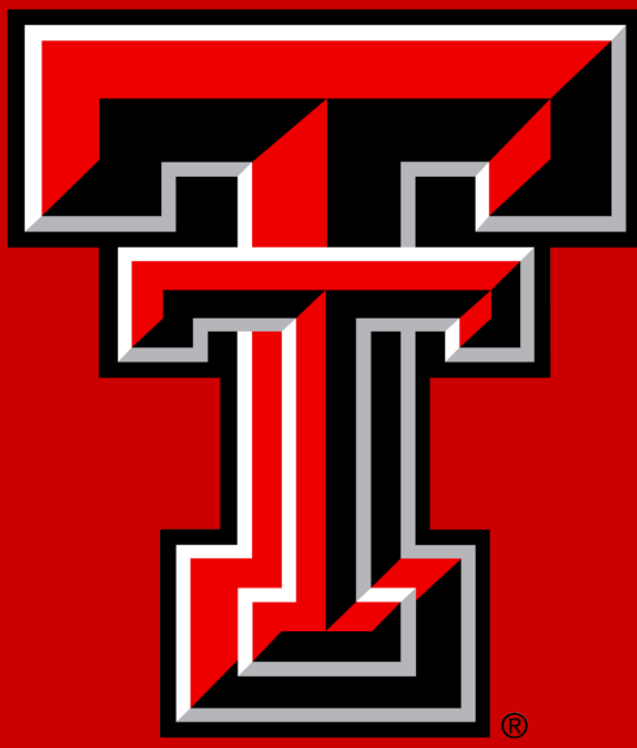


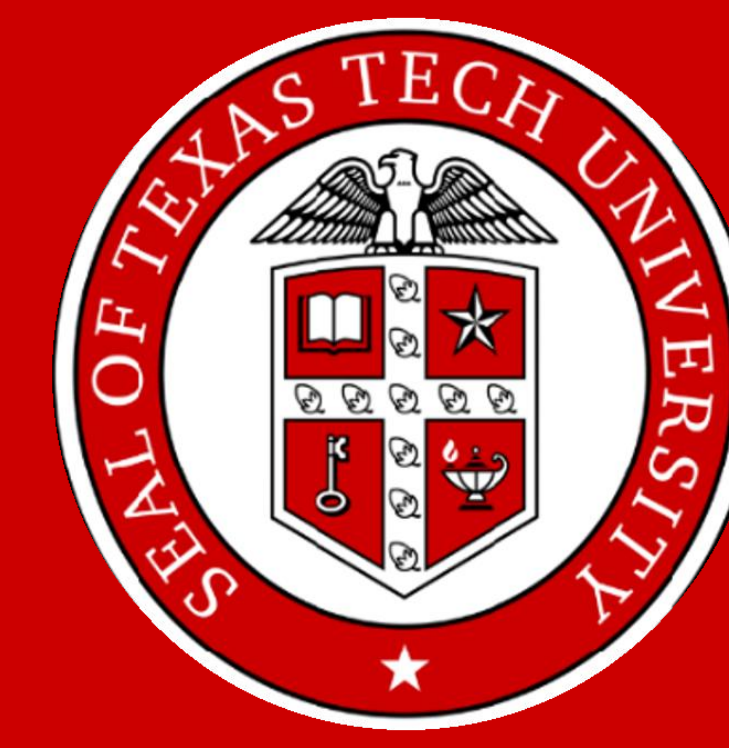


# Modeling Diffusion Kinematics in a Helium-3 Enrichment Manifold System

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## INTRODUCTION

### Significance of Helium-3 as a Fusion Fuel

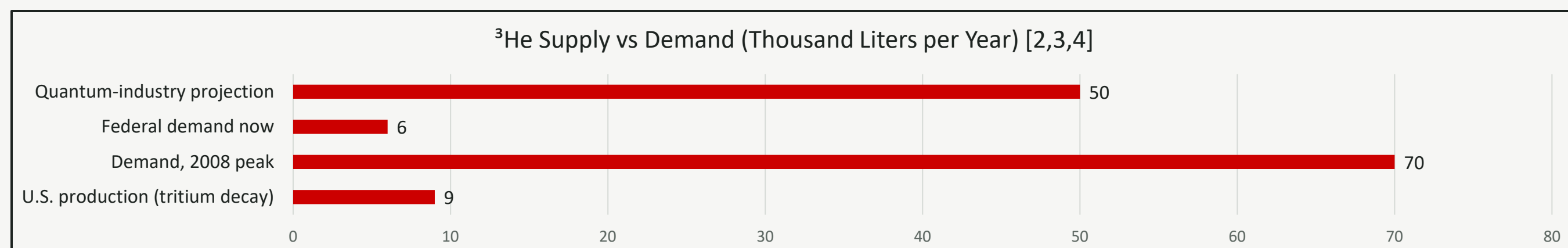
Helium-3 is a rare form of helium and one of the best fuels we have for fusion. When it fuses with deuterium the energy comes out as charged particles that can be turned straight into electricity, and the main reaction makes no neutrons [1]. The catch is supply. Almost all of the <sup>3</sup>He we have comes from the slow radioactive decay of tritium, about 8,000–10,000 liters a year in the U.S. [2,3]; demand reached 70,000 liters a year in 2008 and the gas sells for \$2,000–3,000 a liter [3,4].

