MODELING NOISE HAZARD TO THE HUMAN EAR

Background and Approach
Development of the Mathematical Model
Validation of AHAA-CAT
Making the Human Model
Validation of the Model– Albuquerque Studies
Rating Impulses in the Literature
From the Model toward a DRC

Presented at the Panel Review of the HRED Method for Accessing the Risk of Auditory Injury for Hearing-Protected Soldiers Exposed to Impulse Noise
30-31 January 2001

The American Institute of Biological Sciences
- a national center for biologists & the biological sciences since 1947

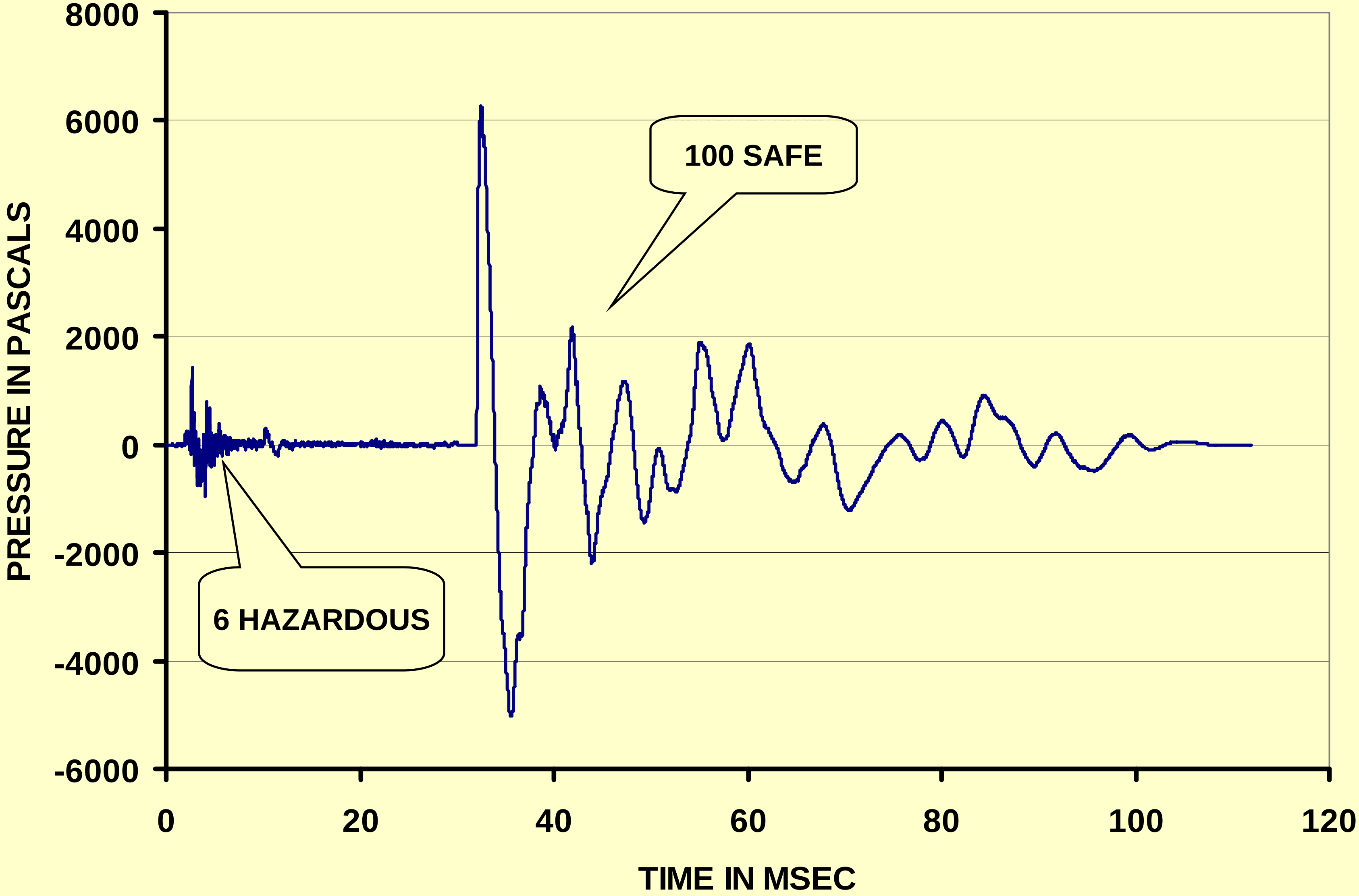
MODELING NOISE HAZARD TO THE HUMAN EAR

THE BACKGROUND AND APPROACH

Problems with Existing Standards

- Suppose A-weighted energy used as a method for rating hazard:
  - 2000 - 3000 J/M^2 measured under a muff acceptable for cannon impulses (Johnson & Patterson, 1994)
  - Would allow 2000+ rounds unprotected exposure from a rifle
  - In fact, fewer than 10 rounds hazardous

Or Consider Use of Peak Pressure and Duration as in MIL STD-1474 or Pfander or Smoorenburg



Common Perceptions About Impulse Noise Hazard

Impulse noise is a special problem

Exceedingly high variability in impulse noise exposures

Pulse duration makes a difference - longer pulses better or worse depending on experiment.

Rise time and peak pressure are critical; but their effects are poorly understood

"The precise mechanism behind hearing loss is poorly understood" I. Flindell (1999)

BASIC CONSIDERATIONS IN APPROACH

- First need to understand <u>ear's</u> response to intense sound
- Basic research with animal model useful in identifying issues and establishing principles (scaling another problem)
- Primary site of loss intracochlear
- Mammalian cochleas similar

BASIC CONSIDERATIONS IN APPROACH

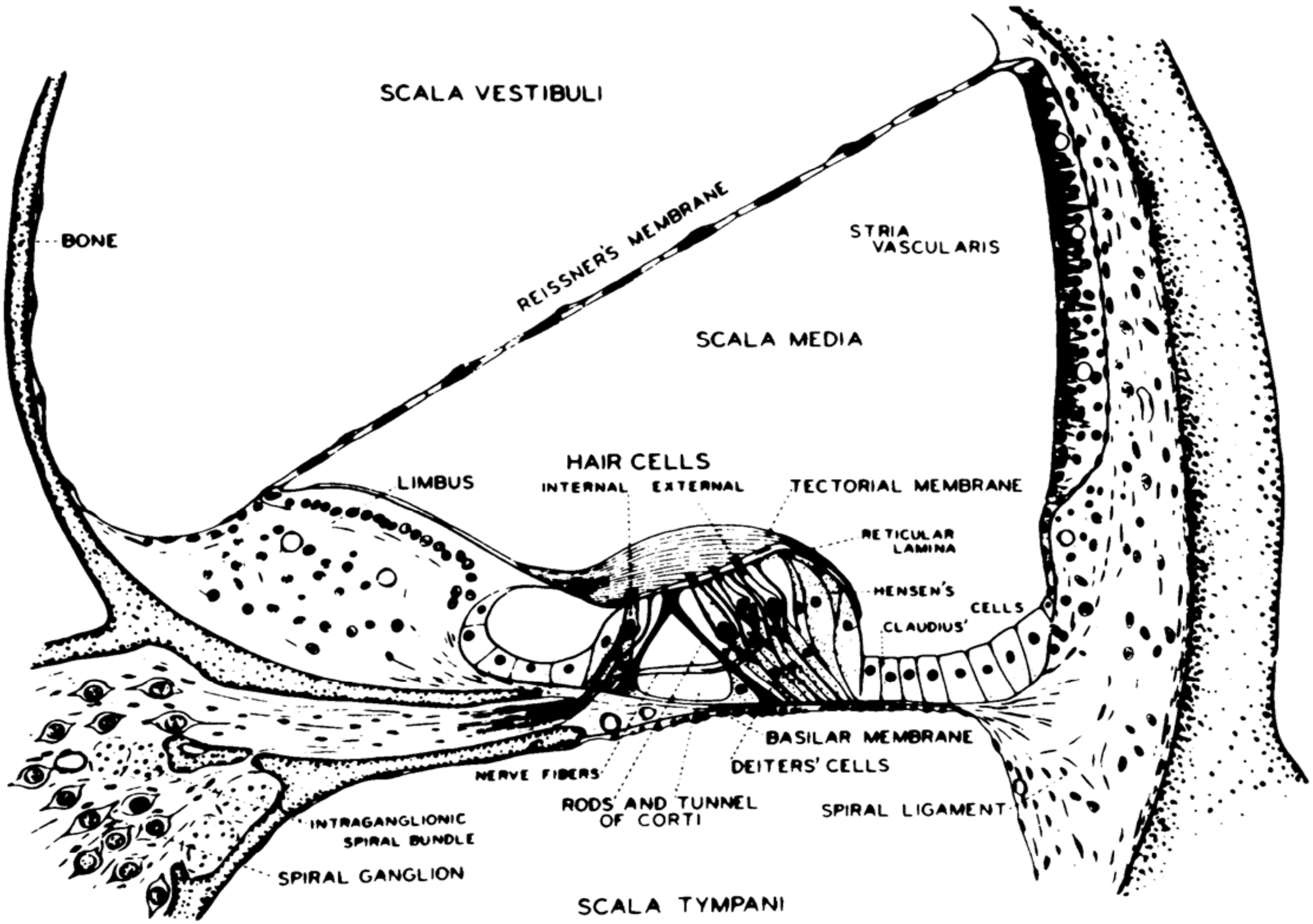
- External and middle ears control properties of conductive path to cochlea
- A selective reading of the basic research needed to find those pieces that pin down basic mechanisms
- Should make theoretical sense
- Begin by following sound into cochlea

The External and Middle Ears

- The external ear (head reflectivity and canal and pinna resonances) provides about 20 dB of emphasis at 4 kHz (cat)
- The middle ear's resonance is at about 1kHz (cat)
- Low frequency sensitivity falls off at about 6 dB/Oct (too stiff)
- High frequency falls off at about 18 dB/Oct (too massive)

INSIGHTS FROM BASIC RESEARCH

- At high levels, mechanical stress at the level of the hair cell primary loss mechanism



SCALA VESTIBULI
BONE
REISSNER'S MEMBRANE
STRIA VASCULARIS
SCALA MEDIA
HAIR CELLS
INTERNAL
EXTERNAL
LIMBUS
TECTORIAL MEMBRANE
RETICULAR LAMINA
HENSEN'S
CELLS
CLAUDIUS'
BASILAR MEMBRANE
DEITERS' CELLS
NERVE FIBERS
RODS AND TUNNEL OF CORTI
SPIRAL LIGAMENT
INTRAGANGLIONIC SPIRAL BUNDLE
SPIRAL GANGLION
SCALA TYMPANI

INSIGHTS FROM BASIC RESEARCH

- At high levels, mechanical stress at the level of the hair cell primary loss mechanism
  - Tip links most vulnerable
  - Upward displacement of basilar membrane puts tissue in tension - primary failure mode
- Damage grows very rapidly at high levels

Growth of Damage

- As level goes up, loss goes from log-time to linear-time relationship
  - In the human ear
    - Ward, Selters and Glorig, 1961
    - Clicks from speaker
    - Threshold shift measure
  - In the cat ear
    - Price (1968, 1972)
    - Pure tone excitation
    - Loss in cochlear microphonic sensitivity

Growth of Damage

- Above critical level, loss grows about 7 dB per dB increase in level
  - In the human ear
    - Ward, Glorig and Sklar, 1962
    - Clicks from speaker
    - Threshold shift measure
  - In the chinchilla ear
    - Patterson et al.
    - Impulses from a speaker
    - Threshold shift, behavioral measure

Growth of Damage - Implications

- Above critical level, loss grows about 7 dB per dB increase in level
  - And in the cat ear
    - Price and Wansack (1985; 1989)
    - Impulse from primer
    - Threshold shift, evoked response measure

Growth of Damage - Implications

- Once loss begins (and middle ear is in linear range of operation and middle ear muscles are not growing in effect), in 10 - 15 dB
  - Threshold shift >80 dB
  - Outer hair cells gone
- Recovery prolonged
  - Loss may even increase for hours
    - Luz and Hodge (1971)(sunburn model)
    - Hamernik, Ahroon and Patterson (1988)
  - Presumption: mechanical repair in cochlea going on

INSIGHTS FROM BASIC RESEARCH

- At high levels, mechanical stress at the level of the hair cell primary mechanism
  - Tip links most vulnerable
  - Upward displacement of basilar membrane puts tissue in tension - primary failure mode
- Damage grows rapidly
- Stapes displacement limited by annular ligament

The Annular Ligament

- In cat, uniform width (about 40 microns)
- Promotes piston-like movement
- Tough - stapes likely to be destroyed before it can be removed from oval window
- On basis of physical considerations, not likely to displace by more than 20 microns

Annular Ligament

- In man, asymmetrical (15 microns at one end, 150 at other end)
- Promotes rocking of footplate along long axis of stapes - less efficient
- Effective maximum displacement for piston about same as cat

INSIGHTS CONTINUED

- Evidence for non-linearity
  - Measured by Guinan and Peake (1967)
  - Calculable from physical considerations (Price, 1974)
  - Inferable from Nixon and Sommer (1973) airbag simulation
  - Measured effect on intracochlear pressure (Dancer, 2000)

INSIGHTS CONTINUED

- Implications of limited displacement
  - Earliest non-linearity (others follow)
  - Ossicular chain stiffens
  - Peak clips intense sounds - if linear, would try to displace 2000 or more microns to large caliber weapon impulse
  - In complex sounds, low frequencies modulate higher frequencies
  - <u>Linear weighting schemes can’t work at very high pressures.</u>

Insights from Basic Research
The Middle Ear Muscles

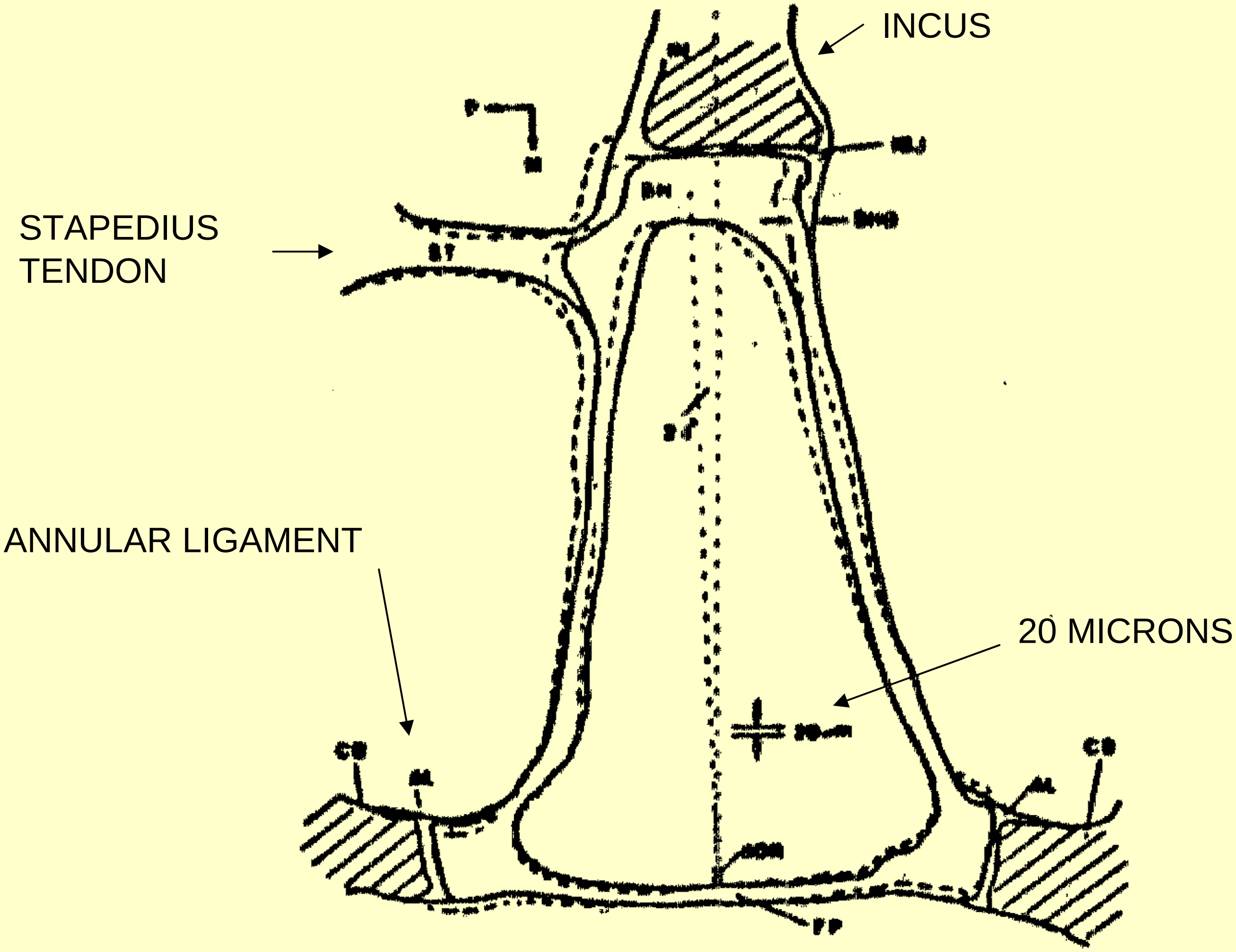
- Middle ear muscle contraction protective
  - If elicited, too late to affect short impulse
  - If anticipatory or already elicited, protects
- Middle ear muscle reflex conditionable in cat and at least some men
- Middle ear muscle reflex also part of facial reflex

Insights -- Middle Ear Muscles

- Stimuli in impulse noise exposures 40 - 60 dB more intense than those used in the lab
- At gunfire levels, impulse also tactile
- Propose that in case where moment of firing known, should assume middle ear muscle reflex active
- A <u>conservative</u> assumption for a model

Insights -- Middle Ear Muscles

- Stapedius responsible for most of middle ear muscle effect
- Attached to neck of stapes, acts by rocking stapes to side
  - Incudo-stapedial joint sides, capsule deforms
  - Annular ligament stiffens

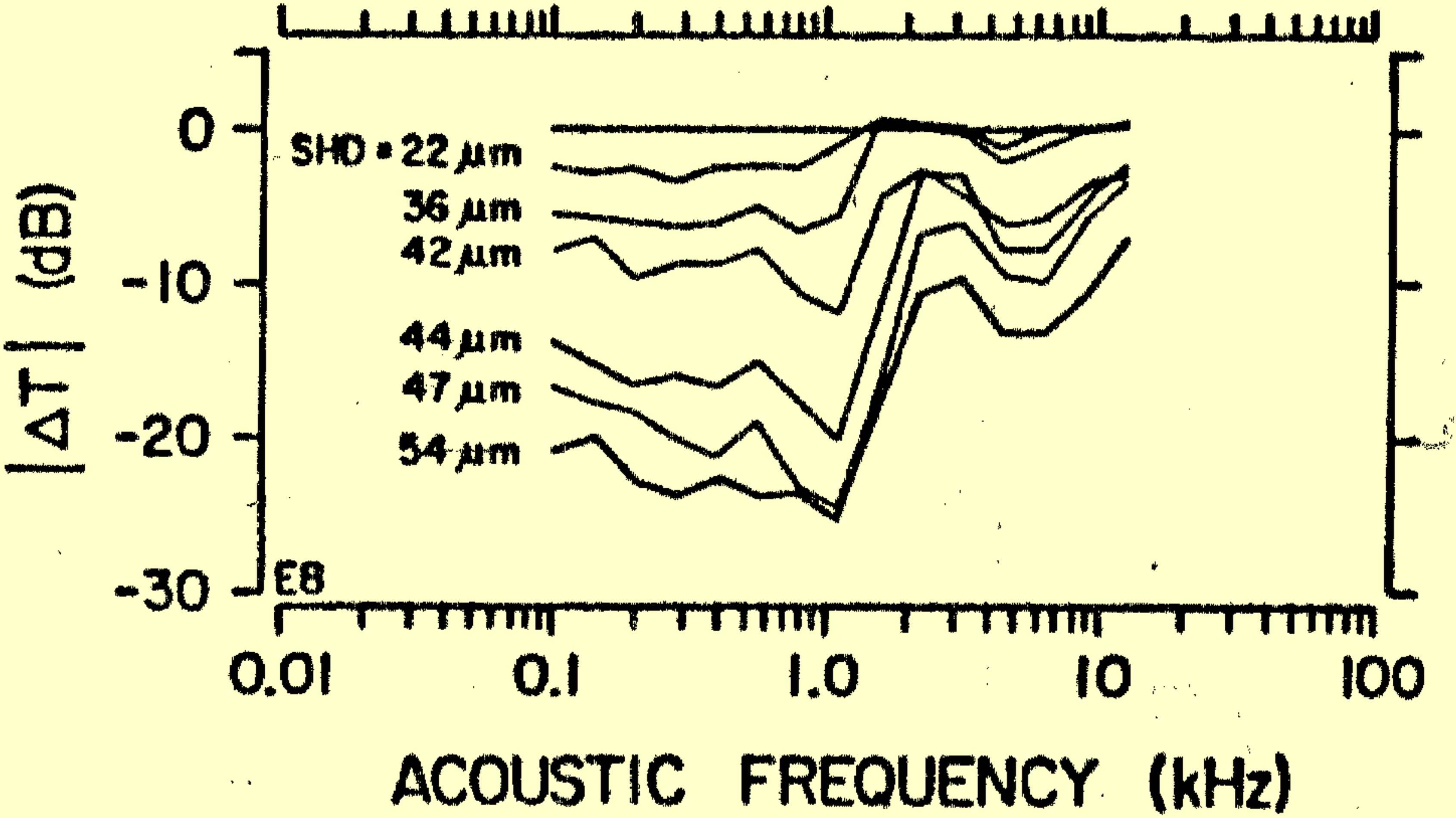

INCUS
STAPEDIUS
TENDON
ANNULAR LIGAMENT
20 MICRONS

Insights -- Middle Ear Muscles

- Stapedius responsible for most of middle ear muscle effect
- Acts by rocking stapes to side, stiffening annular ligament
- Effects proportional to displacement angle
- Action affects low frequencies most, high frequencies less

EFFECT OF STAPEDIUS CONTRACTION (CAT)

(from Pang and Peake)



The Bottom Line: To Predict Hazard We Need to Account for

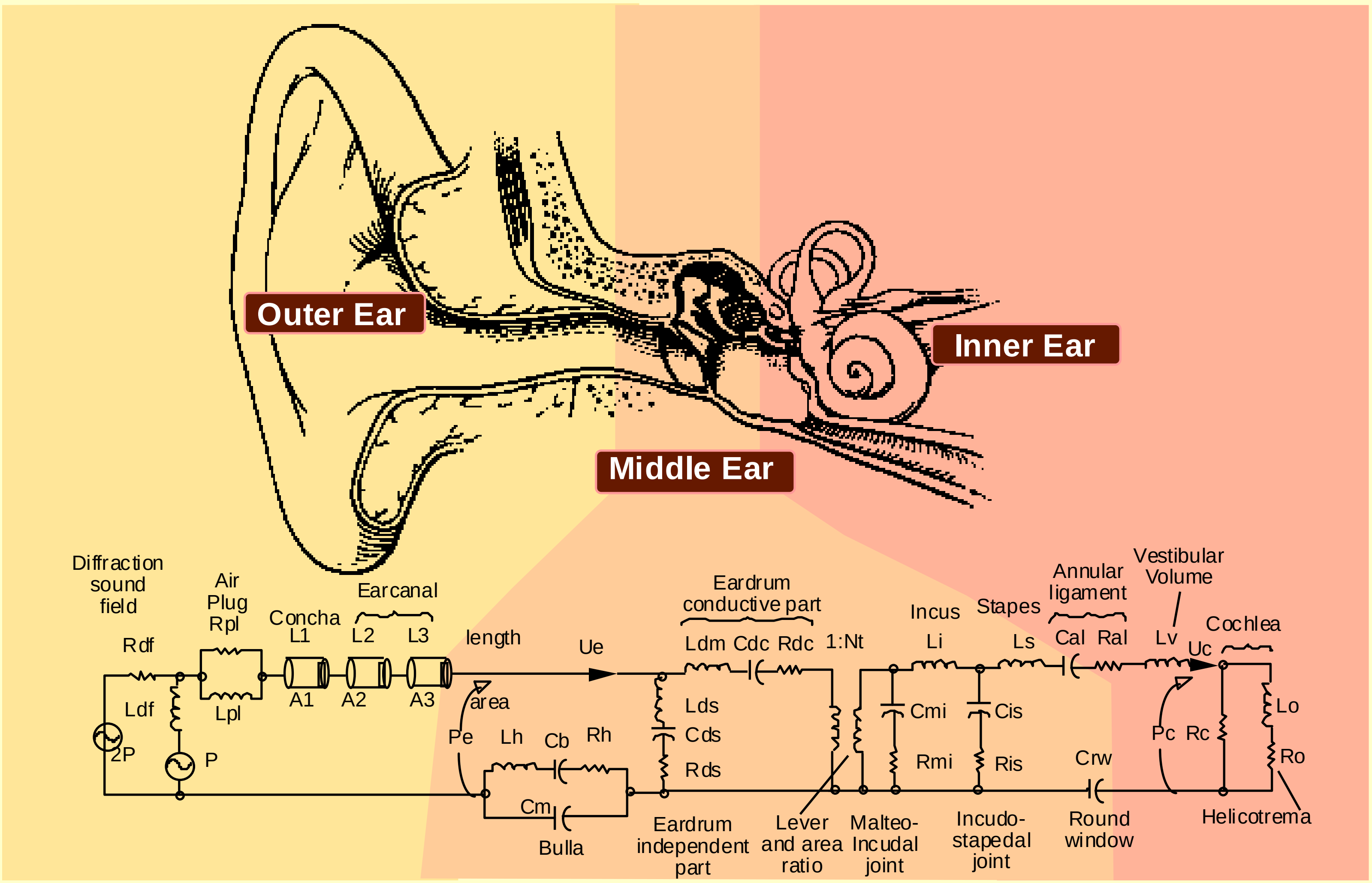
- Conductive properties of the external and middle ears
- Stapes non-linearity at high displacements
- Middle ear muscle dynamics and effect
- Mechanical loss process within cochlea

A Computer Based Model Is Needed!

The Modeling Approach to a DRC: Problems and Advantages

- Relatively difficult to do well
- Makes use of a wide range of data about the ear - minimizes the arbitrary
- Theoretical basis makes for generalizability (lowers risk with new data sets)
- Simple in use
- Reduces arbitrary decisions in application
- Encourages remediation rather than palliation (*fix* rather than patch!)

AHAA Developed - Conformal with ear structure



Next, Development of the Model

- For DRC, could present model as fait accompli. (Once a structure is built, you tear down the scaffolding! OR Like sausage, it's best not to watch it being made).
- But a strength of the approach is that the structure is built around theory - promotes generalizability.
- Therefore, in next talks will examine the building and validation processes

Development of the Mathematical Model

The Modeling Details

Creating a Mathematical Model

- Which modeling domain?
  - Simulation
  - Mechanical
  - Finite Element
  - Electro-acoustic

Strengths of an Electroacoustic Model

- Designs microphones and loudspeakers
- Ear anatomy translates to circuit elements
- Parts of ear often modeled by circuits
- Visualize signal flow through network
- Time and frequency response calculable
- Merges signal flow in air, solid structures and liquids in cochlea

Choice of the Cat Ear

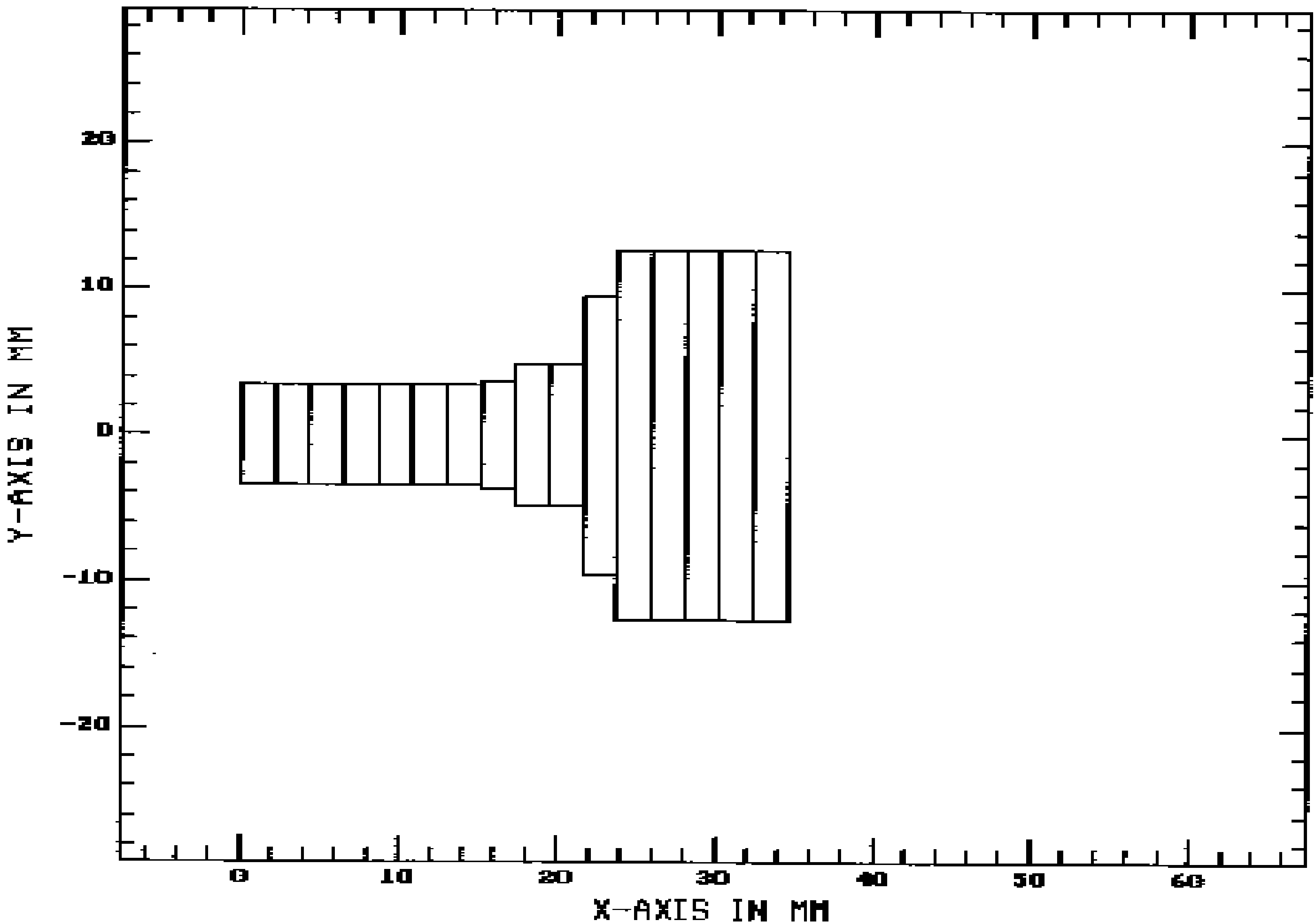
- Much detail available for cat ear
- Similar to human ear
  - Cochleas highly similar
  - Middle ears similar
    - high and low frequency slopes of sensitivity
    - tuned about 1 1/2 octaves higher
    - more absolute sensitivity
    - but less sensitive to change in frequency
- Animal already in use in lab

Goal (s) of Model

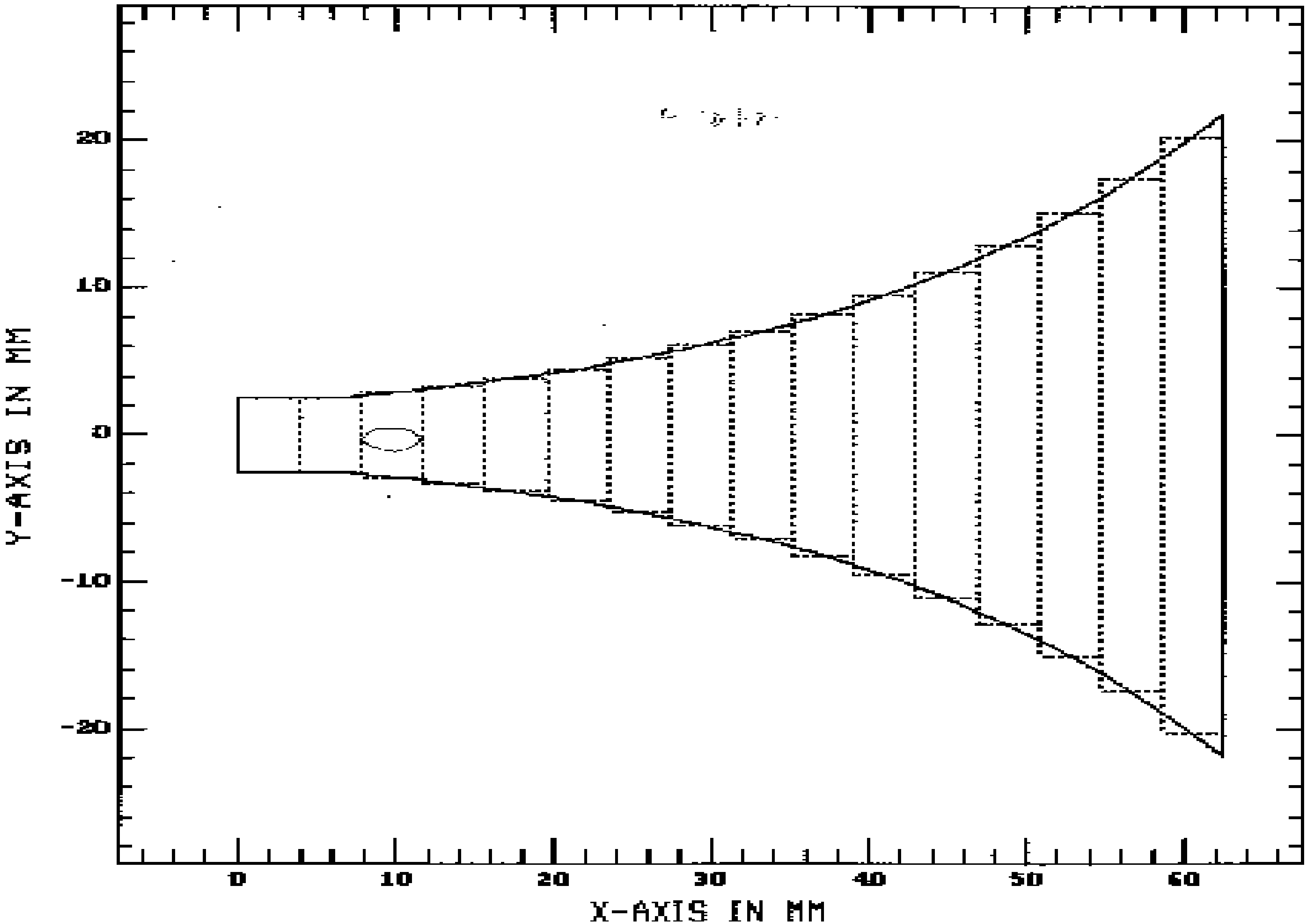
- Combine model parts into a whole
- Predict hazard to ear for any intense sound
- Work from first principles
- As complex as necessary, but not more complex
- Conformality with physiology of ear
- Provide insight into processes
- Adaptable to other species

