O_2 Distribution in Scaled VHTR Confinement During Helium Leak from Vessel: Data & Calculation

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Note: All slides summarizing experiment produced by A. Abubakar

Team Participants, Collaborators, and References

- City College of New York (CCNY)

M. Kawaji, Dinesh Kalaga, Zayed Ahmed, Mathieu Davis

- Collaborators

R. R. Schultz (IdahoStateU), H. Bindra (KansasStateU), K. P. Chen (UPitt), D. McEligot (INL), F. Shahrokhi (Framatome); Lead UK Collaborator: S. He (USheffieldUK)

References:

Masahiro Kawaji, Dinesh Kalaga, Abdullah Abubakar, Richard R. Schultz, Hitesh Bindra, Kevin Chen, Farshid Shahrokhi, Donald M. McEligot NEUP Project 19-17173 Final Report: Mixing of Helium with Air in Reactor Cavities Following a Pipe Break in HTGRs, City College of New York Report, September, 2023

A. Abubakar, Helium-Air Mixing in Simulated Reactor Cavities of High Temperature Reactors, PhD Dissertation, City College of New York, 2025.

E. Ali, MSc Thesis (in progress), to be published 2026.

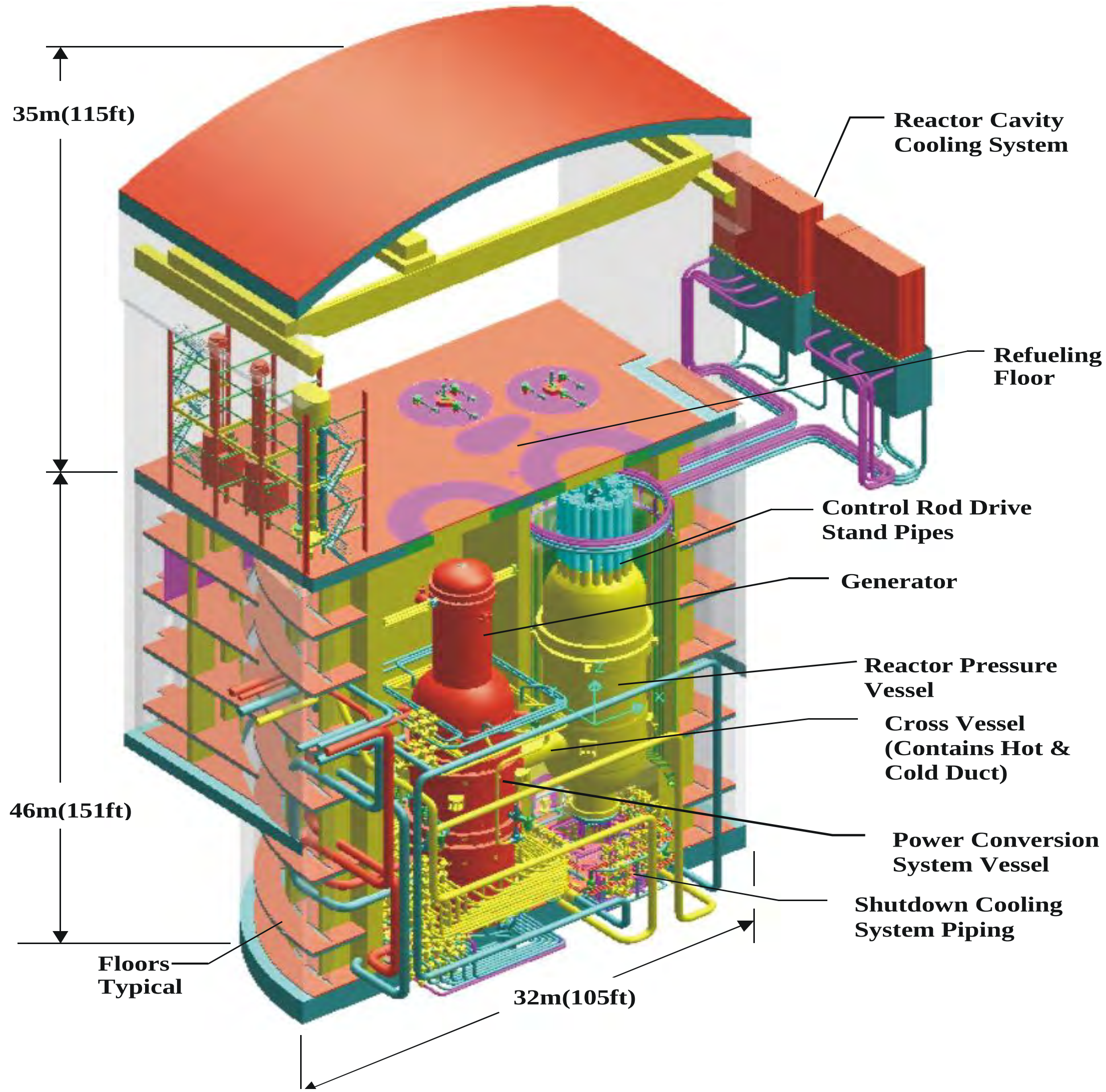
Research objectives

- To obtain experimental validation data on mixing of helium and air in reactor building cavities following a primary pipe break in Very High Temperature Reactors.
- Measurement of the spatial distributions of air and helium concentrations, gas mixture velocity and temperature fields in simulated reactor building cavities.

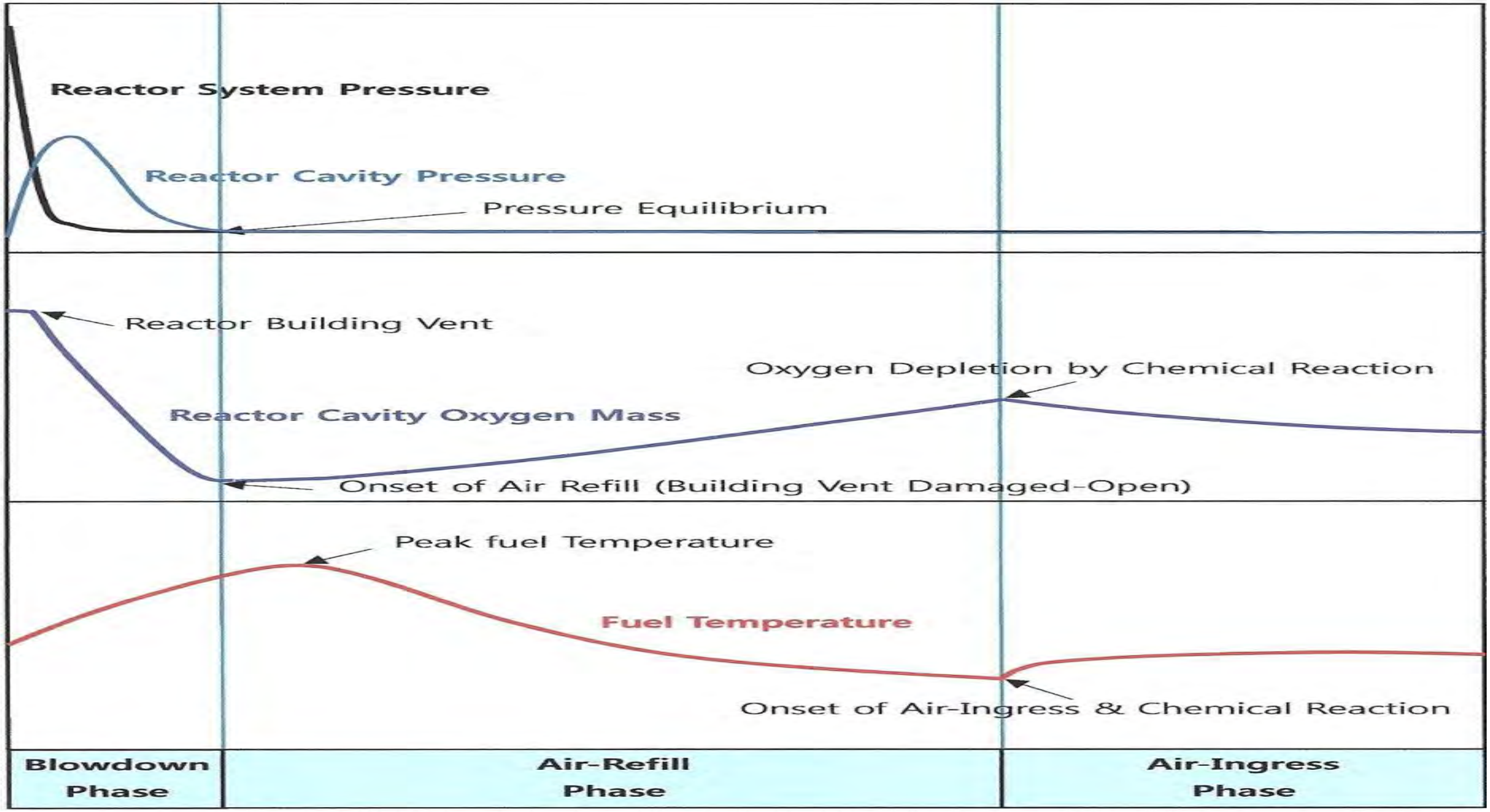
Need

- Under operational conditions the reactor cavity is filled with air at near atmospheric conditions.
- During a loss-of-helium scenario hot, pressurized helium from the reactor vessel will leak into the reactor cavity.
- Following the vessel depressurization, the containment gases adjacent to the leak will be convected into the reactor vessel via stratified flow at rates dictated by the density gradients between the remaining hot helium (exiting the vessel into the containment) and the localized containment gas present adjacent to the leak site.
- Oxygen convected into the reactor vessel will react exothermally with the hot graphite in the structural supports and within the core—and will lead to structural deterioration.
- .Need: Evaluate the oxygen concentration adjacent to the leak site for various leak sizes and configurations.

Gas-Cooled Reactor Configuration

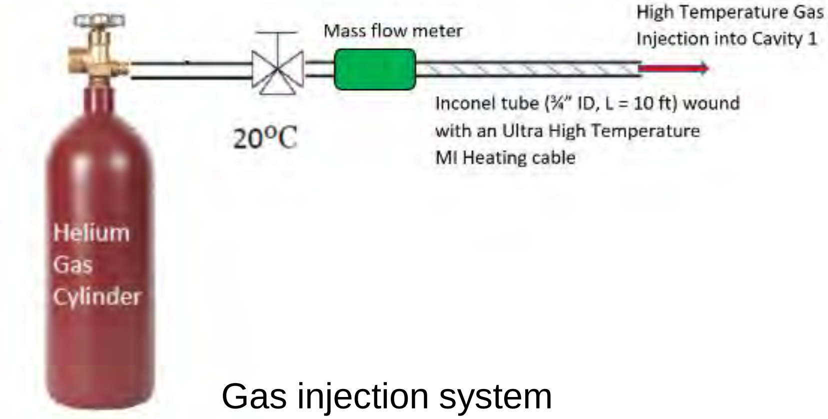


Description of Design Basis Postulated Scenario

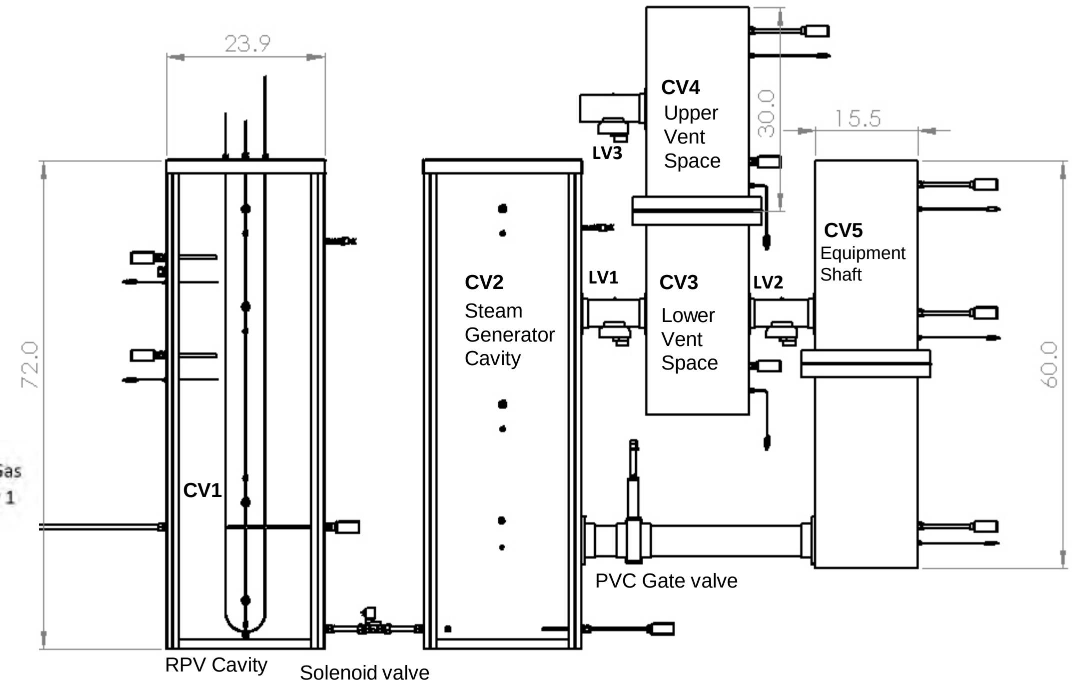


Reactor Building Cavity Facility

* CV – Cavity
  LV – Louvered Vent



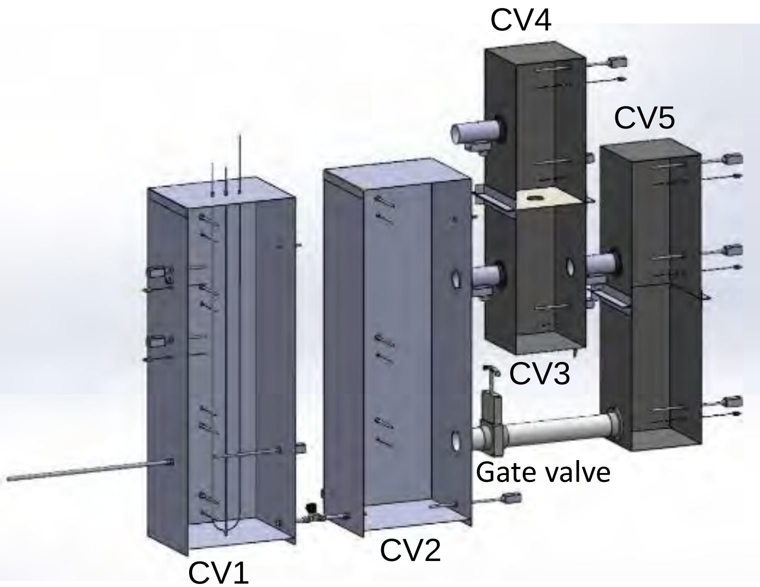
Gas injection system



CCNY Reactor Cavity Test Facility (units in inches)

Fabrication of Facility

- Cavities 1 and 2 fabricated from commercially available steel storage cabinets measuring 72''x24''x24''
- Cavities 3-5 fabricated from steel cans measuring 30''x15.5''x15.5''
- A variety of sensors installed to measure conditions within the cavities and heating pipe.
- Solenoid valve and louvered vents used to control gas flow between cavities.



