIGA test environment to the anticipated VHTR operating conditions.

The corresponding temperature/neutron field map reconstruction techniques and optimization of in-core detector positioning to minimize uncertainties will also be performed. The advantages of real-time in-core monitoring will be illustrated.

3.2. Background

3.2.1. VHTR In-Core Environment

The very high temperature reactor (VHTR) is considered one of the possible designs for the next generation of nuclear reactors. The proposed Next Generation Nuclear Plant (NGNP) will be a full-sized demonstration VHTR. The development of instrumentation that can function in the unique environment inside the reactor was identified as a principal technical risk to the NGNP.[1]

Table 1. Normal operating conditions of a VHTR

Temperature	VHTR In-Core Environment
Coolant Inlet temperature	490° to 600°C for prismatic cores, 350°C for pebble bed cores
Coolant Outlet temperature	900° to 950°C
Max fuel temperature	1250°C to 1400°C
Coolant pressure	7 MPa for prismatic cores, 9 MPa for pebble bed cores
Peak neutron fluence*	1.7E20 – 1.67E21 [n/cm ²] over 1 year

*The peak neutron fluence is the expected fast fluence ($E > 0.1$ MeV) for reactor internals which receive the most dose, namely the fuel and the inner reflector.

Instrumentation is needed to measure temperatures, neutron fluence, and the coolant flow rate. The high temperatures present in a VHTR during normal operation make it a challenging environment for sensors. Developing sensors that can withstand the temperatures present at the core outlet for an acceptable period of time will be a challenge.[2]

Sensors that are capable of measuring the high-temperature coolant flow will also need to be developed. Being able to accurately measure coolant flow is especially important a graphite block prismatic gas-cooled reactor where radiation-induced graphite deformations would block coolant channels.

Finally, sensors are needed that can measure the neutron flux in the reactor. The in-core flux is not significantly harsher than what is found in conventional reactors, but could pose a challenge as the radiation measuring instrumentation must be able to withstand the harsh temperature environment as well. Table 1 summarizes the normal operating conditions of a VHTR.[3,4,5]

In the proposed designs for the NGNP, the core is cooled by high-pressure helium. Reactor instrumentation must be able to withstand these high pressures (shown in Table 1). Additionally, any impurities in the coolant, as those summarized in Table 2, could raise material compatibility issues with instrumentation.[6,7,8]

Table 2. Impurities in historical gas-cooled reactors*

Reactor	H ₂	H ₂ O	CO ₂	CO	CH ₄	N ₂	O ₂
Dragon	2	0.1	<0.04	1.2	0.3	0.3	N/A
Peach Bottom	<i>10</i>	<i>~0.5</i>	<i><0.5</i>	<i>0.5</i>	<i>1.0</i>	<i>0.5</i>	<i>N/A</i>
AVR	30	3	10	10	-	-	N/A
Ft. St. Vrain	2-7	<1	0.5-3	1-10	0.1-0.8	N/A	N/A
HTTR	<3.0	<0.2	<0.6	<3.0	<0.5	0.2	<0.04

*Italicized values are in ppmv, while the rest of values are in pressure units (Pa).

The sensors could also be affected by the graphite dust that is expected to be present. Graphite dust is primarily an issue in pebble bed type reactors. A test size pebble bed reactor core is projected to contain about 10-50 kg of dust. Dust in prismatic core would be at least an order of magnitude less and would be deposited unevenly around the core.[6,9]

Of final concern are anticipated transients and accident conditions. In-core instrumentation would not be expected to survive accident conditions, but they are nonetheless presented for completion. Temperature is the primary attribute of concern during accident conditions.

In most accident conditions, fuel temperatures are not expected to exceed 1600°C.[4,10,11] Of additional concern would be the depressurization and air-ingress accident. This would result in a drop to atmospheric pressure and complications as a result of air entering the core.

3.2.2. Candidate Sensors for VHTR In-Core Flux and Temperature

There are several sensor types which can be used in the VHTR core. The high-temperature and high-radiation environment present significant challenges to sensor design and operational reliability characteristics.

The desire to use the sensors inside the VHTR core also places restrictions on their size. The primary candidates for in-core neutron detection are fission chambers, self-powered neutron detectors (SPNDs), and fiber optic sensors.

In-core fission chambers have been developed for use in French fast breeder reactors. In core fission chambers have primarily been used during startup and shutdown, when counting rates

are too low to use detectors under the vessel. They have also been used during core loading to closely monitor reactivity.

Fitting the necessary electronics into a package small enough to be used inside the core can be difficult; however, all engineering challenges for the use of in-core fission chambers in sodium fast reactors have effectively been solved, but such reactors only operate at about 600° C. In-core fission chambers are also used in the HTTR, but, once again, the temperatures do not exceed about 600° C.[12,13]

Self-powered neutron detectors are advantageous because of their simpler electronics. Generally speaking, fission chambers are more accurate and sensitive than SPNDs. The advantages of SPNDs are their reliability, robustness, small mass, small size, and small power requirements.

Work has been done regarding the feasibility of using SiC SPNDs gas turbine-modular helium reactors. Research found that such detectors could not survive the 850°C coolant temperatures or the fast fluence present in the core.

To mitigate these problems, the sensors must be placed in the central reflector, where the temperature is lower and the neutron spectrum is softer.[14,15]

The final candidate for potential use in in-core neutron measurements is a fiber optic based sensor. The use of fiber optic sensors for neutron flux measurements has not been proven to the extent of other the other detectors, namely SPNDs and fission chambers.

Initial research has shown that such fiber optic sensors could measure gamma flux as well as thermal, epithermal, and fast neutron fluence, and operate at temperatures up to 720° C. These sensors are currently capable of providing neutron and gamma measurements once every 18 seconds.[16,17]

The primary candidates for temperature detection are specialty thermocouples and fiber optic sensors. Thermocouples exist that are capable of operating at temperatures above 1000° C. The HTTR uses N-type thermocouples (Nicrosil-Nisil) to measure coolant temperatures of 1100° C. Fiber optic sensors also exist which can be used as distributed temperature sensors.

Initial research has proven the use of such sensors to measure temperatures up to 850° C with a spatial resolution of 1 cm. The distributed nature of the sensor provides a significant advantage over the point reading that is generated by a thermocouple; however more research is needed to develop fiber optic sensors that could operate at the temperatures found inside a VHTR core.[18,19,20]

3.2.3. Fiber Optic Temperature/Neutron/Gamma Mapping for VHTRs

Luna Innovations has previously demonstrated the key technical elements required to develop a highly distributed fiber optic temperature, neutron fluence, and gamma flux mapping system for the VHTR environment.

Key elements shown in previous tests include:

- Fiber survivability in very high temperatures (>1000°C),
- Fiber survivability in high-radiation environments (2×10^{19} n/cm² and 87 GRad),

- Distributed temperature measurement using the Rayleigh backscatter technique,
- Measurement of neutron fluence using single point optical sensors.

While previous tests successfully demonstrated fiber performance under each condition independently, limited combined environment testing has been conducted.

Sensors require longer duration testing at combined high temperature, high radiation conditions with real-time distributed measurement of neutron fluence to be qualified for VHTR service.

Standard optical fiber degrades rapidly at temperatures above 800°C. Specialty fibers and coatings that exhibit orders of magnitude improvement in useful fiber life relative to standard fiber at temperatures exceeding 1000°C have been developed and demonstrated for distributed temperature measurements with operational temperatures up to 1100°C.

Standard optical fiber has also been shown to darken, or brown, in the presence of relatively low gamma fields.

Survivability of specialty fibers and low reflectivity fiber Bragg gratings (FBG) in very high neutron and gamma fields has been demonstrated using the novel Luna Innovations fiber optic sensor system.

Low reflectivity (5%) gratings were exposed to 2×10^{19} n/cm² (>1 MeV) and 8.7×10^{10} Rad over a 60-day test. The FBGs were still functional at this dose level and showed excellent signal to noise ratios.

Typical FBG sensors are difficult to fabricate in fibers that have robust coatings necessary for high-temperature environments. Luna Innovations has developed capability that enables highly distributed temperature measurement using the intrinsic Rayleigh backscatter (RBS) signature that is present in all optical fiber.

This approach has been demonstrated using metal-coated fiber (i.e. gold, nickel, or other coatings currently being investigated) to obtain temperature measurements at 1 mm intervals along the fiber at temperatures up to 850°C, and in high-radiation environments; long-duration testing of the fibers under combined high temperature/high radiation environments has not been completed to date.

The result of continued development of FBG sensors that take advantage of RBS will be robust, environmentally tailored sensors available at greatly reduced cost.

Experimental observations of FBG sensor performance indicate a predictable sensitivity to neutron and gamma radiation. Using passive, non-scintillating, optical transducers previously developed, point sensors have been used to measure both neutron fluence and gamma flux in real-time.

This work indicates that contributions from neutron energies in the thermal, epi-thermal, and fast bands can be discerned. Initial neutron fluence monitors have shown an error of only 5% at a total fluence of 4.5×10^{17} n/cm².

Accuracy can be further improved by correcting for gamma cross-sensitivity. The current work will demonstrate distributed neutron and gamma sensing capability.

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4. High Fidelity Modeling Approach

4.1. 3D VHTR/NGNP Configuration Model

To create advanced nuclear energy systems it is desirable to have a high fidelity modeling-based design development that relies on simulating features of the entire life cycle of the system before actual physical prototyping - from concept development to detailed design, prototyping, and safety analysis. A 3D whole-core exact-geometry model of a VHTR hexagonal-block configuration with a detailed component representation has been developed and implemented for calculations with MCNP/MCNPX and Serpent.[1] Earlier benchmark studies validated applicability of the modeling approach to correctly represent design features and performance characteristics of HTRs.[2,3]

The model is based on the NGNP pre-conceptual design features. Figure 1 illustrates details of this model. The model color scheme demonstrates the ability to quantify physics characteristics while varying properties per block. The model allows tracking environments in fuel and coolant channels. The sequence is being implemented as MatLab shell that will later be transformed into a stand-alone auxiliary module.[2] The applied modeling approach and tools have been validated in previous efforts.

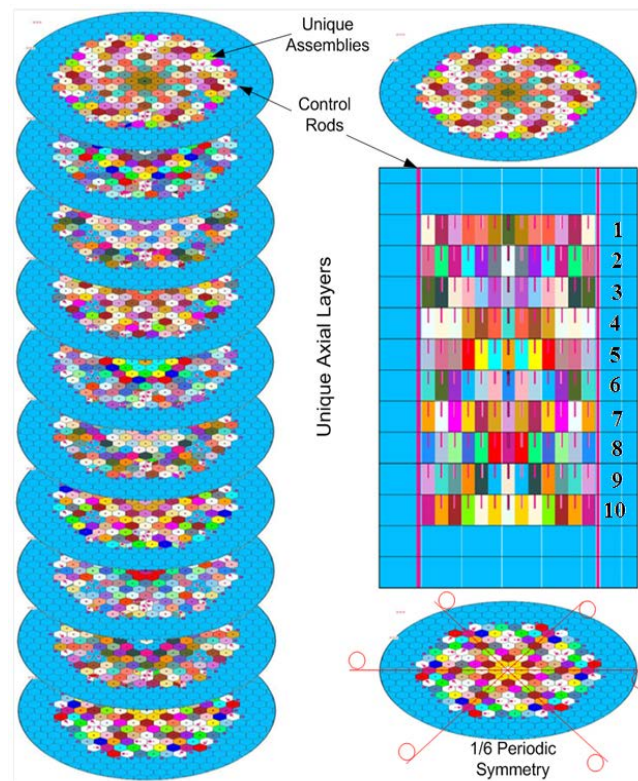


Fig. 1. Reference VHTR model with fuel and coolant channel neutron field tracking.

To capture and visualize performance characteristics, the detailed 3D maps are being produced at each block location as shown in Fig. 1 for a sample configuration. These maps allow for tracking of the HTR core loading patterns, in-core sensor responses, control schemes, fluence distributions, power peaking, and etc.

A sample fluence map is shown in Fig. 2. Color and size of each dot correspond to variations in values of performance characteristics.

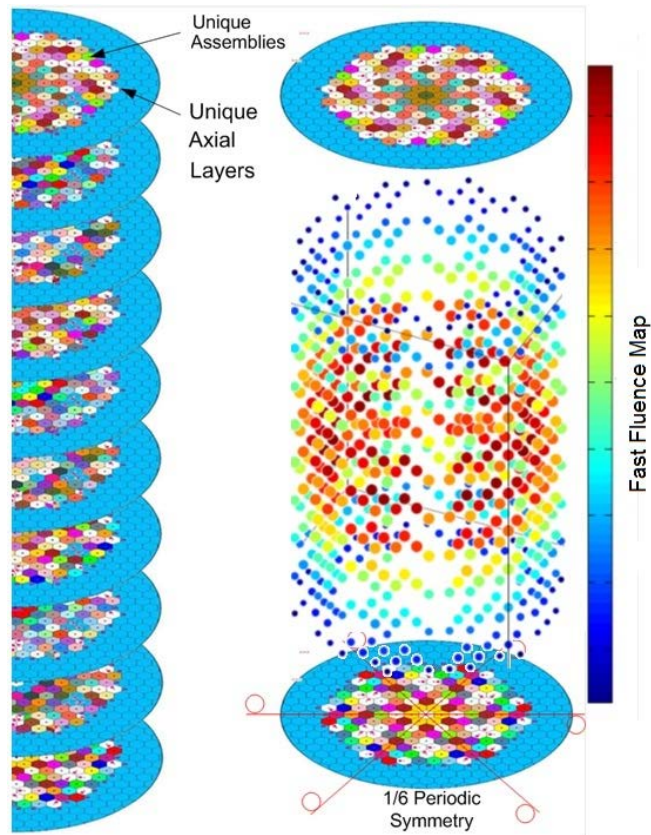


Fig. 2. High fidelity VHTR modeling for 3D mapping – sample VHTR fast fluence map.

Figure 3 provides an example of the developed 3D high fidelity approach to identify, track and visualize power hot spots in a HTR core during its lifetime. In this case, a hot spot range has been selected so that not only the true max power peaking location can be identified and visualized but also values in some proximity to the maximum.

Simulations of the reactor operation over 12 years reveal 3D migration of the hot spot locations within the HTR core (per block). From the perspective of tracking irradiation histories per block, these migration effects are important to identify blocks approaching their lifecycle limits due to radiation damage effects.

Based on the 3D performance maps for HTRs it is possible to determine safety characteristics, sensor locations, as well as optimize control and monitoring strategies. The optimization

objectives could include requirements to minimize numbers of needed in-core sensors, sensor locations, identify optimum control scenarios to maximize operational time and fuel utilization efficiency and others. These 3D maps also vary as a function of fuel type. The HTR cores fueled with LEU-, Th- and TRU-compositions exhibit different power production distributions within their respective core configurations.

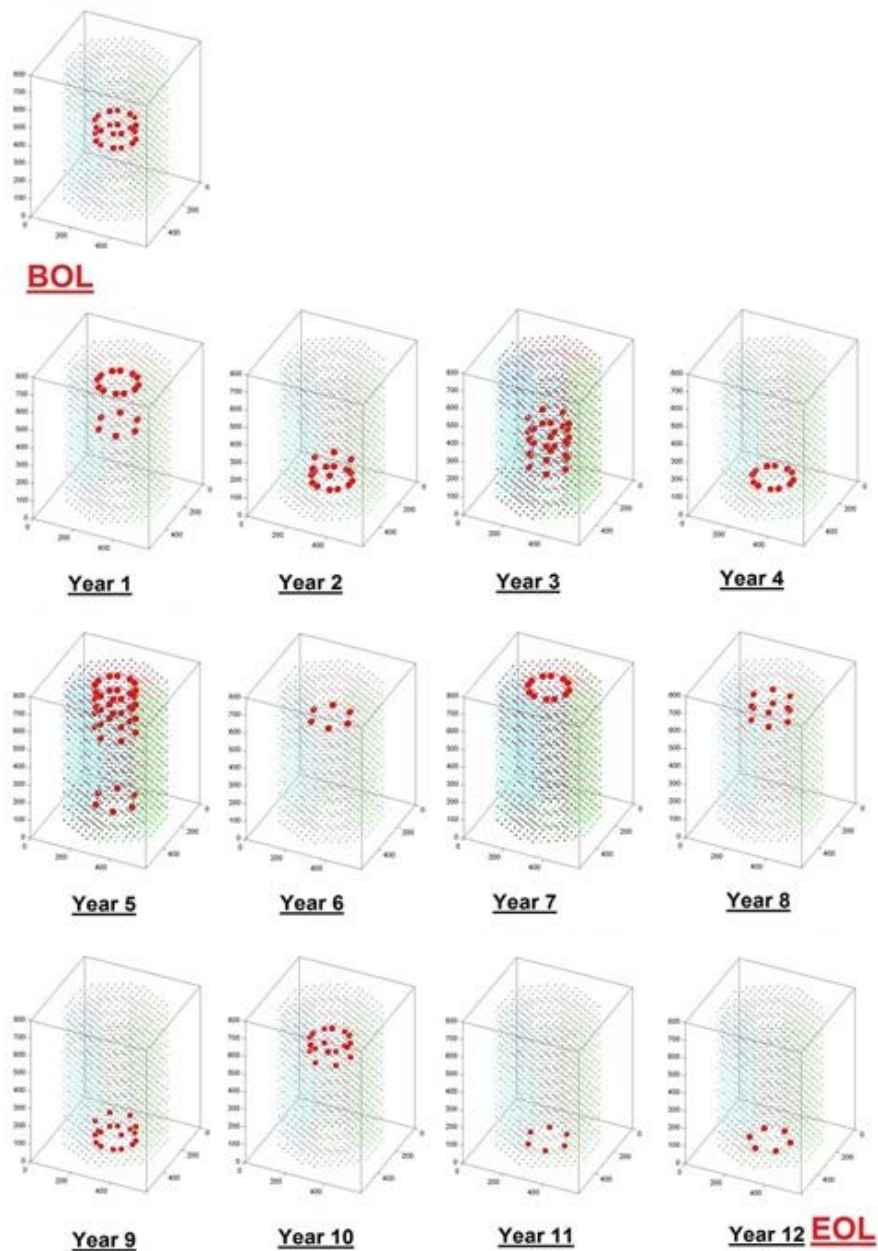


Fig. 3. In-core hot spot identification and evolution during the VHTR operation lifetime.

4.2. Image Reconstruction Applied to 3D Flux Data

4.2.1. Test Problem

A reference flux distribution was generated with a 3D mesh tally. The dimensions of the mesh tally are given in Table 1. A finer mesh tally was also generated with MCNP and applied within the project.

Table 1 Mesh Tally Data for a Reference Flux Distribution

Mesh Tally Parameter	x	y	z
Total number of bins	200	200	24
Mesh cell dimensions [cm]	3	3	46.25

In both 2D and 3D test problems, random and grid placed sensors were considered. Since it is assumed that the fiber optic sensors will span the full length of the core, a grid or random sensor arrangement was generated for a single xy slice, then this arrangement was used for all axial levels of the core.

Since the interpolation scheme used was mesh based, the placement process was analogous to generating a 2D mesh for a single xy slice and extruding it into a 3D mesh over the whole core. Figure 1 illustrates this point. Sensors are located on the vertices of the mesh. The meshes were generated in Matlab by Delaunay triangulation.

Many of the figures of merit used to assess the accuracy of the reconstruction methods are the same for 2D and 3D cases. Since the overall goal of the flux reconstruction is to pinpoint hot spot location, the primary figure of merit considered was the error in the predicted hotspot location. This was quantified using an L-2 norm:

$$\text{norm of error in hot spot location} = \left\| \vec{h}_{\text{reconstructed}} - \vec{h}_{\text{actual}} \right\|_2,$$

where $\vec{h}$

4.3. Emulation of VHTR Conditions in TRIGA

Emulation of the VHTR conditions requires three criteria to be met: the neutron energy spectra, operational temperatures, and the environment of the TRIGA test (including radiation fields, mechanical characteristics, etc.) and the VHTR conditions must closely match or be scalable from TRIGA to VHTR

At the experimental proof-of-performance stage of the project, the Texas A&M University's TRIGA (Training, Research, Isotope Production, and General Atomics) Mark I research reactor with a nominal operational power of 1MW is being utilized to emulate operating conditions in VHTRs.

Because this is a light water reactor operating at much lower operational temperatures than VHTRs, a specialized test device is required to emulate the VHTR high temperature conditions. The sensor test assembly is planned to be irradiated to fluence levels of 2×10^{19} n/cm² or higher and operate at 1000°C. This will provide the basis of supporting the use of the fiber optics within a reactor environment. A high temperature test furnace has been developed to achieve this goal.[4]

The furnace design is an adaptation of the original General Atomics furnace developed in 1970s for HTR fuel testing in TRIGA reactors. The overall TRIGA setup configuration of the experiments is shown in Fig. 1.

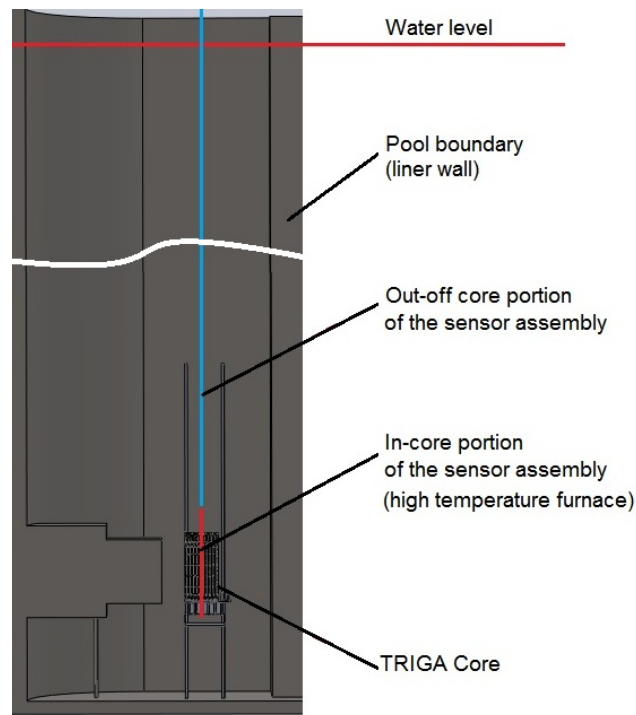


Fig. 1. TRIGA-based high temperature testing assembly.

There are significant space constraints on developing experiments within the reactor core, such that a larger furnace that could be used to harden the thermal spectrum becomes unfeasible. Using an external beam port for this purpose is also impractical due to the low neutron fluence and mechanical difficulties of operating the beam port for long irradiation periods.

Placing preferential absorbers to focus the desired spectrum reduces the fluence rate such that the required fluence levels will not be achievable within a single year timeframe.

Thus, the neutronics environment of VHTRs will require scaling and equivalence analysis to relate experimental results to the VHTR operating conditions.

The high temperature furnace will be inserted into a designated location of the TRIGA core. Figure 1 shows the overall layout of the furnace assembly including the in-core portion of the sensor assembly tube (void tube) and neighboring fuel elements.

The furnace will spend approximately 218 days in the TRIGA reactor core. Although the TRIGA does not operate continuously (24/7), the furnace will be on and data will be collected from the fibers when the reactor is in operation.

This means that the power will be varied over the course of data acquisition, and that the fibers will be subjected to significant thermal cycling that would not be present under normal operating conditions if installed in a VHTR.

This cycling could lead to early failure of the fibers that may not be seen without the cycling. Details of the complex irradiation schedule will be accounted for at the scaling stage of the data post-processing when TRIGA results will be related to VHTR conditions.

Some of the design challenges include: operation at 1000°C without inducing incipient boiling; temperature of the coolant adjacent to the furnace assembly must be maintained below the Technical Specification's Limiting Safety System Setting (525°C), and design compliance to the 10 CFR Part 50.59.

Figure 2 shows cross-sectional view of the overall layout of the developed high temperature furnace assembly.

There are four major components.

- The graphite heater provides the thermal heat required to attain 1000°C.
- The addition of two concentric niobium thermal shields minimizes the needs for active heat removal systems.

These shields are supported within aluminum housing to provide a pressure boundary for vacuum conditions.

- The assembly is contained within another tube used for displacing the water in the TRIGA experimental location.

Additionally, this outer tube is pressurized above the hydrostatic pressure of the surrounding water to prevent water leakage into the furnace assembly.

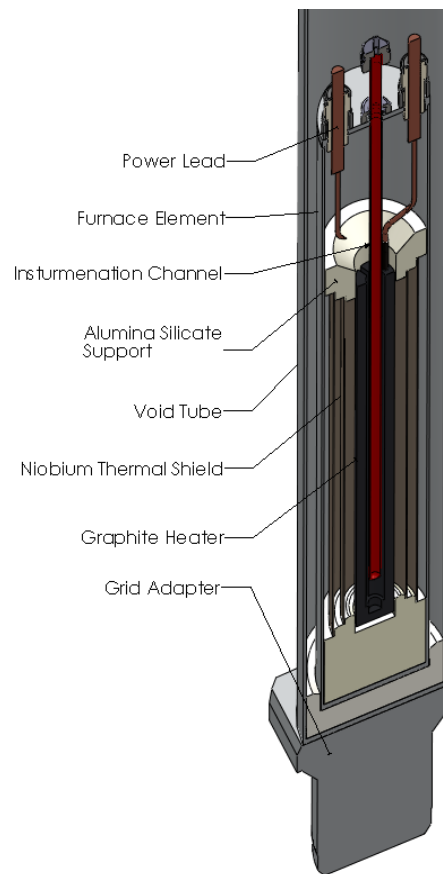


Fig. 2. High temperature furnace emulating VHTR conditions for advanced sensor testing in TRIGA reactors.

High fidelity computational continuum mechanics (CCM) simulations of the furnace assembly performance characteristics are the basis for the selected design parameters. Initial sizing constraints were based on geometrical restriction within the reactor lattice and shield size and number were determined with 1D heater transfer calculations.

The high temperature furnace assembly has been designed based on the results of high fidelity simulations using STAR-CCM+ and MCNP.[1,5]

Figure 3 provides the results of the furnace thermal performance simulations with STAR-CCM+. As can be seen, the design is capable attaining high temperatures at the sensor location while restricting outside temperatures to near ambient levels. The high temperature region is completely shielded from the TRIGA in-core environment and does not result in elevated temperatures outside of the furnace assembly.

Thus, it has been demonstrated computationally that the developed test assembly design can attain the desired 1000°C-levels at the sensor location without causing an increase in temperature levels outside of the furnace assembly void tube.

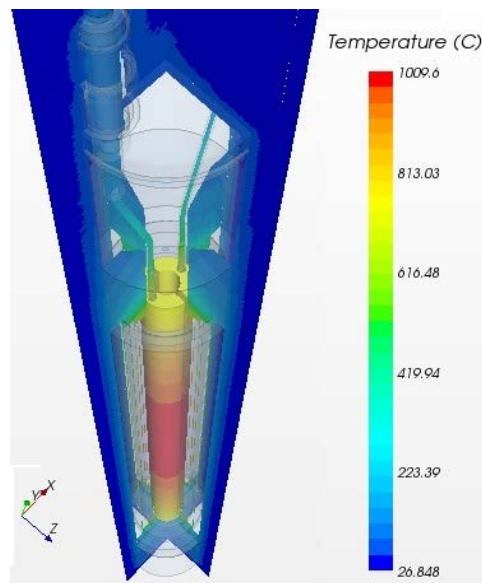


Fig. 3. Thermal performance of the high temperature furnace simulated with STAR-CCM+.

Although high temperatures are attainable, the neutronics conditions of VHTR cores are more difficult to emulate in the TRIGA reactor core because of the inherent physics features. The TRIGA Mark I fuel design uses a zirconium hydride metal lattice which places moderator directly in the fuel. Zirconium hydride comprises 70% of the fuel meat mass, diminishing the fast spectrum.

Figure 4 shows the resulting differences between the neutron spectra in the TRIGA core and the VHTR spectrum. The TRIGA Mark I fuel design uses a zirconium hydride metal lattice which places moderator directly in the fuel.

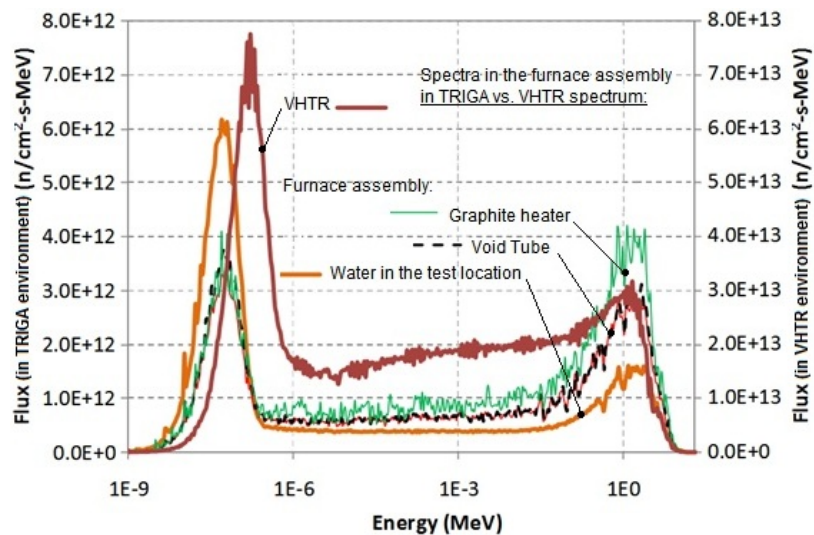


Fig. 4. Neutron energy distributions in the TRIGA test location and in the VHTR core.

Figure 5 shows the local heater-to-VHTR flux ratios. None of the energy regions yields flux ratios equal to unity, although the intermediate energy range exhibits the least variation between spectral conditions in these two reactors.

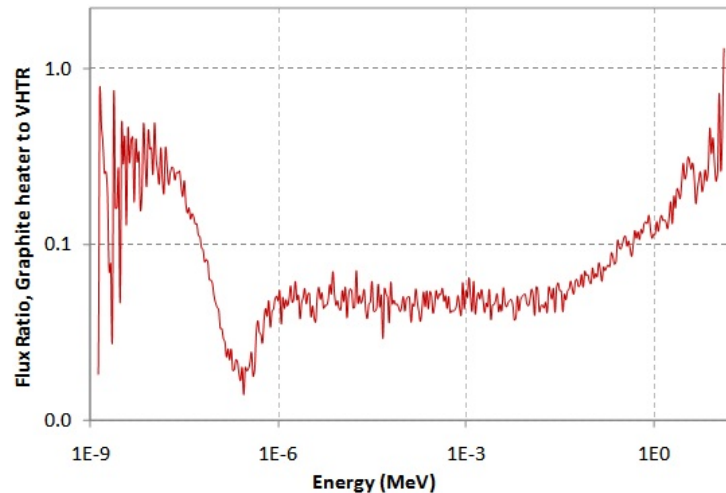


Fig. 5. Scaling and potential spectrum tailoring needs to relate TRIGA test results to VHTR in-core conditions.

Such ratio sets based on flux, fluence and reaction rate calculations will have to be used to determine performance levels that would be equivalent to the VHTR core environment from the corresponding values obtained in the experiments with the high temperature furnace installed in the TRIGA reactor core.

The observed differences between neutronics conditions in TRIGA and VHTR cores will require further scaling and equivalency studies to establish relationships between experimental data and anticipated performance characteristics.

4.4. Safety Evaluations and Validation Program

The design basis for this experimental device is the possibility of water ingress and subsequent steam rupture. Due to the proximity of the furnace to the fuel, roughly 0.4 in, this event could result in fuel cladding damage. To prevent this incident, various measures were taken: a double enclosure of 0.065 in Al-6061 T6 tubing is used and the outer enclosure is pressurized to 400 kPa (the hydrostatic pressure is about 200kPa) with UHP helium.

Additionally, material usage and temperatures are limited on the basis of reducing the thermal storage within the furnace. Temperatures are limited on the basis that there is a perfect amount of water, such that it all completely absorbs all the thermal energy and converts to steam, the volume required at the failure pressure is equal to open volume of the furnace. This includes the partial pressure of helium.

This leads to the assumption that the graphite heater shuts off. There are pressure switches on the furnace to assure proper performance.

4.4.1. Thermal Conditions

Validation efforts of neutronics and thermal simulations were completed following operational tests of equipment and with experimental data from the TRIGA reactor. These included validation efforts of radiation modeling and fluence measurements.

The first series of validations were completed for radiation modeling of the graphite heaters. Each heater was constructed to allow for power lead contacts with a variable current power supply and placed in vacuum of 10^{-4} torr.

Figure 1 shows the mesh of the graphite heater. Mesh refinement studies concluded this mesh would be suitable.

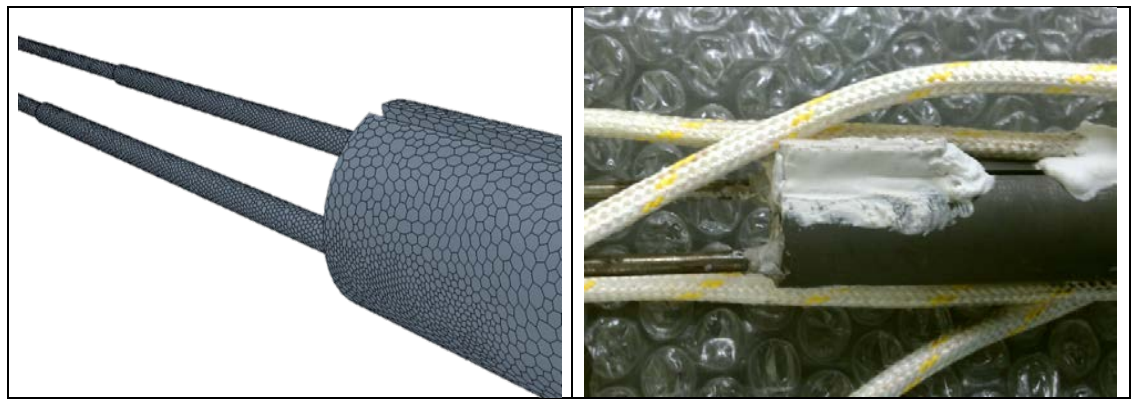


Fig. 1. Polyhedral computational mesh for the graphite heater to be used in STAR-CCM+ radiation simulations compared to the actual graphite heater.

A distributed fiber optic test system will be used to provide data for validating the thermal modeling. Using an Optical Backscatter Reflectometer (OBR), the distributed temperature within the high temperature test device can be measured.

The OBR is capable of measuring temperature every 0.5 cm down the length of an attached optical fiber up to temperatures of 850°C with a 0.1°C resolution. Fiber survivability has been shown above 1000°C.

Table 1 outlines the primary results of the validation efforts. The largest errors resulted in determination of the heat flux from the graphite. This is attributed to lack of modeling of the thermocouple contacts and from contact resistances of the supports for the graphite heater and power leads.

The reflection of radiation from the surface of the vacuum chamber was also neglected, but the surface temperature of the chamber and the environmental temperature of the model were equivalent in all simulations.

Additionally, during the process of heating the graphite, system resistivity was determined with a multimeter and applied to the model as shown in Fig. 2. Inconsistent coupling between the leads and power supply required experimental validation of values applied in models for each heater that was tested.

