Development of an analytical transient evacuation model for the fairing jettison process

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Introduction

- **The James Webb Space Telescope (JWST) features large expanses of thin membrane sunshield layers, carefully folded prior to launch and supported by Unitized Pallet Structures and Membrane Release Devices**
- **Project personnel were particularly concerned about pressure differentials developing during ascent that could potentially damage these large, delicate fabrications**
  - Similar concerns regarded similar effects on other large blankets and across instrument enclosures
  - Some thermal engineers are also concerned that related disturbances could affect the radiative performance of multilayer insulation (MLI) blankets
- **While fairing ascent depressurization analyses usually consider conditions during the first 1-2 min. after launch, the project was made aware that residual pressure levels at fairing jettison can also be high enough to potentially cause damage due to the rapid evacuation that occurs during that event**

VA256 (JWST) Ready for Launch

JWST During Fairing Jettison Event

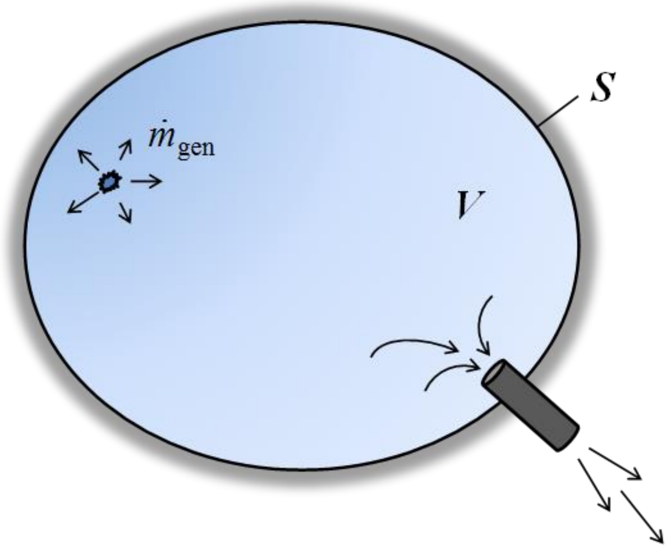
Objective

- **The objective of this presentation is to describe development of an analytical model used to predict fairing pressure evolution during jettison**
  - Explore impact of certain parameters
  - Predict overpressure responses for various payloads subjected to the fairing jettison pressure environment

Mass Conservation Statement

- **General mass accumulation rate**
  - Mass generation rate within volume rigid *V*
  - Net rate vented across bounding surface *S*

$$\frac{d}{dt}\iiint_V \rho\, dV = \dot{m}_{\text{gen}} - \oiint_S \rho\mathbf{u}\cdot d\mathbf{S}$$



- **For fairing jettison, neglect**
  - Any mass generation rate due to venting of payloads into the fairing
  - Outgassing and desorption
  - Ascent vent performance
- **However, consider that air density ρ, volume, and vent area *A* due to fairing separation will all change rapidly with time**

General Solution

- **The volume integral becomes**

$$\frac{d}{dt}\iiint\limits_V \rho\, dV = V\frac{d\rho}{dt} + \rho\frac{dV}{dt} = \rho V\frac{d}{dt}\left(\ln \rho V\right)$$

- **Velocity associated with venting in the surface integral is constrained by sonic conditions across the separating fairing halves to near-space conditions**
  - $\mathbf{u} = a = \sqrt{\gamma R T} = \sqrt{\frac{2\gamma R T_0}{\gamma+1}}$
- **Assuming the gas may be treated as having lumped, homogeneous properties at any point in time within the fairing, the surface integral becomes**

$$\oiint\limits_S \rho\mathbf{u}\cdot\mathbf{dS} = \rho a A$$

General Solution (cont.)