### Terrestrial Sources and Isotopic Abundance

Natural helium wells carry a tiny amount of <sup>3</sup>He mixed in with ordinary <sup>4</sup>He: about 0.2 parts per million near Amarillo [2] and up to 14.5 parts per billion at a new well in Minnesota [5]. To use it we have to separate the two isotopes, and we can only trust a separator if we can measure what it did.

### Research Objective

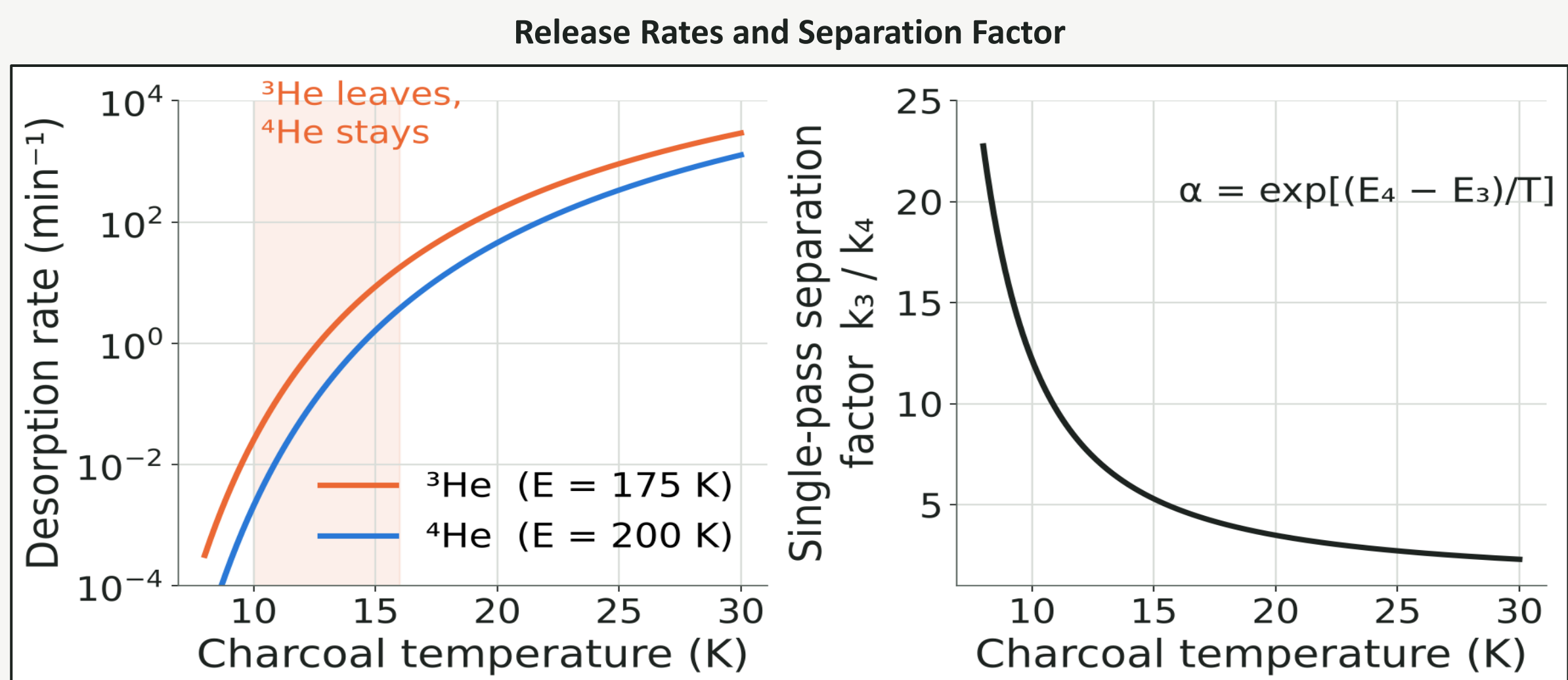
Model how enriched <sup>3</sup>He travels from the cold charcoal cell of our CCS-TRAP/204 cryostat, through the tubing, to the gas analyzer, and, along the way, measure how well our charcoals hold helium and whether the RGA can resolve <sup>3</sup>He from <sup>4</sup>He.



