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All classical wave propagation is characterized by spreading loss and attenuation of the medium. Although initially high, the rate of spreading loss decreases rapidly with range while the rate of attenuation remains constant. In underwater acoustics, it has been found that when the attenuation loss becomes dominant a "curtain effect" can exist resulting in rapidly increasing propagation loss. A mathematical expression for this condition is derived.

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Spreading Loss and Attenuation in Classical Physics: Lessons From Underwater Acoustics

A Paper Presented at the Spring Meeting of the New England Section of the American Physical Society, South Hadley, Massachusetts, 10-11 April 1987

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PREFACE

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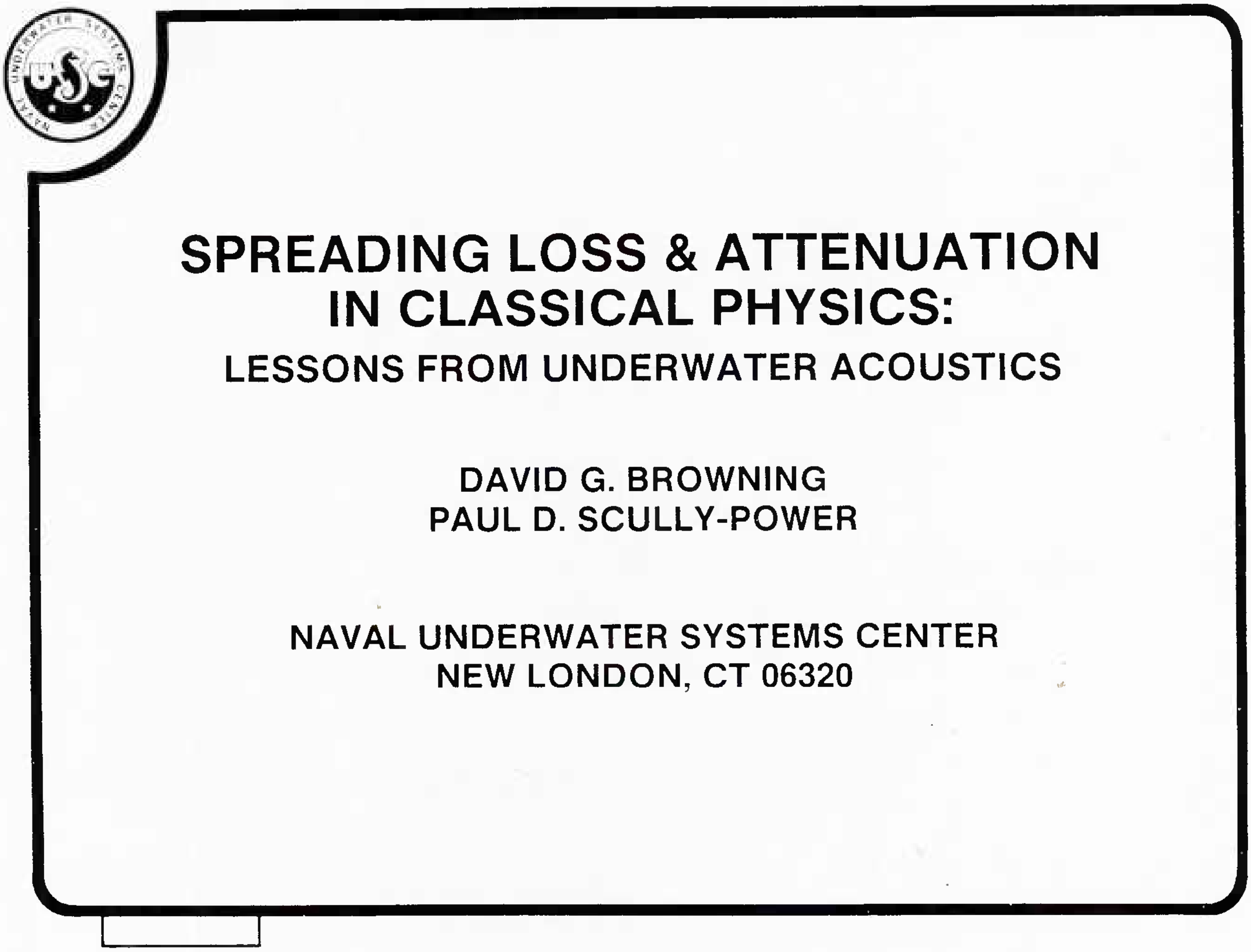

SPREADING LOSS & ATTENUATION IN CLASSICAL PHYSICS:

LESSONS FROM UNDERWATER ACOUSTICS

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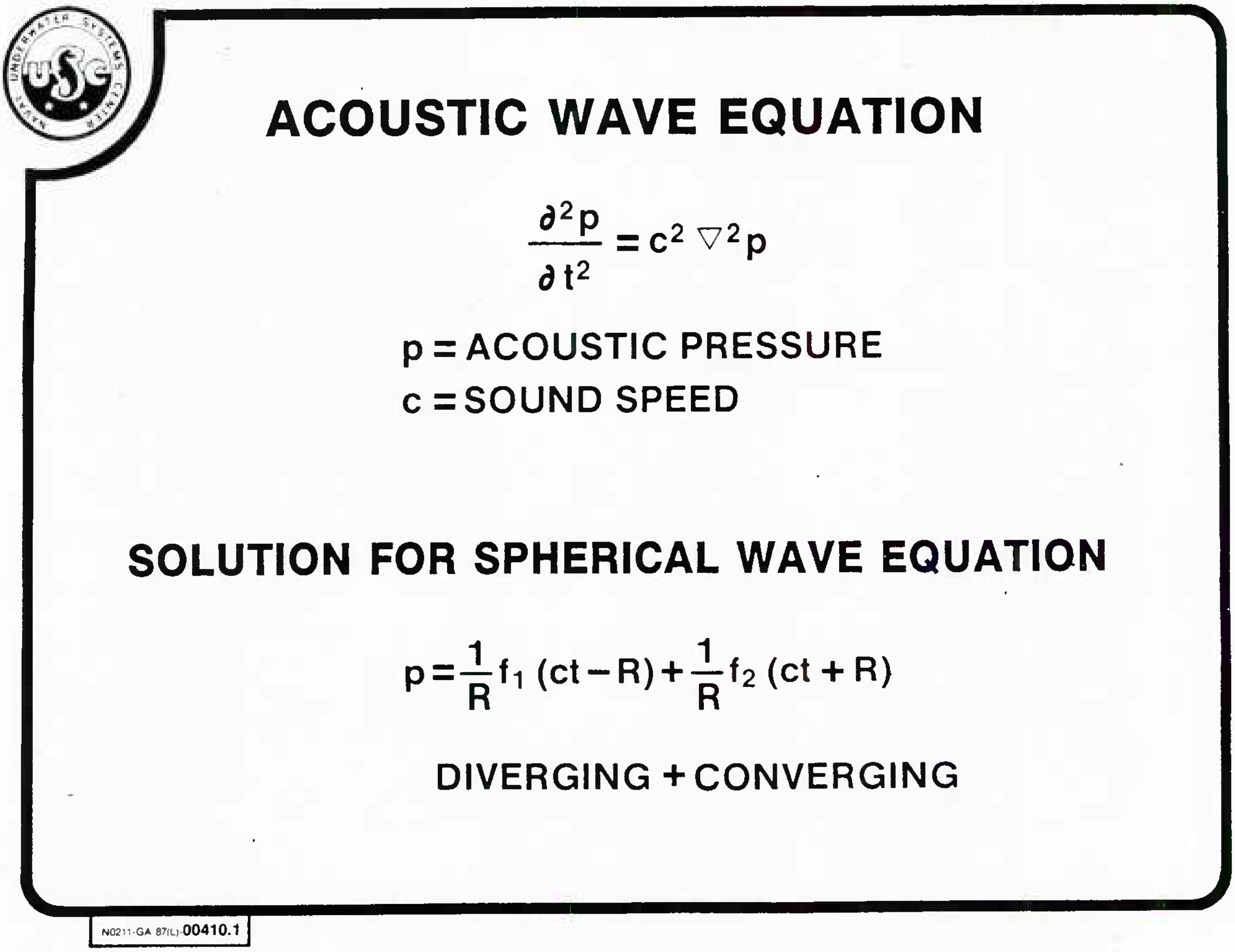
VIEWGRAPH 1

All areas of physics share a wave equation. For most realistic large scale (farfield) experiments in classical physics, two critical factors impact the solution: spreading loss and the attenuation of the transmission medium. In acoustics we have found that the interrelationship between these two factors can result in a "curtain effect" which we will describe in this paper.



