National Aeronautics and Space Administration

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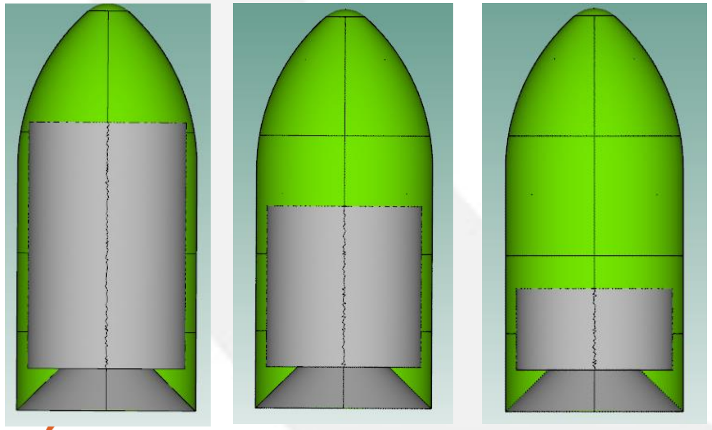
SPACE LAUNCH SYSTEM

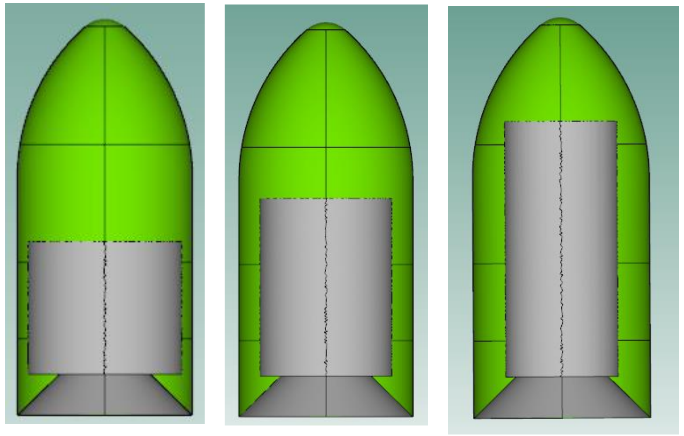
Payload Fairing Acoustic Trade Study: Fill Effect Modeling

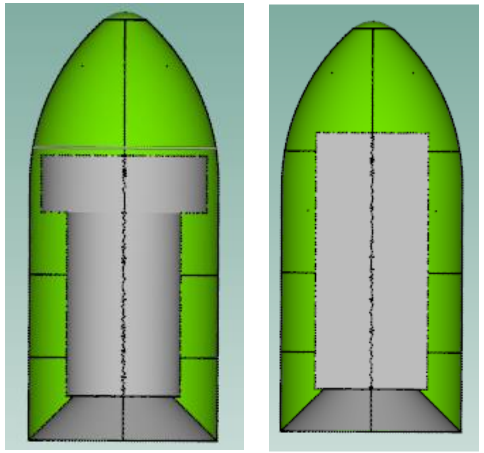
Lucas Shearer
Samantha Bittinger
NASA-GRC/LMD

Purpose and Overview

- **The purpose of this study is to compare the "Fill Factor" described in NASA-STD-7001b to the fill effect observed in numerical/statistical models**
- **Overview**
  - Introduce fill effect and the "Fill Factor"
  - Describe simulated payload shapes used in this study
  - Investigate fill factor through two approaches
    - Affect of fill effect on **full cavity average**, enabling variable isolation
    - Affect of fill effect on **zone of interest**, the traditional localized approach
  - Look at spatial variation within the zone of interest at low frequency
  - Conclusions







Acoustic Fill Effect / Fill Factor

- **Fill effect is the term used to describe how the sound pressure level within a payload fairing changes due to the presence of a payload**
  - The sound pressure level inside of a payload fairing generally increases as it is filled
- **Acoustic models of fairings often don't include a payload**
  - A specific payload/mission might not yet be known
  - Flight level predictions require a fill effect correction for payload designers
  - The internal acoustic environment of SLS mission guide assumes a 60% fill
- **Historically, fill effect had been estimated using one of a handful of fill factor curves**
  - C. Tanner, 1984 (Aerospace Corporation)
  - Y. Lee & W. Henricks, 1992 (Lockheed)
  - J. Manning, 1991 (Cambridge Collective)

Fill effect history and NASA-STD-7001B review

- **A NASA standard was developed to reduce disputes between organizations using different fill factors**

- **The predictive technique developed by Jerome Manning in 1991 was validated by experiment and published in a 1994 NASA TM (W. Hughes, M. McNelis, J. Manning)**
  - The Manning/LeRC Fill Factor
    - Generally, in agreement with Tanner, 1984
    - Lower than Lee & Henricks, 1992

- **NASA-STD-7001B (2007) references the Acoustic Fill Factor Report written by Jerome Manning et. al, of Cambridge Collaborative and the 1994 NASA TM**

Fill Factor Derivation

Spatial and time average
Mean square pressure → $\langle p_i^2 \rangle = \rho c^2 \left(\frac{N_i}{V_i}\right) e_i$ (SEA theory)

- **Assume energy per mode, e, is the same for filled and empty model**

$$Fill\ Factor(dB) = 10Log_{10}\left[\frac{V_{empty}N_{filled}}{V_{filled}N_{empty}}\right]$$

- **The number of acoustic modes within a frequency band is expressed mathematically in terms of the cavity volume and separation distance from the fairing wall, H**
  - N_{filled} shown here for annular space (appropriate for cylindrical payloads)

$$N_{empty} = \frac{4\pi f^2}{c_0^3} V_{empty}[1 + \phi_1]\Delta f \qquad N_{filled} = \frac{4\pi f^2}{c_0^3} V_{filled}\left[1 + \frac{c_0}{2fH}\right]\Delta f$$

Fill Factor Derivation

- **Limits:**
  - Ratio of number of modes limited by the term, ϕ
    - At low frequency ($fH << c_0$), the modal ratio limited to 1
    - At high frequency ($fH >> c_0$), the modal ratio is 1-VolumeRatio

$$\frac{N_{filled}}{N_{empty}} = \frac{V_{filled}}{V_{empty}} \frac{\left[1 + \frac{c_0}{2fH}\right]}{[1 + \phi_1]} \qquad \phi_1 = \frac{V_{filled}}{V_{empty}} \frac{c_0}{2fH}$$

$$V_{filled} = V_{empty} - V_{payload}$$

$$\frac{V_{filled}}{V_{empty}} = 1 - \frac{V_{payload}}{V_{empty}} = 1 - VolRatio$$

$$Fill\ Factor = 10Log_{10}\left[\frac{1 + \frac{c_0}{2fH}}{1 + \left[\frac{V_{filled}}{V_{empty}}\right]\frac{c_0}{2fH}}\right] = 10Log_{10}\left[\frac{1 + \frac{c_0}{2fH}}{1 + (1 - Vol\ Ratio)\frac{c_0}{2fH}}\right]$$

Fill Factor Curves

NASA-STD-7001B

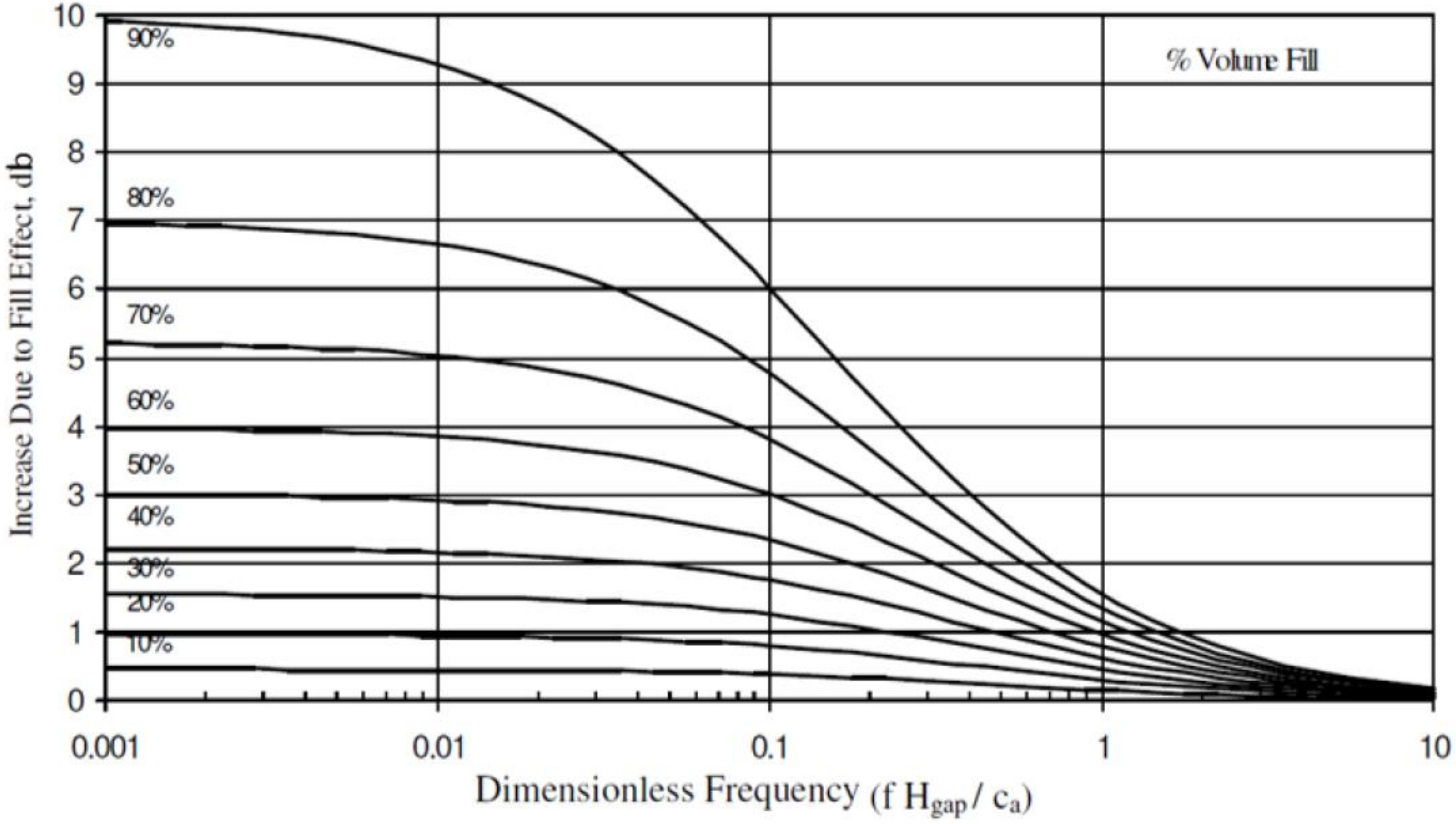


Figure 1—Fill Factor Design Chart

- **Testing was conducted using unblanketed Atlas-Centaur payload fairings**
  - 4 simulated payload shapes, made of 1" thick particle board wood, 4 lb/ft^2
  - Filled with polyurethane foam
- **SPL in the barrel region of the fairing was of primary concern**

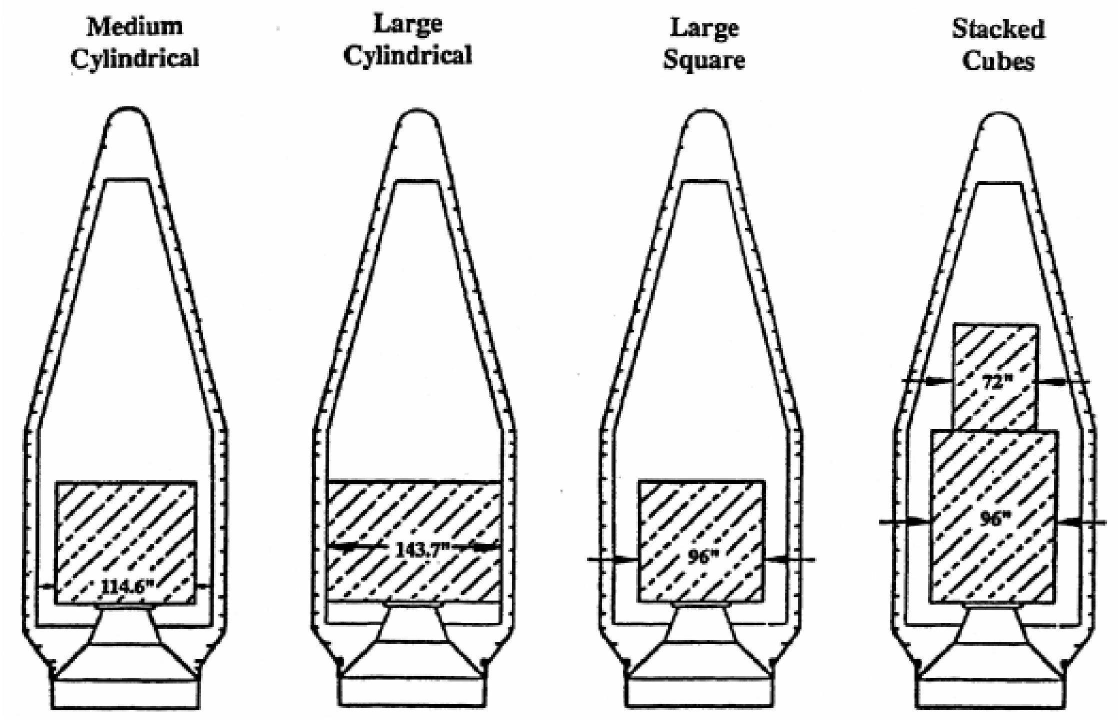
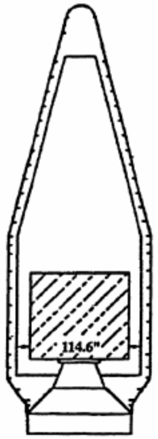


Figure 2.—Mock spacecraft configurations.

Hughes, William O., Mark E. McNelis, and Jerome E. Manning. "NASA LeRC's acoustic fill effect test program and results." *NASA Technical Memorandum* 106688 (1994).

Fill Effect Theory/Experimental Comparison

Medium Cylindrical



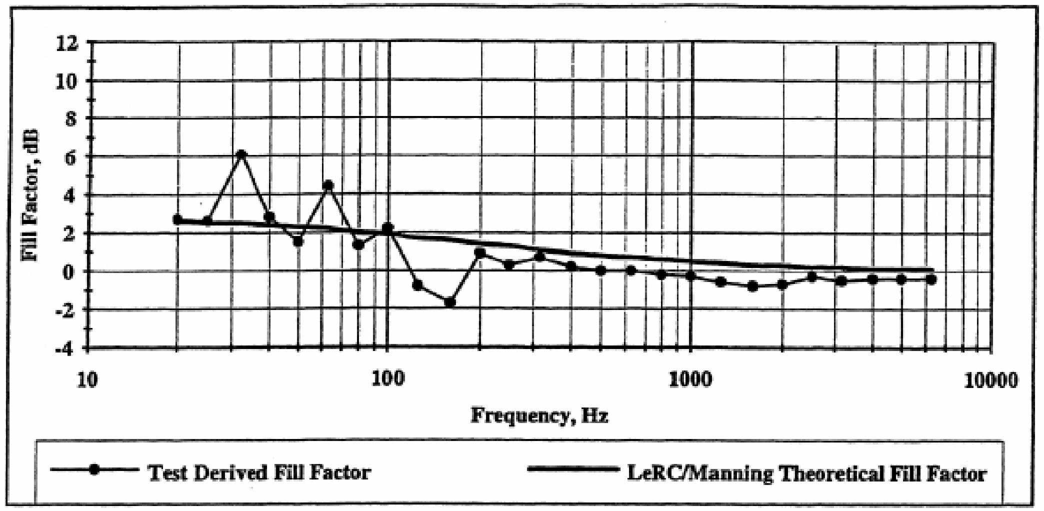
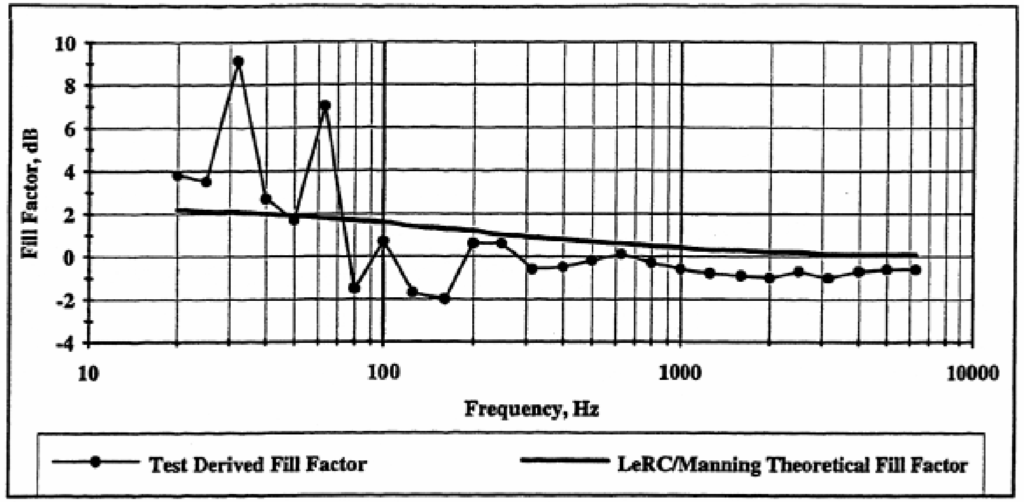


Figure 13.—Comparison of fill factor predictions for medium cylindrical fill/zone 3.

