The MiniBooNE Horn: Design and Operating Experience

NBI2003

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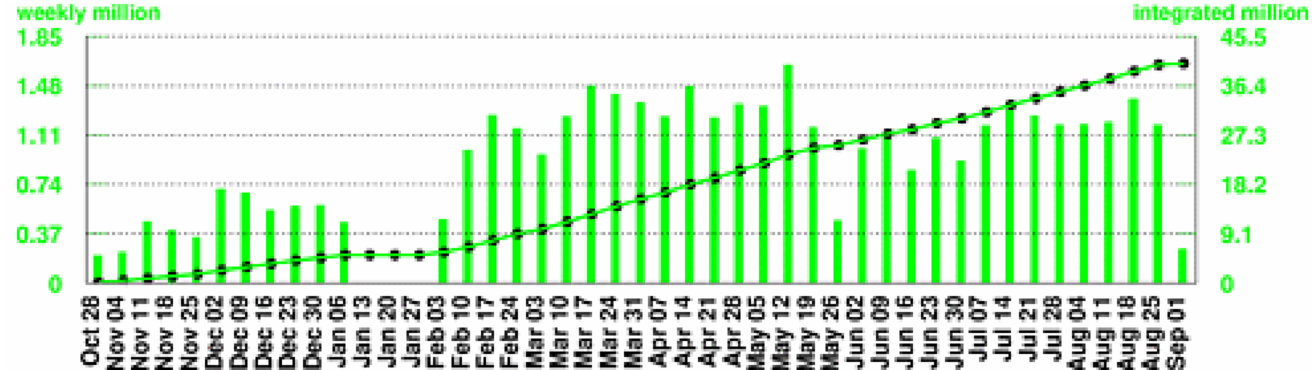
Topics to be covered:

- Brief history of horn operation
- Main design features that make the MiniBooNE horn unique
- Useful pre-prototypes we built
- Lessons learned from other horns
- New directions in MiniBooNE horn fabrication

Brief history of horn operation

- Horn assembly was completed in July of 2001. First pulse was on 7/27/01
- Horn was tested without beam or target for 10 million pulses, 170 kA, 5 Hz average rep.
- In 2/02, the Target was installed and another million pulses were added (no beam)
- Horn was installed in beam in 7/02 and took another 40 million pulses this year
- Total horn pulses: >51 million!!!

