Gigacycle Fatigue in Horns

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Outline

- The MiniBooNE horn and my evolving understanding of fatigue
- Facts of fatigue
- Theoretical understanding of fatigue *for design*
  - Fatigue factor of safety and confidence limits
  - The difference between ferrous and non-ferrous materials
- Brief history of fatigue testing
  - Old technology
    - RR Moore machines,etc
  - New Technology
    - Ultrasonic fatigue testing
- Where gigacycle fatigue testing is relevant today
- Future horn applications

The MiniBooNE Horn

- The MiniBooNE experiment has been running since 2004 (8 years!) on the second of three horns built
- The first horn failed at 96 million pulses
  - It failed by galvanic corrosion that lead to a water leak and a ground fault
- The second horn now has **386 Megacycles** on it
  - The galvanic corrosion condition that killed the first horn was eliminated
  - The only problems this horn has had are failures of subsystems like water pumps

The MiniBooNE horn on the test stand at MI-8

Horn fatigue design in 1999

- MiniBooNE could not afford more than a one-horn system and it had to live *forever*.

- Horns have a complex stress cycle structure because the beam and current pulses are different lengths
  - Thermal stresses and magnetic stresses peak at different times

Horn fatigue design in 1999 cont'd

- We analyzed the stress cycle by superimposing quasi-static stresses from a 2D axisymmetric FEA model
  - It was a time consuming and painful process
  - We did not have the computational power then to do a true transient solid model including all effects simultaneously—*we really don't now either*
    - Ichikawa-san has since done transient FEA on solid T2K horn models to look at the symmetry of the magnetic field from current distribution
    - People are starting to use multiphysics modelers like Comsol on horns
- I could not find any data on aluminum that went past 5E8 cycles in 1999.

Facts of Fatigue

- Parts fail at lower* stresses than yield stress when the load is applied and removed more than once.
  - More cycles, lower stress at failure

  *Some materials (like annealed steel) increase in strength from cyclic stress. (We don't care about this for horns.)
- You can do things to parts that can either decrease or increase the fatigue life of a part
  - Some coatings and platings increase fatigue life, others reduce it
  - Environmental conditions can reduce fatigue life
- We are limited in design by lack of **data**, not by material properties

Horn Facts of Fatigue

- Inner conductors heat up and expand putting them in compressive loading most of the time
  - This effect can be modified by choices at horn assembly
  - Inner conductors are susceptible to buckling because they are thin
    - Spiders protect ICs from buckling
- Because the inner conductor is in compression, the outer conductor is in tension
  - Outer conductors are always thick so stresses are very low
- End caps are thin and in complicated bending states
- The magnetic field tries to turn the cylinder of the horn into a sphere
  - Radial inward pressure on the IC, outward on the OC

Horn Fatigue Facts 2

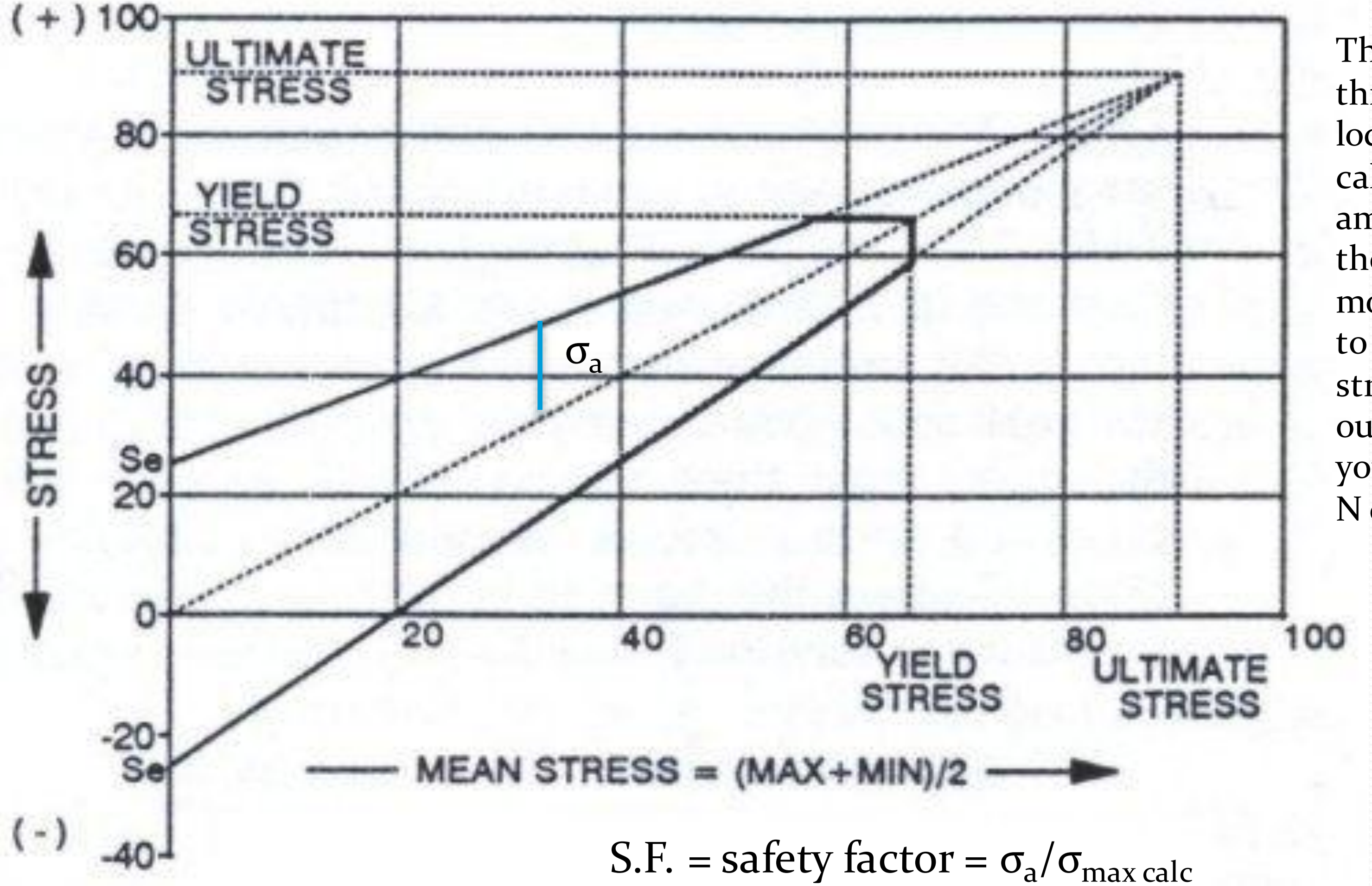
- Because of the mean compressive stress in the inner conductor, fatigue will not happen here first (in general)
  - Compression tends to close fatigue cracks
- Fatigue failure happens first in areas that alternate between compressive (or zero) and tensile stress
  - The MiniBooNE downstream end cap is the most likely place on the horn to fail in fatigue
  - *This is what I'm waiting for!*
- If the compressive stress in the IC is high enough to cause buckling (with associated bending stresses,) then failure can happen along the IC
  - This may be what killed the first K2K horn

“Primitive” Theoretical Understanding of Fatigue

- Undergraduate engineering (in my day!) taught that there was a fundamental difference between ferrous and non-ferrous metals
  - Ferrous alloys could exhibit an “endurance limit”
  - If the metal was stressed below the endurance limit it would never fail in fatigue (forever = 10^7 cycles)
  - Non ferrous alloys never exhibited an endurance limit
- The modified Goodman diagram can be used to calculate a safety factor for fatigue
- I could not figure out how the safety factor could be used to predict the “extra” life of a part
  - We developed a statistical model from MIL-SPEC data

Modified Goodman Diagram

σ_a = stress amplitude



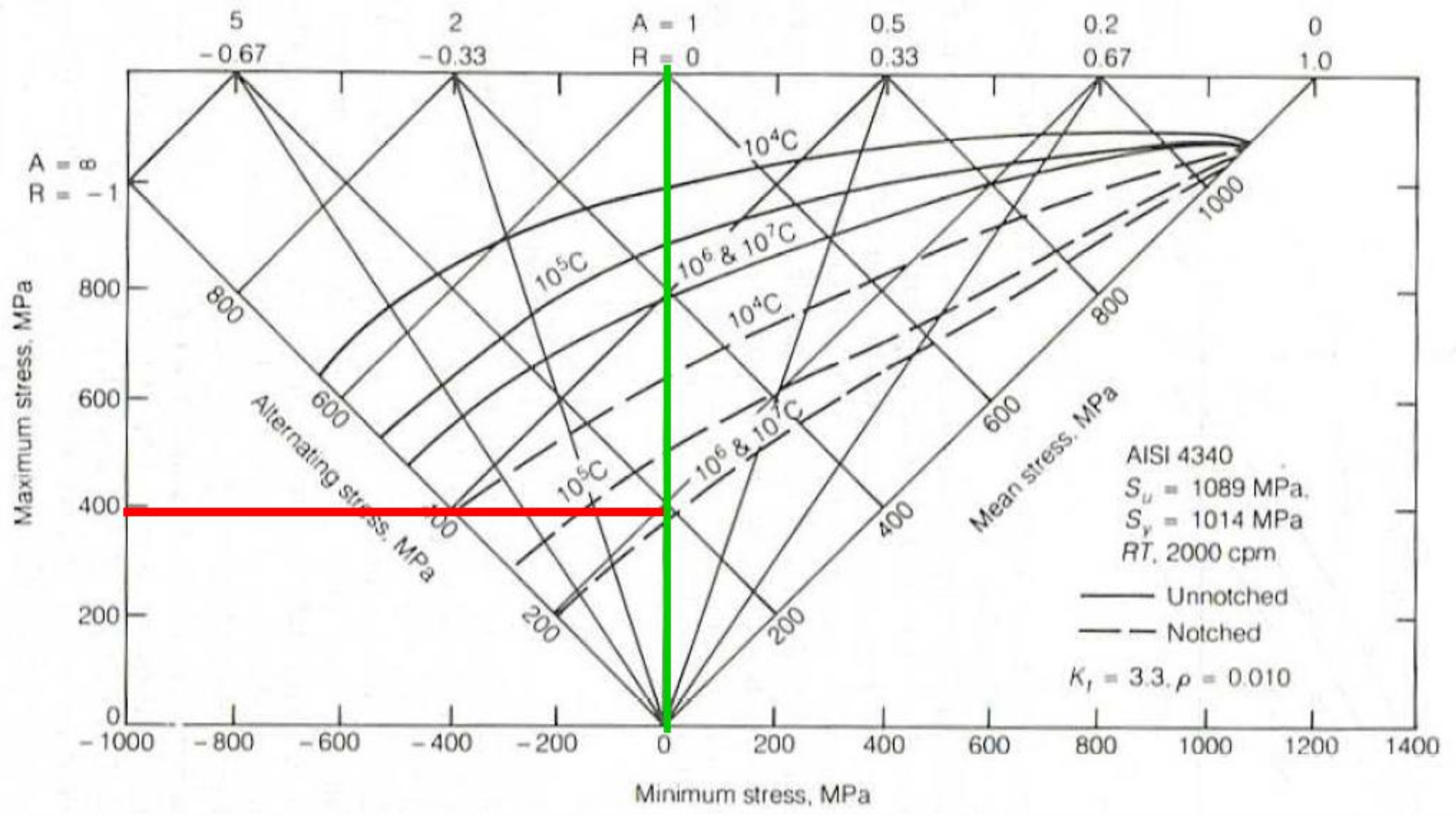
The boundary of this plot is a failure locus. If the calculated stress amplitude is inside the locus, you get more than N cycles to failure. If the stress amplitude is outside the locus, you get fewer than N cycles to failure.