## THEORY

### Isotope-Selective Desorption from Activated Charcoal

Below about 10 K both isotopes stick to activated charcoal. <sup>3</sup>He is the lighter atom, so it sits a little looser on the surface (its zero-point energy is larger) and needs less heat to let go. As we warm the cell, <sup>3</sup>He comes off first and <sup>4</sup>He stays behind. One pass separates them by the ratio of the two release rates,  $\alpha = \exp[(E_4 - E_3)/T]$ , largest at the lowest temperature that still frees <sup>3</sup>He (Fig. 1).



## OUR DESIGN AND PROCESS

### Apparatus and Configuration

Our apparatus is a Janis / Lake Shore CCS-TRAP cold-trap cryostat on a 204-series closed-cycle cold head [6]. A small copper cell packed with activated charcoal sits on the cold tip inside the vacuum jacket. One feed line runs from the cell up to a four-way cross; the other three arms go to the <sup>3</sup>He–<sup>4</sup>He mix cylinder, the vacuum pump and the residual gas analyzer (RGA), each behind its own valve. The feed line is the only way in or out of the cell, so it carries the mix in while we load and the enriched gas out while we warm up.

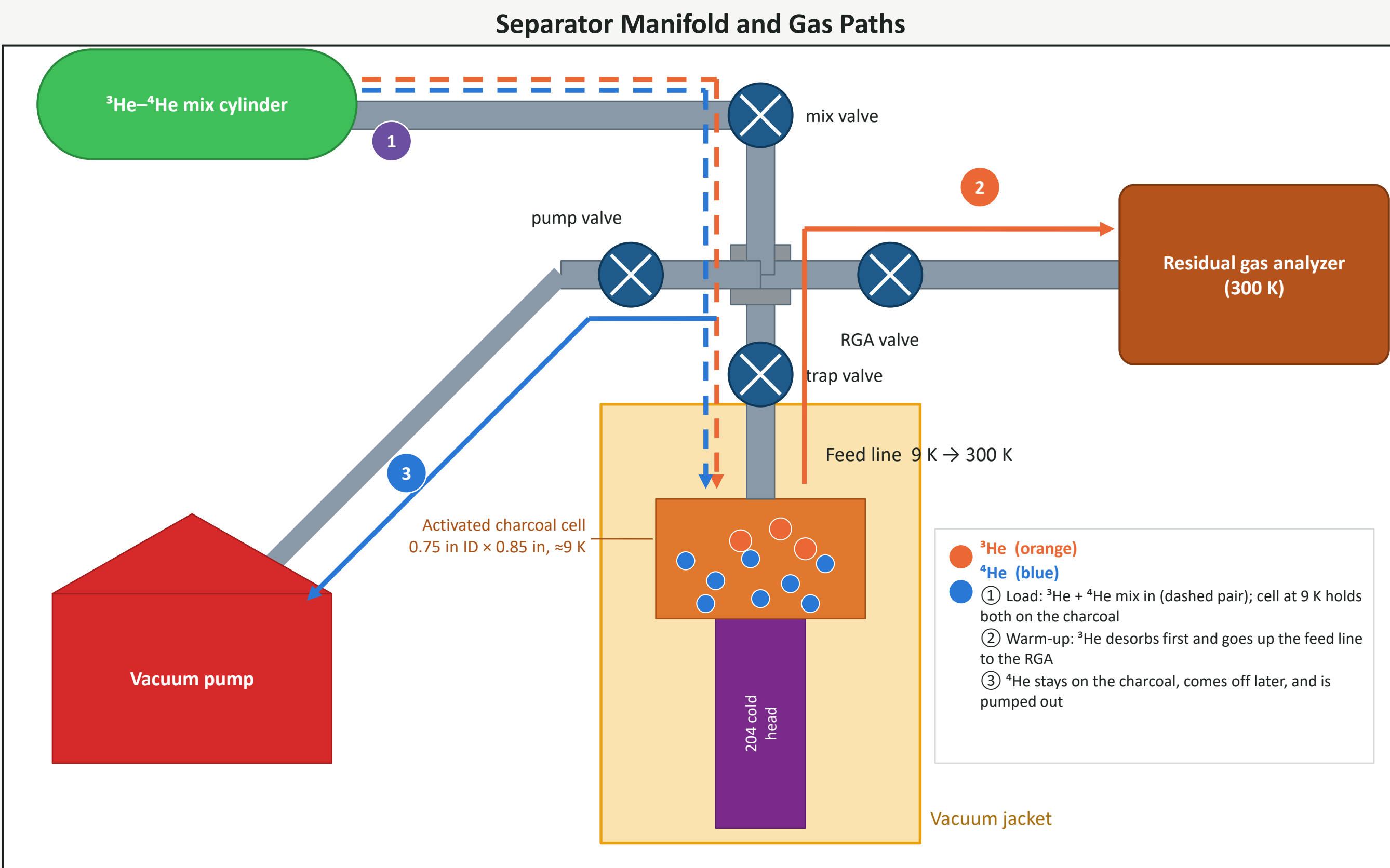


Fig. 2 The separator manifold (redrawn from the lab P&ID) with the gas paths: the mix enters along ①, <sup>3</sup>He (orange) leaves first along ② to the RGA, <sup>4</sup>He (blue) is held on the charcoal and leaves later along ③ to the pump. Blue-and-white circles are valves.