http://www-boone.fnal.gov/publicpages/progress_monitor.html

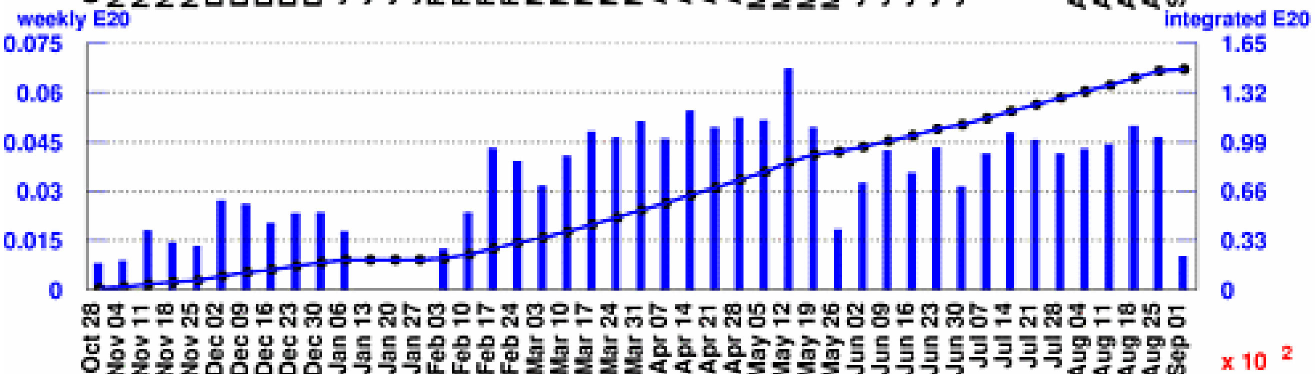


Number of Horn Pulses

To date: 40.54 million

Largest week: 1.63 million

Latest week: 0.25 million

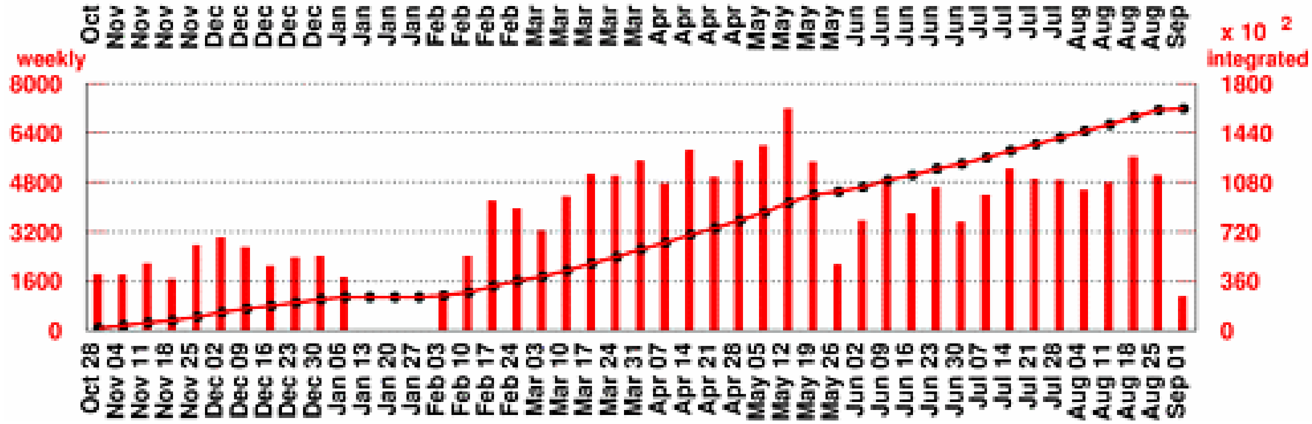


Number of Protons on Target

To date: 1.4769 E20

Largest week: 0.0671 E20

Latest week: 0.0101 E20

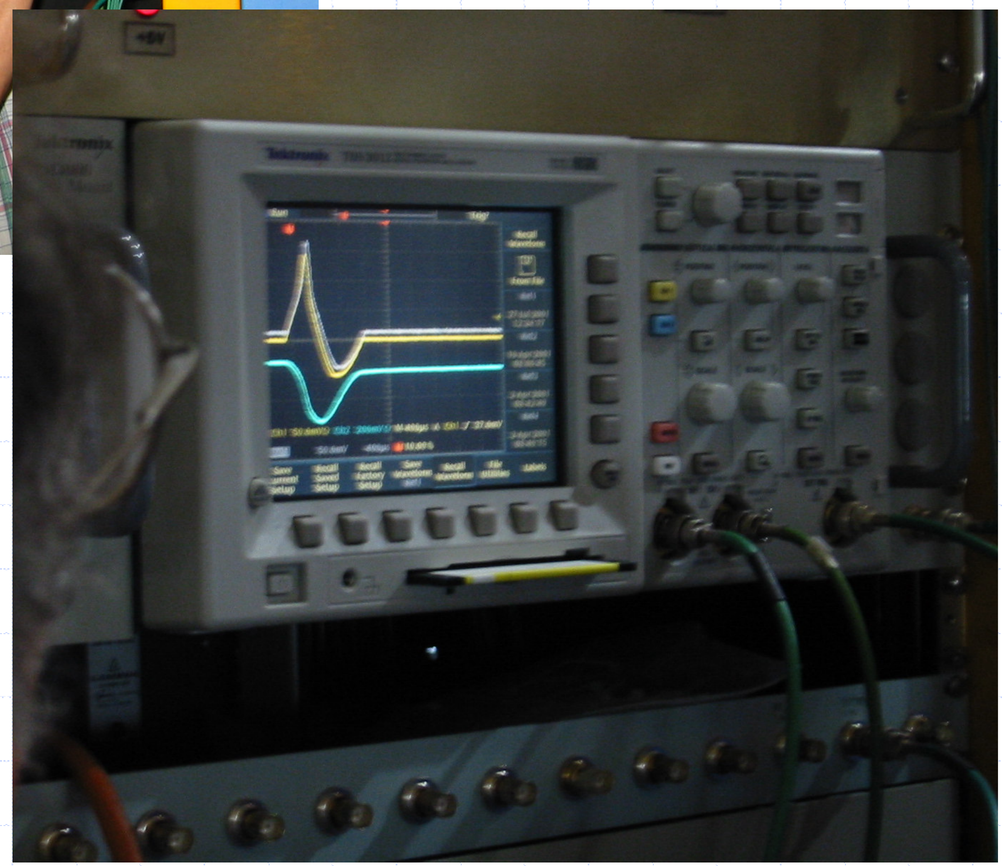


Number of Neutrino Events

To date: 161838

Largest week: 7192

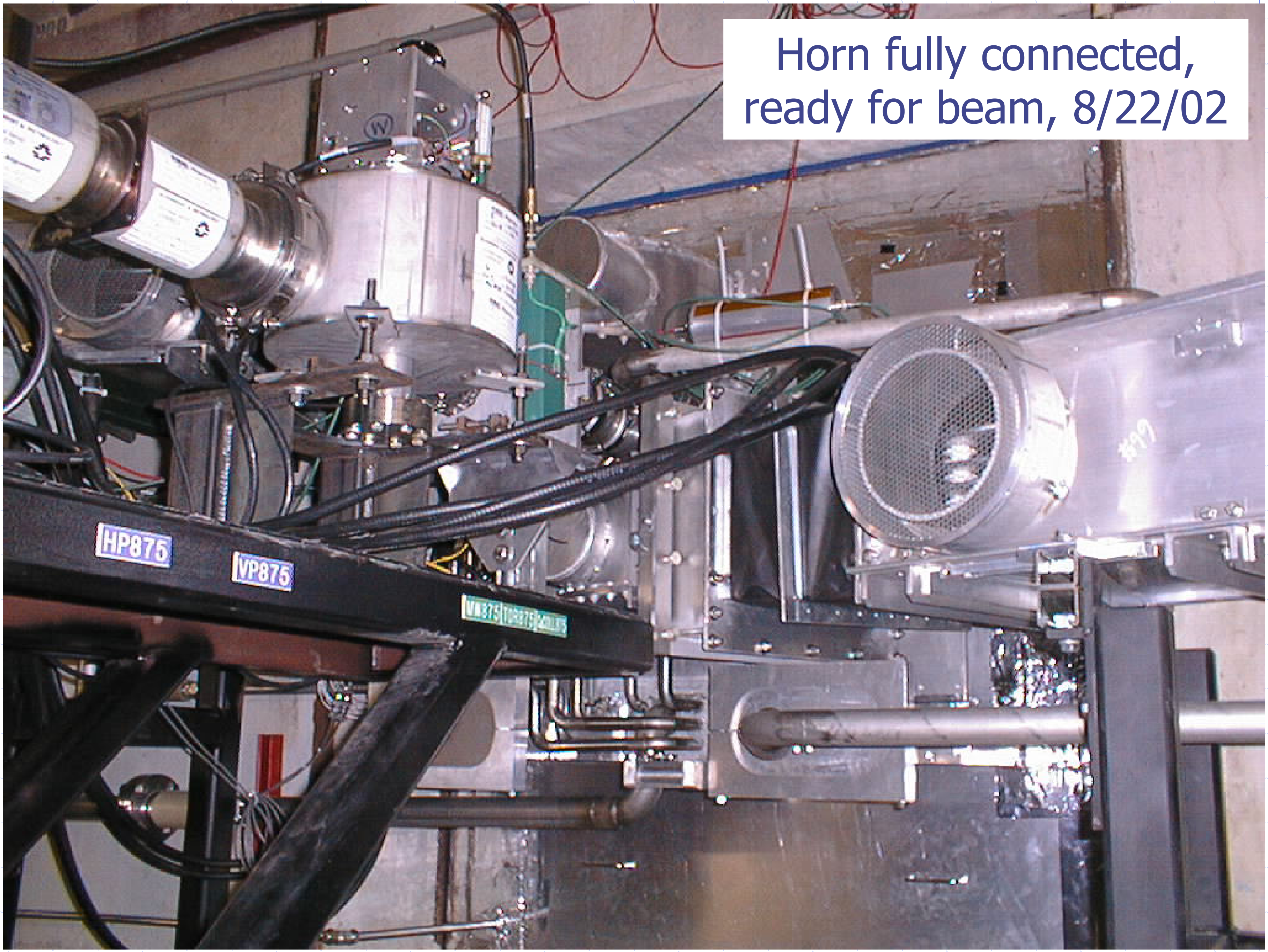
Latest week: 1091



First pulse in MiniBooNE horn during testing at MI-8, 7/27/01

First installation of target into horn box, 2/02

Horn Box installed in beam line vault at MI-12, 7/17/02



Horn fully connected, ready for beam, 8/22/02

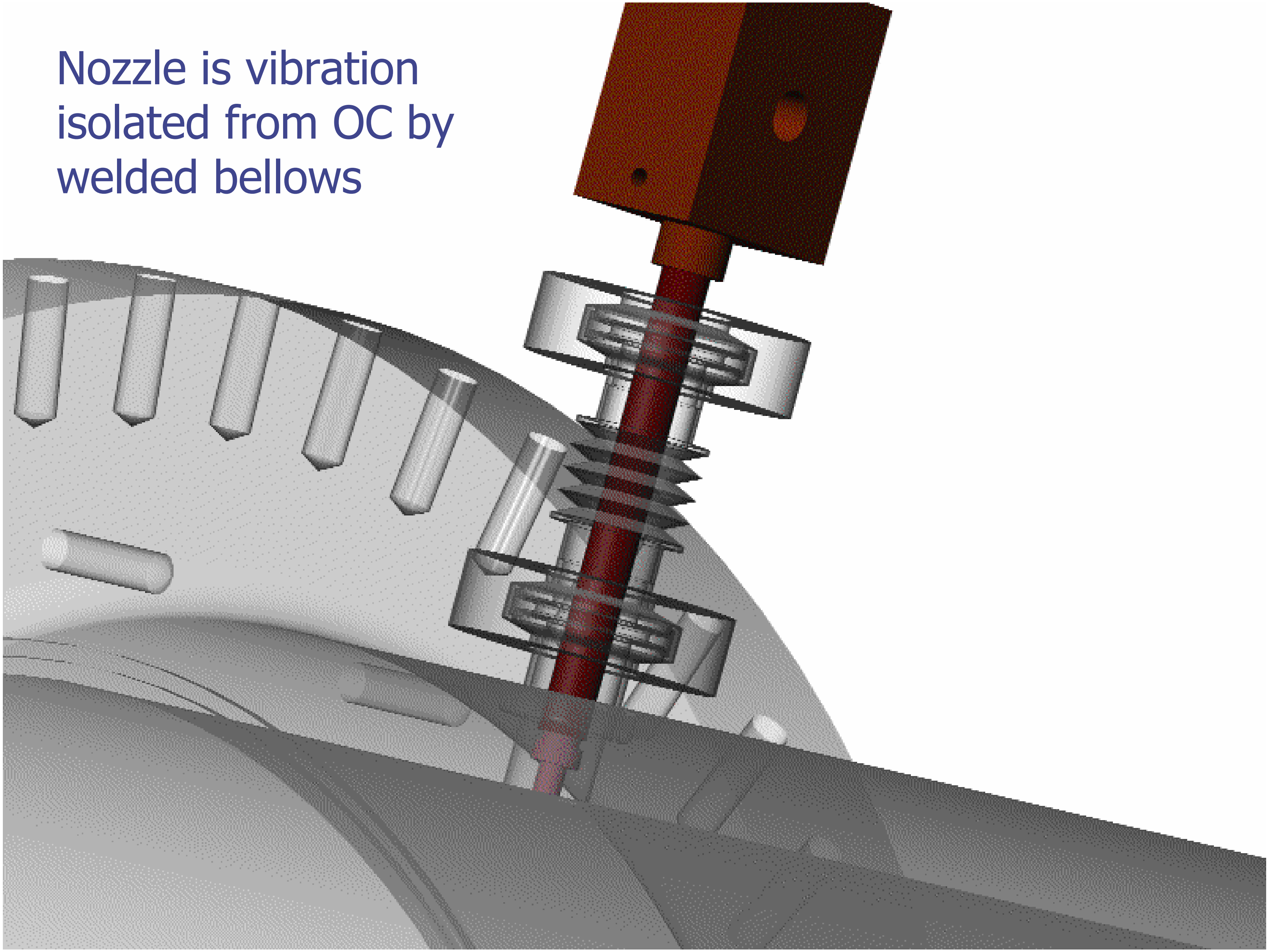
Unique Horn Design Features

- The MiniBooNE horn operates at an average pulse rate of 5 Hz
  - The horn carries 170 kiloamps of current in a pulse 143 microseconds long.
  - The pulse repeats 10 times in a row, 1/15 sec between each pulse, then the horn is off until 2 seconds from the first pulse in the train.
- Horn Design Lifetime: $>10^8$ cycles
  - Need to get as many pulses as possible
  - NuMI horn design life: 10^7 cycles

