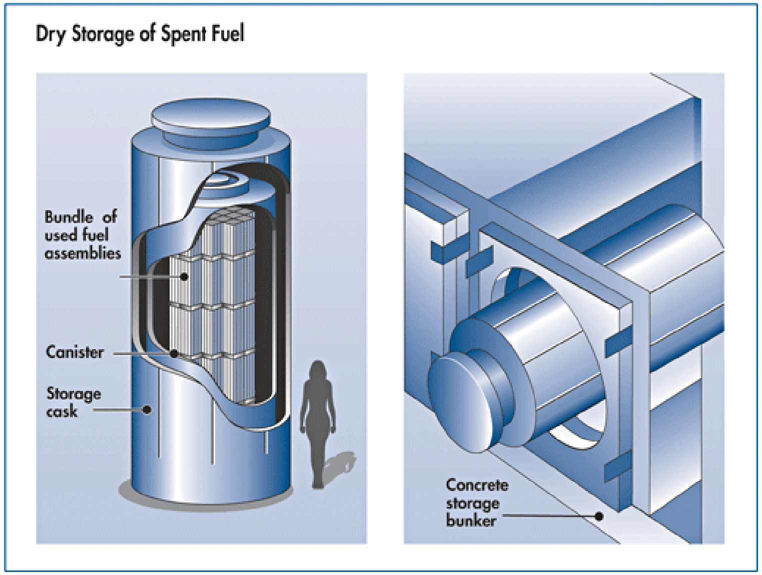
Experimental Determination and Modeling of Used Fuel Drying by Vacuum and Gas Circulation for Dry Cask Storage

Travis W. Knight
Professor and Director
Nuclear Engineering Program
twknight@sc.edu, 803-777-1465

UNIVERSITY OF SOUTH CAROLINA
College of Engineering and Computing

Motivation and Goals

- Quantify water remaining in dry cask after typical industry drying operation
- Science based understanding of the cask drying process
- Evaluate range of conditions, features likely to encounter for storage of used fuel
- Develop modeling tools for utilities, vendors, regulators



Team*,**

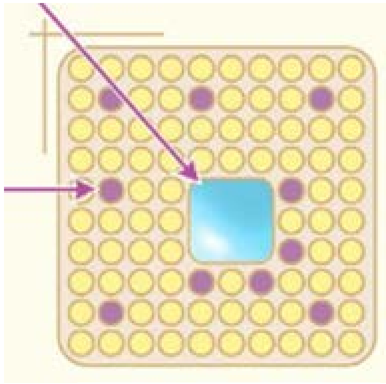
- Travis W. Knight, ME, USC (PI)
- Tanvir Farouk, ME, USC
- Jamil Khan, ME, USC
- James Ritter, ChE, USC
- Armin Ebner, ChE, USC
- Elwyn Roberts, ME, USC
- Joshua Tarbutton, ME, USC
- James S. Tulenko, UF
- Musa Danjaji, SCSU
- Bill Bracey, Areva
- Kevin Elliot, Areva
- Tom Galioto, Areva
- Paul Murray, Areva

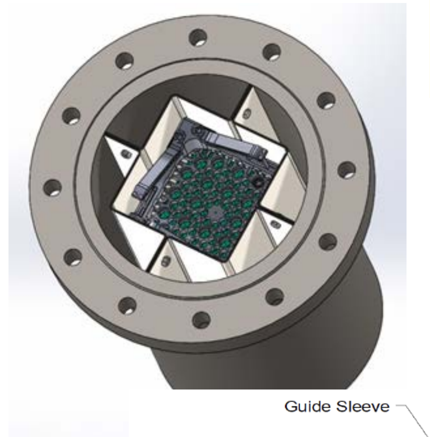
*

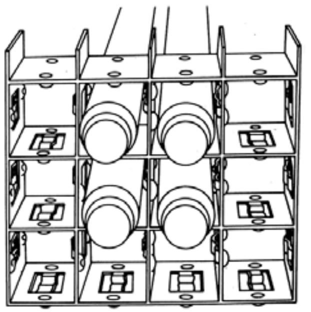
** University teams include graduate students and undergraduate researchers and post doctoral staff

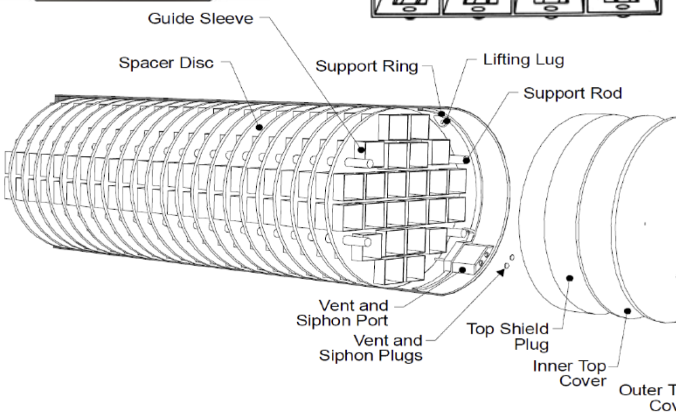
Key assembly features to evaluate

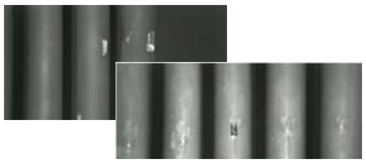
- Some key features must be evaluated per the RFP or require consideration in modeling and design of the experiment for scaling purposes:
  - BWR water rods
  - PWR dashpot in guide tube
  - Failed fuel rods
  - Neutron absorber sheet; i.e. Boral
  - Cask spacer disks
  - Trapped spaces between hardware
  - Surface area: rods, hardware, structures









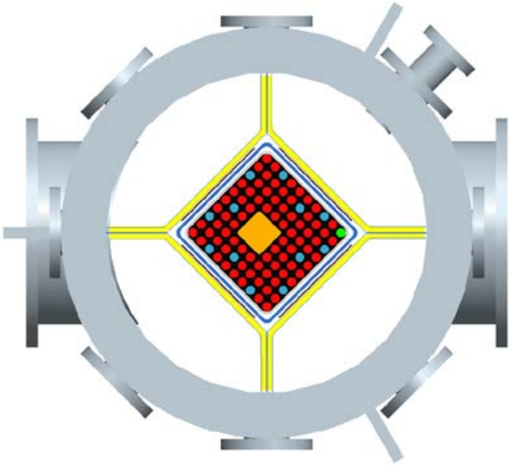


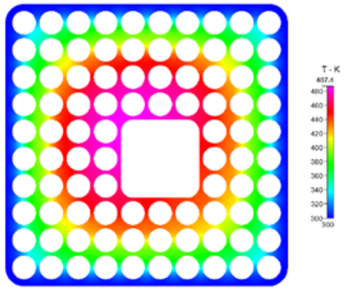
Key conditions to simulate

- Vacuum and forced circulation
- Sequence, number, timing of stages in drying process
- Low/high power (simulate decay heat with heater rods)
  - 0.25 to 1 kW (likely range); may need higher to match temperature in key locations.
- Ice formation
  - Is ice formed under standard practice for difficult drying conditions/scenarios?
  - What conditions would allow for ice formation (margin assessment)?

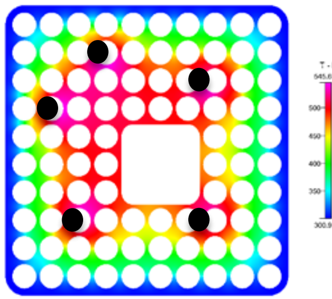
Key parameters to measure or evaluate indirectly

- Temperature: rods, heater rods, gas (forced circulation: inlet, outlet)
  - Thermocouples, IR cameras
- Chamber pressure
- Gas composition: RGA, OES
- Gas flow rate
  - Vacuum drying
  - Forced circulation
- Water removed as a function of time
- Indication of ice formation





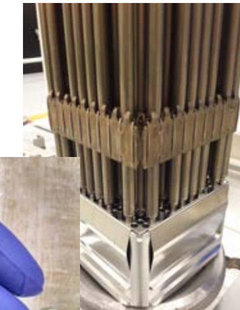
90 heated rods, heat load of 0.5 kW. Temperature distribution @ Z = 2.4 m (mid plane)

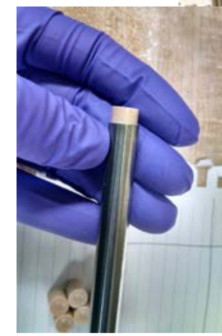


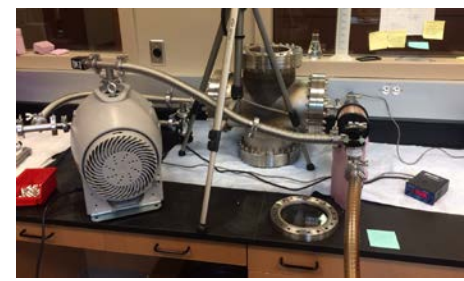
5 heated rods, heat load of 0.5 kW. Temperature distribution @ Z = 2.4 m (mid plane)

Major Accomplishments/Status

- Milestone 1: Test plan
- Milestone 2: Experimental design
- Milestone 3: Report on approaches to modeling
- Facility mod to be completed end of January 2016
- Mock fuel assembly with heater rods and hardware fabrication completed.
- Chamber in fabrication deliver first week in Feb. 2016
- Testing with small chamber (vacuum and forced circulation)
- Instrument testing (OES, guided wave, IR camera, thermocouples, etc.)

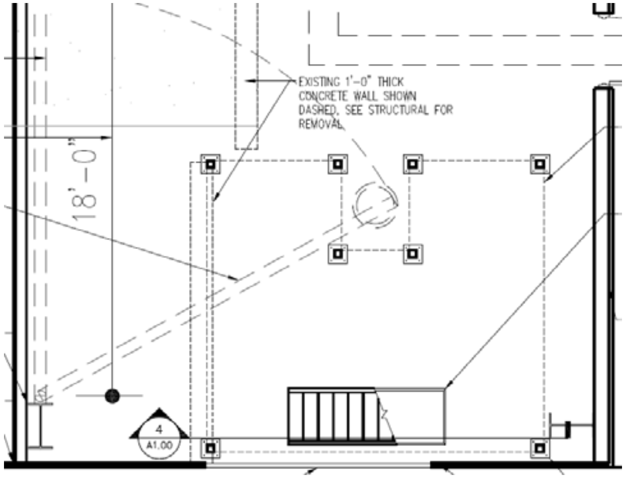


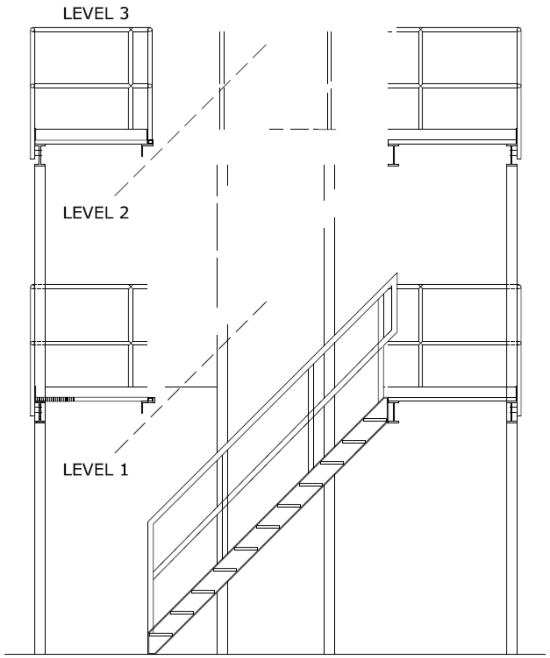


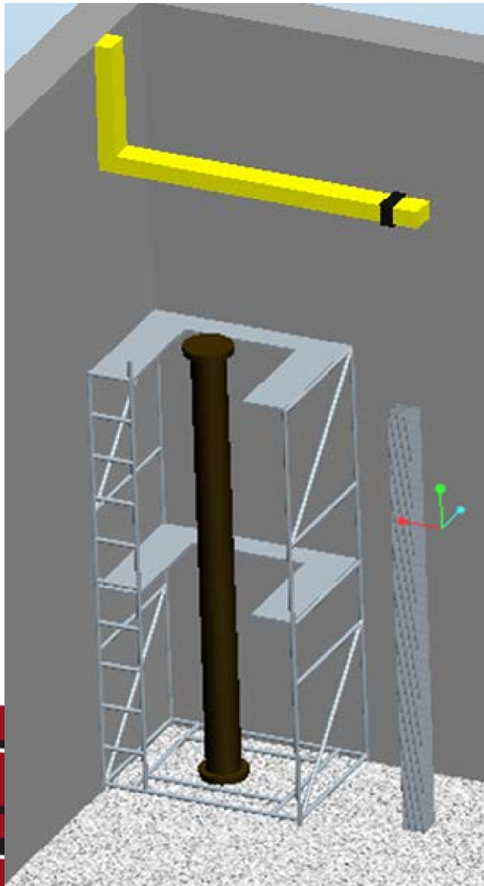


Facility Modification

- High ceiling for jib crane, test stand
- Power, water, insulation, climate control, lighting, wall enclosure

