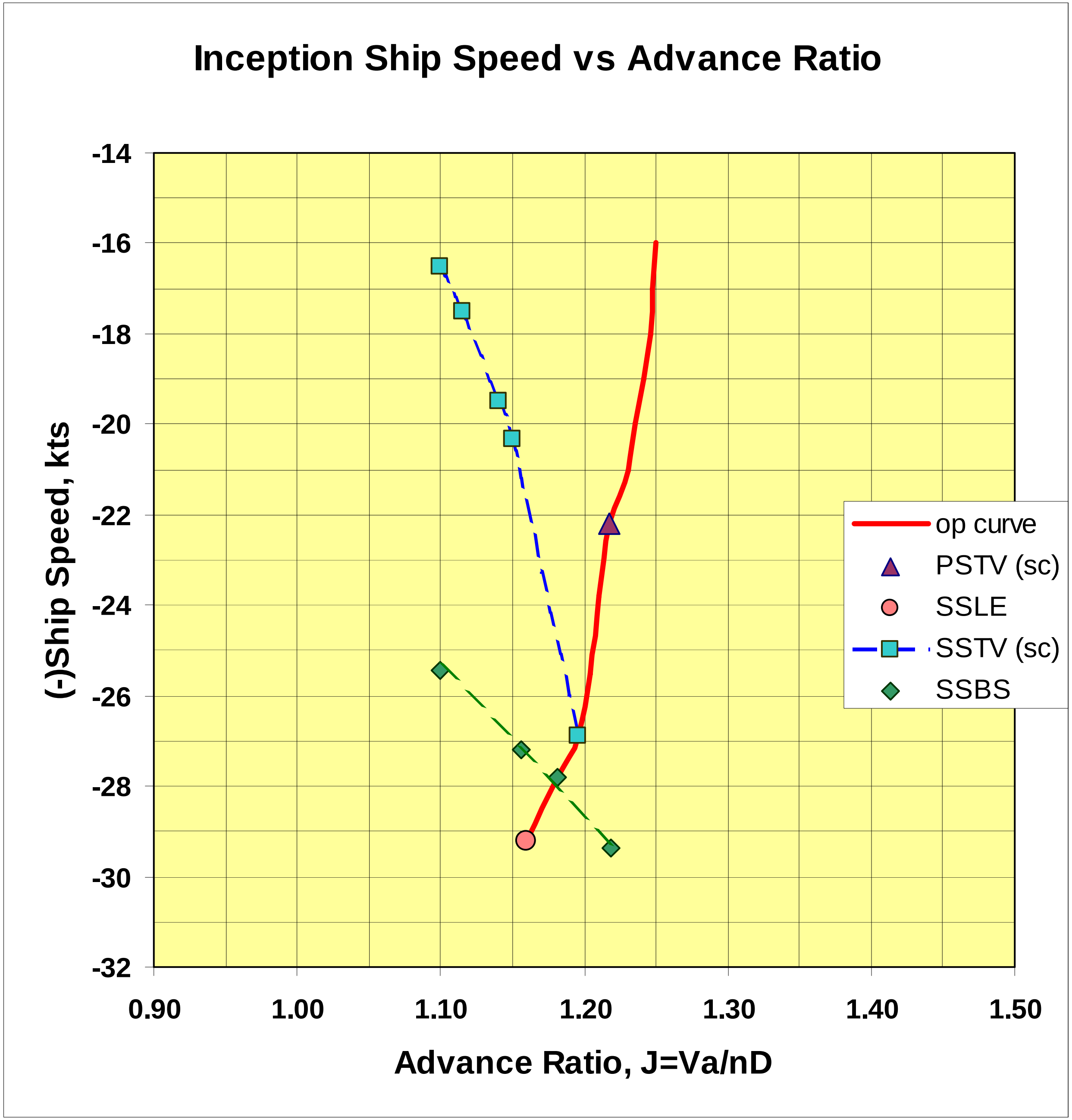
Existing/Future Technology to Address Radiated Noise by Modifying Vessel Propulsion and Operating Parameters

(& a few other un-scheduled topics)

N. A. Brown

2007 NOAA Vessel-Quieting Symposium



As ship speed increases, various forms of propeller cavitation are found to begin and then grow in size and intensity. For large, slowly turning propellers the inceptions can be delayed to higher ship speeds.

<u>P</u>ressure <u>S</u>ide

<u>S</u>uction <u>S</u>ide

<u>B</u>lade <u>S</u>urface

<u>T</u>ip <u>V</u>ortex

<u>L</u>eading <u>E</u>dge

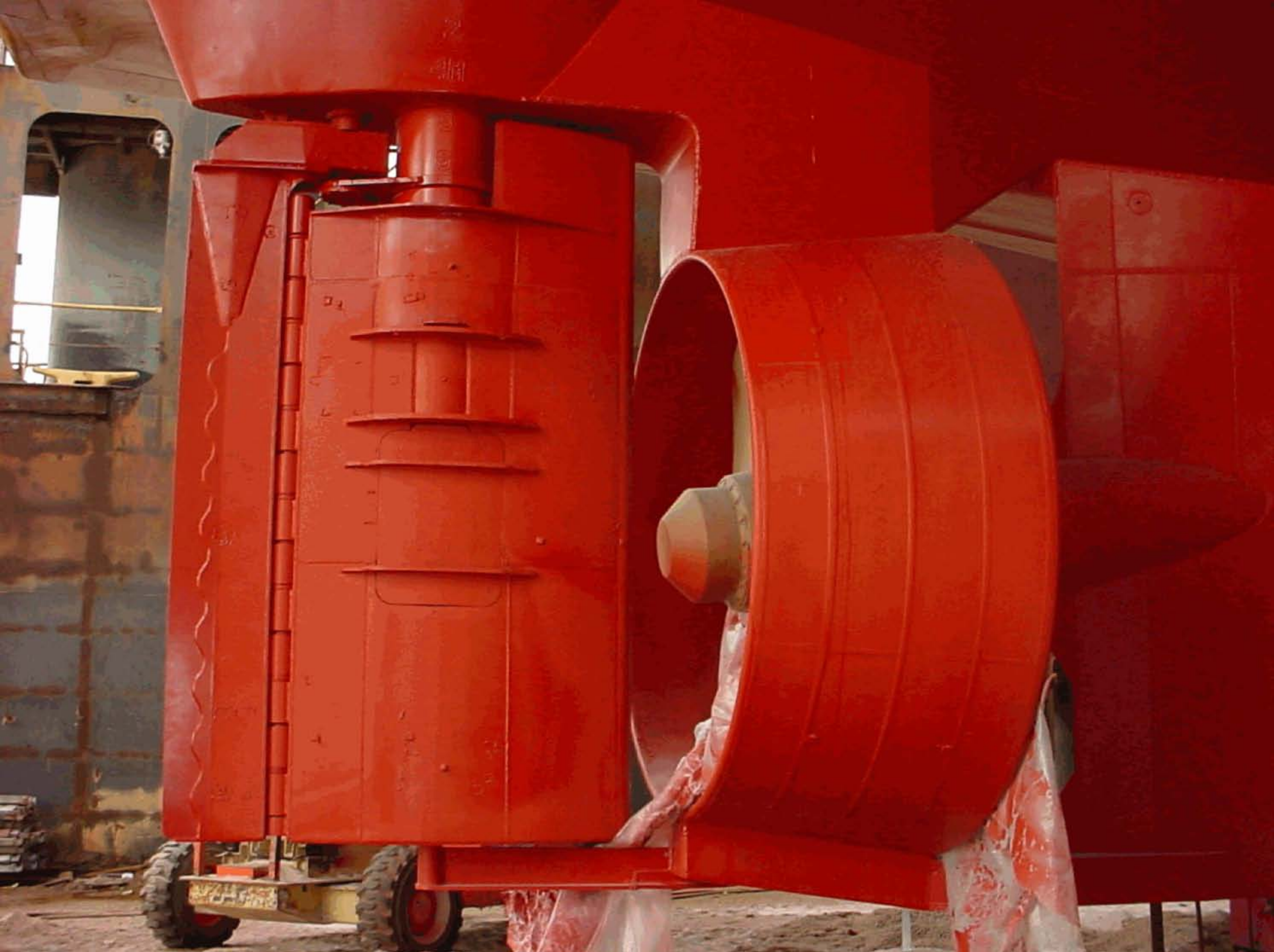
Propeller cavitation is generally governed by a parameter, aptly named the “cavitation number”:

$$\sigma = \frac{p - p_v}{\frac{\rho}{2} U^2}$$

This is the ratio of pressure-above-vapor-pressure - ***to*** **- dynamic pressure.**

Cavitation of one sort or another will occur (incept) when σ falls below a particular value.

Given a submergence pressure, propeller cavitation is mitigated by reduction of propeller tip speed.



Single-screw ships enjoy a propulsive efficiency benefit by recovering the frictional drag energy in the wake.

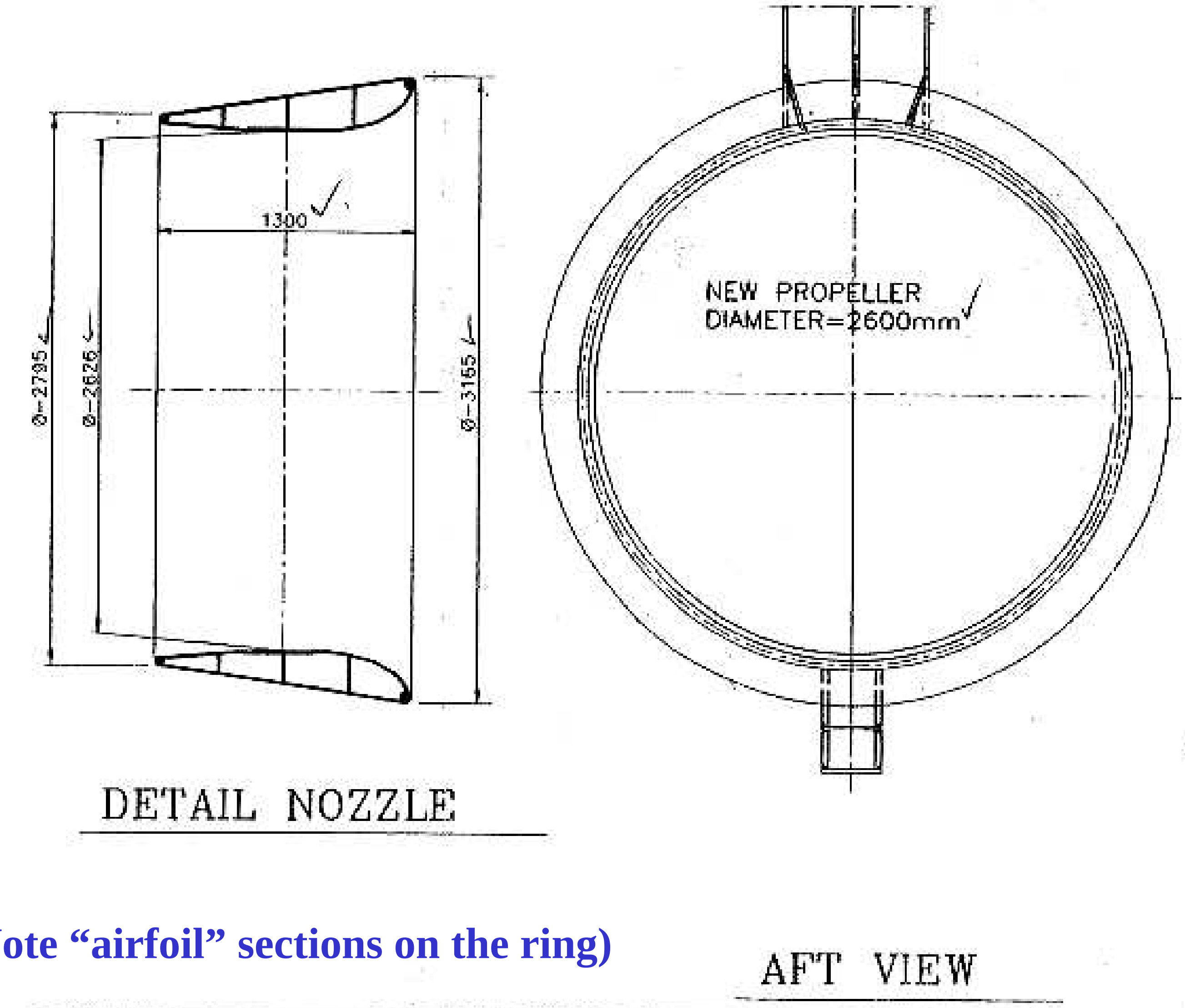
Unfortunately, where lift is generated, as in propeller blades, by angle-of-attack (✂) the cavitation number can be expanded to:

$$\sigma_e = \sigma / \alpha^2$$

For Kort-nozzle propellers, the inflow is accelerated - which smooths the wake non-uniformities of velocity.