Table 1. Comparison of STAR-CCM+ Values to Experimental Values.

Current (amps)	Surface Temp (°C)	Measured Temp (°C)	Heat Flux (W/m ²)	Power Error	Temp. Error
3.50	39.74	37.7825	82.44	-0.0944	0.0063
4.50	47.17	46.4325	134.83	-0.0919	0.0023
6.00	60.22	57.8975	236.13	-0.0948	0.0070
8.00	79.77	78.4425	411.73	-0.0981	0.0038
10.00	100.47	100.6	632.5	-0.0948	-0.0003
12.00	121.55	121.18	898.15	-0.0862	0.0009
13.50	137.32	135.4875	1126.97	-0.0849	0.0045
15.00	152.95	150.53	1381.29	-0.0876	0.0057
17.00	173.46	169.1375	1760.26	-0.0896	0.0098
18.50	188.55	182.6175	2074.49	-0.0887	0.0130
20.00	202.72	194.7725	2399.59	-0.0936	0.0170
21.25	215.48	205.822	2717.25	-0.0875	0.0202
23.00	232.1	220.4275	3170.96	-0.0799	0.0237
24.50	246.03	232.18	3587.32	-0.0800	0.0274
26.00	259.68	243.9025	4028.76	-0.0760	0.0305
6.00	60.22	59.5475	236.13	-0.0948	0.0020
10.00	100.47	101.23	632.5	-0.0897	-0.0020
17.00	173.46	171.2675	1760.26	-0.0865	0.0049
26.00	259.68	246.9625	4028.76	-0.0907	0.0245
28.00	277.42	262.15	4656.07	-0.0943	0.0285
30.00	294.68	276.7925	5327.23	-0.0959	0.0325
32.00	311.48	290.3725	6041.94	-0.0959	0.0375
34.00	327.84	303.8825	6800.1	-0.0849	0.0415
36.00	343.81	317.1455	7601.9	-0.0842	0.0452
39.00	367.08	338.59	8887.66	-0.0755	0.0466
41.00	382.2	348.185	9801.78	0.0196	0.0548
44.00	404.39	365.8425	11262.82	0.0531	0.0603
46.00	418.92	376.8275	12300.6	-0.0011	0.0648
47.50	429.72	385.5925	13144.9	-0.0172	0.0670

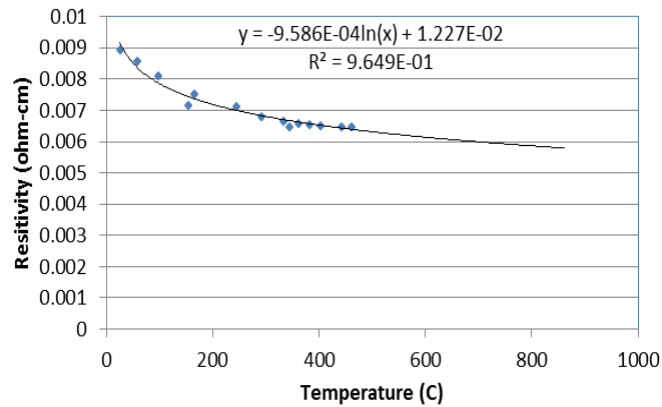


Fig. 2. Resistivity as a function of average graphite temperature.

Validation efforts continued following the completion of the furnace fabrication. The efforts included bench top testing of the furnace in an open pool environment. The parameters that are compared with are: furnace, void tube, and heater surface temperatures.

4.4.2. Heater Stress Testing

The controller for the furnace will be operated with LabView. This allows for control of the power supply, either manually or automatically, given a desired temperature for any given thermocouple input. Various thermal stress/transient tests to demonstrate heater fabrication were completed. These showed satisfactory cementing of thermocouples and power leads.

Heater stress testing has been successful for the most severe of possible transients, although cooling transients were limited in scope. Figure 3 illustrates transient temperature fluctuations. Maximum temperature condition did not fail during steam rupture evaluations.

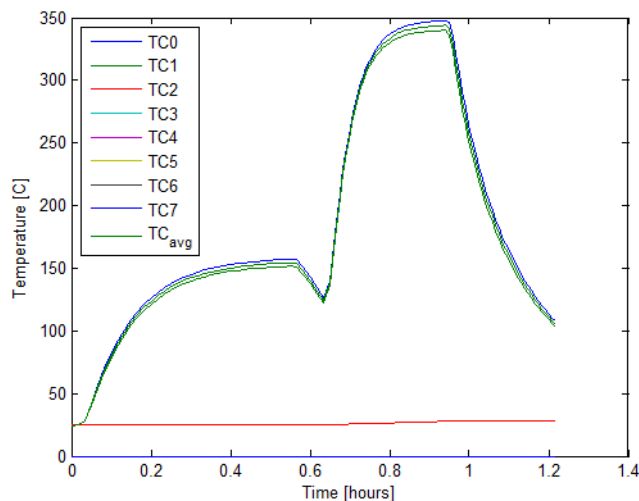


Fig. 3. Sample temperature transient.

4.4.3. Physical tests

Spatial continuous instrumentation has been developed in recent years to measure temperature in a single dimension. Unlike other measurement systems that measure at finite location, fiber optic technology allows for such continuous measurements.

Figure 4 illustrates continuous measurements via the distributed fiberoptics test system.

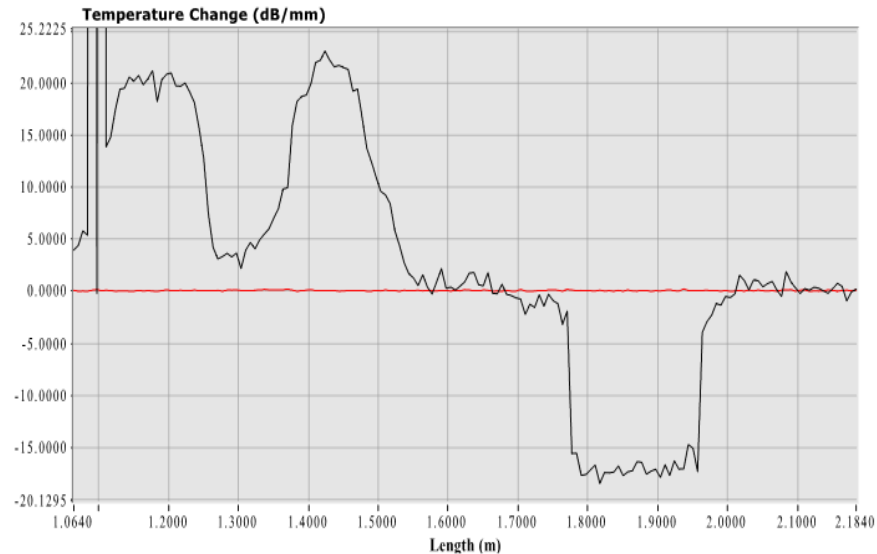


Fig. 4. Continuous temperature measurement showing heated and cooled regions.

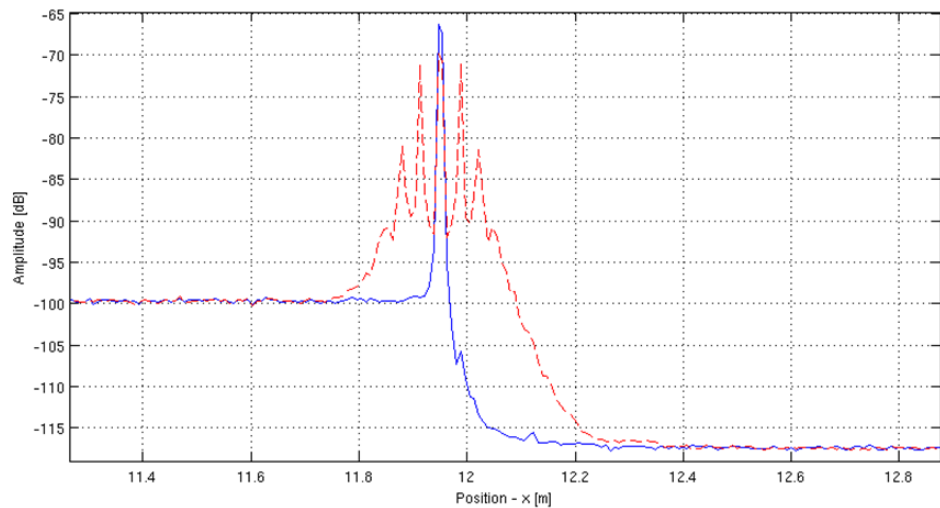
Inherently, any material structure will expand during temperature changes within the material. Fiber optic measurements take advantage of this phenomenon by using spectral backscatter analysis to determine the strain induced within the fiber as a result of this expansion. It is then known, that any geometry change in the fiber will induce a change in the strain in the fiber optic.

It was investigated whether this greatly affects the measurement accuracy and to what extent the vibrations might affect coupling joints. It was shown that the measurement was particularly affected by certain vibrations, those specific in the “fan” range, and the magnitude of those vibrations induced further error.

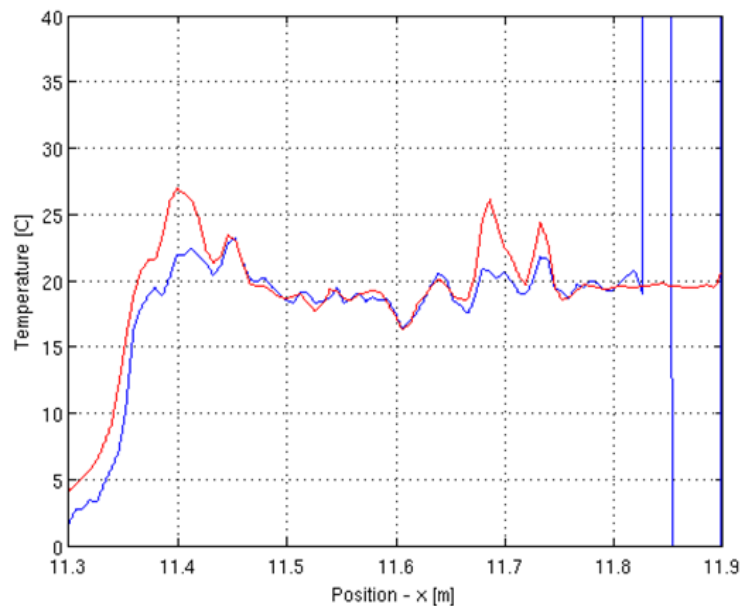
The fiberoptics sensors are expected to be capable to reliably operate within the reactor vessel internals. The most desirable placement locations of interests are within the core itself. Emerging fiberoptics performance issues in these environments need to be evaluated and quantified.

Under nominal, steady-state conditions, there is a significant amount of coolant flowing through coolant channels and assemblies. There are massive 10MW pumps. These and other system features will contribute to mechanical vibrations. With the measurement systems distributed throughout the reactor, all these vibrations can be expected to impact the fiberoptics systems. It is the object of this study to determine, based on the operating conditions of the TRIGA facility and other supporting equipment, on whether vibration-induced measurement errors can be expected, tolerated, or even avoided.

The effects of various components, present during the tests, are examined. These components are the turbo and scroll pump, computer, and power supply. The computer and power supply do have a fan and it is suspected that these are enough to alter the measurements. Figure 5 illustrates effects due to vibrations on the return losses and temperature distributions.



(a) Vibration effect on the return losses at the fiber end.



(b) Vibration effect on the temperature distribution measurement.

Fig. 5. Sample fiberoptics performance effects due to vibrations.

4.5. Conclusions

Results of the high fidelity simulations indicate that the furnace assembly should be capable of emulating VHTR temperature conditions in TRIGA experiments. The furnace allows the sensor location to reach 1000°C-levels while being completely shielded from the TRIGA core environment. Calculations indicate that no active heat removal systems (i.e. via flowing gas) will be required to maintain temperatures below the TRIGA limiting safety system setting (525°C) at the outer surface of the furnace void tube. While the VHTR temperature environments can be emulated directly with TRIGA experiments using the high temperature furnace assembly, the neutronics conditions will require further scaling and equivalency analysis of the experimental results of the TRIGA core to the expected VHTR operational conditions.

4.6. References

1. J.S. Hendricks, G.W. McKinney, J.W. Durkee, J.P. Finch, M.L. Fensin, M.R. James, et al., MCNPX, Version 2.6.0, Los Alamos National Laboratory Report LA-UR-08-2216, 2008.
2. P. V. Tsvetkov, "Coupled Hybrid Monte Carlo - Deterministic Analysis of VHTR Configurations with Advanced Actinide Fuels," *Proc. ICAPP'06*, pp. 1984 - 1990 (2006).
3. D. E. Ames II, P. V. Tsvetkov, "Benchmark Efforts to Support Studies of Advanced VHTRs," *Proc. 4th Intern. Conf. HTRs*, HTR2008-58206, ASME (2008).
4. E. E. Anderson, S. Langer, N. L. Baldwin and F. E. Vanslager, "An In-Core Furnace for the High-Temperature Irradiation Testing of Reactor Fuels," *Nucl. Techn.*, **11**, pp. 259-265 (1971).
5. Star-CCM+ v5.06.007, distributed by CD-adapco Group, Inc., Melville, NY.

5. Distributed Fiberoptics-Based Measurement System

5.1. Preliminary Design of the Test Probe Housing

Figure 1 illustrates a feasible configuration for the test probe housing. The top and bottom close-ups of the sensor locations show where either 3 or 4 quartz four bore tubes will hold the 3 different kinds of sensing fibers near each other. The lower Swagelok fitting is for attachment to the test housing, the upper Swagelok is for attachment to the lead out tubing. The niobium tube will be sealed at the distal end (not shown).

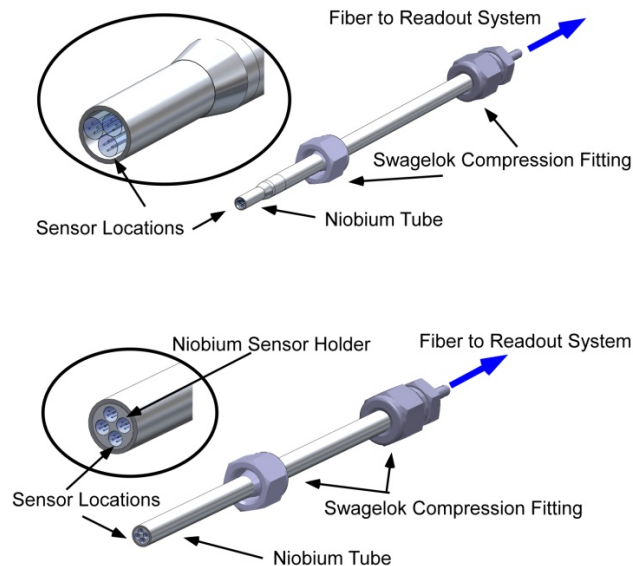


Fig. 1. Preliminary design of the test probe housing.

5.2. Fiberoptics Probe Design for Distributed Measurements

Luna has developed the sensor hardware design to support distributed measurements in the project. The probe design is shown in Fig. 1. The design for the probe consists of several sections: the lead, high pressure, and vacuum areas.

The lead section consists of twelve radiation resistant optical fibers housed in 20AWG fiberglass sheathing. These are then bundled in 0AWG fiberglass sheathing. To protect the optical fibers from the reactor pool, the bundle is housed in a corrugated stainless steel tube; this allows flexibility while preventing water ingress. The lead section passes through a 3/8" NPT aluminum fiber optic feed through. This will be tested up to 100 PSI for safety.

The high pressure section follows the leaded section after the feed through. The twelve optical fibers are bundled into four 20AWG fiberglass sheaths and the set of four is bundled in a 0AWG fiberglass sheath. At 3.5meters of optical fiber in this section allows TAMU to be flexible in positioning the probe and can be used for different configurations. The bundle of optical fibers enters a niobium tube that has a welded niobium 1/4"NPT thread and is held in place with Miller-Stevens 907.

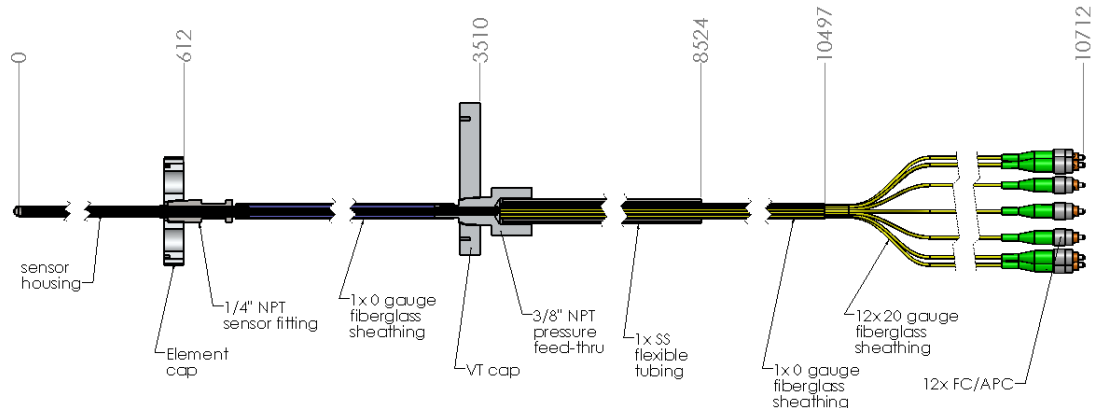


Fig. 1. Design drawing of the distributed optical fiber probe (dimensions in mm unless shown otherwise).

Next is the vacuum section, this consists of the niobium tubes and the sensors. The four bundles of three optical leads are housed in side of the niobium tube and transition to the sensing fibers at the top of four 4-bore quartz tubes. The niobium tube has been welded closed to provide a vacuum barrier for the sensors.

The sensing fibers consist of a single temperature, neutron fluence, and gamma flux sensing fiber each ~60.8m in length. Each fiber has been stripped of the protective coating due to the coatings behavior in high temperature and radiation environments. This stripping however makes fabrication difficult as it increases the possibility of breakage. The fibers have been terminated to allow distributed monitoring close to the tip of the quartz 4-bore. The 4 quartz 4-bores are held in place with ceramic wool to provide slight vibration protection. Figure 2 shows the locations of the fibers and 4 bores inside the niobium tube.

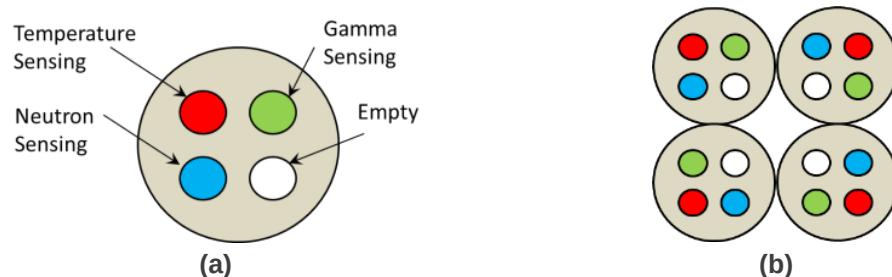


Fig. 2. (a) Location of the optical fiber in a single quartz 4-bore, (b) location of the quartz 4-bores in the niobium tube.

5.3. Fiberoptics Performance Monitoring

Luna provided a report to TAMU on several optical fiber health problems that could be seen in the optical sensing fiber. This report provides examples for health monitoring while in-situ at TAMU. These problems include: a break, a crush, and a splice. Examples of this are shown in Fig. 1.

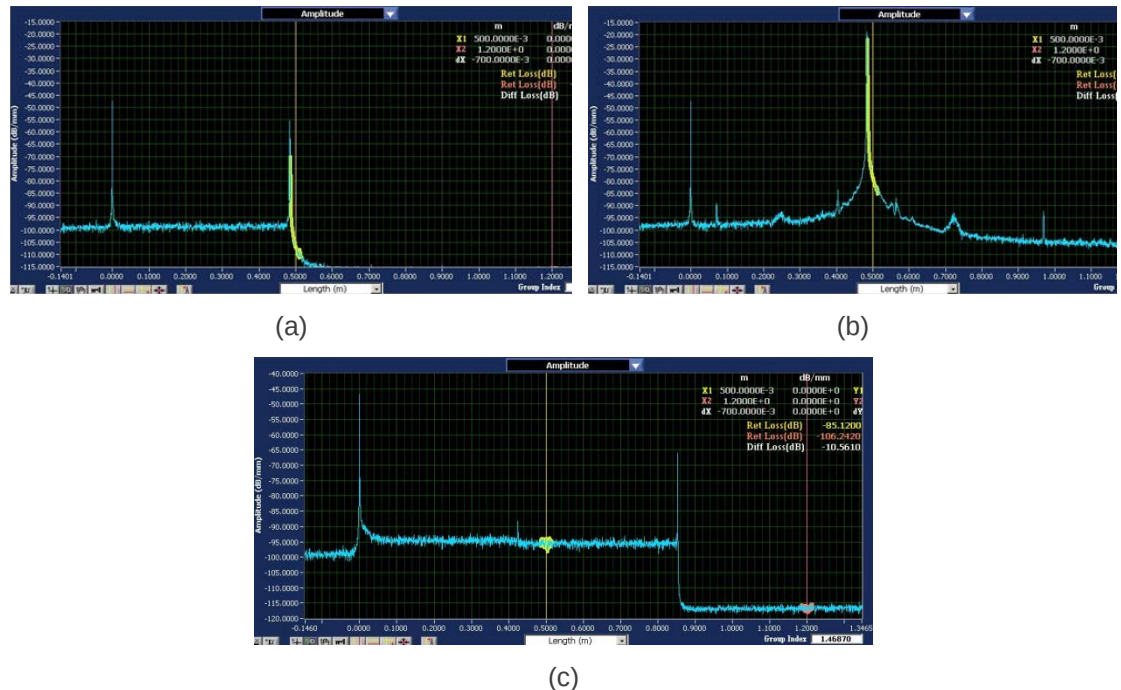


Fig. 1. (a) A brake in the Temperature sensing fiber. (b) A crush in the temperature fiber. (c) A splice in a temperature sensing fiber.

These results and conclusions are being incorporated into the independent fiberoptics performance assessment report that will outline expected limitations, potential solutions and further anticipated technology improvements as well as viability evaluations of fiberoptics uses for in-core instrumentation applications.

5.4. Fiberoptics Data Acquisition Software

An auxiliary software package was developed to extract the neutron fluence and gamma flux information from the radiation sensitive fibers. Simulated fiber data sets were used to develop the algorithms for the sensing fibers used at Texas A&M University.

Figure 1 shows a screenshot of the simulated data and the corresponding radiation signal. The top graph shows the reference and signal data gathered using an OBR. A clear radiation signal is seen at a length of 14 meters in lower graph showing the calculated radiation effect.

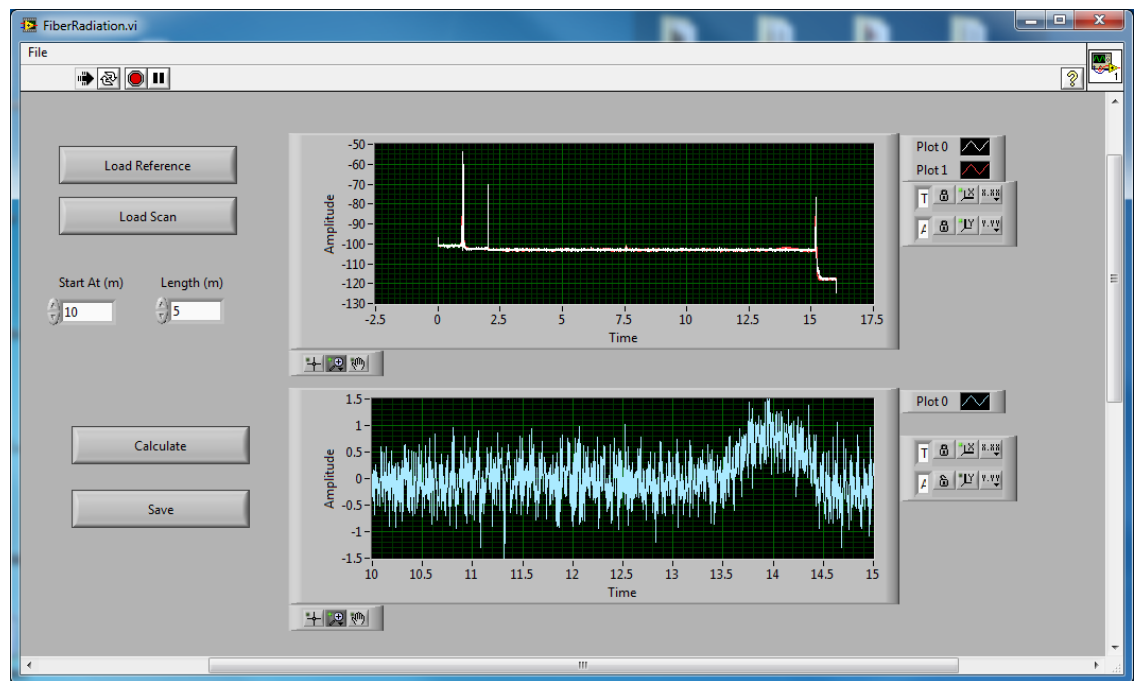


Fig. 1. Screenshot of the fiber radiation software using simulated data.

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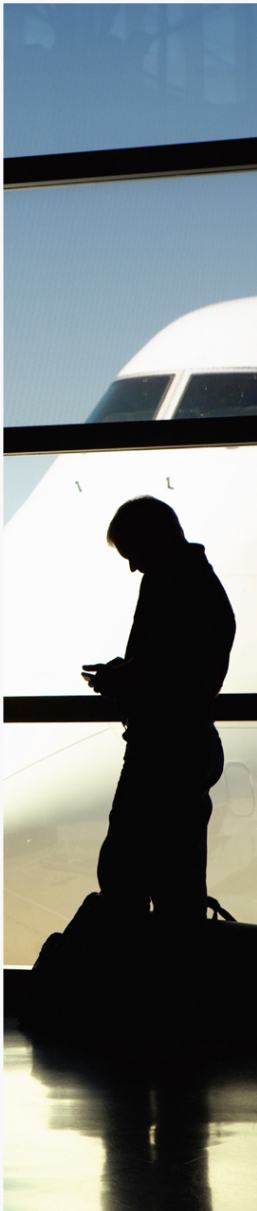
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6. Conclusions

Given the harsh environments of high temperature reactors, new in-core instrumentation has to be developed. Existing approaches may fail prematurely in VHTRs. The report discusses efforts to develop suitable advanced in-core instrumentation technologies and corresponding experimental confirmation approaches for their performance in VHTRs via emulation of VHTR in-core conditions in TRIGA reactors.

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7. Publications

- 2011
 1. M. P. Johnson*, T. G. Lewis*, P. V. Tsvetkov, "3D High-Fidelity VHTR Modeling for Performance Optimization Simulations: Monitoring and Operation", *Trans. Amer. Nucl. Soc.*, **104**, pp. 81-82, USA (2011).
 2. P. V. Tsvetkov, S. M. Bragg-Sitton, J. M. Johns*, T. G. Lewis III*, A. B. Alajo*, M. P. Johnson*, "Distributed Sensor Networks for Online 3D In-Core Monitoring in VHTR Environments", *Trans. Amer. Nucl. Soc.*, **104**, pp. 931-933, USA (2011).
 3. J. M. Johns*, M. P. Johnson*, P. V. Tsvetkov, S. M. Bragg-Sitton, A. B. Alajo*, "Emulation of VHTR Operating Conditions in TRIGA Reactors", *Trans. Amer. Nucl. Soc.*, **104**, pp. 78 - 80, USA (2011).
- 2012
 4. J. M. Johns*, P. V. Tsvetkov, "Development of TRIGA-Based Experimental Device for Fiber Optics In-Core Instrumentation Testing for VHTRs", Paper 202, *Proc. ANS Topical Meeting on Advances in Reactor Physics (PHYSOR2012)*, April 15-20, 2012, Knoxville Convention Center, Knoxville, TN USA (2012).
 5. P. V. Tsvetkov, S. M. Bragg-Sitton, J. M. Johns*, M. P. Johnson*, "3D In-Core Monitoring in Advanced Reactor Environments", *Trans. Amer. Nucl. Soc.*, **106**, pp. 626-627, USA (2012).
- 2013
 6. J. M. Johns*, M. P. Johnson*, P. V. Tsvetkov, S. M. Bragg-Sitton, "Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments", *Trans. Amer. Nucl. Soc.*, **109**, pp. 1033-1036, USA (2013).
 7. M. P. Johnson*, P. V. Tsvetkov, "3D Mapping and Reconstruction for In-Core Monitoring in Advanced Reactors", *Trans. Amer. Nucl. Soc.*, **109**, pp. 1120-1122, USA (2013).

"*" designates participating students.

8. Presentations

- 2011
 1. M. P. Johnson*, "3D High-Fidelity VHTR Modeling for Performance Optimization Simulations: Monitoring and Operation", *ANS 2011 Annual Meeting, June 26-30, 2011, Hollywood, FL, the Westin Diplomat Resort and Spa* (2011).
 2. P. V. Tsvetkov, "Distributed Sensor Networks for Online 3D In-Core Monitoring in VHTR Environments", *ANS 2011 Annual Meeting, June 26-30, 2011, Hollywood, FL, the Westin Diplomat Resort and Spa* (2011).
 3. J. M. Johns*, "Emulation of VHTR Operating Conditions in TRIGA Reactors", *ANS 2011 Annual Meeting, June 26-30, 2011, Hollywood, FL, the Westin Diplomat Resort and Spa* (2011).
 4. S. M. Bragg-Sitton, "In-Core Testing of Distributed Fiber Optic Sensors", *TRTR Meeting, September 2011, INL* (2011).
- 2012
 5. J. M. Johns*, "Development of TRIGA-Based Experimental Device for Fiber Optics In-Core Instrumentation Testing for VHTRs", *PHYSOR2012, April 15-20, 2012, Knoxville Convention Center, Knoxville, TN* (2012).
 6. P. V. Tsvetkov, "3D In-Core Monitoring in Advanced Reactor Environments", *ANS 2012 Annual Meeting, June 24-28, 2012, Hyatt Regency Chicago, Chicago, IL* (2012).
- 2013
 7. P. V. Tsvetkov, "Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments", *ANS 2013 Winter Meeting, November 10-14, 2013, Omni Shoreham Hotel, Washington D.C.* (2013).
 8. P. V. Tsvetkov, "3D Mapping and Reconstruction for In-Core Monitoring in Advanced Reactors", *ANS 2013 Winter Meeting, November 10-14, 2013, Omni Shoreham Hotel, Washington D.C.* (2013).

"*" designates participating students.



9. Participating Students

Name	Citizenship	Major	Project Area
Dr. Ayodeji B. Alajo	Nigeria	Post-doctoral researcher, Nuclear Engineering	VHTR/TRIGA model development and scaling analysis tasks.
Eloura Durkee	U.S.	Undergraduate student, Nuclear Engineering	Test article design, fabrication, and NSCR integration, VHTR/TRIGA model development
Dr. Tom G. Lewis III	U.S.	Post-doctoral researcher, Nuclear Engineering	System and sensor network modeling, mapping and reconstruction, scaling, V&V
Jesse Johns	U.S.	Graduate student, Nuclear Engineering	Test article design, fabrication, and NSCR integration, experimental program
Matthew Johnson	U.S.	Graduate student, Nuclear Engineering	Distributed sensor network mapping and optimization
Sathish Lakshmipathy	India	Graduate student, Nuclear Engineering	VHTR core operation characteristics modeling algorithm development (core shuffling)
Carl Mullins	U.S.	Graduate student, Aerospace Engineering	Test article design, fabrication and NSCR integration, hardware-software interface via Lab View
Eric Myers	U.S.	Health Physics	System diagnostics; neutron and gamma sensor selection and validation of fiber optics; characterization of overall fiber performance

10. Appendix

10.1. Procurement and Fabrication Process

Void Tube, Aluminum Tubing, OD: 3.0", Thick: 0.083", Length: 12'

- Feedthroughs
 - TCs
 - Power, Solid sealing technology, <http://www.solidsealing.com/>
 - Fiber Optics, Supplied by Luna
 - Helium Flow x2, Swagelok, <http://www.swagelok.com/>
- Aluminum block for grid plug
- Alumina spacer for furnace element

Furnace Element, Aluminum tubing, OD: 2", Thick: 0.049"

- Feedthroughs
 - TCs
 - Nextel insulation.
 - Conax Buffalo, <http://www.conaxbuffalo.com/details.aspx?cid=T6&pid=T623>
 - Pave Tech., http://www.pavetechnologyco.com/design/thermo_productindex.html
 - Power, Solid sealing technology, <http://www.solidsealing.com/>
 - Fiber Optics, Supplied by Luna
 - Helium flow, Swagelok, <http://www.swagelok.com/>

Niobium Thermal Shields: \$1500, Admat, <http://www.admatinc.com/>

Alumina baffles, Alumina Silicate possesses the properties that would be more fitting.

Piping/Flow Tubing

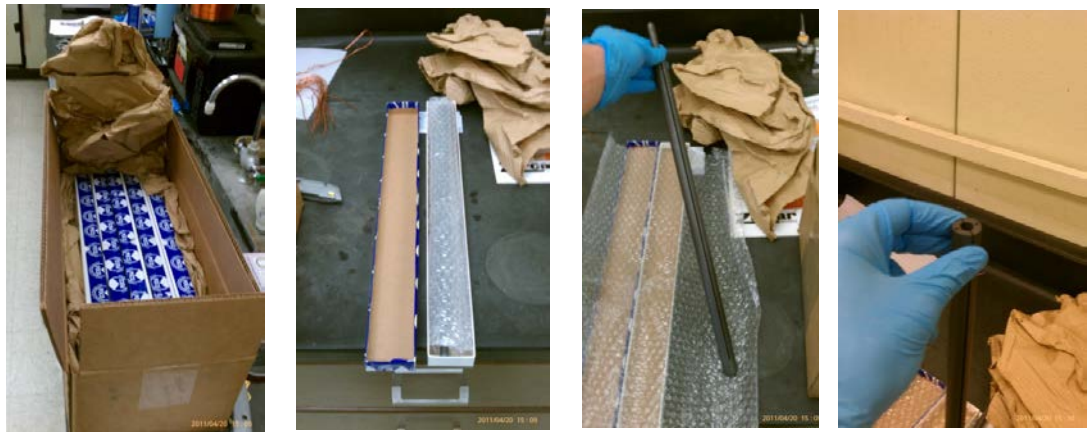
- Swagelok, <http://www.swagelok.com/>
- Pressure relief valves, Spring Loaded and Power Operated
- Solenoid valves
- Power relief valves

Wiring and Thermocouples, K type, SLE

Computer Rack

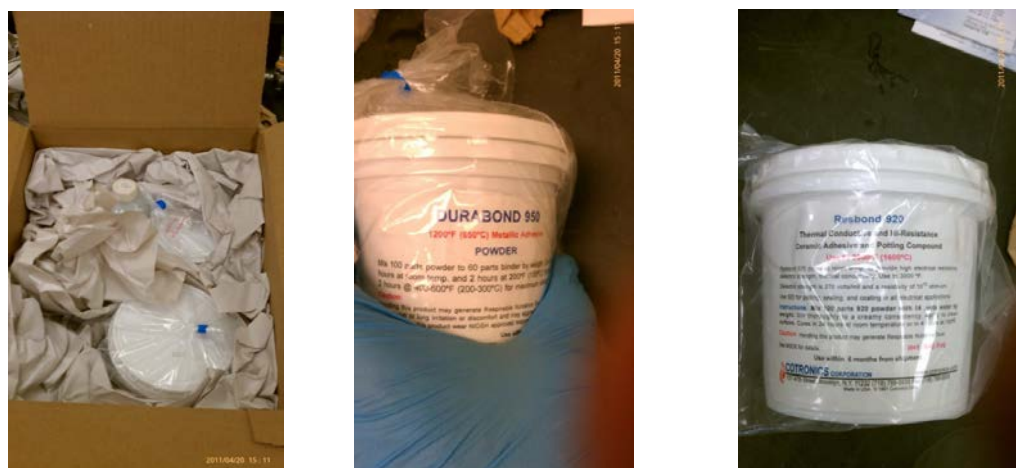
Graphite heaters:

These were ordered from Poco Graphite. They have a plant in Decatur, Texas. Their response was prompt and they were helpful with the material choice of the graphite, which was chosen to be AXZ-5Q. The quoted price was: \$2586.00 (all images were taken some time after receipt). All heaters were visually checked.



