Meet the presenter

Dr. Mitchell Farmer is a Senior Nuclear Engineer in the Nuclear Science and Engineering (NSE) Division at Argonne National Laboratory. He has over twenty-five years of experience in various R&D areas related to reactor development, design, and safety. A principal career focus area has been light water reactor (LWR) severe accident analysis and experiments.

More recently, he has also been involved in the analysis, design, and conduct of experiments related to operations and safety of Generation IV reactor concepts including sodium fast reactors, as well as high-temperature gas cooled reactors. He has over 200 publications in the above-mentioned technical areas. Dr. Farmer also manages the LWR Programs within Argonne’s NSE Division in which these and other programs are carried out.

Dr. Farmer earned his Bachelor’s degree in Nuclear Engineering from Purdue University, his Master’s degree in Mechanical Engineering from the University of Nebraska, and his Ph.D. in Nuclear Engineering from the University of Illinois.

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Motivation

- The reactor accidents at Fukushima Daiichi reinforced the need for fully passive safety systems that will ensure safe shutdown of a nuclear reactor
  - BWR Mark I’s are a first-vintage (1960’s) design with heavy reliance on active cooling and safety systems

- Best attempts are made to account for all possible accident scenarios, but the design philosophy should not require specific considerations
  - Fully passive – NO reliance on active power, AC or DC
  - Always on – no human intervention required to active
  - ‘Walk away’ safety

Backup diesel generator at Fukushima engulfed in water due to Tsunami  
Courtesy of TEPCO
GenIV initiative defines 8 technological goals, of which 3 are safety related:

- “S&R 1 – System operations will excel in safety and reliability”
- “S&R 2 – Very low likelihood and degree of reactor core damage”
- “S&R 3 – Eliminate the need for offsite emergency response”

The reactor cavity cooling system (RCCS) has emerged as a leading concept for meeting these goals:

- Possibility to provide inherently safe and fully passive means of decay heat removal
- Offers a high level of performance with relative simplicity in design
- Has been under consideration since 1950’s

Though the RCCS is our focus, our ultimate objective is to support the continued development of safe and reliable nuclear power:

- Multi-institutional effort has brought together federal, industry, national laboratories, and universities
Project Scope and Reach

- Goal of inherent safety & fully passive decay heat removal
  - Simplistic, ex-vessel design provides cross-cutting opportunities
  - Heat flux alone off RPV serves as the mode of heat transfer

- Concurrent with a broader purpose including multiple US universities, industry, CFD modeling, and 1D analysis
  - Experimental efforts at multiple scales, using both air & water
RCCS Overview

- Unique to recent generation of HTGR
  - Natural circulation in laminar and turbulent flow
  - Radiative (primary) and convective heat transfer
- Air and water under consideration
- Considered for both active cooling duration normal operation, and with other designs operating solely as a passive safety system during an accident transient
- Several designs, each unique in geometry, but sharing a common concept, are under design

<table>
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<tr>
<th>Reactor</th>
<th>RCCS Coolant</th>
<th>Cooling Mode</th>
<th>Country</th>
<th>Power</th>
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<tr>
<td>HTR-10</td>
<td>Water</td>
<td>Natural</td>
<td>China</td>
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<td>Water</td>
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Decay heat load requirements

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<td>Height Scaling</td>
<td>1:1</td>
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<td>Total RCCS Height</td>
<td>55.2 m</td>
<td>26 m</td>
<td>$\ell_R$</td>
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<td>Heated Riser Section</td>
<td>13.86 m</td>
<td>6.82 m</td>
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<td>Decay Heat</td>
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<td>56.07 kWt</td>
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<td>6.82 kW/m²</td>
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<td>System Flow Rate</td>
<td>12.2 kg/s</td>
<td>0.456 kg/s</td>
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<td>Heated $\Delta T$</td>
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RCCS heat removal is a function of vessel temperature and ambient air temperature. A constant 43°C (110°F) ambient air temperature is assumed for this analysis. For the depressurized cooldown accident, there is very little convective heat transfer from the core to the top head. Decay heat is primarily removed by conduction horizontally through the reflector to the vessel sidewall. Vessel temperature peaks at 441°C (824°F) just above the core midplane at 120 hours after shutdown. All major RCCS parameters also peak at 120 hours. Peak RCCS parameters are as follows:

- RCCS heat removal: 1.50 MW
- Air flow rate: 12.2 kg/sec (9.68 x 10⁴ lbm/hr)
- Maximum panel temperature: 219°C (424°F)
- Air outlet temperature: 164°C (326°F)

NSTF at Argonne (legacy)

- Original NSTF built to provide confirmatory data for the GE PRISM RVACS design
- Successfully operated through the late 1980’s
Beginning in 2010, the aging facility was revisited

Several design aspects were reused, however focus shifted to include features of newer high temperature gas-cooled reactors

Many components were updated to latest technologies…
The Natural Convection Shutdown Heat Removal Test Facility (NSTF) was initiated in FY2010 in support of DOE programs NGNP, SMR, and now ART

- Program operates according to Nuclear Quality Assurance (NQA)-1 standards

The top-level objectives of the NSTF program are:
1. examine passive safety for future nuclear reactors
2. provide a user facility to explore alternative concepts
3. generate benchmark data for code V&V

Concurrent collaborations for a broader scope
- Experimental facilities at multiple scales (½, ¼, etc.) for both air and water designs
- Complimenting CFD modeling and 1D systems level analysis
- Collaborating towards the development of a central data bank for the RCCS concept
Quality Assurance

- Experimental data generated by the NSTF program is suitable for licensing initiatives by US vendors
  - The program meets requirements of ASME NQA-1 2008 w/ 2009 addendum
  - Regular audits maintain compliance to NQA-1
  - Small team of dedicated individuals with strong management support

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<td>Winter 2019</td>
<td>☐ MA☑ Internal☐ External</td>
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</table>
Facility Overview

A. Inlet downcomer
B. Inlet plenum
C. Heated cavity
D. Riser ducts (7.5-m)
E. Outlet plenum
F. Chimney ductwork
Facility Overview

- Fan Loft
- Heated Sections (22 ft.)
- Inlet Plenum
- Exit Plenum
- Exhaust thru. roof

Heated Sections (22 ft.)

Inlet Plenum

Test Section

Deep Pit

15.62 ft.

83.8 ft.
Accurate Boundary Conditions

- Two plates provide a physical representation of the RPV surface for heat transfer
  - Mill scale, surface $\varepsilon$ between 0.7 and 0.9 (verified)
  - 2.5 cm thick, SAE 1020 low carbon steel
Test Matrix

- Shakedown/Calibration/Isothermal Characterization
- Baseline testing (QR = 1, ΔT = 1)
- Scaling verification
  - Integral power variation
  - Reduced physical scale
- Heated profile shaping
- GA-MHTGR accident scenario
  - Full time history of decay power profile
- Performance testing
  - Single chimney configuration
  - Forced flow operation
  - Blocked riser channels (incrementally block up to 6 out of 12 ducts)
  - Adjacent chimney roles (N. vertical stack inlet, S. vertical stack outlet)
- Repeatability / Weather
  - Repeat tests performed at baseline, GA-MHTGR accident scenario
  - Repeat tests performed in unfavorable or varied weather conditions
  - Regular repeats of baseline case
Baseline Testing Conditions

- Electric (240 / 480VAC)
- Thermal ($mC_p\Delta T_{heated}$)

Graph showing power (kW) over time (hour) with distinct markers at 25, 30, and 45 hours.
Repeatability

\[ \sigma = \pm 2.5\% \text{ (kW)} \]
GA-MHTGR Accident Scenario

Peak heat load of 56.07 kWt at 84.85 hr

Initiating events occur at t=0 after operating at 26.16 kWt steady-state
GA-MHTGR Accident Scenario
The prototypic full scale design places the entire reactor core below grade.

Thus, both inlet and outlet ductwork run adjacent along a majority of their length.