This beneficially reduces the ✂'s - but, unfortunately, decreases the pressure, hence ☞!

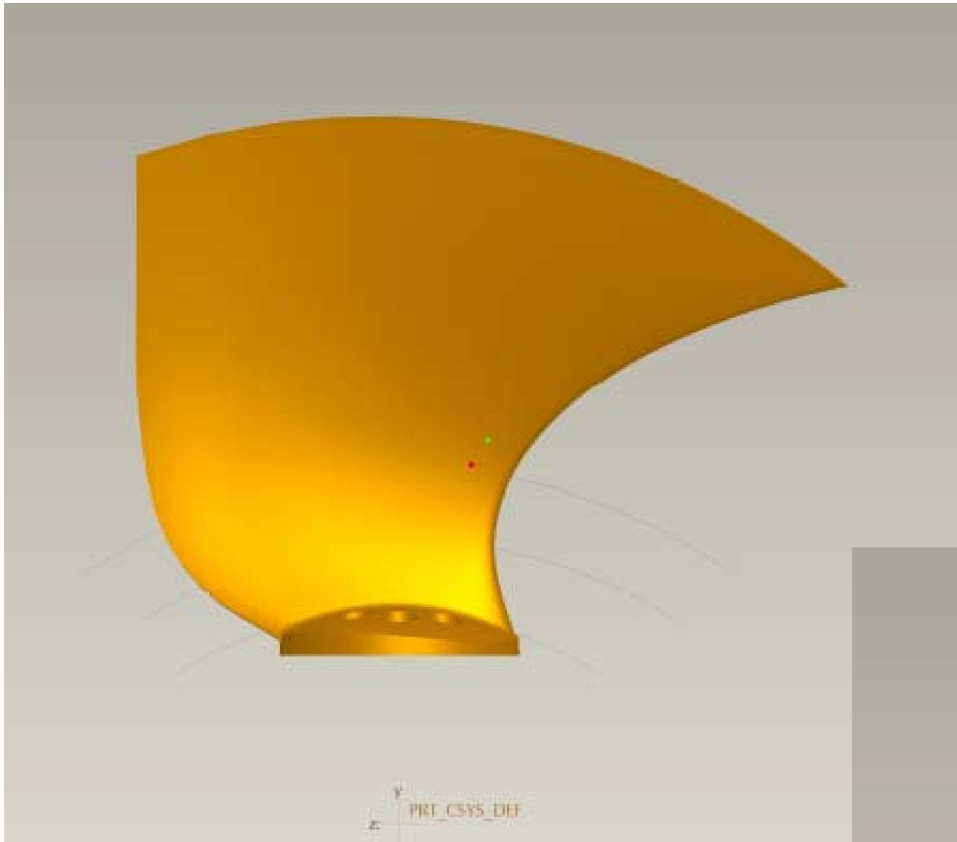
A Typical Propeller Nozzle - for Heavily Loaded Props



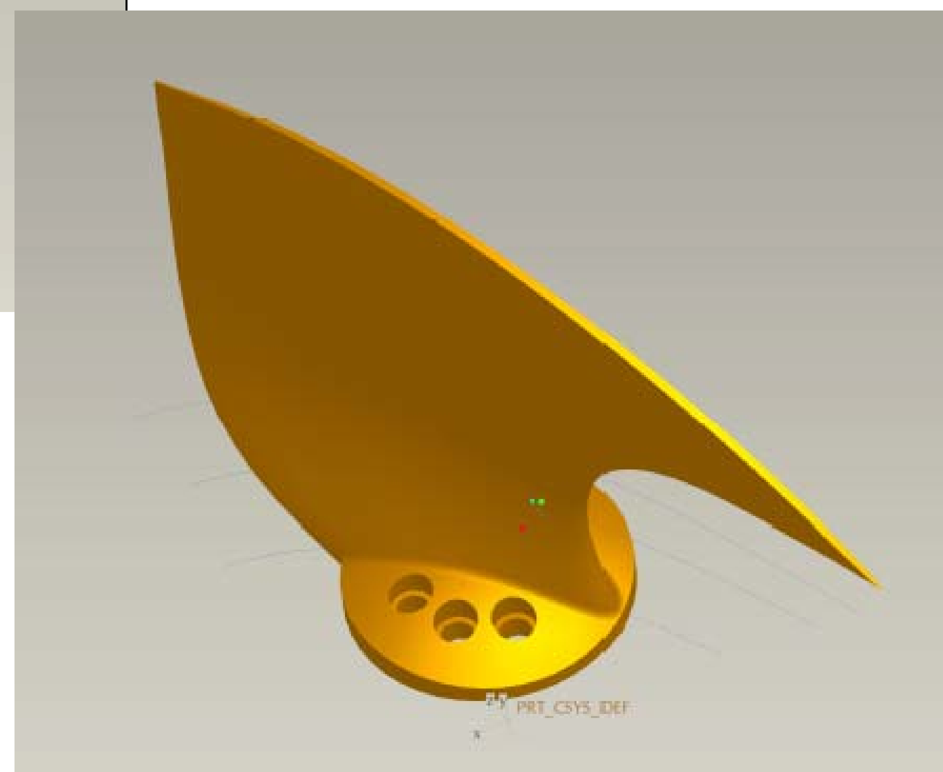
(Note "airfoil" sections on the ring)


TB60

An improved blade design for nozzle propellers is at hand - which promises to delay inception of cavitation and accommodate pitch changes on CRP's



The New Forward-Skewed Nozzle-Propeller Blade



Expected to increase cavitation inception speeds, hence lower cavitation noise levels.

(three precedents did it!)

Why Twin Screws?

Observation of published data for families of propellers will show that optimum efficiency over a range of pitch-diameter ratios implies relative constancy of K_t, throughout.

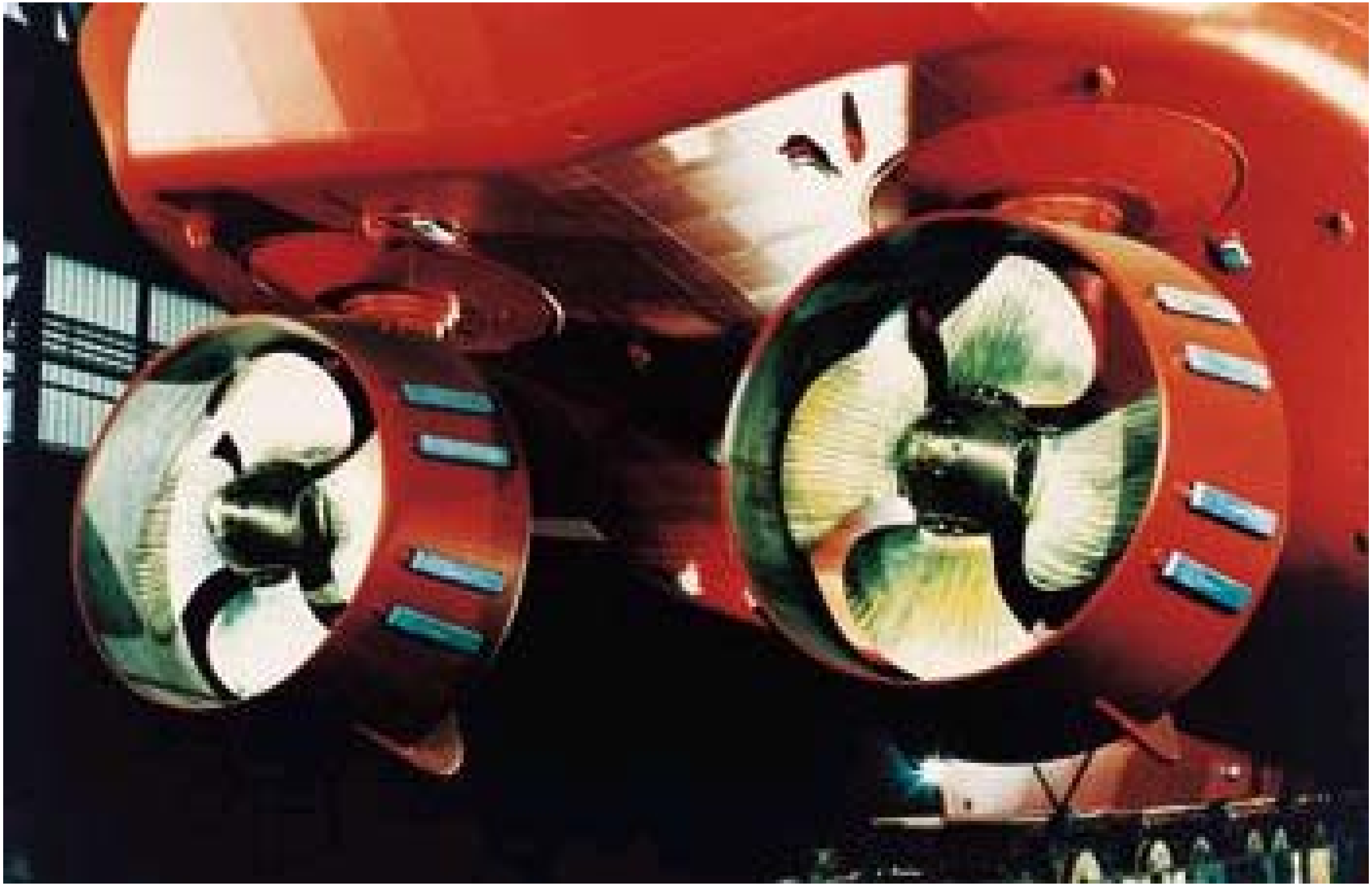
For a given required thrust, T, then, there is some constancy of the product: nD^2, or $(nD)D$. The first part is proportional to tip speed: $U_t =$ 👌nD. ***So the tip speed is found to be inversely proportional to diameter, roughly.***

To maintain higher values of the cavitation number - in order to avoid or minimize cavitation - ***use large diameter propellers and turn them slowly.***

Twin screws can do this much more readily than single screws.