Epoxy/Cement:

These were ordered from Cotronics. Shipment was swift, though the staff were not very helpful with respect to questions about their materials. The packaging was neat and tight. No apparent damage to the box.



10.2. Fiberoptics Testing

Failure modes

There are various failure modes available for the fiber optics. The fibers are inherently fragile, so mishandling them can cause the ends of the fibers to inadvertently break. Avoiding this as the fibers are being put into place is paramount.

Moreover, the fibers can be subjected to various materials, environmental conditions, and physical constraints that would further induce fiber degradation and failure.

Signs of various failures

How to determine that a fiber is about to fail, and by what mode. For example, water ingress on the coupling reduces the return loss. A signal enhancement is noticed initially.

Mostly, the failures are mechanical, such that they would be induced in or outside of a reactor environment.

Signal interference

Due to the inherent flexibility in the fiber optics, users of the measurement system will most generally attempt to apply the fiber optics in unusual geometries, most generally to reach locations that vintage measurement system would not reach.

Since light generally travels un-impeded in the fibers, users might become complacent in the geometry of which the fiber measurement system is placed.

Therefore, quantification of various degree of bending should be done. When fiber optics are bent, there may be some light loss due to the impinging photon on the surface overcoming the index of refraction.

To conduct these tests, it is suggested that three phases of testing are done.

- First, the fiber would be calibrated normally and put into a relatively "straight" geometry. Then a series of measurements are taken with the fiber bent, as not to enforce curvature changes in the fiber itself, as various point along the measurement path. The resulting changes in the measurements will be noted. This will be repeated for various degrees in the curvature.
- Second, the fiber should be put into highly curved geometries, then calibrated. After straightening out the fiber optic, then measurements are taken. This is to ensure that the calibration point does not impede the measurement accuracy.
- The third phase would be to determine the number of bends, at various degrees that would begin to vary the measurements at the end of a very long fiber.

Bending in the fiber can be read as strain, which can be incorrectly interpreted as temperature difference. If I understand correctly, the fiber calibration should be performed with the fiber in the correct configuration for the final application – e.g. if there will be bends, then we need to calibrate with those bends.

Calibration after installation will be required at standard ambient temperature to provide a baseline for subsequent measurements at elevated temperature.

The suggestion to perform some benchtop testing to determine hysteresis-type effects is good – basically run some tests on straight fiber, curve it to simulate bending that could occur during installation, then straighten it again and repeat the original tests to ensure that the measurements have not changed (within measurement error).

Effects of vibrations

Due to the high velocity of Helium in the VHTR, vibrational effects will be fairly noticeable. The testing of vibrational effects on the measurement integrity and fiber integrity should be completed.

Testing can be conducted through mechanical means; for instance, with a pump or other device attached to the measurement device or measurement location, or through venturi in a flow field (generally used for pressure drop, but can induce eddy controlled eddies).

This can be used to replicate the expected flow oscillations in the VHTR during operating conditions.

Fluence induced measurement error

Naturally, in a reactor environment, the fission rate density (prompt and delay/fission product contributions) imposes the highest contribution to the gamma and neutron fluence; therefore, the effects of activation products can be ignored, such as nitrogen-16 production.

However, shutdown conditions tell another story - though the fluence rate will be significantly smaller.

Inherently, though, over time the measurements will begin to drift. This drifting will need to be quantified and incorporated in the calibration to imposed proper operation and accurate measurement. Since no other distributive system is available, either passive systems, like iron wire or Cd/Au foil analysis, or active systems will need to be used for validation purposes.

There currently are 3mm diameter fission chambers that may be used. They cost \$18,000 for 10. These would provide excellent feedback as to the fiber performance.

Temperature effects on gamma/neutron measurements

There might be some alteration in the gamma/neutron measurement as a function of the temperature of the fiber optic. This is inherent to the cross-section of neutrons in a material changing as a result of the nuclei vibrations.

The composition and functionality of these fibers, however, is unknown - so the testing will be done pretty much as a shot in the dark.

Conducting these kinds of tests will be through the use of manually varying furnace temperature. Simply changing the temperature should not change the gamma or neutron

fluence, so, in this regard, we can understand the temperature related effects of the neutron/gamma interactions.

Operational temperature ranges

The upper temperature limit of the fiber optic systems would be important to determine. This would help determine the instrumentation strategy.

Moreover, during severe accidents, it would be important to know that the fiber measurements would not lose their validity if the temperature were to rise significantly.

The furnace can be removed from the reactor to do this test. The temperature limit is set to prevent the total heat storage in the furnace to cause a steam rupture and to prevent creep in the high pressure aluminum structure.

A short test would not be cause for any concern.

Chemical attack reference times

As stated by Luna, water and other alkalis attack the fiber optic and eventually render it useless. Determining, under various temperature conditions, the length of time these fibers are expect to last would be imperative to a safety analysis of their implementation.

For example, water ingress in HTRs that use water-secondary systems would possibly cause degradation very quickly at the expected 488C inlet temperature conditions if the encapsulation were impaired.

Time response

Testing the speed at which data can be reliably obtained is fairly important. Whether transient conditions, albeit slow, can be accurately measured could lead to further validation techniques.

It is our understanding that this may not be possible with a single OBR, but having multiple OBRs to measure at a given periodicity would, perhaps, suffice. This would not be do-able for the current project.

An additional requirement is that the fiber optic reaches equilibrium quickly. Temperature, gamma, and neutron response should be quick to allow for a "snap shot" to be captured. The OBR does its measurement very quickly; however, computation and display of the data is fairly lengthy. The OBR will not be an issue in this. It was determined that the return-to-normal time for the temperature fiber exceeded 15 minutes when the fiber was removed from a cold source.

Spatial Resolution

When producing measurement data for code validation and determining hotspot information, the spatial resolution of the fiber optic is very important. This is the primary capability of the fiber optic, so it is very important to have this feature documented.

Due to the nature of the Raleigh scattering, the phenomena of spatial discretization is actually continuous. Interpreting how to define the spatial resolution then, might be a bit

tricky. According to the OBR manual general resolution is +/- 10um over 30 m, the sensing resolution is +/- 2cm. There is also a "data segment size" of 1.0 mm.

The testing of the spatial properties will be fairly straight forward, except in the case of the neutron fibers. Temperature distributions are easily produced and manipulated. With the proper measurements of the fiber and by applying various gradients, the spatial resolution can be determined.

For the gamma fibers, shielding will need to be used in conjunction with high activity sources. Using the La source against the dry cell may be an option. With the neutron fiber, simply using the core is our only option. There may be some opportunities to use paraffin or cadmium to force spatial changes. Even more so, determining thermal to fast fluence ratios might be possible.

Calibration requirements

This is more important for the temperature fiber; ideally the furnace will not be shutdown - just put into a low power state to prevent unnecessary thermal transients in the furnace. The fiber may, with time, drift due to radiation induced re-structuring in the fiber. This will change the strain parameters, surely, and therefore change the temperature measurement as a result.

The proposed testing would be simply to add fibers during various intervals of the irradiation period. This would introduce fresh, calibrated fibers to compare with the already irradiated fiber optics. Since this would require a complete shutdown of the furnace, the choice of re-calibrating the irradiated fibers will need to be made.

The choice to do this would allow for a new baseline to be established. Additionally, the fibers can be compared at the cold iron condition. Conversely, not allowing for re-calibration allows for comparison at operating temperatures and preserves a fluence history of the calibration of the fibers. This will also introduce a determination of the integrity of an initial calibration over the fiber life-time.

10.3. VHTR Control Rod Modeling

10.3.1. Design Details

The design for the control rods was taken from the General Atomics design for the MHTGR.[1,2] The control rods are modeled as an annular graphite matrix containing 40 wt% B₄C particles. The control rods are clad with Incoloy-800. The particles properties are given in Table 1.

Table 1 Properties of the B₄C Pellets in VHTR Control Rods

Boron composition	90% B-10, 10% B-11
B ₄ C kernel radius	100 μm
Graphite buffer coating thickness	18 μm
PyC coating thickness	23 μm

Figure 1 provides the VHTR control rod geometry details as modelled in the present evaluations.

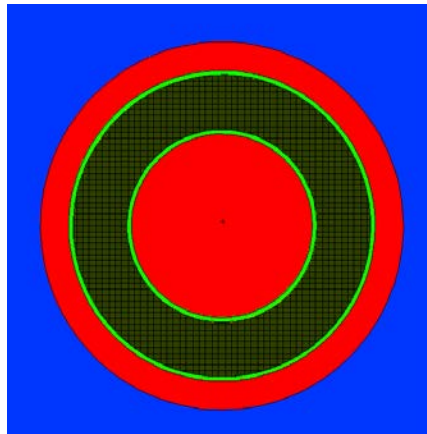


Fig. 1. XY view of the VHTR control rod geometry. The red material is He inside the control rod channel. The blue shows the graphite block material.

The B₄C kernels used in the burnable poison compacts were the same as those in Table 1 except natural boron was used. Determination of the optimal burnable poison loading in the core for a given reloading scheme is a sizable project in and of itself and, as such, it was left outside the scope of the present analysis. This project has considered nominal loadings necessary to yield critical configurations. B₄C particle packing fractions around 3% were found to be sufficient.

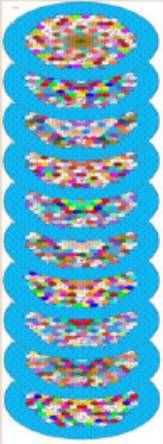
10.3.2. References

1. Wright, J.K., Lloyd, W.R. Analysis of Potential Materials for the Control Rod Sleeves of the Next Generation Nuclear Plant. INL/EXT-06-11614 (2006).
2. "Preliminary Prismatic Coupled Neutronics Thermal Fluids Benchmark of the MHTGR-350 MW Core Design", Draft (December 2010), Idaho National Laboratory (2010).

10.4. Presentations

10.4.1. 3D High-Fidelity VHTR Modeling for Performance Optimization

TEXAS A&M★ENGINEERING



3D High-Fidelity VHTR Modeling for Performance Optimization Simulations: Monitoring and Operation

Matthew Johnson, Tom G. Lewis III,
Pavel Tsvetkov
Department of Nuclear Engineering
Texas A&M University

Tuesday, June 28, 2011
Research by U.S. DOE NEUP-Sponsored Students
2011 ANS Annual Meeting

TEXAS A&M★ENGINEERING

A Distributed Fiber Optic Sensor Network for Online 3D Temperature and Neutron Fluence Mapping in a VHTR Environment
Texas A&M University, Luna Innovations, General Atomics, INL

The 3-year project will provide three key deliverables:

1. produce a highly distributed fiber optic network capable of 3D temperature and neutron fluence mapping in the VHTR environment;
2. demonstrate reliability and performance of the proposed sensor network; and
3. provide a computational model to evaluate expected sensor performance and lifetime in VHTR environments, to scale experimental results to VHTR conditions, to optimize sensor network, and to assess VHTR performance taking advantage of the 3D fiber-optics imaging and performance reconstruction.

TEXAS A&M★ENGINEERING

3D High-Fidelity VHTR Modeling Objectives

- Predict core behavior
- Develop methodologies for 3D flux (and power density) reconstruction
- Predict hotspots and off normal conditions with a limited amount of sensors
- Reconstruction will rely on knowledge of the expected core behavior, hence the current focus on high fidelity modeling

TEXAS A&M★ENGINEERING

Benefits

- Predictive evaluation of potential failure modes for in-core components
- Hot spot management assistance
- Determine the fluence in reflector blocks, especially the replaceable inner reflector
- Assistance in determining lifecycle limits and longevity of in-core components

TEXAS A&M ENGINEERING

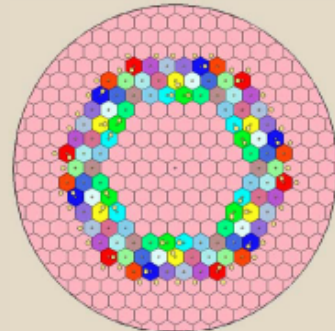
Methodology

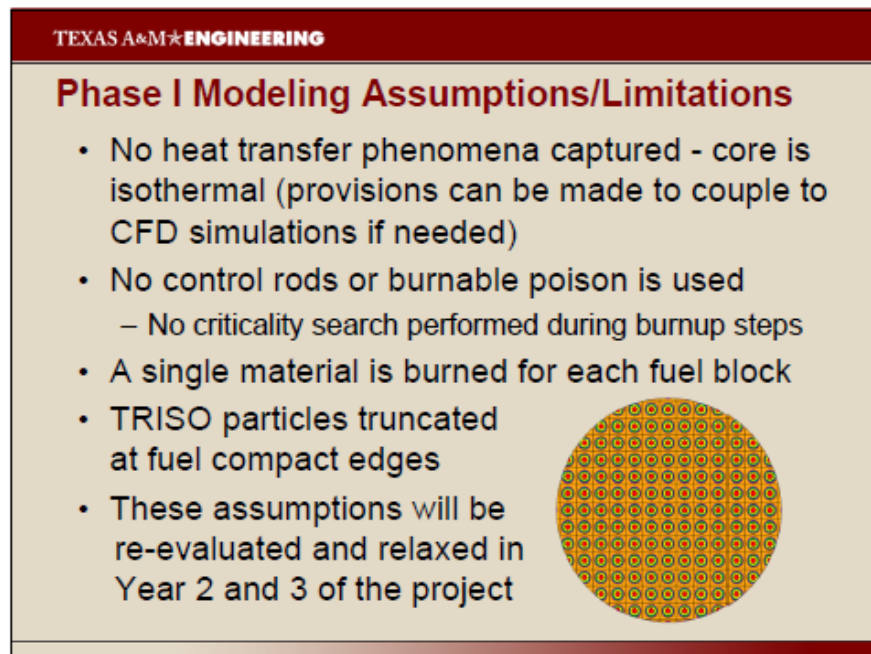
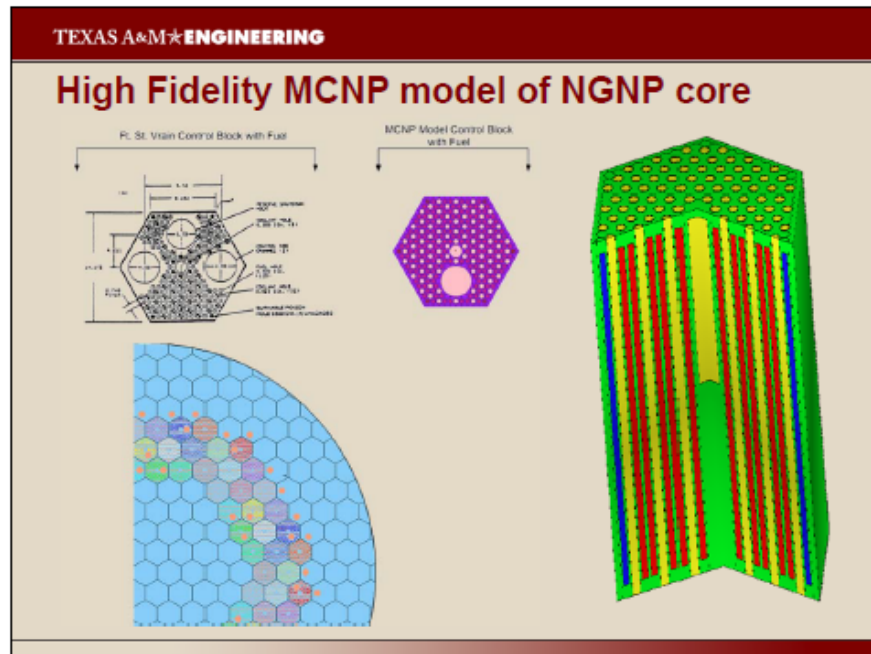
- Using well tested codes:
 - Current analysis is done in mcnp 2.6.0 and its built-in coupling to CINDER90
 - Monte Carlo methods are robust for VHTR modeling and reduce challenges associated with geometry and cross sections processing for advanced systems.
 - Pre-processing is automated via scripting. Input files are generated with a Python script, which makes the input easier to manipulate and understand

TEXAS A&M ENGINEERING

High Fidelity MCNP model of NGNP core

- Full core is modeled with 1/6 periodic symmetry in materials. The symmetry in materials is used to reduce the number of burnable regions and therefore memory requirements during fuel depletion runs. The full core is still modeled so, for non-burnup runs, the effects of an uneven control rod insertion can be modeled.
- Detectors are modeled using cell flux tallies. This allows for fluxes to be tallied for each unique fuel block. TMESHes are used to visualize the fundamental mode flux distributions

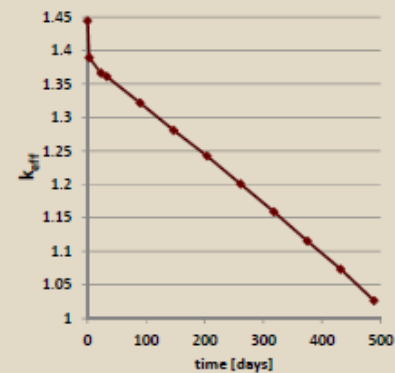




TEXAS A&M ENGINEERING

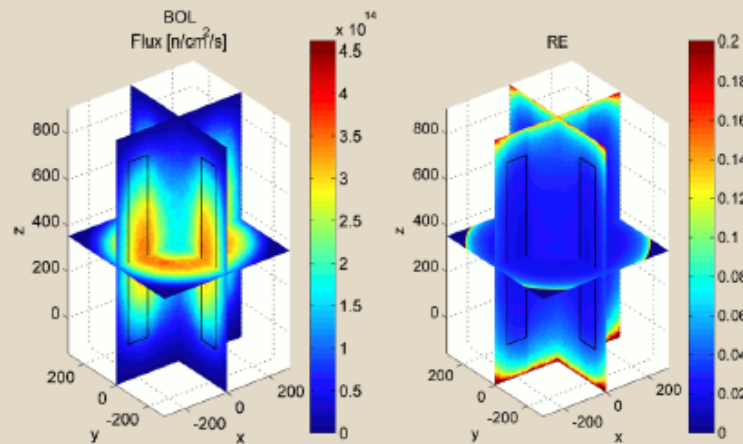
Core lifetime

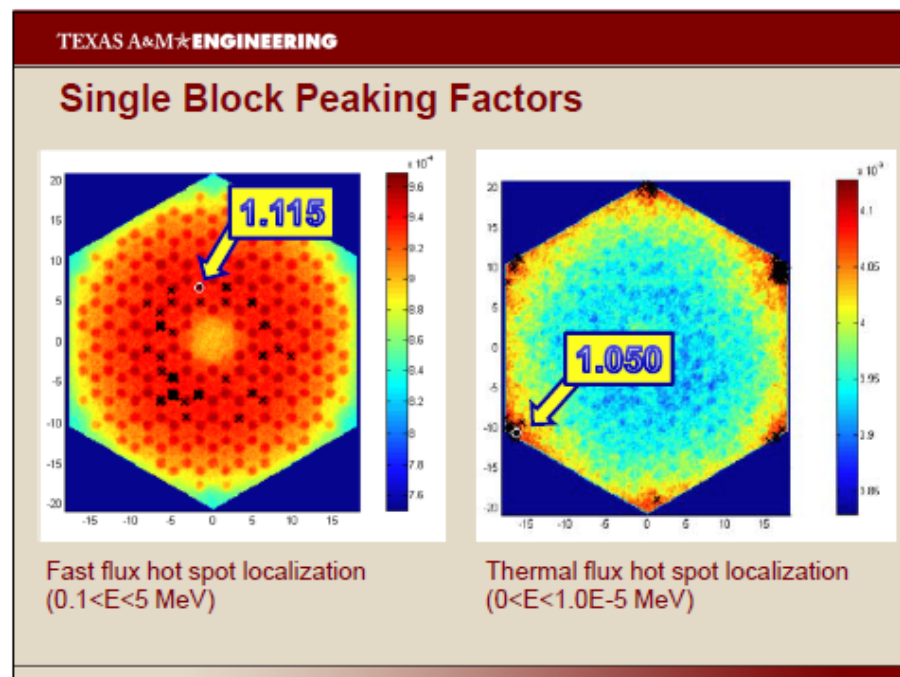
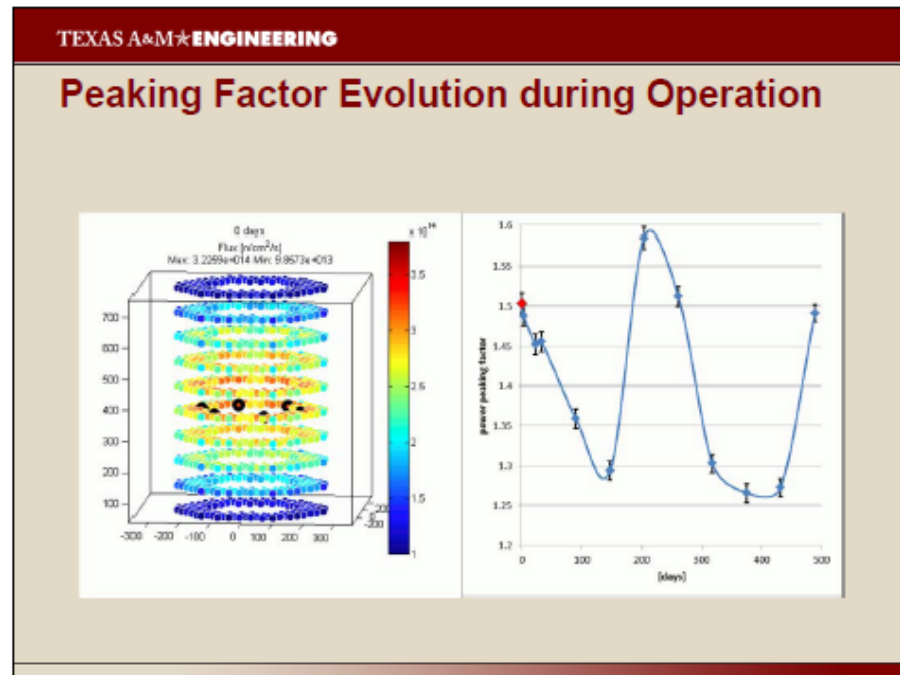
- k_{eff} results for a representative 3-ring 600 MWth core
 - 15% enriched Uranium fuel
 - 25 vol% packing fraction of TRISO in fuel compacts
 - Kernel radius of 150 μm
- Core lifetime of ~17 months



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Hot Spot Migration and Localization with the Core





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Time stepping during burnup runs representing reactor operation conditions

- Acknowledged as a source of error, especially given the sometimes abrupt changes in hot spot locations
- Currently computational resources restrict fidelity of kcode intermediate calculations
- Possible solutions: alternative codes (Serpent, MCNP5 + Monteburns or MOCUP); access to faster computational clusters (ex. INL HPC)

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Graphite Fast Fluence in Estimation

- Compared against the GA report
- Fast fluence is defined for $E > 0.1$ MeV

16.3 Month Fast Fluence [n/cm ²]	
min	6.31E+20
max	1.77E+21
mean	1.30E+21

Max 36 Month Fast Fluence [n/cm ²]	
16 month extrapolated	GA report
3.90E+21	1.7E+21

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Conclusions

- 3D high-fidelity modeling approach is being developed for applications in performance simulations studies targeting monitoring and operational aspects of VHTRs.
- The modeling approach allows for development and applications of in-core 3D performance map reconstruction techniques accounting for novel direct 3D in-core measurement approaches for extreme environments of HTRs.
- Presented sample results showed 3D mapping capabilities of performance characteristics.
- The simulation methodology and reconstruction techniques are being developed for sensor array optimization studies targeting in-core 3D monitoring options.

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Conclusions

Key milestones:

- Development of theoretical approach to estimating neutron fluence distributed along the length of the sensing fiber.
- Test furnace engineering design with reactor safety board approval.
- Fiber optic sensor design and completion of out-of-core laboratory testing.
- Test furnace fabrication, assembly and completion of out-of-core testing.
- Delivery of sensor strings with connectors to university; installation in test furnace.
- Assembly installation in TRIGA and completion of irradiation test matrix.
- 3D VHTR and TRIGA modeling with representation of distributed sensor network elements, performance reconstruction and optimization of the network design.
- Modeling validation using test measurements and scaling to the prototypical VHTR conditions.

10.4.2. Distributed Sensor Networks for Online 3D In-Core Monitoring





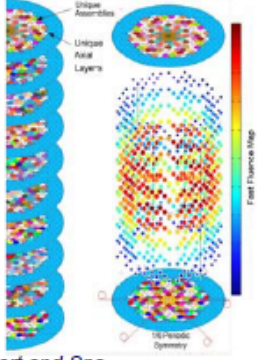
Distributed Sensor Networks for Online 3D In-Core Monitoring in VHTR Environments

**Pavel V. Tsvetkov, Shannon M. Bragg-Sitton
Jesse M. Johns, Tom G. Lewis, Ayodeji B. Alajo,
Matthew P. Johnson**

**Department of Nuclear Engineering
Texas A&M University**

Advances in Small and Medium Sized Reactor Designs

Wednesday, June 29, 2011, ANS 2011 Annual Meeting
June 26-30, 2011, Hollywood, FL, The Westin Diplomat Resort and Spa



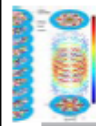






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TEXAS A&M



Distributed Sensor Networks for Online 3D In-Core Monitoring in VHTR Environments

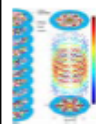
- Overview
- High-Fidelity Modeling Approach
- Emulation of VHTR Conditions in TRIGA
- Validation Efforts
- Current Status
- Conclusions



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Distributed Sensor Networks for Online 3D In-Core Monitoring in VHTR Environments

Overview

Small and Medium Sized Advanced Reactors Safety, Reliability, Autonomy, Economics, ...

- Robust in-core measurement systems capable to provide characteristic operational information
- Longevity of sensor performance
- Real time operation
- Ability to predict hot spot formation conditions



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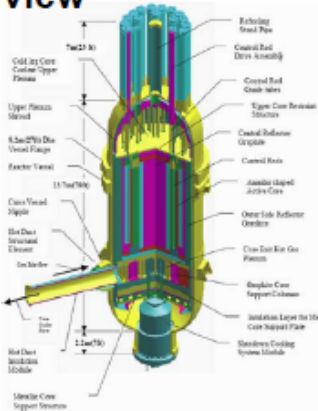


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Distributed Sensor Networks for Online 3D In-Core Monitoring in VHTR Environments

Overview



- **In-core monitoring challenge** – reliable long-term operation in extreme high-temperature high-fluence environments
- **Use of fiber optic sensors** – direct in-core 3D monitoring for in-core management (loading, hot spots, temperature and fluence maps)

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Distributed Sensor Networks for Online 3D In-Core Monitoring in VHTR Environments

Overview

Collaboration of University, Nat. Lab., Industry
Texas A&M University, Project Lead
 Luna Innovations, Primary Industry Partner
 General Atomics, Advisor
 Idaho National Laboratory, Advisor

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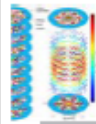


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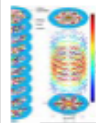


Distributed Sensor Networks for Online 3D In-Core Monitoring in VHTR Environments

- Overview**
- **Goal:** Real-time mapping of the temperature and neutron fluence distribution in proposed NGNP / VHTR cores
 - **Challenges:**
 - Harsh environment (750° C to 950° C coolant outlet)
 - Long refueling cycle (~18 months) – high radiation
 - **Benefits of Proposed Sensors:**
 - Real-time assessment of reactor performance
 - Sensor network can be placed throughout the reactor core (axial and transverse dimensions)
 - Benchmarks for simulation and analysis codes used in core design and modeling
 - Optimization of design margins
 - Reduced uncertainty in local phenomena assessment / prediction
→ reduced safety margins in design



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Distributed Sensor Networks for Online 3D In-Core Monitoring in VHTR Environments

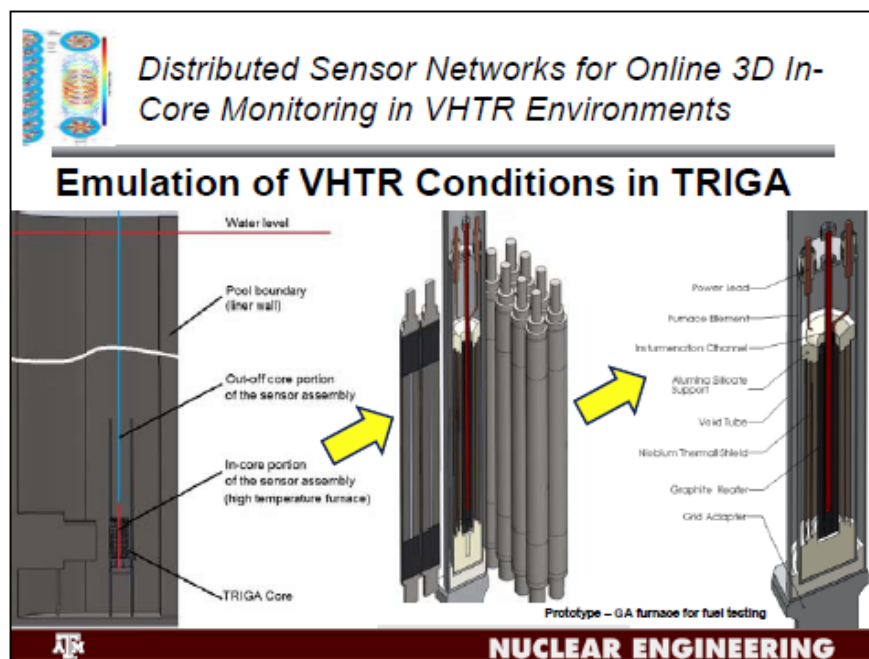
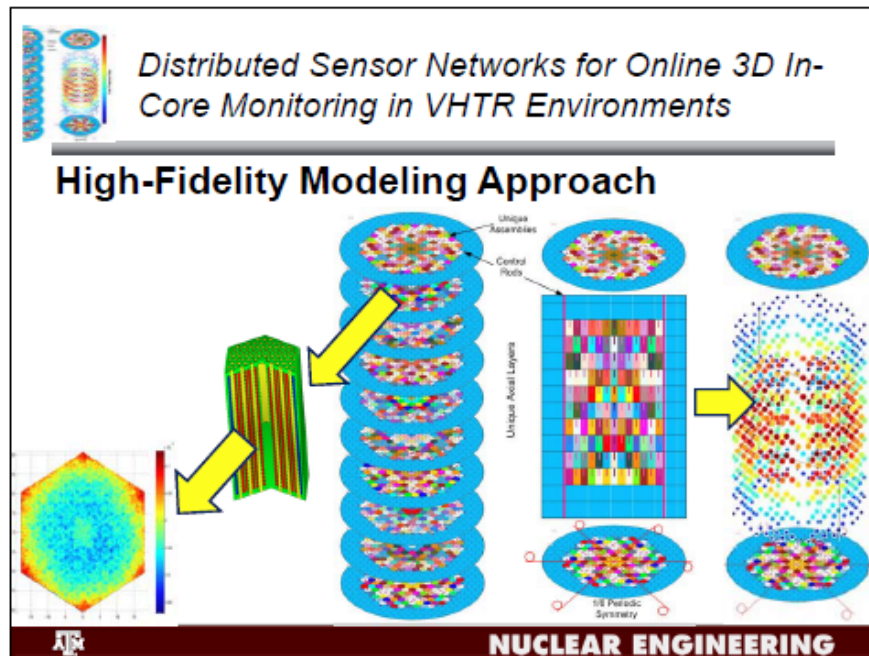
Overview

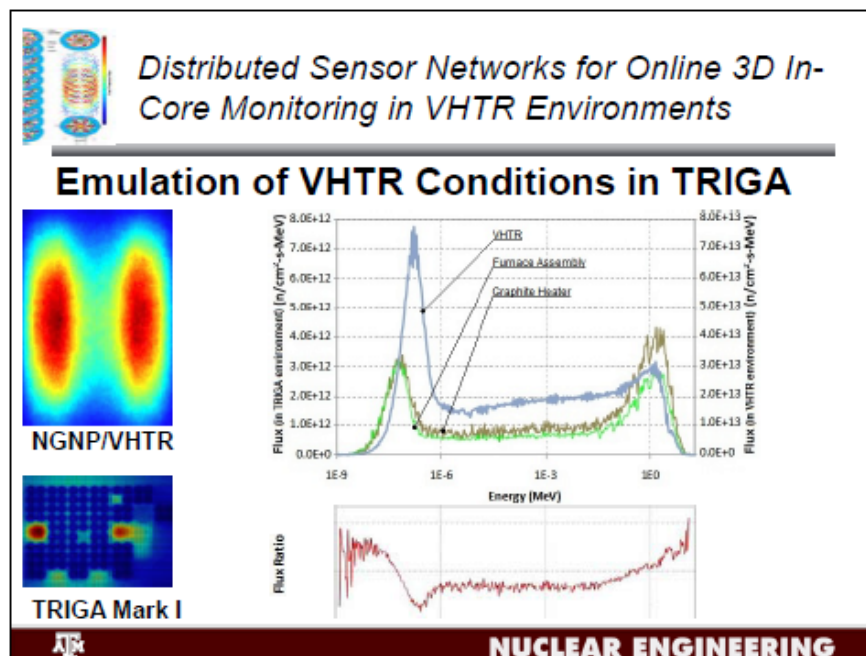
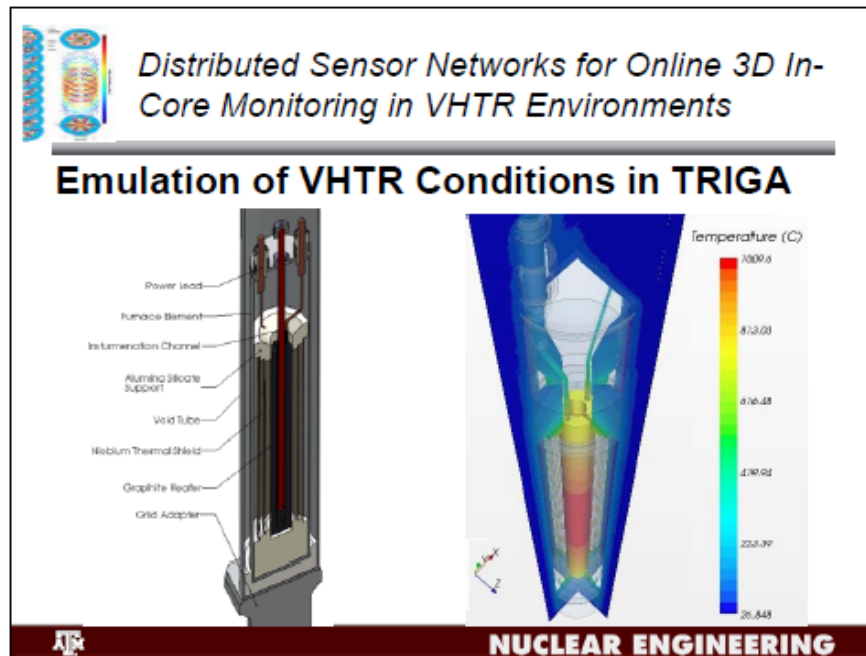
The 3-year project will provide three key deliverables:

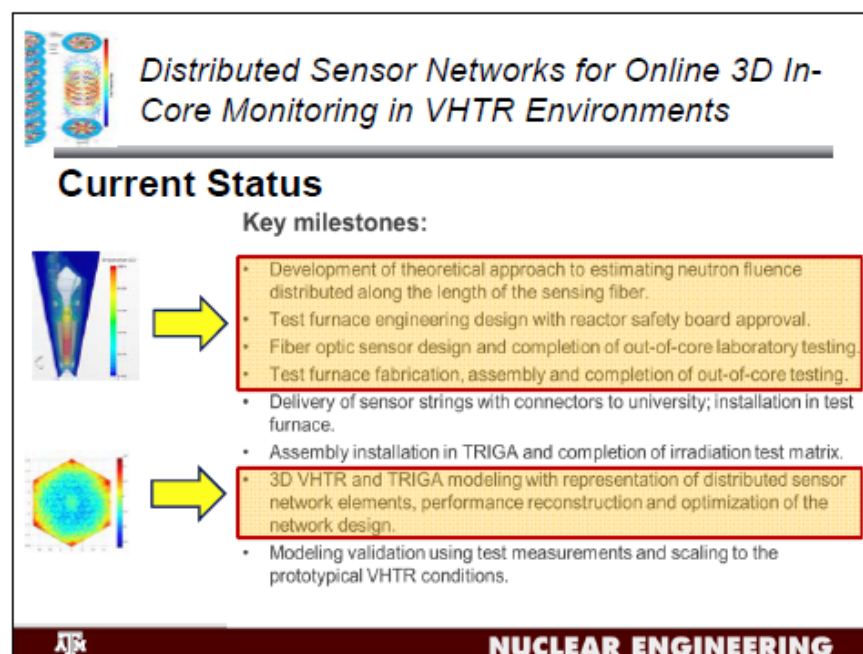
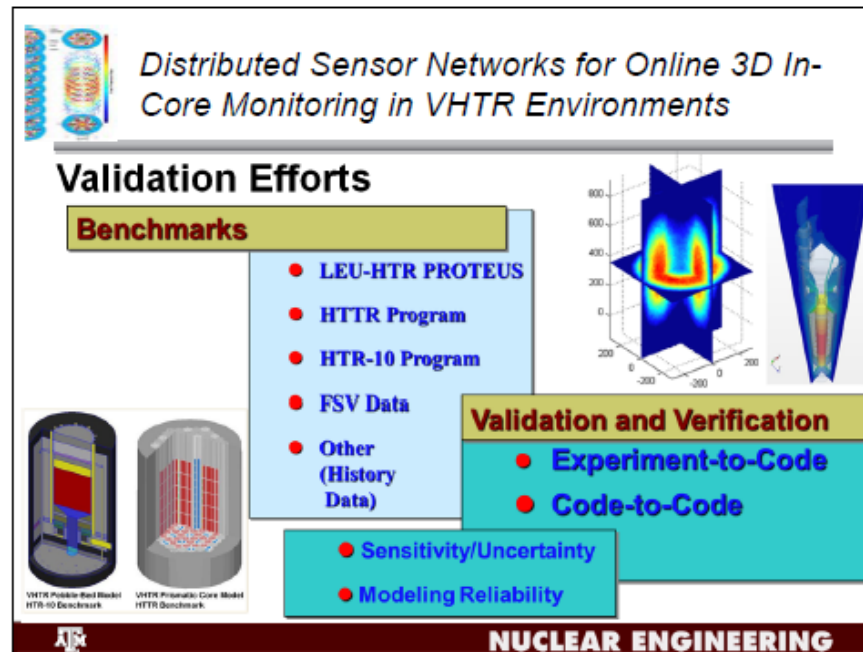
1. produce a highly distributed fiber optic network capable of 3D temperature and neutron fluence mapping in the VHTR environment;
2. demonstrate reliability and performance of the proposed sensor network; and
3. provide a computational model to evaluate expected sensor performance and lifetime in VHTR environments, to scale experimental results to VHTR conditions, to optimize sensor network, and to assess VHTR performance taking advantage of the 3D fiber-optics imaging and performance reconstruction.