3D Model of Cavity Test Facility

Cavity Test Facility

Instrumentation and vents

Sensor	Range	Accuracy
Type-K thermocouple	-270 – 1260 °C	+/- 2.2 °C
Honeywell Oxygen probe	0 – 100% O_2 concentration	+/- 2.0 %
Pressure Transducer	0 – 5 PSIG	0.08%
Flow meter	0 – 3000 SLM	0.8%

Type K thermocouple

Honeywell Oxygen probe

Pressure Transducer (PX409)

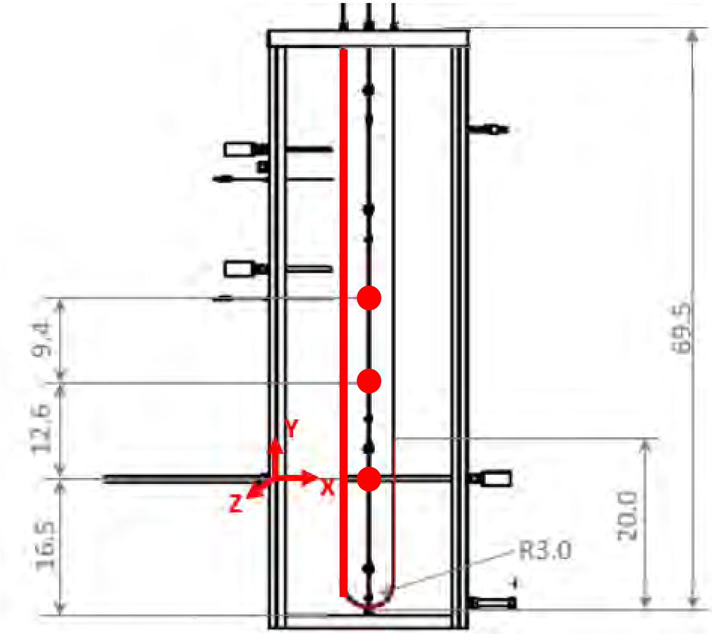
Flowmeter

Louvered Vent

Solenoid valve

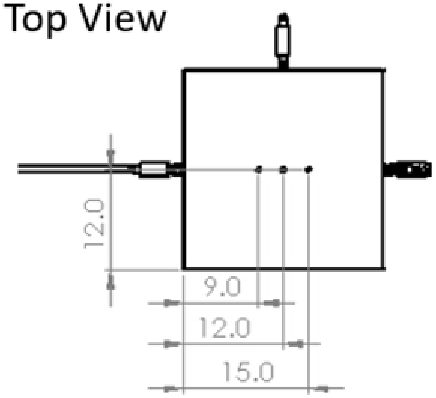
Optical Fiber Sensors

- All measurement locations are shown in inches.
- Purdue's Luna fibre sensor is shown as a red outline in the u-tube and provides a vertical gas temperature profile along the fiber.
- Pittsburgh's fiber sensor measures gas temperature and velocity at three measurement points indicated by red circles.



Front View

Top View



Experimental Procedure and Test Cases

- Multiple experiments were performed in collaboration with the University of Pittsburgh and Purdue University, utilizing their sensors for additional temperature and flow data in cavity 1.
- The parameters investigated are the gas injection temperature, flowrate, injection location, and nozzle injection geometry.
- In these experiments helium gas was continuously injected into cavity 1, whose pressure increases as a result.
- The solenoid valve and louvered vents are programmed to open when cavity 1 pressure reaches 1 psig, at which point the gas mixture is purged into the other cavities.
- Gas injection continues until the oxygen concentration in cavity 1 drops to approximately 5%, the gas injection is then cut off and the experiments end shortly after. The experimental matrix is shown below.

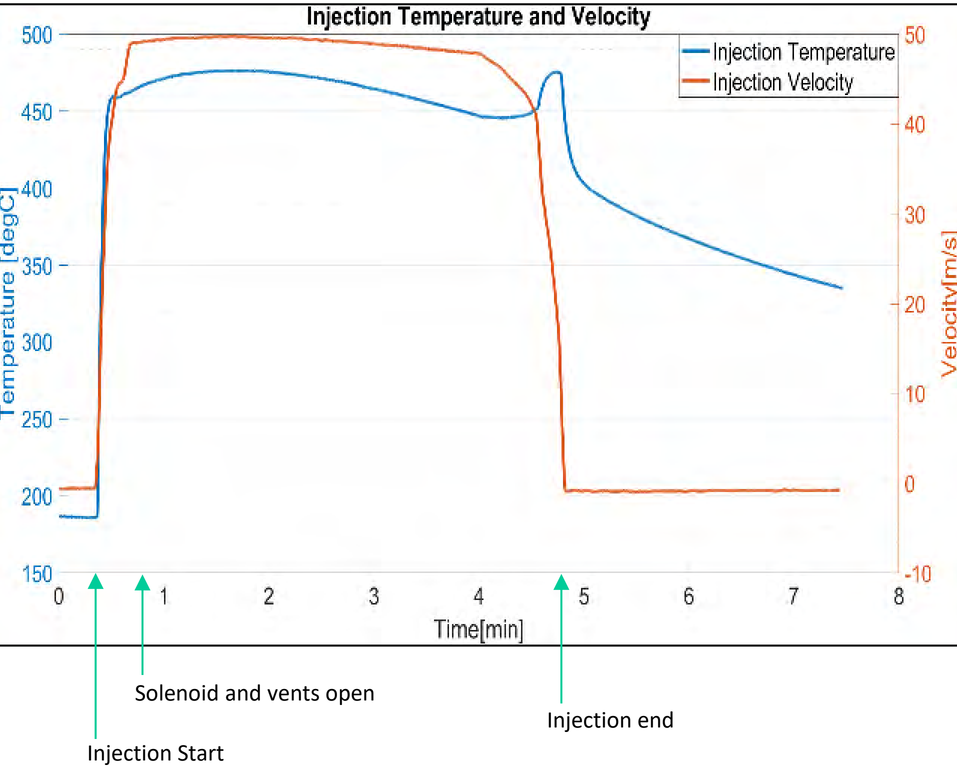
Case	Injection Temperature	Injection Velocity	Injection Location	Nozzle Geometry
1	500	50	Lower	Open pipe
2	500	50	Upper	Open pipe
3	500	120	Lower	Rectangular end slot
4	500	80	Lower	Side slot up
5	500	80	Lower	Side slot down

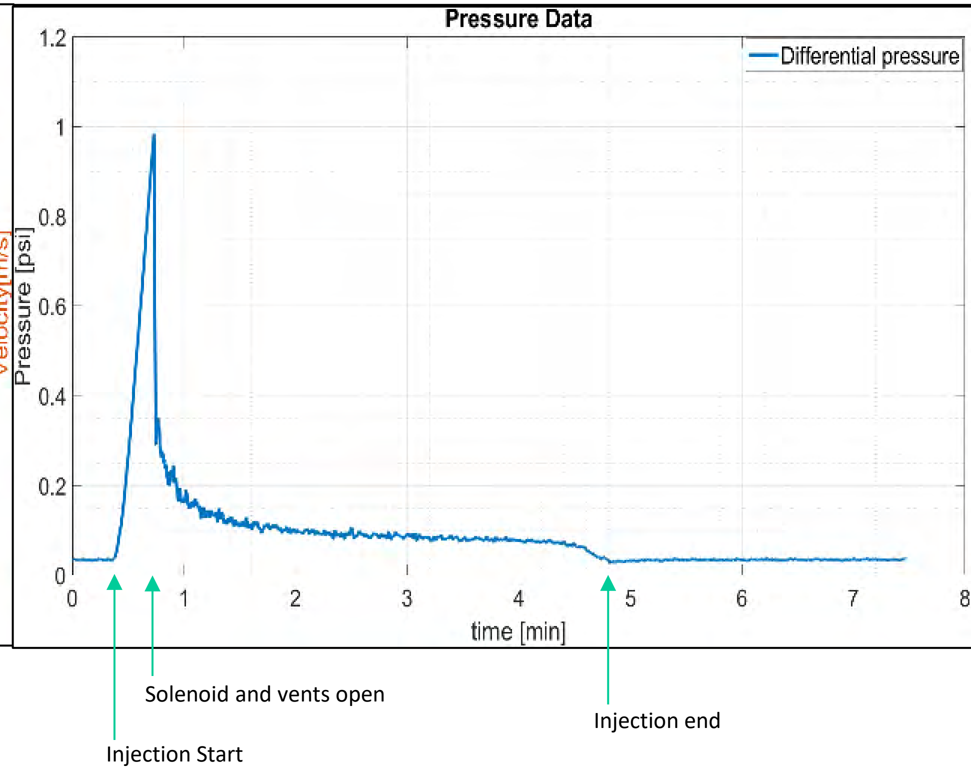

(a) Open pipe (13.8 mm inner hole diameter)


(b) Rectangular end slot (5.4 mm x 10.7 mm)


(c) Rectangular side slot (8.6 mm x 10.0 mm) facing vertically upward or downward

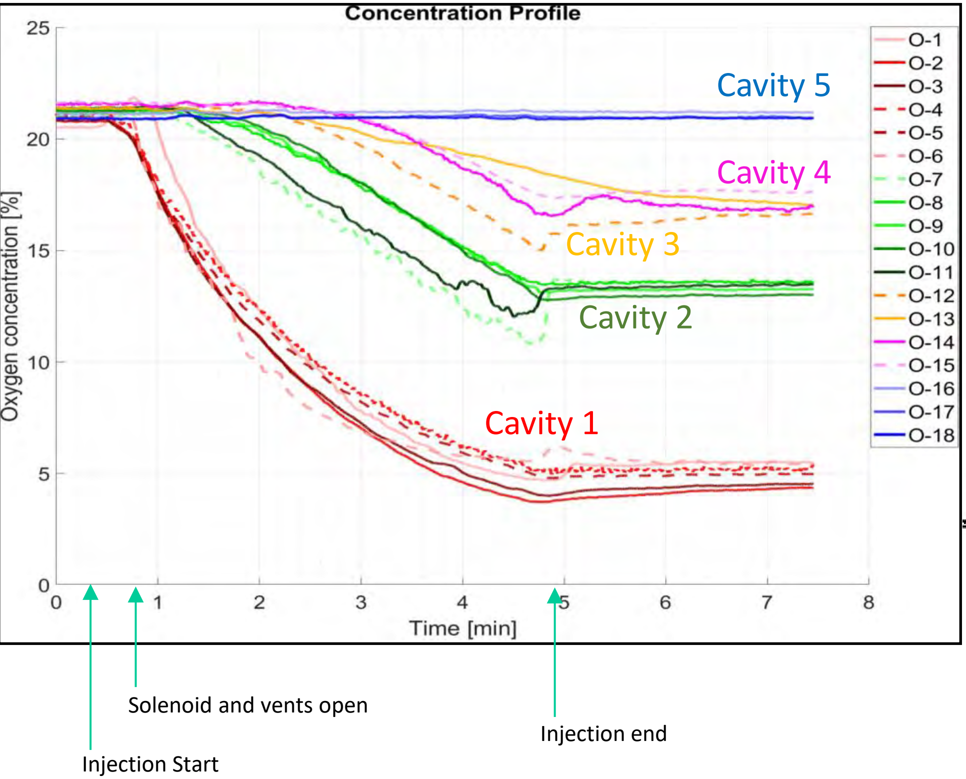
Lower gas injection at 500 °C and 50m/s

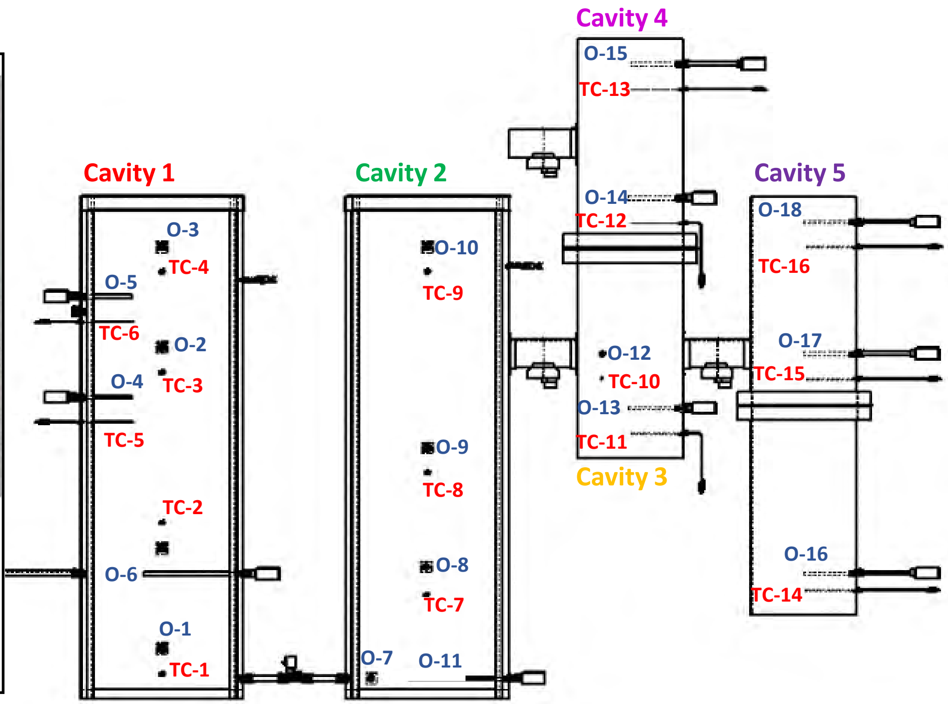




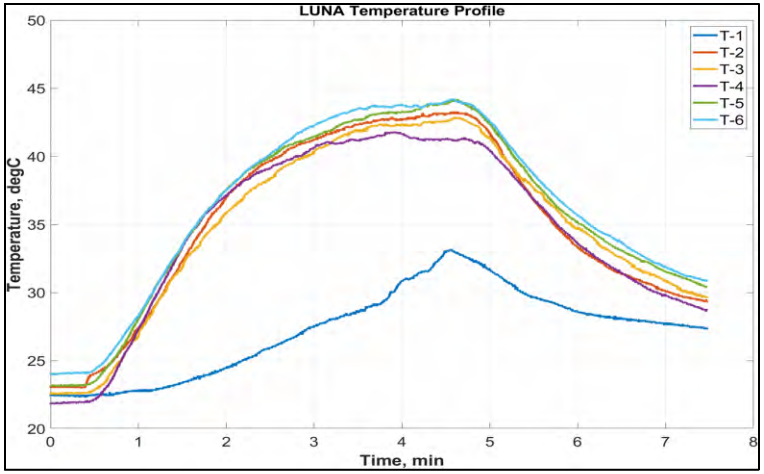
Solenoid valve and louvered vents were programmed to open when the differential pressure between cavities 1 and 2 reached 1 psi.

