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# Insonification for Area Denial

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# 1 INTRODUCTION

A need has been expressed for technology to deny large areas and facilities within them to an invasive group in a way which does not kill or permanently injure members of that group. Desired features for systems which might accomplish this include

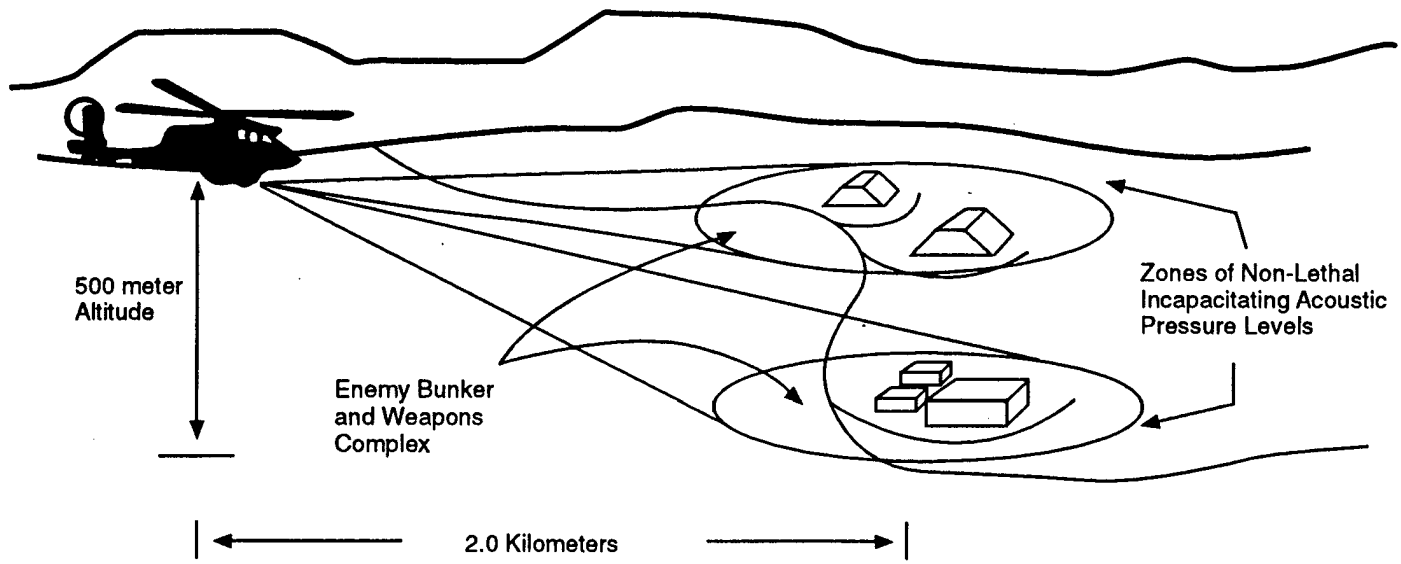
1. area coverage which may extend to as much as 1 km<sup>2</sup>;
2. persistent coverage (certainly many minutes, perhaps months);
3. capability for use in unfriendly areas from a remote transportable platform (e.g. a helicopter).

The production and maintenance of intense local air disturbances has been suggested as a way of achieving this. Two methods have been proposed for injecting a large amount of energy into air and rapidly directing that energy to another location.

- (a) Exploiting an essentially incompressible type air motion, generally the creation and propagation of vortices (e.g. "smoke rings").
- (b) Using the compressibility of the air to store and transport that energy as sound or shock waves. There has been interest and support for using very intense insonification of an area to accomplish the goal (see Figure 1) and we shall consider below only that method.<sup>1</sup>

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<sup>1</sup>A main contributor has been Scientific Applications and Research Associates, Inc. (SARA) sponsored by the Advanced Research Projects Agency (ARPA) and the U.S. Missile Command. We shall refer to SARA's Phase 1 Final Report "Selective Area/Facility Denial Using High Power Acoustic Beam Technology" (10 March 1995) as SARA in our discussion.