Large Square



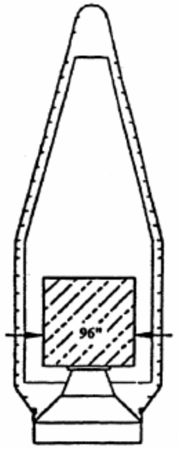
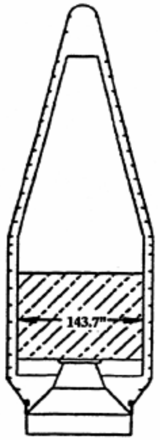
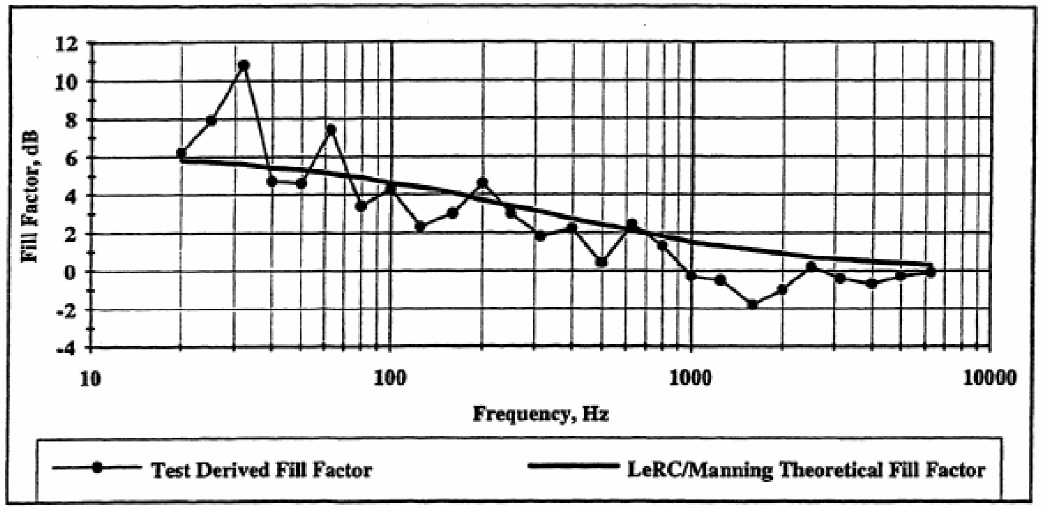


Figure 15.—Comparison of fill factor predictions for large square fill/zone 3.

Large Cylindrical





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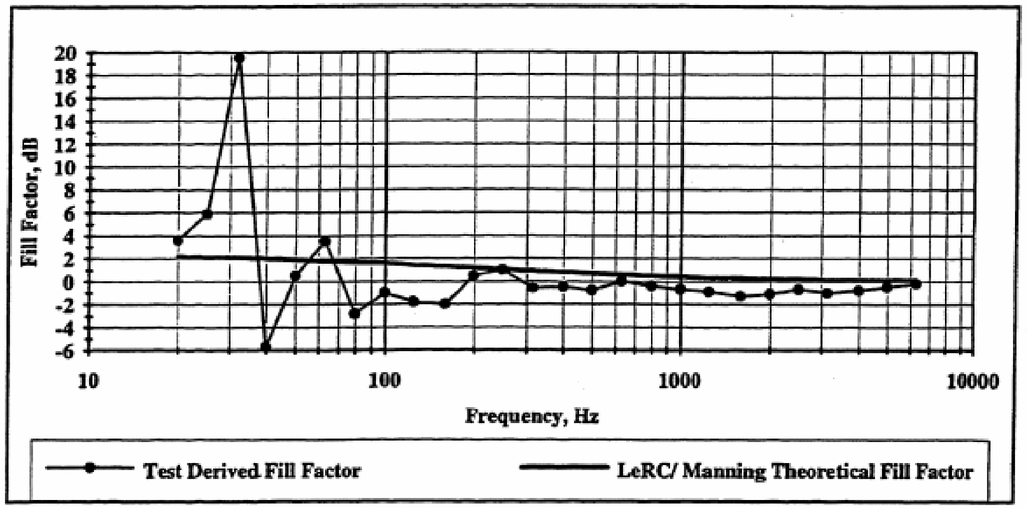
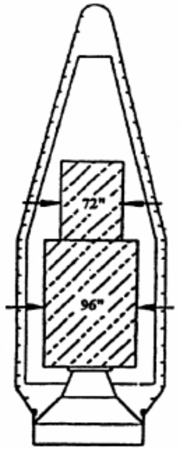
Stacked Cubes





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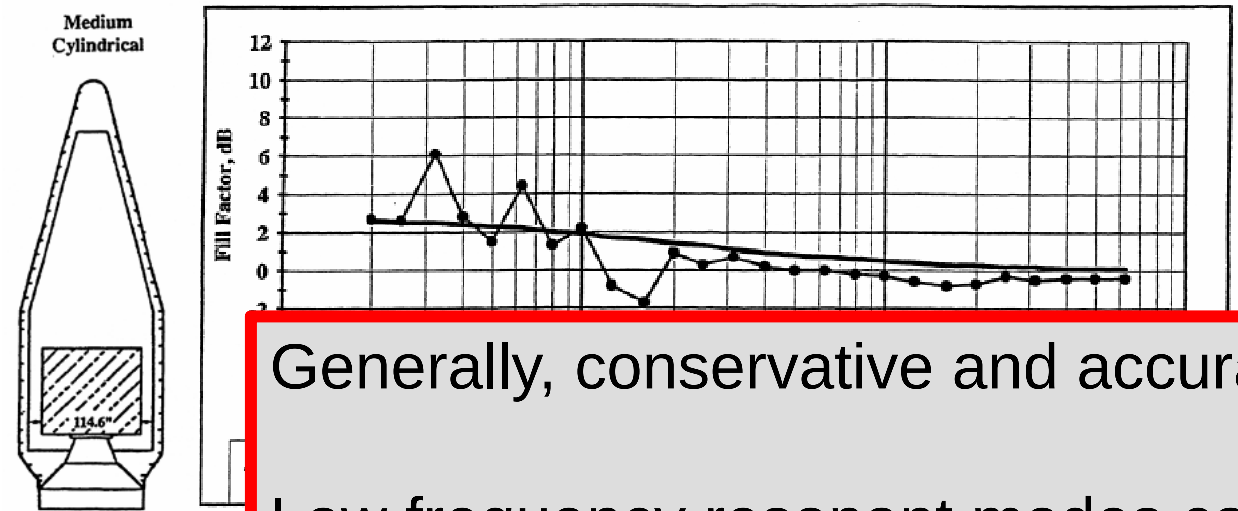
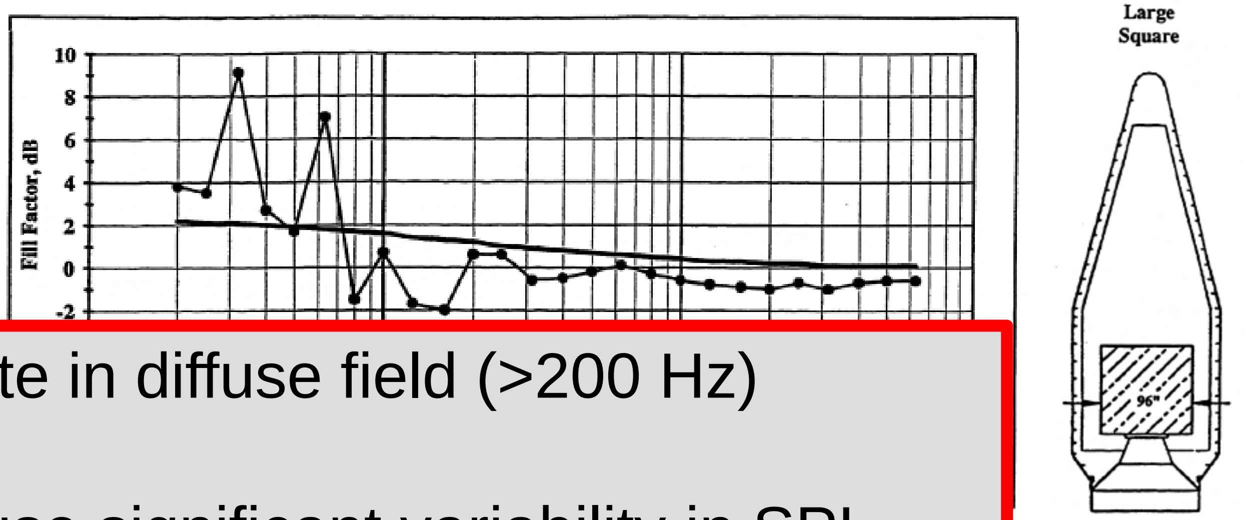
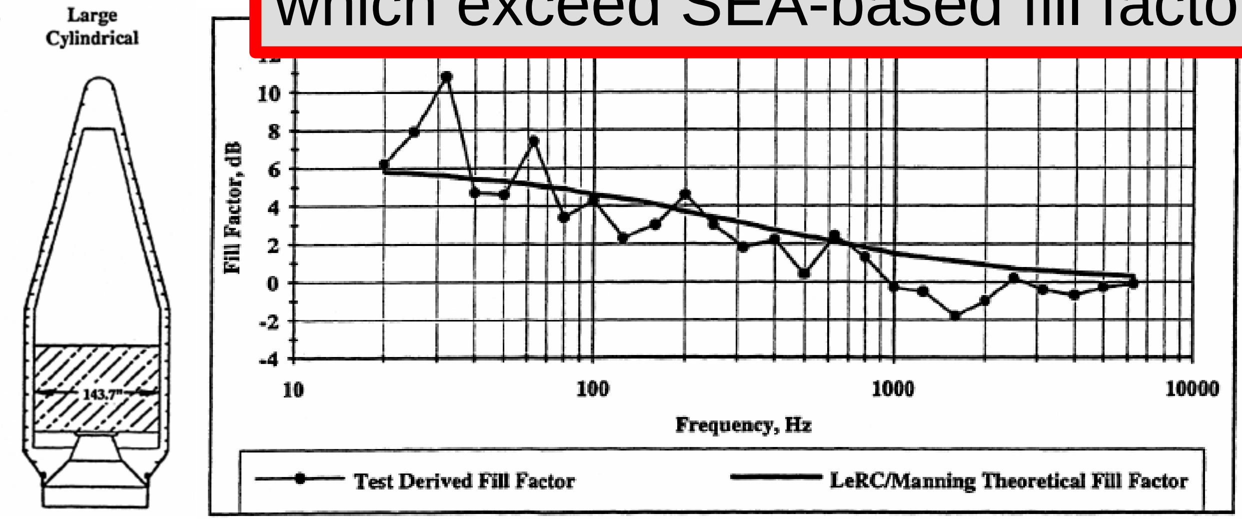
Fill Effect Theory/Experimental Comparison





Generally, conservative and accurate in diffuse field (>200 Hz)

Low frequency resonant modes cause significant variability in SPL which exceed SEA-based fill factor predictions



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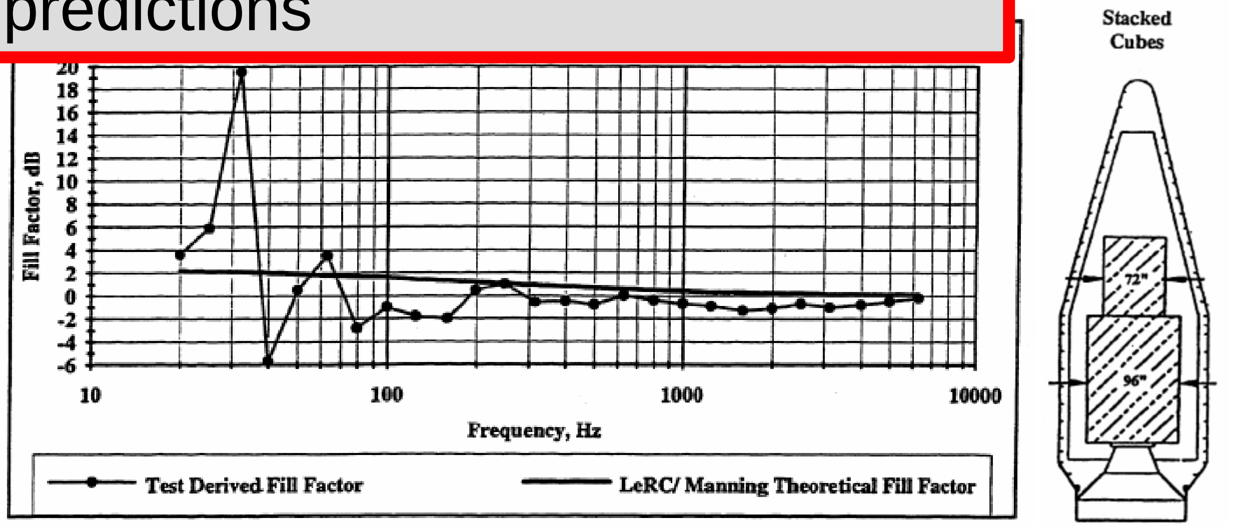

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VAOne Modeling

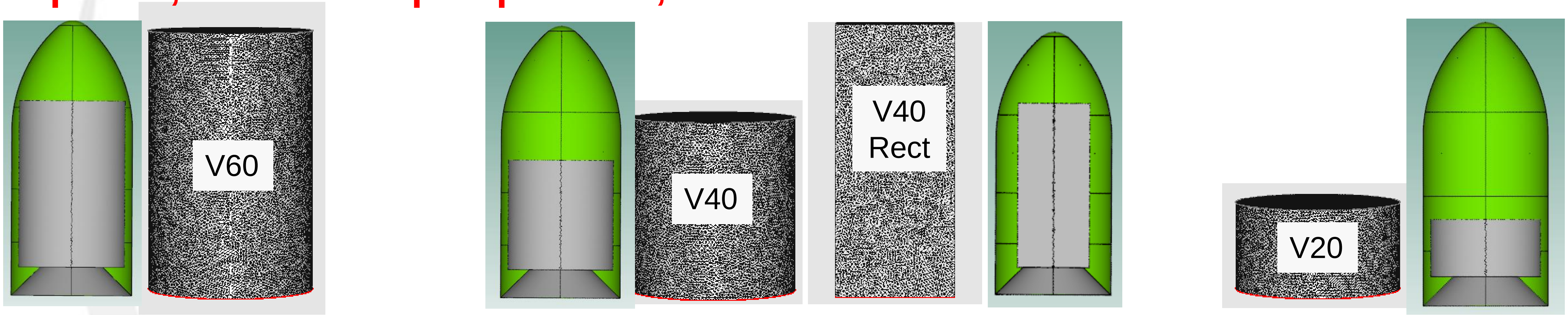
- **Modern vibroacoustic modeling software can incorporate complex cavity geometries**

- **We are interested in how 'unfilled' FE and SEA models with a fill factor correction would compare to models which incorporated a simulated payload volume cutout**

- **FE and SEA, 18+ total models**
  - Baseline - No cutout, 0% fill
  - Varied Volume Cylindrical, 60%, 40%, 20% fill
  - Rectangular, 40% fill
  - Varied Radius, Inner mold -20in, -40in, -60in (each ~33% fill)
  - Stepped Cylinder ~33% fill

Cutout Shapes

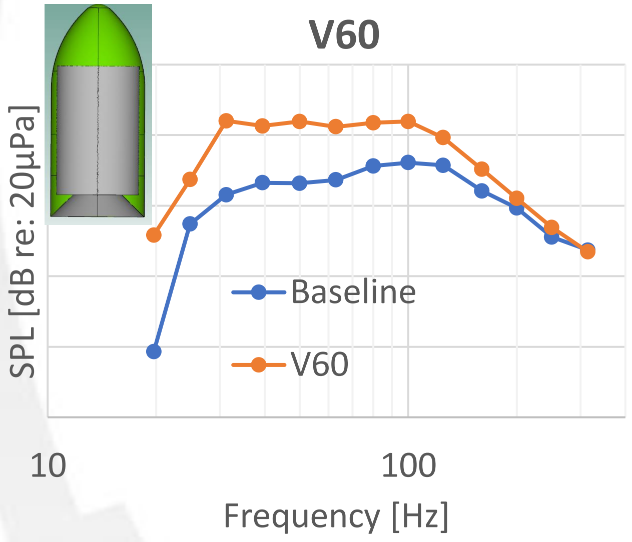
Top Row, All -20in Gap Separation, Varied Volume Fill