General Modeling Approach

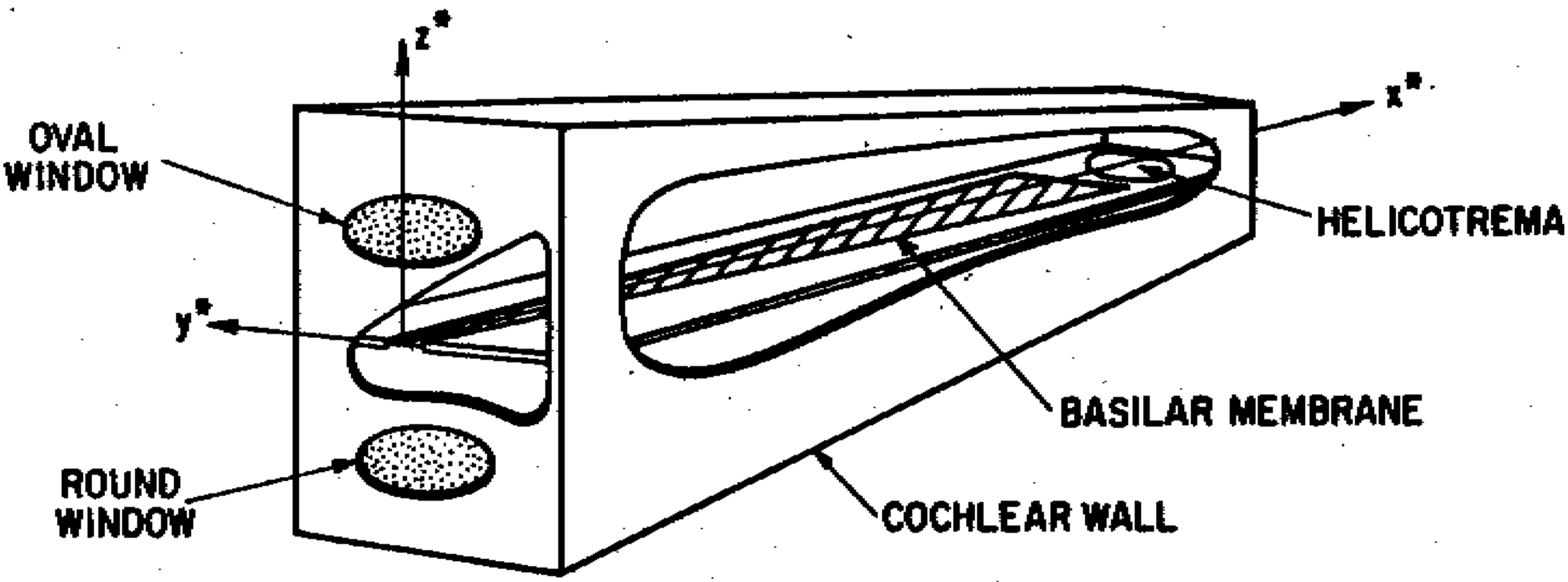
- Integrate existing partial models
  - Free field to ear drum - Two sound fields, three tubes
  - Middle ear
    - Two pistons, transformer, stapes limits, aural reflex, cochlear interface
  - Cochlea
    - Taper in geometry and mechanics
    - WKB solution obtained separately



20
10
0
-10
-20
Y-AXIS IN MM
0
10
20
30
40
50
60
X-AXIS IN MM



20
10
0
-10
-20
Y-AXIS IN MM
0
10
20
30
40
50
60
X-AXIS IN MM


z*
OVAL
WINDOW
x*
HELICOTREMA
y*
BASILAR MEMBRANE
ROUND
WINDOW
COCHLEAR WALL

Modeling specifics

- **Free field to ear drum**
  - **Wiener - one tube becomes horn**
  - **HRTF at other angles of incidence**

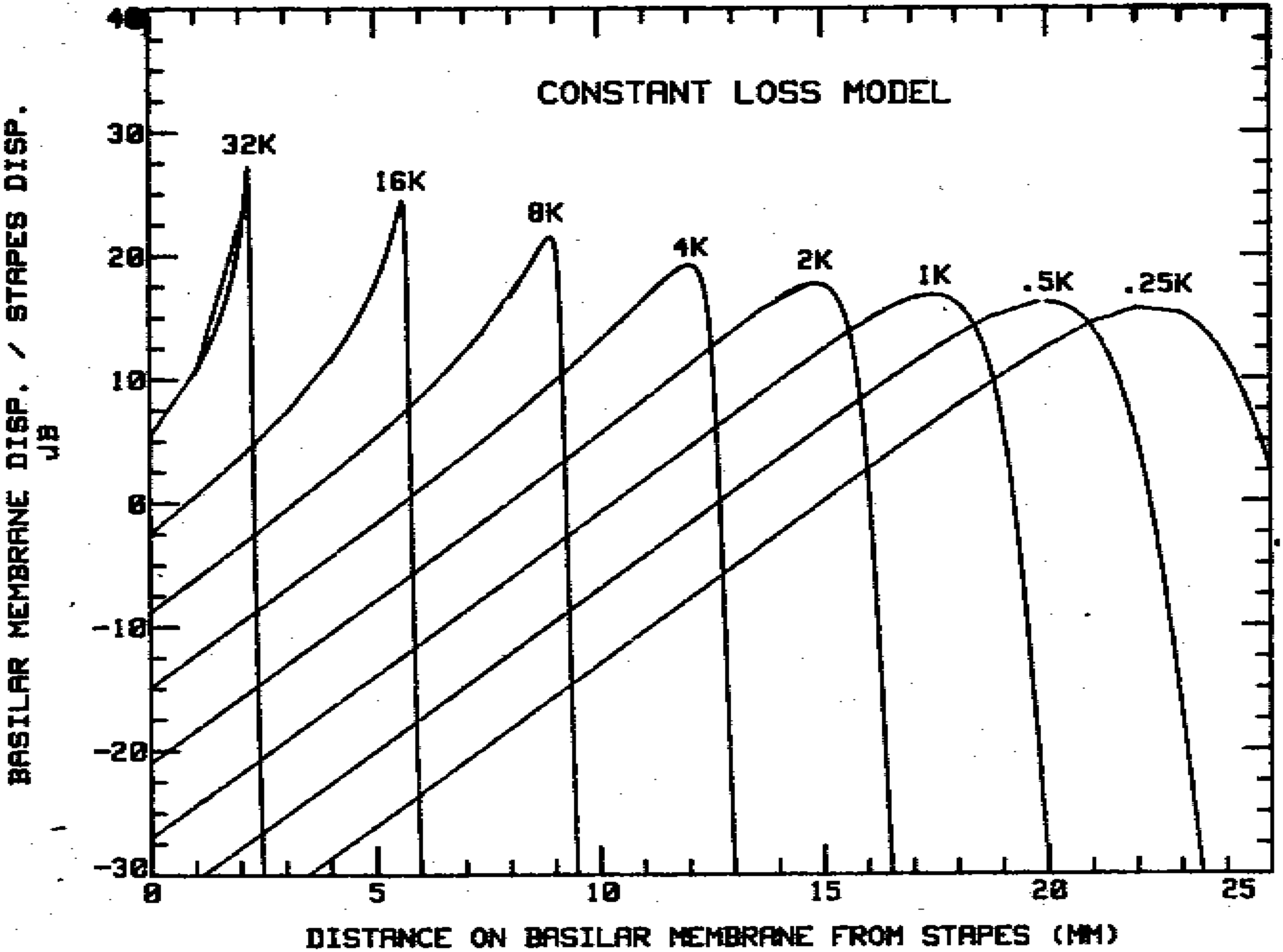
- **NOTE: model can be entered at FF, ECE or EDP level - important where HPD included**

Middle ear models specifics

- Tympanometry - Zwislocki, Lutman
- Bulla resonance in cat - Zwislocki
- Evidence of clipping at stapes
- Aural reflex effect on eardrum impedance
- Details of cochlear interface - annular ligament model - Nedzelnitsky, Lynch

Cochlear model(s)

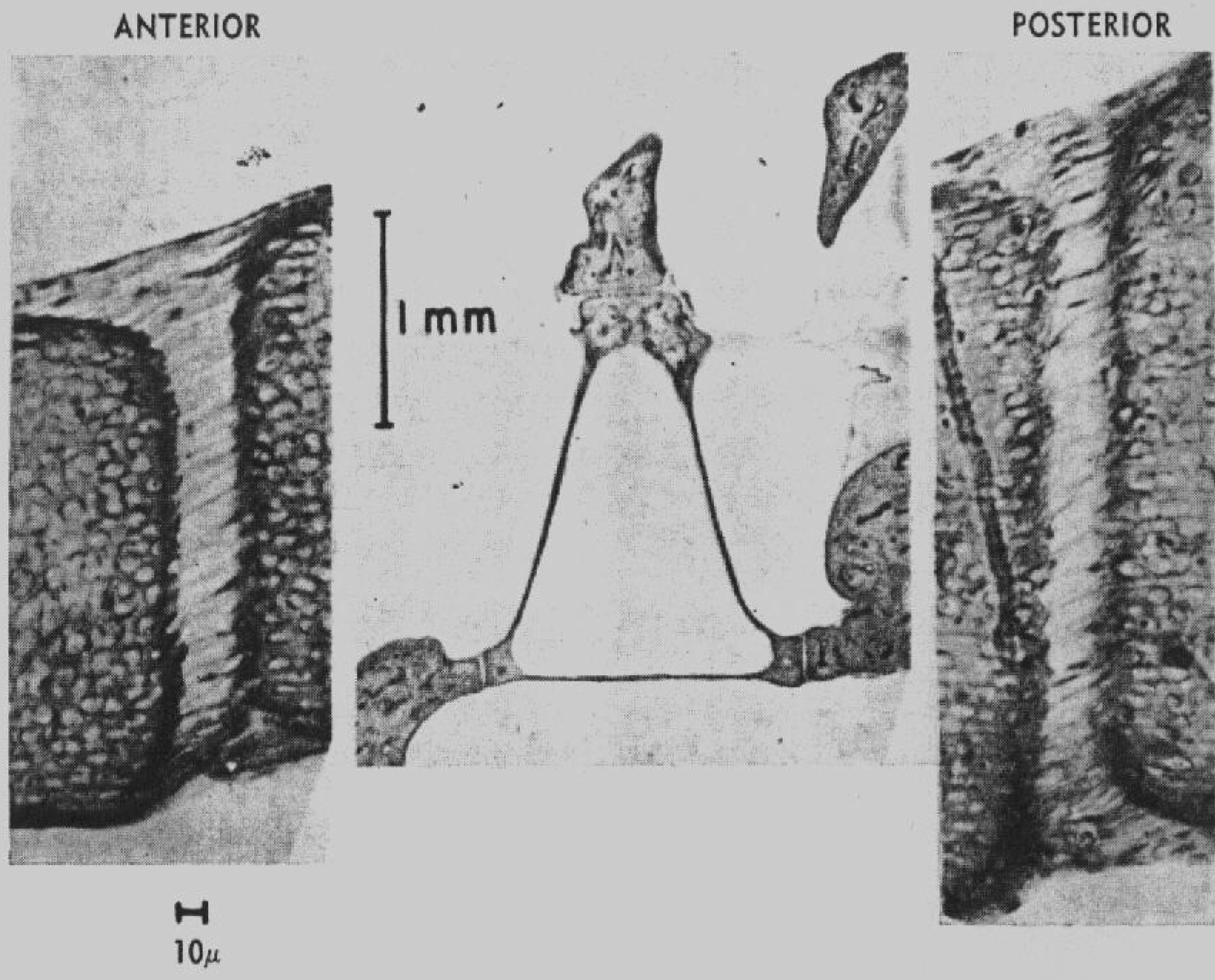
- WKB vs. difference equation
- Include what WKB does, limits
- Taper feature (Type 2 cochlea)
- What about low frequency cut-off at apex?
- Active/ dead cochlea feature (Ca)

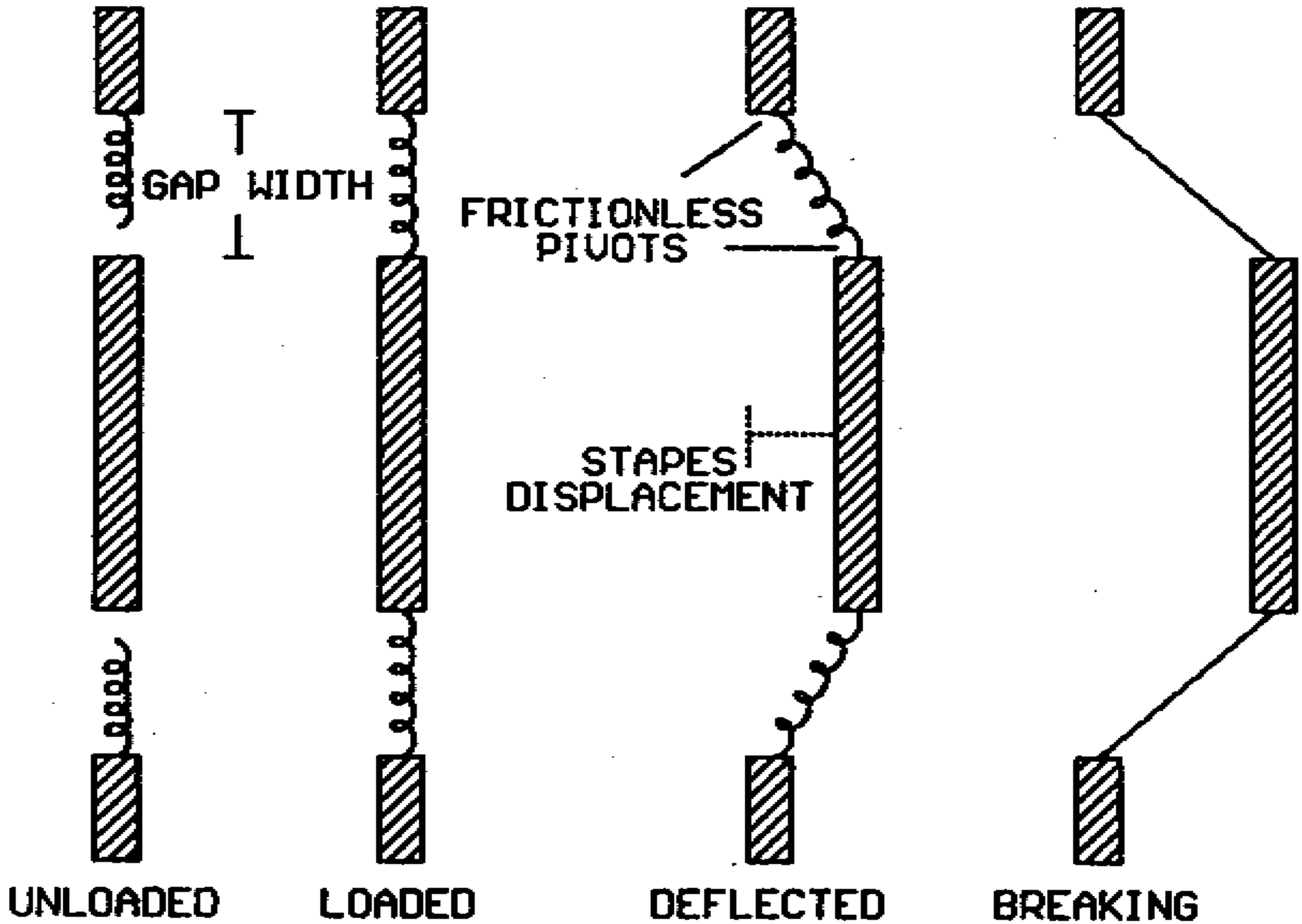


CONSTANT LOSS MODEL
32K
16K
8K
4K
2K
1K
.5K
.25K
BASILAR MEMBRANE DISP. / STAPES DISP.
dB
40
30
20
10
0
-10
-20
-30
0
5
10
15
20
25
DISTANCE ON BASILAR MEMBRANE FROM STAPES (MM)

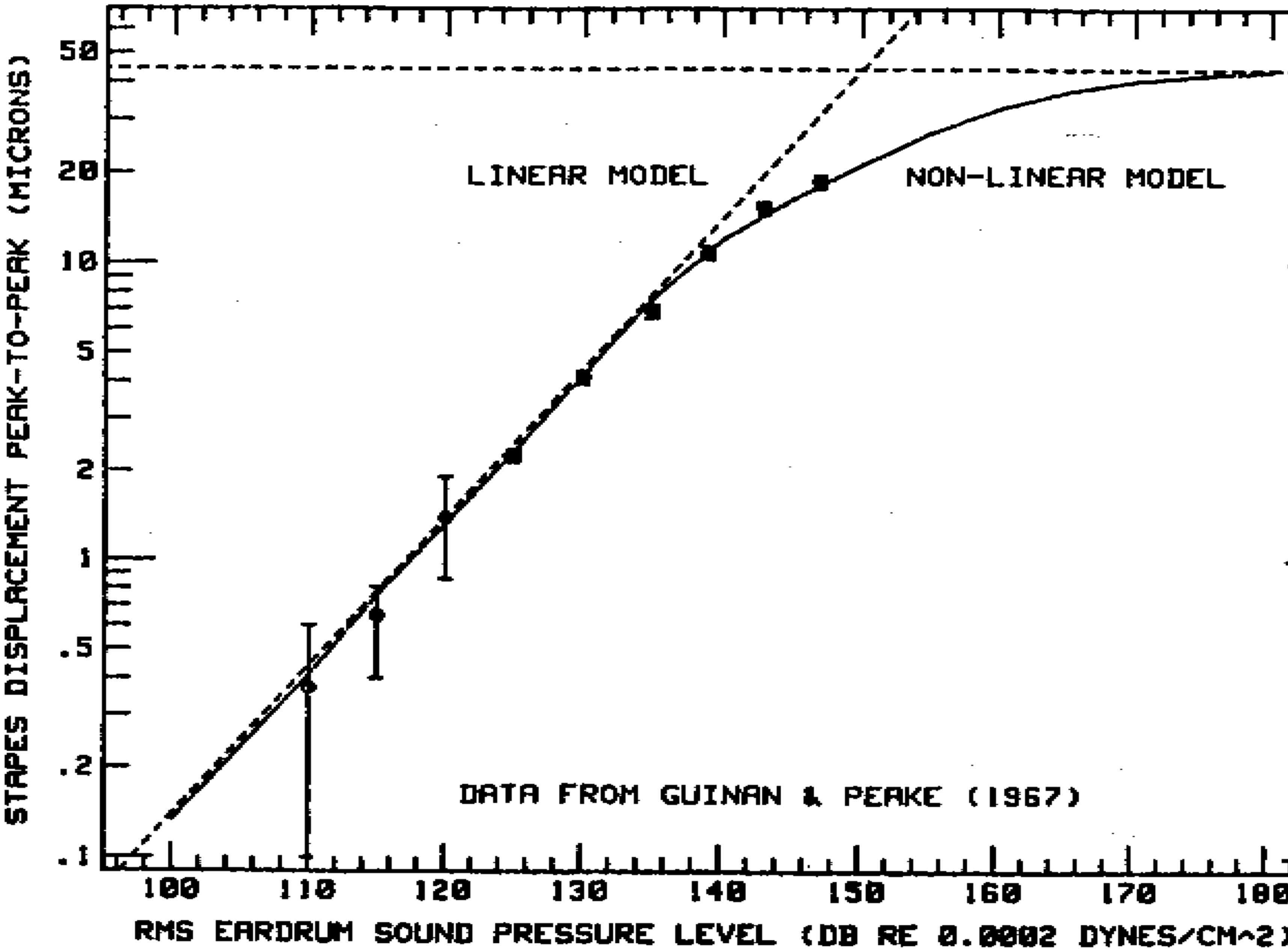
5 Unique Features of Model

1. Stapes suspension
   - Basis (Price, 1974 argument)
     - Annular ligament requires it
     - Annular ligament first/strongest non-linearity
   - Design of model
   - Effect
     - Low intensity/displacement
     - High intensity/displacement
   - Nixon & Sommer (1973) observation supports
   - Dancer (2000) measure supports

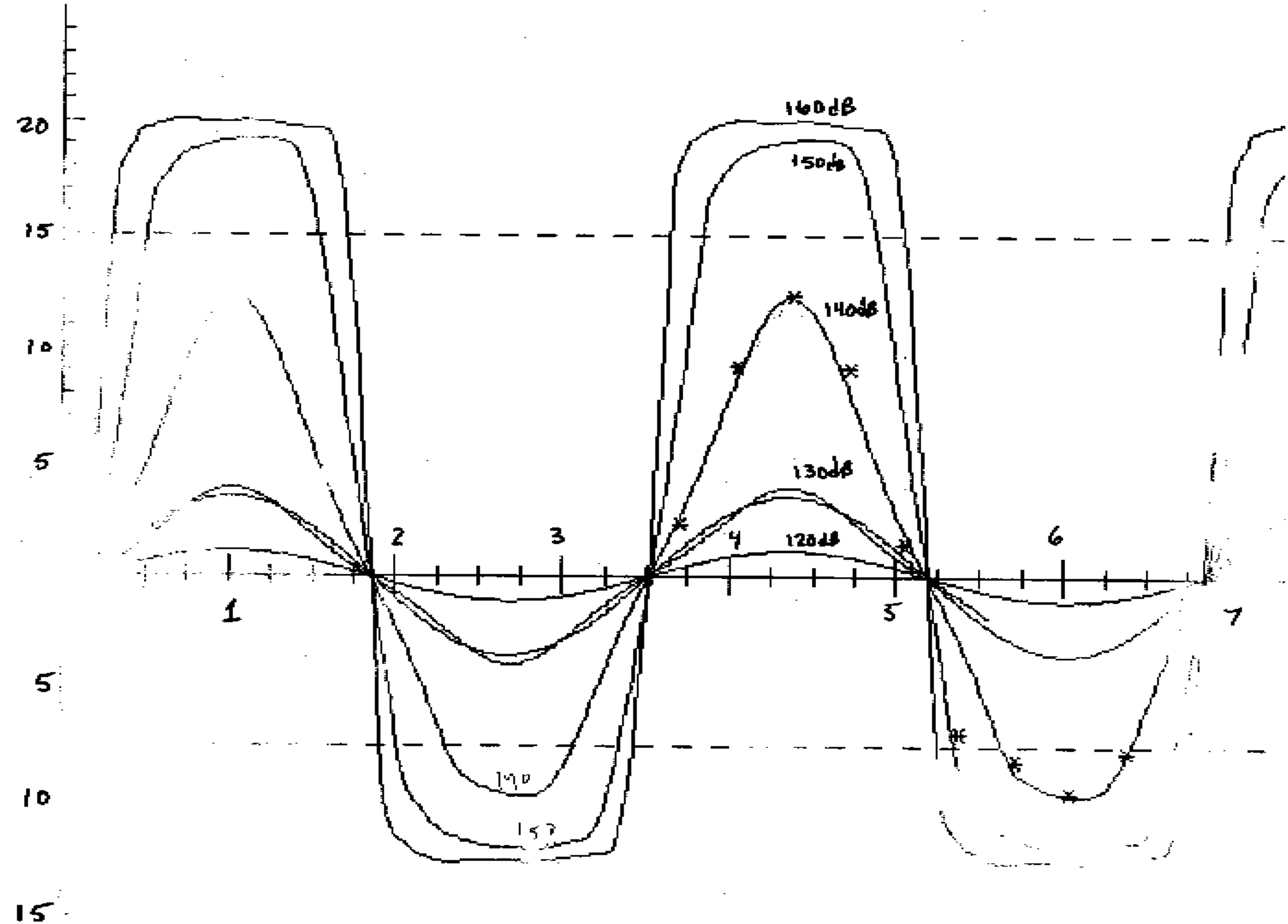

ANTERIOR
POSTERIOR
1 mm
10μ



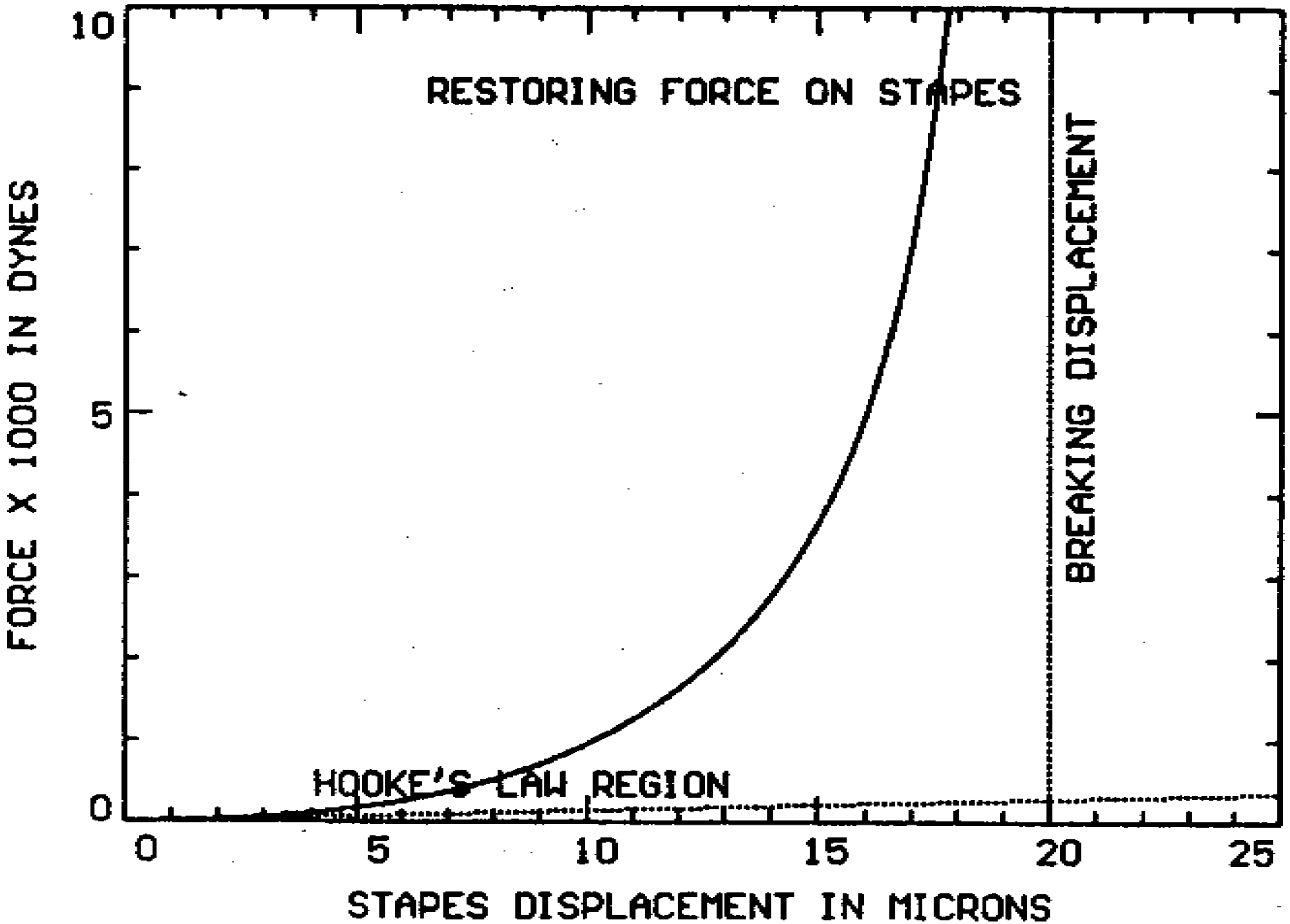
ANNULAR LIGAMENT MODEL STATES



STAPES DISPLACEMENT PEAK-TO-PEAK (MICRONS)
50
20
10
5
2
1
.5
.2
.1
LINEAR MODEL
NON-LINEAR MODEL
DATA FROM GUINAN & PEAKE (1967)
100
110
120
130
140
150
160
170
180
RMS EARDRUM SOUND PRESSURE LEVEL (DB RE 0.0002 DYNES/CM^2)



20
15
10
5
5
10
15
1
2
3
4
5
6
7
160dB
150dB
140dB
130dB
120dB
140
150



RESTORING FORCE ON STAPES
BREAKING DISPLACEMENT
HOOKE'S LAW REGION
FORCE X 1000 IN DYNES
STAPES DISPLACEMENT IN MICRONS
0
5
10
15
20
25

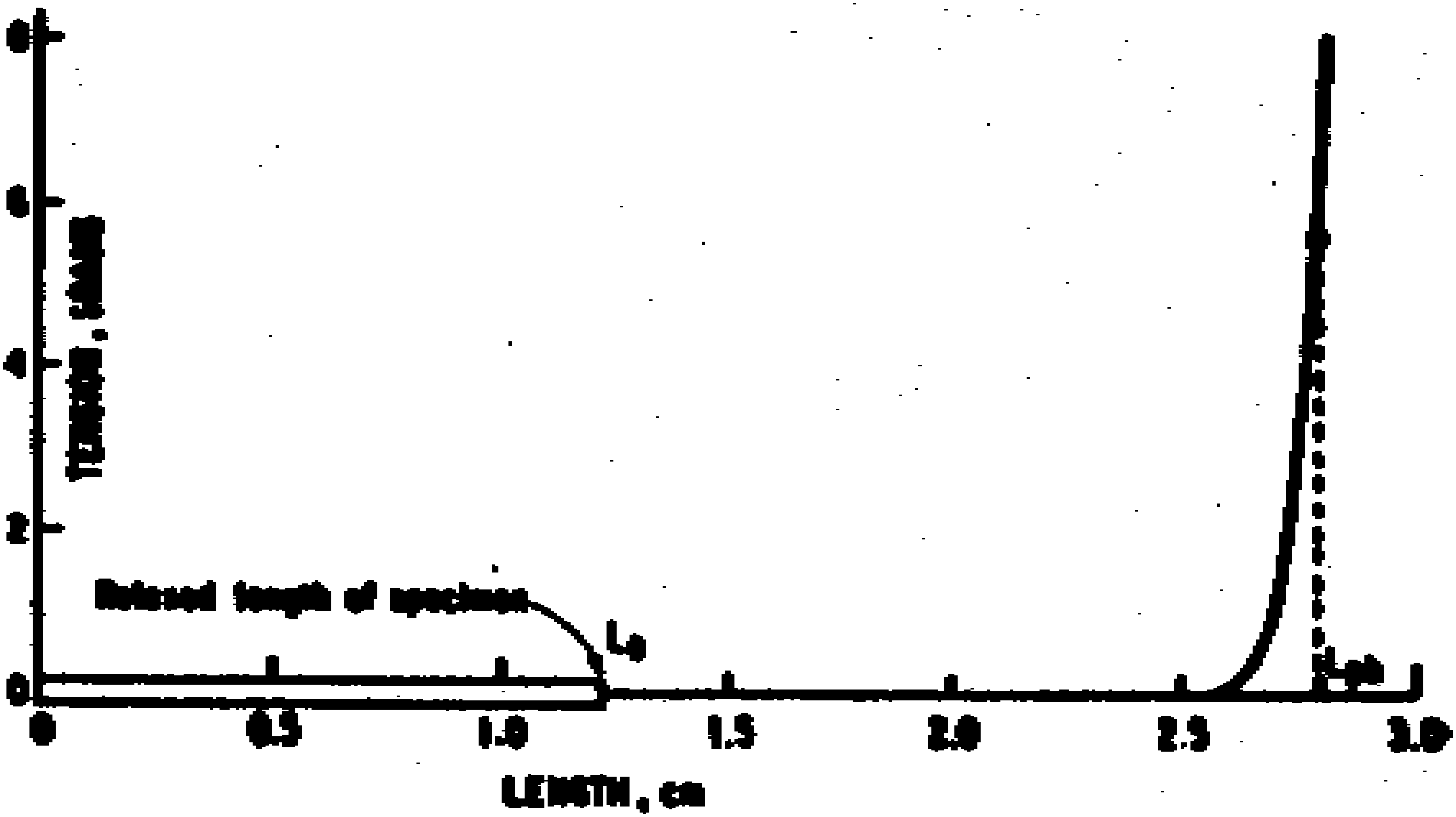
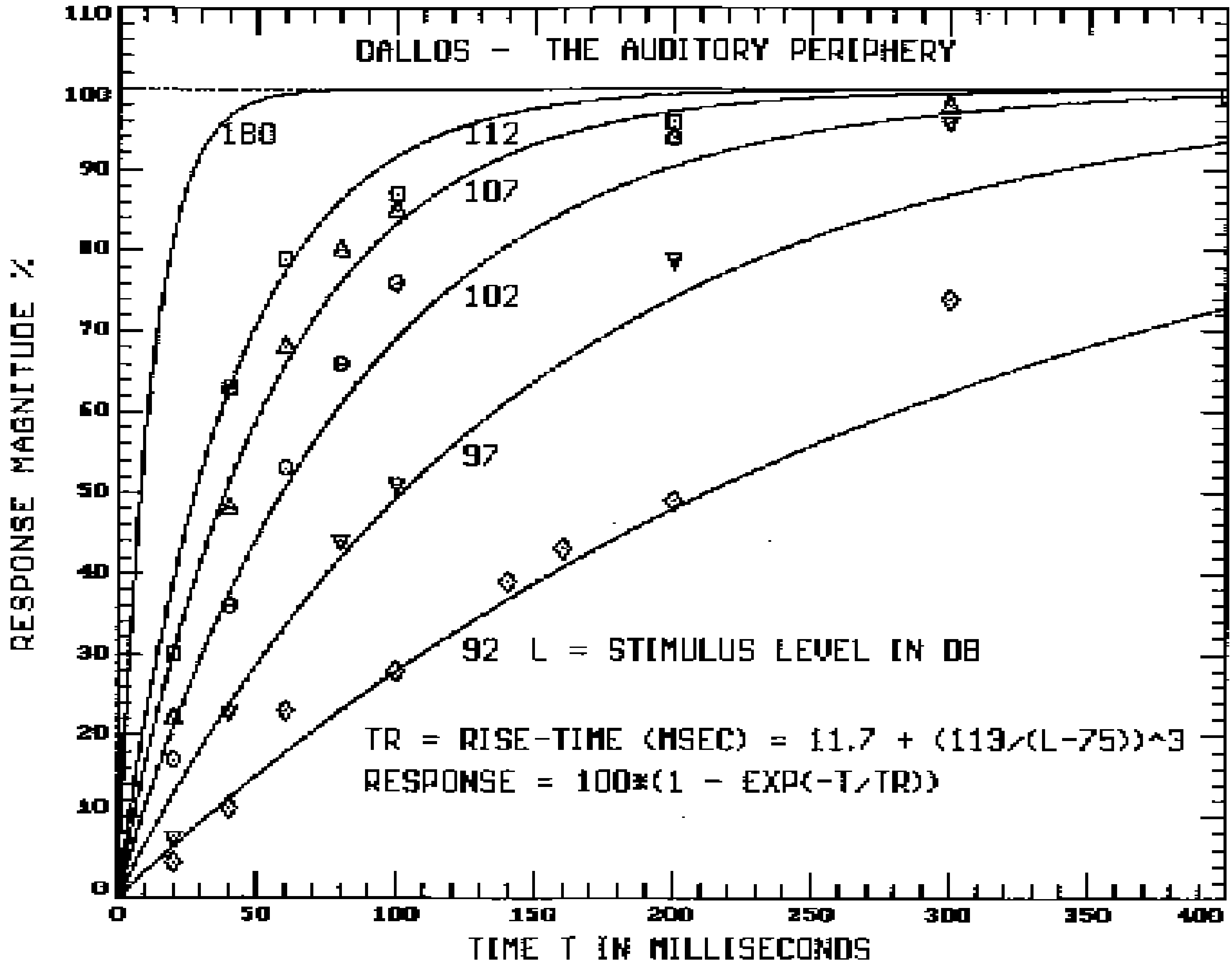


FIG. 2. Load-deflection curve of a rabbit mesentery in tension. The state corresponding to the naturally spread-out mesentery is marked by the small circle. The point l_0 marks the relaxed length of the specimen.