**Figure 1.** Concept for Aircraft Based High Energy Acoustic Beam Incapacitation Weapon Denial of Access or Activity at a Selected WMD Facility. From SARA, loc. cit. (WMD = Weapons of Mass Destruction)

## 2 RANGE

The range of high frequency sound is severely limited by the viscosity of air. Sound intensity  $i$  drops with propagation range  $r$  according to

$$i(r) = i_o \exp(-\alpha r); \quad (2-1)$$

in reasonable approximation

$$\alpha = 16\pi^2 \nu^2 \eta / 3\rho_o c_s^3 \quad (2-2)$$

Here

$\eta$  = dynamic viscosity of air ( $183\mu$  poises)

$\rho_o$  = density of air ( $\sim 10^{-3} g \text{ cm}^{-3}$ )

$c_s$  = speed of sound ( $\sim 3 \cdot 10^4 \text{ cm s}^{-1}$ )

$\nu$  = the sound frequency.

Then for sound in air

$$\alpha \sim 2 \cdot 10^{-13} \nu^2 \text{ cm}^{-1}, \quad (2-3)$$

with  $\nu$  in Hz. Thus for a desired projection range of a kilometer or so the insonification frequency should be limited to

$$\nu \leq 10^4 \text{ Hz.}$$

### 3 EFFECTS OF ULTRA-STRONG SONIC INTENSITIES

Sound intensities are generally expressed in decibels (dB):

$$\text{Flux of sonic power in dB} = 10 \log_{10} \left( \frac{i}{10^{-16} \text{watts cm}^{-2}} \right),$$

where  $i = (\Delta P)^2 / \rho_0 c_s$  and  $\Delta P$  is the pressure change amplitude. Then the sonic pressure in dB =  $20 \log_{10} \left( \frac{\Delta P}{2 \cdot 10^{-10} \text{atmos}} \right)$ .

Some effects of typical audio-frequency intensities (in dB) are

**Table 1.**

Effect or Source	dB
Threshold for hearing	0
Normal conversation (at mouth)	65
Threshold for audio-pain	120
Next to a jet engine (Figure 2)	160
Reports of lethality to small animals	170
Next to a rocket engine exhaust (Figure 2)	180

The published literature about effects on humans of relatively brief exposures (several minutes) to extraordinarily intense sound waves (frequencies  $\nu < 10$  Hz) seems largely anecdotal.

According to SARA

“Strong incapacitation effects will set in between 140 dB and 150 dB for nearly all frequencies ... Potential lethal effects will set in above the 160 dB to 170 dB regime for sustained or modest exposure.”

Certainly in the  $\nu \rightarrow 0$  limit the pressure change  $\Delta P$  for the insonifications of Table 1 are easily tolerated. For example 150 dB corresponds to  $\Delta P \sim 10^{-2}$  atmos., the pressure at the bottom of a bathtub filled to about