ACOUSTIC WAVE EQUATION

$$\frac{\partial^2 p}{\partial t^2} = c^2 \nabla^2 p$$

p = ACOUSTIC PRESSURE
c = SOUND SPEED

SOLUTION FOR SPHERICAL WAVE EQUATION

$$p = \frac{1}{R} f_1 (ct - R) + \frac{1}{R} f_2 (ct + R)$$

DIVERGING + CONVERGING

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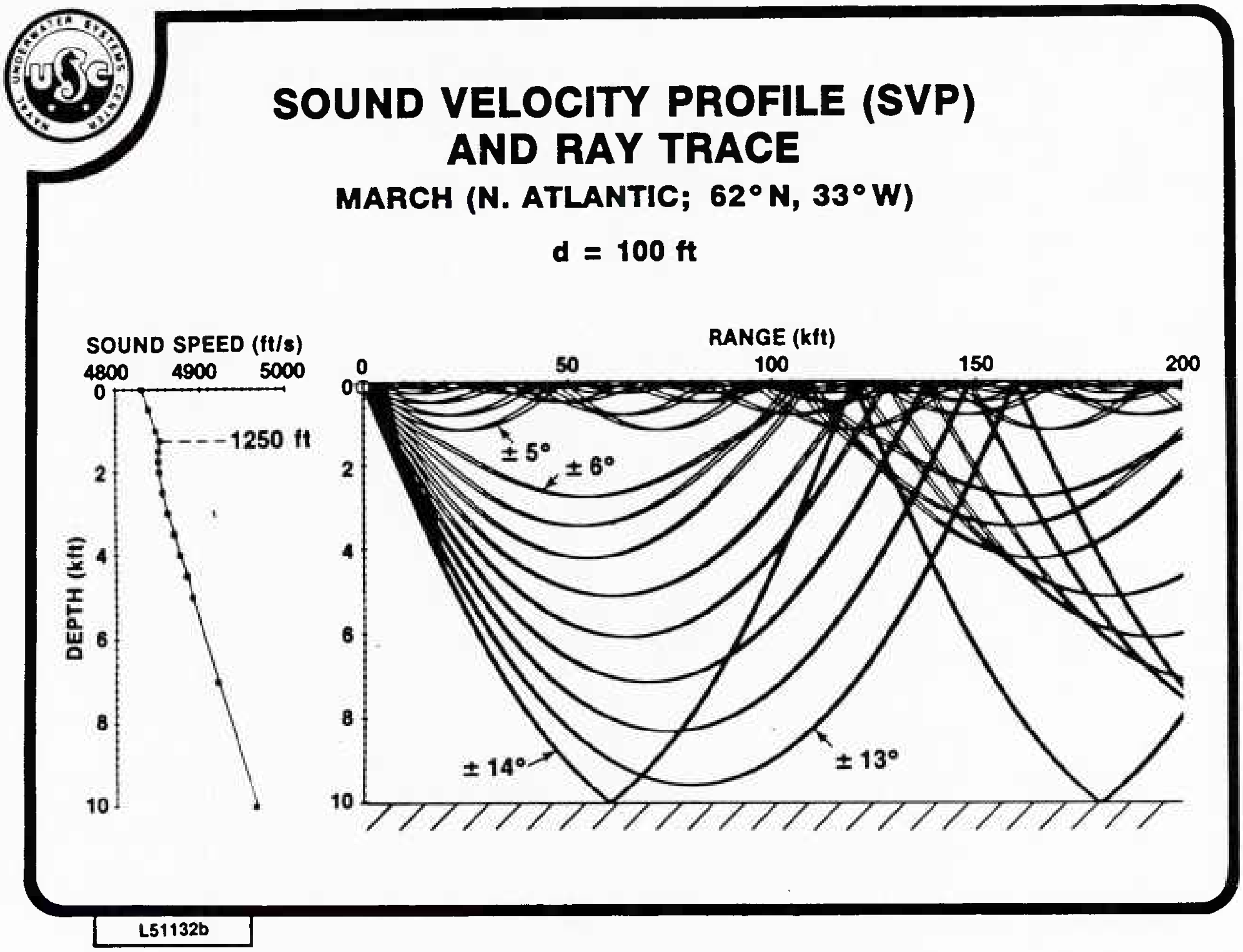
VIEWGRAPH 2

The wave equation in acoustics has the expected form. The well-known solution can be represented as the sum of diverging and converging waves; the latter is usually neglected. For a spherical (3-dimensional) wave equation the solution has a 1/R factor: this is spreading loss. Further loss is introduced by the attenuation of the medium.



SOUND VELOCITY PROFILE (SVP) AND RAY TRACE

MARCH (N. ATLANTIC; 62° N, 33° W)

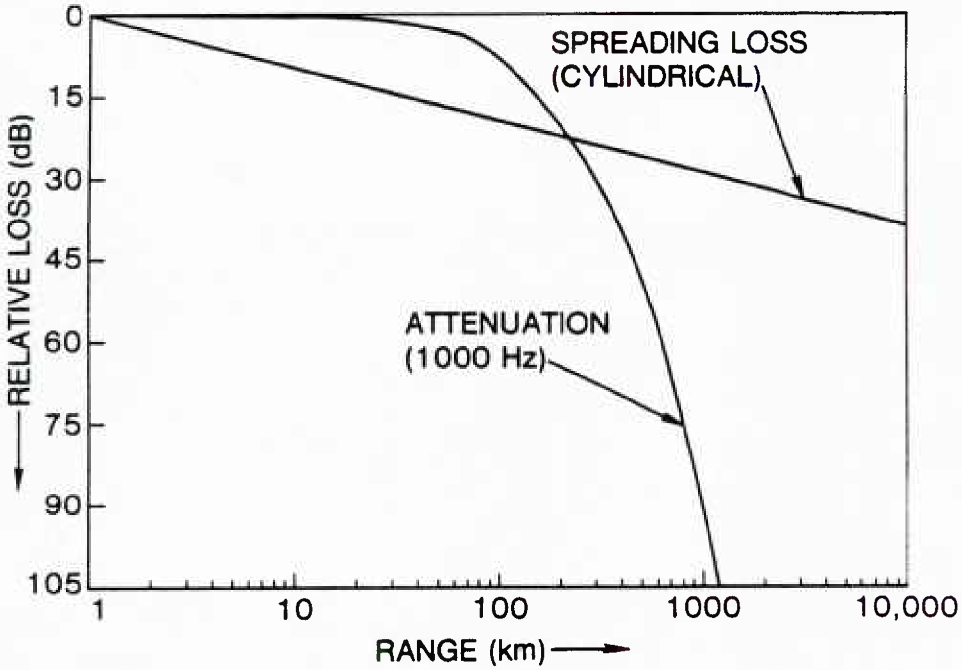
d = 100 ft

L51132b

VIEWGRAPH 3

In underwater acoustics the ocean can be thought of as the peel of an orange-size earth. We have, therefore, basically a waveguide in the vertical dimension. Hence, spreading loss occurs in two dimensions (cylindrical spreading) rather than three dimensions (spherical spreading) for all but the shorter ranges.

