Lift-Off Acoustics Prediction of Clustered Rocket Engines in the Near Field

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JPL

AEROSPACE

Outline

- Launch Environment
- Near Field
- Deflector, Shielding
- PAD Updates
  - *Directivity*
  - *Water Suppression*
  - *Clustered Nozzles*
- Summary

Launch Acoustic Environment

- Clustered rocket engines
- Ground reflections
- Near-field OASPL levels are high (160-170 dB)
  - *Water injection provides up to 10 dB reduction*
  - *Exhaust ducts can reduce SPL to some extent*
- Remember that slides are visual aids — not a document
  - *Supply handouts to audience with more information*
- Near-field produces random vibroacoustic impact
  - *Vehicle*
  - *Payload*
  - *Ground support equipment*
- Accurate near-field acoustic description is critical
  - *Next generation launch vehicles*

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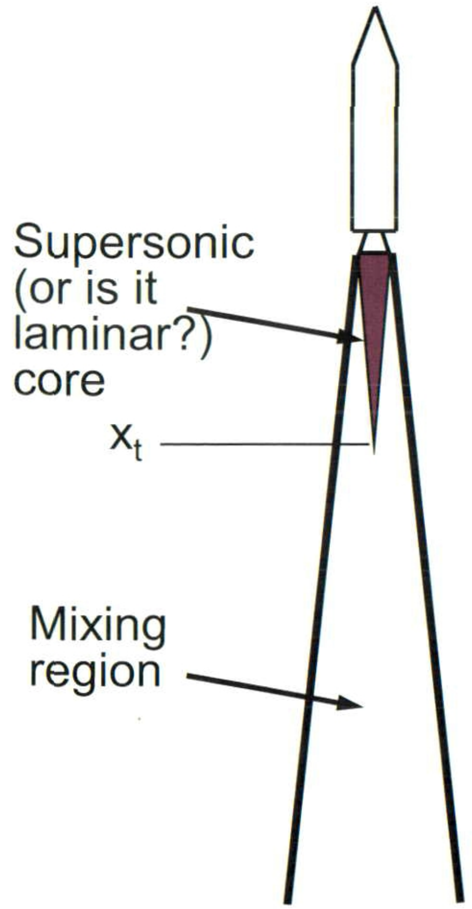
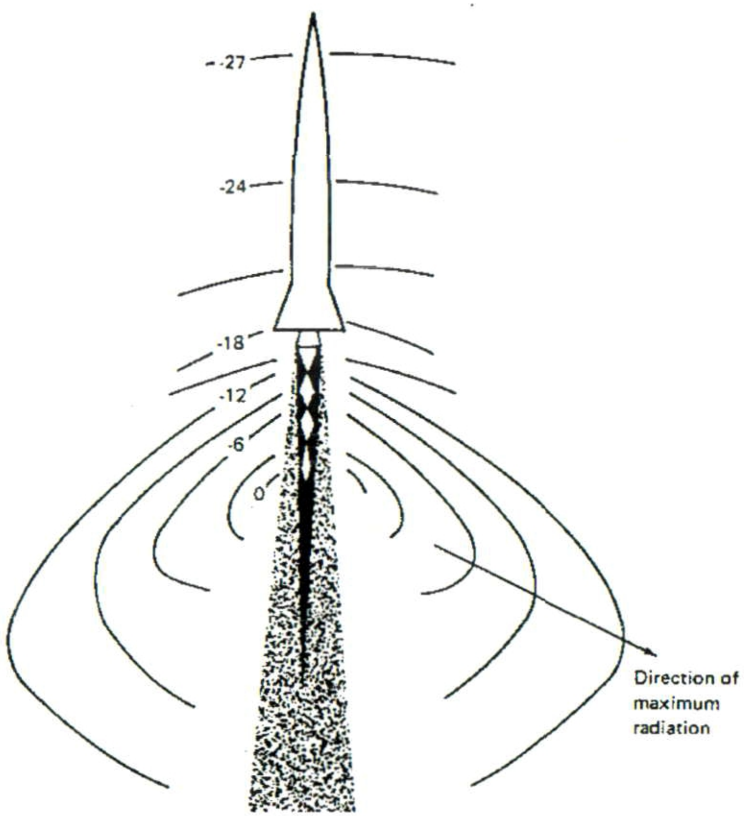
Rocket Noise Generation

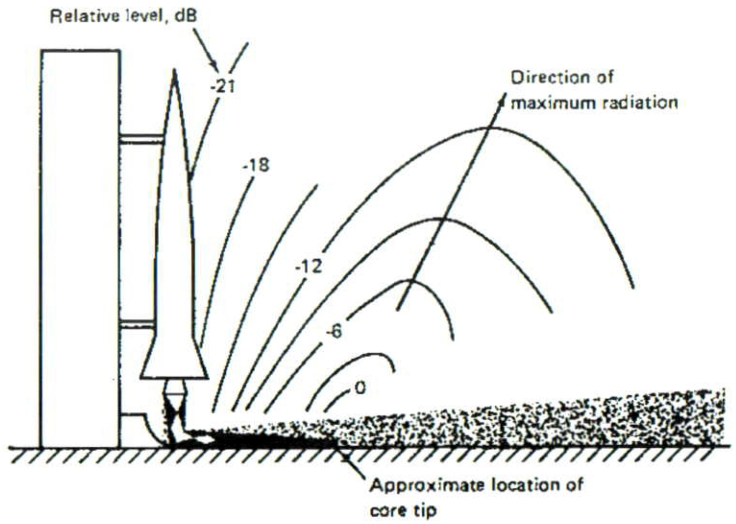


- Scales with nozzle diameter De, core length x_t , exit velocity Ve, thrust
- Distributed sources along axis
- Directivity
- Spectrum
- Far field: single directivity and spectrum
- Near field: spectrum and directivity vary along x
  - *Scale with x/x_t, Sn*
  - *Sn based on De or x*

Lift-off vs. Free-Flight Environment



Free flight



Lift-off

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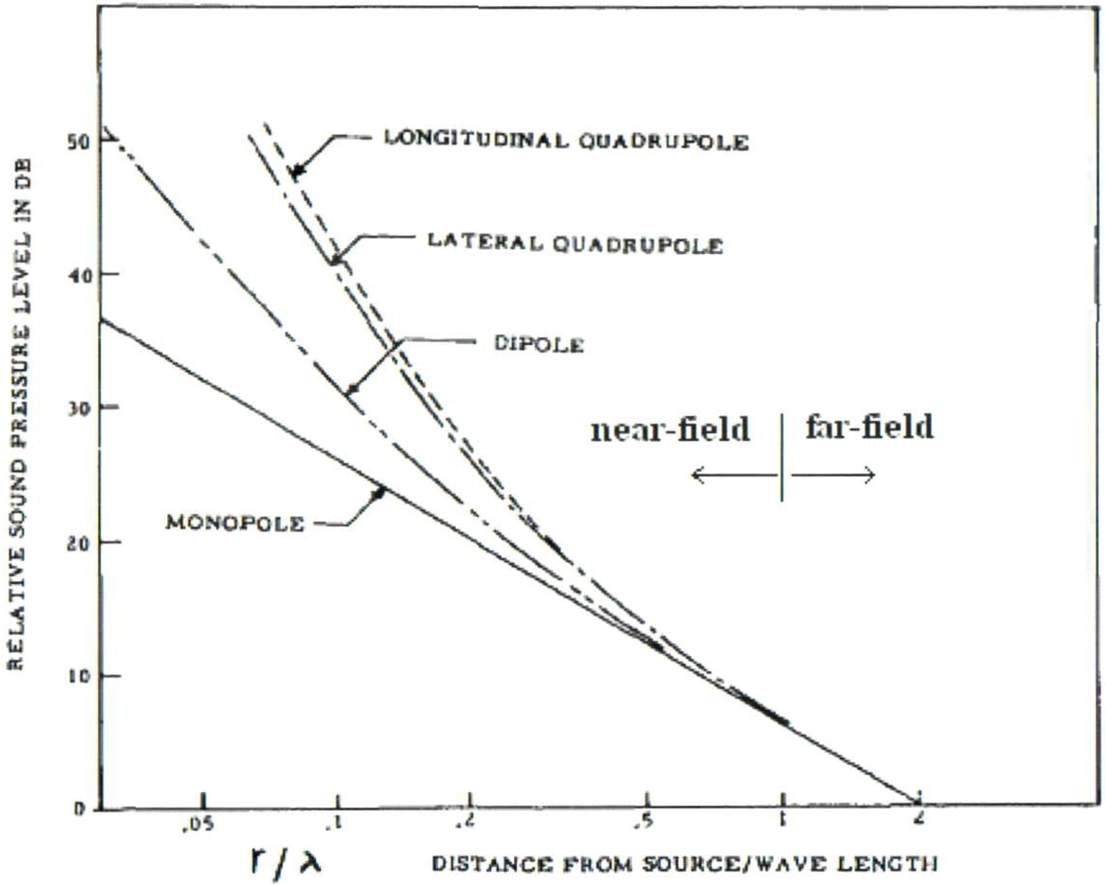
Near-Field Jet Acoustics