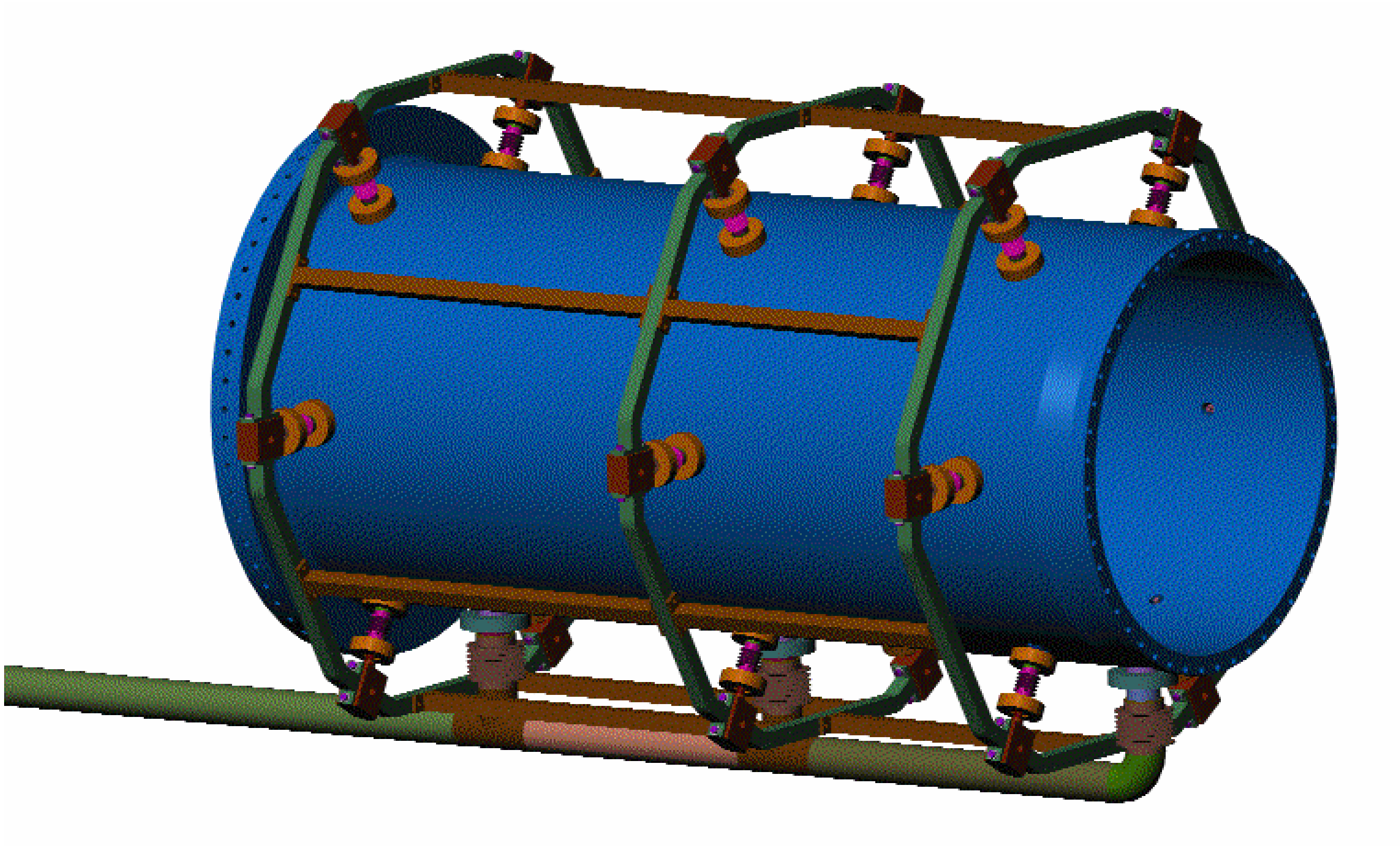
Unique Horn Design Features

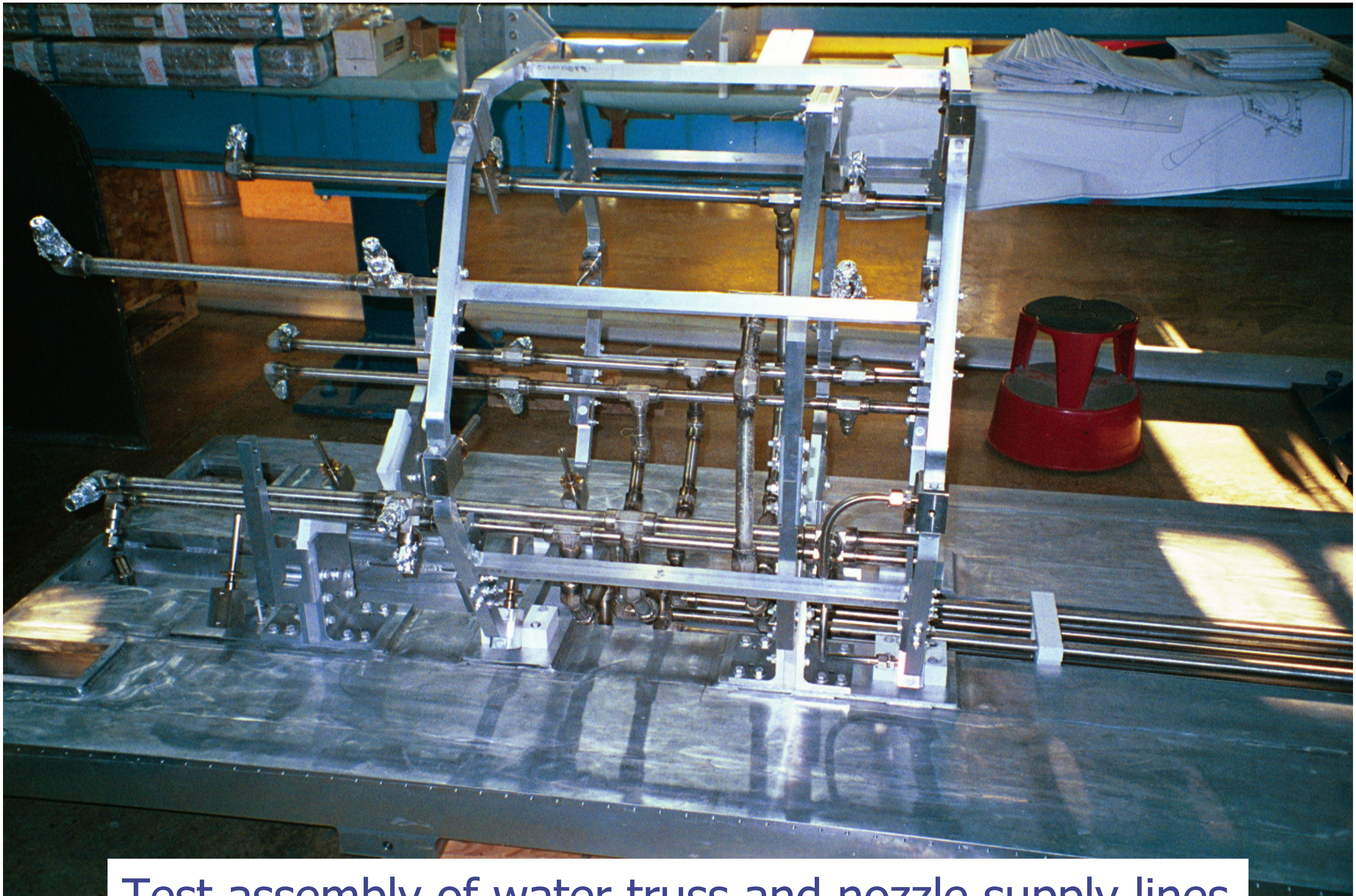
- Vibration isolated water spray nozzle system
- Restatement of fatigue data to express it in terms of confidence to failure
  - Horn designed to 97.5% confidence of reaching at least 100 million cycles
- Careful control of materials used in horn assembly, target and RAW system
  - No copper allowed anywhere (except as alloyed)
  - No plating except in stripline electrical contacts
  - No anodizing of aluminum for insulation

