Induction Bakeout EXperiment (IBEX) at LIGO Caltech

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2 Oct 2025

DCC: LIGO-G2502145

Outline

- Motivation
- Overview
- Implementation
- Preliminary Results
- Modeling
- Prospects for the Future: Scaling to Cosmic Explorer (CE)

Motivation (1/2)

Induction Heating Experiment

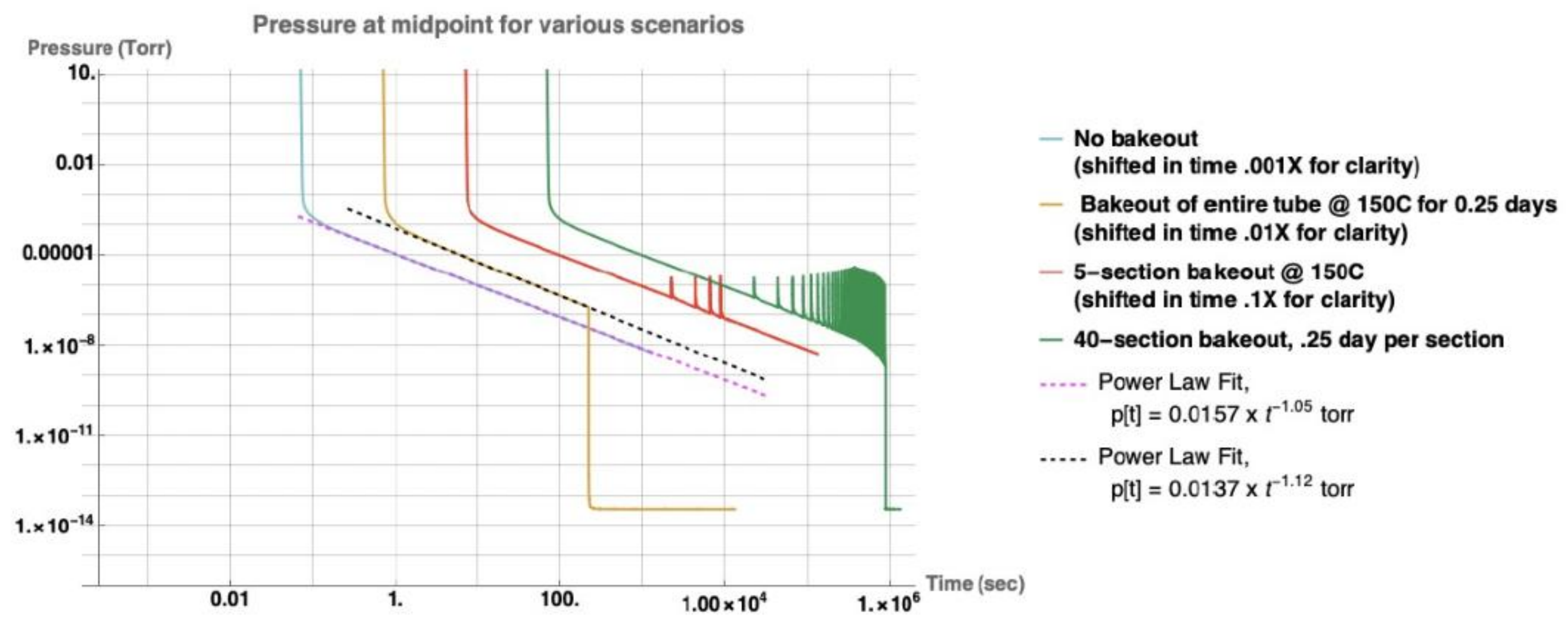
- Mild steel is an attractive option for CE because it has a much lower (<100x) H_2 outgassing rate due to its manufacturing process and its much lower cost because it's use in the pipeline industry.
- Mild steel pipe resistivity too low for practical I^2R heating. Alternate method needed.
- Magnetic and eddy current losses of mild steel make it ideal for induction heating. Works best with highly permeable materials but can be used with austenitic stainless steel (SST).
- Simulate zone heating scenario using isotherm models. See tech note LIGO-T2400167.
- Multiple zone bake appears to work just as well as baking the entire system, back diffusion does not seem to effectively repopulate adsorption sites if pumping is adequate.
- Perform experiment on system, with length-diameter (l/d) ratio ~ 60x, of pipe steel.

A zone bakeout appears to be effective as an entire-tube bakeout if performed correctly

Motivation (2/2)

Sectional (sequential) bakeout experiment

- Modeling suggests that a zonal bakeout can achieve acceptable residual water outgassing rate



Isotherm models showing the water pressure in various bakeout scenarios.

Overview

Induction Heating Experiment

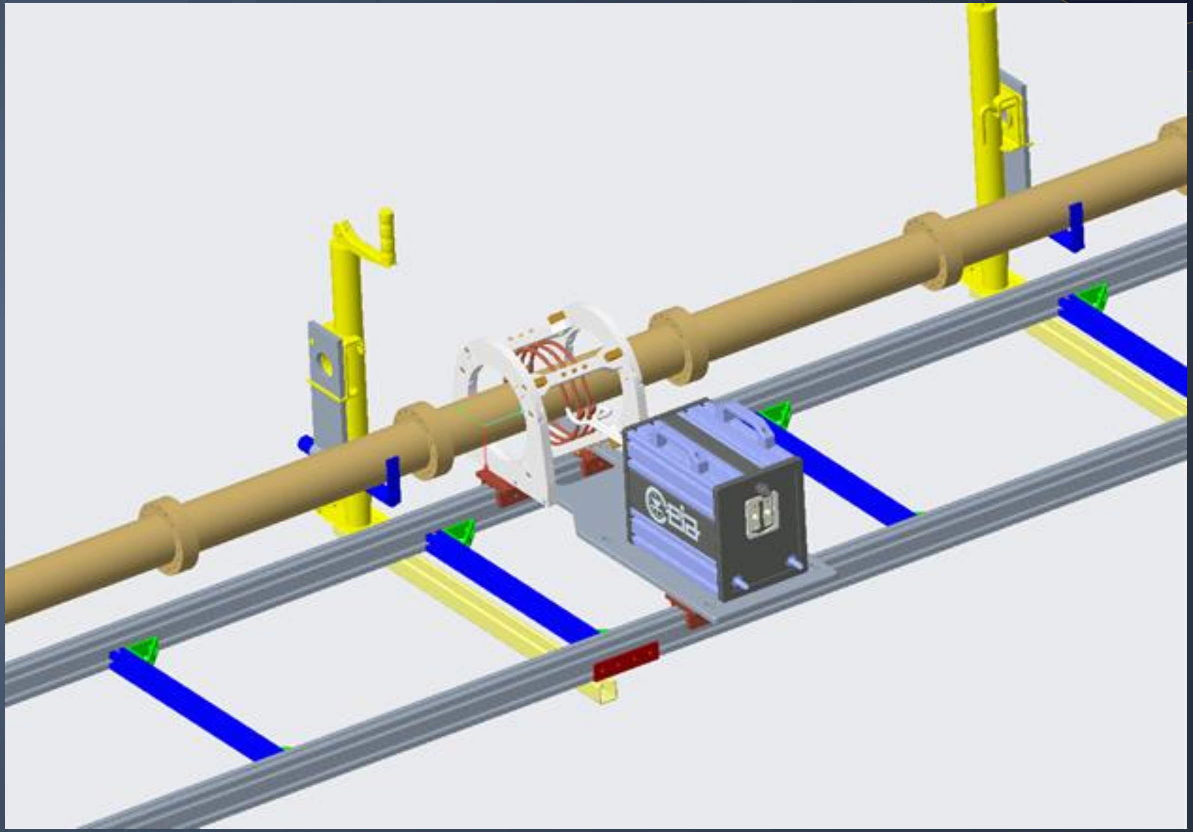
Goal: Determine if a "zone bakeout" described by isotherm modeling can be applied to a mild steel vacuum system.