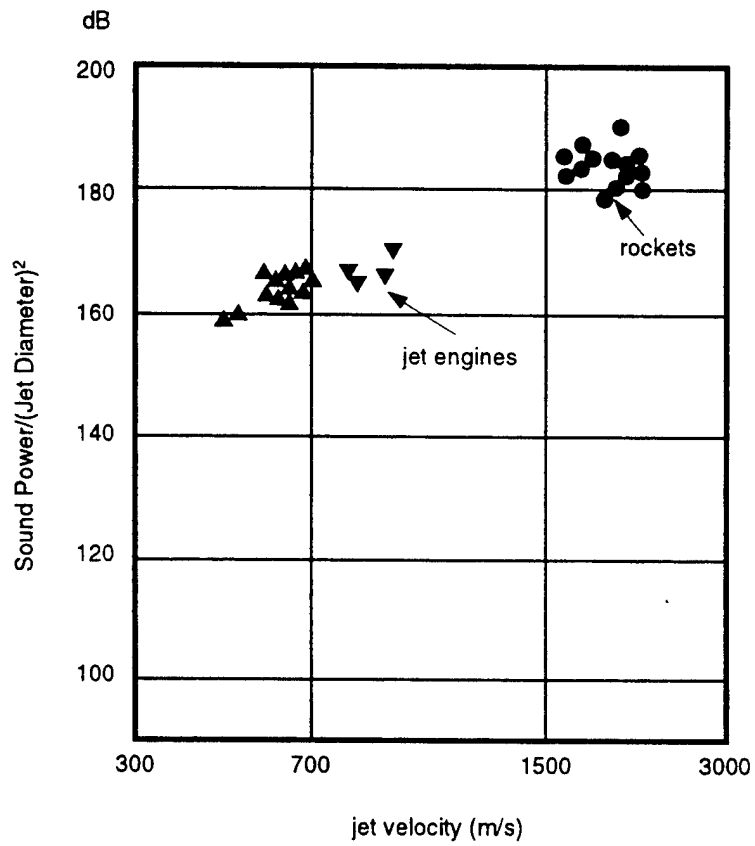


Figure 2. Acoustic power levels (from Chobotov & Powell: 1957 Ramo Woolridge Corp. Rep. EM-7-7). ● rocket; ▼ turbojet (afterburning); ▲ turbojet (military power)

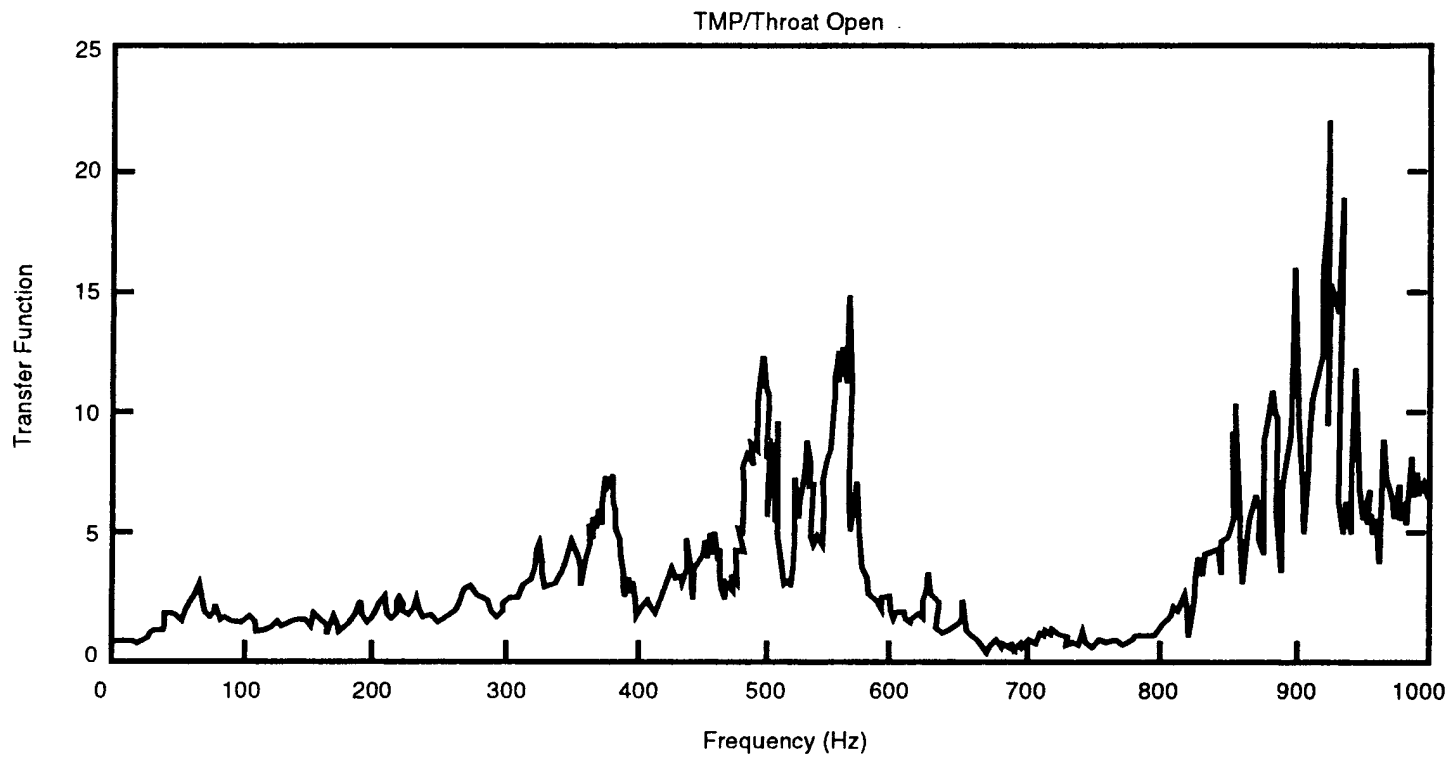


4 inches of water. Variations of such pressures on a time scale of order a few tenths of a second or longer are clearly inconsequential. (The maximum net force on a body exposed to such  $\Delta P$  is comparable to the redistribution of external force difference on us when we lie down or roll over.) Clearly important effects from insonification must begin only at higher frequencies. A summary given by SARA of reported effects at higher frequencies is shown in Table 2.