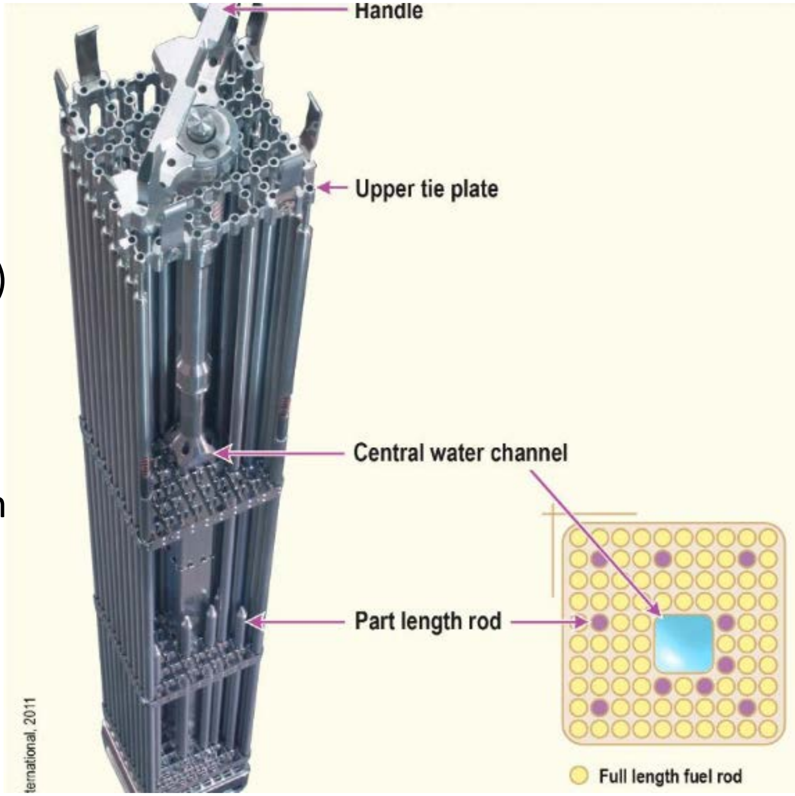






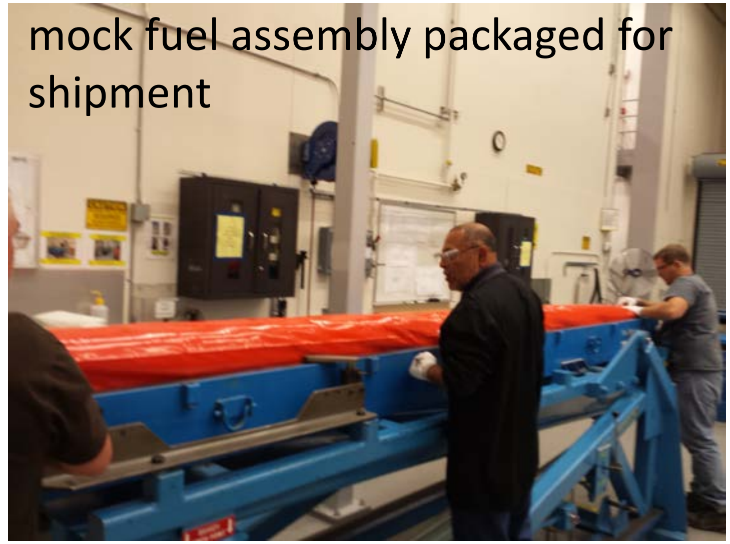
Mock Fuel Assembly Design

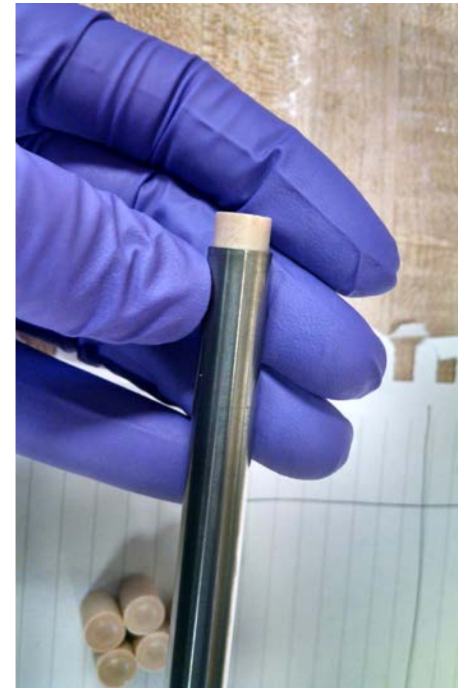
- 10x10 Atrium 10A BWR assembly
  - DU rods
  - Heater rods to simulate decay heat
  - Instrumentation, thermocouples
- Interchangeable rod position on the corner of assembly on diagonal of water channel for symmetry:
  - Simulated failed fuel rod (perforation at 175 cm in height, not occluded by spacer grid; Swagelok fitting at top for filling with water, CeO2 pellets to simulate UO2)
  - PWR guide tube with dashpot (simulated by Zr-4 tube plugged at bottom, weep holes at 40 & 43 cm height not to be occluded by spacer grid)
  - BWR water rod (Zr-4 tube, weep holes at 175 & 178 cm height not to be occluded by spacer grid, plugged at bottom)
- No part length fuel rods
- No empty rod positions

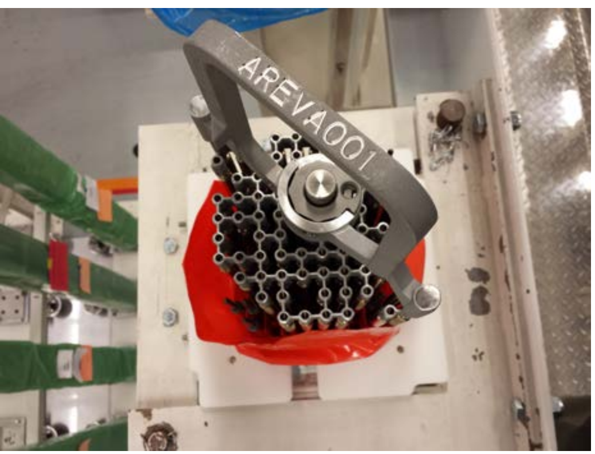


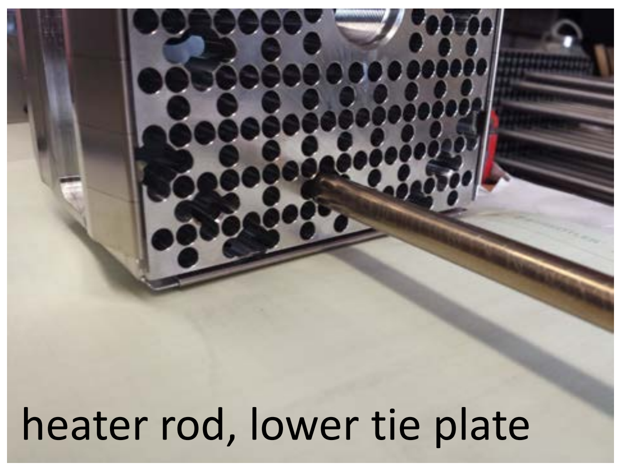
Mock Fuel Assembly

- Areva Atrium 10A design, modified
- Heater rods, DU rods, interchangeable rod
- Ceria pellets for simulated failed fuel rod


