Thermal Vacuum Chamber Repressurization with Instrument Purging

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Outline

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  - Rarefied
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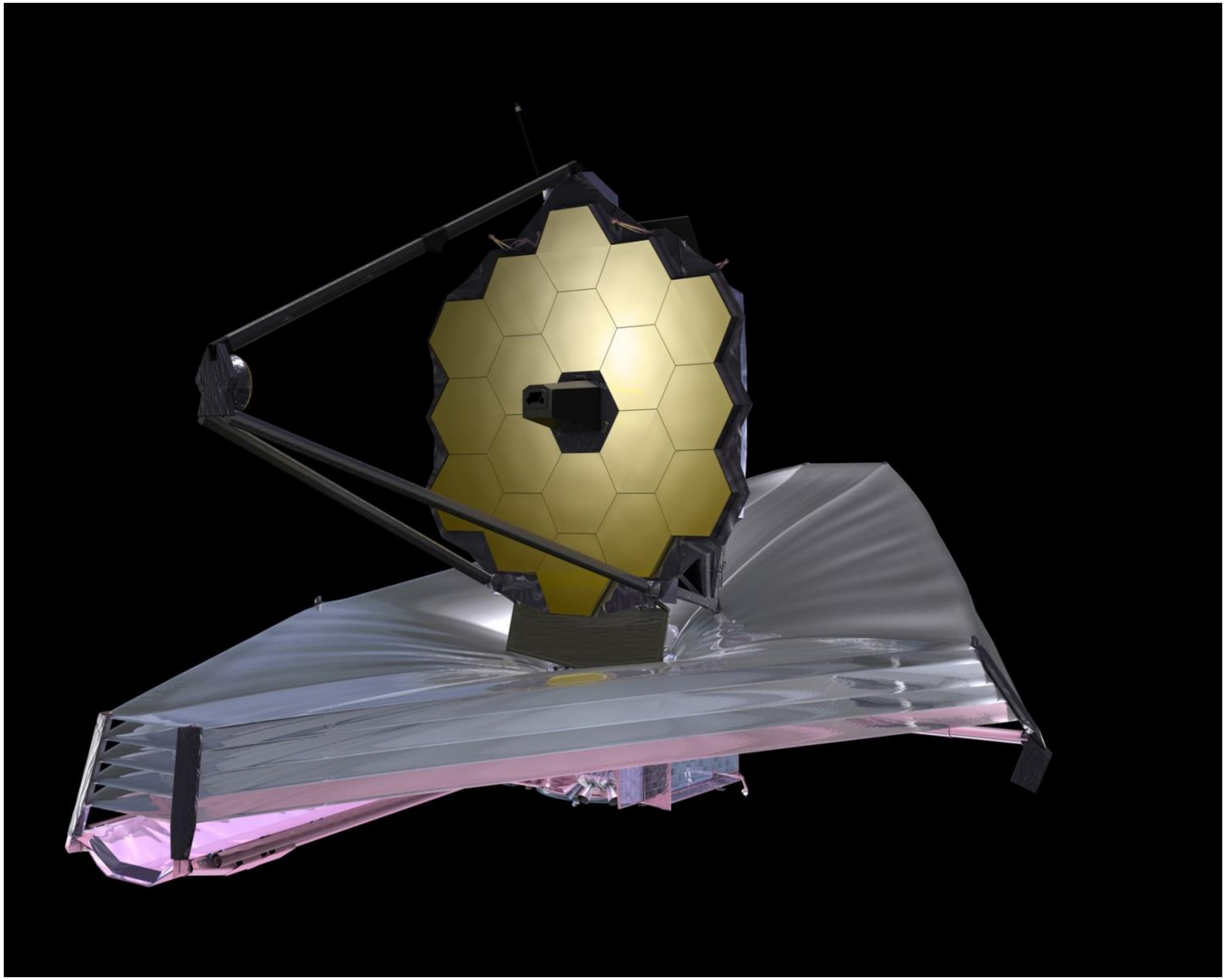
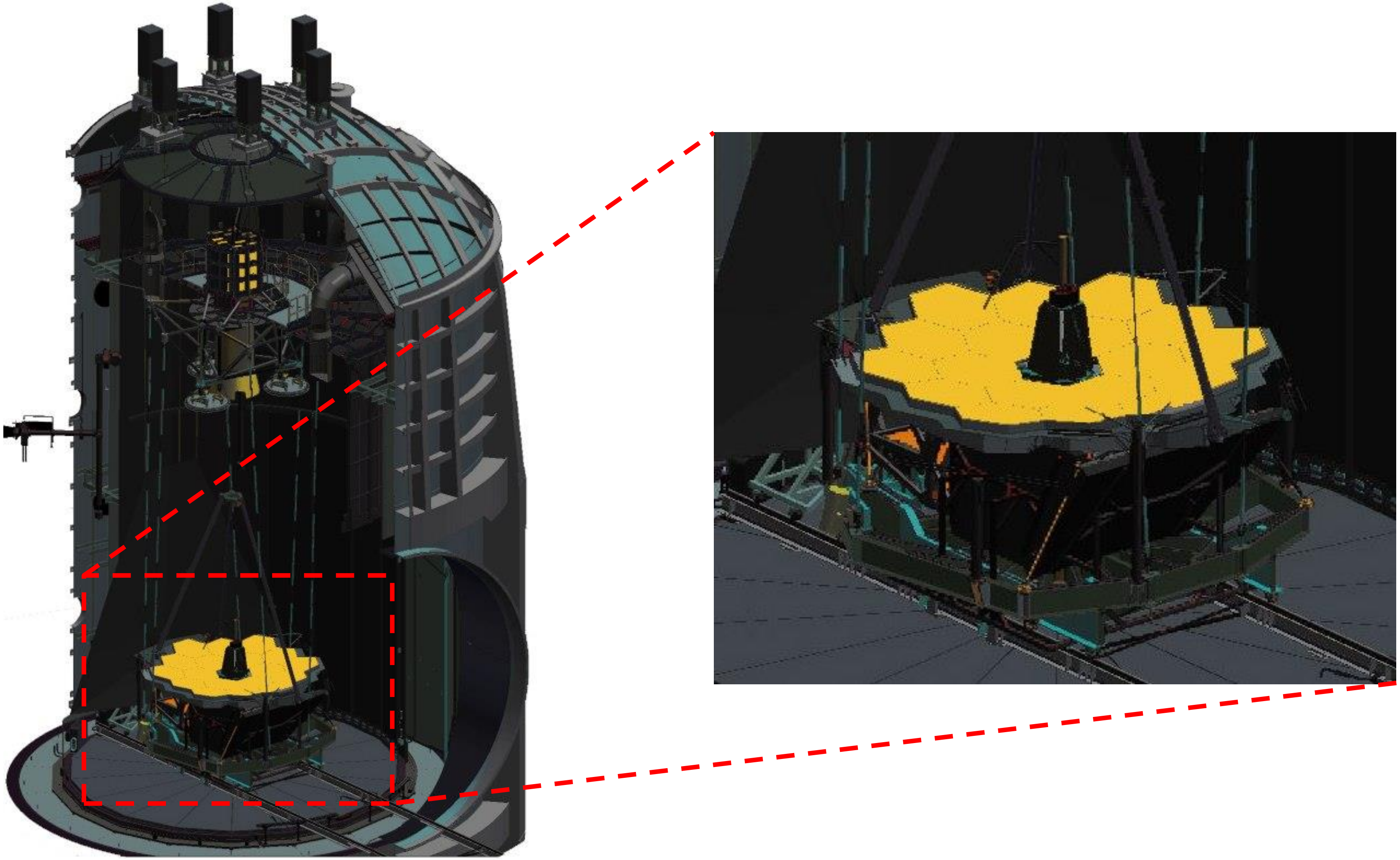
James Webb Space Telescope (JWST)



