Air/Moisture-Ingress Furnace Development

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AGR TRISO Fuels Program Review
Idaho Falls, ID
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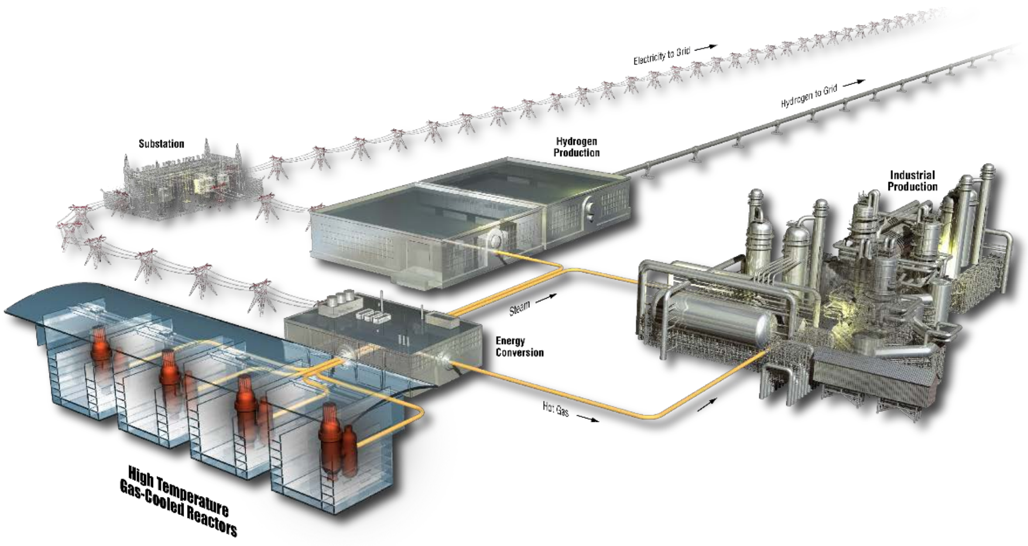

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Outline

- Purpose for air/moisture-ingress testing
- Data to be collected
- Test conditions
- Samples to be tested
- Development and current status

Purpose of Safety Testing in Air and Steam

- Safety testing of AGR fuel has only been under helium (FACS/CCCTF)
- Accident scenarios in HTGRs include depressurized conduction cooldown events:
  - Main coolant line break with air-ingress
  - Steam generator tube leak with moisture-ingress
- Fuel oxidation will occur when exposed to air or steam at high temperatures:
  - Compact matrix and particle OPyC layer oxidation
  - SiC generally resistant to but will slowly oxidize as well
- Small amounts of fission products accumulate in compact matrix during irradiation
- Oxidation of matrix and OPyC will mobilize fission products outside of the OPyC
- Exposed kernels (from as-fabricated defects or failures) vulnerable to hydrolysis
- This activity falls under elements 3 and 5 of the Technical Program Plan (TPP-3636)
  - #3 Safety testing
  - (#4 Fuel performance modeling)
  - #5 Fission product transport and source term

Air/Moisture Ingress Furnace Goals

- Test irradiated TRISO fuels in oxidizing environments representative of air and moisture ingress accidents in HTGRs
- Measure fission product releases as a function of time
- Relate fission product releases and release rates to fuel irradiation history, test conditions, and extent of fuel oxidation
- Use collected data for:
  - Fuel qualification and licensing
  - Input to and comparisons with predictive models and simulations
  - Reactor accident source term analysis

Air/Moisture Ingress System Bounding Conditions

Total test pressure (kPa)	~85 (ambient)
Air Partial Pressures (kPa)	0.1 to 85
Moisture Partial Pressures (kPa)	0.1 to 85
Temperature Range (°C)	$T_{min} \leq 800$, $T_{max} \geq 1650$
Flow velocity at the sample (m/s)	0.1 to 0.2
Test durations (hr.)	100 +

1. Preliminary Safety Information Document for the Standard MHTGR, Vol. 1, HTGR-86-024 (1986).
2. Oh, C.H., et. al., "Final Report on Experimental Validation of Stratified flow Phenomena, Graphite Oxidation, and Mitigation Strategies of Air Ingress Accidents," INL/EXT-10-20759, Idaho National Laboratory (2011).
3. Liu, R., et. al., "High temperature oxidation behavior of SiC coating in TRISO coated particles," Journal of Nuclear Materials, **453**, 107-114 (2014).
4. Huang, W., et. al, "The relationship between microstructure and oxidation of selected IG- and NBG-grade nuclear graphites," Journal of Nuclear Materials, **454**, 149-158 (2014).
5. "Fuel performance and fission product behaviour in gas cooled reactors," IAEA-TECDOC-978, International Atomic Energy Agency (1997).
6. Petti, D.A., et. al., "Modular Pebble-Bed Reactor Project Laboratory-Directed Research and Development Program FY2002 Annual Report," INEEL/EXT-02-01545, Idaho National Engineering and Environmental Laboratory (2002).
7. Montgomery, F.C., "Evaluation of Need for Integral Fuel Oxidation Tests," DOE-HTGR-86-002, GA Technologies, Inc. (1987).
8. Yanhua, Z., Lei, S., and Yan, W., "Water-ingress analysis for the 200 MWe pebble-bed modular high temperature gas-cooled reactor," Nuclear Engineering and Design, **240**, 3095-3107 (2010).
9. Richards, M., "REACT_COMPACT: A Computer code for Modeling Graphite Corrosion and Fuel Hydrolysis," Proceedings of the HTR 2016, Las Vegas, NV, November 7-10 (2016).
10. Iniotakis, N. and C.B. von der Decken, "Radiological consequences of a depressurized accident combined with water ingress in an HTR Module-200," Nuclear Engineering and Design, **109**, 299-305 (1988).
11. Lohnert, G.H., "The consequences of water ingress into the primary circuit of an HTR-Module—From design basis accident to hypothetical postulates," Nuclear Engineering and Design, **134**, 159-176 (1992).
12. Wolters, J., Bongartz, R., Jahn, W., and Morroman, R., "The Significance of Water Ingress Accidents in Small HTRs," Nuclear Engineering and Design, **109**, 289-294 (1988).

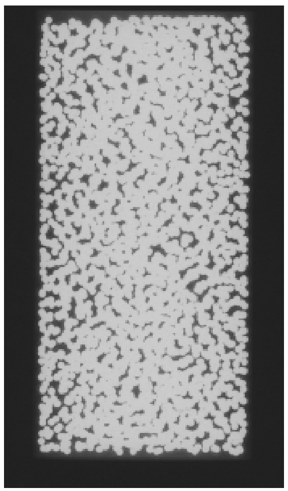
Data Collection

- Fission product releases as a function of test time
  - Fission product gases:
    - Kr-85 (indicates failure of all three TRISO layers)
    - Xe-133 (could be measured from tests following re-irradiation)
  - **Never before done in air/moisture:** condensable fission products
    - Ag-110m
    - Cs-134/137 (indicates SiC layer failure)
    - Eu-154/155
    - I-131 (measured from re-irradiated samples)
    - Sr-90
- Extent of sample oxidation as a function of time