- 100mm ID x 6m long (l/d=60) mild steel beamtube (5.7mm thick), composed of ten spool pieces (API 5L) with DN100CF flanges (A572).
  - Each spool piece could fit into Sun Steel furnace if magnetite coating desired.
  - Mild steel zero-length reducers (better CTE match @ DN40CF flange).
- Cleaned and processed at Caltech. LIGO class-A vacuum bake showed no hydrocarbons (HCs) in residual gas analyzer (RGA) scan.
  - Cleaned with mild acidic cleaner (Citrajet)
- Main tube made of mild (pipe) steel that will be baked with induction heater.
  - End sections with pumping and instrumentation (all SST parts) baked with fiberglass heat trace.
- RF system (generator, transformer, optical pyrometer, chiller) procured, tested at vendor site, and integrated at Caltech. Working as intended!
  - Vendor (Inductronix/CEIA USA) designed the induction coil, utilizing Comsol finite element analysis (FEA) models to meet our requirement (RT to 250°C in < 1min). Multiple coil designs considered and final selection was a clamshell coil.
- Translation rail system designed and assembled at CIT. Traveling heater!
- Isotherm model $p_{H2O}(t)$ for zone bake.

Implementation

Induction Heating System

- **25 kW** x 40 kHz RF generator. Output power **adjustable**.
- Impedance matching network coil-auto tuning
- **IR feedback** w/ emissivity for temp control
- Thermocouple reference for setting **emissivity**
- Mild steel pipe and CFFs. 100mm ID x 6m length
- Efficient RF coupling; magnetic
- RT to bake temp (150-250°C) in ~5 seconds
- **Symmetrical pumping** and gauging system
  - Two each 300 L/s TMPs, cold cathode gauges, Prisma RGA only at one end currently
- Linear bearing track with variable speed gearmotor
- Average bake duration ~30 minutes end to end
- CFF flanges have been unreliable > 150°C (CTE mismatch w/ Cu gasket)
  - Considered sourcing Helicoflex spring seals
  - Seals reliable when power capped at 30% max output

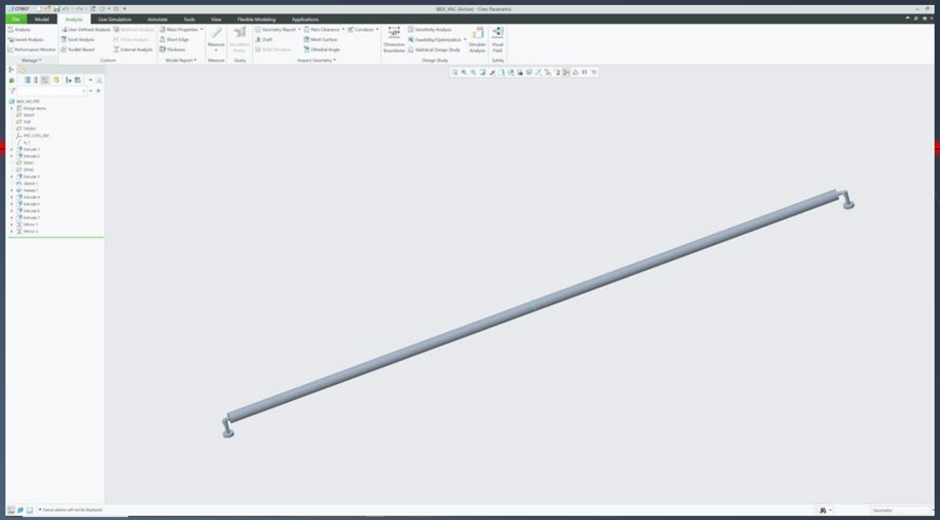


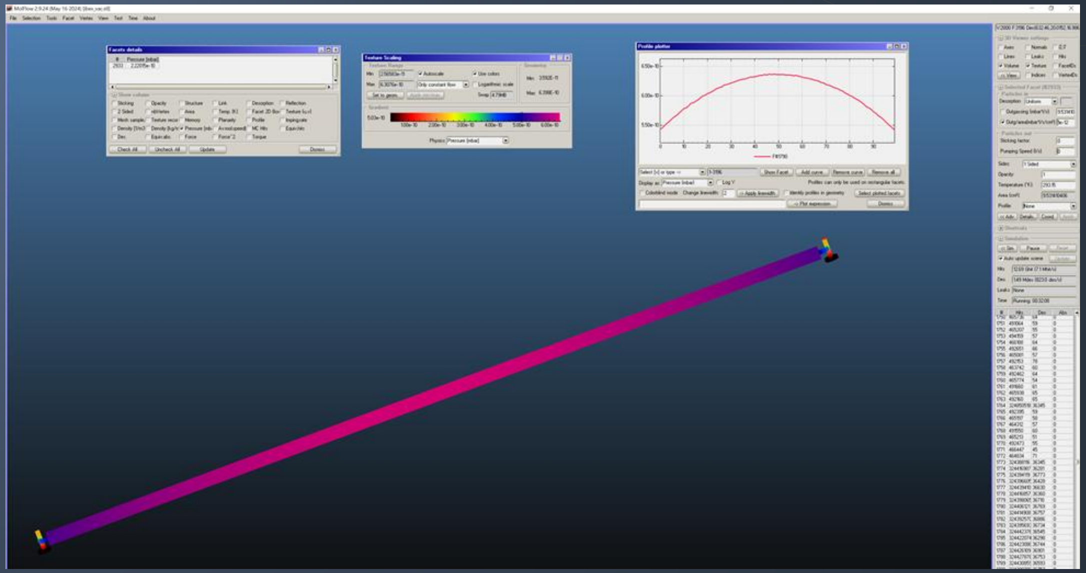
Model of the setup of the induction bakeout experiment (IBEX), showcasing the translation track, induction heater head, clamshell coil, mild steel beamtube sections, and supports.

Modeling (1/3)

Computer-Aided Design (CAD) and Molflow+

- CREO/ProE solid model of vacuum volume
- Create Molflow model from imported .stl file
- Use Molflow to calculate outgassing rate H_2, H_2O using partial pressure at RGA. Adjust molecular speed and effective pump speed.
- Calibrate RGA with Penning gauge.
- Simple linear calibration, assume same ionization efficiency (1) for all ions.
- E-multiplier needed- too low pressure for Faraday. Errors due to ion productions. Prisma does not count ions.
- Tube pressure **5.3e-10 mbar after 30 min bake** and ambient pumping.
- Pressure rises to ~e-4 mbar when heating.
- **Pump speed** at tube ends **< 50 l/s (est.)** throttled by conductance of plumbing.





CAD and Molflow+ model of the mild steel vacuum chamber.