DALLOS - THE AUDITORY PERIPHERY
RESPONSE MAGNITUDE %
TIME T IN MILLISECONDS
180
112
107
102
97
92
L = STIMULUS LEVEL IN DB
TR = RISE-TIME (MSEC) = 11.7 + (113/(L-75))^3
RESPONSE = 100*(1 - EXP(-T/TR))

Unique Features of Model

2. “Ramp” variable

- **Increase in resistance proprtionate to level**
- **Needed to keep model from “ringing”**
- **Physiological basis**
  - **Middle ear suspension ‘soft’**
  - **Alternate modes of vibration not in conductive path possible**
  - **Beksey observed change in mode of stapes vibration in cadaver ear**

Unique Features of Model

3. Dynamic middle ear muscle contraction

- **Stapedius contraction rocks stapes in window**
- **Annular ligament in tension**
- **Model increases stiffness and resistance dynamically - charging capacitor model**
- **Model matches dynamic model of Dallos**

Unique Features of Model

4. Model of loss within cochlea

- **Basis for loss assumed to be mechanical stress at level of hair cell**
- **Keep track of <u>number</u> of flexes for upward displacements (puts tip-links in tension), squares peak (in microns)**
- **Sums at 23 locations along cochlea**

Unique Features of Model

5. Movie of development of hazard

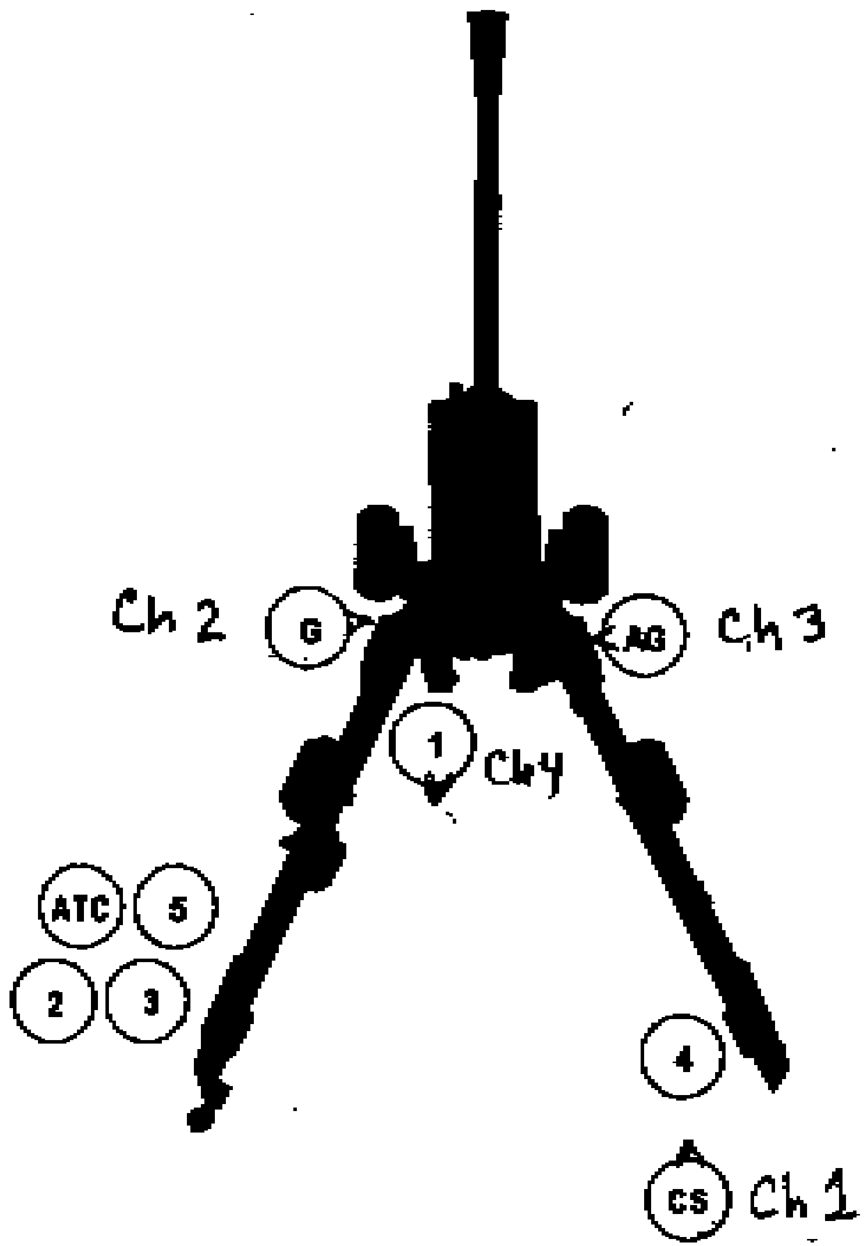
- **Data from cochlear model re-arranged**
- **Played back in sequence along with waveform**
- **Hazard development portrayed**
- **Provides insight into processes producing damage**

More Uniqueness - HPD and Azimuth Calculations

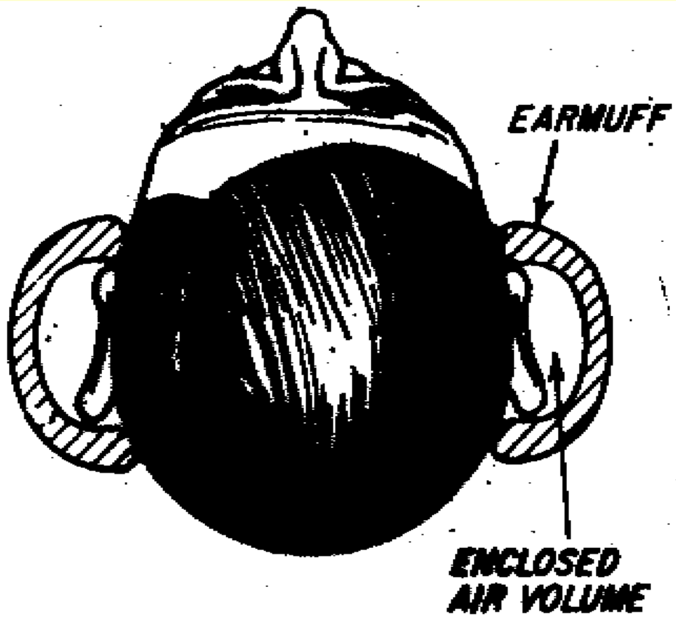
- If measures under a HPD not available
- Effects calculable two ways
- First: from attenuation data
  - REAT tests or ATF measures
  - Minimum-phase filter calculated and applied to waveform
    - Assumes linearity
    - Assumes one conduction path
  - Calculation proceeds as before

More Uniqueness - HPD and Azimuth Calculations

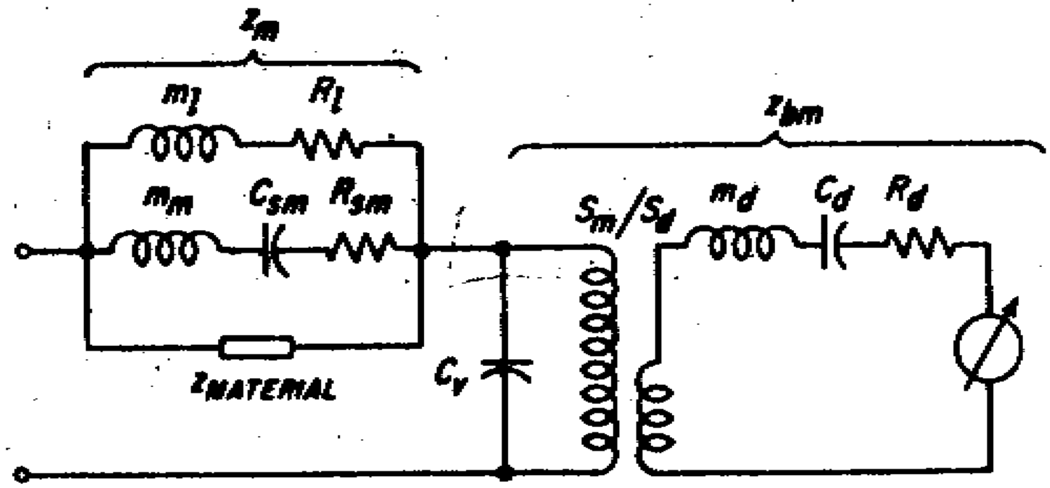
- Second, calculation of effect from mathematical model of HPD
- Properties of device (as fitted) must be known
- Model must be “created”
- Result calculated on waveform and new waveform applied to model.



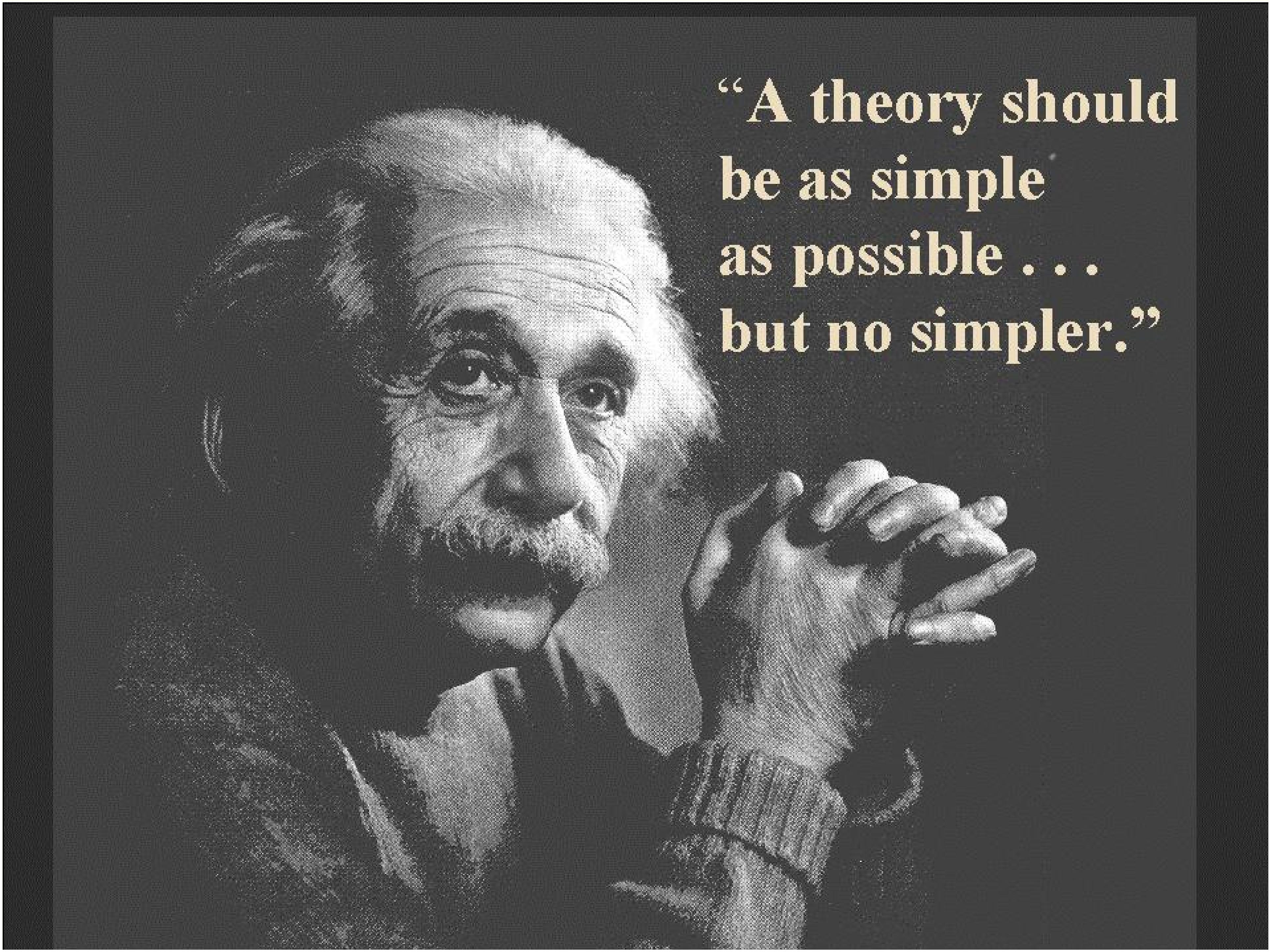
PIECE PREPARED FOR ACTION



EARMUFF
ENCLOSED AIR VOLUME



z_m
m_l
R_l
m_m
C_{sm}
R_{sm}
$z_{MATERIAL}$
C_v
z_{bm}
S_m/S_d
m_d
C_d
R_d


"A theory should
be as simple
as possible . . .
but no simpler."

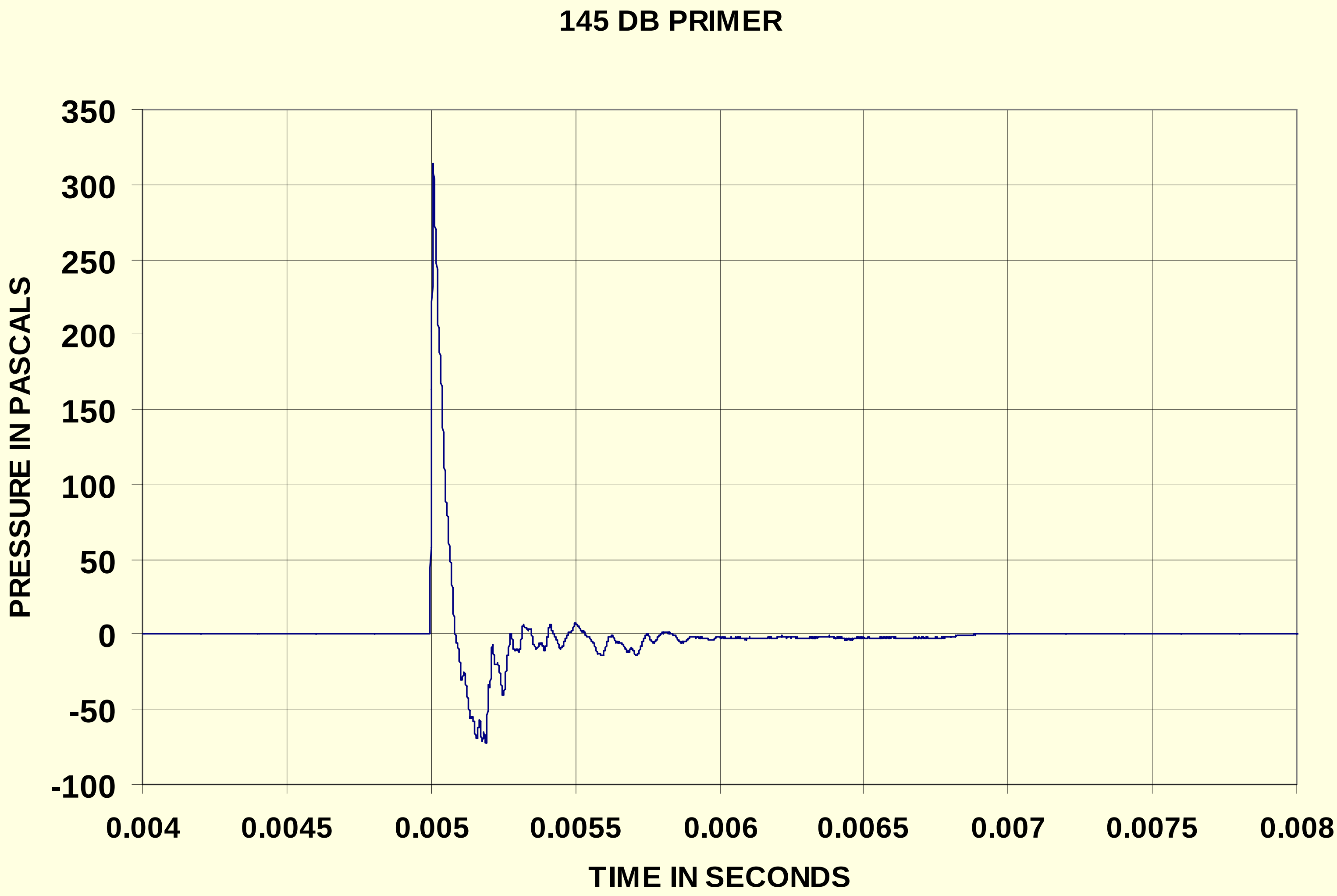
Validation of AHAA - CAT

- Real ears tested (cat)
- Groups of 10 (2 ears tested)
- Electrophysiological measures of hearing used (BSER)
  - Etymotic headphone used
  - 1, 2, 4, 8, 16 kHz tested
- Animals anesthetized for exposure and test
  - Immobilized
  - Eliminated acoustic reflex

Validation

- Wide range of impulses challenged model
  - Primer impulses - predicted maximum susceptibility
    - **Peak pressures 135, 140, 145 dB**
    - **50 impulses**

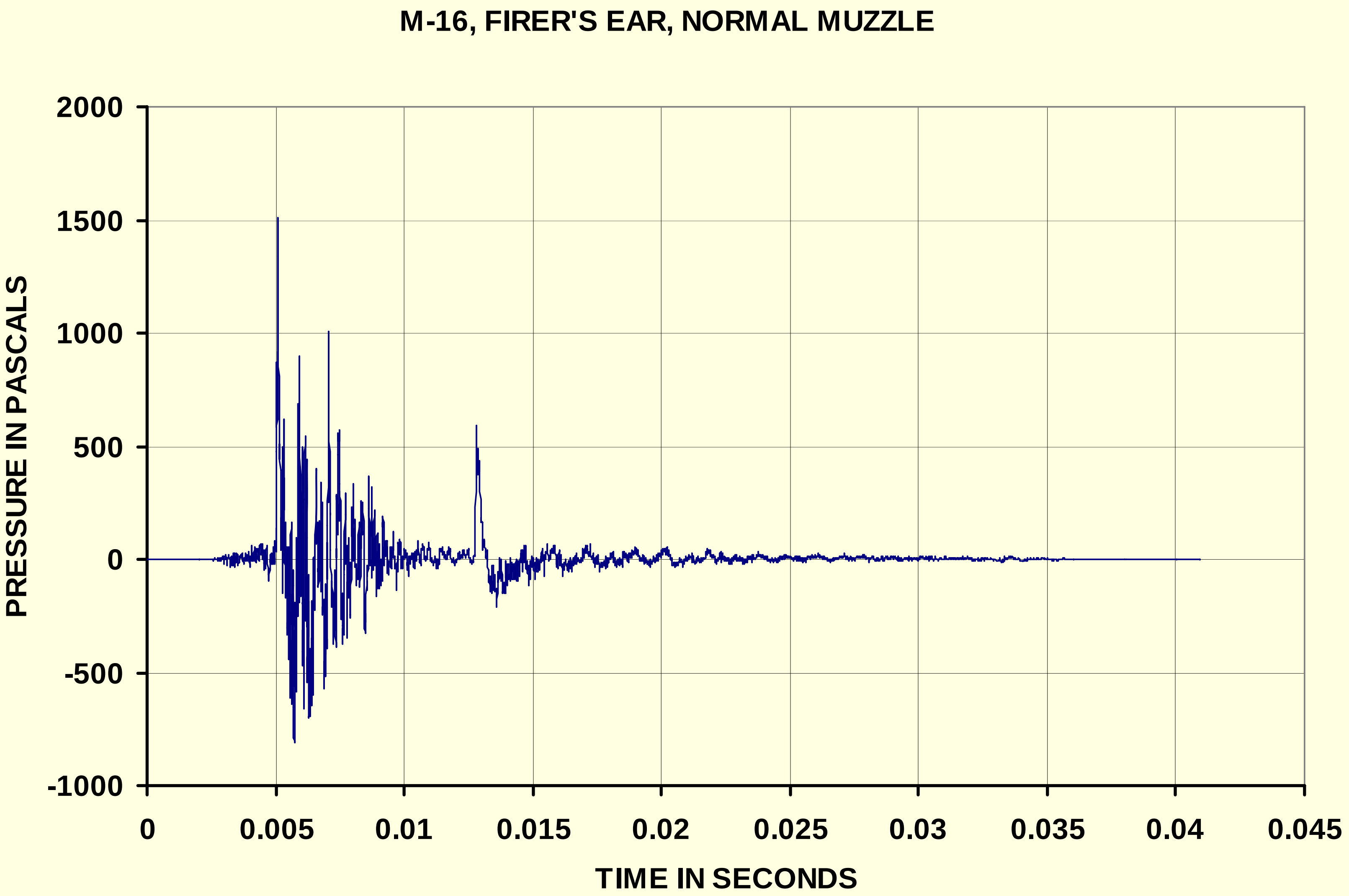
Validation Impulses



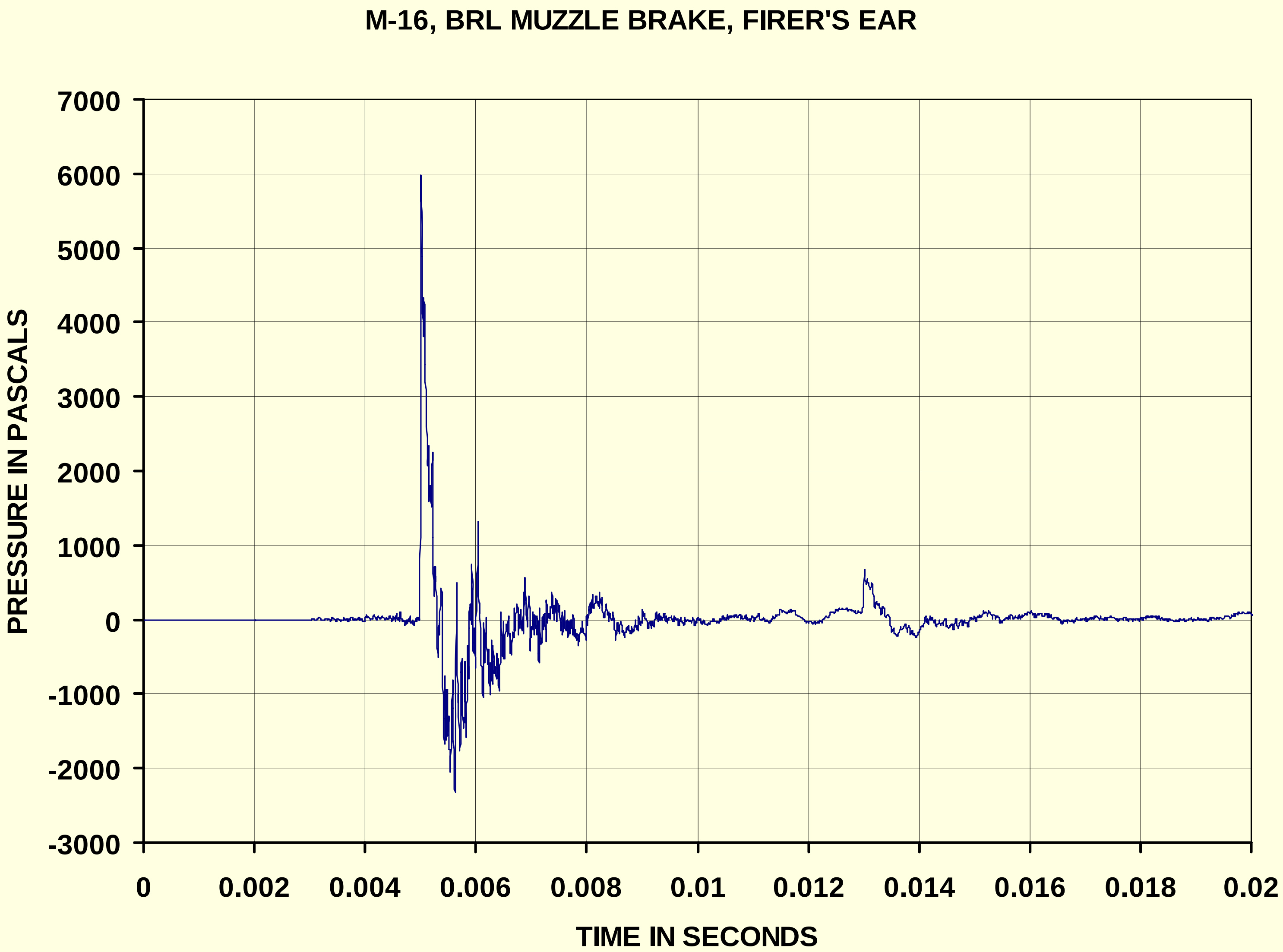
Validation

- Wide range of impulses challenged model
  - M-16 Rifle impulses
    - **At firer's ear**
      - **Normal muzzle - high peak, complex, 1 impulse**
      - **Muzzle brake - very high peak, 1 impulse**
      - **Same spectrum**
      - **8-10 times the energy in the high peak**

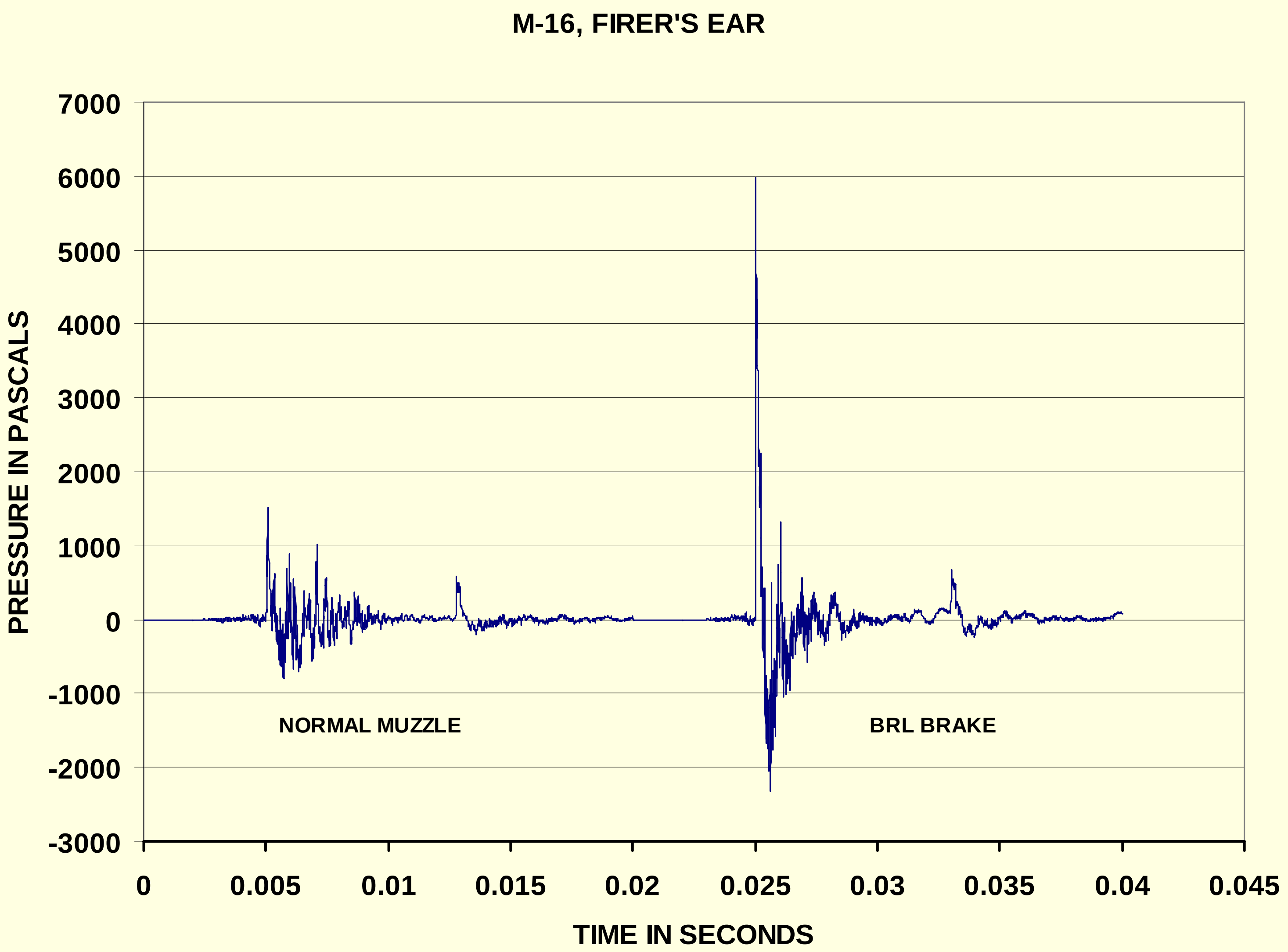
Validation Impulses



Validation Impulses



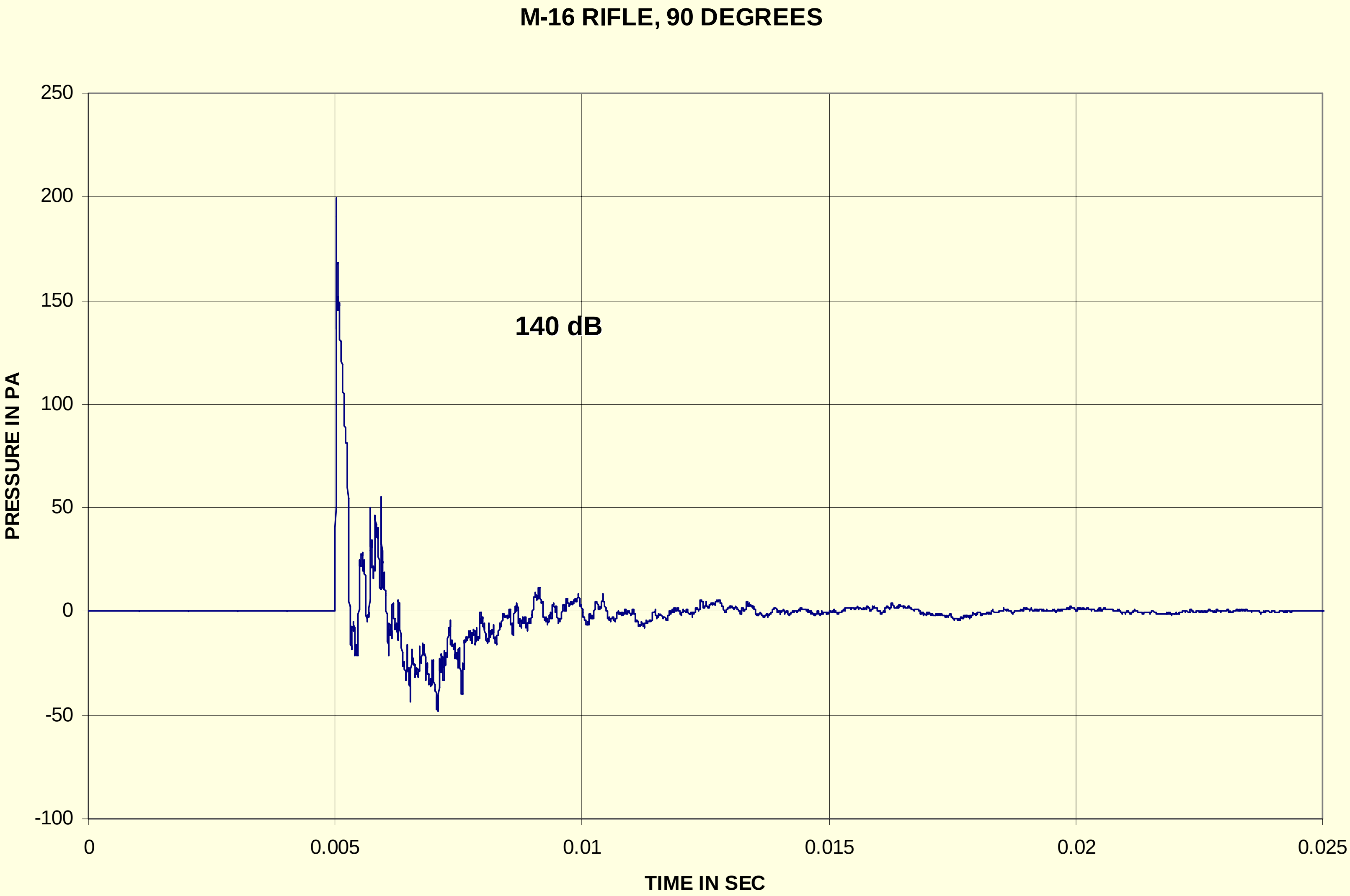
Validation Impulses



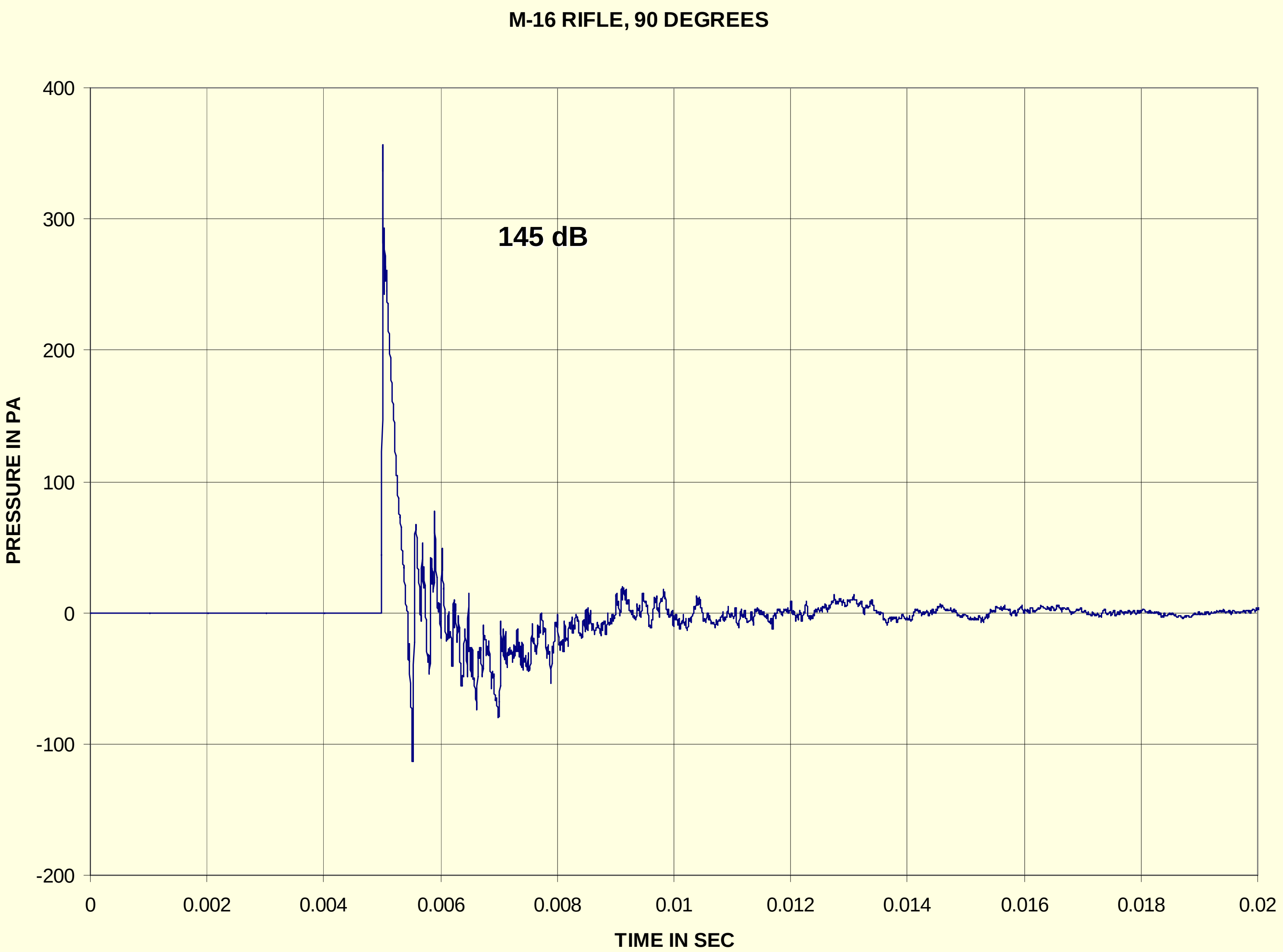
Validation

- Wide range of impulses challenged model
  - M-16 Rifle impulses
    - At 90 degrees
      - 140 dB peak, 50 rounds
      - 145 dB peak, 50 rounds