- So with these simplifications, our mass conservation statement is distilled to

$$\frac{d}{dt}(\ln \rho V) = -\frac{aA}{V}$$

- Integrating over time with initial conditions designated by subscript *0*:

$$\frac{\rho}{\rho_0} = \frac{V_0}{V}\exp\left(-a\int_0^t \frac{A(t)}{V(t)}dt\right)$$

- Since the jettison process occurs very rapidly, one may assume a polytropic thermodynamic process where $p \propto \rho^k$ (isentropic $k = \gamma$; isothermal $k = 1$)
- Transient fairing pressure may be described by

$$\boxed{p(t) = p_0\left(\frac{V_0}{V(t)}\right)^k \exp\left(-ka\int_0^t \frac{A(t)}{V(t)}dt\right)}$$

Observations

$$p(t) = p_0 \left(\frac{V_0}{V(t)} \right)^k \exp\left(-ka \int_0^t \frac{A(t)}{V(t)} dt \right)$$

- **The polytropic exponent doesn't factor into the integral**
  - May be treated as a time-dependent variable independent of volumetric expansions or transient changes in vent area to approximate heat transfer effects
- **For a multiple-step jettison process, the solution describes each step of the process by suitable adjustment of the local time variable**
  - Each step may be linked back to initial conditions
    - If the fairing separation process is meant to be repeatable, launch after launch, then the solution should be linearly proportional to the initial jettison pressure
- **Lumped conditions, so angular variation around launch vehicle (LV) main axis and possible localized flow features that may develop are ignored**

Constant Separation Rate Response

- **If increases in transient volume and vent area follow constant rates, then**

$$V(t) = V_0 + \dot{V}t; \qquad A(t) = A_0 + \dot{A}t.$$

  - Neglecting nominal ascent venting prior to fairing jettison, let $A_0 \approx 0$
- **After some rearrangement, the general equation reduces to**

$$p(t) = p_0 \left(\frac{V_0}{V_0 + \dot{V}t} \right)^{k(t)} \exp\left(-k(t)\, a \int_0^t \frac{\dot{A}t}{V_0 + \dot{V}t} dt \right) = \boxed{p_0 \left(\frac{V_0 + \dot{V}t}{V_0} \right)^{k(t)\left(a \frac{\dot{A}V_0}{\dot{V}^2} - 1 \right)} \exp\left(-k(t)\, a \frac{\dot{A}t}{\dot{V}} \right)}$$

- **For constant *k*, an exponential time constant presents itself:** $\tau \equiv \dot{V} / ka\dot{A}$
  - But its impact on the solution is obscured by the power-law dependent term

Flow Regime Check

- **We tend to think of fairing separation as quite a violent process, but to a point (for short elapsed times), homogenized, continuum conditions are not unreasonable**
- **Separation velocity for a fairing half ~ 10 m/s**
  - Speed of sound ~ 340 m/s in air; most probable molecular speed ~ 410 m/s
- **Fairing pressure at jettison often on the order of 100 Pa**
  - Hard sphere mean free path length in air $\lambda < 0.07$ mm at 100 Pa
  - Distance L between fairing half and payload begins at 100 mm to 1000 mm or longer
- **So arguably as a generality, the state of the gas begins within the continuum regime (*Kn* < 0.01) and it can readily transmit lateral disturbances associated with fairing separation (quasisteady)**
  - Assumptions seem to apply for the first few tenths of a second