Modeling (2/3)

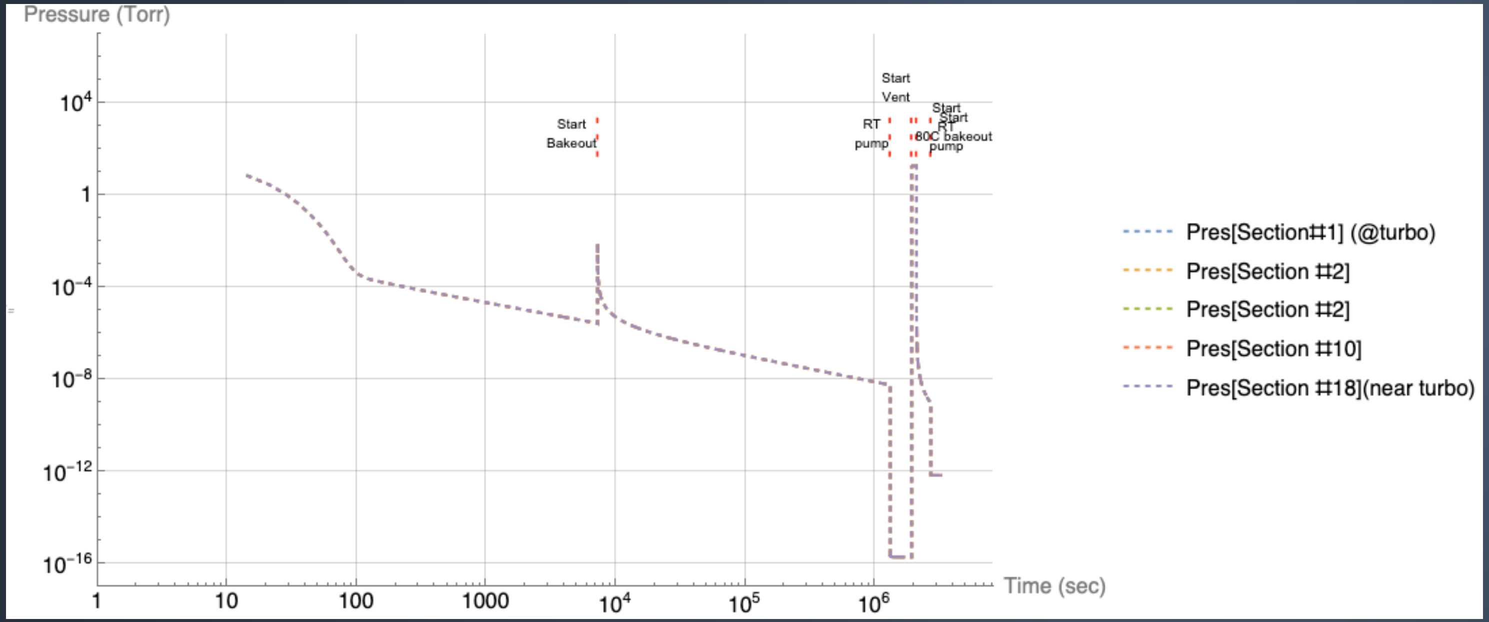
Modeling a high-temp bake → vent → low-temp bake

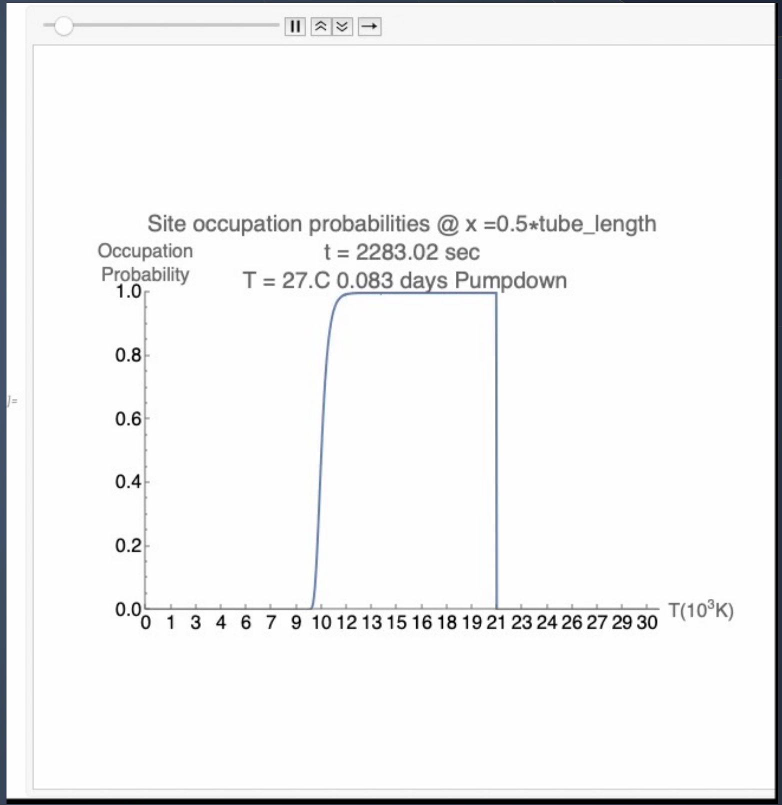
Using the updated Dubinin-Radushkevich (D-R) model originally implemented by Rai Weiss in the late 1990s for the initial LIGO bakeout, we can:

- Model a high-temp (150°C) bake followed by low-temp (80°C) rebake after a vent to atmosphere
- Visualize how the D-R isotherm model predicts the H_2O site occupancy changes during bake, vent and rebake
  - After a high-temp bake the lowest binding energy sites are depleted
  - A subsequent vent starts to slowly repopulate the weakest bound sites, hardly affecting the population at high energies left after the high-temp bake
  - A low-temp bake afterwards seems adequate to deplete the weaker bound sites

Modeling (3/3)

Modeling a high T bake → vent → low T bake





Figures: (Left) Isotherm model of high temp bake followed by vent and low temp bake. (Right) Video showing the occupation probabilities at various sites energies.
**Link to ~8 min animation: https://wm1693.box.com/s/6aj8f6vptn7wo5u2blsx12n5vxevfgs2*

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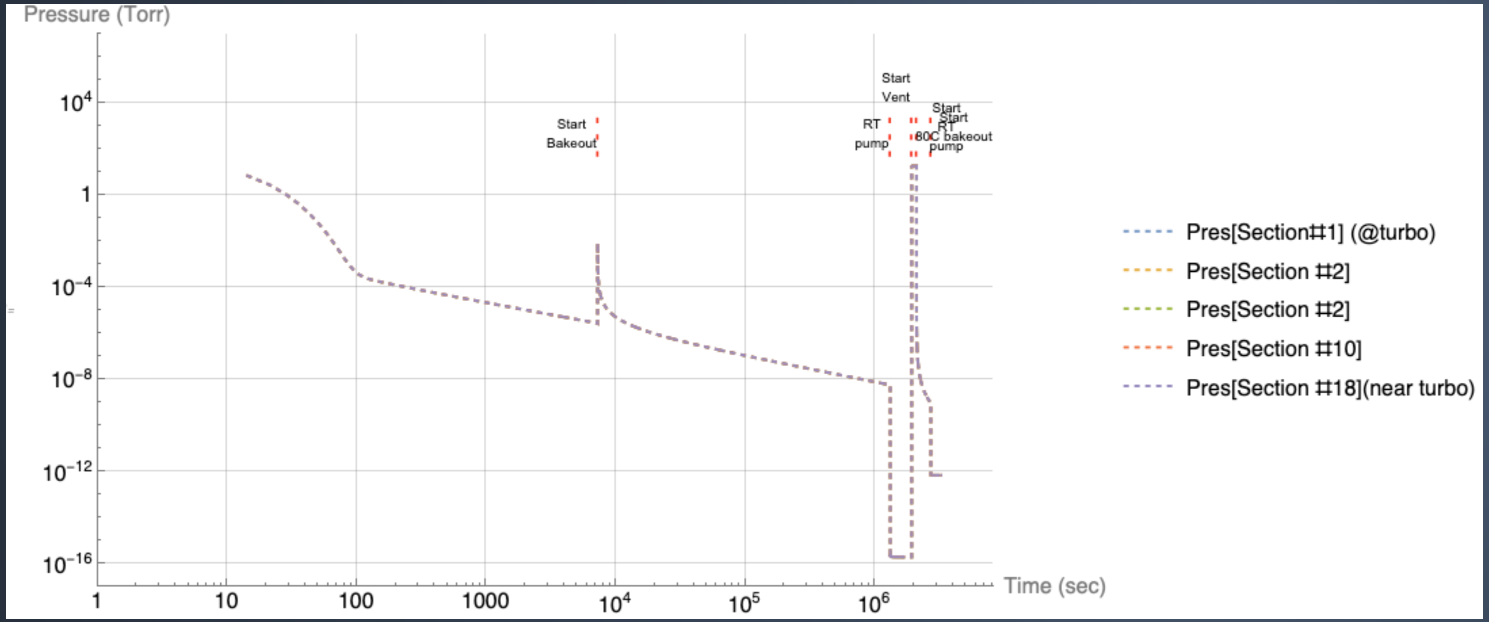

