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FY-17 Status Report for the Development of Infrared Thermography for In-Pile Fuel Behavior Applications

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ABSTRACT

Under a Department of Energy Office of Nuclear Energy (DOE-NE) initiative to develop in-pile instrumentation, an activity has been initiated to develop an infrared thermography (IRT) approach for in-reactor monitoring of fuel behaviors. The project will focus on leveraging mature, mainstream IRT techniques for use on nuclear fuel systems inside a nuclear reactor through unique adaptations for remote applications – an extremely challenging engineering and measurement objective – never before accomplished in-pile. To this end, some of the most important issues to be addressed include identifying an optimal IRT configuration (of many possible) and components for detecting specific structural evolutions such as fuel cracking and fuel void formation and migration; developing a long distance imaging system to transmit high resolution infrared images from a small specimen surface in the harsh environment of a reactor core to a IR camera or other detector array; and ultimately, integrating a complete experimental system to create a full in-reactor experiment. This document provides an overview of potential in-pile applications of IRT, a brief overview of IRT techniques, a detailed research plan and schedule for the project, and a summary of activities that have been initiated in the closing months of Fiscal Year 2017.

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1. Introduction

Infrared thermography (IRT) is a versatile technique used by many industries for non-destructive evaluation (NDE) applications[i]. IRT is based on the principle of measuring thermal radiation emitted from objects to create an image. Contrast in the image is related to temperature variations across the object. Cracks, voids and discontinuities in a fuel pellet create barriers to thermal conduction and steep temperature gradients which are revealed in the IRT image as shown in Figure 1.[ii,iii]

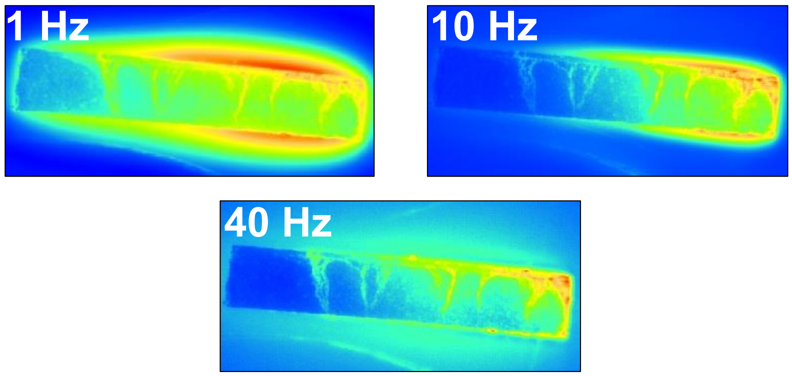

Figure 1. Examples of phase images from lock-in thermography of a cross-section of ZrC taken at different frequencies. Images demonstrate strong sensitivity to cracks in the material as well as changes in thermal properties.

IRT has a number of advantages for in-pile measurements. It is a non-contact technique which requires only optical access to the object. Images can be created in real time and the signal strength increases with increasing temperature. IRT is well developed in commercial industry and has been used for crack detection in high temperature applications. Furthermore, commercial innovations in IRT cameras and detectors can be leveraged for in-reactor measurements.

Under a Department of Energy Office of Nuclear Energy (DOE-NE) initiative to develop in-pile instrumentation, an activity has been initiated to develop an infrared thermography (IRT) approach for in-reactor monitoring of fuel behaviors. The project will focus on leveraging mature, mainstream IRT techniques for use on nuclear fuel systems inside a nuclear reactor through unique adaptations for remote applications – an extremely challenging engineering and measurement objective – never before accomplished in-pile. To this end, some of the most important issues to be addressed include identifying an optimal IRT configuration (of many possible) and components for detecting specific structural evolutions such as fuel cracking and fuel void formation and migration; developing a long distance imaging system to transmit high resolution infrared images from a small specimen surface in the harsh environment of a reactor core to a IR camera or other detector array; and ultimately, integrating a complete experimental system to create a full in-reactor experiment. This document provides an overview of potential in-pile applications of IRT, a brief overview of IRT techniques, a detailed research plan and schedule for the project, and a summary of activities that have been initiated in the closing months of fiscal year 2017.

1.1 Potential In-Pile Applications

IRT has applicability for several important fuel performance parameters. Structural changes to the fuel and cladding can have a profound influence on fuel performance and behavior. In some cases such as fuel facture and central void formation, the structural changes can take place in the first few hours after startup. In other cases such as fuel cladding interaction, structural changes may happen over a time span ranging from months to years under normal operation and down to seconds or less for power ramping and accident condition fuel behaviors. In all cases, the phenomena lends well to detection by IRT. This section summarizes several potential applications of IRT in nuclear fuel. The initial focus of this project is on deployment of IRT with the primary goal of measuring fuel fracture behaviors.

Fuel Fracture

In ceramic fuels, fracturing of the ceramic pellets greatly influences the performance of the fuel. Recent modeling work suggests that substantial radial cracking forms within the first few hours of the initial power ramp. The cracks are formed as a result of high tensile hoop and axial stresses in the peripheral regions of the pellets created by large thermal gradients. As power ramps down, the resulting thermal gradients cause the formation of circumferential cracks. These cracks play a critical role in the fuel performance as they extend the effective diameter of the fuel, closing the fuel-cladding gap, while introducing interfacial thermal resistances lowering the effective thermal conductivity of the fuel. Recent activities in fuel performance modeling have focused on developing mechanistic approaches for predicting fuel fracture behavior in fuel performance codes such as the MOOSE-based BISON code. The effort has resulted in simulation results that produce reasonable cracking profiles. However, the availability of data to validate such detailed model results is limited.