S.F. = safety factor = $\sigma_a/\sigma_{\text{max calc}}$

This curve represents the locus for a single fatigue lifetime of N cycles

From: http://www.ckit.co.za/secure/conveyor/papers/troughed/modern/modern.htm

Example Master Fatigue Diagram for 4340 steel



Fatigue testing yesterday and today

- Fatigue testing used to require samples chucked in a machine similar to a lathe and mechanically stressed at a rate of <200 cycles per second until they broke
- Getting to megacycles took a long time. Gigacycles was out of the question
- The development of high speed fatigue testing started early in the 20th century, but didn't become cheap and practical until 1950 when Mason used piezoelectric transducers at 20 kHz
  - Higher frequencies have been tried but modern systems typically run at 20 kHz

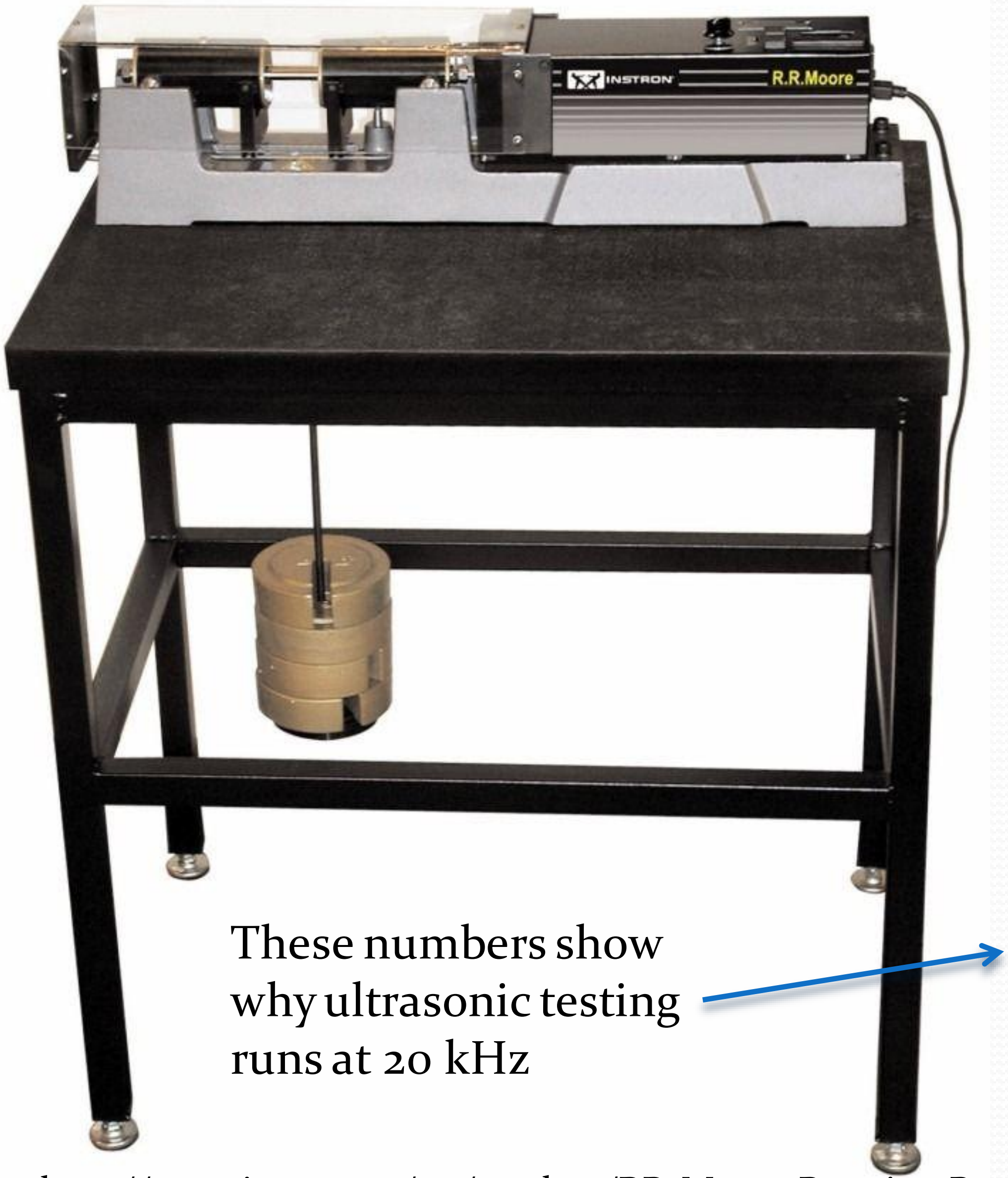
Fatigue Testing Standards

- Test standards for traditional fatigue testing are available such as at:
  - http://www.astm.org/Standards/fatigue-and-fracture-standards.html (for ASTM standards)

and:

  - http://www.iso.org/iso/home/store/catalogue_tc/catalogue_tc_browse.htm?commid=53562 (for ISO standards)
- **One problem of ultrasonic fatigue testing is lack of standards.**
- Ultrasonic testing is more experimental but easy to set up a custom test stand

R.R. Moore rotating beam fatigue testing machine by Instron



This is a traditional fatigue testing machine using a specimen in bending rotated about its axis

It operates at 500-10,000 RPM. (This is fast for this type of machine.)

This translates to a maximum frequency of 167 Hz. (Typical machines operate at 20 Hz.)

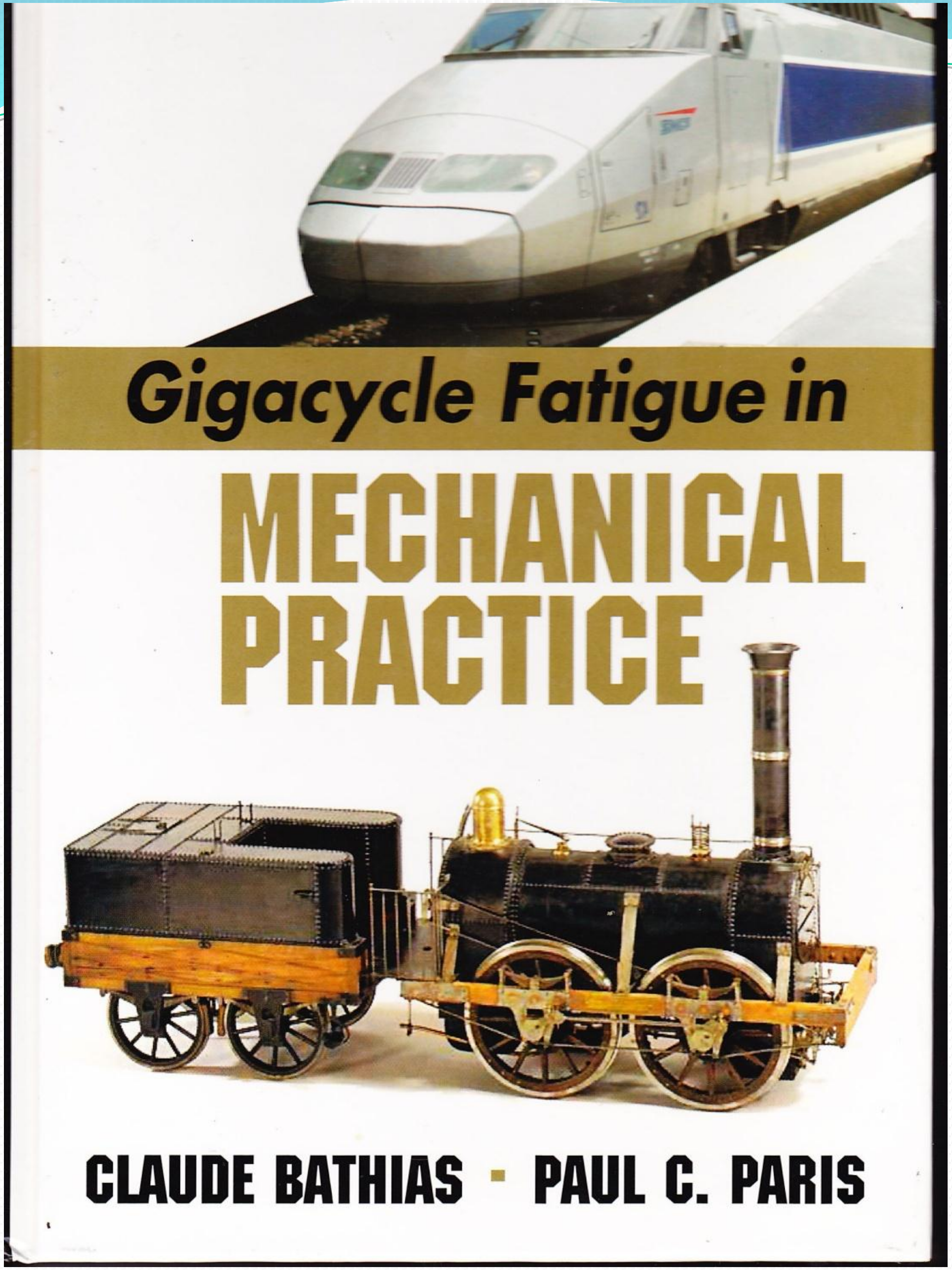
At 500 RPM it takes 3.8 years to get to 10^9 cycles

At 10,000 RPM it takes 70 days to get 10^9 cycles. (I don't know if the machine can run at that speed for that long.)

