# Transformational Challenge Reactor Instrumentation and Controls

Presented at NEET ASI Webinar
October 23, 2019

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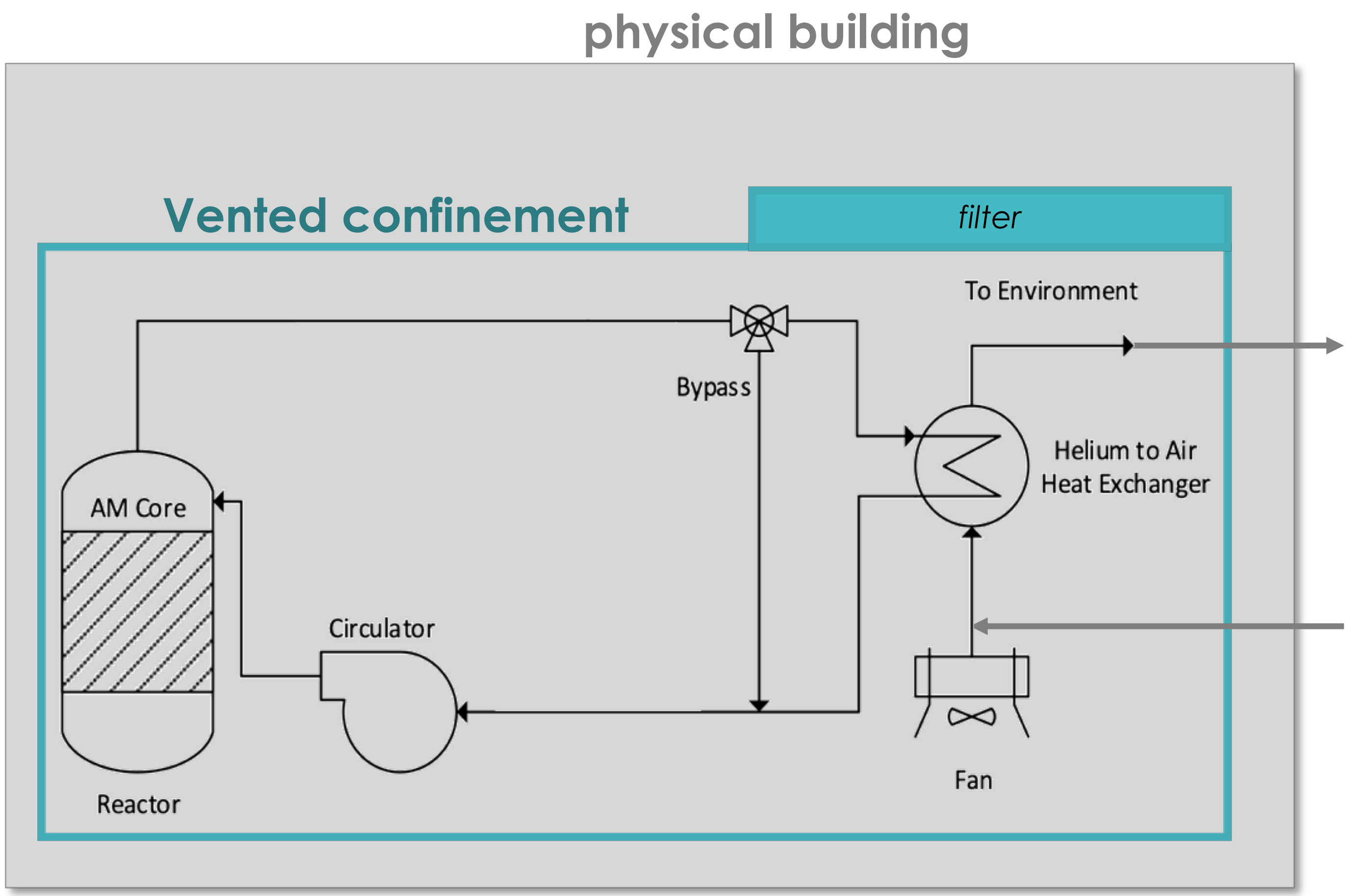
# Overall System Description

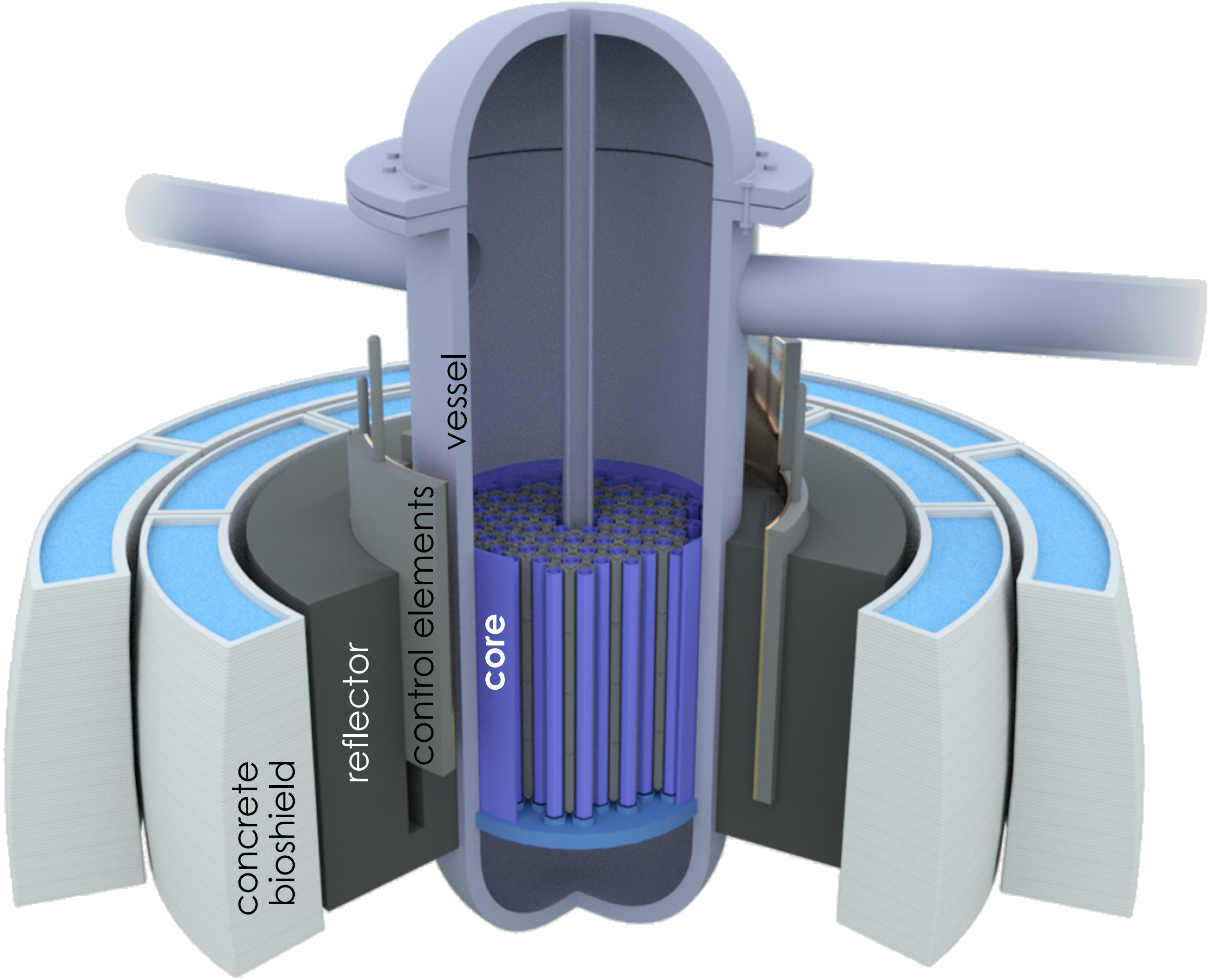
# Transformational Challenge Reactor (TCR) is a microreactor using helium as the working fluid