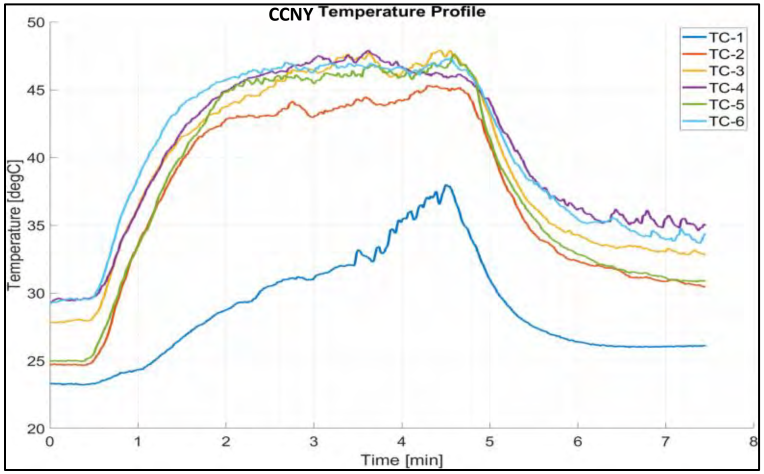
Lower gas injection at 500 ^{o}C and 50m/s

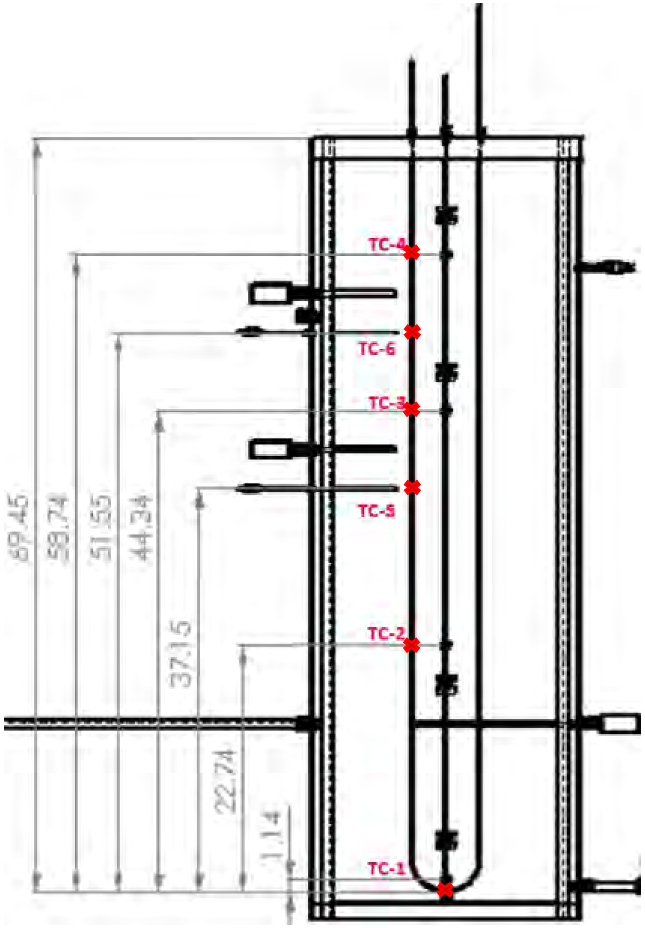




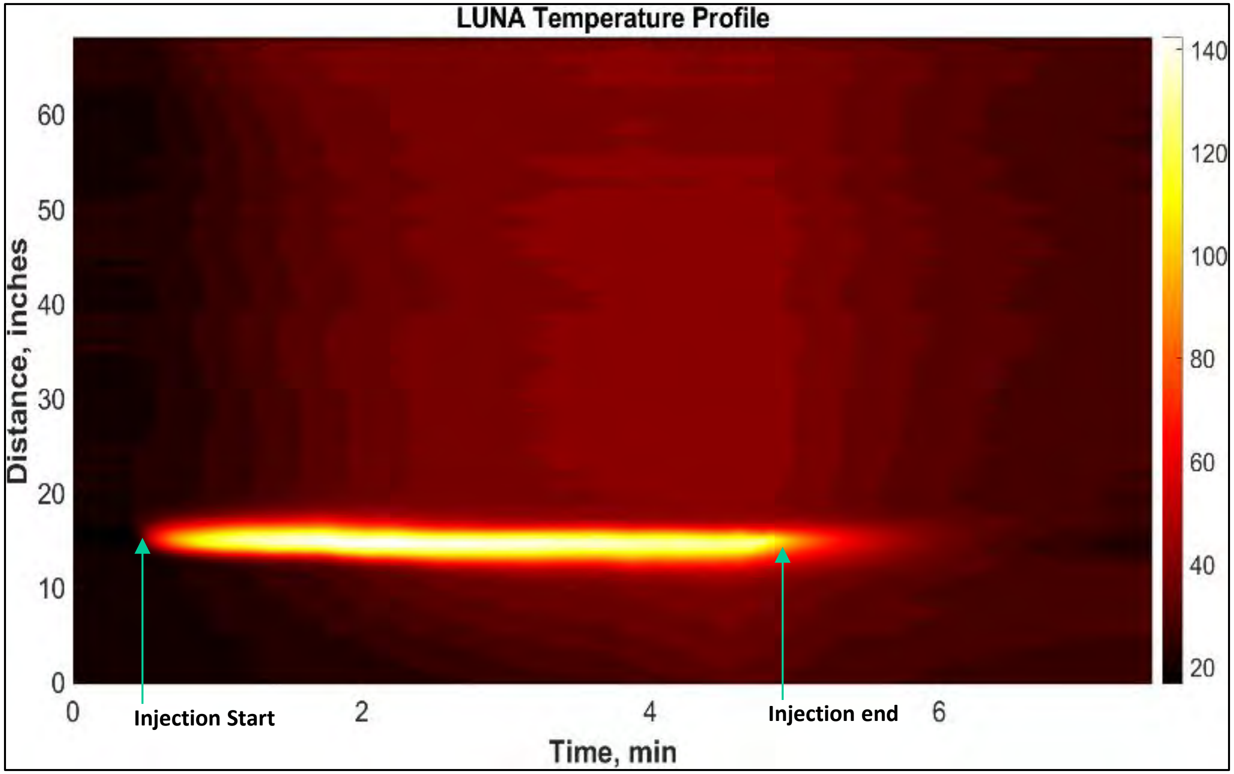
Lower gas injection at 500 ^{0}C and 50m/s

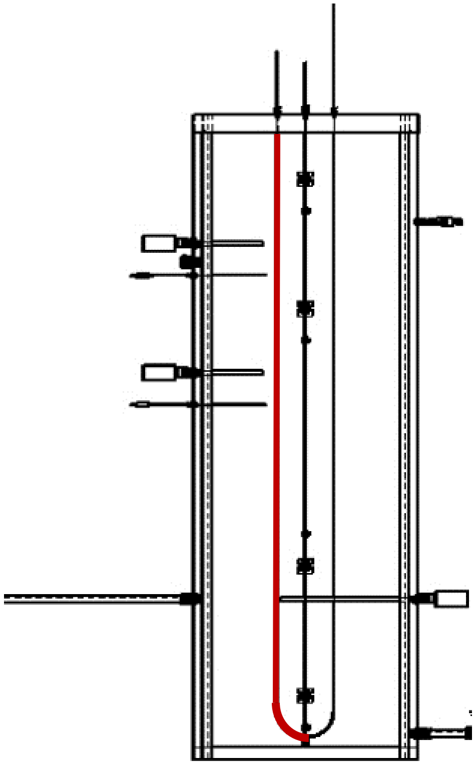






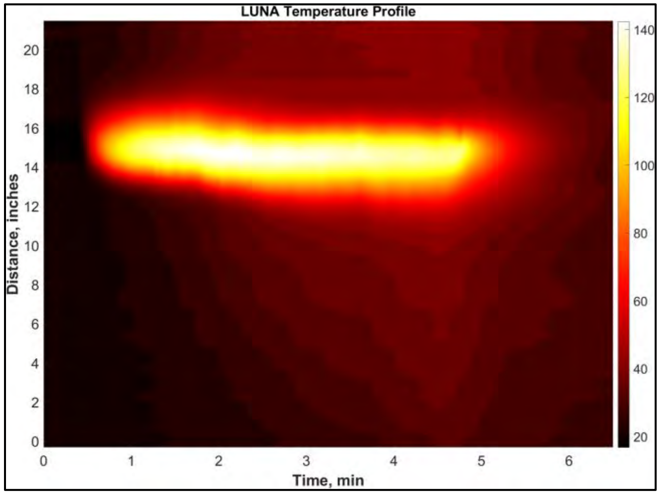
Lower gas injection at 500 ^{o}C and 50m/s



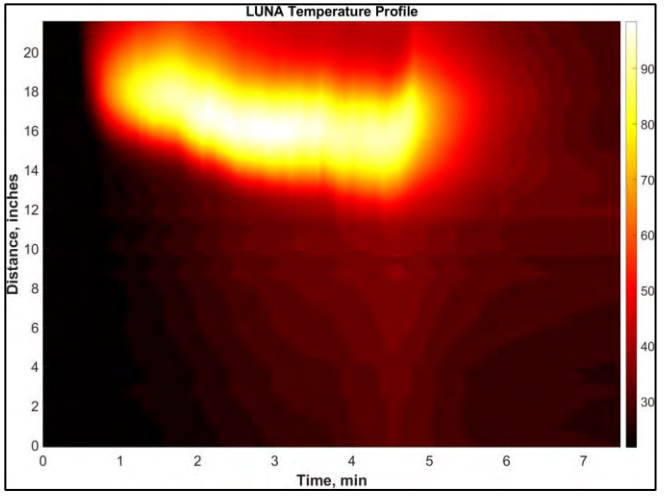


- LUNA profile shows high temperatures at the injection location. Temperatures rapidly drop above and below the injection point.
- The profile also shows that the region below the injection point remains at a lower temperature compared to the rest of the cavity.

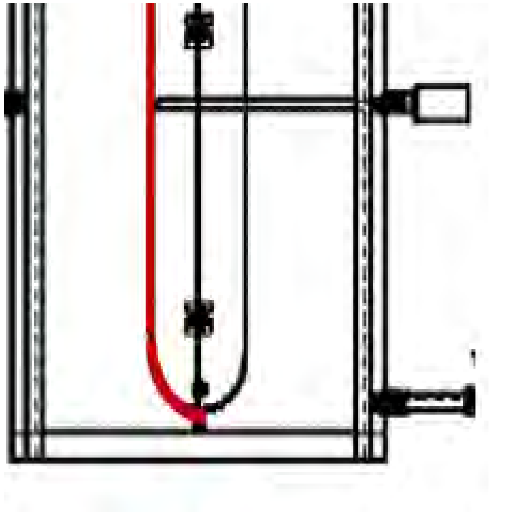
Lower gas injection at 500 ^{0}C and 50m/s