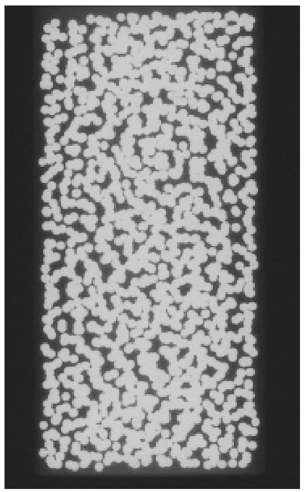
Potential Samples

- Irradiated fuel compacts, fuel bodies, pebbles, graphite with fission products

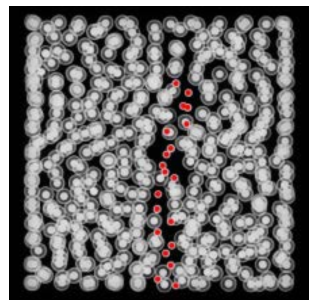
AGR-2 UCO



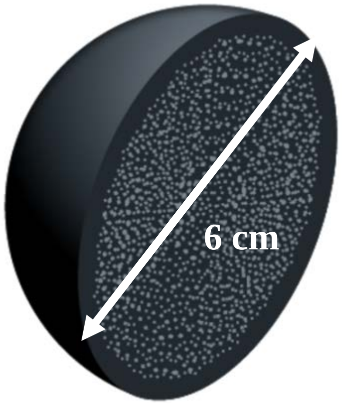
AGR-2 UO_2



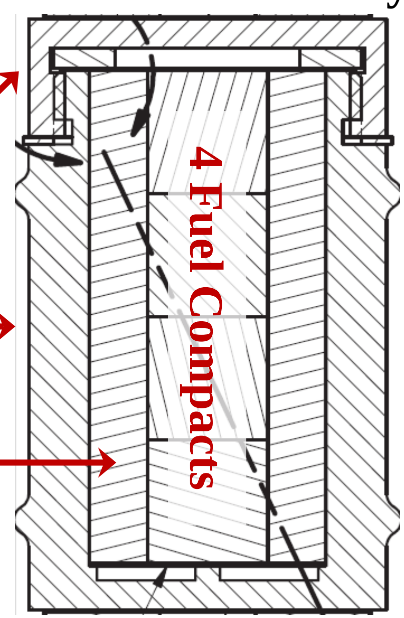
AGR-3/4 UCO and DTF



Pebble

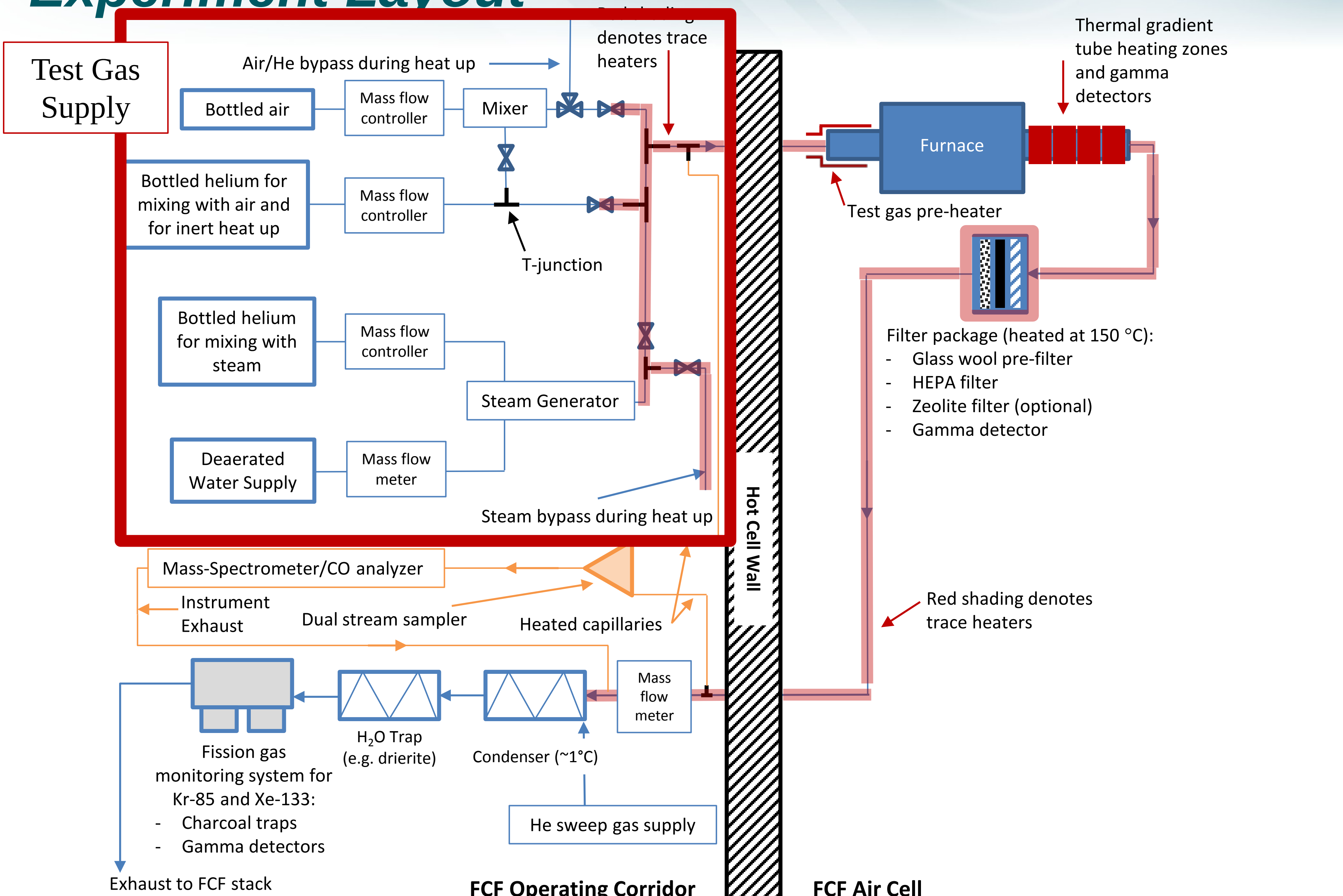


AGR-3/4 Fuel Body

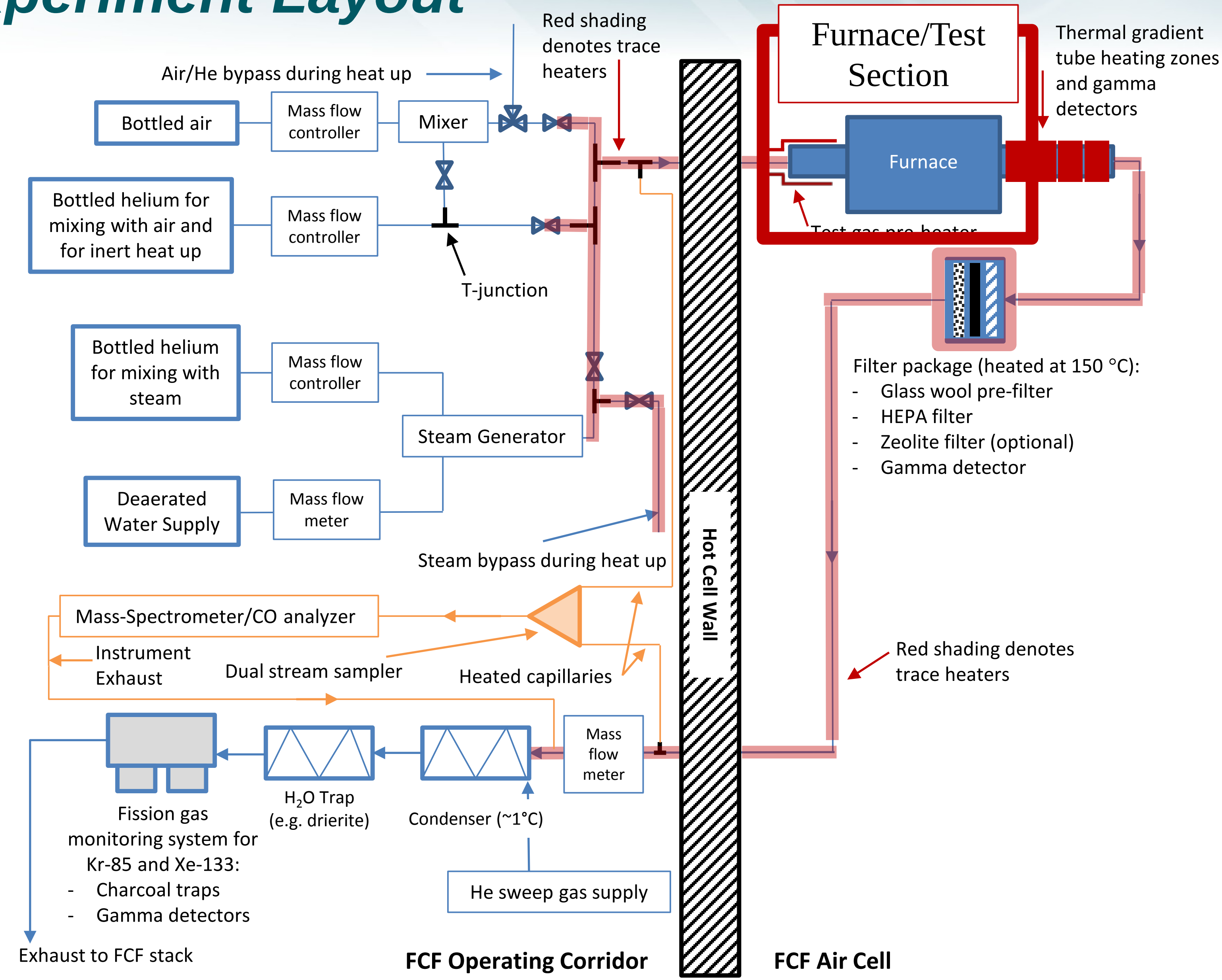