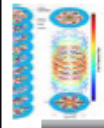


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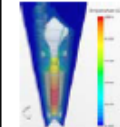
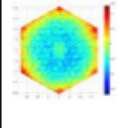


Distributed Sensor Networks for Online 3D In-Core Monitoring in VHTR Environments

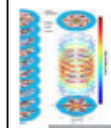
Current Status

Key milestones:

- Development of theoretical approach to estimating neutron fluence distributed along the length of the sensing fiber.
- Test furnace engineering design with reactor safety board approval.
- Fiber optic sensor design and completion of out-of-core laboratory testing.
- Test furnace fabrication, assembly and completion of out-of-core testing.
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- 3D VHTR and TRIGA modeling with representation of distributed sensor network elements, performance reconstruction and optimization of the network design.
- Modeling validation using test measurements and scaling to the prototypical VHTR conditions.

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Distributed Sensor Networks for Online 3D In-Core Monitoring in VHTR Environments

Conclusions

Year 1 results indicate that the furnace should be capable of emulating VHTRs

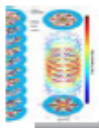
The HT furnace is suitable for providing initial performance evaluations of the candidate in-core sensors in VHTRs

It has been demonstrated computationally that the developed design can attain the 1000oC-levels at the sensor location without causing an increase in temperature levels outside of the furnace

The next phase will be irradiation testing of the fiber optic sensors in the TRIGA and evaluations of the data in relation to the VHTR conditions.

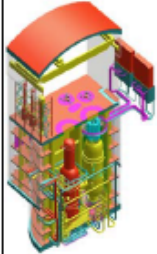
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Distributed Sensor Networks for Online 3D In-Core Monitoring in VHTR Environments

Acknowledgements



This paper is based upon work supported by the U.S. Department of Energy Nuclear Energy University Program Award Number 09-241.





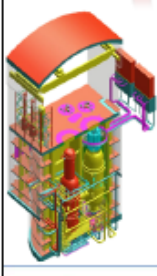
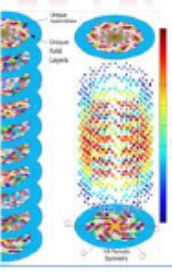
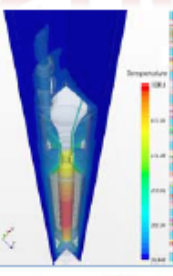
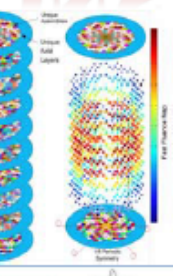


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Distributed Sensor Networks for Online 3D In-Core Monitoring in VHTR Environments

QUESTIONS?








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10.4.3. Emulation of VHTR Operating Conditions in TRIGA Reactors



Emulation of VHTR Operating Conditions in TRIGA Reactors



Jesse Johns, Mathew Johnson, Ayodeji Alajo,
Pavel Tsvetkov, Shannon Bragg-Sitton,
Department of Nuclear Engineering
Texas A&M University

Tuesday, June 28, 2011

Research by U.S. DOE NEUP-Sponsored Students
2011 ANS Annual Meeting

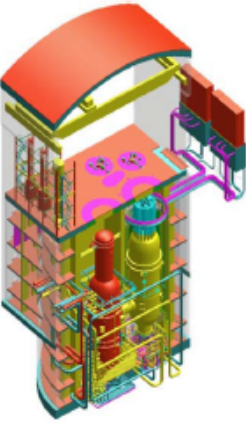








Introduction



- **In-core monitoring challenge** – reliable long-term operation in extreme high-temperature high-fluence environments
- **Use of fiber optic sensors** – direct in-core 3D monitoring for in-core management (loading, hot spots, temperature and fluence maps)









Introduction

A Distributed Fiber Optic Sensor Network for Online 3D Temperature and Neutron Fluence Mapping in a VHTR Environment

Texas A&M University, Project Lead

Luna Innovations, Primary Industry Partner

Advisors:

General Atomics

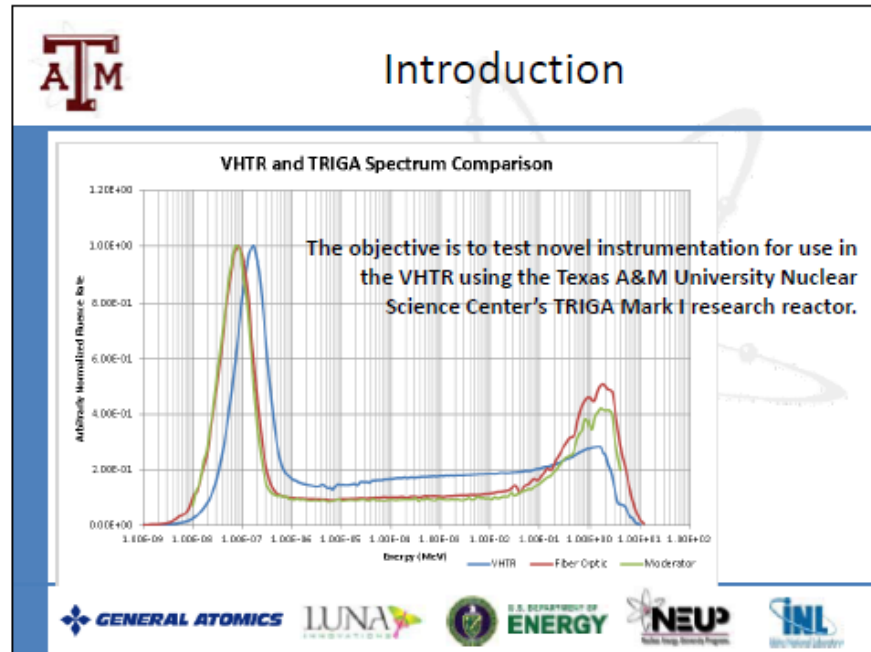
Idaho National Laboratory



Introduction

- **Goal:** Real-time mapping of the temperature and neutron fluence distribution in proposed NGNP / VHTR cores
- **Challenges:**
 - Harsh environment (750° C to 950° C coolant outlet)
 - Long refueling cycle (~18 months) – high radiation
- **Benefits of Proposed Sensors:**
 - Real-time assessment of reactor performance
 - Sensor network can be placed throughout the reactor core (axial and transverse dimensions)
 - Benchmarks for simulation and analysis codes used in core design and modeling
 - Optimization of design margins
 - Reduced uncertainty in local phenomena assessment / prediction
→ reduced safety margins in design





Introduction

The 3-year project will provide three key deliverables:

1. produce a highly distributed fiber optic network capable of 3D temperature and neutron fluence mapping in the VHTR environment;
2. demonstrate reliability and performance of the proposed sensor network; and
3. provide a computational model to evaluate expected sensor performance and lifetime in VHTR environments, to scale experimental results to VHTR conditions, to optimize sensor network, and to assess VHTR performance taking advantage of the 3D fiber-optics imaging and performance reconstruction.

Logos: GENERAL ATOMICS, LUNA, U.S. DEPARTMENT OF ENERGY, NEUP, INL

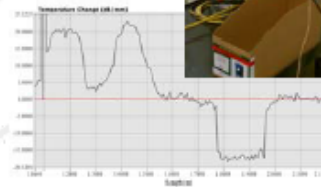


Distributed Sensing

Fiber optic sensors promise to provide detailed distributed measurements.

- Online hot spots determination and flux mapping
- Continuous code validation becomes possible

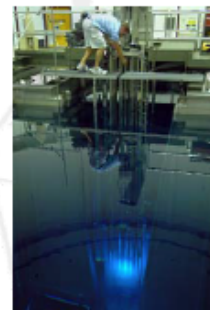
Test fibers in the operating conditions that would be expected in the VHTR.



Challenges

The TRIGA reactor sits in a pool of light water open to the atmosphere.

- Thermal flux ~ peak at .09 eV
- Low temperatures
 - Fuel ~ 390°C
 - Coolant ~ 26°C
- Low fluence rate ~ 4e12 n/cm²/s
- Safety and experimental limitations
 - Temperature, thermal storage, size, reactivity





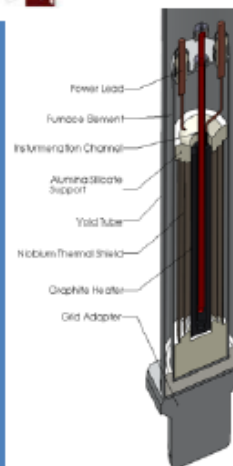
Experimental Design

Design an experimental apparatus to emulate the conditions of a VHTR in a TRIGA reactor for advanced instrumentation testing.

- Operate at +1000°C
- Sustained operation for 1 year, to a neutron fluence of $2e19 \text{ n/cm}^2$
- Accessibility for fiber optics and instrumentation replacement
- Conform to 10 CFR 50.59
 - Required safety criteria for experimental authorization
- Passive cooling – heater in vacuum



Experimental Design



- Extended from an earlier furnace design from the 70's designed by General Atomics for use in the TRIGA Mark I
 - KING TRIGA designed originally to test fuels – Too small for our purposes
 - Required forced cooling and located in a fuel position

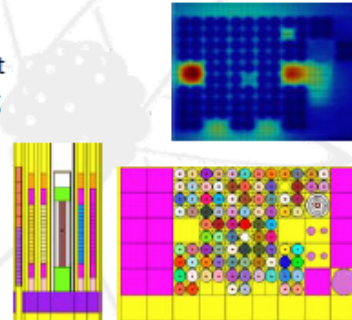




Modeling - Neutronics

MCNP5/X 2.6 was used for simulating the TRIGA reactor and simplified furnace model.

- The model includes the latest cross-section data, scattering kernels, and temperature induced broadening.
- Temperature data from NSC-written and validated sub-channel code



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Modeling - Neutronics

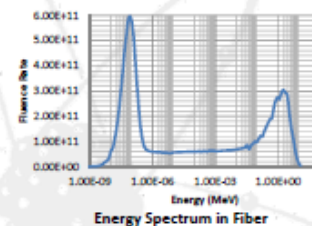
Verification & Validation

MCNP model was scaled to matched Au/Cd flux foils data from the D3 core location.

- Nominal scaling was high by ~5.5%
- Fast (epithermal) to thermal flux ratios were comparable to 13.1%

Absolute fiber optic irradiation time expected to be roughly 230 days.

Used BOL fuel concentrations. BURN was not suitable due to memory requirements. MCNPX 2.7 will allow for MPI runs.



Core	Location	Flux (neutrons/cm²-s)	Flux (neutrons/cm²-s)	Flux (neutrons/cm²-s)	Flux (neutrons/cm²-s)	Flux (neutrons/cm²-s)	Flux (neutrons/cm²-s)	Flux (neutrons/cm²-s)	Flux (neutrons/cm²-s)
1	100	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10
2	100	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10
3	100	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10
4	100	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10
5	100	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10
6	100	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10
7	100	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10
8	100	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10
9	100	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10
10	100	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10	1.79E+10



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Modeling – Heat Transfer

Started with 1D Matlab script to begin design iterations.

- Radiative heat transfer
- Free convection correlations
- Failure criteria
 - Steam production/stress failure
 - Safety factor of 2.75
 - 2.0 required by facility Tech Specs

Still provides maximum operating conditions for safety controllers.



Modeling – Heat Transfer

Computation continuum mechanics software package used to support analysis of fiber optics.

- STAR-CCM+ v6.02, developed by Cd-adapco

Provides extra temperature data to Matlab script for total thermal storage and allows for behavioral study of furnace operation.

Temperature limited to either:

- ~160°C on aluminum housing
- 1138°C averaged operating temperature





Modeling – Heat Transfer

Verification & Validation

Physics model verification done concurrently with furnace model development –

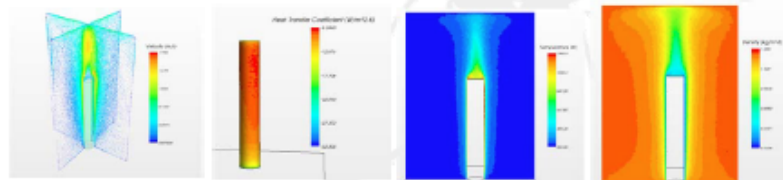
- Conduction
 - Near perfect agreement, even with poor mesh refinement – max error: 1.169% in surface heat flux
- Forced convection (incomplete)
- Radiation
 - Near perfect agreement, even with poor mesh refinement – max error: 0.79% in surface heat flux



Modeling – Heat Transfer

Verification & Validation

- Natural convection (incomplete)
 - Fair agreement with generalized empirical relationships
>20% error on local heat transfer coefficients depending on model and mesh refinement
 - V2F non-linear and k- ϵ RAS turbulence models





Modeling – Heat Transfer

Verification & Validation

Validation modeling to proceed as procurement process continues, providing validation of fiber optic sensing and STAR-CCM+/Matlab calculations



- Graphite heater in vacuum chamber
- Instrumented with k-type TCs with Nextel coating
- LabView PID controller to interface with power supply and safety systems



Modeling – Heat Transfer

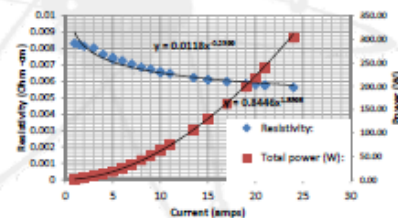
Verification & Validation

Experiments provide better material information

- Resistivity as a function of power/temperature

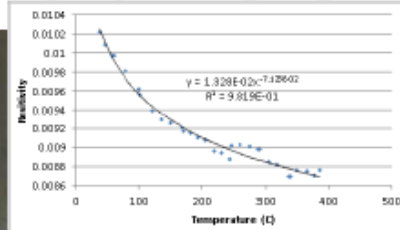
Ohmic heating is well approximated with constant volumetric heat generation.

Convection validation to wait for bench top testing of completed furnace.





Modeling – Heat Transfer Radiation Validation



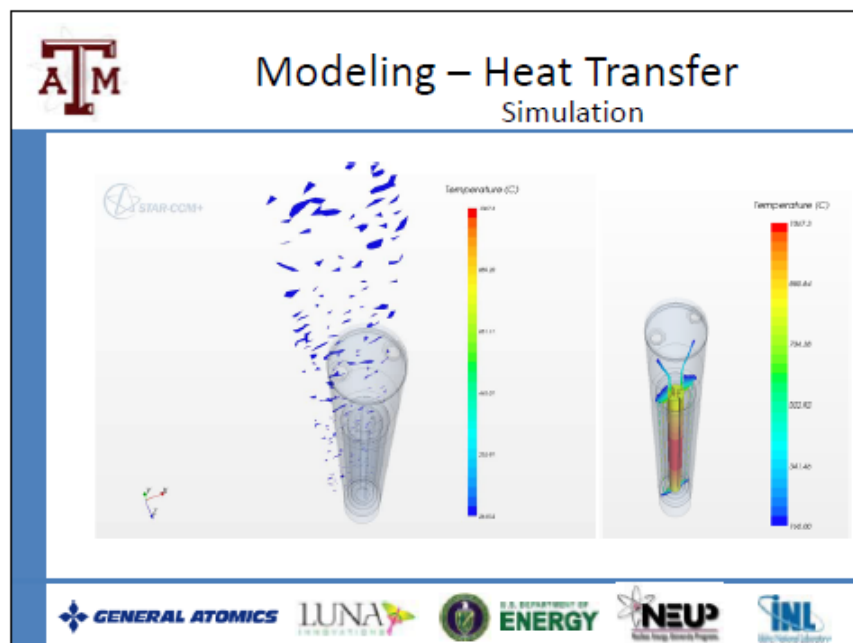
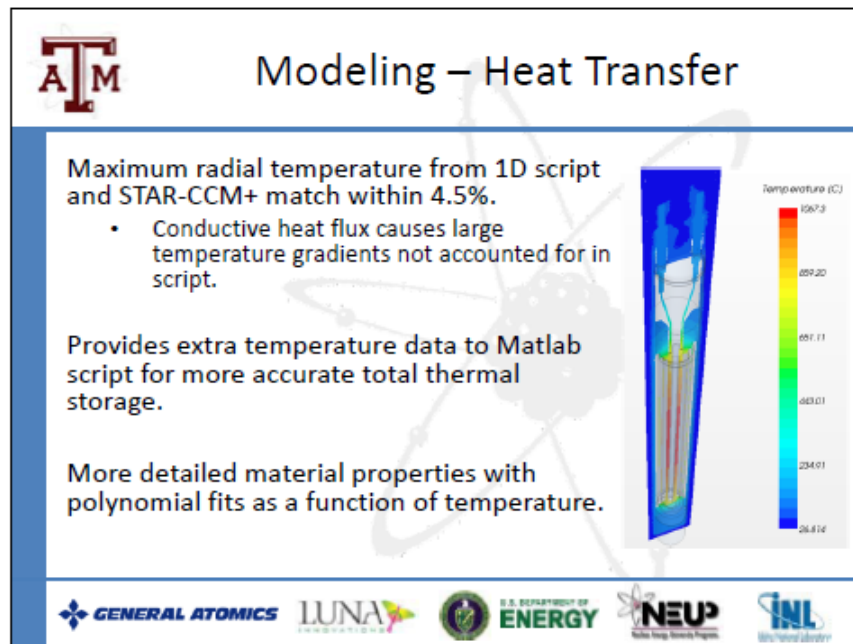
Modeling – Heat Transfer Radiation Validation

$$\rho = 1.636e-13T^4 - 3.74e-10T^3 + 3.221e-7T^2 - 1.259e-4T + 2.794e-2 \text{ [ohm/m]}$$



Constant Volumetric Heat Generation					Ohmic Heating				
Power Density [W/m³]	Surface Temp [C]	Relative Error	Heat Flux [W/m²]	Relative Error	Current [amps]	Surface Temp [C]	Relative Error	Heat Flux [W/m²]	Power Error
70366.49215	60.2	0.001961241	235.91	-0.095641894	6	60.22	0.002021356	236.13	-0.094798526
187434.555	100.02	-0.00323201	627.27	-0.097255514	10	100.47	-0.002030023	632.5	-0.089728685
519790.5759	173.02	0.003943364	1751.86	-0.090859548	17	173.46	0.004933424	1760.26	-0.086500307
1195183.246	260.54	0.026104929	4058.63	-0.08398001	26	259.68	0.024451441	4028.76	-0.090721575
1386806.283	278.99	0.031458995	4715.5	-0.082783338	28	277.42	0.02852606	4656.07	-0.094343127
1589528.796	296.71	0.036217423	5411.13	-0.081710635	30	294.68	0.032526128	5327.23	-0.095948785
1802722.513	313.76	0.041502336	6145.18	-0.080470403	32	311.48	0.037456357	6041.94	-0.095918646
2004397.906	328.61	0.043852872	6838.32	-0.079708383	34	327.84	0.041518459	6800.1	-0.084851977
2239162.304	344.62	0.046543638	7645.72	-0.078929651	36	343.81	0.045171444	7601.9	-0.084208592
2593193.717	366.65	0.051027742	8864.21	-0.077927516	39	367.08	0.051734122	8887.66	-0.075488201
2885026.178	383.26	0.056451029	9869.35	-0.077218712	41	382.2	0.071288456	9801.78	0.019600351
3321884.817	405.99	0.062829376	11374.97	-0.076311202	44	404.39	0.090458448	11262.82	0.053070318
3607748.691	419.72	0.065990746	12360.73	-0.075796032	46	418.92	0.083064355	12300.6	-0.00114669
3874607.33	431.83	0.070190552	13280.66	-0.07540413	47.5	429.72	0.081375894	13144.9	-0.017164137







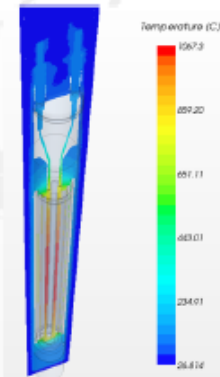
Modeling – Heat Transfer

Maximum radial temperature from 1D script and STAR-CCM+ match within 4.5%.

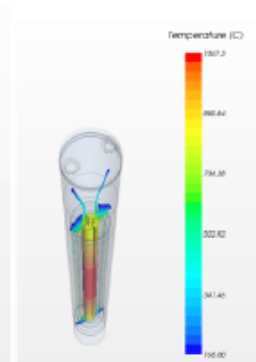
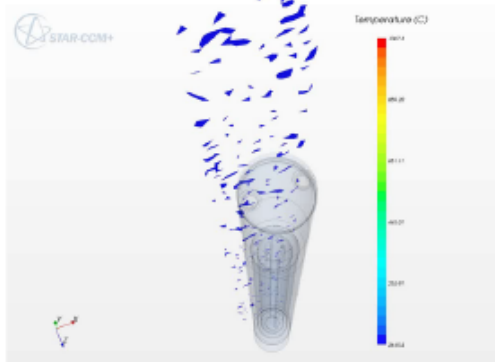
- Conductive heat flux causes large temperature gradients not accounted for in script.

Provides extra temperature data to Matlab script for more accurate total thermal storage.

More detailed material properties with polynomial fits as a function of temperature.



Modeling – Heat Transfer Simulation





Final Remarks and Conclusions

Key milestones:

- Development of theoretical approach to estimating neutron fluence distributed along the length of the sensing fiber.
- Test furnace engineering design with reactor safety board approval.
- Fiber optic sensor design and completion of out-of-core laboratory testing.
- Test furnace fabrication, assembly and completion of out-of-core testing.
- Delivery of sensor strings with connectors to university; installation in test furnace.
- Assembly installation in TRIGA and completion of irradiation test matrix.
- 3D VHTR and TRIGA modeling with representation of distributed sensor network elements, performance reconstruction and optimization of the network design.
- Modeling validation using test measurements and scaling to the prototypical VHTR conditions.



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Final Remarks and Conclusions

- Results of the high fidelity simulations indicate that the furnace assembly should be capable of emulating VHTR temperature conditions in TRIGA experiments.
- The furnace allows the sensor location to reach 1000oC-levels while being completely shielded from the TRIGA core environment.
- Successful completion of the work concludes the first phase of the project. The next phase will be to build, test, and verify prior to implementation. These efforts are in progress.



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Final Remarks and Conclusions

Confident that the safety of the NSC reactor core will not be impacted.

Temperature requirements, following bench top tests, may change.

Temperature fiber optic sensors perform, under normal conditions, as expected. Gamma and neutron fibers have not been tested yet.



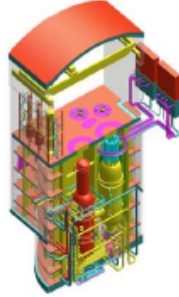
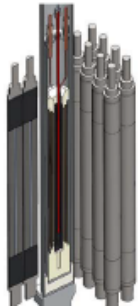
Acknowledgements

This paper is based upon work supported by the U.S. Department of Energy Nuclear Energy University Program Award Number 09-241.





Emulation of VHTR Operating Conditions in TRIGA Reactors

Questions?


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10.4.4. In-Core Testing of Distributed Fiber Optic Sensors



This project is supported by a 2009 Nuclear Energy University Programs award.



In-Core Testing of Distributed Fiber Optic Sensors

Co-PIs: Shannon Bragg-Sitton, Pavel Tsvetkov
 Graduate Students: Jesse Johns & Matt Johnson
 Texas A&M University

Joseph French and Bryan Dickerson,
 Luna Innovations, Primary Industry Partner

Project Advisors: General Atomics, Idaho National Laboratory

E-mail: sitton@tamu.edu





Project Scope



- **Goal:** Real-time mapping of the temperature, neutron fluence and gamma flux in an operating reactor. (e.g. VHTR)
- **Challenges:**
 - Harsh environment (750°C to 950°C coolant outlet)
 - Long refueling cycle (~18 months) – high radiation
- **Benefits of Proposed Sensors:**
 - Real-time assessment of reactor performance
 - Sensor network can be placed throughout the reactor core (axial and transverse dimensions)
 - Benchmarks for simulation and analysis codes used in core design and modeling
 - Optimization of design margins
 - Reduced uncertainty in local phenomena assessment / prediction
→ reduced safety margins in design

Sensor Technology



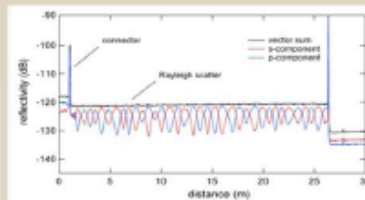
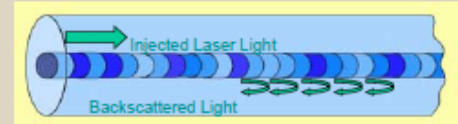
Fiber optic sensors will be used to monitor

- Total Neutron Fluence
- Gamma Flux
- Temperature

The sensor interrogation uses an Optical Backscatter Reflectometer (OBR™) system



The OBR measures the Rayleigh Backscatter of the optical fiber

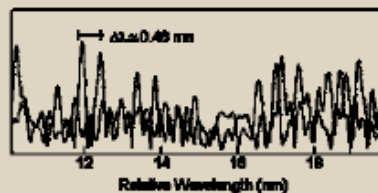


Radiation and Temperature stimuli change the Rayleigh backscatter of the optical fiber

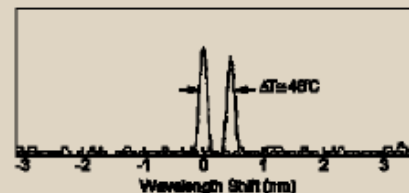
Strain, temp., etc. cause Rayleigh fingerprint to stretch – shift in the mean period between perturbations leads to a shift in optical frequency.



Fiber Temperature Performance



(a) Wavelength spectra along a 5 mm fiber interval for a heated (solid) and unheated (dotted) measurement scan.



(b) Cross correlation of the heated spectra with reference (unheated) spectrum.

Demonstration of a thermal shift of an optical fiber.