The NSTF was modified to best represent this configuration.
Adjacent Chimney Configuration

Difficulty establishing “normal” flow direction

Emergency fans & aborted test
Completion of Air Testing

▪ Air-based testing program officially concluded on July 5th 2016
  • Final modeling report documented in ANL-ART-46
  • Final project report documented in ANL-ART-47
  • Formal internal audit for all 18 elements of NQA-1 2008 June 29th 2016

▪ All program requirements were completed
  • High level program objectives drafted in 2005, prior to facility design and assembly
  • Experimental objectives drafted in 2013, prior to testing campaign
  • Items identified during early 2016 data review meeting, prior to testing conclusion
    • Attendees included the DOE, NRC, INL, AREVA, GA, and US Universities

▪ Program accomplishments
  • 33-month testing campaign duration
  • 2,250 active hours of heating
  • 27 conducted tests (16 accepted)
    • Multiple baseline repeats, GA-MHTGR accident scenario, blocked risers, power variations, azimuthal and cosine skew, adjacent chimney roles, meteorological variations, I-NERI test series
  • 24 publications since inception (numbered reports, journals, and conference)
Air-Testing Observations

- Ambient temperature
  - While heat removal performance remains largely unaffected, flow rates / absolute temperatures vary dramatically

- Meteorological perturbations
  - Systems exhibits sensitivity to such phenomena
  - Engineering controls (e.g. anti-draught cowls)

- Power Sensitivity & Low Power Start-up
  - At low powers, system may be unstable
  - Exhibits robust performance once flow is developed and system is operating at higher powers

- Blocked Riser Channels
  - Performance is relatively unaffected by blocked risers
Disassembly and Storage

- Disassembly of the air facility commenced on July 5, 2016, after acceptance of final scheduled test
- Generated data backed up, stored within locked storage cabinets at two separate buildings
- Process was performed according to a written procedure and in an archival style manner

![Disassembly and Storage Image]

Metal label plate indicating installed position secured to front face

NSTF personnel hoisting riser duct #11 from heated cavity
Air to Water Conversion

- With conclusion of air-based testing, program has shifted to a water-based operation of the existing test facility
- Water-cooled NSTF based on concept design for Framatome 625 MWt SC-HTGR (formally AREVA)
  - DOE sponsored HTGR Technology Economic/Business Analysis and Trade Studies
    Argonne performed scaling studies, geometric parameter simulations, thermal and stress calculations, tank depletion time estimates, steam quality/flow rate determinations, etc.
## Water Test Section Design

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<th>$\varepsilon$ (-)</th>
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<td>Pipe</td>
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## Water Instrumentation

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<th>Mfg.</th>
<th>Model</th>
<th>Range</th>
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<td>Flowrate</td>
<td>Magnetic</td>
<td>Inlet header</td>
<td>x1</td>
<td>Krohne</td>
<td>Optiflux 4000</td>
<td>±5kg/s</td>
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<td>Flowrate</td>
<td>Magnetic</td>
<td>Inlet riser</td>
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<td>Krohne</td>
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**Legend**
- Flow meter
- Static pressure
- Diff. pressure
- Thermocouple (pt.)
- Thermocouple (ras)
- RTD
- Void RBI
- Differential
- Steam Quality
- Sight Glass
- Control Glass
- Heated Valve
- Pump
- 3-way valve

![Gamma Densitometer](image-url)

Electromagnetic flow meters
Water Accomplishments

- May 2018 – Completed installation of test facility
  - Primary components: test section, water storage tank, and network piping
  - All sensors, hardware, control valves, etc.
- July 2018 – Shakedown and instrument verification
  - Signed verification sheets
- November 2018 – Single-phase demonstration test
  - Install and verify network piping sensors
  - Initial fill of test loop and system leak-test
- January 2019 – First accepted matrix test at single-phase conditions
  - Baseline ‘normal operation’; steady-state with 30°C inlet temperature
- August 2019 – Completion of single-phase parametric series
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Acknowledgements

This work was supported by the U.S. Department of Energy Office of Nuclear Energy, Office of Advanced Reactor Concepts under contract number DE-AC02-06CH11357
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<td>13 November 2019</td>
<td>Czech Experimental Program on MSR Technology Development</td>
<td>Dr. Jan Uhliř, Research Center Řež, Czech Republic</td>
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<td>18 December 2019</td>
<td>TRISO Fuels</td>
<td>Dr. Madeline Feltus, DOE, USA</td>
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<td>29 January 2020</td>
<td>Thermal Hydraulics in Liquid Metal Fast Reactors</td>
<td>Dr. Antoine Gerschenfeld, CEA, France</td>
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