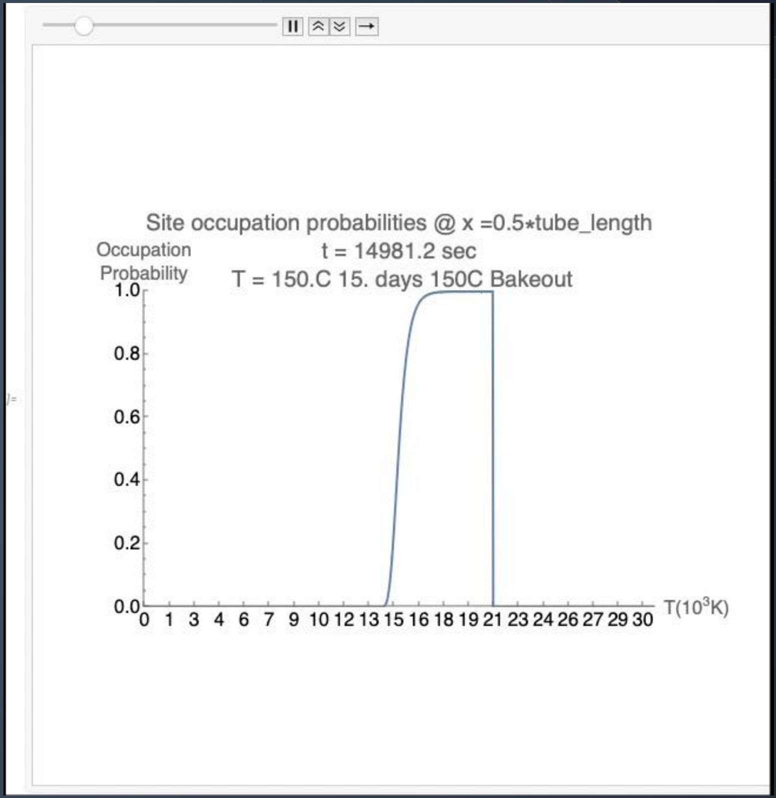

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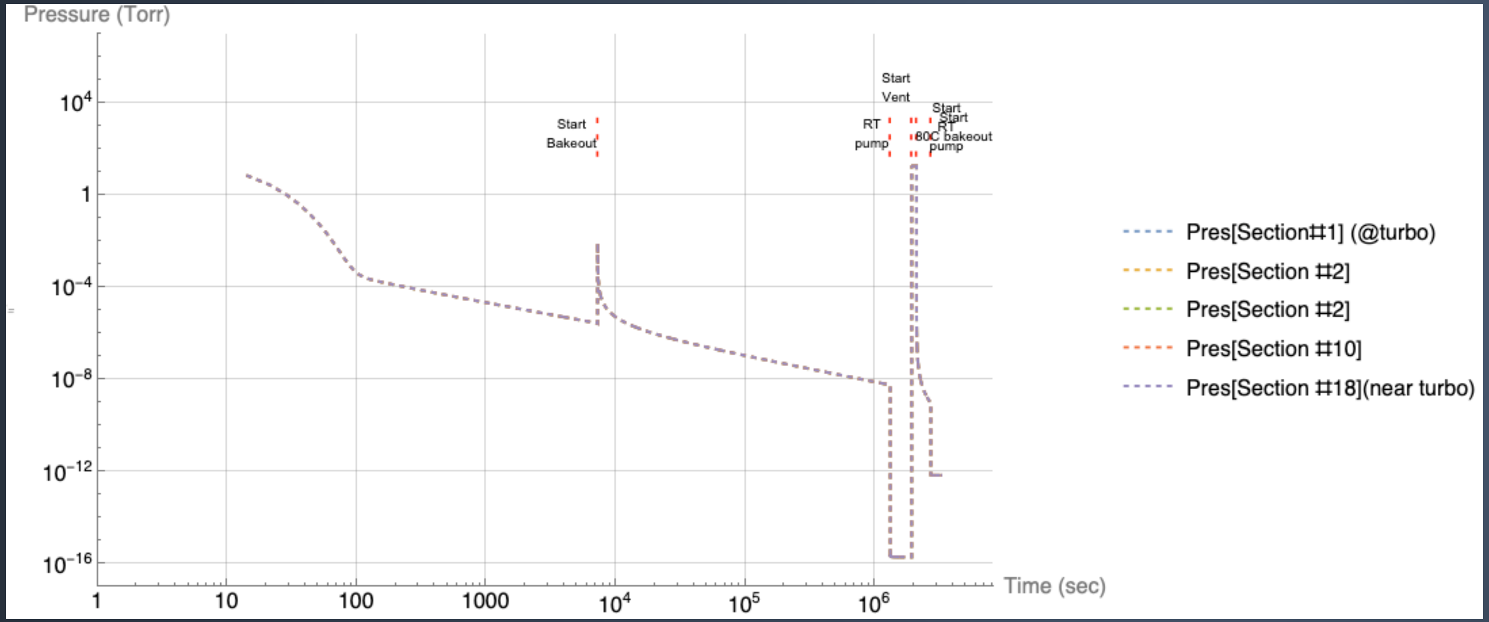