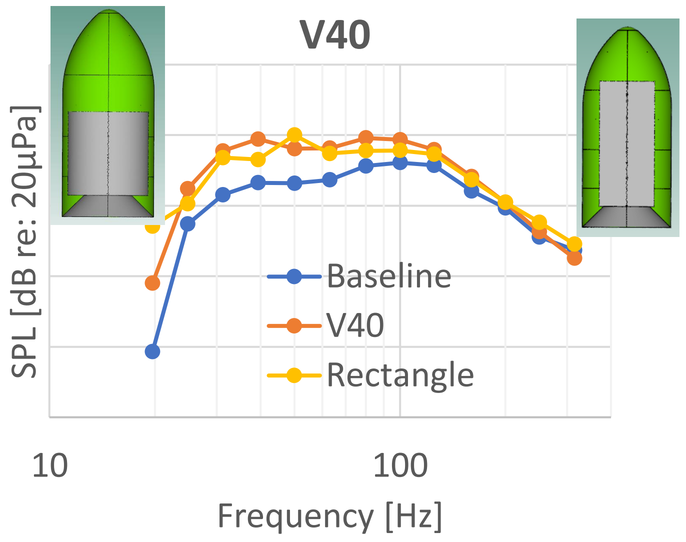


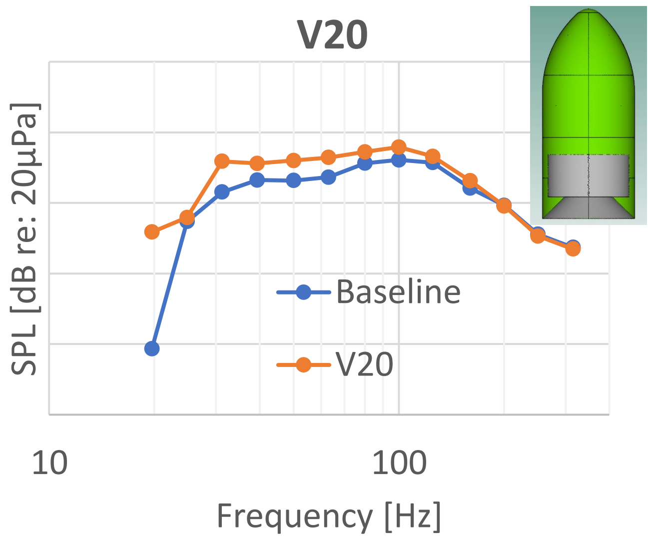
Simulated payload cutout boundaries are modeled as **rigid**

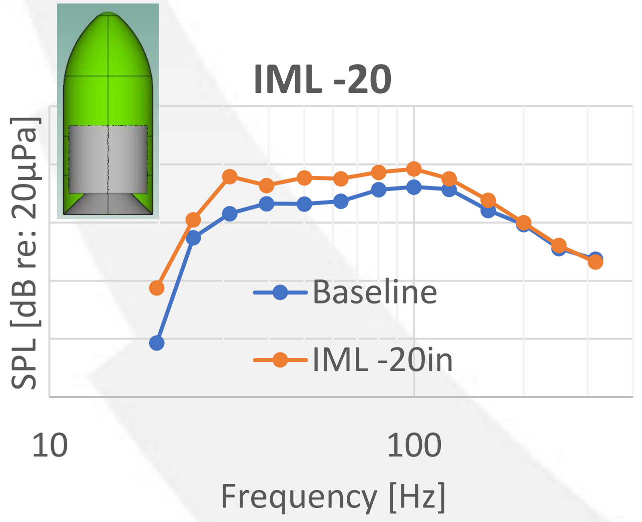
Bottom Row, All 33% Fill, Varied Separation Gap Distance

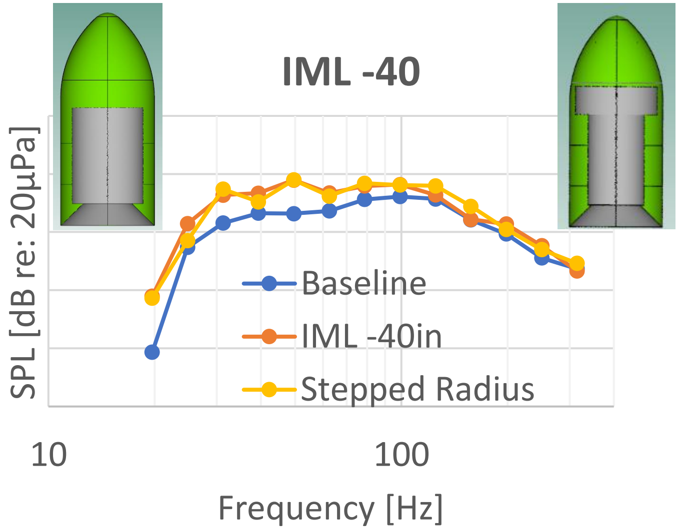
FE (Low Freq) Model Results, Overall Cavity Average

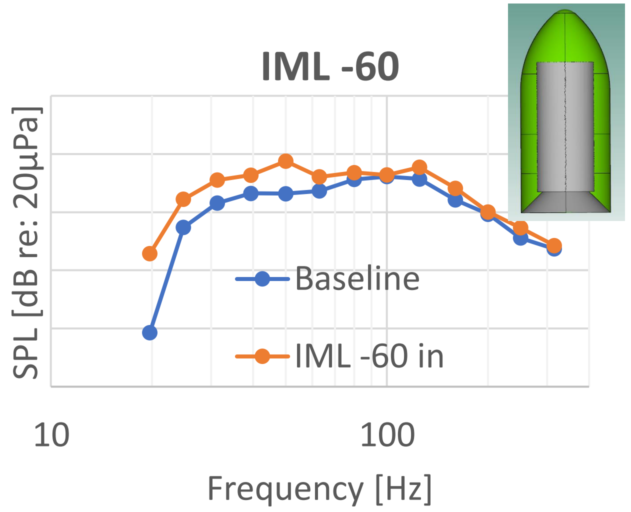




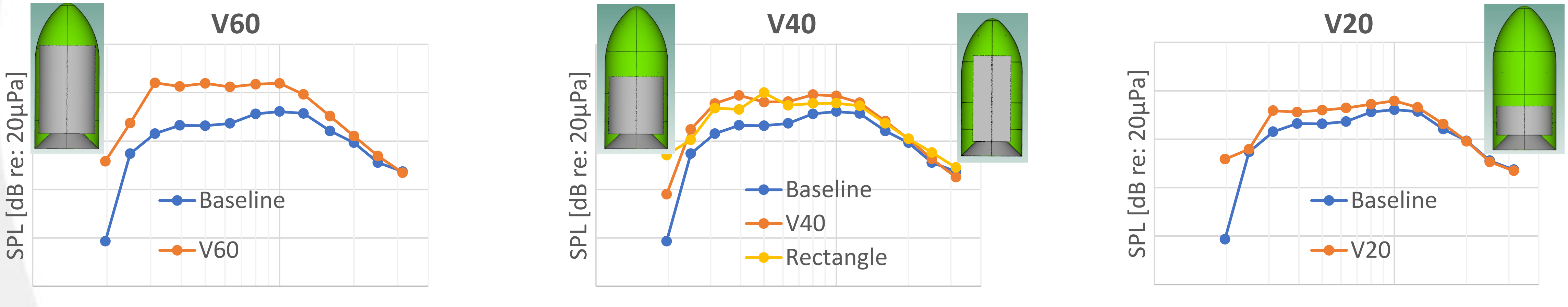




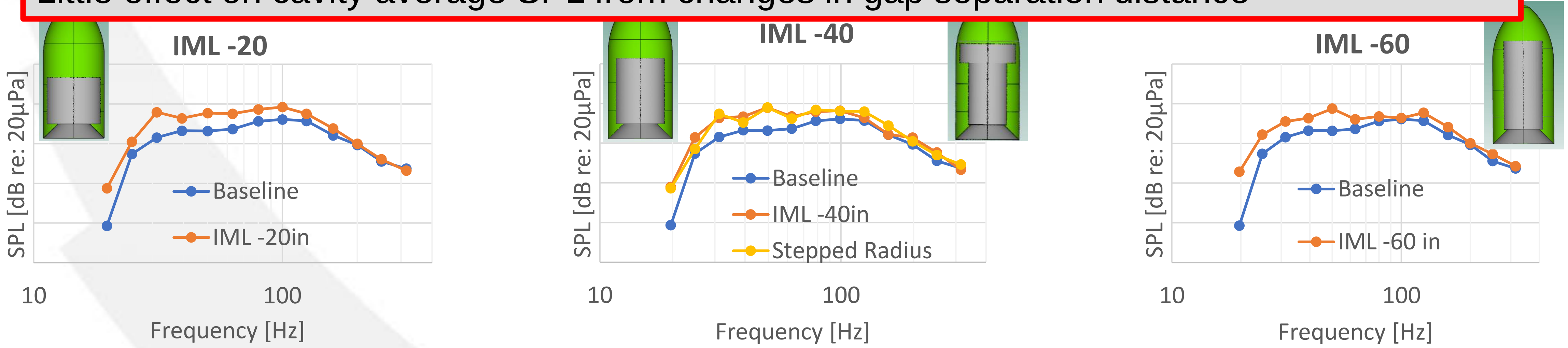




FE (Low Freq) Model Results, Overall Cavity Average

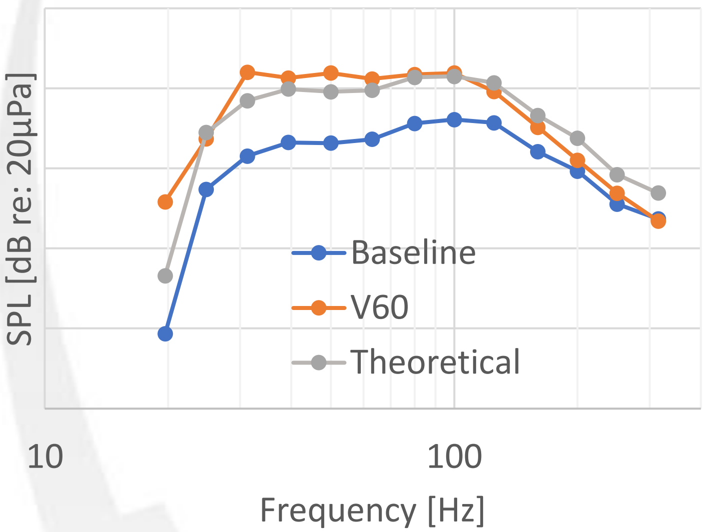


We observe significant increases in overall cavity average SPL with increases in volume fill
Little effect on cavity average SPL from changes in gap separation distance