Twin Screws

Azipod Trainable "Puller" Props on a Cruise Ship
(bow to the left)

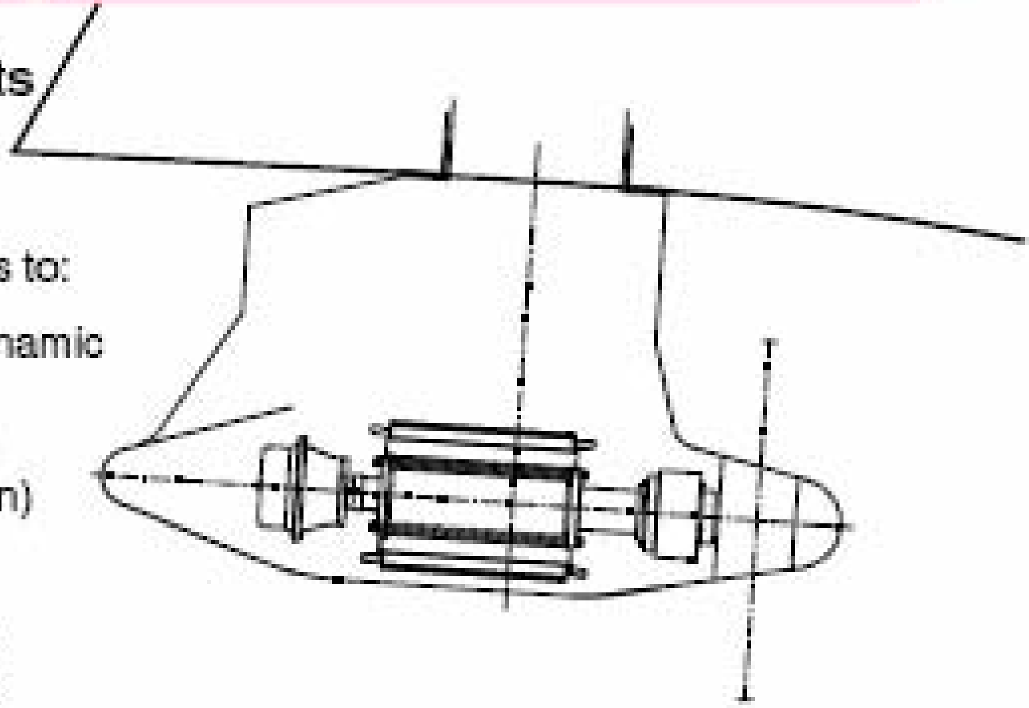


Twin Trainable, Controllable-Pitch, Nozzle Propellers

Azipod Concept

Operational Benefits

Hydrodynamics

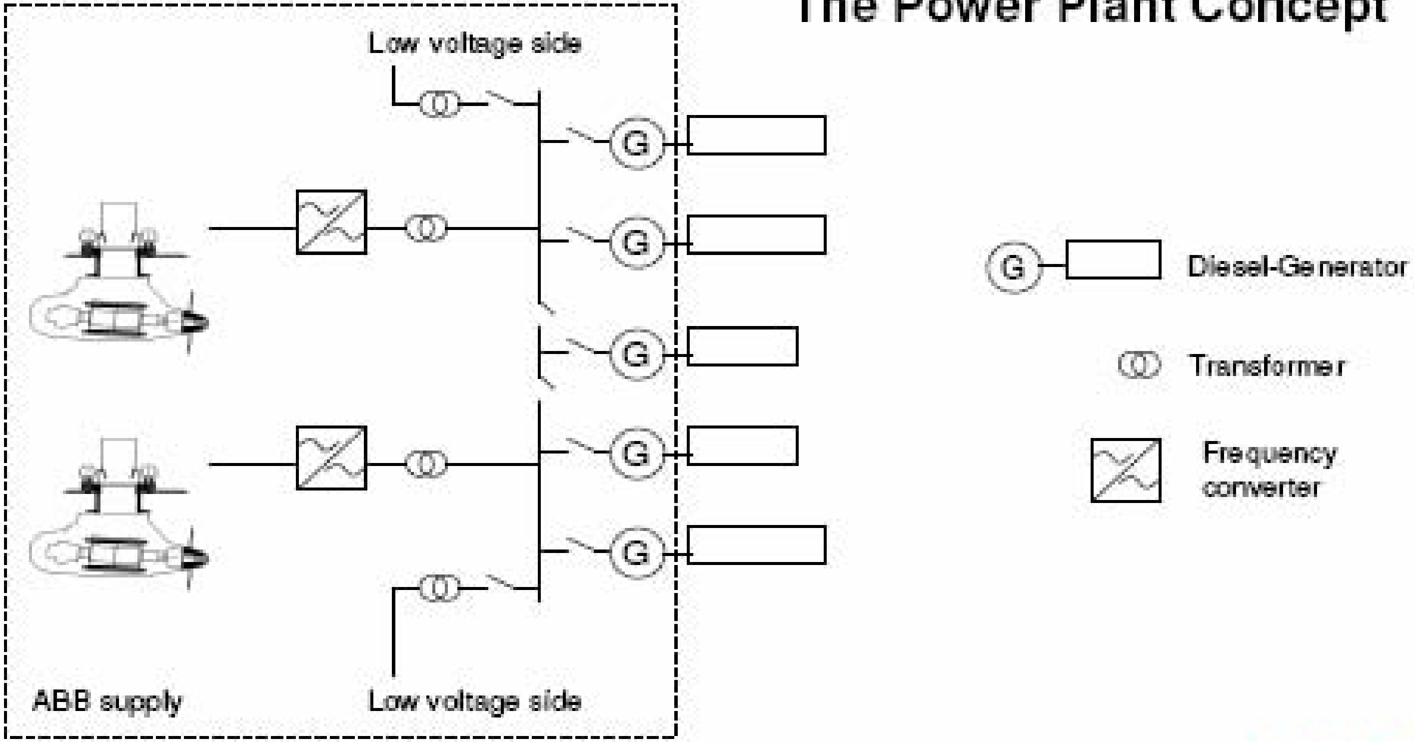


Excellent wake field leads to:

- Improved hydrodynamic efficiency (an 8% improvement was recorded on Elation)
- Less cavitation
- Reduced propeller induced vibrations
- Reduced noise levels

Diesel-Electric Propulsion

The Power Plant Concept



"Short Seas Shipping"

Developing coastal trade to employ fast, highly-powered ships - to replace/augment over-the-road trucking

Speeds 24 to 32 kts; powers to 120,000 SHP considered

Operate through potentially sensitive areas

Expect a future noise threat to MMs

BUT

Highest-speed ships will employ WaterJet propulsion

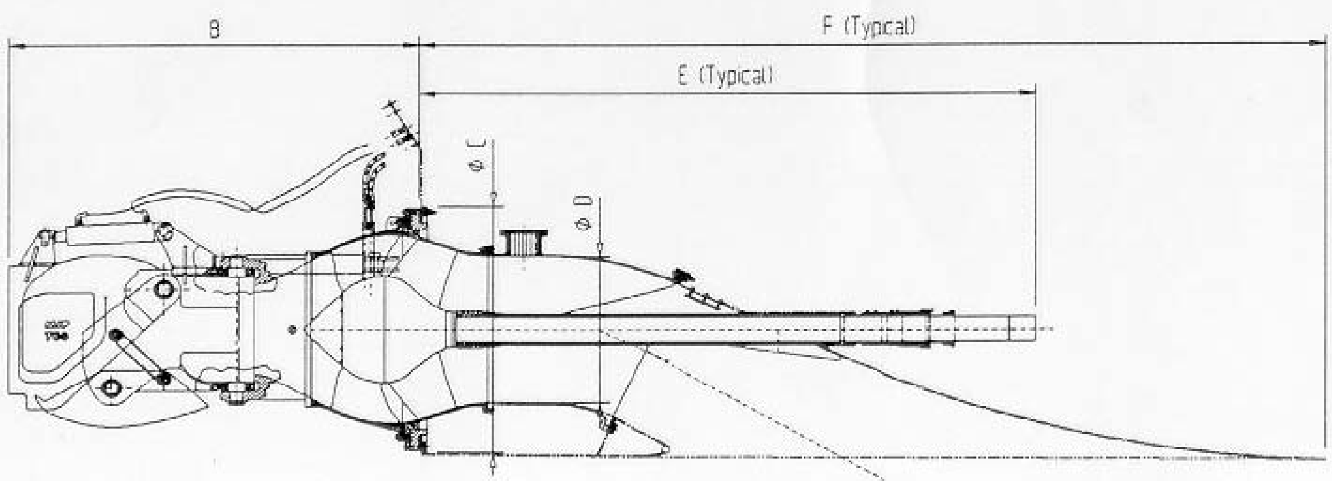
We have learned how to quiet them

A Family of WaterJet Propulsors (they’re a lot bigger now!)

Size	*Nom kW	Max kW	A	B	∅ C	∅ D	E	F	G	H	Weight per unit kg**	
											Steerable	Booster
500	1200	1800	510	1290	855	500	2050	3400	575	460	815	575
550	1500	2250	560	1412	940	550	2250	3790	630	505	1090	710
650	2100	3150	665	1680	1120	650	2675	4510	750	600	1560	1035
750	2800	4200	765	1900	1255	750	3075	5180	860	690	2105	1460
850	3700	5550	880	2100	1440	850	3540	5890	990	795	3145	2125
950	4900	7350	1010	2460	1610	950	4070	6590	1100	915	4330	3000
1100	6950	9750	1200	2845	1890	1100	4820	7630	1350	1090	6040	4080
1350	9200	13800	1355	3490	2110	1350	5560	9370	1555	1250	8450	5830
1550												
1750												
2050												

* Above figures are nominal, final data in accordance to technical specification.

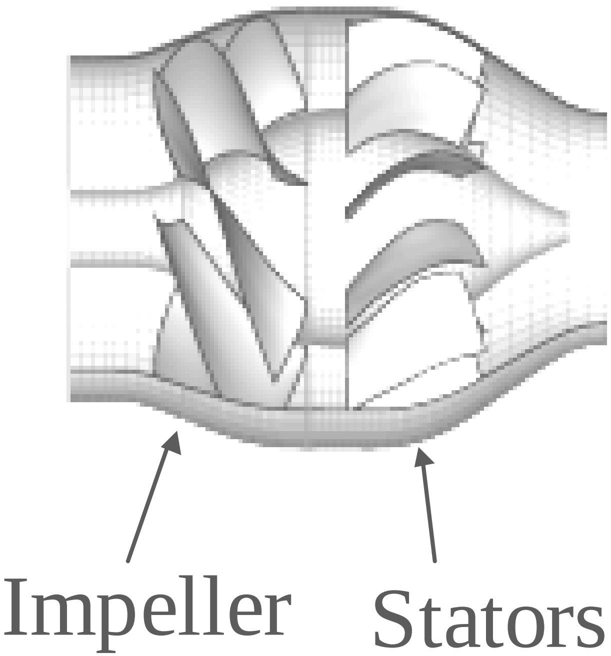
** Weight figures incl hudraulics, excl shafting & intake.