Validation Impulses



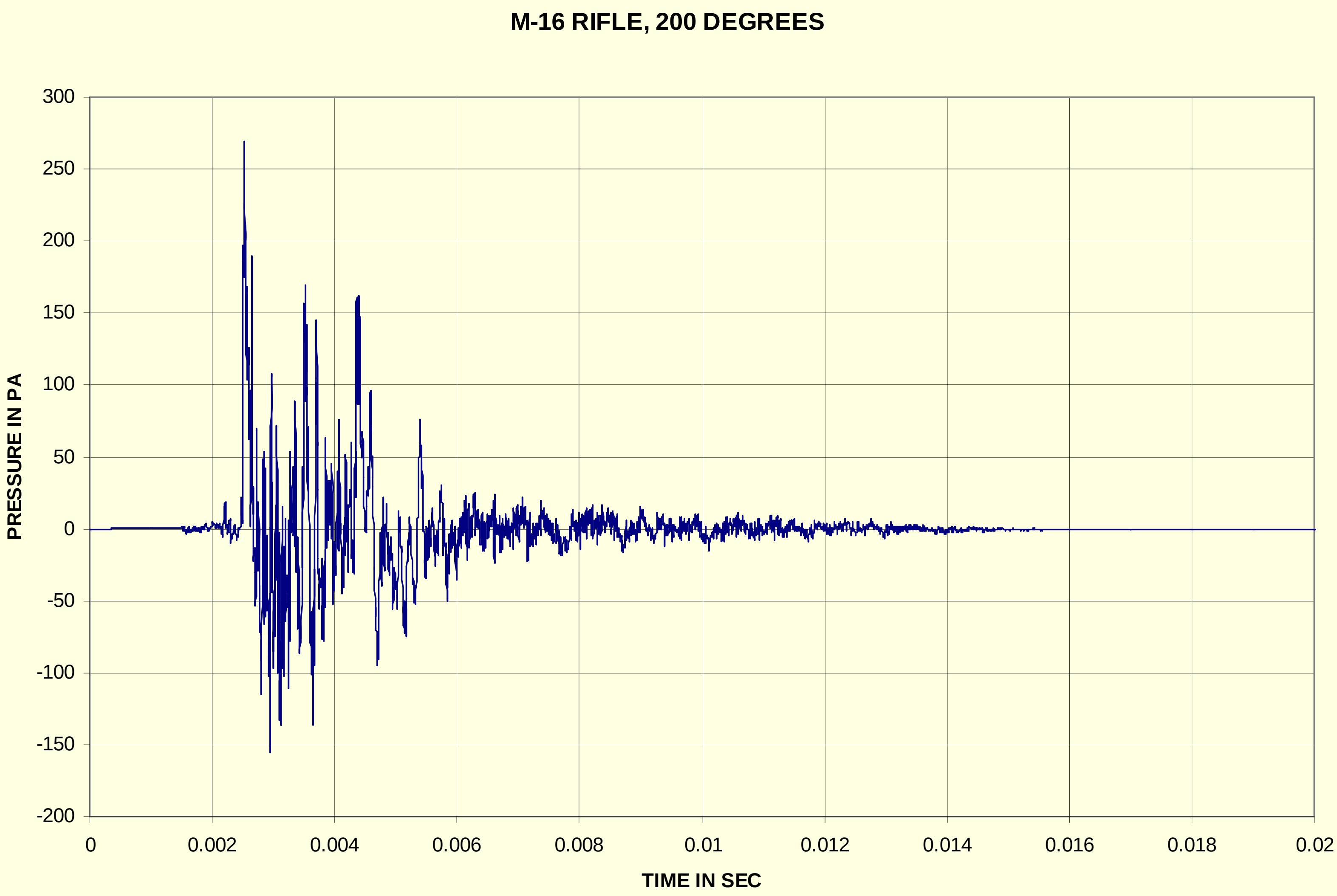
Validation Impulses



Validation

- Wide range of impulses challenged model
  - M-16 Rifle impulses
    - **At 200 degrees**
      - **142 dB peak**
      - **Complex wave**
      - **6 and 12 rounds**

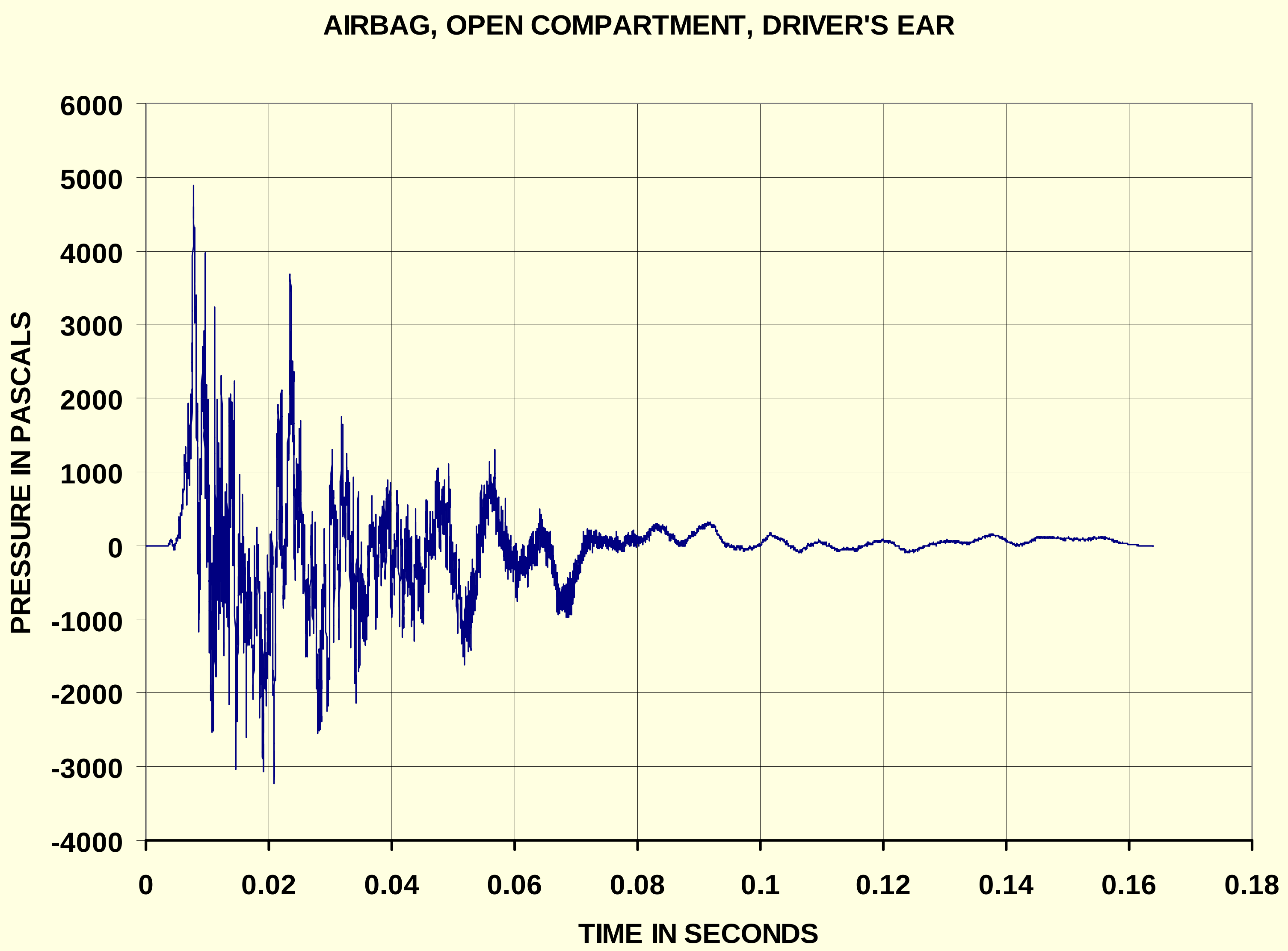
Validation Impulses



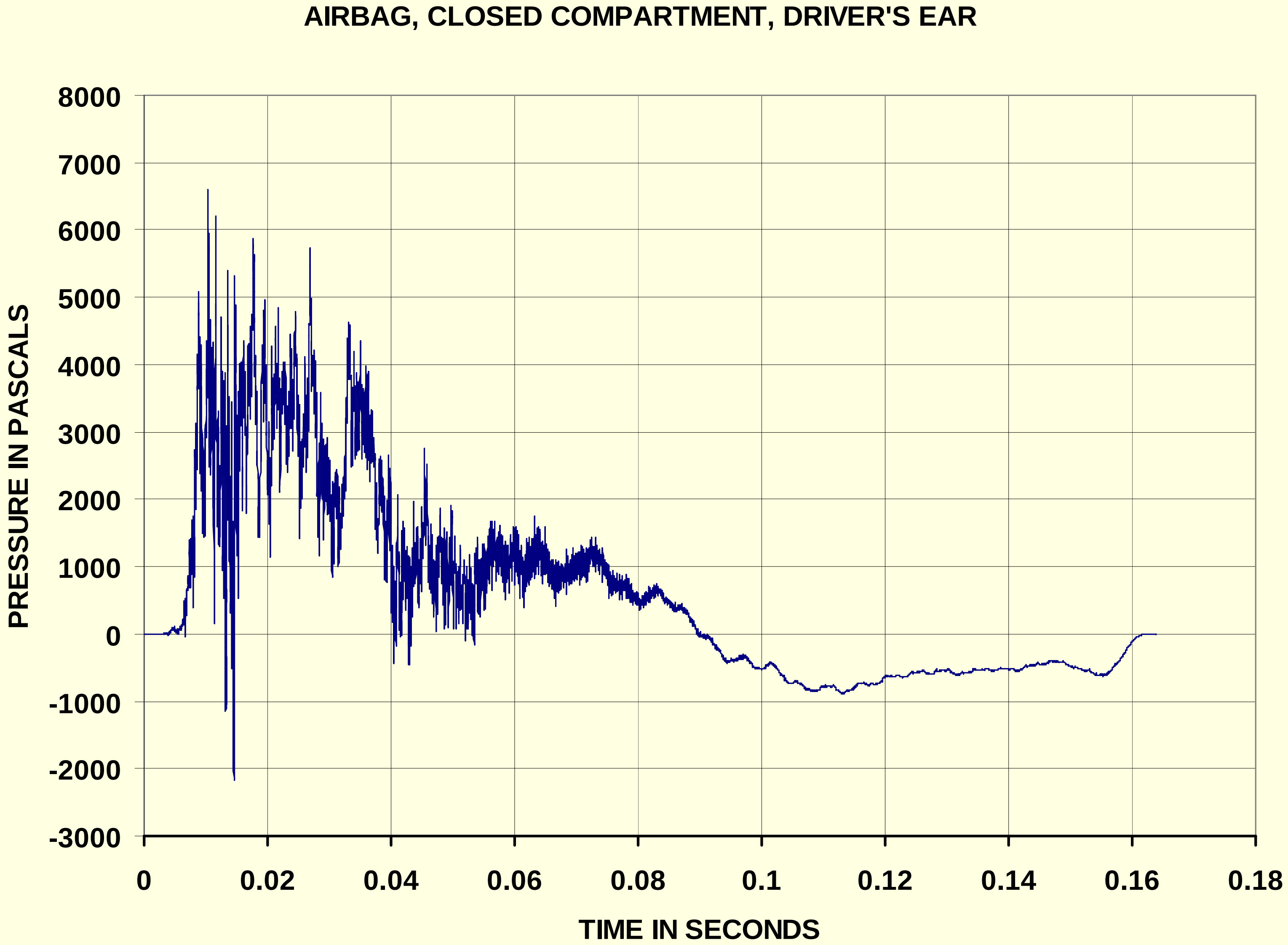
Validation

- Wide range of impulses challenged model
  - Airbags
    - **Open compartment**
    - **Closed compartment**
    - **Sealed compartment**
    - **One deployment**

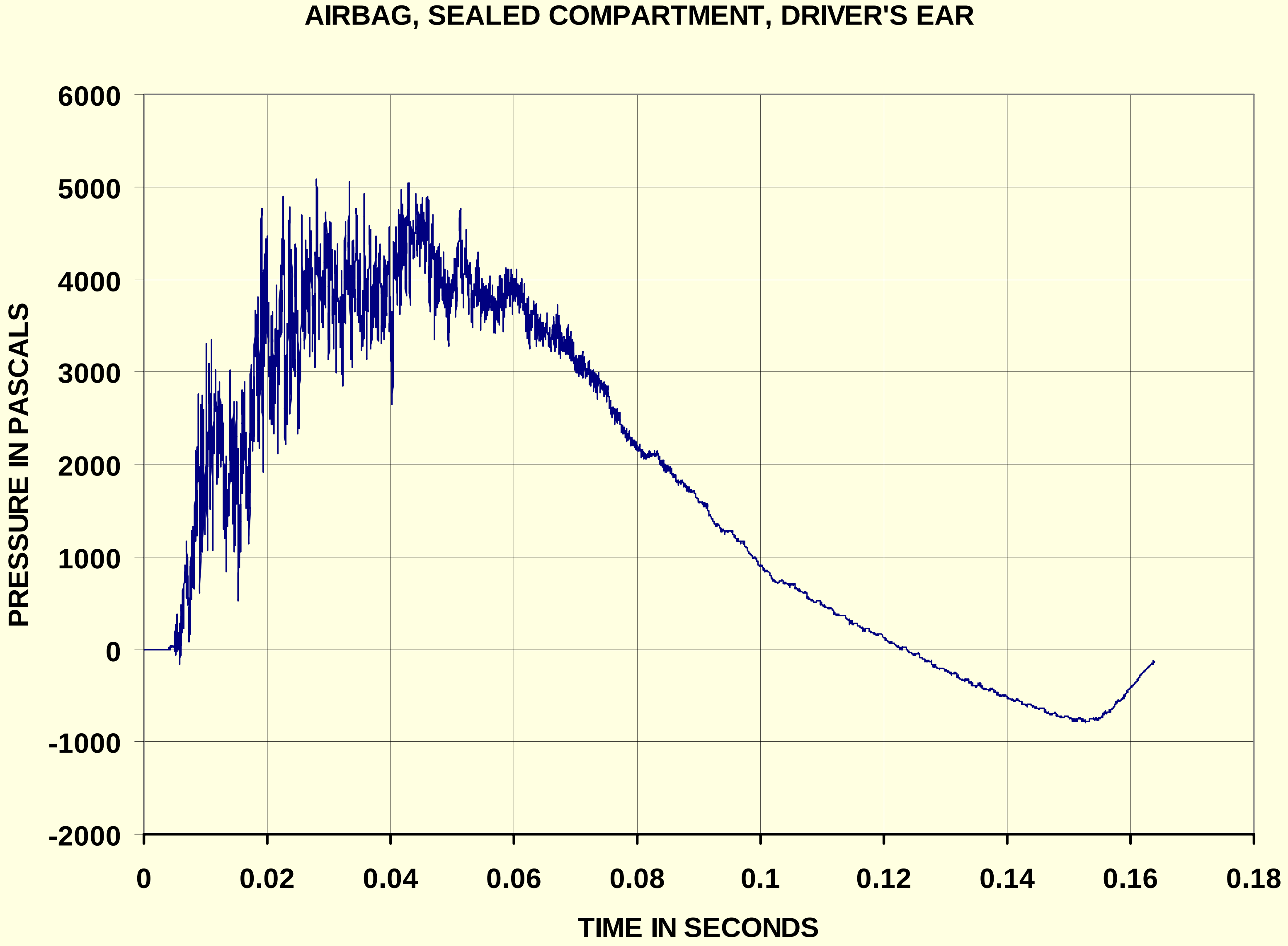
Validation Impulses



Validation Impulses



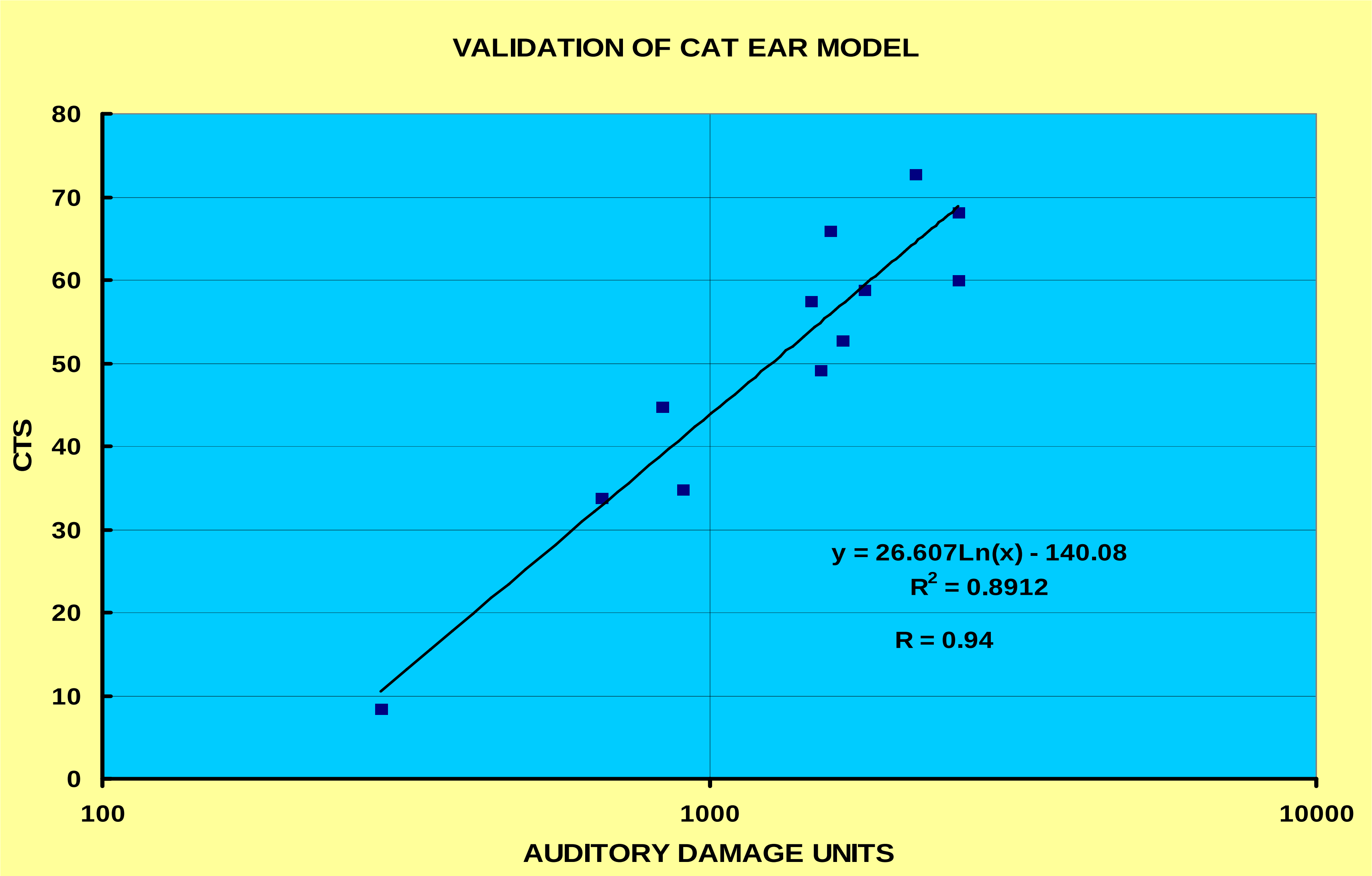
Validation Impulses



Validation Data: Prediction of CTS

- Mean data for group reported
- At frequency of maximum threshold shift (usually 4.0 kHz)
- Shift measured at about 1/2 hour (first measure)
- 12 Different exposures
  - 135 - 170 dB peak
  - 1, 6, 12, 50 impulses

Validation of Cat Ear Model



Validation

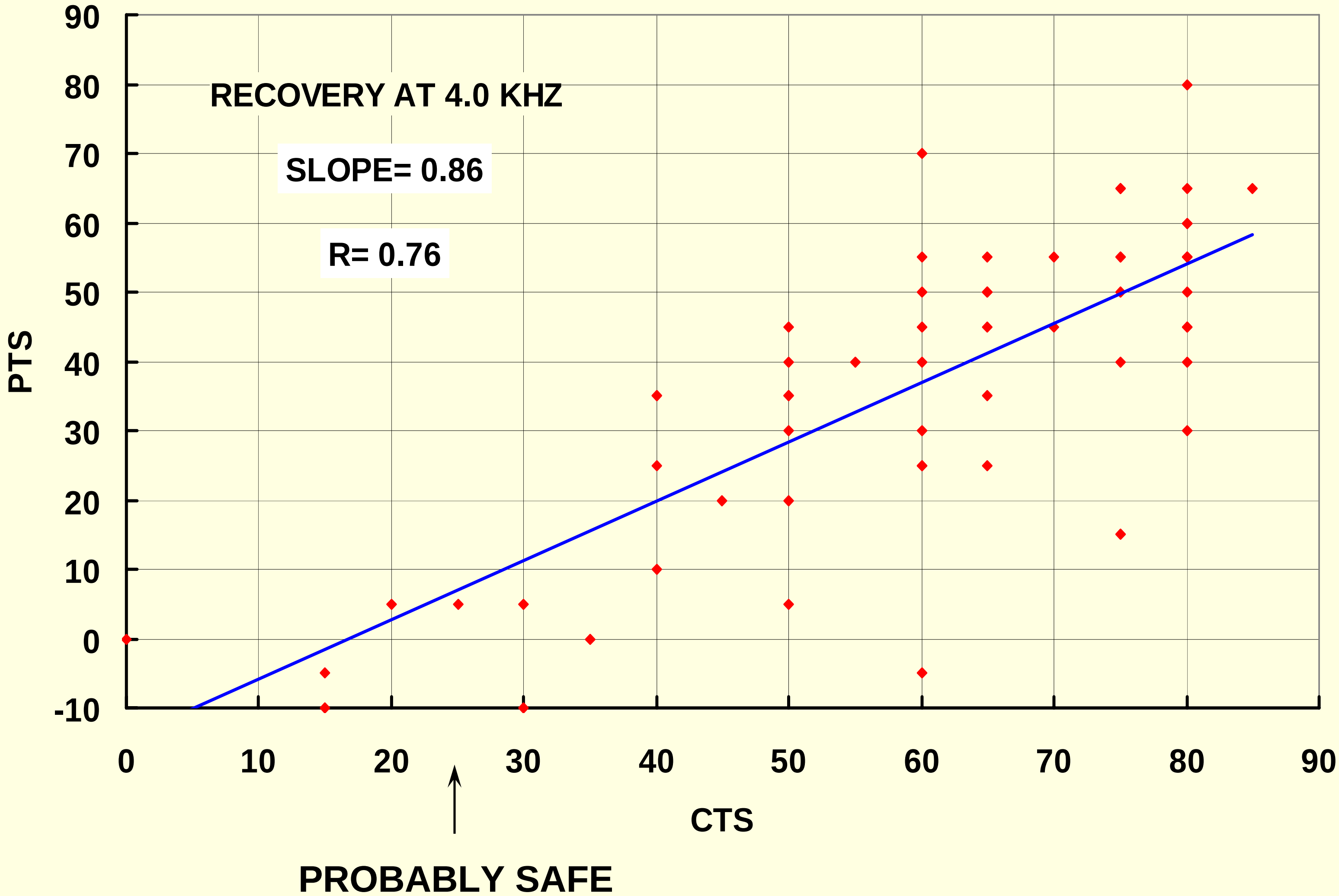
- Correlation <u>very</u> high - little variance left to explain
- Note equation relating CTS to ADUs:

$$CTS = (26.6 \times LN\ ADUs) - 140.1$$

Validation Results
CTS-PTS

- Animals allowed to recover one - two months
- Retested (same procedure)
- Next slide shows relationship between CTS and PTS for airbag experiments
- Data points represent one ear at 4.0 kHz
- Data are “typical” for this type plot

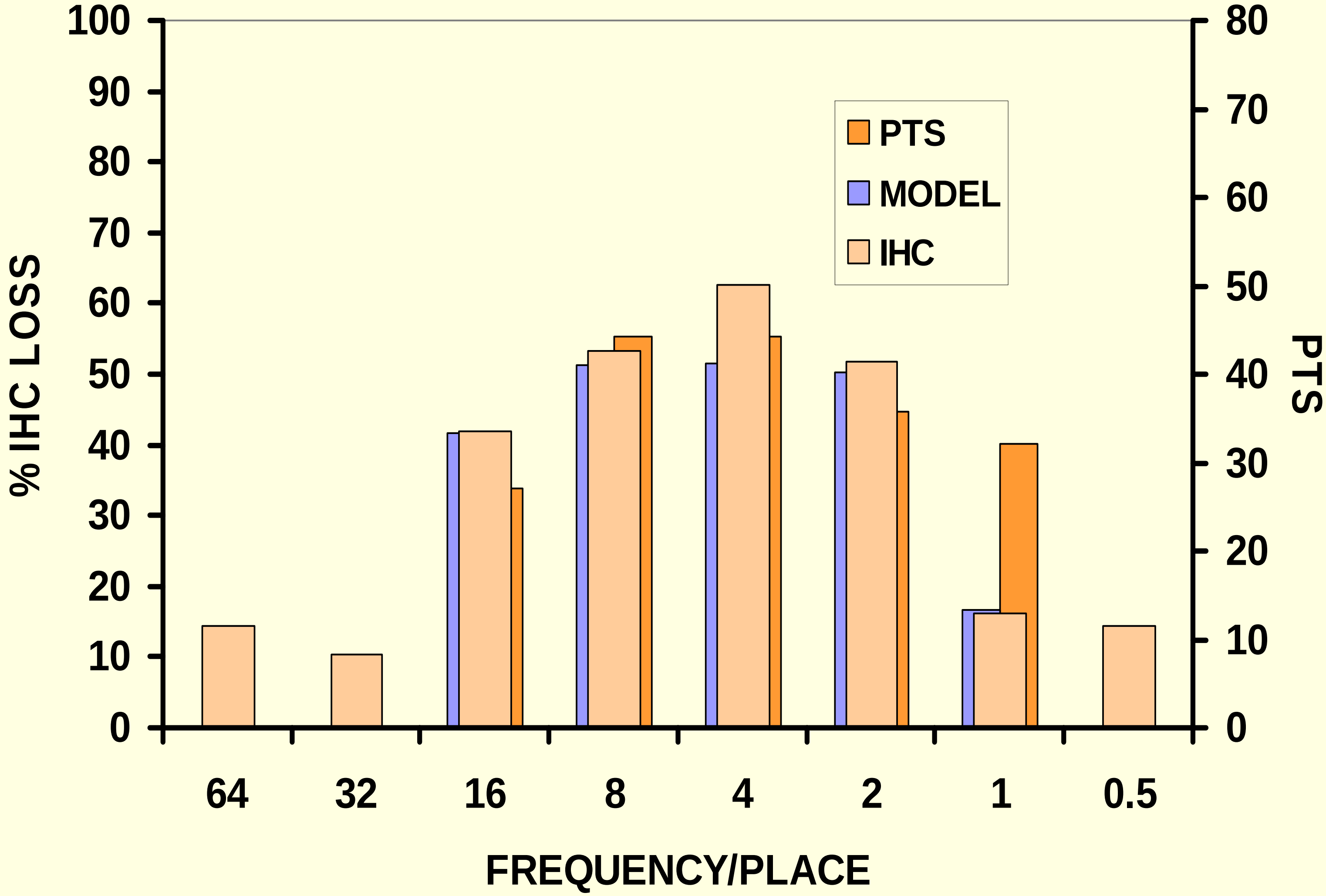
CTS-PTS Relationship



Validation Results
Histology (Location of Damage)

- On airbag tests, had CTS, PTS and histology on 16 ears
- Animals retested and sacrificed at 1 month.
- Model predicted location and amount of loss
  - Location on “dead” cochlea
  - CTS corrected to PTS (on basis of previous chart)
- Inner hair cell loss plotted (OHC similar, more loss as expected)

Location of Damage



So In The End

- ADUs predict CTS
- ADUs predict PTS
- ADUs predict hair cell loss
- Most variance explained

CONCLUSION:

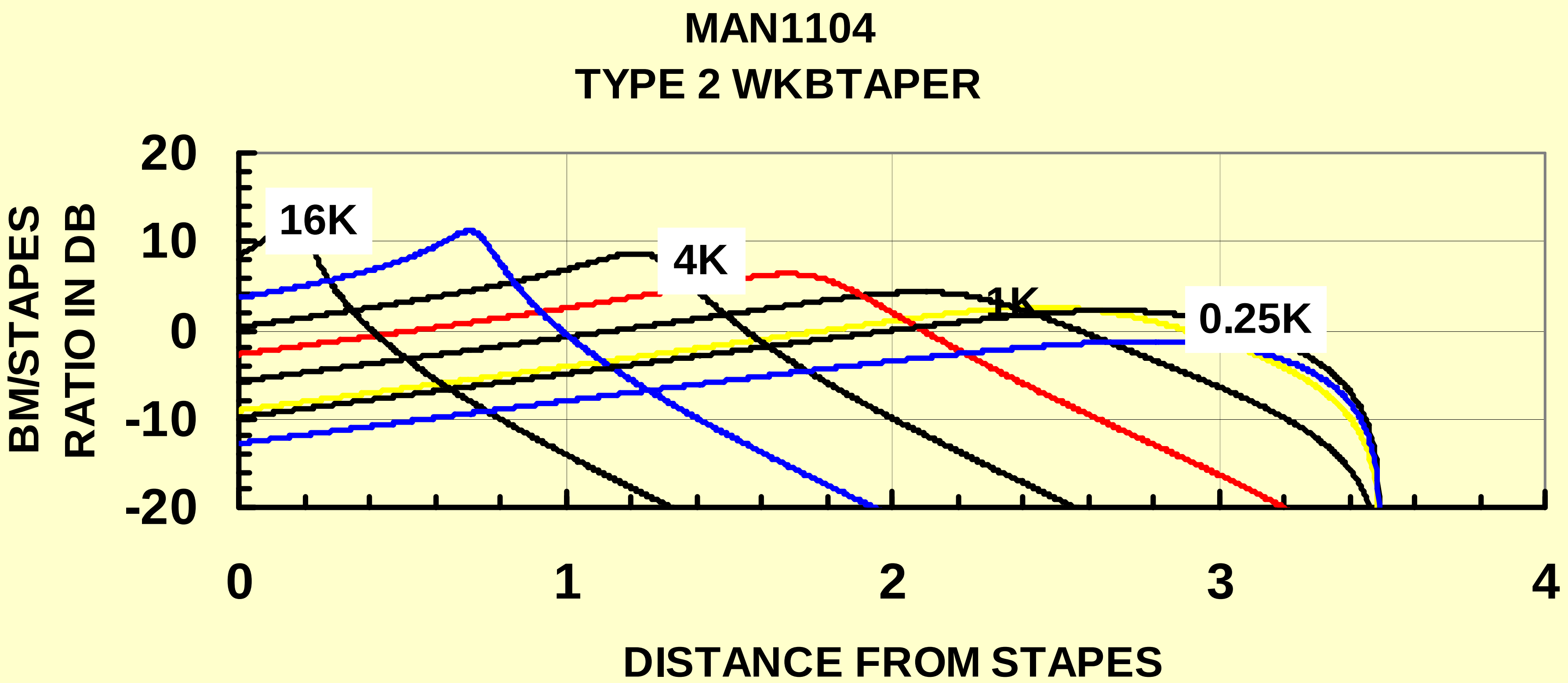
MODEL IS FUNDAMENTALLY READY!