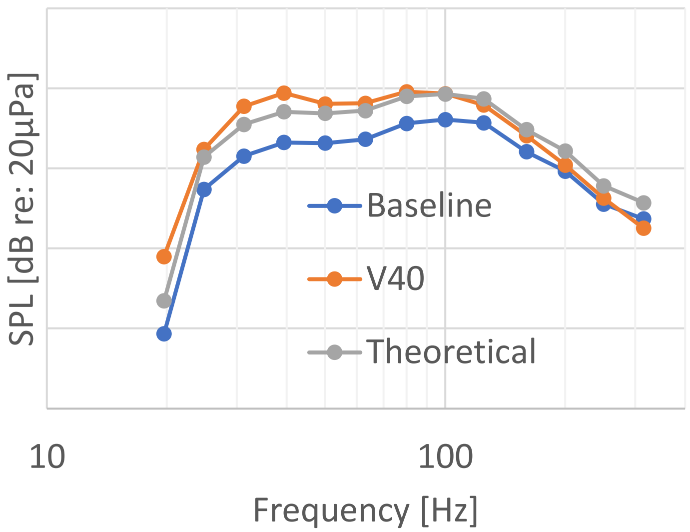


FE (low freq) model results, Overall Cavity Average

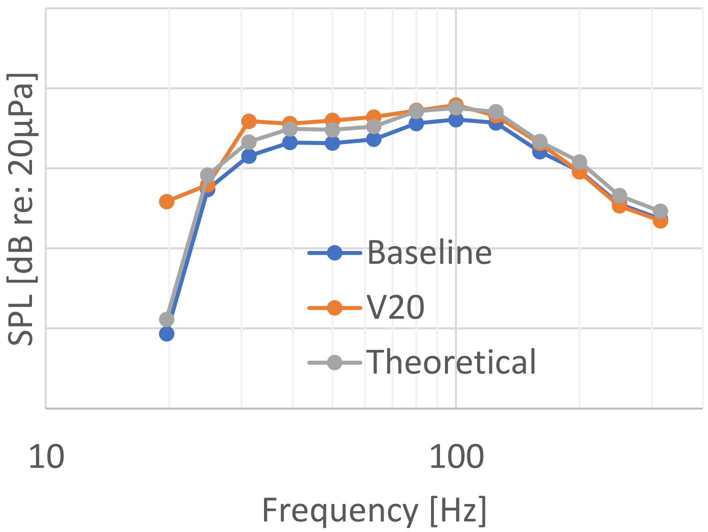
V60



V40

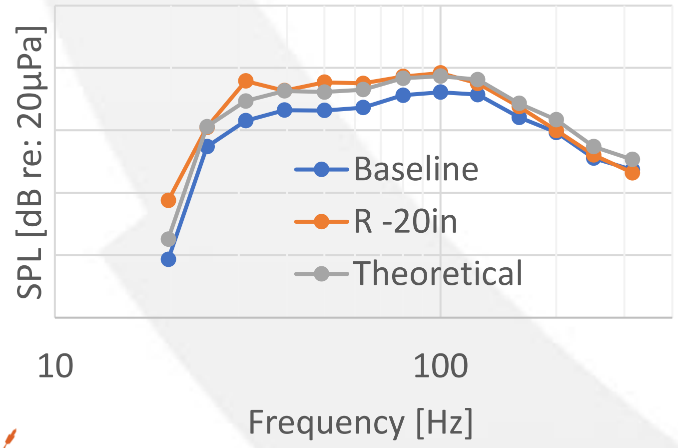


V20

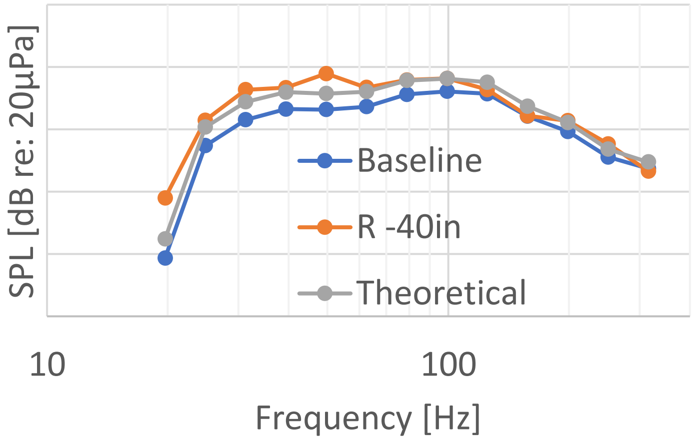


The FE model results and the theoretical fill factor capture similar trends

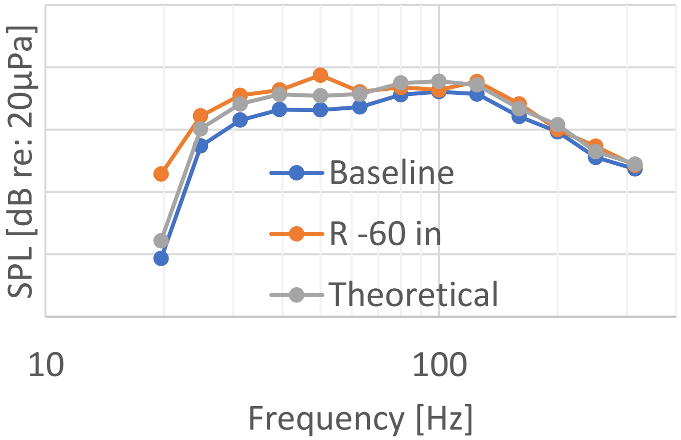
IML -20 in



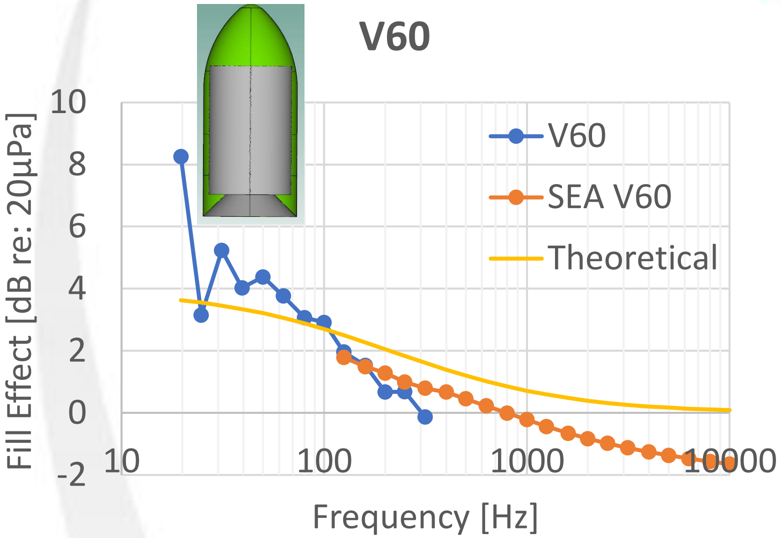
IML -40 in

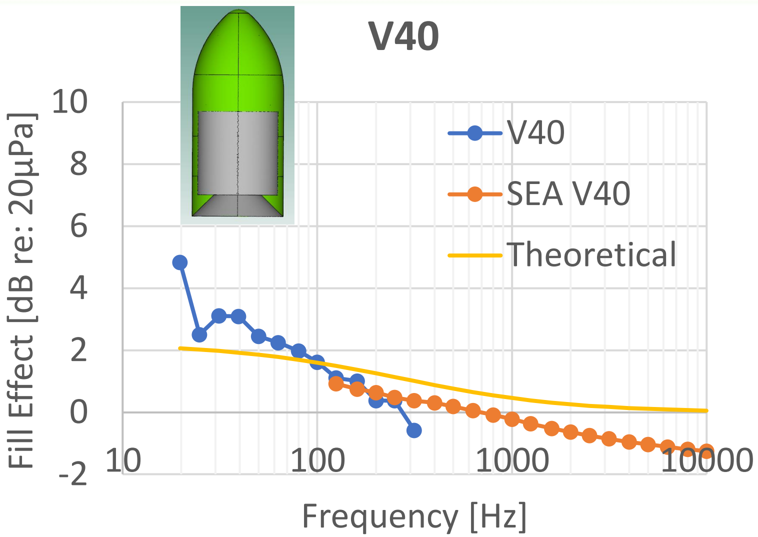


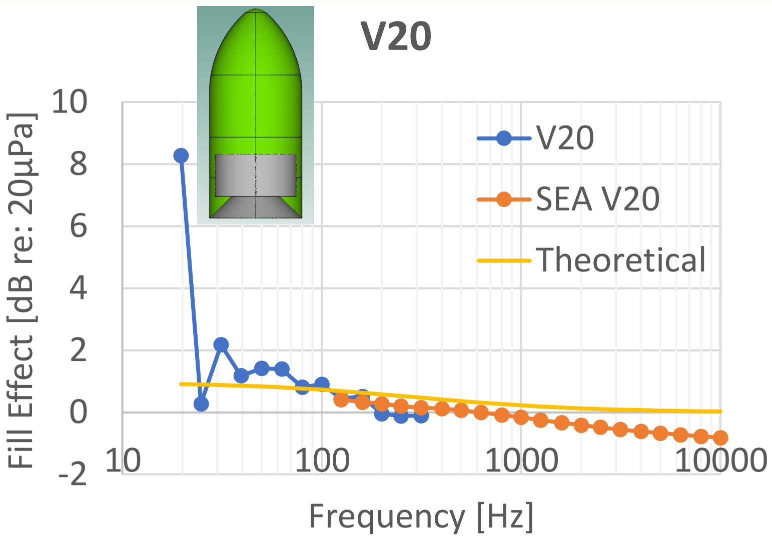
IML -60 in

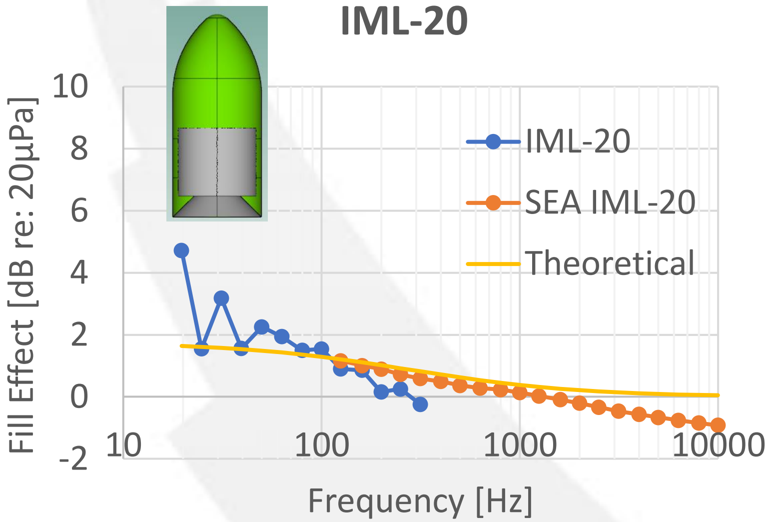


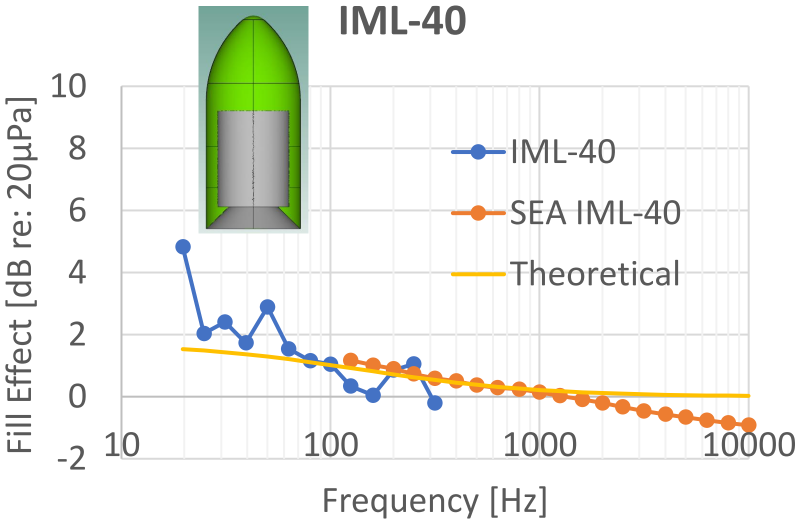
Comparison of modeled fill effect to fill factor

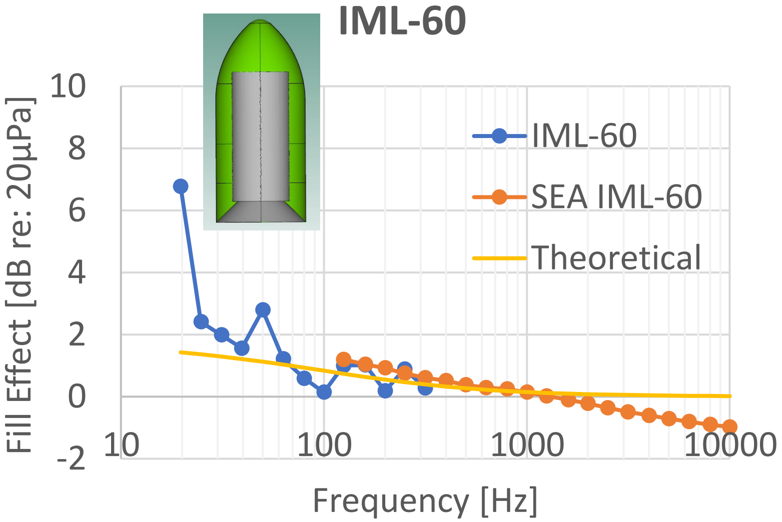










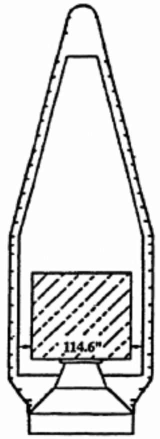


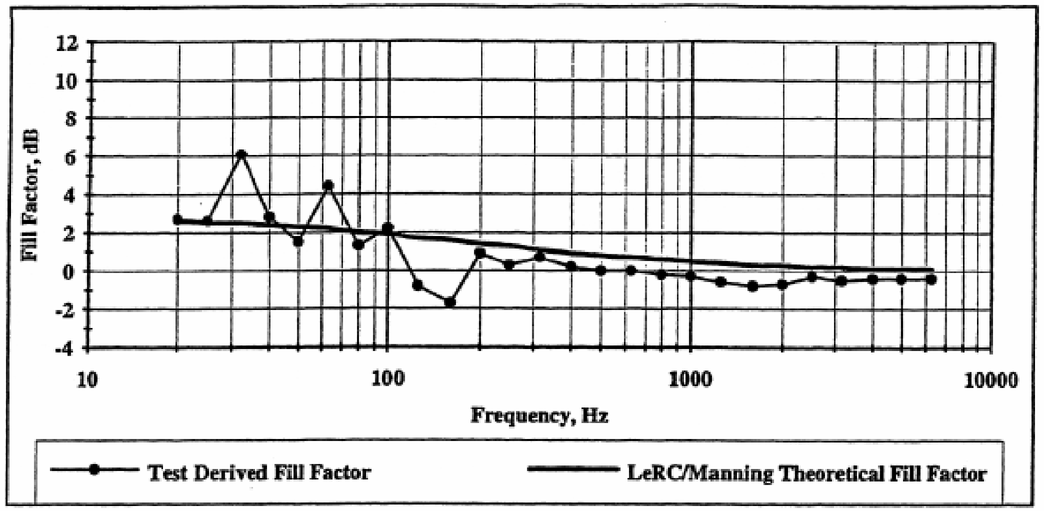
When a diffuse field is obtained in the cavity (>80 Hz), the fill factor is a suitable correction of the overall average SPL

Diffuse field loosely has 20 modes in band, uniform SPL

Fill Effect Theory/Experimental Comparison

Medium Cylindrical





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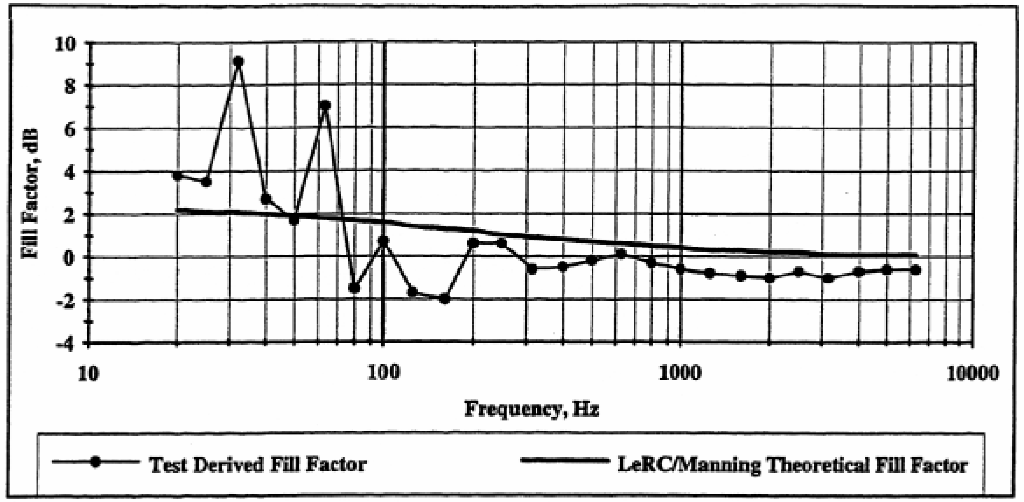
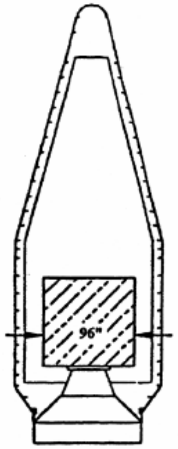


Large Square



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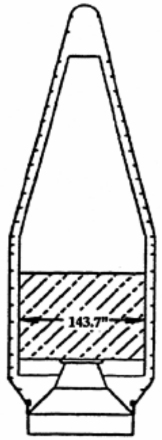

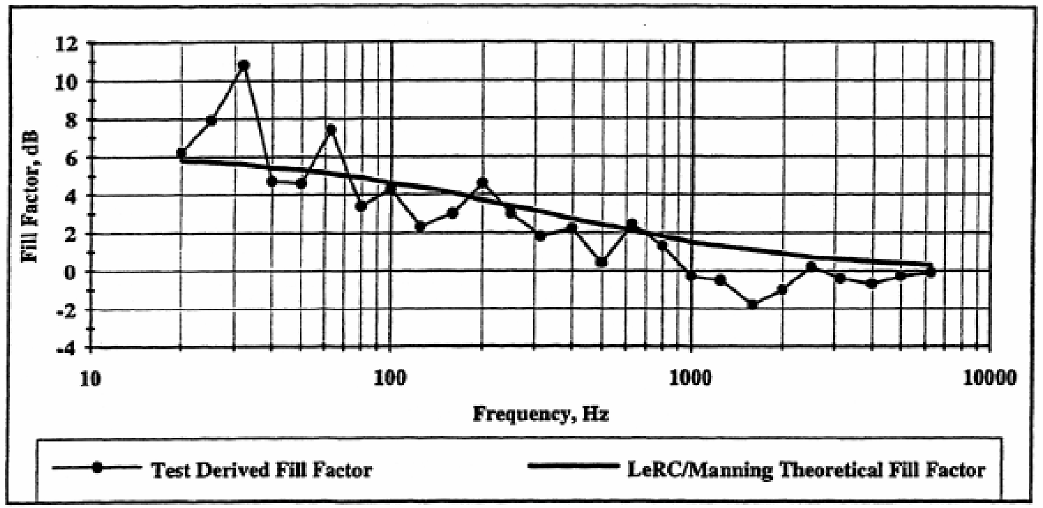

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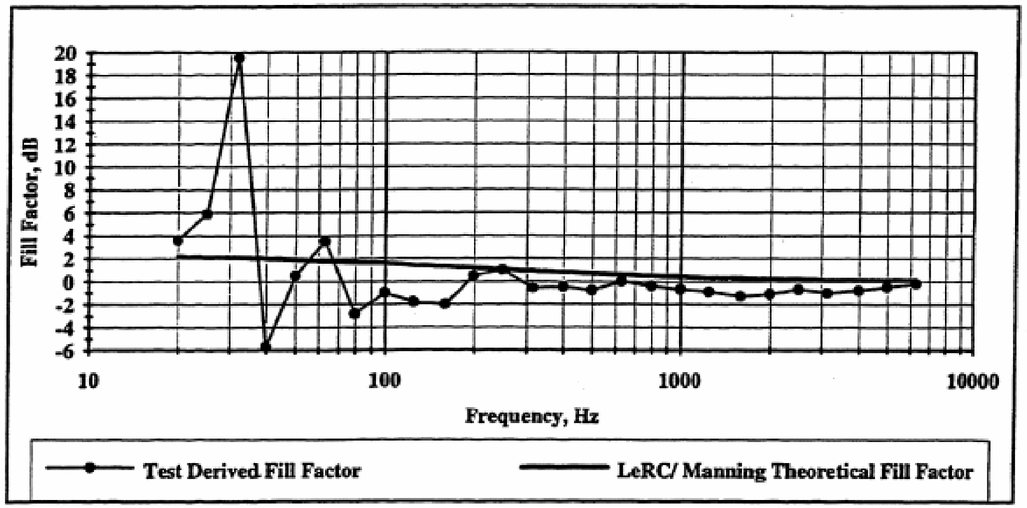
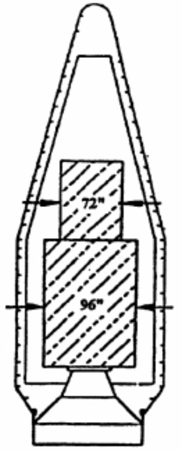