AGR-3/4 DTF particles simulate exposed kernels or failed particles

Experiment Layout



Experiment Layout



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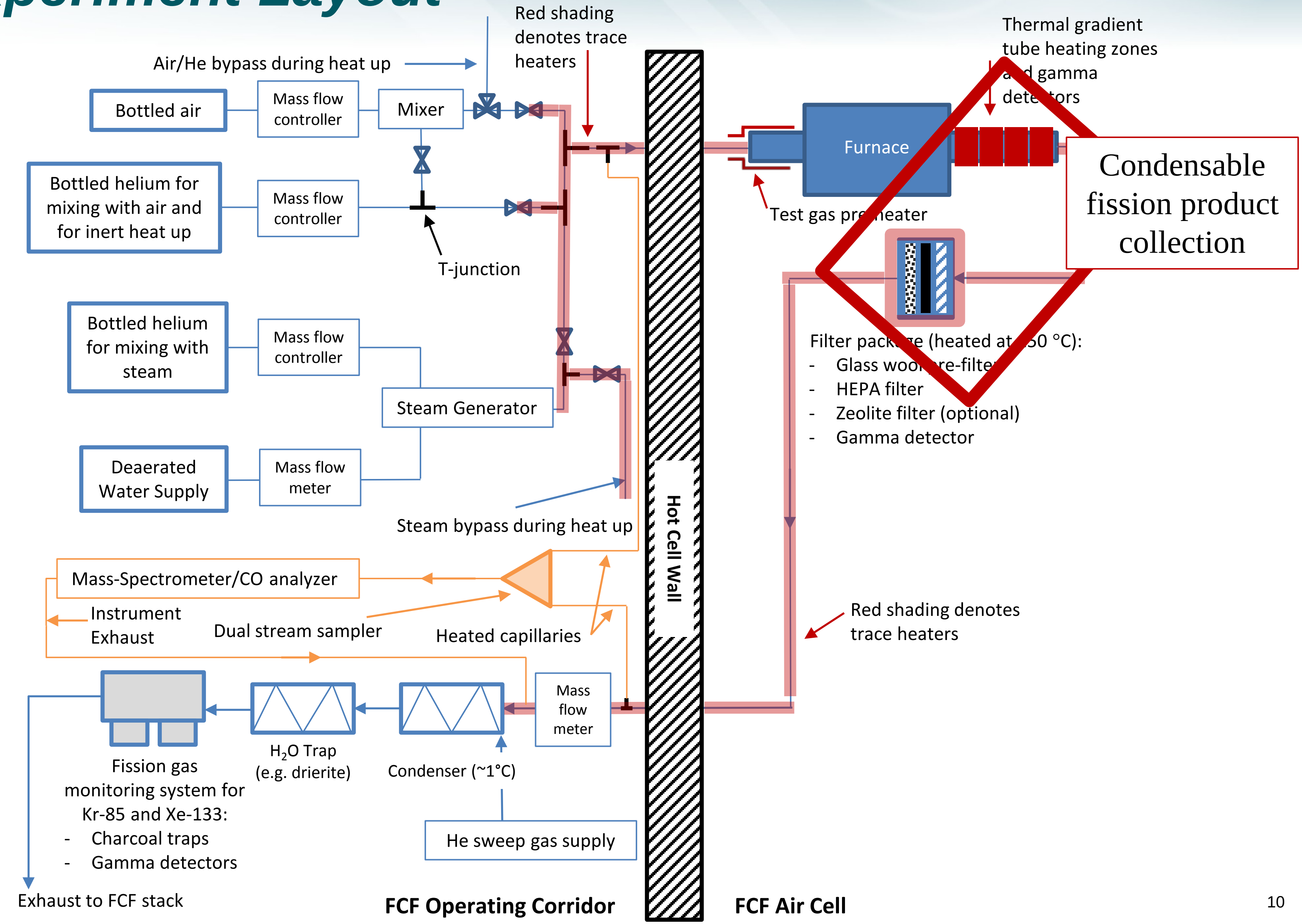

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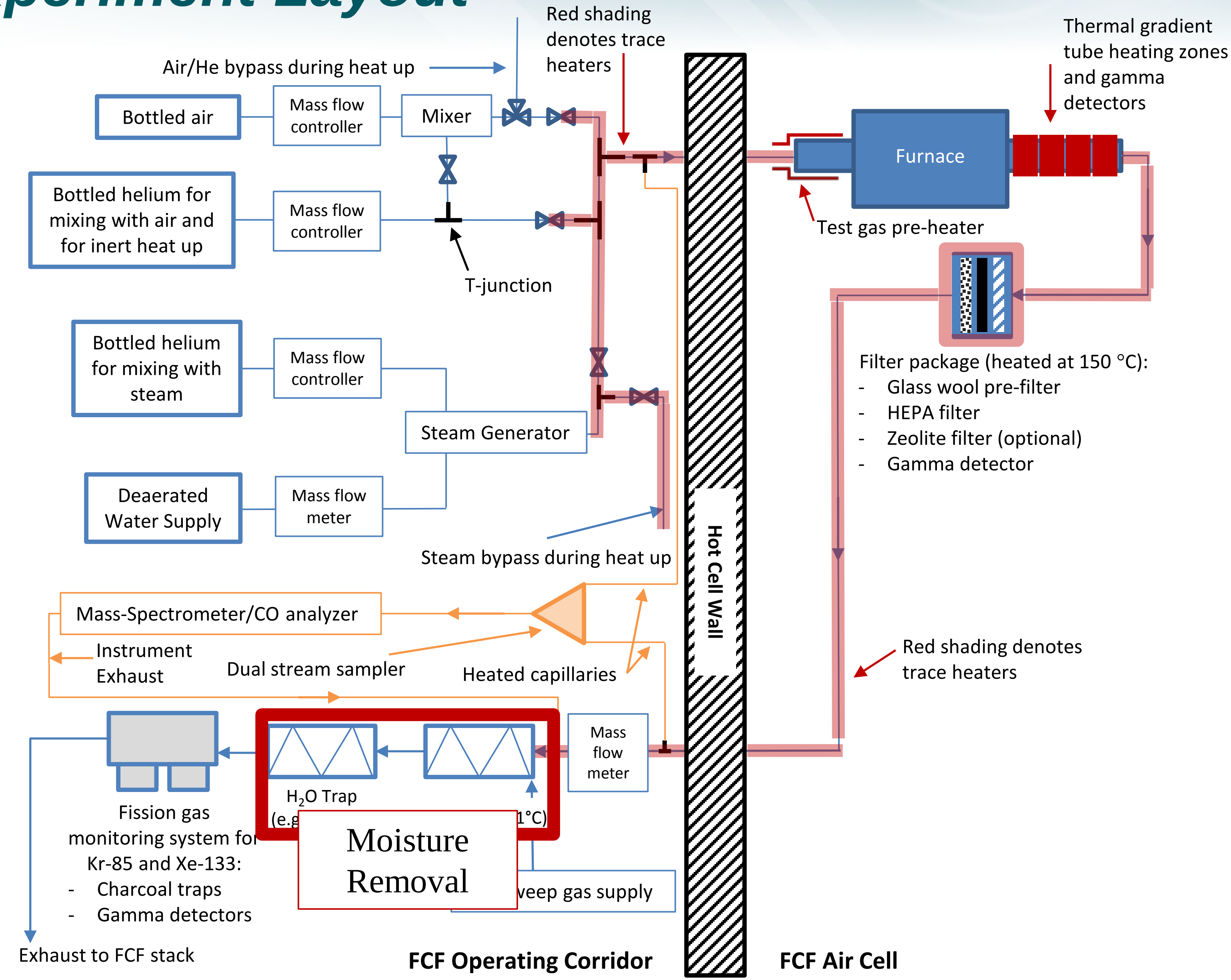

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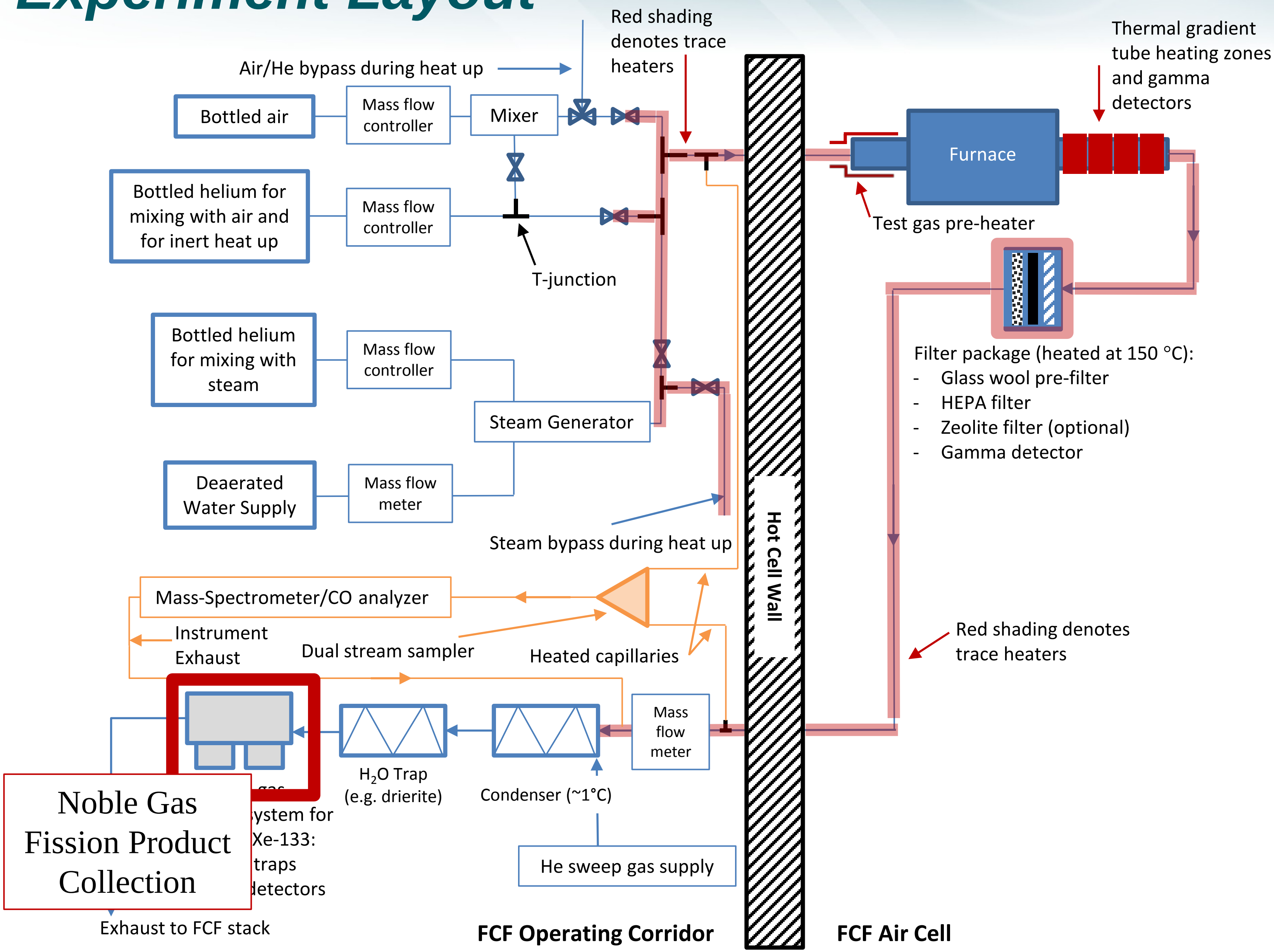