10^{10} cycles = 700 days, 2 years

These numbers show why ultrasonic testing runs at 20 kHz

http://www.instron.us/wa/product/RR-Moore-Rotating-Beam-Fatigue-Testing-System.aspx

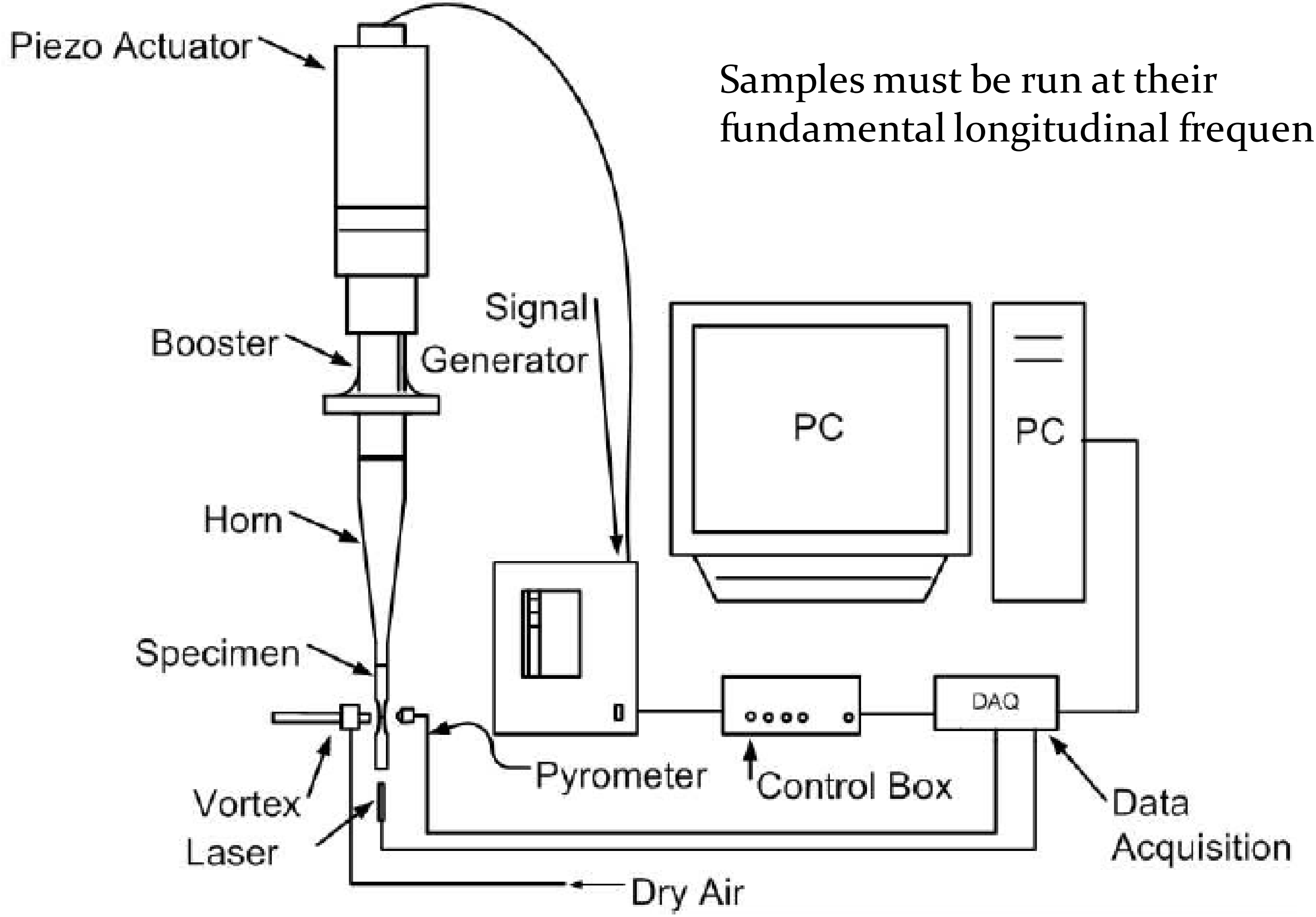


Much of what I learned about gigacycle fatigue came from this book. Claude Bathias' name features prominently in any searches on ultrahigh cycle fatigue.

Ultrasonic fatigue test machines must include the following three things:

1) A power generator that outputs a 20 kHz sinusoidal electrical signal
2) A piezoelectric or magnetostrictive transducer that transforms the electrical signal into longitudinal ultrasonic waves of the same frequency
3) An ultrasonic horn that amplifies the transducer vibration to achieve the required strain in the specimen

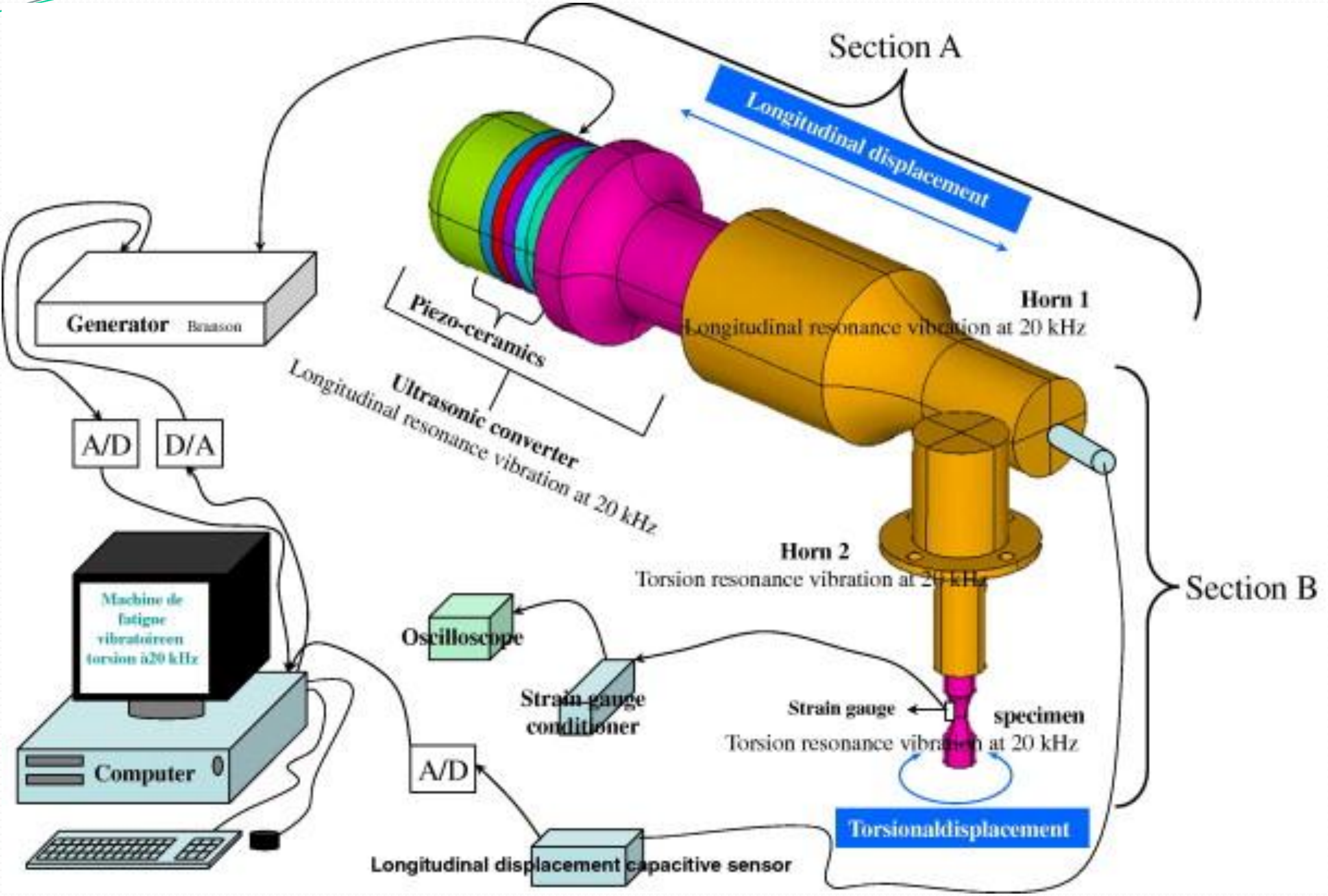
Layout of an ultrasonic testing machine for axial loading



Samples must be run at their fundamental longitudinal frequency

From: https://uhra.herts.ac.uk/dspace/bitstream/2299/8373/1/Paper_VHCF5_102.pdf

Diagram of an ultrasonic torsional testing machine



Marines-Garcia,Israel. Doucet,Jean-Pierre. Bathias,Claude. "Development of a new device to perform torsional ultrasonic fatigue testing.“ <u>International Journal of Fatigue</u>, Volume 29, Issues 9–11, Sep–Nov 2007, Pages 2094–2101

Some issues with ultrasonic fatigue testing

- Data from slower traditional testing may not match over the same range when done ultrasonically
- Temperature of the sample goes up rapidly in ultrasonic testing—for megacycle fatigue tests, not gigacycles
  - Temperature must be monitored and the test stopped when it exceeds a given value, or continuous cooling must be supplied
- Samples with a free end are tested at R=-1, fully reversed stress
  - To modify the stress cycle for other values of R you need a cone and transducer at both ends of the sample