| CCS-TRAP/204 as specified by the vendor [6] |                                               |
|---------------------------------------------|-----------------------------------------------|
| Cell temperature range                      | < 8 K to 450 K (< 5 K on request)             |
| Cell body                                   | Copper, 0.75 in ID × 0.85 in, charcoal getter |
| 204 cold head                               | ≈ 9 K base, 0.5 W at 20 K, 50 min cool-down   |
| Compressor                                  | 2.0–2.1 kW, 208/220 VAC, water- or air-cooled |

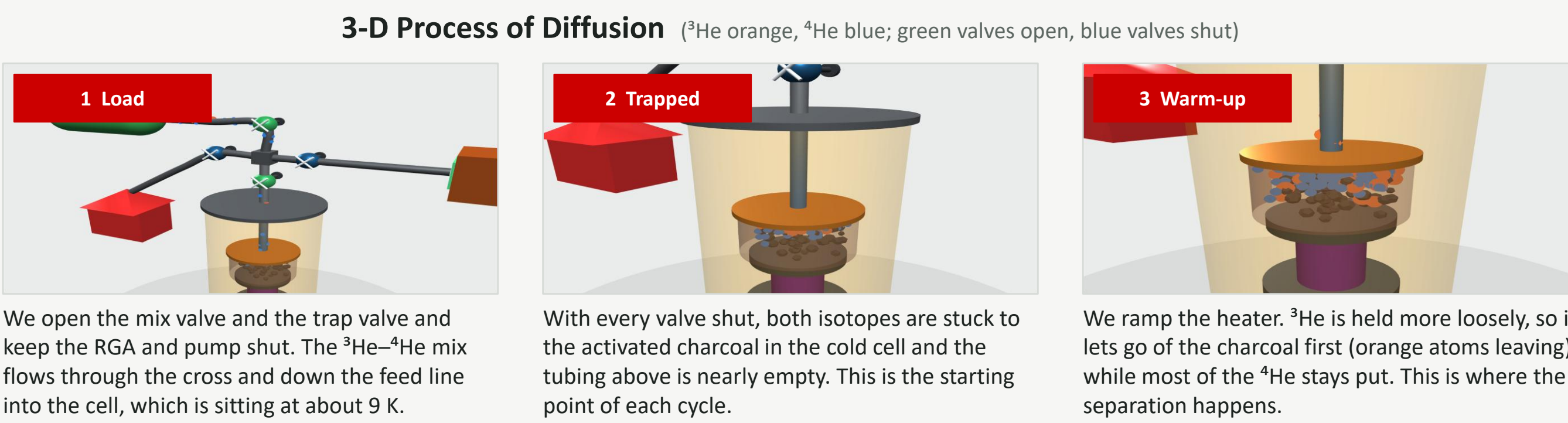
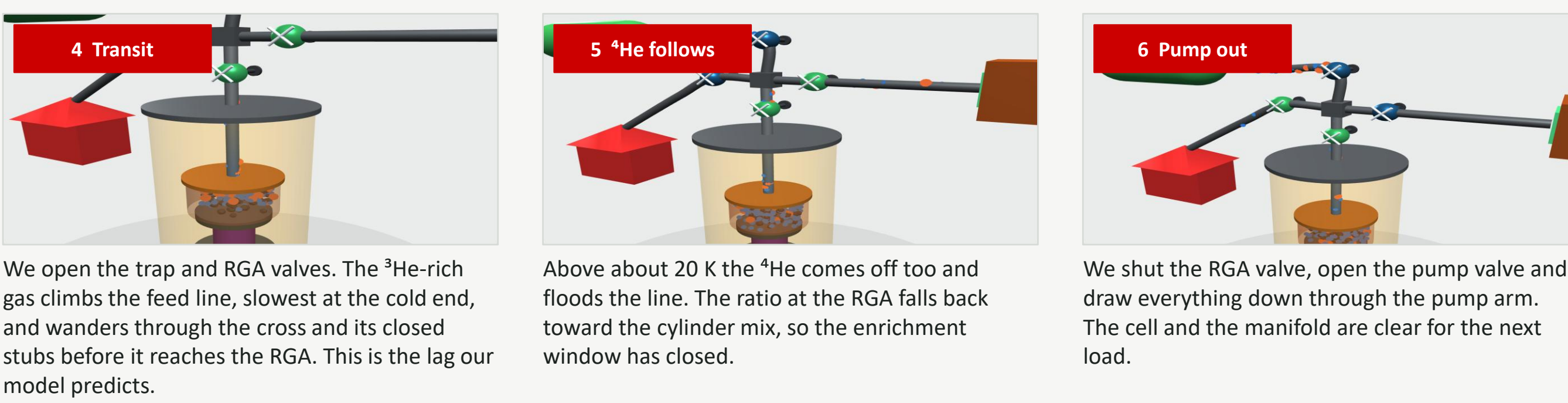
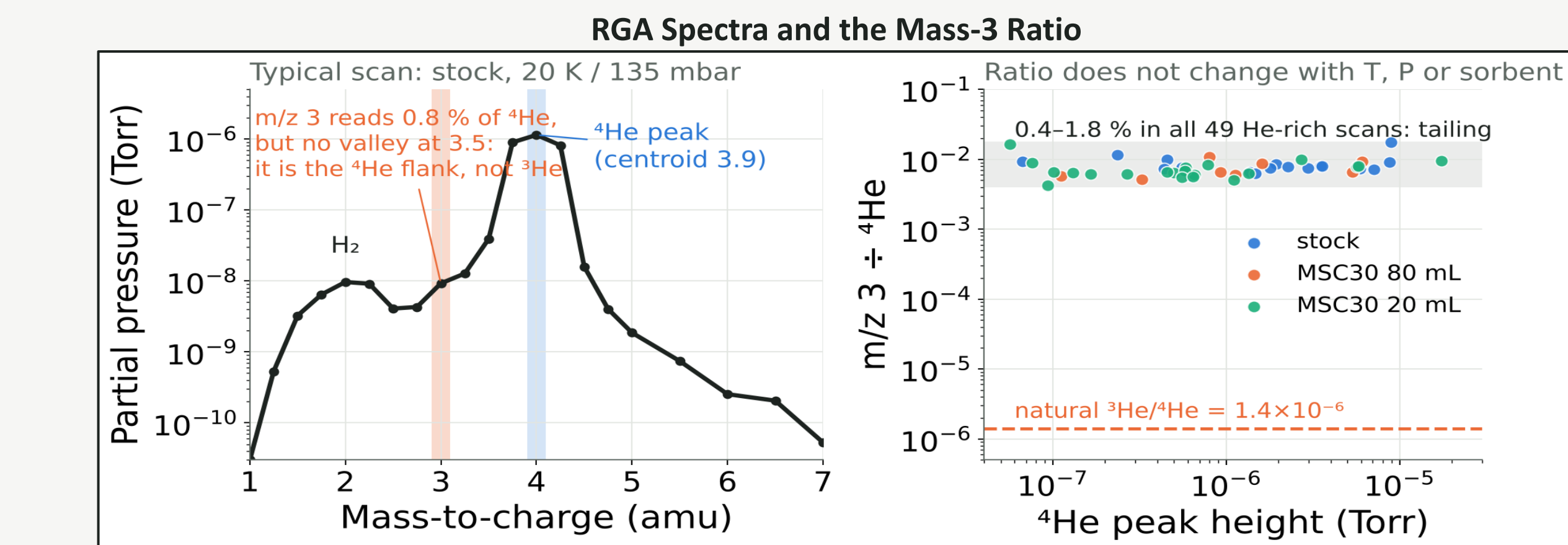