Central Void Formation in Fuels

The formation of a central void in MOX fuels is another phenomenon that happens on an hours-to-days time frame following the initial power ramp. Due to the relatively poor thermal conductivity associated with typical oxide fuels, the maximum temperature gradient is in excess of 105 K/m. In addition to severe thermal stresses, this gradient is a driving force for atomic transport. The movement of small voids requires transfer of atoms or vacancies form the leading edge to the trailing surface. As these voids move up the thermal gradient, they coalesce in the fuel interior forming a large central void. Fission gas release, swelling, embrittlement, creep and thermal conductivity are strongly related to the motion and growth kinetics of voids. The ability to image the formation of the central void would give computation material scientists unparalleled insight into the kinetics that govern void growth and motion.

Fuel-Cladding Interaction

Additionally, fuel-cladding interaction is of great interest for the continued development of both metallic and oxide fuels. In metallic fuels, internal pressure in the fuel pin builds rapidly with burnup from resulting fission gas release, while the metallic fuel remains somewhat plastic during fissioning. For modern fuel designs, direct fuel-cladding mechanical interaction (FCMI) is not problematic. However, fuel-cladding chemical interaction (FCCI) is of great importance for predicting fuel performance behavior and is a complex, multicomponent diffusion problem. FCCI results in weakening of cladding and formation of low-melting point compositions in the fuel. The problem is customarily studied by exposing diffusion-couples to high temperatures. In light water reactor oxide fuels, exposure to high pressure water environments causes the cladding to creep down onto the fuel pellet surfaces. Thermal gradients resulting from power increases in the fuel result in fuel fracture as previously described, while fission product accumulation causes fuel swelling. The increase of fuel external diameter and creeped-down cladding becomes critical for predicting fuel behavior. Power increases cause thermal expansion of the pellets, opening of pellet cracks, and release of fission gas that all cause further increase of fuel diameter. The result of these phenomena is the potential for cladding failure stemming from stress corrosion cracking and delayed hydride cracking in the cladding.

Material Thermal Properties

The basic principle of measurement for active mode IRT is equivalent to techniques used to measure thermal properties including laser flash, all classified as photothermal radiometry techniques. More details regarding the thermal properties evolution and its importance to fuel behavior may be found elsewhere. Thermal properties measurement is not the near-term focus for IRT development but briefly mentioned here to highlight an additional important potential application that may be enabled by its development[iv].

2. Method Overview

The basic principle of IRT is by way of detection of radiated electromagnetic energy from a sample at a given temperature, governed by Planck's Law. The temperature response of a thermally stimulated sample is dependent on the thermal conductivity, specific heat capacity, and density of all materials in the sample. Heterogeneous structures such as voids, cracks, delaminations in multilayered materials, represent regions of differing thermal properties, which result in perturbations in the temperature field. Experimental configurations and data reduction techniques capitalize on these dependencies to create the highest possible sensitivity to the targeted measurement parameter(s) in a given specimen. In radiometry measurements, the detected radiation is a function of sample emissivity with directional and spectral dependencies as well as effects from direct or reflected radiation from surroundings. Further measurement dependencies result from the detector characteristics including particular wavelength sensitivity bandwidths. Other experimental impacts may need to be considered such as added wavelength dependencies due to optical components in the transmission path between the specimen and detector. Because of the many dependencies resulting in the measured and processed signal from an IR detector, experiment design and data processing and interpretation must be carefully approached to ensure accurate measurements. While some radiometric measurements may be point wise and even scanned to create an image, IRT has the advantage of capturing an entire image in a single measurement composed of potentially thousands of points of data. Detailed reviews of IRT may be found in [v,vi].

2.1 Relevant Technique Variations

IRT may be divided into two approaches termed passive and active approaches. The simplest in terms of experimental setup, passive approaches are used to detect infrared emission from naturally existing temperature fields. Active IRT requires an external stimulus to induce thermal contrast in a specimen. Figure 2 shows a general schematic of an IRT setup. When heat stimulation is provided by photons such as with lamps or laser beams, the methods are also called photothermal techniques. When detection is comprised of a single spot, the technique is generally referred to as photothermal radiometry rather than thermography. Several approaches to active thermography have been developed and classified depending on the external stimulus, such as pulse or flash IRT, lock-in IRT, scanning-laser IRT, and vibrothermography. Innumerable data processing techniques have been studied for nearly each of these many modes of operation. Data analysis techniques will not be reviewed in depth here due to the wide ranging studies that have been done in this area. As an example, a summary of processing algorithms for flash IRT is documented in [vii].