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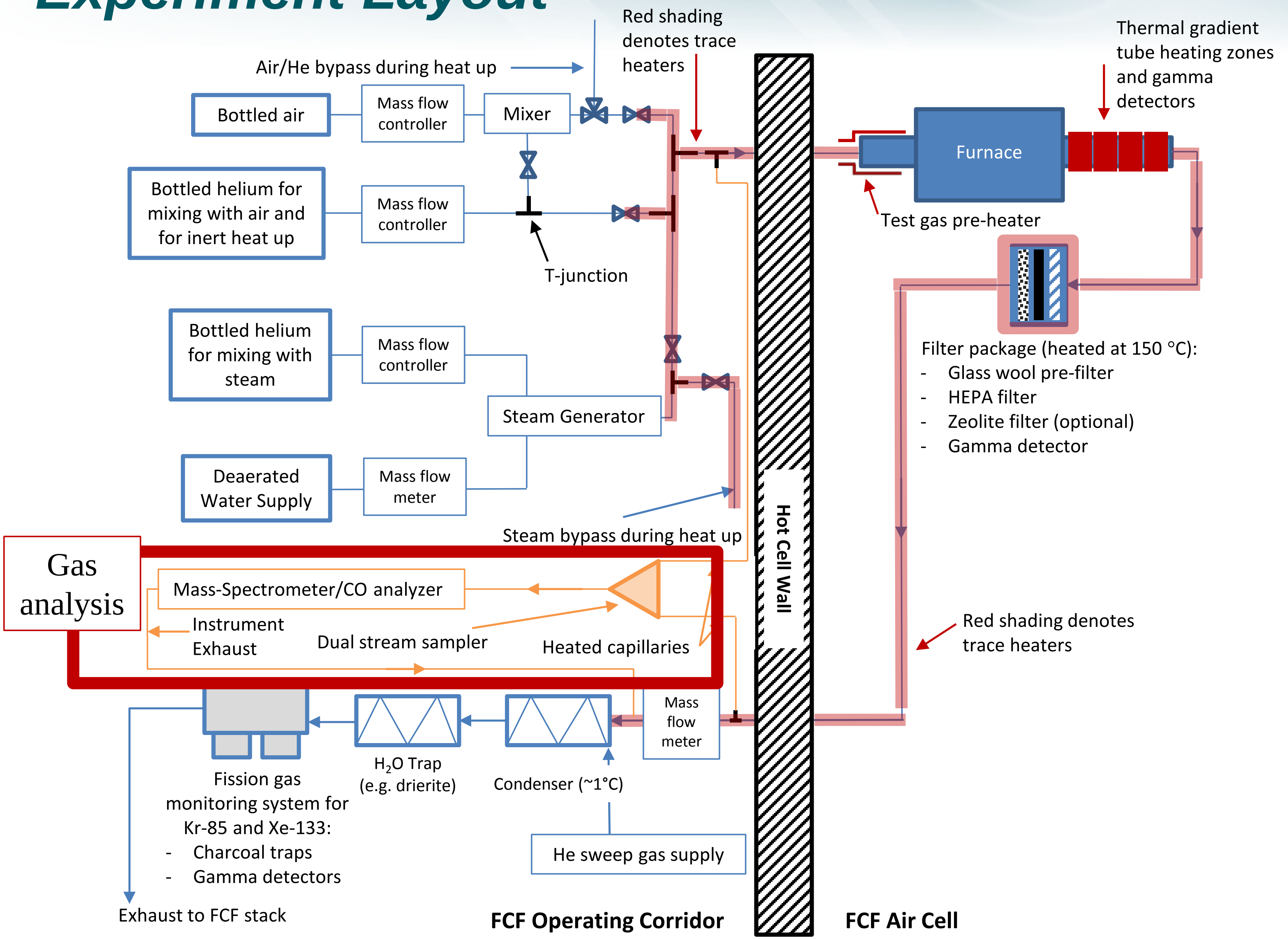
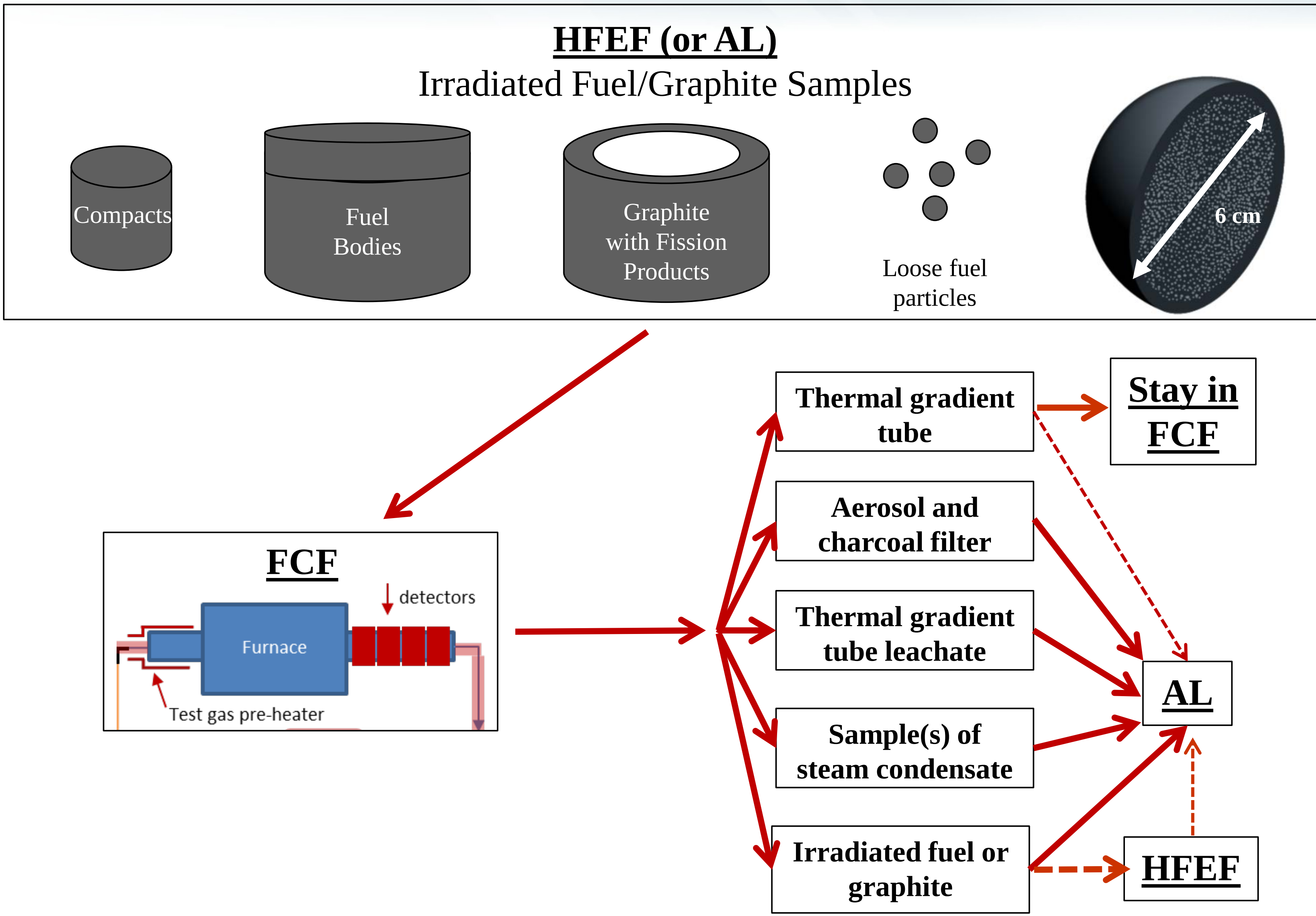
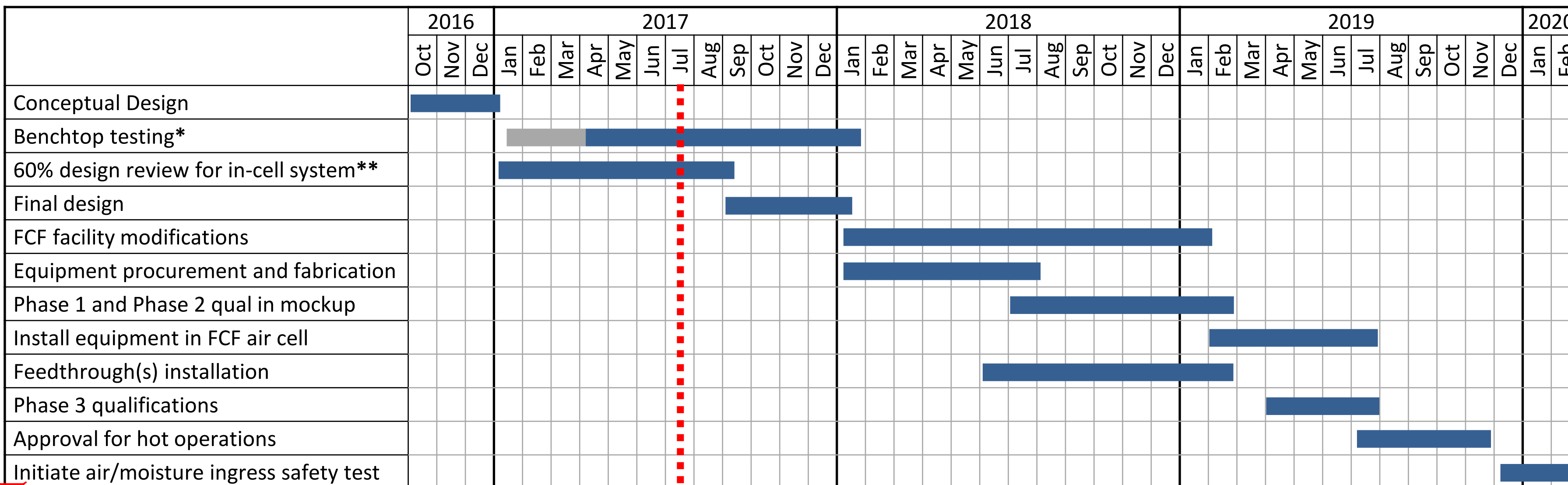