- TCR adopts a simple loop design with air-dump heat exchangers
- Modest thermal power offers inherent safety and reduced source term



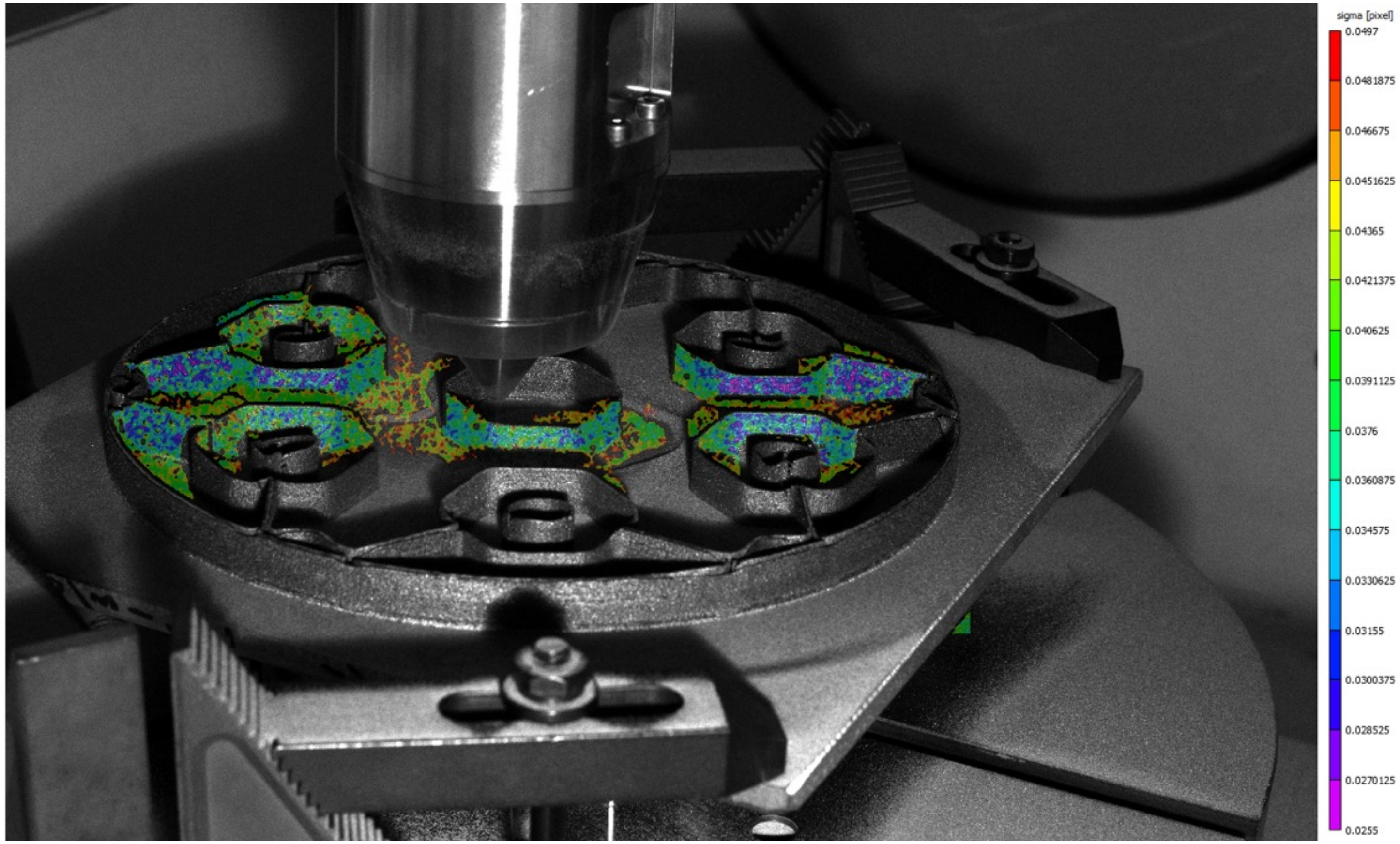
# TCR core design seeks to bring to bear the latest advances in manufacturing, materials, and computational sciences

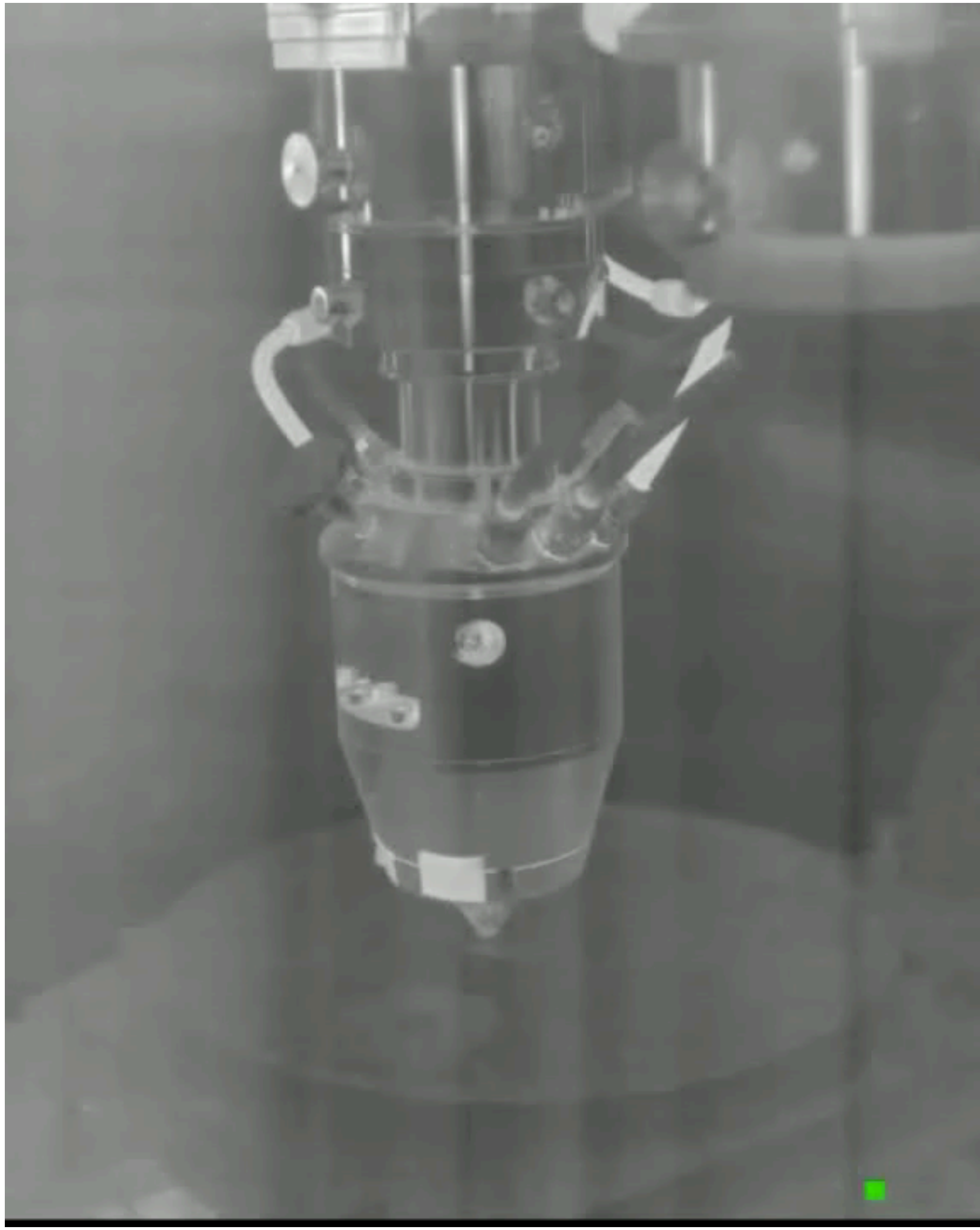
- Compact, optimized, innovative core design that exploits unique advantages of additive manufacturing
- Uses materials that have industrial pedigree
- Novel ex-vessel control and protection schemes