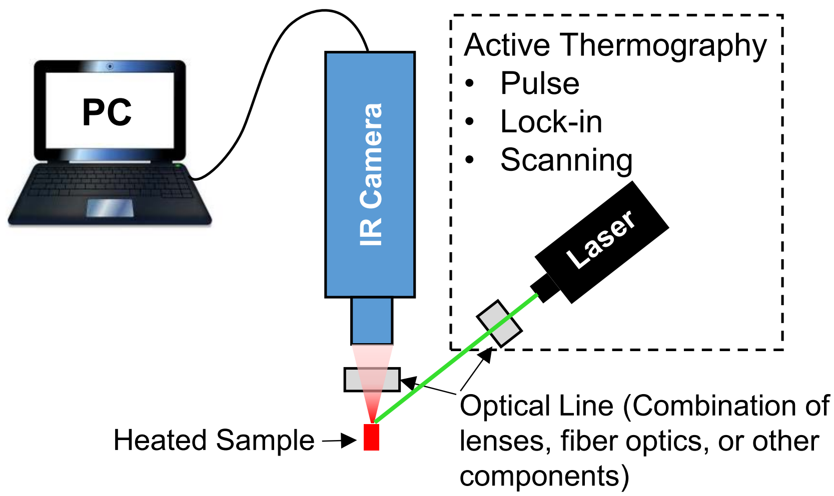

Figure 2. Schematic representation of a basic infrared thermography (IRT) setup based on laser heating. The boxed region is required for active mode IRT. The boxes representing the optical line are specific to measurement configuration.

In conventional active IRT setups, sample surfaces are heated with a spatially uniform distributed heat source such as a flash or halogen lamp. The resulting temperature response is recorded with the IR camera revealing the heat flow into the sample. Due to a predominantly one-dimensional (1-D), in-depth heat flow into the sample, the technique is most sensitive to structures oriented to alter thermal diffusion in this direction, or with characteristics parallel to the heated surface. Cracks and other defects oriented perpendicular to the surface will have lesser effect on heat flow and will not be well detected. For this reason, IRT techniques may also employ point or line heat source approaches to generate heat flow parallel to the plane of the measured surface.

Further distinction of experimental approaches may be made based on the configuration of detection relative to the heat source. In same-side detection mode, the heat source and detector are located on the same side of the inspected specimen while back-side detection mode the heat source and detector are located on opposite sides of the specimen. Same-side detection will generally provide higher sensitivity to defects close to or on the heated surface while transmission mode allows better sensitivity to defects close to the rear surface as well as integral heat transfer effects through the thickness of the sample.

Pulse IRT is one of the most popular active mode IRT techniques due to its general simplicity and relatively quick application time. In this case, heating is applied in a sharp pulse to cause fast temperature rise where energy is absorbed on the specimen. The temperature response at the heated face then proceeds to decay as energy diffuses through the material. Defect structures typically manifest as areas of heat accumulation and thus higher surface temperatures over the defect. Time dependency provides information about the depth of the defects. For plane heat sources, the Fourier number = 1 = $\alpha \cdot t \cdot d^{-2}$ or $t = d^{2} \cdot \alpha^{-1}$ provides a first order approximation of the observation time as a function of the square of the subsurface defect depth. In homogenous isotropic materials, a rough rule of thumb is that the radius of the smallest detectable defect should be at least 1-2 times larger than its depth under the surface[v]. Variations of this technique include plane heat source and spot and line heat sources operated in either pulse or scanning modes.

Lock-in IRT is well-established technique utilizing a modulated heat source to stimulate a highly dissipative periodic temperature response in a target specimen with mathematical representation similar to evanescent waves. Due to the “wave” nature of the response, this technique is classified as a thermal wave method. Thermal wave methods have the distinct advantage of relating the measured temperature response to the applied heat source taking advantage of both measured amplitude and phase response from the measurement. A powerful attribute of thermal wave methods is the thermal diffusion length, the distance each “wave” travels before the temperature amplitude decays to 1/e of the amplitude at the heated surface. Thermal diffusion length, $\mu=(\alpha/\pi f)^{1/2}$, where α is material thermal diffusivity and f is the heating modulation frequency. Using the frequency-dependent thermal diffusion length, these techniques then have the advantage of non-destructively depth-profiling the sample with knowledge of sample thermal and geometric parameters.

Scanning-laser or “flying-spot” IRT uses a continuous laser to scan the interrogation surface and has been studied extensively in regards to crack detection due to its ability to detect a wide range of defect geometries and orientations and potential commercial applicability. The technique is still far slower than general 1-D pulse thermography but is best focused on localized regions, like would be the case for typical nuclear fuel experiments. Detailed review of recent developments can be found in [viii,ix].

Vibrothermography is performed by launching an ultrasonic wave into a material and measuring temperature induced response from heat dissipated at defect locations in a cold sample. The principle of the technique requires crack surfaces to be in contact. This technique is referenced here due to its specific application to detecting and quantifying cracks in materials. Recent developments are reviewed in [x,xi].

2.2 Crack Imaging

IRT has been utilized by several industries for NDE applications related to cracking in materials in addition to other common techniques such as dye penetrant, magnetic particles, eddy currents, and x-rays[i]. For more detailed review of IRT applied to crack studies see [viii,ix,xi]. Several recent studies have focused on modeling crack thermal response for IRT applications. In particular, a recent work has particularly strong relevancy to this project with a focus on modeling lock-in IRT using a laser spot in the vicinity of a crack[xii].