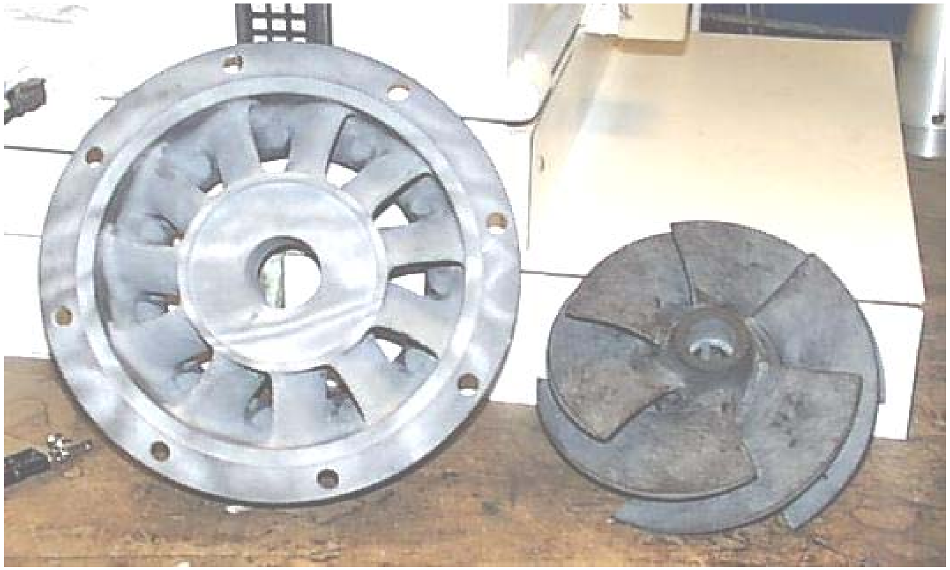


Conventional Waterjets

- Dominate market share of Intercoastal transport
- Propulsion of Choice in the 30-45kt range
- Beyond 45 kts, cavitation breakdown leads to excessive unit size
- Water jet efficiency poor at 15kt cruise speeds
- Robust, modular, off the shelf, designs
- Can be difficult to fit inside the hull
- Blading:
  - Typically very large blade area, low aspect ratio
  - Forward rotor with postswirl stator blades

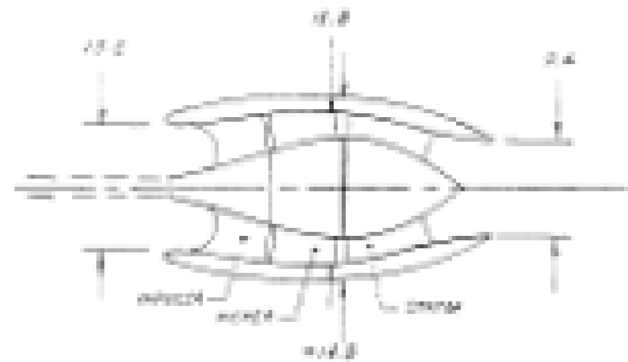
The Guts of most Waterjets: Mixed Flow Pump





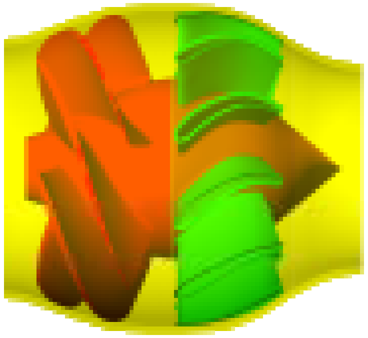
Conventional Waterjets

- Waterjet efficiency good in low sea states at operational speeds, 40kts
- Water jet efficiency poor at 15kt cruise speeds
- Navy's SES100A w/ waterjets attained 74-78 knot speeds
- Breaking the 45-50 kt Speed Limit
  - Rotor cavitation
  - Inlet, passage. stator cavitation
- ***Breaking the 50 kt Speed Limit requires advanced design features***
  - Large blade area, tandem rotor, Inducer/kicker
  - Careful inlet design
  - Advanced blade shaping, Forward skew



AWJ-21™ Pump

- Advanced Mixed Flow pump
  - Forward skewed blades
  - Thick blade sections to increase cavitation free speeds
- Propulsor designed with recent MIT lifting surface design tools
  - Not empirically designed (traditional approach)
- Pump flow validated with RANS

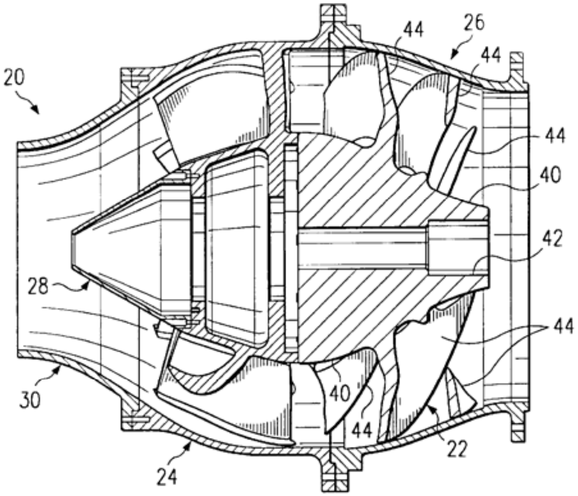


Blade surface flow visualization

U.S. Patent Oct. 24, 2000 Sheet 2 of 4 6,135,831

U.S. Patent Oct. 24, 2000 Sheet 3 of 4 6,135,831

FIG. 2



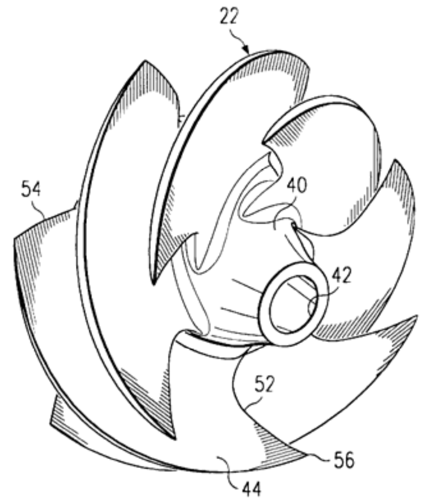


FIG. 4

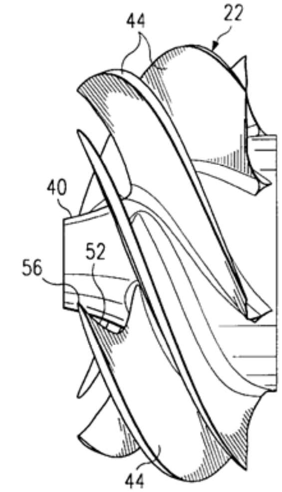
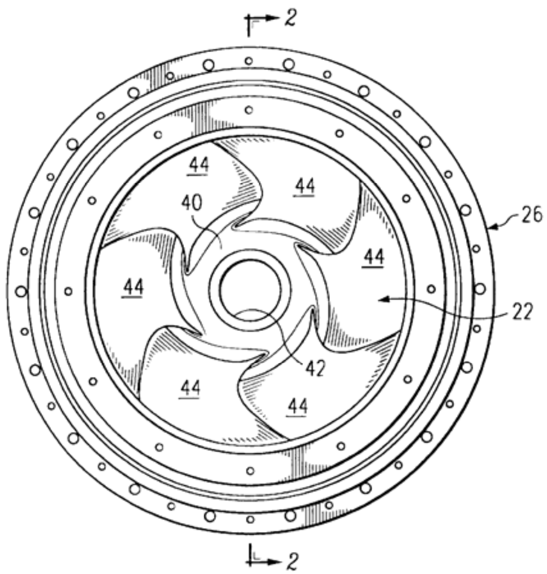


FIG. 6

FIG. 3



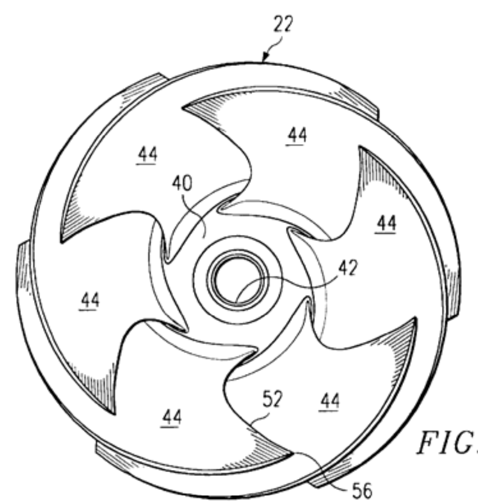


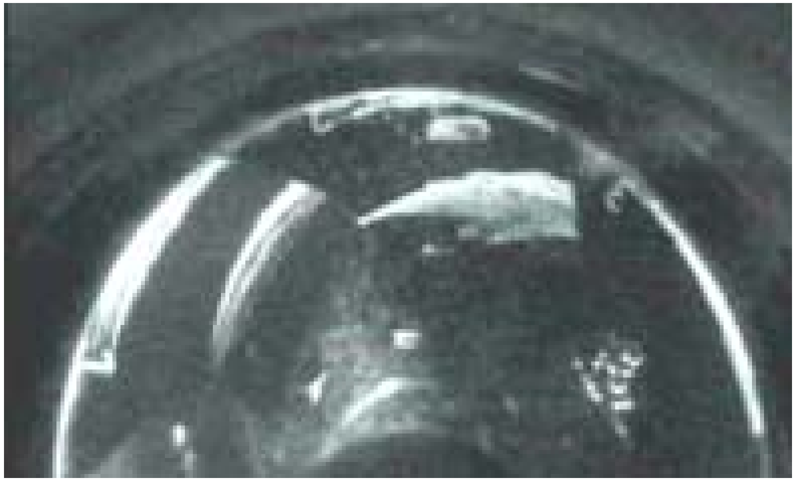
FIG. 5

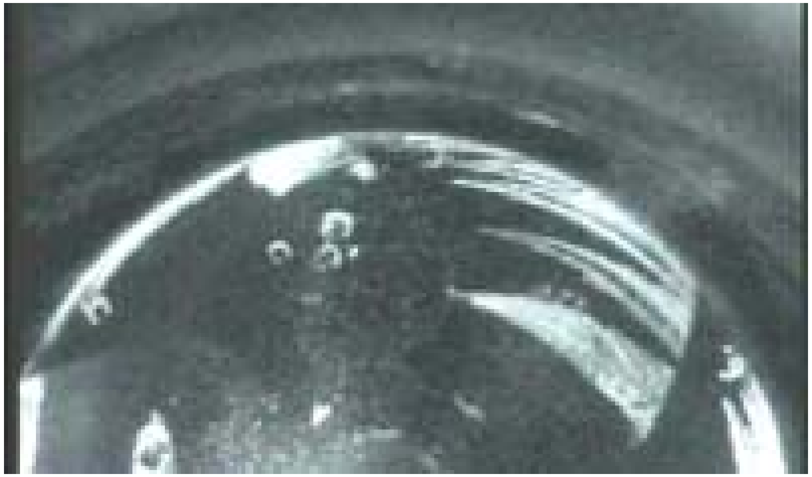
Drawings of the Fwd-Skewed Pump Rotor - from the Patent

Advanced Impeller Design - Cavitation Views

Stills from videos

Shaft camera looking at upstream side of blade





- Observe streak cavitation emanating from blade surface imperfections and traveling bubble cavitation

- NO leading edge cavitation observed!

Estimation of Propeller Cavitation Radiated Noise

$$L_s = 163 + 10\,Log\left(B\,D^4 N^3 f^{-2}\right) + 10\,Log\left(A_c / A_d\right)$$

dB//(1 µPa x m)^2/Hz.

in an upper frequency range above a peak frequency, $\boldsymbol{f_p}$, defined by:

$$f_p = \frac{28}{D\left(A_c / A_d\right)} \sqrt{\frac{10.08}{H_s + 10.08}}$$

where: ***B*** is the total number of propeller blades (10),
D is the propeller diameter in meters (1.4),
N is the revolution rate in RPS,
f is the frequency in Hz.,
$\boldsymbol{A_c}$ is the swept area of cavitation on each blade, in the projected view,
$\boldsymbol{A_d}$ is the projected disc area of a propeller,
$\boldsymbol{H_s}$ is the submergence depth of the shaft in meters (1.97), and
10.08 is the atmospheric pressure head in meters of sea water.