Introduction

- Thermal vacuum testing of JWST's Optical Telescope Element (OTE) combined with its Integrated Science Instrument Module (ISIM)—OTIS—will occur in NASA JSC's enormous Chamber A
  - OTIS Cryo-Vacuum (CV) Test
- ISIM somewhat isolated from certain chamber processes, configuration details, etc.
  - Faces vertically upward with optical, contaminant access across its exposed aperture
    - Aft Optics Subsystem (AOS)

OTIS CV Configuration



NASA

Introduction (cont.)

- At the end of TV testing, there are concerns that particulate matter will be stirred up by the chamber repressurization process
- Plan is to counteract possible particulate intrusion by first implementing an aggregate instrument purge for one hour before activating chamber repress system
  - Both flows consist of nitrogen gas
- Will this approach be effective? Overall process ranges from molecular flow (free molecule—FM) to continuum conditions across nearly nine orders of magnitude in pressure!

Objective

- Present a series of models designed to describe this process using control volume approaches in tandem as the chamber repressurizes
  - Regarding ISIM overpressure across the AOS aperture
- Apply an approximate energy balance to estimate net velocity
- Use creeping flow analysis to determine the maximum particle size that may be lofted, keeping smaller particles from settling within ISIM

Venting Equations

- The interaction between the ISIM volume and TV Chamber A will be described by a set of coupled equations
  - Conservation of mass statements for equilibrium gas at room temperature
  - Mass accumulation rate = (production rate) – (net venting rate)
  - ISIM purge vents into chamber; chamber pumps are off for repress
    - Early on, ISIM purge venting becomes chamber production rate
  - May write in terms of pressure *p*, gas load *Q*, and conductance *F*
    - I = ISIM, A=Chamber A

$$V_I \frac{dp_I}{dt} = Q_I - F(p_I - p_A)$$

$$V_A \frac{dp_A}{dt} = Q_A + F(p_I - p_A)$$

Venting Equations, Purging Only

- In this example problem, say
  - ISIM volume $V_I = 40\ \text{m}^3$
  - Chamber A volume $V_A = 10000\ \text{m}^3$
- In first hour, $Q_A = 0$, and because $V_A >> V_I$

$$V_A \frac{dp_A}{dt} = Q_I - V_I \frac{dp_I}{dt} \approx Q_I; \qquad \dot{p}_A = \frac{Q_I}{V_A}$$

$$V_I \frac{dp_I}{dt} = Q_I - F\left(p_I - \dot{p}_A t\right)$$

Gas Load, Conductance

- ISIM purge gas load acts as generation term Q_I
  - Product of upstream pressure and volumetric flow rate G
  - Example: G = 1200 L/hr at a supply pressure of two atm

$$Q_I = p_0 G \approx 507 \text{ Torr L/s}; \qquad \dot{p} = \frac{Q_I}{V_A} = 5.1\times10^{-5} \text{ Torr/s}$$

- Conductance F defined for passages between volumes in terms of a venting gas load divided by pressure difference

$$F_{1-2} \equiv \frac{Q}{p_1 - p_2} = \frac{p_1 G}{p_1 - p_2} = \frac{\dot{m}RT}{p_1 - p_2}$$

- Notice [F] = [G], but they are not the same parameter!

Model Repressurization Phases

- Require different models to analyze various phases, evaluating a variety of constraints
  - Molecular flow (Free Molecule, FM)
  - Continuum flow, sonic constraint
  - Subsonic flow
    - General
    - Small disturbance
- The pressure environment estimated at the end of one phase provides initial conditions for the next phase

Molecular Flow Phase

- FM flow governed by Knudsen number $Kn > 1$
  - Continuum behavior found when $Kn < 0.01$
    - Transition regime occurs in between these two limits
- Ignore transition regime deviations, assume FM conditions exist until reaching continuum limit
  - Apologies to RGD cohort!
- For an effective ISIM aperture diameter of 30 cm and an effective hard sphere nitrogen molecular diameter of 3.75 angstroms, crossover occurs at an ISIM pressure level of 0.017 Torr

Molecular Flow Solution (Phase 1)

- In FM flow, $F = A\sqrt{RT/2\pi}$ = constant with respect to pressure

$$p_I(t) = p_{I,0}\, e^{-\frac{t}{\tau}} + (q - \dot{p}_A)\tau\left(1 - e^{-\frac{t}{\tau}}\right) + \dot{p}_A t, \quad \text{where} \quad (\tau, q) \equiv \left(\frac{V_I}{F}, \frac{Q_I}{V_I}\right)$$