mock fuel assembly packaged for shipment

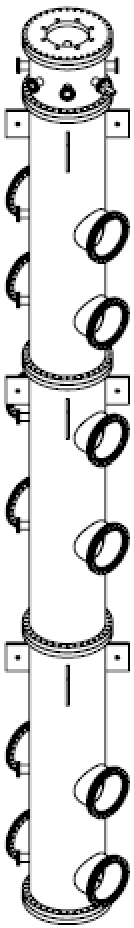


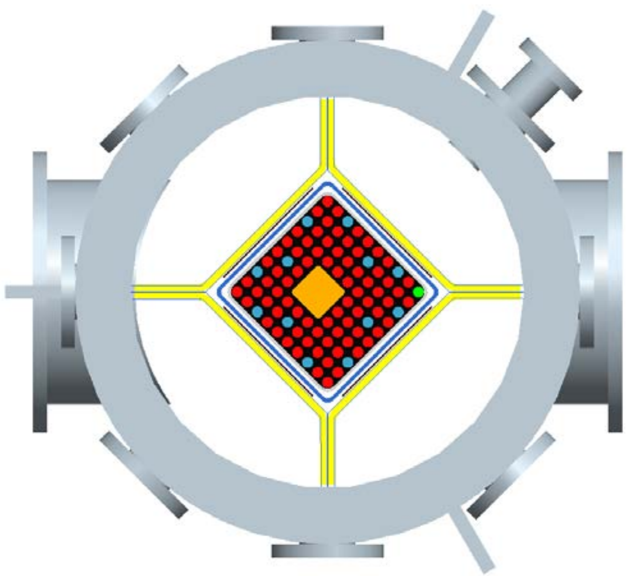


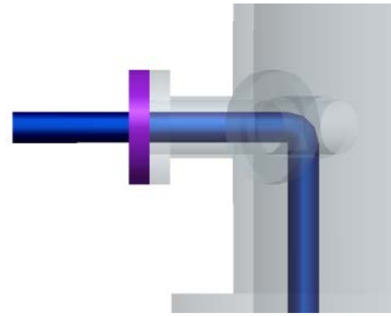

heater rod, lower tie plate


Ceria pellets

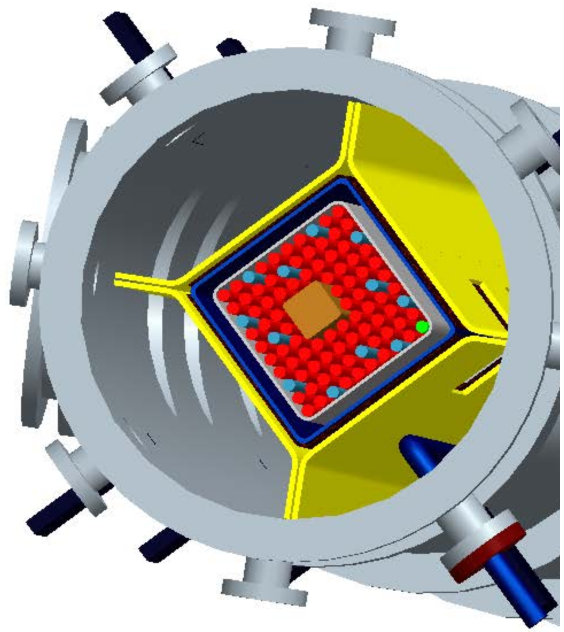
Vacuum Chamber



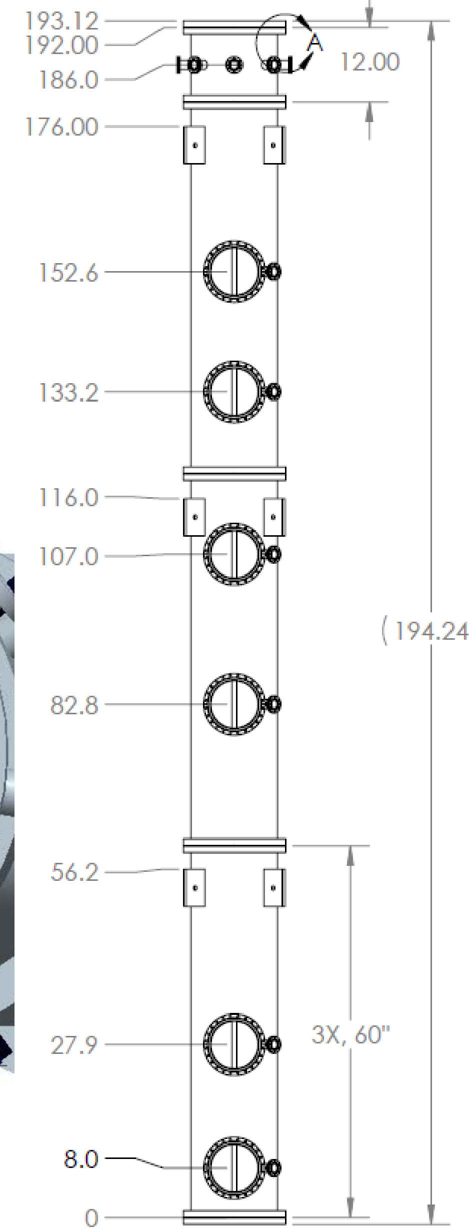




siphon tube



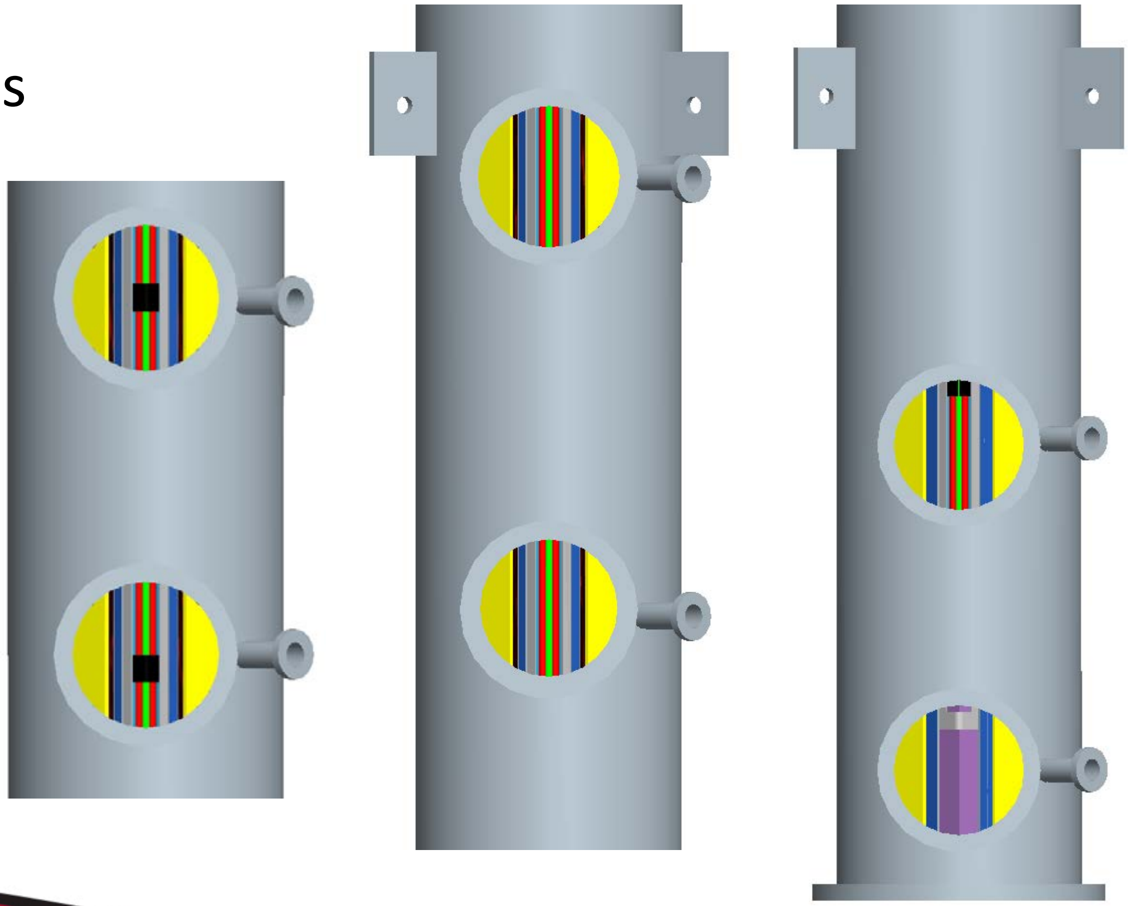
View ports,
instrumentation ports



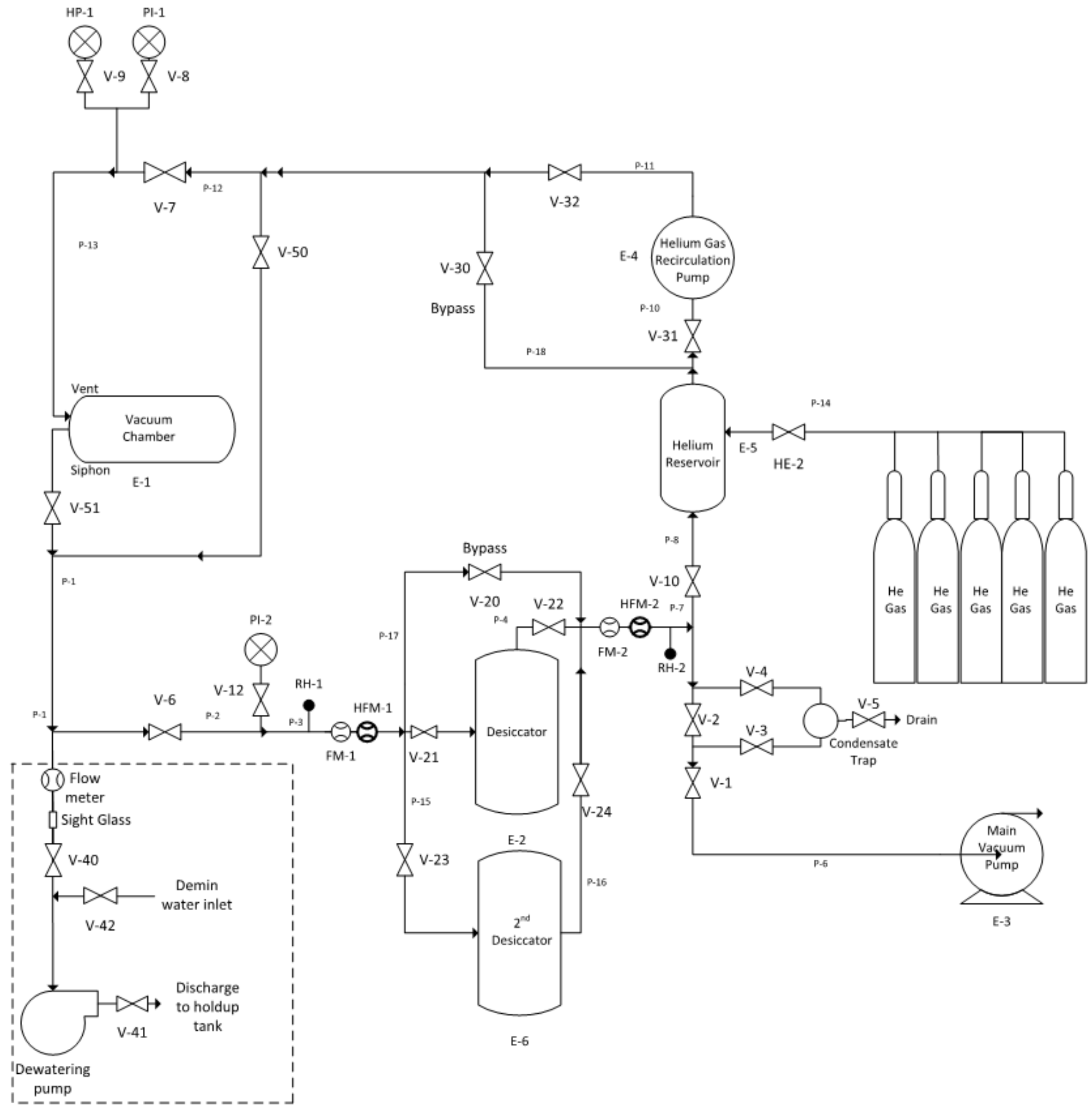
black=spacer grid
green=interchangeable rod
red=DU rod
light blue=heater rod
orange=BWR channel
blue=basket/box 1/8” stainless steel
brown=Boral sheet 0.075” thick
yellow=basket/rails 3/16” stainless steel

Chamber – View Ports

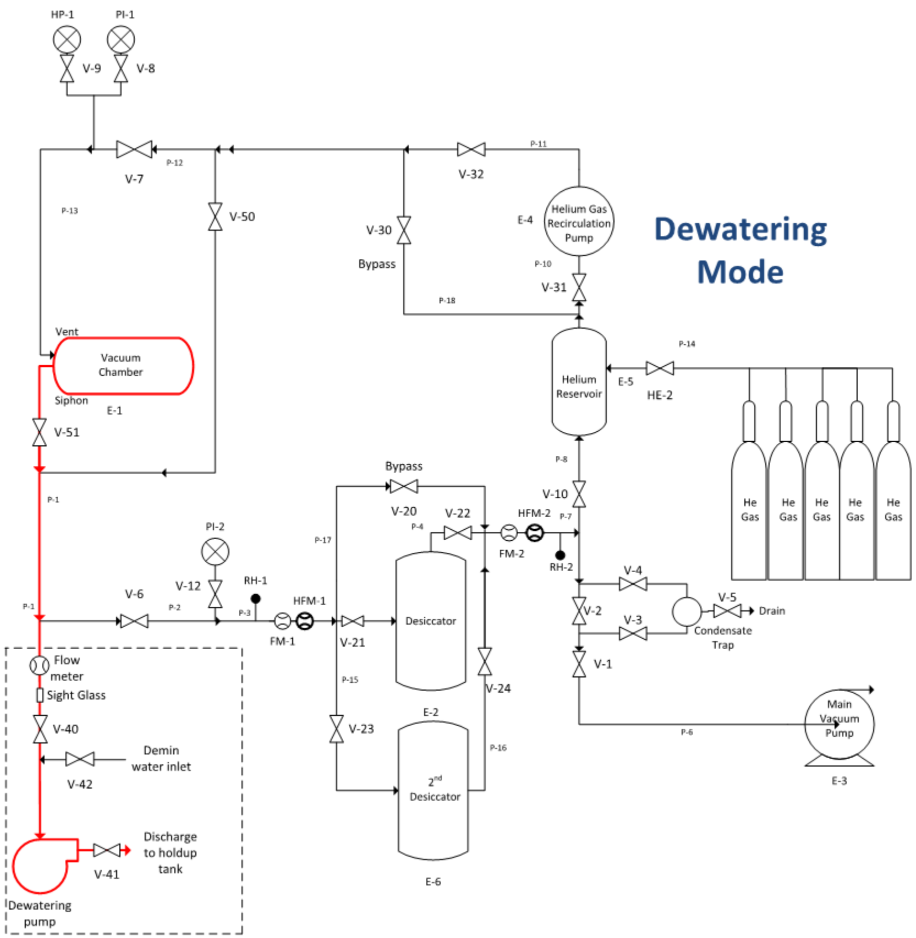
- View ports 5 and 6 (left) and view ports 3 and 4 (middle), view ports 1 and 2 (right).
- View/monitor key locations
  - VP1=Lower tie plate
  - VP2=Dashpot
  - VP3=Failed rod defect
  - VP5=Top spacer grid
  - VP6=Center spacer grid