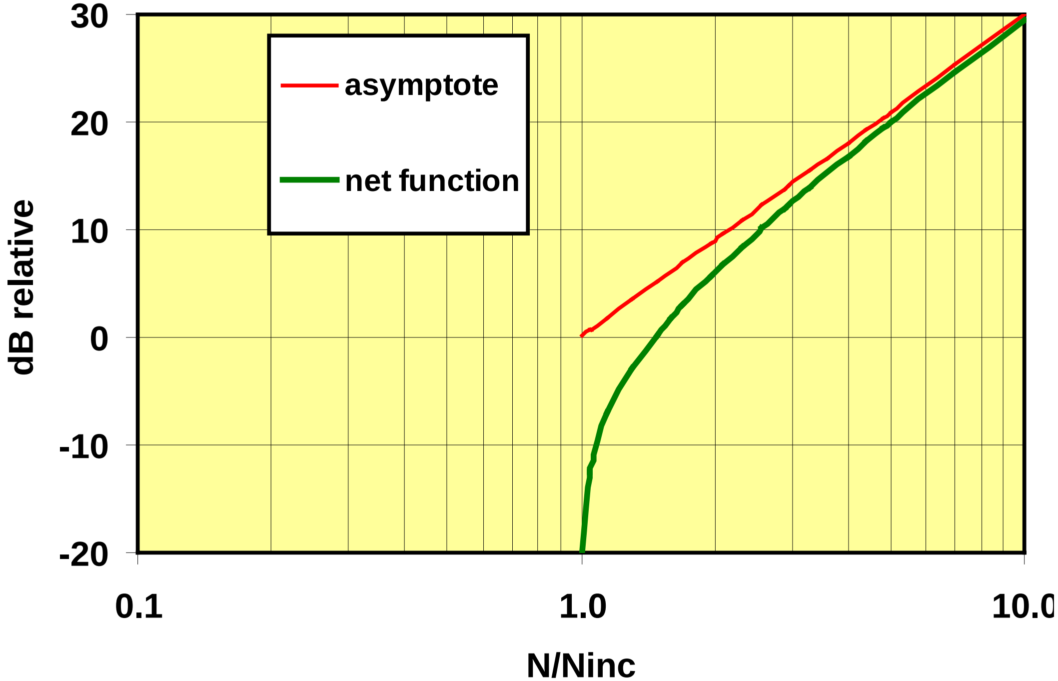
Below the peak frequency, the spectrum level is presumed flat in frequency at the peak-frequency level.

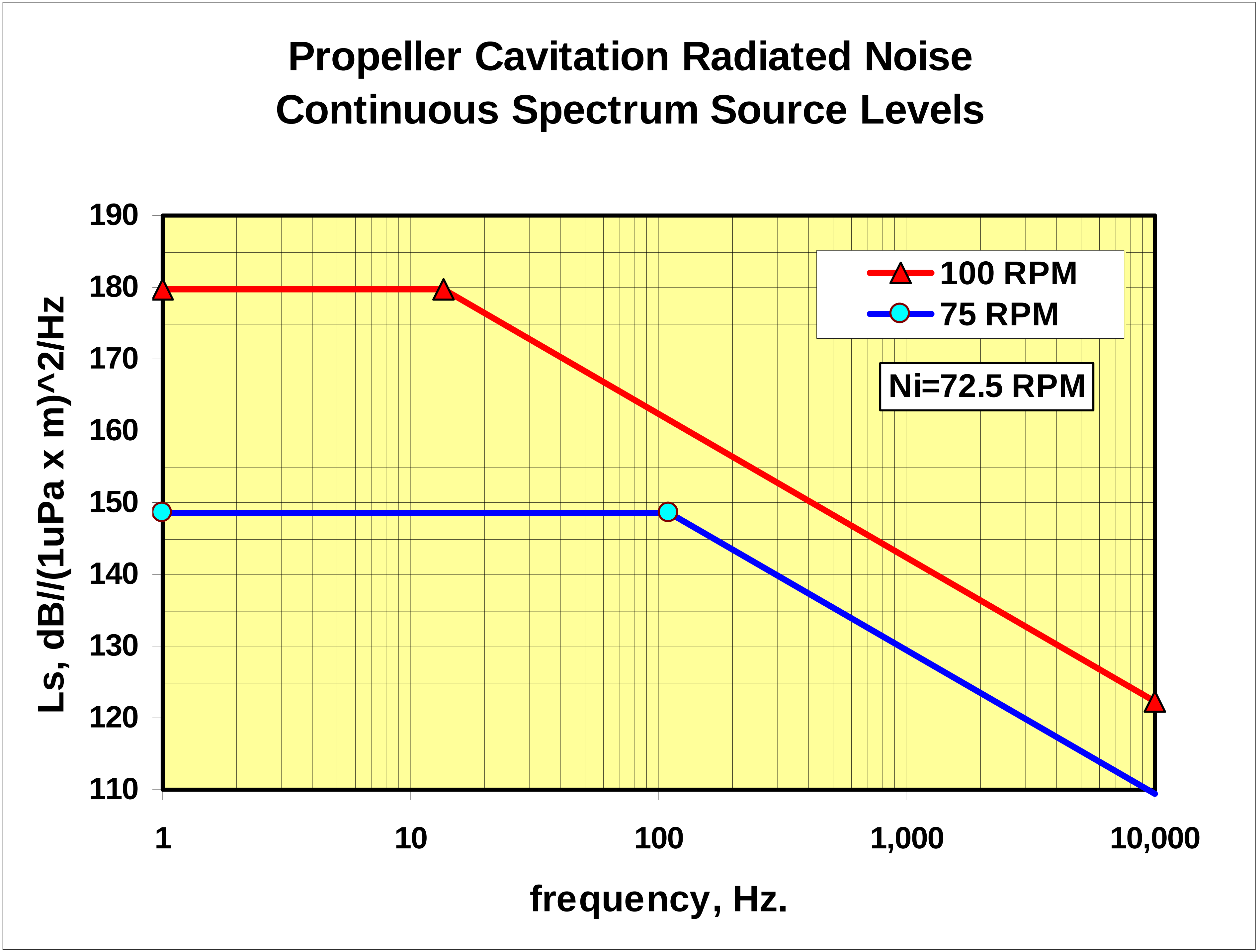
Radiated Noise Estimation, Continued

In the absence of any quantitative observed or computed information, the swept area of cavitation, A_c, is presumed to vary in a simple manner:

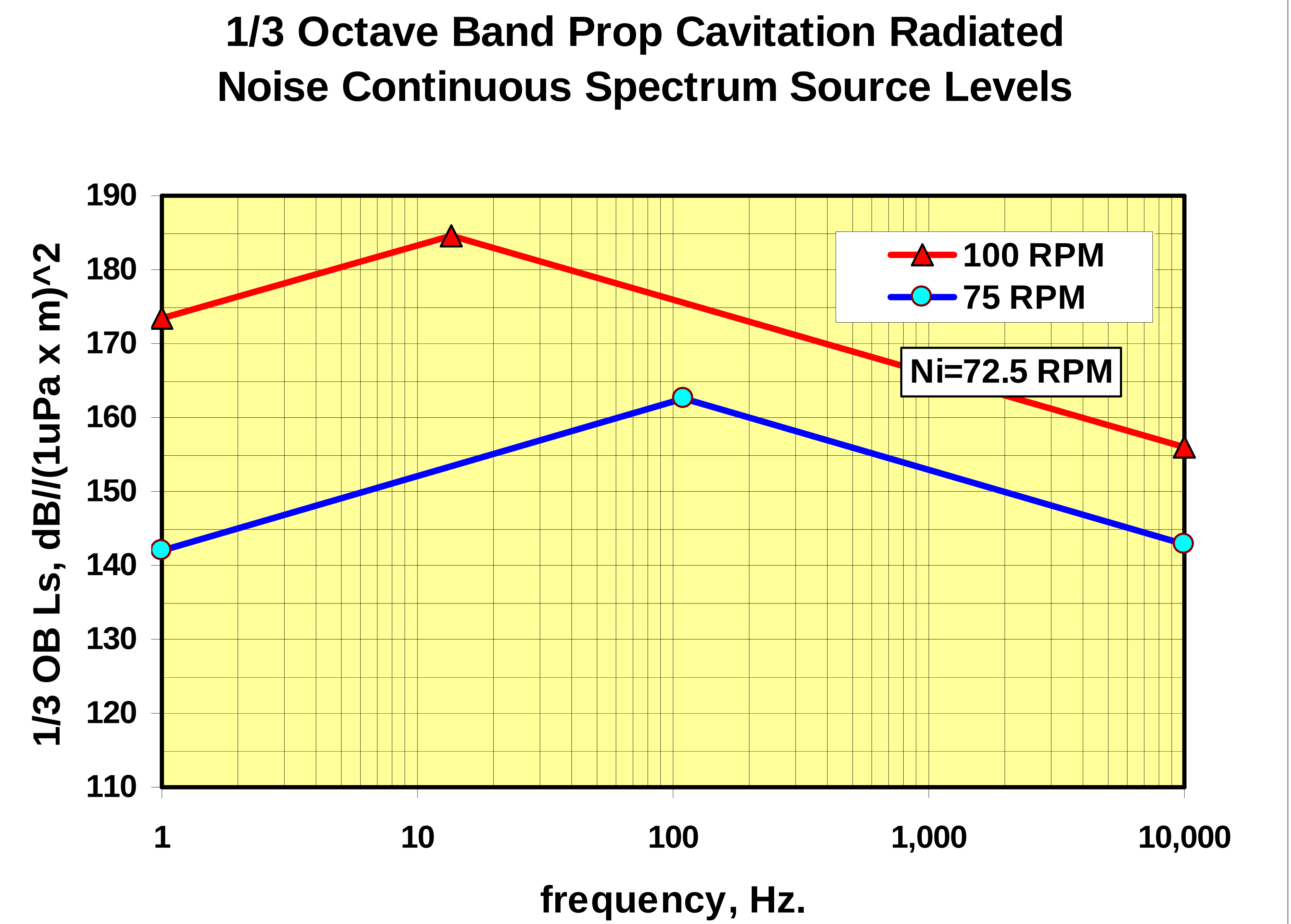
$$A_c / A_d = \frac{N/N_i - 1}{N/N_i}$$

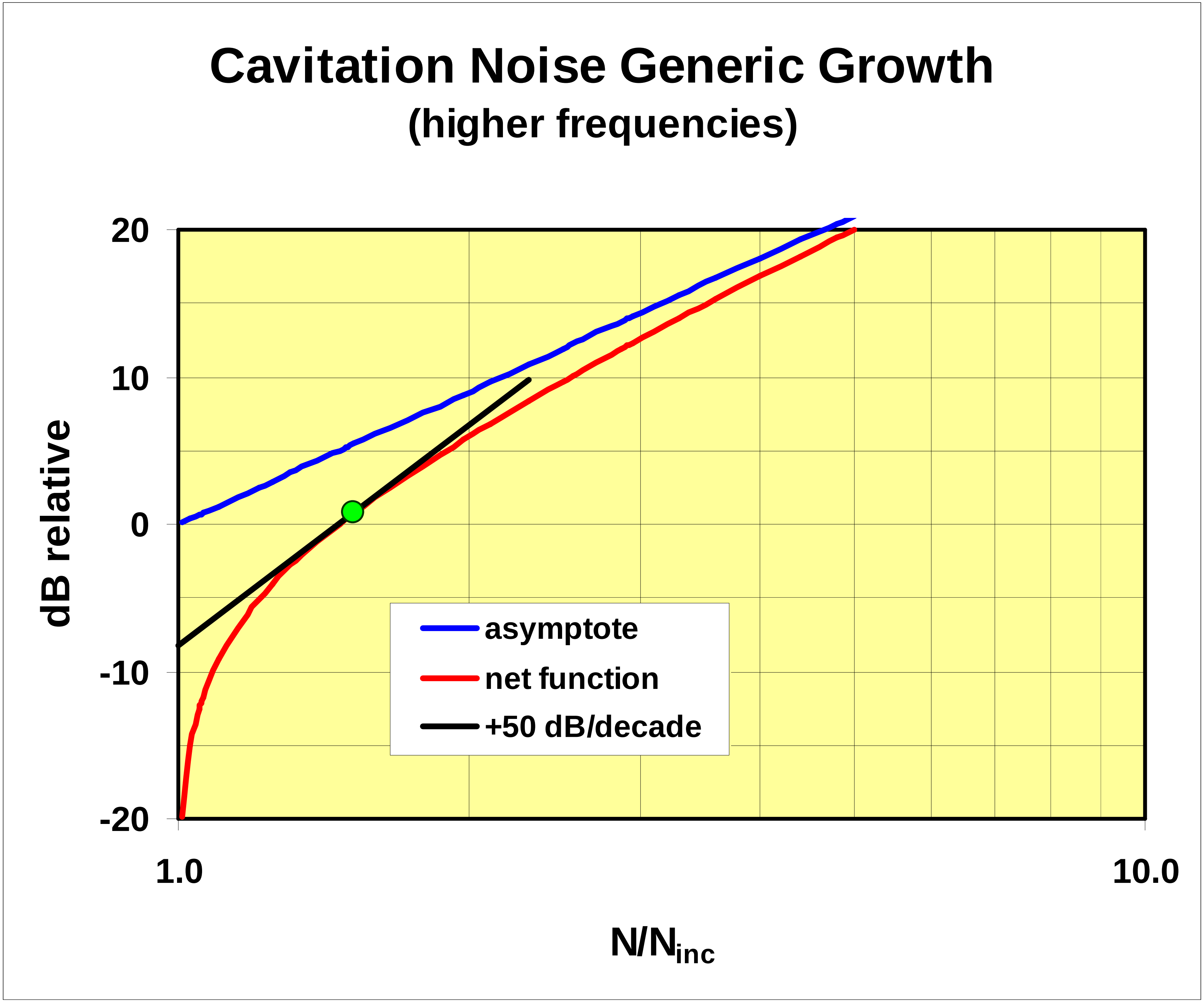
where N_i is the revolution rate at inception, and which yields a growth of radiated noise level at a fixed (higher) frequency according to the following plot.