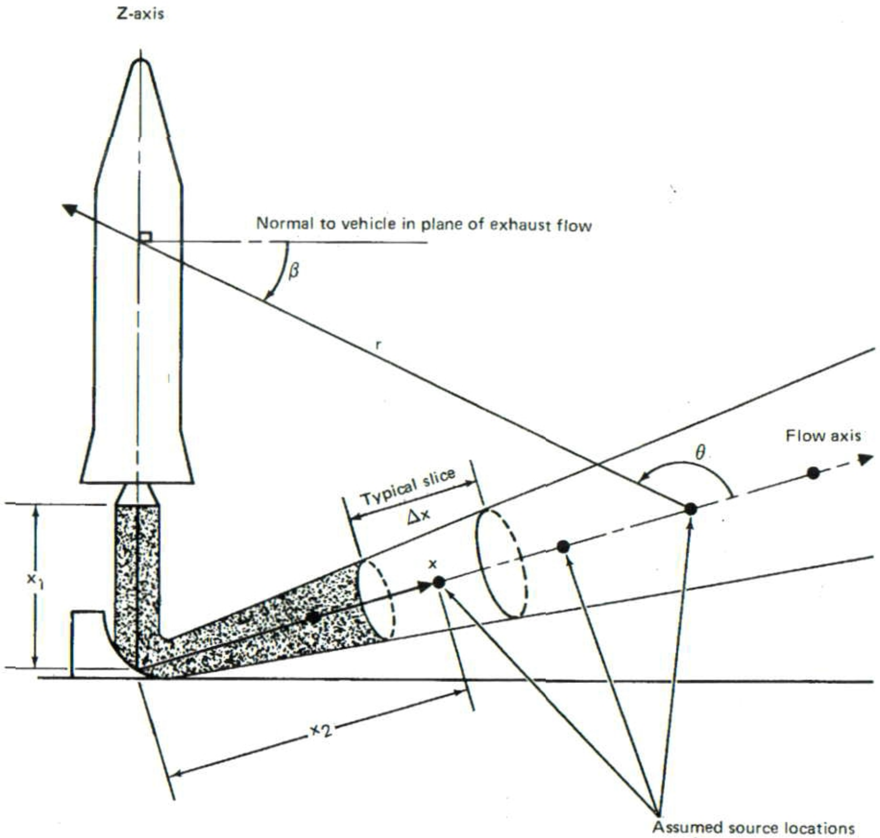
- Near-field definition: typically within 40 jet diameters (~300 ft for modern rockets)
- Near-field jet noise is complex relative to far field
- Noise generation and radiation
  - *Spatial source distribution*
  - *Hydrodynamic effects in addition to acoustic disturbance*
    - Nonlinearity
    - Convection, turbulence, jet interaction, shock waves
  - *High frequency*
  - *Refraction of sound*
- Ground and vehicle reflections
- Launch vehicle drift
- Water sound suppression

Near-Field Character of Isolated Sound Sources



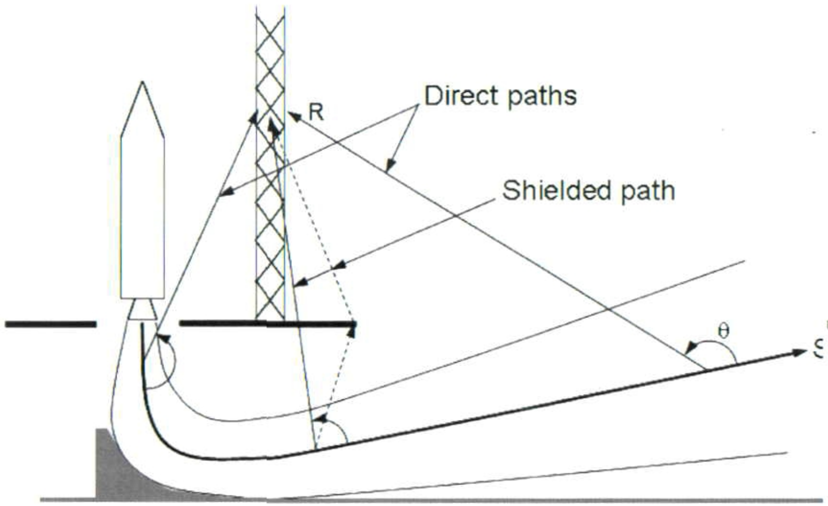
Ref: Morgan, Sutherland, and Young, WADD-TR-61-178, 1961

Rocket on Launch Pad

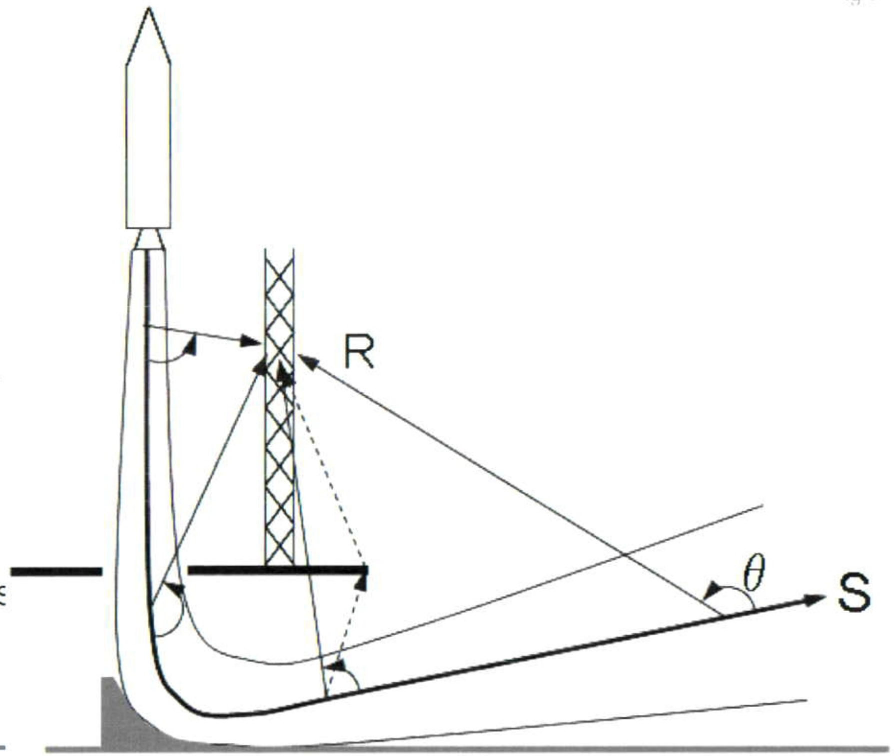


- Figure from SP-8072
- Deflector turns flow
- Deflector may change flow properties
- Near field, need distributed source
- Launcher deck or deflector tunnel blocks noise