**Table 2. Reported Effects on Intense Sound.**

Acoustic Frequency	Intensity	Reported Biological Effect
7-17 Hz	110-130 dB	Bodily discomfort. Intestinal pain
~ 10 Hz	110-130 dB	Severe nausea
175 Hz	120-140 dB	Severe nausea. Shutdown of airbase
196 Hz	120 -150 dB	Internal organ damage
$10^3 Hz$	140 dB	Incapacitation of personnel
2.6 KHz	120 - 150 dB	Permanent physical disability
5-30 kHz	120 - 160 dB	Cavitation, thermal burns, fatigue, lethality of animals

The SARA report gives the detailed frequency dependent response of a microphone inserted inside a particular scientist's mouth to an externally incident sound wave (Figure 3). It is indicated that this response reflects the frequency sensitivity of the scientist's internal respiratory structures to monochromatic insonification. The sharp peaks' half widths and separations are much less than the internal structure scale variations among people (certainly greater than 10%). Thus even if single frequency might give a sharply resonant response for some individual, that same frequency would not do so for other members of a group. Only relatively broad frequency intervals would be expected to have a robust significance in designing an insonification strategy. In this sense while one may accept the claim of SARA that "our own analysis of human coupling physiology suggests that specific frequencies within ... 100 Hz to several kilohertz may have optimized effects," those precise frequencies would not be predictable because they would vary greatly within a group.



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**Figure 3.** Acoustic absorption spectrum for the human respiratory tract and sinus passages, indicating possible frequency bands for enhancement of high energy acoustic weapon area/WMD Facility Denial. From SARA, loc. cit.

## 4 INSONIFICATION LIMITS

We consider first the sound radiated by a spherical surface of radius  $R$  oscillating at an angular frequency  $\omega = 2\pi\nu$  and maximum radial speed

$$v = Mc_s, \quad (4-1)$$

( $M$  is the Mach number.)

The maximum sonic power from this monopole acoustic source, generally the most efficient of all sonic radiators, is

