Methodology for Inferring Reactor Core Power Distribution from an Optical Fiber Based Gamma Thermometer Array

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What is a gamma thermometer?

- A gamma thermometer consists of:
  - Thermal mass, in which heat energy is deposited due to gamma rays ($q'''$)
  - Outer sheath, which contains the thermal mass
  - Gas gap, which is responsible for a thermal resistance ($R$) between the thermal mass and outer sheath, thus resulting in a $\Delta T$

- If one measures $\Delta T$, and the relationship between $q'''$ and $\Delta T$ is known, then one can determine $q'''$ ($q''' = \Delta T/R$)
What is an optical fiber based gamma thermometer (OFBGT)?

- Optical fibers monitor the temperature of the thermal mass and the outer sheath
  - Using OFDR with a Luna Optical Backscatter Reflectometer
- The relationship between $q'''$ and $\Delta T$ is determined by calibration with a nichrome heating wire
- The gas gap is an inert gas
- The OFBGT, unlike a thermocouple based GT, can be used as a distributed sensor
We have developed a 3-step method for inferring the power distribution in a reactor core based on the OFBGT response:

1. **Energy Balance Method:** MCNP used to generate response functions (energy deposition rate in each OFBGT segment / power produced in each core assembly segment)
   - Each OFBGT segment provides an estimate of power in each core assembly segment
2. **Weighting Scheme:** The power estimates from each OFBGT segment are weighted in accordance to their energy contribution from the particular core assembly segment, and then averaged together.
3. **Uncertainty Propagation:** Modeling and experimental uncertainty is propagated through Steps 1 and 2.

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**Data Analytic Methodology**

- **Measured OFBGT Response** ($\Delta T$)
- **Modelled Parameters**
- **Updated Power Estimates**
- **Updated Power Profile** ($P \pm \delta P$)
- **Response Functions**
- **Experimental Uncertainty**
- **Modeling Uncertainty**
- **Energy Deposited**
- **Power Produced**

- **Core Assembly Segment**
- **OFBGT Segment**
Mathematical Overview: Energy Balance Method

- $P_{A,z'}$ is the power produced in fuel assembly segment $A, z'$
- $\dot{D}_{F,z}$ is the energy deposited (dose rate) in OFBGT segment $F, z$
- $\Delta \dot{D}_{A,z' \rightarrow F,z}$ is the incremental dose rate from fuel assembly segment $A, z'$ to OFBGT segment $F, z$
Mathematical Overview: Energy Balance Method

- We call $R_{A,z' \rightarrow F,z}$ the response function from $A, z'$ to $F, z$
  \[ R_{A,z' \rightarrow F,z} = \frac{\Delta \dot{D}_{A,z' \rightarrow F,z}}{P_{A,z'}} \]

- $F_{A,z' \rightarrow F,z}$ is the fraction of energy deposited in $F, z$ due to $A, z'$
  \[ F_{A,z' \rightarrow F,z} = \frac{P_{A,z'} R_{A,z' \rightarrow F,z}}{\sum_{A,z'} P_{A,z'} R_{A,z' \rightarrow F,z}} = \frac{\Delta \dot{D}_{A,z' \rightarrow F,z}}{\dot{D}_{F,z}} \]

- One can show that:
  \[ \left( P_{A,z'}^* \right)_{F,z} = \frac{\Delta \dot{D}_{A,z' \rightarrow F,z}}{R_{A,z' \rightarrow F,z}} \]

\[ \text{Measured} \quad \text{Modeled} \]
All the power estimates for each fuel assembly segment from each gamma thermometer segment are averaged as follows:

\[
\left\langle P_{A,z'}^* \right\rangle = \frac{\sum_{F,z} \left( P_{A,z'}^* \right)_{F,z} w_{A,z'\rightarrow F,z}}{\sum_{F,z} w_{A,z'\rightarrow F,z}}
\]

where \( w_{A,z'\rightarrow F,z} = \Delta \dot{D}_{A,z'\rightarrow F,z} \)

Weighting by the incremental dose rate allows us to effectively localize our analysis.

- OFBGT segments will provide a more heavily weighted estimate of nearby fuel assembly segments.
1D Reactor Example

- Assuming that the power follows some theoretical cosine distribution
- Assuming response functions are proportional to $\frac{1}{r^2}$
• What if a particular gamma thermometer reads high, and we assume it is physical?

• These results verify that we can localize the perturbation
• The question is, how accurate is the updated power
1D Reactor: Perturbation in Power

- Consider a perturbation in the “true” power which is different than the modeled power
  - What happens when we try to measure the true power with OFBGTs?
  - We tested the original 9 OFBGT configuration as well as 100 OFBGTs equally distributed across $x$
2D Reactor Example

- 2D Reactor as shown below with same assumptions as 1D reactor

![2D Reactor Diagram]

- \( \text{o} \) = OFBGT
- \( \text{Gray} \) = Fuel Assembly Segment
2D Reactor Example Cont.
2D Reactor: Perturbation in Dose Rate

- Need to do further analysis to test accuracy of perturbation measurement, like with the 1D case.
3D Reactor Example

- 3D reactor case with same assumptions as 1D and 2D

3D Reactor Example

- 3D reactor case with same assumptions as 1D and 2D

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3D Reactor Example

- 3D reactor case with same assumptions as 1D and 2D
3D Reactor: Cont.

Gamma Dose Rate (mW)

-5 0 5

x-location (in)

-5 0 5

y-location (in)

-5 0 5

z-location (in)

OFBGTs 1, 3, 10, 12
OFBGTs 2, 6, 7, 11

Assumed Power (kW)

-5 0 5

z-location (in)

Gamma Dose Rate (mW)

-5 0 5

z-location (in)
3D Reactor: Perturbation in Dose Rate

\[ (\text{Updated Power}) - (\text{Assumed Power}) \]

- OFBGTs 1, 3, 10, 12
- OFBGTs 2, 6, 11
- OFBGTs 4, 5, 8, 9
- OFBGT 7

High Reading

Perturbed Response

Gamma Dose Rate (mW)
- z-location (in)
A Look Ahead

• Test accuracy with regard to inferring a perturbed power distribution for 2D and 3D theoretical reactors.
  – Analyze impact of increasing number of OFBGT segments/OFBGTs

• Integrate uncertainty propagation into the methodology
  – We have the underlying mathematics developed
  – We have preliminarily begun integrating uncertainty propagation into theoretical models
    • Assume that inputs act as normally distributed random variables

• Develop data analytic methodology code for processing MCNP data from OSU Research Reactor
  – We are currently updating the MCNP model to make it as accurate as possible to reduce epistemic uncertainty

• Questions?