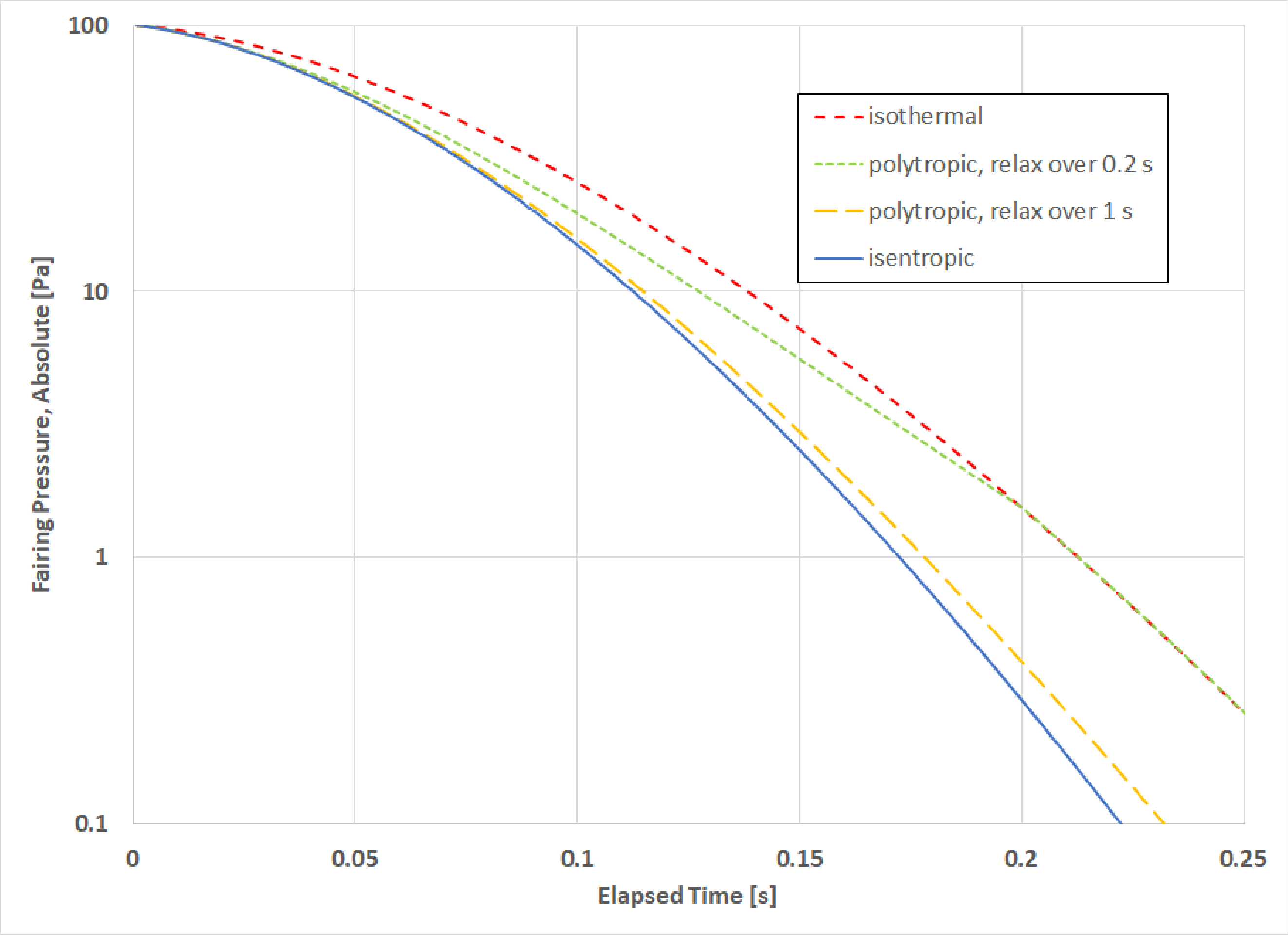
Parametric Analysis—Baseline Values

- **Assumed baseline initial conditions for a large launch vehicle (LV):**
  - p_0 = 100 Pa
  - V_0 = 300 m^3
  - L_0 = 5 m (fairing diameter)
  - $k = \gamma = 1.4$ (isentropic process; no heat transfer to gas)
  - Plotted as solid blue curve in subsequent figures
- **Rate changes due to separation process:**
  - $\dot{V}$ = 1000 m^3/s
  - $\dot{A}$ = 250 m^2/s
  - $\dot{L}$ = 10 m/s
  - $\dot{k} = (1 - \gamma)/t_c$ (for varying heat transfer effect over arbitrary time t_c)

Parametric Analysis—Thermodynamic Process

- **Initially thought to be isentropic throughout, but separate observations show it is difficult to sustain an isentropic process**
  - Probably an isentropic process throughout, but
  - For modeling flexibility allow for crude relaxation process over some arbitrary period
- **Add response for isothermal process (perfect heat transfer, constant temperature)**
- **Isentropic and isothermal results span the range of possibilities for pressure response based on the assumed conditions**