Measurement Approach



In a single scan, the *entire* fiber is recorded

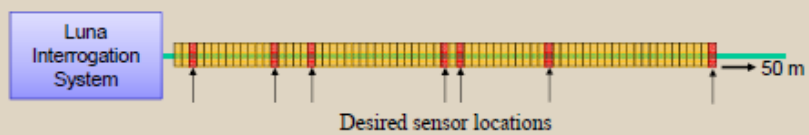


[How Strain is Measured](#)

Measurement Approach



In a single scan, the *entire* fiber is recorded



Software settings determine where along the fiber strain is reported

Measurement Approach



Software settings determine where along the fiber strain is reported

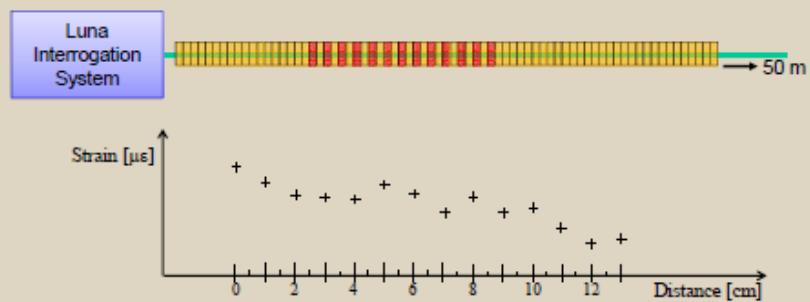


The software displays strain as a function of distance, with the option of scanning, and updating, continuously

Measurement Approach



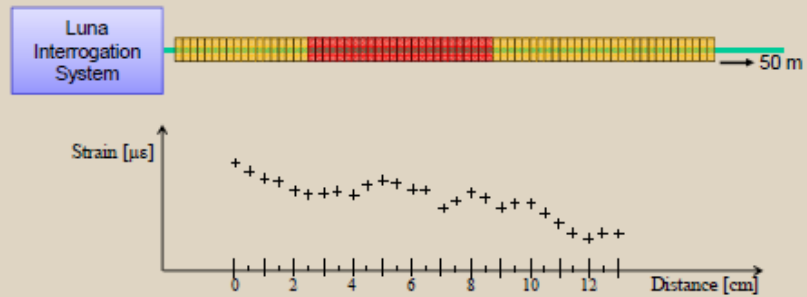
Regions of distributed sensing can be defined as well



Measurement Approach



Regions of distributed sensing can be defined as well

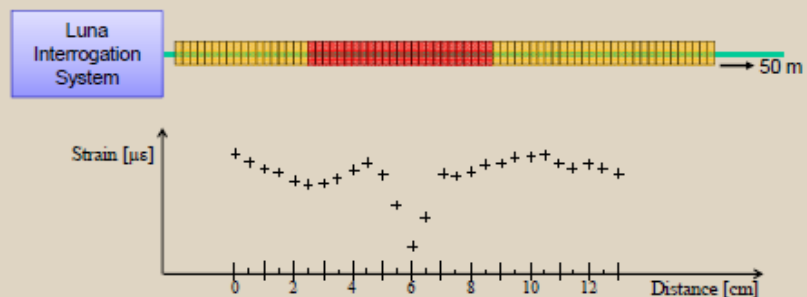


Spatial resolutions as small as 0.5 cm can be defined in software

Measurement Approach – High Definition Sensing



Regions of distributed sensing can be defined as well



Extremely useful observing how strain changes continuously over a region

Small, localized events can be observed, where larger foil gages would have averaged, and washed out the response

Measurement Approach



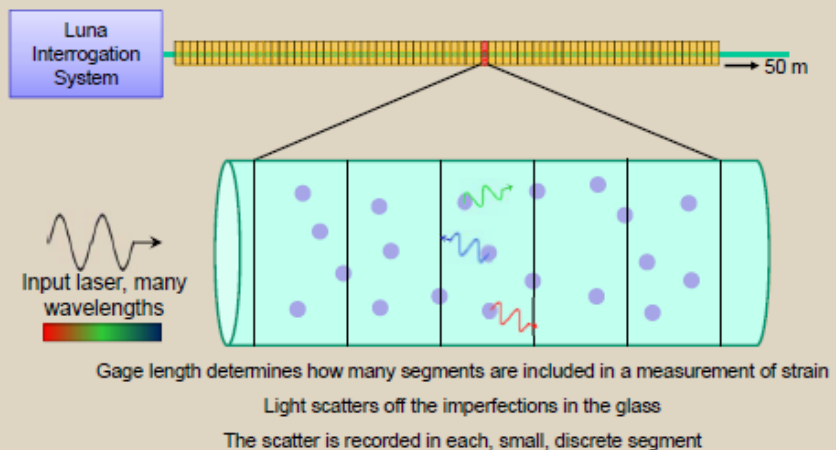
Multiple configurations can be defined for the same fiber sensor to acquire as much, or little, data as required:

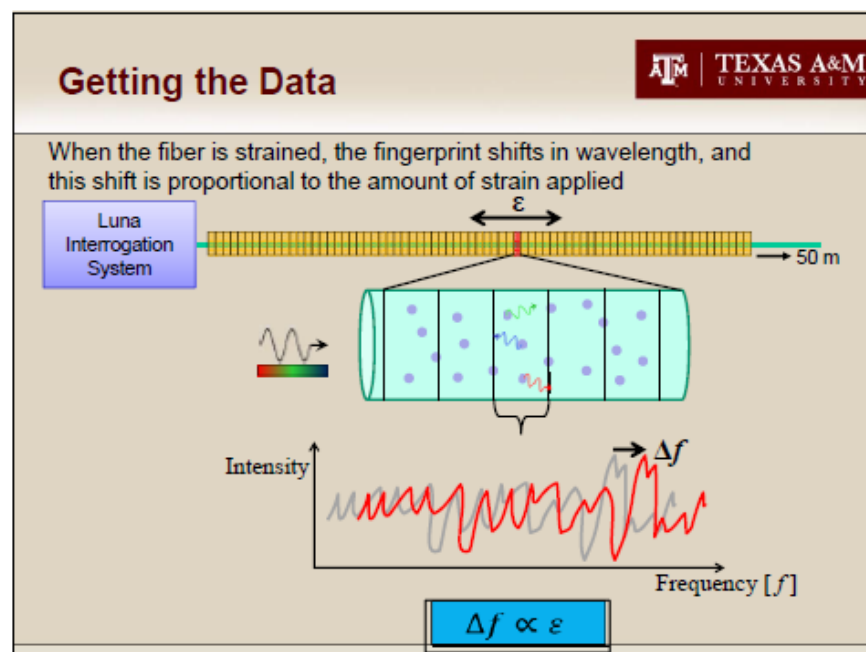
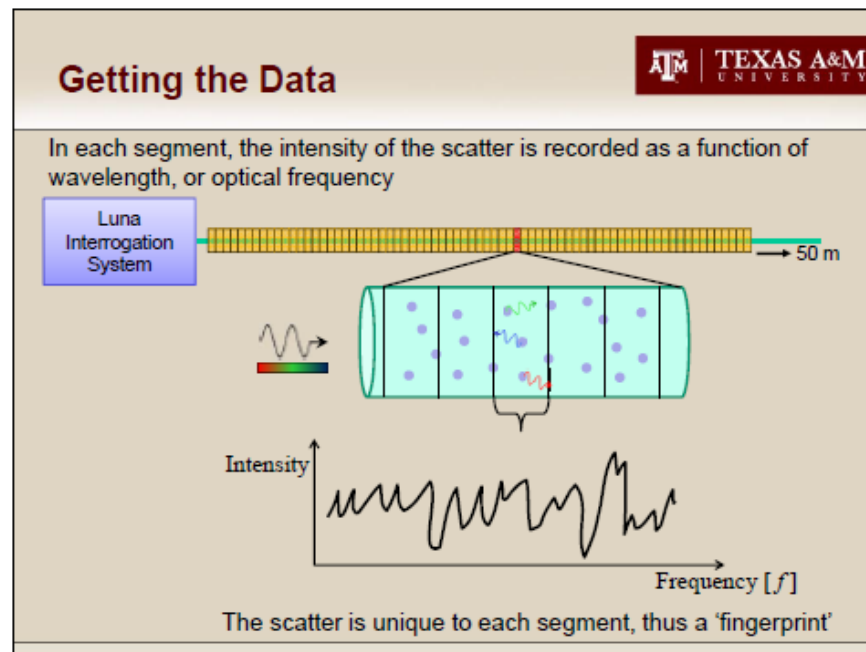


Digging Deeper



In a single scan, the *entire* fiber is recorded in small, discrete segments



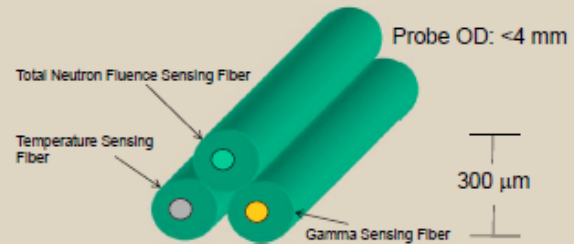


Temperature & Radiation Sensing

- Three optical fibers:
 - Thermal sensing
 - Gamma flux sensing
 - Neutron fluence

**Each fiber specifically selected to enhance response sensitivity to individual stimuli

Fiber Type	Relative Sensitivity		
	Thermal	Gamma	Neutron
Temperature Sensing	High	Extremely Low	Low
Gamma Sensing	Low	High	Low
Neutron Sensing	Low	Extremely Low	High



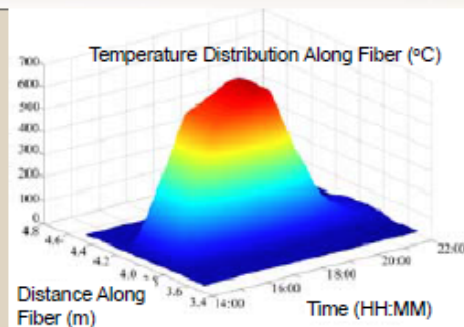
Proposed Sensor Performance

Sensitivities

Total Neutron Fluence - TBD
 Gamma Flux - TBD
 Temperature - $\pm 1\%$
 Spatial Resolution - 1 cm

Demonstrated Operating Ranges

- Temperature Range up to 800°C with brief excursions to 1050°C
- Total Neutron Fluence levels $\sim 5 \times 10^{19}$ n/cm²



Distributed temperature map produced using a fiber optic temperature sensor and OBR.

Experimental Demonstration



- Sensors testing in a relevant environment over a long duration
- Real-time data acquisition
 - Allows assessment of fiber performance, degradation, etc. without removal and visual observation
 - 3-4 fiber bundles inserted into test device (3 fibers per bundle)
 - With available switch, 8 fibers can be monitored with one OBR (higher capacity switches available, or additional OBRs can be used to increase sensor monitoring capability)
 - Mechanical disconnect to switch to other installed fibers if failure occurs
 - Damaged fibers can be removed for analysis and replaced if necessary

Experimental Apparatus



- Design an experimental apparatus to emulate VHTR conditions VHTR in a TRIGA reactor (as much as possible)
- Operating environment:
 - Sensor temperature: +1000°C
 - Sustained operation for 1 year
 - Total neutron fluence $\geq 2 \times 10^{19}$ n/cm²
- Design guidance:
 - Accessibility for fiber optics and instrumentation replacement
 - Conform to 10 CFR 50.59
 - Required safety criteria for experimental authorization
 - Resistive heating, passive cooling
 - Graphite heater in vacuum
 - Niobium thermal radiation shields

Test Facility – Nuclear Science Center Reactor

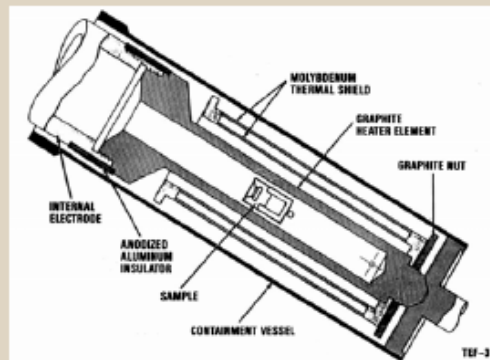


- TRIGA Mark I reactor design
- 1-MW operating power
- Refueled in 2006, LEU U-ZrH
- Neutron fluence rate:
 - 10^{12} n/cm²-s to 1.4×10^{13} n/cm²-s thermal
 - 10^{11} n/cm²-s epithermal
- Gamma dose (reactor face): $\sim 2 \times 10^7$ rad/hr
- Various test positions possible
 - Options limited due to test duration and need to leave some positions open for other test articles

Previous GA King Furnace Design



- Licensed for use in TRIGA facilities in early 1970s (NRC licenses R-38 and R-67)
- Designed to aid in analysis of the in-pile behavior of high-temperature gas-cooled reactor fuels
- Allowed fuel samples to be tested in a radiation environment at temperatures up to 1800 °C
- Heating provided by a cylindrical graphite element
- Radiation shields used to drop the temperature from centerline to surface
- Designed to fit a "standard" TRIGA core fuel element position (3.73 cm OD); ~20 cm (8") in length



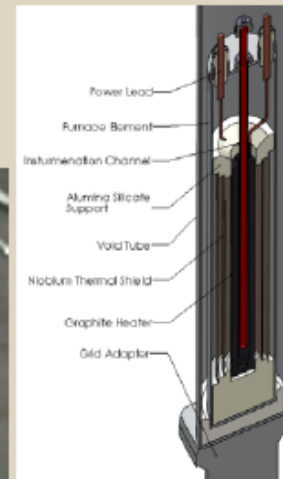
Test Furnace Design



- Design basics:
 - Aluminum housing to minimize activation
 - Heating provided by a specially-designed graphite element
 - Refractory metal thermal shields
 - Central instrumentation channel
- Failure criteria:
 - Steam production/stress failure
 - Safety factor of 2.75 (Facility TSR: 2.0)
- Temperature limitations
 - ~160°C on aluminum housing
- Engineering design complete and approved by NSCR Safety Analysis Committee



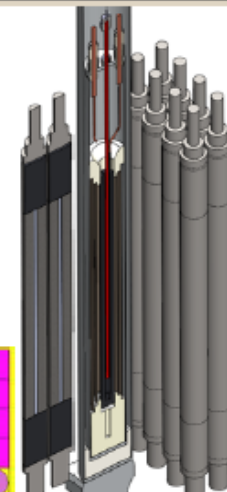
Graphite Heater Element



Test Furnace Design



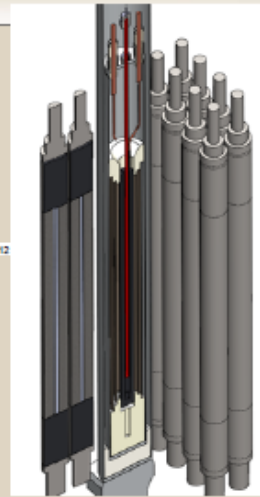
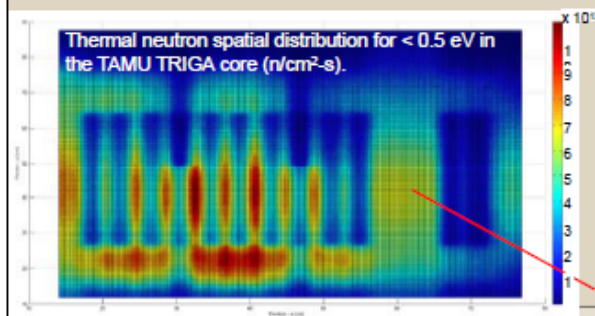
- Multi-fiber probe installed at the center of the test furnace
- Fiber optic measurements verified using standard instrumentation in close proximity
 - Thermocouples
 - Activation wires
 - Miniature fission chambers and gamma detectors
- Test furnace position
 - Occupies a full, 4-element grid position
 - Surrounded on three sides by fuel to achieve higher fluence



Test Furnace Design



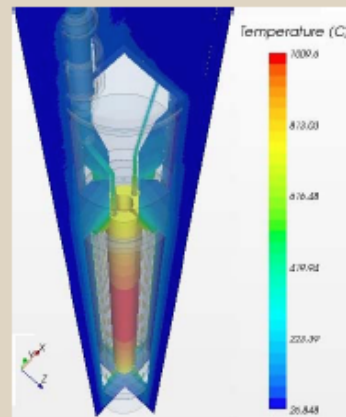
- Neutronic modeling of the furnace performed to predict the neutron and gamma fluence rates at the experiment position
 - Maximum possible neutron fluence rate is expected to be $1.72 \times 10^{13} \text{ n/cm}^2\text{-s}$ over the full neutron energy spectrum ($5.74 \times 10^{12} \text{ n/cm}^2\text{-s}$ below 0.5 eV)



Thermal Modeling: STAR-CCM+



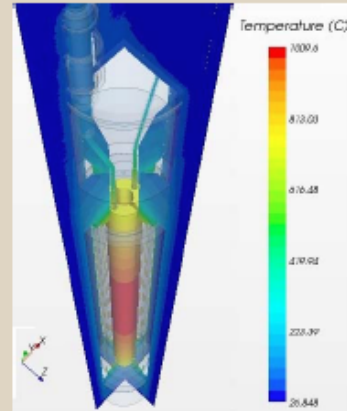
- Continuum, multi-physics package selected to produce a highly resolved model of experimental performance for both steady state and transient conditions
- Parameters selected to achieve a maximum of 1000°C at the sensor position while maintaining the safety of the TRIGA reactor core (limiting safety system setting)
- High-fidelity model developed concurrently with an analytical model to facilitate the design process and provide model verification



Planned Operating Conditions



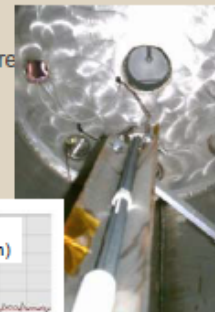
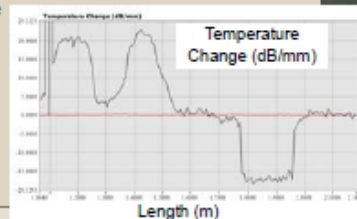
- Test fixture voided
- Two refractory metal thermal shields minimize heat transfer to the external boundary and neighboring core positions
 - Self-heating in the thermal shields is predicted to not exceed 15 W and 22 W for the inner and outer shields
 - Predicted maximum 10°C rise in the furnace external temperature
- Heater operating conditions:
 - 348 W
 - Predicted temperatures:
 - 1008°C at centerline
 - 165°C at tube surface



Initial Benchtop Testing



- Initial heater element and fiber tests at elevated temperature have been conducted in a vacuum environment to:
 - Verify analytical and STAR-CCM+ models for thermal radiation and conduction
 - Support behavioral studies, including heater element resistivity changes as a function of temperature and current
 - Support equipment tests, including power supply load and tuning for PID controllers
- In-air testing
 - Vibration sensitivity
 - Effect of large temperature gradients
 - Determination of fiber conductivity



Current Status



- Continuation of fiber optic benchtop testing
- All major furnace components received
- Minor components now in shipment
- Furnace assembly and installation ~Nov / Dec 2011



Acknowledgements



- Significant credit goes to graduate student Jesse Johns for all his work in the design and analysis of the test furnace.
- This paper is based upon work supported by the U.S. Department of Energy Nuclear Energy University Program Award Number 09-241.

Extra Slides

Primary Deliverables

The 3-year project will provide three key deliverables:

1. produce a highly distributed fiber optic network capable of 3D temperature and neutron fluence mapping in the VHTR environment;
2. demonstrate reliability and performance of the proposed sensor network; and
3. provide a computational model to evaluate expected sensor performance and lifetime in VHTR environments, to scale experimental results to VHTR conditions, to optimize sensor network, and to assess VHTR performance taking advantage of the 3D fiber-optics imaging and performance reconstruction.

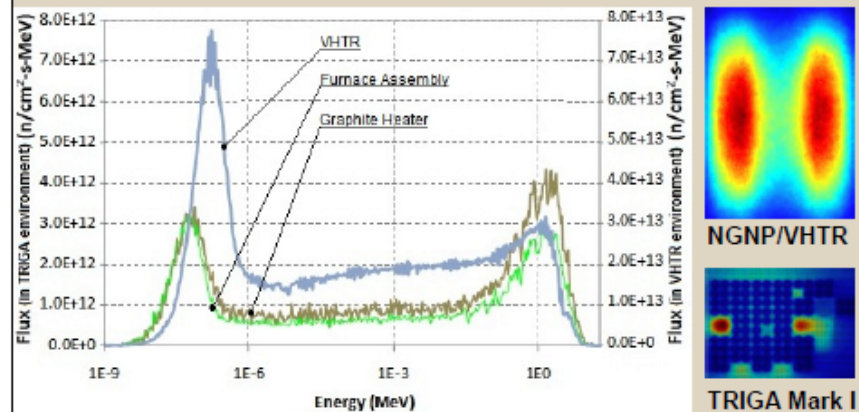
Key Milestones



Key milestones necessary to achieve the desired goals include:

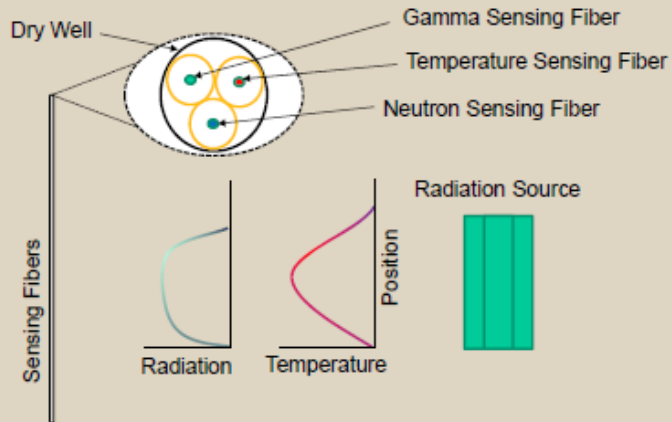
- Development of theoretical approach to estimating neutron fluence distributed along the length of the sensing fiber.
- Test furnace engineering design with reactor safety board approval.
- Fiber optic sensor design and completion of out-of-core laboratory testing.
- Test furnace fabrication, assembly and completion of out-of-core testing.
- Delivery of sensor strings with connectors to university; installation in test furnace.
- Assembly installation in TRIGA and completion of irradiation test matrix.
- 3D VHTR and TRIGA modeling with representation of distributed sensor network elements, performance reconstruction and optimization of the network design.
- Modeling validation using test measurements and scaling to the prototypical VHTR conditions.

VHTR vs TRIGA Neutron Spectrum



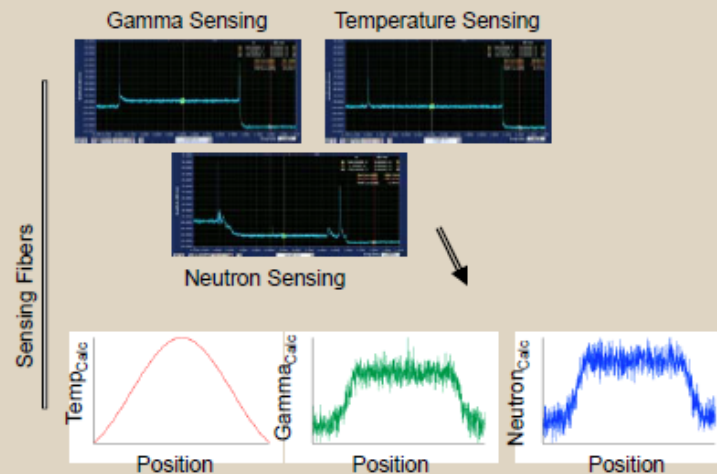
Spectrum not ideal, but sufficient to provide initial sensor performance characterization.

Distributed Sensing with Radiation



Each sensing fiber experiences the radiation and temperature though the radiation cross sensitivity is minimized in the Temperature sensing fiber.

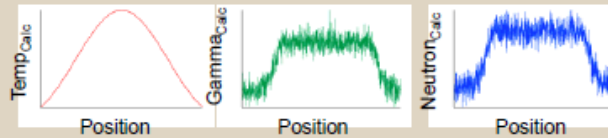
Distributed Sensing with Radiation



Temperature Compensation

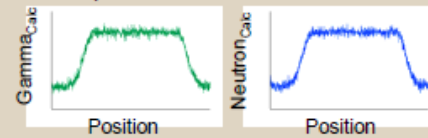


Temperature increases the noise in the Radiation Calculations



While each fiber measures their fiber temperatures, the Temperature sensing fiber is used to compensate the other two fibers

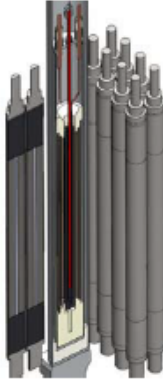
After Compensation



10.4.5. TRIGA-Based Experimental Device for Fiber Optics Testing



Development of TRIGA-based Experimental Device for Fiber Optics In-core Instrumentation Testing for VHTRs



Jesse Johns, Pavel Tsvetkov
Department of Nuclear Engineering
Texas A&M University

Thursday, April, 19th 2012

Research by U.S. DOE NEUP-Sponsored Students
2011 ANS Annual Meeting









Introduction

A Distributed Fiber Optic Sensor Network for Online 3D Temperature and Neutron Fluence Mapping in a VHTR Environment

Texas A&M University, Project Lead
Luna Innovations, Primary Industry Partner

Advisors:
General Atomics
Idaho National Laboratory









Introduction

- **Goal:** Real-time mapping of the temperature and neutron fluence distribution in proposed NGNP / VHTR cores
- **Challenges:**
 - Harsh environment (750° C to 950° C coolant outlet)
 - Long refueling cycle (~18 months) – high radiation
- **Benefits of Proposed Sensors:**
 - Real-time assessment of reactor performance
 - Sensor network can be placed throughout the reactor core (axial and transverse dimensions)
 - Benchmarks for simulation and analysis codes used in core design and modeling
 - Optimization of design margins
 - Reduced uncertainty in local phenomena assessment / prediction
→ reduced safety margins in design



Introduction

The 3-year project will provide three key deliverables:

1. produce a highly distributed fiber optic network capable of 3D temperature and neutron fluence mapping in the VHTR environment;
2. demonstrate reliability and performance of the proposed sensor network; and
3. provide a computational model to evaluate expected sensor performance and lifetime in VHTR environments, to scale experimental results to VHTR conditions, to optimize sensor network, and to assess VHTR performance taking advantage of the 3D fiber-optics imaging and performance reconstruction.





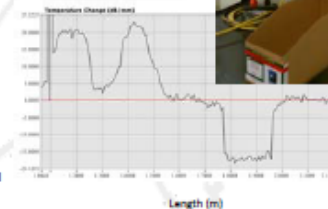
Distributed Sensing

Fiber optic sensors promise to provide detailed distributed measurements.

- Online hot spot determination and flux mapping
- Continuous code validation becomes possible

Test fibers in the operating conditions that would be expected in the VHTR.

[1] A. K. Sang, M. E. Froggatt, D. K. Griford, S. T. Kregar, and B. D. Dickerson, "One centimeter spatial resolution temperature measurements in a nuclear reactor using Rayleigh scatter in optical fiber," IEEE Sens. J. 8(7), 1375-1380 (2008).



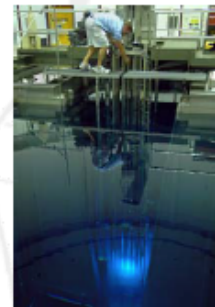
Challenges

The TRIGA reactor sits in a pool of light water open to the atmosphere.

- Thermal flux ~ peak at .09 eV
- Low temperatures
- Low thermal fluence rate: $4 \times 10^{12} \frac{n}{cm^2 s}$
- Safety and experimental limitations
 - Temperature, thermal storage, size, reactivity

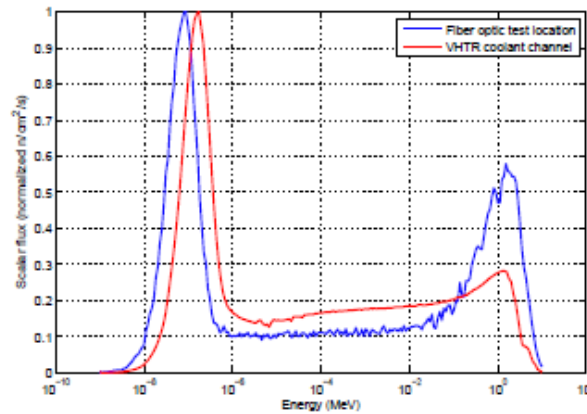
[2] G. Cheymol, H. Long, J. F. Villard, and B. Brichard, *High level gamma and neutron irradiation of silica optical fibers in CEA OSIRIS nuclear reactor*, IEEE Trans. Nucl. Sci. 55(4), 2252-2258 (2008)

[3] R.S.Fielder, D.Klemer, K.L.Stinson-Bagby, *High neutron fluence survivability testing of advanced Fiber Bragg Grating sensors*, AIP Conference Proceedings, vol. 699, n° 1, Feb. 2004, pp. 650-657.





Challenges Energy Spectrum



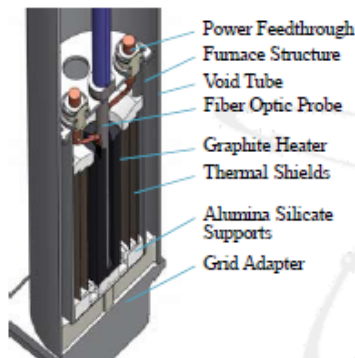
Experimental Design

Design an experimental apparatus to emulate the conditions of a VHTR in a TRIGA reactor for advanced instrumentation testing.

- Operate at ~1000°C
- Sustained operation for 1 year, to a neutron fluence of 2e19 n/cm²
- Accessibility for fiber optics and instrumentation replacement
- Conform to 10 CFR 50.59
 - Required safety criteria for experimental authorization
- Passive cooling – heater in vacuum



Experimental Design



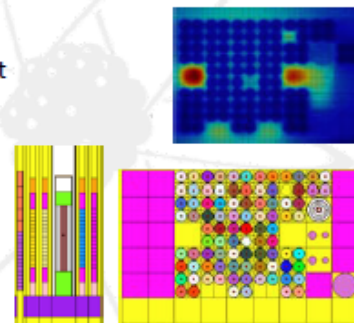
- Extended from an earlier furnace design from the 70's designed by General Atomics for use in the TRIGA Mark I
- KING TRIGA designed originally to test fuels – Too small for our purposes
- Required forced cooling and located in a fuel position



Modeling - Neutronics

MCNP5/X 2.6 was used for simulating the TRIGA reactor and simplified furnace model.

- The model includes the latest cross-section data, thermal scattering data, and
- Temperature data from NSC-written and validated sub-channel code



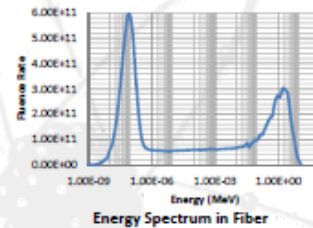


Modeling - Neutronics

Verification & Validation

MCNP model was scaled to matched Au/Cd flux foils data from the D3 core location.

- Nominal scaling was high by ~5.5%
- Fast (epithermal) to thermal flux ratios were comparable to 13.1%



Absolute fiber optic irradiation time expected to be roughly 230 days.

Core Zone	Material Zone	Material Name	Material Density (g/cm ³)	Material Volume (cm ³)	Material Mass (g)	Material Molar Mass (g/mol)	Material Moles (mol)	Material Radioactive Decay (s)	Material Radioactive Decay (h)	Material Radioactive Decay (d)
1	10	U-235	19.04	1.00E+01	1.90E+02	238.02891	7.98E-01	4.46E+08	5.14E+06	5.95E+07
1	10	U-238	19.04	1.00E+01	1.90E+02	238.02891	7.98E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-239	19.04	1.00E+01	1.90E+02	239.04643	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-240	19.04	1.00E+01	1.90E+02	240.05381	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-241	19.04	1.00E+01	1.90E+02	241.05658	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-242	19.04	1.00E+01	1.90E+02	242.05935	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-243	19.04	1.00E+01	1.90E+02	243.06212	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-244	19.04	1.00E+01	1.90E+02	244.06489	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-245	19.04	1.00E+01	1.90E+02	245.06766	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-246	19.04	1.00E+01	1.90E+02	246.07043	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-247	19.04	1.00E+01	1.90E+02	247.07320	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-248	19.04	1.00E+01	1.90E+02	248.07597	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-249	19.04	1.00E+01	1.90E+02	249.07874	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-250	19.04	1.00E+01	1.90E+02	250.08151	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-251	19.04	1.00E+01	1.90E+02	251.08428	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-252	19.04	1.00E+01	1.90E+02	252.08705	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-253	19.04	1.00E+01	1.90E+02	253.08982	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-254	19.04	1.00E+01	1.90E+02	254.09259	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-255	19.04	1.00E+01	1.90E+02	255.09536	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-256	19.04	1.00E+01	1.90E+02	256.09813	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-257	19.04	1.00E+01	1.90E+02	257.10090	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-258	19.04	1.00E+01	1.90E+02	258.10367	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-259	19.04	1.00E+01	1.90E+02	259.10644	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-260	19.04	1.00E+01	1.90E+02	260.10921	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-261	19.04	1.00E+01	1.90E+02	261.11198	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-262	19.04	1.00E+01	1.90E+02	262.11475	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-263	19.04	1.00E+01	1.90E+02	263.11752	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-264	19.04	1.00E+01	1.90E+02	264.12029	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-265	19.04	1.00E+01	1.90E+02	265.12306	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-266	19.04	1.00E+01	1.90E+02	266.12583	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-267	19.04	1.00E+01	1.90E+02	267.12860	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-268	19.04	1.00E+01	1.90E+02	268.13137	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-269	19.04	1.00E+01	1.90E+02	269.13414	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-270	19.04	1.00E+01	1.90E+02	270.13691	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-271	19.04	1.00E+01	1.90E+02	271.13968	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-272	19.04	1.00E+01	1.90E+02	272.14245	8.00E-01	4.46E+08	5.14E+06	5.95E+07
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1	10	Pu-274	19.04	1.00E+01	1.90E+02	274.14799	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-275	19.04	1.00E+01	1.90E+02	275.15076	8.00E-01	4.46E+08	5.14E+06	5.95E+07
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1	10	Pu-277	19.04	1.00E+01	1.90E+02	277.15630	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-278	19.04	1.00E+01	1.90E+02	278.15907	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-279	19.04	1.00E+01	1.90E+02	279.16184	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-280	19.04	1.00E+01	1.90E+02	280.16461	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-281	19.04	1.00E+01	1.90E+02	281.16738	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-282	19.04	1.00E+01	1.90E+02	282.17015	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-283	19.04	1.00E+01	1.90E+02	283.17292	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-284	19.04	1.00E+01	1.90E+02	284.17569	8.00E-01	4.46E+08	5.14E+06	5.95E+07
1	10	Pu-285	19.04	1.00E+01	1.90E+02	285.17846	8			



Modeling – Heat Transfer

Computation continuum mechanics software package used to support analysis of fiber optics.

- STAR-CCM+ v6.02, developed by Cd-adapco

Provides extra temperature data to Matlab script for total thermal storage and allows for behavioral study of furnace operation.

Temperature limited to either:

- ~160°C on aluminum housing
- 1138°C averaged operating temperature



Modeling – Heat Transfer

Verification & Validation

Physics model verification done concurrently with furnace model development –

- Conduction
 - Near perfect agreement, even with poor mesh refinement – max error: 1.169% in surface heat flux
- Forced convection (incomplete)
- Radiation
 - Near perfect agreement, even with poor mesh refinement – max error: 0.79% in surface heat flux





Modeling – Heat Transfer

Verification & Validation

Validation modeling to proceed as fabrication is completed



- Graphite heater in vacuum chamber
 - Instrumented with k-type TCs with Nextel coating
- LabView PID controller to interface with power supply and safety systems

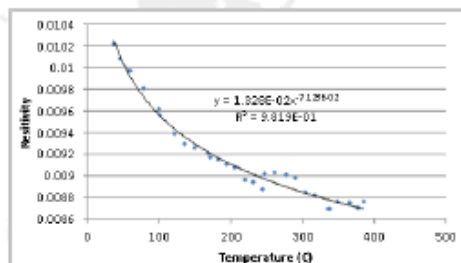


Modeling – Heat Transfer

Verification & Validation

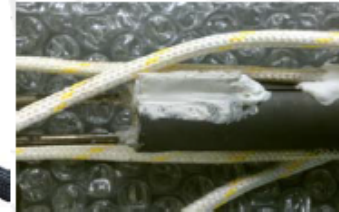
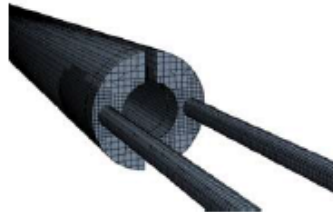
Experiments provide better material information

- Resistivity as a function of power/temperature
Ohmic heating is well approximated with constant volumetric heat generation.





Modeling – Heat Transfer Radiation Validation

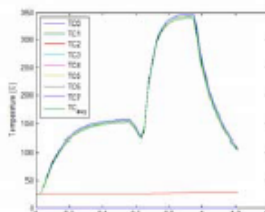


Current (amps)	Measured Temp (°C)	Surface Temp (°C)	Heat Flux (W/m²)	Power Error	Temp Error
3.50	37.79	39.74	82.44	-0.0944	0.0063
6.00	59.55	60.22	236.13	-0.0948	0.0020
10.00	101.23	100.47	632.5	-0.0897	-0.0020
17.00	171.27	173.46	1760.26	-0.0865	0.0049
26.00	246.96	259.68	4028.76	-0.0907	0.0245
30.00	276.79	294.68	5327.23	-0.0959	0.0925
47.50	385.59	429.72	13144.9	-0.0172	0.0670

- Environmental temperature
- Power leads directly modeled without contact resistance
- Thermocouples not included

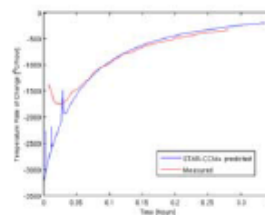
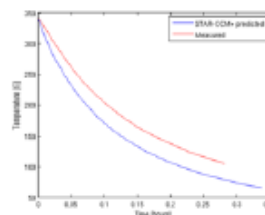


Modeling – Heat Transfer Stress Test



Verify cementing method for power leads and thermocouples.

Verify transient analysis of thermal models.





Modeling – Heat Transfer

Gas physics modeled with V2F non-linear eddy viscosity model, with heat transfer coupling.

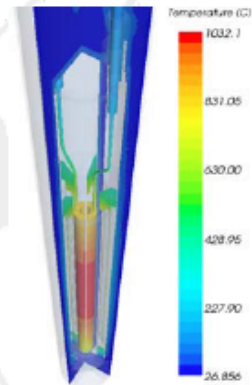
Surface to surface radiation modeling, with constant emissivity.

Constant volumetric heat generation in heater and thermal shields.

- MCNPX predicts 14.7 and 21.2 W for the inner and outer shields

Power requirements:

- 390W – $T_{gh} = 1116C$, $T_s = 190C$
- 348W – $T_{gh} = 1008C$, $T_s = 165C$



Current Progress

Furnace Fabrication

Poep.