Making the Human Model

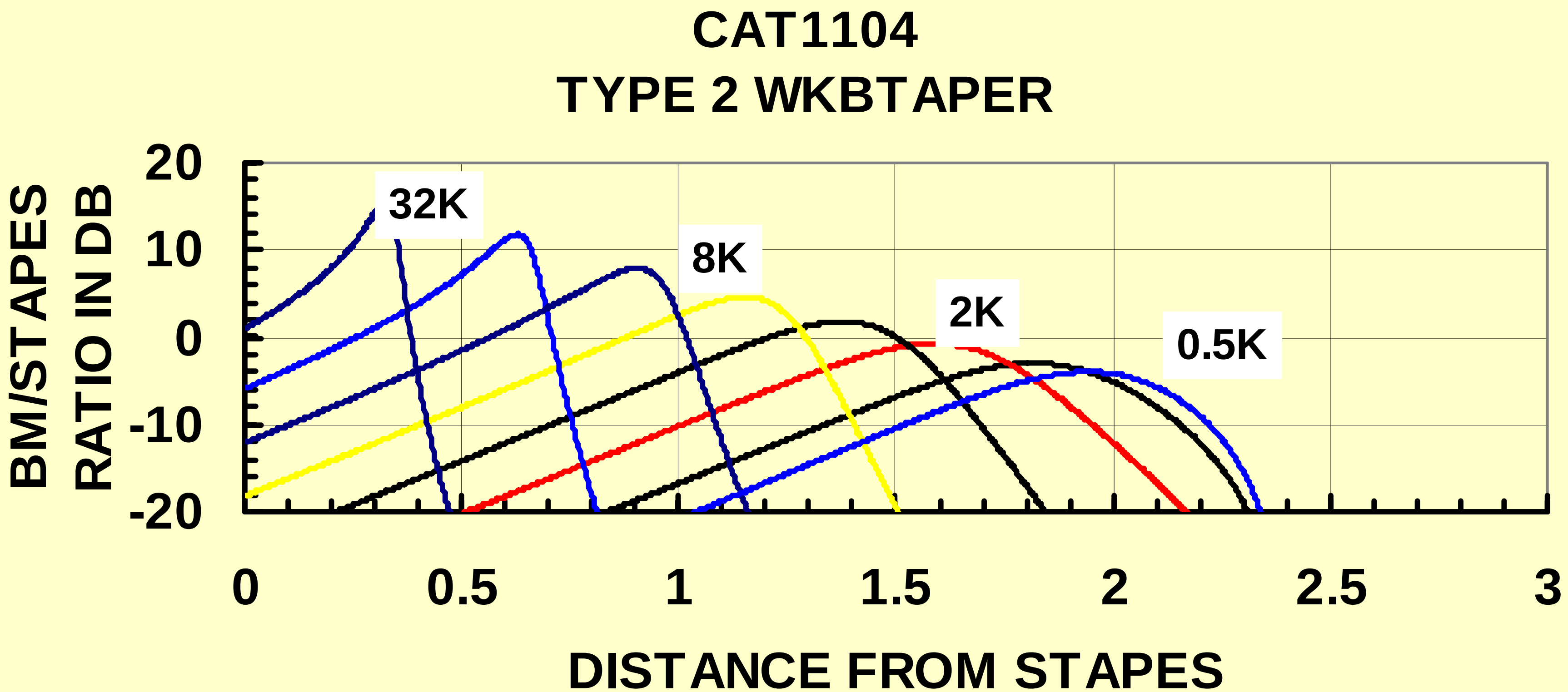
- **Assume that in most sensitive range, the stapes to basilar membrane displacement ratio is the same for cat and man.**
- **Adjust middle ear muscle effect to “moderately strong” (similar to effect in cat)**
- **Susceptibility: Modeled as an effective increase in sensitivity with a 6 dB SD, I.e. SPL increased 10 dB for 95th percentile ear.**

Making the Human Model

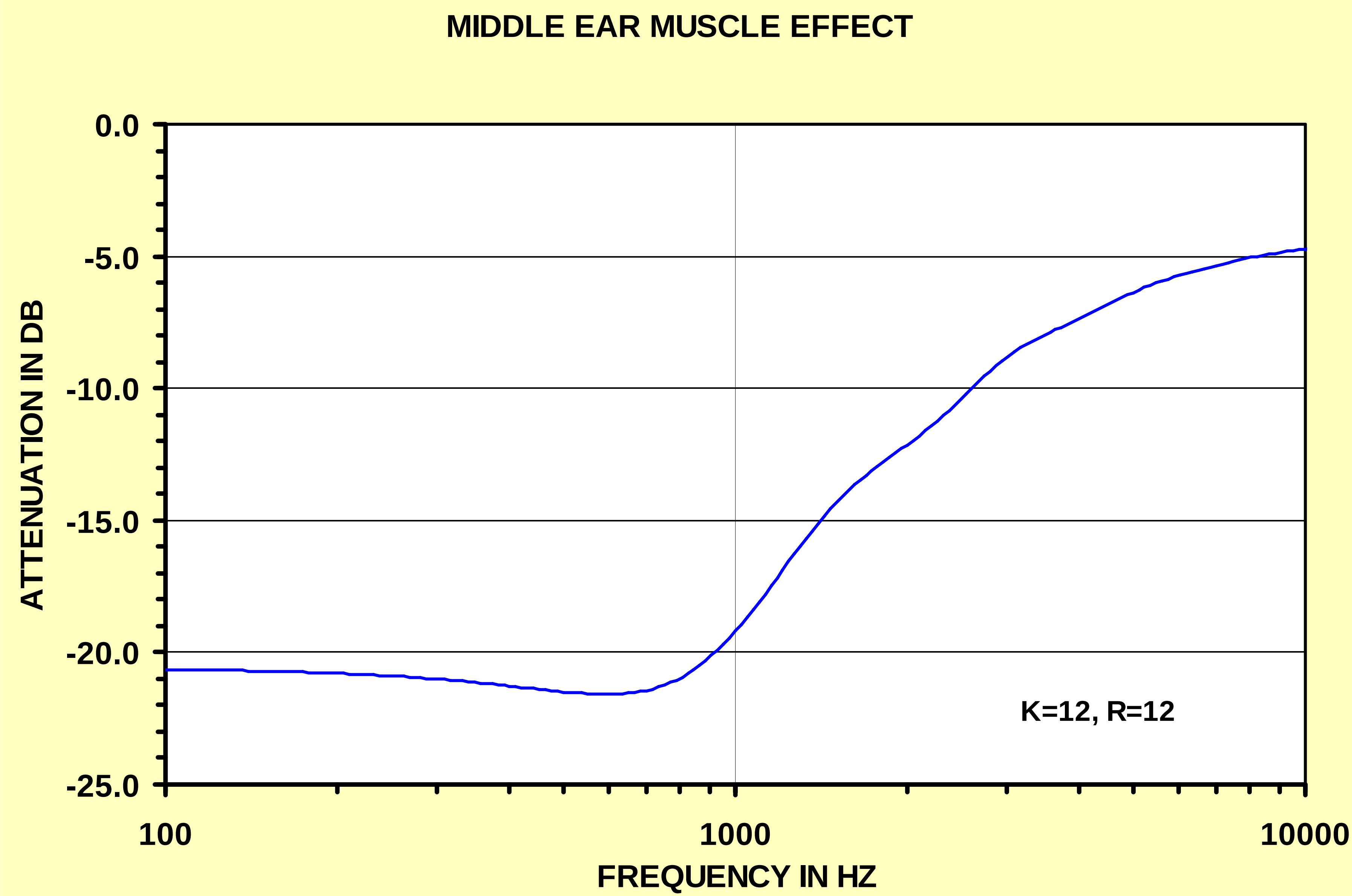
- Model design fixed (02/26/98) before human data run through it
- Human hearing loss data not used in setting model parameters



MAN1104
TYPE 2 WKBTAPER
BM/STAPES RATIO IN DB
20
10
0
-10
-20
16K
4K
1K
0.25K
0
1
2
3
4
DISTANCE FROM STAPES



CAT1104
TYPE 2 WKBTAPER
BM/STAPES RATIO IN DB
20
10
0
-10
-20
32K
8K
2K
0.5K
0
0.5
1
1.5
2
2.5
3
DISTANCE FROM STAPES


MIDDLE EAR MUSCLE EFFECT
0.0
-5.0
-10.0
-15.0
-20.0
-25.0
ATTENUATION IN DB
K=12, R=12
100
1000
10000
FREQUENCY IN HZ

Modeling “Susceptibility”

- For the susceptible ear, it is as though it were stimulated by a more intense impulse
- Assume susceptibility normally distributed with 6dB SD
- Operationally, raise SPL of impulse 10 dB and recalculate ADUs

Validation of Human Model

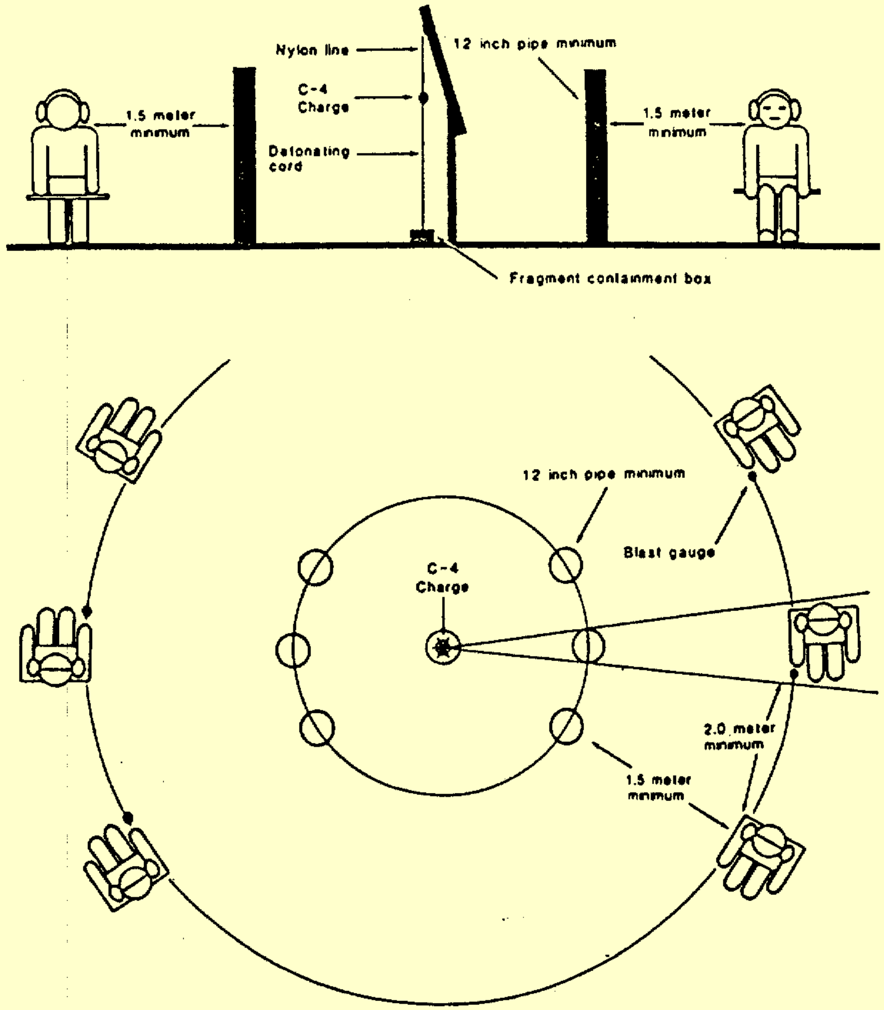
- Model's hazard prediction had been developed with cat noise exposures
- Model adapted to human scale
- Model to be tested with human hearing loss data (data sets not used in the development of the model)
- Adjustment to follow as needed to refine and improve model

Validation of AHAAH
Exposures with the Human Ear

The U. S. Army Albuquerque Studies

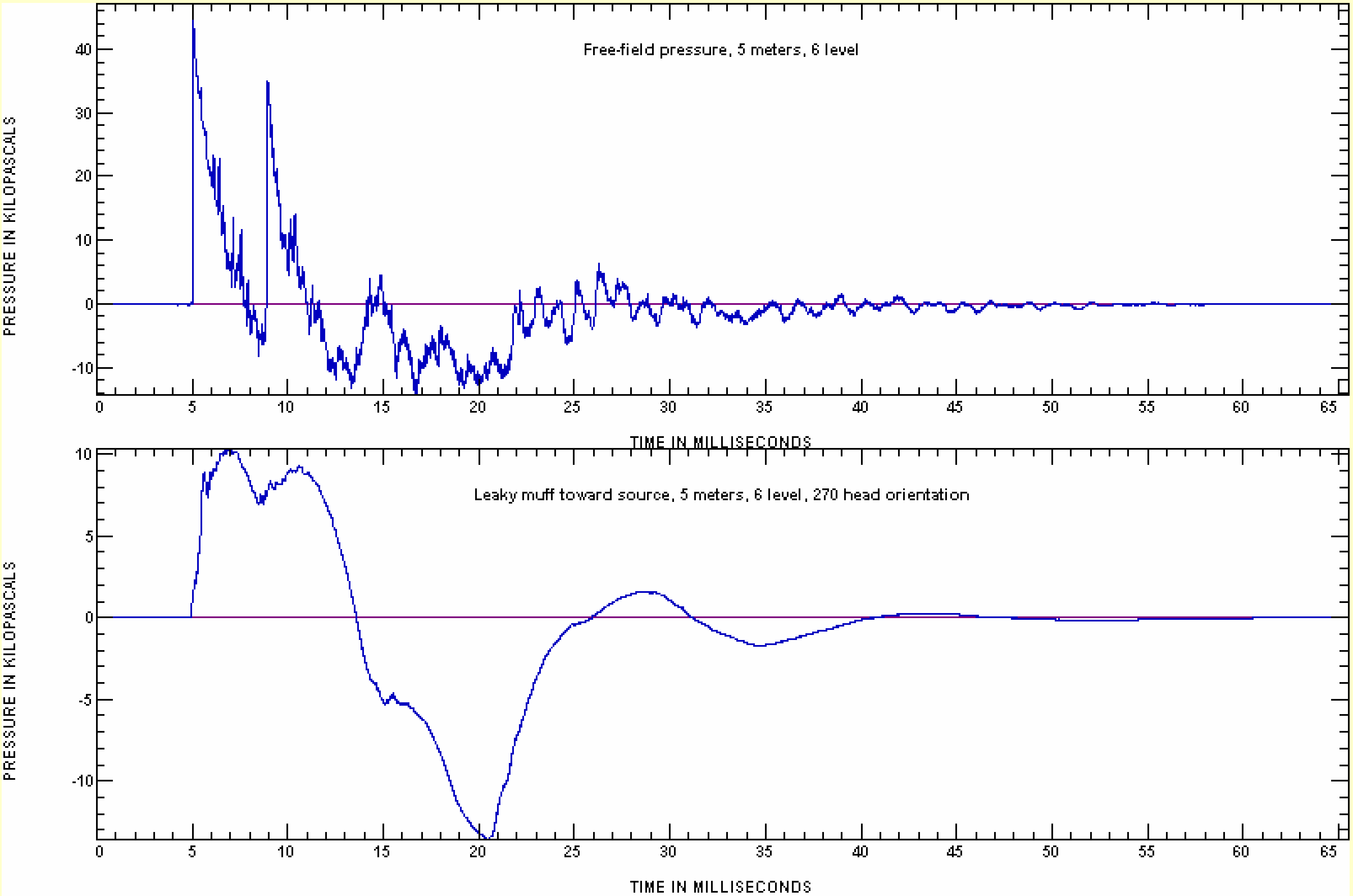
The Albuquerque Studies

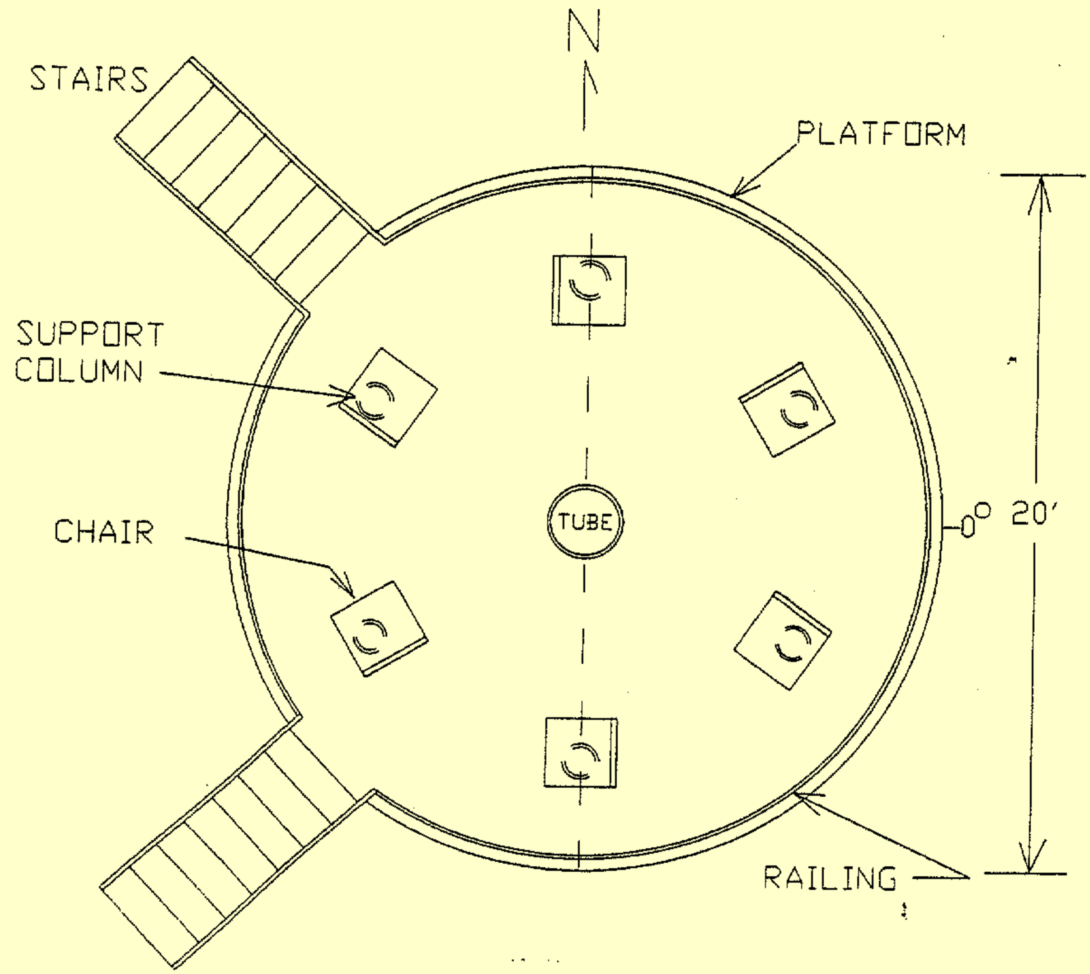
- Aimed at definitive test of human tolerance to intense sound - both auditory and non-auditory
- Custom facility built for purpose
- Explosive sources used to simulate large caliber weapons
- 3 types of impulse in free field
  - A-durations of 2.9, 1.4 and .8 msec
  - Simulating gunfire in free field
- 1 reverberant impulse (rocket in bunker simulation)



LAYOUT OF 5 METER EXPOSURE APPARATUS

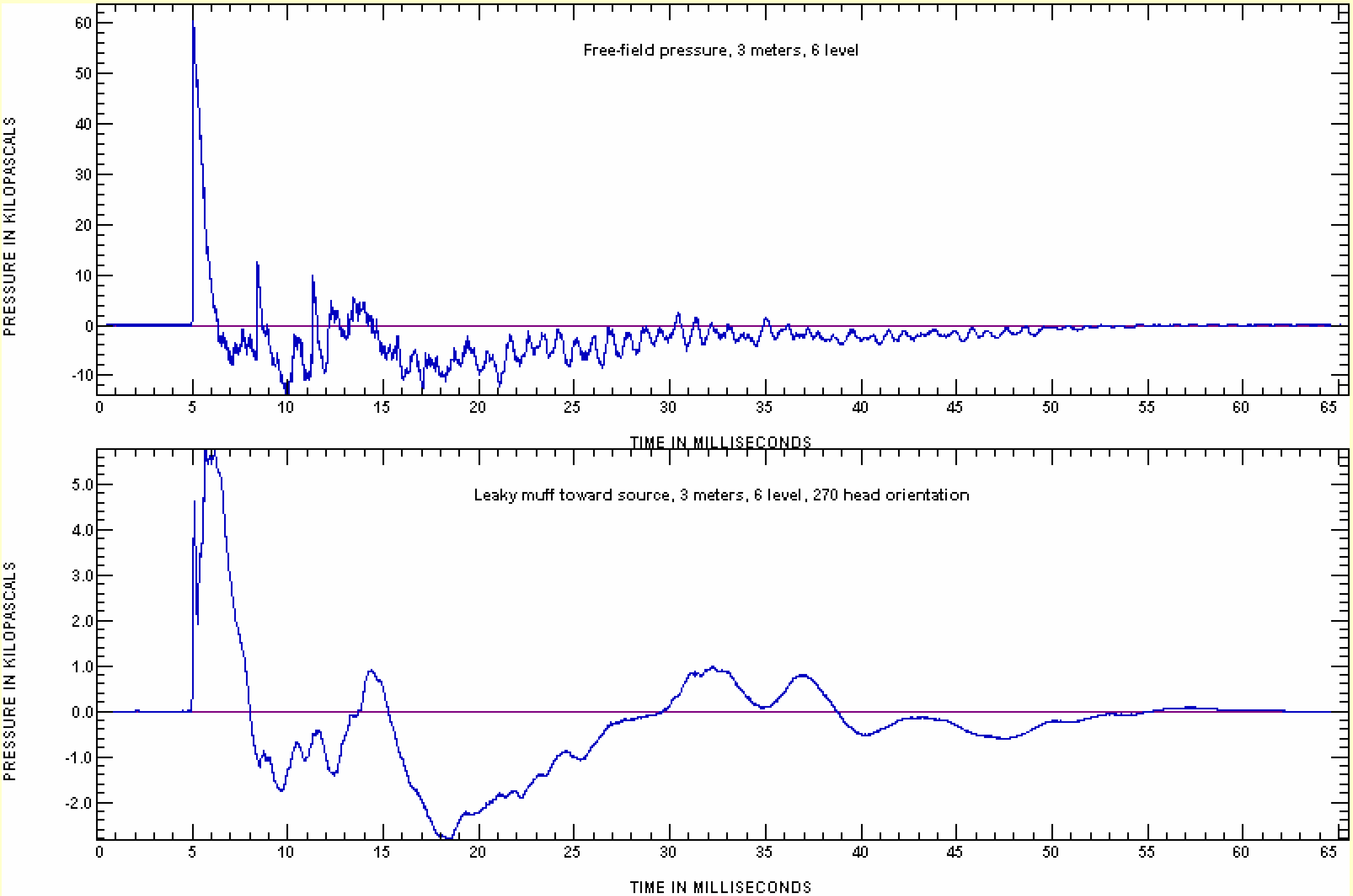
5 Meter Impulse

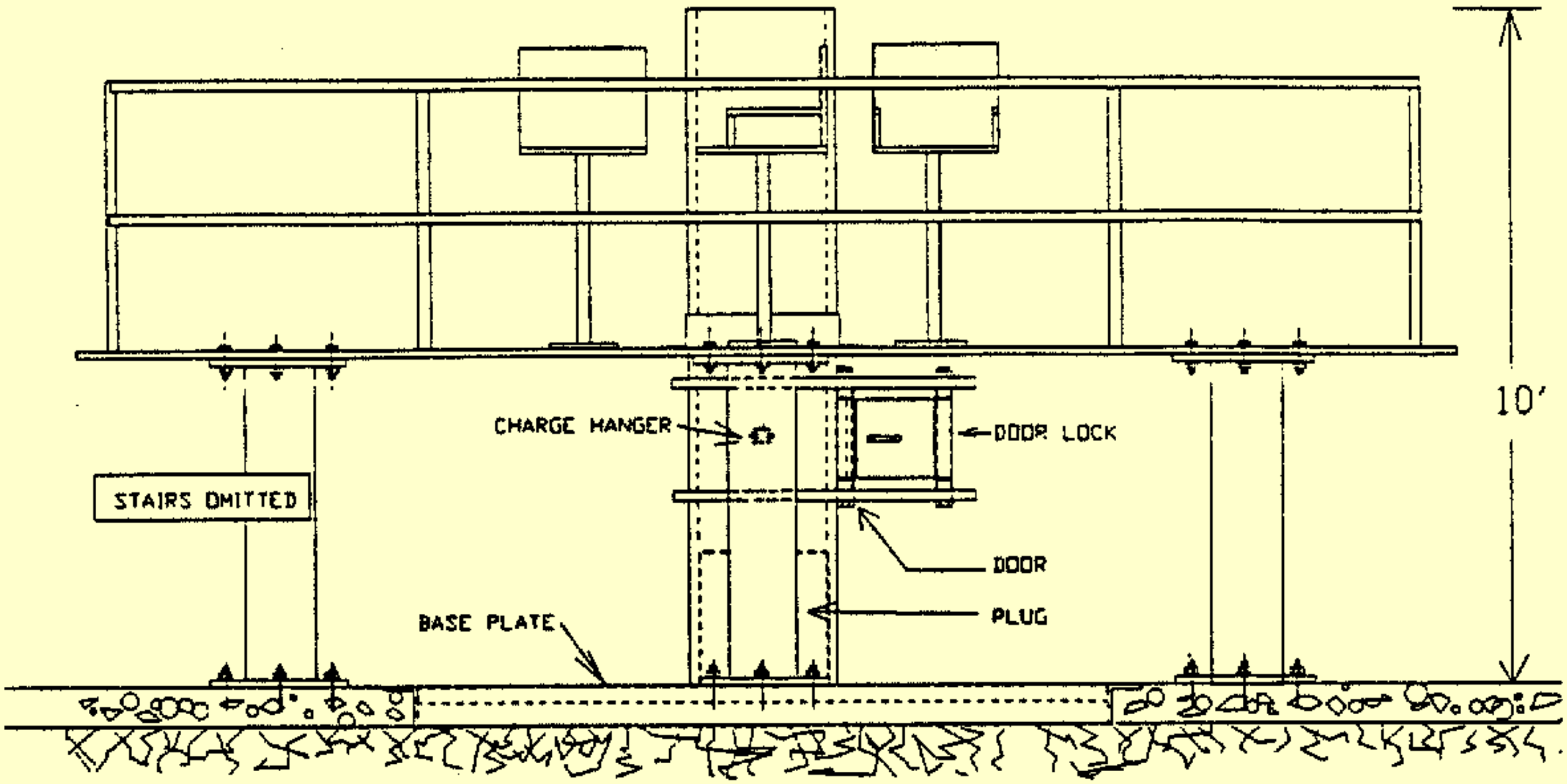




TOP VIEW, 3 METER EXPOSURE DEVICE ("MORTAR")

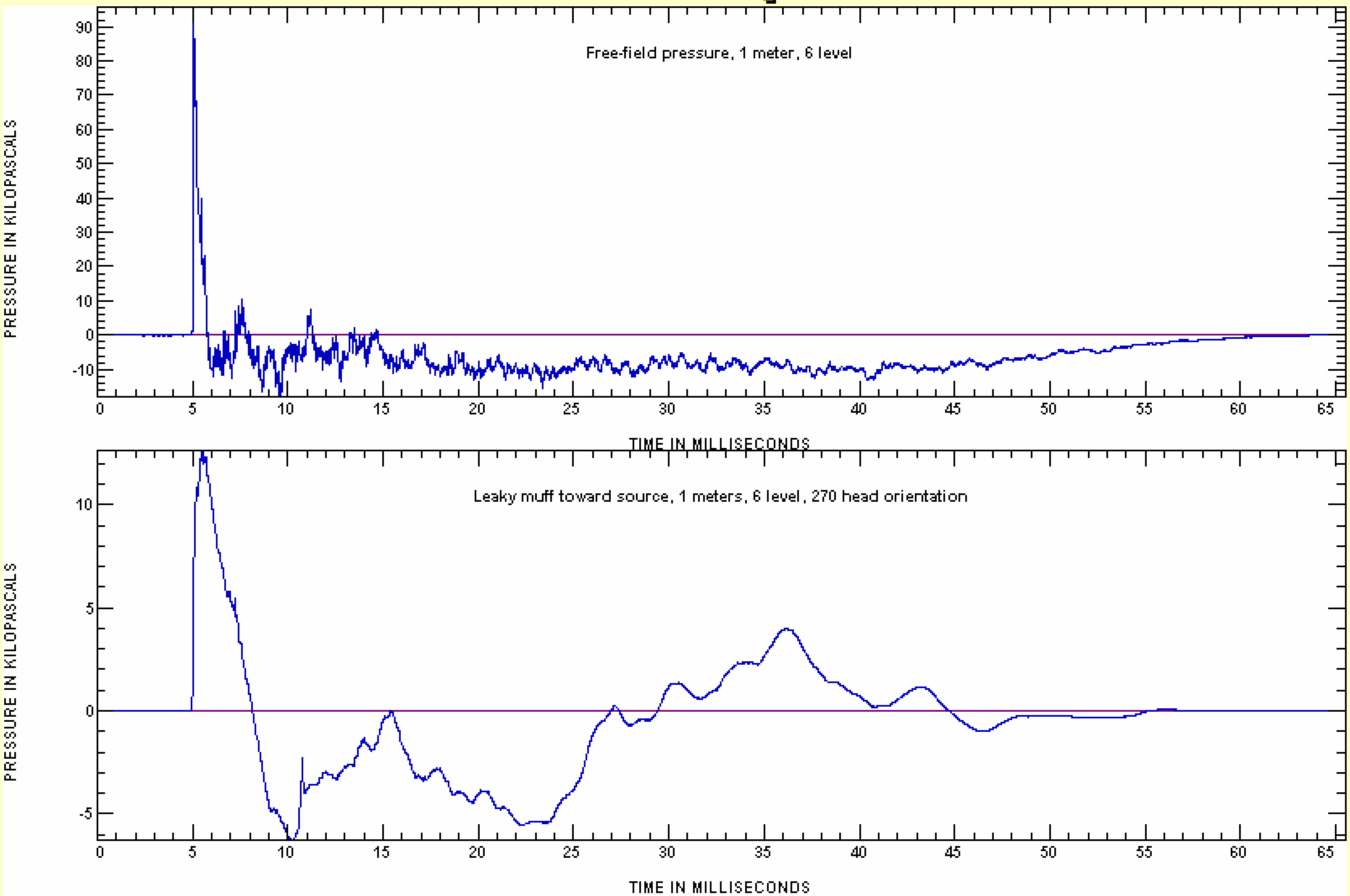
3 Meter Impulse

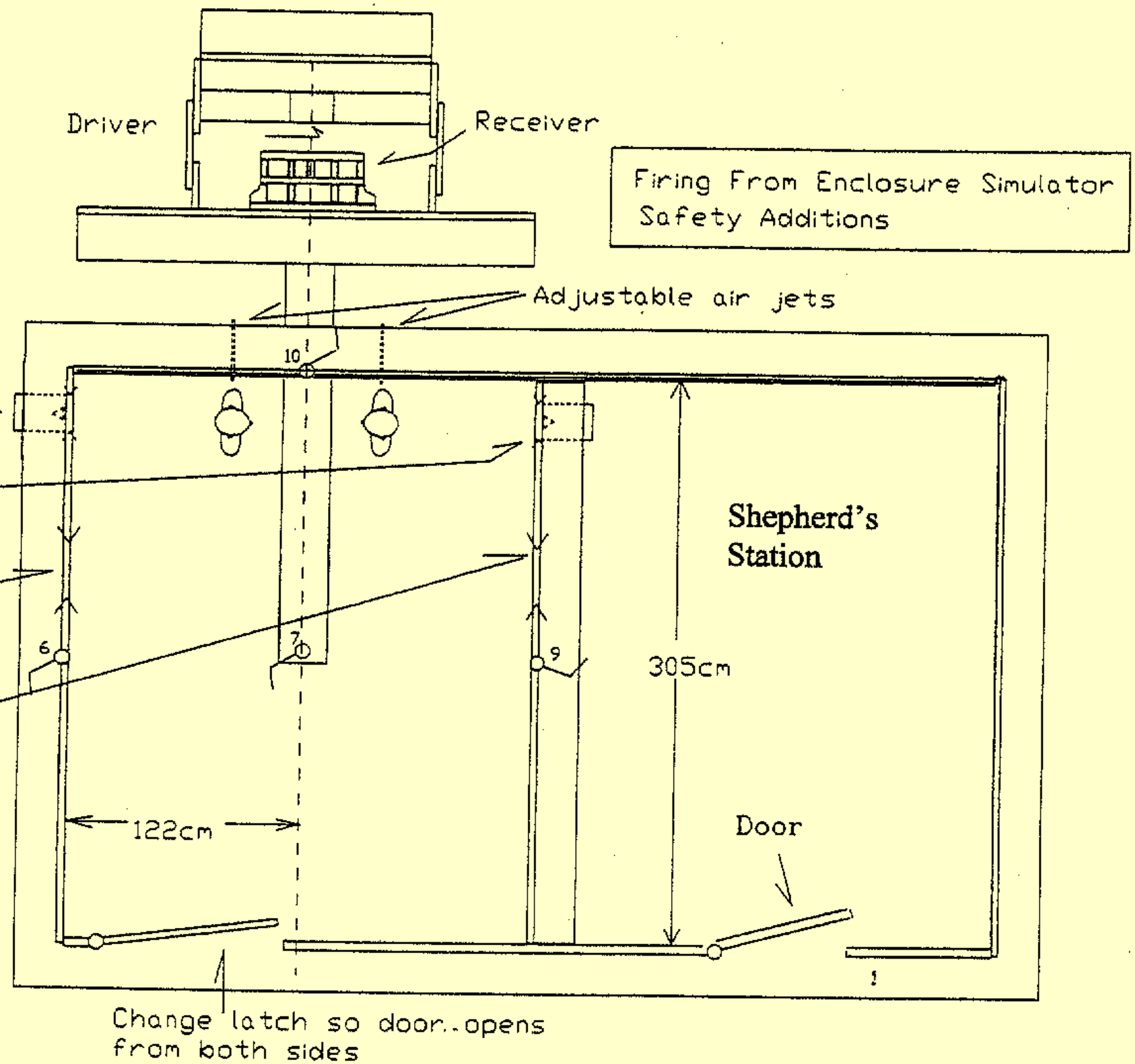




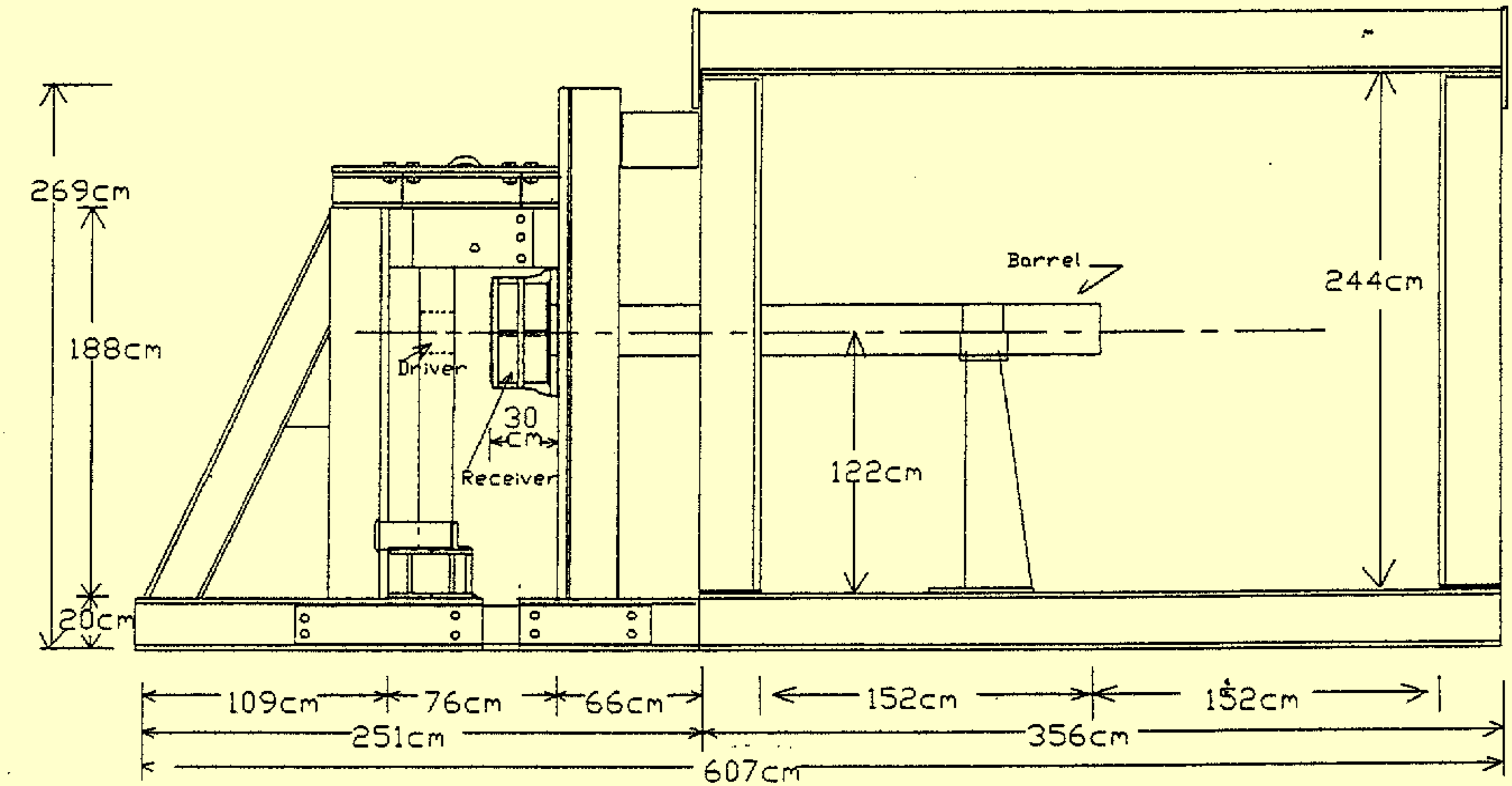
SIDE VIEW, 1 METER EXPOSURE DEVICE ("MORTAR")

1 Meter Impulse



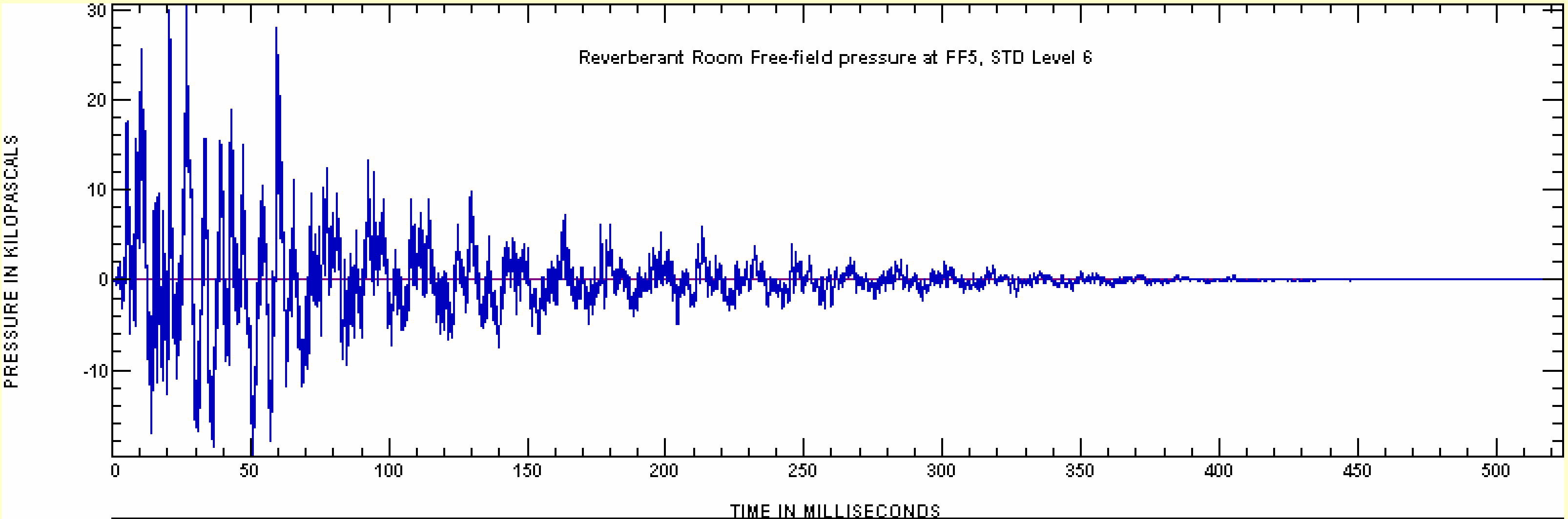


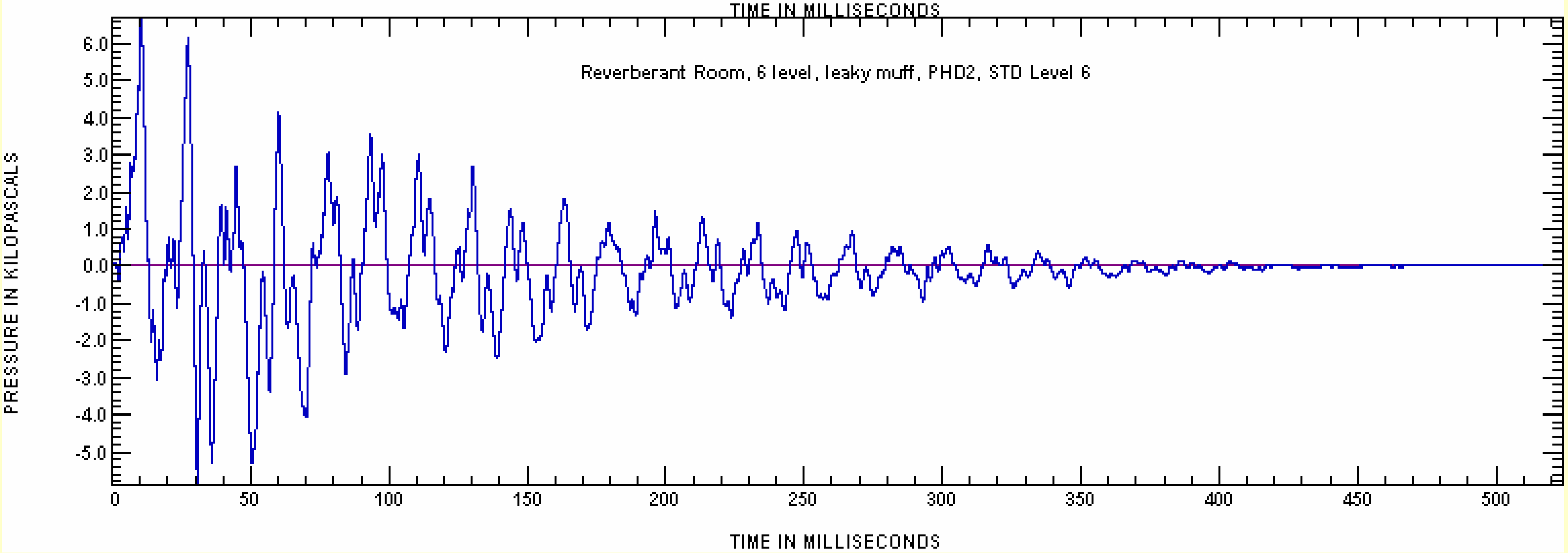
TOP VIEW, REVERBERANT EXPOSURE CHAMBER



SIDE VIEW, REVERBERANT EXPOSURE CHAMBER

Reverberant Impulse





The Albuquerque Studies

- 7 levels per impulse (up to 194+ dB peak free field in 3 dB steps)
- 6, 12, 25, 50, 100 round exposures
- One impulse per minute rate
- RACAL muff first level protection
  - Good but not wonderful attenuation
  - Fit under helmet
  - Had peak-limited talk-through circuit
- Count-down to exposure (Necessary!)