Nozzle is vibration isolated from OC by welded bellows



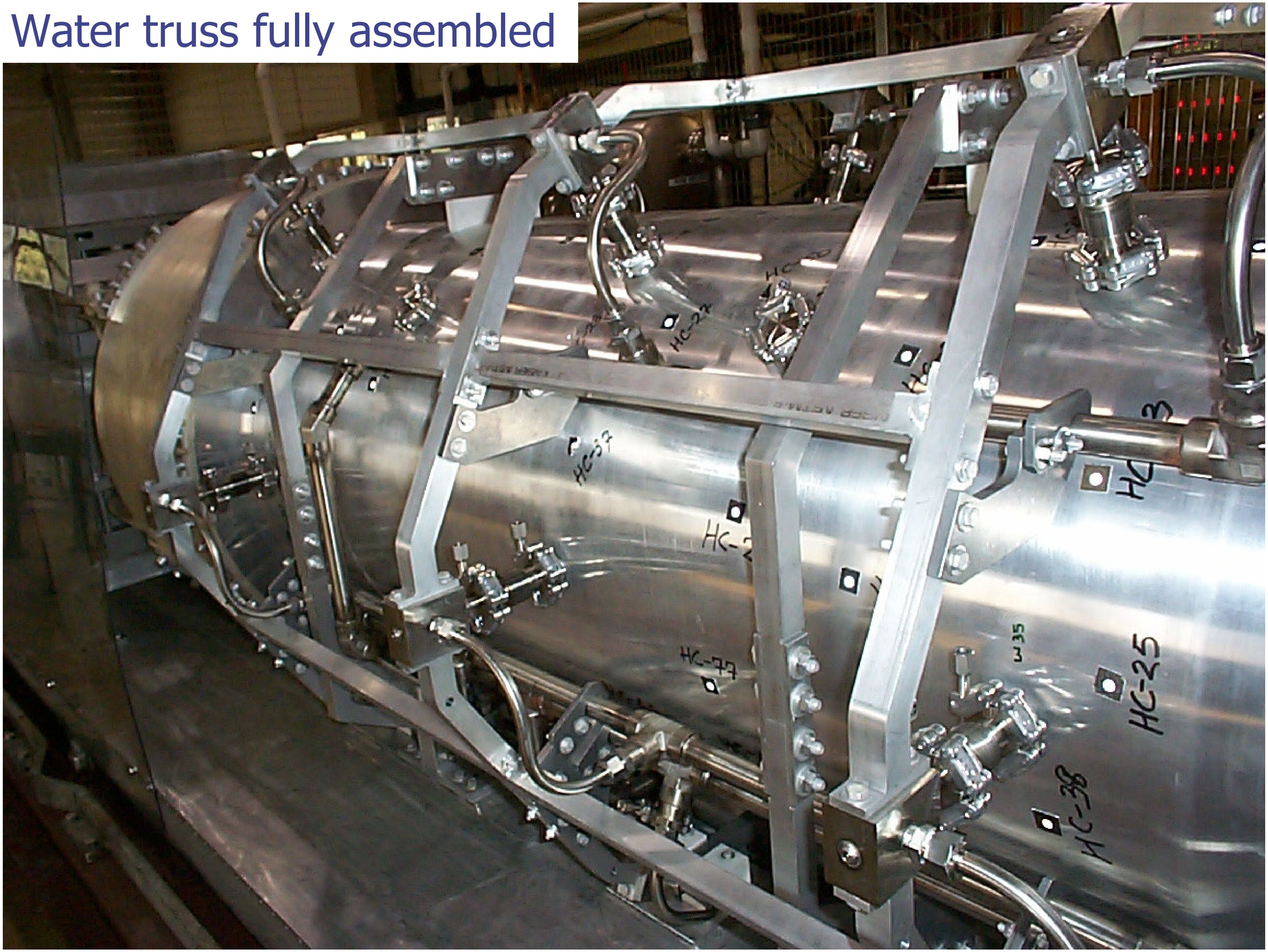
Water nozzles supported by independent truss not in direct contact with OC





Test assembly of water truss and nozzle supply lines

Water truss fully assembled



Work on restating fatigue data

1 January 1984 MIL-HDBK-5D Change Notice 1

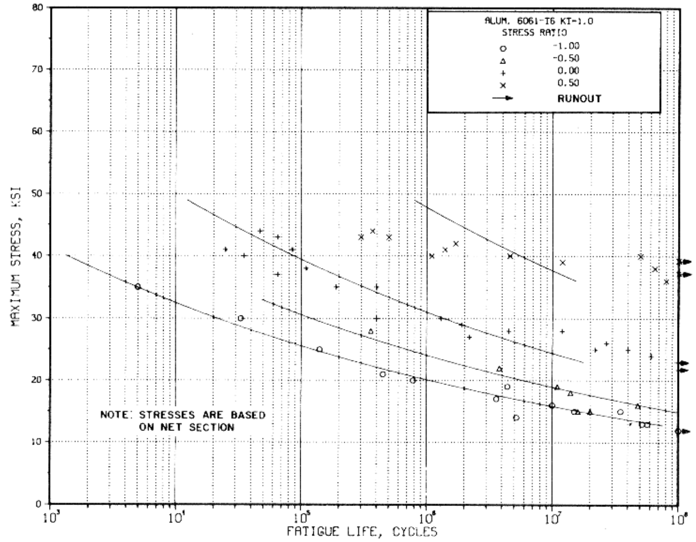


FIGURE 3.6.1.2.8. *Best-fit S/N curves for unnotched 6061-T6 aluminum alloy, various wrought products, longitudinal direction.*

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:

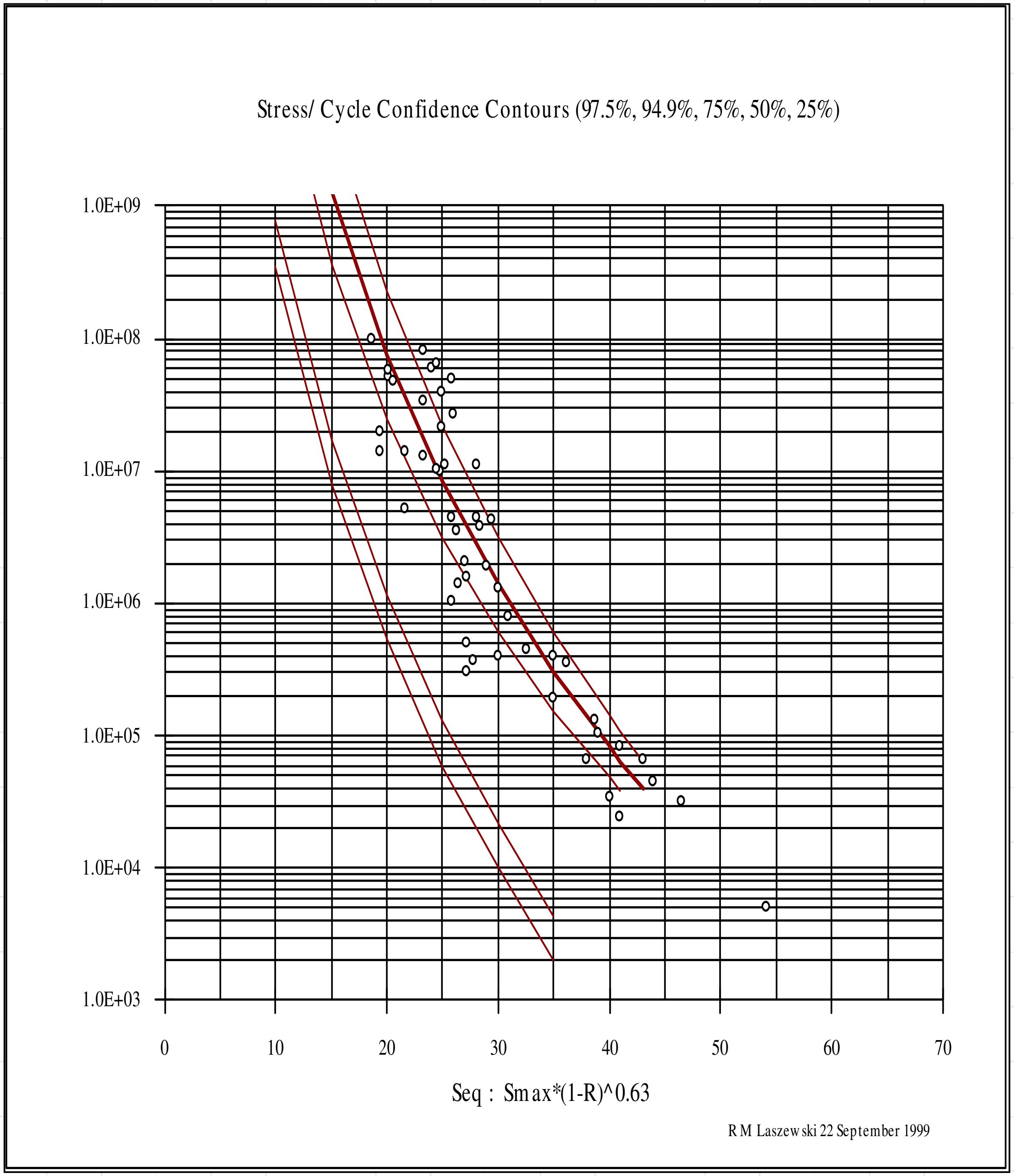
$\text{Log } N_f = 20.68 - 9.84 \log (S_{eq})$
$S_{eq} = S_{max} (1-R)^{0.63}$
Standard Error of Estimate = 0.48
Standard Deviation in Life = 1.18
$R^2 = 83\%$

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 biggest problem with this data presentation style is that the trend lines represent 50% confidence at a given life and we need >95% confidence of ability to reach at least 100 x 10^6 cycles.
- I could see whether a point on the horn was below these stress values, but had no way of saying how much life that represented



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.