Left section of LUNA fibre



Right section of LUNA fibre



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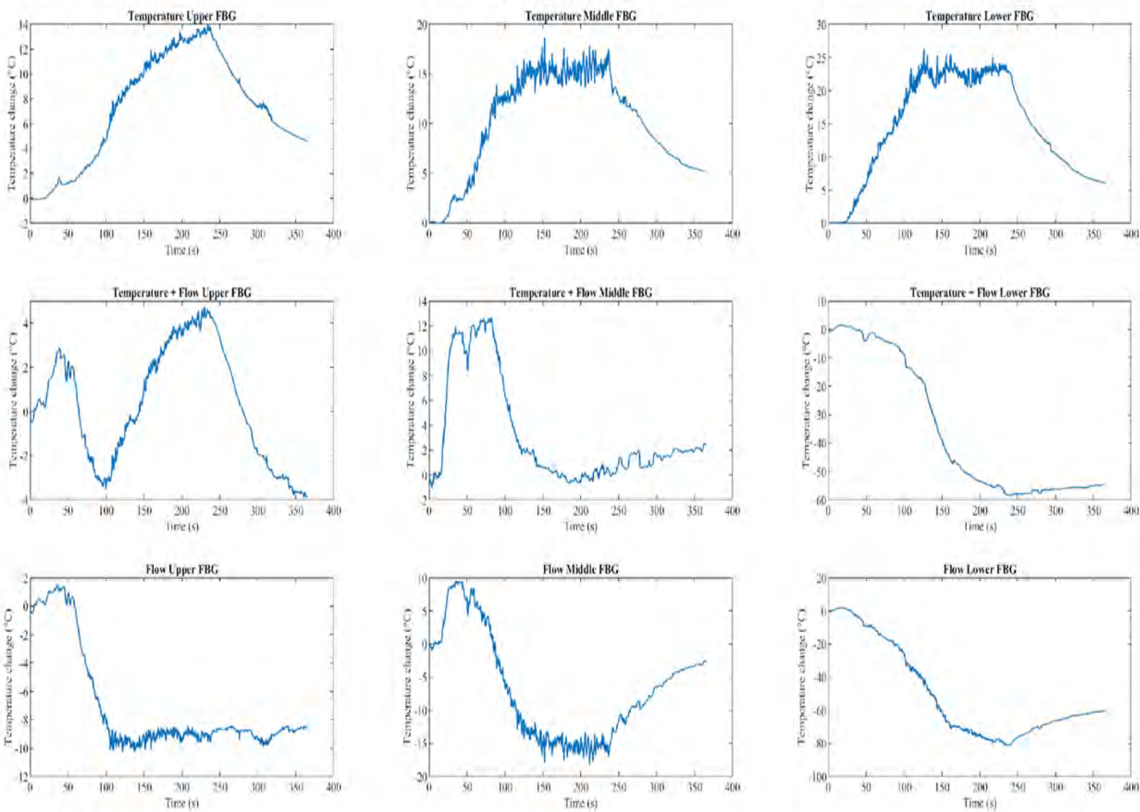
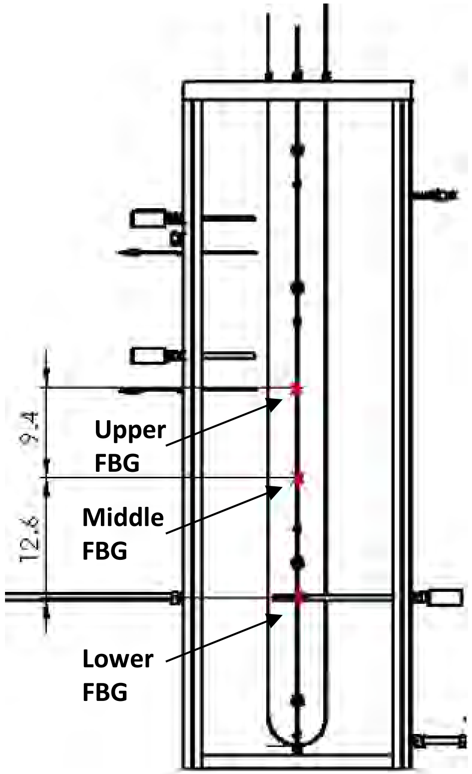
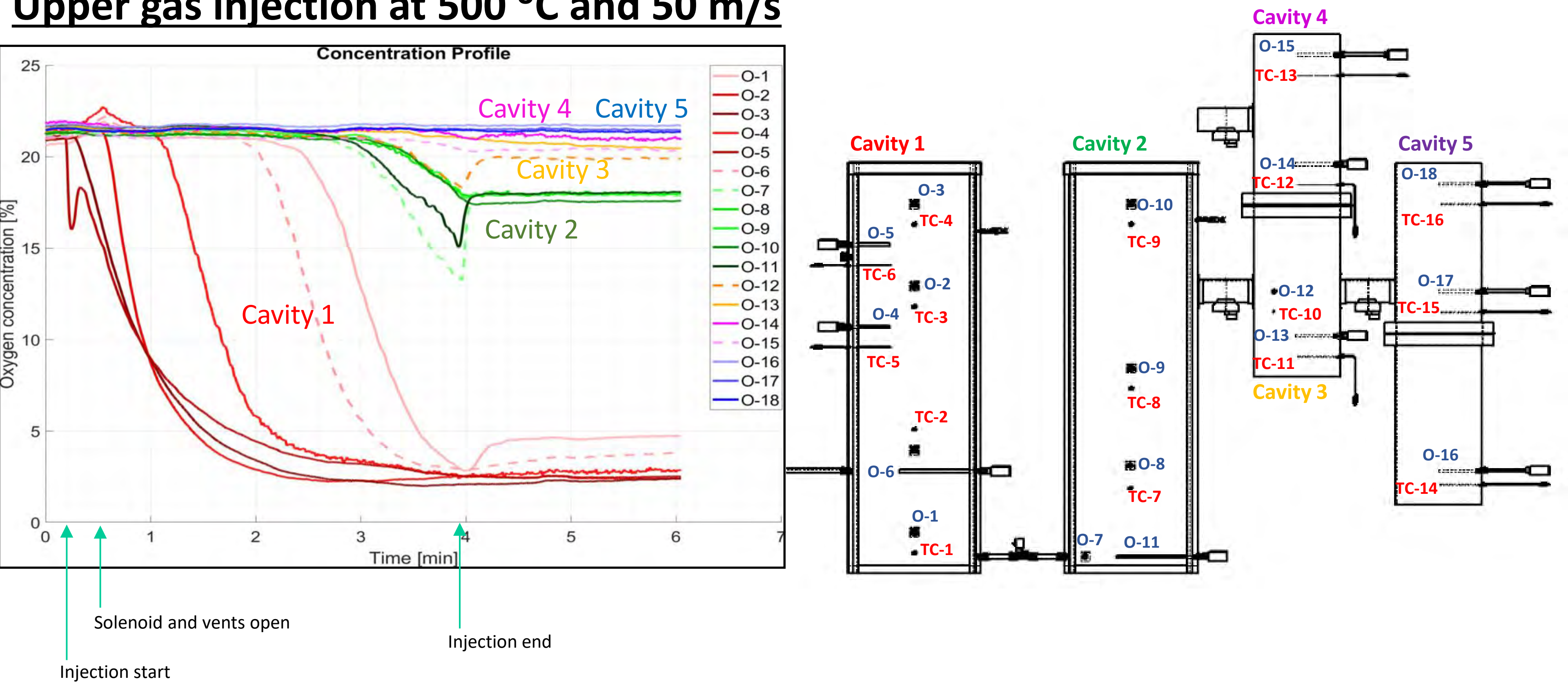
University of Pittsburgh Sensor Data

Helium injection at 500 deg C and 50 m/s



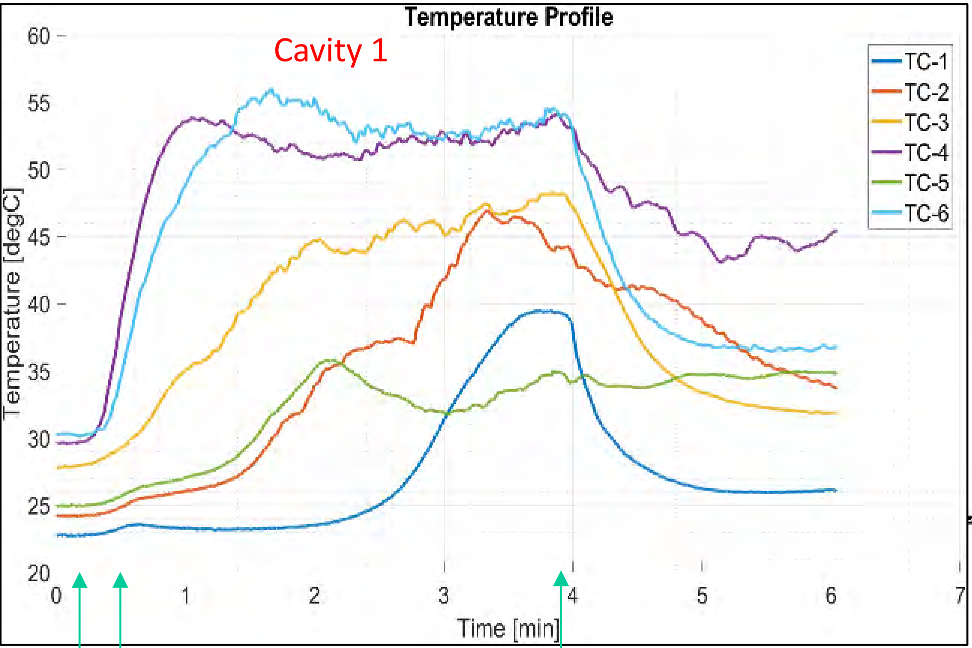


Upper gas injection at 500 ^{0}C and 50 m/s



- Helium initially accumulates in the top half of the cavity and fills the cavity from top to bottom shown by the sequential drop in local oxygen concentration.
- Cavity appears to be relatively well mixed with slight variations in the oxygen concentration at different points.

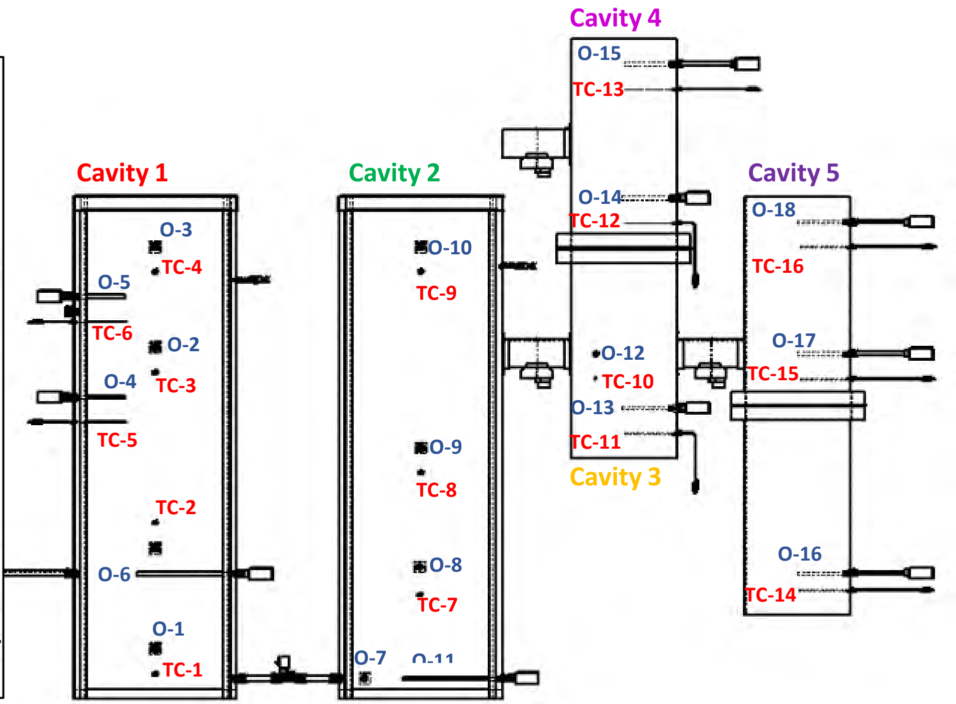
Upper gas injection at 500 ^oC and 50 m/s



Solenoid and vents open

Injection end

Injection Start



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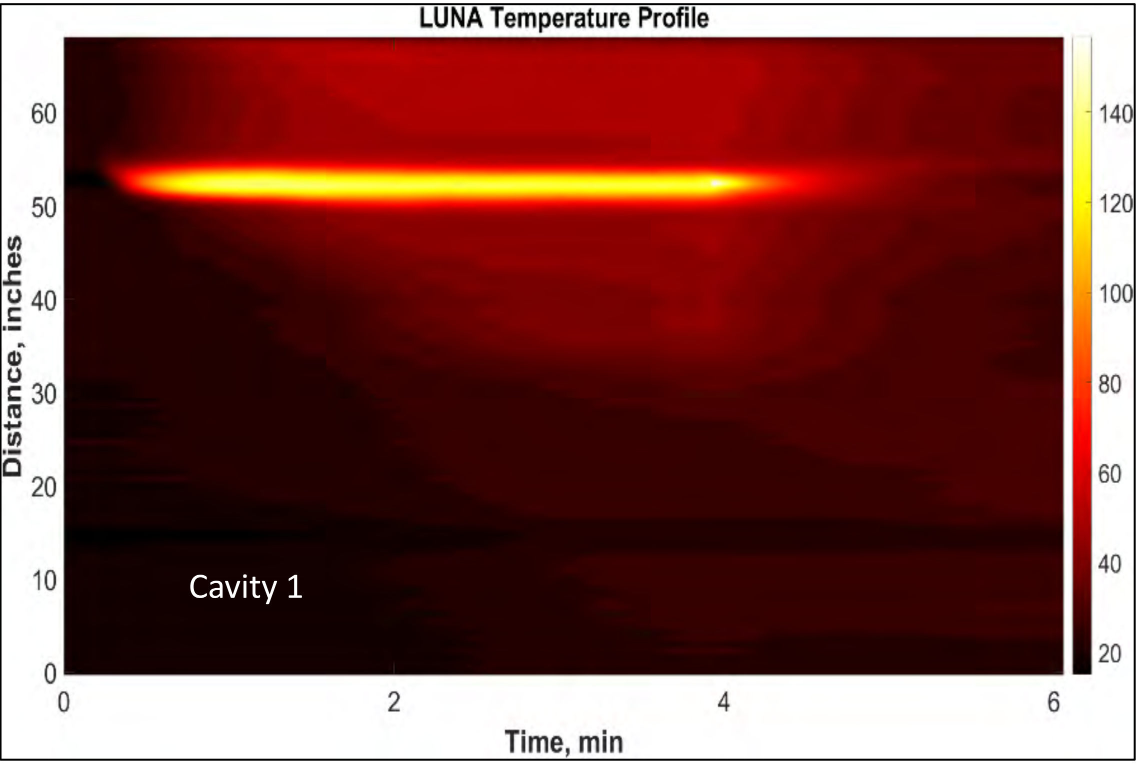
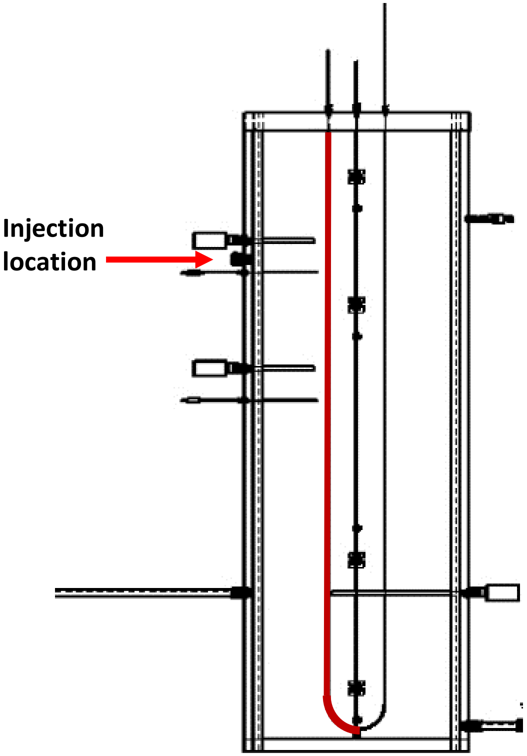
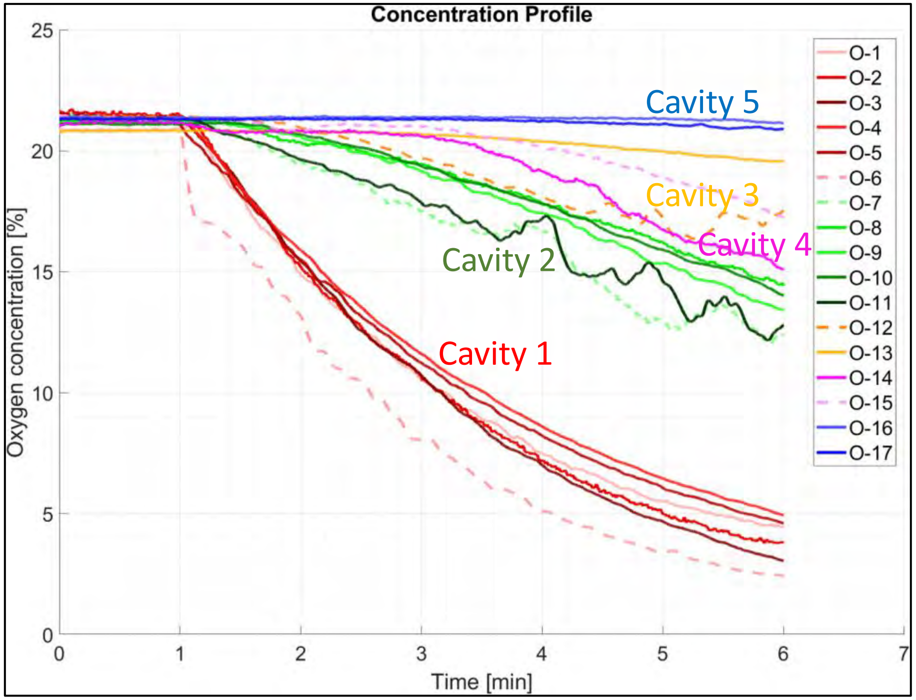
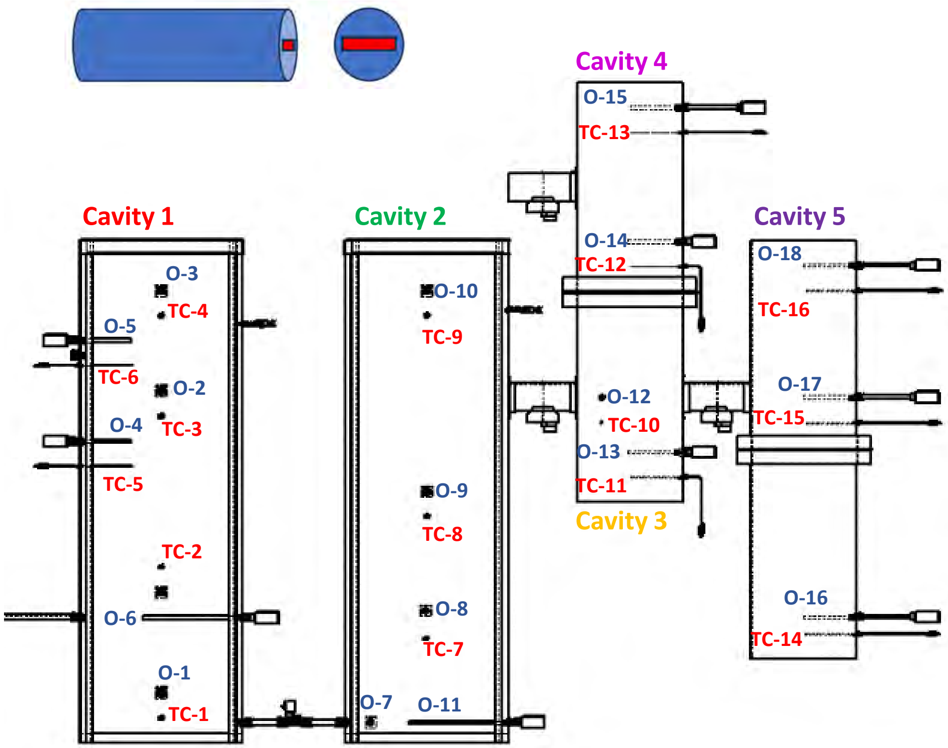
Upper gas injection at 500 ^{o}C and 50 m/s