The Albuquerque Studies

- Audiometry
  - Automated
  - Baselines clearly established
  - Repeatability very high
  - Tested just before, immediately afterward and followed until recovery
  - Pre- test had to match baseline

The Albuquerque Studies

- Right ear exposed under muff, normal incidence
- Left had double protection, shadowed
- Protection fitted and checked
- Aimed at 60 subjects per condition
  - Interest in protecting 95%ile ear
  - Wanted 95% confidence, 95%ile ear tested
  - 95%ile ear found between 1 and 6 failures

The Albuquerque Studies

- Failure:
  - – Full auditory failure (> 25dB TS)
  - – Conditional failure (> 15 dB TS)
    - Implication that higher exposure might produce unacceptable TS
    - Next higher exposure not given

The Albuquerque Studies Exposure Paradigm

- Begin at low level, single protection, 6 impulses
- Proceed upward in level until a failure occurs
- Drop in level and go to next higher number of rounds.
- If highest level reached (level 7), drop back to Level 6 and go upward in number of rounds - 12, 25, 50, 100
- Go to double protection and continue

Pattern of Exposure

		NUMBER OF IMPULSES			
LEVEL	6	12	25	50	100
7		x	x	x	x
6					
5					
4					
3					
2					
1					

Pattern of Exposure

- Began with long A-duration impulse ("5 meter exposures")
- DRCs all predicted failure would occur
- Surprise outcome: NO Failures
- Strategic decision - defeat muff seal to simulate field fit and re-run study
- Muff had almost no attenuation below 1Khz, modest attenuation above

Defeated RACAL Muff

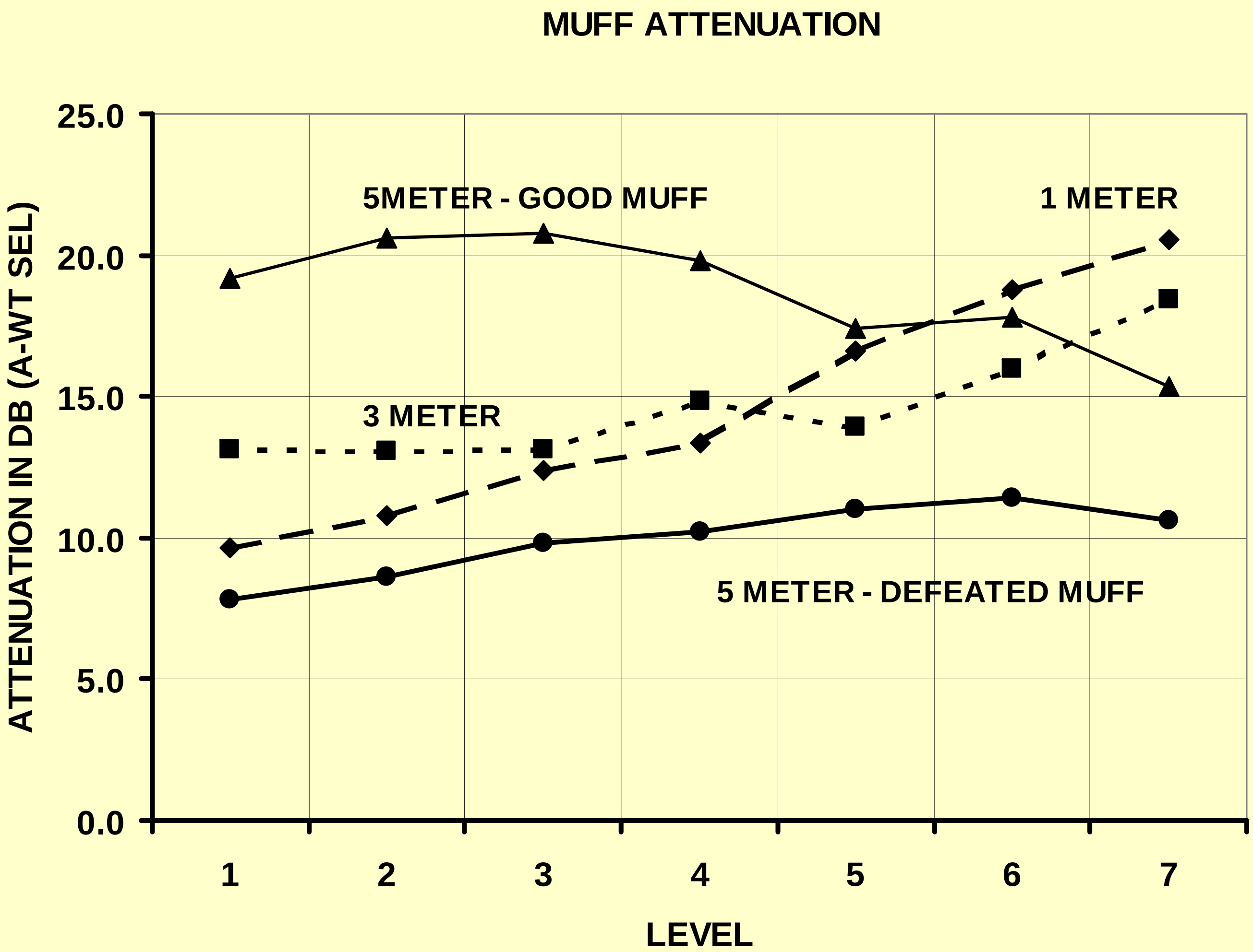
Pattern of Exposure

- 5 meter condition re-run (new Ss),
  - Some failures
  - Single protection only
- 3 meter condition run
  - More failures
  - Single protection only
- 1 meter condition run
  - Many more failures
  - Single protection only

The Problem of the Defeated Muff

- **Almost all HPDs linear with respect to amplitude at all pressures**
- **BUT:**

Hearing Protector Performance



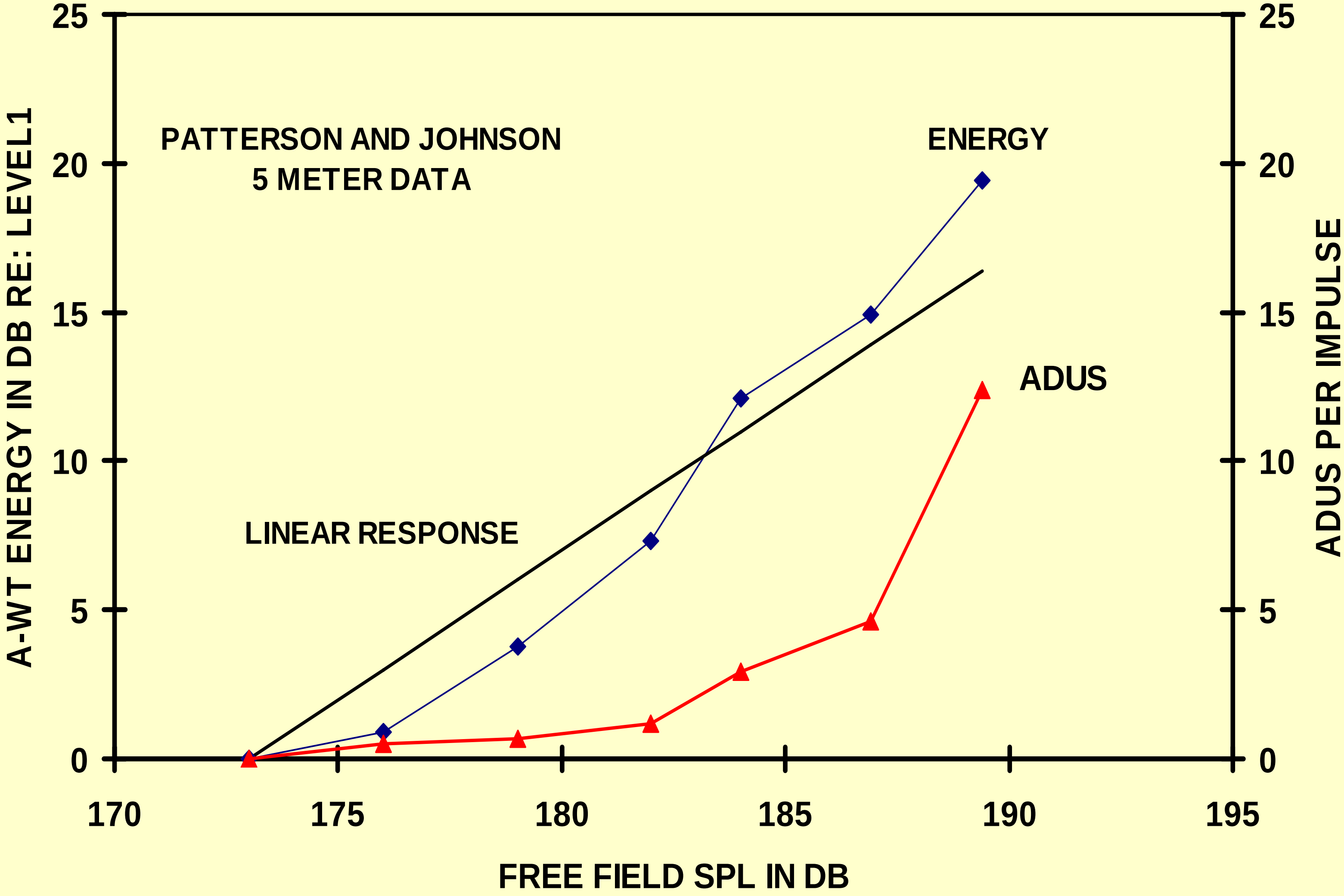
The Problem of the Defeated Muff

- **The defeated muff became *non-linear* (got better at as level rose)**
  - **4.6 dB (5M)**
  - **5.3 dB (3m)**
  - **10.9 dB (1M)**
- **Even the good muff became non-linear (got worse as level rose)**
  - **5.4 dB (5M)**

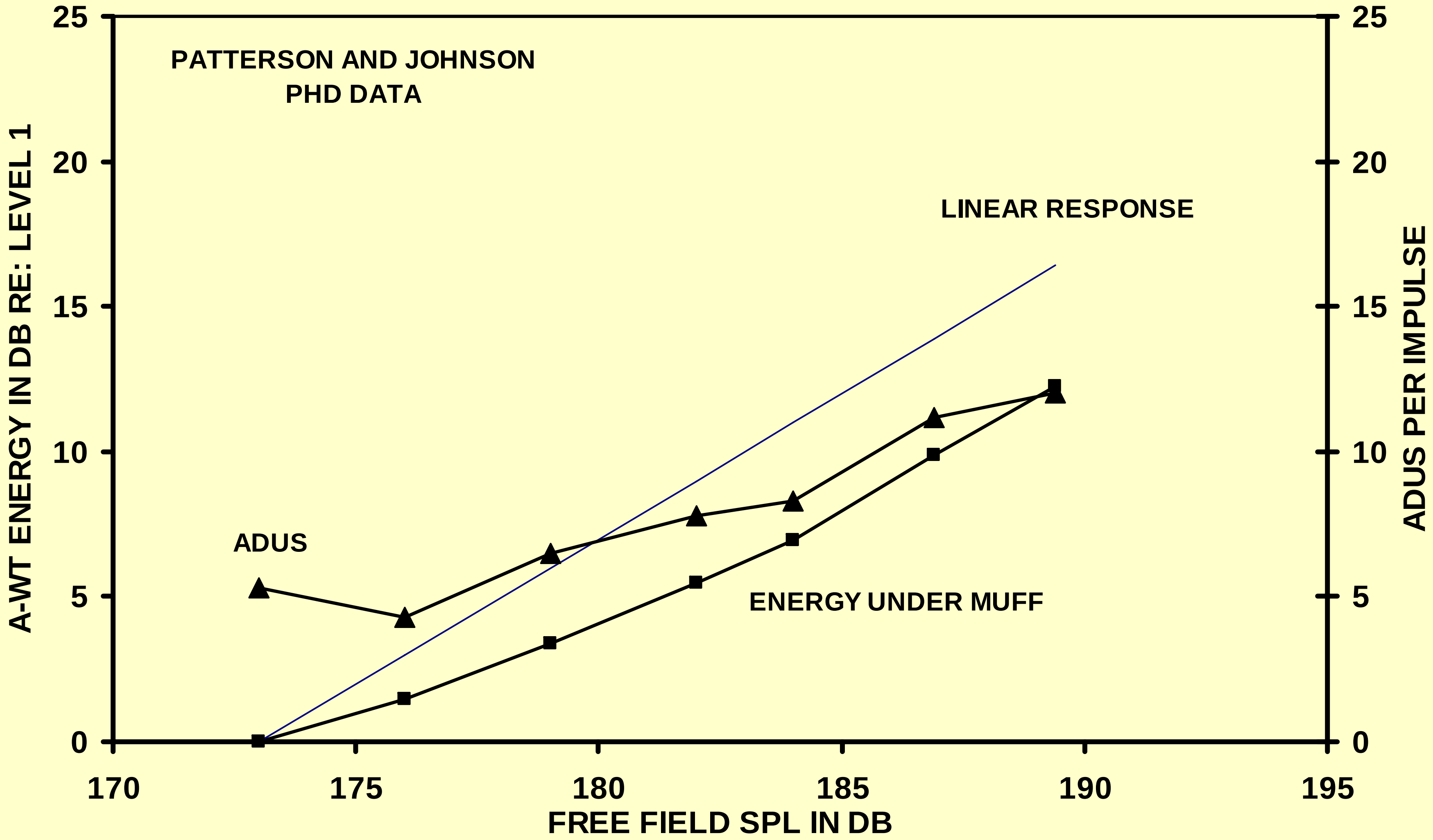
Analysis of the Data with AHAAH

- **Presume middle ear muscles contracted before pulse arrives (Warned ear)**
- **Use under-muff pressure histories and enter AHAAH at ECE**
- **Failure taken as more than 500 ADUs**
- **Given failure at 'N' impulses, presumptive failure at > N impulses**
- **But failure at one level not counted as failure at higher level - growth of ADUs not monotonic with level**

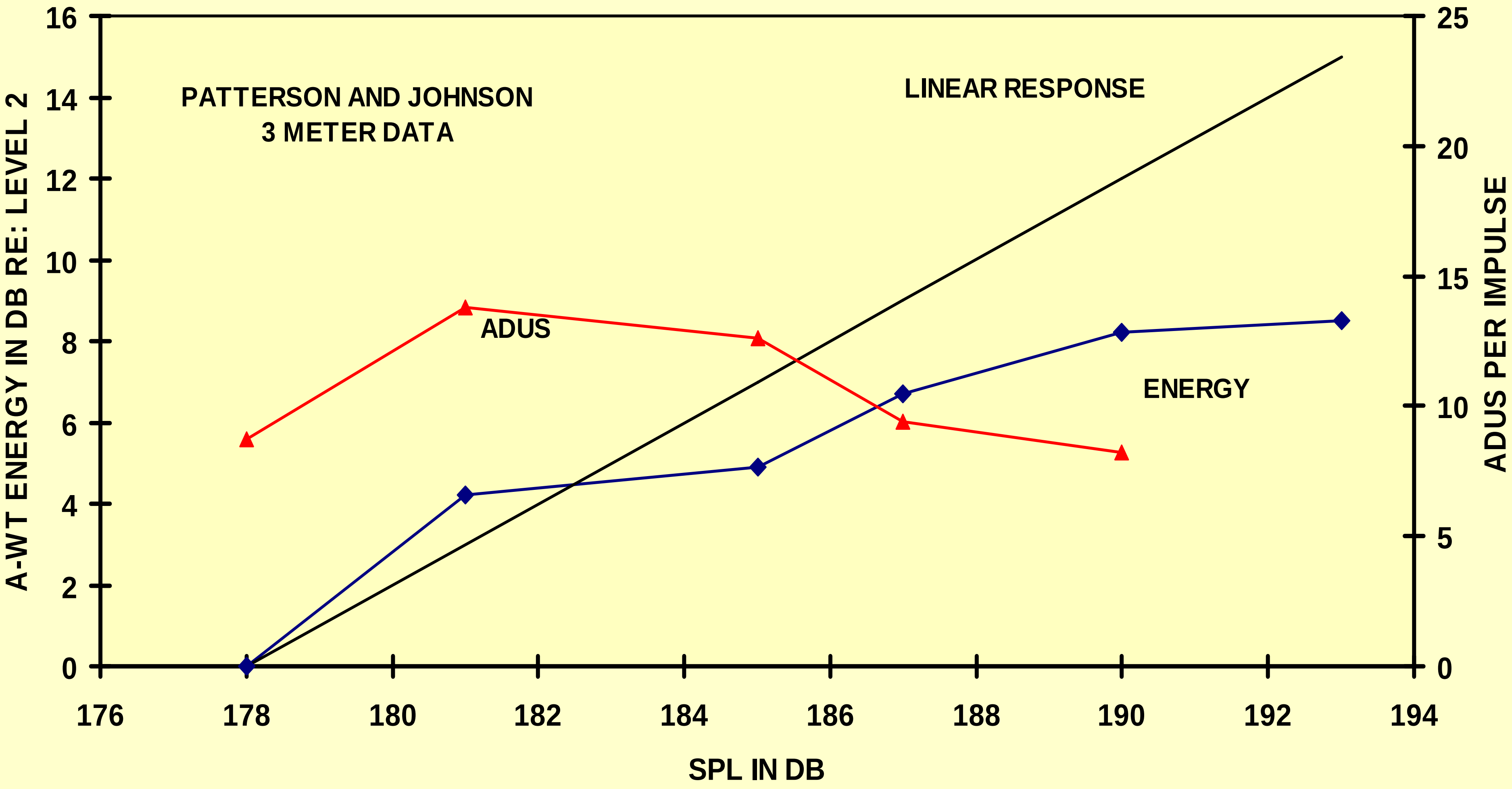
5 Meters - Good Muff



5 Meters - Defeated Muff

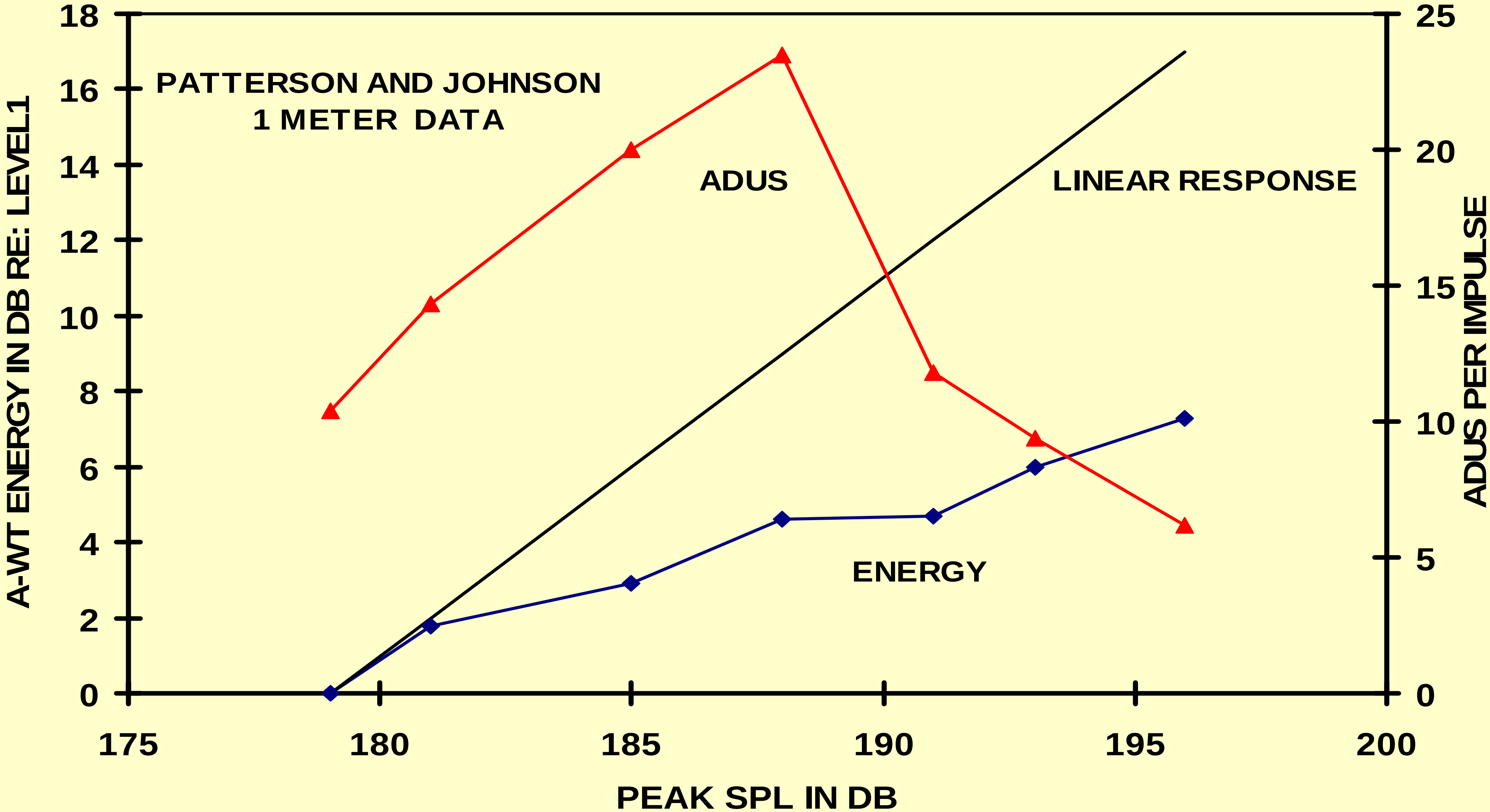


3 Meter Data



PATTERSON AND JOHNSON
3 METER DATA
LINEAR RESPONSE
ADUS
ENERGY
A-WT ENERGY IN DB RE: LEVEL 2
ADUS PER IMPULSE
SPL IN DB
0
2
4
6
8
10
12
14
16
0
5
10
15
20
25
176
178
180
182
184
186
188
190
192
194

1 Meter Data



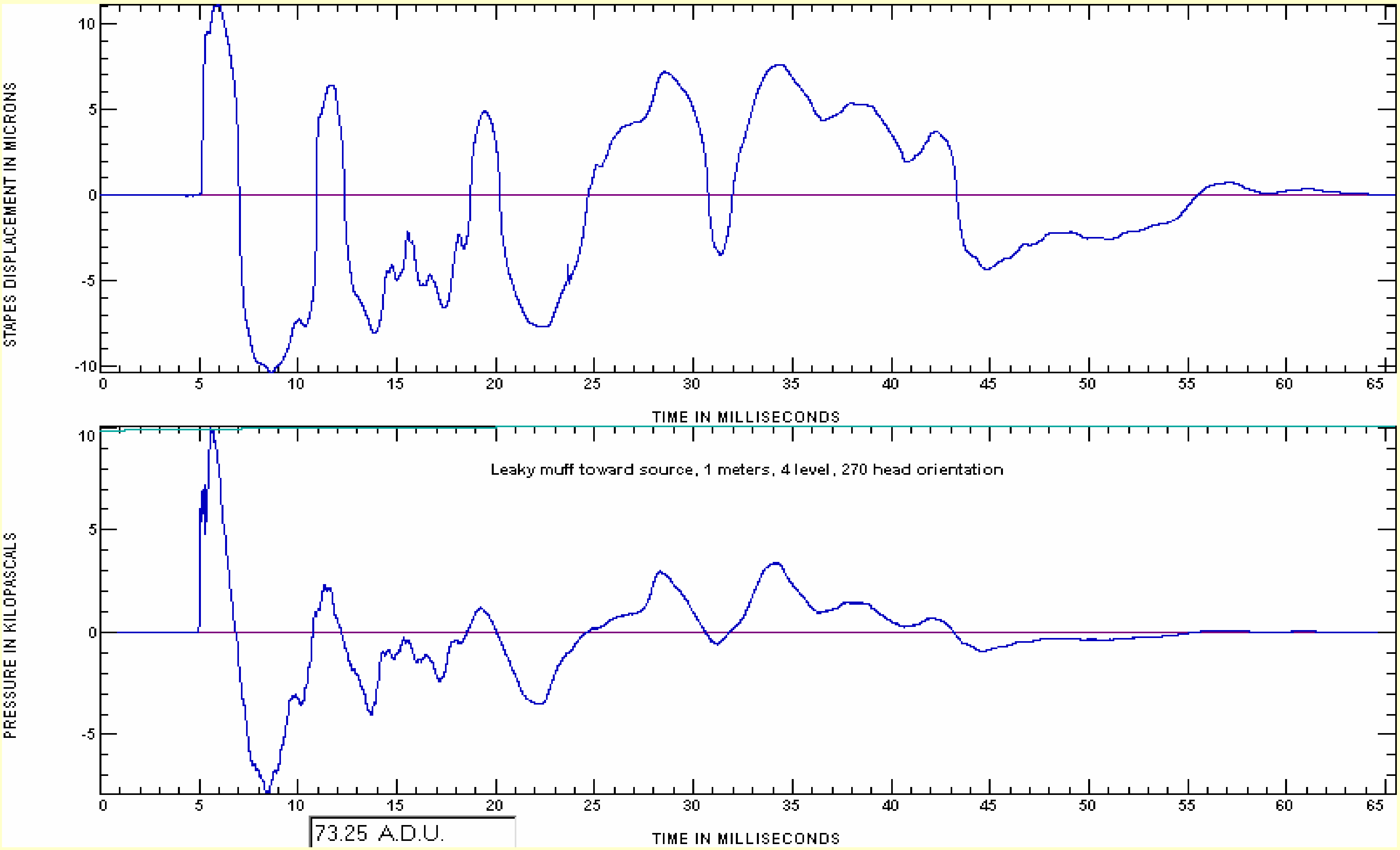
PATTERSON AND JOHNSON
1 METER DATA
ADUS
LINEAR RESPONSE
ENERGY
A-WT ENERGY IN DB RE: LEVEL1
ADUS PER IMPULSE
PEAK SPL IN DB
0
2
4
6
8
10
12
14
16
18
0
5
10
15
20
25
175
180
185
190
195
200

Does Non-Monotonicity Make Sense?