Rocket on Mobile Launcher

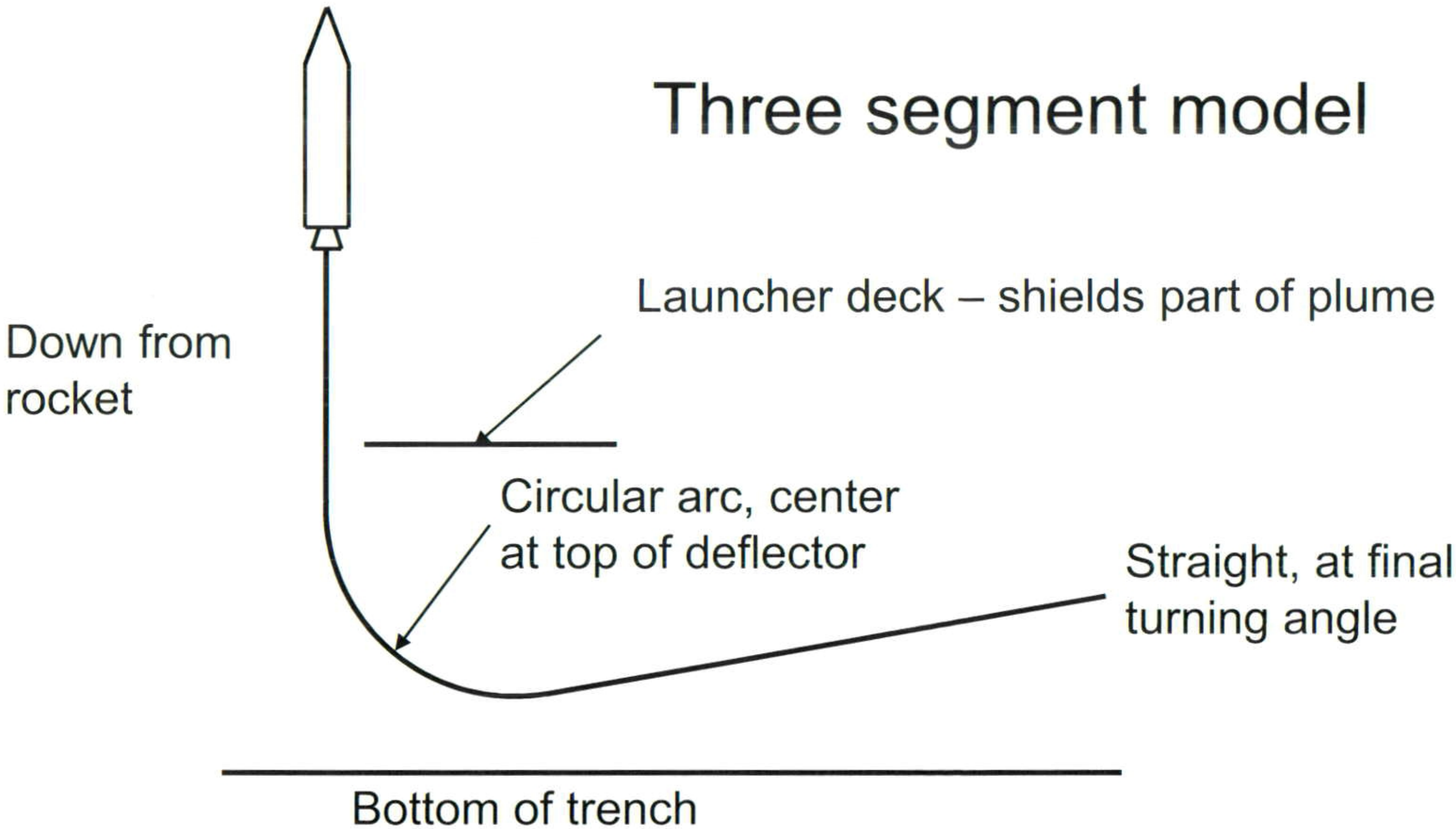


On pad, before lift-off

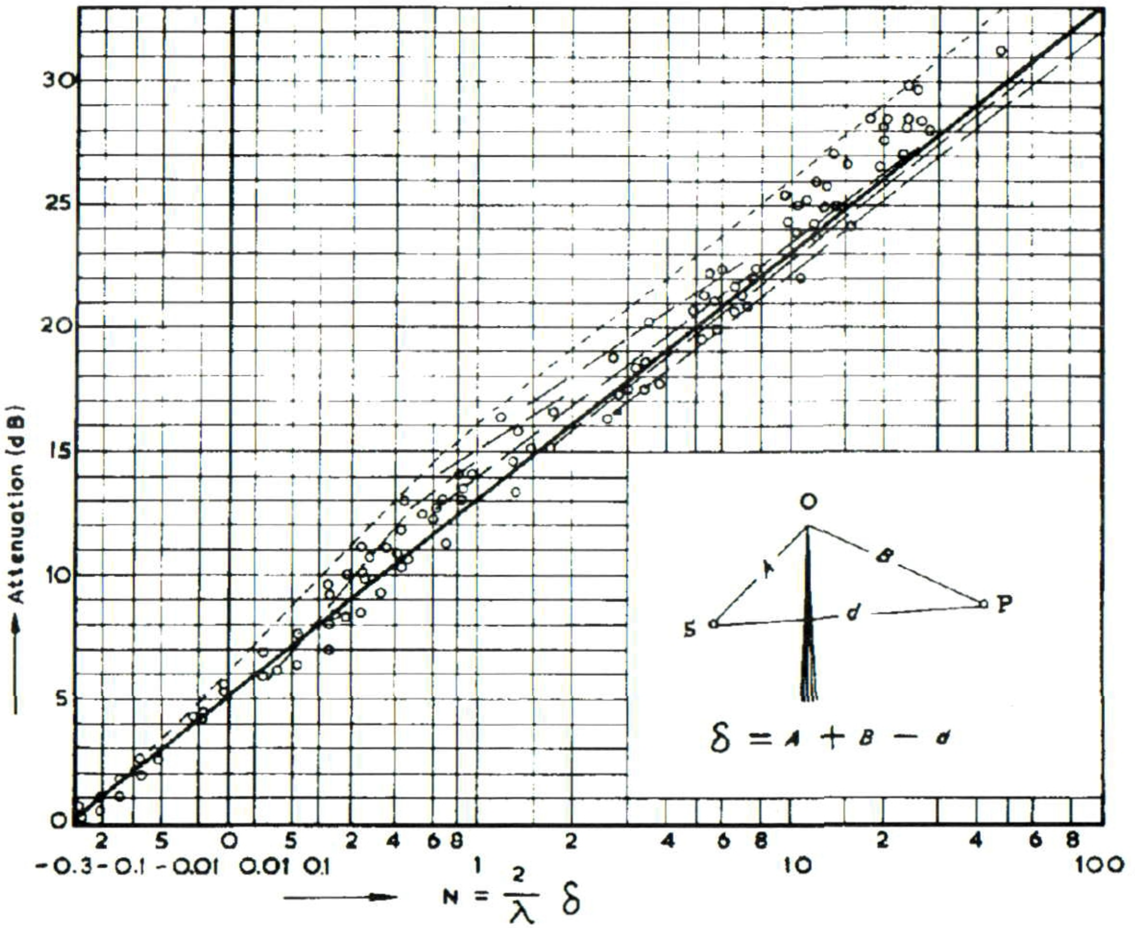


Above pad, after lift-off

Modeling Deflected Plume Axis



Acoustic Shielding



<u>Ref</u>: *Noise Reduction by Screens*, Z. Maekawa, Applied Acoustics, 1968, pp.157-163

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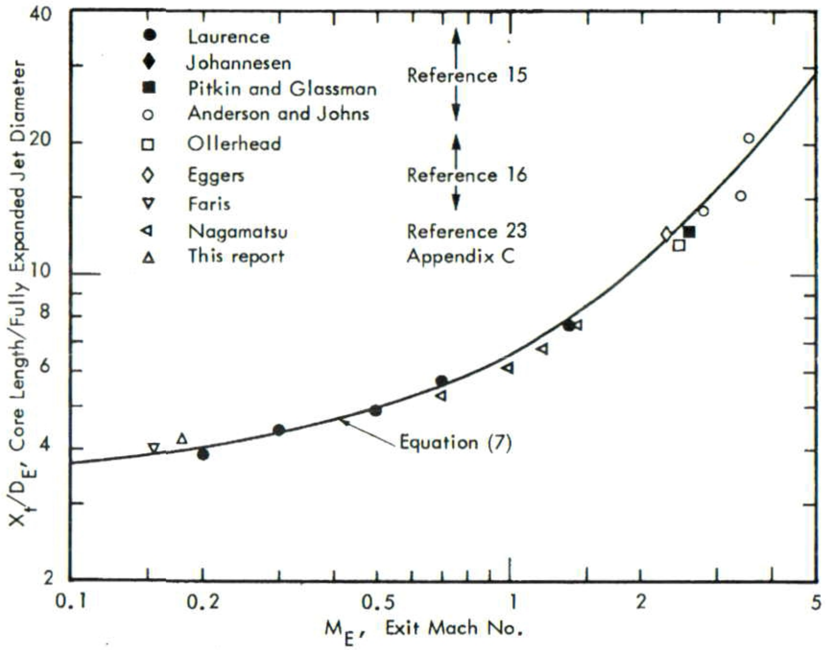
Core Length



Ref: Eldred (SP-8072)

$$\frac{x_t}{d_e} = 3.45(1 + 0.38M_e)^2$$

Other literature at variance with 8072 core length:

- Shirie and Seubold, 1967
- Varnier et al 1998 – nominally 40% of 8072 for SRM
- Recent fits by Jared Haynes supports Varnier
- Consistent with Laufer et al, 1976

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PAD Code Development

- Predict Ares-I launch noise levels and spectra at about 50 locations on launcher
- Use classic methods: WR 68-2, SP-8072, updated as necessary
- 2007 Effort: no suppression, vertical lift
- 2008 Effort: water suppression, drift
- 2010 Effort: two-zone method

Required Components

- Total sound power level of rocket
  - *Sutherland, 1993-1996*
  - *Consistent with Lighthill's theory*
- Distribution of source along x
- Spectrum – depends on x, Sn
- Directivity – function of x, f, Sn
- Effect of deflector

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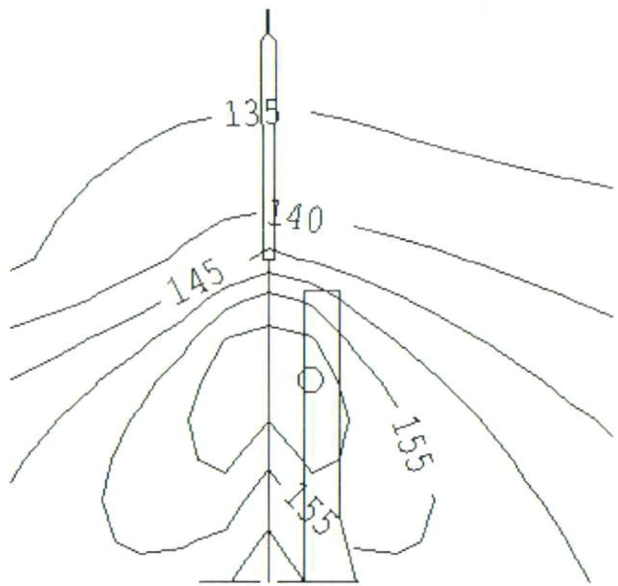
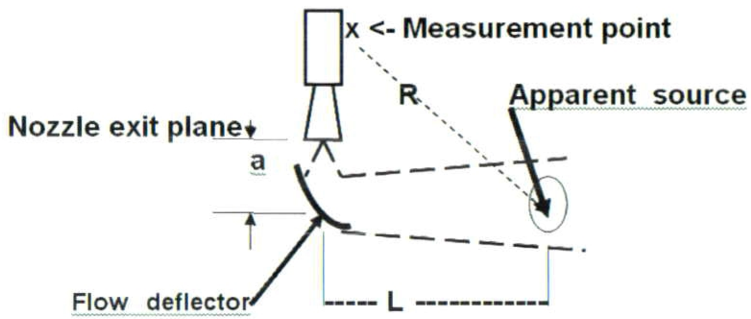
PAD Implementation

- Computes spectra in vicinity of launch pad, using the components described thus far
- Outputs at specific points or on a grid
- Fortran code, input/outputs are simple ASCII files
- Companion graphical display program.
- Xt multiplier (xtscale) scales Eldred core length



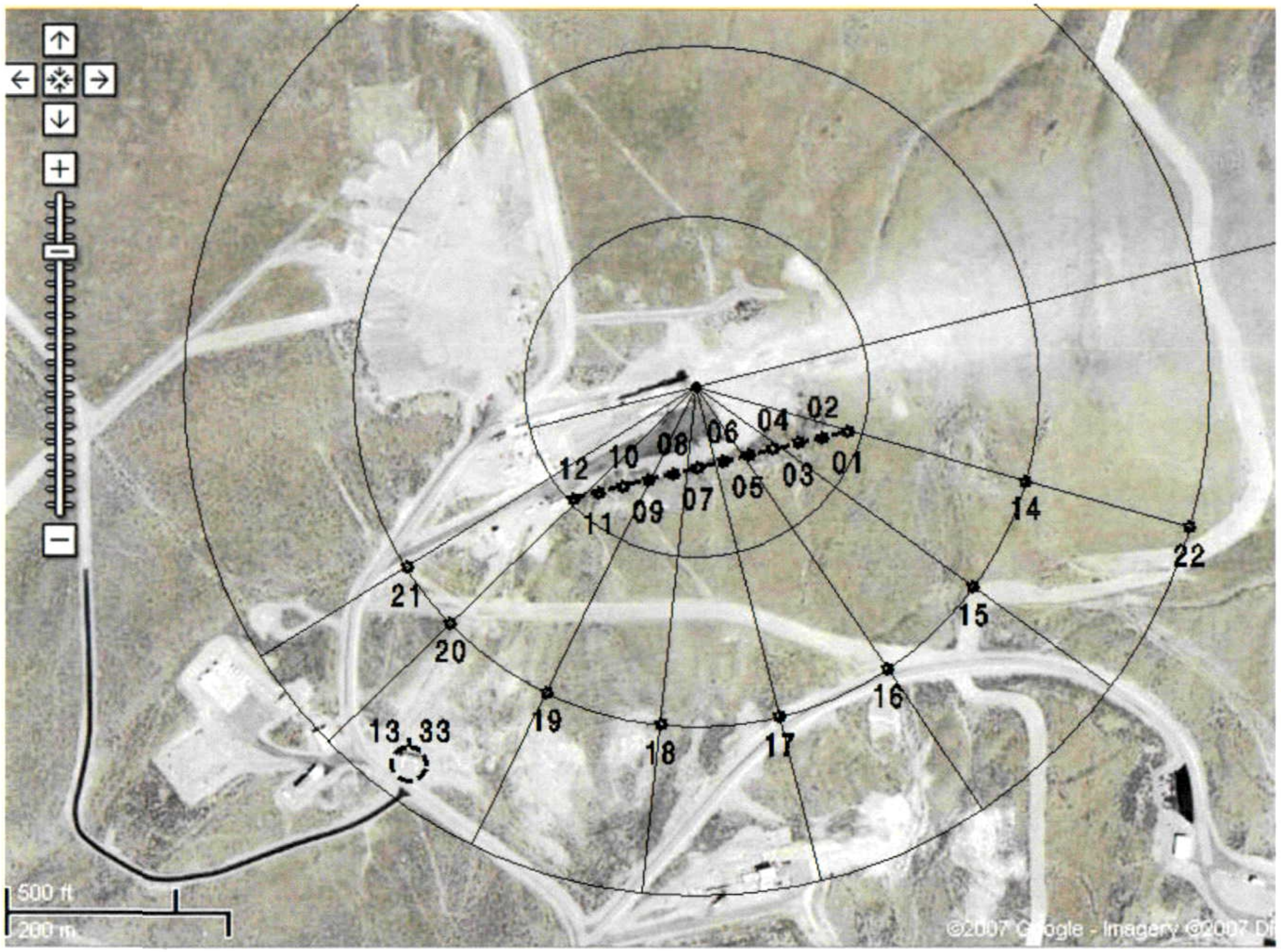
Source Spectrum



- Full method in PAD
- Spectrum at each x, per axial Sn fit
- Directivity per new DI fit

- Older "Dyer" or "Franken" method
- Single dominant frequency at each axial distance
- Amenable to empirical fit from actual rocket firings