As described in Section 1.1, fuel pellet cracks may frequently be classified as having radial or circumferential orientation, each forming at different stages of fuel power history. Prototypic temperature distributions in oxide fuel result in large gradients of hundreds of Kelvin per millimeter across the radius of the fuel pellet as heat flows in this direction. Due to a dominance of radial heat flow, passive mode IRT techniques are expected to provide the best sensitivity to circumferential cracks and much less sensitivity to radial cracks. Spatially uniform heating in active mode IRT will result in high sensitivity to defects such as cracks oriented parallel to the imaged surface. For this reason, active mode approaches based on spatially nonuniform heating such as spot or line heat source methods, should provide important capability to target defects oriented in a variety of directions relative to the imaged surface. However, introducing a heat source (likely a laser spot) to a sample also introduces additional complexity to the experimental setup, a non-trivial, yet manageable consideration for in-pile deployment. Due to these considerations, the research plan will include exploration of both passive and active approaches to IRT.

3. Research Plan

Many potential nuclear fuel applications of IRT techniques exist as described in Section 1.1, however, the initial target application for this research will be imaging the evolution of fuel cracking. Other potential applications may be explored to a limited extent during the R&D studies performed with a focus on fuel cracking. The primary challenges to the application of IRT for the detection of fuel fracture and central void formation involve the standard in reactor issues including high radiation and also the ability to gain optical access to the sample. Coherent fiber optic bundles, such as those used in some borescopes, can be used to transmit images through pressure boundaries and along curved, non-linear paths. Investigation of IRT image transmission and its impact on image quality and crack detection will be one of the primary focus areas of this research. Another important challenge specific to nuclear fuel measurement is the wide range of temperatures experienced by the fuel which can saturate one area of the image and provide insufficient illumination in other areas. Under normal operating conditions, fuel temperature can drop by several hundreds of degrees over the few millimeters of the radial dimension. Methods for dealing with the large temperature range will also be addressed during the course of the research.

Tasks for the successful development of a thermographic imaging system for in-pile investigation of fuel cracking and central void formation are described in more detail below. Initially an IR thermography camera system will be procured and an experimental test set up will be developed to allow investigation of the various passive and active imaging techniques on surrogate samples at elevated temperatures. Development of image transmission and modelling of relevant fuel parameters will be conducted concurrently with the initial technique investigation. Image transmission techniques including coherent fiber optic bundles and free space image relay will be will be identified and tested. Image transmission will then be integrated into the thermographic imaging system and a prototype in-pile imaging system will be designed. The prototype will be used to demonstrate the ability to detect cracks in surrogate samples at elevated temperatures. Finally, lessons learned during prototype development will be used to design a capsule which incorporates the IRT imaging system for in-reactor testing.

Table 1 shows a research plan outline and associated schedule. Task planning for FY19 and beyond is subject to adjustment based on the results of research conducted during FY18.

Table 1. Research plan outline and schedule for the development of an in-reactor infrared thermography system (assuming continuous funding beyond FY-17).

Tasks	FY17				FY18				FY19				FY20			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1.0 Develop Thermography Station																
1.1 Identify and Procure Camera System	-	-	-	■	■											
1.2 Design Experimental Setup	-	-	-		■	■	■									
2.0 Investigate Thermography Techniques on Surrogates																
2.1 Investigate Passive Techniques	-	-	-		■	■										
2.2 Investigate Active Techniques	-	-	-			■	■	■								
3.0 Develop Image Transmission System																
3.1 Investigate Remote Imaging Techniques	-	-	-	■	■	■										
3.2 Image Transmission Testing	-	-	-			■	■	■								
3.3 Integrate Image Transmission	-	-	-					■	■	■	■					
4.0 Modeling and Simulation																
4.1 Fracture Modelling	-	-	-	■	■	■	■	■	■	■						
4.2 Infrared Measurement Response Modelling	-	-	-	■	■	■	■	■	■	■	■					
5.0 Develop Prototype In-Pile Measurement System																
5.1 Design Thermography System	-	-	-						■	■	■					
5.2 Evaluate Prototype Performance	-	-	-							■	■	■	■			
5.3 Incorporate Prototype Findings into Final Desgin	-	-	-										■	■	■	
6.0 Deploy Thermography Crack Detection System																
6.1 Begin Deployment of Thermography System	-	-	-												■	■

The following section provides a detailed description of research tasks listed in table 1.

1. Development of a lab-based thermography station for crack detection

    1.1. Identify & Procure Thermography Camera – This task will involve identifying and procuring commercially available thermography equipment to allow initial testing of thermography techniques.

    1.2. Design Experimental Set Up for Fuel cracking detection – An experimental setup will be developed that can be used to test thermography techniques. This setup will be the "work bench" for research and component testing that will lead to the development of the in-pile thermographic imaging system. It will allow for imaging of surrogate samples with induced cracks in a high temperature environment.

2. Investigate Thermography Techniques on Surrogate Samples

    2.1. Passive Thermography Techniques – The experimental setup developed under task 1.2 will initially be used to investigate the use of passive thermography for crack detection. Passive thermography is the simplest thermographic technique and involves capturing a thermographic image of the sample. Abnormal temperature profiles indicate flaws or discontinuities that alter the heat flow and cause hot spots. Abnormal temperature profiles as indicators of fuel cracking will be investigated. In particular, the question of sensitivity to radial vs circumferential cracks will be addressed.