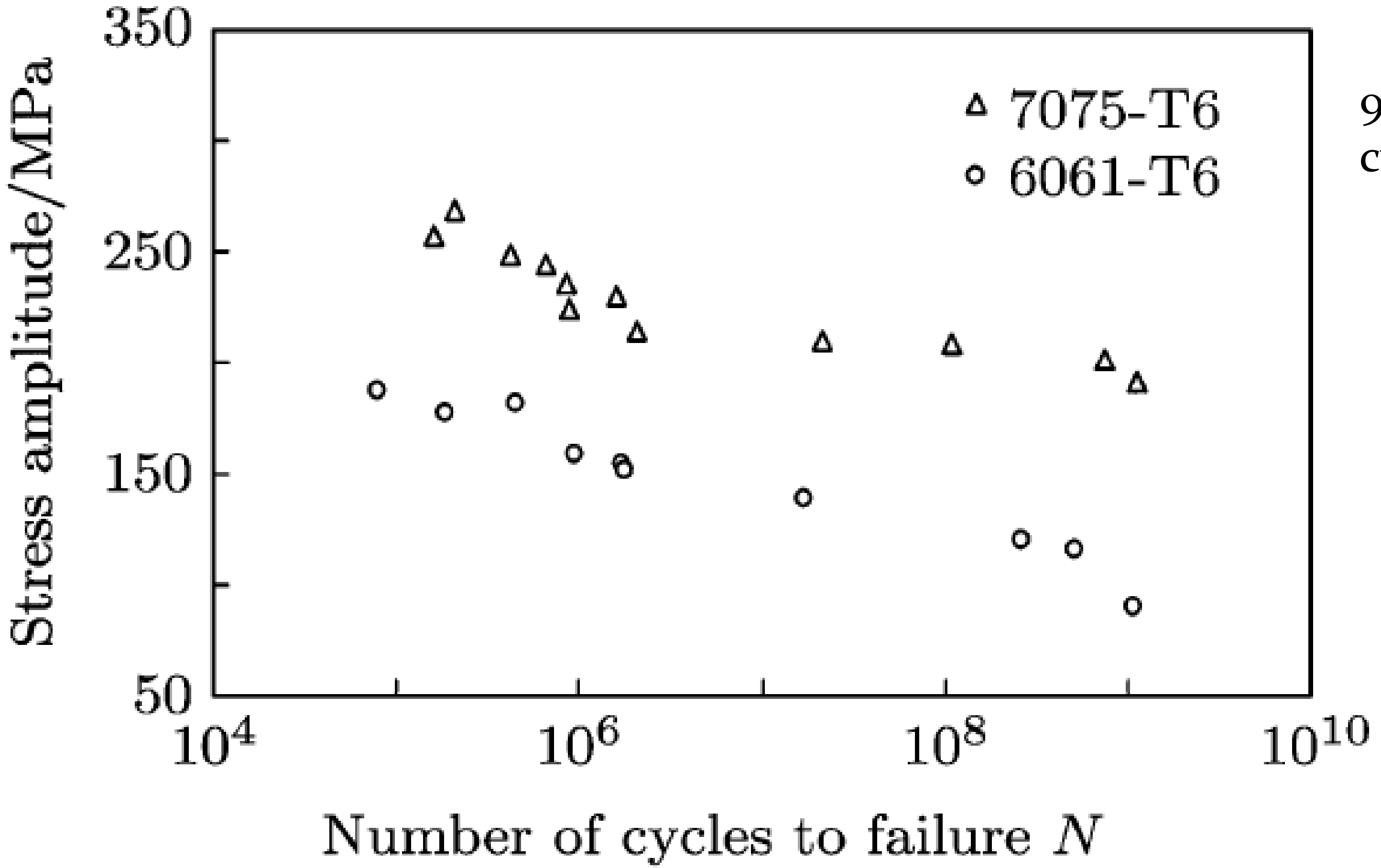
Ultrasonic fatigue testing issues cont’d

- Sample shapes and cones must be designed with FEA to create shapes with the right natural frequencies to achieve resonance in the sample
    - FFTs can be used to scan the device to determine the natural frequencies
- Temperature variations cause changes in the natural frequency of the sample
    - Feedback loops must be used on the frequency to keep the stress constant
- Some machines measure the displacement with strain gages, some with laser transducers
    - Strain gages are very sensitive to temperature changes

What has been learned from ultrasonic fatigue testing

- **There is no such thing as infinite life in any metals including ferrous alloys**
  - High cycle fatigue is data up to 10^7 cycles. Ultrahigh cycle fatigue starts there and goes up to 10^{10} cycles and beyond.
- Fatigue strength of steels plateaus between 10^6 -10^8 cycles, but then drops above 10^8 cycles
  - *This was taken to be the endurance limit*
- Fatigue failure occurs from cracks initiated **at the surface** of the material below 10^7 cycles
- Above 10^7 cycles cracks initiate **below the surface** in the bulk material (probably at inclusions) (with exceptions)
  - Failure mechanism not fully understood yet

Plot of stress vs cycles to failure of Al alloys in ultrasonic fatigue at 20 kHz



90 MPa at 10^9 cycles = 13.05 ksi

Q. Y. Wang, N. Kawagoishi, and Q. Chen, Int. J. Fatigue, 1572 (2006)

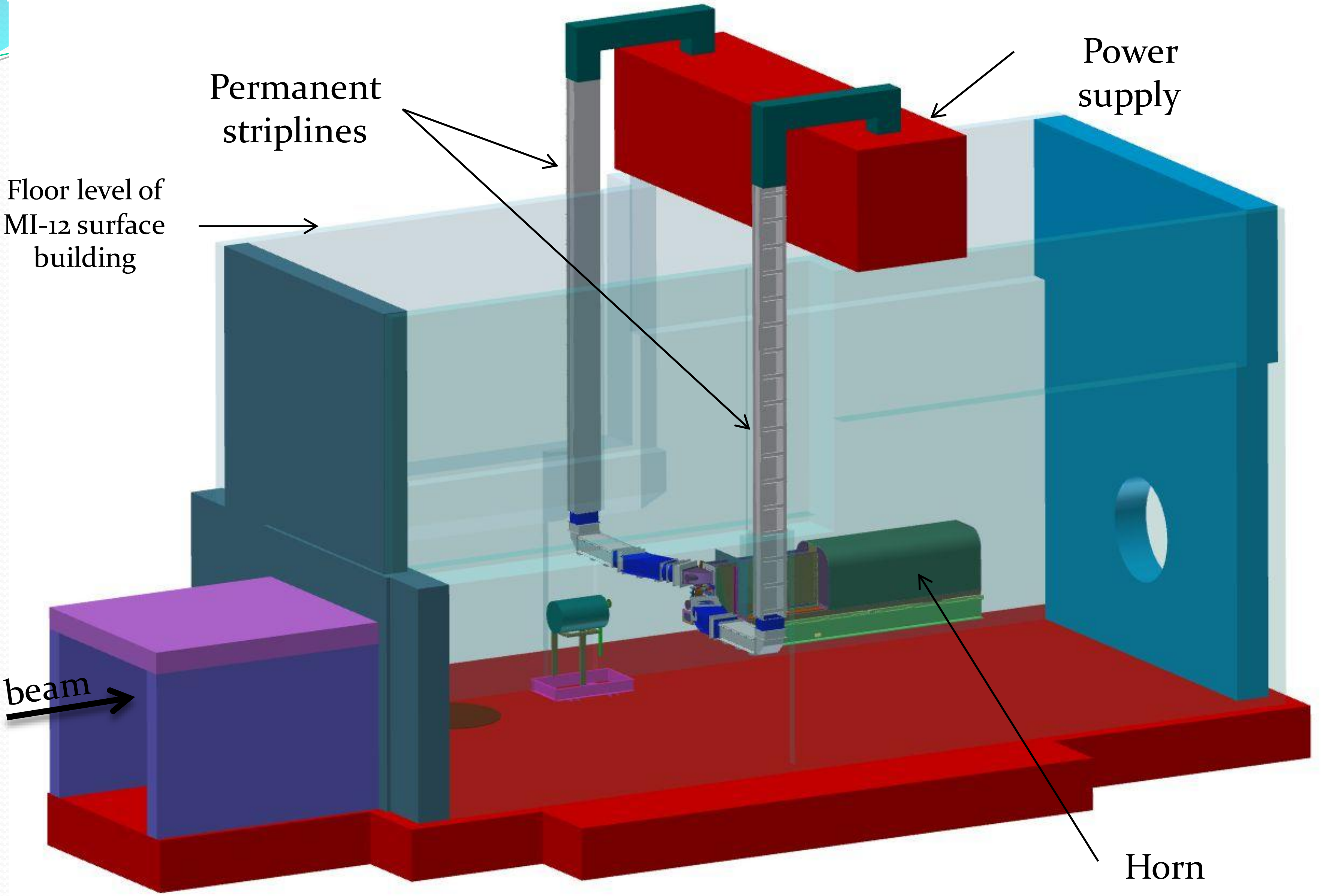
Comments about ultrasonic test data

- There are only a few data points so it is difficult to create a statistical model with the data shown
- Given how easy it is to set up ultrasonic fatigue testing, we (the horn community) should be running these tests to create a better data set
- Not enough attention has been paid to Al 6061 yet in the ultrasonic testing literature
- Striplines are made from Al 6101 so that material needs testing too

Where Gigacycle fatigue is relevant to horns today

- MiniBooNE is still running
- MicroBooNE uses the same beam line and horn
- MicroBooNE is approved to run for 2-3 years, 6.6E20 POT
- The MiniBooNE target hall is now called the "Booster Neutrino Beam" (BNB) target hall
- The BNB will be run for many years from now
- The target hall total system has already seen .48 Gigacycles of pulsing from the power supply to the horn
  - Would be more but it's been shut down since 4/12 until spring 2013.
- European projects like Euronu want to run at 50 Hz!!