Data Validation



TEM-13 Measurements 1 Nov 07

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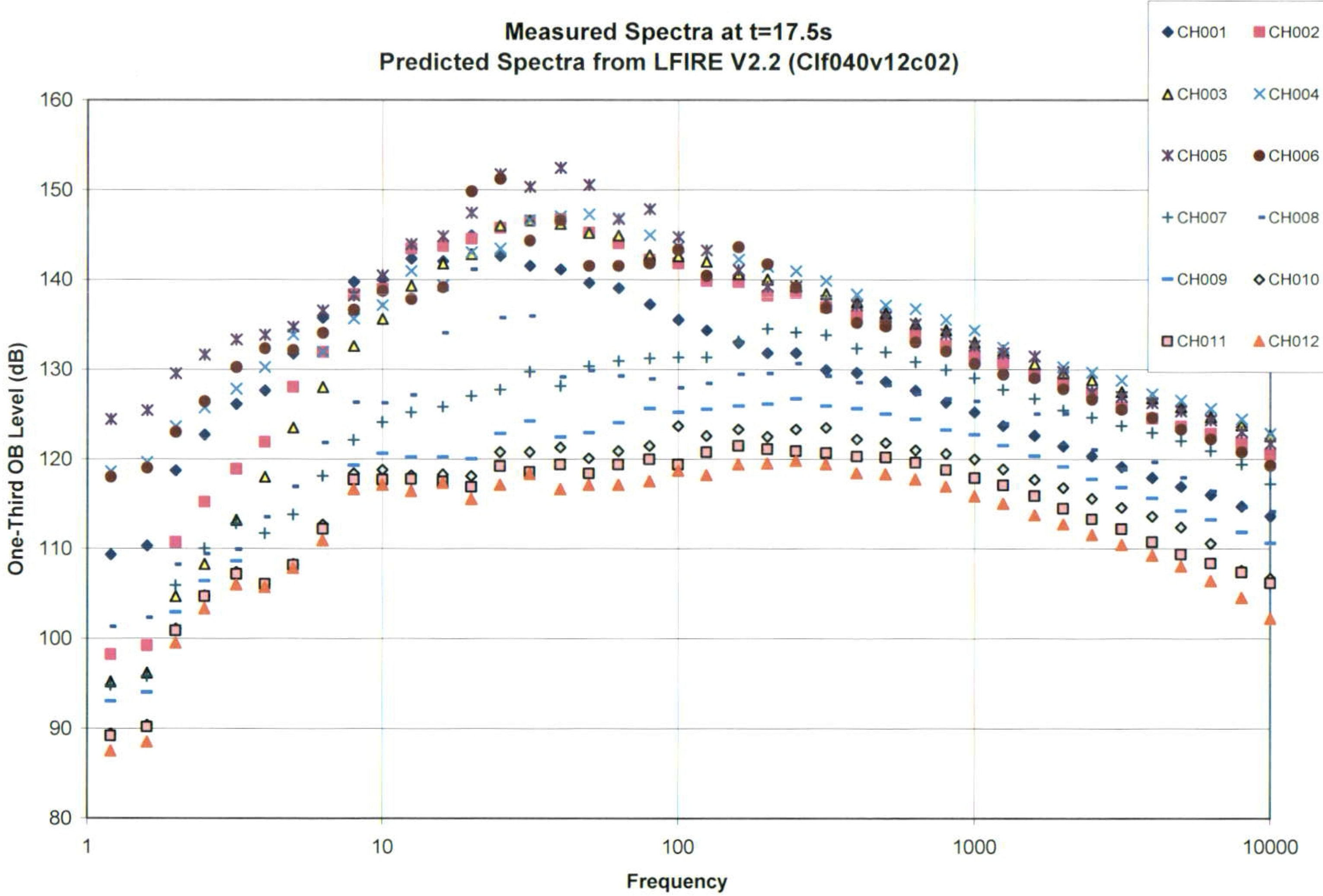
Data Validation (cont.)



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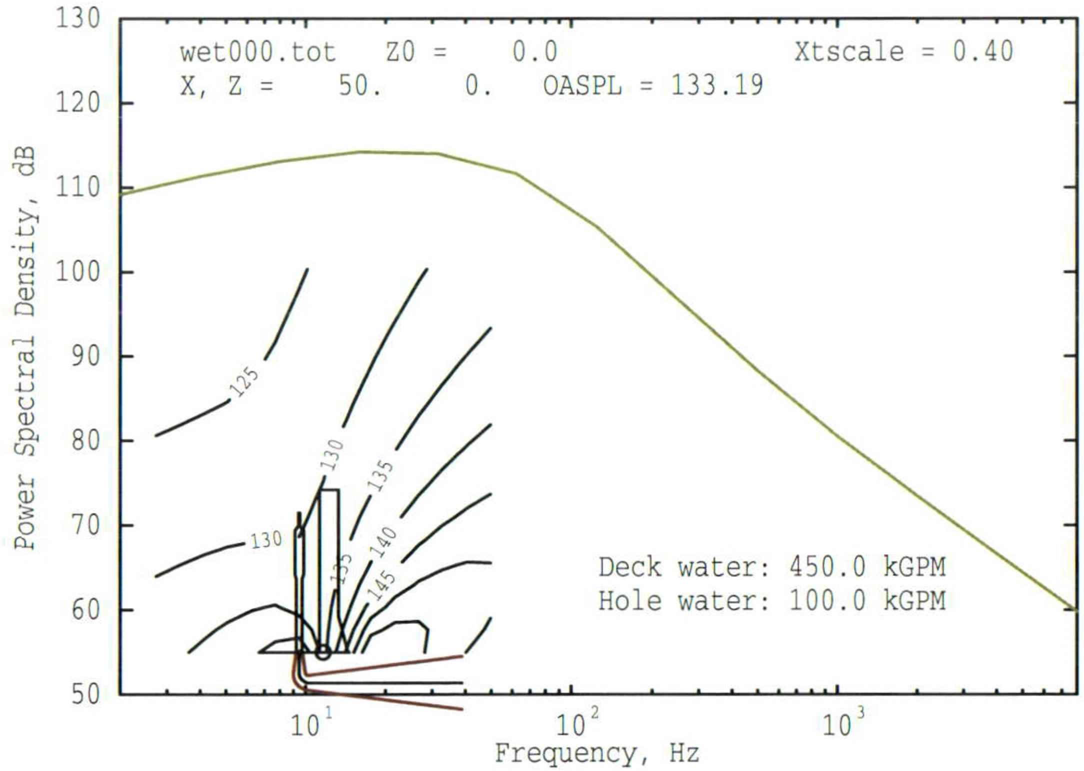
Suppression of Rocket Noise with Water Injection

- Data from Full Scale and Model Tests
- Extensive Data on Change in Acoustic Efficiency with Water Injection
- Limited Data on Octave Band Levels in Near Field with Water Injection
- Basic Variable is Ratio, R_{mf} of Mass Flow Rate of Water to Rocket Exhaust
- Reasonable validation of water injection effect based on acoustic efficiency vs. ratio of water to rocket mass flow rate
- Scale model tests recommended for any new configuration
- Further evaluation of theory and detailed water injection methods, water nozzle shape, etc, may be desirable

Water Suppression Implementation

- Simple method: OASPL goes down per regression, proportional to R_{mf}
- Complex details:
  - *Effect of location and distribution of water injectors*
  - *Effect on distribution of noise sources within the exhaust*
  - *Addressed up to the limit of credible models*



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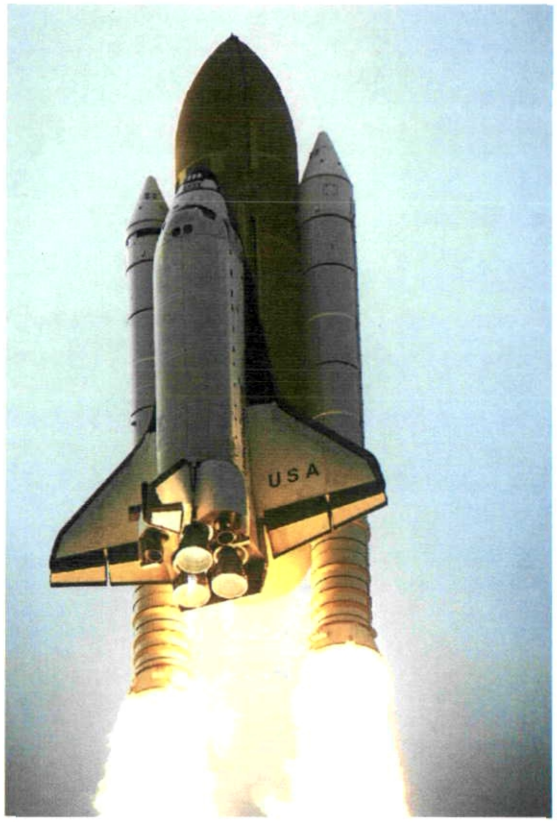
Launch Drift

- Flat plate deflection
  - *PAD assumed exhaust always went through hole, never impinged on launcher deck*
  - *Need to adapt flat plate deflector data for partial impingement*
- 3-D geometry for shielding
  - *PAD uses simplified geometry, exploiting everything in one plane for current non-drift cases*

