Transonic Tones and Excess Broadband Noise in Overexpanded Supersonic Jets

Noise characteristics of convergent-divergent (C-D) nozzles in the overexpanded regime are the focus of this paper. The flow regime is encountered during takeoff and landing of certain airplanes and also with rocket nozzles in launch-pad environment. Experimental results from laboratory-scale single nozzles are discussed. The flow often undergoes a resonance accompanied by emission of tones (referred to as ‘transonic’ tones). The phenomenon is different from the well-known screech tones. Unlike screech, the frequency increases with increasing supply pressure. There is a staging behavior – odd harmonic stages occur at lower pressures while the fundamental occurs in a range of relatively higher pressures. A striking feature is that tripping of the nozzle’s internal boundary layer tends to suppress the resonance. However, even in the absence of tones the broadband levels are found to be high. That is, relative to a convergent case and at same pressure ratio, the C-D nozzles are found to be noisier, often by more than 10dB. This excess broadband noise (referred to as ‘EBBN’) is further explored. Its characteristics are found to be different from the well-known broadband shock-associated noise (‘BBSN’). For example, while the frequency of the BBSN peak varies with observation angle no such variation is noted with EBBN. The mechanisms of the transonic tone and the EBBN are not completely understood yet. They appear to be due to unsteady shock motion inside the nozzle. The shock drives the flow downstream like a vibrating diaphragm, and resonance takes place similarly as with acoustic resonance of a conical section having one end closed and the other end open. When the boundary layer is tripped, apparently a breakdown of azimuthal coherence suppresses the resonance. However, there is still unsteady shock motion albeit with superimposed randomness. Such random motion of the internal shock and its interaction with the separated boundary layer produces the EBBN.

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(1) Zaman**, Dahl, Bencic & Loh**, *JFM 2002* (Transonic tones)

(2) Zaman, **Bridges & Brown**, *AIAA #2009-0289*, Jan, 2009 (EBBN)

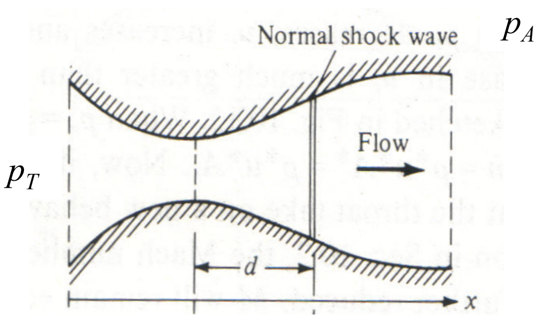
Outline of talk:

★ Brief overview of NASA Aeronautics

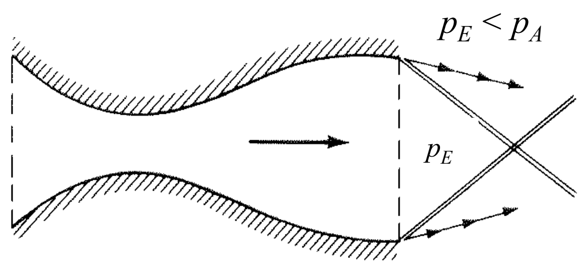
★ Noise from overexpanded Jets

- Introduction
- Transonic tones ('x-tones')
- Excess broadband noise ('EBBN')
- Summary

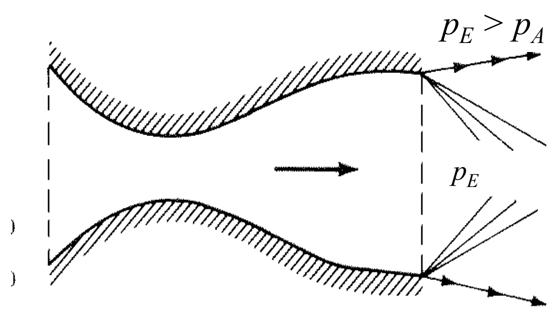
Flow through a convergent-divergent nozzle



Shock inside nozzle

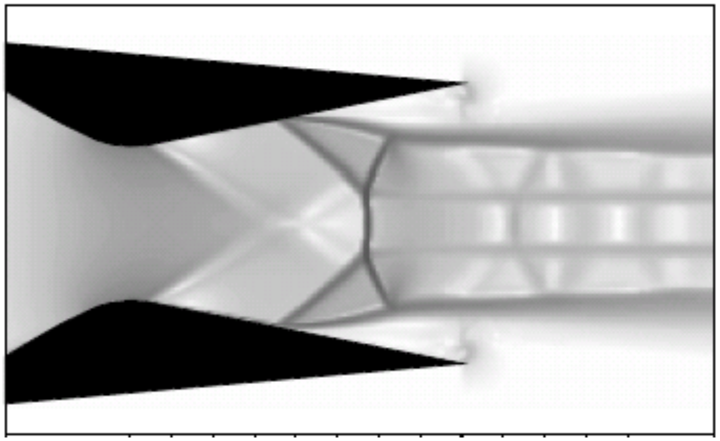


Pressure at exit
less than ambient pressure
oblique shock forms
flow turns inward
(Overexpanded)



Pressure at exit
greater than ambient pressure
Expansion fan forms
flow turns outward
(Underexpanded)

Shock inside nozzle



CFD (C.A. Hunter 1998)

Behaves like overexpanded flow
This is the condition when x-tone and EBBN occur

Supersonic jet noise components
In addition to turbulent mixing noise

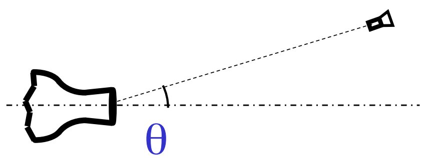
1. Screech *(Powell 1953)*
2. Broadband shock associated noise 'BBSN' *(Harper-Bourne & Fisher 1973)*