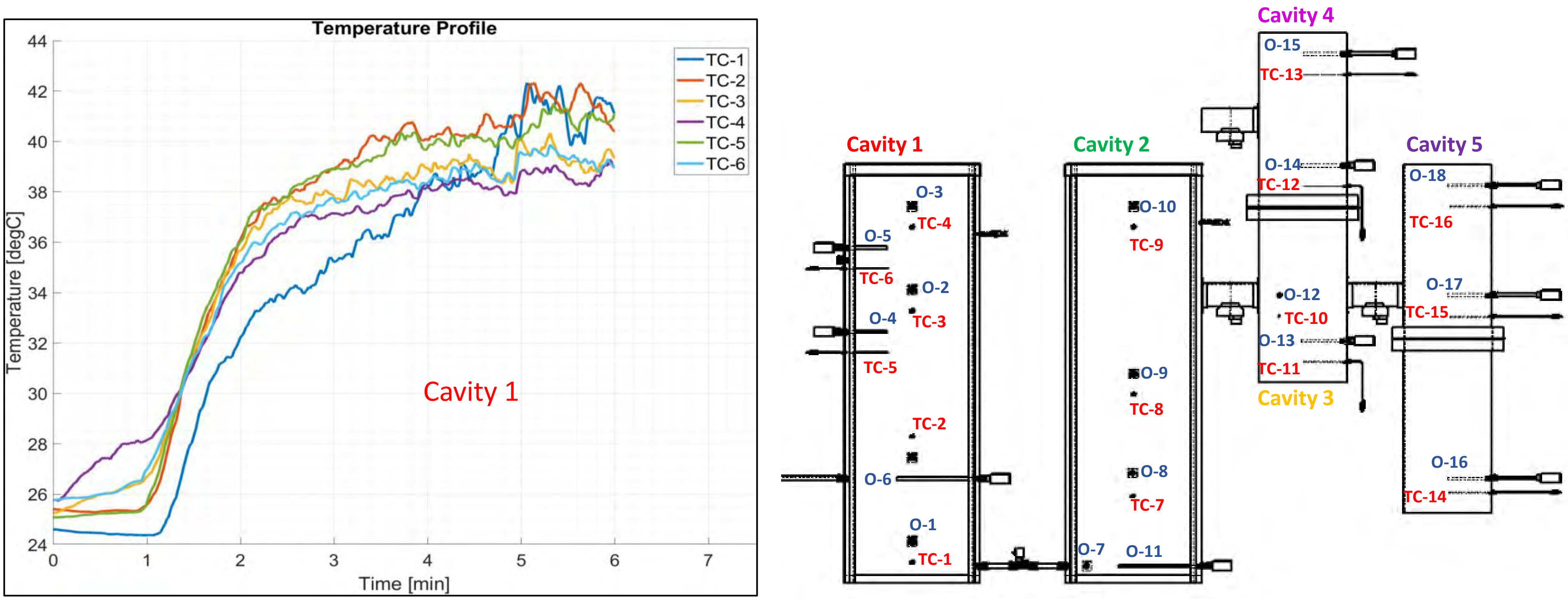


End slot injection at 500 ^{o}C and 120 m/s

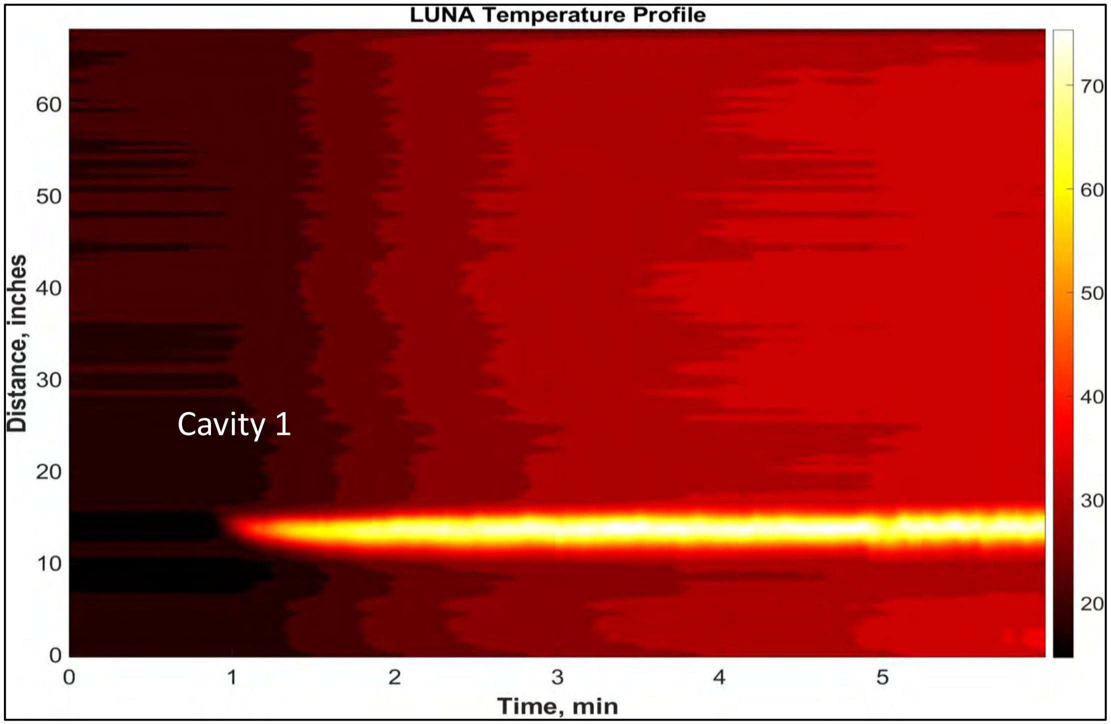


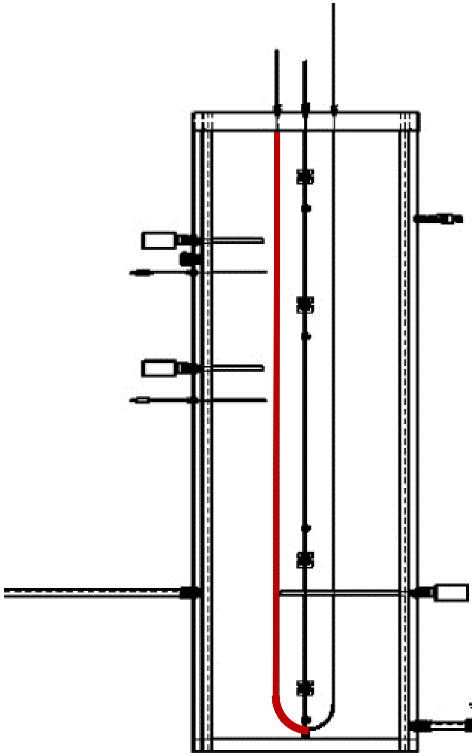


End slot injection at 500 ^{o}C and 120 m/s

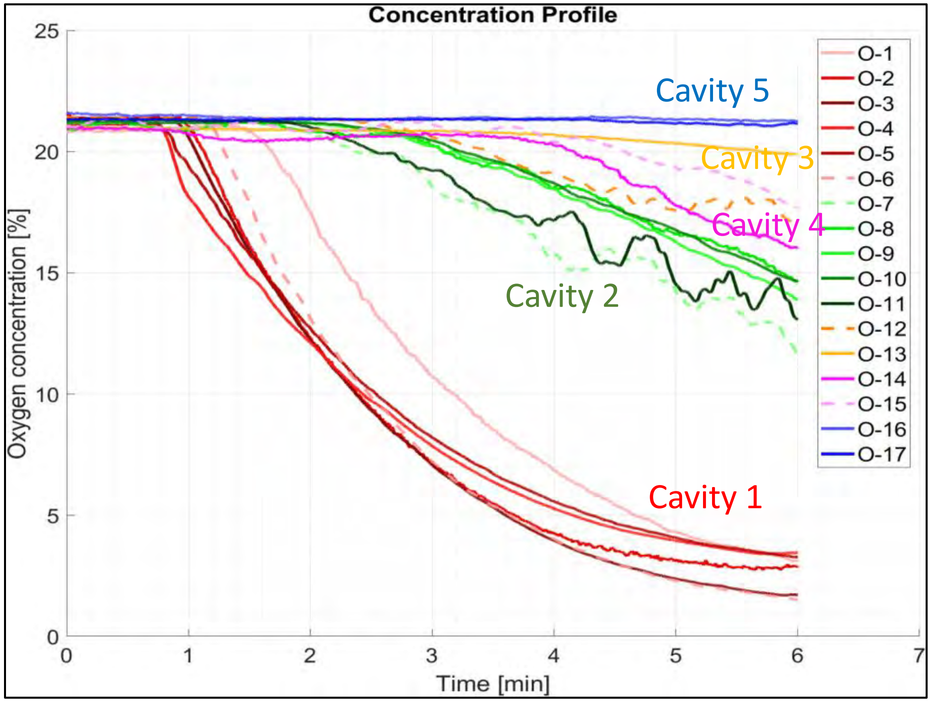


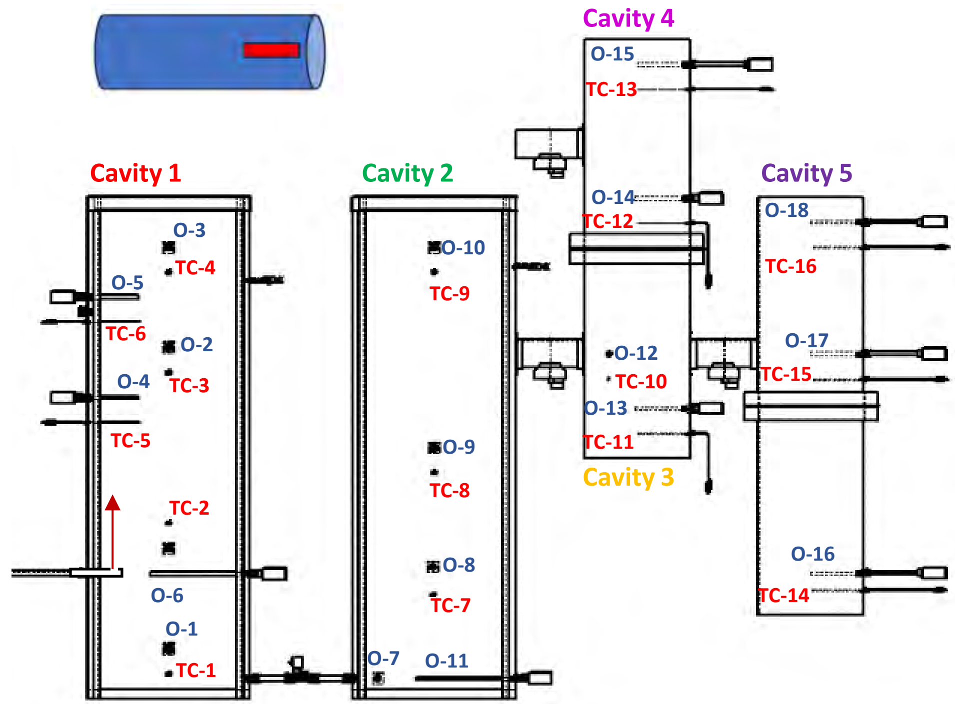
End slot injection at 500 ^{o}C and 120 m/s