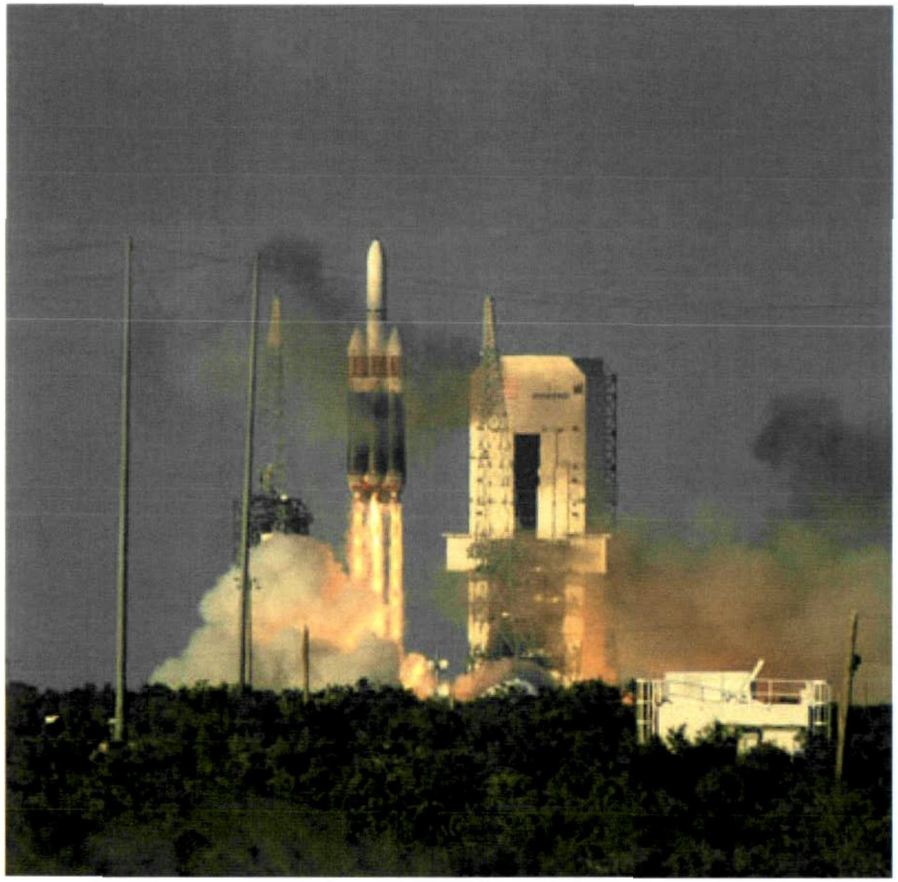
Clustered Rocket Engines



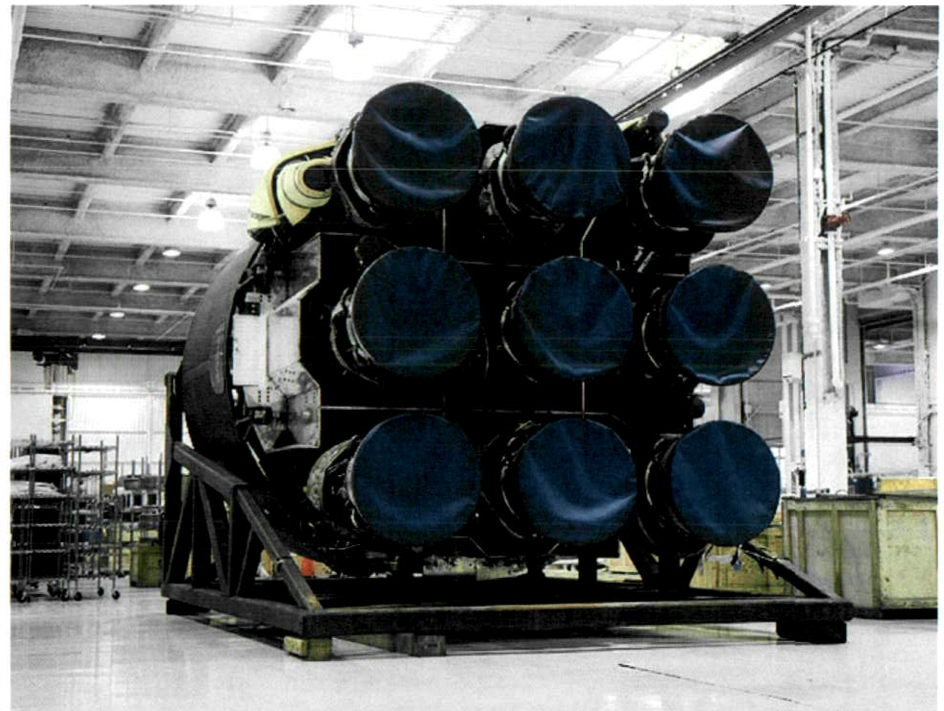
Space Shuttle

CFD (Ref: Slotnick, Kandula & Buning, AIAA-94-1860)

Clustered Rocket Engines (cont.)



Delta IV



Falcon 9

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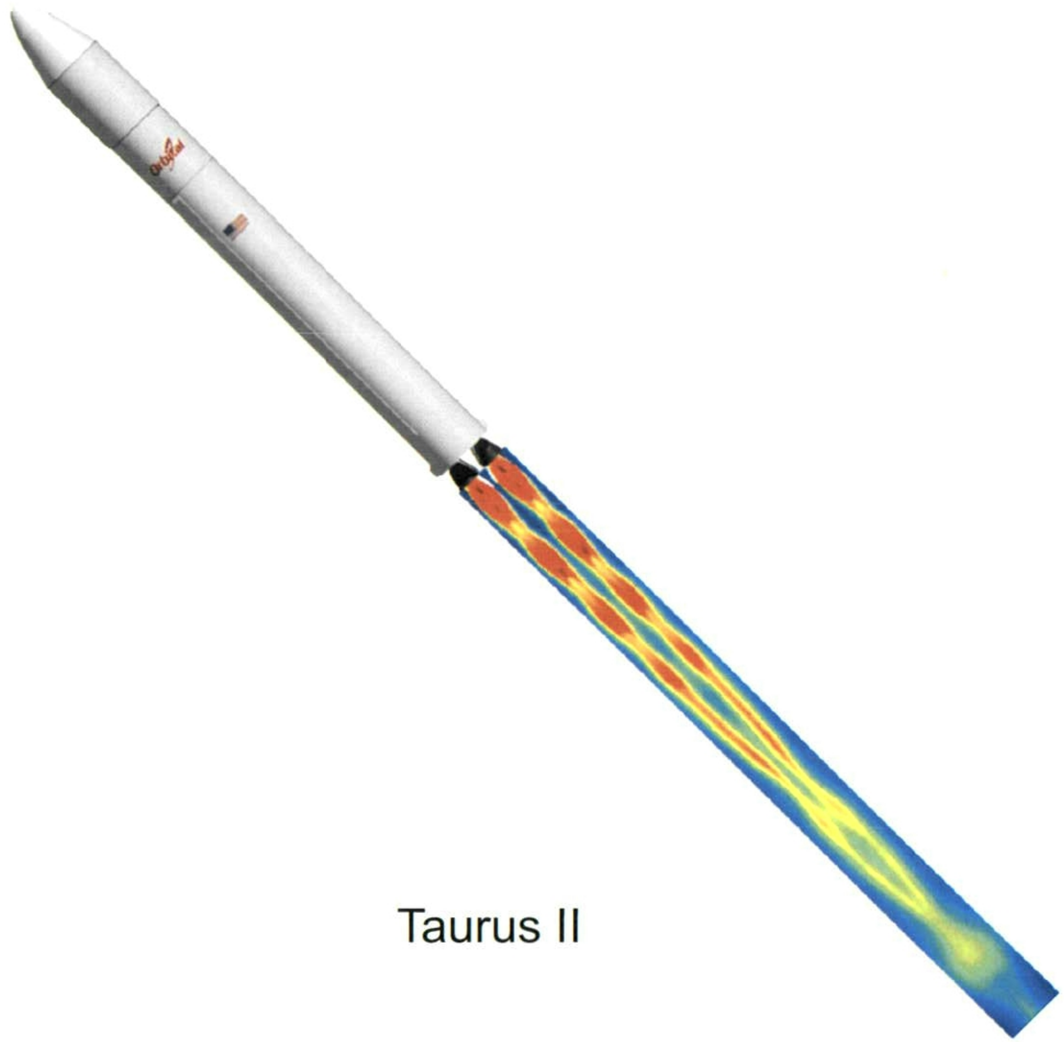
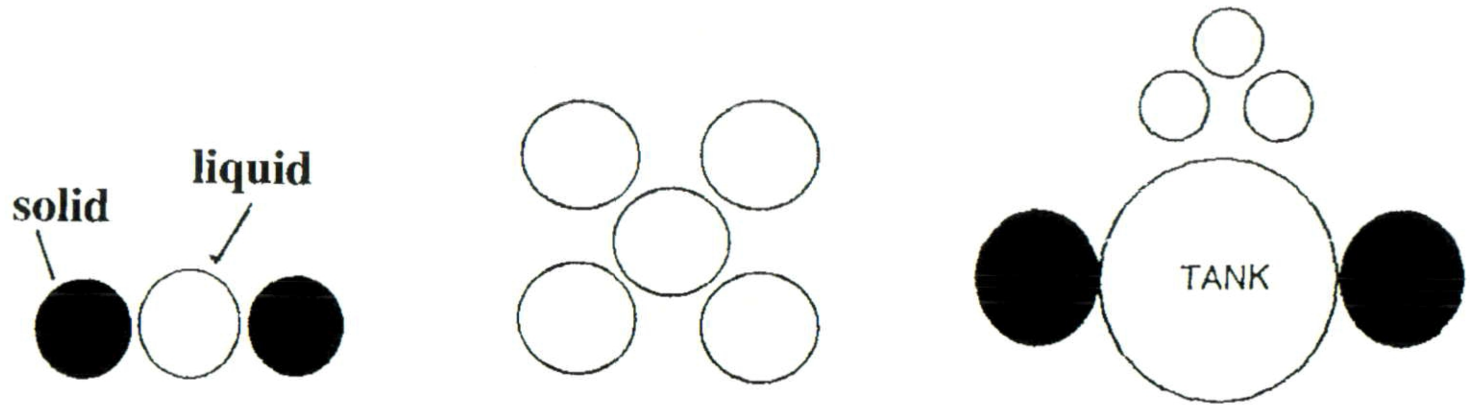
Clustered Rocket Engines (cont.)