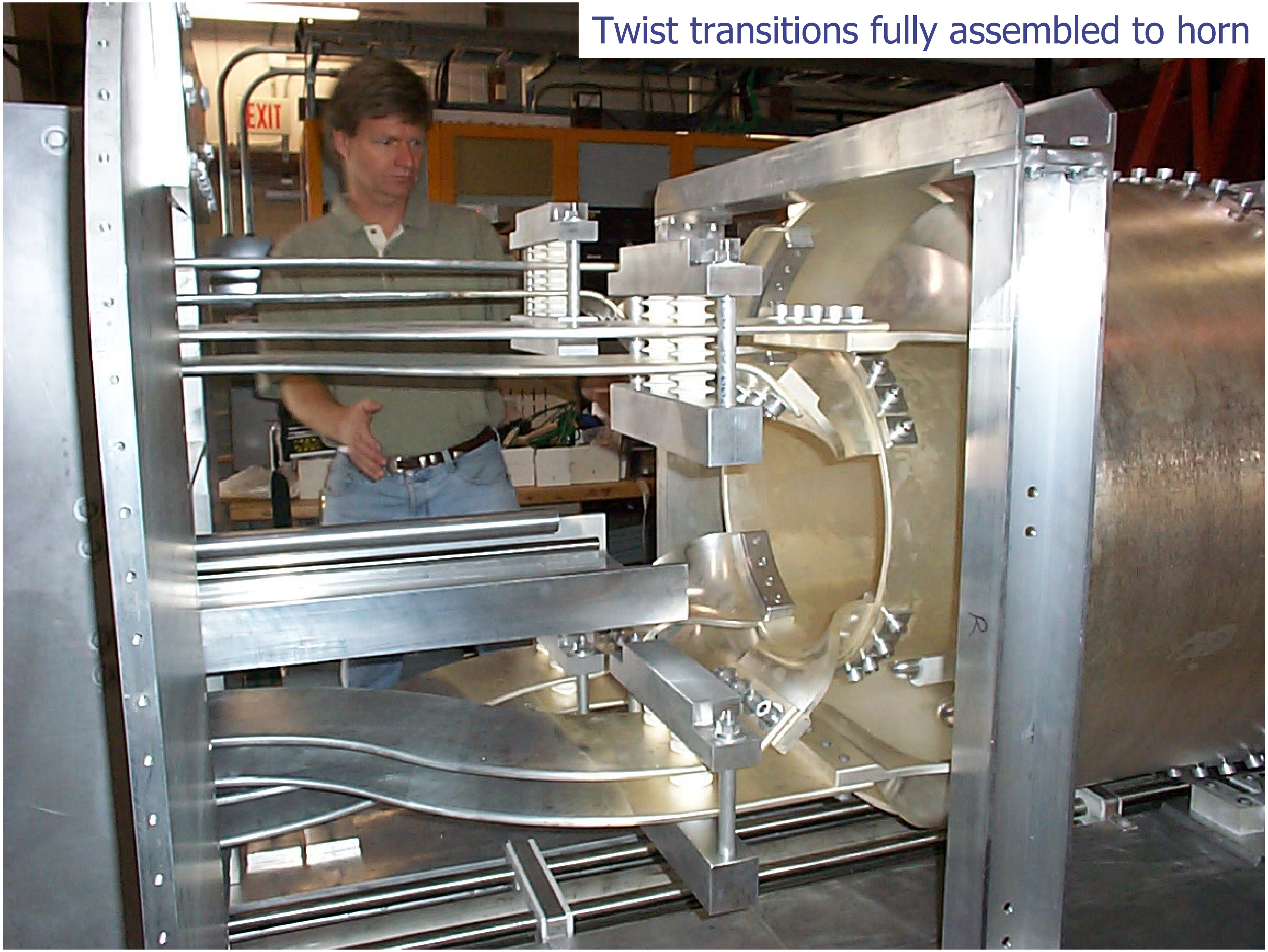
From this graph we concluded that the equivalent stress for >97.5% confidence at 2e8 cycles was 10 ksi.

Unique Horn Design Features

- Unique solution to the geometry problem of transferring the current from a flat narrow stripline to a cylindrically symmetrical horn
  - CNC machined twist transitions
  - “Half shells” to allow the current to spread out into uniform cylindrical distribution
  - Length of half shells calculated from looking at the minimum reactance shape of the current sheet as it spreads out

High voltage twist transitions test fit on half shells

Twist transitions fully assembled to horn



Things I learned from K2K:

- Do not make the target part of the inner conductor
  - The stresses become too high as target heats up—very difficult engineering problem
- Do not let anything cantilever off the outer conductor
  - Vibration can fatigue water lines

Things I learned from NuMI

- Don’t anodize the horn
  - Anodizing reduces fatigue strength
  - NuMI uses it, but they are designing to a lifetime of 10 million pulses
- Don’t fix the spray nozzles to the outer conductor
  - They were the inspiration for the vibration isolated water system

Things I learned from CERN

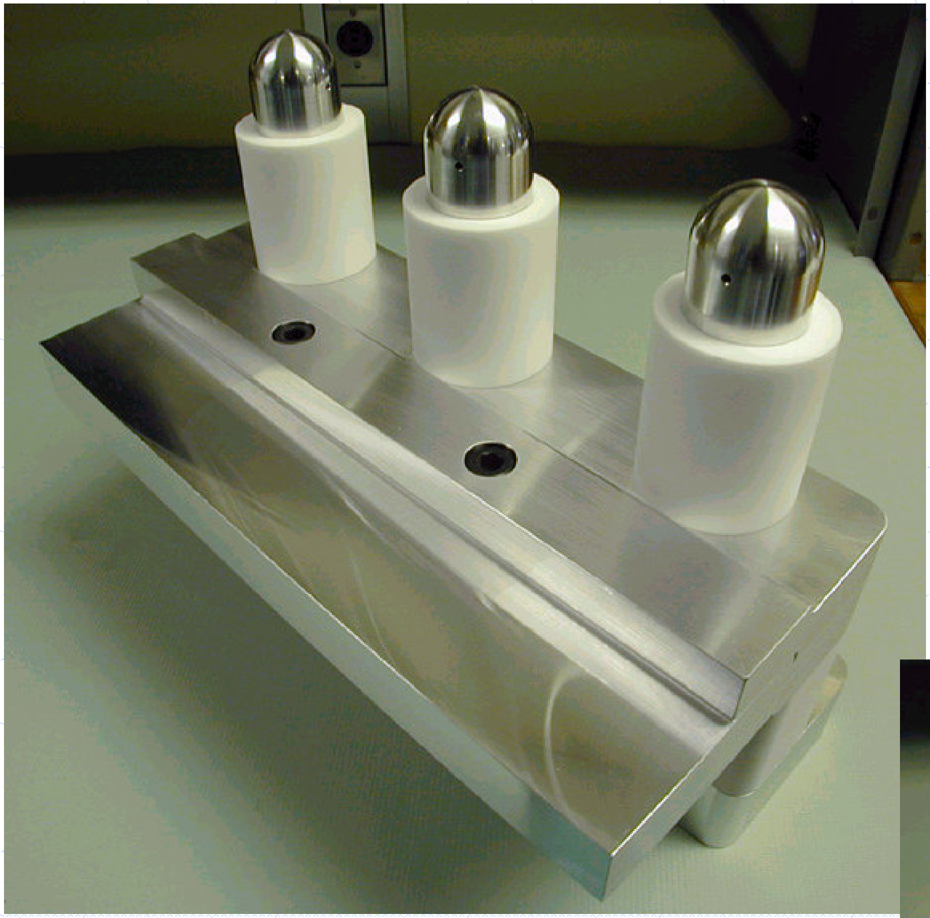
- The only aluminum that comes out of a radiation area looking OK is bare aluminum (and that's not great!)
  - Stephen Rangod tested various platings on unstressed Al blocks and saw corrosion exacerbated by radiation-induced chemistry
  - I am waiting to see the effect of radiation on all of NuMI's platings

Things I learned from BNL

- The Brookhaven E734/E776 horn that MiniBooNE's design is based on survived 13 million pulses at higher current and voltage than MiniBooNE's
- They were very careful about elimination of copper from water system and voltage stand-off characteristics of the design
- They designed a very clever drip cooling system