Stacked Cubes



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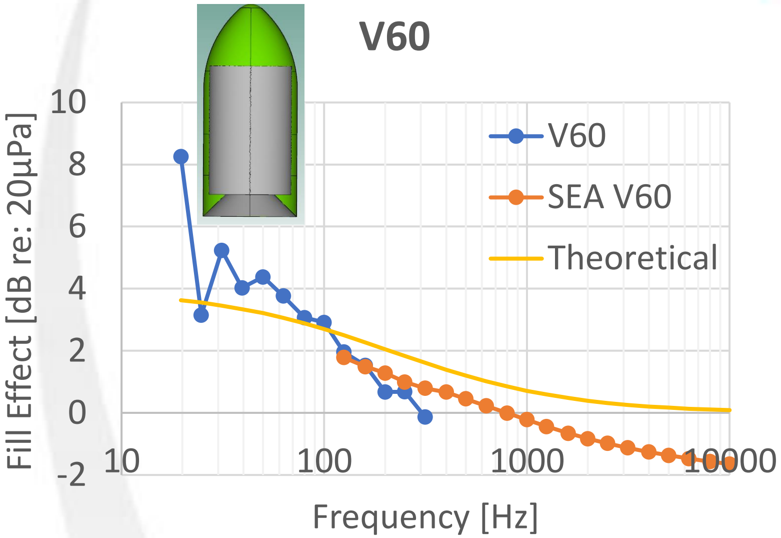
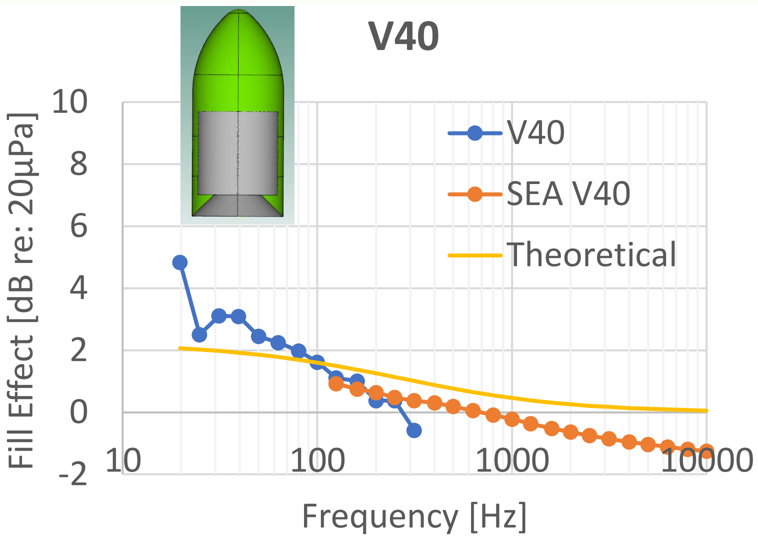
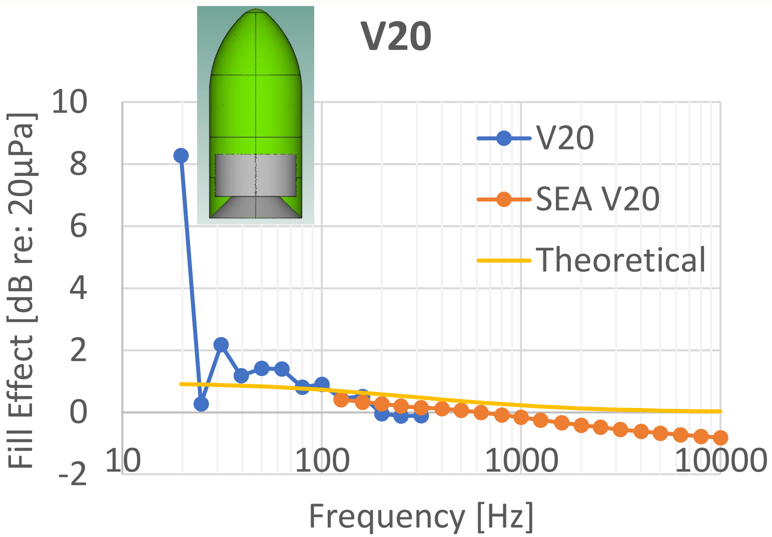
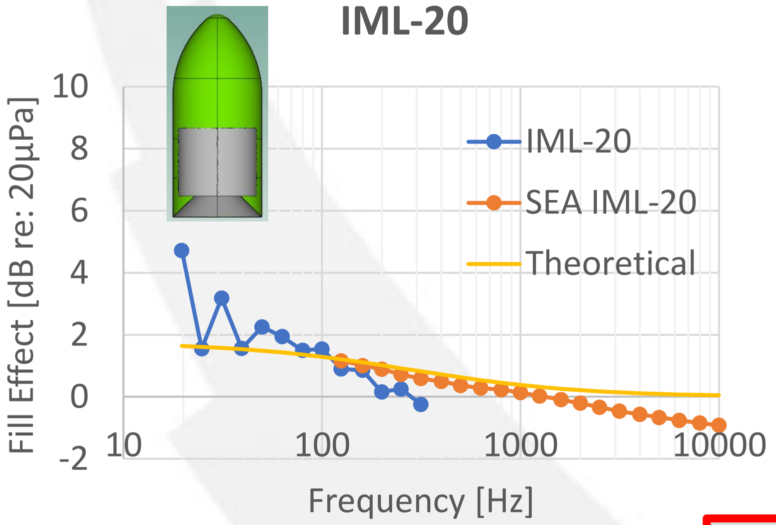
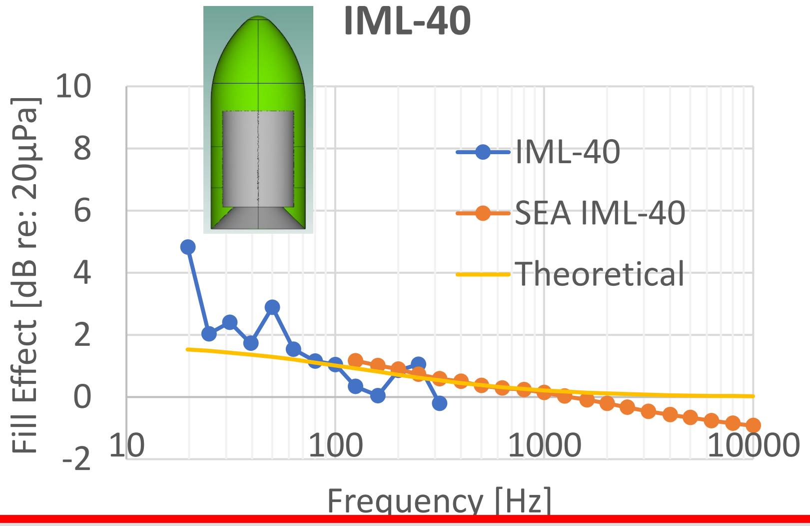
Comparison of modeled fill effect to fill factor

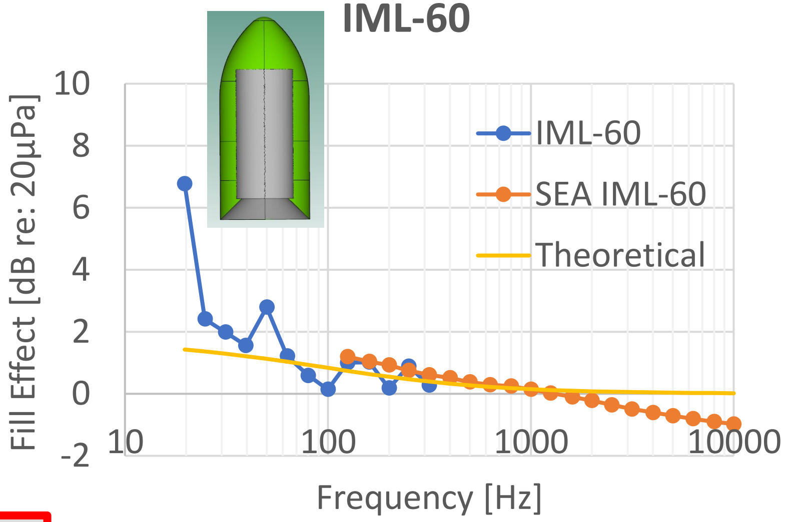












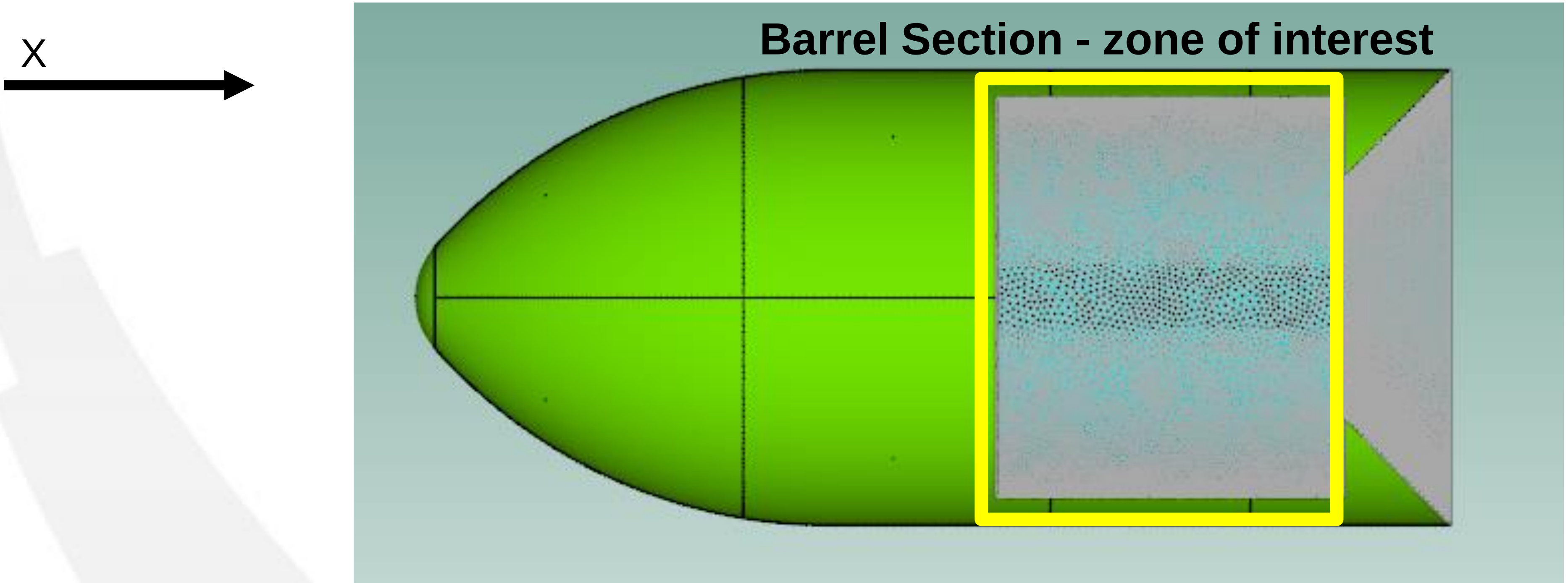
Similar profile to the 1994 NASA experiment

Overall Cavity Average Fill Effect

- **Theoretical fill factor based on statistical methods will not resolve individual modes**
  - Unable to capture discrete modes and their peaks and troughs
- **It is thought that the fill factor is appropriate for general usage because it is not overly penalizing for payload programs**
  - Provides a good target for design and testing in 1/3 octave band
- **Fill effect on overall cavity average was reviewed to isolate volume and gap separation variables**
  - Varied volume fill percentages were highly influential in the cavity OASPL, gap separation less influential on overall average

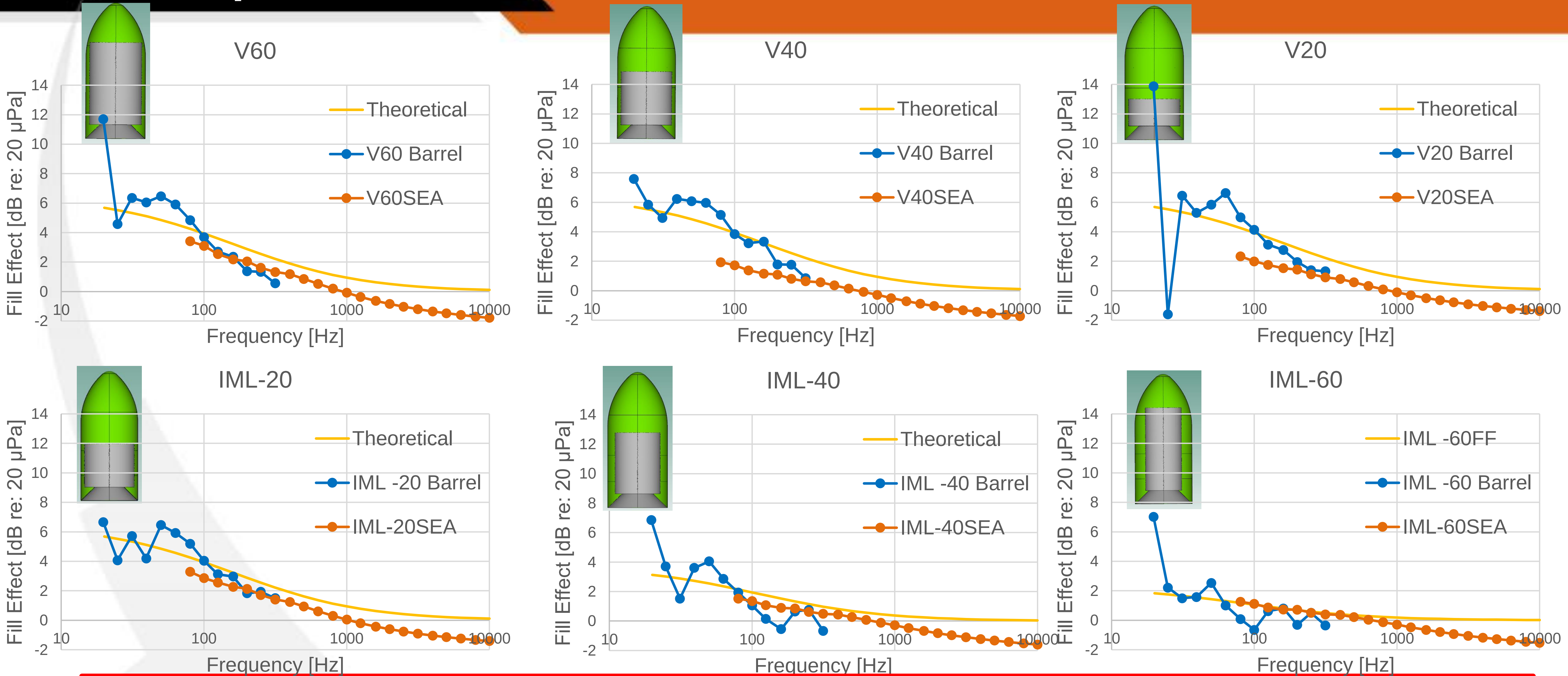
Local Fill Effect

The Fill Factor should be applied on a more local level
We investigate how redefining the "zone of interest" effects the fill factor performance



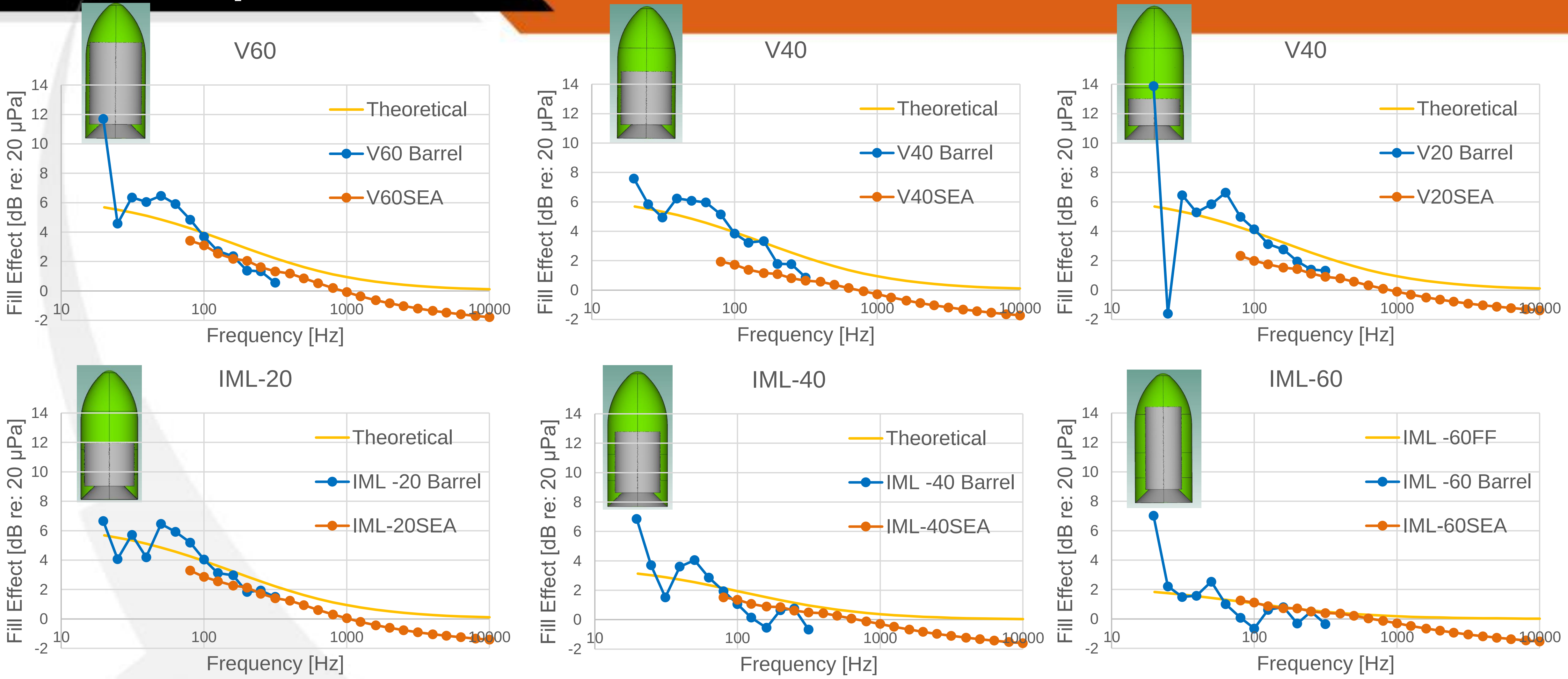
Every geometry will have its own zone of interest, the annulus around the payload cutout

Comparison of modeled fill effect to fill factor



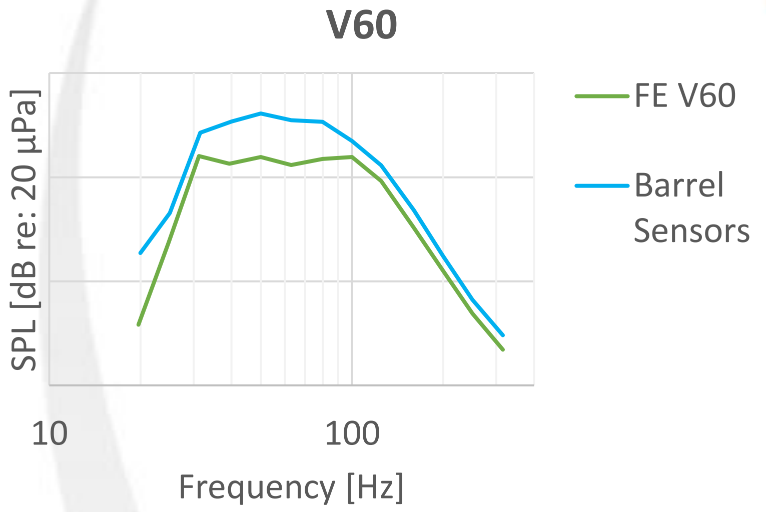
The Fill Factor was adjusted to address only the local area of interest, near the payload.
The V60, V40, V20, and IML-20 models now are **all considered 77% fill** in the zone of interest
The IML-40 model is **57% filled,** and the IML-60 model is **40% filled.**