**Concept rendering of TCR nuclear island**

# Monitoring to assess quality during advanced manufacturing (in situ)

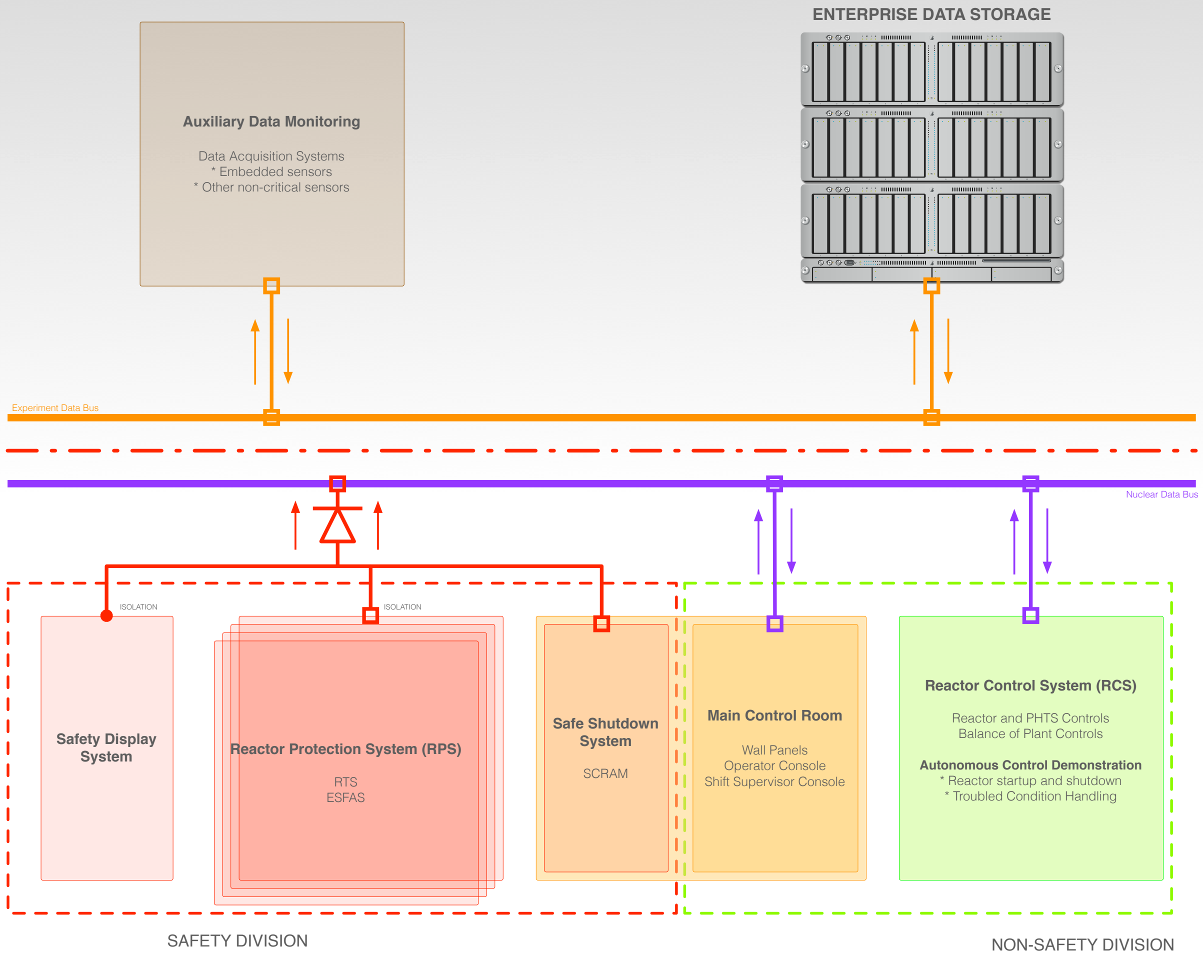


# Instrumentation and Control System Design

## Conceptual I&C System Architecture

- TCR I&C will follow a simplistic design approach
  - Reduce potential regulatory risk
  - Employ endorsed platforms with known industrial pedigree
- Reactor Protection System (RPS)
  - Analog platform is our baseline
  - Eliminates the potential common-cause risk
  - Inherently addresses the diversity requirement
- Reactor Control System (RCS)
  - An endorsed digital platform
  - FPGA options are being considered
  - Must be able to support autonomous control demonstration
- All auxiliary data acquisition (embedded sensors) will be handled by a commercial-grade independent platform