    2.2. Active Thermography Techniques – Active thermography introduces a heat source on the sample to increase the temperature differential and aid in flaw detection. Pulse and Lock-in thermography will be investigated. Pulse thermography uses a single heating pulse and records the heat decay curve, while lock-in thermography uses repetitive pulses and records temperature phenomena at the repetition rate. These techniques will be implemented with the goal of determining their ability to detect cracks in surrogate samples and their potential advantages as compared to the passive approach.

3. Develop Image Transmission System

    3.1. Investigate remote imaging techniques – This task will investigate remote imaging techniques with the goal of determining the current state of the art in image transmission and identifying commercially available methods. Initially, requirements for IR image transmission will be identified. This will involve identifying optimal wavelengths for transmission while considering detector wavelength sensitivity and temperature range. Design targets will include image transmission over more than 20 meters and imaging a sample area of ~1cm^2. With image requirements identified, borescope techniques, coherent fiber bundles, hollow fibers and image relay systems will be investigated. Specifications of commercially available borescope systems will be analyzed to identify overlap between off the shelf systems and requirements for IR thermography. Parameters of coherent fiber bundles including IR transmission windows, pixel size and core/cladding ratios will be detailed. Fiber material constituents will also be investigated and documented and efforts will be coordinated with the detailed review of irradiation effects in optical fiber performed under separate research activities in the In-Pile Instrumentation Initiative. Considerations will include estimation of susceptibility to radiation induced darkening based on that review and the effects of IR radiation absorption/emission. Multiple lens image relay systems will also be reviewed for the case that the deployment location should allow such a system. The most promising techniques will be identified for further evaluation.

    3.2. Image transmission testing - This task will involve setting up an image test station, procuring, and testing viable image transmission options. Initial testing will involve CCD cameras and simple targets. Image transmission options will first be tested using visible light to determine parameters such as resolution, magnification, coupling efficiency, object spacing, optimal lens specifications, etc. Knowledge gained during the initial testing phase will be used to down select the image transmission options and formalize the requirements for IR transmission. IR image transmission testing will then be conducted.

3.3. Image transmission integration - When image transmission testing and development has been finalized, the image transmission system will be integrated into the thermography system. Modifications for active thermography will be incorporated and overall system testing will be conducted.

3.4. Explore feedthrough - feedthrough options for image transmission may be explored depending on ultimate system design and progress in cross cutting technology efforts being addressed under other work package initiatives. If modifications to the general feedthrough solutions developed are required they will be addressed. Since it is not known if this task will be necessary in the ultimate reactor experiment, it is not included in the Gantt chart.

4. Modeling & Simulation – Computational and analytical studies will support all phases of R&D. The modeling effort will be focused on two areas including (1) fuel fracture modeling using BISON and (2) infrared measurement response to fuel cracking.

4.1. Fuel fracture modeling using BISON – Fuel fracture modeling will assist the development of an IRT system in a number of ways. Modelling will lead to a better understanding of the desired parameters for a fuel fracture experiment which will aid in the design of the eventual in-pile experiment. The fuel fracture model will also provide a representative temperature field which can be used to predict the response of the thermography system. The modeling targets should include specific parameters affecting the experimental setup, including: heating configuration and boundary conditions to understand resulting temperature distribution and its effect on stress states in the sample. Simulation of potential test reactor power input profiles in UO2 will aid selection of the appropriate reactor and radiation requirements to stimulate desired behavior to be measured from the fuel. Later modeling will be required to support more detailed characterization of the ultimate fuel-cracking thermography experiment design.

4.2. Infrared Measurement Response to Fuel Cracking – This task will focus on the ultimate interpretation of measured IR images to detect sample cracking. Modeling development will include comparisons of active vs. passive mode thermography approaches, studies of active mode heating parameters and thermal wavelengths, integral effects of detection system characteristics such as detected wavelength bandwidths, integration times, etc.

5. Develop a prototype in-pile measurement system

5.1. Design Prototype In-Pile Thermography System – This task will use input from all of the previous tasks to design an integrated passive and/or active thermography system. The system will be implemented in a configuration compatible with in-pile measurements. A target deployment location will be identified which will determine design parameters such as the method of image transmission.

5.2. Explore Prototype Performance - The performance of the prototype in-pile crack detection system will be evaluated using the experimental test setup. Crack detection resolution and other system operational parameters will be determined.

5.3. Incorporate prototype findings - The finding from prototype evaluation will be incorporated into a final system design for in-pile measurements.

6. Deployment - The in-pile deployment of an experimental setup will be based on the performance outcomes of full prototype system and determined at later stages.

4. FY-17 Activities Summary

The primary accomplishments to date represent the beginning of activities in several areas of the research plan. The following sections summarize the work performed based on each participating organization and research focus.

4.1 Lab-based Thermography Station for Fuel Cracking

A functional thermography test station which will allow research and component testing is an important early step in the development of an in-pile thermography crack detection system. To this end, procurement of a commercial thermography system was initiated as soon as FY-17 funding was available. Investigation led to two vendors that supply systems with the software and accessories required for active thermography. The vendors contacted were InfraTec and MovieTherm. MovieTherm is a third party vendor who develops thermography systems using FLIR IR cameras. Both vendors were responsive and the features and capabilities of their systems were similar. MovieTherm proposed a system based on the FLIR A6753sc infrared camera while InfraTec proposed using an ImageIR 8300 series camera. Both cameras are mid-IR and respond to radiation in the 3 to 5µm wavelength range and both have 640 x 512 pixel formats. Lead times for both systems was in the 6 to 8 week range which led to a tight schedule for delivery prior to the end of FY-17. Ultimately, the InfraTec system was selected due to higher frame rates, an integrated radiation intensity filtering system, and in-house software development at the same price level. An order was placed and the system has been shipped and will be received prior to FY-17 closeout.