Current Progress Furnace Fabrication



Current Progress Furnace Fabrication

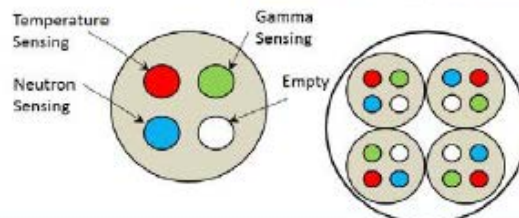
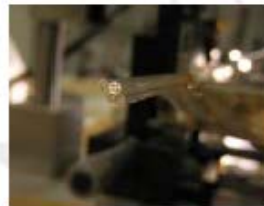




Current Progress Furnace Fabrication



Current Progress



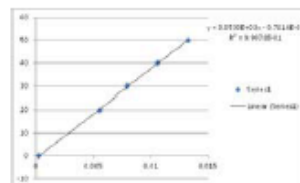


Current Progress

Pressure Sensor Calibration

Ensure proper safety system response.

Comply with NEUP QA requirements.



Final Remarks

and Conclusions

Key milestones:

- Development of theoretical approach to estimating neutron fluence distributed along the length of the sensing fiber.
- Test furnace engineering design with reactor safety board approval.
- Fiber optic sensor design and completion of out-of-core laboratory testing.
- Test furnace fabrication, assembly and completion of out-of-core testing.
- Delivery of sensor strings with connectors to university; installation in test furnace.
- Assembly installation in TRIGA and completion of irradiation test matrix.
- 3D VHTR and TRIGA modeling with representation of distributed sensor network elements, performance reconstruction and optimization of the network design.
- Modeling validation using test measurements and scaling to the prototypical VHTR conditions.





Final Remarks and Conclusions

Confident that the safety of the TRIGA reactor core will not be impacted by the experiment.

Temperature requirements, following bench top tests, may change , but operation to 1000°C is expected to be achievable.

Temperature fiber optic sensors perform, under normal conditions, as expected. Gamma and neutron fibers test have not yet been done in depth.



Acknowledgements

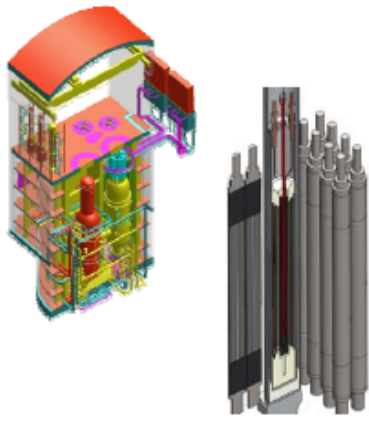
This paper is based upon work supported by the U.S. Department of Energy Nuclear Energy University Program Award Number 09-241.

All fabrication was performed at the Texas A&M University Nuclear Science center.





Emulation of VHTR Operating Conditions in TRIGA Reactors



Questions?

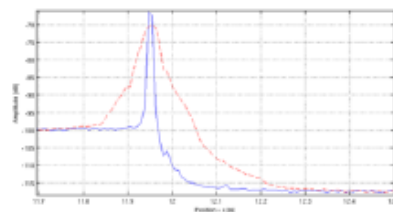
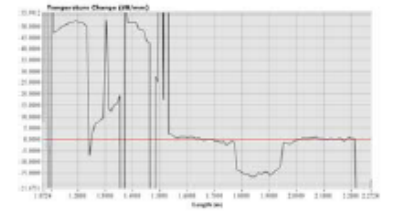


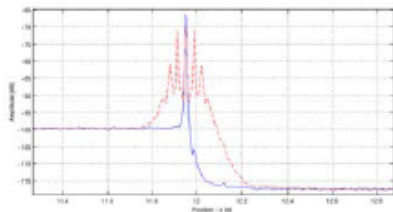
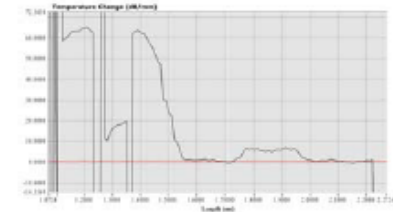






Engineering Challenges

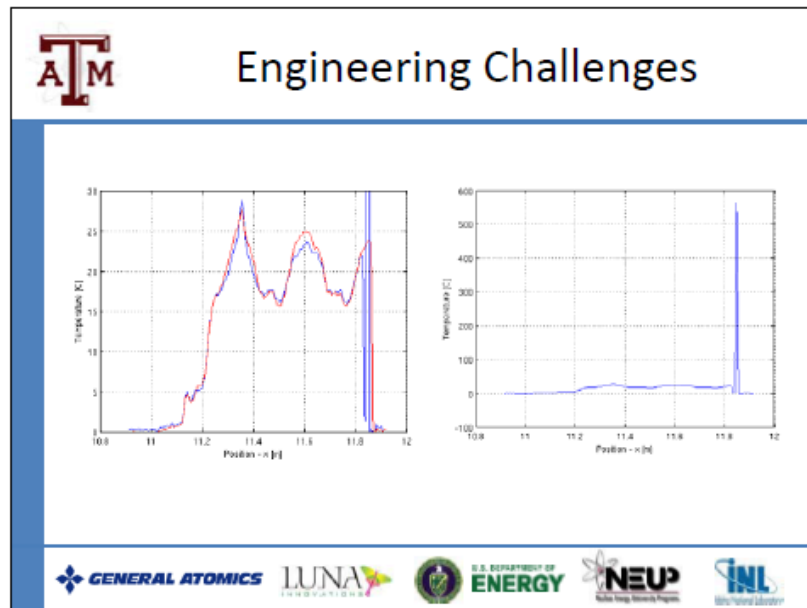



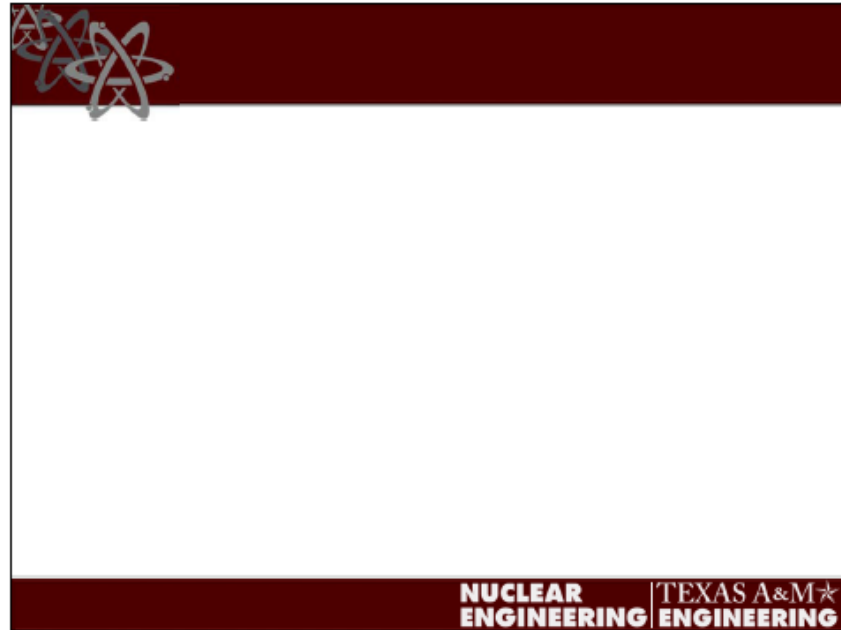








10.4.6. 3D In-Core Monitoring in Advanced Reactor Environments





3D In-Core Monitoring in Advanced Reactor Environments

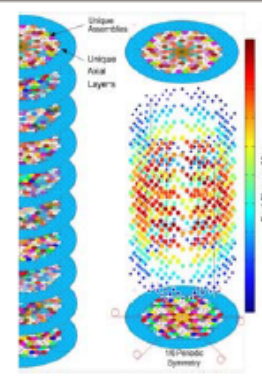
**Pavel V. Tsvetkov, Shannon M. Bragg-Sittton
Jesse M. Johns, Matthew P. Johnson**

**Department of Nuclear Engineering
Texas A&M University**

Presented on behalf of the authors by Ahmad Al Rashdan

Advanced Reactors

*Thursday, June 28, 2012, ANS 2012 Annual Meeting
June 24-28, 2012, Hyatt Regency Chicago, Chicago, IL*



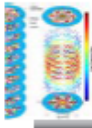






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3D In-Core Monitoring in Advanced Reactor Environments

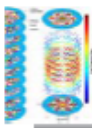
- Overview
- High-Fidelity Modeling Approach
- VHTR Environments in TRIGA
- In-Core Environment Reconstruction
- Current Status
- Conclusions









3D In-Core Monitoring in Advanced Reactor Environments

Overview

Sensors for Advanced Reactors

Safety, Reliability, Autonomy, Economics, ...

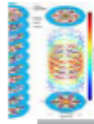
- Robust in-core measurement systems capable to provide characteristic operational information
- Longevity of sensor performance
- Real time operation
- Ability to predict hot spot formation conditions





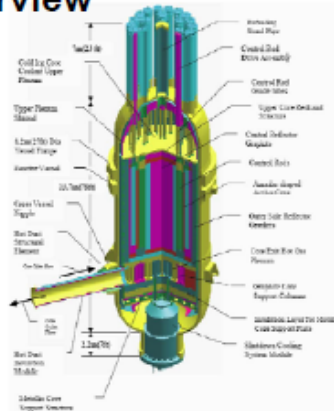




3D In-Core Monitoring in Advanced Reactor Environments

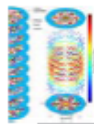
Overview



- **In-core monitoring challenge** – reliable long-term operation in extreme high-temperature high-fluence environments
- **Use of fiber optic sensors** – direct in-core 3D monitoring for in-core management (loading, hot spots, temperature and fluence maps)



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3D In-Core Monitoring in Advanced Reactor Environments

Overview

Distributed Sensor Networks for Online 3D In-Core Monitoring in VHTR Environments

- Collaboration of University, Nat. Lab., Industry
- **Texas A&M University, Project Lead**
- Luna Innovations, Primary Industry Partner
- General Atomics, Advisor
- Idaho National Laboratory, Advisor



➔ **GENERAL ATOMICS**

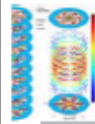
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► **GENERAL ATOMICS**

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ENERGY

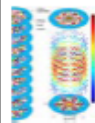


3D In-Core Monitoring in Advanced Reactor Environments

- Overview**
- **Goal:** Real-time mapping of the temperature and neutron fluence distribution in proposed NGNP / VHTR cores
 - **Challenges:**
 - Harsh environment (750° C to 950° C coolant outlet)
 - Long refueling cycle (~18 months) – high radiation
 - **Benefits of Proposed Sensors:**
 - Real-time assessment of reactor performance
 - Sensor network can be placed throughout the reactor core (axial and transverse dimensions)
 - Benchmarks for simulation and analysis codes used in core design and modeling
 - Optimization of design margins
 - Reduced uncertainty in local phenomena assessment / prediction
→ reduced safety margins in design



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3D In-Core Monitoring in Advanced Reactor Environments

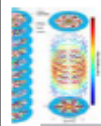
Overview

The 3-year project will provide three key deliverables:

1. produce a highly distributed fiber optic network capable of 3D temperature and neutron fluence mapping in the VHTR environment;
2. demonstrate reliability and performance of the proposed sensor network; and
3. provide a computational model to evaluate expected sensor performance and lifetime in VHTR environments, to scale experimental results to VHTR conditions, to optimize sensor network, and to assess VHTR performance taking advantage of the 3D fiber-optics imaging and performance reconstruction.



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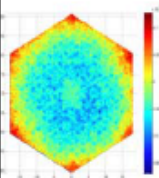


3D In-Core Monitoring in Advanced Reactor Environments

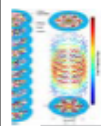
High-Fidelity Modeling Approach

Objectives

- Predict core behavior
- Develop methodologies for 3D flux (and power density) reconstruction
- Predict hotspots and off normal conditions with a limited amount of sensors
- Reconstruction will rely on knowledge of the expected core behavior, hence the current focus on high fidelity modeling

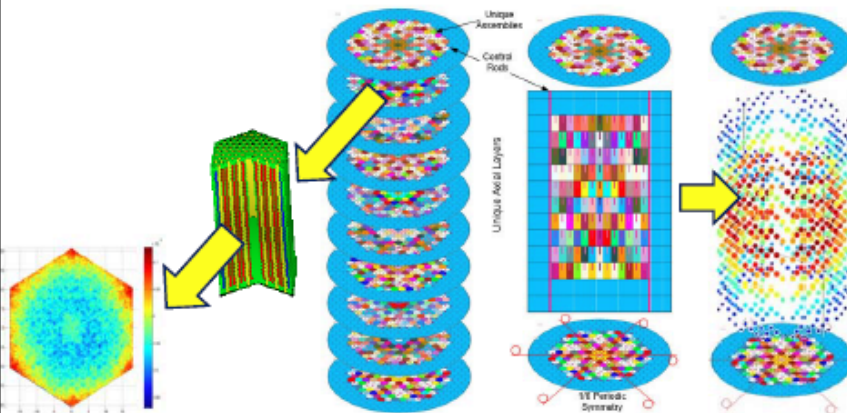


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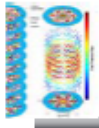


3D In-Core Monitoring in Advanced Reactor Environments

High-Fidelity Modeling Approach



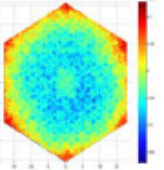
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3D In-Core Monitoring in Advanced Reactor Environments

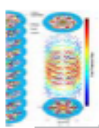
High-Fidelity Modeling Approach

Methodology and Tools



- MCNPX whole core modeling with unique block tracking
- Runtime automation to capture core performance
- Sensor modeling using cell flux tallies
- Sensor grid optimization to maximize predictive capability
- Sensor failure effect evaluations

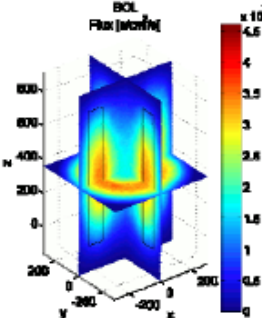

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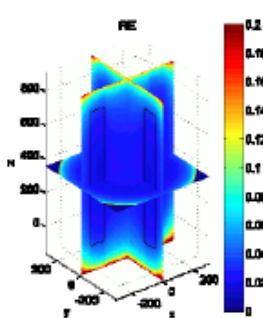
3D In-Core Monitoring in Advanced Reactor Environments

High-Fidelity Modeling Approach

Hot Spot Migration and Localization with the Core

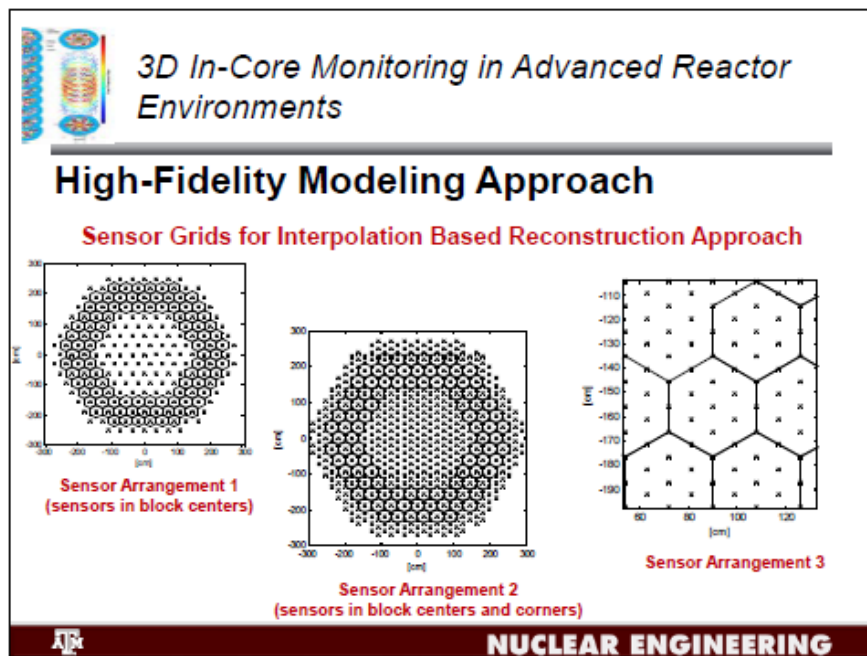
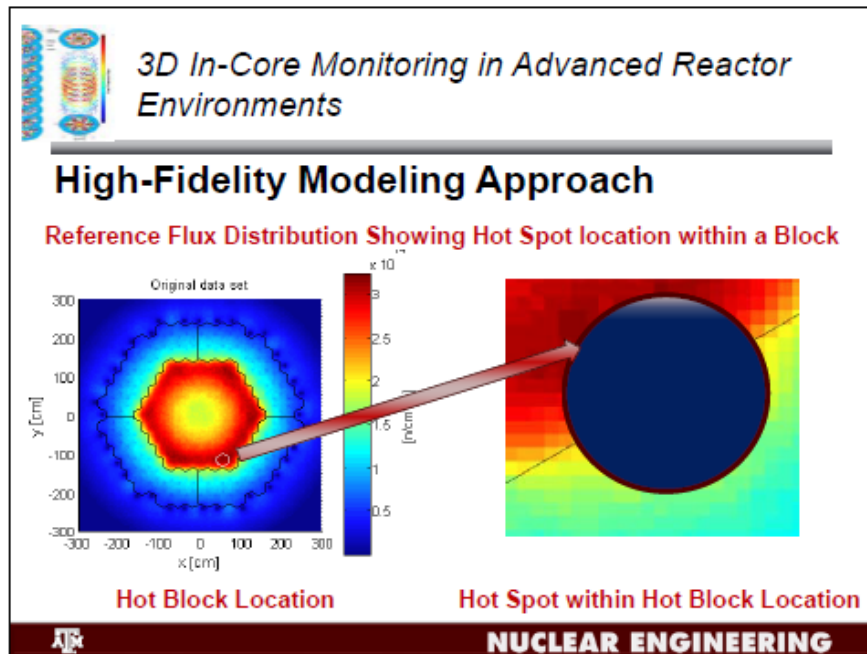


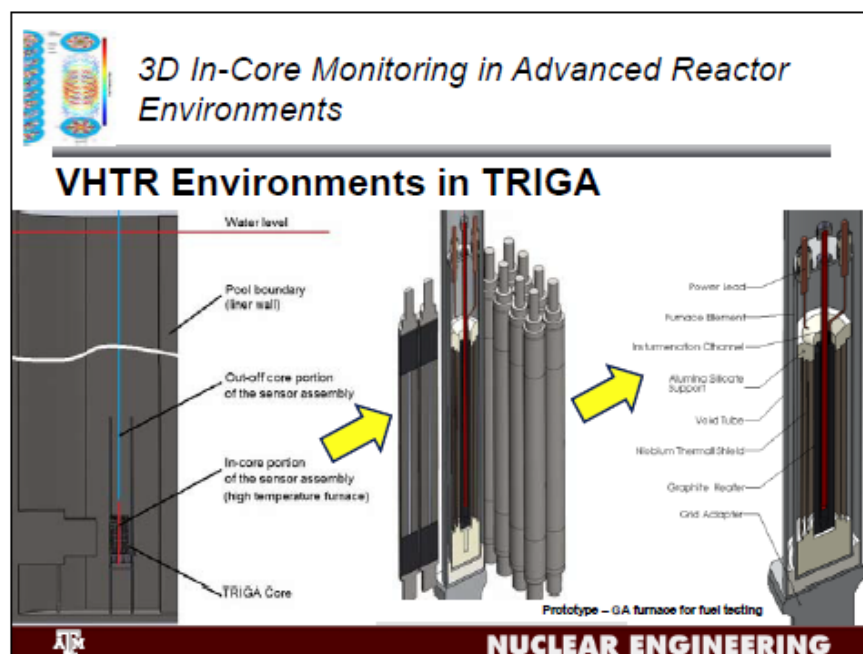
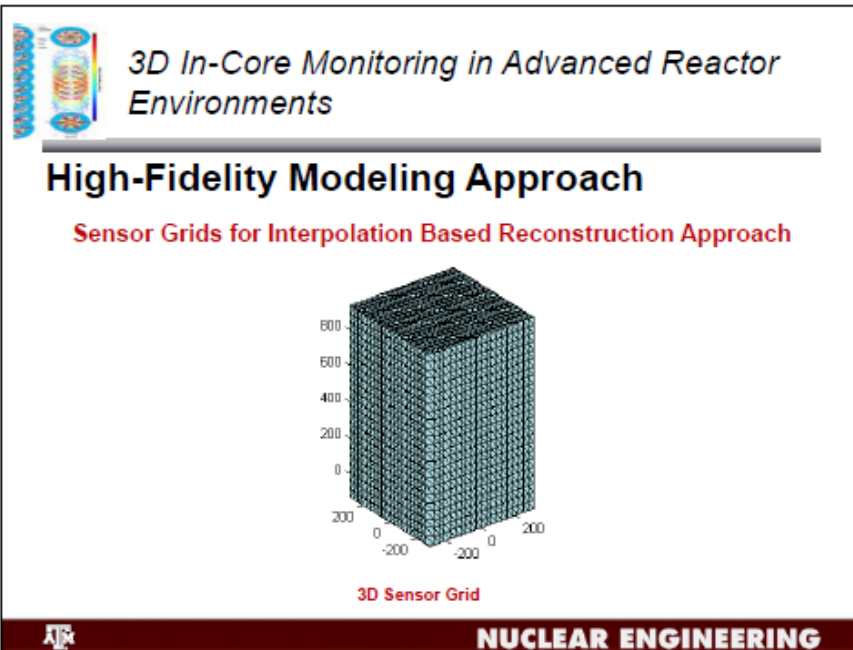
BCL Flux (MW/m²)

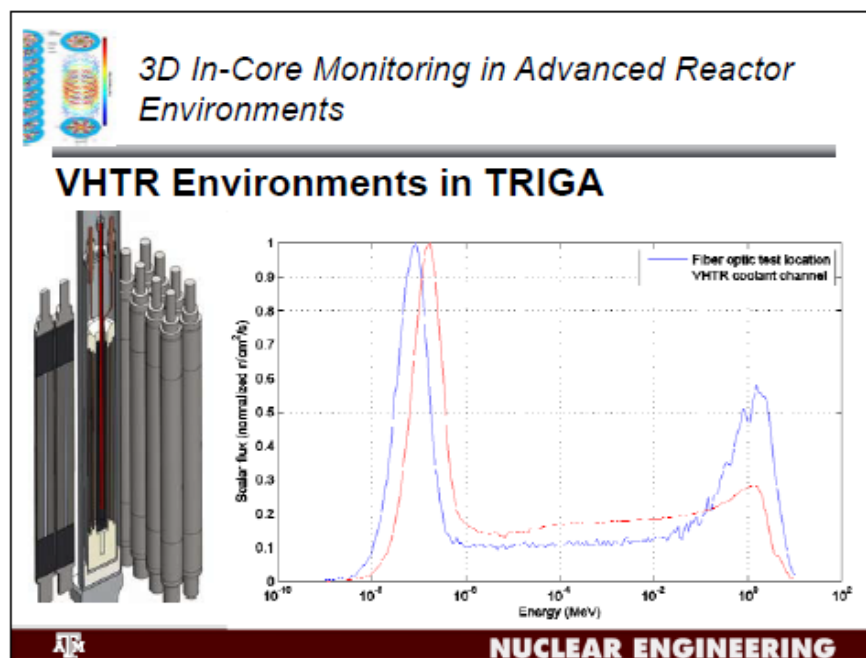
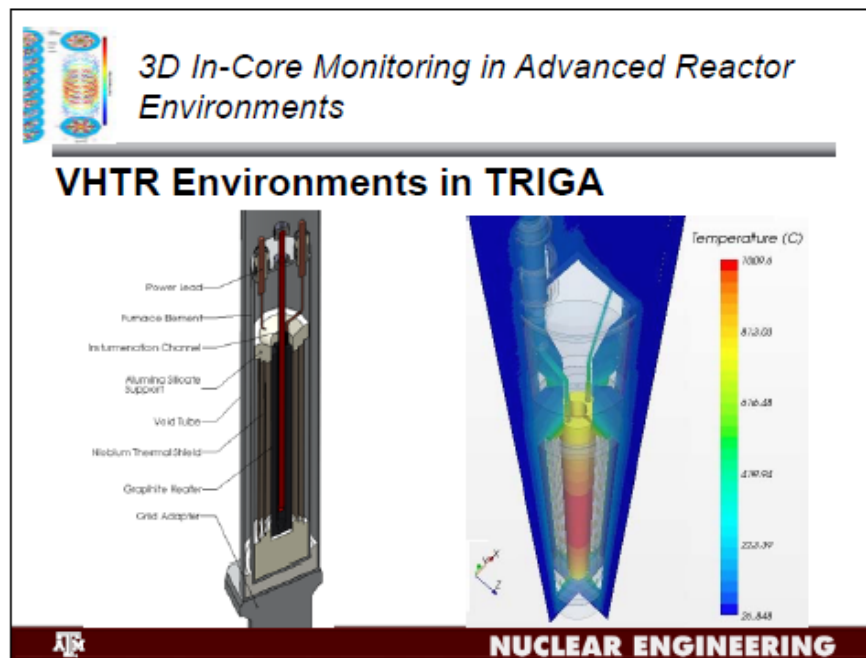


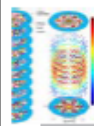
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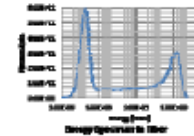


3D In-Core Monitoring in Advanced Reactor Environments

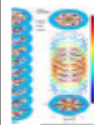
VHTR Environments in TRIGA



- MCNP model was scaled to matched Au/Cd flux foils data from the D3 core location.
- Nominal scaling was high by ~5.5%
- Fast (epithermal) to thermal flux ratios were comparable to 13.1%
- Absolute fiber optic irradiation time expected to be roughly 230 days.
- Used BOL fuel concentrations.

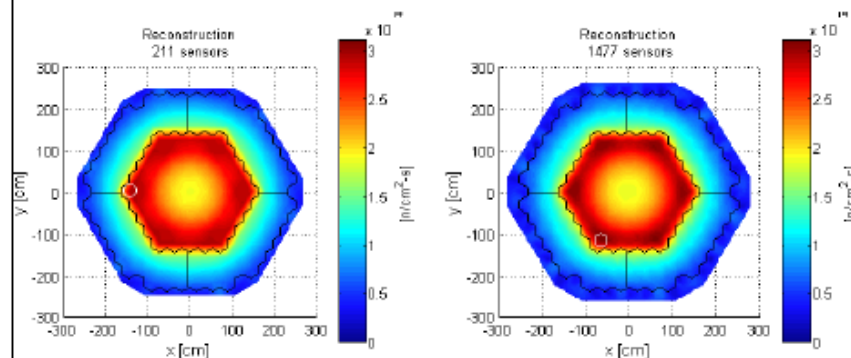


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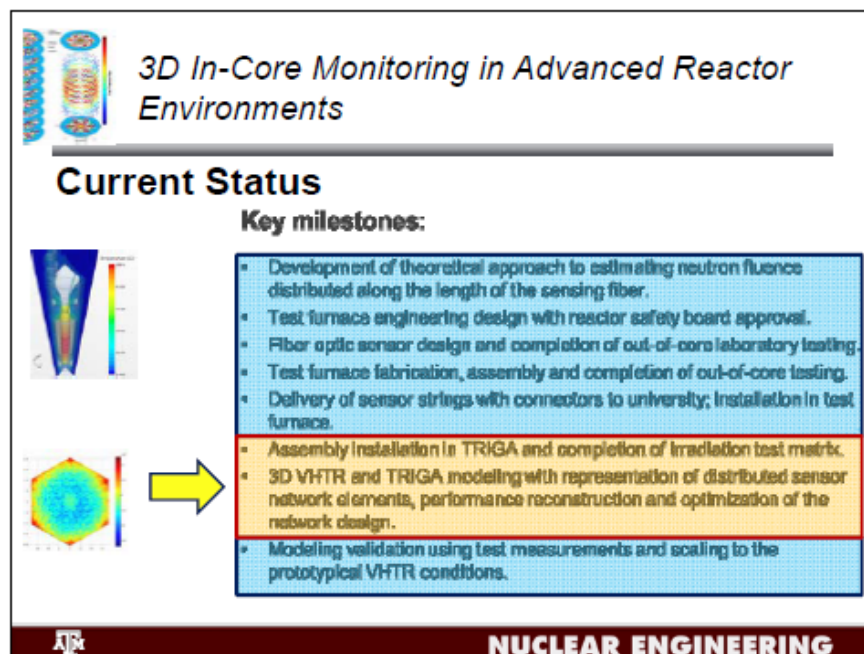
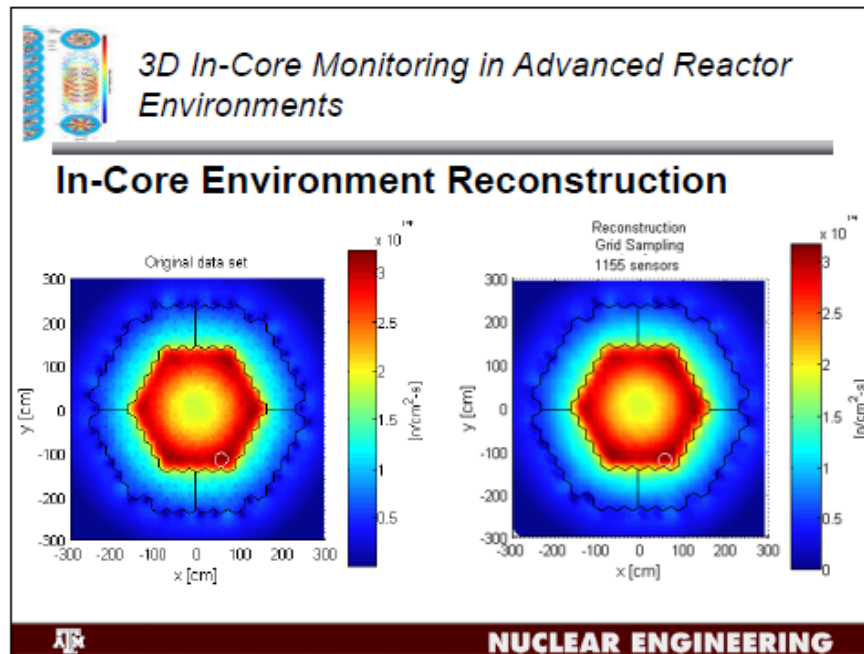


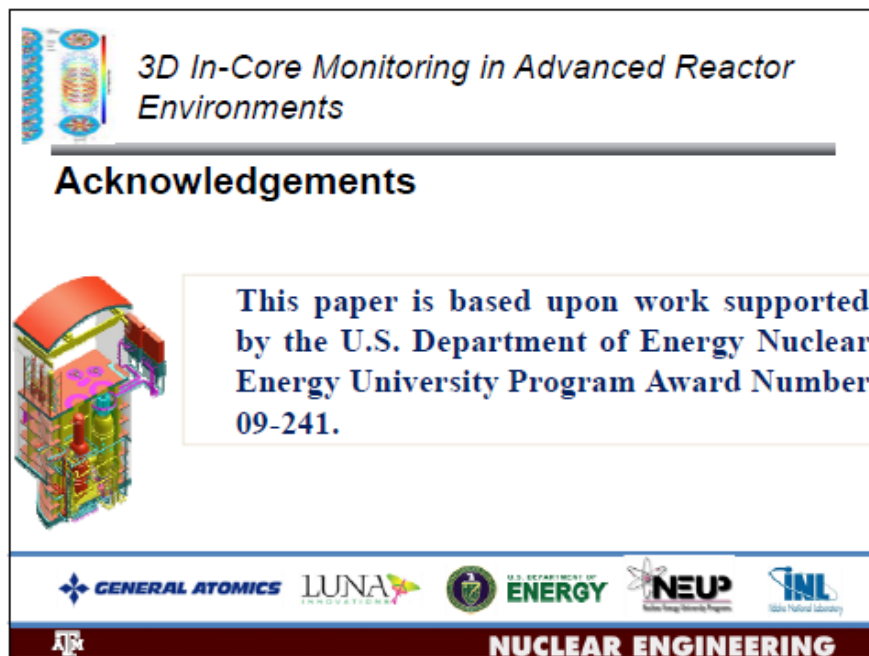
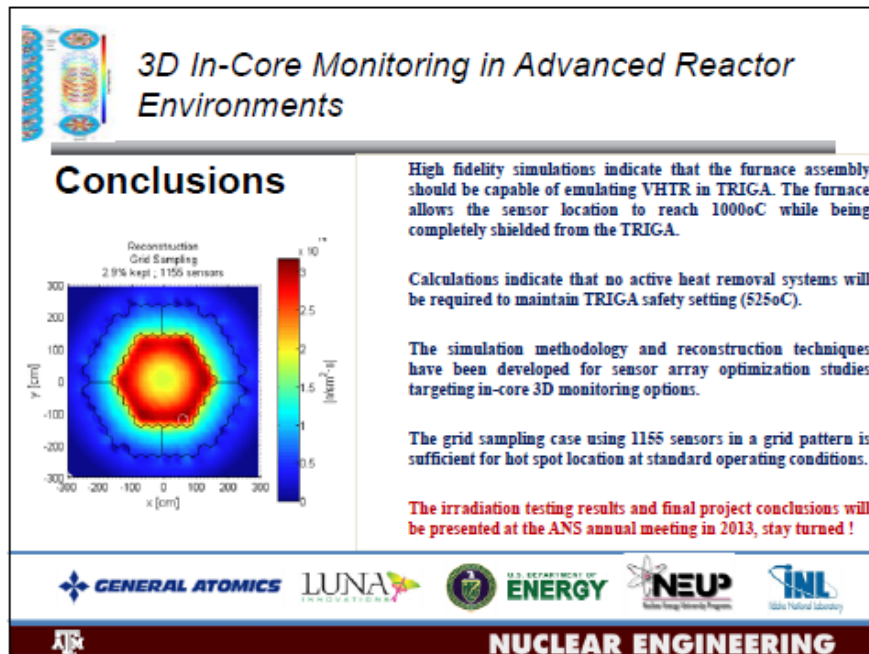
3D In-Core Monitoring in Advanced Reactor Environments

In-Core Environment Reconstruction



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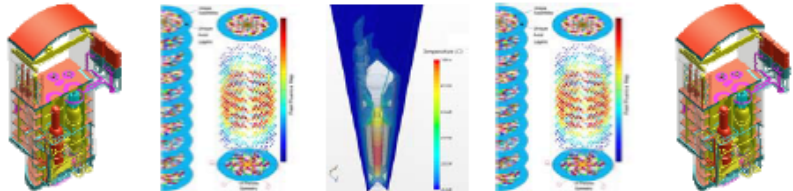





3D In-Core Monitoring in Advanced Reactor Environments

QUESTIONS?