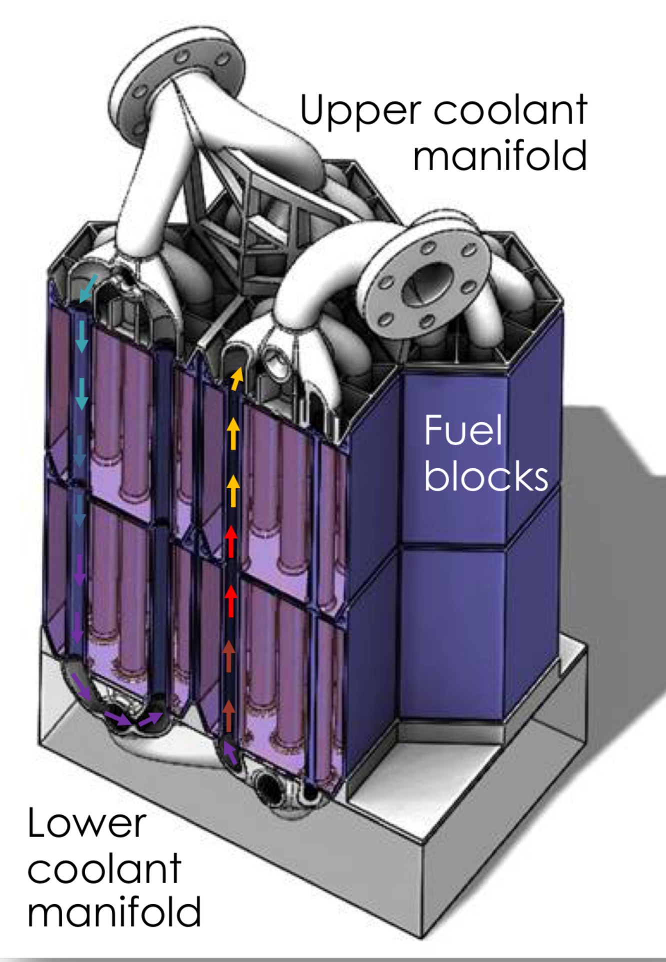


# Instrumentation and Control System Design

## Development of TCR I&C requirements

- We will issue System Design Description (SDD) documents for systems
  - Input to SAR
- Requirements will be drawn from Interim Staff Guidance (ISG) issued to replace NUREG-1537 Chapter 7

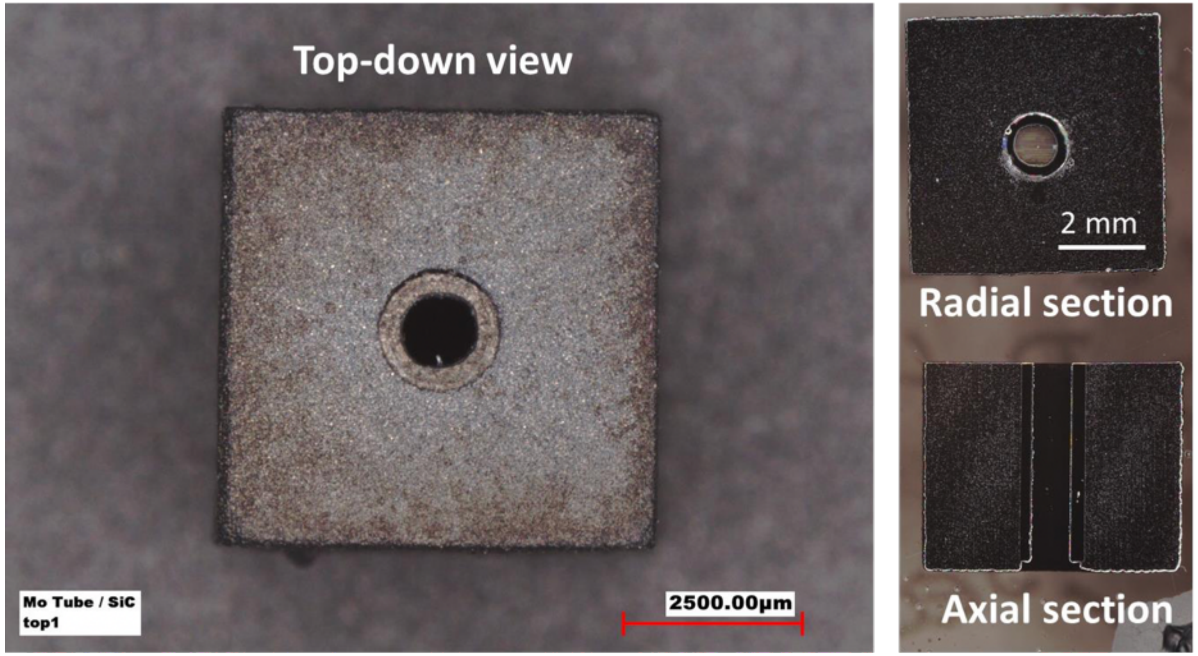
| Criteria | Access Control, Cyber Security, Digital I&C | RCS 7.3 | RPS 7.4 | ESFAS 7.5 | Control Console 7.6 | Rad Monitoring 7.7 |
|---|---|---|---|---|---|---|
| Single Failure | | | X | X | | X |
| Independence | | X | X | X | X | |
| Equipment Qualification | | | X | X | | |
| Fail Safe | | X | X | X | X | |
| Effects of Control System Failures | | X | | | | |
| Prioritization of Functions | | | X | | X | |
| Set points/Performance | | | X | X | | |
| Bypass/Permissives and Interlocks | | X | X | X | | |
| Completion of Protective Action | | | | X | | |
| Surveillance | | X | X | X | X | X |
| Classification and Identification | | | X | X | | |
| Human Factors | | | X | X | X | X |
| Display and Recording | | | | | | X |
| Annunciators | | | | | X | |
| Quality | | X | X | X | X | X |
| Access Control and Cyber Security | X | | | | | |
| Use of Digital Systems | X | | | | | |



# Embedment of Sensors into Additively Manufactured Structures

# TCR is targeting incorporation of existing sensors into core structural components to provide supplementary data for enhanced operation health monitoring