4.2 Modeling Infrared Measurement Response to Fuel Cracking

Preliminary analysis has been performed to model the image of the cracked fuel detected by an IR camera under a typical light reactor conditions. Figure 3 plots 2D contour of temperature profile in fresh fuel and cracked fuel. The crack is assumed to be circumferential. Perfect radial cracks are not expected to have an impact on the temperature profile. Presence of the crack results in expansion of the hottest region towards the crack as the outflow of generated heat is blocked by the crack. The impact of this hot spot on emitted IR irradiation was calculated assuming blackbody radiation and the results are plotted in Figure 4.

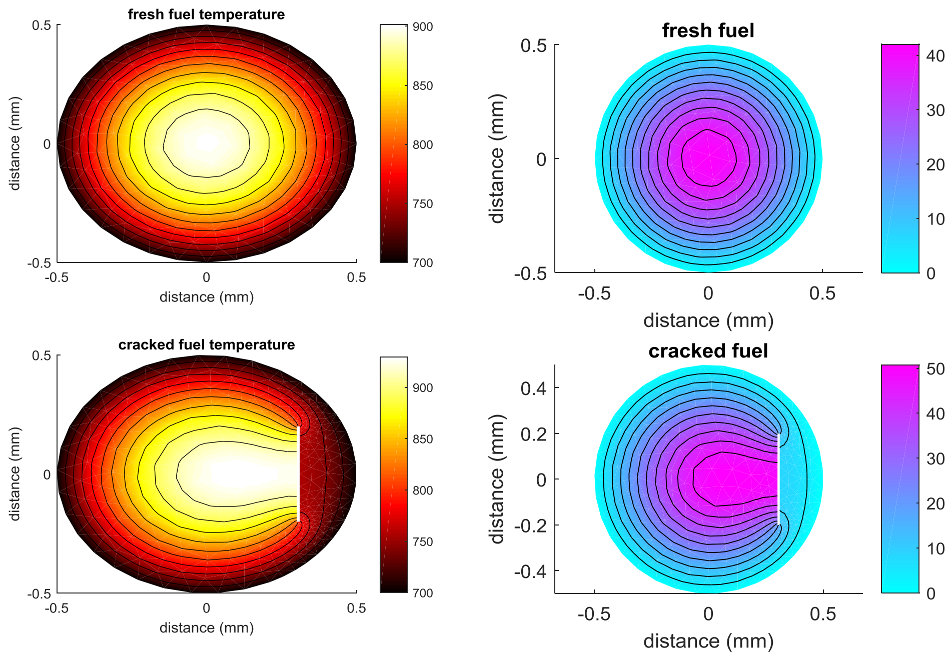

Figure 3. Left: Calculated temperature profiles under typical LWR conditions, corresponding to steady state heating of 10mm diameter UO2 fuel pellet. Right: corresponding infrared emission profiles.

Images shown in Figure 3 correspond to profiles that exist on the surface of the sample. The quality of the measured profiles will be impacted by the resolution of the imaging system. Figure 4 shows preliminary results of a modeling analysis that demonstrates the loss of the image quality due to low resolution. Here only line scans perpendicular to the crack and along the center of the pellet are shown for comparison to emphasize the most important features. It can be seen that while the 20 µm resolution image (red dashed line) clearly reveals the crack, the 100 µm resolution image (yellow dash-dot line) makes it harder to resolve the location of the crack as it lacks a sharp temperature drop, a characteristic feature associated with the crack. Nevertheless, the features of the 100 µm image of the cracked fuel are still noticeably different from the image of the uncracked fuel (dotted line) and exhibit an asymmetric temperature profile. This analysis will be further refined to account for the details of the optical configuration and will be used to establish the specifications for the imaging system.