- Results show that pressure “skyrockets” through FM and transition regimes in 1.5 seconds after purge initiation!
  - Model purge mass flow rate for 507 Torr L/s is less than six grams per sec.
  - When ISIM pressure reaches 0.017 Torr, TV Chamber A pressure is only about 0.000077 Torr

Continuum—Sonic Constraint

- Assuming isentropic conditions,

$$\frac{p_A}{p_I} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{\frac{-\gamma}{\gamma - 1}}$$

- Mach number M maximizes this ratio at 0.528 when $M = 1$
  - Until the chamber pressure p_A can catch up to this level, it will not influence the ISIM pressure, and the ISIM venting term may be replaced by

$$Q_{I,\text{out}} = \dot{m}RT = p_I A \sqrt{\gamma RT} \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{2(\gamma - 1)}} = \zeta p_I$$

Sonic Phase Solution (Phase 2)

- Substitution into gas load equation for ISIM yields

$$V_I \frac{dp_I}{dt} = Q_I - \zeta p_I$$

$$p_I(\Delta t) = p_{I,02}\, e^{-\frac{\Delta t}{\tau_S}} + \frac{Q_I}{\zeta}\left(1 - e^{-\frac{\Delta t}{\tau_S}}\right), \quad \text{where} \quad \tau_S \equiv \frac{V_I}{\zeta}$$

- The sonic condition holds until p_A catches up

$$p_{A,02} + \dot{p}_A \Delta t = 0.528\, p_I$$

- For example conditions
  - ISIM pressure quickly settles to a constant 0.036 Torr
  - sonic constraint no longer holds at 6.3 minutes after purge initiation when p_A reaches 0.019 Torr

Subsonic Conductance Formula

- Beyond 6.3 min., rising chamber pressure begins to influence ISIM internal pressure across the vent
- Venting term must be recast in terms of both p_I and p_A
  - Based on relationship between mass flow rate, gas load, and conductance, the isentropic, compressible flow expression becomes

$$F = \sqrt{\frac{2\gamma RT}{\gamma - 1}} \frac{p_I A}{p_I - p_A} \left(\frac{p_A}{p_I}\right)^{\frac{1}{\gamma}} \sqrt{1 - \left(\frac{p_A}{p_I}\right)^{\frac{\gamma-1}{\gamma}}}$$

  - Decide to solve pressure gas load equations numerically

Subsonic, Purge Only (Phase 3)

- Elapsed time during this phase: $\Delta t = n\delta t$

$$p_I^n(n\delta t) = p_I^{n-1} + \frac{Q_I \delta t}{V_I} - \frac{p_I^{n-1} A \delta t}{V_I} \sqrt{\frac{2\gamma RT}{\gamma - 1}} \left(\frac{p_A^n}{p_I^{n-1}} \right)^{\frac{1}{\gamma}} \sqrt{1 - \left(\frac{p_A^n}{p_I^{n-1}} \right)^{\frac{\gamma-1}{\gamma}}}$$

$$p_A^n(n\delta t) = p_{A,03} + \dot{p}_A n\delta t$$

- Calculations were performed out to the one hour mark, beyond which the chamber repress valves were opened
  - Required a timestep of 0.2 s or less for a stable solution throughout this period
  - p_I = 0.1851 Torr, p_A = 0.1834 Torr

Chamber Valve Effect

- At the end of the first hour, chamber repress valves are opened and the chamber pressure is allowed to increase 0.75 Torr/min
  - Much higher than the 5.1e-5 Torr/s (0.003 Torr/min) rate experienced by the chamber due to the instrument purge gas load
  - This additional effect will drastically decrease any overpressure benefit within ISIM produced by the instrument purge
  - Will it be overwhelmed ($p_A > p_I$)?
- As the pressure difference between the two volumes decreases, the timestep in the numerical solution routine must decrease in order to maintain stability
- Can simplify effort, gain analytical insight through use of small-disturbance approximation