View of the horn installed in MI-12



Permanent striplines

Power supply

Floor level of MI-12 surface building

beam

Horn

Walls of the underground enclosure rendered transparent, shielding blocks invisible

Aging striplines in the BNB target hall

- The permanent striplines in MI-12 have seen every pulse of both horns, about .5 gigacycles
- I don’t know how many gigacycles it will take for a fatigue failure of these striplines
- Stresses are low so the life could be $>10^9$ cycles
  - The failure will be from cracking initiated at a sub-surface defect
- I don’t know exactly where to expect such a failure
  - Long stretches of stripline have the same stress levels
- It will likely be a costly repair when one does happen

Future Horn applications

A 50 Hz horn designed by Stephane Rangod for a neutrino factory

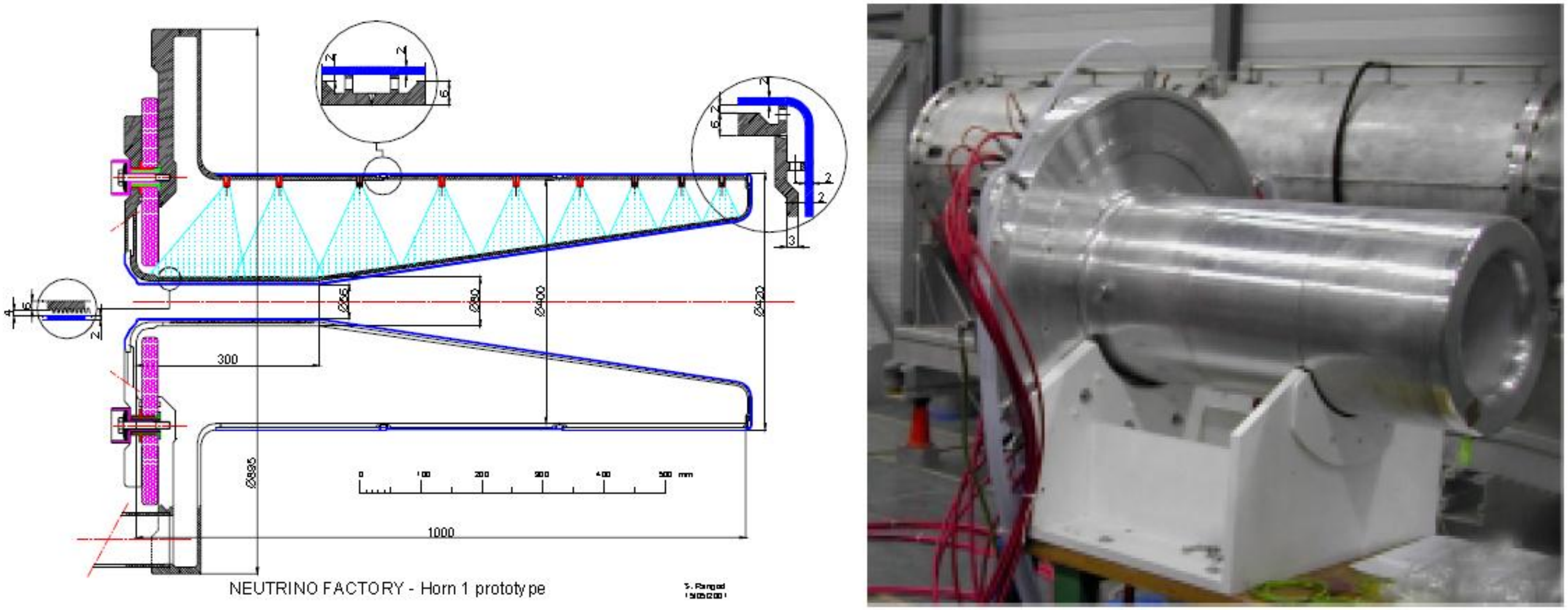
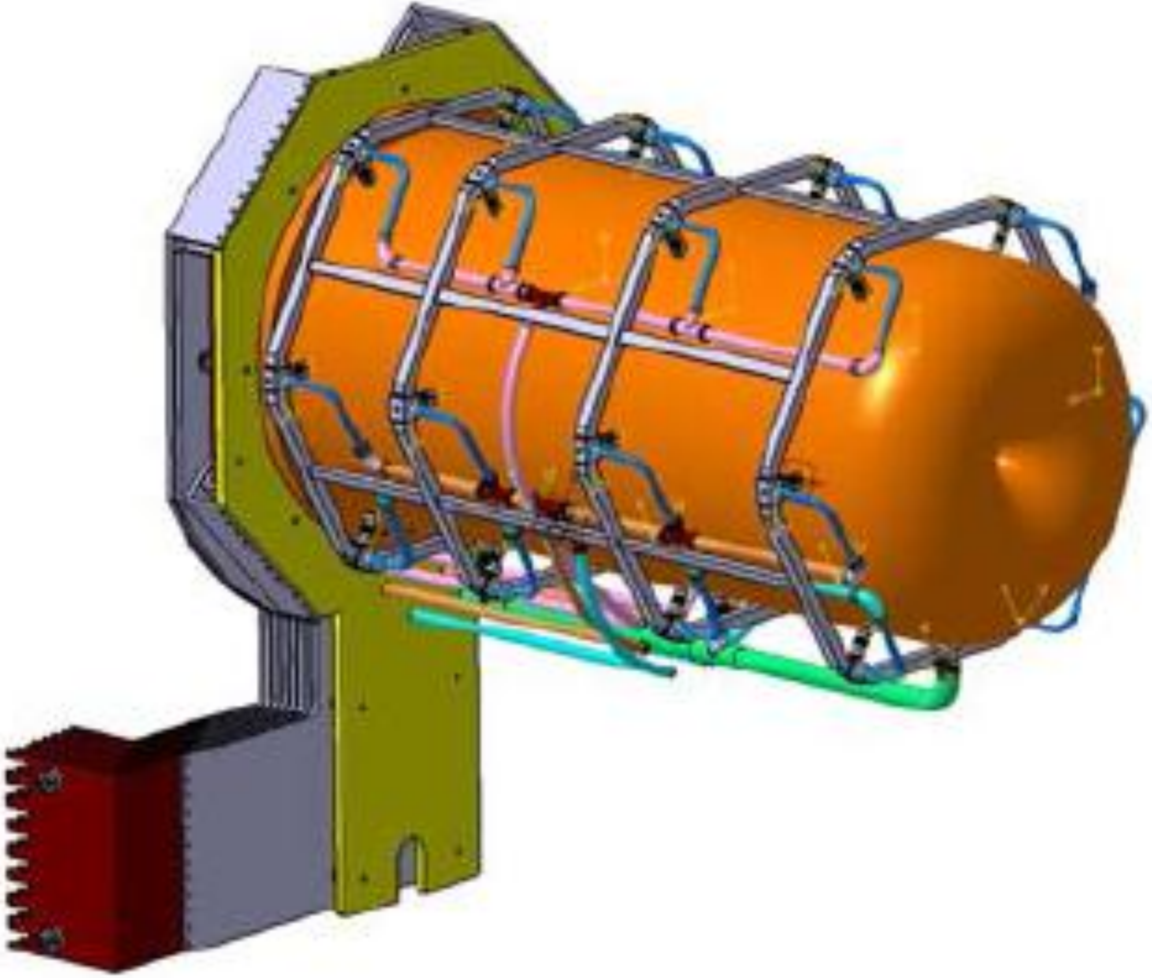


Figure 5 : Left: horn design for a neutrino factory or low energy high intensity neutrino beam;

http://dpnc.unige.ch/users/blondel/fondsnational/report3abnu.pdf

Newer concept for a 4 horn system operating at 12.5 Hz based on the MiniBooNE horn design



http://www.comsol.com/cd/direct/conf/2012/papers/12068/12561_lepers_paper.pdf

Final comments

- We were not limited by aluminum in the design of the MiniBooNE horn, we were limited by the **data** we had about aluminum
  - The material has proved to be better than we thought
- The first MiniBooNE horn failure was **not** fatigue related at all, but corrosion related
- We must be even more careful in the design of auxiliary systems because they can kill a horn before fatigue will
- We should be expanding the fatigue data set for the materials we are interested in

Backup slides

Sources of Fatigue Data for AL 6061-T6 used in the MiniBooNE analysis

- MIL-SPEC Handbook #5, Metallic Materials and Elements for Aerospace Vehicles
- ASM Metals Handbook Desk Edition
- ASM Handbook Vol. 19, Fatigue and Fracture
- “Aluminum and Aluminum Alloys”, pub. by ASM
- “Atlas of Fatigue Curves”, pub. by ASM
- “Fatigue Design of Aluminum Components and Structures”, Sharp, Nordmark and Menzemer

How well do sources agree?

- For unwelded, smooth specimens, R=-1, room temperature, in air, $N=5*10^7$

MIL-SPEC	$\sigma_{max}=13$ ksi (89.6 MPa)
Atlas of Fatigue Curves	$\sigma_{max}=17$ ksi (117.1 MPa)
Fatigue Design of Al…	$\sigma_{max}=16$ ksi (110.2 MPa)
Metals Handbook ($N=5*10^8$)	$\sigma_{max}=14$ ksi (96.5 MPa)

- These numbers represent 50% probability of failure at $5*10^7$ cycles (except for the last one).
- The highest value is 30% higher than the lowest
  - Sources do not agree all that well