Sample Process Flow



Simplified Overall Schedule



*L4 milestone to initiate benchtop development testing by 3/31/17

**L2 milestone to complete 60% design review by 9/15/17

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Elapsed Timeline

Nov 2015
TCT Meeting and Input

May 2016
- Chose lab for benchtop testing
- FOR-284 rev. 0

June 2016
TEV-2729 rev. 1

July 2016
- Selected FCF air hot-cell window A3
- Assembled design team
- Initiated bi-weekly design meetings

Aug 2016
- Acquired bench testing furnace
- FOR-284 rev. 1

Sept 2016
- Initiated equipment specifications
- Began soliciting vendor quotes for benchtop equipment

Oct 2016
- Outlined conceptual design report
- Initiated SDD

Nov 2016
- Initiated material request for gas analysis equipment
- Furnace moved into lab for benchtop testing

Elapsed Timeline (continued)

Jan 2017
- In-cell furnace conceptual design review
- Completed conceptual design document merging F&ORs with necessary specifications

Feb 2017
- Completed focused review of benchtop development furnace laboratory instruction (LI)

Mar 2017
- Initiated benchtop testing with zirconia furnace tube

Apr 2017
- Completed benchtop systems design and P&ID
- Completed benchtop pressure safety document
- Placed orders for all tubing, valves, mass flow controllers, data acquisition, custom thermocouples, segmented tube for TGT concept

May 2017
- Released LI-805
- Started benchtop valve board construction

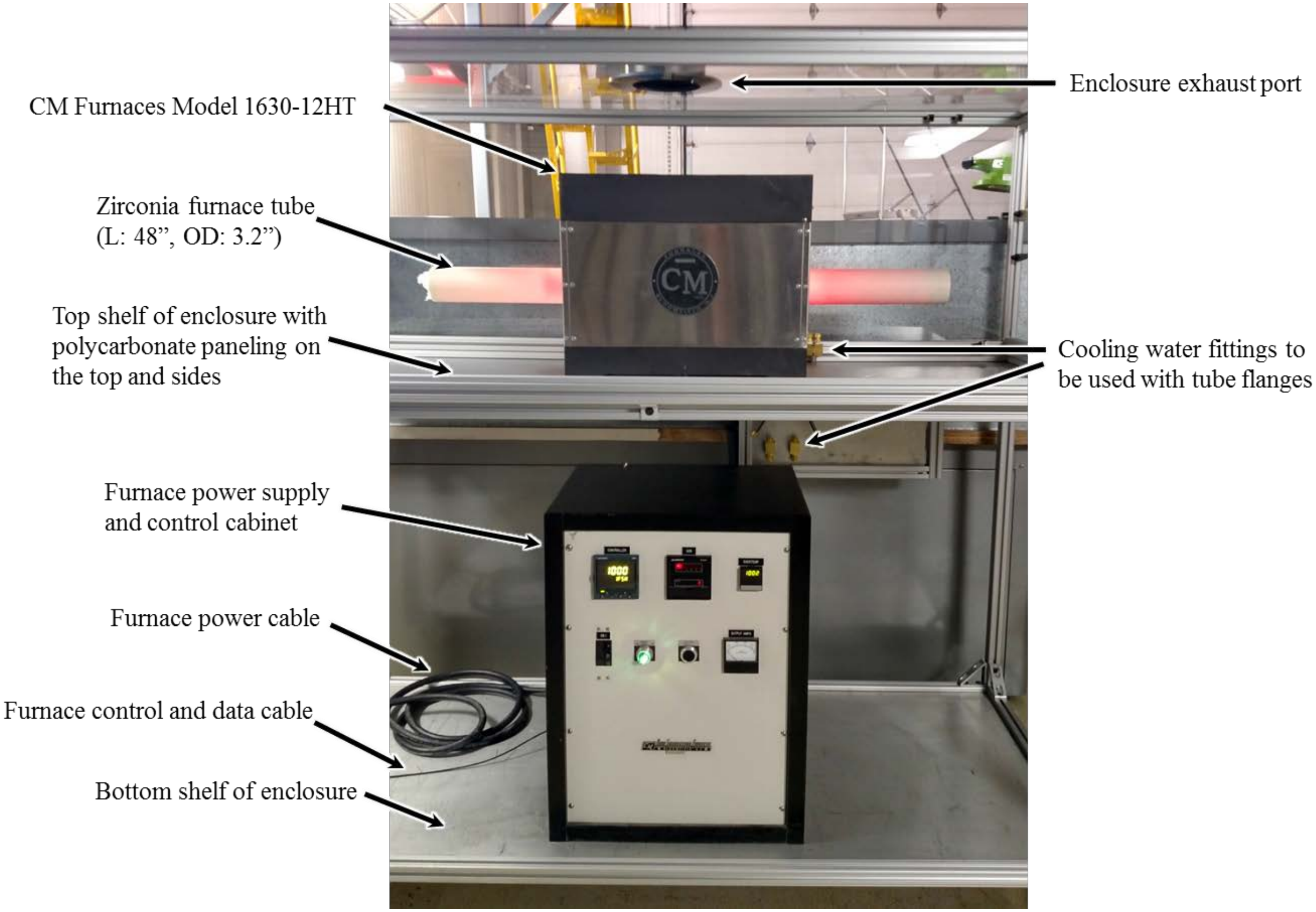
Jun 2017
- Received MS/CO analyzer
- Tested furnace flanges

Jul 2017
- Installed and trained on MS/CO analyzer
- Began testing $LaBr_3$

Remainder of FY17
- Complete benchtop system construction
- Benchtop testing of graphite with air/He and steam/helium mixtures, stable fission product surrogate testing
- **Aug-Sept: in-cell system 60% design review**