Parametric Analysis—Thermodynamic Process



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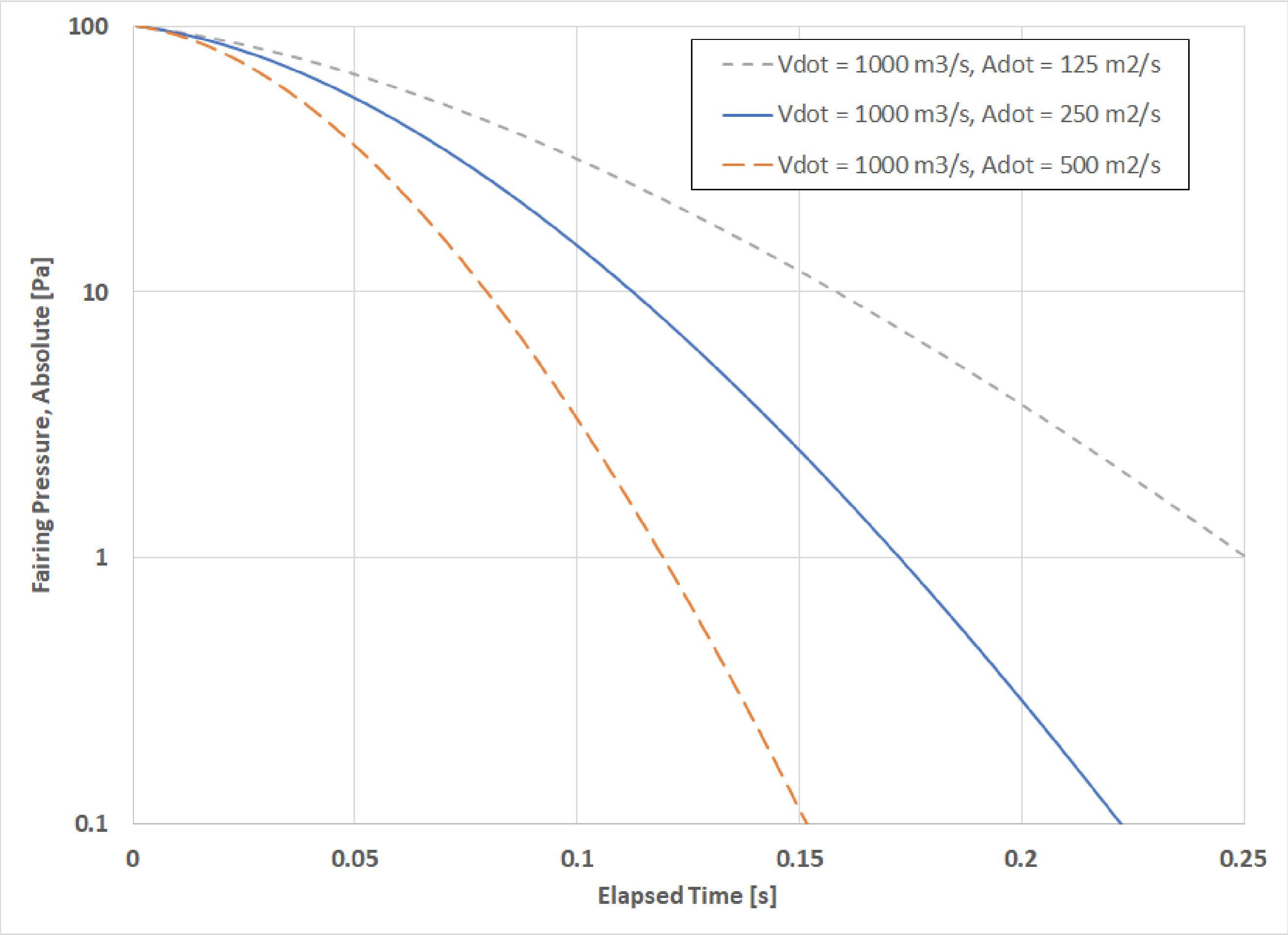
Parametric Analysis—Vent Area Rate