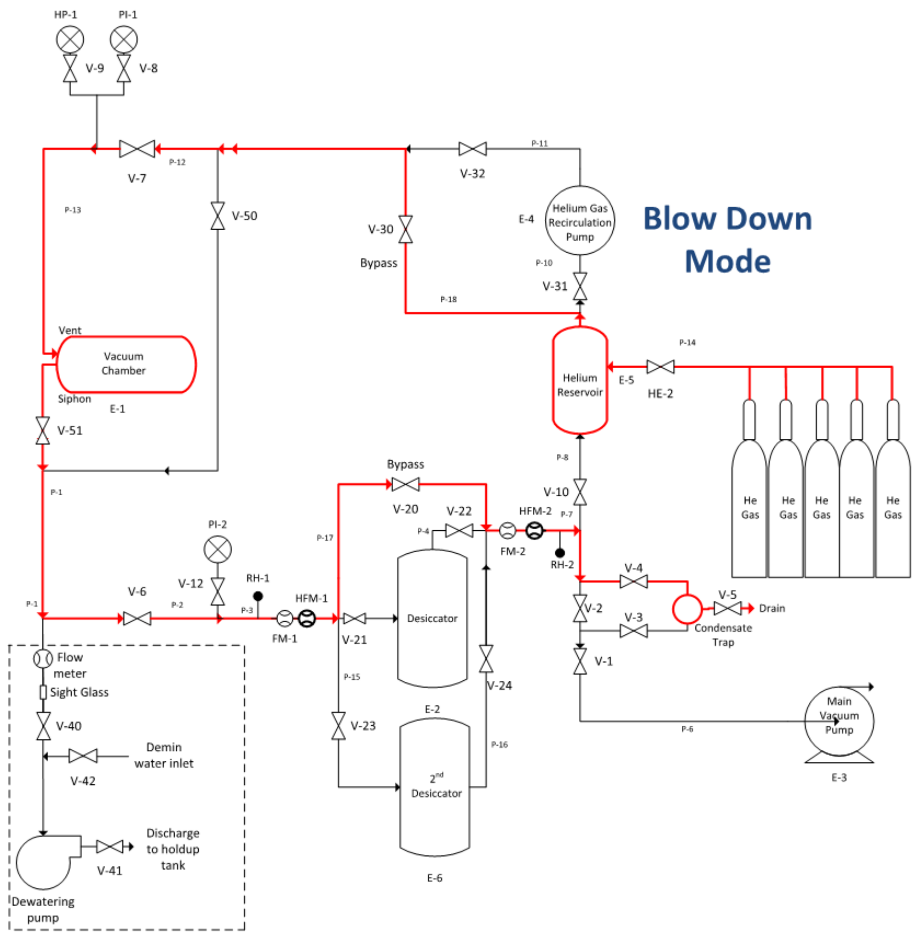


Experimental Design

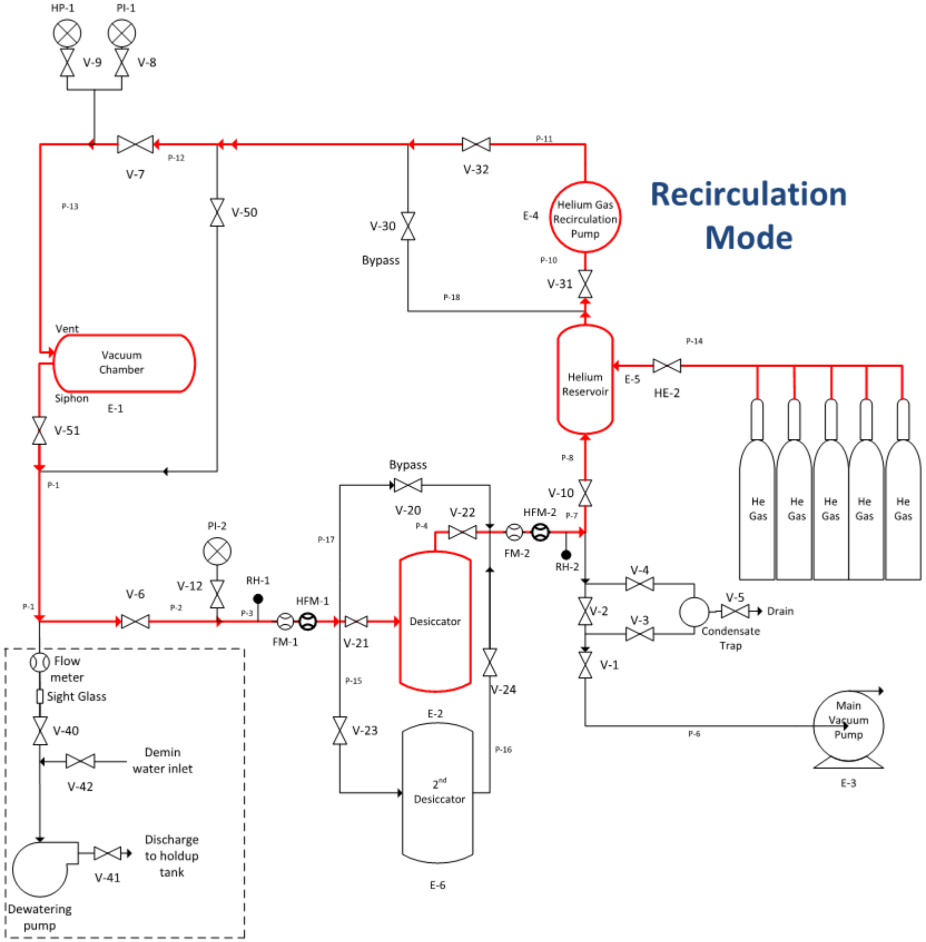


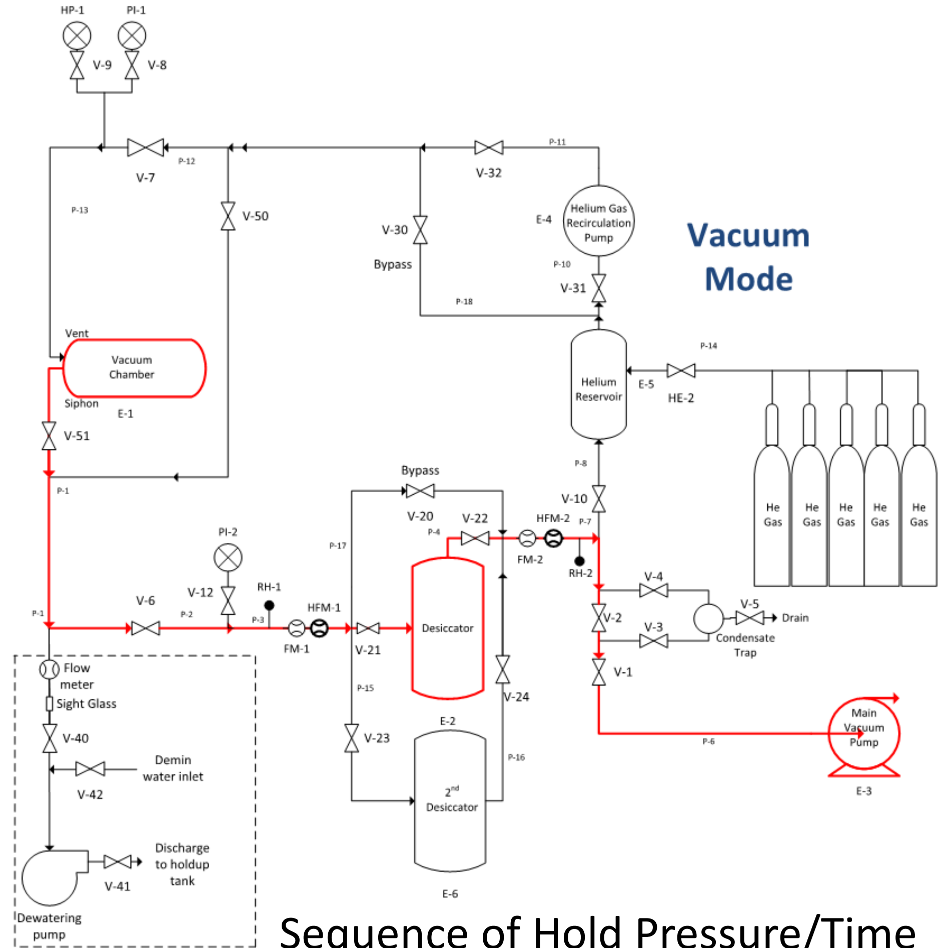
Experimental Design





Experimental Design

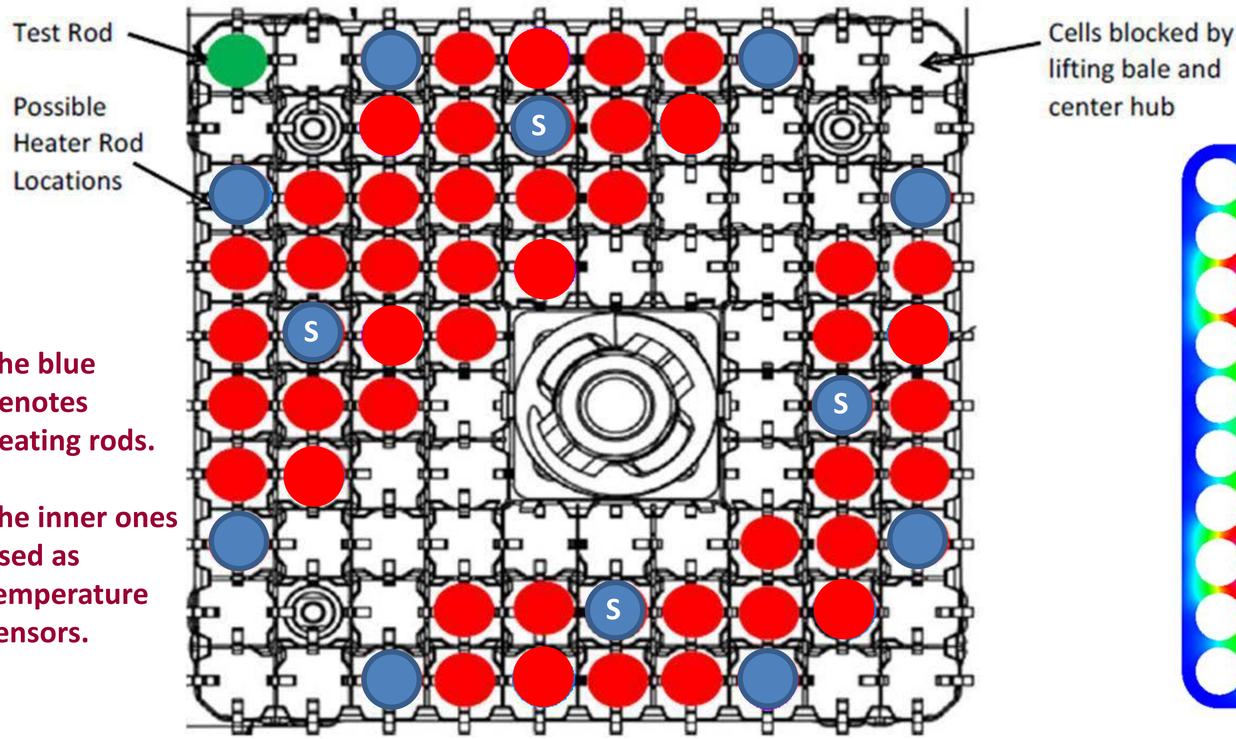




Sequence of Hold Pressure/Time

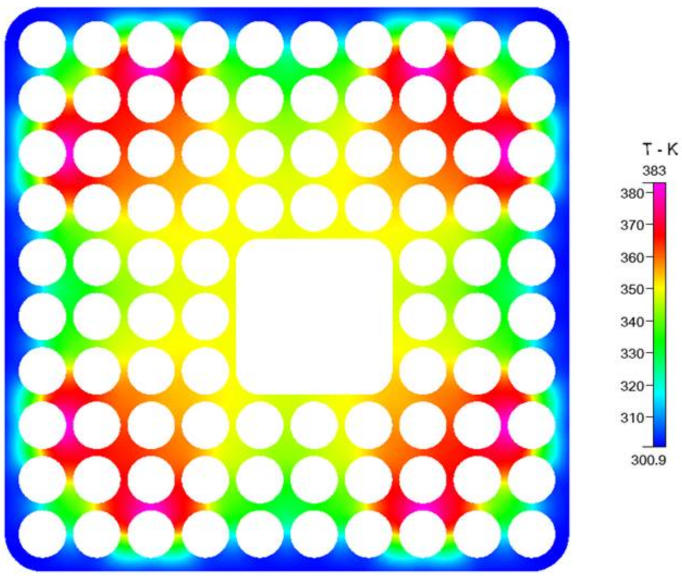
Vacuum Step, Hold Pressure	Hold Time	Criteria to Proceed to Next Step
<50 torr	5 min.	<100 torr
<25 torr	5 min.	<50 torr
<15 torr	5 min.	<25 torr
<10 torr	5 min.	<15 torr
<5 torr	5 min.	<10 torr
<3 torr	5 min.	<5 torr
<2 torr	30 min.	<2.6 torr