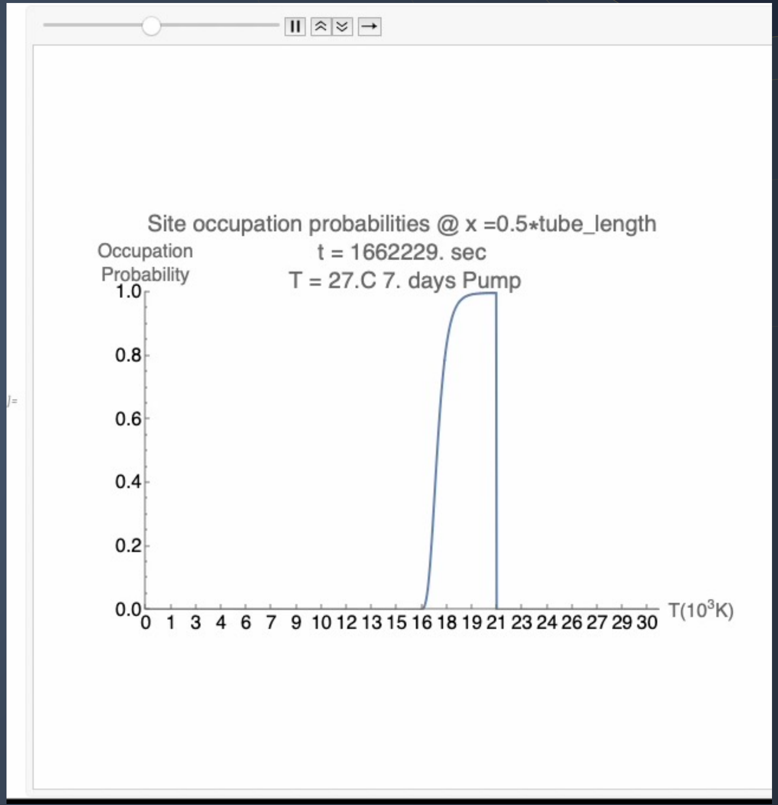

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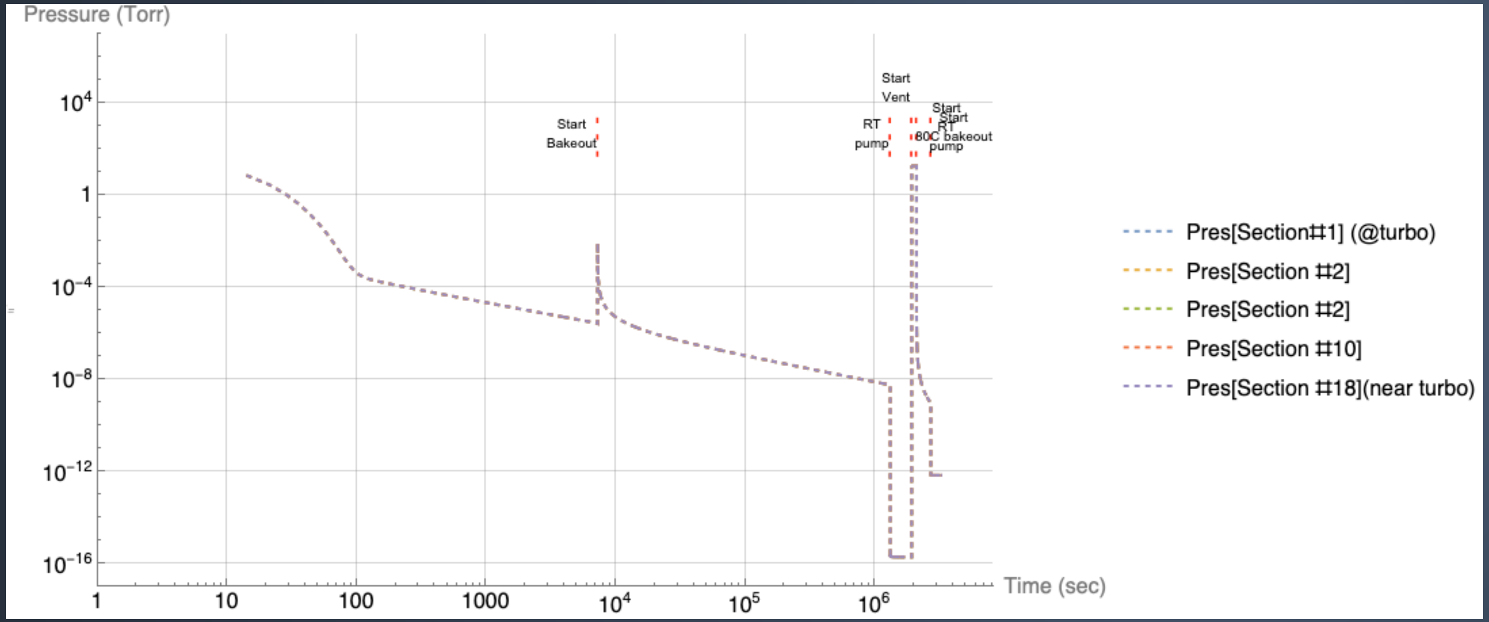