Small Disturbance Approximations

- Background development presented in previous SPIE meetings
- When $\varepsilon \equiv \Delta p / p \ll 1,\ (1+\varepsilon)^a \approx 1 + a\varepsilon$

$$F_{\mathrm{sm}} \equiv F(\Delta p \ll p_A) \approx A\sqrt{2RT\frac{p_A}{\Delta p}}\left(1 - \frac{1}{\gamma}\frac{\Delta p}{p_A}\right) \approx A\sqrt{2RT\frac{p_A}{\Delta p}}$$

- Already noted the chamber repress rate >> purge rate such that

$$\dot{p} \equiv \dot{p}_{I,4} = \dot{p}_{A,4}$$

- Our coupled set of ODE's may be replaced by algebraic ones

$$V_I\,\dot{p} = Q_I - A\sqrt{2RT}\sqrt{p_A(p_I - p_A)}$$

$$p_A(\Delta t) = p_{A,04} + \dot{p}\Delta t$$

Purge + Chamber Repress (Phase 4)

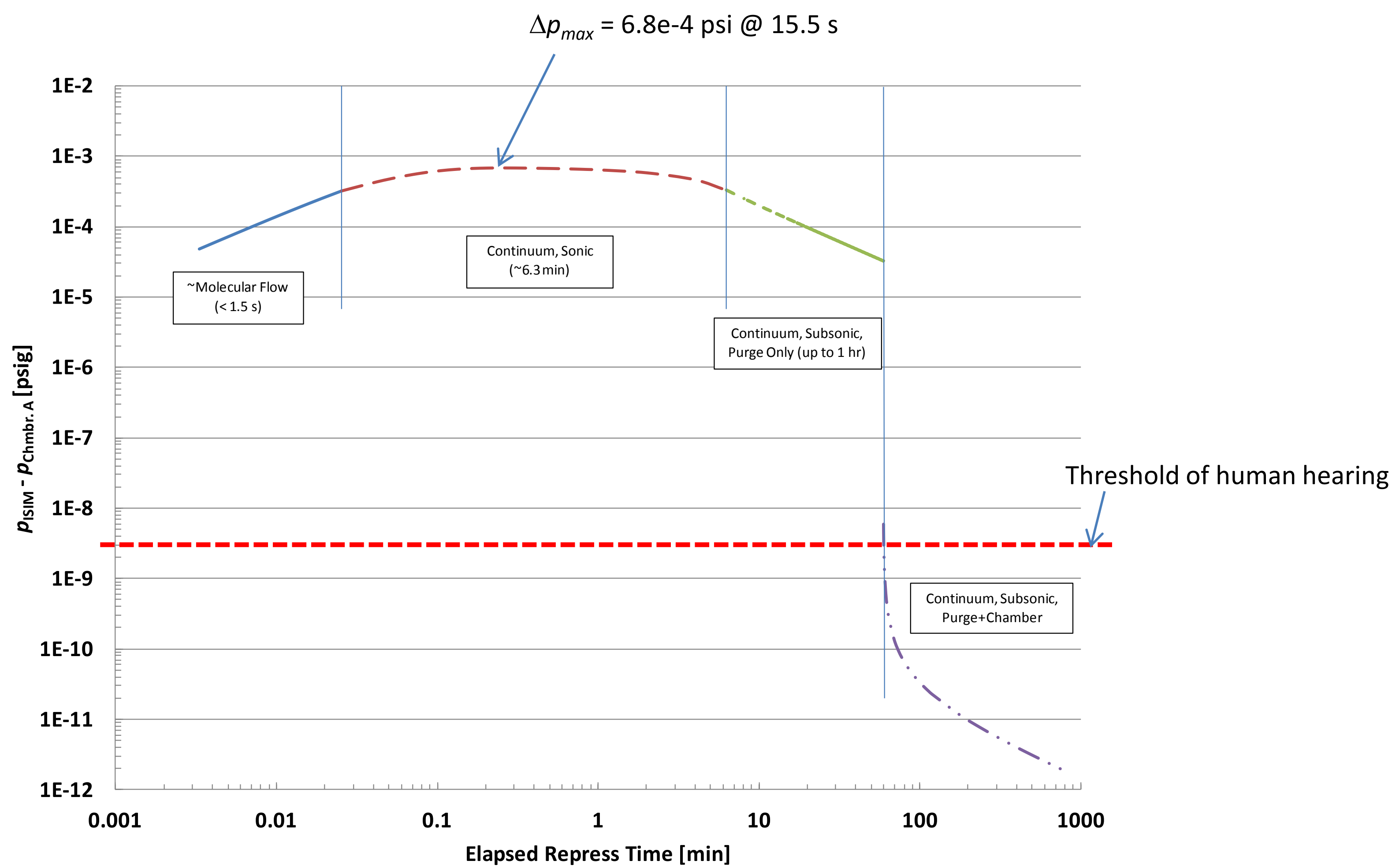
- The ISIM pressure solution becomes

$$p_I = p_A + \frac{1}{2RTp_A}\left(\frac{Q_I - V_I\,\dot{p}}{A}\right)^2$$

- Remarks
  - ISIM overpressure is small, decreases inversely with time
  - Equation reveals the necessary condition for ISIM overpressure in numerator

$$Q_I - V_I\,\dot{p} > 0$$

ISIM Overpressure, Example Conditions



Net Velocity Calculation

- Wish to convert net overpressure to an aperture velocity for keeping particulate matter at bay
- Use conservation of energy equation, assume