- **Peak pressure did rise in free-field, though less under the muff**
- **But 'interior' details of waveform changed**
- **Model suggests clipping affects stapes displacement and driving of cochlea**
- **Result, for 1 Meter condition, for example, Level 4 <u>worse</u> than Level 7**

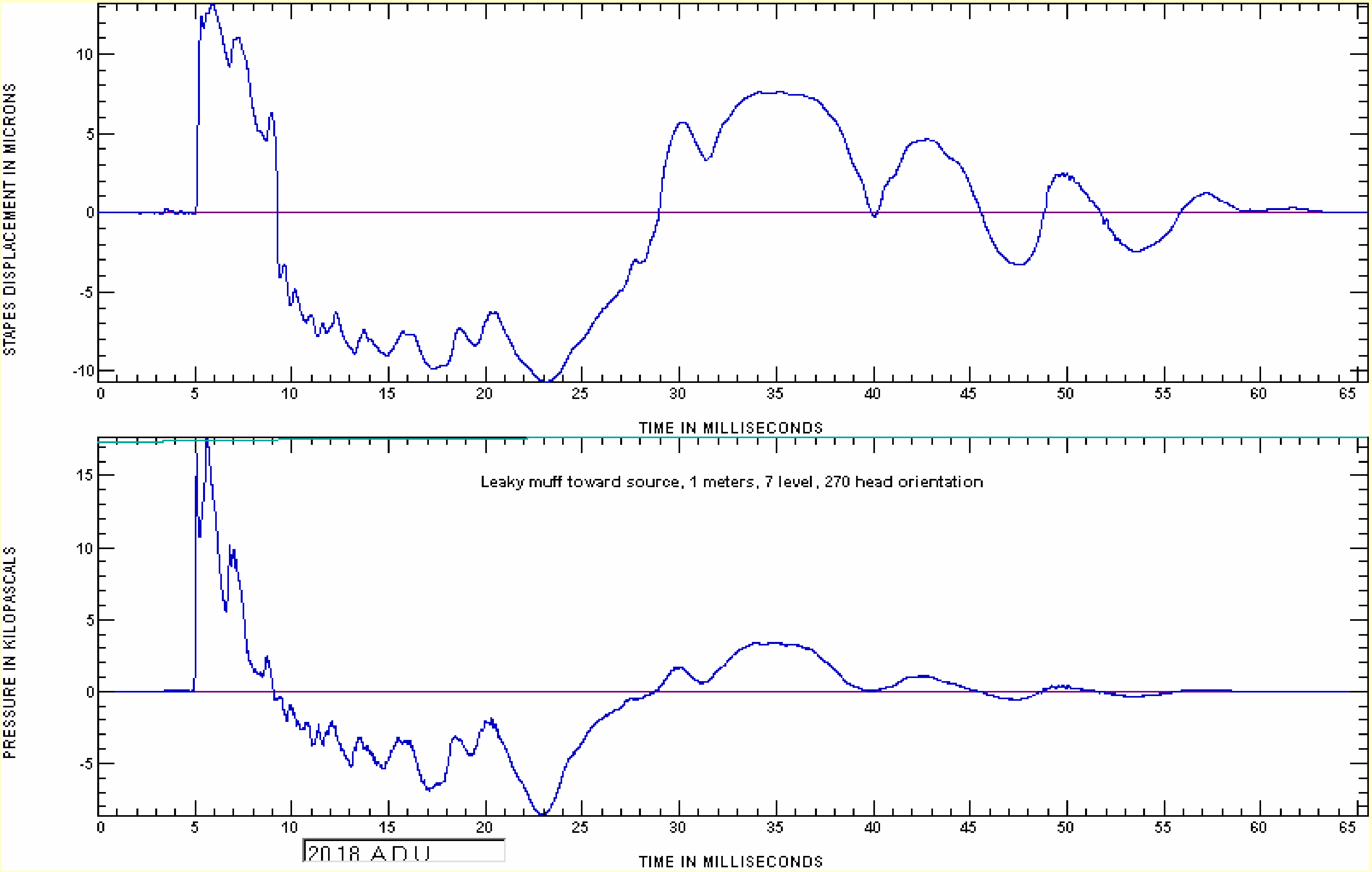
Model Analysis Shows

LEVEL 4 IMPULSE



Model Analysis Shows

LEVEL 7 IMPULSE



Analysis of the Threshold Shift Data

- **Samples of 5 or more waveforms used where available**
- **Mean ADUs established**
- **Exposure = ADUs/impulse x Number**
- **If >500, failure predicted**
- **Full audiometric failure and presumptive failures both counted as failures**

1 METER DATA					
LEVEL	NUMBER OF IMPULSES				
	6	12	25	50	100
7	56\2				
6	59\0	56\2	54\8	49\10	37\13
5	63\1	3\2	4\2	7\5	12\9
4	64\0				
3	64\0				
2	65\2				
1	66\0				

3 METER DATA					
LEVEL	NUMBER OF IMPULSES				
	6	12	25	50	100
7	56\2				
6	62\2	62\3	58\7	57\9	36\11
5	66\2	2\2	1\1	3\3	3\3
4	69\1				
3	68\0				
2	68\0				
1	68\0				

5 METER DATA MODIFIED MUFF					
LEVEL	NUMBER OF IMPULSES				
	6	12	25	50	100
7	57\0				
6	60\1	60\1	60\1	60\2	62\4
5	60\1				
4	61\0				
3	61\0				
2	61\0				
1	61\0				

5 METER DATA GOOD MUFF					
LEVEL	NUMBER OF IMPULSES				
	6	12	25	50	100
7	49\0				
6	58\0	56\0	53\0	44\0	39\0
5	59\0				
4	62\0				
3	62\0				
2	62\0				
1	62\0				

REVERBERANT DATA			
LEVEL	NUMBER		
	1	2	3
7	59\0		
6	59\0	59\0	58\1
5	61\0		
4	61\0		
3	63\0		
2	63\0		
1	64\0		

Evaluation Diagram

		OUTCOME	
		SAFE	HAZARDOUS
PREDICTION	SAFE	CORRECT RATING	UNDER-ESTIMATE AUDITORY CASUALTIES POORER COMMO MISSION ENDANGERED
	HAZARDOUS	OVER-ESTIMATE LESS EFFECTIVE WEAPONS MISSION ENDANGERED EXCESS CASUALTIES	CORRECT RATING

Rating Hit or Miss

- If a rating scheme said hazardous level had been reached and
  – No subject had failed - over-prediction
  – One or more had failed - correct
- If a rating scheme said “safe” and
  – Up to six failed - correct
  – More than six failed - under-prediction

Rating Schemes

- Three rating schemes compared
  - MIL-STD 1474
  - A-Weighted Energy
    - 8.7 J/m^2 safe (85 dB L_{AEQ8HR})
  - AHAAH

EVALUATION BY MIL STD-1474

PREDICTION	OUTCOME: SAFE	OUTCOME: HAZARDOUS
SAFE	01 T1 T2 F1 F2 F3 G1 G2 G3 R1 R2	
HAZARDOUS	O2 O3 O4 O5 O5 O7 O8 T3 T4 T5 T6 T7 T8 F4 F5 F6 F7 F8 F9 G4 G5 G6 G7 G8 G9 GF GH R3 R4 R5 R6 R7 R8	O9 OF OH T9 TF TH FF FH R9

EVALUATION BASED ON A-WEIGHTED ENERGY

PREDICTION	OUTCOME: SAFE	OUTCOME: HAZARDOUS
SAFE	G1 G2 G3 R1	
HAZARDOUS	O1 O2 O3 O4 O5 O6 O7 O8 T1 T2 T3 T4 T5 T6 T7 T8 F1 F2 F3 F4 F5 F6 F7 F8 R2 R3 R4 R5 R6 R7 R8 R9 G4 G5 G6 G7 G8 G9 GF GH	O9 OF OF T9 TF TH FF FH F9

EVALUATION BY AHAAH

OUTCOME

		SAFE	HAZARDOUS
PREDICTION	SAFE	O1 O2 O3 O4 O5 O6 O7 O8 T1 T2 T3 T4 T5 T6 T7 T8 F1 F2 F3 F4 F5 F6 F7 F8 G1 G2 G3 G4 G5 G6 G7 G8 G9 R1 R2 R3 R4 R5 R6 R7 R8	
	HAZARDOUS	GF GH	O9 OF OH T9 TF TH F9 FF FH R9

EXPOSURE CODES					
CODE	CONDITION	LEVEL/RDS	CODE	CONDITION	LEVEL/RDS
O1	1-METER	L1/6	F6	5-METER	L6/6
O2	1-METER	L2/6	F7	5-METER	L7/6
O3	1-METER	L3/6	F8	5-METER	L6/12
O4	1-METER	L4/6	F9	5-METER	L6/25
O5	1-METER	L5/6	FF	5-METER	L6/50
O6	1-METER	L6/6	FH	5-METER	L6/100
O7	1-METER	L7/6	G1	5-M GOOD MUFF	L1/6
O8	1-METER	L6/12	G2	5-M GOOD MUFF	L2/6
O9	1-METER	L6/25	G3	5-M GOOD MUFF	L3/6
OF	1-METER	L6/50	G4	5-M GOOD MUFF	L4/6
OH	1-METER	L6/100	G5	5-M GOOD MUFF	L5/6
T1	3-METER	L1/6	G6	5-M GOOD MUFF	L6/6
T2	3-METER	L2/6	G7	5-M GOOD MUFF	L7/6
T3	3-METER	L3/6	G8	5-M GOOD MUFF	L6/12
T4	3-METER	L4/6	G9	5-M GOOD MUFF	L6/25
T5	3-METER	L5/6	GF	5-M GOOD MUFF	L6/50
T6	3-METER	L6/6	GH	5-M GOOD MUFF	L6/100
T7	3-METER	L7/6	R1	REVERBERANT	L1/1
T8	3-METER	L6/12	R2	REVERBERANT	L2/1
T9	3-METER	L6/25	R3	REVERBERANT	L3/1
TF	3-METER	L6/50	R4	REVERBERANT	L4/1
FH	3-METER	L6/100	R5	REVERBERANT	L5/1
F1	5-METER	L1/6	R6	REVERBERANT	L6/1
F2	5-METER	L2/6	R7	REVERBERANT	L7/1
F3	5-METER	L3/6	R8	REVERBERANT	L6/2
F4	5-METER	L4/6	R9	REVERBERANT	L6/3
F5	5-METER	L5/6			

Accuracy for the Albuquerque Data Set

- **53 different exposures evaluated**
- **Mil STD-1474 - 37.7% correct**
  - **Errors often large**
- **A-Weighted Energy - 24.5% correct**
  - **Errors often very large**

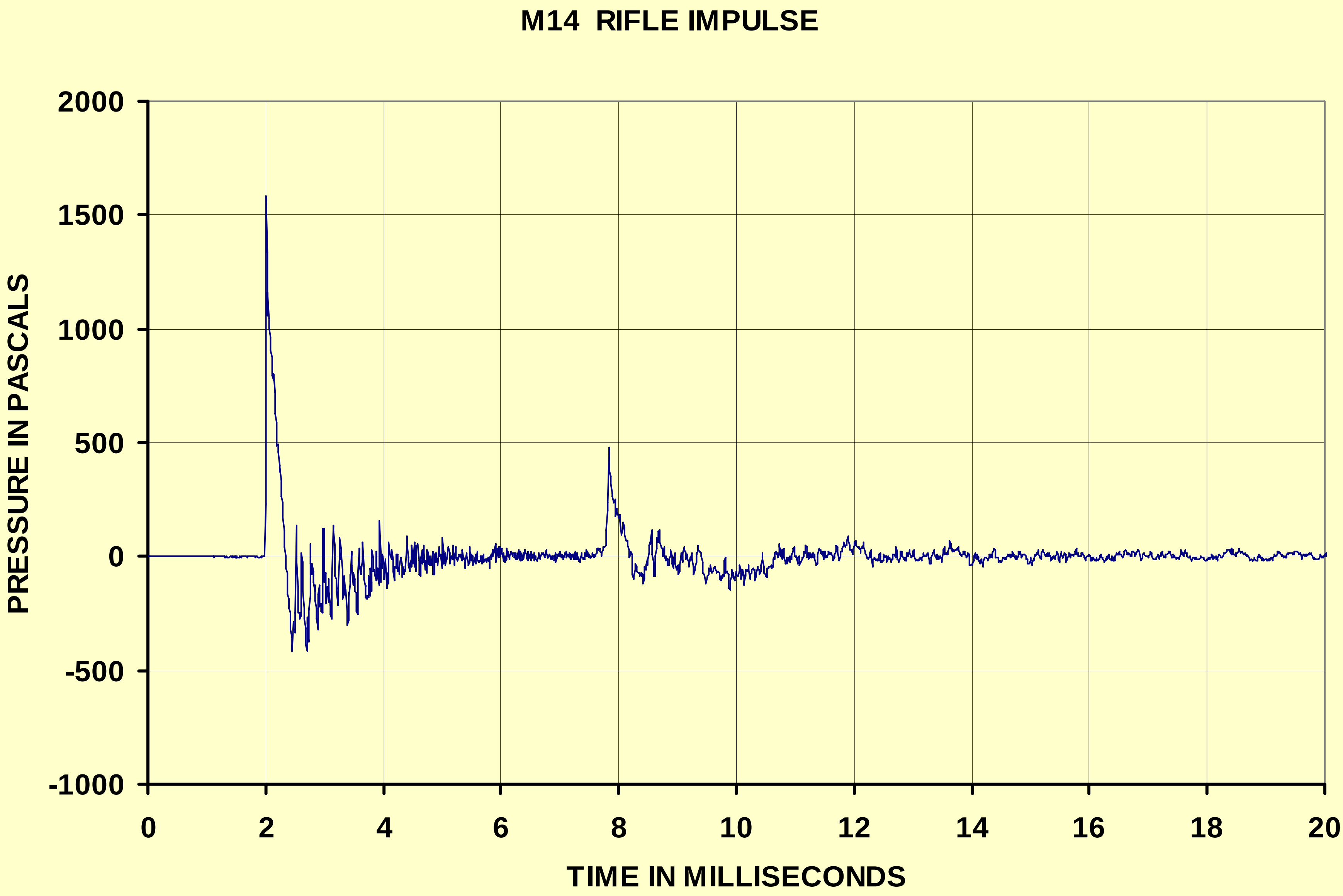
AHAAH - 96.2% correct

Rating Impulses in the Literature

Free-field Impulses (Mostly)

New Look at Old Data

- Need good waveform for AHAAH analysis
  - Published waveforms usually don't have enough detail
- Data reported vary with study - model can calculate equivalent data for comparison
- Keep criterion of 25 dB threshold shift as hazardous

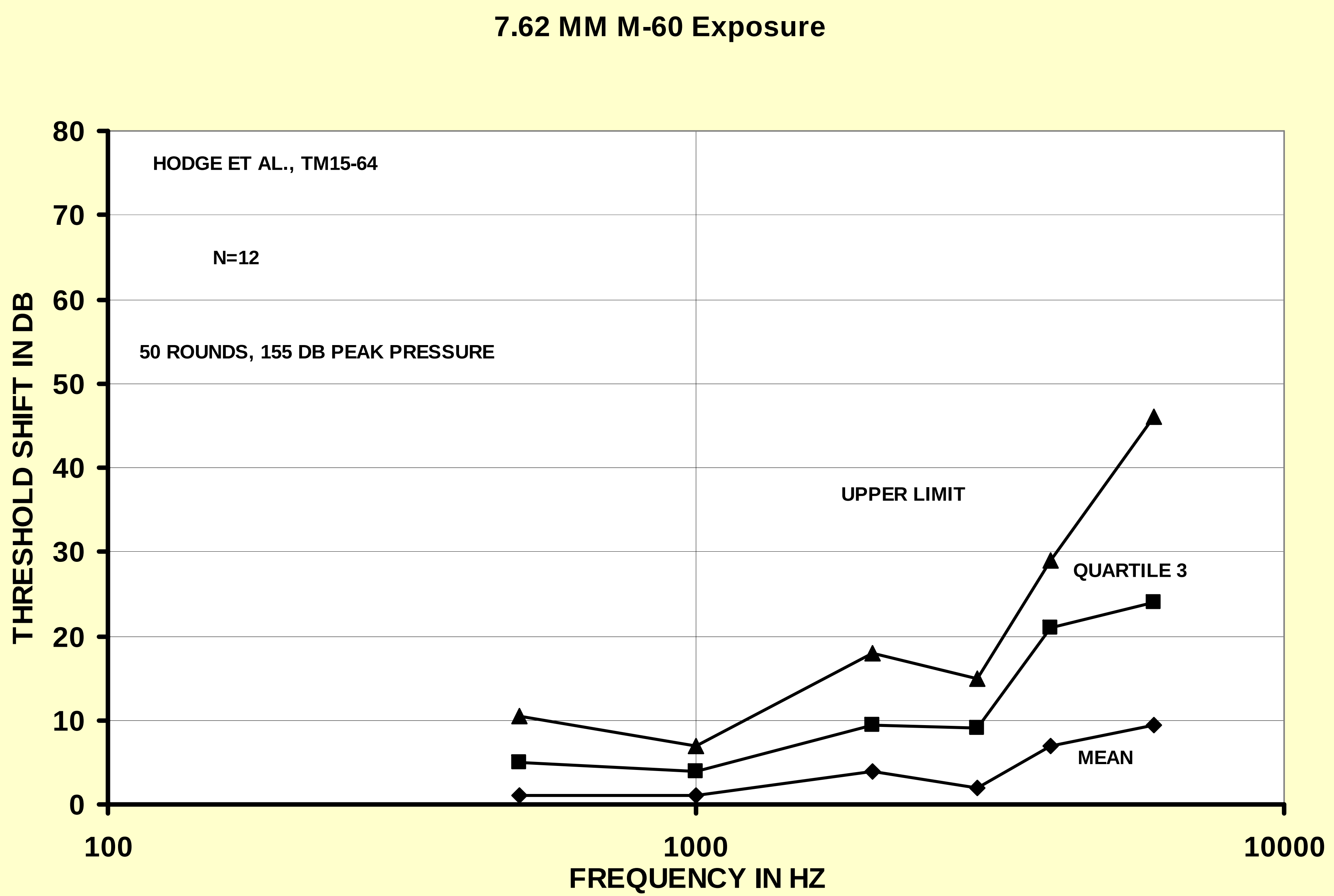

M14 RIFLE IMPULSE
PRESSURE IN PASCALS
2000
1500
1000
500
0
-500
-1000
0
2
4
6
8
10
12
14
16
18
20
TIME IN MILLISECONDS

7.62 mm Rifle Exposures

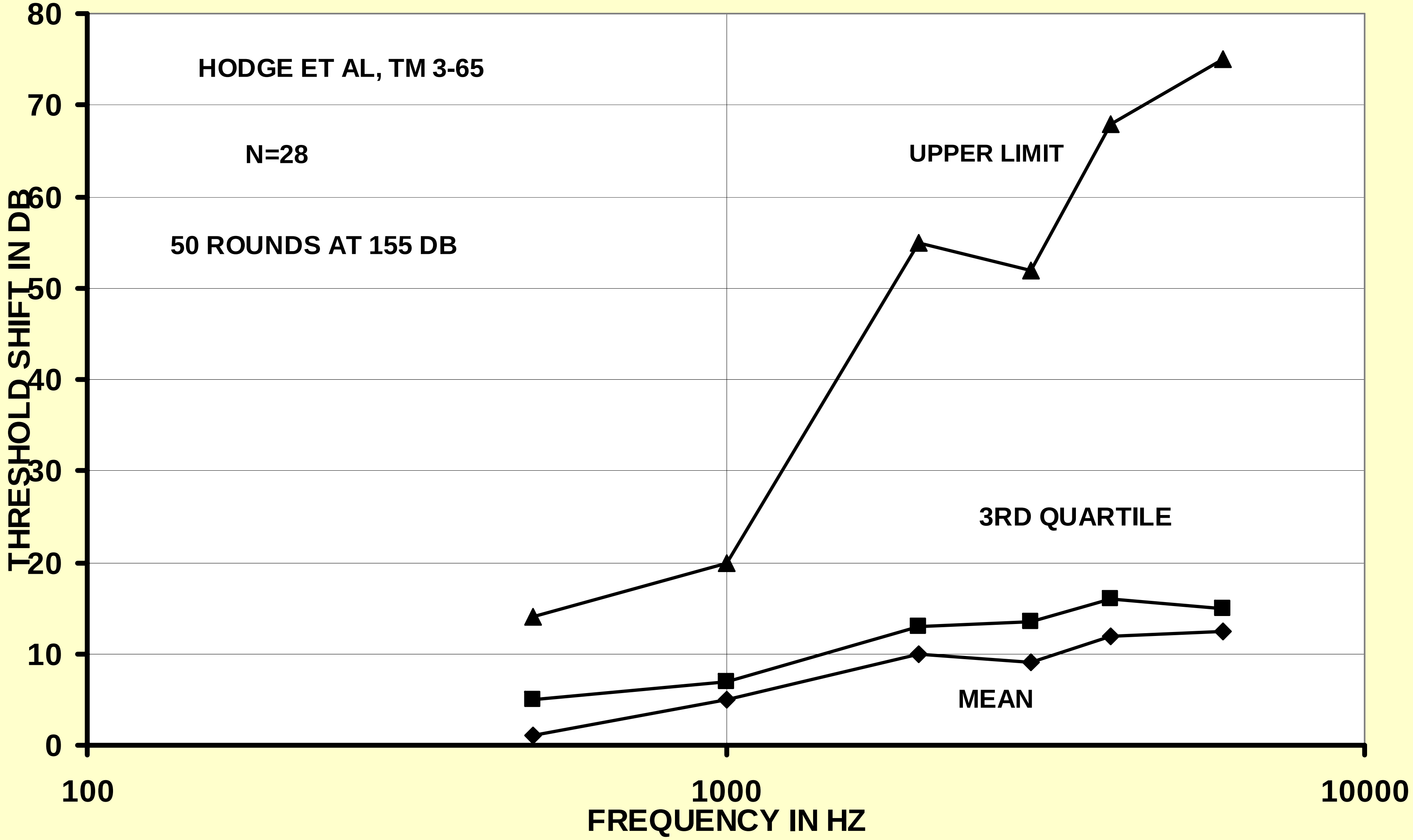
- Impulse used by Hodge et al. 1964 -1966
- Unprotected left ear exposed
- 50 or 25 impulses
- 5 sec inter-pulse interval - automated
- 155 and 158 dB peak pressure
- Subjects seated (ear at 62” height) to side of muzzle, 7’4” and 11’1” away
- Varying numbers of Ss (7,12, 28)
- Report extremes, mean, median, quartiles
- Shift data ‘corrected’ to TTS_2

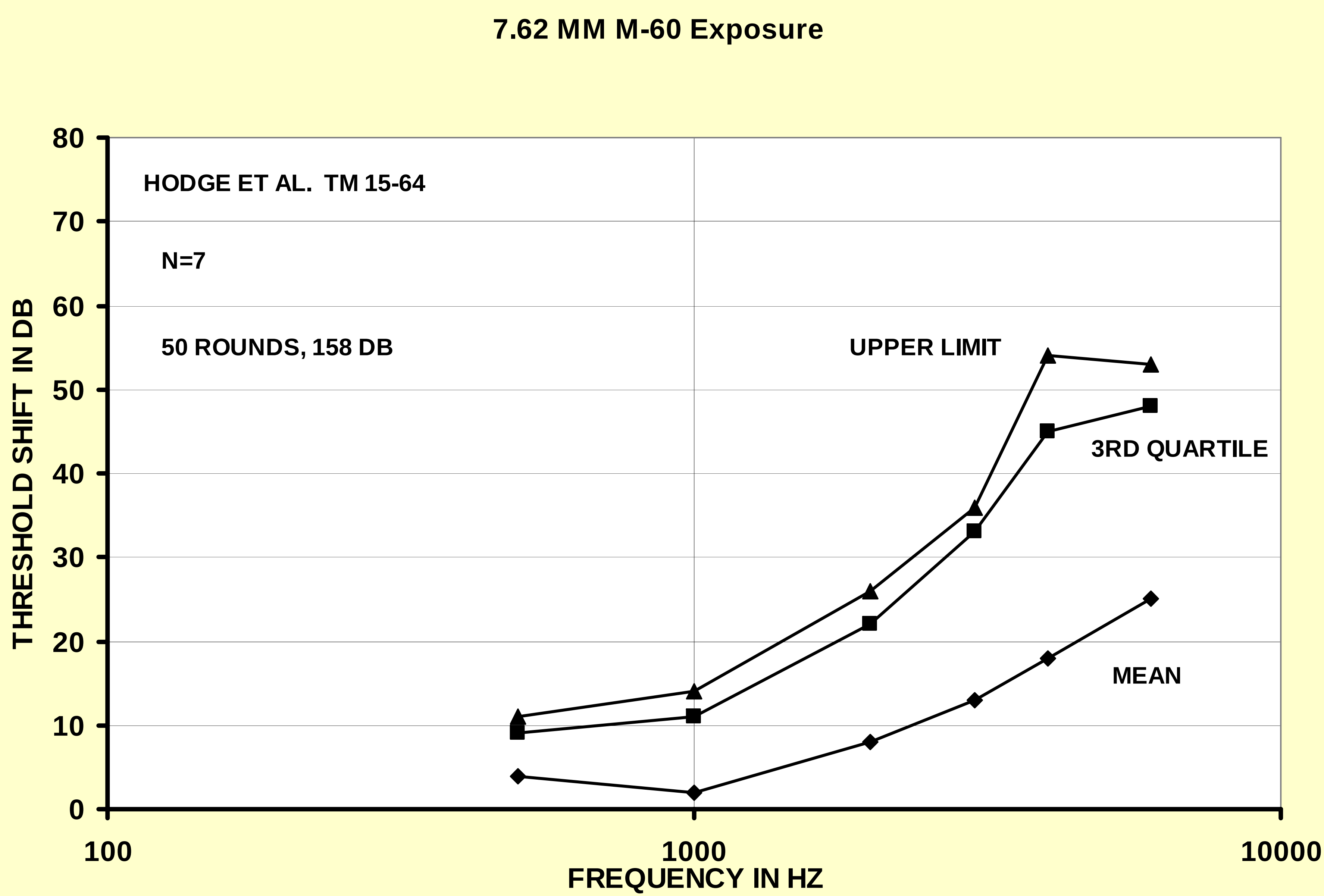
Threshold Shift Data

- The 3 conditions produced large shifts
  - 50 rounds at 155 dB
  - 50 rounds at 158 dB
  - 25 rounds at 158 dB
- Shifts of 40, 50, 70 dB - third quartile above 25 dB -- all 3 rate as hazardous
- Noted 25 impulses at 158 dB less hazardous than 50 impulses at 155 dB (no statistical test)

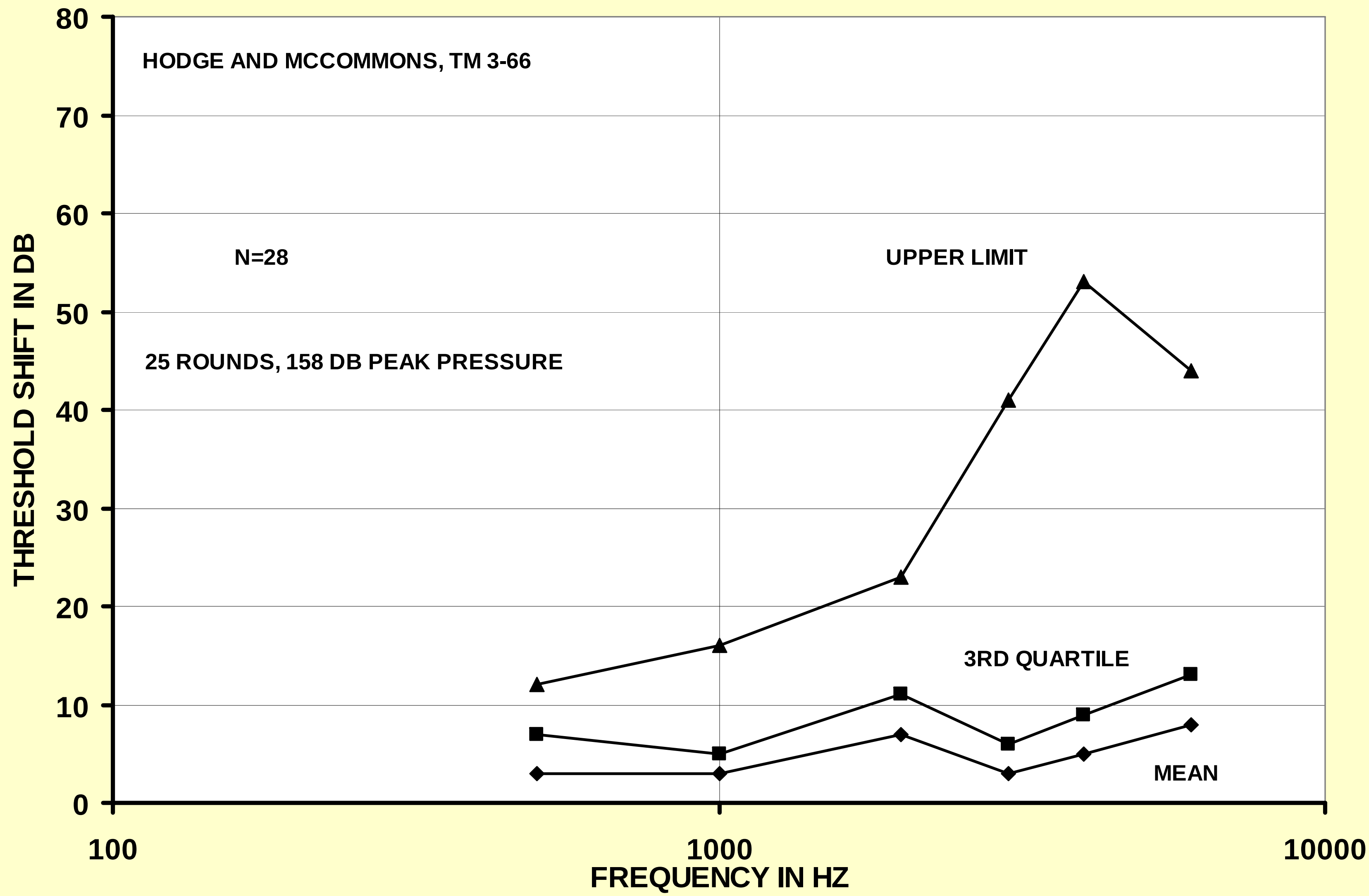

7.62 MM M-60 Exposure
HODGE ET AL., TM15-64
N=12
50 ROUNDS, 155 DB PEAK PRESSURE
UPPER LIMIT
QUARTILE 3
MEAN
THRESHOLD SHIFT IN DB
FREQUENCY IN HZ
0
10
20
30
40
50
60
70
80
100
1000
10000

7.62 MM M-60 Exposure




7.62 MM M-60 Exposure
HODGE ET AL. TM 15-64
N=7
50 ROUNDS, 158 DB
UPPER LIMIT
3RD QUARTILE
MEAN
THRESHOLD SHIFT IN DB
FREQUENCY IN HZ
0
10
20
30
40
50
60
70
80
100
1000
10000

7.62 MM M-60 Exposure

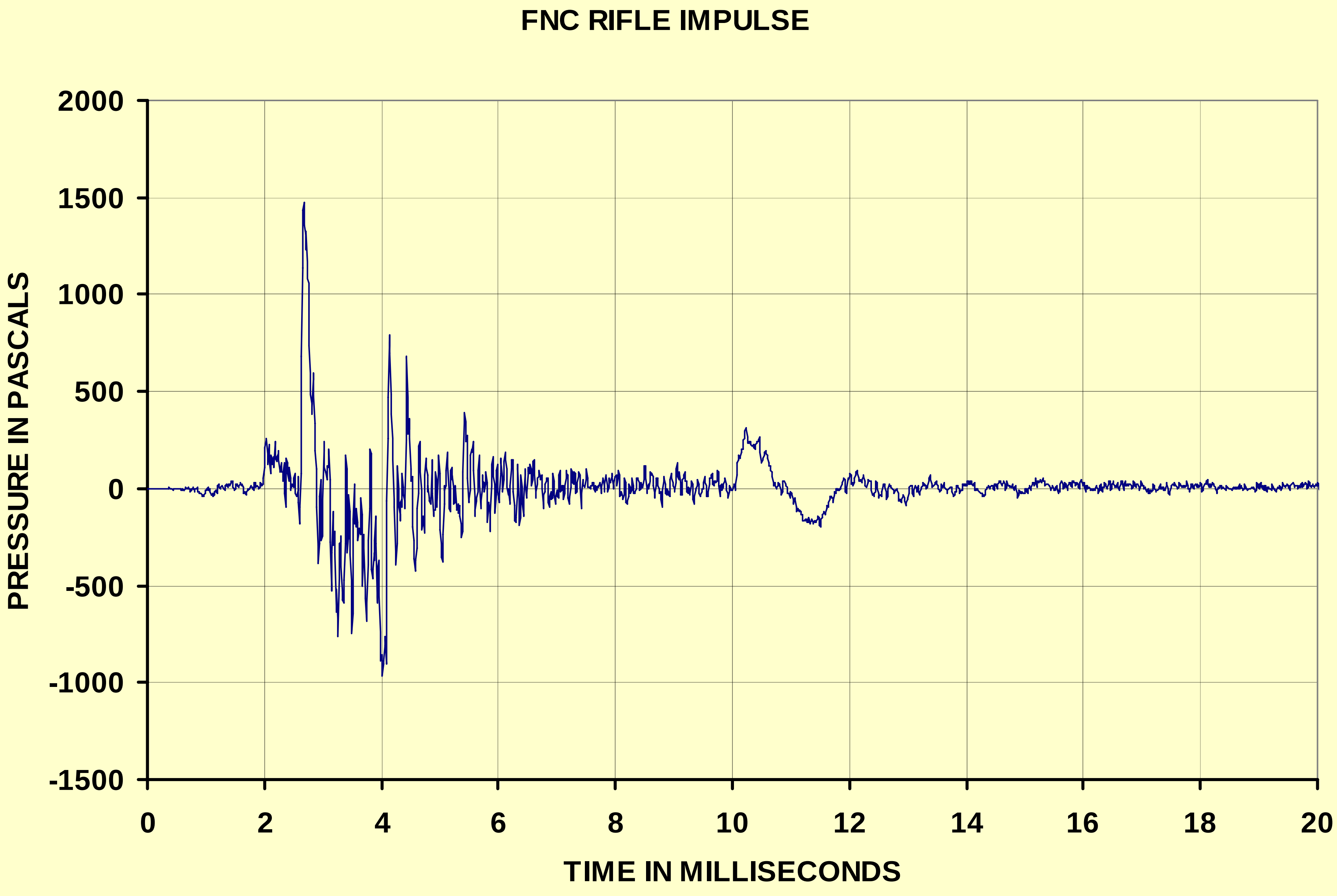


Analysis of 7.62mm Rifle Impulses with AHAAH

- Timing of impulses warrants “warned” calculation (for second and later impulses)
- 155 dB peak pressure
  - 16.6 ADUs/impulse (W); 118 ADUs(U)
  - 50 impulses = 830 ADUs (hazardous)
- 158 dB peak pressure
  - 22.3 ADUs/impulse (W); 153 ADUs(U)
  - 25 impulses = 558 ADUs (hazardous)
  - 50 impulses = 1115 ADUs (hazardous)

Summary of Predictions

- 7.62mm, 50 at 155 - correct
- 7.62mm, 25 at 158 - correct
- 7.62mm, 50 at 158 - correct



FNC RIFLE IMPULSE
PRESSURE IN PASCALS
2000
1500
1000
500
0
-500
-1000
-1500
0
2
4
6
8
10
12
14
16
18
20
TIME IN MILLISECONDS

FNC Rifle Analysis

- Brinkmann (2000) re-measured Belgian Rifle
  - 51 subjects fired 6 rounds standing
  - 53 subjects fired 5 rounds standing
  - Data reported
    - **Primarily, time to recover**
    - **Some clues as to amount of TS**
- Case 1:
  - 11 Ss shifts > 25 dB (hazardous)
- Case 2:
  - 9 Ss shifts >25 dB (hazardous)
- Recovery times 30 minutes to 16 hours

FNC Rifle Analysis with AHAAH

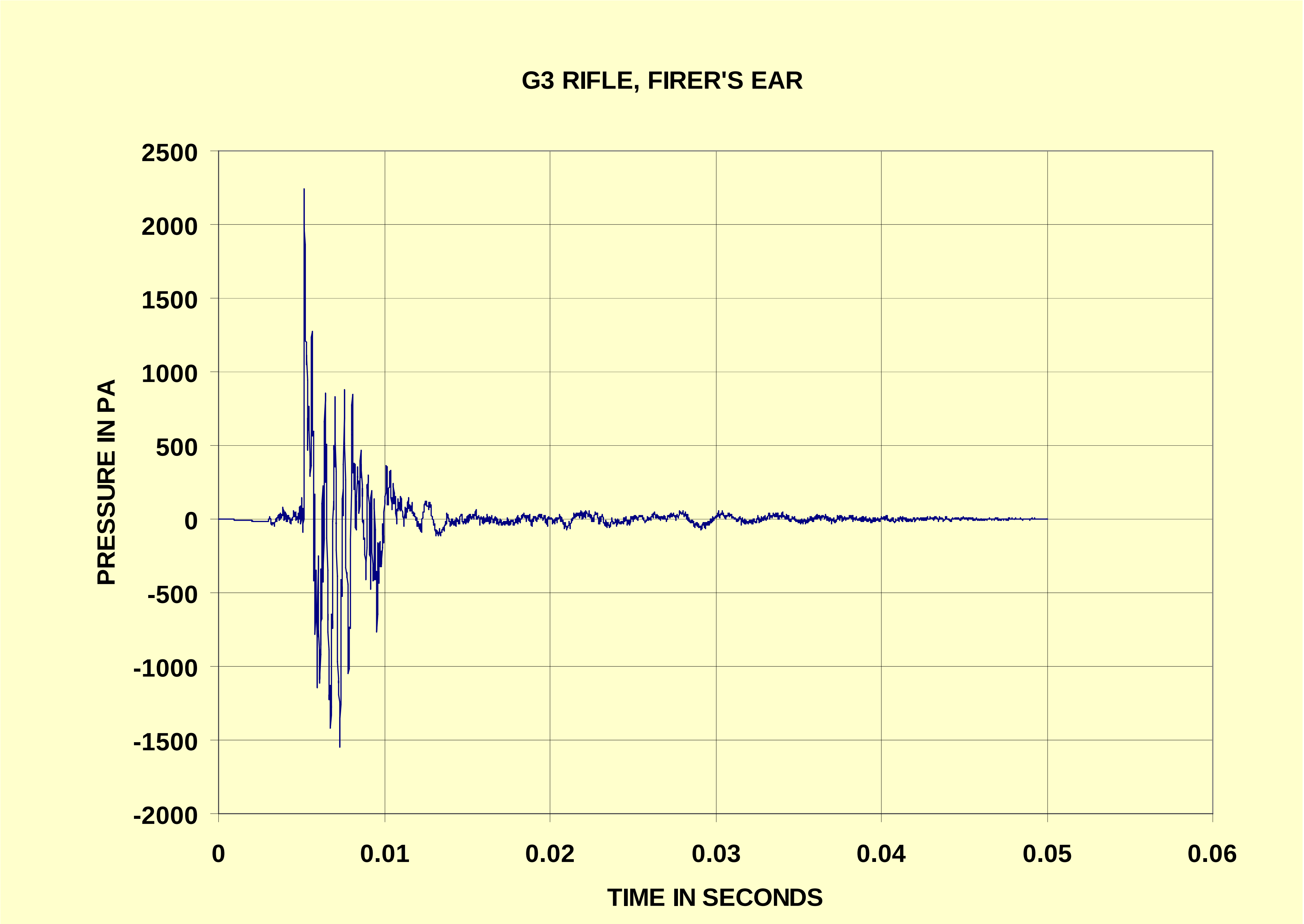
- Brinkmann supplied recorded waveform
- Soldiers fired own weapon - warned exposure
- Average of 156.8 ADUs per impulse
- Exposures of 940 and 784 ADUs
- Matches threshold shift data

FNC Rifle Analysis with A-weighted Energy

- Impulses contained 1.4 j/m²
- Exposures contained 8.4 and 7 j/m²
- Both rated as <u>safe</u>
- Were<u> hazardous</u> - only case of under-conservative criterion!