Heater Rod Configuration



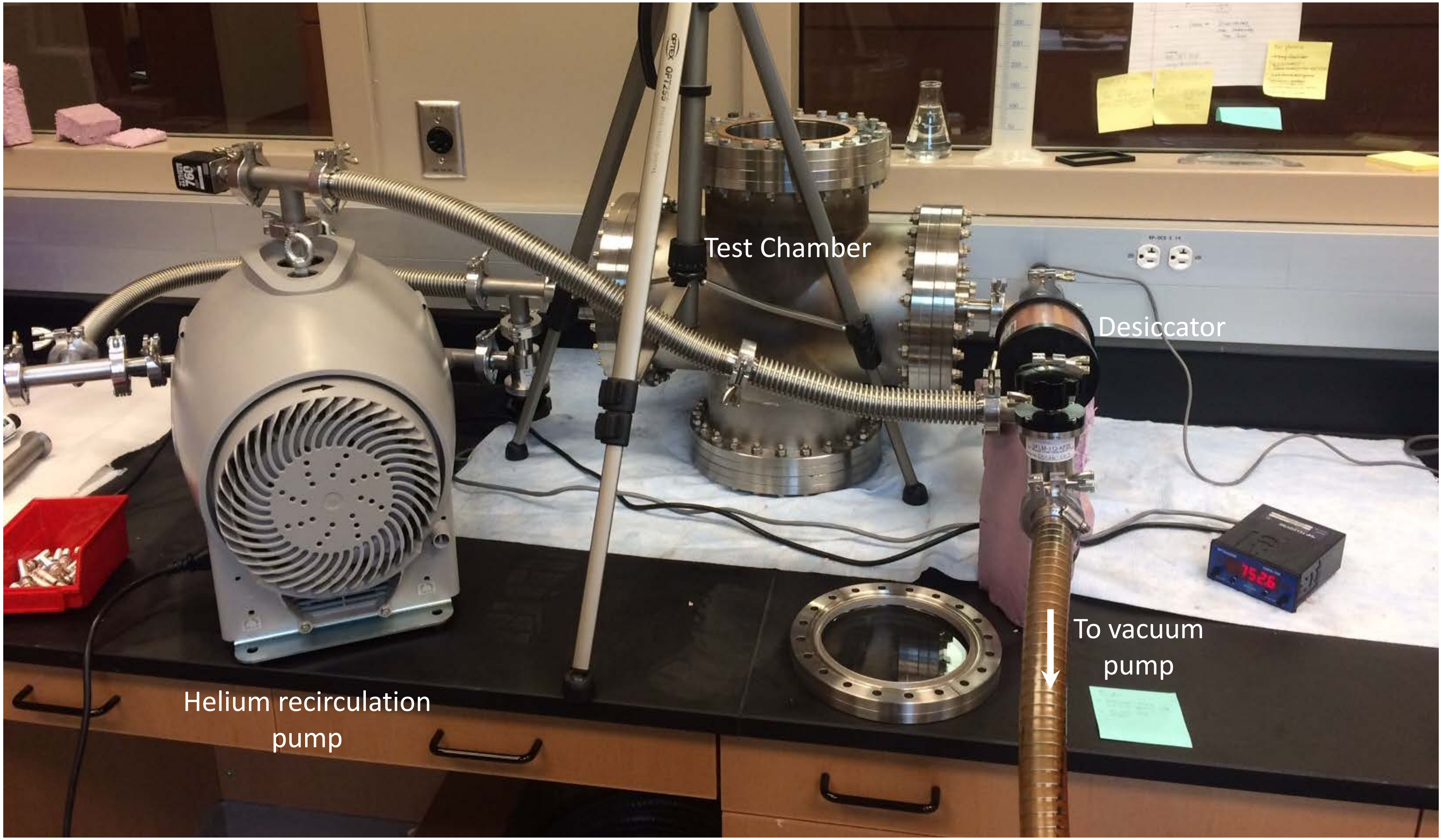
The blue denotes heating rods.

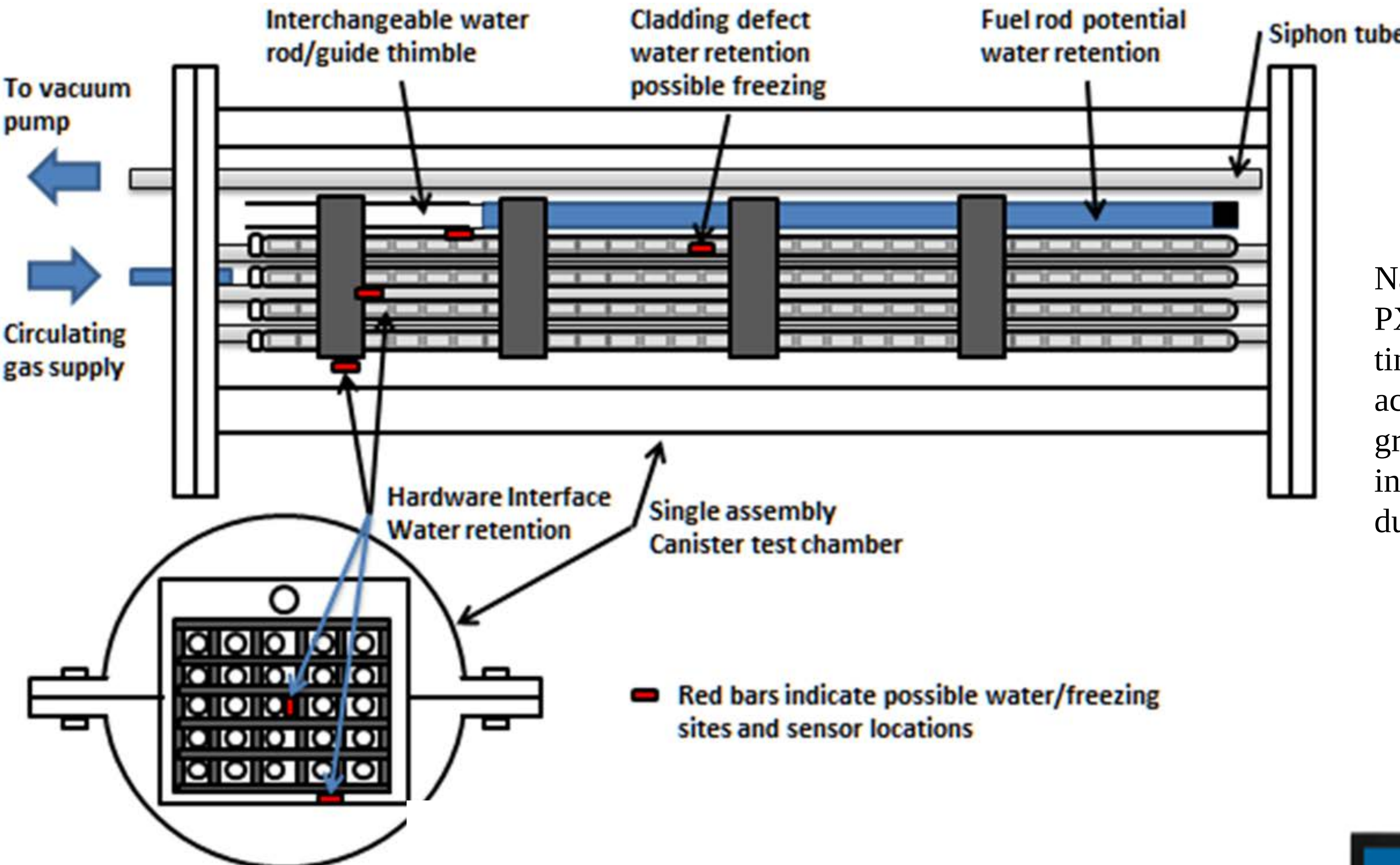
The inner ones used as temperature sensors.



8 heated rods, heat load of 0.5 kW. Temperature distribution @ Z = 2.4 m (mid plane)

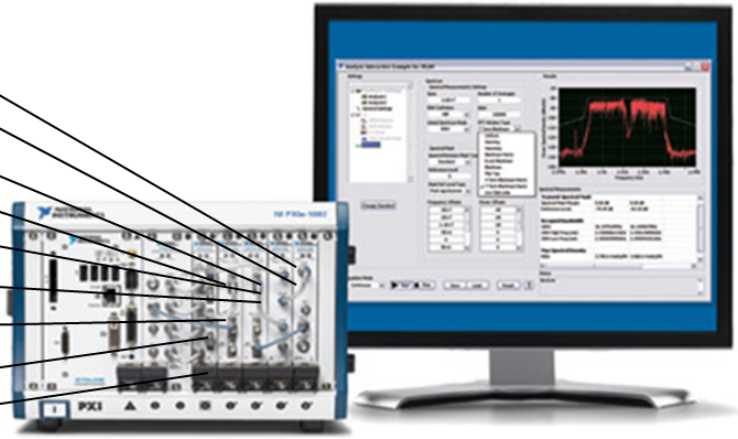
Small Test Chamber, Closed Recirculation Loop





National Instruments PXI chassis with real-time controller, data acquisition cards, and graphical interface for instrument monitoring during vacuum.

Pressure (global, local)
Temperature (global, local)
Water vapor content
Mass flow
Water mass balance
Infrared emission of surfaces
The local acoustic transmission
Local electrical resistance/impedance
Natural frequency of mechanical components

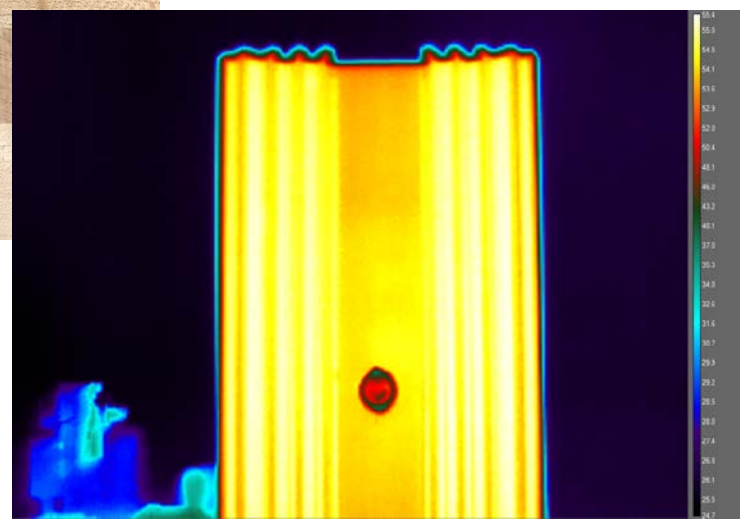


Temperature Measurement using FLIR IR Camera

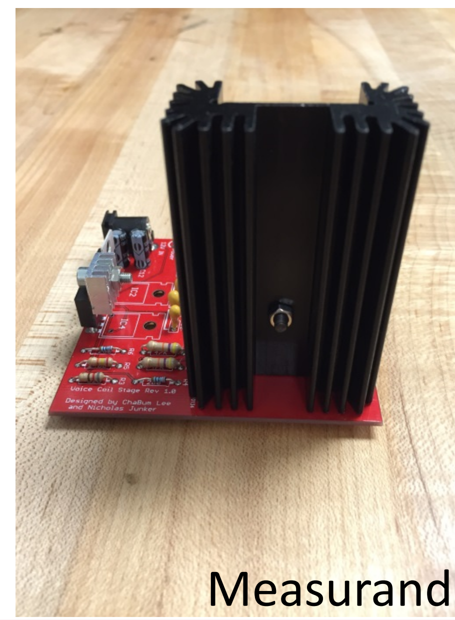
- Capture temperature in vicinity of hardware and characteristic features
- Used in thermal model validation and in drying model development