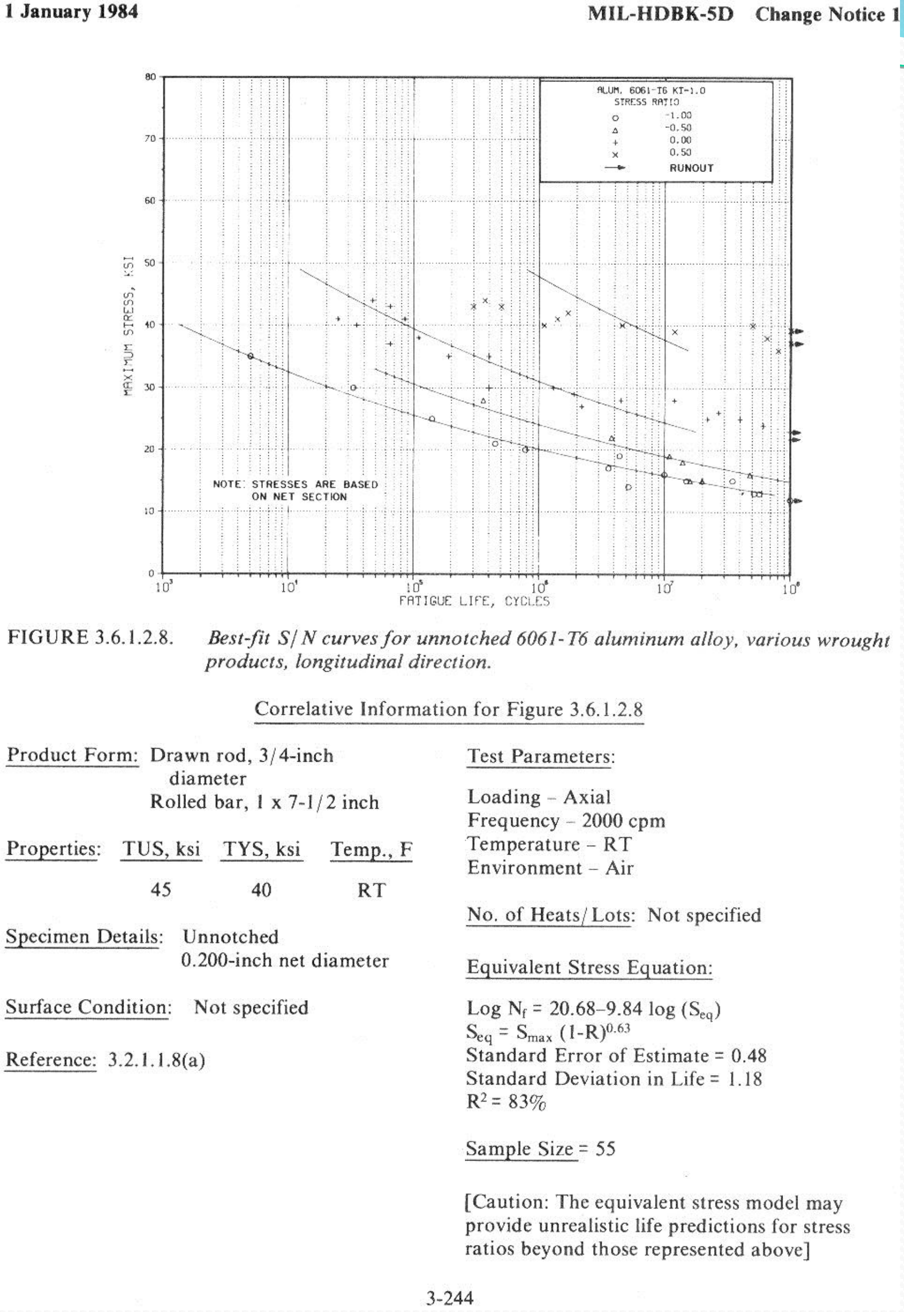
Determining the allowable stress

- To be sure that the horn would last to at least 200 Megacycles we compared the calculated stress from the FEA for every element in the model to an allowable stress: $S_{calc} \leq S_{allow}$
- The allowable stress was calculated by multiplying modifying factors to a base stress level because the fatigue strength changes with varying conditions of stress and environment
  - This method is outlined in Shigley's "Mechanical Engineering Design"
- $S_{allow} = S_{eq} * f_R * f_{moisture} * f_{weld}$
  - S_{eq} = 10 ksi (68.9 MPa) (from the statistical analysis shown later)

Effects that lower fatigue strength, 1: stress ratio

- The stress ratio influences fatigue strength:
  - Stress Ratio, R, is defined as the ratio of the minimum to maximum stress.
    - Tension is positive, compression is negative
  - $R=S_{min}/S_{max}$ varies from $-1 \le R \le 1$
    - $R = -1 \Rightarrow$ (alternating stress) $\sigma_{max}=16$ ksi
    - $R = 0 \Rightarrow (S_{min}=0)$ $\sigma_{max}=24$ ksi, (1.5X at R=-1)
    - $R = .5 \Rightarrow$ $\sigma_{max}=37$ ksi, (2.3X at R=-1)
  - These values are for $N=10^7$ cycles, 50% confidence
- Stress ratio is a variable modifier to maximum stress. Whole stress cycle must be known.
  - We used a large spreadsheet to calculate R for every element in the FE model

MIL-SPEC Data Showing Effect of R



1 January 1984

MIL-HDBK-5D Change Notice 1

FIGURE 3.6.1.2.8. *Best-fit S/N curves for unnotched 6061-T6 aluminum alloy, various wrought products, longitudinal direction.*

Correlative Information for Figure 3.6.1.2.8

Product Form: Drawn rod, 3/4-inch diameter
Rolled bar, 1 x 7-1/2 inch

Properties:	TUS, ksi	TYS, ksi	Temp., F
	45	40	RT

Specimen Details: Unnotched
0.200-inch net diameter

Surface Condition: Not specified

Reference: 3.2.1.1.8(a)

Test Parameters:

Loading – Axial
Frequency – 2000 cpm
Temperature – RT
Environment – Air

No. of Heats/Lots: Not specified

Equivalent Stress Equation:

$\text{Log } N_f = 20.68 - 9.84 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.63}$
Standard Error of Estimate = 0.48
Standard Deviation in Life = 1.18
$R^2 = 83\%$

Sample Size = 55

[Caution: The equivalent stress model may provide unrealistic life predictions for stress ratios beyond those represented above]

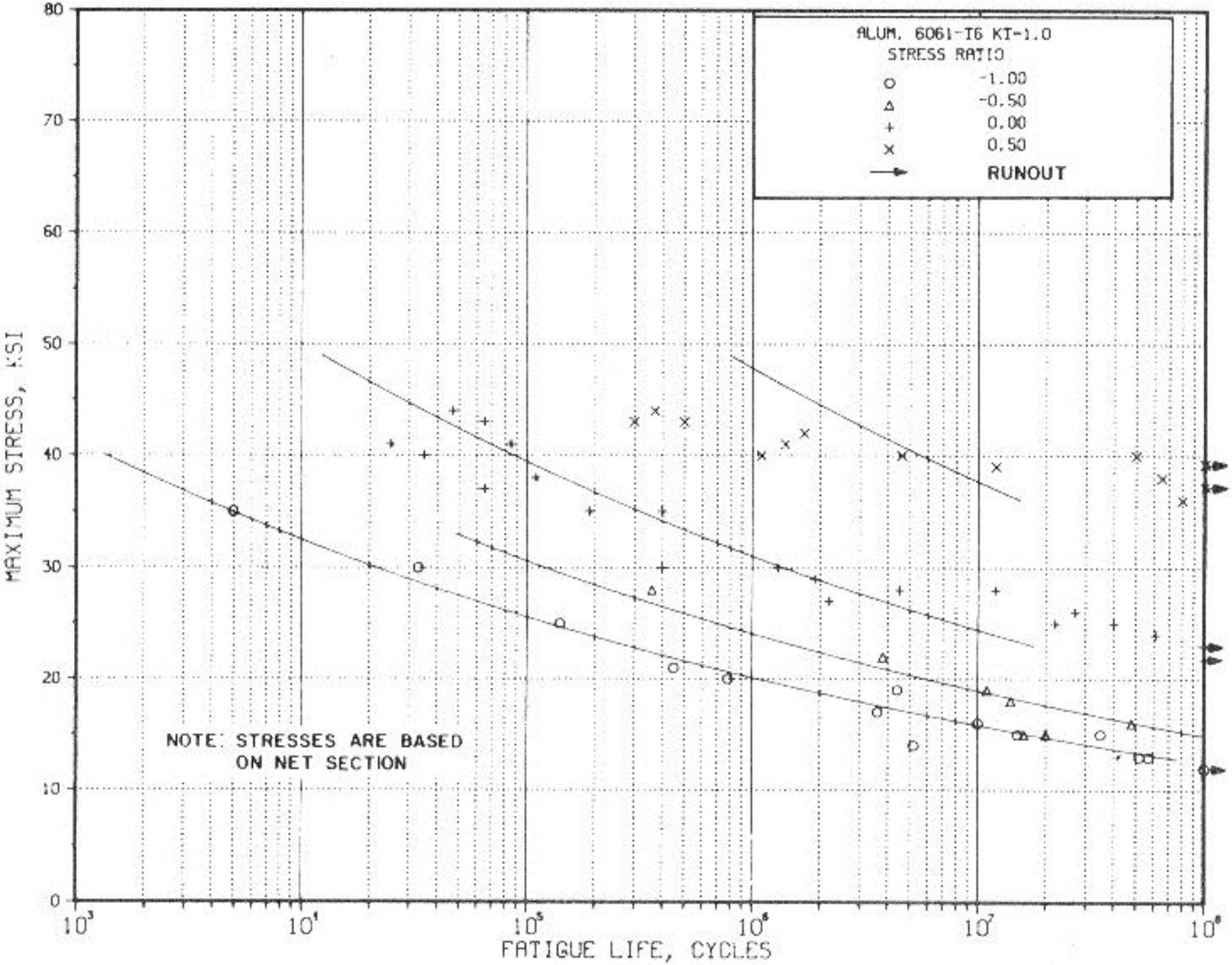
3-244

This is the page from the MIL-SPEC handbook that was used for the statistical analysis of the scatter in fatigue test data.

The analytical model assumes that all test data regardless of R can be plotted as a straight line on a log-log plot after all the data points are corrected for R.

The biggest problem with this data presentation style is that the trend lines represent 50% confidence at a given life and we needed >95% confidence of ability to reach 200 x 10^6 cycles.