ATTENUATION vs. SPREADING LOSS



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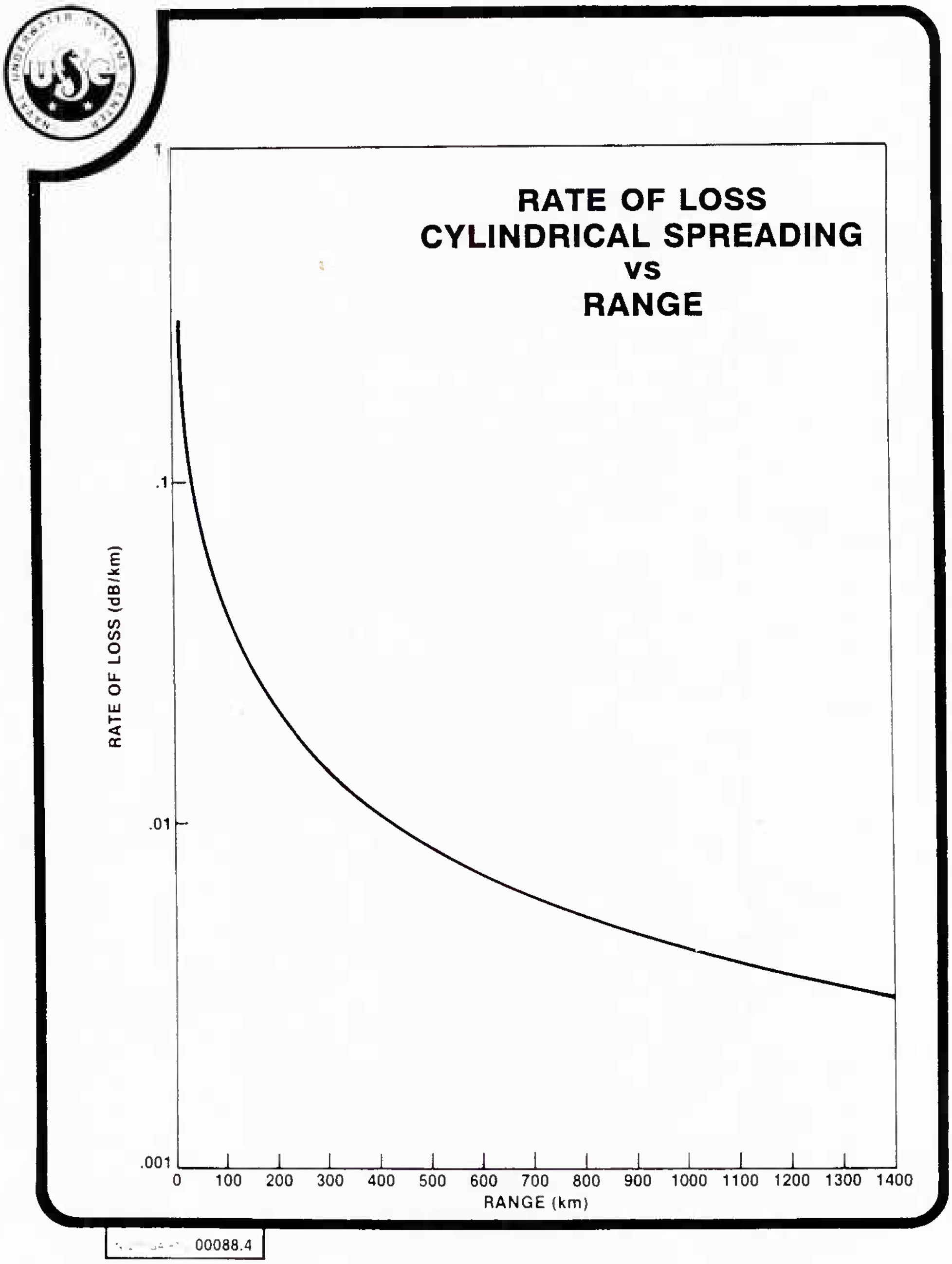
VIEWGRAPH 4

If we plot these two principal components of transmission loss versus range (on a log scale), you can see that the contribution due to the attenuation of the medium is initially small compared to the spreading loss. However, at longer ranges attenuation becomes dominant, effectively limiting the range that can be obtained. This results in what we term the "curtain effect" and the range at which attenuation starts to dominate we call the "cross-over range" (R_C).