- **Strictly speaking, it generally isn't possible to compare cases for a LV type where changes in vent area rate and fairing volume rate change independently, but here we just look at the mathematical sensitivity of the pressure response to changes in these parameters**
  - In reality, it would be like comparing the results for two different LV types having different characteristic geometric configurations
- **Putting that observation aside, it is found that the jettison evacuation process is very sensitive to the vent area rate created by the gap broadening between fairing halves**
  - Plot results having ±2*x* variation
  - Halving or doubling the baseline rate has a greater effect on results than the entire range of possibilities for the thermodynamic process

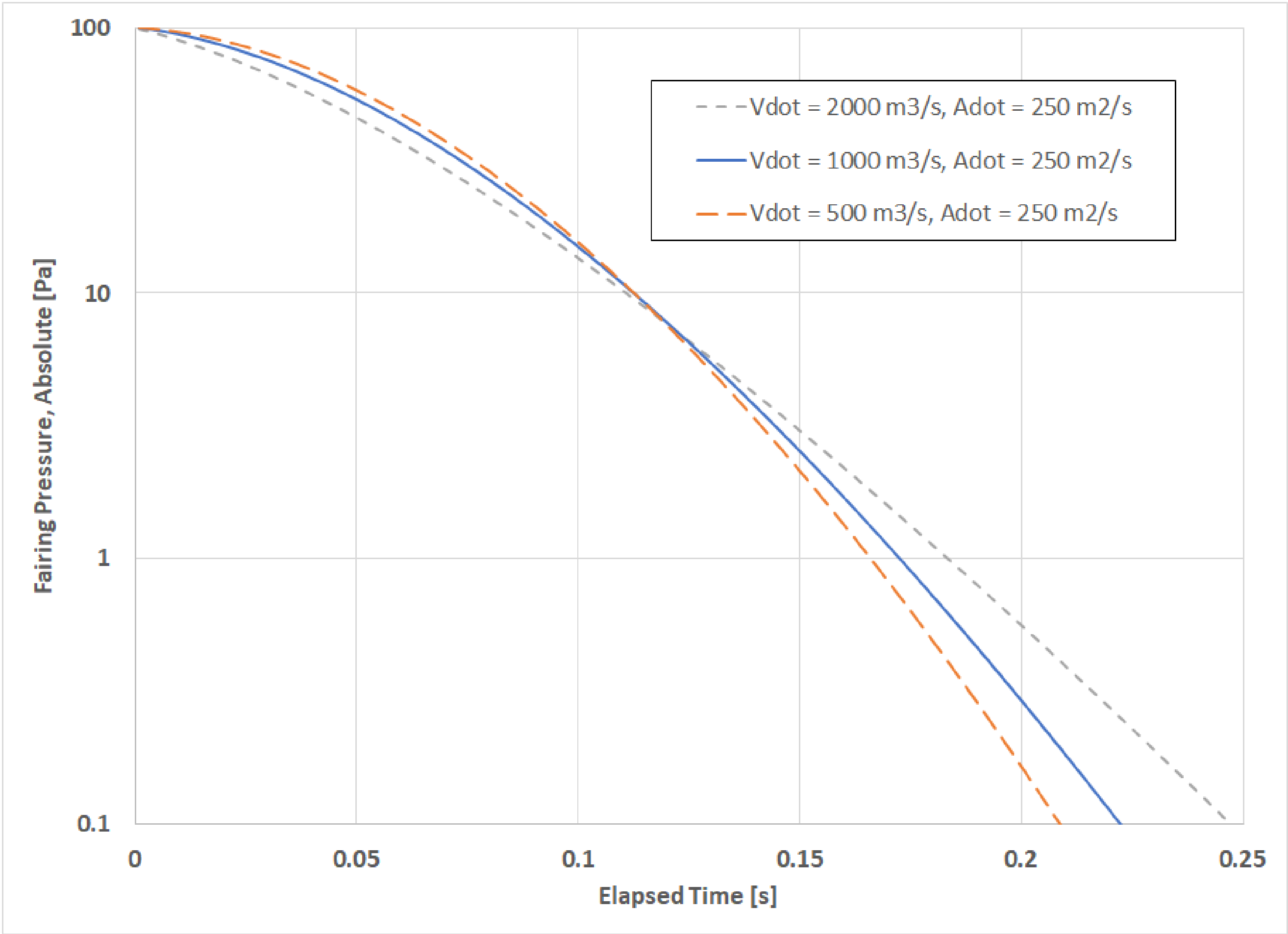
Parametric Analysis—Vent Area Rate



Parametric Analysis—Volumetric Expansion Rate

- **Vary volume expansion rate by ±2*x*, keeping vent area rate fixed somehow**
- **Observe much less variation in pressure response than the other parametric comparisons**
- **Surprisingly, a seeming crossover point appears where evacuation due to slower volume expansion rates accelerates faster than results due to faster rates**
  - Not actually a fixed point in elapsed time, but occurs with relative insensitivity
  - Derivation provided in SPIE 2022 manuscript
- **Crossover time between cases appears to result from two competing mechanisms**
  - Lower $\dot{V}$ produces higher fairing pressures early on
  - Higher pressures produce higher gas load potentials to drive higher venting later on
  - Ultimately, this power potential creates steeper evacuation profiles relative to cases where $\dot{V}$ is higher

Parametric Analysis—Volumetric Expansion Rate



Internal Payload Response

- **Payloads within a fairing will develop overpressures relative to fairing conditions (subscript *f*) as jettison occurs**
- **Consulting our mass conservation statement with no upstream mass addition from the payload perspective, and assuming venting into the fairing occurs across orifices**
  - For purposes of demonstration, assume simplest process for payload venting (isothermal, rigid)

$$\frac{dp}{dt} = -pa_0 \frac{A_{eff}}{V} \sqrt{\frac{2}{\gamma - 1}} \sqrt{\left(\frac{p_f}{p}\right)^{\frac{2}{\gamma}} - \left(\frac{p_f}{p}\right)^{\frac{\gamma+1}{\gamma}}}$$