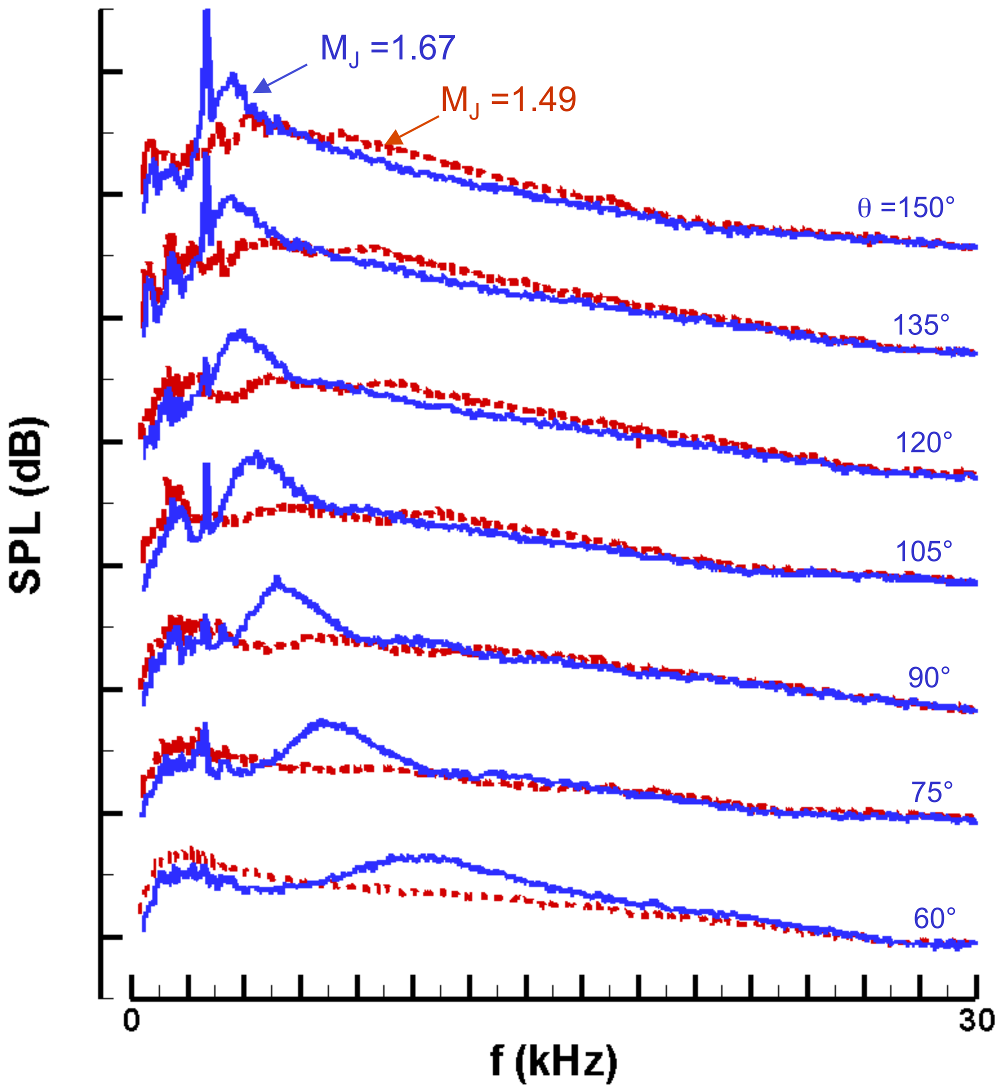
Occurs in both overexpanded and underexpanded regimes