Taurus II

Familiar Cluster Configurations



Titan   Saturn V   Space Shuttle

Classification of Clustered Nozzles

- Nozzle Spacing
  - *Widely spaced (clustered)*
    - Isolated nozzles (superposition)
    - Single peak frequency
  - *Closely spaced*
    - Single effective nozzle (total equivalent thrust)
    - Single peak frequency
  - *Intermediate spacing*
    - Two zones (isolated zone/mixed zone)
    - Double peak in frequency spectrum
- Homogeneous vs. heterogeneous clusters

Methods for Clustered Nozzles

- Single zone NASA SP-8072 method (Eldred 1971)
  - *Applicable for isolated nozzles or tightly spaced nozzles*
    - Assumes single effective nozzle diameter $\left(d_e = \sqrt{n}\, d\right)$
    - Based on rocket noise data (wide thrust level range): spectral similarity, directivity
  - *Unsuitable for intermediate cluster spacing*
- Two-Zone methods for intermediate cluster spacing
  - *Eldred's model (1963)*
  - *Employ NASA-SP method for*
    - Isolated nozzle zone
    - Mixed zone
  - *Combine the two flows*

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Eldred's Model

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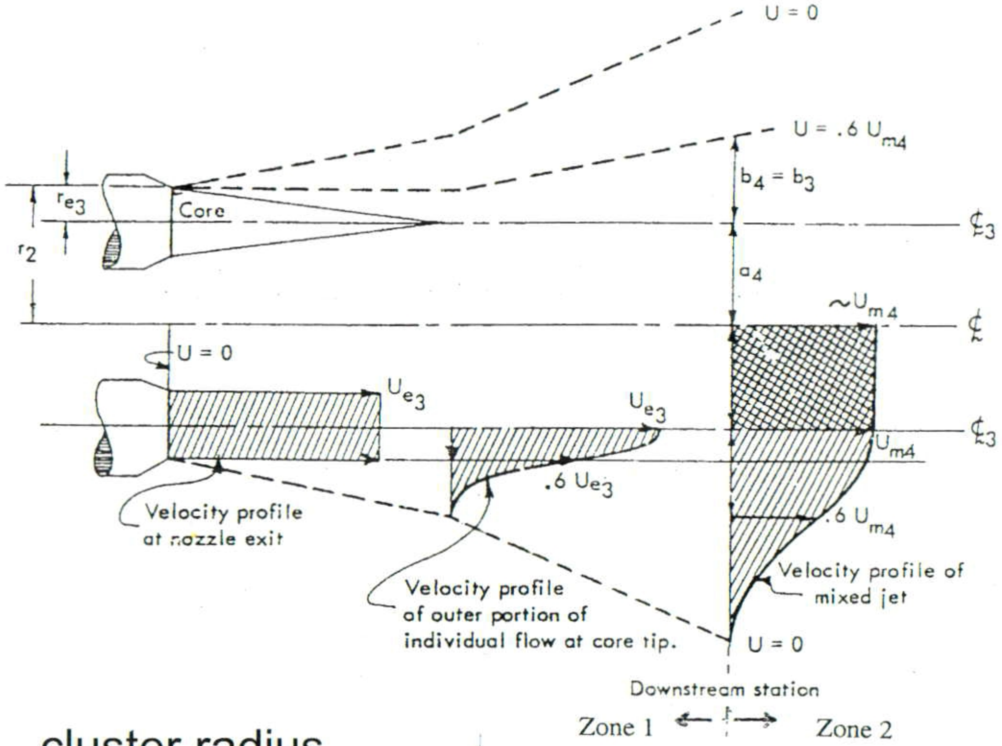


$$\frac{x_4}{x_t} = \begin{cases} \dfrac{2(r_2 / r_{e3} - 1)}{n^{1/2} - 1} & x_4 > x_t \\ \dfrac{(r_2 / r_{e3} - 1)}{n^{1/2} - 1} & x_4 \le x_t \end{cases}$$

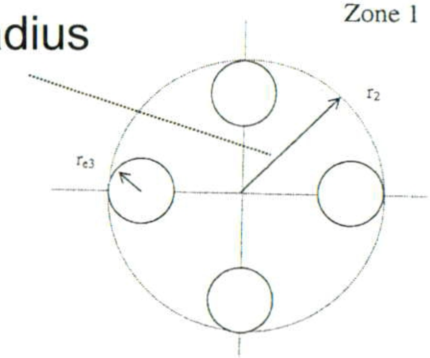
where x_t = core length

x_4 = length of mixing region

r_2 = radius of the cluster perphery

r_{e3} = radius of the individual nozzle

cluster radius



- **Jet entrainment**
- **Mass, momentum & energy conservation**

Properties of Combined Stream

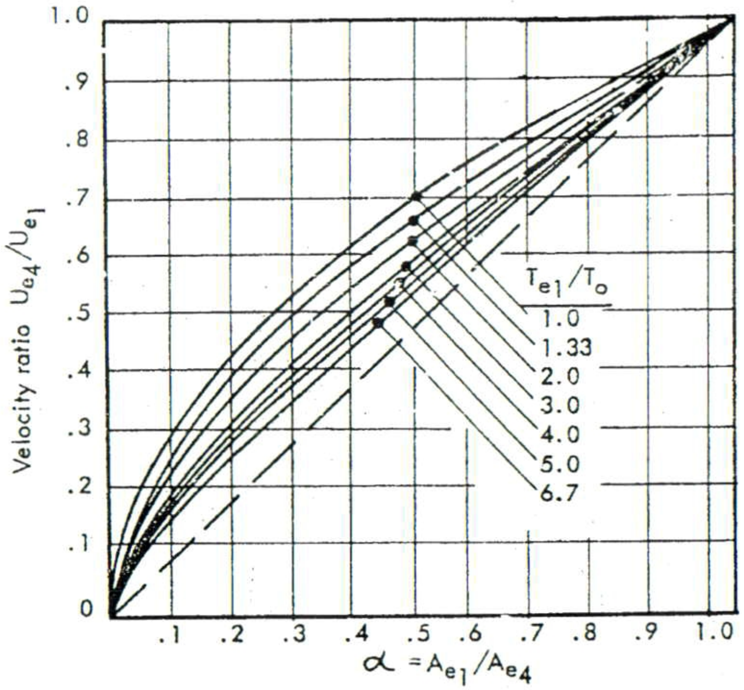
$$\frac{U_{e4}}{U_{e1}} = \frac{1}{2}\left\{\alpha(1-\beta) \pm \sqrt{\eta^2(1-\beta)^2 + 4\alpha\beta}\right\}$$

$$\frac{T_{e4}}{T_0} = \frac{U_{e4}T_0}{U_{e4} - \alpha U_{e1}(1-\beta)}$$

where $\alpha = \frac{A_{e1}}{A_{e4}} = \frac{\left(n^{1/2}-1\right)^2}{\left(r_2/r_{e3}-1\right)^2}$, $\beta = \frac{T_0}{T_{e1}}$