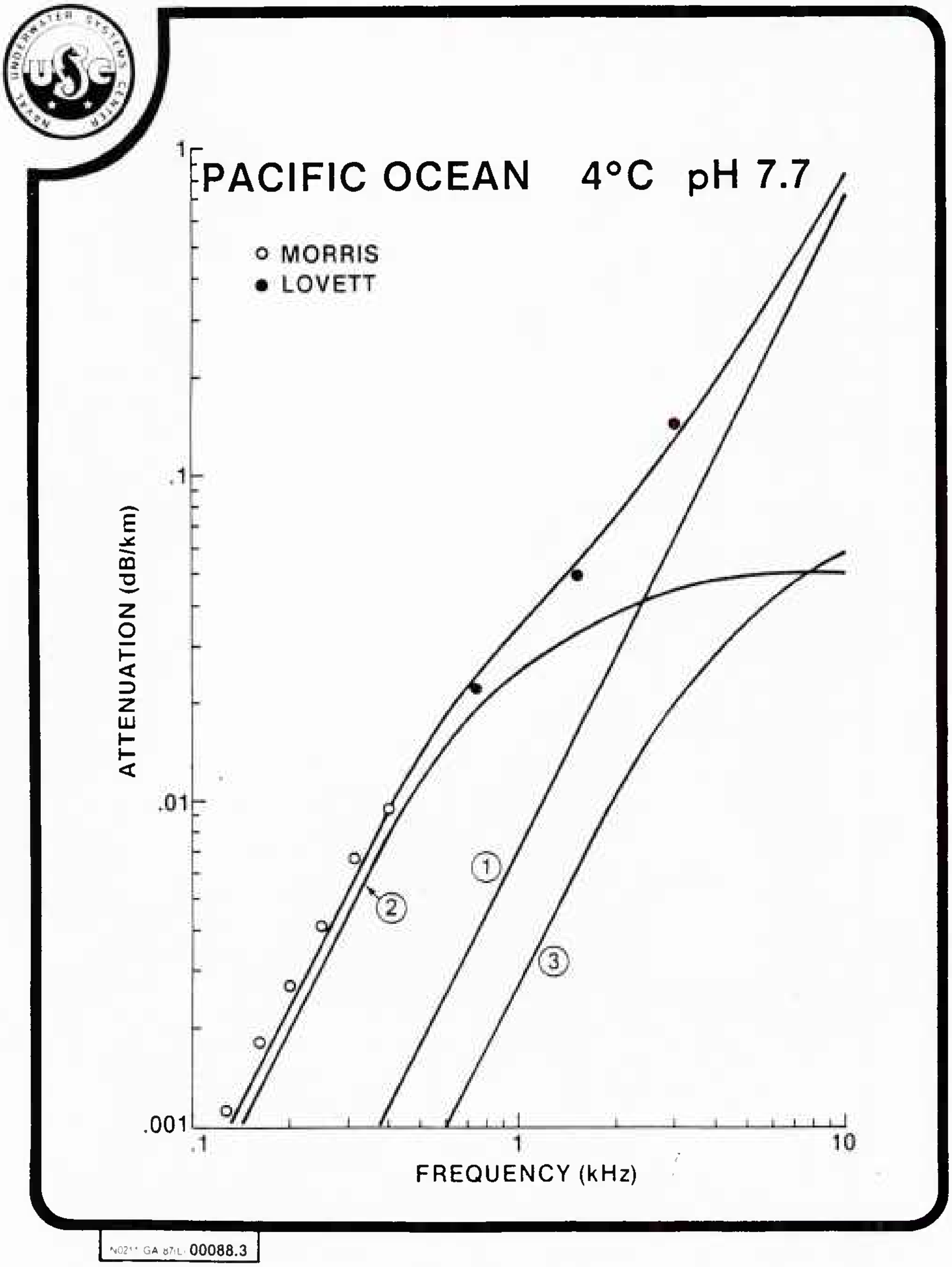


RATE OF LOSS
CYLINDRICAL SPREADING
VS
RANGE

00088.4

VIEWGRAPH 5

We found that the most meaningful comparison was between the rate of spreading loss and attenuation (they are dimensionally the same). In acoustics we measure loss and rate of loss in decibels. A decibel is a logarithmic ratio to a reference standard at a specific range. For cylindrical spreading the loss in decibels is 3 dB per distance doubled; hence, the rate of loss is initially very high but decreases rapidly with range.



PACIFIC OCEAN 4°C pH 7.7

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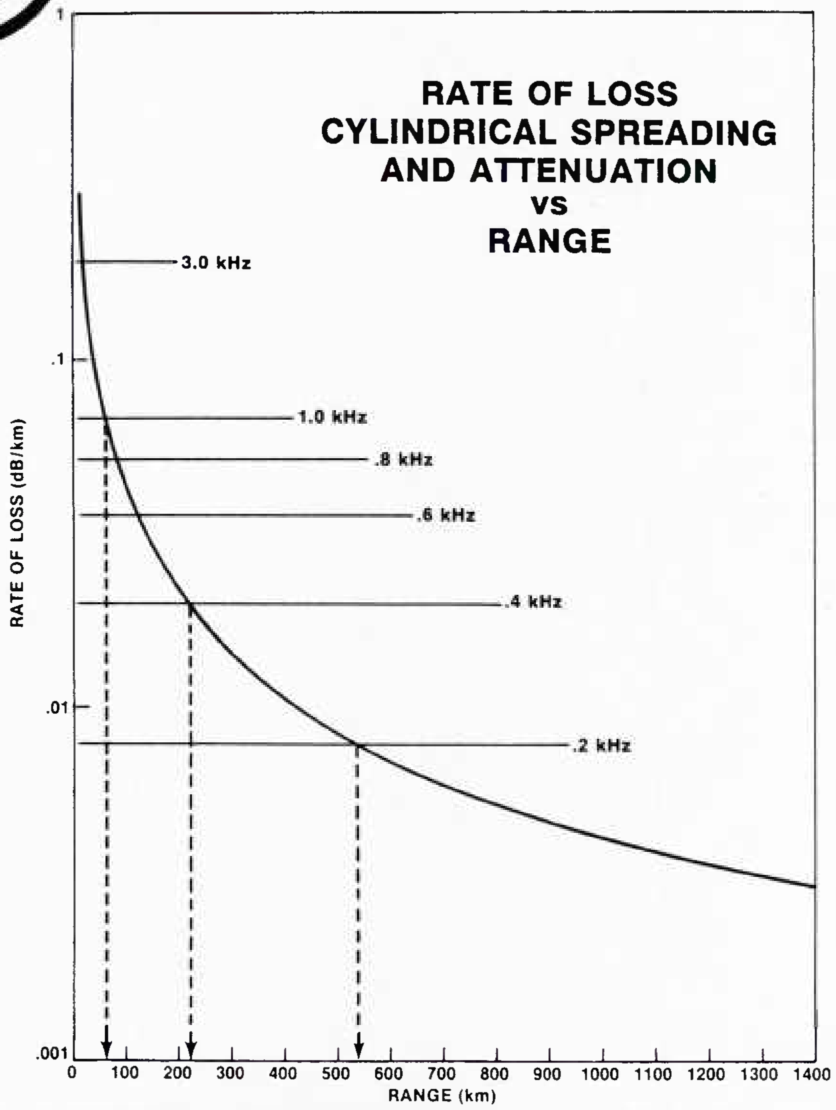
VIEWGRAPH 6