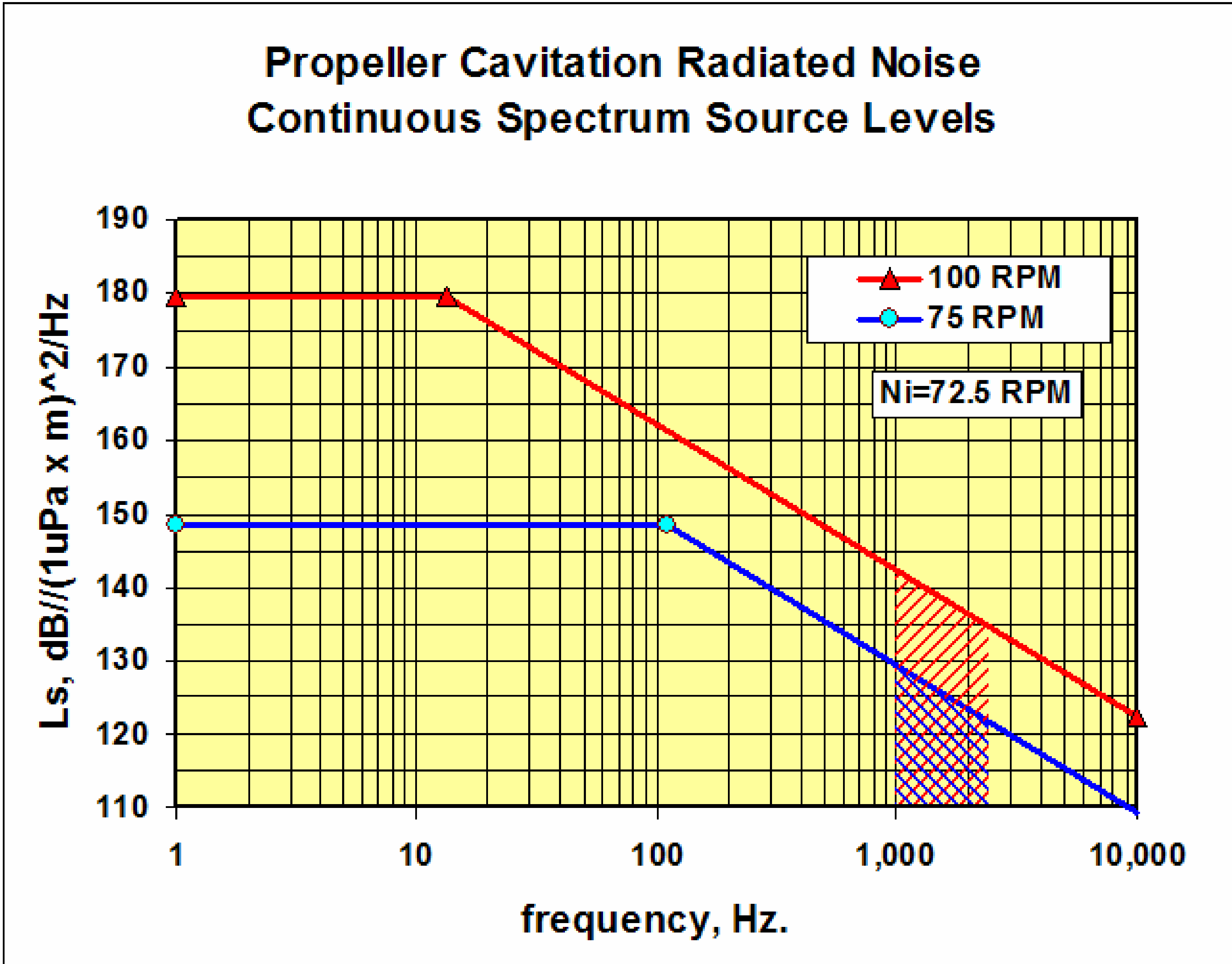


Propeller Cavitation Radiated Noise
Continuous Spectrum Source Levels
100 RPM
75 RPM
Ni=72.5 RPM
Ls, dB//(1uPa x m)^2/Hz
190
180
170
160
150
140
130
120
110
1
10
100
1,000
10,000
frequency, Hz.


1/3 Octave Band Prop Cavitation Radiated
Noise Continuous Spectrum Source Levels
100 RPM
75 RPM
Ni=72.5 RPM
1/3 OB Ls, dB//(1uPa x m)^2
190
180
170
160
150
140
130
120
110
1
10
100
1,000
10,000
frequency, Hz.



Cavitation Noise Generic Growth
(higher frequencies)
20
10
0
-10
-20
dB relative
asymptote
net function
+50 dB/decade
1.0
10.0
N/N$_{inc}$


Propeller Cavitation Radiated Noise
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100 RPM
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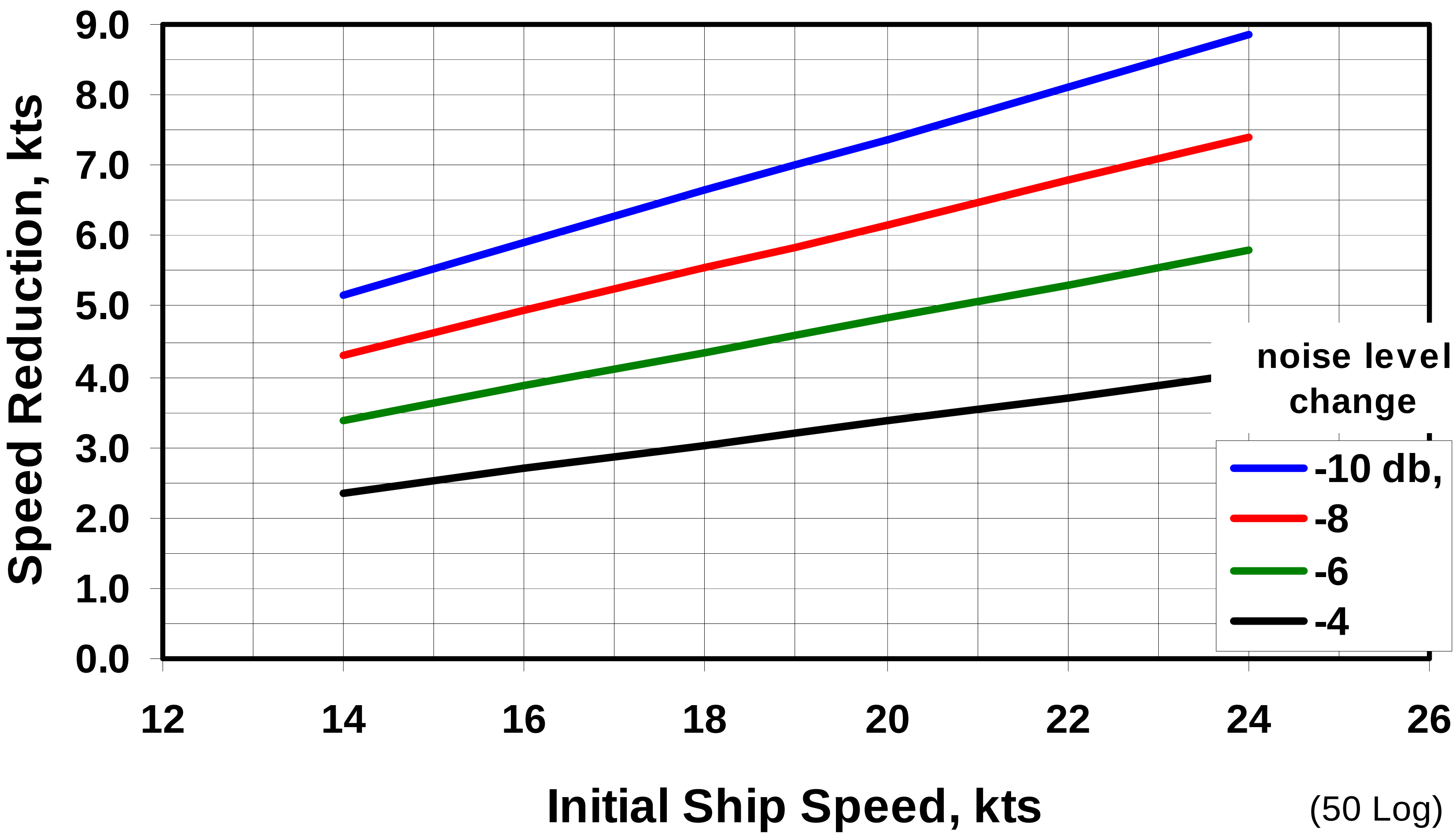
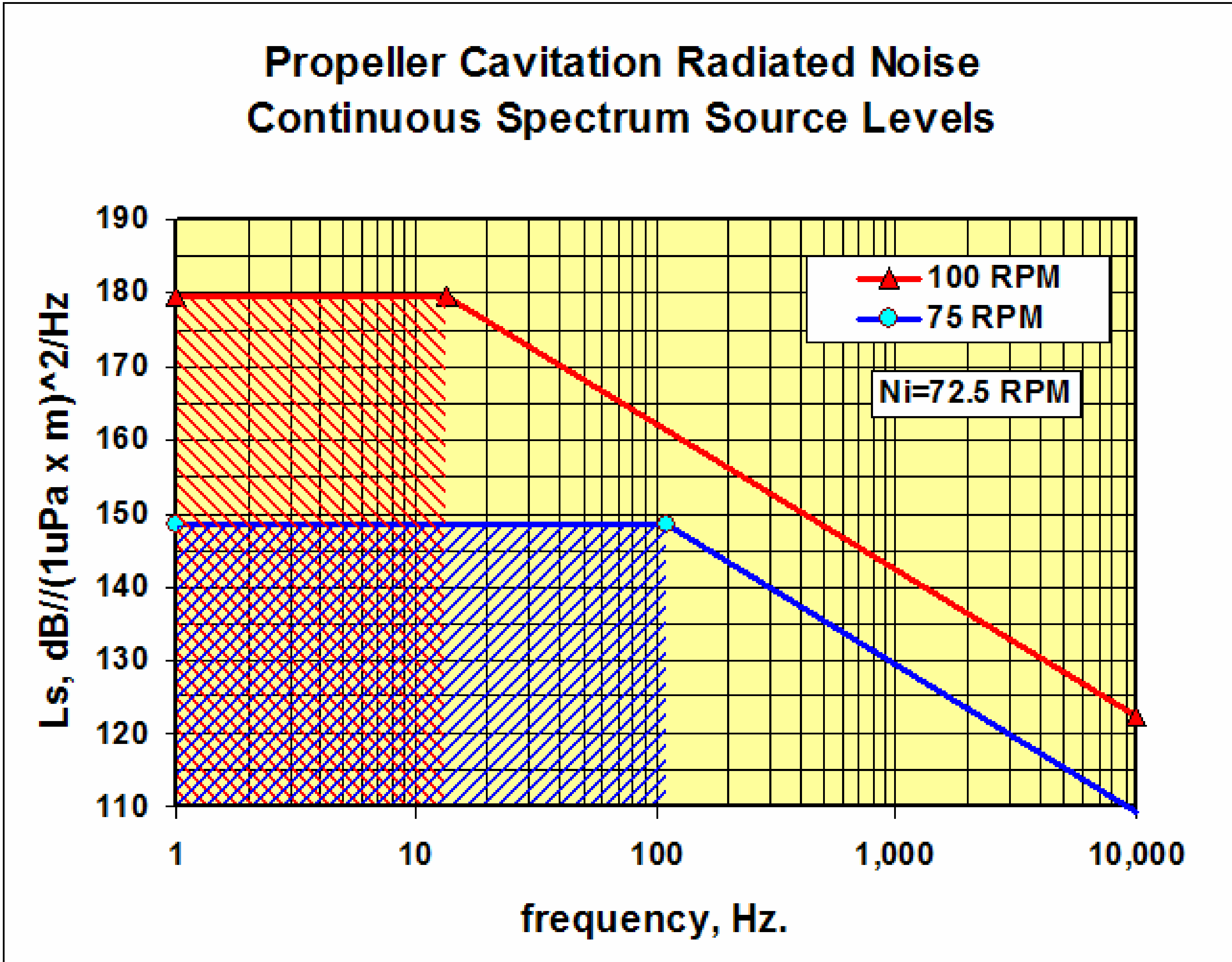
Ls, dB//(1uPa x m)^2/Hz
190
180
170
160
150
140
130
120
110
1
10
100
1,000
10,000
frequency, Hz.