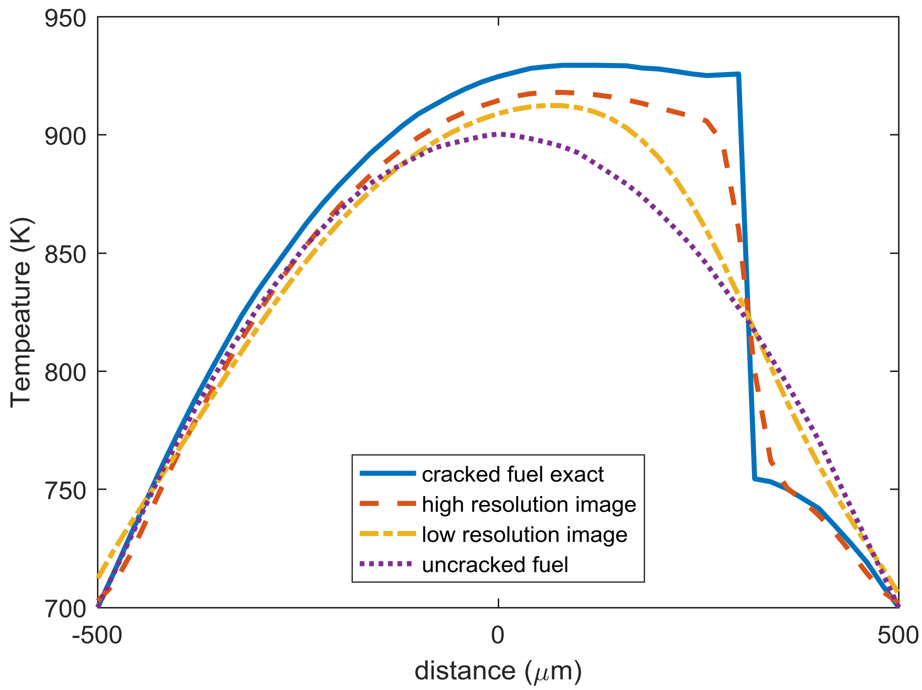

Figure 4. Temperature profiles along the diameter of the pellet and perpendicular to the crack. High and low quality images assume resolutions of 20 and 100 µm, respectively.

4.3 Fuel Fracture Modeling using BISON to Support Experiment Design

The goal of this work is to model the formation and propagation of cracks based on actual measurements from experiments to support experiment design and interpretation. The first step of the work has been done by using MOOSE framework and its associated XFEM (Extended FEM) module that is still under development with incomplete documentation. Unlike the standard FEM, the XFEM module can solve the discontinuities by automatically adjusting the approximation domains to allow tracking of strong (fracture) and weak discontinues. Two types of fracture separation have been tested including opening mode (I) and shearing mode (II) with various initial conditions. Figure 5 and Figure 6 show the distribution of predicted temperature and displacement from a mode II model, shearing fracture with different grid resolutions. In Figure 5, only the diffusion kernel is taken into account with BISON. In Figure 6, external stress causes an initial displacement of 0.1 from both left and right boundaries. Thus, both solid mechanics and diffusion kernels are coupled in the calculation for tracking the thermal and mechanical responses of the fuel pellets.

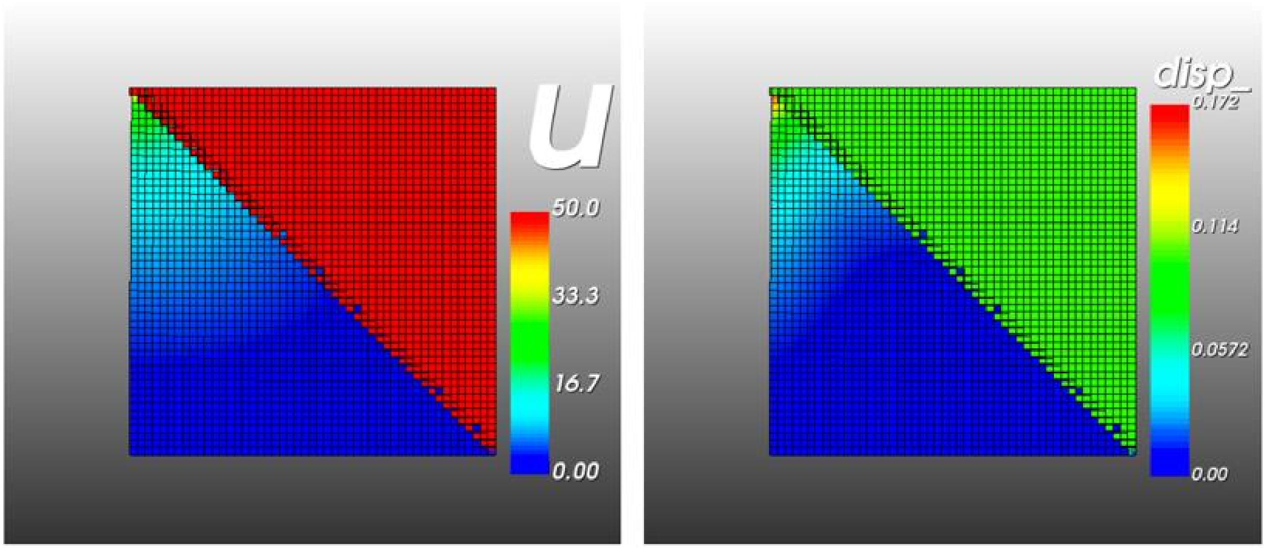

Figure 5. Predicted temperature (left panel) and displacement (right panel) distributions of a mode II, shearing fracture at t=2.5, with a grid resolution of 49 by 49. The cut data used is [0.0, 25, 25.5 0.1]. Only the diffusion kernel was included in the calculation.