In contrast attenuation is constant with range and in most cases highly frequency dependent. (Spreading loss being independent of frequency if we neglect dispersion.)



RATE OF LOSS CYLINDRICAL SPREADING AND ATTENUATION VS RANGE

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VIEWGRAPH 7

When we compare rate of spreading loss to attenuation, the attenuation at a specific frequency is constant with range and decreases with decreasing frequency. On the other hand, the rate of spreading loss as we mentioned earlier, is initially high but changes rapidly with range. The resulting cross-over ranges (shown by the arrows) change as a function of frequency. This dependence is relatively small at the higher frequencies: relatively large at the lower frequencies.

CRITICAL RANGE (R_C)

CYLINDRICAL SPREADING:

$$\frac{dI}{I} = \frac{-dR}{R}$$

I = INTENSITY

R = RANGE

ATTENUATION:

$$\frac{dI}{I} = -NdR$$

N = CONSTANT

WHEN EQUAL:

$$\frac{dR}{R_C} = NdR$$

$$\frac{1}{R_C} = N$$

VIEWGRAPH 8

We can derive a general expression for this cross-over range (R_C) based on the fundamental formulas of spreading loss and attenuation.

For spreading loss we will use intensity (I) which is directly related to pressure but is more general.

The expression for cylindrical spreading is simply

$$\frac{dI}{I} = \frac{-dR}{R} .$$

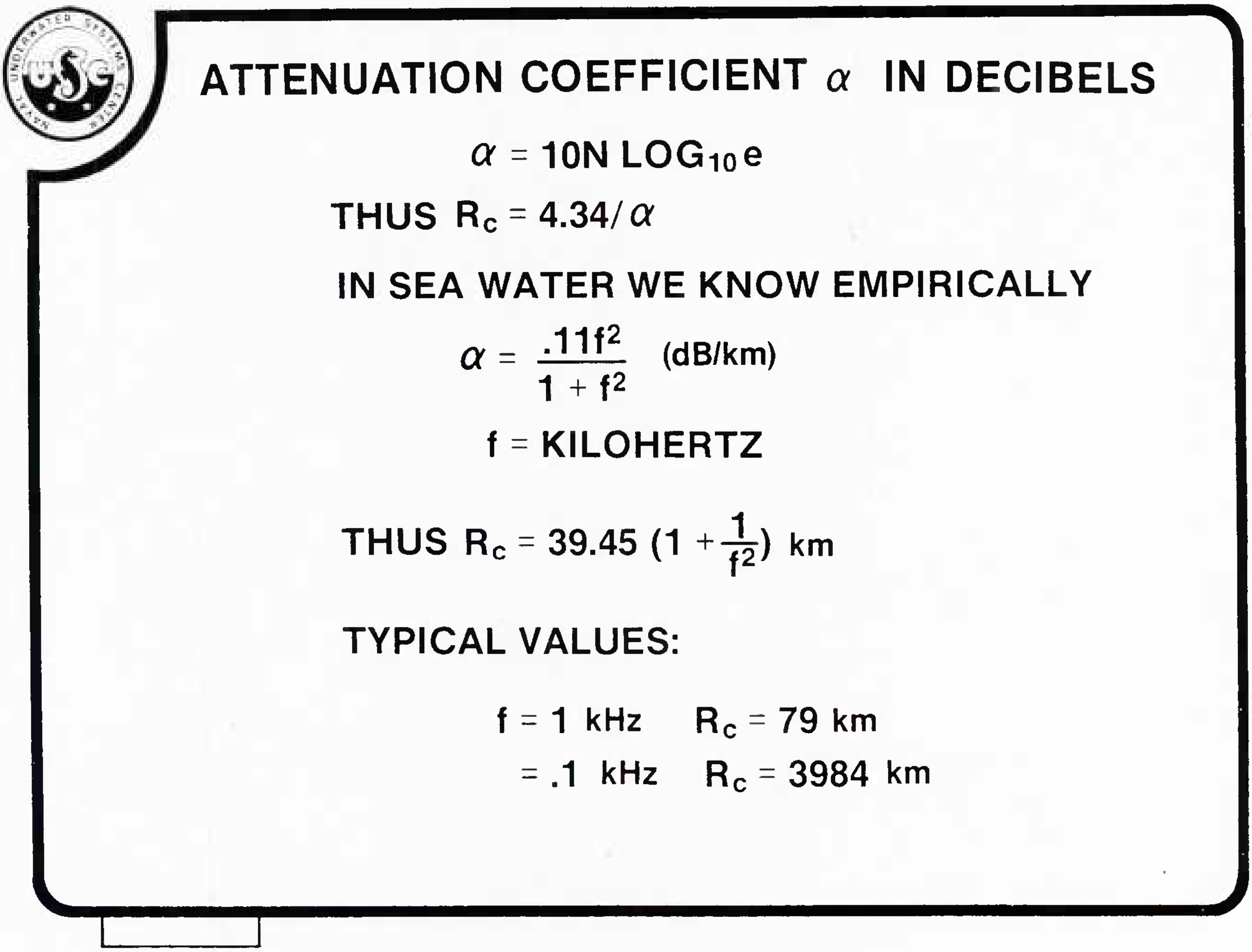
Similarly, attenuation can be expressed as