3. Transonic tone ('x-tone') — overexpanded regime
4. Excess broadband noise 'EBBN' — overexpanded regime

Screech and BBSN from M_D = 1.5 nozzle

Norum & Seiner data NASA TM 1982
Format of *Tam 1991*

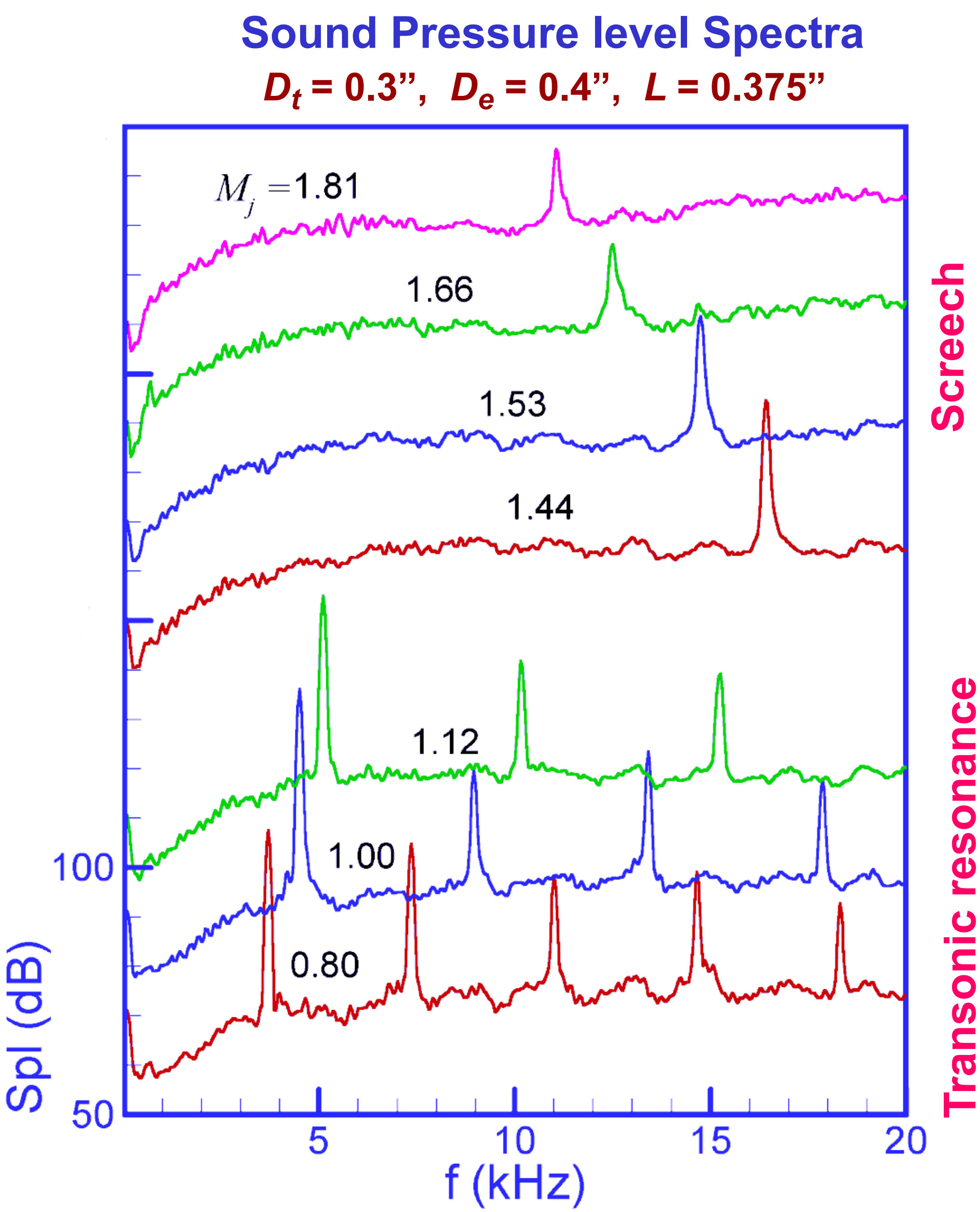


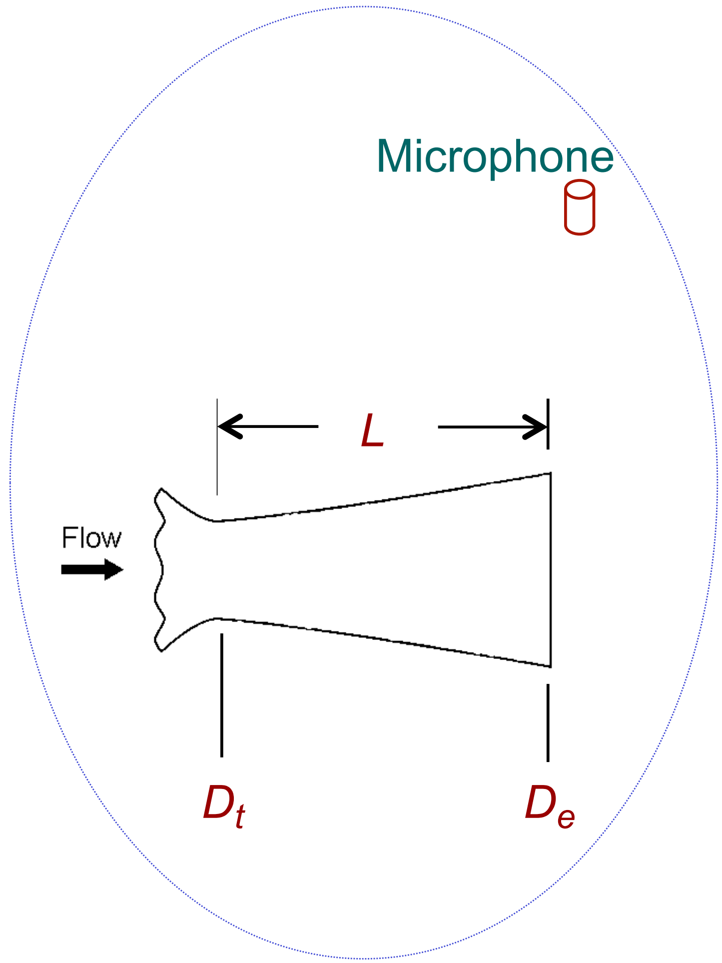


$$M_j = (((p_T / p_A)^{(k-1)/k} - 1)\frac{2}{k-1})^{1/2}$$

is 'Fully expanded jet Mach number'