Useful Pre-prototypes we built

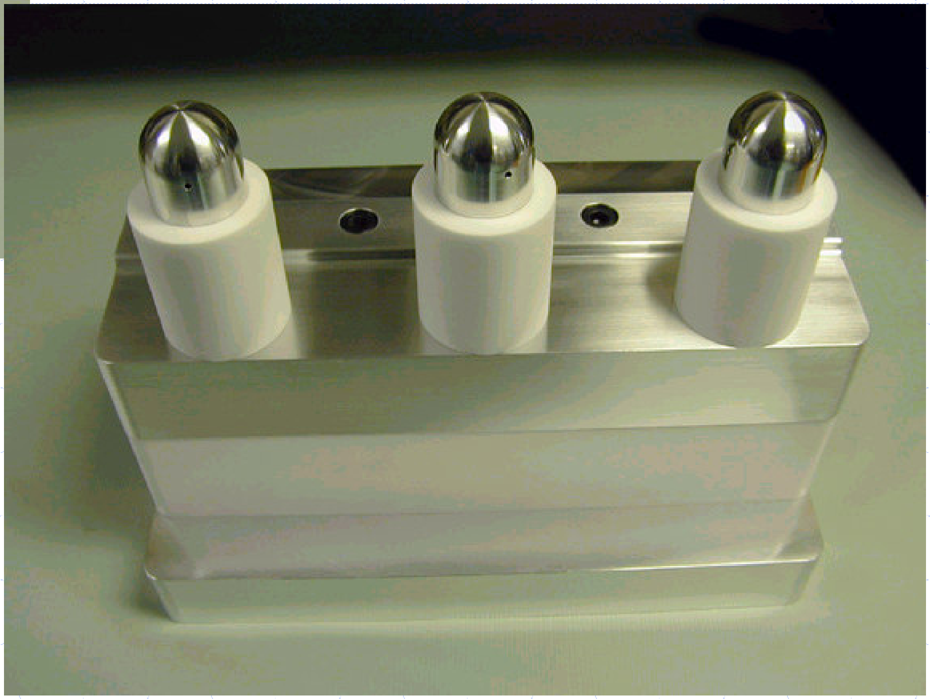
- Corona test of the geometry of the upstream end of the horn
  - We discovered that fasteners inside ceramic tubes can become cylindrical capacitors that concentrate the electric field enough to cause breakdown in air
- Spray nozzle cooling test
  - We couldn’t scale NuMI geometry to ours to estimate the heat transfer coefficient of our water spray, so we built our own test



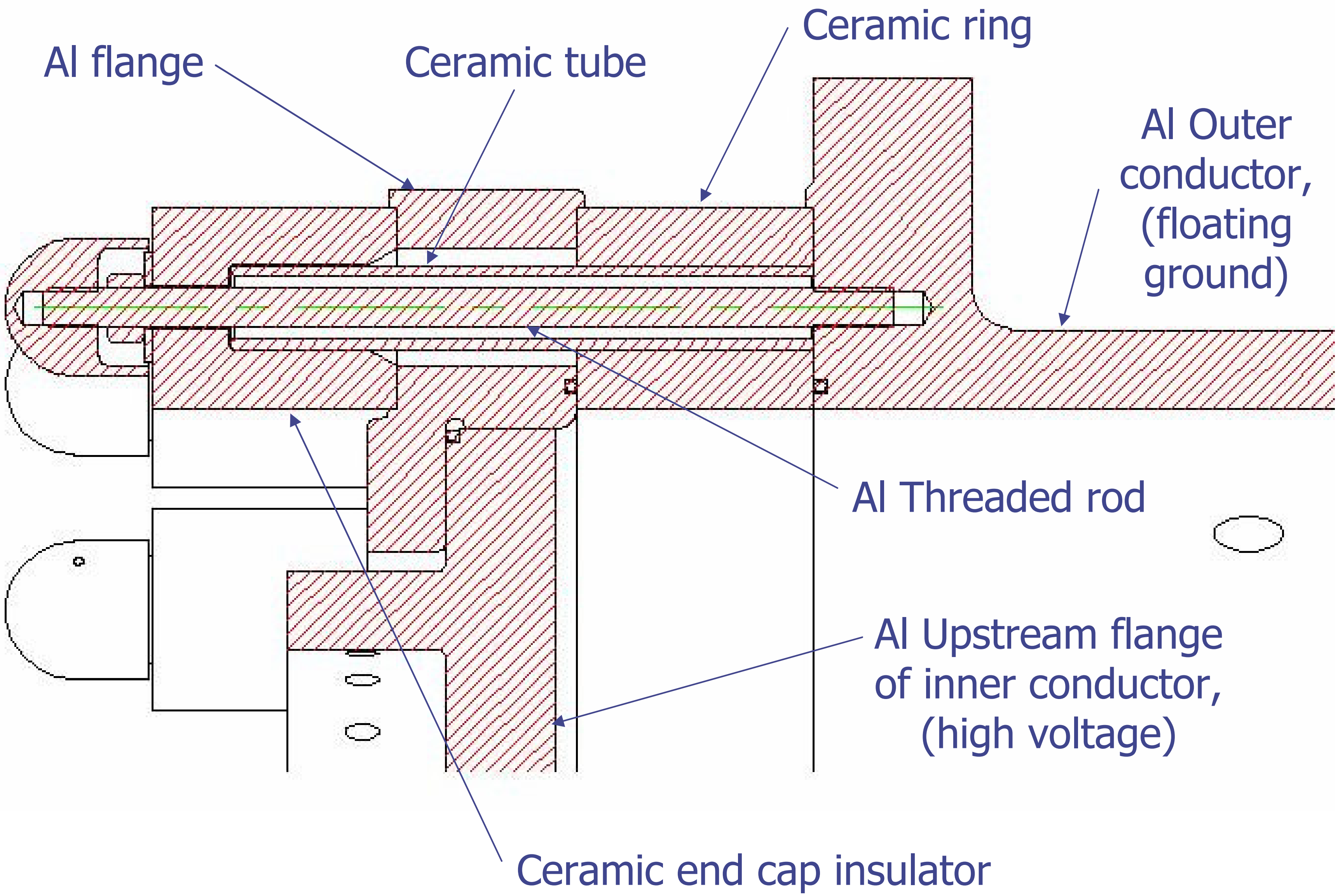
High voltage corona test

- This model simulates the upstream end of the horn
- We tested up to 20kV

We discovered we had to taper and enlarge the ceramic holes to avoid voltage breakdown around the fasteners



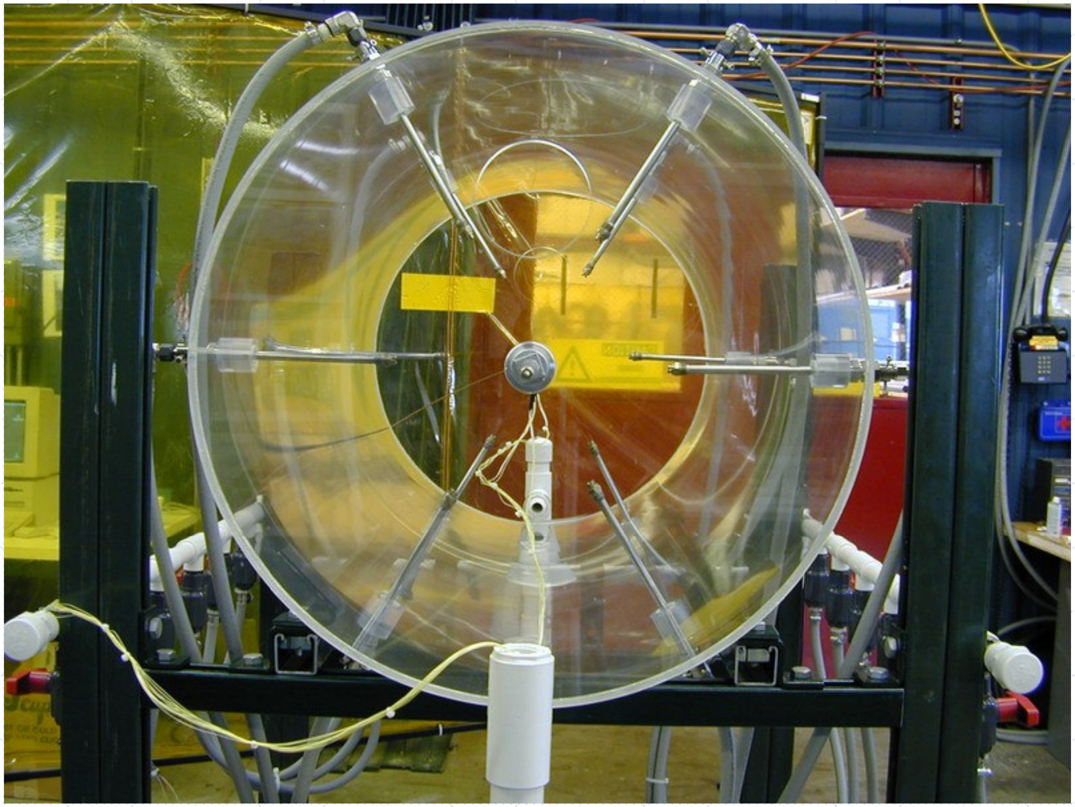
Section view of ceramics and threaded rod that clamps the inner conductor to the outer