T_0 = ambient temperature

U_{e1}, T_{e1} = individual jet exit conditions



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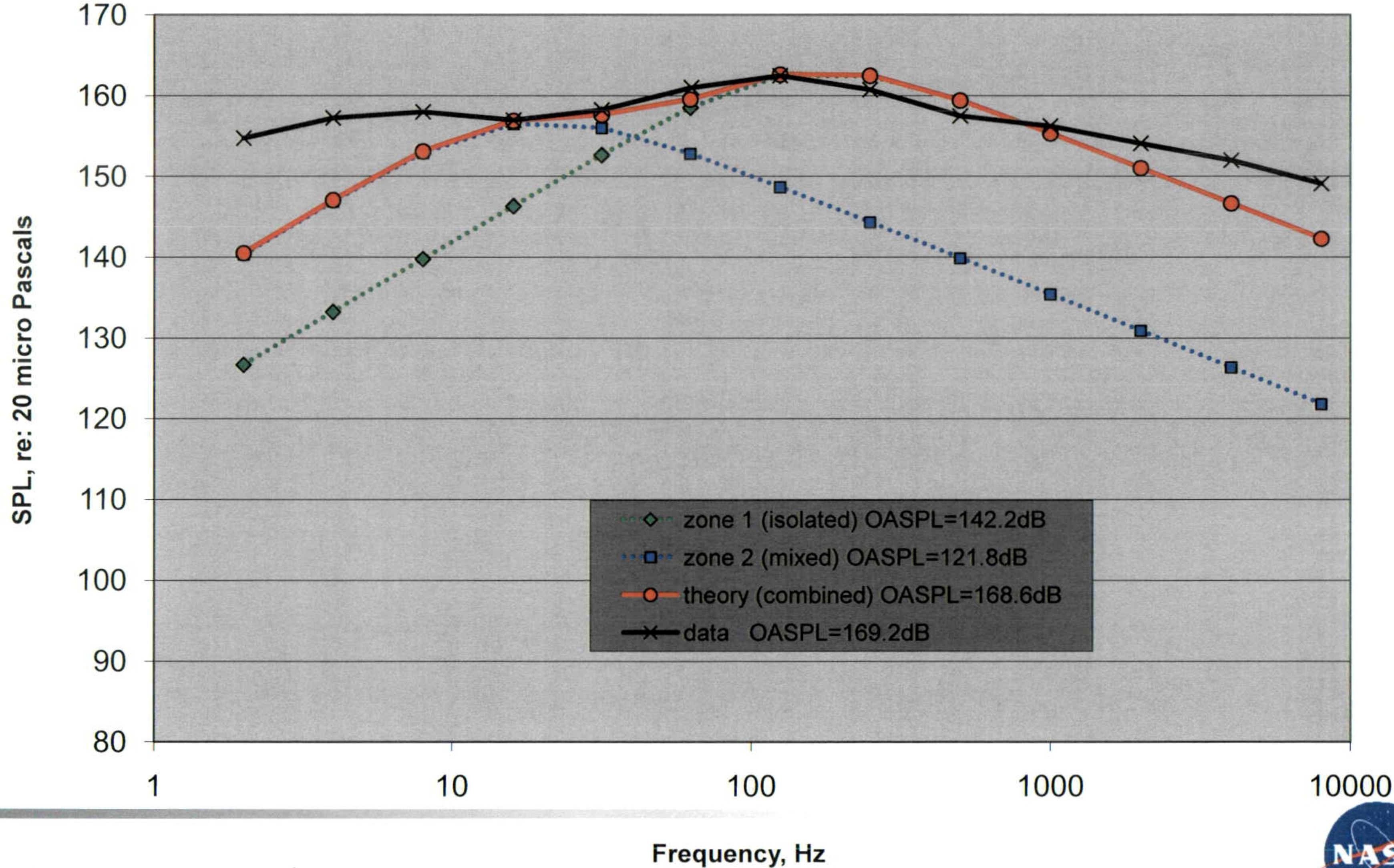
Saturn V



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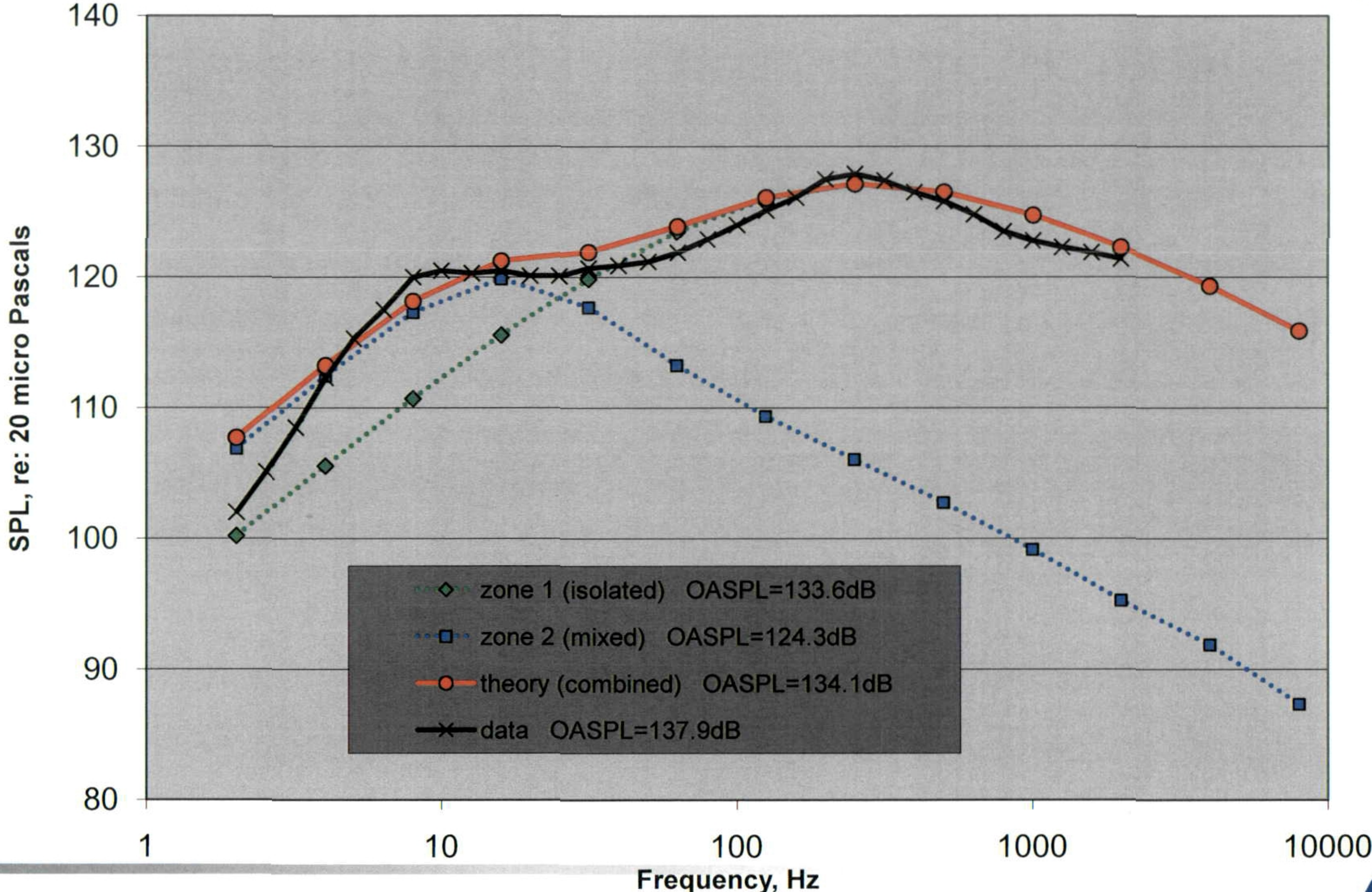
Titan IV



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Summary

- PAD is software implementation of launch noise
- Core length, source distribution are moving targets. TEM-13 data validation. More tests are needed
- Drift will require partial flat plate deflection modeling, some geometry extensions in PAD
- Water suppression method was implemented
- Two-zone method was included in PAD to account for clustering effect due to 2 peak frequencies
  - *Isolated zone peak (non-interfering jets)*
  - *Mixed zone peak (considerably lower frequency)*
  - *Eldred' model compares well with the data for clustered nozzles*

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