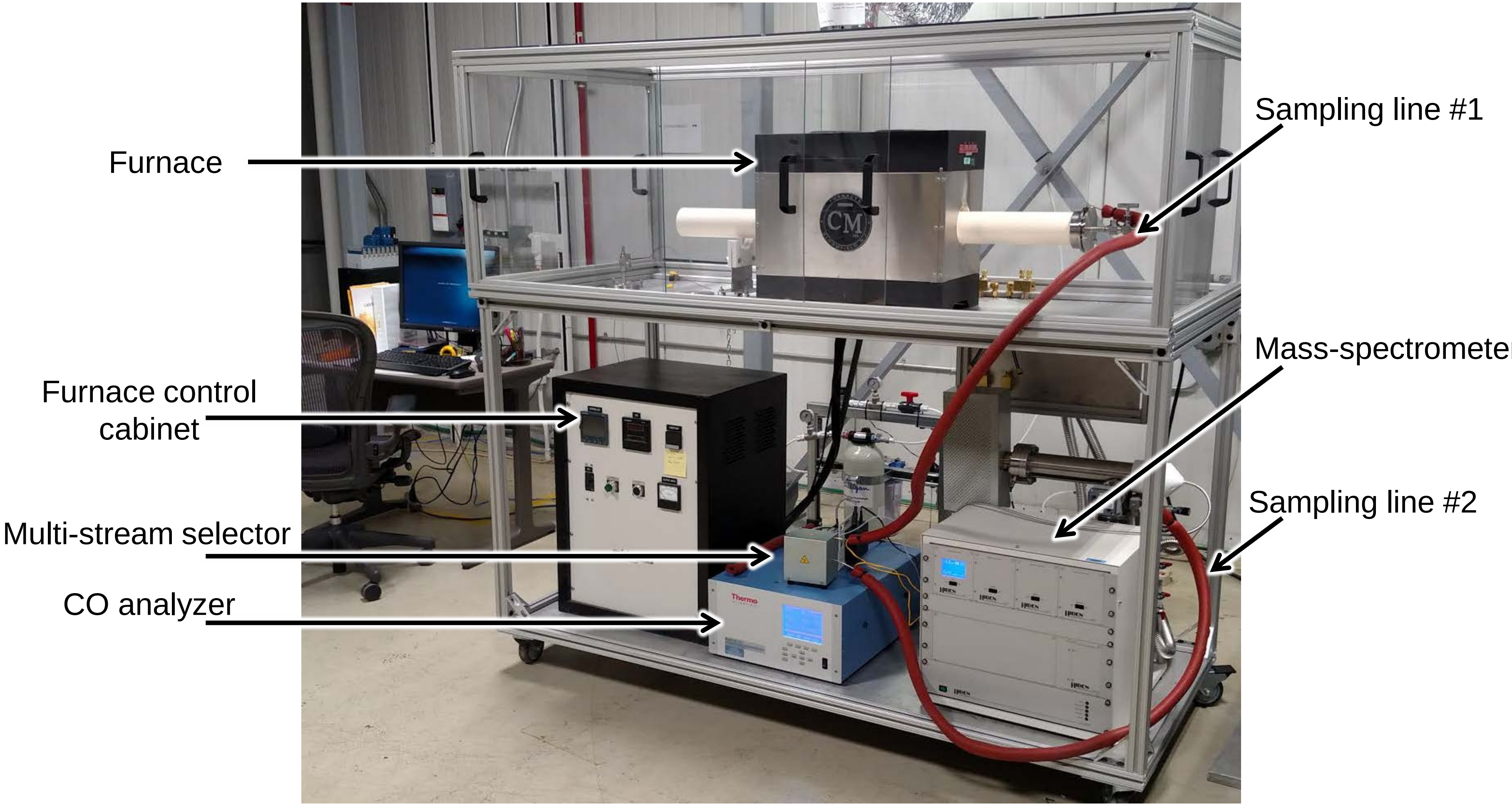
Current benchtop testing – tube materials/flanges

- Currently testing with Al_2O_3 and ZrO_2
- Ramp rates of 200°C/hr have been used successfully with ZrO_2
- Faster ramp rates may be tested



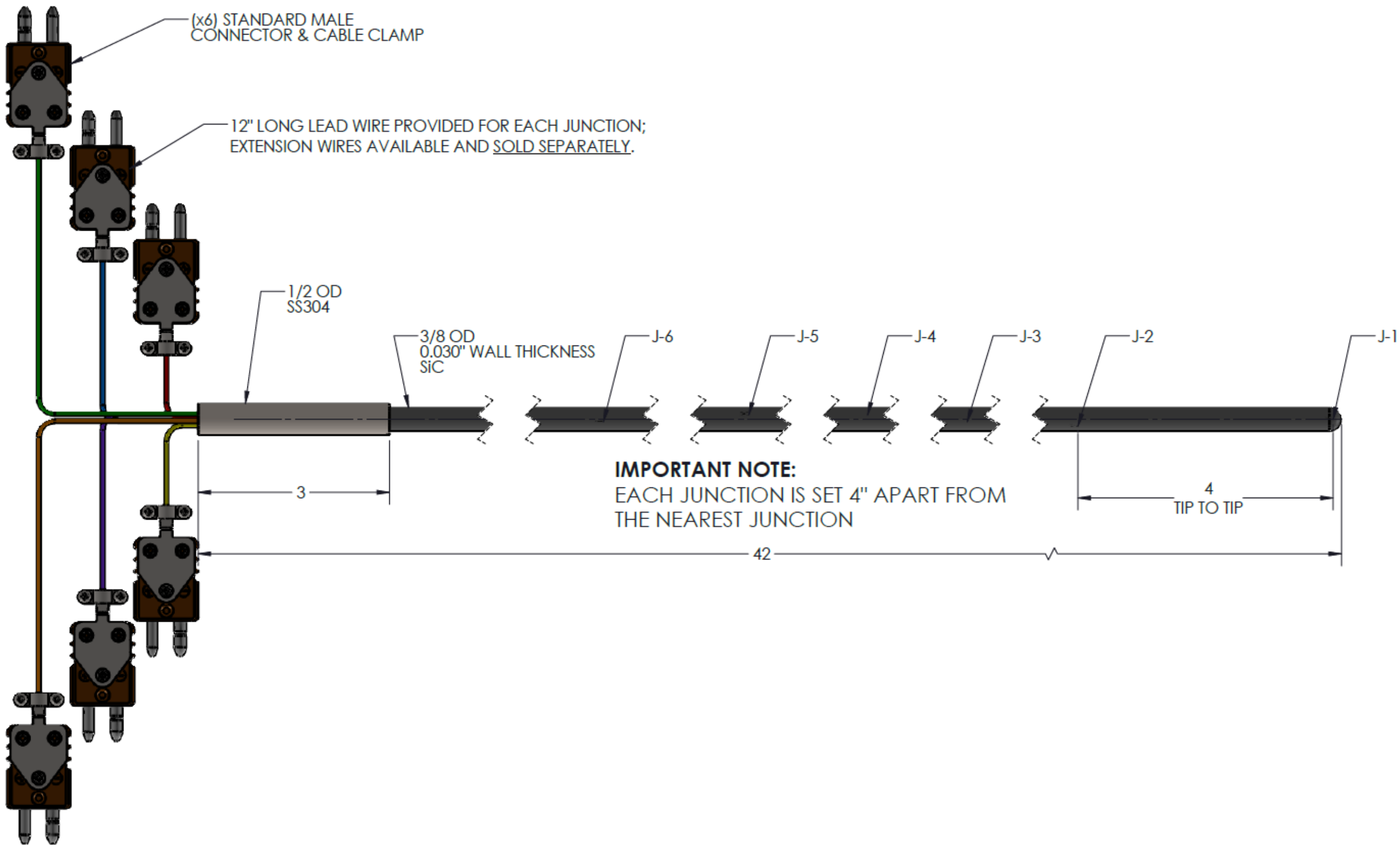
Current benchtop testing – gas analysis

- Mass spectrometer, CO analyzer, multi-stream selector to measure oxidation products from reaction of carbon with H_2O/air (CO, CO_2, H_2, etc.)



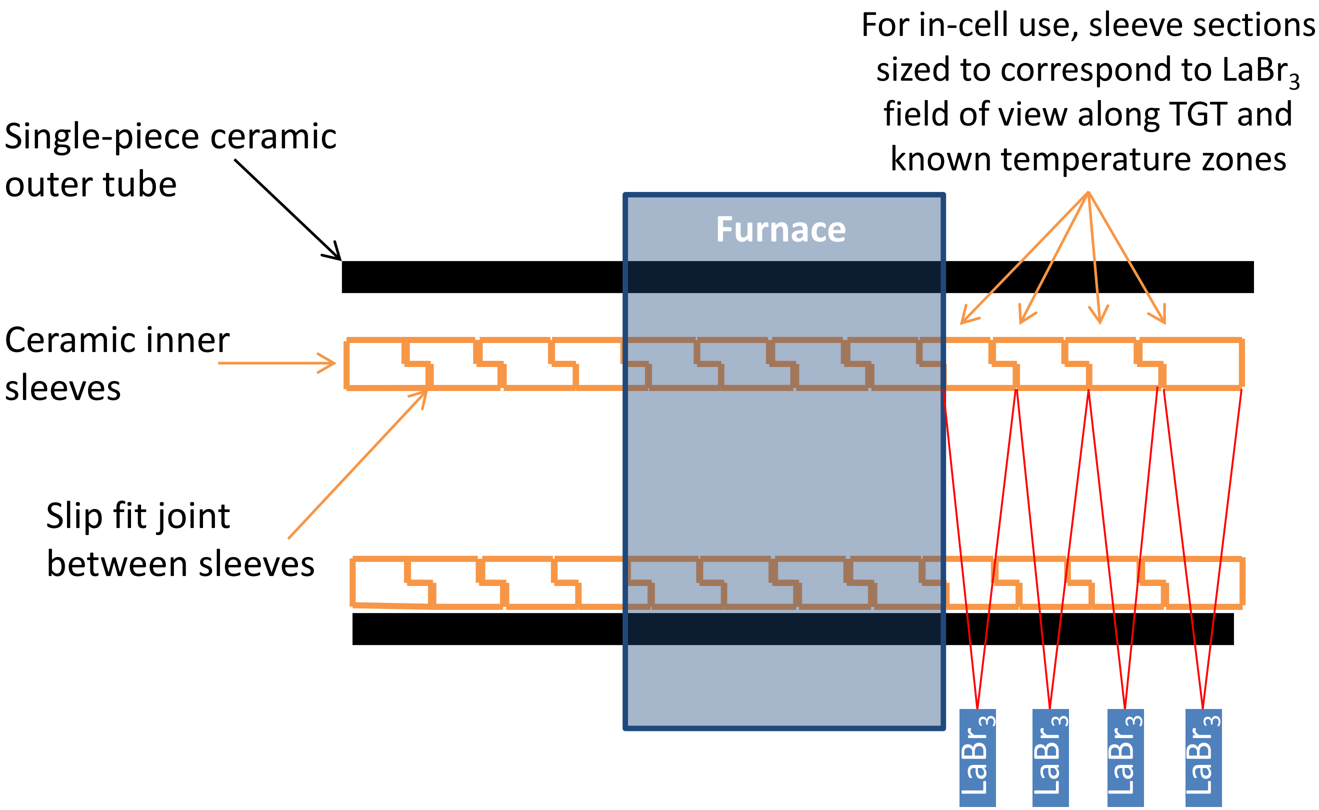
Current benchtop testing – furnace temperature profiling