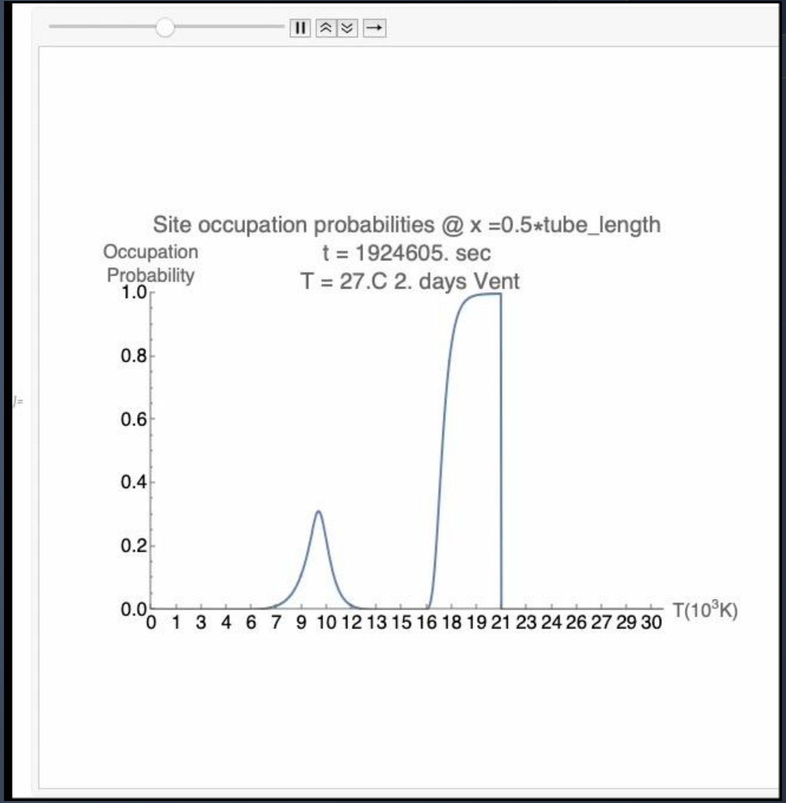

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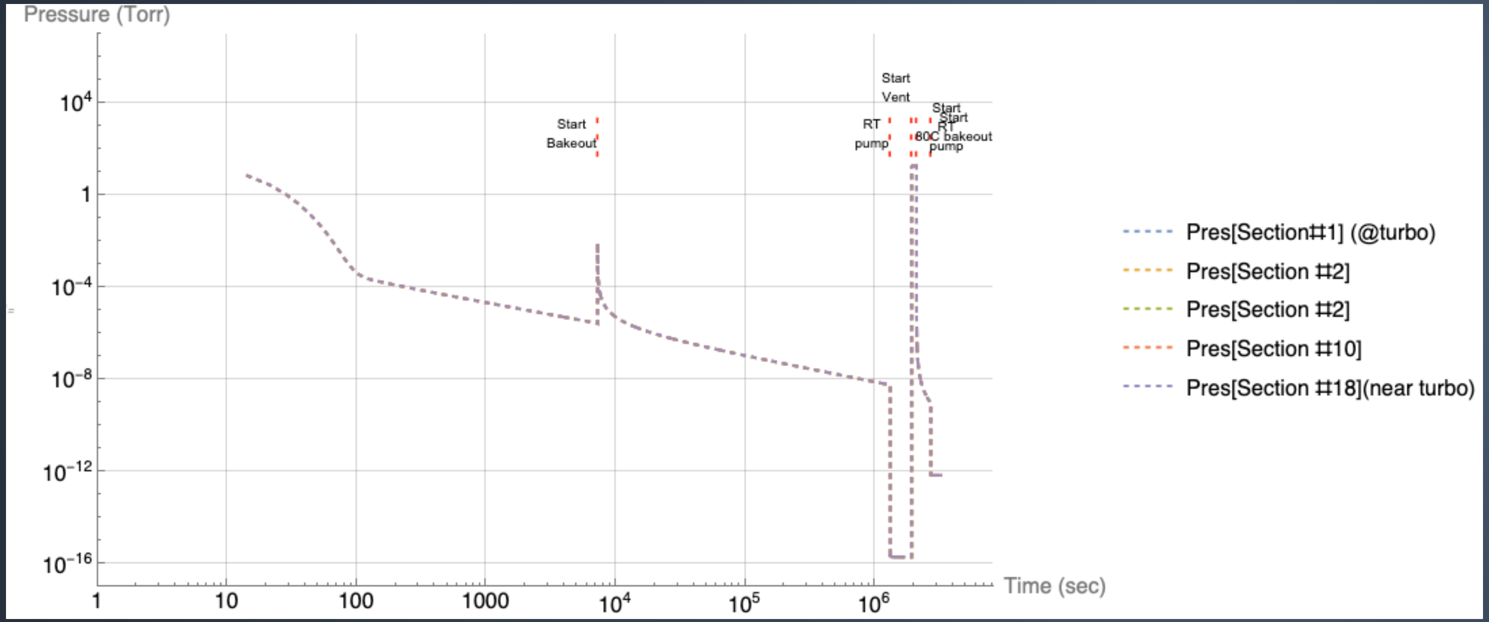

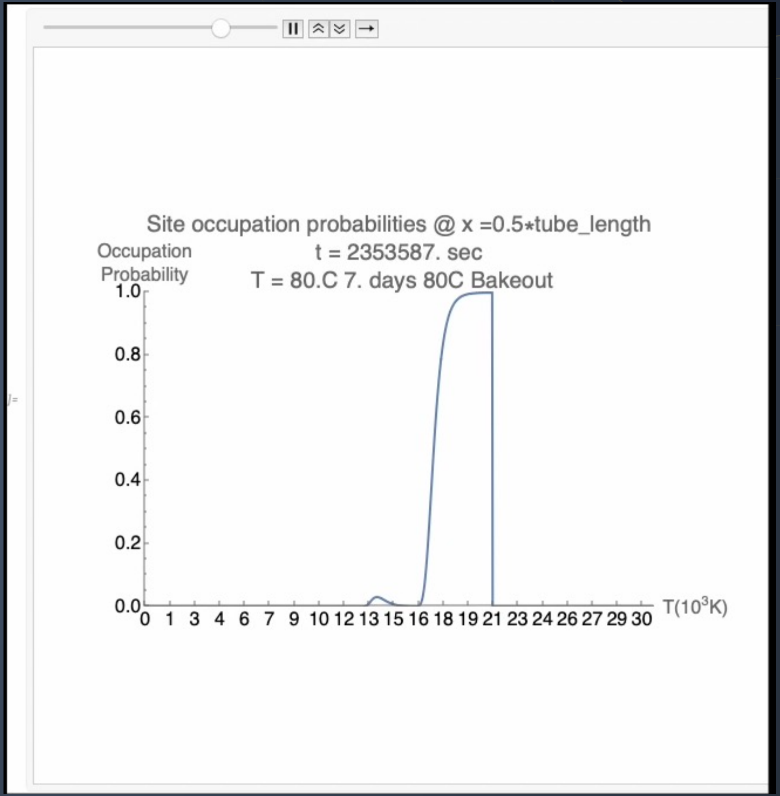

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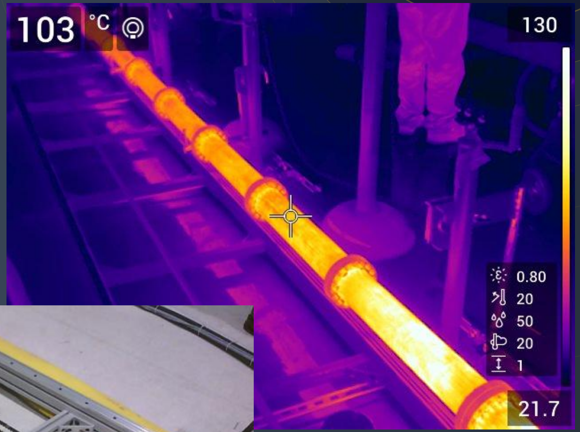
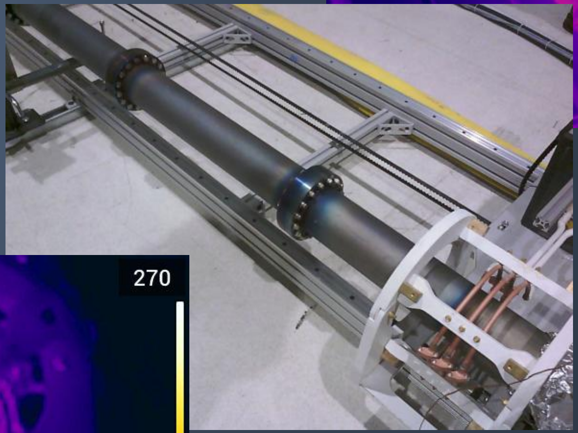
Preliminary Results (1/3)

Lessons learned from preliminary bakeouts

- Bakes performed at **150°C to 250°C**, with pressures reaching e-9 and e-10 mbar range after cooldown.
- Speed **~2 mm/sec** across entire length of tube
  - Speed can be adjusted
- RGA scans show mainly water; very **low hydrogen**
- High temp bakes sprung leaks due to SST hardware on mild steel conflat flanges
  - Swapped all with high strength steel hardware
- Surface emissivity changed after bakeouts
  - Welded studs onto tube for thermocouple connection to calibrate pyrometer emissivity
- Automated translation to be integrated that features a rotary encoder for precise positioning and additional safety measures