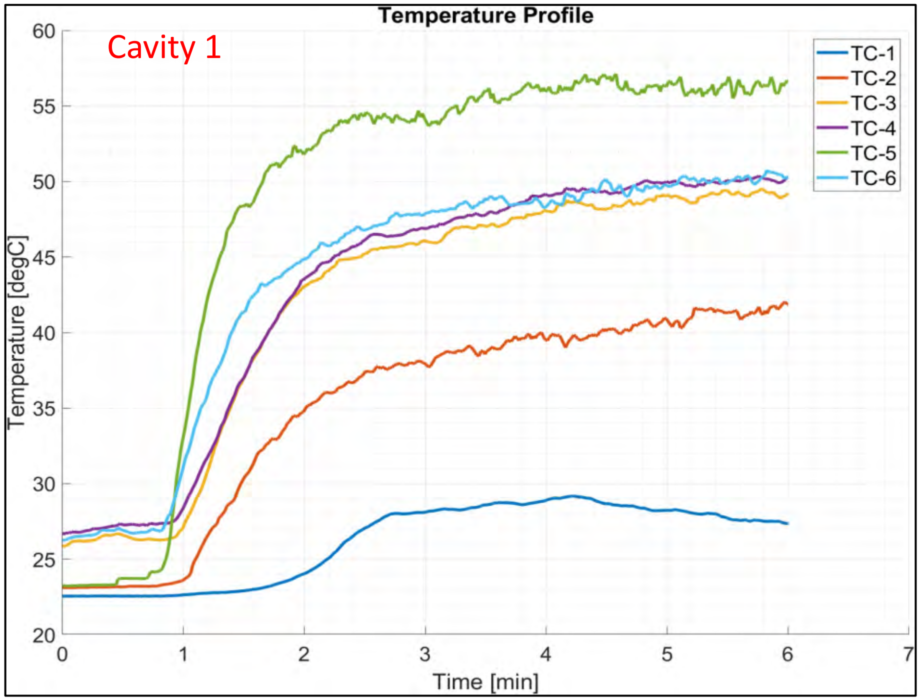


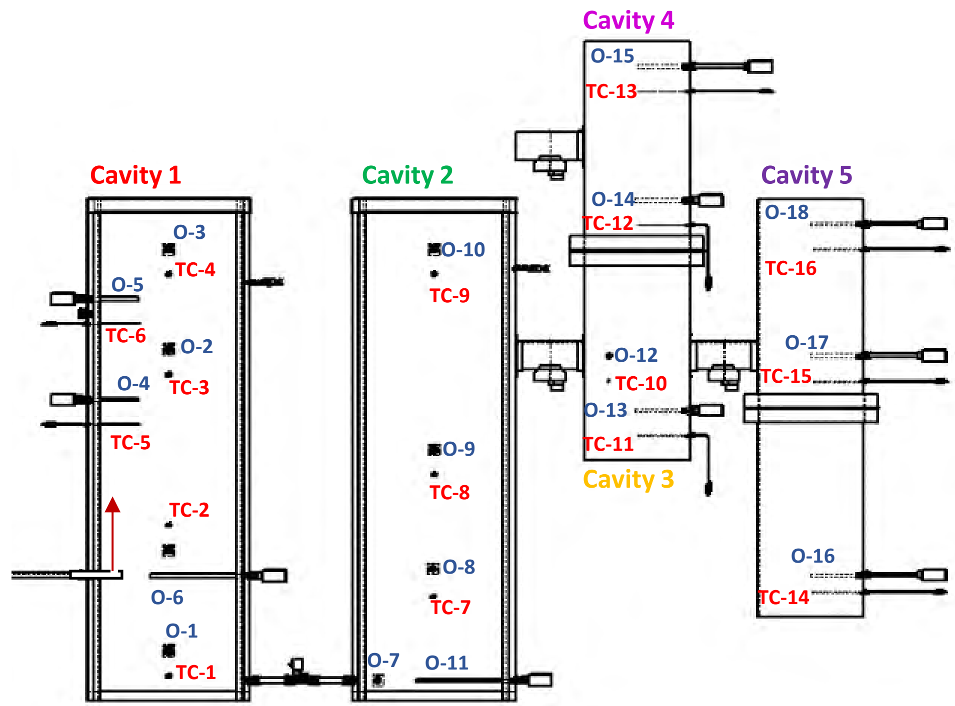
Side slot upward injection at 500 ^oC and 80 m/s



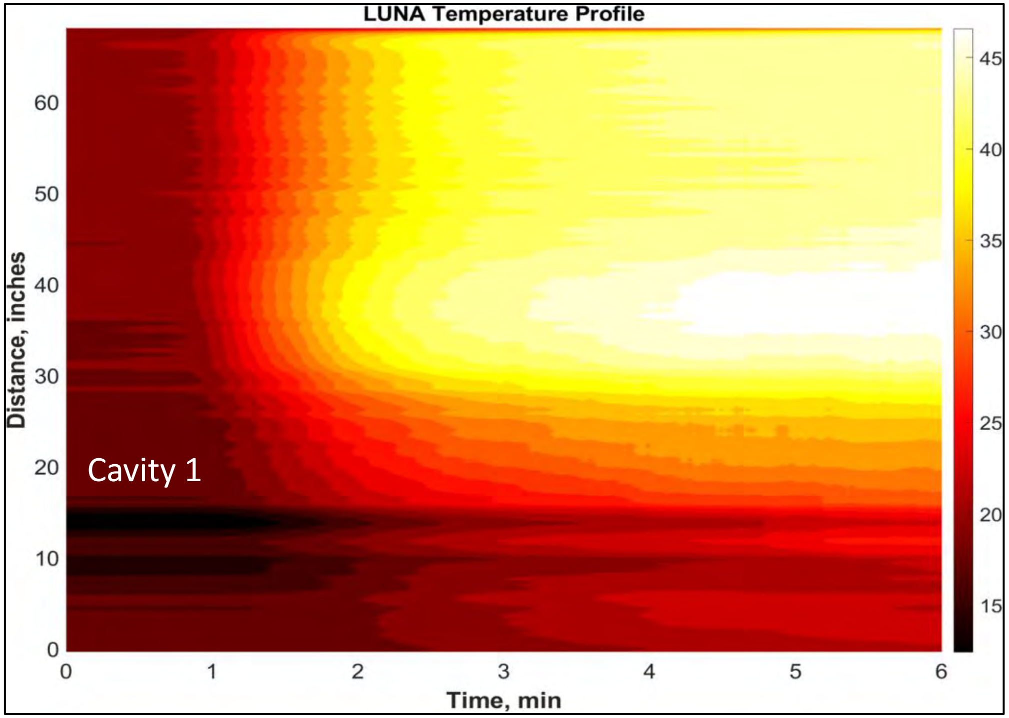


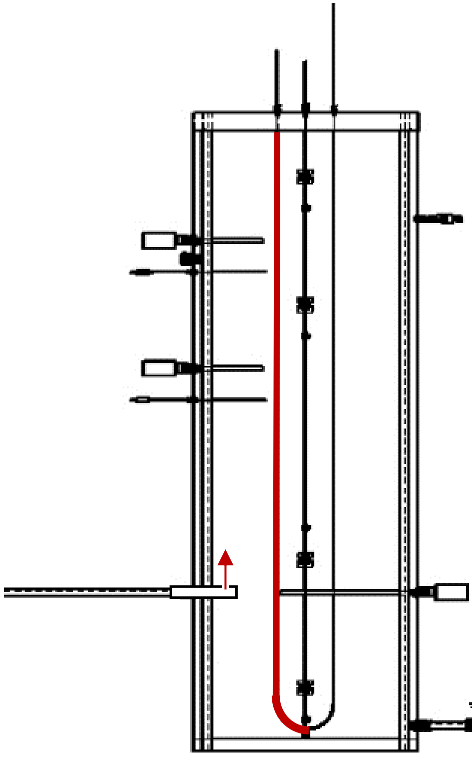
Side slot upward injection at 500 ^oC and 80 m/s





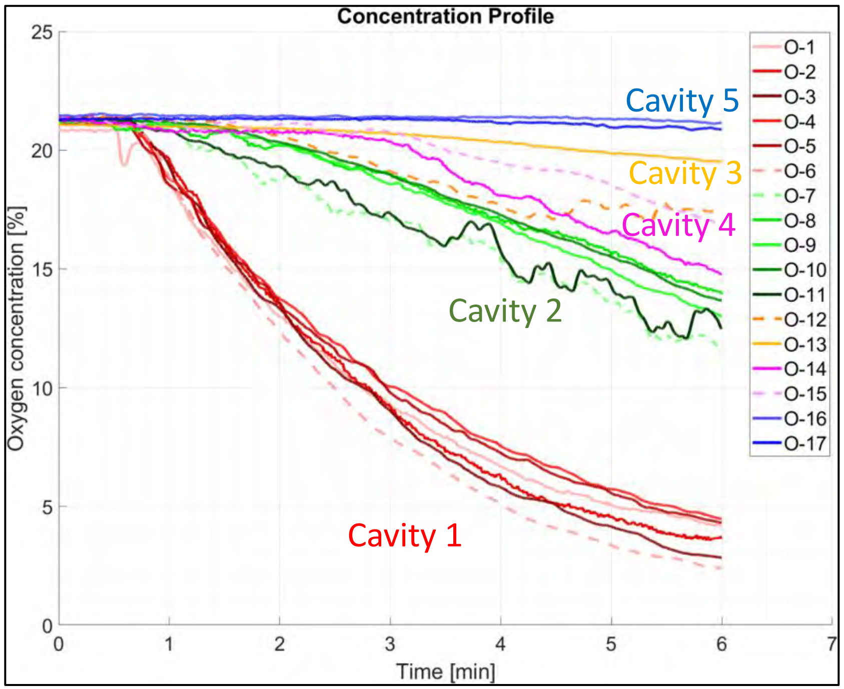
Side slot upward injection at 500 ^oC and 80 m/s

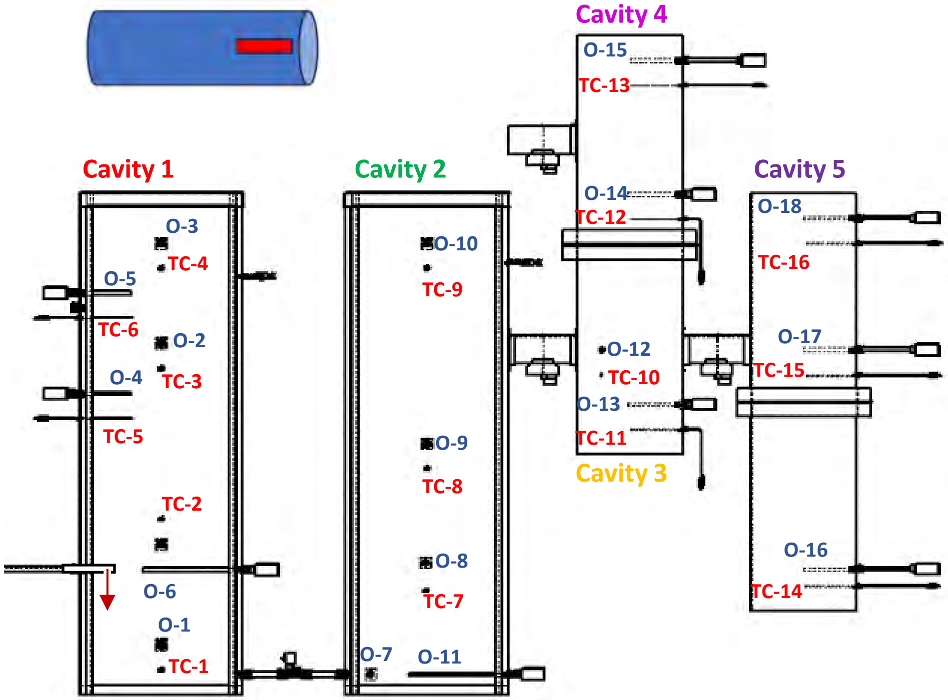




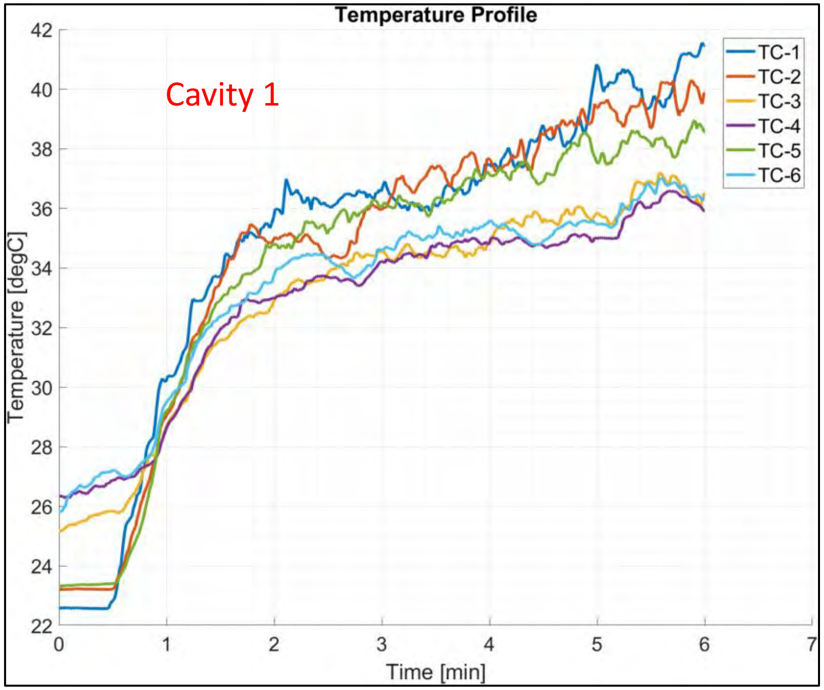
* Red arrow indicates the jet direction

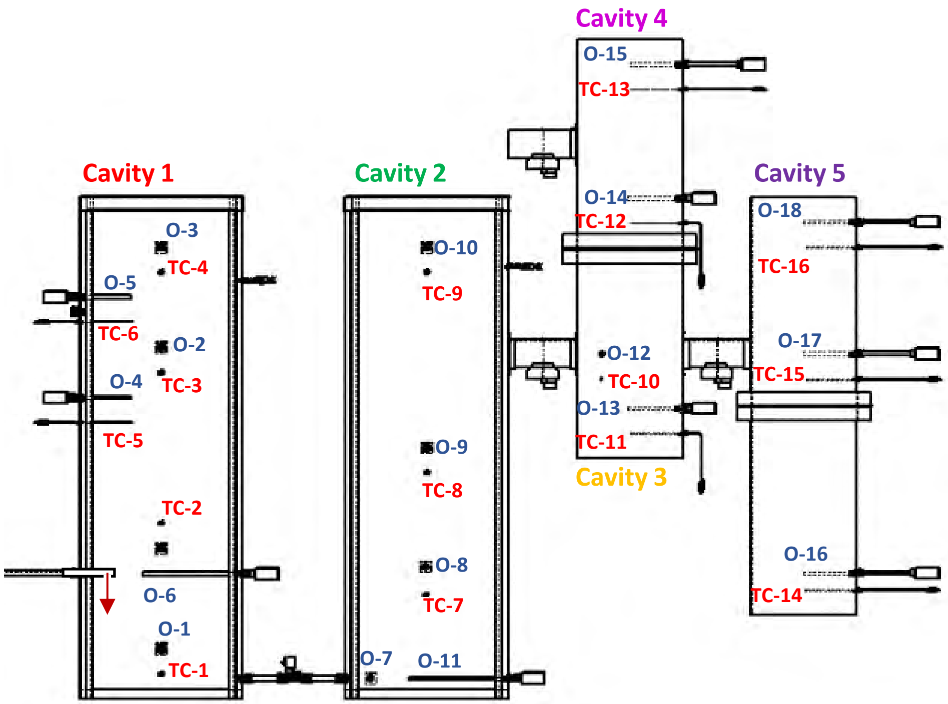
Side slot downward injection at 500 ^{o}C and 80 m/s