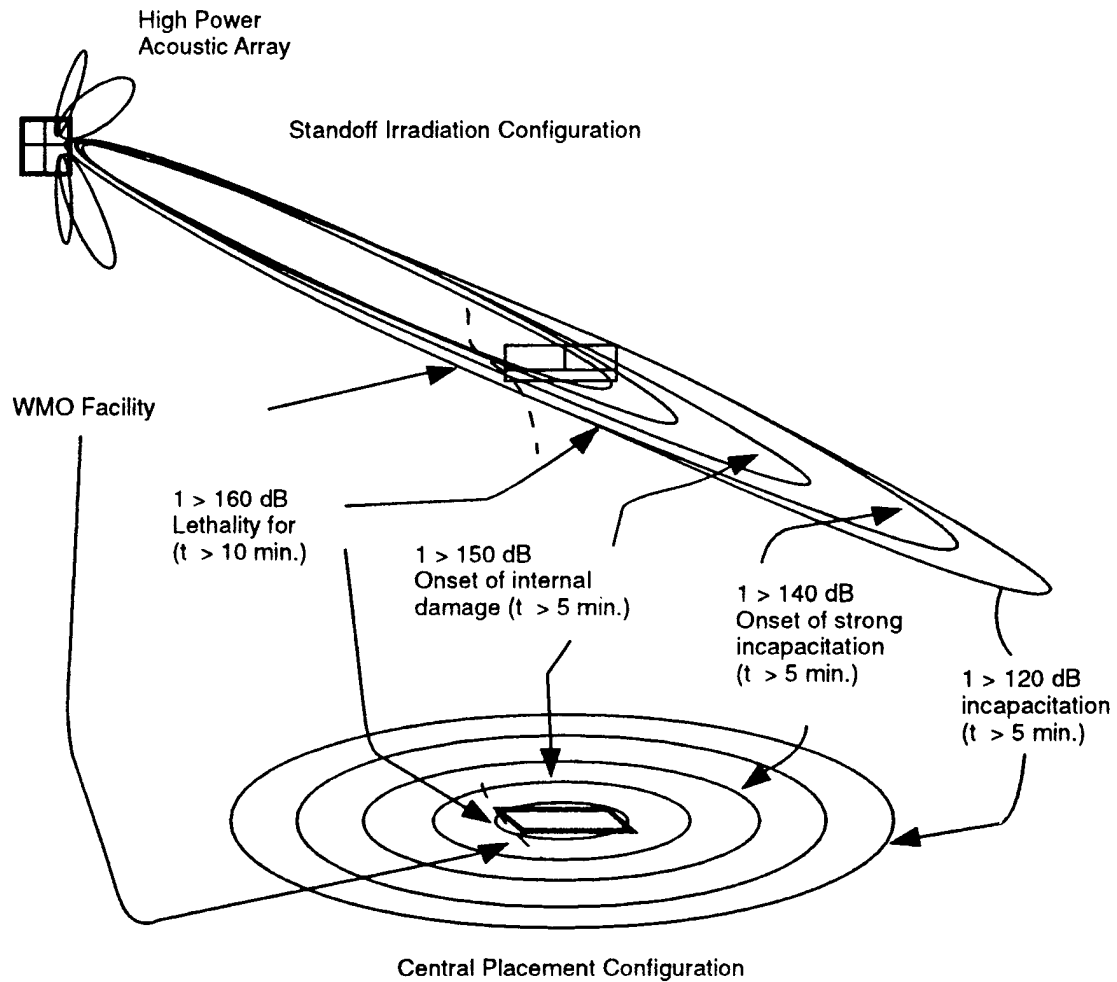
$$\text{Power} = \rho_o c_s^3 M^2 (R/\bar{\lambda})^2 A \quad (4-2)$$

where  $A=4\pi R^2$  is the surface area,  $\bar{\lambda} = c/\omega$ , and  $\bar{\lambda} \gg R$ . When  $R > \bar{\lambda}$

$$\text{Power} \Rightarrow \rho_o c_s^3 M^2 A \quad (4-3)$$

For higher multipole emission Equation (4-2) is reduced by an additional factor  $(R/\bar{\lambda})^{2n}$  with  $n$  the multipolarity, but Equation (4-3) is unchanged.

The goal of a typical area denial geometry is sketched in Figure 4 from a SARA final report: a sound source about 2 km from a targeted area insonifies a 1 km radius region to various intensities; insonification reaches 160 dB in the central region, and drops to 140 dB about half-way out. The total deposited sonic power would be of order 300 MW ( $\sim 10^{-2}$  watts  $\text{cm}^{-2} \times 3 \times 10^{10}$   $\text{cm}^2$ ) supplied from an acoustic source on a helicopter whose horn area may be, roughly, of order 1  $\text{m}^2$ . Is this a plausible goal? This would, of course, be a huge sonic power output even for 100% efficient conversion of input energy into sonic power. (Entire electric utility power plants are typically more powerful.) How much acoustic power can be emitted from an acoustic source of effective area several square meters? Optimal power cannot come from a compact source for which  $\bar{\lambda} \gg R$  so we assume  $\bar{\lambda} < 10^2$  cm, or  $\nu > 50$  Hz. The appropriate bound to emitted power is then Equation (4-3): the



**Figure 4.** Basic concept for ground based standoff and central illumination denial of a WMD facility by a high energy acoustic weapon source. From SARA, loc. cit.

radiated acoustic power from any effective diaphragm area should satisfy the inequality

$$\text{Power} < 3 \cdot 10^7 M^2 \left( \frac{\text{Area}}{\text{meter}^2} \right) \text{ watts.}$$