Fig. 6 Left: every scan is <sup>4</sup>He with 0.6–2 % H<sub>2</sub>; the mass-3 reading is the flank of a <sup>4</sup>He peak centered at 3.9 amu. Right: that ratio stays at 0.4–1.8 % in all 49 helium-rich scans (of 55) whatever the T, P or sorbent, so it is instrument tailing, not <sup>3</sup>He (natural <sup>3</sup>He/<sup>4</sup>He = 1.4×10<sup>−6</sup>).

## EXPERIMENTAL RESULTS

### Characterization of the Cold Trap

Before the enrichment cycle could be run against the model, we characterized the trap itself: how the two charcoals hold helium at each temperature, and whether our RGA can tell <sup>3</sup>He from <sup>4</sup>He. 55 RGA scans and sealed-system pressures, Sep 23 – Oct 6 2026, comparing the stock charcoal shipped in the CCS-TRAP with our own custom MSC30 charcoal.

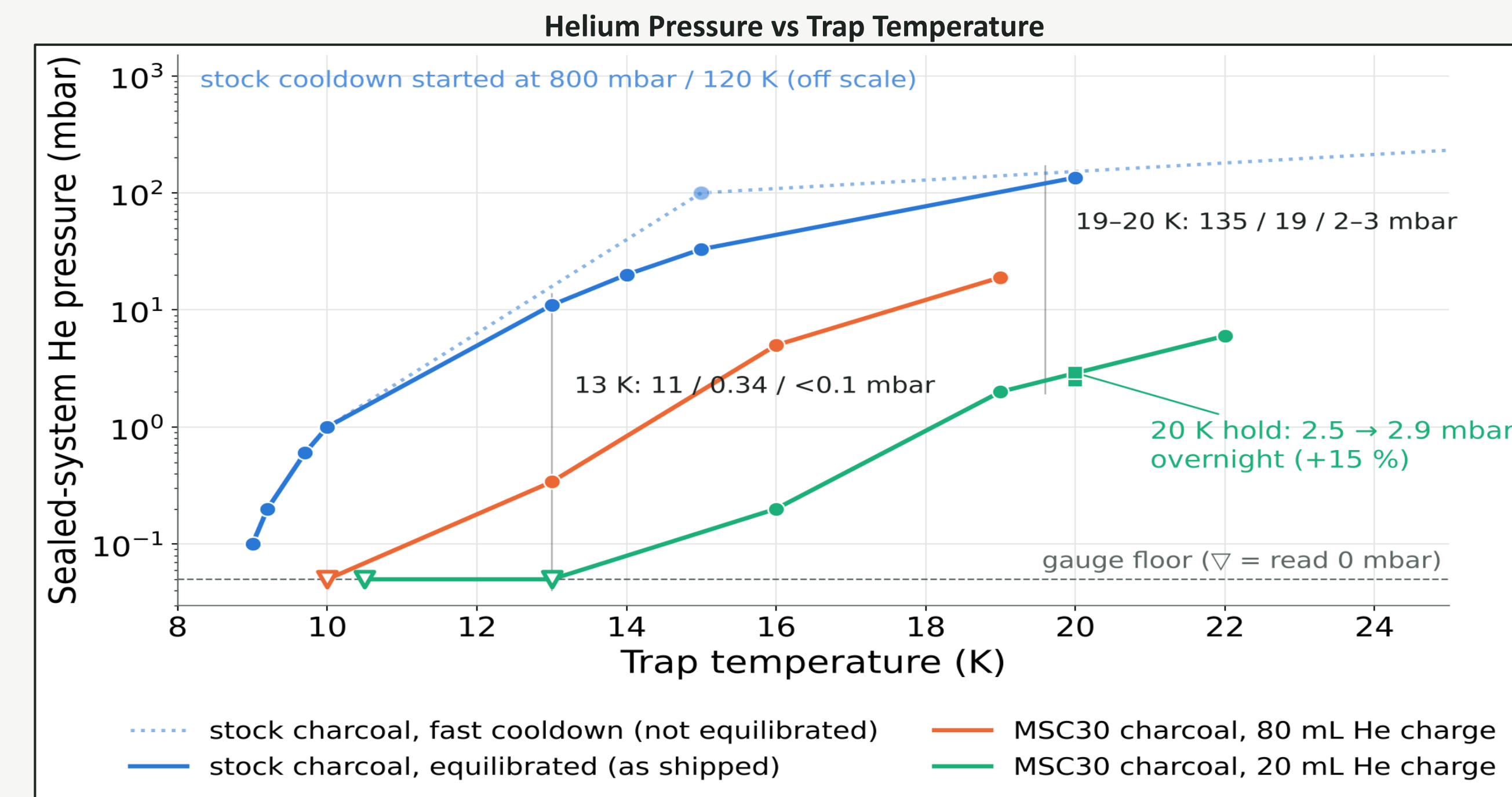


Fig. 5 Sealed-system helium pressure vs trap temperature. Stock charcoal is already releasing helium by 15–20 K; MSC30 (20 mL charge) holds it 30–50× more tightly at the same temperature. Triangles are readings at the gauge floor.

| TRAP PERFORMANCE                                                                            | BINDING ENERGY                                                                      | DETECTOR LIMIT                                                                                                |
|---------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------|
| <b>30–50×</b><br>lower He pressure over MSC30 (20 mL charge) than stock charcoal at 13–20 K | <b>1.1–1.9 kJ/mol</b><br>how tightly MSC30 holds helium (stock: 0.7–0.9 above 13 K) | <b>&lt; 0.5 % of <sup>4</sup>He</b><br>smallest <sup>3</sup> He signal our RGA can see at the current setting |

### Interpretation of the Measurements

(1) Stock charcoal: 800 mbar at 120 K falls to 0.1 mbar at 9 K, so nearly all the helium is on the charcoal below about 10 K; its apparent binding is 1.4–2.4 kJ/mol below 10 K and flattens above 13 K as the inventory moves into the gas. (2) MSC30 holds helium far more tightly: at 13 K the stock trap sits at 11 mbar, MSC30 at 0.34 mbar (80 mL charge) or below the gauge (20 mL), and its slope stays steep, 1.1–1.9 kJ/mol, right through 22 K. (3) Loading matters: four times the charge raised the pressure 9–25×, so the 80 mL bed is near capacity and 20 mL is in the linear regime. (4) Kinetics: a 20 K hold crept from 2.5 to 2.9 mbar overnight, our one settling-time number so far. Caveat: the stock run's helium inventory was not recorded, so part of its offset is loading rather than binding.