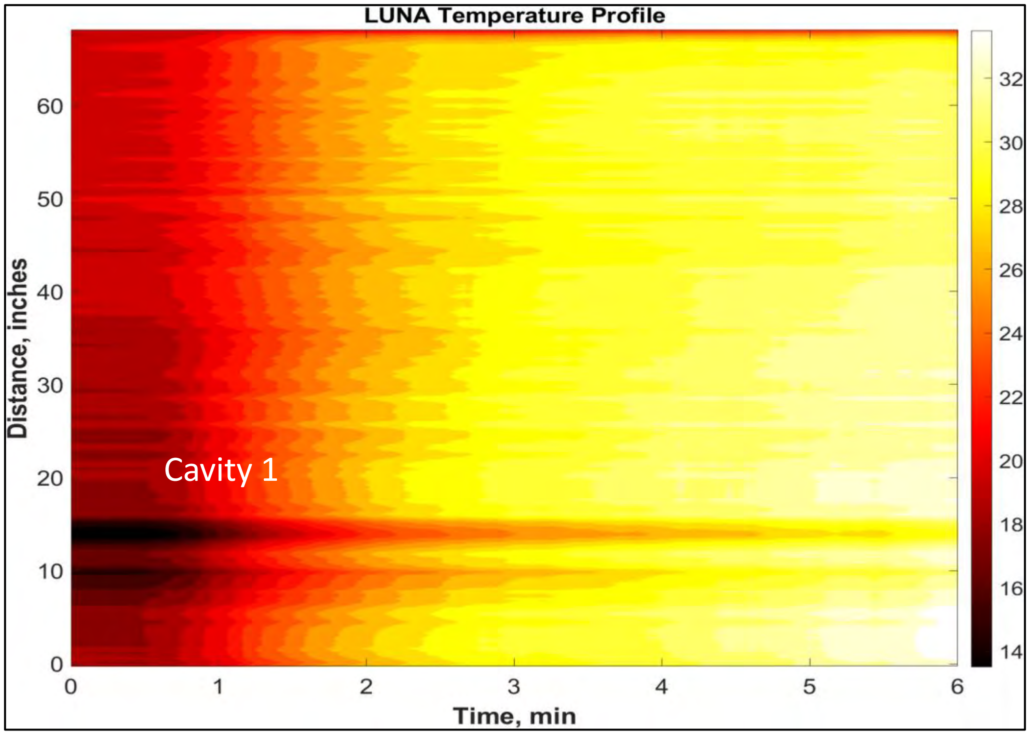


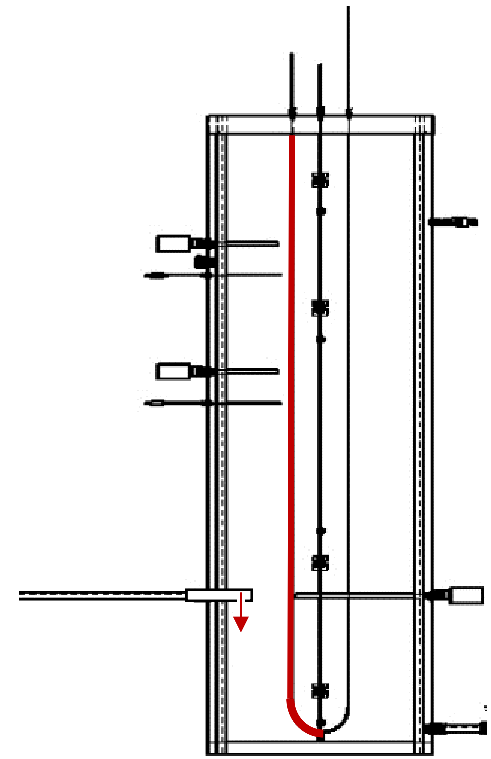
Side slot downward injection at 500 ^oC and 80 m/s





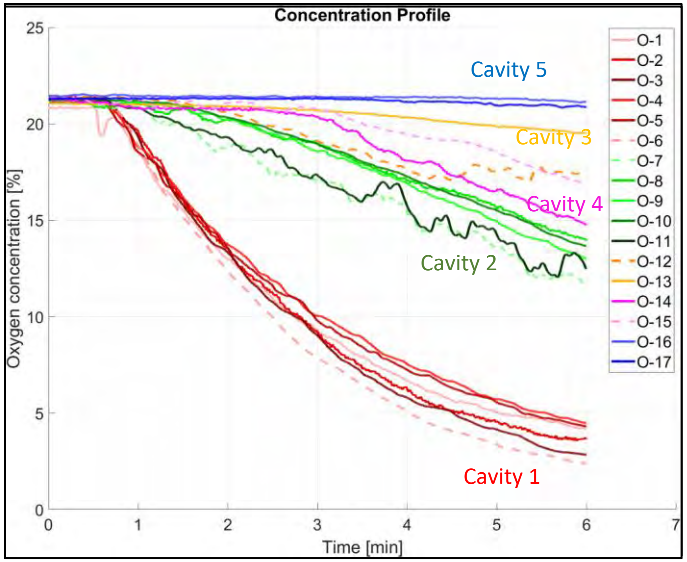
Side slot downward injection at 500 ^{o}C and 80 m/s



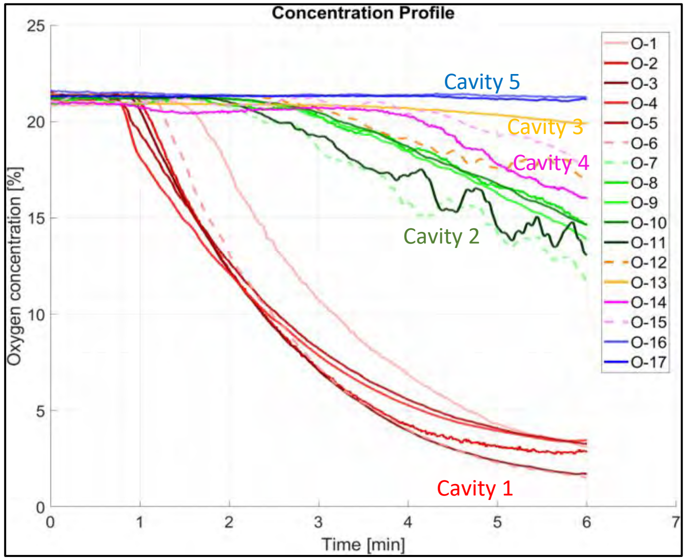


* Red arrow indicates the jet direction

Downward injection vs upward injection



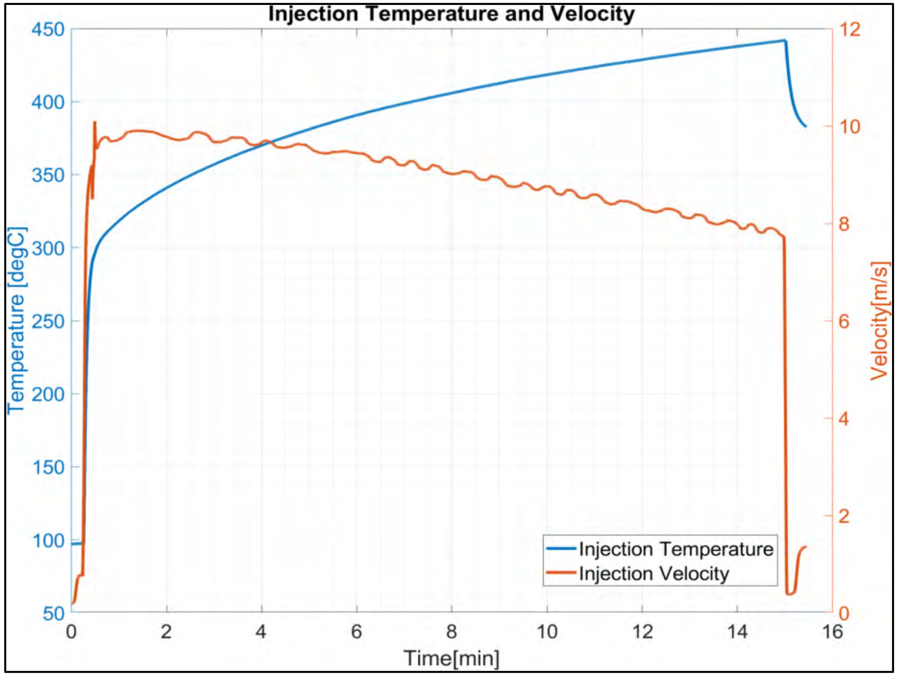
Side slot downward injection

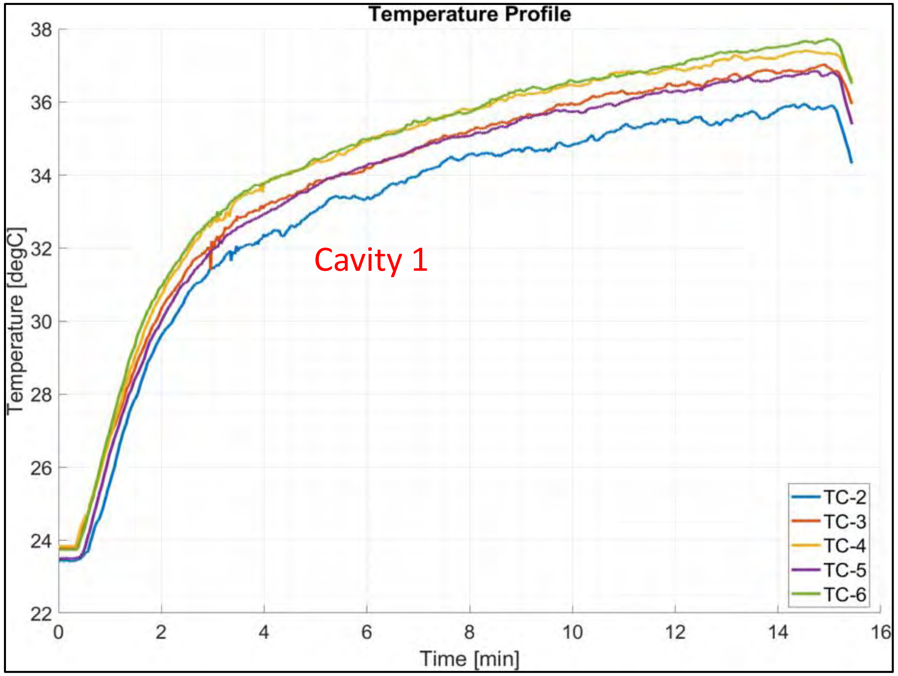


Side slot upward injection

Air into air calibration experiment for NEK5000 simulations

- Solenoid valve remained open for the duration of the experiment

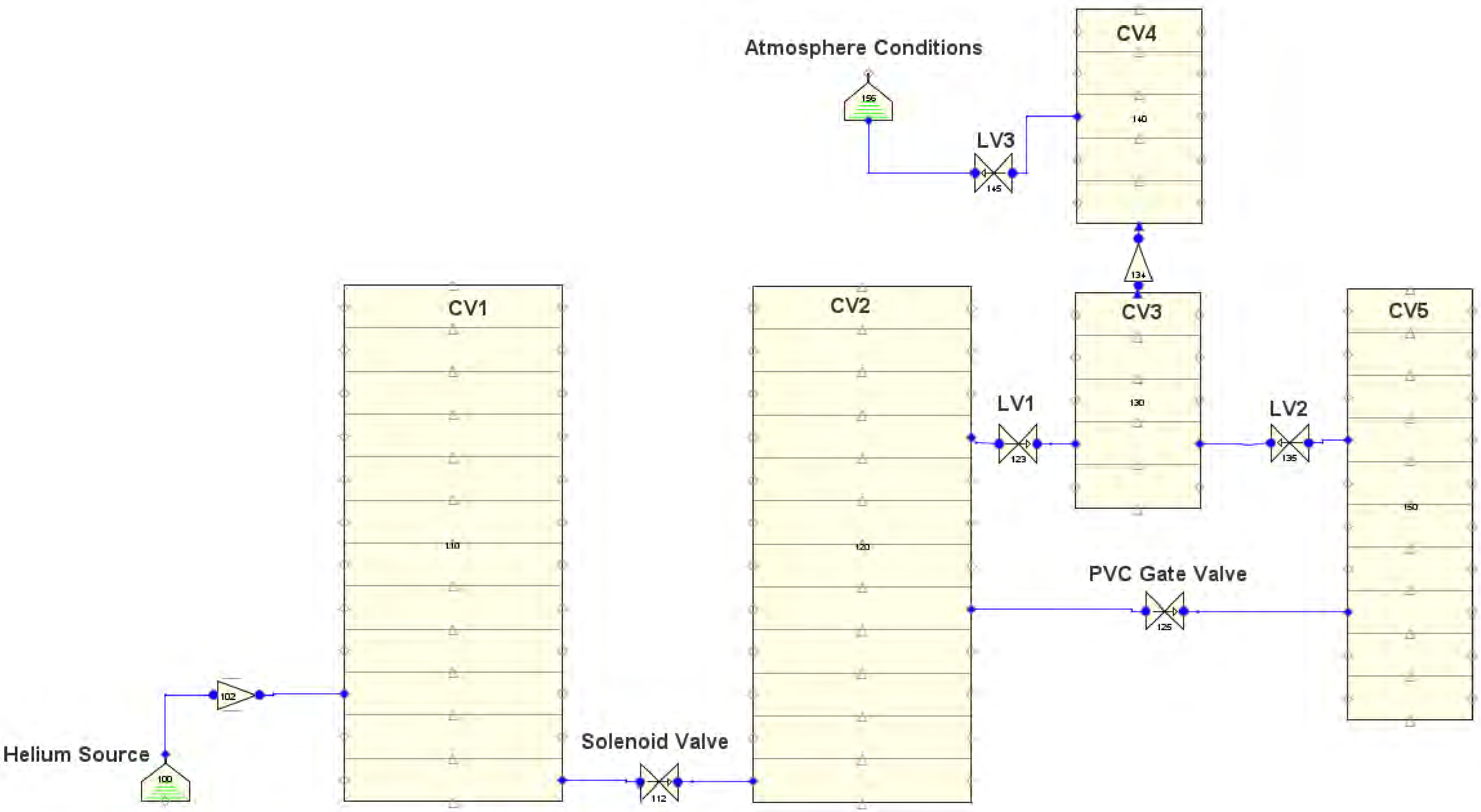




Summary of Results

- Lower break locations resulted in relatively higher oxygen concentrations in the RPV cavity.
- Upper break location poses less of a risk, as air is pushed away from the nozzle opening by the helium rich mixture.
- Break nozzle geometry and jet direction strongly influence the air-helium mixing process.