Close-up of graph on previous slide

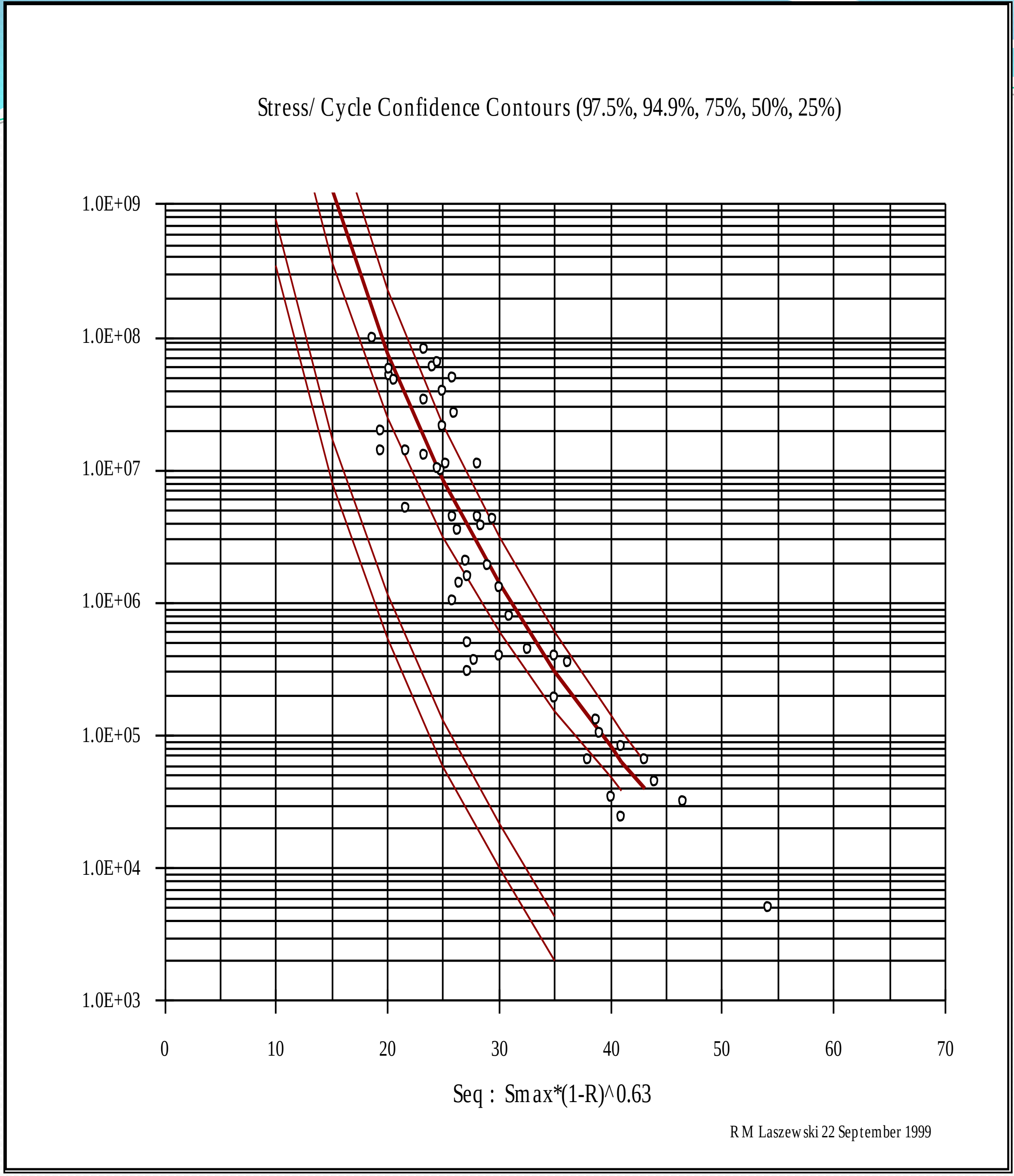


NOTE: STRESSES ARE BASED ON NET SECTION

Scatter in the maximum stress data in fatigue

- The MIL-SPEC data is a population of 55 test specimens that shows the extent of scatter in the test results.
  - Trend lines in the original graph indicate 50% chance of part failure at the given stress and life.
  - The source gave a method of plotting all the points on the same curve when corrected for R.
- We used statistical analysis to create confidence curves on this sample set.

Confidence Curves on Equivalent Stress data plot



This graph plots all of the MIL-SPEC data points corrected for R by the equation at bottom. The y axis is number of cycles to failure, the x axis is equivalent stress in ksi.

From this graph we concluded that the equivalent stress for >97.5% confidence at 2e8 cycles was 10 ksi.

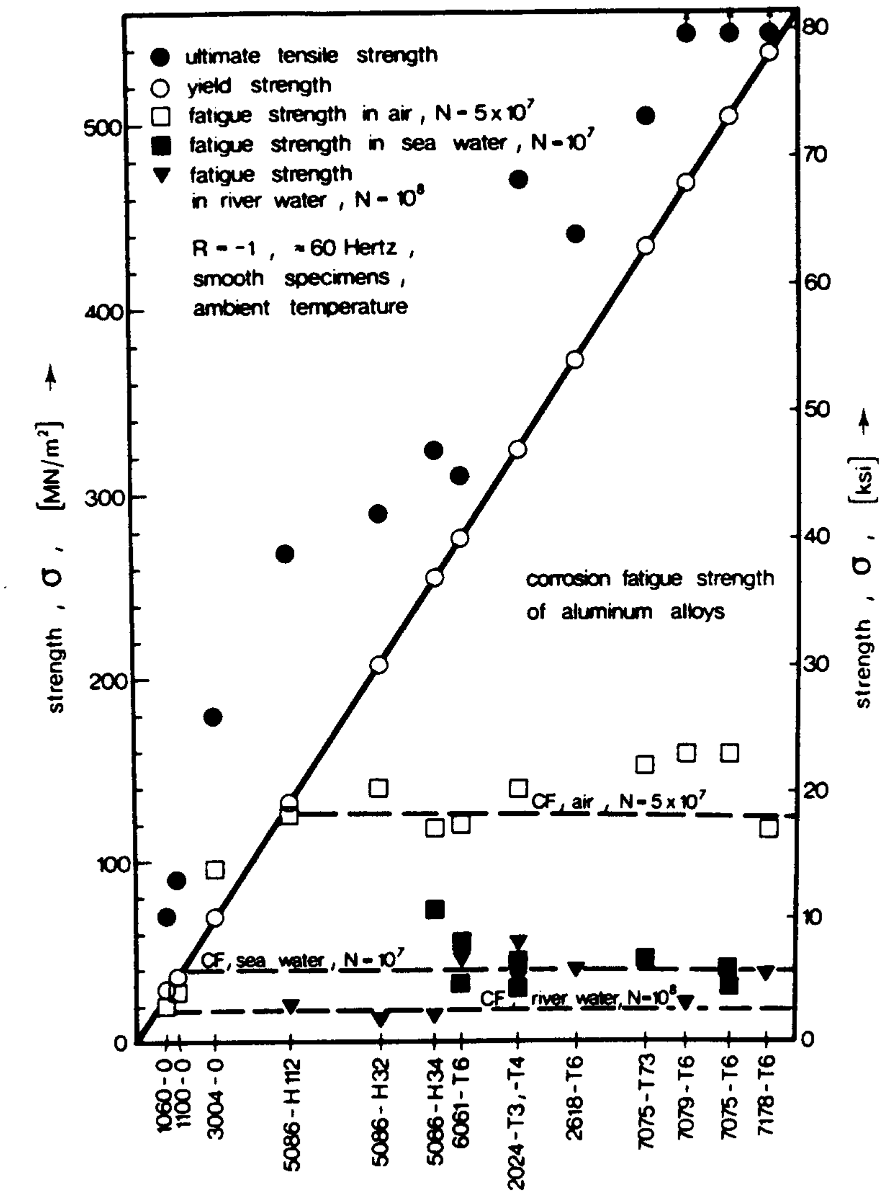
Calculation of stress ratio correction factor:

- First correction is for R, stress ratio
  - We determined that the minimum stress was thermal stress alone after the horn cooled between pulses just before the next pulse.
  - Maximum stress happened at time in cycle when magnetic forces and temperature were peaked “simultaneously” (some manual adding here)
  - R was calculated by taking the ratio in every horn element in the FEA of the maximum principal normal stresses at these two points in time
- $S_{max} = S_{eq}/(1\text{-}R)^{.63}$ therefore: $f_R = 1\ /(1\text{-}R)^{.63}$

Effects that lower fatigue strength, 2: Moisture

- Every horn is cooled by water running on aluminum
- Moisture reduces fatigue strength
  - For R = -1, smooth specimens, ambient temperature:
    - $N=10^8$ cycles in river water, $\sigma_{max}= 6$ ksi
    - $N=10^7$ cycles in sea water, $\sigma_{max}\sim 6$ ksi
      - Hard to interpret this data point
    - $N=5*10^8$ cycles in air, $\sigma_{max}= 14$ ksi
  - *See data source on next slide*
  - *Note curve of fatigue crack growth rate in humid air, second slide*
- We assumed that $f_{moisture} = 6/14 = .43$

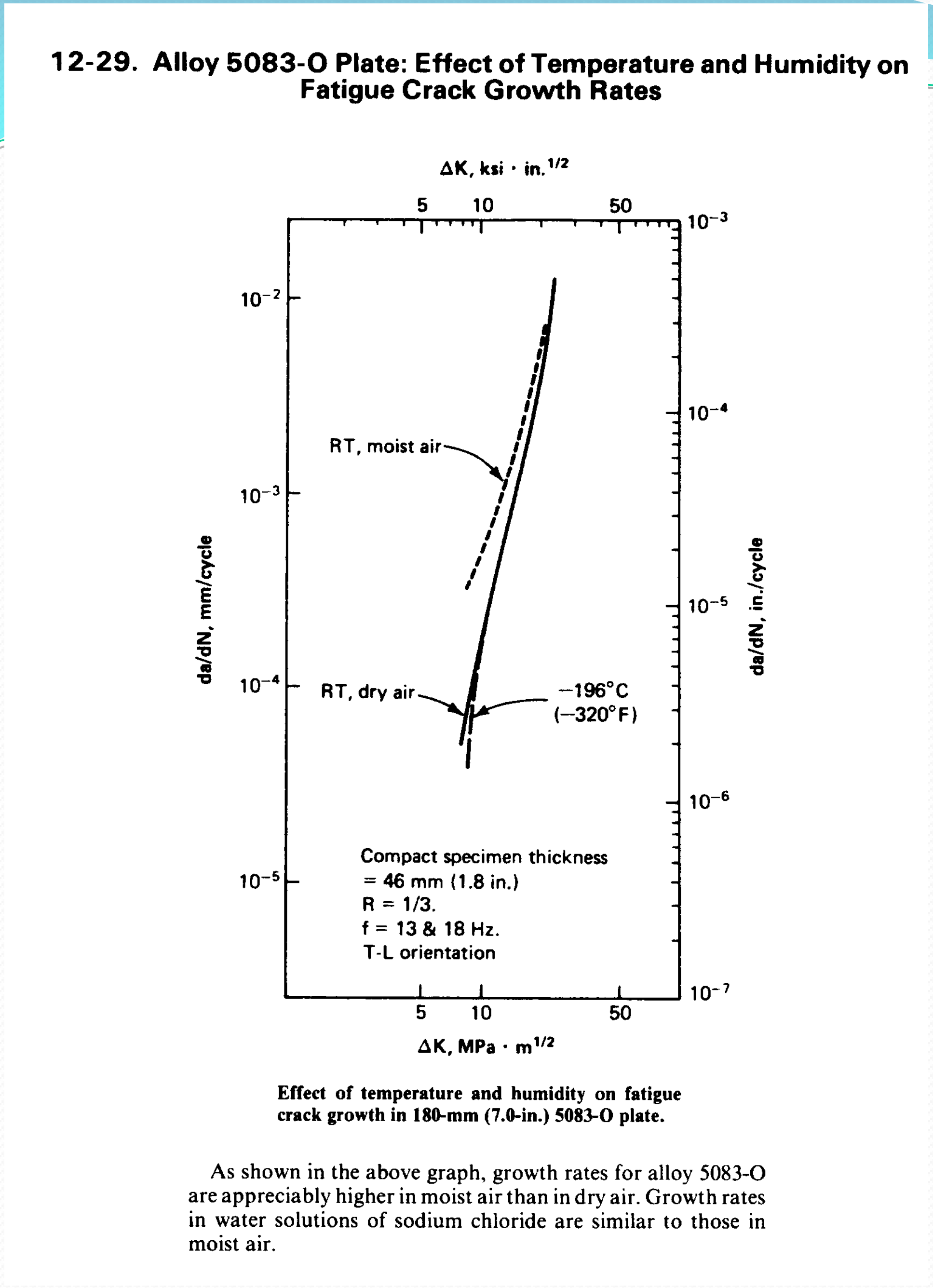
12-3. Aluminum Alloys (General): Yield Strength vs Fatigue Strength



ASM data on corrosion fatigue strength of many Al alloys

Graph from “Atlas of Fatigue Curves” showing that the corrosion fatigue strength of aluminum alloys is almost constant across all commercially available alloys, independent of yield strength.