$$dI/I = -N\ dR,$$

where N is a constant representing the attenuation loss.

At the critical range where both losses are the same, we obtain the simple expression

$$1/R_C = N.$$



ATTENUATION COEFFICIENT α IN DECIBELS

$$\alpha = 10N\ \mathrm{LOG}_{10}e$$

THUS $R_c = 4.34/\alpha$

IN SEA WATER WE KNOW EMPIRICALLY

$$\alpha = \frac{.11f^2}{1+f^2} \quad (\mathrm{dB/km})$$

f = KILOHERTZ

THUS $R_c = 39.45\left(1 + \frac{1}{f^2}\right)$ km

TYPICAL VALUES:

$f = 1$ kHz $\quad R_c = 79$ km

$= .1$ kHz $\quad R_c = 3984$ km

VIEWGRAPH 9

For a decibel scale, the attenuation coefficient becomes

$$\alpha = 10N \log_{10}e.$$

Thus

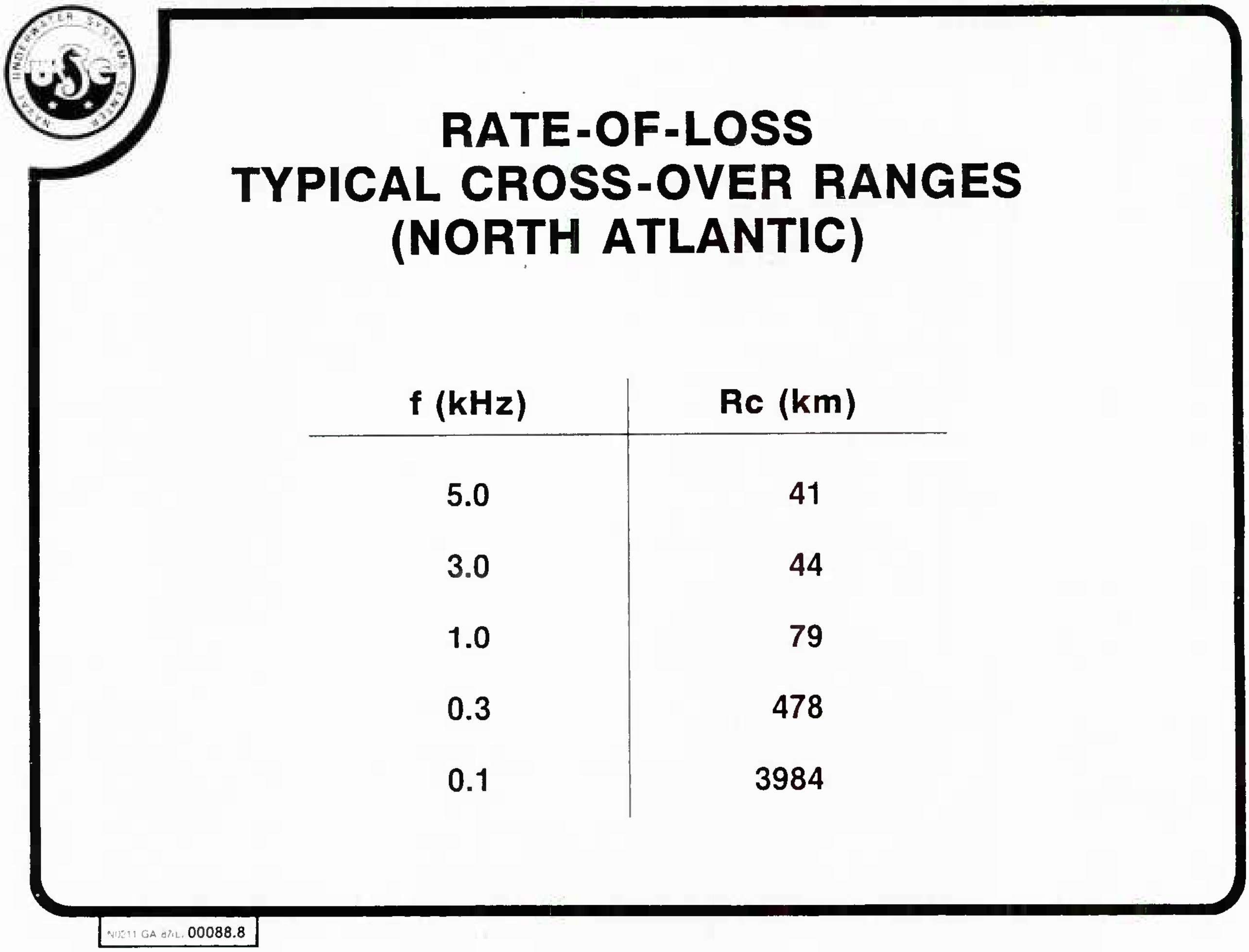
$$R_c = 4.34/\alpha.$$

In sea water, we have found empirically that the attenuation coefficient for acoustic waves can be given as

$$\alpha = 0.11f^2/1+f^2 \ (\mathrm{dB/km})$$

$$f = \text{kilohertz (valid for } f < 5 \text{ kHz)}.$$

Plugging this in we can obtain typical values for the cross-over range.