## SIMULATION RESULTS

### Compartment Model of the Sampling Path

Our compartment model of the sampling path (charcoal cell → feed line with its temperature gradient → cross with two closed arms → RGA) predicts what the RGA should see during a warm-up.

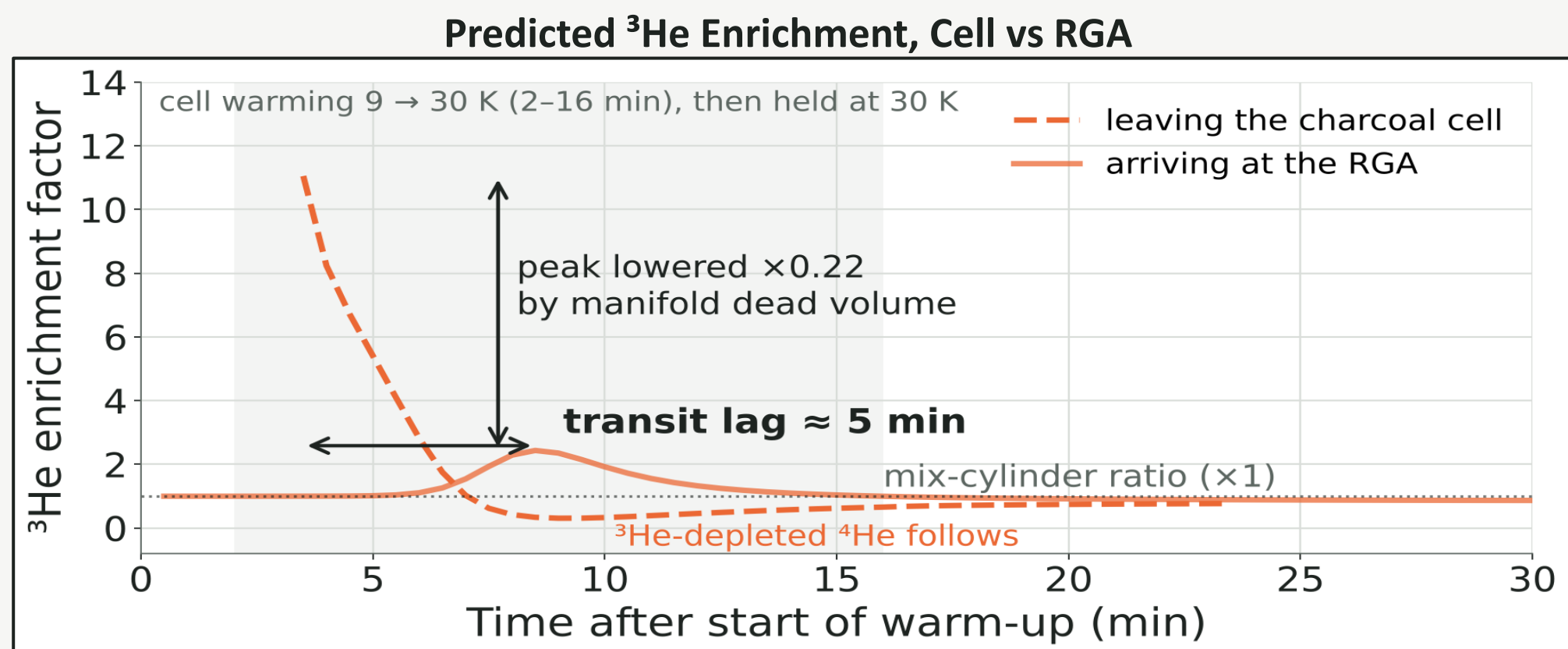


Fig. 3 <sup>3</sup>He enrichment leaving the cell (dashed) and reaching the RGA (solid): about a 5-minute lag and a peak lowered ×0.22 by the dead volume of the cross. Illustrative parameters: 30 cm line, D = 0.5 cm<sup>2</sup>/s, 9 → 30 K in 14 min.