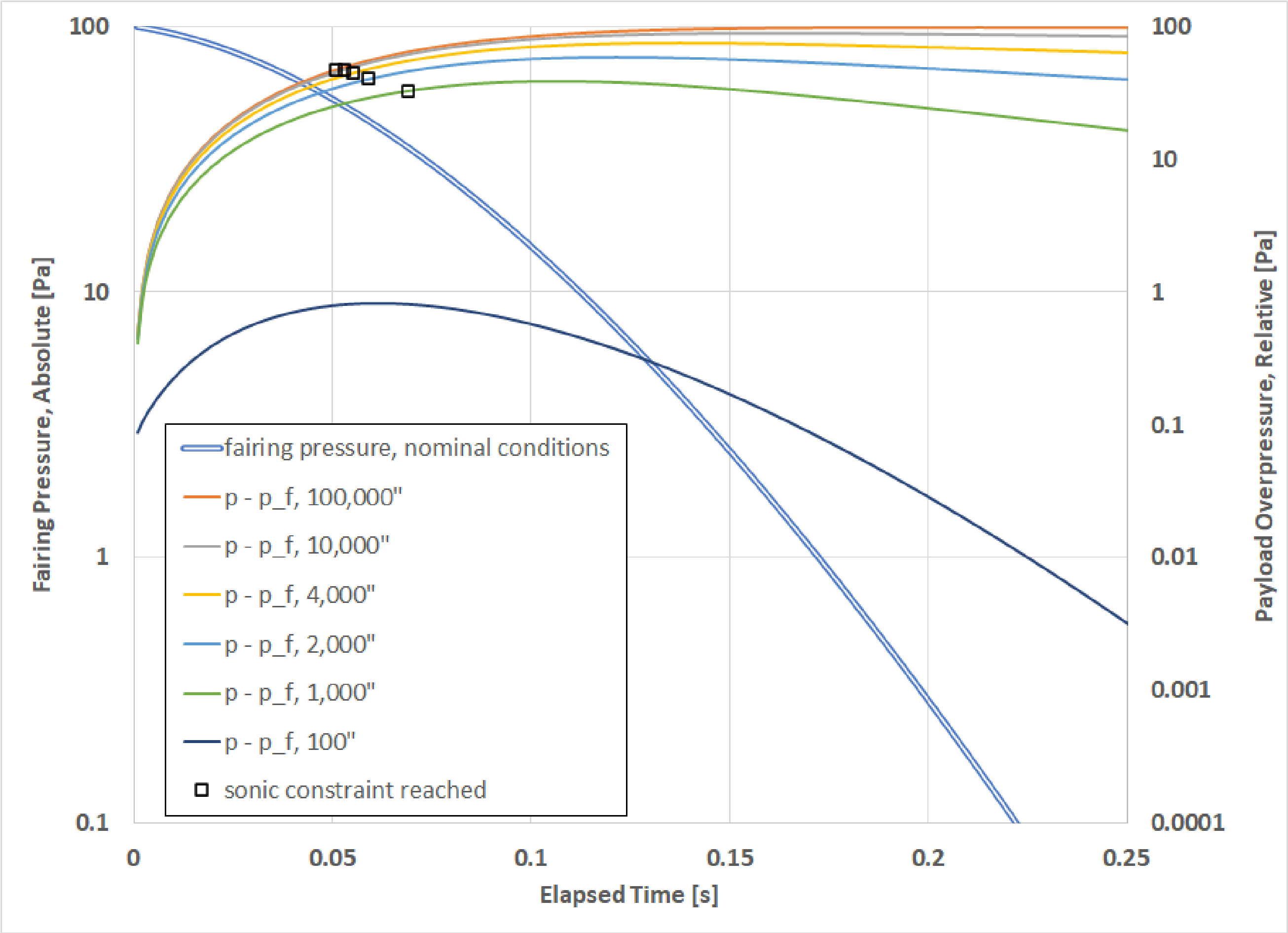
- **Transient payload pressure may be found by numerically integration, where p_f drives the solution until a sonic limitation occurs, after which the pressure ratio is replaced with a constant expression and fairing conditions no longer drive payload response**

$$\left(p_f / p\right)_{crit} = \left[2/\left(\gamma + 1\right)\right]^{\frac{\gamma}{\gamma-1}} \quad \left(\text{about } 0.528 \text{ for air}\right)$$

Internal Payload Response—Cases

- **A convenient, although imprecise way often employed to meet overpressure requirements is to specify a maximum volume to vent area ratio, such as V/A_{eff} = 2000 inches**
  - Does not account for fairing evacuation behavior
- **Construct cases for various V/A_{eff} ratios assuming a rigid payload volume V = 1 m^3**
- **Find that payload volume pressures with ratios of 1000 inches or above cannot keep up with fairing evacuation during the jettison process, with sonic constraints being reached soon after the fairing pressure drops below ~0.528x of its initial value**
  - About 0.30x for V/A_{eff} = 1000"
- **Conversely, volumes having a venting ratio of 100 inches can match fairing evacuation pretty closely, but this is not a practical ratio for most configurations**
  - May be consistent with certain venting guidelines for a square MLI blanket, ¼" thick, with A = 1 m^2 having about ten percent of its effective perimeter left unsealed

Internal Payload Response Case Plot



Concluding Remarks

- **An analytical model has been developed to describe fairing conditions during jettison**
- **Although it assumes lumped properties, it is general enough to characterize the jettison process over a wide range of conditions**
- **A parametric analysis was performed for a number of parameters**
  - Some dependence on assumption of thermodynamic process
  - Relatively sensitive to area rate of expansion
  - Volume expansion rates give rise to an approximately stable point for pressure some time after jettison is initiated
- **Payload overpressure response was evaluated for a representative volume**
  - Volume to vent area ratios $\geq$ 1000” don’t track well with fairing evacuation
  - V/A_{eff} = 100” configuration tracks well
    - Potentially consistent with vented MLI blanket designs

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