If the Mach number M for the real or virtual diaphragm exceeds unity, shock waves will be emitted giving a very broad sonic frequency range. For an assumed monochromatic emission,  $M < 1$ , so that radiated acoustic power flux would not exceed

$$\rho_o c_s^3 \sim P_{\text{atmos}} \cdot c_s \sim 3 \text{ Kw/cm}^2$$

over the diaphragm area, and even this would require an astonishingly large diaphragm motion. The diaphragm displacement<sup>2</sup> would be  $\frac{v}{\omega} = \frac{Mc_s}{\omega} \sim \frac{c_s}{\omega} = 50 \left( \frac{10^2 \text{ Hz}}{\nu} \right) \text{ cm}$ , a truly enormous oscillation amplitude for almost supersonic motion. Fuel weight, conversion efficiencies for fuel burning to sonic power ( $10^{-2}$  seems a plausible goal), limits to source size, beaming inefficiencies etc. suggest very much more modest goals for area denial, perhaps even less than  $10^{-2} \text{ km}^2$  at considerably less than 140 dB.

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<sup>2</sup>In practice such motion, if achieved, might not efficiently transfer expended power into a monochromatic sound beam because the Reynolds number of the induced air flow

$$Re \sim \frac{v \rho_o A^{1/2}}{\eta} \sim \frac{c_s \rho_o A^{1/2}}{\eta} \sim 10^5 \left( \frac{A}{\text{cm}} \right)^{1/2}$$

is so high that strong turbulence would be expected.

## 5 COUNTERMEASURES

Suppose, however, that a very much smaller area than 1 km<sup>2</sup> has been insonified to the intensity needed for denial (probably by sound waves with  $\nu \geq 10^2$  Hz because much lower frequencies are less efficiently produced and directed). How might a determined area occupier defend against such a sonic barrier? The answer appears to be — rather easily (quite apart from simply shooting the sound source or a hovering helicopter which carries it).

We are all familiar with the very great reduction from outside audio intensities achieved by closing a window. Some commercial airliners mount a pair of jet engines adjacent to the passenger compartment. Despite what might be intolerable sound levels outside the fuselage during full power engine thrusts, the noise level for a passenger separated from the jet by a thin fuselage or a window is generally not even uncomfortable. This suggests that sound intensity in such a circumstance could be diminished by at least several tens of dB. Completely surrounding individuals by effective sonic screens can be accomplished in several ways — from employing simple heavy plastic envelopes to just climbing into a vehicle and rolling up the windows. To be somewhat more quantitative we will consider some idealizations of such sound barriers.

Simplest of all is representing the separation of a targeted individual from the acoustic source by the interpolation of a thin infinite (i.e. no edges) wall. If the wall is free to move in response to an incident sound wave the fraction of the incident energy which passes through the wall is

$$|T|^2 = \left(1 + \frac{\sigma^2 \omega^2}{4 \cos^2 \theta \rho_o^2 c_s^2}\right)^{-1}, \quad (5-1)$$

where

$\sigma$  = surface mass density

$\theta$  = angle between the incident beam direction and the surface normal.

For  $\sigma = 3g \text{ cm}^{-2}$  and  $\nu = 10^3 \text{ Hz}$  a wall would transmit a fraction

$$|T|^2 \sim 10^{-5} \cos^2\theta$$

of the incident intensity. There would then be a > huge 50 dB reduction in sound intensity behind such a wall, rendering any plausible incident insonification innocuous.<sup>3</sup>

In the above idealization only wall inertia was included in the response of the wall to the incident sound. There are changes when the separation wall supports structural resonances. We may represent a relevant one by mounting the wall on a spring so that it has the resonance frequency  $\omega_o$  for wall motion in the normal direction. Equation (5-1) becomes

$$|T|^2 = \left[ 1 + \frac{\sigma^2(\omega^2 - \omega_o^2)^2}{4\omega^2 \cos^2\theta \rho_o^2 c_s^2} \right]^{-1}. \quad (5-2)$$

The frequency averaged transmission for a broad band of width  $\Delta\omega$  centered on the angular frequency  $\omega_o$  is

$$|\bar{T}|^2 \sim \frac{\pi \cos\theta \rho_o c_s}{2\Delta\omega\sigma}. \quad (5-3)$$

For

$$\begin{aligned} \Delta\omega &= \omega_o/2 = \pi \cdot 10^3 \text{ s}^{-1} \\ |\bar{T}|^2 &\sim 4 \cdot 10^{-3}. \end{aligned}$$