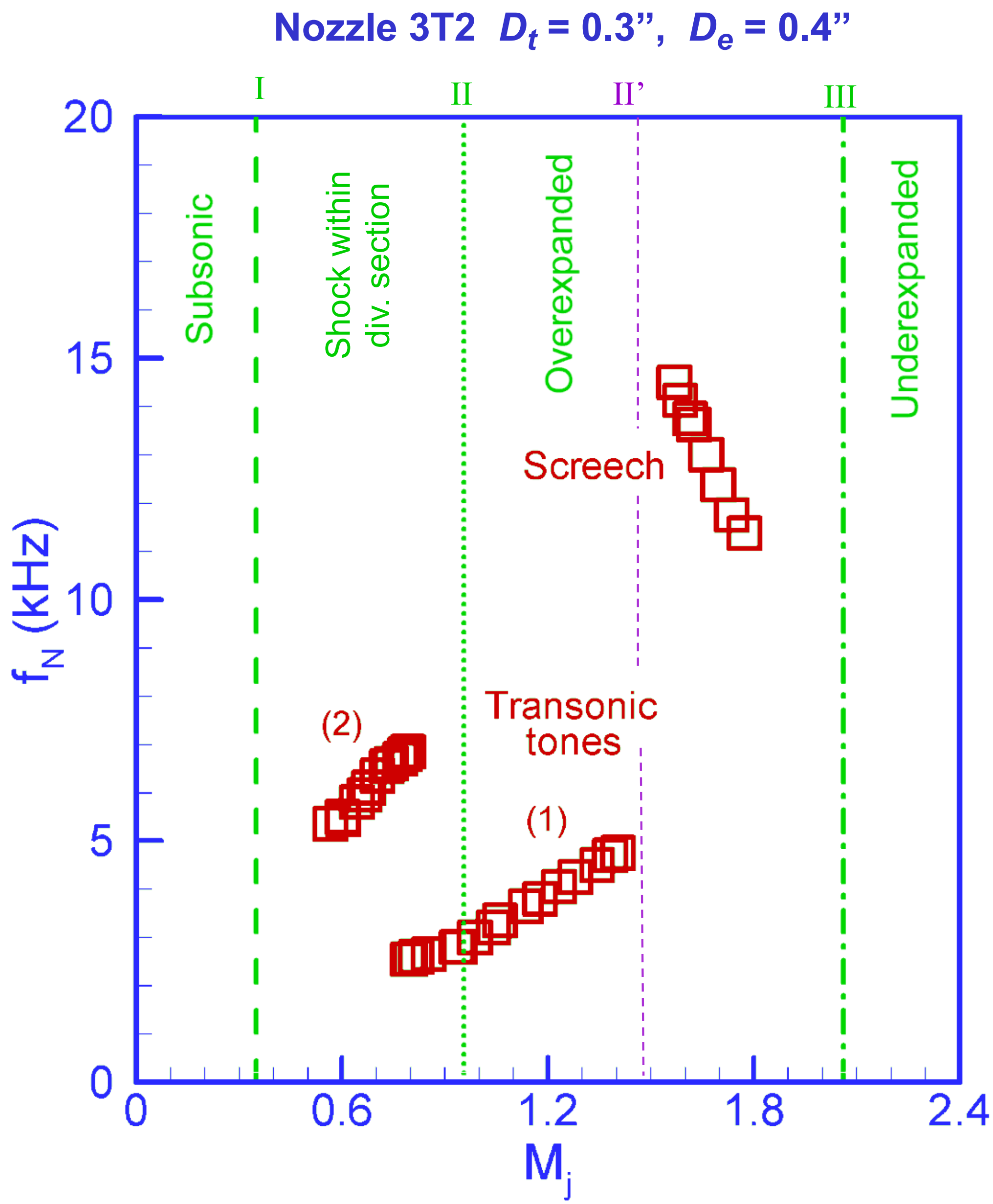
Transonic Tone





(Zaman/Dahl/Bencic/Loh JFM 2002)

Tone Frequency versus M_j

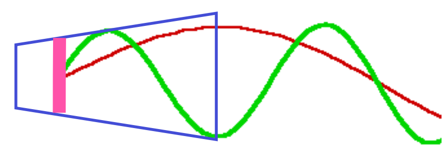


Green boundaries based on 1-D analysis

Boundary II
In practice is to the right
Marked by purple line

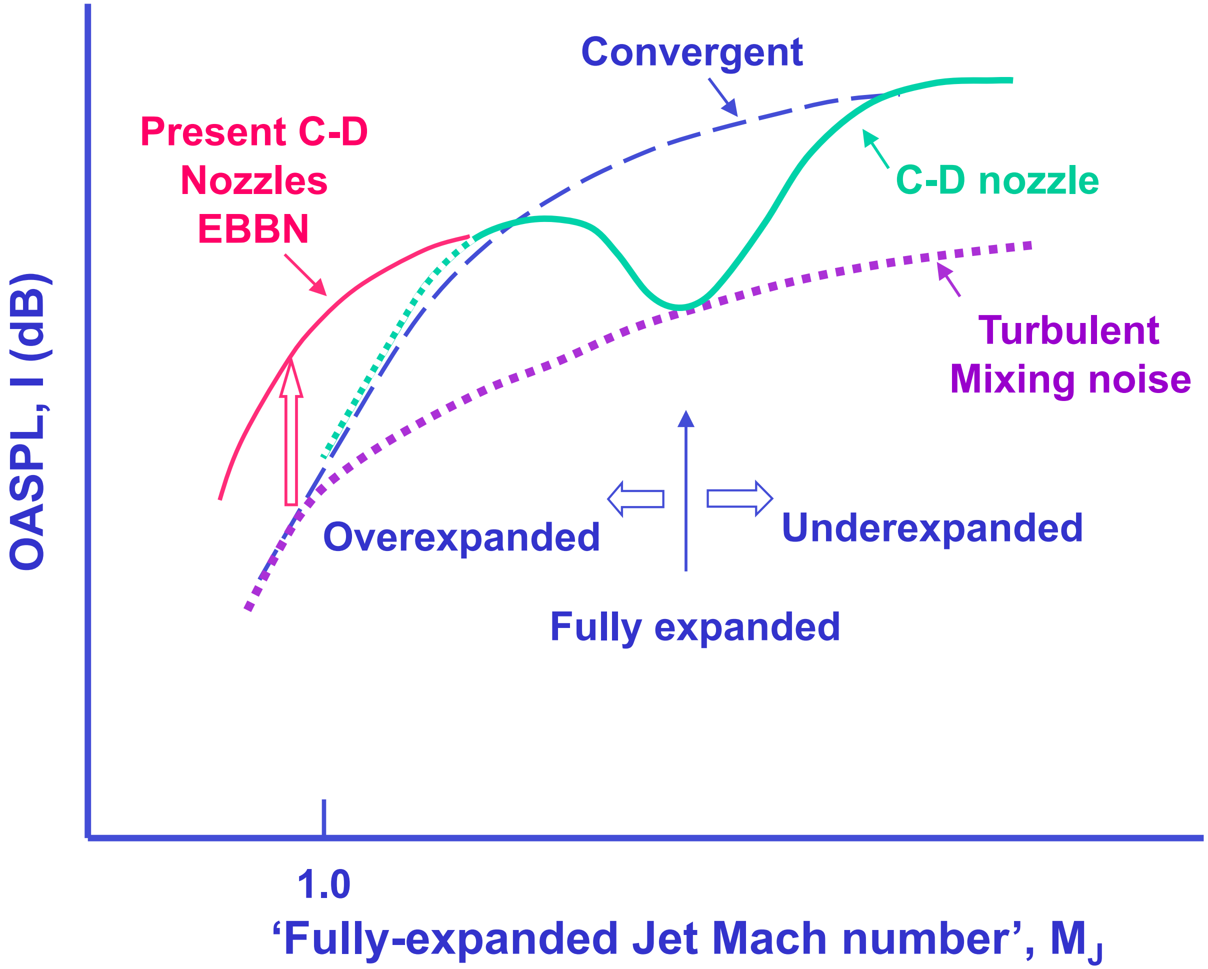
X-tones may occur when there is a shock in the divergent section

Mechanism:



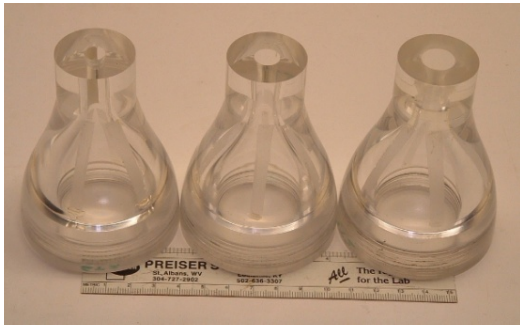
Excess broadband noise EBBN

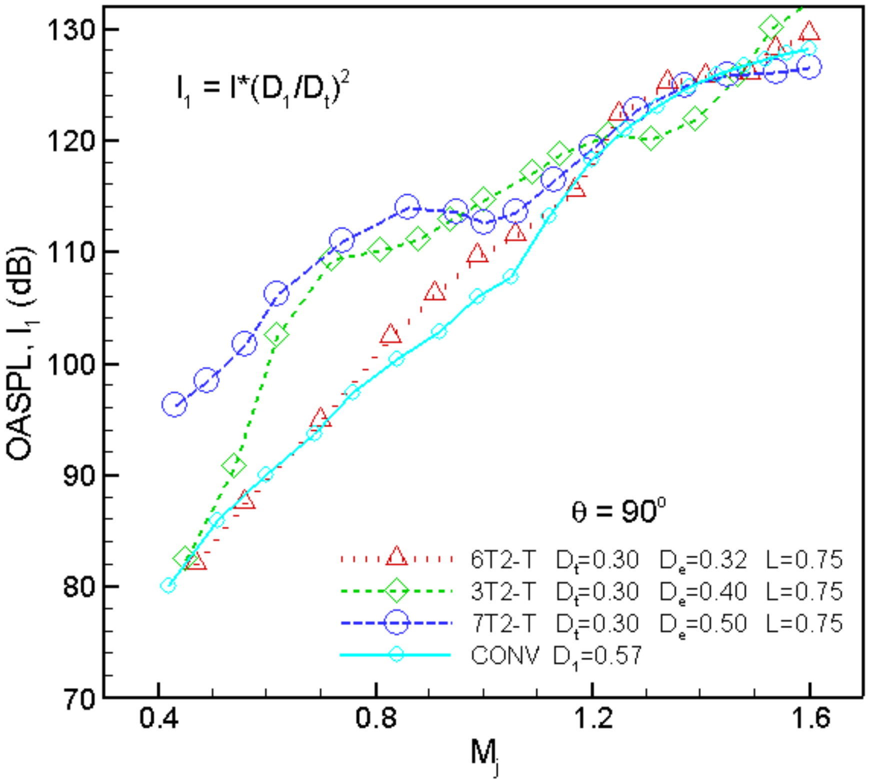
Schematic of Overall Sound Pressure Level (OASPL) vs. M_J
C-D vs. Convergent nozzle
(*Tam & Tanna* 1982)



Earlier results

(Zaman, *AIAA Paper #2008-25*)





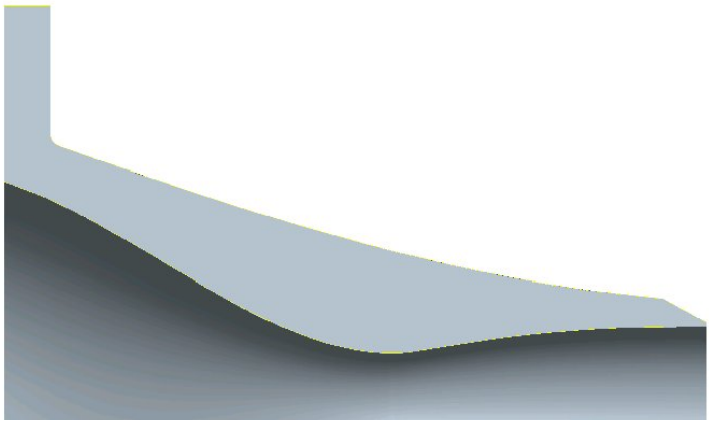
Difficulties:

-- Nozzles were tiny

-- Divergent sections straight cones
would EBBN occur with
well designed nozzles?

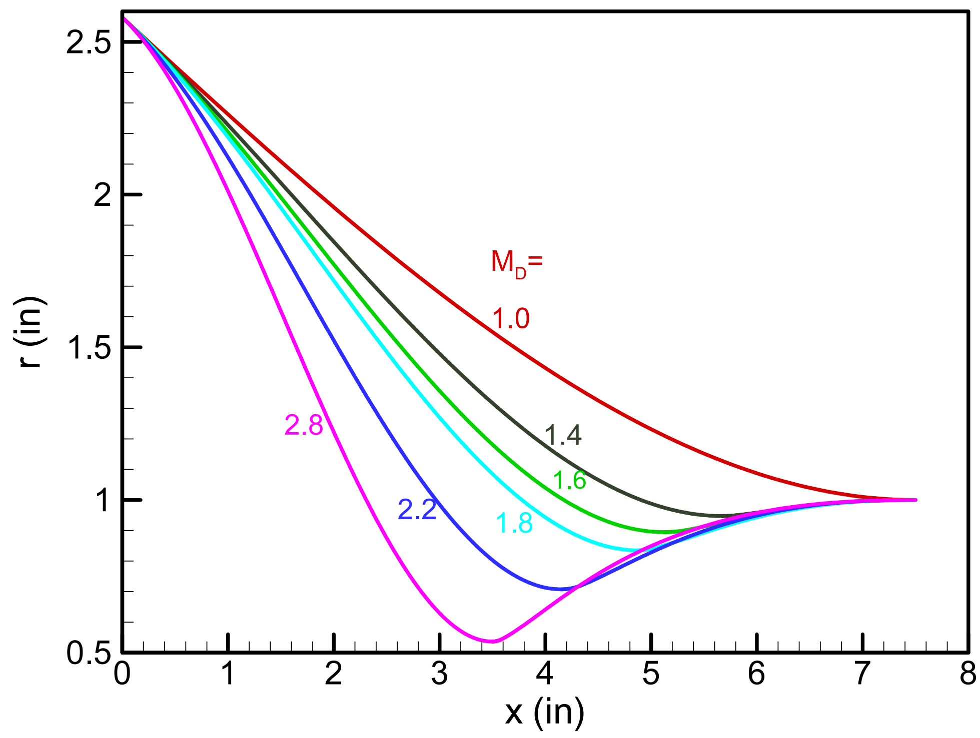
-- Diameters varied
data from nozzles of same size
desirable

New Nozzles



Nozzle**	Throat diameter, D_t	Divergent section length
M10	2	0
M14	1.8952	1.83
M16	1.7900	2.38
M18	1.6702	2.63
M22	1.4148	3.35
M28	1.0730	4.00

Suffix ‘T’ denote tripped boundary layer



Internal contours

All nozzles: exit diameter = 2”, Length = 7.5”