The water spray nozzle tester

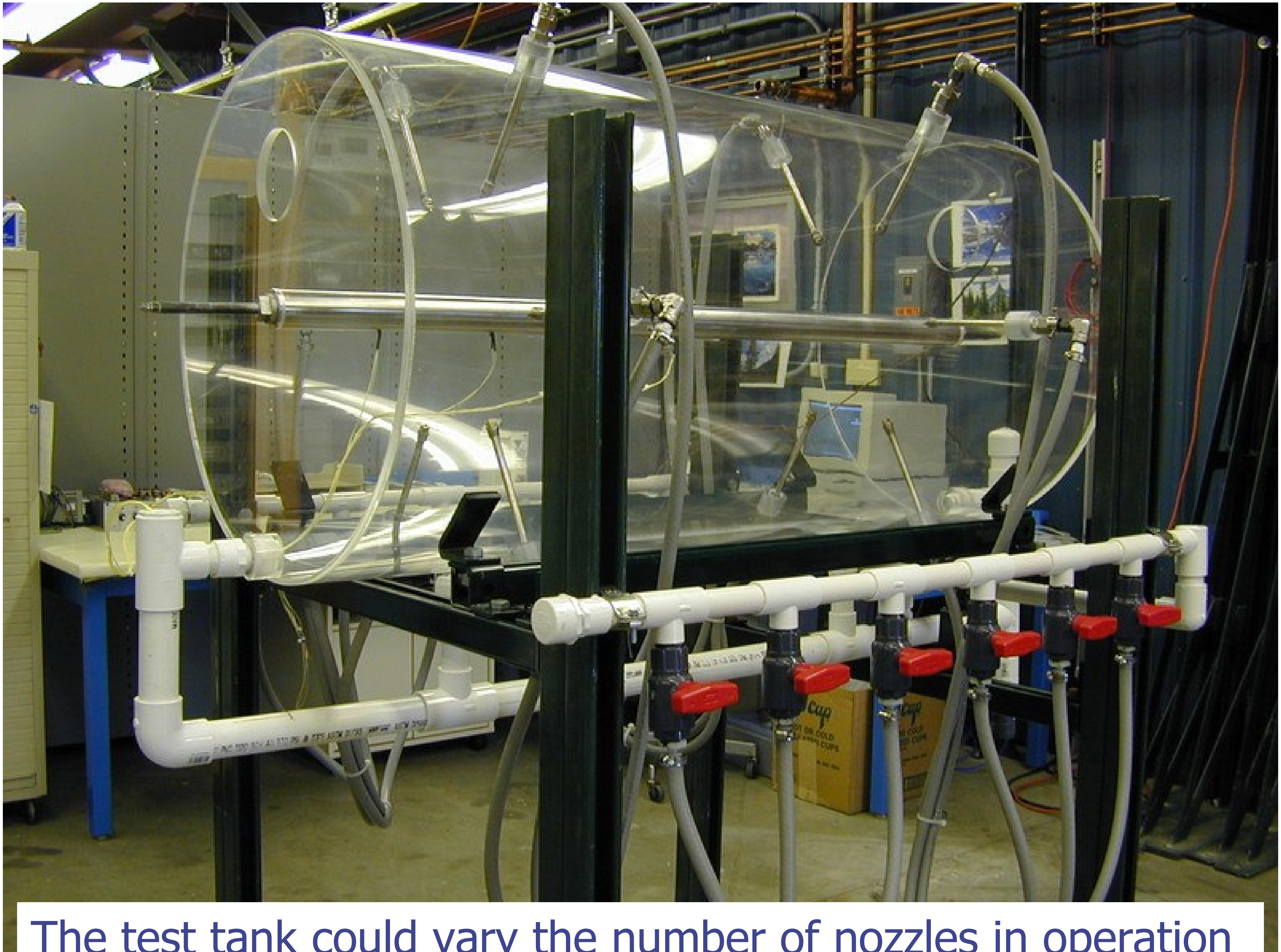
- NuMI ran a test to measure the heat transfer coefficient of the water spray against their inner conductor
  - Very important measure of the efficiency of inner conductor cooling
- NuMI's horn 1 is much smaller in radius than MiniBooNE's. We use identical nozzles to theirs, but we could not figure out how to scale their results to our geometry
  - An electric heater in the center simulated beam and current heating of the inner conductor

The water spray nozzle tester

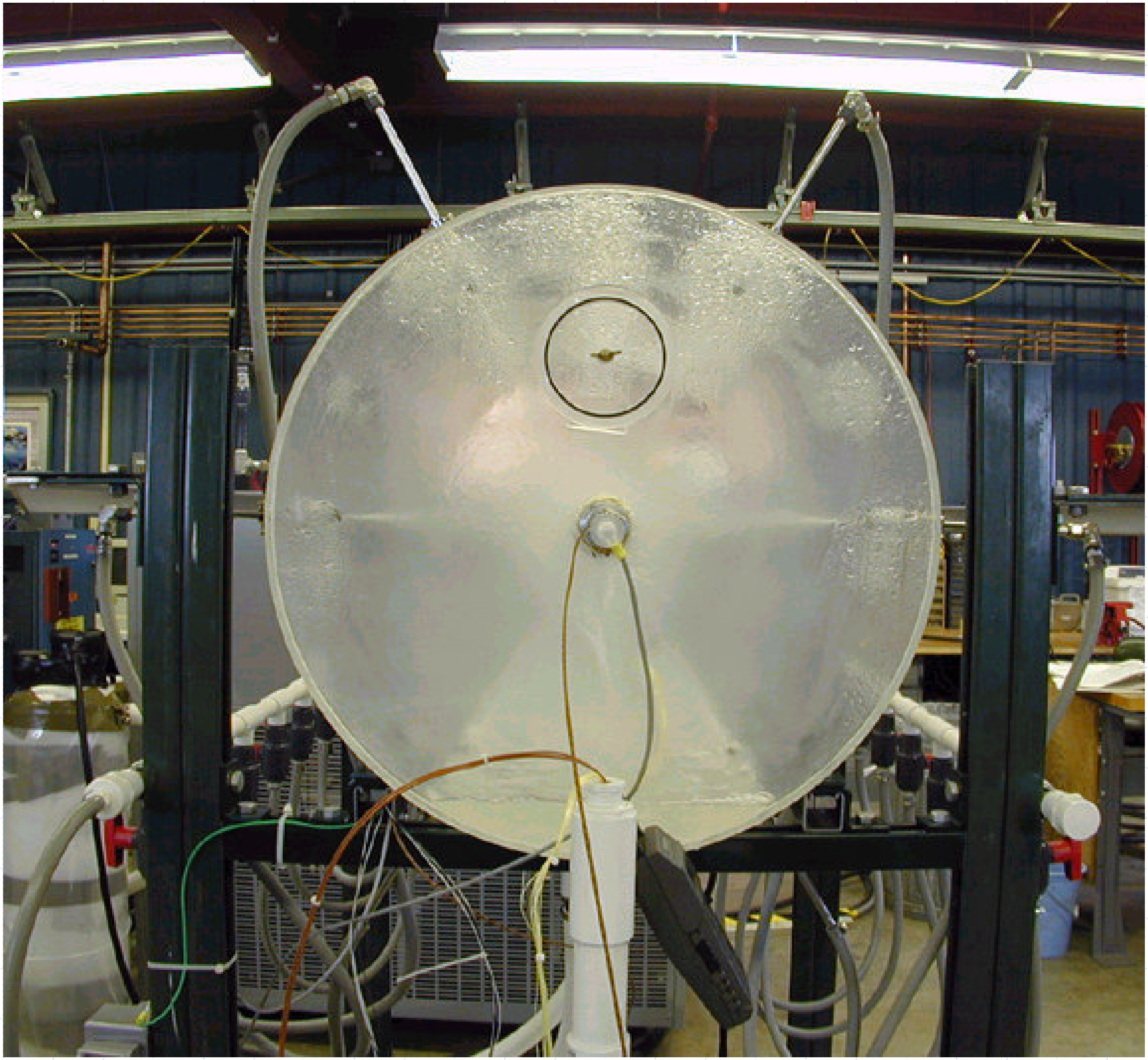


This tank is the same diameter as the MiniBooNE horn, but we mounted the nozzles to vary their distance from the inner conductor.

This picture shows the nozzles in the NuMI horn 1 configuration. We could re-create NuMI results, as well as determine the result for our geometry



The test tank could vary the number of nozzles in operation



The force of the spray at the inner conductor is very gentle

New directions in horn fabrication

- Changed from two welded upstream pieces of inner conductor to forged piece on spare horn
  - Eliminated one weld
- Forged all pieces for inner and outer conductor
- Discovered residual stress problem with inner conductor forgings
  - After machining, the part is not straight
  - A different forging vendor may eliminate the problem, won't know until we machine the next inner conductor

Why did we change our fabrication technique?