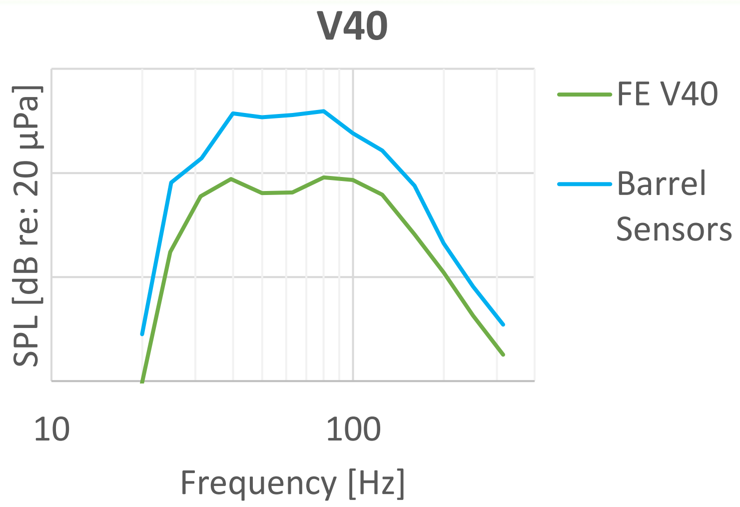
Comparison of modeled fill effect to fill factor

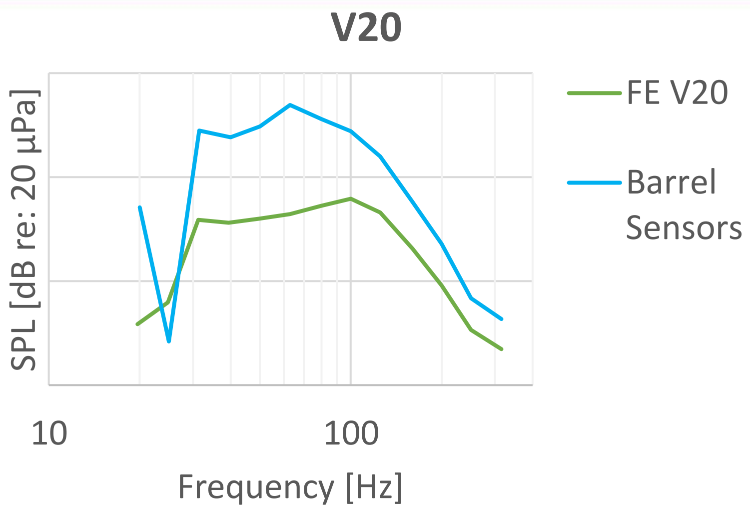


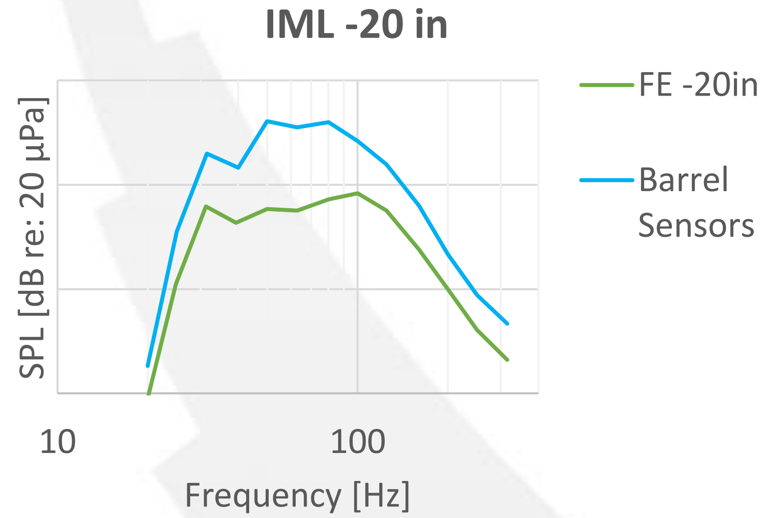
Again, it is observed that the fill effect in the models becomes negative above 1kHz
Large peaks at low frequencies attributed to axial modes in the cavity

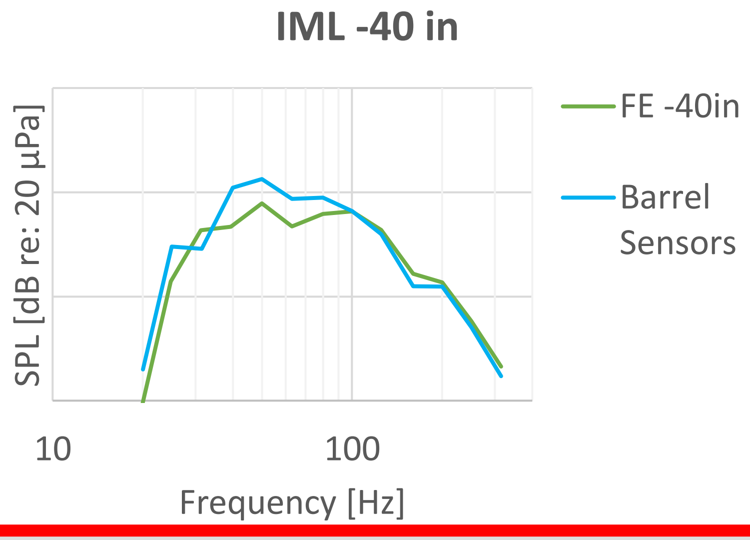
Comparison of zone of interest and overall cavity averages

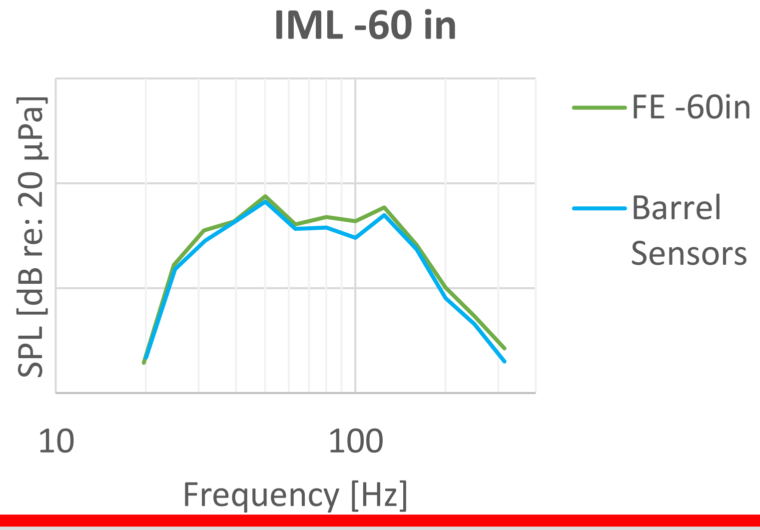












If a payload shape/size is known, it's proper to define our internal acoustic environment using a zone of interest near the payload (blue) rather than an overall cavity average (green).

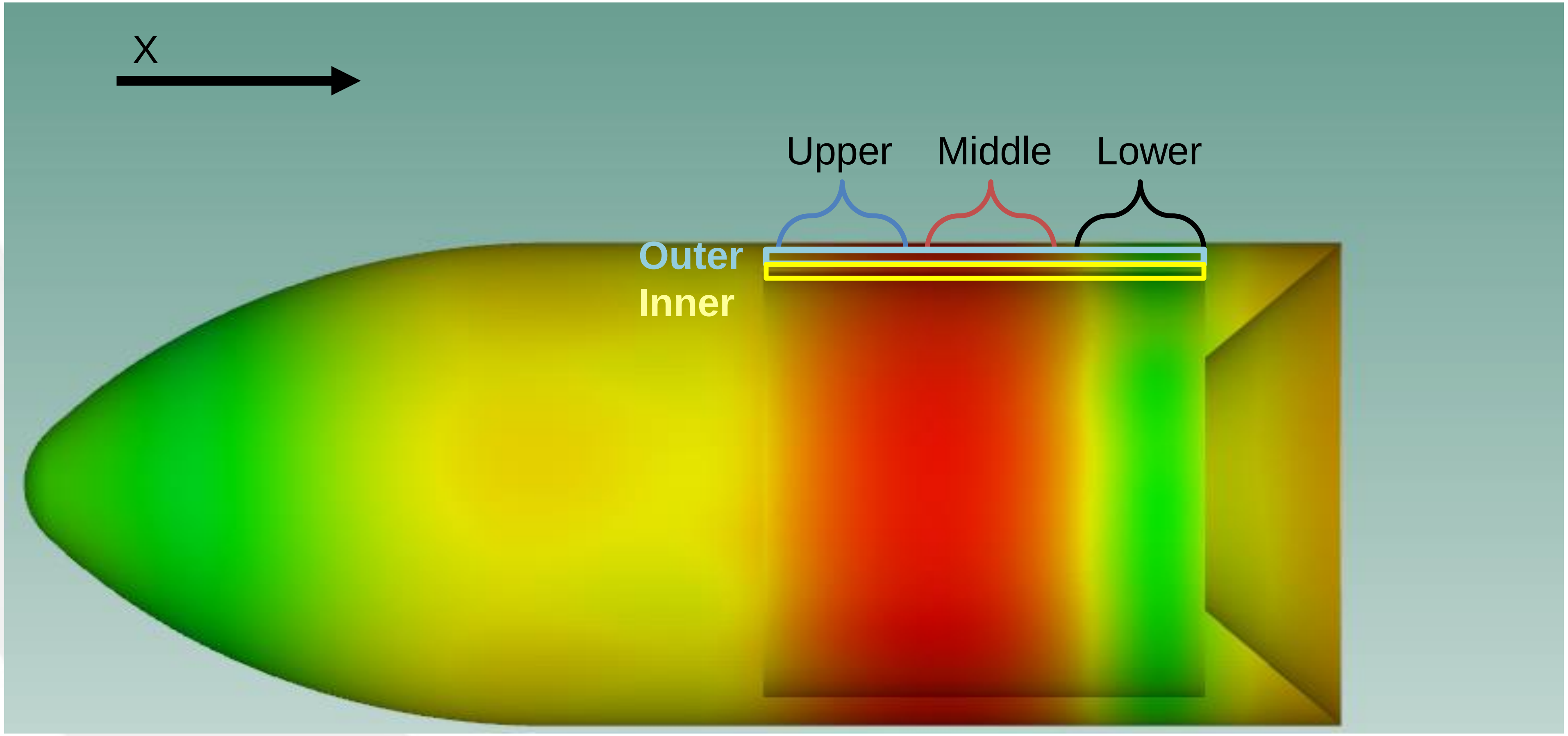
Local Fill Effect

- **Fill factor is intended to be applied locally**
  - Application on a global scale underestimates volume fill %
  - Global factor underestimated fill effect within zone of interest by 1 to 5 dB compared to local fill factor
- **Volume and radius are coupled variables and thus the fill effect can be fully defined by either volume fill or gap separation**
  - Assuming cylindrical payload
  - Difficult to comment on how each variable independently affects fill factor
- **Exceptionally sensitive components with low frequency resonances may require special attention**
  - Observe how axially oriented modes can result in high SPL's along some parts of the payload

Spatial Variation of SPL inside fairing

Example of spatial variation on surfaces at 40Hz:

- We see that the pressure magnitude on the exterior surface is similar to the pressure distribution on the simulated payload cutout surface in this case
- The low frequency modes are axially oriented

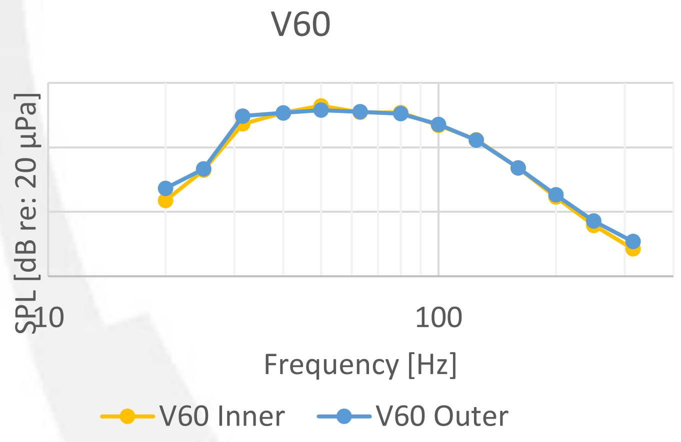


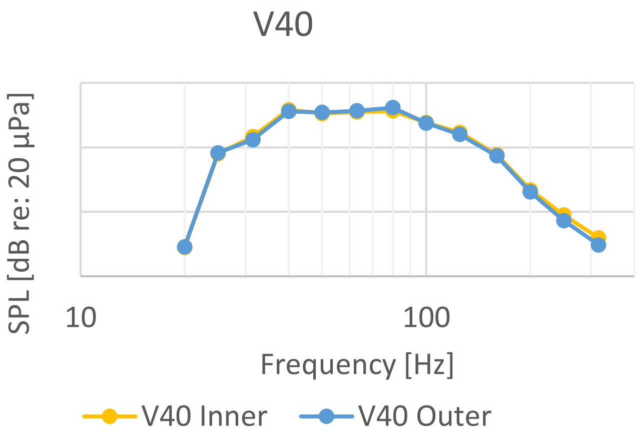
Comparison of radial spatial variation

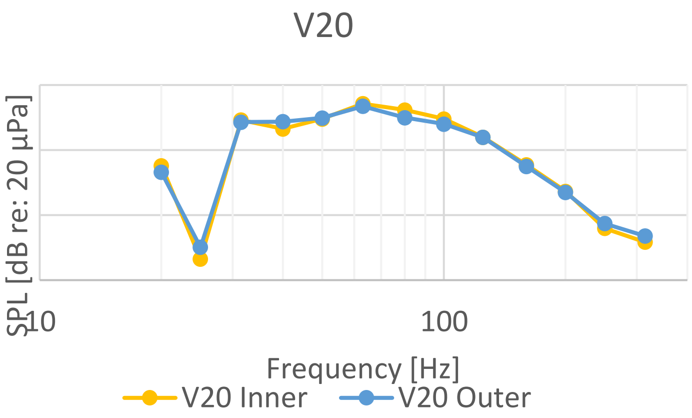
Comparison of virtual sensors nearer the payload cutout (inner) vs. nearer the fairing wall (outer)

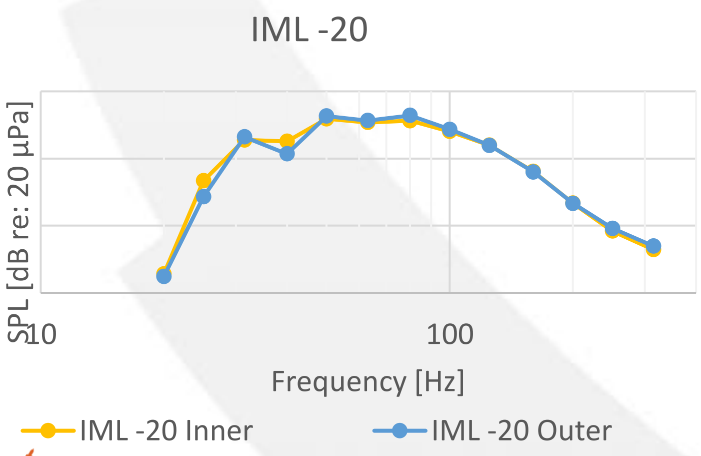
Sensors were averaged down the axial length

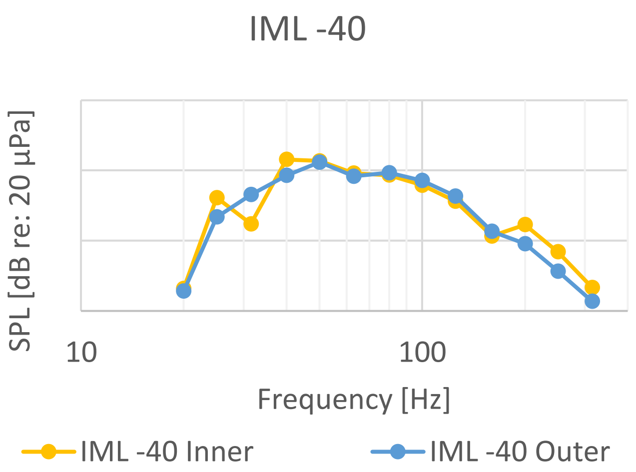
Above 80 Hz we see little spatial variation due to the development of a diffuse acoustic field