- Profiling for test temperatures 800-1600°C in steam/air
- 6 thermocouples, Type-K for low temperature zones, Type-B for high temperature zones
- SiC sheath
- Profile entire furnace length: one probe inserted from left, one probe inserted from right

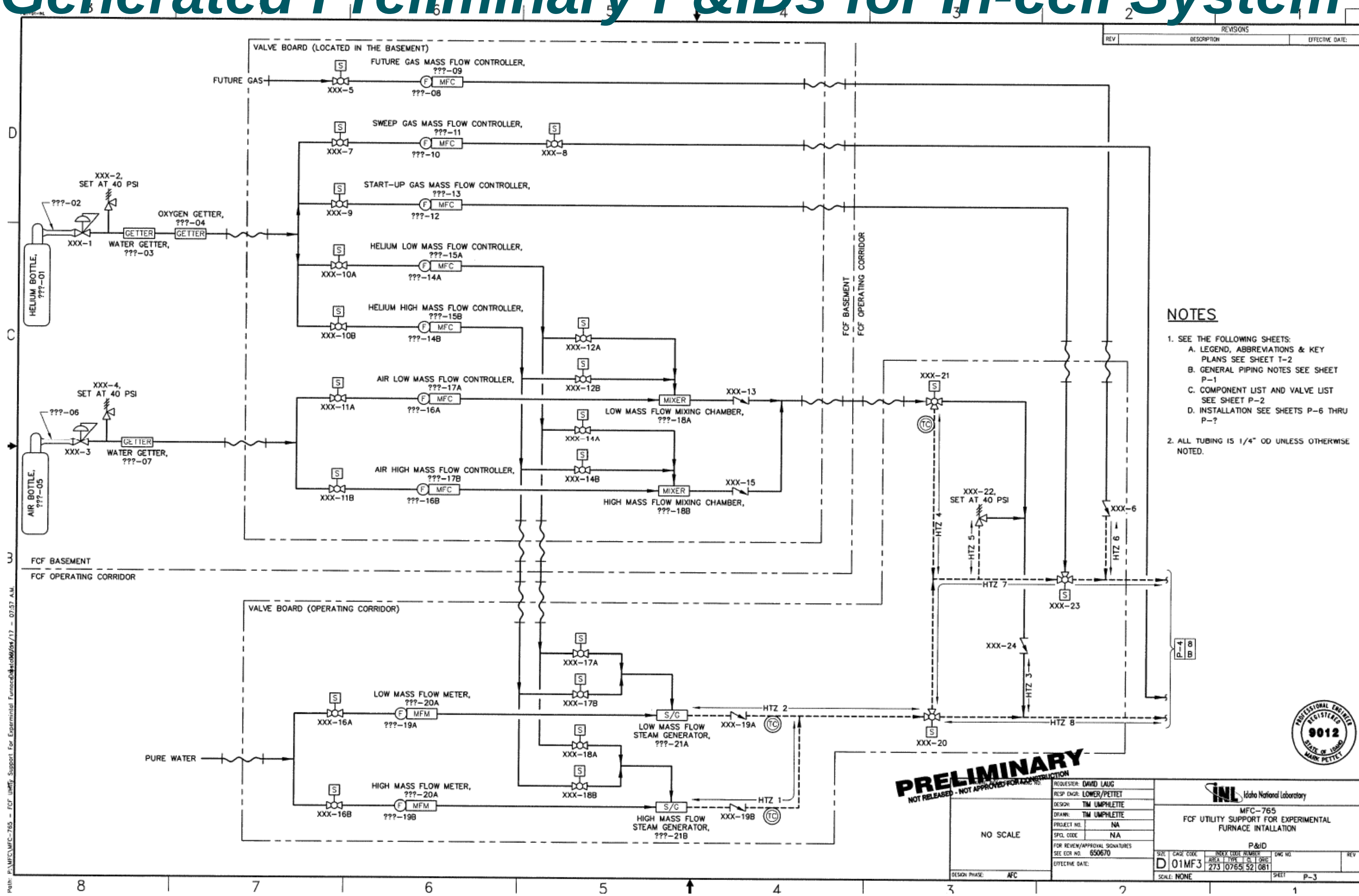


Current benchtop testing – thermal gradient tube design to enable post-test leaching

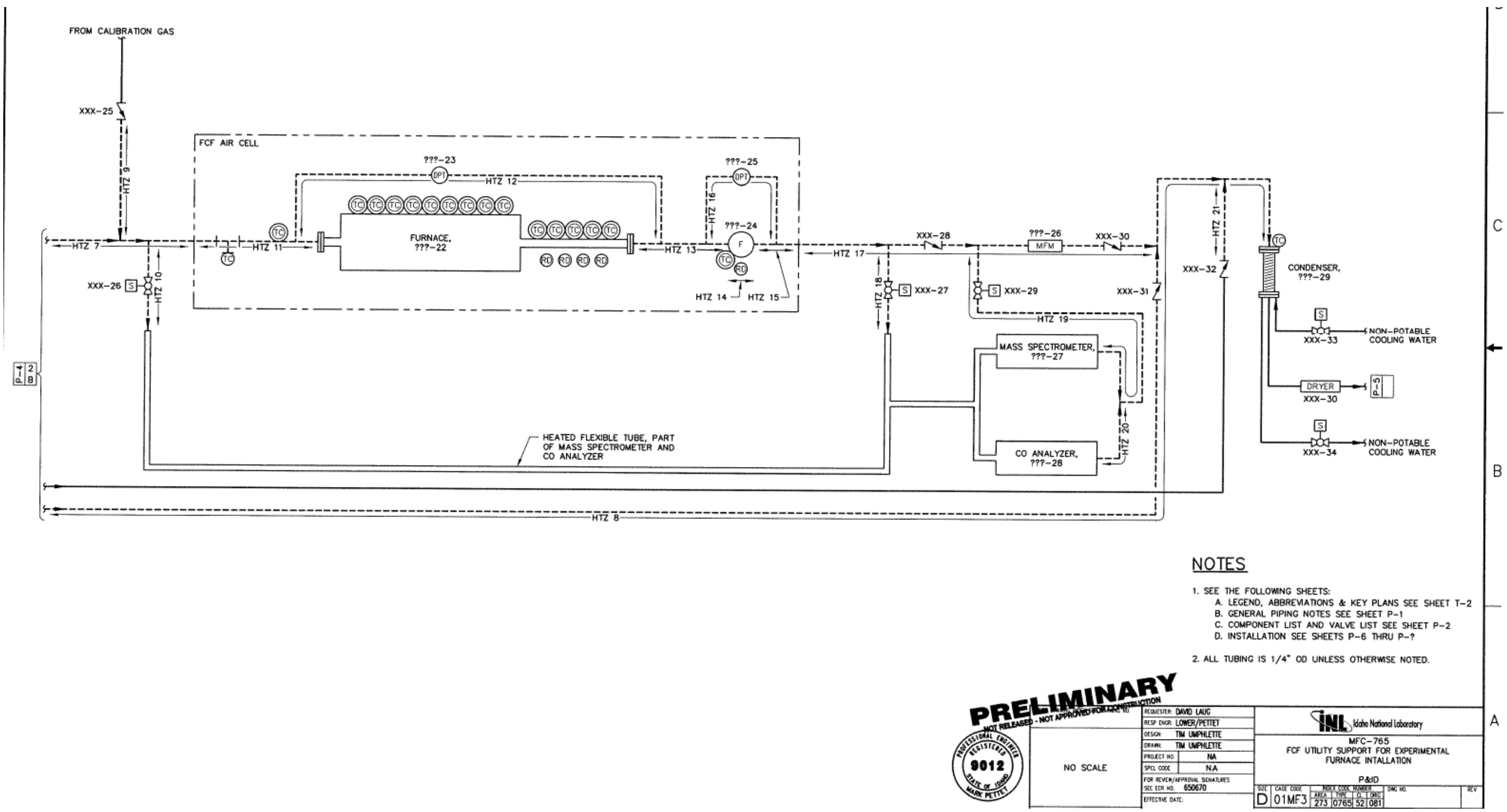
- Multiple tube sleeves inserted inside single piece tube
- Tube end-caps clamp entire assembly together
- Ordered these in ZrO_2 and Al_2O_3
- Test deposition of stable isotopes of: Ag, Cs, Eu, I, Sr



Completed P&ID for Benchtop Development. Generated Preliminary P&IDs for In-cell System