Summary of AHAAH Predictions

- 7.62mm, 50 at 155 - correct
- 7.62mm, 25 at 155 - correct
- 7.62mm, 25 at 158 - correct
- FNC 6 rounds - correct
- FNC 5 rounds - correct


G3 RIFLE, FIRER'S EAR
PRESSURE IN PA
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
0
0.01
0.02
0.03
0.04
0.05
0.06
TIME IN SECONDS

G3 Rifle

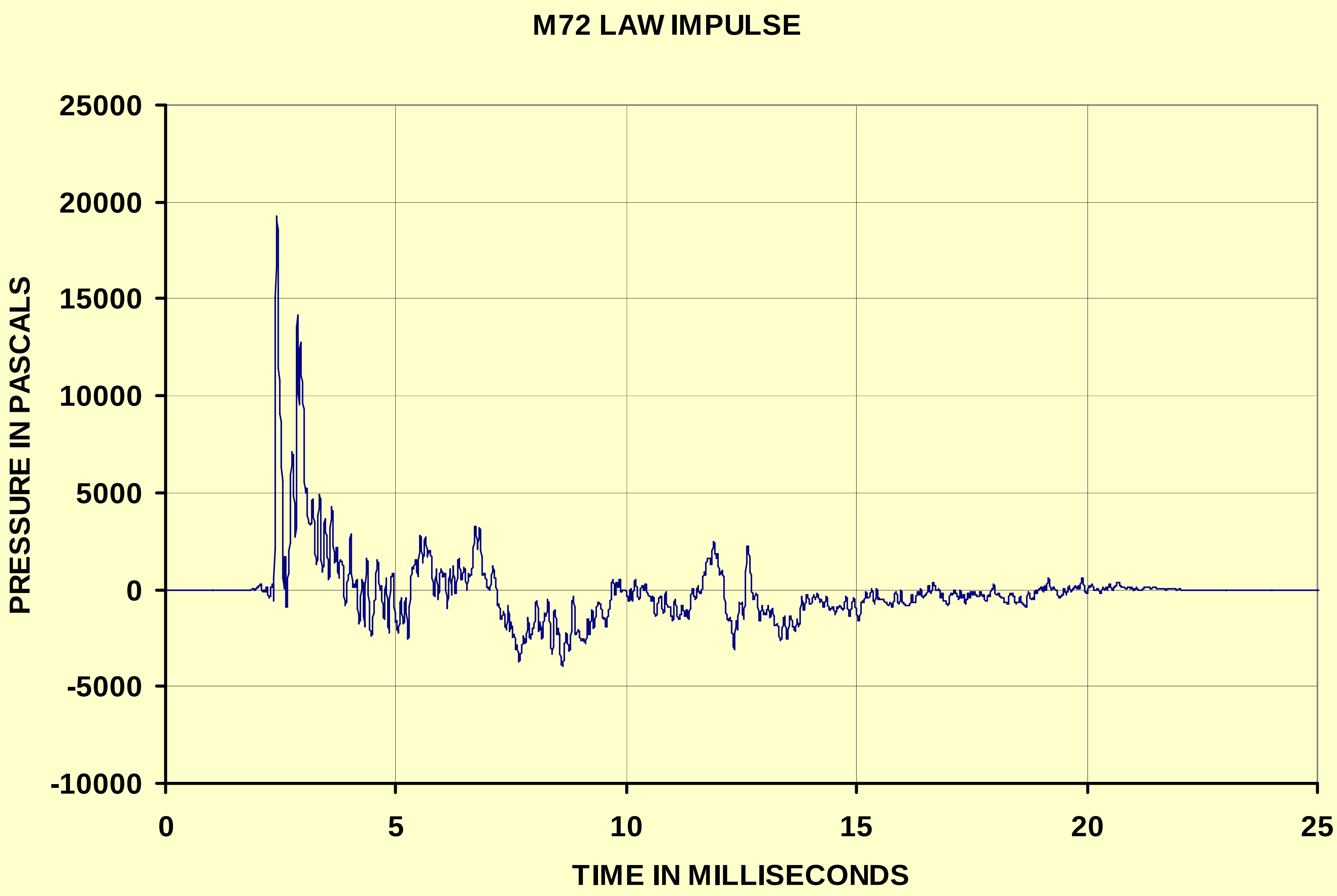
- Pfander (1974) reported
- 78 soldiers fired 5 rounds
- No protection
- Some threshold shifts of 30, 50 dB
- Recovery times of 3-6 days (N=16)
- A hazardous exposure

Analysis by AHAAH

- Brinkmann supplied recorded impulse
- Soldier fired own weapon - warned exposure
- Impulse contained 178.3 ADUs (W)
- Exposure = 892 ADUs (hazardous)

Summary of AHAAH Predictions

- 7.62mm, 50 at 155 - correct
- 7.62mm, 25 at 155 - correct
- 7.62mm, 25 at 158 - correct
- FNC 6 rounds - correct
- FNC 5 rounds - correct
- G3 5 rounds - correct


M72 LAW IMPULSE
PRESSURE IN PASCALS
25000
20000
15000
10000
5000
0
-5000
-10000
0
5
10
15
20
25
TIME IN MILLISECONDS

M 72 LAW Impulse

- Garinther and Hodge used LAW as impulse source
- Exposure at grazing incidence, unprotected
  - 43 Subjects tested (86 ears)
  - 161 dB (8m to left rear)
  - Fired by remote control with some countdown
  - Loss within CHABA limits - considered safe

M 72 LAW Impulse

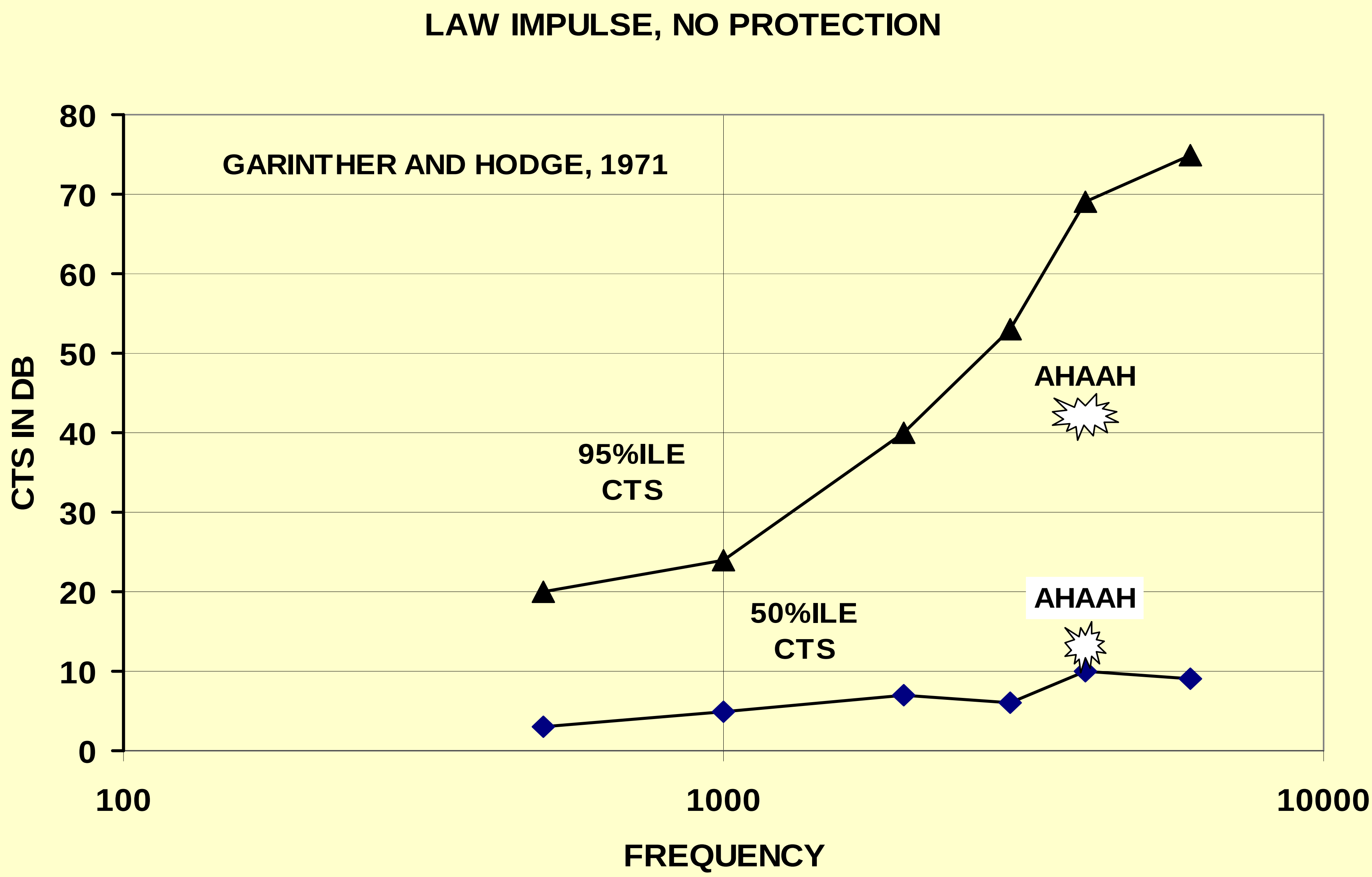
- Exposure to 1 impulse at firer's ear position, unprotected
  - 28 Subjects tested (test cut short)
  - 179 dB peak
  - Self-fired
- <u>Large</u> threshold shifts resulted (very hazardous)

M 72 LAW Impulse

- Exposure to 1 impulse to rear side, V-51R protection
  - 175, 179.6 and 184 dB peak
  - 40, 38, 31 Subjects tested respectively
  - All exposures safe

Analysis with AHAAH

- One waveform from LAW, not sure where recorded. Not truly adequate for purposes.
- Slow recovering Ss dropped from study!
- Use this analysis for ball-park value only
- Pulse adjusted for 161 dB peak (unprotected):
  – 105 ADUs(W), 516 ADUs(UW) - just safe (correct)
- If adjusted for 179 dB peak (unprotected)
  – 921 ADUs(W) and 4217 ADUs (UW) Hazardous! (correct)


LAW IMPULSE, NO PROTECTION
GARINTHER AND HODGE, 1971
CTS IN DB
FREQUENCY
95%ILE
CTS
50%ILE
CTS
AHAAH
AHAAH
0
10
20
30
40
50
60
70
80
100
1000
10000

Analysis with AHAAH

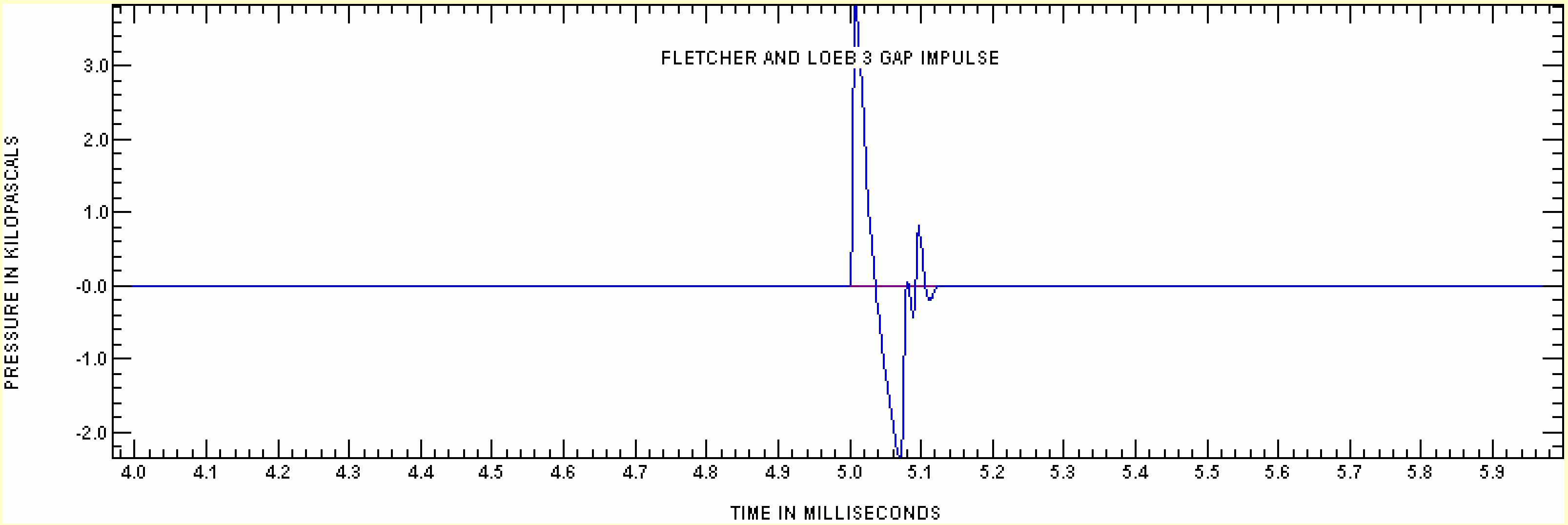
- If adjusted for 175, 179.6 and 184 dB peak (protected with V-51R):
  - <7.3 ADUs(W); <35 ADUs(UW) - safe (correct)

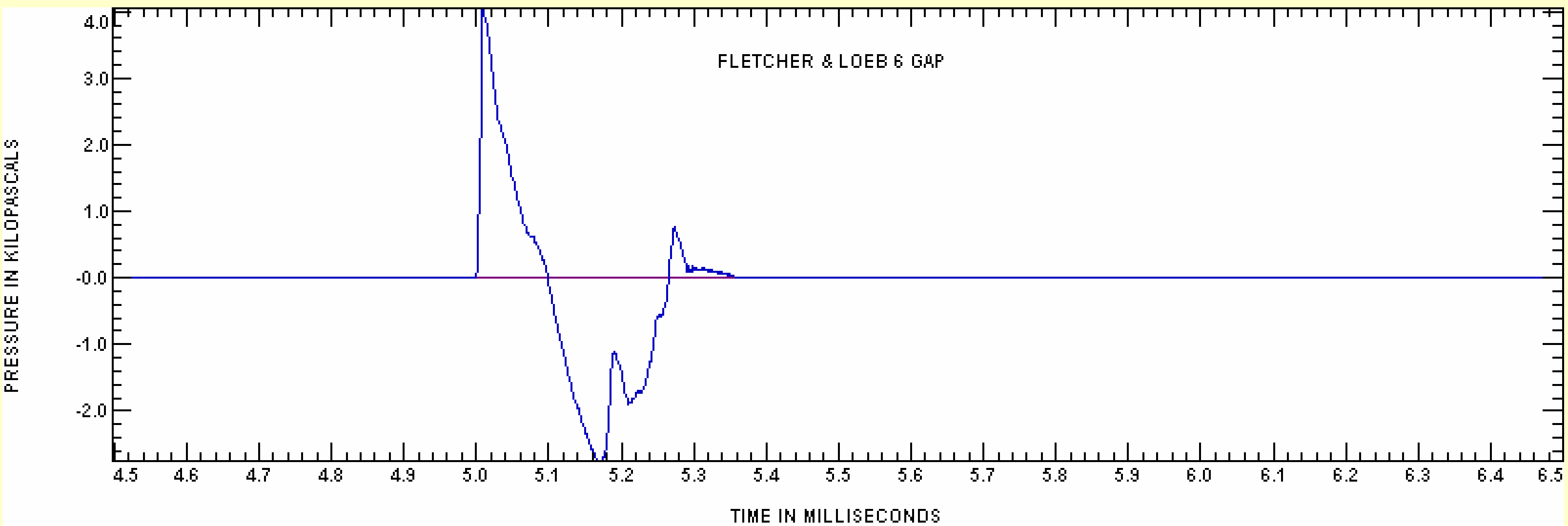
- Conclusion: AHAAH in correct ball park

Summary of AHAAH Predictions

- 7.62mm, 50 at 155 - correct
- 7.62mm, 25 at 155 - correct
- 7.62mm, 25 at 158 - correct
- FNC 6 rounds - correct
- FNC 5 rounds - correct
- G3 5 rounds - correct
- LAW 1 round - correct on 5 different exposures

FLETCHER AND LOEB SPARK GAP IMPULSES





Spark Gap Impulses Fletcher and Loeb

- Peak pressures all 166 dB
- 6 gap impulse spectral peak at 3.0 kHz
- 3 gap impulse spectral peak near 8.0 kHz
- Exposure to 1/sec in anechoic chamber
- 72 Ss, no hearing protection
- Stopped when TS exceeded 30 dB (tested up to 16 kHz)
- Can't specify 95%ile ear from data

Spark Gap Impulses
Fletcher and Loeb

- Interesting data nevertheless:
  - For 6 gap pulse
    - **1 pulse was enough for some ears**
    - **<u>Median</u> number to criterion was 4 pulses**
  - For 3 gap pulse
    - **Some reached criterion in 11 impulses**
    - **<u>Median</u> number to criterion was 88 pulses**

Spark Gap Impulses Analysis with AHAAH

- For rate of 1/sec, presume warned exposure for second and successive impulses
  - For 6 gap pulse
    - **176.1 ADUs (W); 995.4 ADUs (UW)**
      - **Predicts 44 dB CTS for 1 pulse (correct for some)**
    - **56 ADUs (W); 342 ADUs(UW) (Median ear)**
      - **1(UW)+3(W)= 510 ADUs (26 dB CTS) (Correct)**

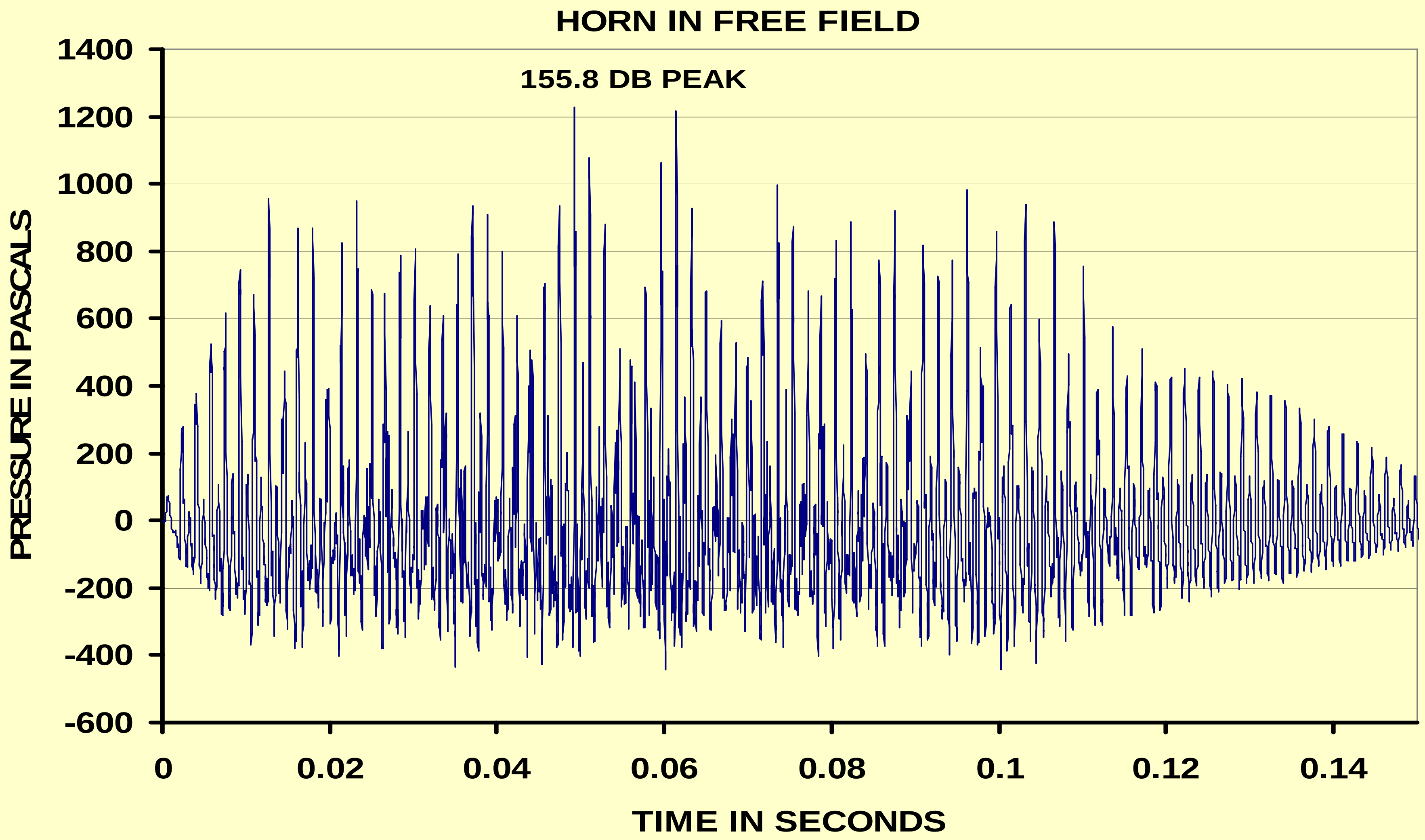
Spark Gap Impulses Analysis with AHAAH

– For 3 gap pulse
  - **31.6 ADUs (W); 186 ADUs (UW)(95%ile ear)**
    - **186+ 10 x 31.6 = 502 ADUs (26 dB CTS) (correct)**
  - **6.5 ADUs (W); 186 ADUs(UW) (<u>Median ear</u>)**
    - **1(UW)+87(W)=751.5ADUs (36 dB CTS) (Correct)**

Summary of AHAAH Predictions

- 7.62mm, 50 at 155 - correct
- 7.62mm, 25 at 155 - correct
- 7.62mm, 25 at 158 - correct
- FNC 6 rounds - correct
- FNC 5 rounds - correct
- G3 5 rounds - correct
- LAW 1 round - correct on 5 different exposures
- Spark Gap impulses - correct on 4 predictions

The Horn That Did Some Damage



Exposure to Horn

- Report of Royster et al. (1999) 39 month old boy exposed self to several toots - complained of ear pain and tinnitus
- At 6 days 50 dB HL (10 dB at 4Khz 3 mos earlier) and 20 dB PTS at 6 mos
- Model shows any number of scenarios (angles, distances, susceptibility, number) producing this effect

Conclusions About Old Data and AHAAH's Predictions

- For six unprotected exposures to rifles, data were adequate for analysis and AHAAH was correct in each case.
- For ten additional predictions, the data were less than desired; but AHAAH was correct in all those cases as well.
- If 16 correct predictions added to the 51 (of 53) from the Albuquerque study, then AHAAH has achieved a 97% hit rate - without adjustment of original model.

From the Model Toward a DRC

The details

Issues to Be Settled

- Percentage of population to be protected
- Correction for angle of incidence?
- Use of hearing protector(s)
- Allowance for ‘field fit’ with a protector
- Instrumentation requirements for acoustic measurements
- What about variability in impulse measures?
- Assumptions with respect to middle ear muscle response
- Which manikin or ATF should be used?

Percentage Protected

- Customary to aim for 95%ile ear
- Experience suggests that <u>occasional</u> shifts of 20-25 dB from intense impulses recover
- Caveat: threshold shift from high level impulse is evidence of mechanical disruption
  - Recovery longer
  - Daily exposure at limit probably <u>not</u> OK.
- In model terms: 500 ADUs a limit
  200 ADUs "safe"

Correction(s) for Angle of Incidence

- Given a source always at particular azimuth
  - Left ear of right handed firer faces source
  - Outside ear faces side airbag
- Head-related transfer function (HRTF) applies
- Two alternatives:
  - From free-field pressure, AHAAH calculates waveform at ear using HRTF
  - Measure waveform with manikin

Correction for Angle of Incidence cont.

- If complex field, random incidence
- Two choices:
  - Use manikin, measure waveform at ECE or drum position
  - Use FF measure and calculate waveform using worst case angle of incidence
- Calculate hazard with AHAAH

Handling Hearing Protection

- For the military, most ears will be exposed while wearing protection.
- In past, 29 dB attenuation assumed for all protectors (35.5 dB for double protection)
  - Details of protector fit and character ignored
  - No incentive to improve designs
- Hearing protection (and use) an important variable in determining hazard
  - Need to protect
  - Need to communicate, stay aware

Handling Hearing Protection CONTINUED

- AHAAH needs a pressure history to calculate
- AHAAH handles protection three ways:

  (1) Pressure measurement on a manikin

  (2) Calculation from free field pressure and attenuation data

  (3) Mathematical model of the protector applied to free-field pressure

Handling Hearing Protection CONTINUED

(1) Measurement on a manikin (or subject)

– Measure at canal entrance or ear drum
– Corrects for incidence
– Includes subtleties of fit - friction, band pressure, etc.
– Non-linearities evaluated in the measure
– Manikin design and standardization a problem

Handling Hearing Protection CONTINUED

(2) Calculation from free-field pressure and attenuation data

– REAT tests commonly available

– Attenuation and its variability evaluated

– AHAAH creates minimum-phase digital filter matching given attenuation

– Filter can be de-rated to match field fit.

– Filter is applied to free-field waveform to calculate effective waveform at ear

– Presumes only one conductive path and a linear protector

Handling Hearing Protection CONTINUED

(3) Create mathematical model of the protector and process free-field pressure

- If behavior of protector fully known, modeling possible
- Model calculation quick and precise
- Discovering behavior of protector at all levels a non-trivial problem
- Modeling a high level technical skill

Recommendations for Hearing Protection in DRC Formulation

- Allowance for hearing protection- measured effect:
  - For muff, prescribe measurement at ECE on manikin head or on subject
    - **Placed at user head location**
    - **Blocked ear canal acceptable**
    - **Oriented for worst case presentation if location not fixed**

Recommendations for Hearing Protection in DRC Formulation

- Allowance for hearing protection- measured effect:
  - For plug, prescribe measurement of EDP on manikin head
    - **Placed at user head location**
    - **Oriented for worst case presentation if location not fixed**

Recommendations for Hearing Protection in DRC Formulation

- Allowance for hearing protection- calculated effect from free-field measure:
  - For muff or plug, prescribe free-field pressure measurement at center of head location (head absent)
  - Calculate effective pressure with 90 degree azimuth, unless other can be justified

Recommendations for Hearing Protection in DRC Formulation

- De-rating protector -
  - Use worst-case angle of incidence
  - Raise measured or calculated level under protector by 6dB (or average standard deviation for device in REAT tests)

Dealing with Measurement Variability

- Analyze <u>all</u> impulses measured for a condition (artifacts rejected)
- Use <u>average</u> ADUs as estimate of hazard for a round/weapon/condition
- Allowable number of rounds = 500/ADUs

Measurement Instrumentation and Conventions

- Measurement system:
  - sampling rate at least 44kHz
  - 16 bit digitization (12 bit or better used)
  - linear up to highest pressure measured (195 dB under protector)
  - linearity: 0.1 Hz to 20 kHz (low frequency limit 20 Hz if lower frequency not in signal)
  - Digitized waveforms stored in ASCII format

Recommendations

- Numbers stored are pressure in Pascals
- Digitizing rate reported (or time column included in file)
- Measurement procedures shall follow best acceptable practice.
  - Mike a blunt cylinder
  - Grazing orientation
  - Minimum 5 impulses per condition measured

Recommendations for Middle Ear Muscle Calculation

- In analysis consider muscles “warned” if:
  - Individual fires own weapon or
  - Firing signal clearly discernable e.g. vocal command, visual signal, etc.
  - Second and successive impulses normally follow closely (as in machine gun).
- Otherwise assume “unwarned”

The Problem of An ATF or Manikin

- Several manikins exist
  - ISL “French Head” (limited numbers)
  - Bruel developing a meter incorporating a head
  - Kemar
  - Head acoustics (AACHEN HEAD)
  - Other
- Recommend interim use of ISL Head
- Recommend development of new manikin

ISL Manikin


CAUTION
NOISE HAZARD AREA
Hearing protection required
at various times. Check
with supervisor.

ISL Manikin in Use

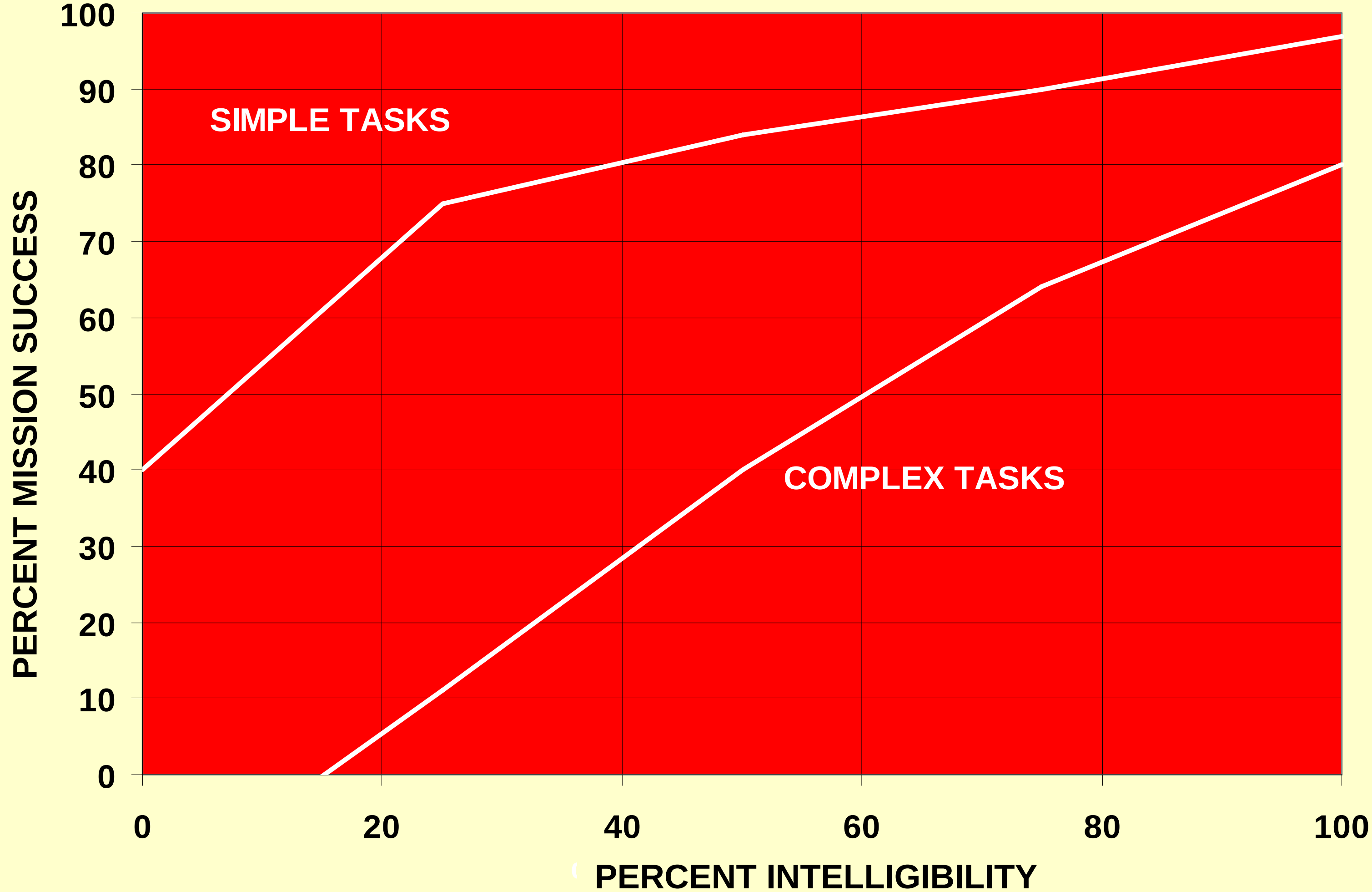
Desiderata in a Manikin

- Head should be sized to simulate 50%ile (alternate sizes desirable)
- Shaped like real head shape to allow mounting of helmet, muffs, masks, etc.
- Pinna and ear canal matching an average ear
- Pinna surround and ear canal of material with near skin characteristics
- Ear canal allow insertion of a plug
- Back path to microphone more attenuating than protectors

Desiderata in a Manikin

- Ear canal terminated with proper impedance
- Body temperature ear canal
- Microphone(s) at
  - Ear canal entrance (blocked canal)
  - Ear drum position
- Microphone characteristics:
  - Small size (ECE Mike)
  - High stability
  - DC to 20+kHz response
  - Linear up to 195+dB
  - Removable for calibration and repair

Effect of Speech Intelligibility on Mission Success



CODES		j/m/imp	J/M^2	ERROR		
			dose	WRTO 85 DB		
O1	ALBUQUERQUE	ONE METER	L1/6	15.01	90.06	10.1 DB
O2	ALBUQUERQUE	ONE METER	L2/6	22.7	136.2	11.8 DB
O3	ALBUQUERQUE	ONE METER	L3/6	29.32	175.92	13.0 DB
O4	ALBUQUERQUE	ONE METER	L4/6	43.73	262.38	14.7 DB
O5	ALBUQUERQUE	ONE METER	L5/6	44.29	265.74	14.8 DB
O6	ALBUQUERQUE	ONE METER	L6/6	59.77	358.62	16.1 DB
O7	ALBUQUERQUE	ONE METER	L7/6	79.48	476.88	17.3 DB
O8	ALBUQUERQUE	ONE METER	L6/12	44.29	531.48	17.8 DB
O9	ALBUQUERQUE	ONE METER	L6/25	44.29	1107.3	20.9 DB
OF	ALBUQUERQUE	ONE METER	L6/50	44.29	2214.5	24 DB
OH	ALBUQUERQUE	ONE METER	L6/100	44.29	4429	27 DB
T1	ALBUQUERQUE	THREE METER	L1/6	3.8	22.8	4.09 DB No data - assume 3dB)
T2	ALBUQUERQUE	THREE METER	L2/6	7.59	45.54	7.09 DB
T3	ALBUQUERQUE	THREE METER	L3/6	20.14	120.84	11.3 DB
T4	ALBUQUERQUE	THREE METER	L4/6	23.57	141.42	12 DB
T5	ALBUQUERQUE	THREE METER	L5/6	35.42	212.52	13.8 DB
T6	ALBUQUERQUE	THREE METER	L6/6	49.1	294.6	15.2 DB
T7	ALBUQUERQUE	THREE METER	L7/6	53.9	323.4	15.6 DB
T8	ALBUQUERQUE	THREE METER	L6/12	49.1	589.2	18.2 DB
T9	ALBUQUERQUE	THREE METER	L6/25	49.1	1227.5	21.4 DB
TF	ALBUQUERQUE	THREE METER	L6/50	49.1	2455	24.4 DB
TH	ALBUQUERQUE	THREE METER	L6/100	49.1	4910	27.4 DB
F1	ALBUQUERQUE	FIVE METER	L1/6	0.63	3.78	-3.7 DB
F2	ALBUQUERQUE	FIVE METER	L2/6	0.78	4.68	-2.8 DB
F3	ALBUQUERQUE	FIVE METER	L3/6	1.51	9.06	0.08 DB
F4	ALBUQUERQUE	FIVE METER	L4/6	3.36	20.16	3.55 DB
F5	ALBUQUERQUE	FIVE METER	L5/6	10.14	60.84	8.35 DB
F6	ALBUQUERQUE	FIVE METER	L6/6	19.67	118.02	11.2 DB
F7	ALBUQUERQUE	FIVE METER	L7/6	54.41	326.46	15.6 DB
F8	ALBUQUERQUE	FIVE METER	L6/12	19.67	236.04	14.2 DB
F9	ALBUQUERQUE	FIVE METER	L6/25	19.67	491.75	17.4 DB
FF	ALBUQUERQUE	FIVE METER	L6/50	19.67	983.5	20.4 DB
FH	ALBUQUERQUE	FIVE METER	L6/100	19.67	1967	23.4 DB