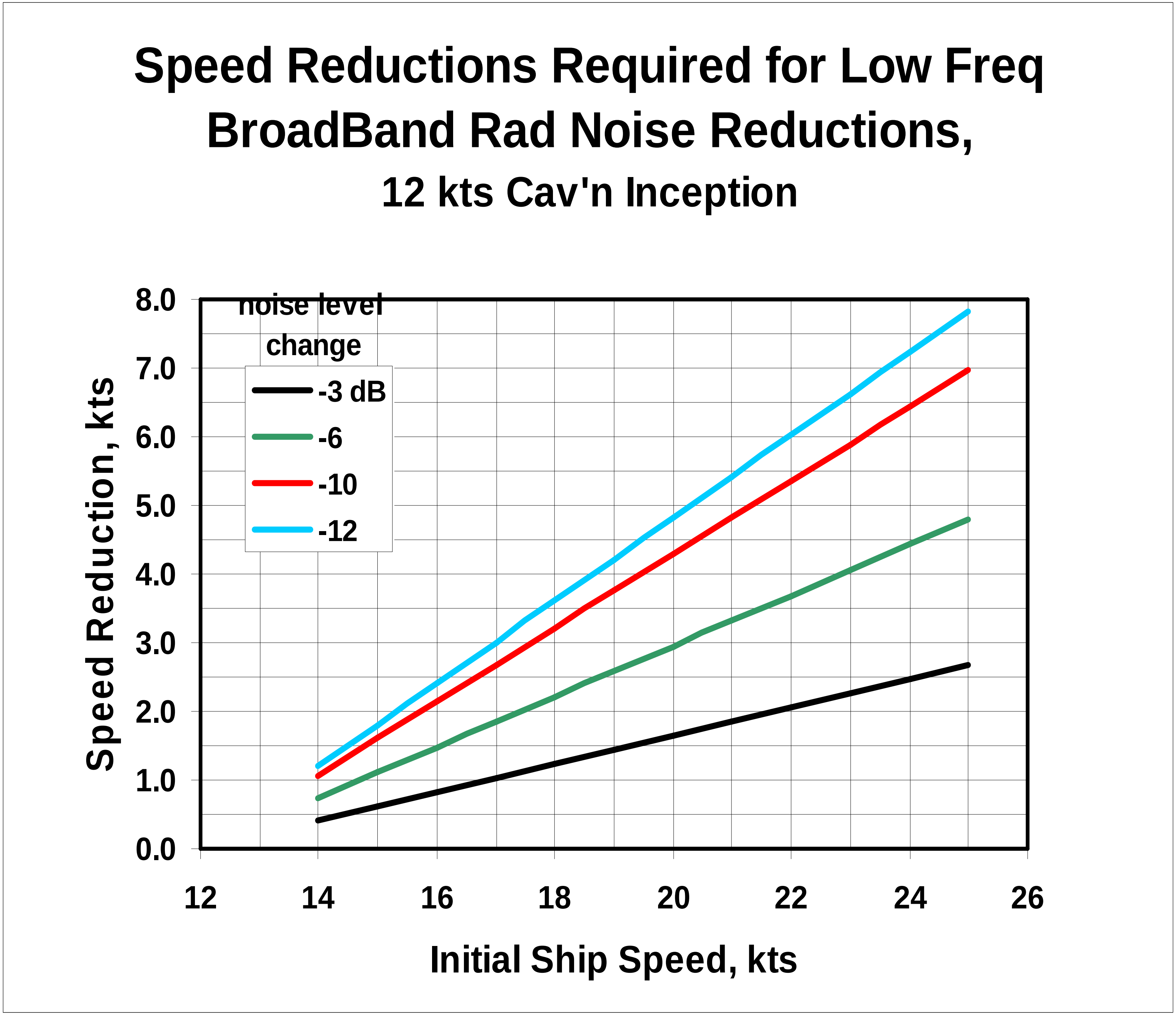
Speed Reductions Required for High Freq Radiated Noise Reductions

(Cavitation partially developed)





Propeller Cavitation Radiated Noise
Continuous Spectrum Source Levels
100 RPM
75 RPM
Ni=72.5 RPM
Ls, dB//(1uPa x m)^2/Hz
190
180
170
160
150
140
130
120
110
1
10
100
1,000
10,000
frequency, Hz.


Speed Reductions Required for Low Freq
BroadBand Rad Noise Reductions,
12 kts Cav'n Inception
noise level change
-3 dB
-6
-10
-12
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Speed Reduction, kts
12
14
16
18
20
22
24
26
Initial Ship Speed, kts

Cost

The cost of noise reduction by temporary vessel slowing is easily estimated.

The increased voyage time represents lost revenue.

The shipping company must be compensated for that loss.

Non-compliance must be similarly penalized.

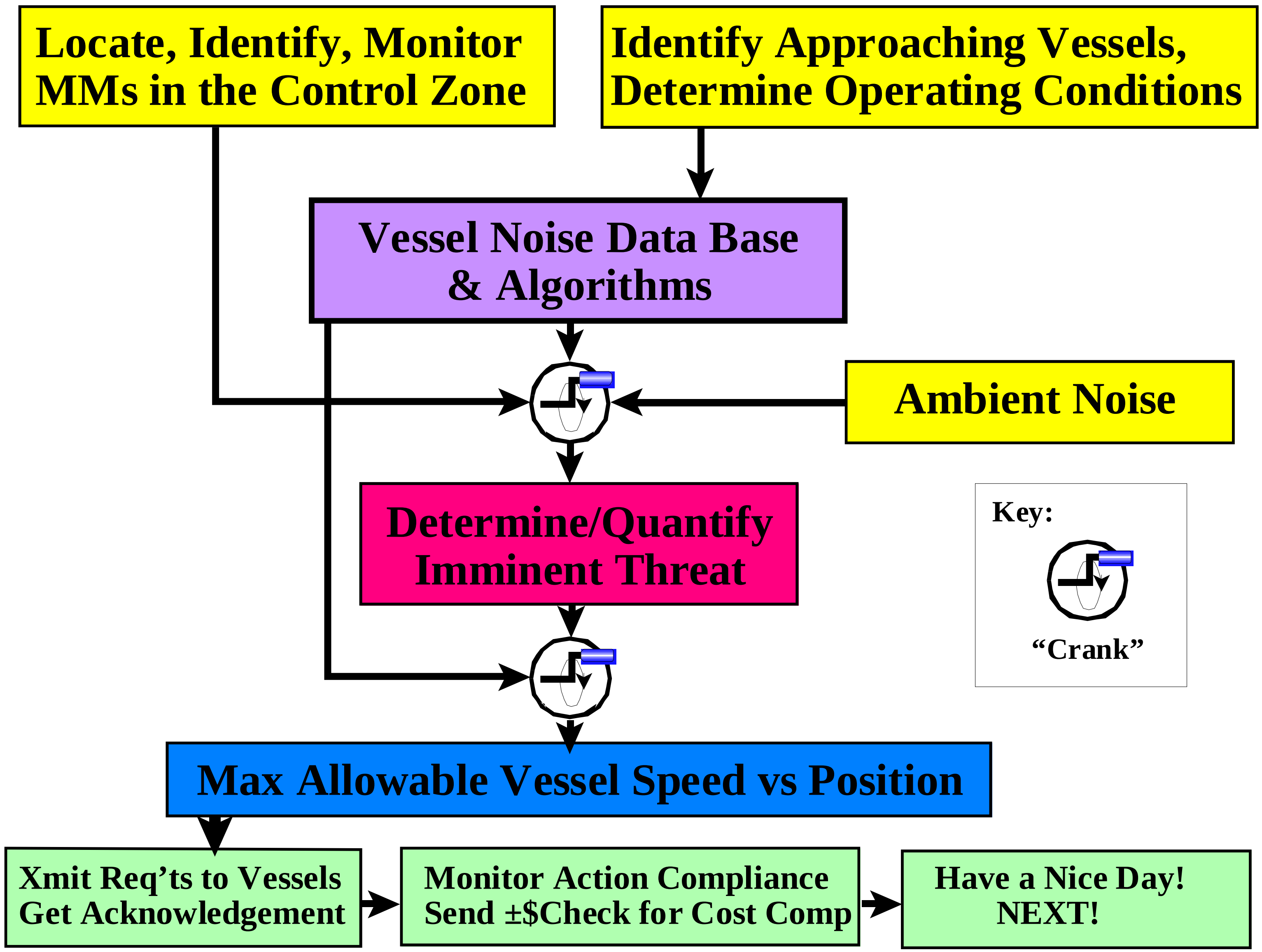
Suggestion:

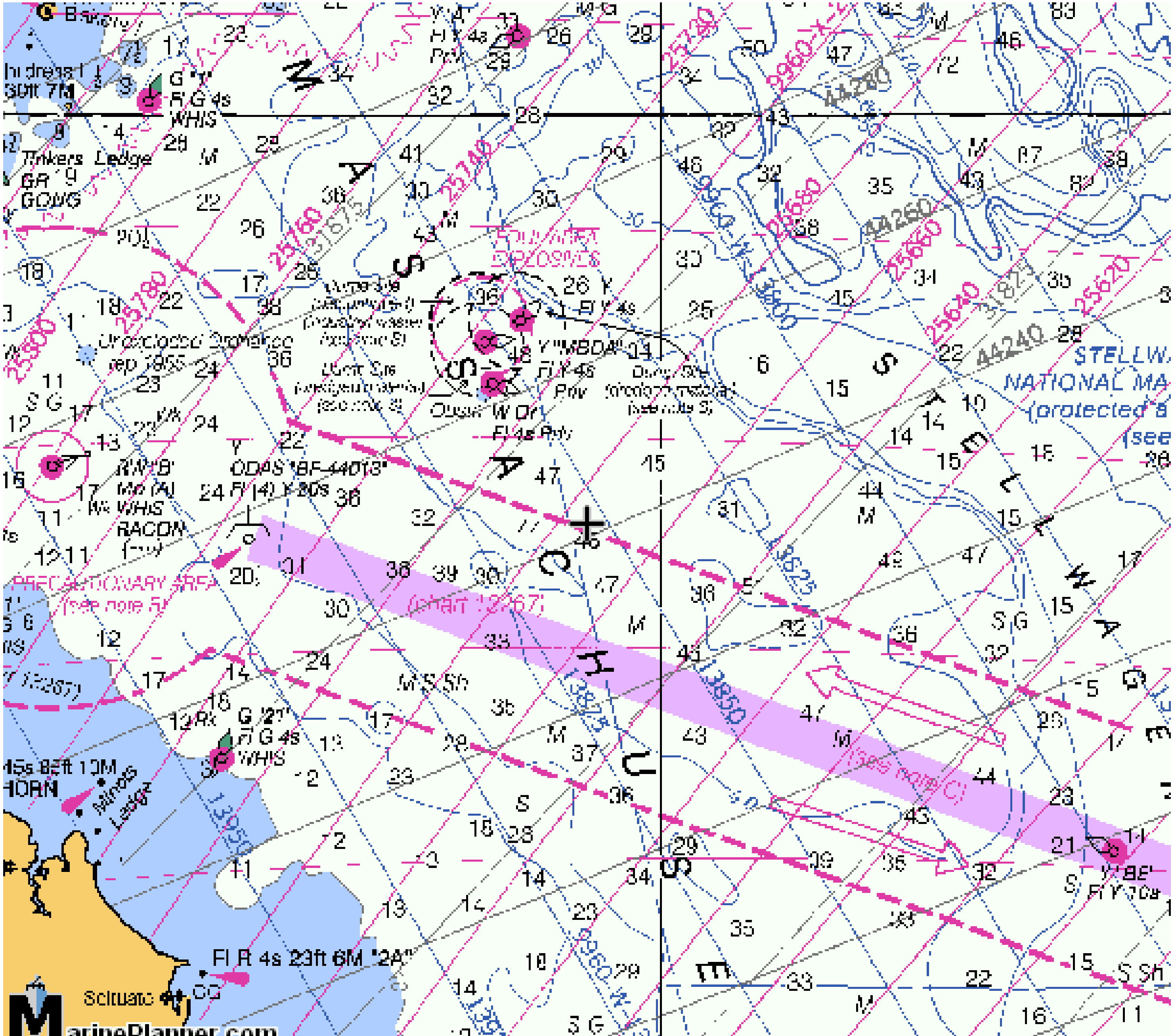
Let us begin the protection of noise-threatened MMs by doing what we know how to do in places that are important and accessible - in a manner that encourages compliance, rather than penalizing it.

Namely:

- **Choose control zones around established, near-shore shipping lanes in sensitive areas**
- **Demand local, temporary speed reductions taylored to the immediate situation**
- **Compensate the cost of compliance & equally penalize for non-compliance**

Noise Control in Marine Corridors Abutting/Traversing MM-Noise-Sensitive Regions

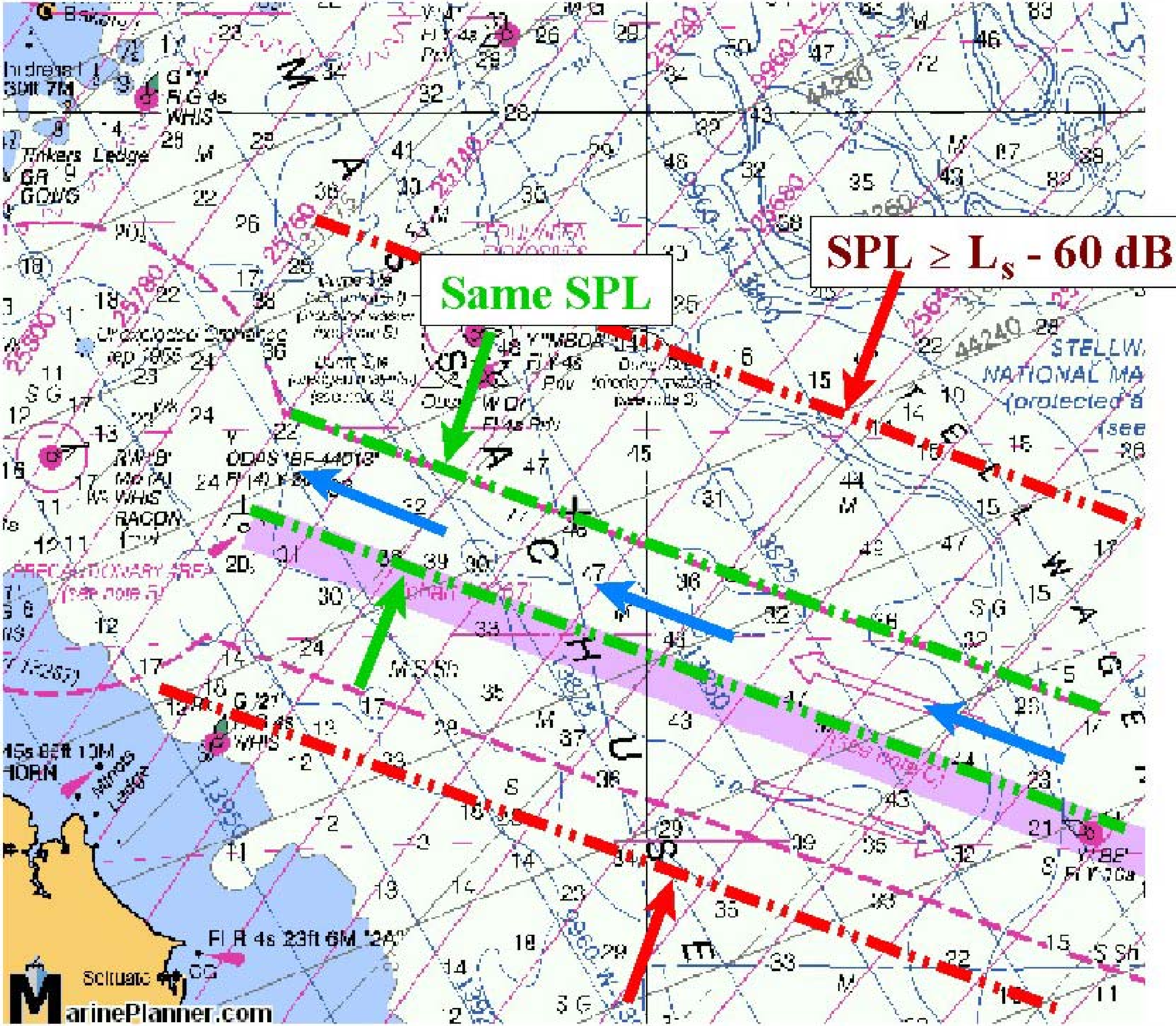




The marine traffic corridors in-bound and out-bound Boston, in Mass. Bay.

They are each 2 NM wide, separated by a 1 NM clearance.

Note location of Stellwagen Bank - a protected area.

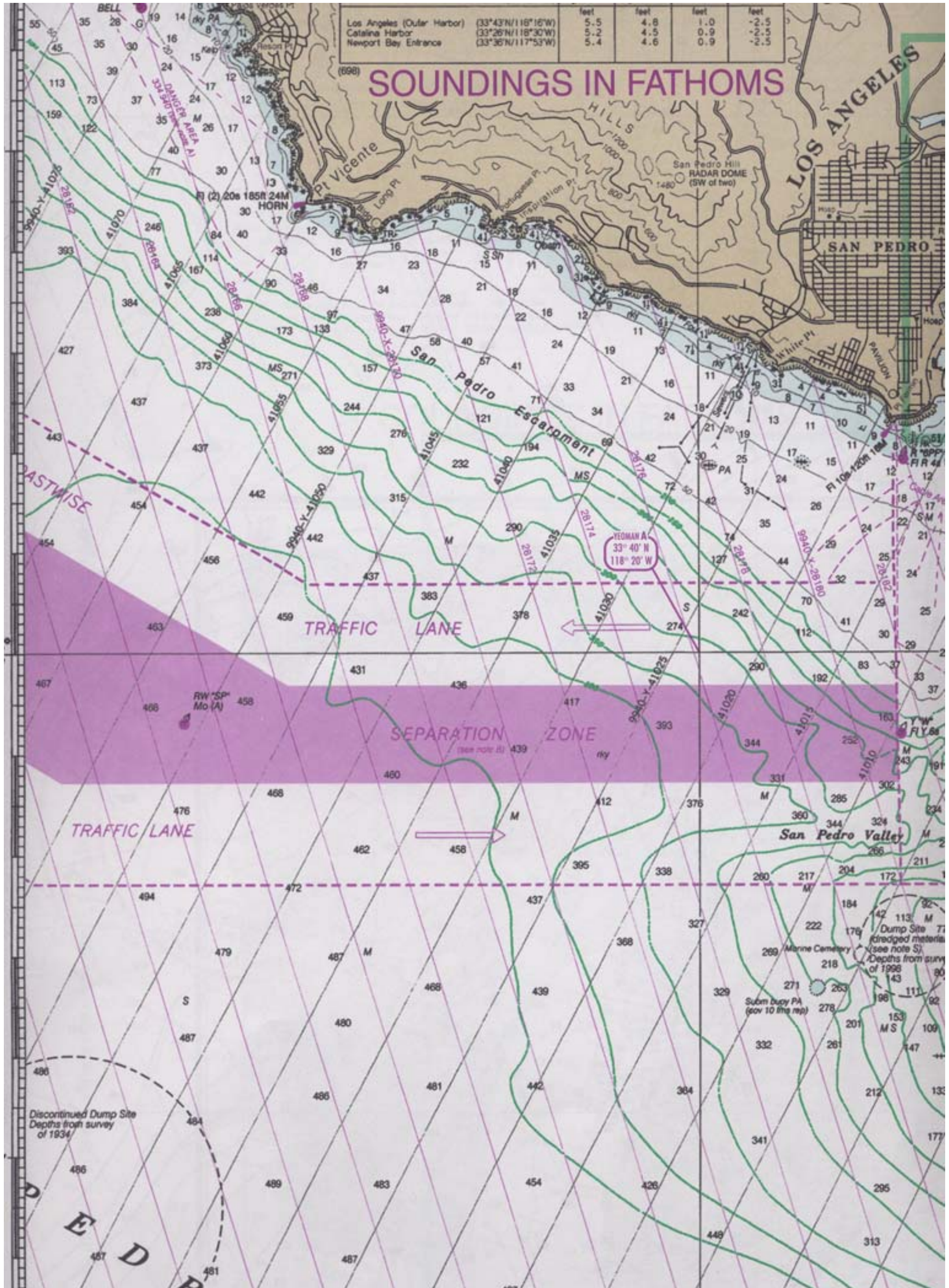


What a 10dB noise reduction will buy in affected area.

A 5 NM radius is reduced to 1 NM for noiselevels above the source -60.

($R^{-1.5}$ prop-agation assumed)

-70dB, 20NM
-75dB, 50NM



In the San Pedro area the traffic corridors are only 1 NM wide, separated by 1 NM

There is a large up-slope toward shore, so the sound propagation is different

Re: Machinery Noise

An external treatment to de-couple the hull from the water is available in the form of an air-bubble blanket.

The effectiveness increases with frequency above a low-frequency “resonance” set by the thickness of an equivalent “solid” air layer.

An air emission system is provided by the Danish firm Odegaard to block propeller noise from entering the hull on cruise ships.

Estimate 5-600 HP compressors on 20 kt ship.