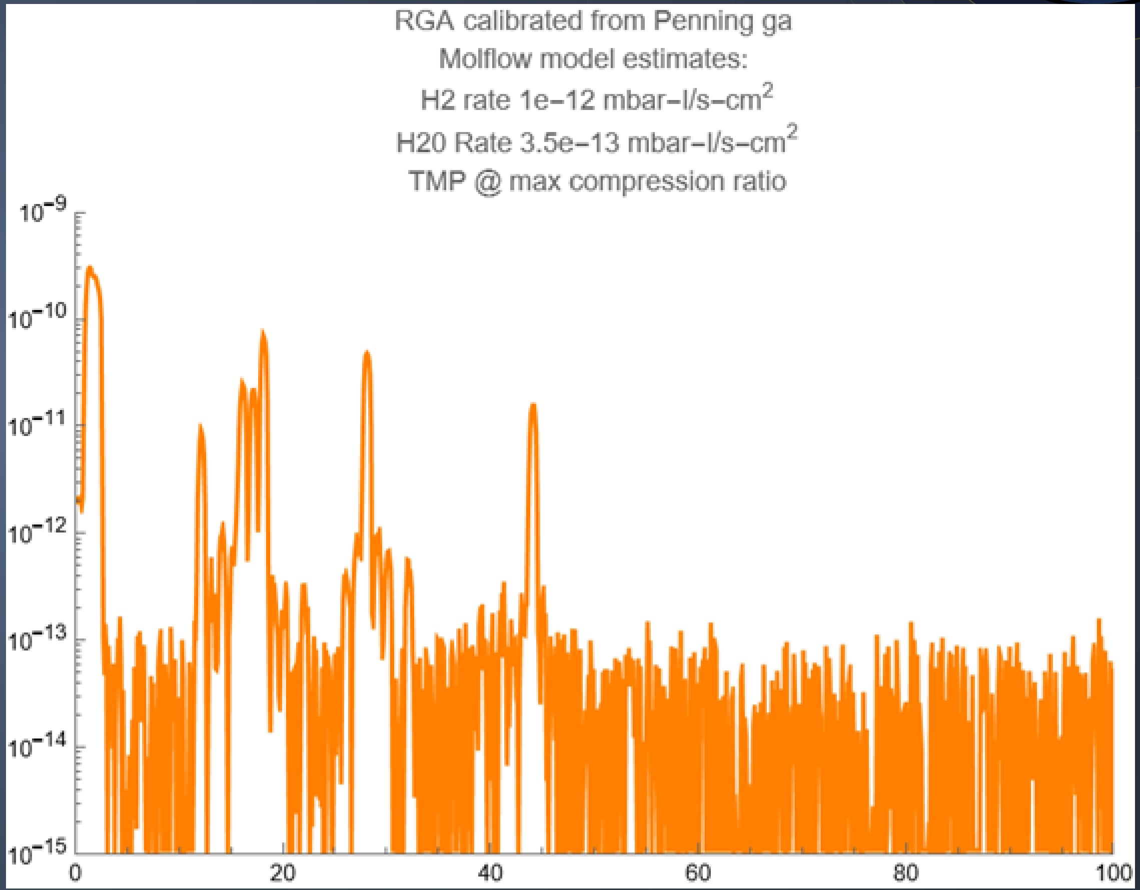


(Bottom Left & Top Right) Images taken with an IR camera during various bakeouts. (Middle) Surface color visibly changed after bakeouts.

Preliminary Results (2/3)

Outgassing rates from RGA + Cold Cathode

- Induction baking is very efficient, zone outgassing effective.
- Depleted water sites do not seem to be refilled.
- Tube vented to atmosphere, baked 30 min end-to-end 150°C when cool **6.7e-10 mbar**.
- Alloy steel typical low H_2 diffusion, includes outgassing of RGA shell, misc. 304 SST components.
  - **1e-12 H_2 mbar-L/s-cm^2**
  - **3.5e-13 H_2O mbar-L/s-cm^2**

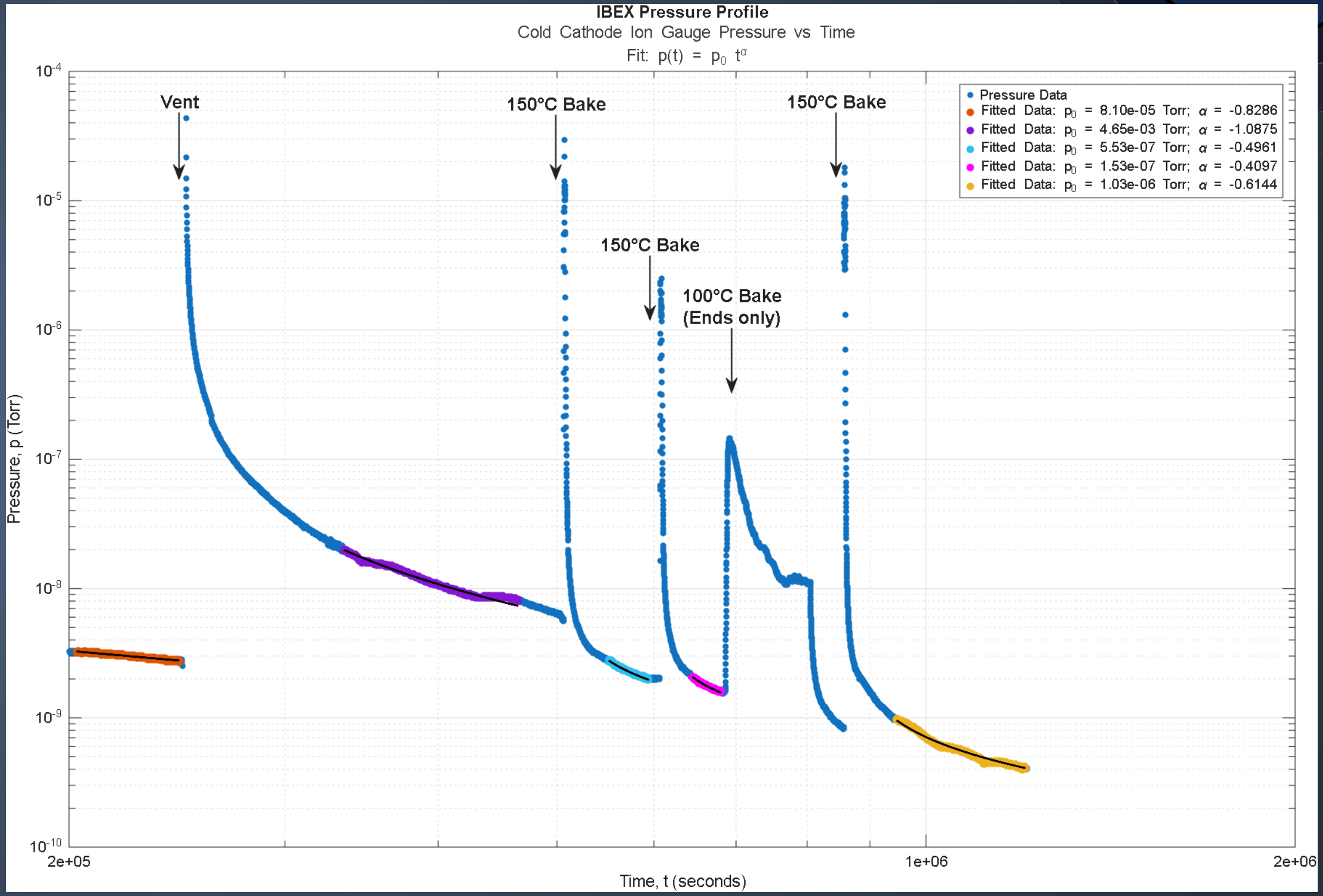


RGA scan used to calculate outgassing rates from 150°C bake on July 24th, 2025. x-axis is amu, and y-axis is ion current.

Preliminary Results (3/3)

Pressure profiles

- Since capping the maximum power output to 30%, bakes set to 150°C have not sprung any leaks