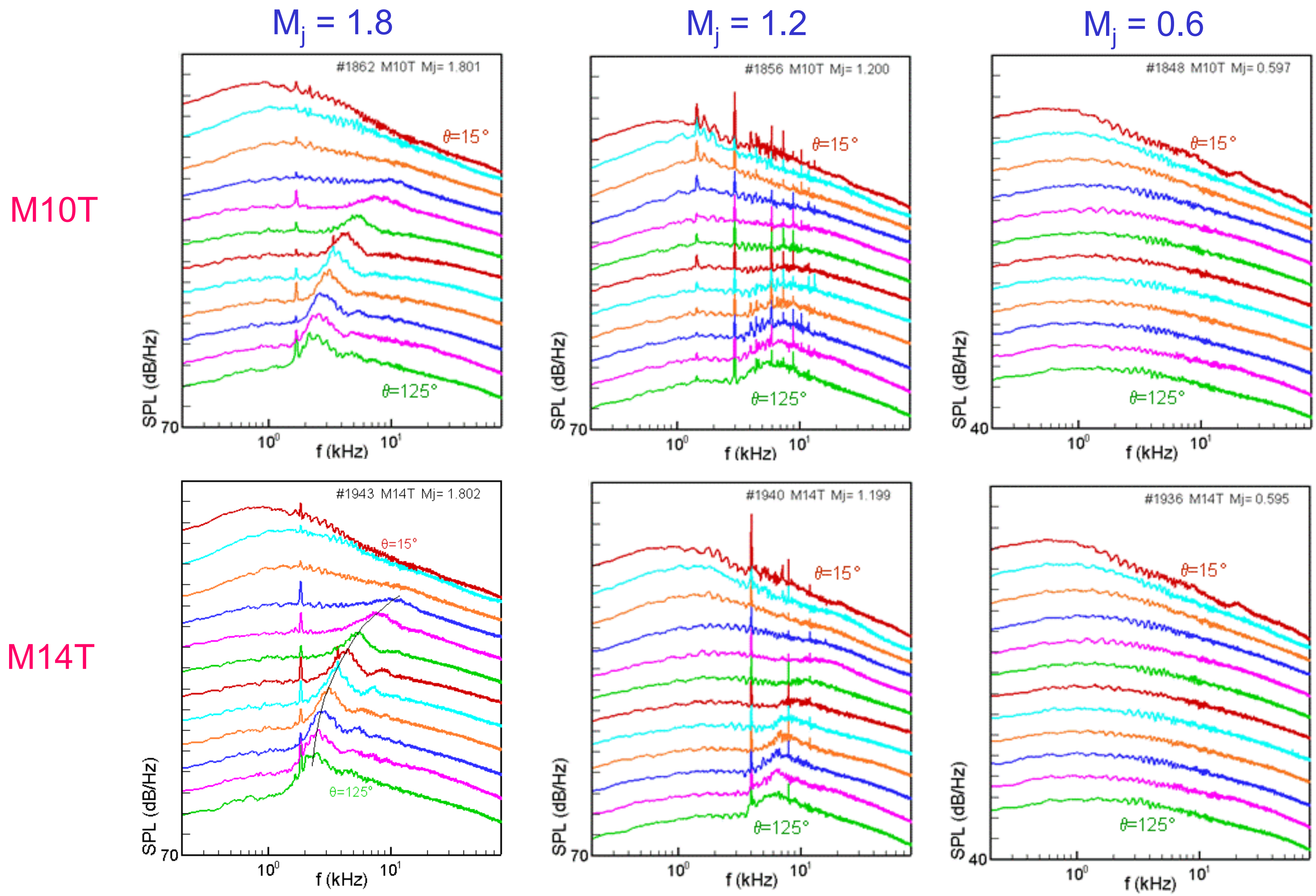
Experimental Facility

AAPL ('Dome')

Set-up for present experiment

SPL spectra acquired for: 24 mics, 7 cases (6 tripped b.l. + 1 untripped)
For 12 M_j ranging 0.3 – 2.0