316L sheathed sensor in AM 316L build

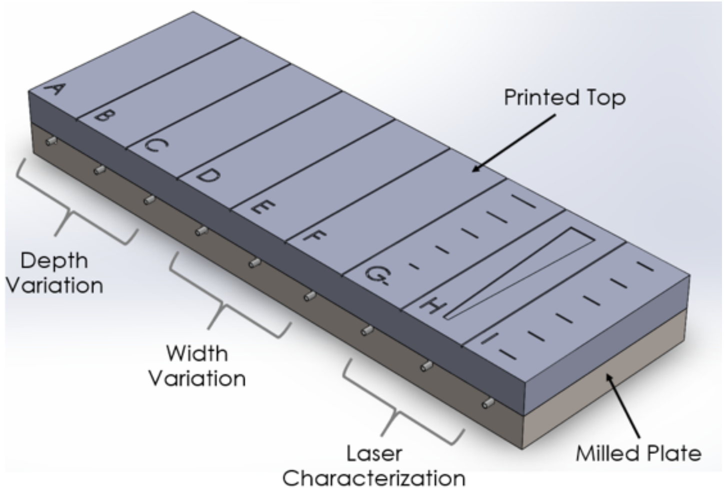


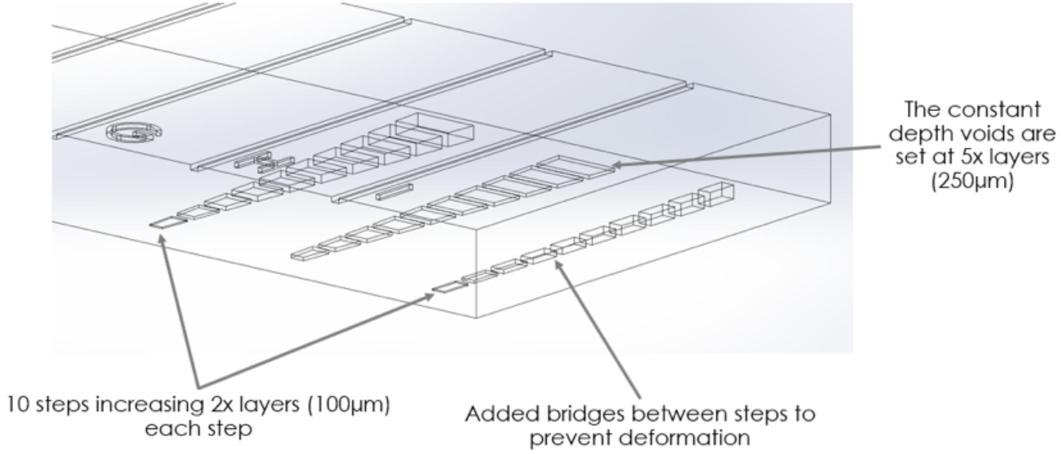

Mo sheathed sensor in SiCbuild

# Goals of TCR FY19 Metal Embedded Sensor Project

- Identify suitable commercial nuclear grade off-the-shelf sensor candidates for embedding
- Quantitatively investigate energy deposition process, melt pool geometry, thermal impacts and dimensional impacts on structure
  - Final build characteristics vs. design
  - Sensor/part interface quality
  - Sensor integrity post build
- Fabricate embedded sensor prototypes that demonstrate feasibility of tortuous routing paths not possible conventionally

**Parametric study build plate**

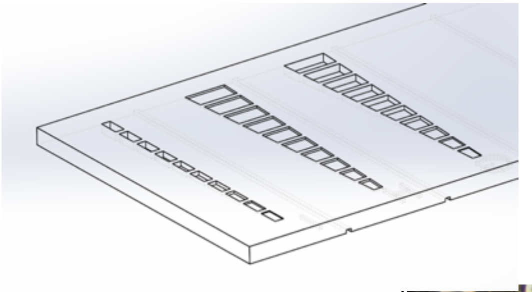


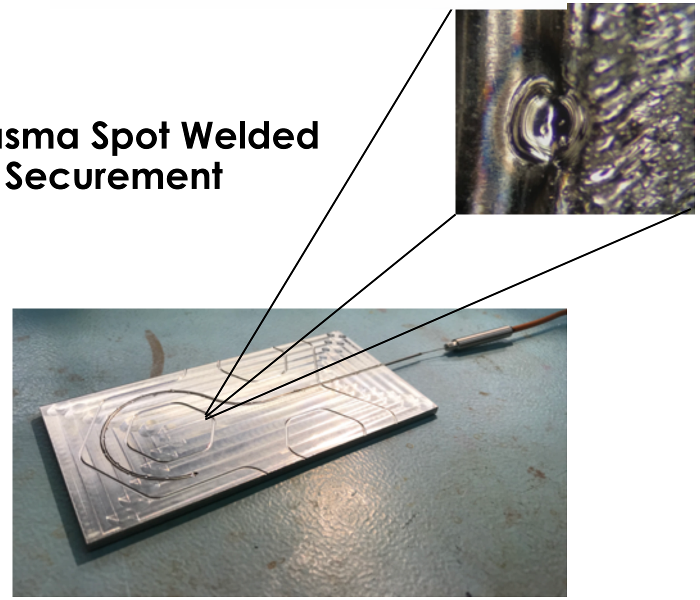
# FY19 Results

- AM build resolutions for Selective Laser Melting (SLM) evaluated for nominal 1 mm TCs
- Parametrically varied build geometry designed for studying AM deposition
- Workflows and methods developed for embedding nuclear grade K-Type Thermocouples
  - ‘Stop and Go’ emplacement strategy pursued
  - Procedures developed for shaping sensor prior to embedment
  - Plasma spot welding parameters defined for securing sensor during AM build

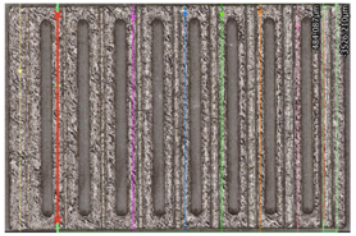
**Void Profile for Parametric Deposition Study**



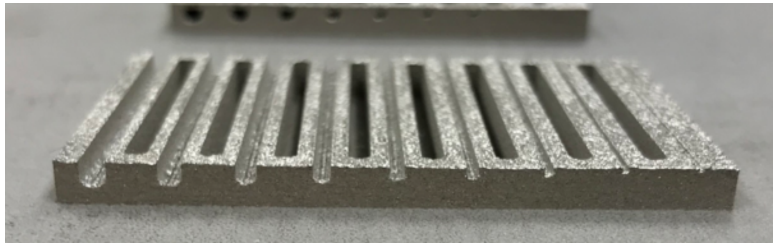
**Plasma Spot Welded TC Securement**



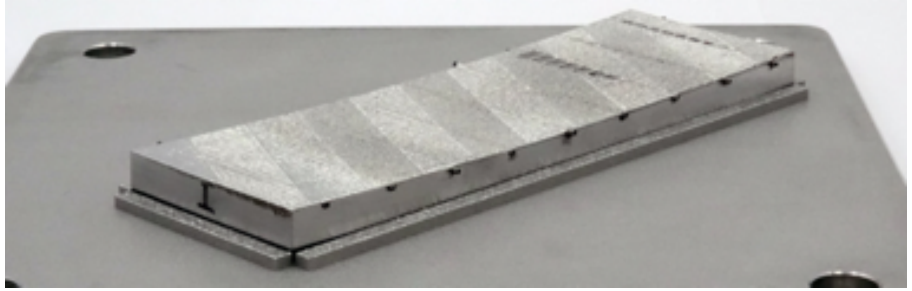
**SLM Prototypes Fabricated for Surface Roughness Characterization**



| | Ra [µm] | Rz [µm] |
|---|---|---|
| Average | 102 | 260 |
| Maximum | 108 | 301 |
| Minimum | 98 | 217 |
| Standard Dev. | 3 | 23 |



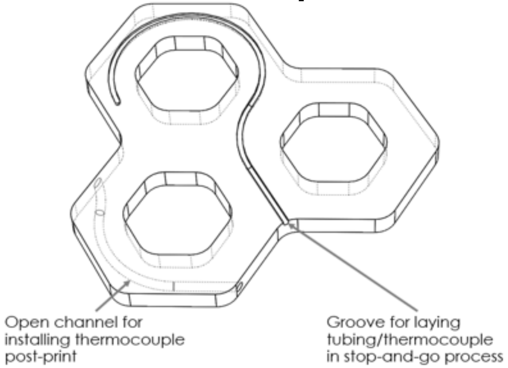
# FY19 results continued



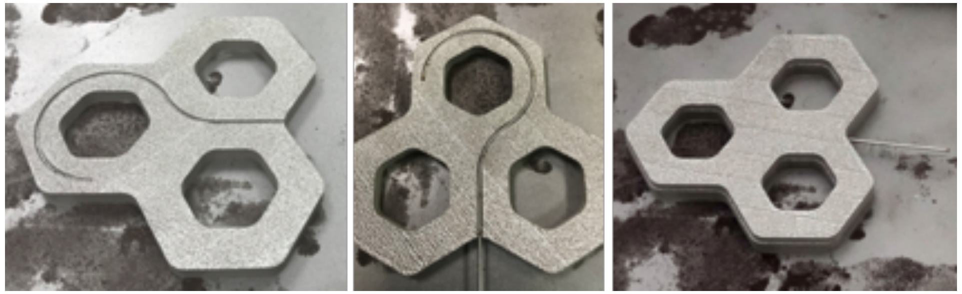
**Failed Parametric Build**

- Initial parametric build prototype failed due to warpage
  - Results currently being X-Ray CT scanned
  - Improved attachment to build plate planned
- First embedded sensor concepts successfully fabricated
  - Build evaluation still ongoing
  - Improved registration approach required to improve alignment following emplacement
  - Temperature cycling performance testing planned for Q1 FY20