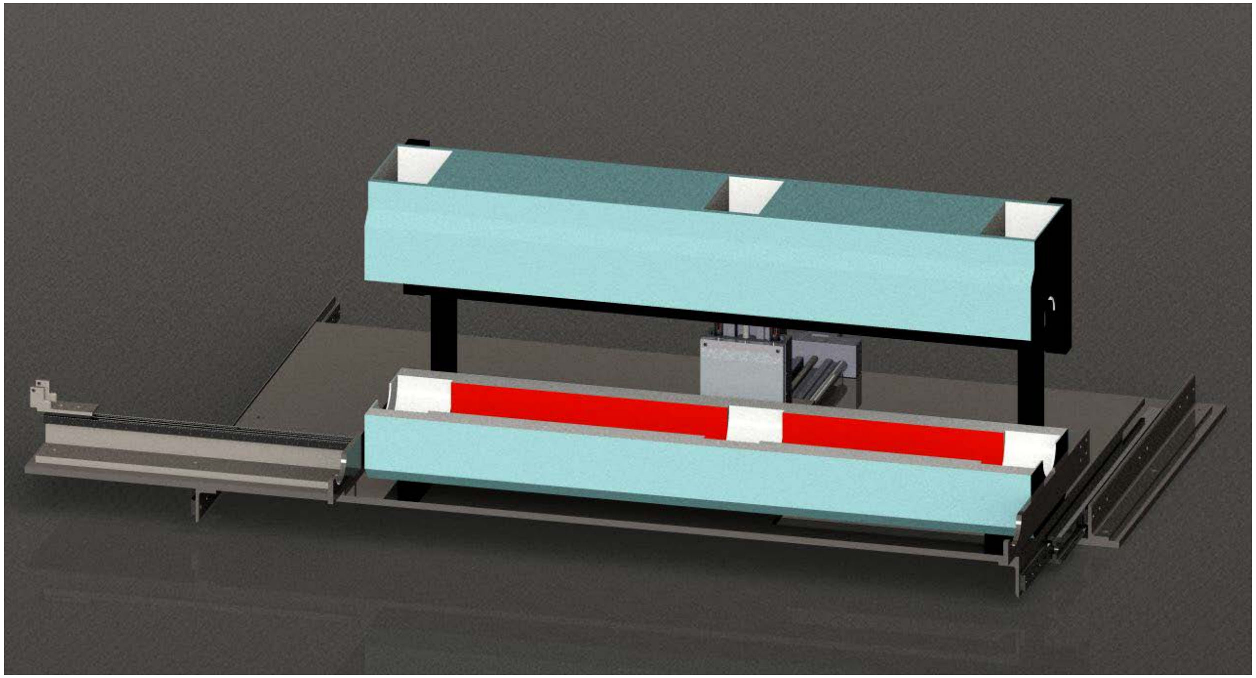
Preliminary In-Cell P&ID Showing Furnace and Furnace Outlet Gas Flow



In-cell System Status

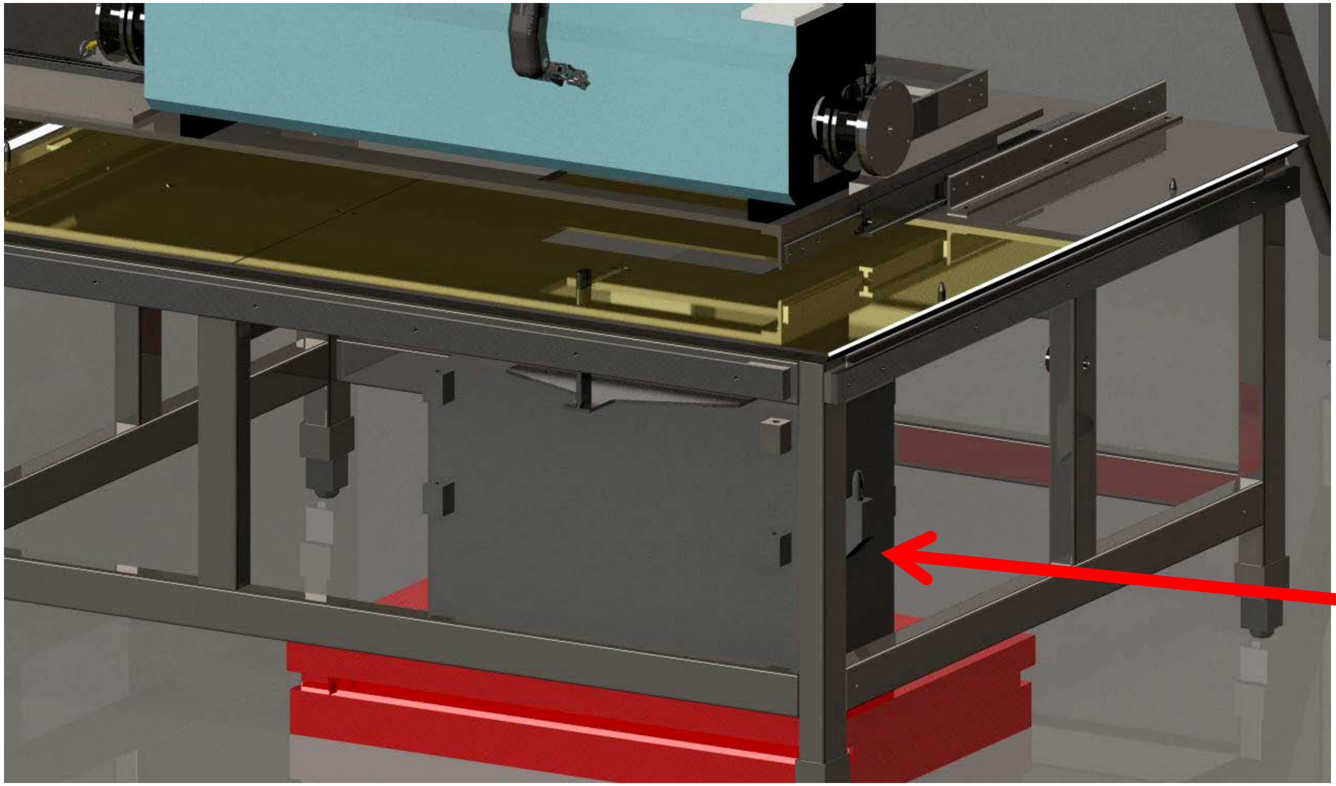
- Secured use of FCF Window A3
- Conceptual design review completed February 2017 (fulfilled L4 milestone)
- 60% design review to be completed end of August 2017 (L2 milestone)
  - Piping and instrumentation diagrams (P&ID)
    - Out-of-cell equipment: gas supply, gas analysis, fission gas monitoring
    - In-cell equipment: gas supply lines, furnace, filters, TGT, etc.
    - Equipment lists/specs
  - Valve boards/equipment layouts in cell corridor and FCF basement
  - Facility electrical diagrams
  - Instrumentation and control: hardware/software
  - Feedthroughs: number, location, inputs/outputs, shell design
  - Mockup: equipment layout
  - Facility: DSA update, draft Criticality Safety Evaluation
- Taking steps to order manipulators this year

In-cell System: Furnace Loading (video)

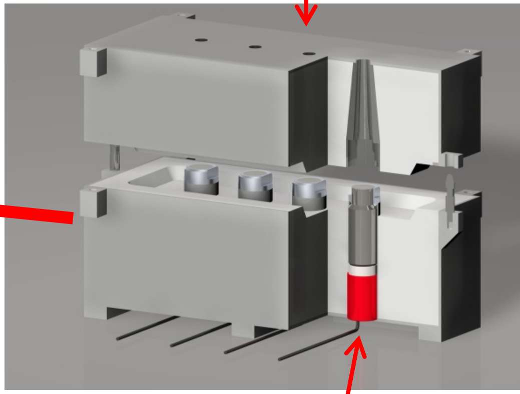


In-cell System: Thermal Gradient Tube Gamma Detectors (video)

- Shutter and detector distance control



Tungsten Shielding/Collimation



LaBr$_3$(Ce) detectors

On-going Work

- In-cell system 60% design review by end of FY2017 (L2 milestone)
- Target for in-cell system final design is March 2018
- Long-lead-time equipment for in-cell system will be purchased at-risk as-appropriate
- Benchtop testing: oxidization of graphite, gas analysis, surrogate fission product transport, etc.
- Benchtop testing will continue beyond in-cell system final design
- Seeking bids from manufacturers for in-cell furnace

Questions and Discussion

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Possible Air-Ingress Accident Conditions

Depressurized Loss of Forced-Convection (DLOFC)

- Safety-Related Design Condition-10 (SRDC-10)[1]
  - Cooling is by conduction and radiation to the reactor cavity cooling system (RCCS)
  - Peak fuel temperature: 1620°C
  - Time to reach peak fuel temperature: 80 hours
  - Air-ingress occurs after depressurization

1. Preliminary Safety Information Document for the Standard MHTGR, Vol. 1, HTGR-86-024 (1986).

Possible Moisture-Ingress Accident Conditions

- Safety-Related Design Condition-6 (SRDC-6)[1]
  - Depressurized conduction cooldown event
  - Moderate steam generator leak duration: < 30 minutes
  - Peak core temperature: 1540°C
  - Time to reach peak temperature: 100 hrs

1. Preliminary Safety Information Document for the Standard MHTGR, Vol. 1, HTGR-86-024 (1986).