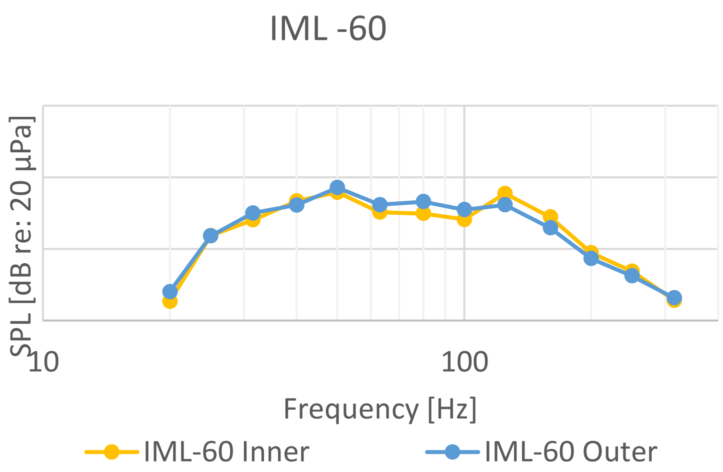










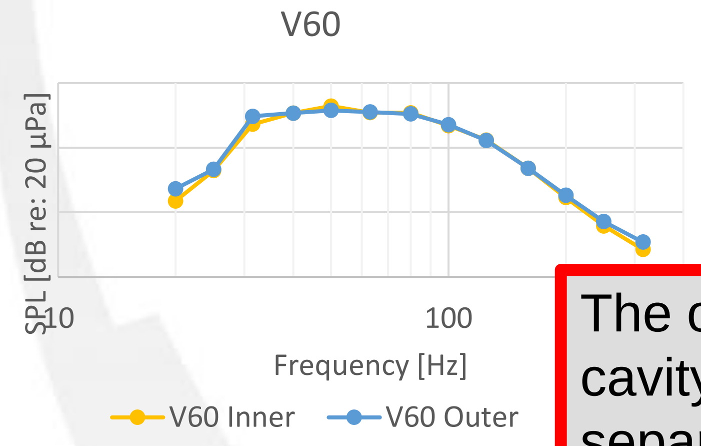


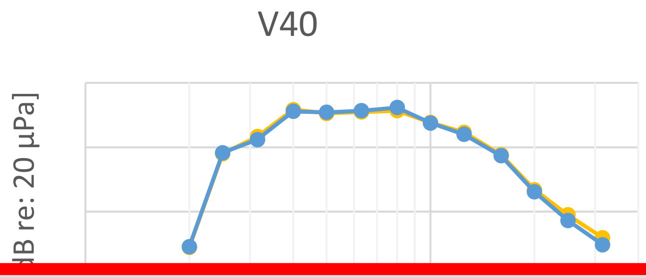
Comparison of radial spatial variation

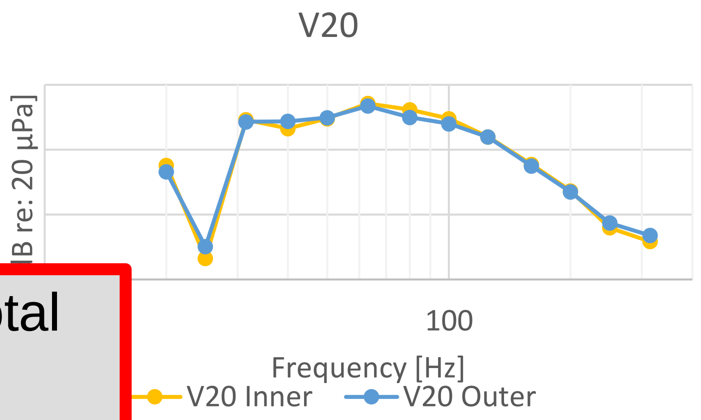
Comparison of virtual sensors nearer the payload cutout (inner) vs. nearer the fairing wall (outer)

Sensors were averaged down the axial length

Above 80 Hz we see little spatial variation due to the development of a diffuse acoustic field

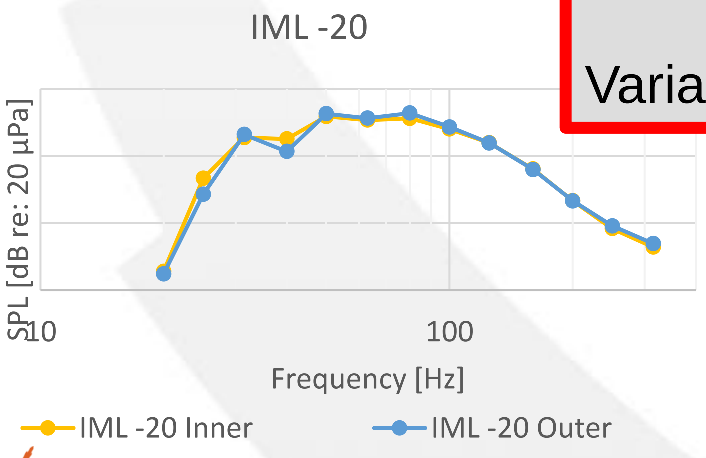


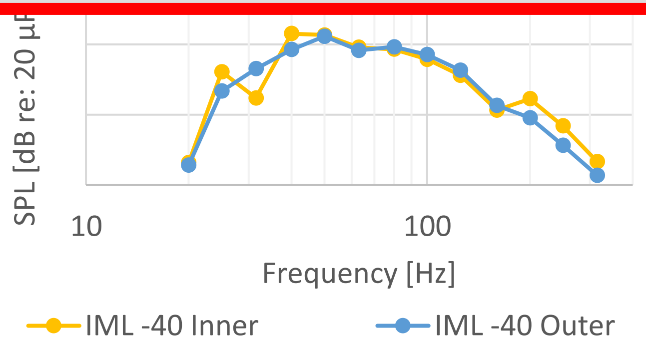


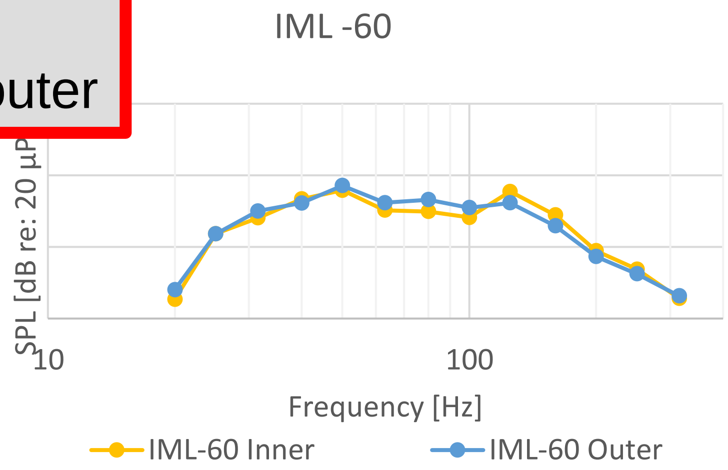


The outer and inner zone SPL exceed the total cavity average for most models, unless separation gap is large (IML-60)

Variation in SPL is not significant, inner vs. outer

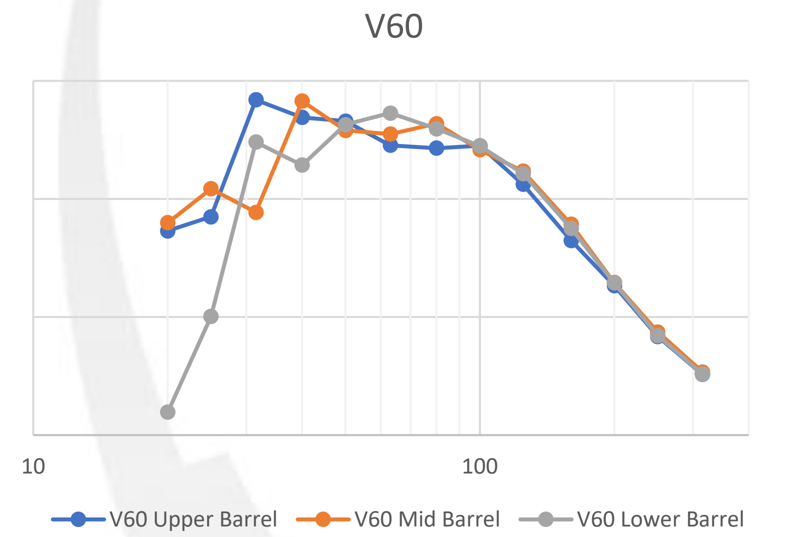


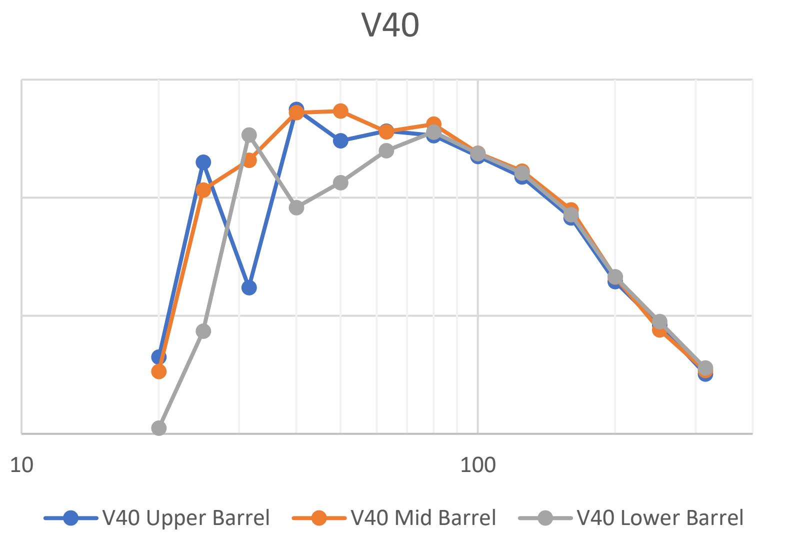


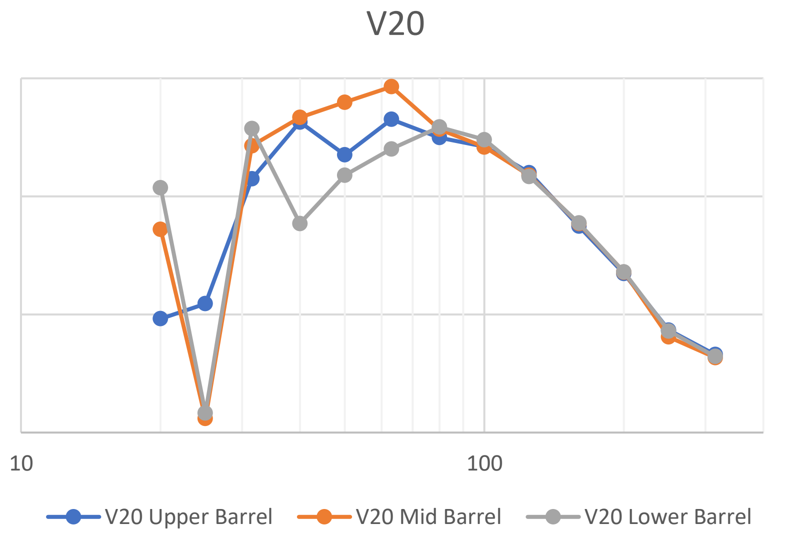


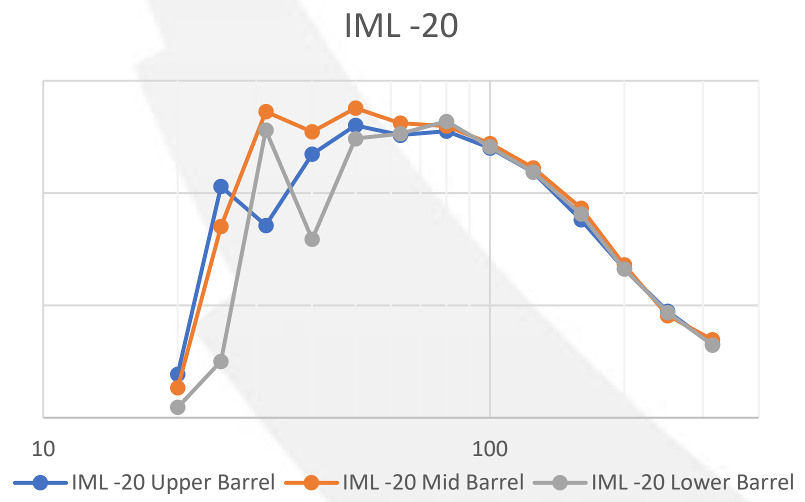
Comparison of modeled fill effect to fill factor

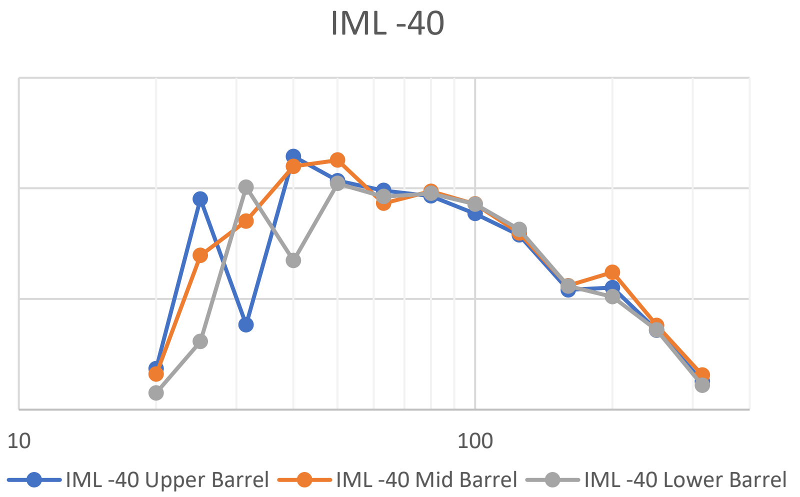
Comparison of virtual sensors nearer Lower, Middle, and Upper part of the barrel section near the payload cutout

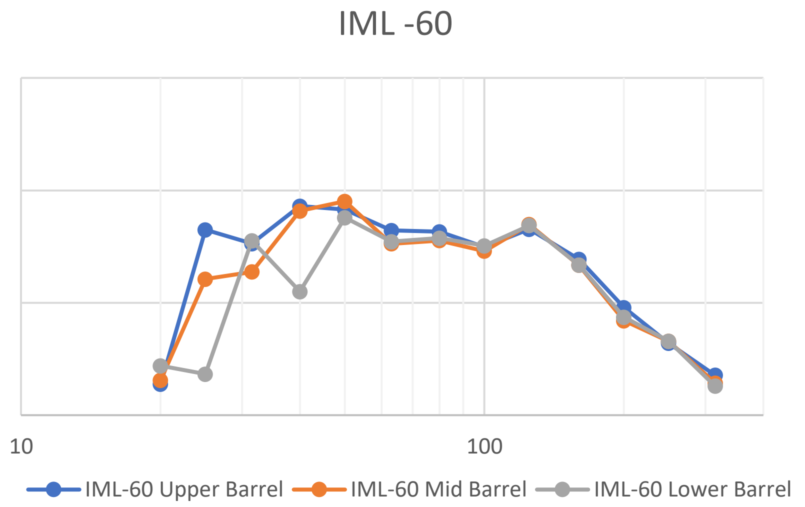






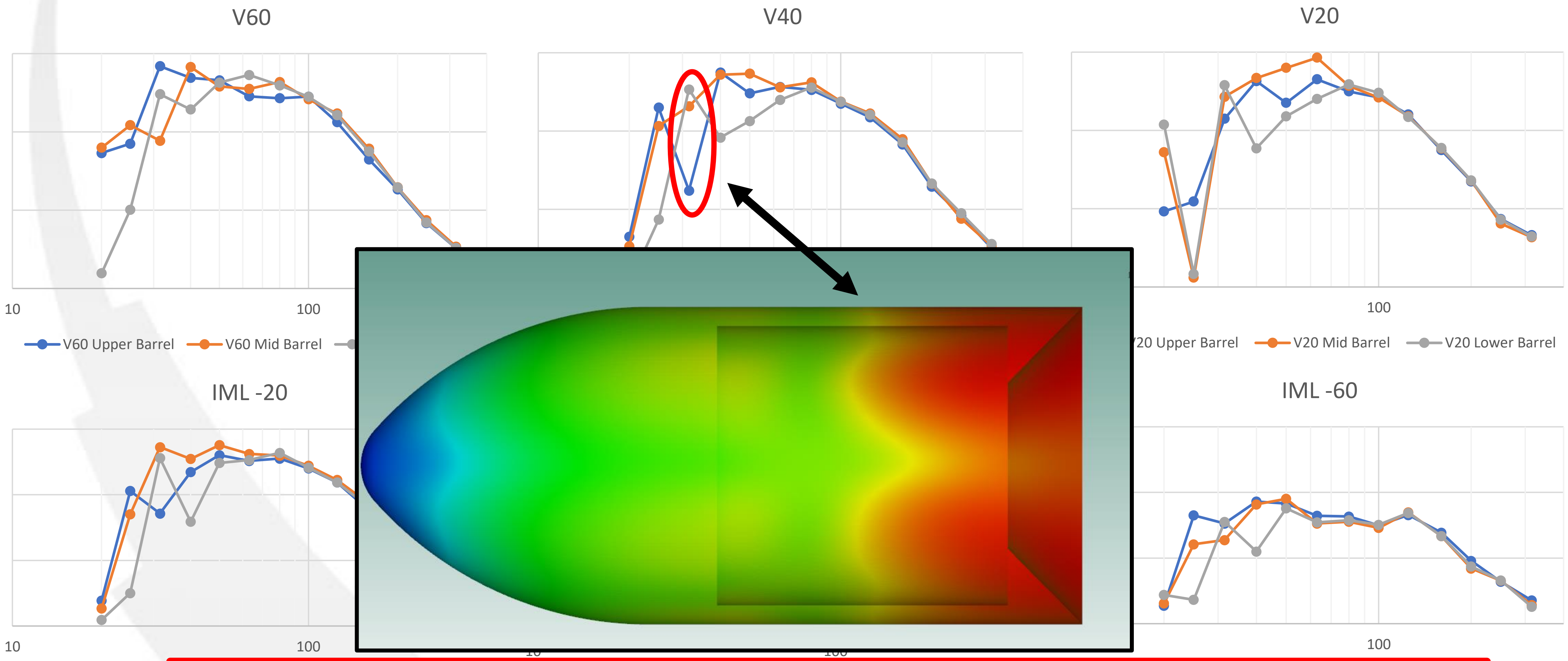






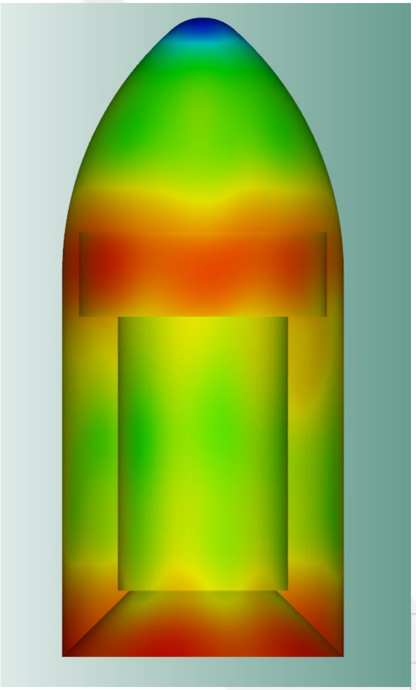
Comparison of modeled fill effect to fill factor