RATE-OF-LOSS TYPICAL CROSS-OVER RANGES (NORTH ATLANTIC)

f (kHz)	Rc (km)
5.0	41
3.0	44
1.0	79
0.3	478
0.1	3984

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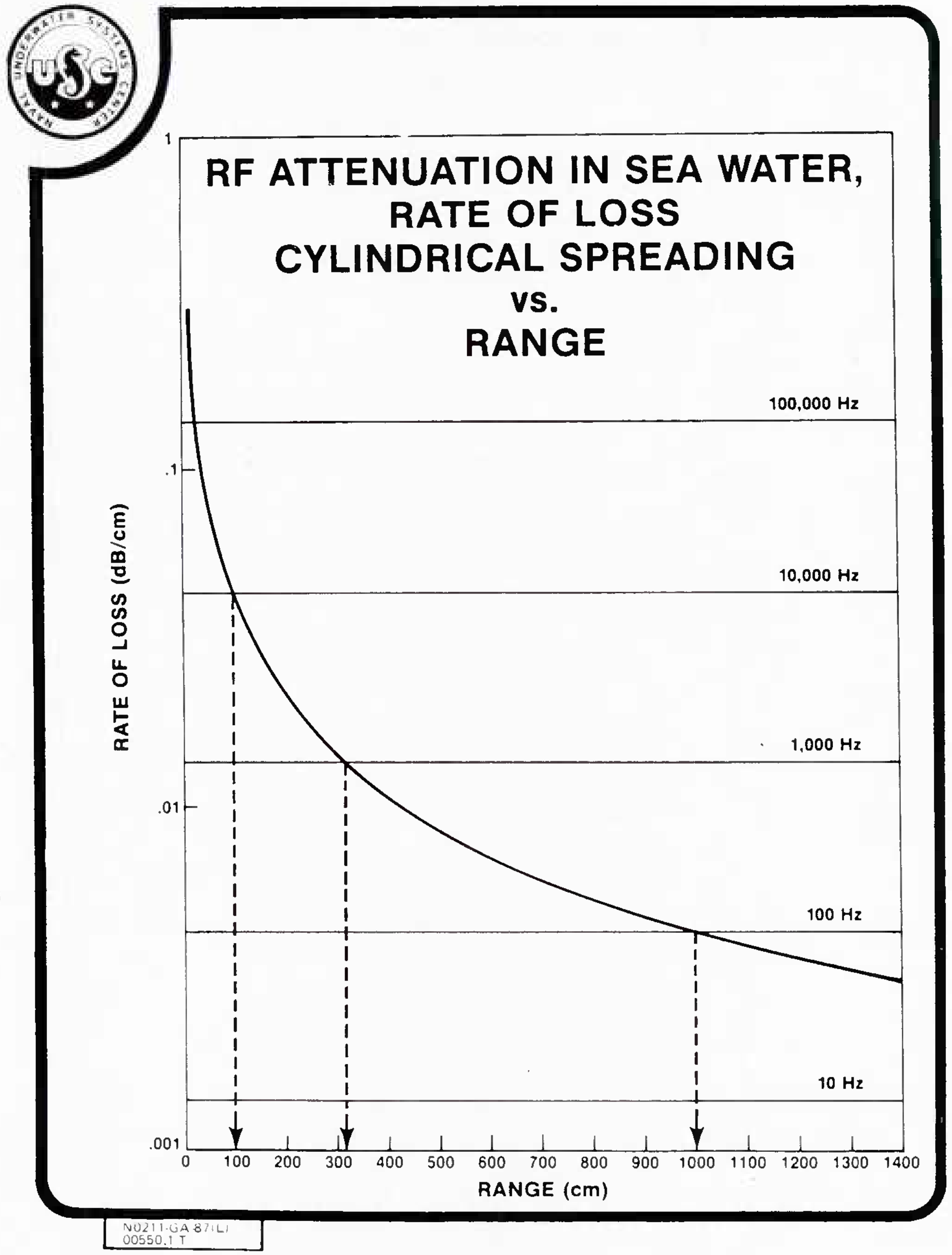
VIEWGRAPH 10

Typical results are summarized in this table. At the higher frequencies, changes in the cross-over ranges as a function of frequency are relatively small when compared to the large changes at low frequencies.



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VIEWGRAPH 11

To illustrate the broad application of this concept let us consider electromagnetic (radio frequency) waves in sea water. On a centimeter scale we can see the same transition pattern as a function of frequency. Below 100 Hz significant ranges can be obtained.

CONCLUSION

WHEN ATTENUATION BECOMES GREATER THAN THE RATE OF SPREADING LOSS A '*CURTAIN EFFECT*' RESULTS

VIEWGRAPH 12

In conclusion, we have found that a curtain effect results when attenuation becomes greater than the rate of spreading loss. We believe this will have a broad application throughout classical physics.

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