Sound pressure level spectra

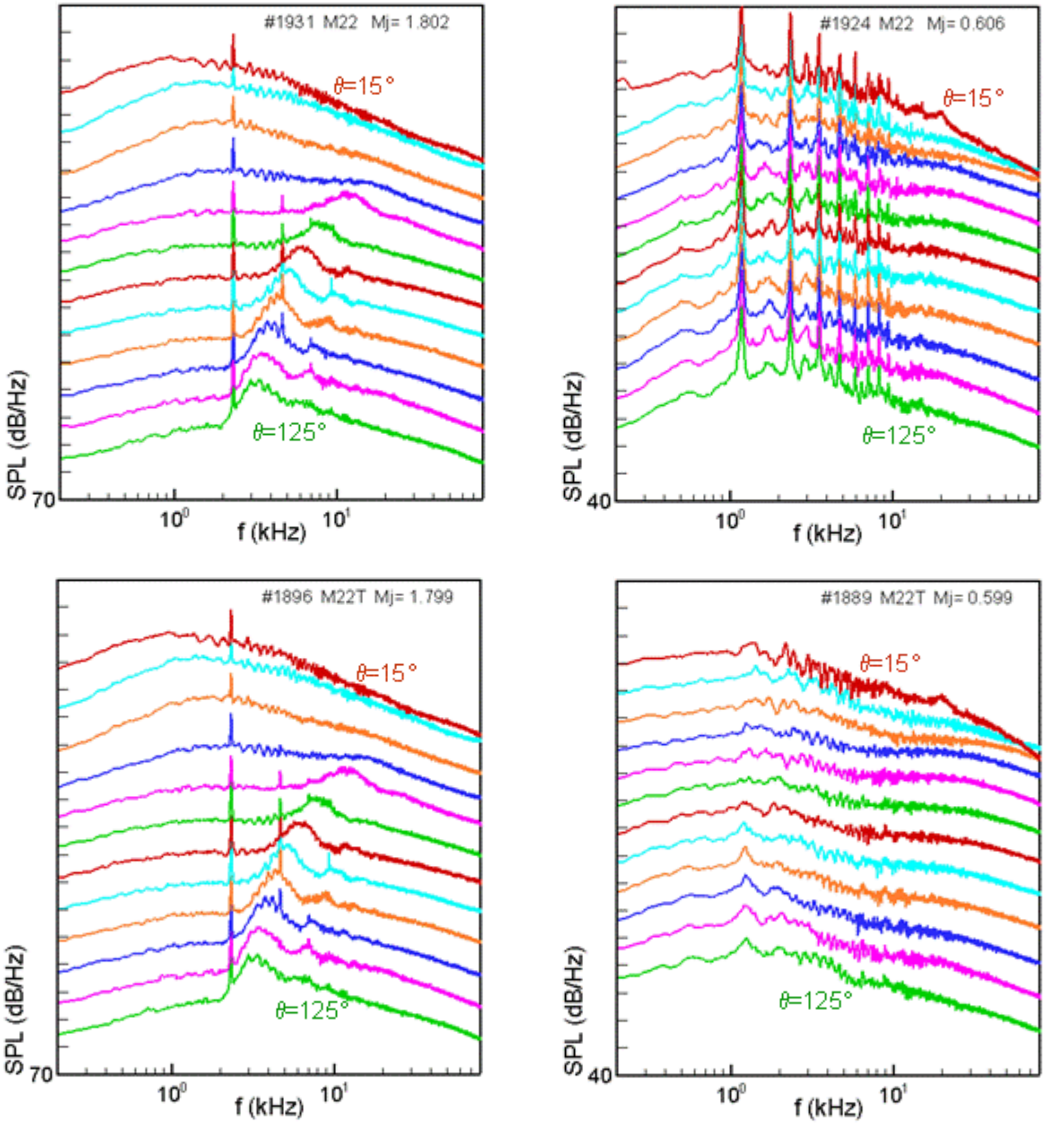


Sound pressure level spectra

M_j = 1.8 M_j = 0.6

M22

M22T

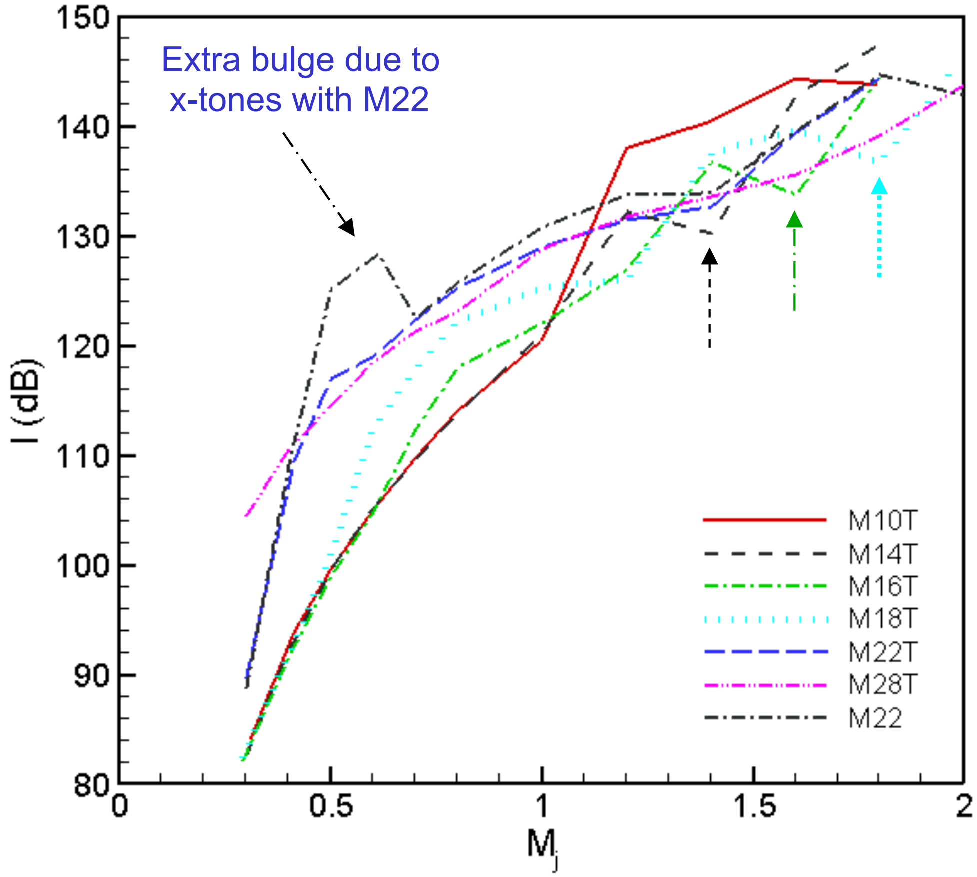


Transonic Tone at 1170 Hz frequency (stage 2) predicted well by correlation given in JFM 2002