Comparison of virtual sensors nearer Lower, Middle, and Upper part of the barrel section near the payload cutout

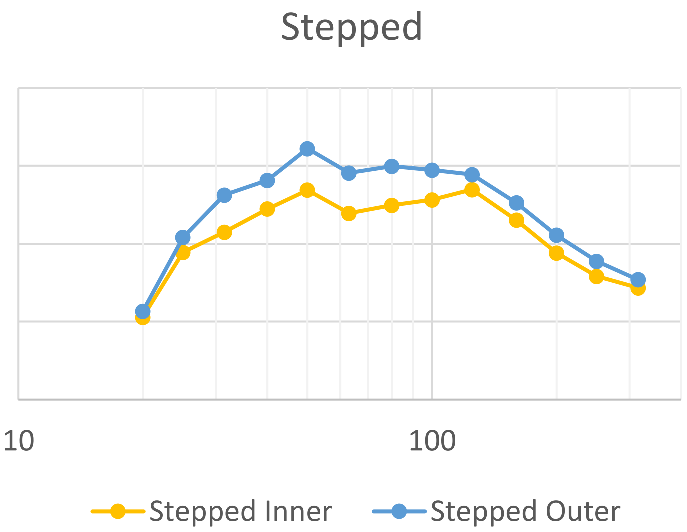


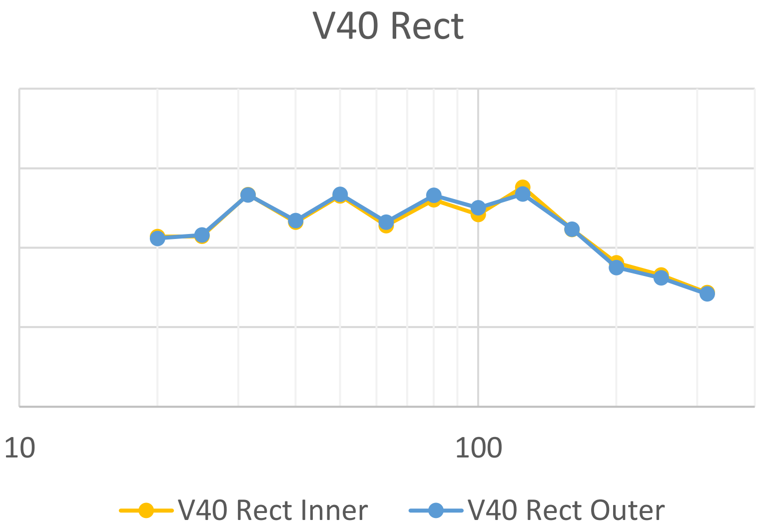
Low frequency axially oriented modes cause spatial variation in SPL, 32Hz shown

Spatial variation of stepped and rectangular geometries

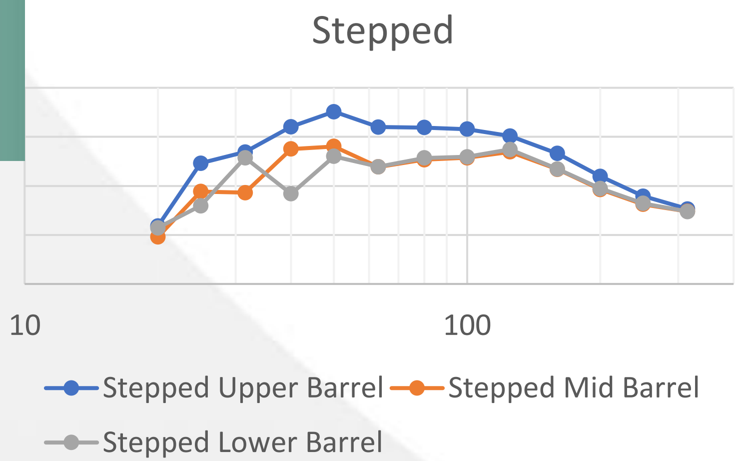


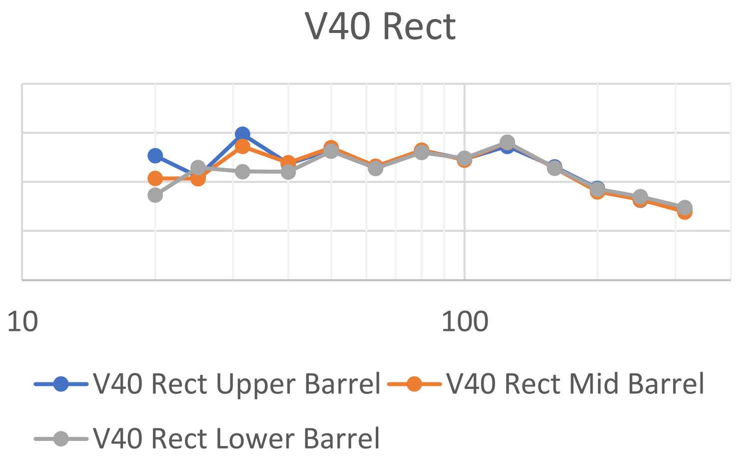
Inner vs. Outer

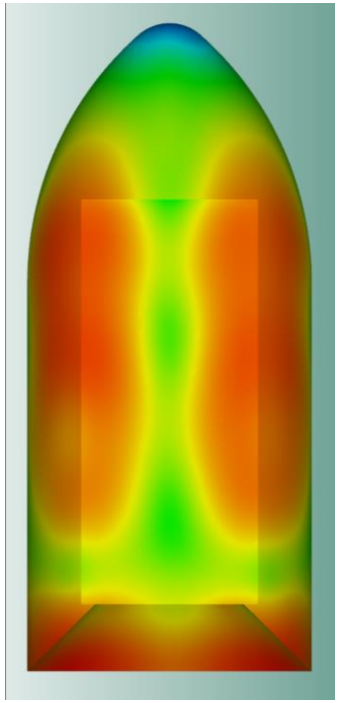




Lower, Middle, and Upper

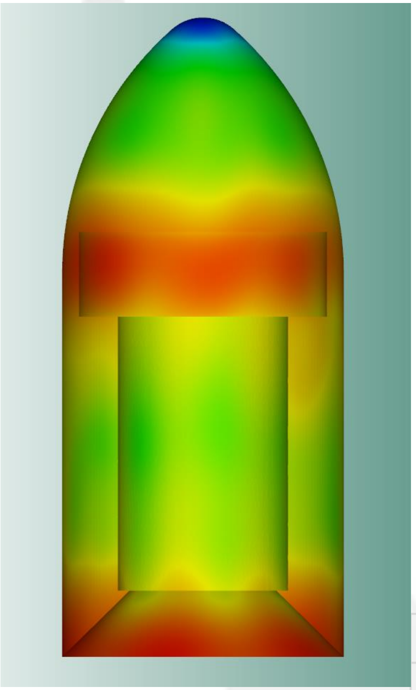




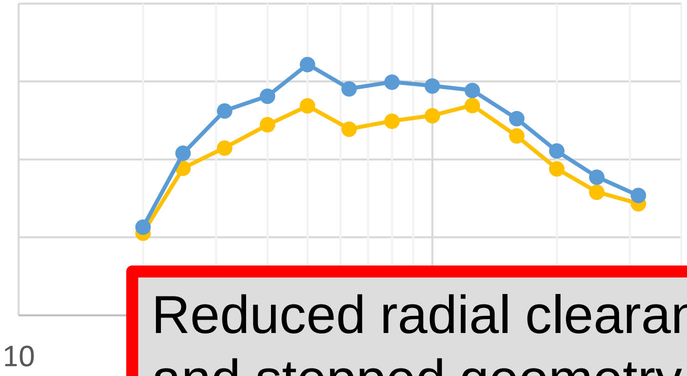


Spatial variation of stepped and rectangular geometries

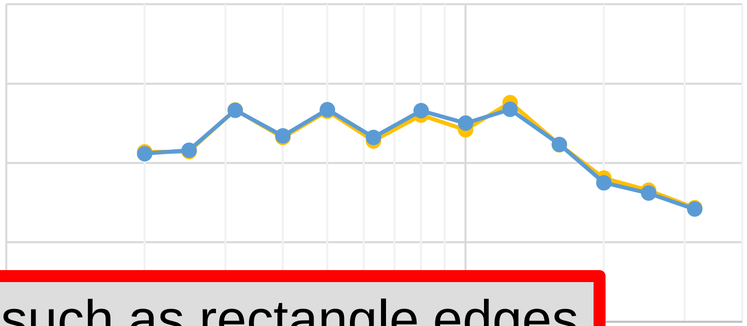
Inner vs. Outer



Stepped



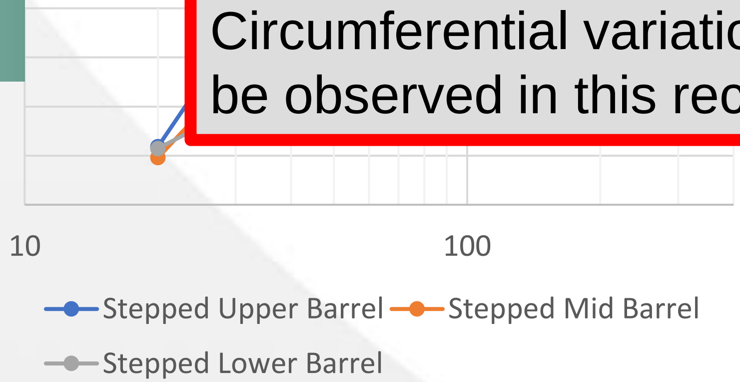
V40 Rect

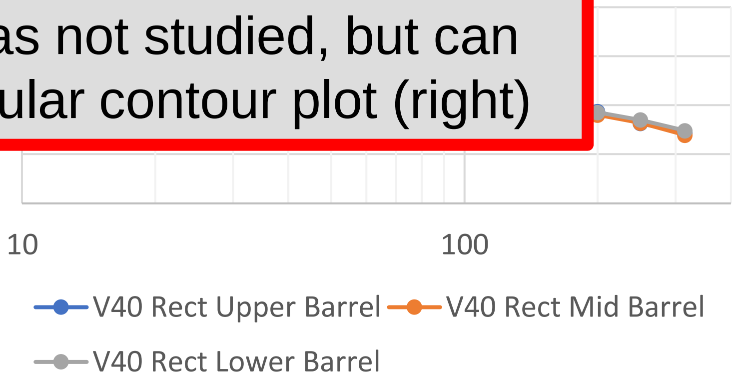


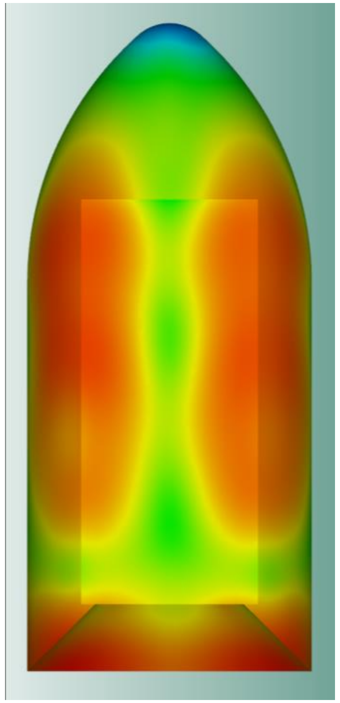
Reduced radial clearance, such as rectangle edges and stepped geometry, results in higher fill effect

The rectangular model has some hot and cold areas not seen in cylindrical models

Circumferential variation was not studied, but can be observed in this rectangular contour plot (right)



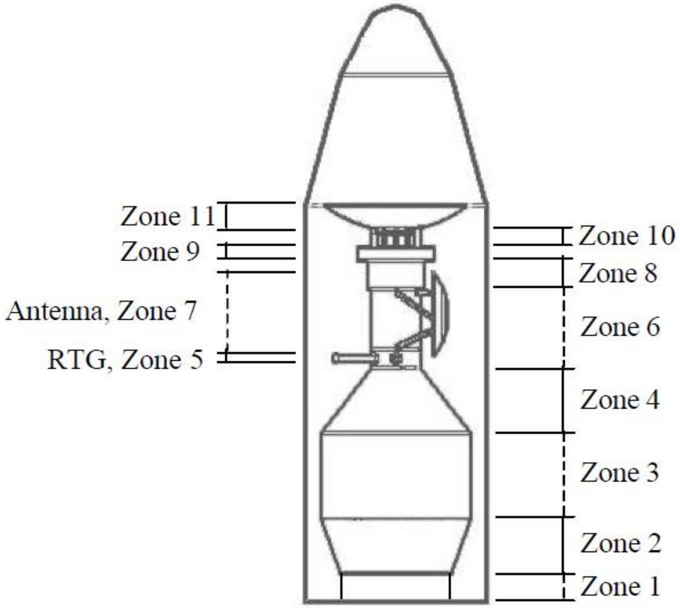




SLS

Conclusions

- **Fill factor is designed to be applied to a zone of interest, not an entire cavity**
  - Global application results in underestimation of fill volume and thus fill factor
  - If the payload section is assumed to be cylindrical, only a radius (or volume fill) is needed to determine the fill factor in that zone
  - Splitting up the fill factor into many little zones has been explored (P. Manning)
  - This procedure, published as “A New Predictive Methodology For Launch Vehicle Fill Factors” limits the low frequency fill factor asymptote and thus was not used here
- **Be careful of underestimating fill factor for “small” payloads by using a global fill volume percentage**



Conclusions

- **VAOne successfully modeled the fill effect**
  - If a payload shape is known, it could be beneficial to use that knowledge and input a simulated volume cutout into the acoustic model
- **However, it's not as quick as referring to the NASA standard**
  - FE models which include the payload may be beneficial if components are sensitive to low frequency acoustics
- **Analytical fill factor performs well at mid- and high-frequency, a few dB conservative**
- **Rectangular and stepped cavity shapes were not significantly different than their cylindrical counterparts on full cavity average**
  - Locally, we can see differences in the pressure fields as gap separation is reduced
    - Rectangle edges
    - Stepped cylinder large radius

Forward Work

- **Is a novel derivation of fill factor based on surface absorption possible?**
  - If a cavity is exposed to a constant sound power, eventually the cavity (with surface area, S) will reach a steady state where the input power has built up to such a level that it equals the power being dissipated due to absorption/leakage.

$$W_{input} = W_{absorbed} = I\bar{\alpha}S$$

  - And since sound intensity is proportional to sound pressure squared,

$$p^2 \propto \frac{W_{input}}{\bar{\alpha}S}$$

  - If we swap out the pressure squared value in the Fill Factor equation, then we'd get something that looks like this.

$$??\,Absorption\ based\ Fill\ Factor?? = 10\log_{10}\left[\frac{\bar{\alpha}_{empty}(f)\ \ S_{empty}}{\bar{\alpha}_{filled}(f)\ \ S_{filled}}\right]$$

- **This equation significantly underestimates fill effect and is not usable in its current form.**
  - Surface area is assumed to be exposed to external sound power. Not the case for internal payload surface area
- **The SEA-based modal energy fill factor remains the only analytical estimate of fill effect**
- **The question remains, can surface absorption or a modal damping scheme be used to model fill effect?**

Acknowledgements

- Samantha Bittinger
- Anne McNelis
- Genevieve Dixon
- SLS Payload Fairing Working Group Leadership
- VAOne Support
- SCLV Workshop

Questions?