  - Not concerned with purge-only period (first hour)
  - ISIM acts as a reservoir (velocity $U_I = 0$)
  - Incompressible, with $p_I > p_A$
  - Approximately valid at each point in time
  - Neglect effects of potential energy differences due to gravity vs. height
- Simplifies to Bernoulli equation

$$\Delta p \equiv p_I - p_A = \frac{1}{2}\rho U_{ap}^2 - \frac{1}{2}\rho U_I^2 \approx \frac{1}{2}\rho U_{ap}^2 \quad \rightarrow \quad U_{ap} = \sqrt{2RT\varepsilon}$$

Creeping Flow Assumption

- For estimating drag effect on tiny particles, creeping flow assumption valid for Reynolds number $Re \leq 1$

$$Re \equiv \frac{\rho U D}{\mu} \leq 1 \quad \rightarrow \quad (UD)_{crit} \leq \begin{cases} 1.56 \times 10^{-5}\ \text{m}^2/\text{s at } 1 \text{ atm} \\ 0.065\ \text{m}^2/\text{s at } 0.1834\ \text{Torr (see Sect. 3.3).} \end{cases}$$

- If U_{ap} = 10 cm/s, creeping flow valid for
  - D = 156 microns at one atmosphere
  - D = 65 cm at initiation of chamber valve opening!
- Looks like we're covered

Critical Lofting Condition

- Apply force balance to particle falling under gravity, counteracted by an upward drag force F_s due to Stokes
  - Very forgiving of actual particle shape versus sphere with radius R