**Hexagonal Concept Demo for Embedded Thermocouple**



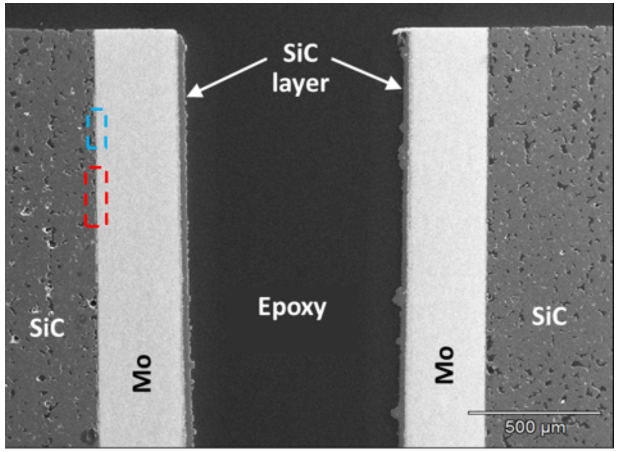

**Embedded Thermocouple Hexagonal Prototype**

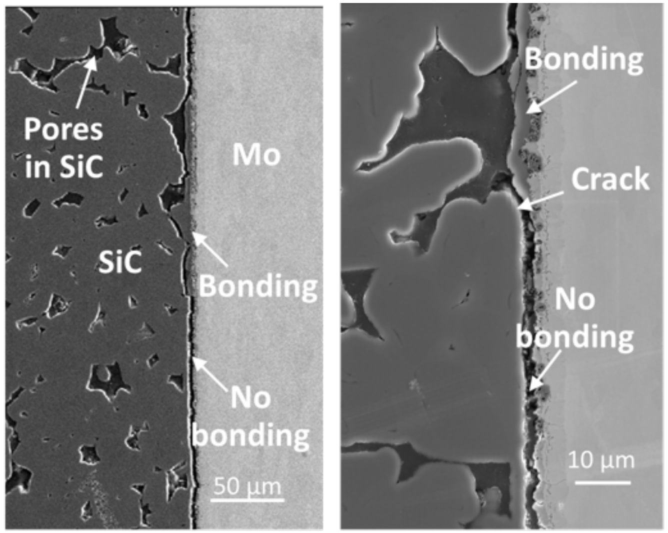


Before embedding Sheath Insertion Final Build

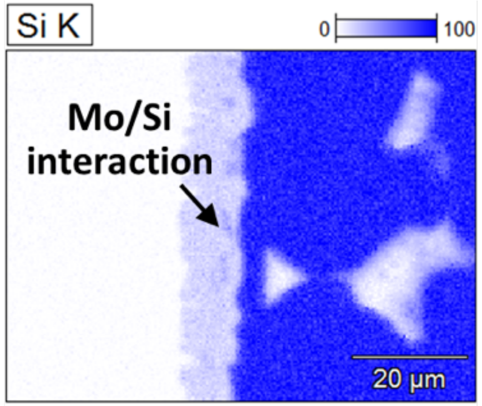
# Embedding sensors in 3D-printed SiC

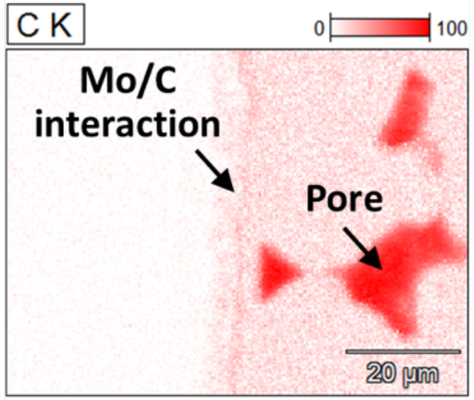
- Sensors must survive CVI process: $H_2$ + HCl, >1,000°C for tens of hours
- Successfully embedded metal sheaths and optical fibers in SiC
- Mo interactions with Si and C limited to a few µm
- W, Nb, and Ta also embedded