Experiment setup

ZnSe windows

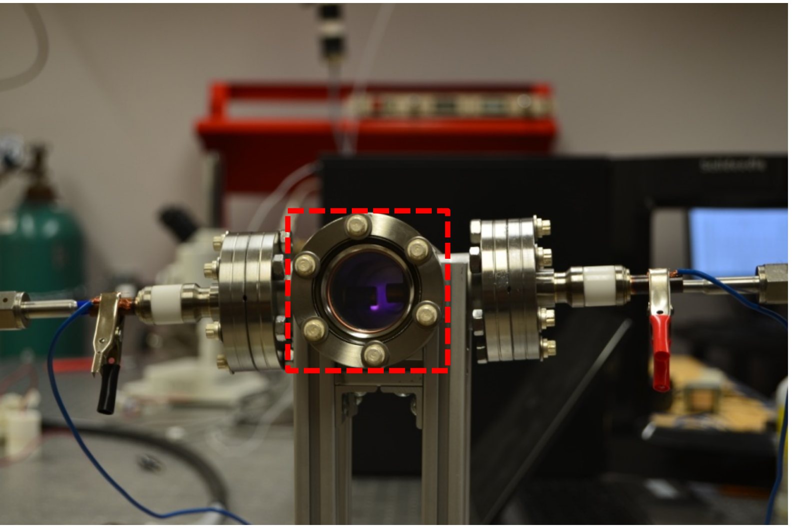


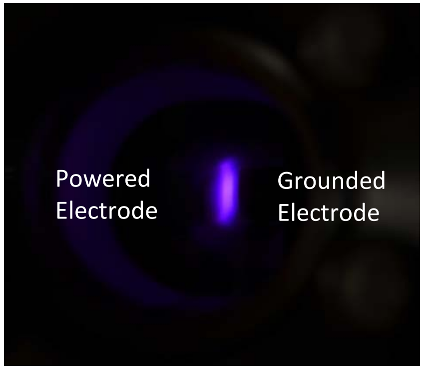
Thermal image acquired

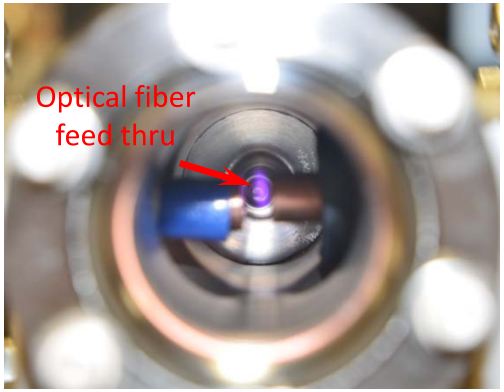


Measurand

Plasma Chamber and OES

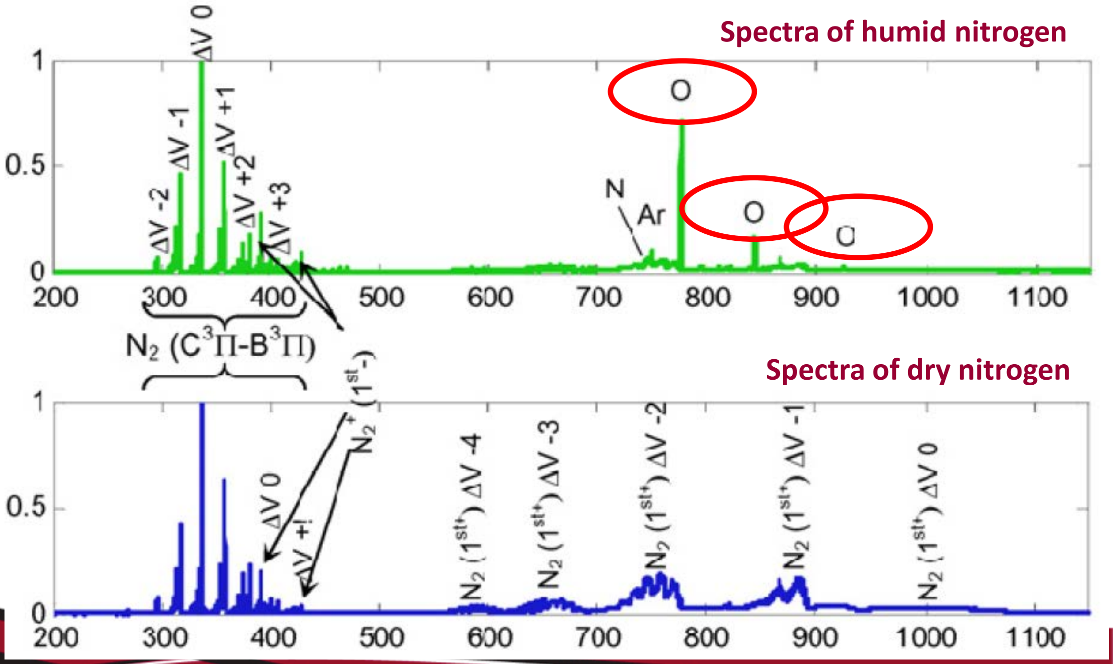




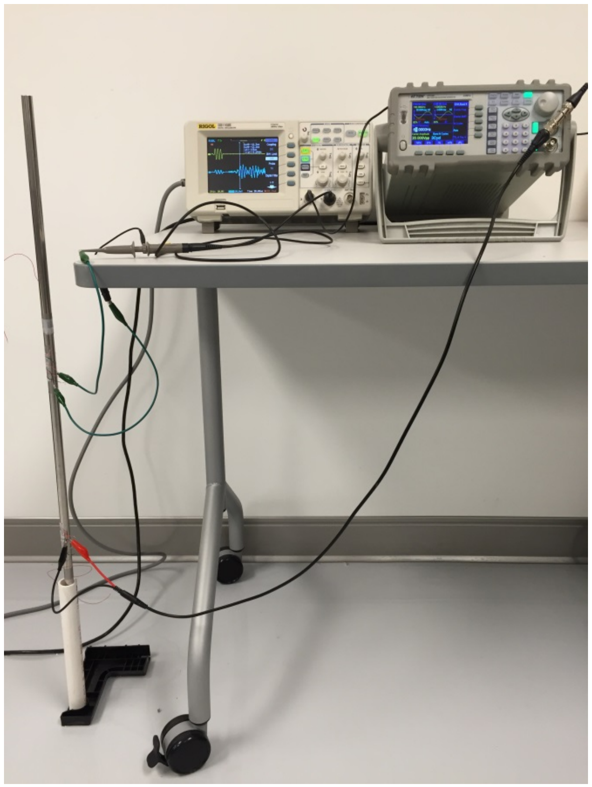


Vacuum plasma chamber (left) for optical emission spectroscopy (OES)

- Emission spectra of dry and humid nitrogen for a DC driven plasma discharge operating at ~ 3 Torr and 4 mA discharge current.
- The oxygen spectra observed are due to the presence of water vapor in the system.
- Calibration curves are being obtained to quantify the water amount.



Water Level Measurement for a Test Rod using Guided Wave Technology

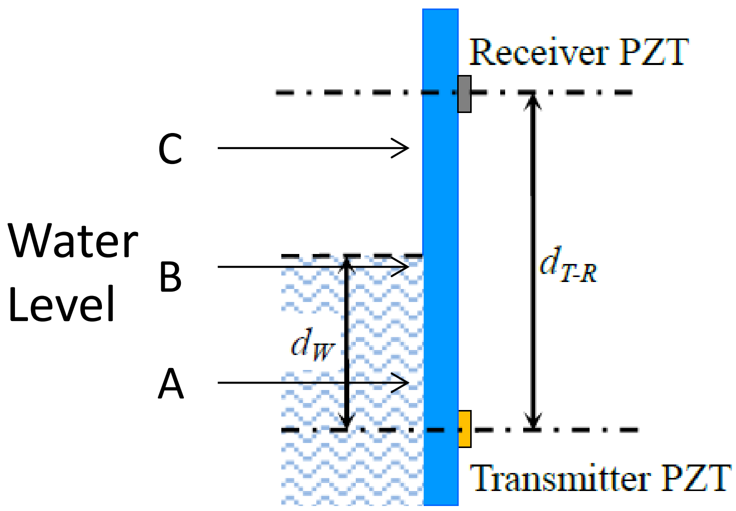


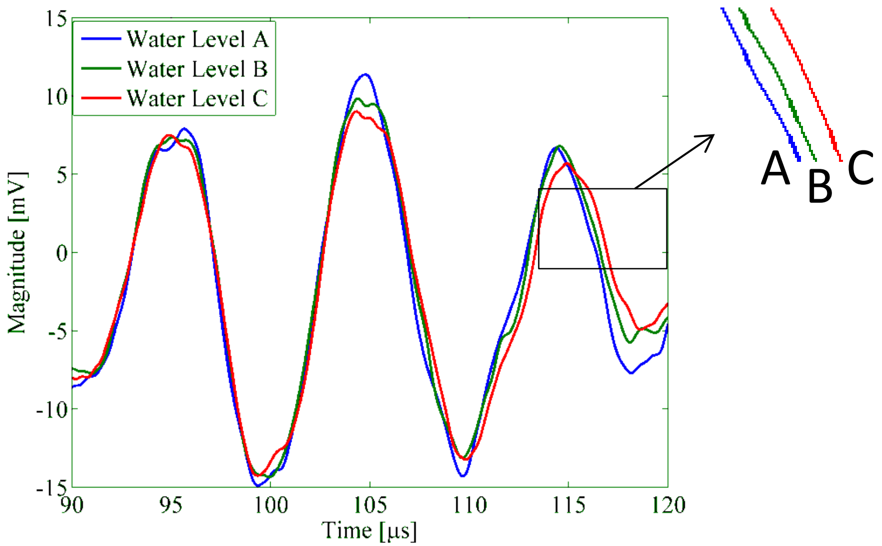
Experimental setup

Piezoelectric sensors

Test rod (stainless steel) and water inside

Water Level Measurement for a Test Rod using Guided Wave Technology





Pitch-catch sensing with PZT sensors for the water level measurement

Three received signals for different water levels (delayed in time domain when water level increases)

Near-term schedule

- Complete mod of lab space - Feb. 2016
- Install large chamber, equipment, mock fuel assembly - Feb. 2016
- Begin shakedown tests - March 2016
- Begin test plan – July 2016