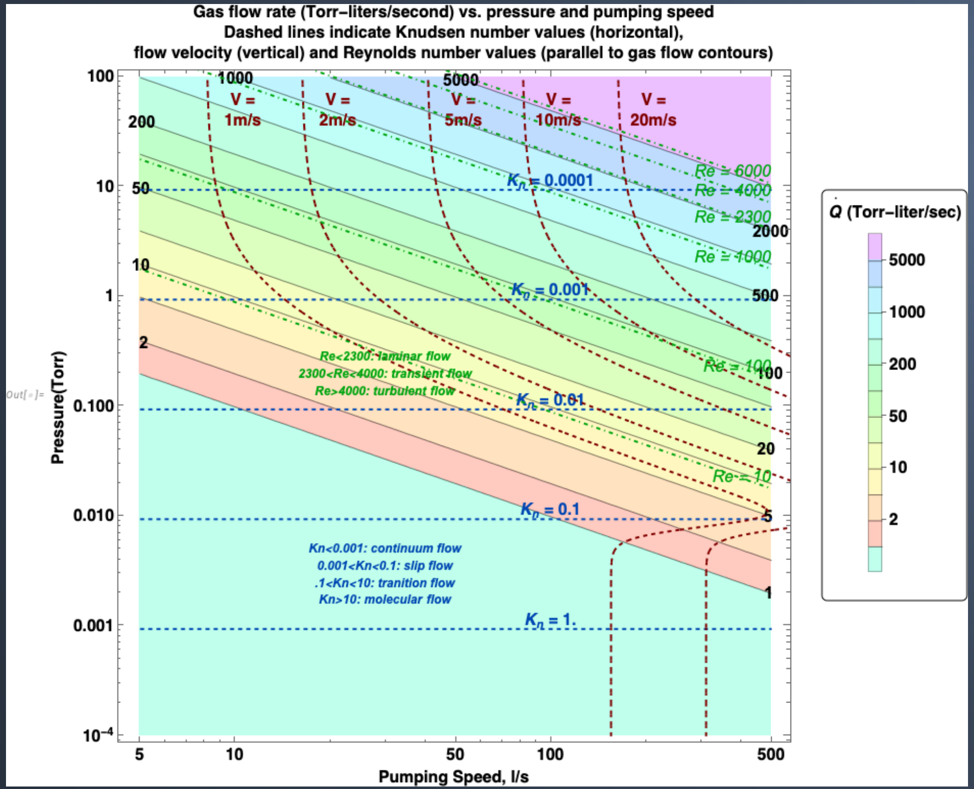


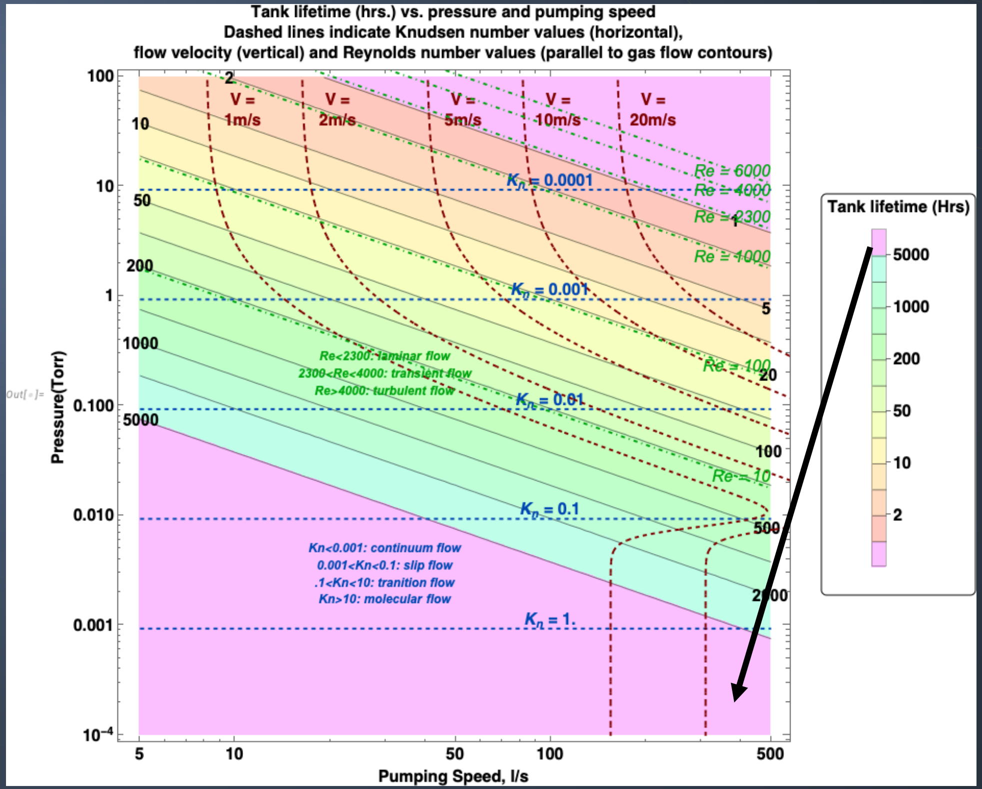
Pressure profiles from the pumpdown following: (orange) an unplanned vent, (purple) planned vent, (cyan, magenta, yellow) 150°C bakes.

Prospects for the Future: Scaling to CE (1/2)

Planning for a bake with circulating dry gas (N_2)

- First back-of-the-envelope parametric study to identify {pressure, pumping speed, V_{N2}} values to use
- Developing a more realistic Navier-Stokes model (steady-state, compressible flow) in Mathematica



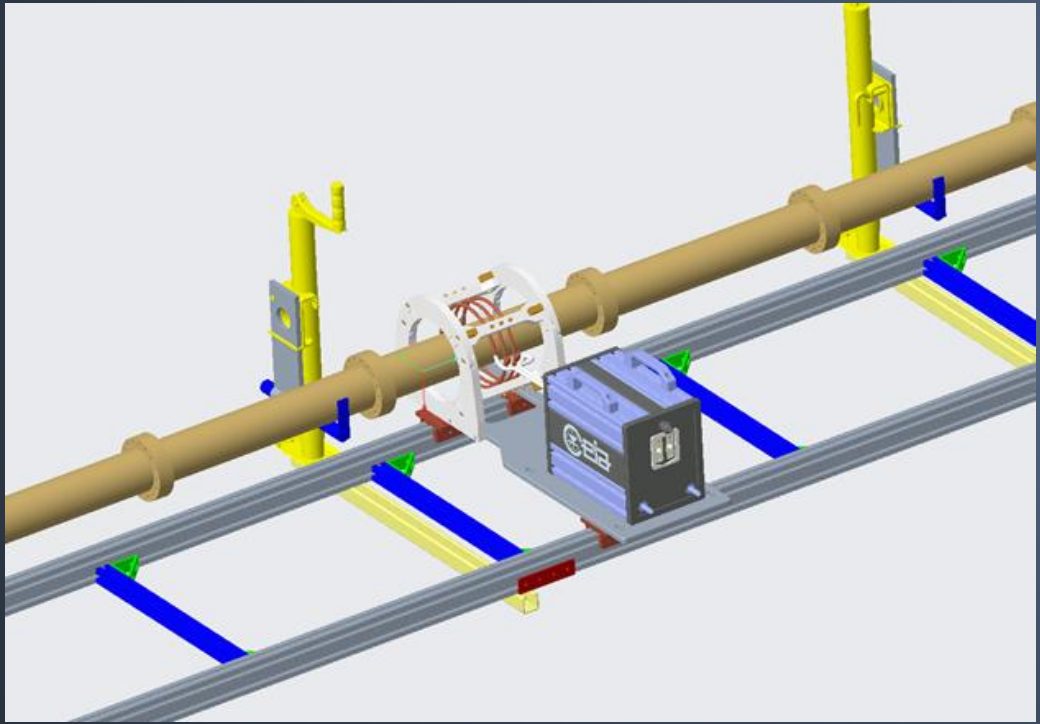


Prospects for the Future: Scaling to CE (2/2)

- If Cosmic Explorer elects a mild steel beam tube, an ohmic heating bakeout approach is not feasible due to lower resistivity of the steel.
- The use of a moving inductive heater is an attractive option.
- Need to address how to move the heater carriage past supports.
- Will need to make sure pumping speed is adequate to remove the outgassed water.
- The use of a circulating dry gas may prove essential to keeping sections clean.

Thanks!

Thank you for your attention!



Thanks!

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