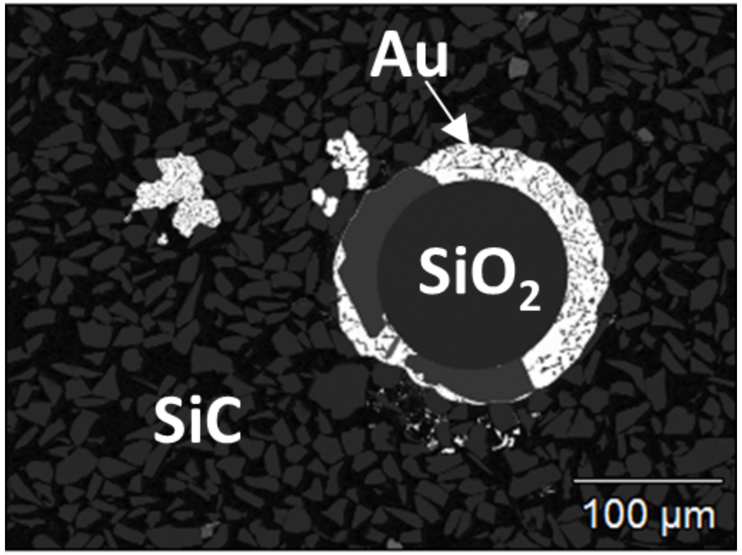



Detail 1 Detail 2




**Embedded Au-coated optical fiber**

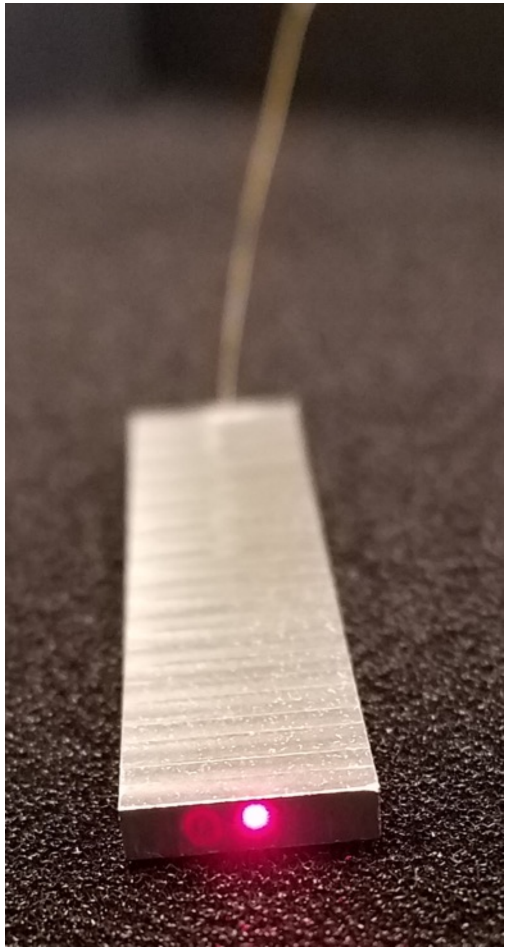
**Embedded moly sensor sheath**

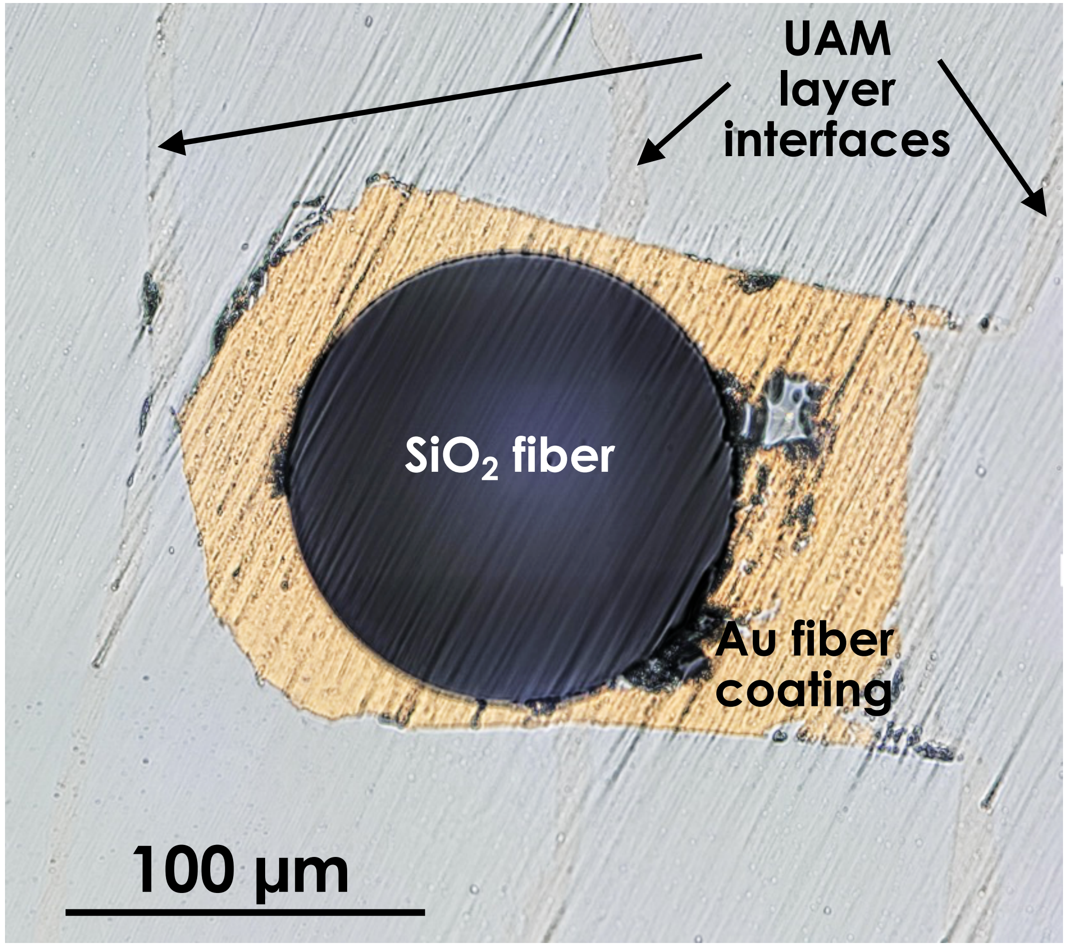



C.M. Petrie et al., "Embedment of sensors in ceramic structures," ORNL/SPR-2019/1301, (2019).

# Embedding fiber optics in metals for high-temperature strain monitoring

- Successful monitoring of thermal strain in embedded fiber sensors to temperatures >500°C [1,2]
- Fibers embedded in SS304 expected to survive to 600-800°C (testing in progress)






**Au-coated optical fiber embedded in SS304 using ultrasonic additive manufacturing (UAM)**

[1] C.M. Petrie, N. Sridharan, M. Subramanian, A. Hehr, M. Norfolk, and J. Sheridan, "Embedded metallized optical fibers for high temperature applications," Smart Materials and Structures, Vol. 28 (2019), p. 055012.
[2] C.M. Petrie, N. Sridharan, A. Hehr, M. Norfolk, and J. Sheridan, "High-temperature strain monitoring of stainless steel using fiber optics embedded in ultrasonically consolidated nickel layers," Smart Materials and Structures, Vol. 28 (2019), p. 085041.