Data from this graph was used to determine the moisture correction factor.



12-29. Alloy 5083-O Plate: Effect of Temperature and Humidity on Fatigue Crack Growth Rates

Effect of temperature and humidity on fatigue crack growth in 180-mm (7.0-in.) 5083-O plate.

As shown in the above graph, growth rates for alloy 5083-O are appreciably higher in moist air than in dry air. Growth rates in water solutions of sodium chloride are similar to those in moist air.

ASM data on effect of moisture on fatigue crack growth rate

Graph from “Atlas of Fatigue Curves”

This graph is for a different alloy than we are using, but the assumption is that moisture probably increases the fatigue crack growth rate for 6061 also.

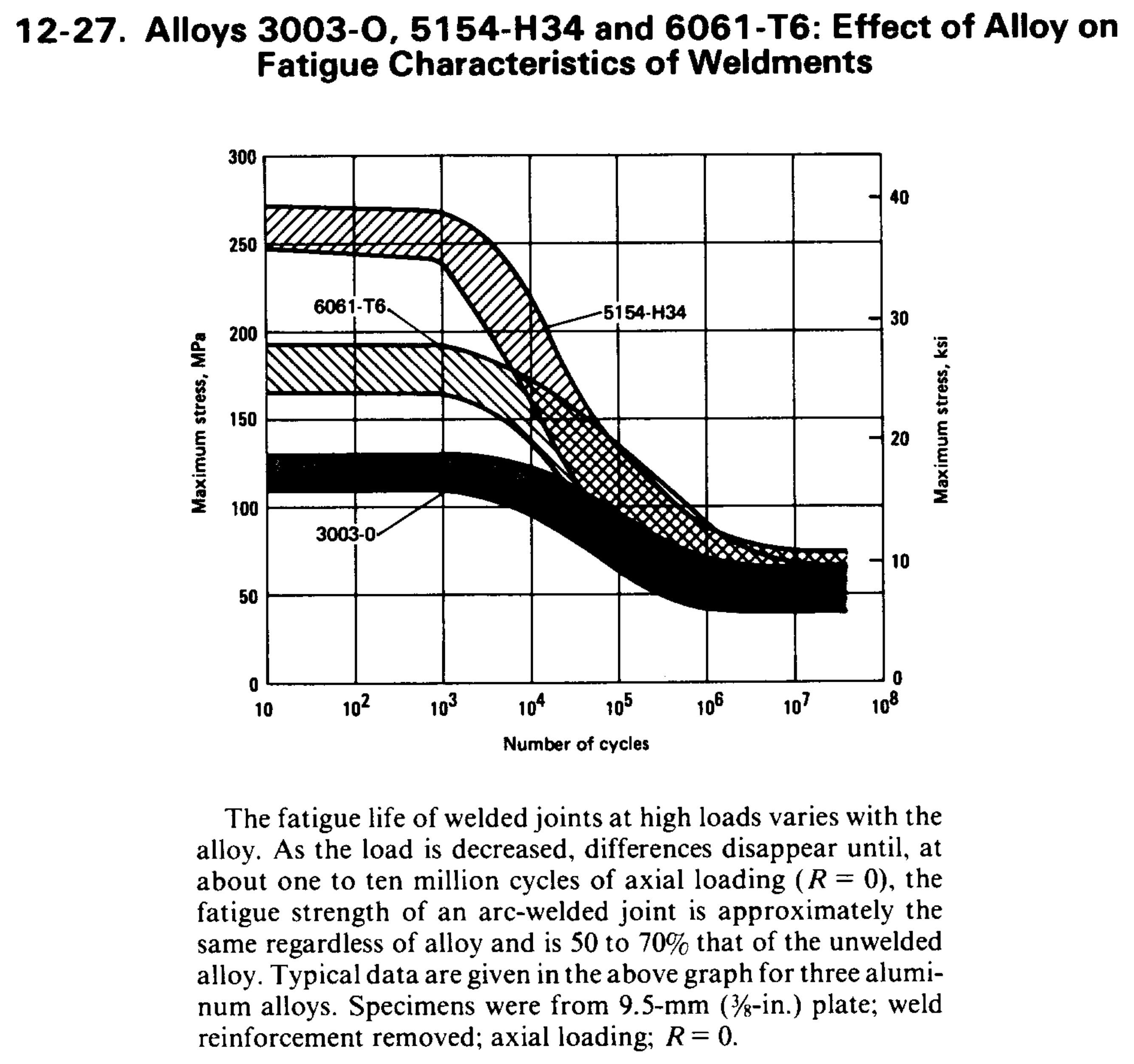
It was considered prudent to correct the maximum stress for moisture based on this curve and the preceding one.

Effects that lower fatigue strength, 3: Welding

- Welding influences fatigue:
  - Welded and unwelded specimens are tested

- **Welding reduces fatigue strength by ~1/2**
  - see graph on next slide

- $f_{weld} = .5$



12-27. Alloys 3003-O, 5154-H34 and 6061-T6: Effect of Alloy on Fatigue Characteristics of Weldments

The fatigue life of welded joints at high loads varies with the alloy. As the load is decreased, differences disappear until, at about one to ten million cycles of axial loading ($R = 0$), the fatigue strength of an arc-welded joint is approximately the same regardless of alloy and is 50 to 70% that of the unwelded alloy. Typical data are given in the above graph for three aluminum alloys. Specimens were from 9.5-mm (3⁄8-in.) plate; weld reinforcement removed; axial loading; $R = 0$.

ASM data showing effect of welding

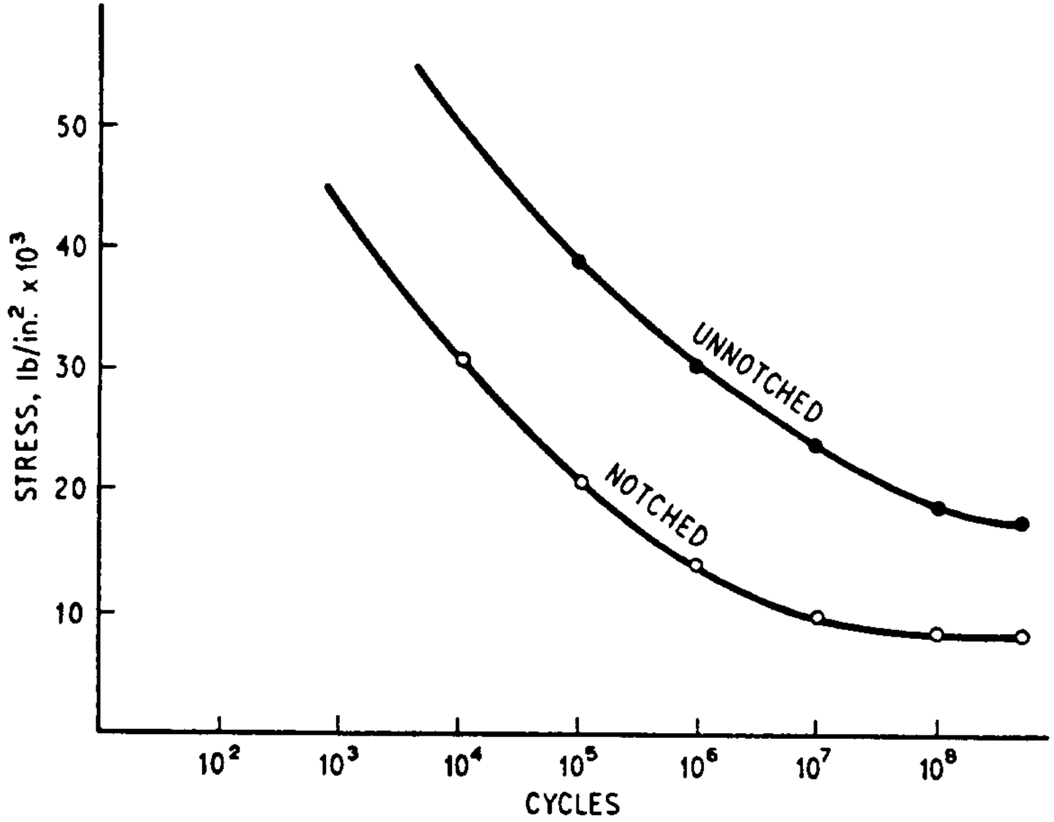
Graph from Atlas of Fatigue Curves

Effects that lower fatigue strength, 4: Notches

- Geometry influences fatigue:
  - Tests are done on “smooth” specimens and “notched” specimens
  - Smooth specimens have no discontinuities in shape
  - Notched specimens have a standard shaped discontinuity to create a stress riser in the material
- **Notches reduce fatigue strength by ~1/2**
  - see graph on next slide
- *We design inner conductors to be as notch-free as possible so there is no notch correction in our calculation of allowable stress* ($f_{notches} = 1.0$)

ASM data showing effect of notches on fatigue strength

12-7. Alloy 2014-T6: Notched vs Unnotched Specimens; Effect on Cycles to Failure



Effect of notch on fatigue of 2014-T6. As is true for most alloys, notches greatly reduce the fatigue properties of aluminum alloys.

Graph from Atlas of Fatigue Curves

Effects of Plating and coating (from NuMI experience)

- Anodizing reduces the fatigue strength of aluminum by 60%
    - The thickened oxide layer appears to offer more crack initiation sites
    - Anodizing is only used on NuMI outer conductors for insulation
        - Fatigue is not an issue on these because of their thickness
- Electroless nickel increases the fatigue strength
    - NuMI inner conductors are nickel plated
    - Multiple effects may contribute to this increase
        - The nickel may prevent the water from lubricating cracks

Effect of resonance

- MiniBooNE has a fast pulse structure
  - 10 pulses separated by 1/15 sec (15 Hz), then off until the start of the next pulse train
  - Pulse trains start on a 2 second cycle
- We needed to understand the natural frequency of the horn structure to make sure that pulses damped out before the next pulse train started
  - If the pulses happen at the natural frequency of the inner conductor resonance will cause the stress to go way up and the fatigue life will suffer
  - Modal analysis of the MiniBooNE horn indicated no benefit from bracing the inner conductor with spiders