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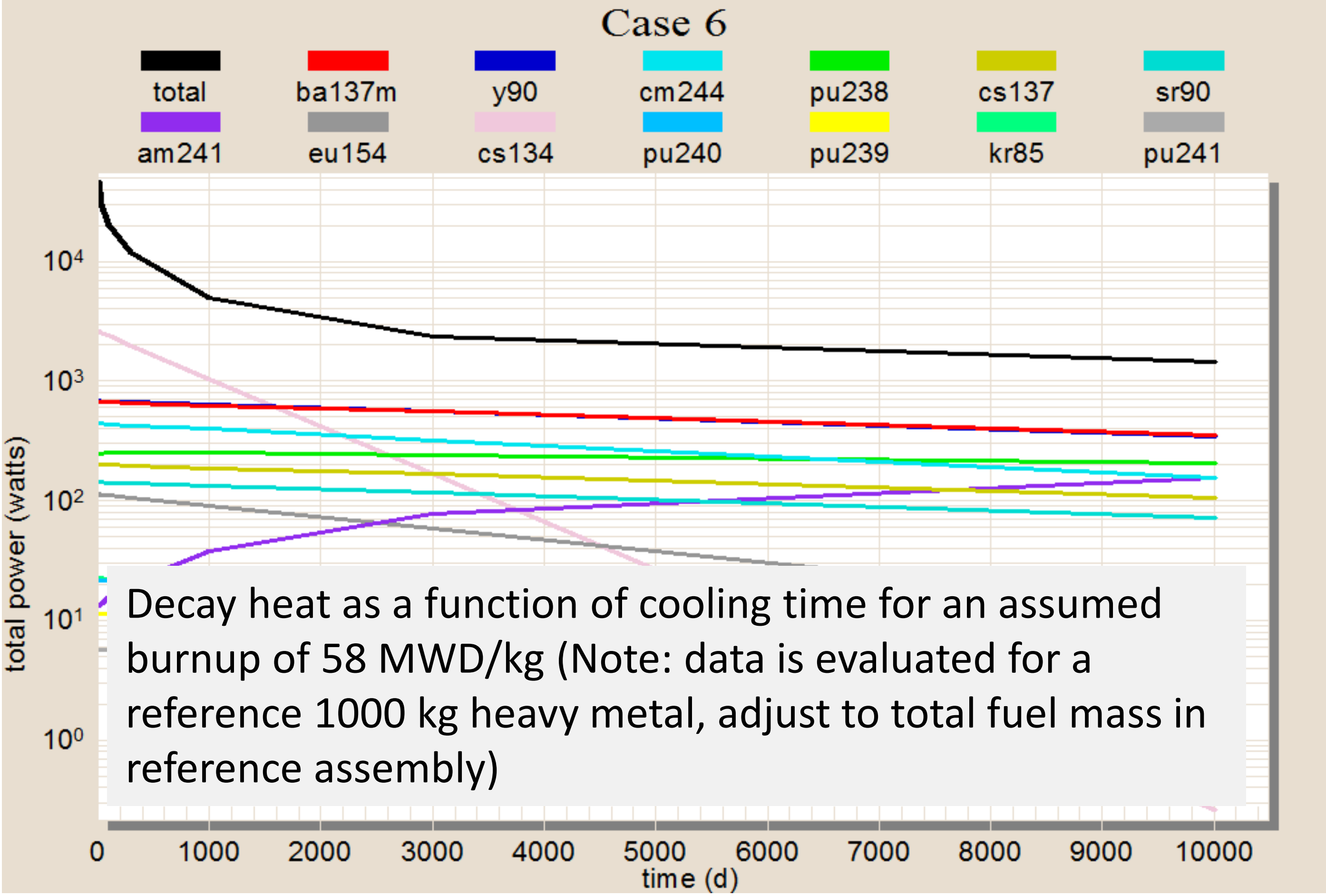
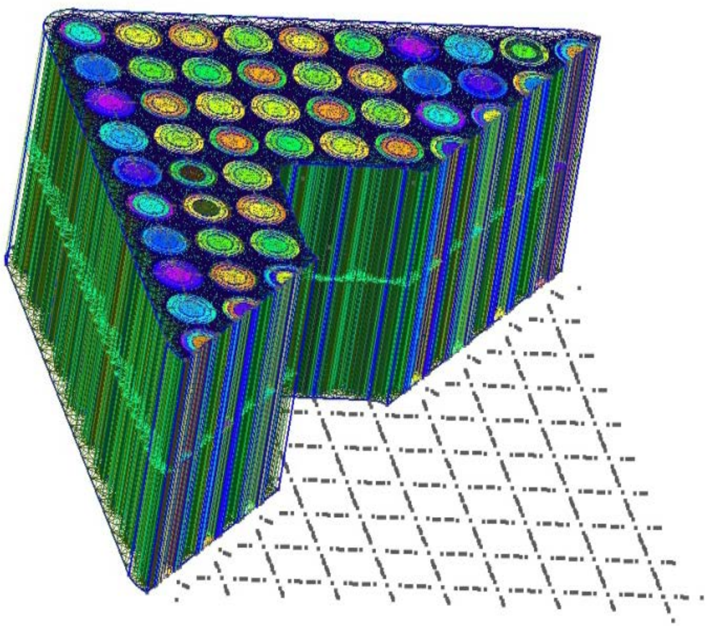
Decay Heat Calculation

A BWR fuel assembly, Areva Atrium-10A design, with approximately 200 kg fuel will be used. Origen-ARP was used to calculate the decay heat for fuel with a burnup of 58 MWD/kg. The decay heat as a function of cooling time is shown at right. The decay heat falls off so that after 27 years the decay heat is about 0.3 kW. Therefore the lower limit of the decay heat for this experiment was revised down. An upper limit of 1kW is observed at about 3 years cooling.



Decay heat as a function of cooling time for an assumed burnup of 58 MWD/kg (Note: data is evaluated for a reference 1000 kg heavy metal, adjust to total fuel mass in reference assembly)

Forced Circulation Drying – Computational Fluid Dynamics Model



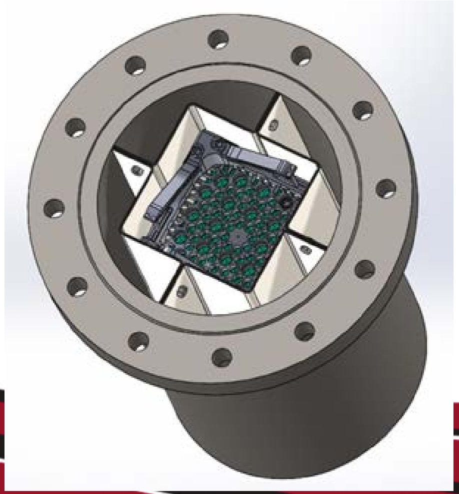
Subsection of the gridded computational domain employed in the OPENFOAM simulations (approximately 1.1 million cells)

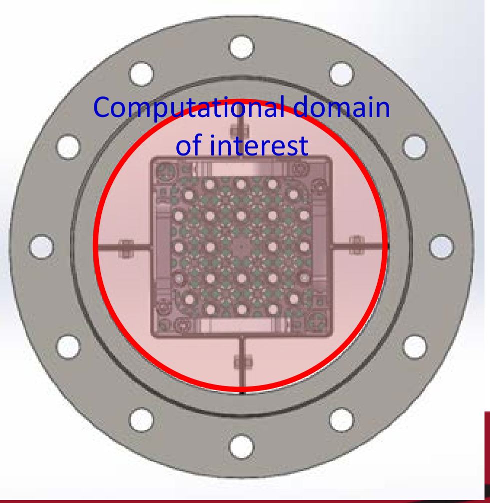
- Axisymmetric
- Transient Calculations
- Mass, Momentum and Energy Conservations
- Hertz-Knudsen expression for evaporation

$$j = \frac{\sigma_c}{\sqrt{2\pi m k}}\left[\frac{P_\infty(T^L)}{\sqrt{T^L}} - \frac{P^V}{\sqrt{T^V}}\right] \qquad 0.060 \le \sigma_c \le 0.1333$$

pressure, temperature dependent evaporation rate

- Finite Volume Method for Numerical Solutions
- OpenFOAM Solver
- Helium flowrate of 12.8 m^3/hr





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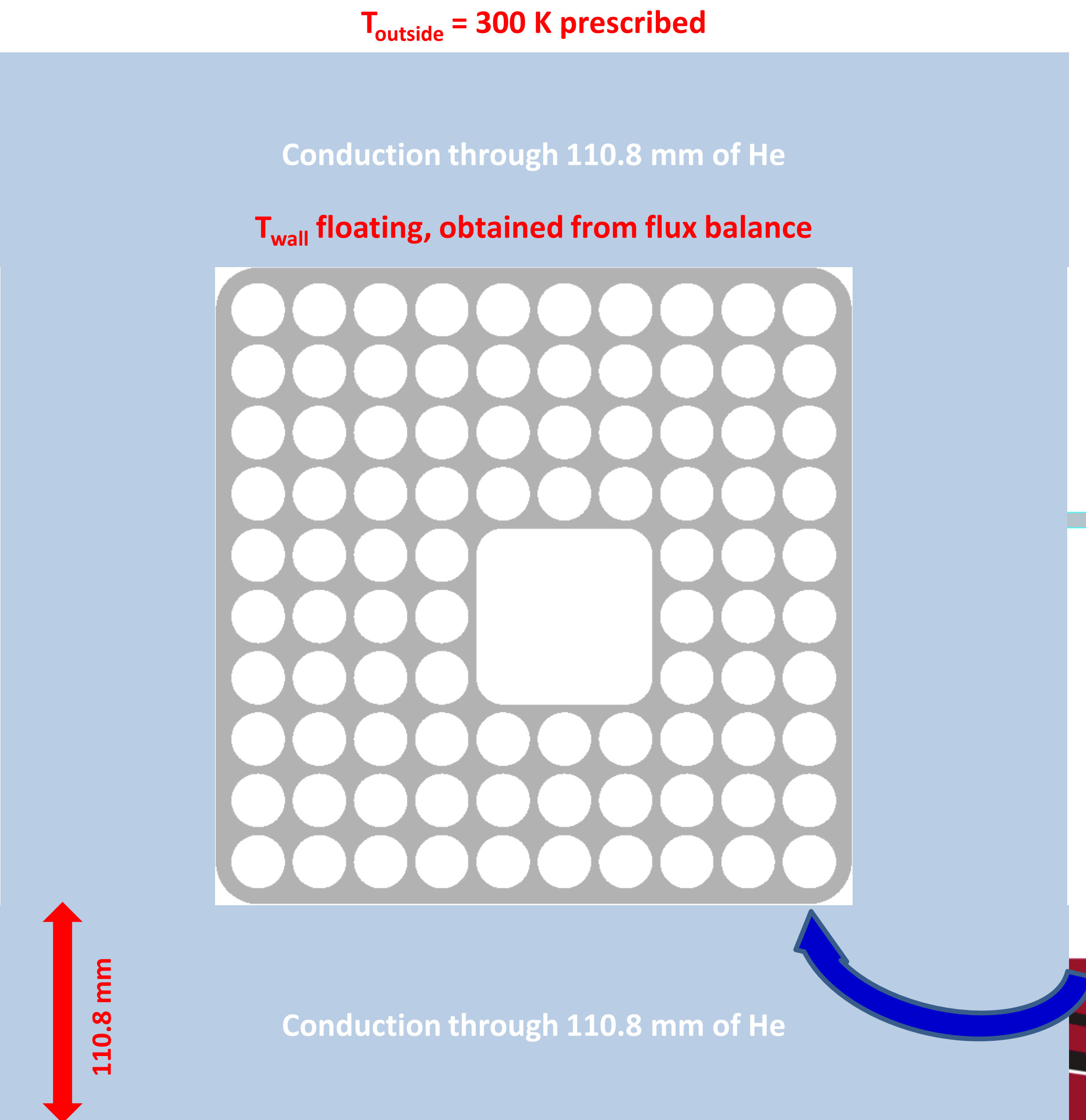
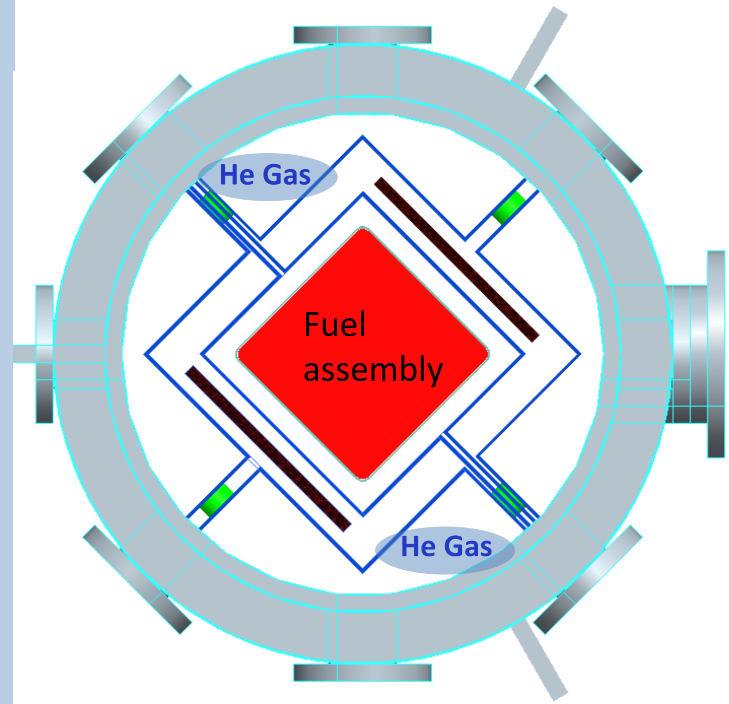
Reduction in Computational Cost



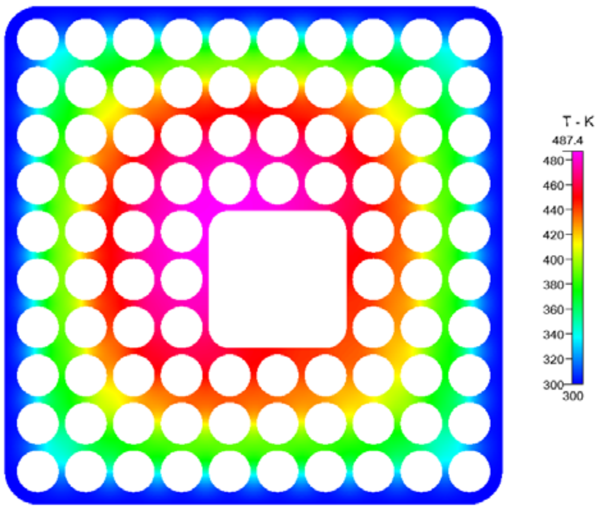
Surrounding gas in between the rail and outside cylindrical shell is not modeled explicitly. Effective conduction through the gas is considered.