# Autonomous Control: Automated Start-Up Procedures

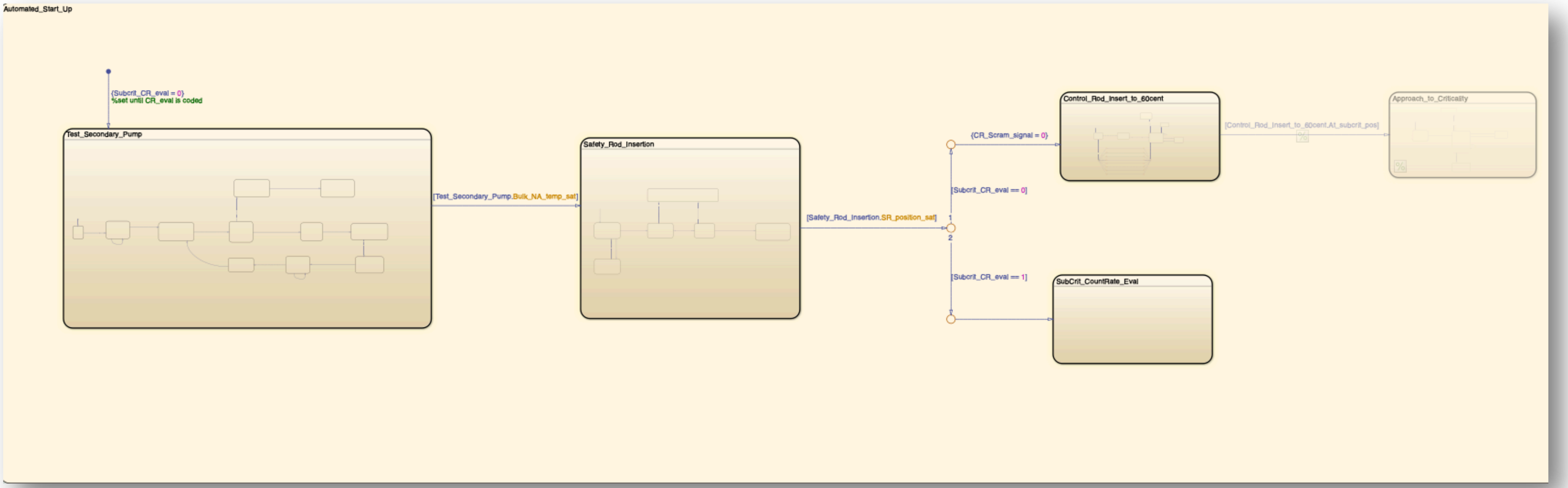
# Overall Flow

1. Test supporting equipment
2. Insert Safety Rods
3. Insert Control Rods to Subcritical position

3b. or perform special data-collection rod insertions

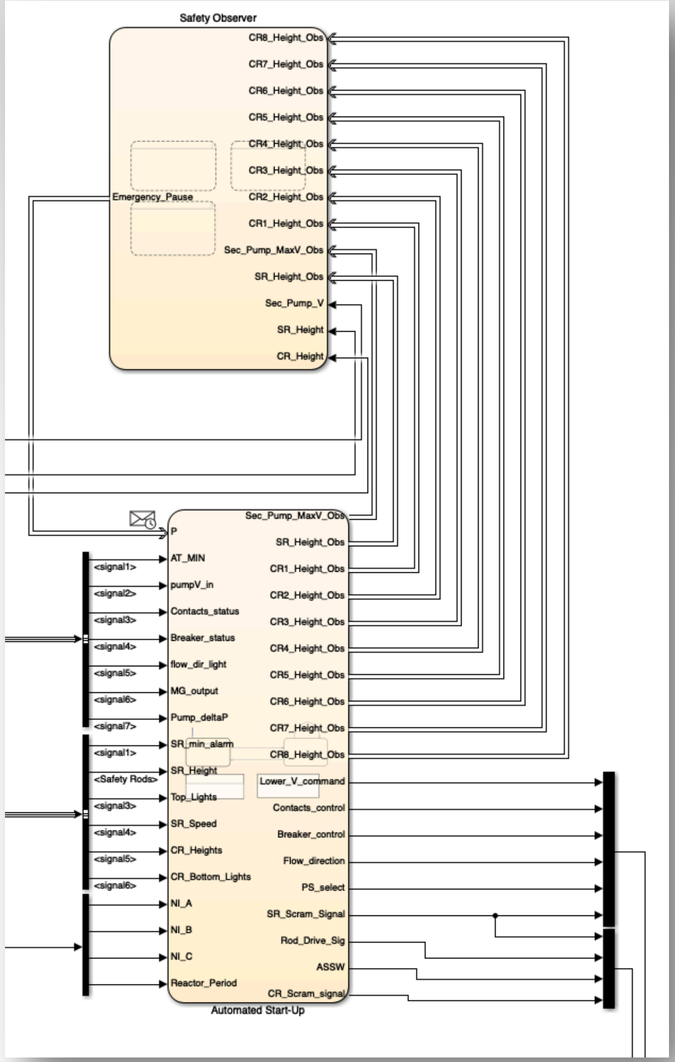
4. Final approach to criticality

Rod insertion order determined by user input before procedure is called

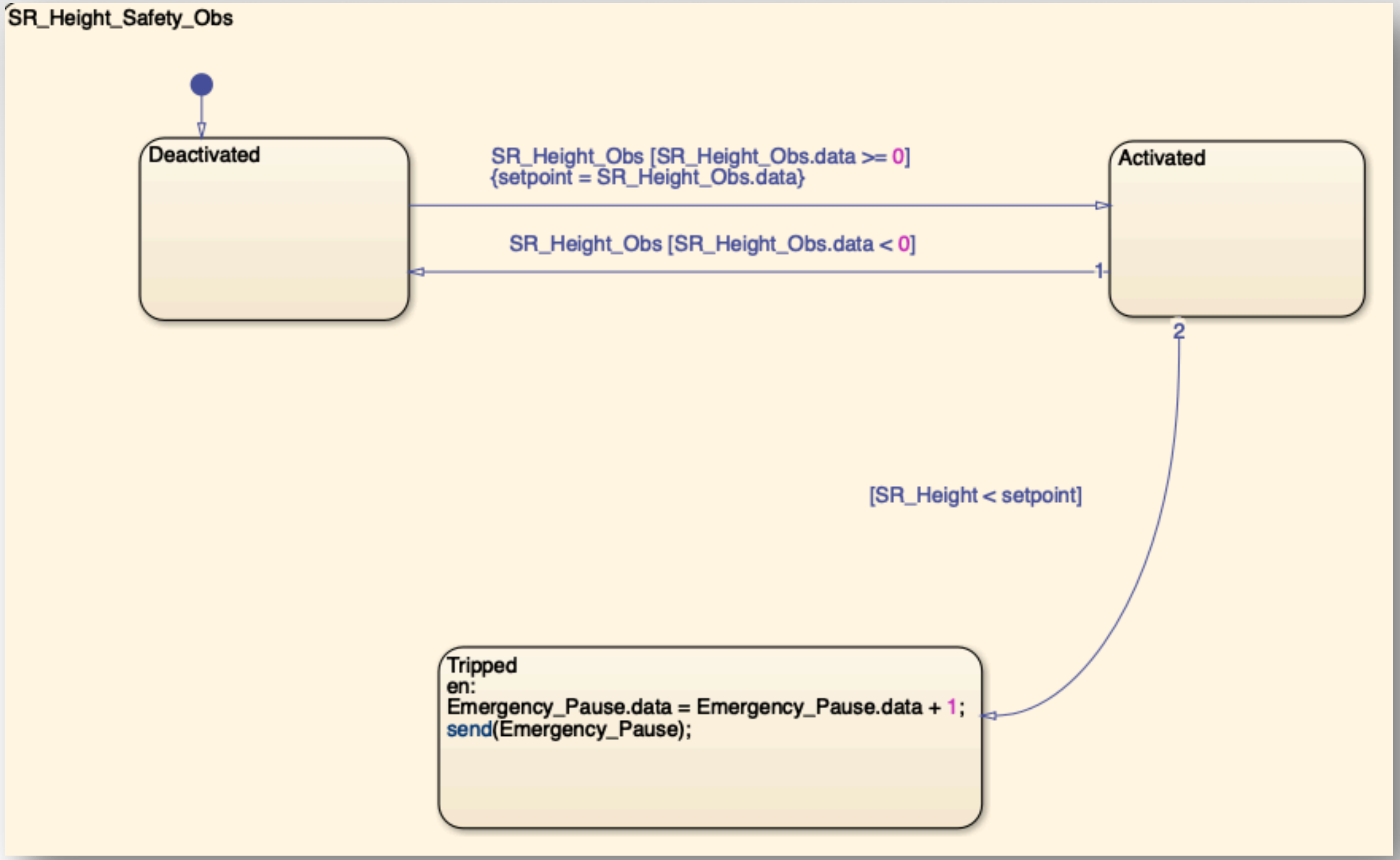


# Maintaining Safety

However, every state cannot be checking that all previous parameters remain SAT
Therefore, introducing a parallel state machine to observe critical parameters




The observer will consist of many parallel machines with 3 states: Deactivated, Activated, and Tripped



ORNL/SPR-2019/1178
M2CT-19OR06090137

## Transformational Challenge Reactor Autonomous Control System Framework and Key Enabling Technologies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**May 31, 2019**

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https://www.osti.gov/biblio/1530084

ORNL/TM-2019/1354

## Embedded Sensor Development in Metallic Structures for the Transformational Challenge Reactor


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**September 27, 2019**

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