Direct your questions about this effort to
 Dr. Tsvetkov (tsvetkov@tamu.edu) and Dr. Bragg-Sitton (sitton@tamu.edu)





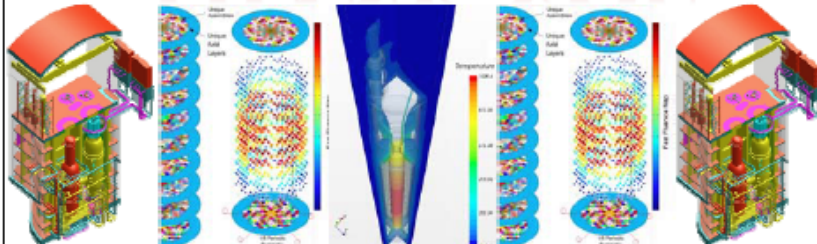




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3D In-Core Monitoring in Advanced Reactor Environments

THANK YOU









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10.4.7. Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring



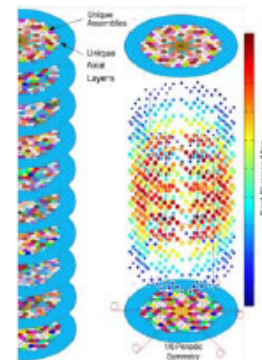
Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

**Jesse M. Johns, Matthew P. Johnson,
Pavel V. Tsvetkov, Shannon M. Bragg-Sitton**

**Department of Nuclear Engineering
Texas A&M University**

Operations and Power: General - I

*Tuesday, November 12, 2013, ANS 2013 Winter Meeting
November 10-14, 2013, Omni Shoreham Hotel, Washington D.C.*

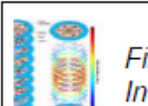






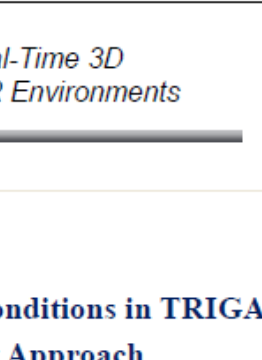


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Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

- **Overview**
- **Fiber Optic Sensors**
- **Emulation of VHTR Conditions in TRIGA**
- **High-Fidelity Modeling Approach**
- **Validation Efforts**
- **In-Core Testing**
- **Conclusions**

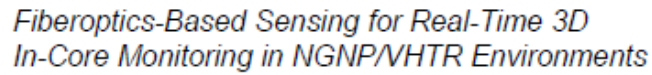








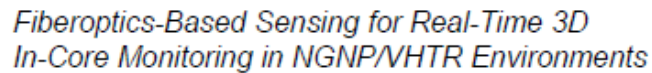
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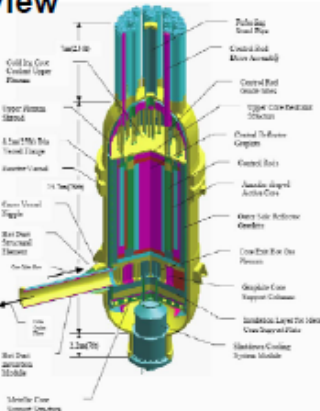
Overview

Small and Medium Sized Advanced Reactors

- Robust in-core measurement systems capable to provide characteristic operational information
- Longevity of sensor performance
- Real time operation
- Ability to predict hot spot formation conditions

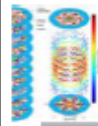


Overview



- **In-core monitoring challenge** – reliable long-term operation in extreme high-temperature high-fluence environments
- **Use of fiber optic sensors** – direct in-core 3D monitoring for in-core management (loading, hot spots, temperature and fluence maps)





Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

Overview

Collaboration of University, Nat. Lab., Industry

Texas A&M University, Project Lead

Luna Innovations, Primary Industry Partner

General Atomics, Advisor

Idaho National Laboratory, Advisor



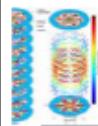
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Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

Overview

- **Goal:** Real-time mapping of the temperature and neutron fluence distribution in proposed NGNP / VHTR cores
- **Challenges:**
 - Harsh environment (750° C to 950° C coolant outlet)
 - Long refuelling cycle (~18 months) – high radiation
- **Benefits of Proposed Sensors:**
 - Real-time assessment of reactor performance
 - Sensor network can be placed throughout the reactor core (axial and transverse dimensions)
 - Benchmarks for simulation and analysis codes used in core design and modeling
 - Optimization of design margins
 - Reduced uncertainty in local phenomena assessment / prediction
→ reduced safety margins in design



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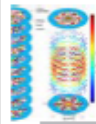


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Fiber Optics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

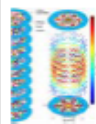
Overview

The 3-year project will provide three key deliverables:

1. produce a highly distributed fiber optic network capable of 3D temperature and neutron fluence mapping in the VHTR environment;
2. demonstrate reliability and performance of the proposed sensor network; and
3. provide a computational model to evaluate expected sensor performance and lifetime in VHTR environments, to scale experimental results to VHTR conditions, to optimize sensor network, and to assess VHTR performance taking advantage of the 3D fiber-optics imaging and performance reconstruction.



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Fiber Optics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

Fiber optic sensors will be used to monitor

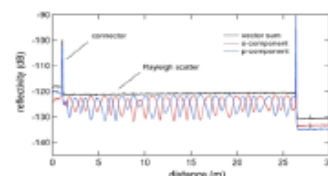
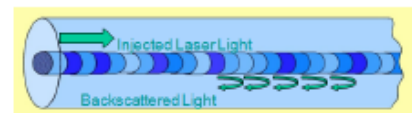
- Total Neutron Fluence
- Gamma Flux
- Temperature

The sensor interrogation uses an Optical Backscatter Reflectometer (OBR™) system



Fiber Optic Sensors

The OBR measures the Rayleigh Backscatter of the optical fiber

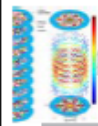


Strain, temp., etc. cause Rayleigh fingerprint to stretch – shift in the mean period between perturbations leads to a shift in optical frequency.

Radiation and Temperature stimuli change the Rayleigh backscatter of the optical fiber



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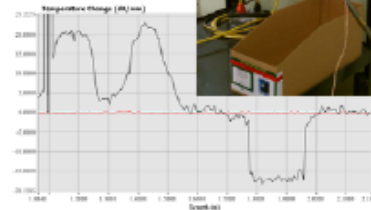
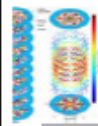
Fiber Optics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

Fiber Optic Sensors

Fiber optic sensors promise to provide detailed distributed measurements.

- Online hot spots determination and flux mapping
- Continuous code validation becomes possible

Test fibers in the operating conditions that would be expected in the VHTR.

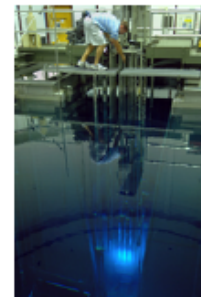

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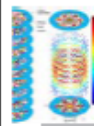
Fiber Optics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

Emulation of VHTR Conditions in TRIGA

The TRIGA reactor sits in a pool of light water open to the atmosphere.

- Thermal flux ~ peak at .09 eV
- Low temperatures
 - Fuel ~ 390°C
 - Coolant ~ 26°C
- Low fluence rate ~ 4e12 n/cm²/s
- Safety and experimental limitations
 - Temperature, thermal storage, size, reactivity


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Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

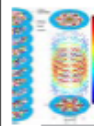
Emulation of VHTR Conditions in TRIGA

Design an experimental apparatus to emulate the conditions of a VHTR in a TRIGA reactor for advanced instrumentation testing.

- Operate at +1000°C
- Sustained operation for 1 year, to a neutron fluence of $2 \times 10^{19} \text{ n/cm}^2$
- Accessibility for fiber optics and instrumentation replacement
- Conform to 10 CFR 50.59
 - Required safety criteria for experimental authorization
- Passive cooling – heater in vacuum

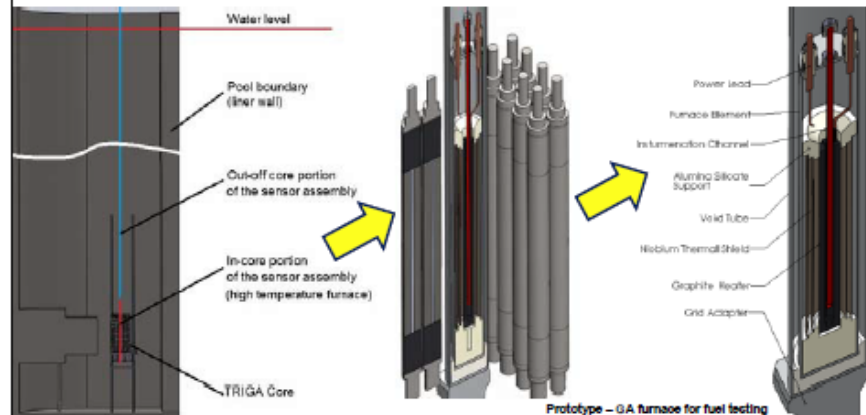


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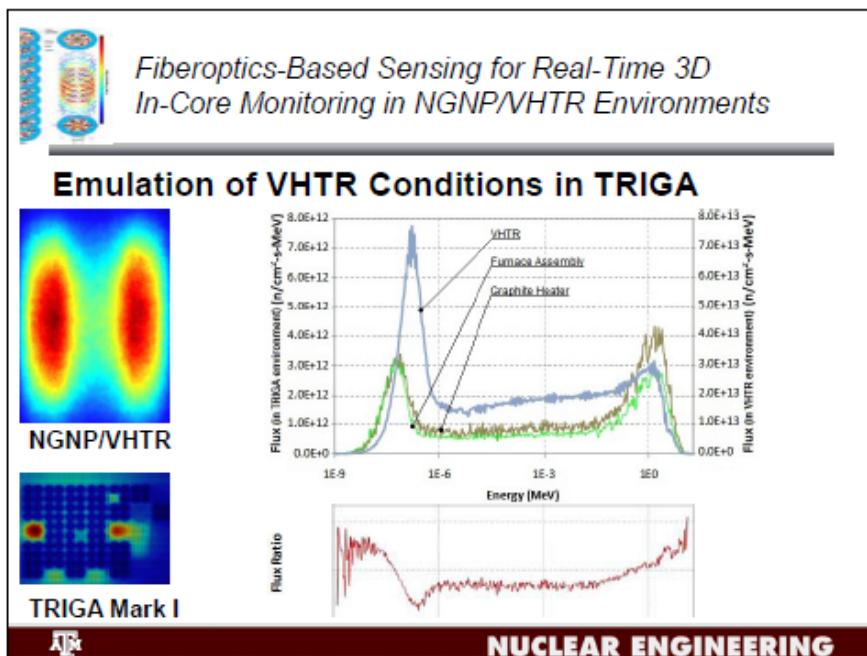
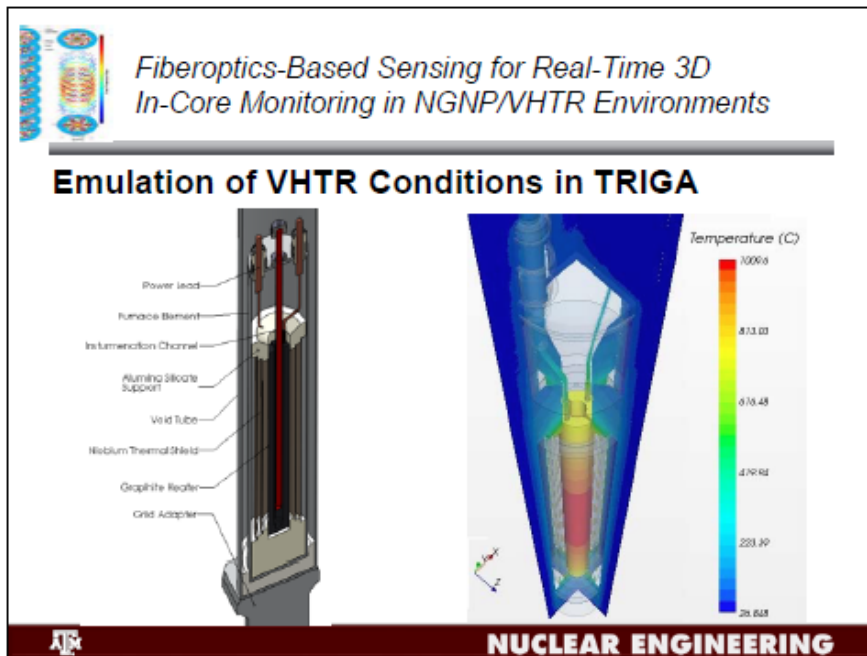


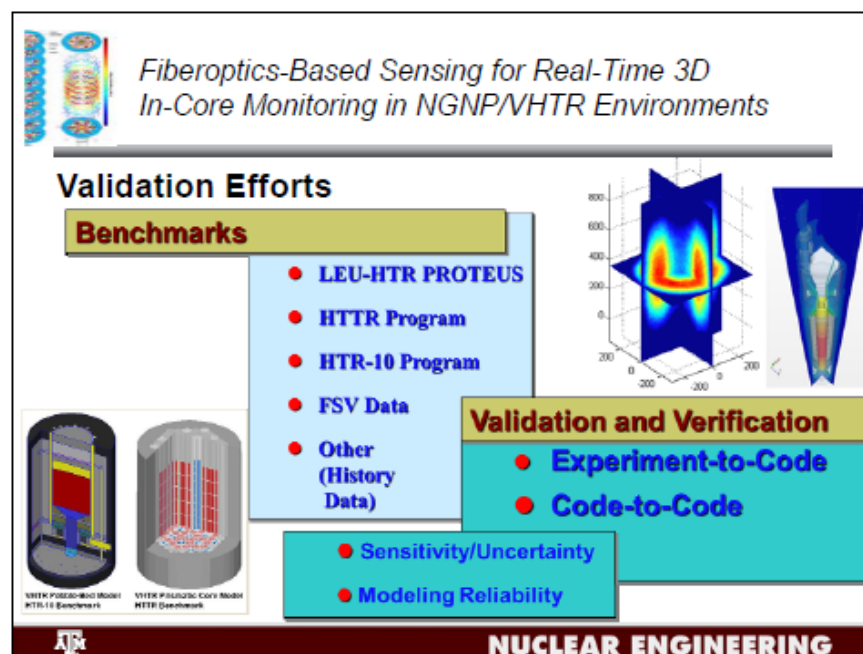
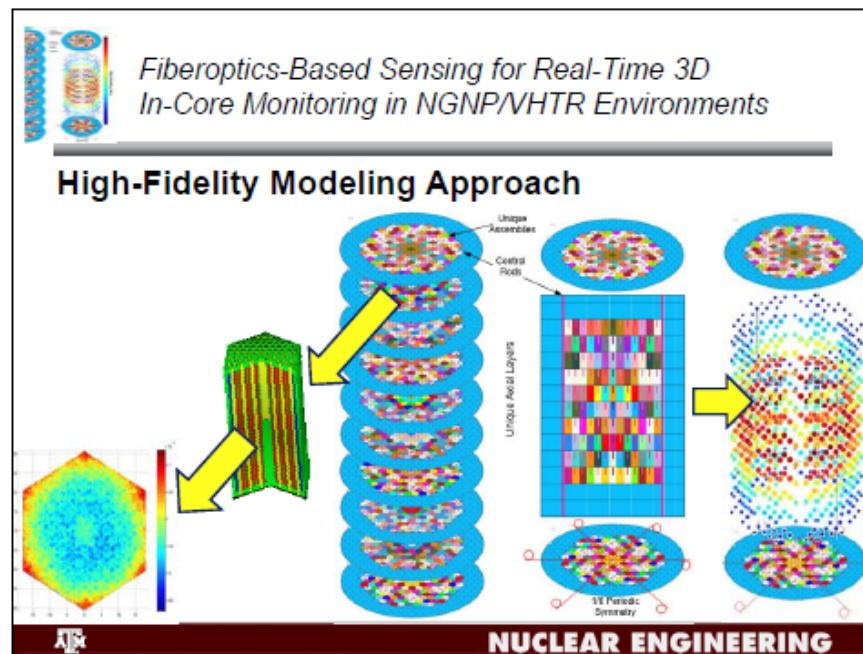
Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

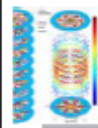
Emulation of VHTR Conditions in TRIGA



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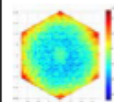
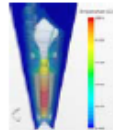




Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

In-Core Testing

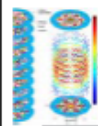
Key milestones:



- Development of theoretical approach to estimating neutron fluence distributed along the length of the sensing fiber.
- Test furnace engineering design with reactor safety board approval.
- Fiber optic sensor design and completion of out-of-core laboratory testing.
- Test furnace fabrication, assembly and completion of out-of-core testing.
- Delivery of sensor strings with connectors to university; installation in test furnace.
- Assembly installation in TRIGA and completion of irradiation test matrix.
- 3D VHTR and TRIGA modeling with representation of distributed sensor network elements, performance reconstruction and optimization of the network design.
- Modeling validation using test measurements and scaling to the prototypical VHTR conditions.



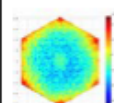
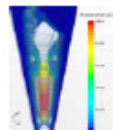
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Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

In-Core Testing

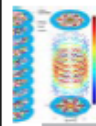
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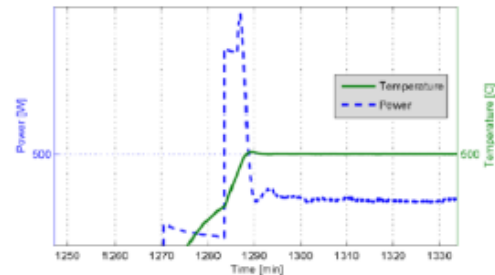


Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

In-Core Testing – High Temperature Furnace



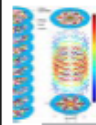
The furnace is capable of an automatic startup triggered by a user input followed by a swap to a auto controller.



The transition limits the temperature gradient from exceeding 0.2 °C/s and prevents overshoot to less than a degree.

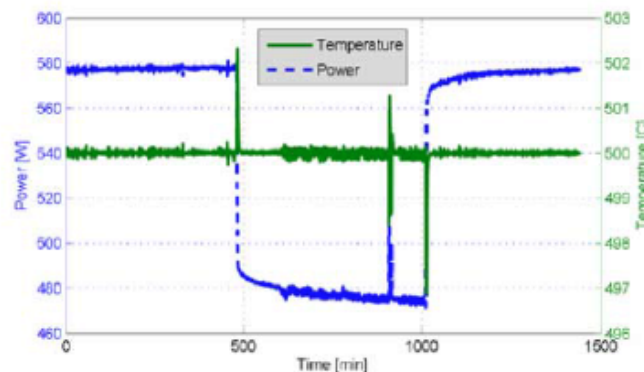
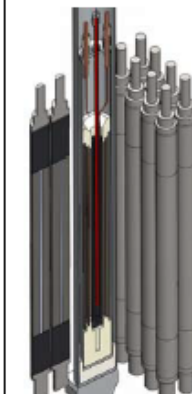


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Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

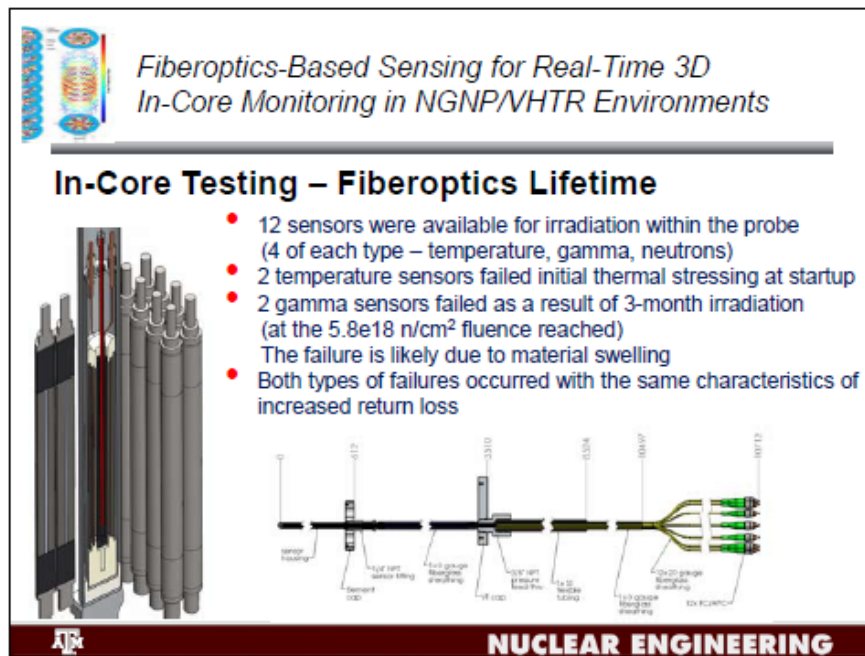
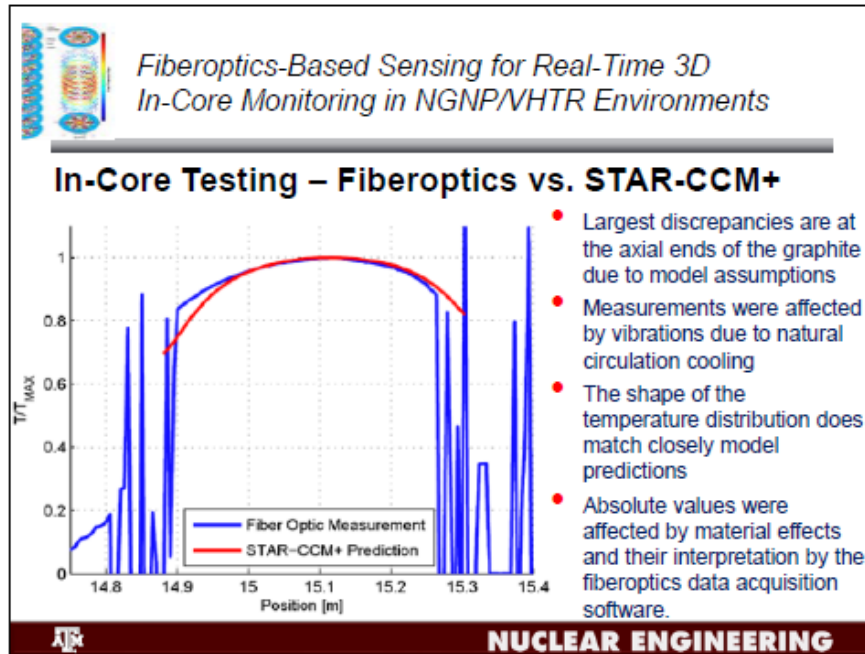
In-Core Testing – High Temperature Furnace

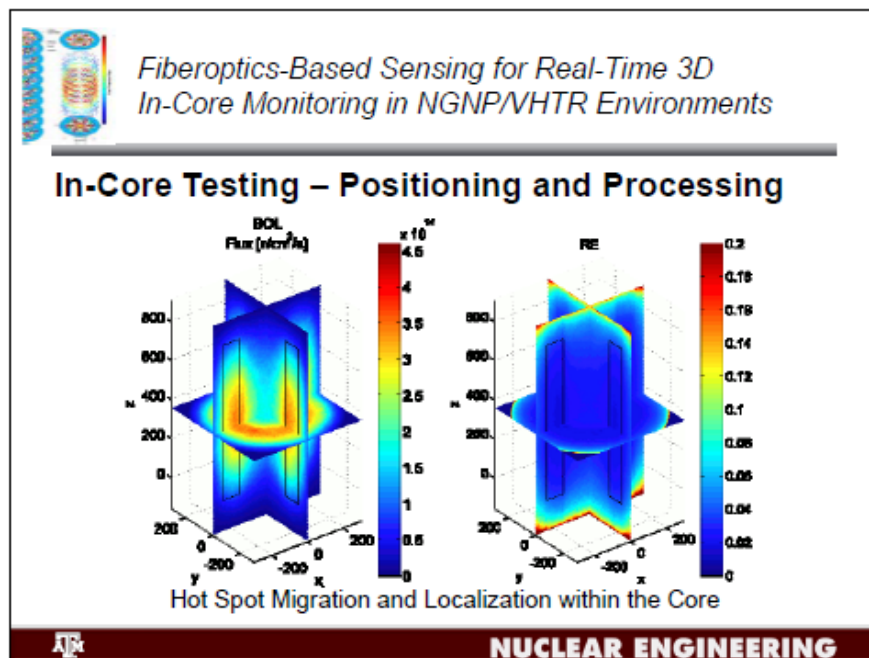
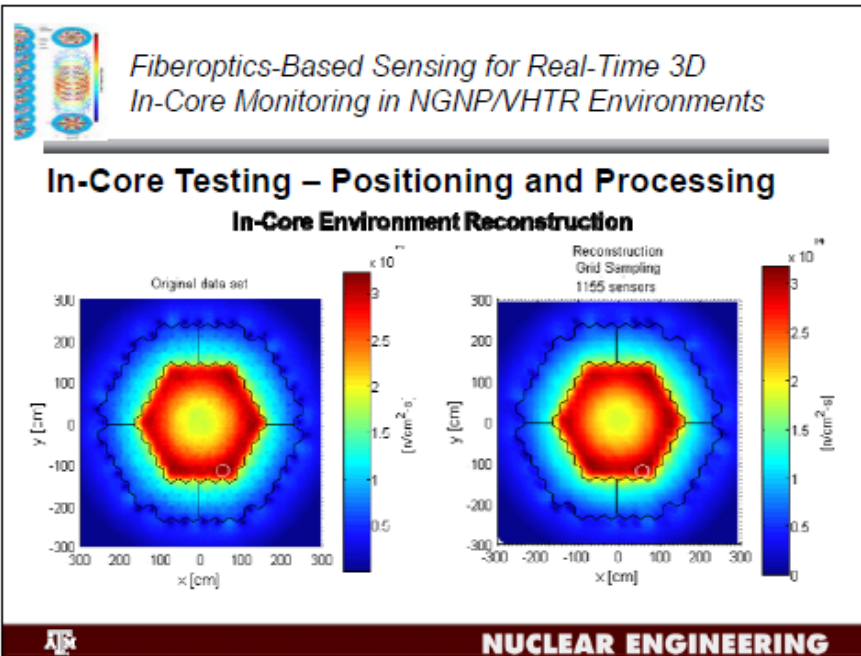


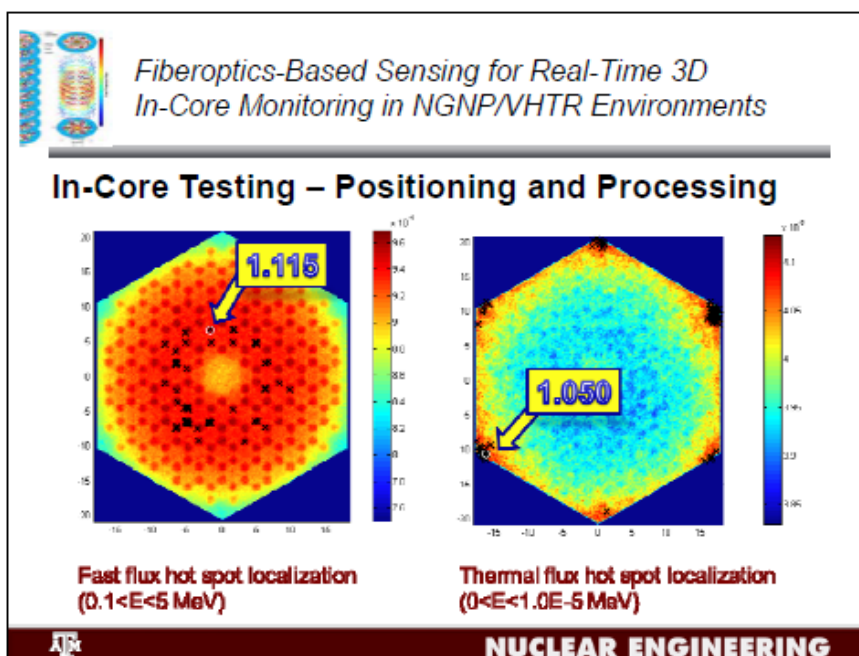
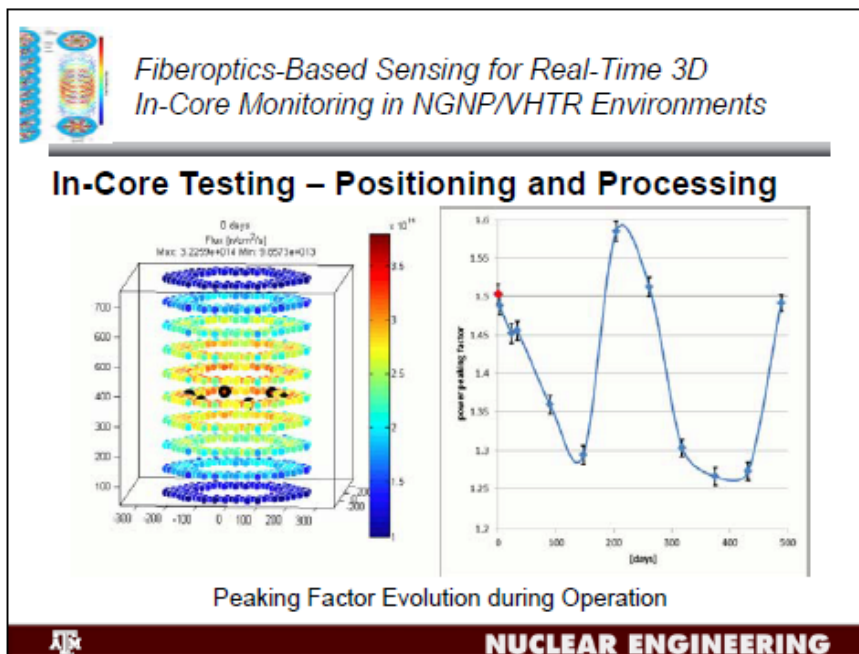
Full day operation of the high temperature furnace

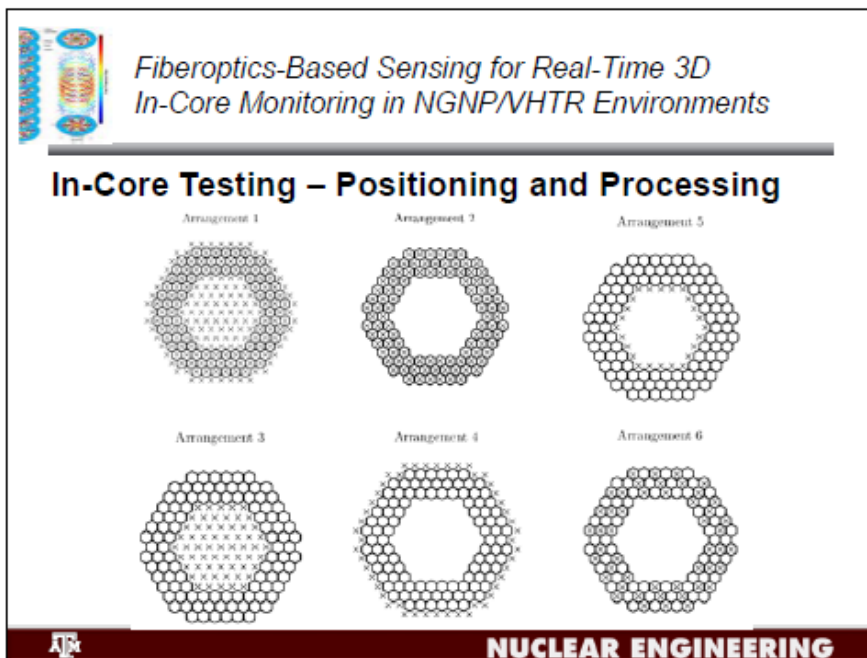
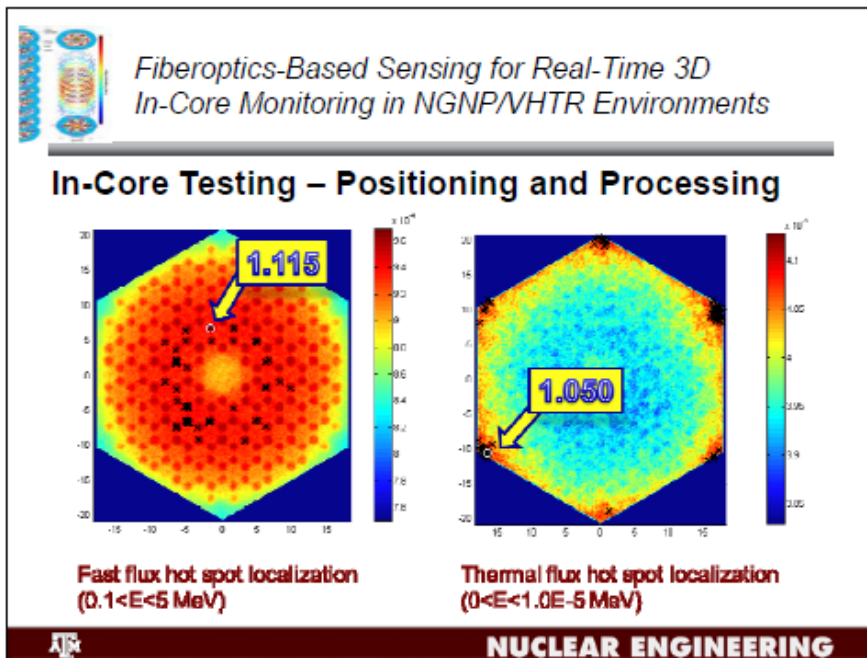


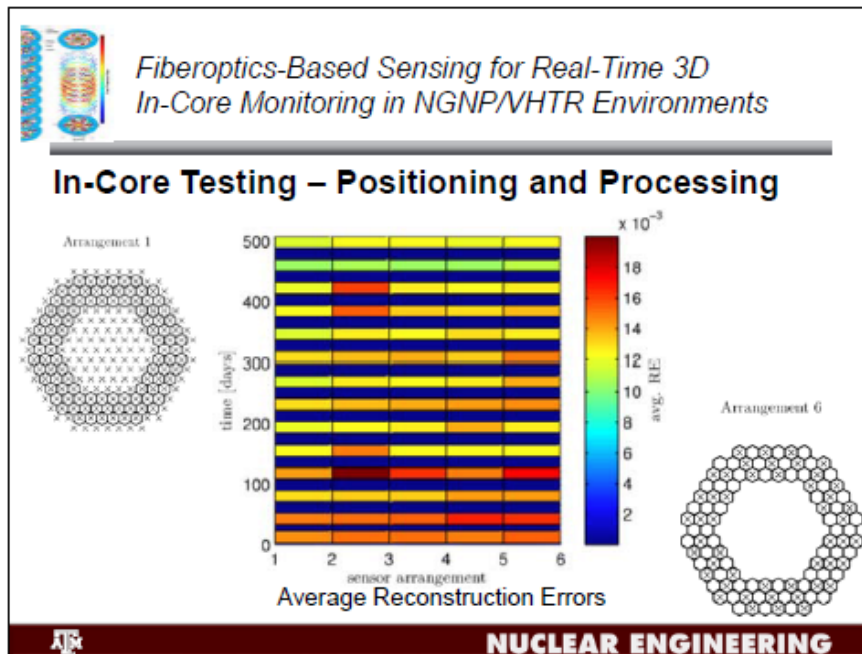
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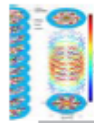
Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

Conclusions

- The gained experience indicate potential opportunities for future applications, especially in the environments which would be either physically hostile or geometrically challenging for traditional sensing technologies.
- Distributed sensing allows gathering more robust data during reactor operation which is essential not only for predictive safety monitoring but also for competitive reliability and economics.
- The project was focused on NGNP/VHTR but the analyzed fiberoptics sensing and 3D in-core monitoring via distributed sensing are of paramount value for LWRs, emerging SMRs and all advanced reactors.