Plausible insonification is again reduced to an easily tolerable level but by a smaller factor than when  $\omega_o = 0$ . We note that for frequencies  $\omega \gg$

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<sup>3</sup>Results could be quite different behind a finite width or height thin shield. Sound can then also be propagated to behind the shield by edge diffraction rather than only by transmission through it. This diffraction is generally maximized by a "sharp" edge in which the shield is terminated over a distance  $\ll \bar{\lambda}$ . The intensity behind the shield would then fall off with distance(s) from the edge to about a fraction  $\bar{\lambda}/2\pi s$  of the incident one. This fraction can be changed by more gradual shield edge fall off, curving the edge, etc. Unless  $s \gg \bar{\lambda}$  (50 cm for  $\nu = 10^2 \text{ Hz}$ ) edge diffraction would be expected to be more important than transmission through the wall.

$\omega_o$  Equation (5-2) of course reduces to Equation (5-1) but it gives a much diminished  $|T|^2$  in the small  $\omega$  limit where

$$|T|^2 \rightarrow \frac{4\omega^2 \rho_o^2 c_s^2 \cos^2 \theta}{\omega_o^4 \sigma^2}, \quad (5-4)$$

which approaches zero.

In the more complicated cases of greatest interest the interpolated infinite wall is replaced by a closed one around each targeted individual. Analysis of the resulting reduction are similar to the infinite wall case. There can be many structural resonances as well as many in which changing pressures from standing interior sound waves give "spring" responses. Again we would conclude that satisfactory protection could be achieved from being within a closed shield (e.g. a vehicle with closed windows or specially designed mobile enclosures). Any potential worrisome structural resonance frequency could rather easily be shifted and/or damped.)

At very low frequencies the important sound wave induced interior pressure fluctuations may be caused by airflow into and out of a "vehicle" through the many seams, cracks, and small openings in the enclosure, certainly the case in an automobile. (In the  $\nu \rightarrow 0$  limit outside pressure increments are completely matched by interior ones so the effective  $|T|^2 \rightarrow 1$ ). The response inside of a thin container of volume  $V$  and  $N$  holes, each of area  $\hat{A}$ , to an exterior sound wave may be analyzed as a Helmholtz type resonator. The (off-resonance) ratio of low frequency sound intensity, (pressure change)<sup>2</sup>, inside such a resonator to that just outside the holes is

$$|T_{HR}|^2 = \left( 1 - \frac{\omega^2}{\omega^2 - \frac{c_s^2 N \hat{A}}{\ell V}} \right)^2 \quad (5-5)$$

with  $\hat{\ell} \sim \hat{t} + \hat{b}$ :  $\hat{t}$  is the thickness of the container wall and  $\hat{b}$  is essentially the minimum hole dimension. (For a round hole  $\hat{b} = 0.8 \hat{A}^{1/2}$ .) For a vehicle with rolled up windows,  $V \sim 5 \text{ m}^3$ ,  $N \hat{A} \sim 10 \text{ cm}^2$  and  $\hat{b} + \hat{t} \sim 1 \text{ cm}$  the



characteristic Helmholtz resonance frequency

$$\nu_{HR} = \frac{c_s}{2\pi} \left( \frac{N\hat{A}}{V\hat{\ell}} \right)^{1/2} \sim 7Hz \quad (5-6)$$

Such frequencies and smaller ones would not be expected to be effective for area denial by insonification because a) sound radiators are so ineffective at such large wavelengths, b) no unusual human response resonances are expected at such low frequencies because we know there are none in the  $\nu \rightarrow 0$  limit, c) whatever resonance might exist, the  $\nu_{HR}$  would differ greatly among vehicles or within any single one from slight adjustments. At much higher frequencies the Helmholtz resonator model for holes, cracks, etc. gives an effective

$$|T_{HR}|^2 \sim \left( \frac{c_s^2 N \hat{A}^2}{\omega^2 \hat{\ell} V} \right)^2 \sim 10^{-5} \left( \frac{10^2 Hz}{\nu} \right)^2. \quad (5-7)$$

In summary, from the above analyses and, above all, our immediate experience in moderating loud audio noise, realistically achievable large area insonification does not appear promising as a way of denying an area to people who can enter and traverse it in vehicles or simpler mobile enclosures as long as they take simple precautions.

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