$$m\ddot{y} = F_s - mg; \qquad F_s = 6\pi\mu R\left(U_{ap} - \dot{y}\right)$$

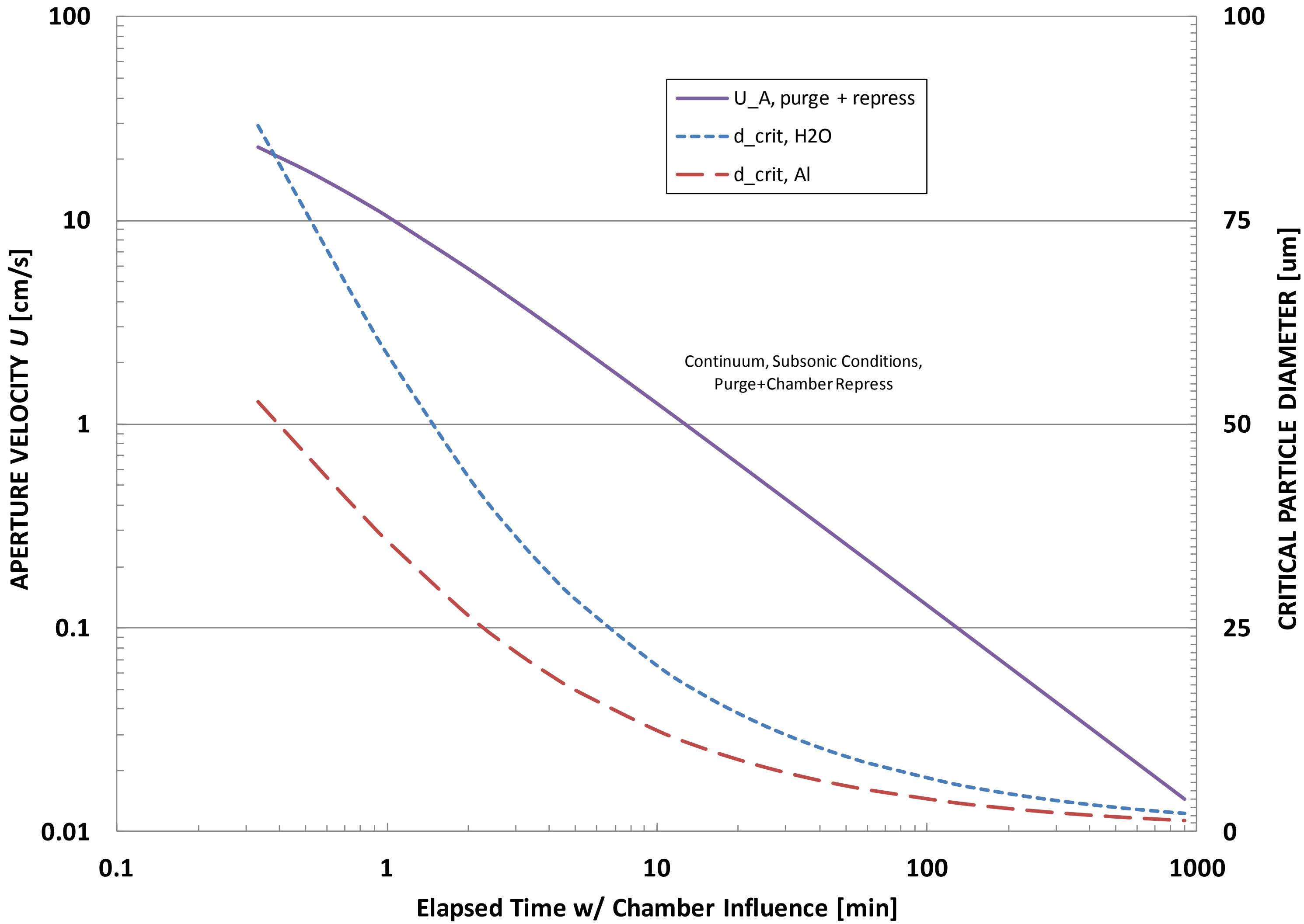
- Critical condition:

$$U_{ap} \equiv \frac{mg}{6\pi\mu R_{crit}} = g\tau$$

  - For an Al particle with D = 100 microns, inertial time constant $\tau = 84$ ms
- May rewrite critical condition as

$$R_{crit} = \sqrt{\frac{9\mu U_{ap}}{2\rho_s g}}$$

Critical Particle Size, Example Conditions



Critical Particle Size Observations

- Surprised to find larger particles may be held aloft at lower pressure than at one atmosphere
  - Drag force dependent on viscosity but not gas density
  - Overpressure decrease with chamber pressure causes net velocity decrease, affecting critical particle size counterintuitively
- For example conditions, worst case occurs at one atmosphere
  - For particle density similar to H_2O, R_{crit} = 2.0 microns
  - For Al, R_{crit} = 1.2 microns
- Since particle fallout distributions are heavily skewed towards high concentrations of small elements, it is possible to reject a large fraction of a fallout ensemble by number, but this ensemble constitutes a relatively small fraction of potential area concealable by such distributions
  - May be difficult to get large particles to locations for threatening ISIM

Concluding Remarks

- A series of models were developed to describe net overpressure across the ISIM aperture during repressurization spanning
  - Molecular flow to continuum conditions
  - Sonic, subsonic compressible, and incompressible environments
  - Effect of purge counteracting chamber valve influence
    - Identified condition for ensuring net outflow from purged, nested volume
- Converted overpressure to flow velocity for applying to force balance on chamber particles that may threaten ISIM interior
- Although example conditions did not produce robust results, the situation could be remedied by increasing the aggregate purge rate (if possible) or slowing down the chamber repressurization rate