RELAP5 Nodalization

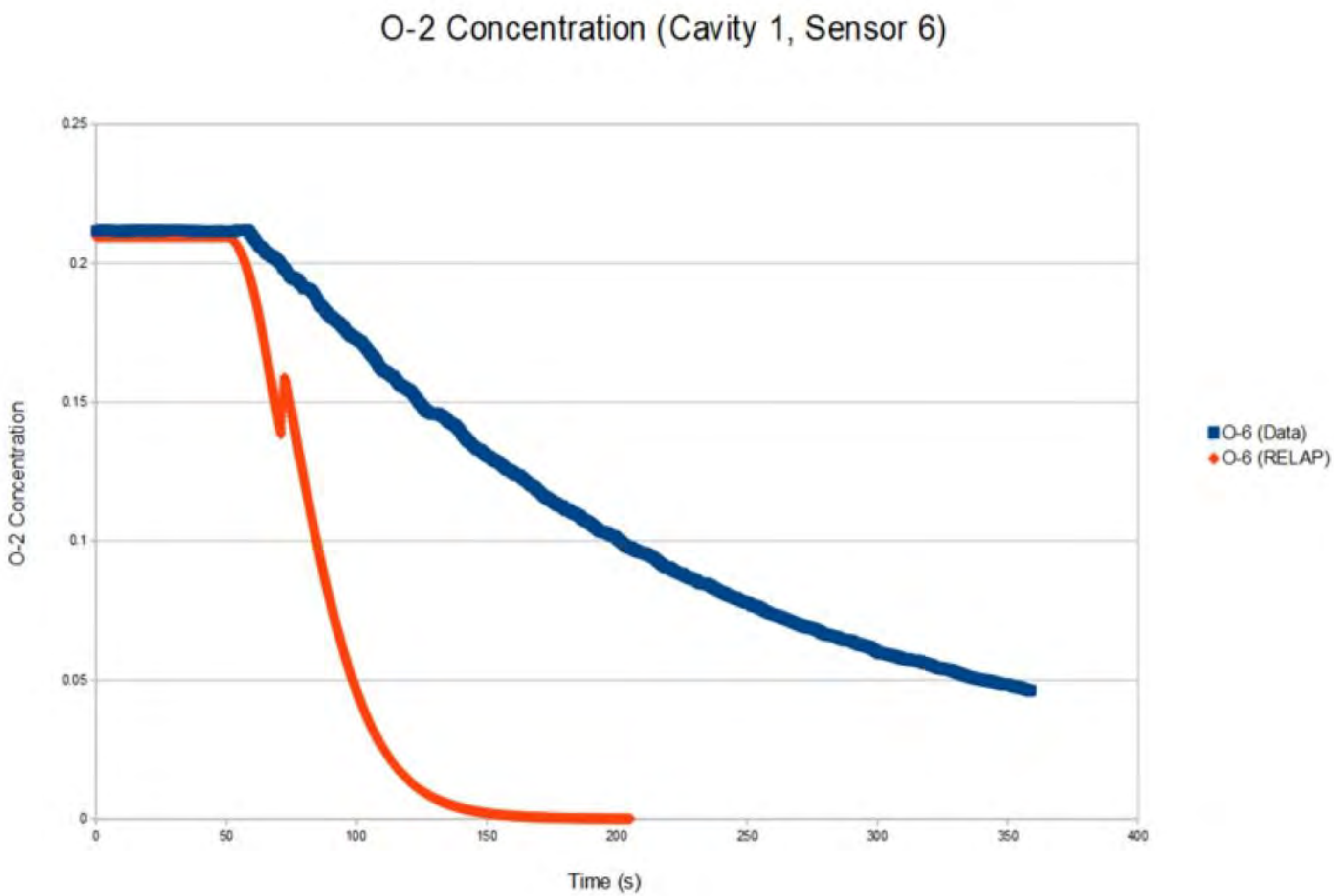


RELAP5 Calculation Performed for Case 3:

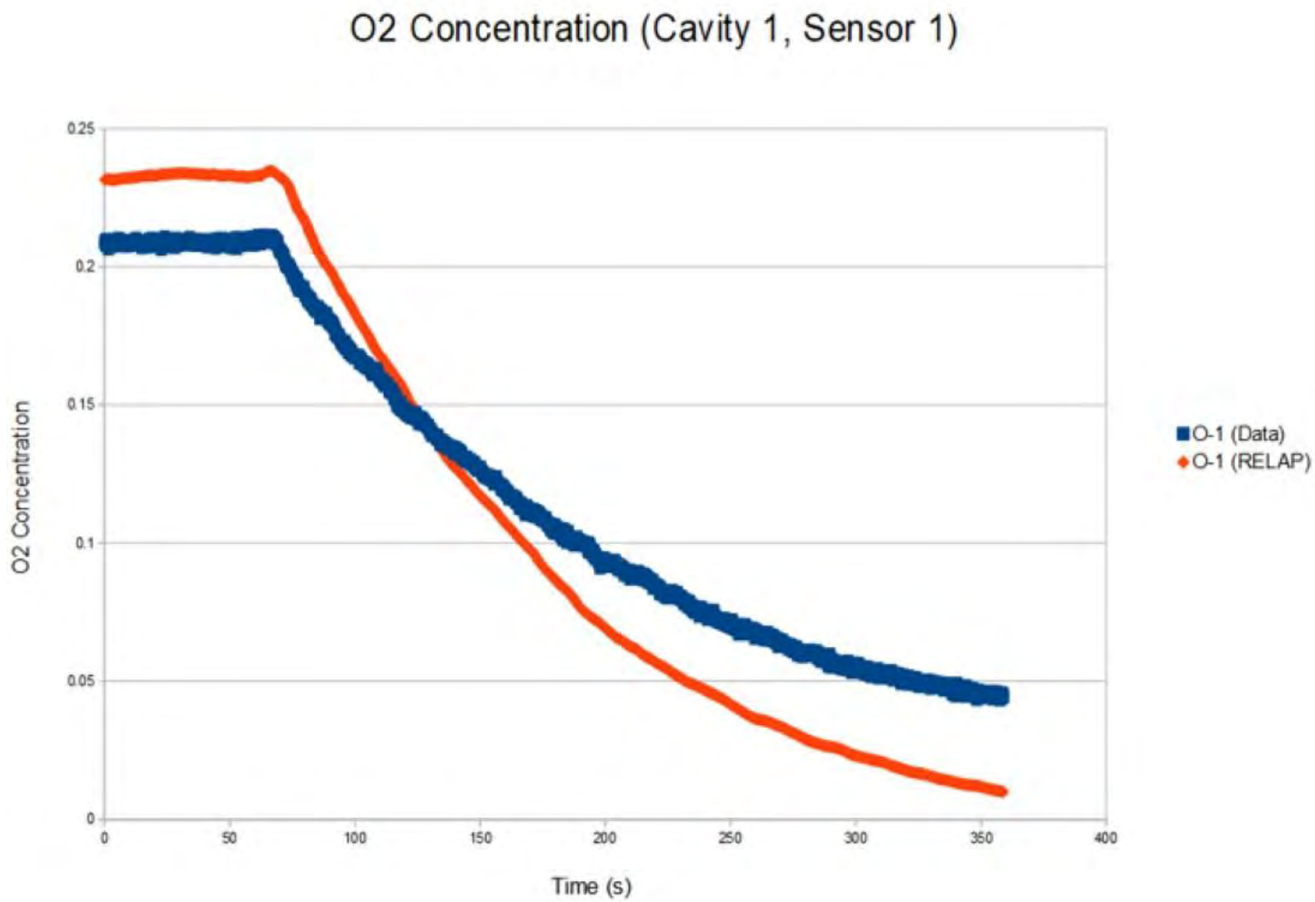
Location of Helium Leak: 16.5 inches above Bottom of Cavity 1.

Helium Jet Velocity 120 m/s Via Rectangular Orifice Configuration with Horizontal Orientation

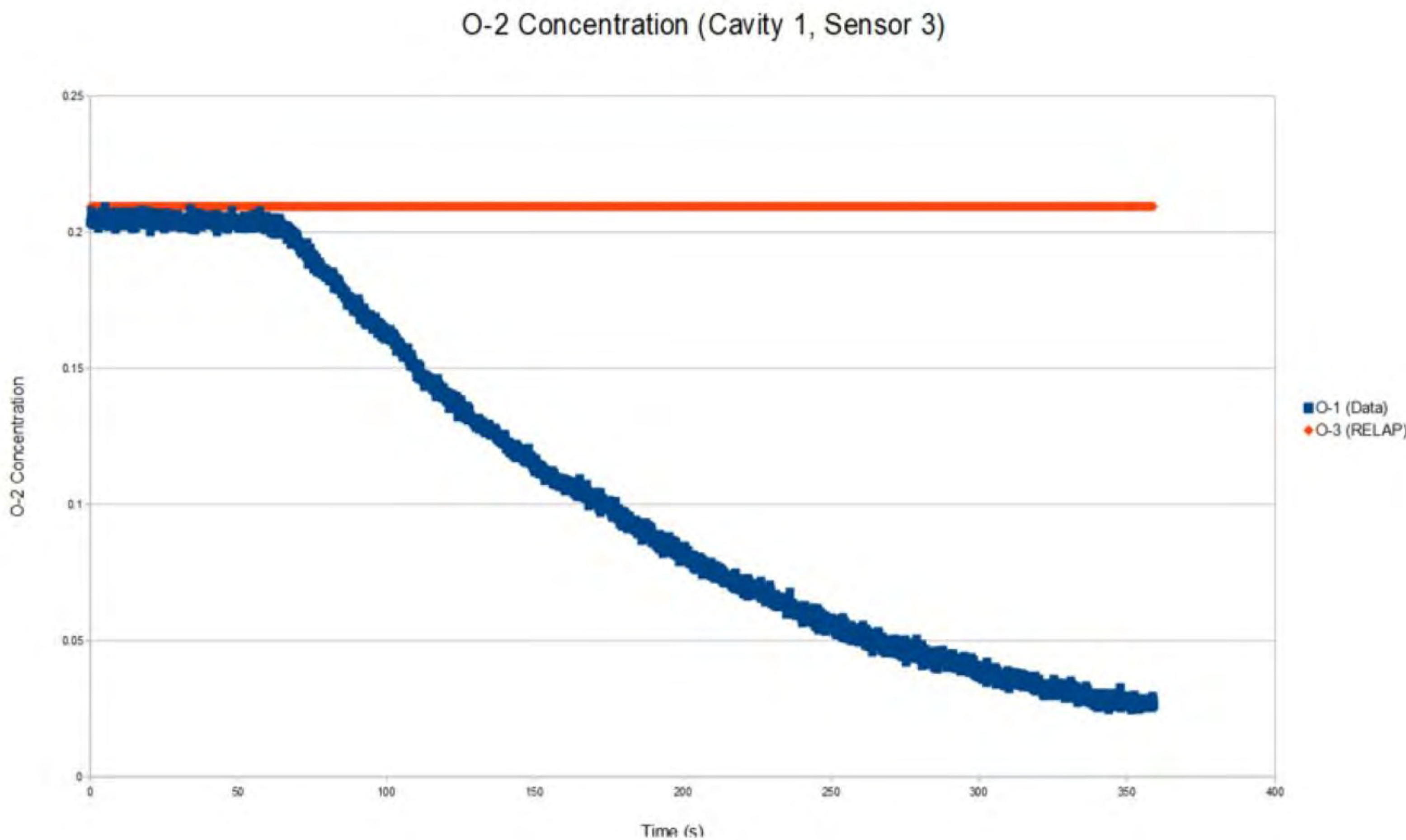
O_2 Concentration: He Injection Site Cavity 1—Data & R5 Calc



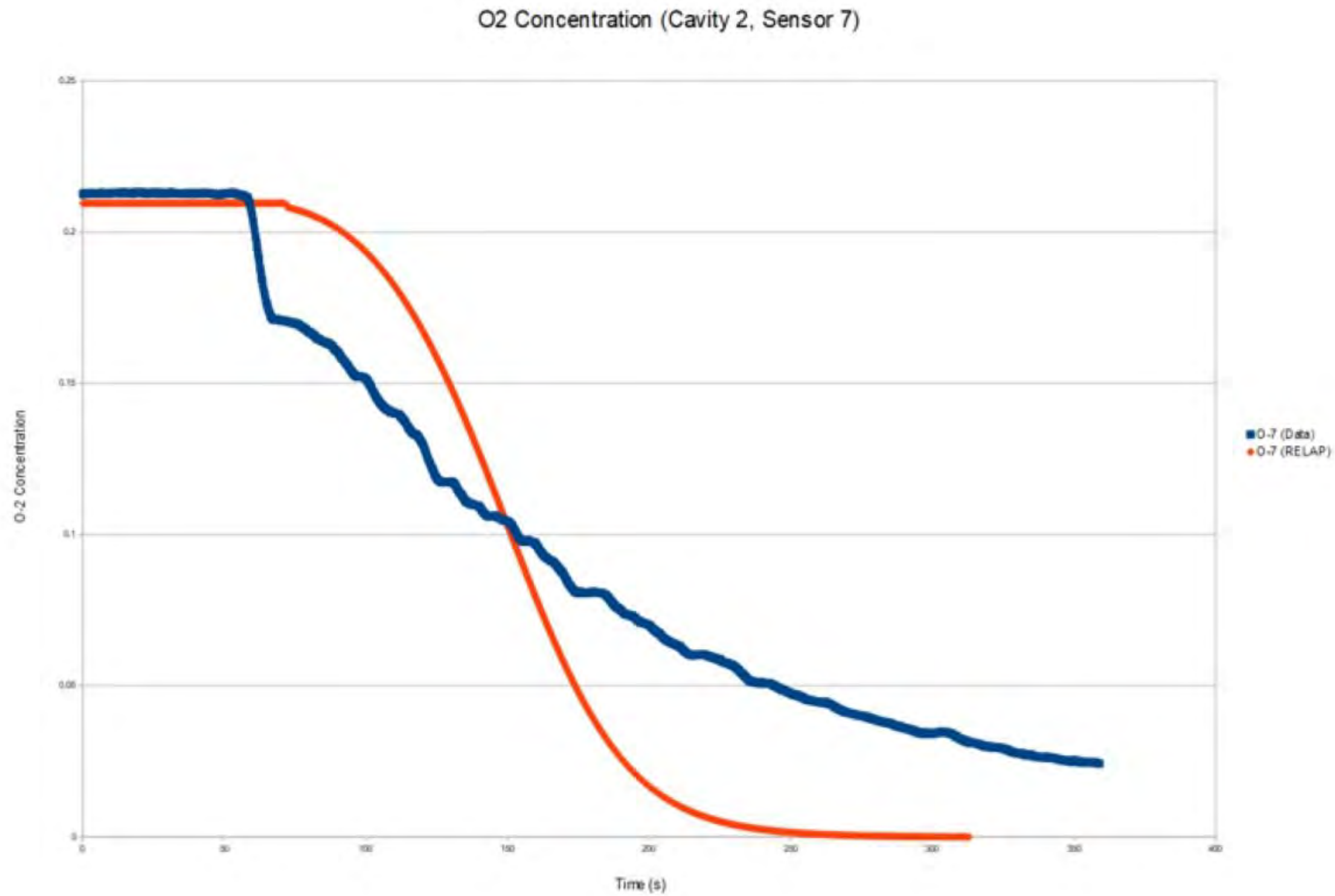
O_2 Concentration: Bottom Cavity 1 Data & RELAP5 Calculation



O_2 Concentration: Top Cavity 1 Data & RELAP5 Calculation



Bottom of Cavity 2



Summary of Calculational Results

- RELAP5 appears unable to capture helium circulation within cavity—as evidenced by zero helium detected in upper regions of Cavity 1.