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Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

Conclusions

The noted challenges include excessive dependencies of sensing system performance characteristics on:

- vibrations due to thermo-mechanical core characteristics,
- noise effects,
- internal fiberoptics material effects,
- accompanying software components to recover and interpret measured performance characteristics,
- frequent calibration needs.

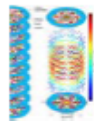
These challenges will have to be resolved in future R&D efforts.



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Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

Acknowledgements



We would like to extend our appreciation to our participating undergraduate students, Hanniel Honang Ndjomou and Carl Mullins, for the hard work and dedication to the success of the project.



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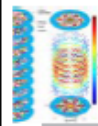

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Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

Acknowledgements



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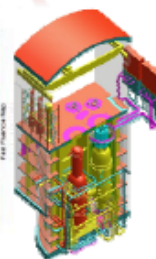
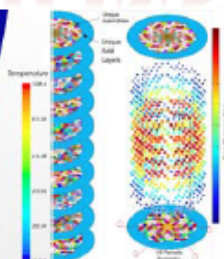
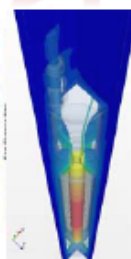
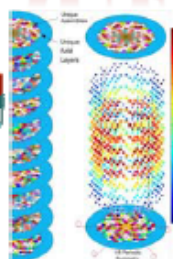
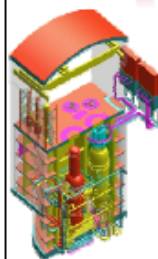


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Fiberoptics-Based Sensing for Real-Time 3D In-Core Monitoring in NGNP/VHTR Environments

QUESTIONS?



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Title: A Distributed Fiber Optic Sensor Network for Online 3D Temperature and Neutron Fluence Mapping in a VHTR Environment

PI Contact Info: Pavel V. Tsvetkov, Texas A&M University, tsvetkov@tamu.edu, 979-845-7078

Technical Workscope Identifier: Gen IV/Methods, TPOC: Abderrafi Ougouag (INL) Federal POC: Stahel Schuppner

Purpose/Objective: Real-time 3D mapping of the temperature and neutron fluence distributions in NGNP/VHTRs

Other Personnel: S. Iyaga-Sitton, Texas A&M University/INL
B. Dickerson, Luna Innovations

Student Personnel: Undergraduate - Hamed Hosang Ndjones
Carl Mullins

Graduate: - Matthew Johnson (M.S.)
(graduated)
- Satish Lakshminipathy (M.S.)
(graduated)
- Jesse Johns (Ph.D.)

Duration: October 2009 – September 2012 (ext. till 05/30/13)

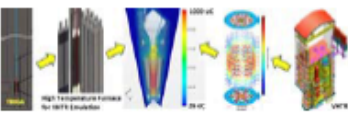
Total Funding Level: \$757,543

Special Tools/Methods and Facilities being used:

Experimental: high temperature furnace emulating VHTR in TRIGA
fluences of 2×10^{19} n/cm² or higher, 1000°C

Computational Modeling or Theory: whole-core exact-geometry modeling of VHTRs and TRIGA

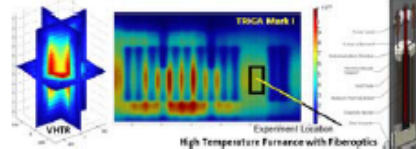
Facilities/Equipment: Texas A&M University TRIGA Mark I IMW



Importance/Tolerance: direct in-core monitoring in real time to enhance safety, instrumentation for benchmarking in design, reduction of uncertainties in local phenomena assessment

Logical Path: (1) evaluate fiber optics for in-core distributed sensor networks in VHTRs and (2) develop a predictive 3D performance reconstruction algorithm for VHTR in-core instrumentation

Impact Areas: real time assessment of reactor conditions, hot spot localization prediction, design margin optimization, 3D in-core instrumentation for code benchmarking



Sample Results:

Confident that the safety of TRIGA will not be impacted

Temperature requirements, following bench top tests, may change
Temperature fiber optic sensors perform, under normal conditions, as expected. The assembly has been installed in the designated TRIGA in-core location, experiments completed

Status of Deliverables:

Year I and II: furnace design, fabrication,

3D VHTR modeling focusing

on in-core performance

reconstruction and sensor networks

Year III: Irradiation, PH, TRIGA/VHTR scaling,

sensor network studies

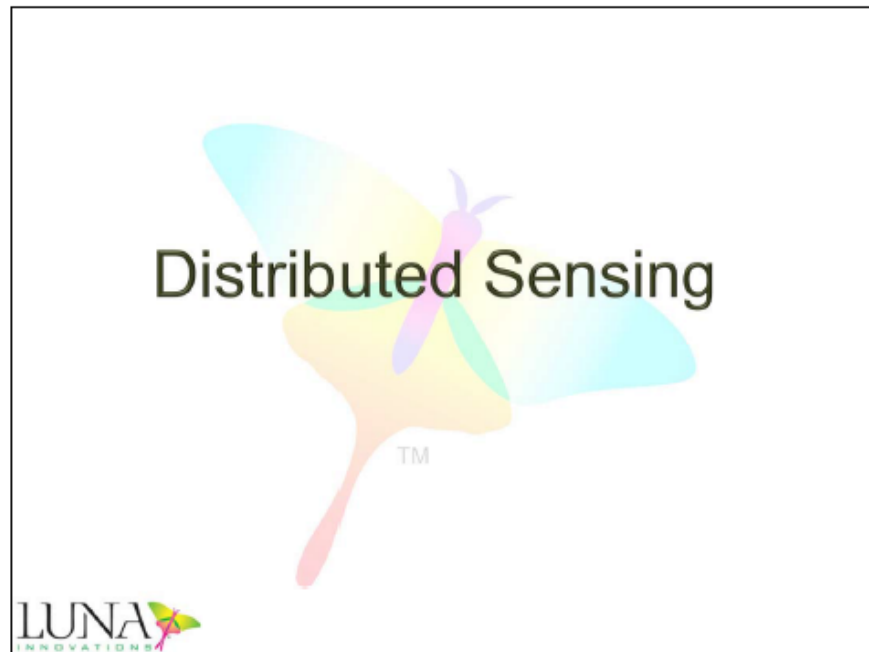
Issues – no principal challenges, design and development

Workscope is completed

Presentations/publications: ANS Annual/Winter

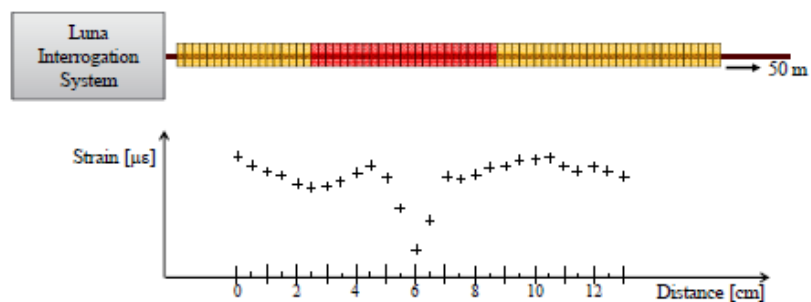
Meetings in 2010 through 13, PHYSOR 2012, ICONE 2012





Luna's Approach – High Definition Sensing

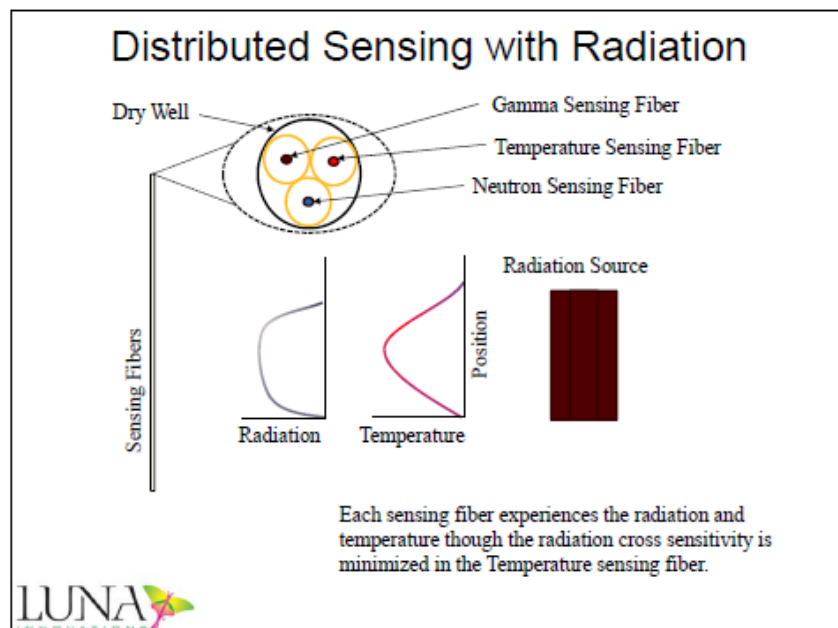
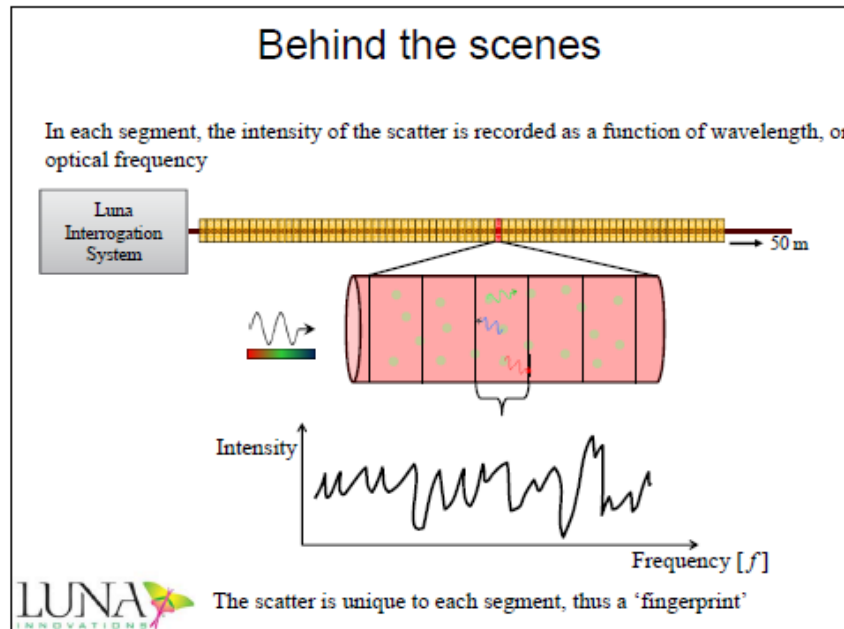
Regions of distributed sensing can be defined as well



Extremely useful observing how strain changes continuously over a region

Small, localized events can be observed, where larger foil gages would have averaged, and washed out the response





10.4.8. 3D Mapping and Reconstruction for In-Core Monitoring

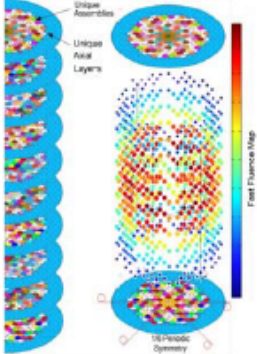


3D Mapping and Reconstruction for In-Core Monitoring in Advanced Reactors

Matthew P. Johnson, Pavel V. Tsvetkov
 Department of Nuclear Engineering
 Texas A&M University

Advanced/Gen-IV Reactors - II

*Thursday, November 14, 2013, ANS 2013 Winter Meeting
 November 10-14, 2013, Omni Shoreham Hotel, Washington D.C.*



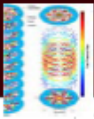






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3D Mapping and Reconstruction for In-Core Monitoring in Advanced Reactors

- Introduction
- Applied Models
- Core Performance
- Flux Reconstruction
- Interpolation Theory
- Proper Orthogonal Decomposition (POD) Theory
- Flux Reconstruction Performance
- Conclusions









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Introduction

HTR background

- Brief history of HTRs
 - DRAGON (1966): 20 MW
 - Peach Bottom (1967)
 - AVR (1967): pebble bed
 - Ft. St. Vrain (1977): full-size power reactor, shut down in 1992
- This work uses three ring VHTR based off of the INL NGNP design
- HTR advantages: flexible in their neutronic design, can be engineered to be intrinsically safe



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Introduction

Need for new sensors

- Potential in-core sensors include
 - Fission chambers
 - Self-powered neutron detectors (SPNDs)
 - Fiber optic sensors
- Current generation fission chambers and SPNDs are not capable of surviving for prolonged periods in the high temperature environment of HTRs
- Fiber optics can survive in high temperatures. They have been used as temperature sensors for some time; however, recently a method for using them as neutron detectors was suggested.
- Fiber optics yield significantly more data than other sensors since they record data along their entire length.



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Applied Models

Core overview

- Prismatic blocks stacked into a cylinder
- Graphite is used as primary structural material
- Active core region is annular
- Graphite inner reflector provides a large heat sink
- Helium selected as a coolant because it is chemically inert
- Electricity generation options: direct Brayton cycle, secondary loop with a Rankine cycle

Power	600 MWth
Fuel	UO ₂
Moderator	Graphite
Coolant	Helium
Coolant pressure	7.12 MPa
Core inlet temperature	490 °C
Core outlet temperature	1000 °C
Core diameter	7 m
Core height	10.7 m

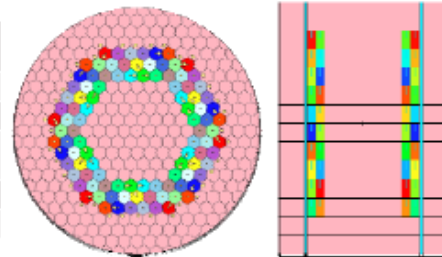


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Applied Models

Core Geometry

Fuel Blocks	1020 (170 unique)
Operational Control Rods	36
Startup Control Rods	12
Reserve Shutdown Channels	8
Power	600 MWth
U Enrichment	15 at. %



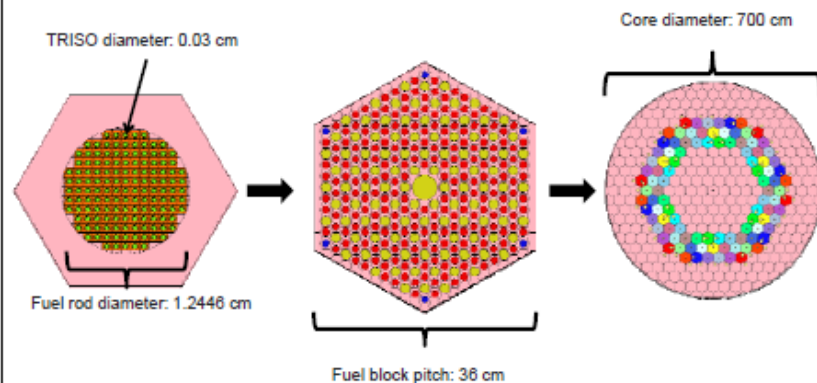
Cross-sectional views of the core. Fuel blocks are color coded according to their burnable material.



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Applied Models

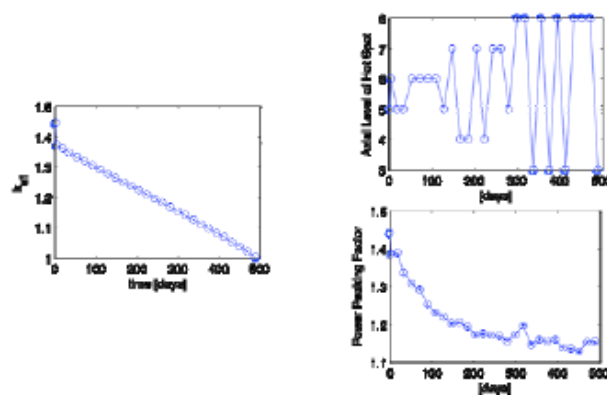
Disparate length scales



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Core Performance

k_{eff} , peaking factor, hot spot location

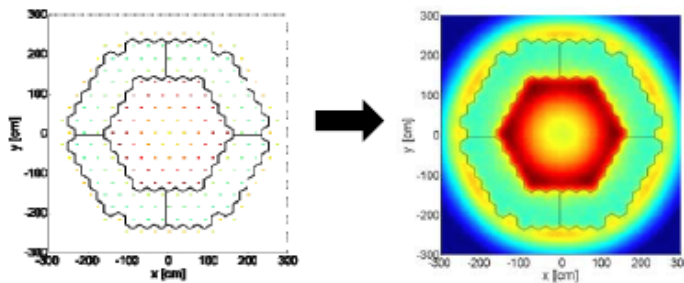


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Flux Reconstruction

Problem statement

- Given flux measurements at discrete locations within the reactor, can the full flux distribution be reconstructed?
- Fiber optic sensors run the full length of the core, so measurement in z is continuous



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Flux Reconstruction

Goals

- Accurate reconstruction of the full-core thermal neutron flux with special emphasis on the location and magnitude of the neutronic hot spot
- norm of error in hot spot location = $\|\vec{x}_{reconstructed} - \vec{x}_{actual}\|_2$
- reconstruction residual = $|A_{reconstructed} - A_{actual}|$
- relative error = $\frac{|A_{reconstructed} - A_{actual}|}{A_{actual}}$
- percent error in $\phi(\vec{x}_{hot}) = \frac{\phi_{reconstructed}(\vec{x}_{hot}) - \phi_{actual}(\vec{x}_{hot})}{\phi_{actual}(\vec{x}_{hot})} \times 100$
- error in hot spot z coordinate = $z_{actual} - z_{predicted}$
- Two different algorithms were investigated: interpolation and POD



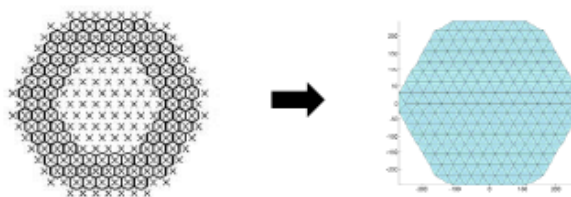
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Interpolation Theory

Overview

- Interpolation is the most straightforward method, but how accurate is it?
- Sensor locations will be related to the hexagonal lattice.
- Interpolation on unstructured grids

Arrangement 1



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Interpolation Theory

Summary

- Construct a mesh whose simplexes are located at the flux measurement locations and interpolate.
- Mesh generation algorithms abound; however, Delaunay triangulations work just fine.
- Barycentric coordinates are commonplace in computational geometry, thus there is plenty of existing software that does the aforementioned calculations. In this work Matlab was used.

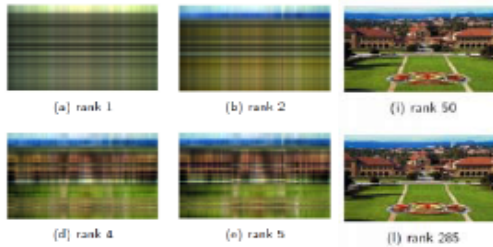


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POD Theory

Proper orthogonal decomposition

- Has connections to image compression*



- In engineering, often used in conjunction with Galerkin projection to form low order models
- Used to analyze time-series data

* source: David Amodeo & Charles Petrait, Stanford University, CME 365 class notes



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POD Theory

Proper orthogonal decomposition

- Given time-series data, POD can be used to represent this data in the following form:

$$\phi(\vec{x}, t) = \sum_{k=1}^M a_k(t) \psi_k(\vec{x})$$

- The POD modes, ψ_k , sometimes referred to as empirical eigenfunctions, are found with the singular value decomposition. Data from m spatial locations at N different times are stored in matrix in $N \times m$ matrix A . Taking the singular value decomposition:
 $A = U \Sigma V^T$
- U is an $N \times N$ orthogonal matrix, Σ is an $N \times m$ matrix whose only nonzero elements lie on its diagonal, and V is an $m \times m$ orthogonal matrix.
- The columns of V are used as the POD modes.



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POD Theory

Gappy reconstruction

- Sensors only measure a small subset of the data. How to accurately find all a_k ?
- Previous researchers have called this gappy reconstruction
- Let Φ be a vector that contains the scalar flux at all locations in the domain at a moment in time. Let n be a mask vector, the same size as Φ , that contains 1 at sensor locations and 0 elsewhere.
- The data from the sensors is then (n, Φ) , where $(\cdot, \cdot)$ represents pointwise multiplication.
- Define the gappy inner product

$$(a, b)_n = [(n, a), (n, b)]$$
- And the gappy norm

$$\|a\|_n^2 = (a, a)_n$$



POD Theory

Gappy reconstruction

- Given a set of gappy data, $g = (n, \Phi)$, find a reconstructed field, $\tilde{g}$, from the POD basis

$$\tilde{g} \approx \sum_{k=1}^M a_k \psi_k$$

- Seek $\tilde{g}$ that minimizes:

$$\|g - \tilde{g}\|_n^2$$

- The above expression is differentiated w.r.t. each a_k to yield the following system of equations

$$Ma = f$$

where $M_{ij} = (\psi^i, \psi^j)_n$ and $f_i = (g, \psi^i)_n$

- Solve for a , calculate $\tilde{g}$, use $\tilde{g}$ to fill in missing entries from g



Flux Reconstruction Performance

FOMs

Review the FOMs used to quantify reconstruction algorithm performance

- norm of error in hot spot location = $\|\vec{x}_{reconstructed} - \vec{x}_{actual}\|_2$
- reconstruction residual = $|A_{reconstructed} - A_{actual}|$
- relative error = $\frac{|A_{reconstructed} - A_{actual}|}{A_{actual}}$
- percent error in $\phi(\vec{x}_{hot}) = \frac{\phi_{reconstructed}(\vec{x}_{hot}) - \phi_{actual}(\vec{x}_{hot})}{\phi_{actual}(\vec{x}_{hot})} \times 100$
- error in hot spot z coordinate = $z_{actual} - z_{predicted}$

These FOMs are calculated at each time step. In order to make visualization and comparison easier, they may be averaged over time. For FOMs that may be positive or negative, the absolute value is taken before averaging.

These FOMs can be calculated for the whole core flux or just the flux in the active core region.



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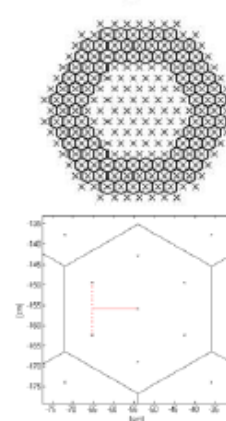
Flux Reconstruction Performance

Interpolation

- In order to test the interpolation algorithm, sensors were placed in all blocks of the inner reflector, all blocks of the active core, and one ring of the outer reflector.
- Within each block, six different sensor configurations were considered:

Configuration	Pitch [cm]
A	0.0
B	3.25563
C	6.511125
D	8.138907
E	11.39447
F	13.02225

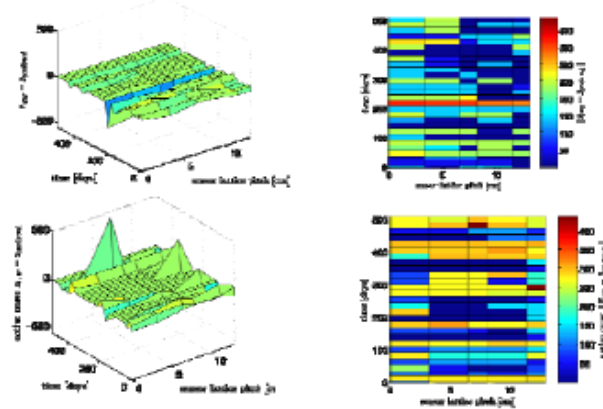
Arrangement 1



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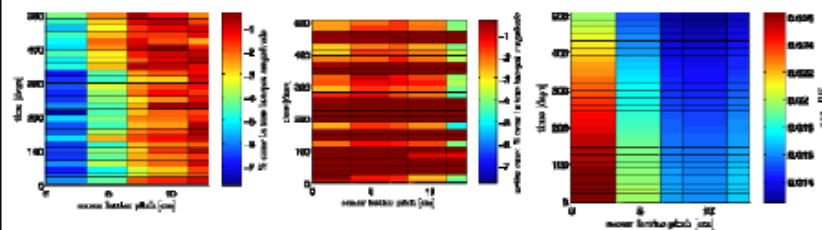
Flux Reconstruction Performance Interpolation Performance

Variable pitch – hot spot location



Flux Reconstruction Performance Interpolation Performance

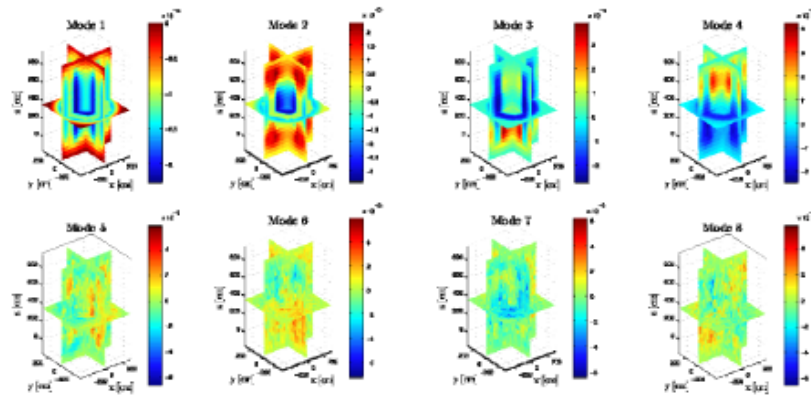
Variable pitch – hot spot magnitude and avg. RE



Interpolation predicts the active core hotspot
magnitude more accurately

Flux Reconstruction Performance POD Performance

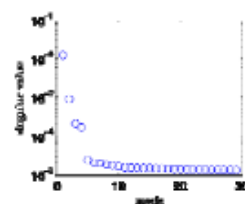
POD modes



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Flux Reconstruction Performance POD Performance

Singular values



Singular values decrease in magnitude rapidly before leveling off. There is a noise floor in the data due to the Monte Carlo solution method.



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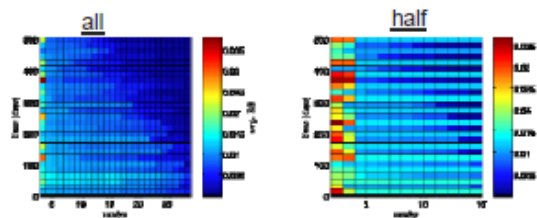
Flux Reconstruction Performance POD Performance

Number of modes used in reconstruction

- Vary number of POD modes used during the reconstruction.
- Two cases: all time steps to create the POD basis, half of the time steps used to create the POD basis

$$A = U\Sigma V^T$$

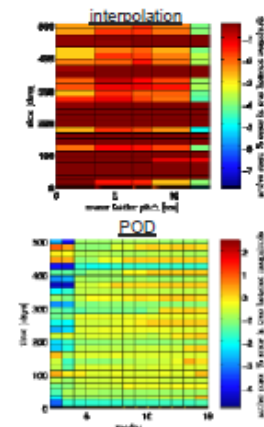
- The second test case is important because in reality, the flux distribution in the reactor will not be an exact match to one of the simulation results



Flux Reconstruction Performance POD Performance

Number of modes used in reconstruction

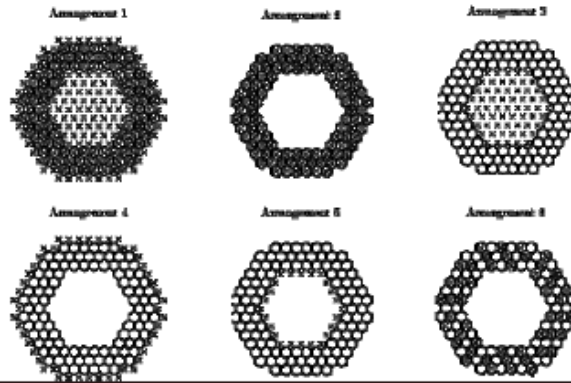
- As expected, using all modes perfectly reconstructs the data
- In reality, the in core flux distribution will not be a perfect match to one of the snapshots used to generate the POD basis. This is simulated by only using half (every other) snapshot when generating the POD basis.
- Only using half of the modes still outperforms the interpolation based reconstruction, especially in the % error in true hotspot magnitude FOM
 - POD results only compare directly to the interpolation results for the zero-pitch arrangement.
- All remaining POD reconstruction results use the POD basis generated from half the data



Flux Reconstruction Performance POD Performance

POD different sensor arrangements

- The high accuracy of the POD method using a single sensor at each block center suggests that even fewer sensors could be used

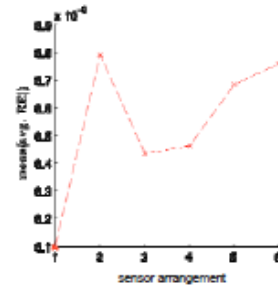
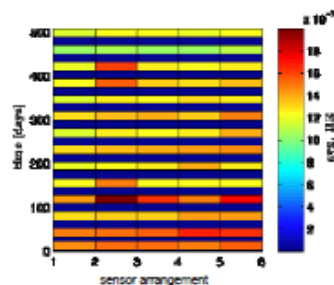


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Flux Reconstruction Performance POD Performance

POD different sensor arrangements

- Reconstruction algorithm run using all 15 modes of the half snapshot POD basis
- From the avg. RE FOM, it is clear that all perform similarly. This is in contrast the interpolation algorithm where simply changing the sensor pitch adjusted the average RE by ~1%



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Flux Reconstruction Performance POD Performance

Summary of results for different sensor arrangements

- There isn't a big difference in any of the FOMs
- Once again, the z coordinate of the hot spot is predicted very well, but it's (x,y) coordinates are not.
- Interesting that arrangement 1 does clearly perform better than the others, even though it contains the most instrumented blocks
- While the margins are slim, arrangements 3 and 5 reproduce the true hot spot's magnitude most accurately.



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Flux Reconstruction Performance

Noise and sensor failure

- What happens when there is noise?
- Uniform noise was added to the sensor signals

$$\Phi_{noisy} = \Phi + \alpha \cdot n \cdot \pi \cdot \Phi$$

where " ." indicates point-wise multiplication, Φ is a $m \times 1$ matrix containing the flux measurements, α is a $m \times 1$ matrix whose entries individually randomly chosen to be 1 or -1, n is the error to be introduced by the noise, and π is a $m \times 1$ matrix of random values between 0 and 1

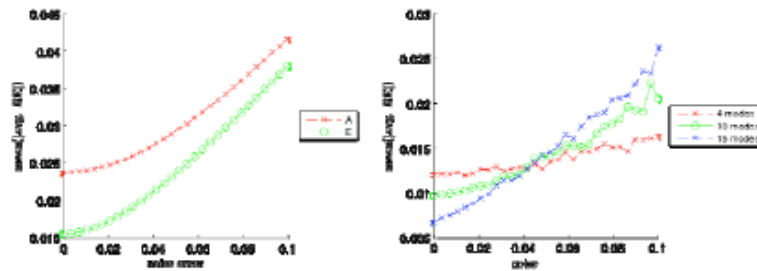
- Interpolation algorithm was run using sensor arrangement 1 with pitches A and E
- POD algorithm was run using sensor arrangement 5, but with a varying number of modes



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Flux Reconstruction Performance Noisy Reconstruction

Avg RE



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Flux Reconstruction Performance Noisy Reconstruction

Conclusions

- The POD method clearly outperforms the interpolation method in the avg. RE and true hot spot magnitude FOMs
- They perform similarly on the hot spot location error metrics. Small levels of noise (< 3%) have almost no effect on POD reconstruction, but after that threshold reconstruction error increases.
- Regarding the number of POD modes used: reconstructions using fewer modes are less effected by noise, but have initially lower accuracy.



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Flux Reconstruction Performance

What if sensors fail?

- Sensors were failed deterministically, according to their closeness to the true hot spot location
- Cases were run for POD using all 15 modes from the half snapshot basis
 - All sensor configurations were tested
- Cases for interpolation were not run because interpolation clearly fails as it has no way of filling in the lost data



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Flux Reconstruction Performance Sensor Failure

Conclusions

- Sensor failure does not have a large effect on the performance of the POD algorithm.
- Sensor arrangements using even few sensors could be considered.



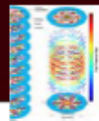
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Summary/Conclusions

- Interpolation and POD were investigated as flux reconstruction techniques because they do not rely on diffusion models
- POD appears to have better performance, although it relies in pre-computed snapshots of the neutron flux. The accuracy of the POD method would degrade rapidly if the reactor flux distribution was significantly different than the snapshots.
- The exact location of the hot spot is hard to predict. Due to core symmetry there should be 6 locations in the core that contain the hot spot. In a real system stochastic phenomena would remove the perfect symmetry in the flux distribution. In a Monte Carlo simulation, the stochastic solution process removes the perfect symmetry.
 - All 6 theoretical hot spots would have the same z coordinate. The reconstruction algorithms are effective at predicting the z coordinate.



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3D Mapping and Reconstruction for In-Core Monitoring in Advanced Reactors

Acknowledgements



We would like to extend our appreciation to our participating undergraduate students, Hanniel Honang Ndjomou and Carl Mullins, for the hard work and dedication to the success of the project.



GENERAL ATOMICS



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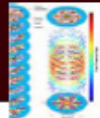


GENERAL ATOMICS



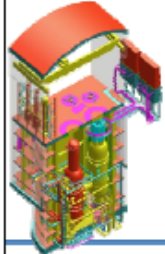
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3D Mapping and Reconstruction for In-Core Monitoring in Advanced Reactors

Acknowledgements



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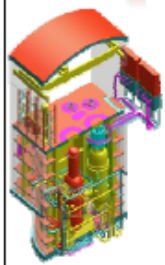
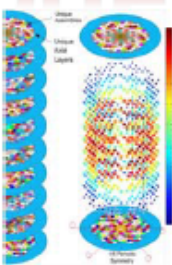
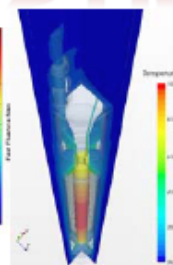
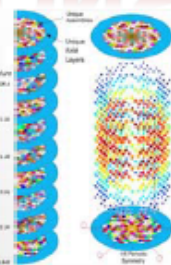
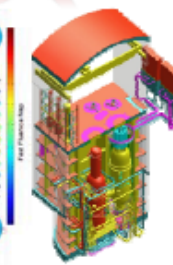


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3D Mapping and Reconstruction for In-Core Monitoring in Advanced Reactors

QUESTIONS?







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Contact Information

Shannon M. Bragg-Sitton

Senior Nuclear Engineer
Fuel Performance and Design
Idaho National Laboratory
P.O. Box 1625 MS 3860
Idaho Falls, ID 83415-3860
Tel 208-526-2367
Fax 208-526-2930
Shannon.Bragg-Sitton@inl.gov

Pavel V. Tsvetkov

Associate Professor
Department of Nuclear Engineering
Texas A&M University
337 Zachry Engineering Center, MS 3133
College Station, TX, 77843-3133
Tel 979-845-7078
Fax 979-845-6443
Tsvetkov@tamu.edu

University Information

Texas A&M University, Department of Nuclear Engineering

337 Zachry Engineering Center, MS3133, College Station, TX, 77843
Tel 979-845-7078
Fax 979-845-6443
<http://engineering.tamu.edu/nuclear>



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