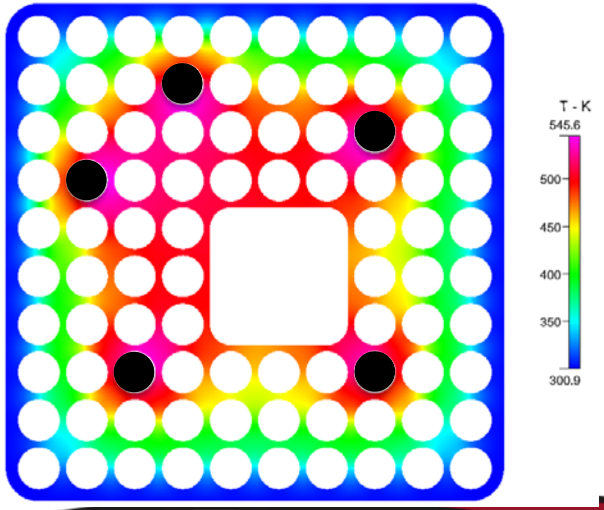
$q = k_{wall}(T_w - T_{outside})/d_n$

No mesh in the helium slab

Heating Rod Configuration



90 heated rods, heat load of 0.5 kW.
Temperature distribution @ Z = 2.4 m (mid plane)



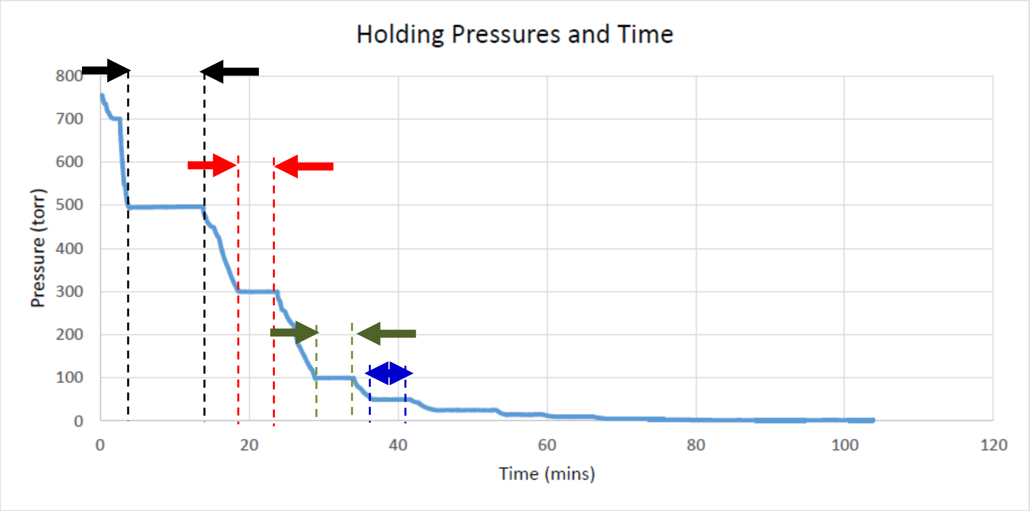
5 heated rods, heat load of 0.5 kW.
Temperature distribution @ Z = 2.4 m (mid plane)

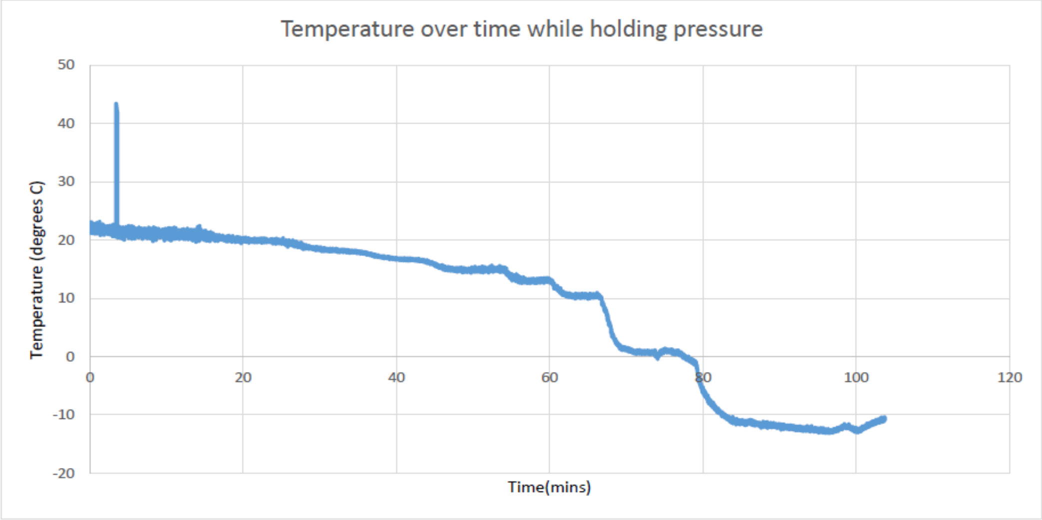
- Simulate heat distribution of a real fuel assembly in the mock assembly through discretely placed heating rod elements.
- "Hot" spots – from discrete heating rod elements – non uniformity.
- Assymetric temperature distribution at steady state condition.
- Heating rod configuration should emulate uniform symmetric temperature distribution

Vacuum Step Down Procedure

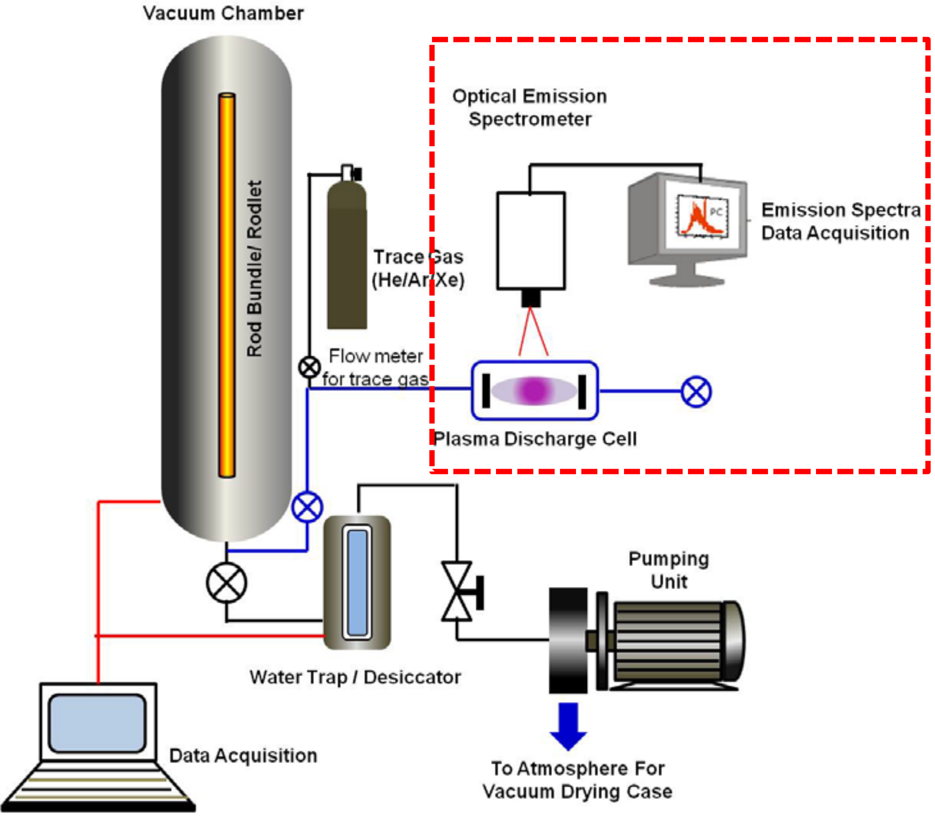
Pressure (Torr)	Hold time (minutes)
500	10
300	5
100	5
50	5
25	5
10	5
5	5
2	30

Initial pressure 760 Torr
Total step down time 1.75 hour

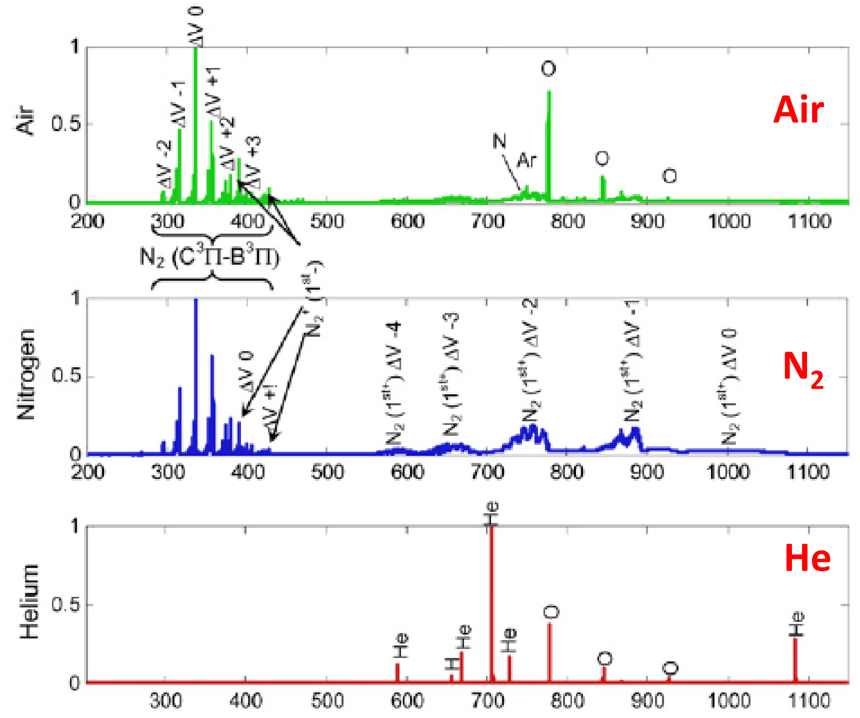




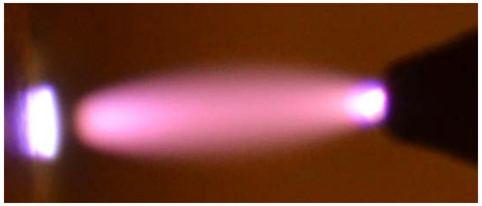
Non-intrusive Detection of Low Concentration Water Vapor



Schematic of the experimental setup with a plasma discharge for optical emission spectroscopy



Emission spectra from a DC glow plasma discharge for different working gases



Exemplar DC glow discharge in nitrogen feed gas