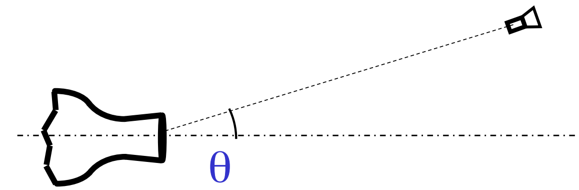
'Trips' suppress x-tones

OASPL versus M_j

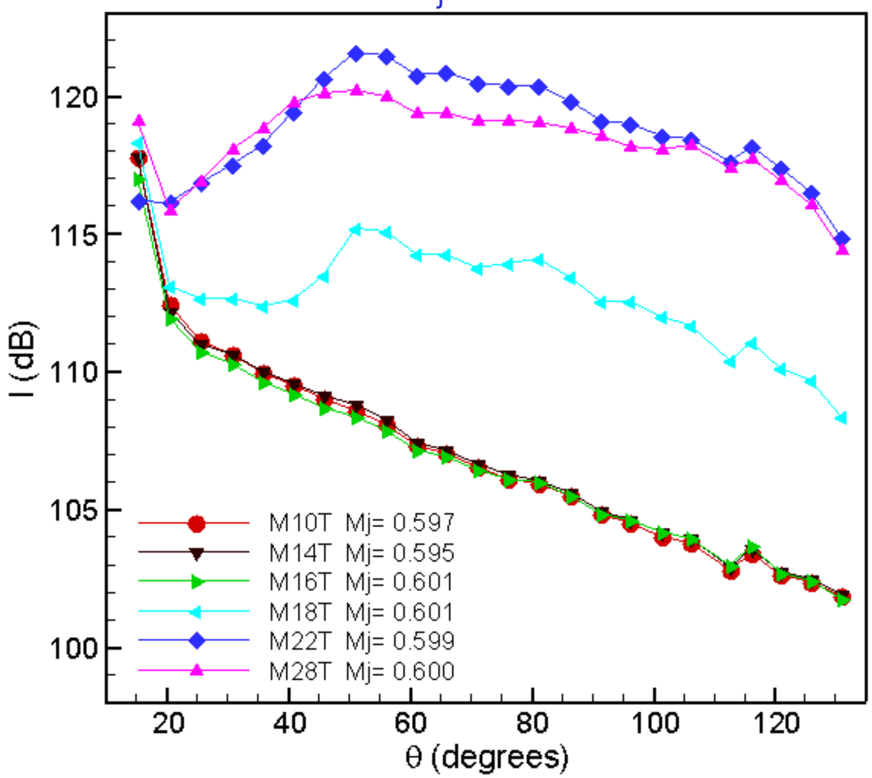
θ = 90°



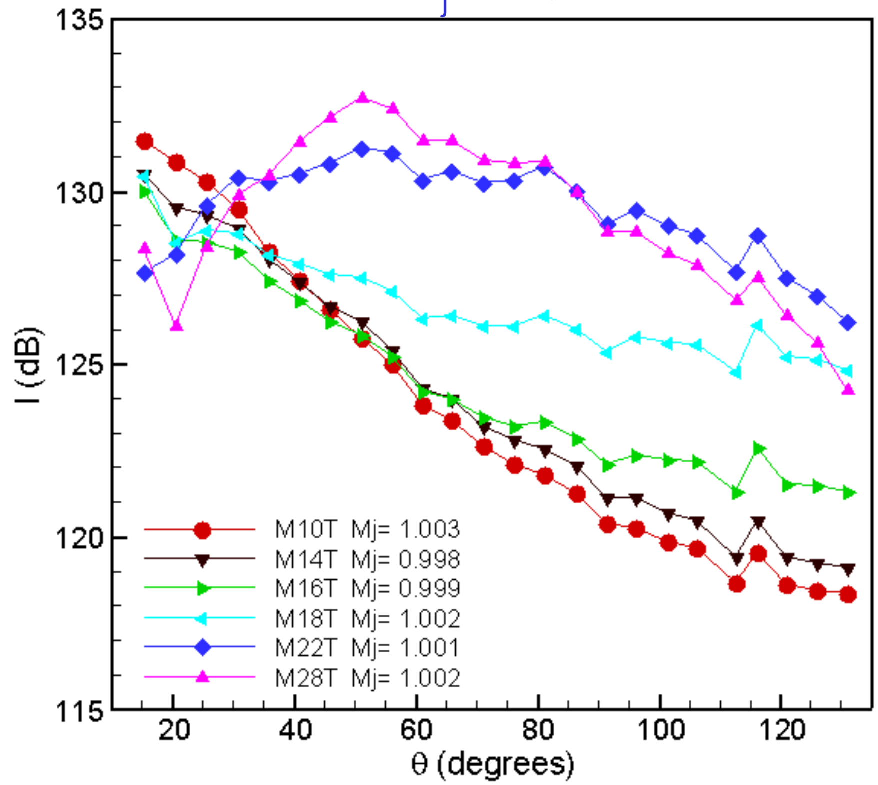
Directivity (OASPL versus θ)



$M_j = 0.6$



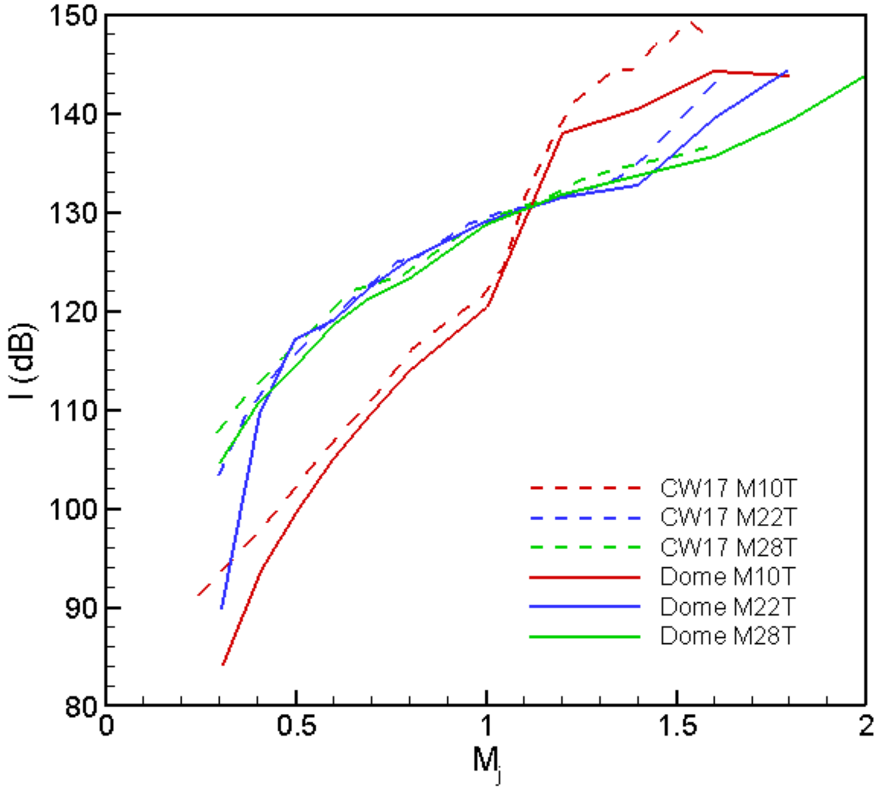
$M_j = 1.0$



OASPL can be 10-15 dB higher with a C-D nozzle due to EBBN

OASPL versus M_j , $\theta = 90°$

With same nozzles
Present (Dome) data Compared to
Data from another facility (CW17)



EBBN is not facility dependent

SUMMARY ON EBBN STUDY

-- EBBN is confirmed with detailed spectral and directivity data

-- Occurs at low pressure ratios in overexpanded regime

-- Amplitudes can be 10-15 dB higher relative to convergent case

-- More pronounced with larger half-angle of divergent section

-- Random shock motion within divergent section is likely source

How important is EBBN?

-- May not be of concern in typical flight conditions

-- Probably relevant to military aircraft in low altitude flight and landing

-- Likely to be relevant to rocket nozzles in launch pad environment

-- Must be considered in supersonic jet noise prediction efforts.