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- [2] P. Newbury, “Evaluation of Earth’s Helium Supply,” PPPL.
- [3] U.S. House Science Committee, “Caught by Surprise: ... the Helium-3 Supply Crisis,” 2010; DOE NDC, “Supply and Demand of He-3.”
- [4] Pulsar Helium, “About ‘He’ (DOE Isotope Program price, 2024–25); GeekWire, Interline agreements, 2025.
- [5] Pulsar Helium, “Helium-3 Discovery at Jetstream #1, Topaz Project,” Oct. 2025.
- [6] Lake Shore Cryotronics, “Cryogen-free cold trap cryostats (CCS-TRAP);” Janis 10 K cryocooler comparison.
- [7] IFM PAN, “Helium-3 isotope separation” (entropy-filter cryostat).
- [8] Chapman & Cowling, The Mathematical Theory of Non-Uniform Gases; Hirschfelder, Curtiss & Bird, Molecular Theory of Gases and Liquids.

## IMPACT AND FUTURE WORK

### Implications of the Transport Model

The RGA only sees the enrichment after the tubing has delayed, smeared and diluted it; the model turns that into when to open the sampling valve, how much to correct the measured ratio, and which tubing to shorten.

### Instrumental Limitations and Next Steps

As set up, the RGA cannot see <sup>3</sup>He below about 0.5 % of <sup>4</sup>He, nearly four orders of magnitude above natural abundance, because the <sup>4</sup>He peak sits at 3.9 amu and its flank covers mass 3. So the next step is instrumental before it is kinetic: re-tune the mass axis so <sup>4</sup>He centers at 4.00, narrow the peak, cut <sup>4</sup>He at the inlet, or run the CEM over 2–5 amu. MSC30’s tighter, steeper binding is good news for the trap: more separation at the temperatures we actually run.

### Future Work: Sequential Purification Cascade

Each stage is the trap-and-cross we have now, with two changes: the vacuum pump becomes a compressor that collects the <sup>4</sup>He-rich gas, and the RGA position becomes a compressor that holds the enriched <sup>3</sup>He, which is the feed for the next stage. Every stage sends its depleted gas to the same place (Fig. 4), the same cascade idea used in entropy-filter separators [7].

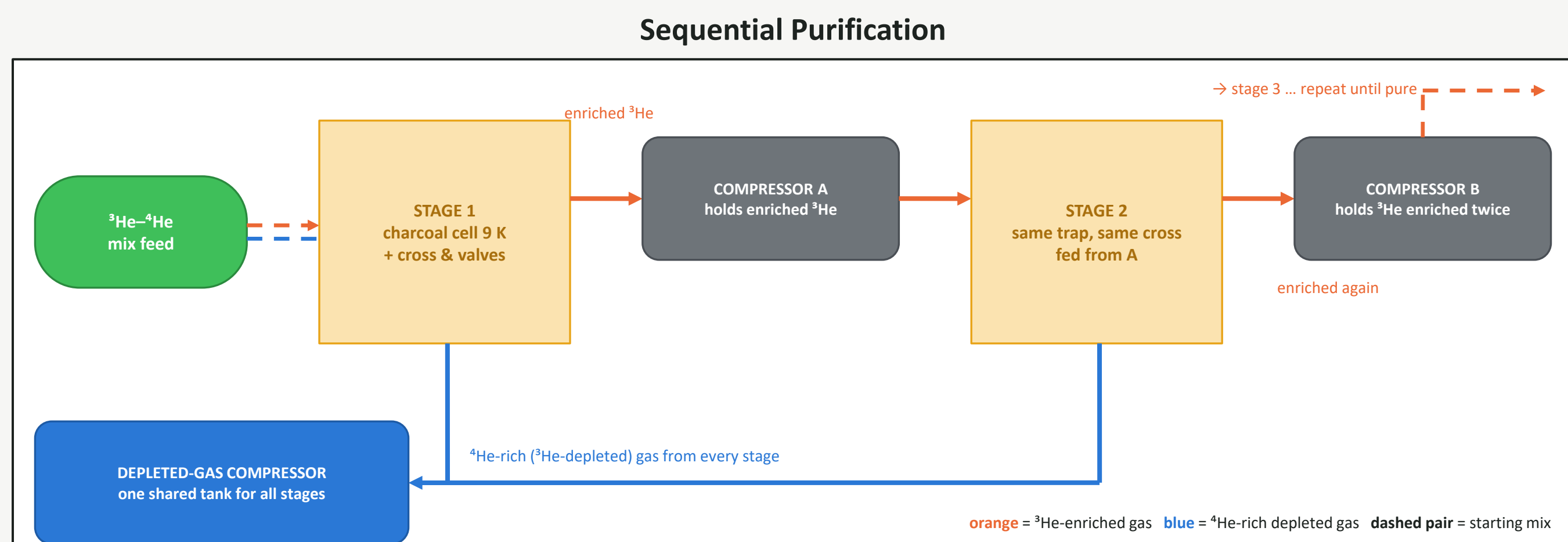


Fig. 4 Sequential purification with the same hardware: each stage’s enriched <sup>3</sup>He is compressed and becomes the next stage’s feed; the depleted gas from every stage goes to one shared tank.