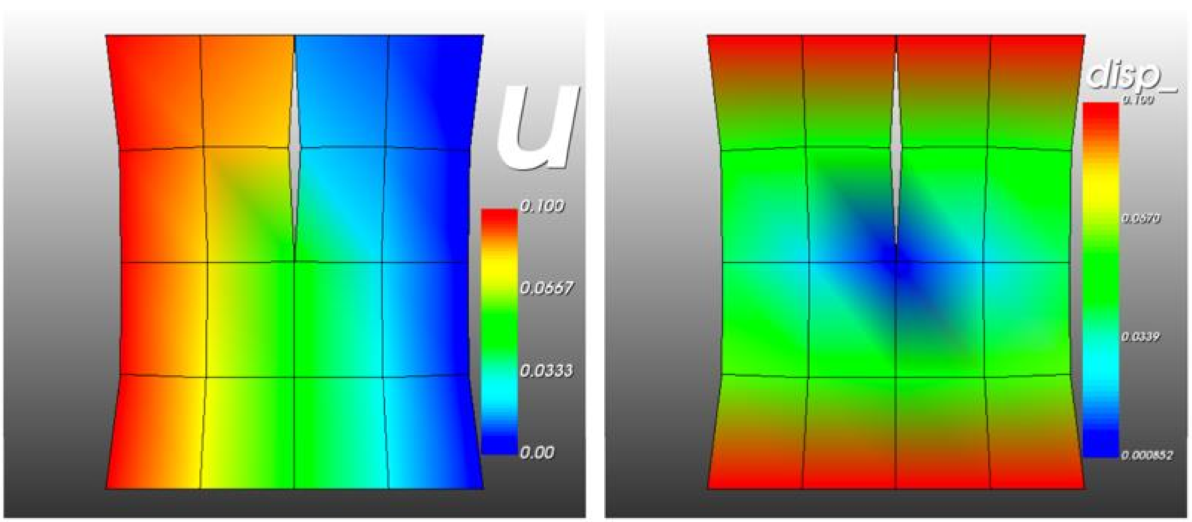

Figure 6. Predicted temperature (left panel) and displacement (right panel) distribution of a mode II, shearing fracture at t=2.5. The cut data used is [0.5, 0.5, 0.5, 1]. Due to external stress causing an initial displacement of 0.1 on the left and right boundaries, both the solid mechanics kernel and the diffusion kernels are used here.

4.4 In-Pile Optical Imaging Techniques Status and Path Forward

The Fiber-optics, Lasers, and Integrated-photonics Research (FLAIR) laboratory at Boise State University is leading Task 3 as described in Section 3 above. Currently, efforts are focused on creating a database of papers and related articles as well as a summary of available commercial technologies related to optical imaging with emphasis on IRT. Specifically, the focus of the work in FY-17 through FY-18 is for:

1. Identifying Coherent Fiber Optic Bundles for IR Thermography

   Working with INL to understand experiment system compatibility, the research is focusing on identifying coherent cluster bundles. This task will be divided as follows:

   a. Image Quality: The coherent fiber bundles will transfer the image from the core to the Infratec camera sensor, and hence the image quality is dependent on the amount of light that the fibers can transmit. The image quality is dependent on the total number of fibers present in a bundle. Since the cladding does not transmit light, they will represent dark areas in the image. Ideally, an extremely thin cladding will be preferred, however this will mean that the fiber is extremely lossy and will not guide light efficiently. The core:cladding ratio will play a significant role in identifying the correct fiber bundle. The effect of core:cladding ratio as a function of different fiber types and wavelengths will be investigated.
   b. Broad Wavelength Operation: The fibers identified should have a broad wavelength range spanning 2000nm -5000nm or 1000nm-3000nm. The focus of research will be to find fibers and fiber types capable of transmitting such broad bandwidth. Optical wavelengths will also be considered as a secondary objective.
   c. Improve Light Transmission Capacity: Since the power of the signal reaching the camera will determine the signal to noise ratio, and hence the quality, it would be crucial to save power wherever possible. Silica:air interface causes 4% reflection of optical power. While anti-reflection coatings can help mitigate this problem, the materials used for these coatings will not survive the high temperature. One commercial approach that has been identified is the creation of nanostructures on fiber ends (moth eye) to reduce reflections at the air:silica interface. This modification has been shown to allow broad wavelength range through the fibers with reflection losses less than 0.5% and may be applied to a wide variety of optical components with flexible application.
   d. Radiation Hardened Fibers: In order for the fiber to be successful in a nuclear reactor, the above methods identified should be applicable to the radiation hardened fibers identified by related work being performed by Boise State University. This focus area also involves identifying potential vendors who can draw such fibers and assemble coherent bundle assemblies for use inside the nuclear reactor.
2. Free Space Optic Based Imaging

   In addition to fiber based approaches, BSU will also investigate free space optics approach to image the fiber core to the nuclear reactor. This work will research and identify radiation hardened optical materials that can be used as lenses and deployed in harsh environment at infrared wavelength. The team will design a periscope type optical system that can be deployed in the reactor based on their research. While this approach will not work inside many steady-state material test reactors, it may hold potential in other nuclear reactor types.

5. Summary and Conclusions

IRT technology is a mature and powerful NDE approach to characterizing a wide variety of structural behaviors in materials in many industries. Even so, to date, in-pile applications have benefited little from its utility, likely in part due to engineering and materials challenges related to obtaining optical images in a reactor environment. Under recent development of a Department of Energy Office of Nuclear Energy (DOE-NE) initiative to develop in-pile instrumentation, Idaho National Laboratory (INL) will lead a project to leverage multi-institutional expertise to investigate IRT applied to nuclear fuels and materials with an initial emphasis on fuel cracking and fuel void formation and migration. A detailed research plan has been presented showing specific tasks that will address IRT experiment design and interpretation and related optical imaging over long transmission distances. In the last months of fiscal year 2017, activities in several areas of the project have been initiated primarily focused on team integration and development of a flexible lab-based IRT setup with an initial focus on fuel cracking studies.

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