- Forging eliminated a very large weld that poured a lot of heat into the inner conductor and affected its metallurgy
- Forging produces a grain structure that follows the contour of the part
  - Normally it produces metallurgy superior to wrought material

This is the welded style of inner conductor used on the first MiniBooNE horn.

The long skinny piece is a separate machined part from the upstream flange and they are welded together.

No problems with straightness were found after final machining.

Weld sample at vendor prior to final welding of two upstream inner conductor pieces

Inner Conductor welding

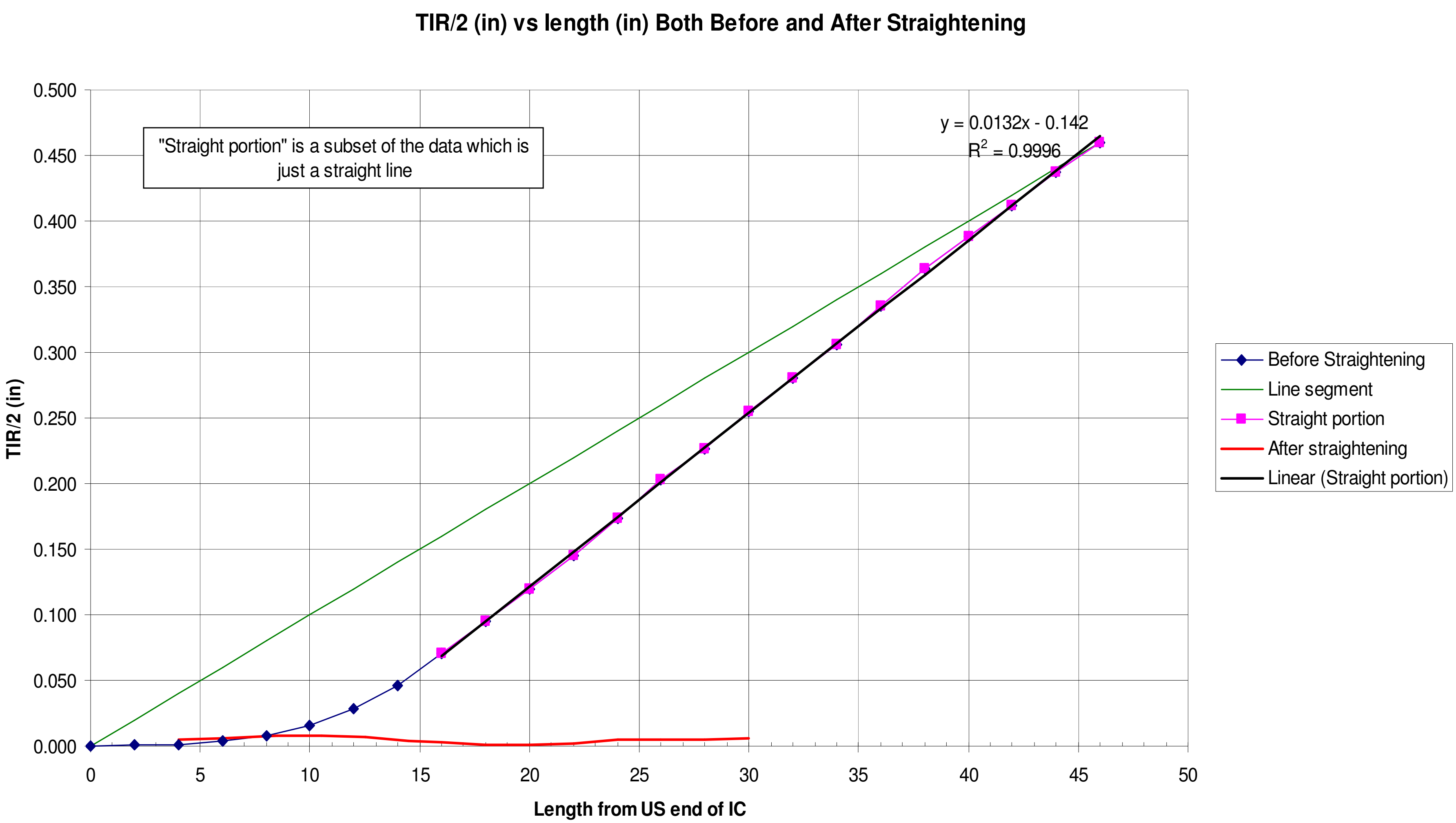
- Once we have all the pieces, we use an automatic welder purchased by both NuMI and MiniBooNE to weld our inner conductors together
- Lots of test welds are necessary to both characterize and warm up the machine
- The machine is capable of very precise application of current

MiniBooNE prototype horn inner conductor on the welding machine

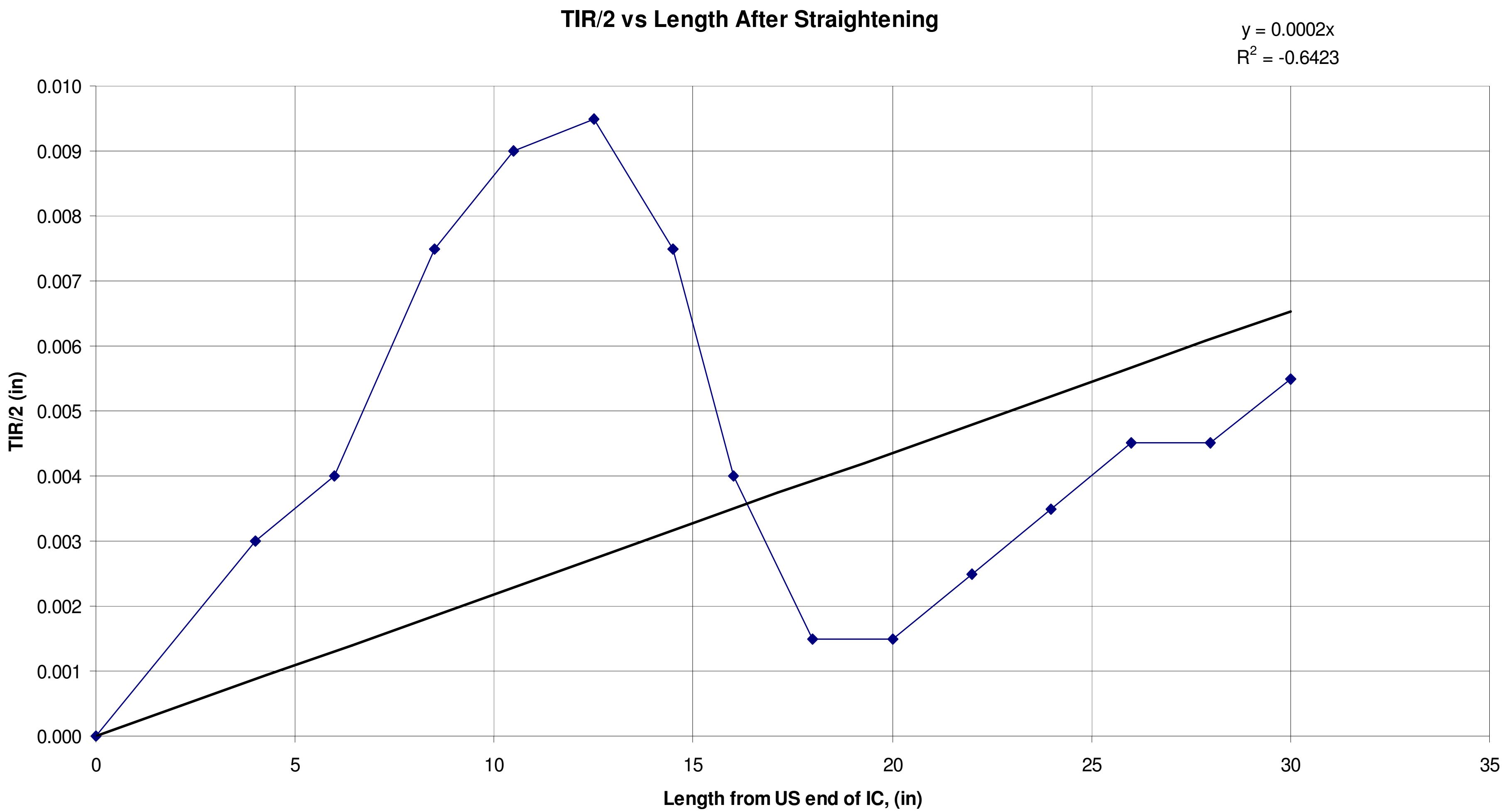
Spare inner conductor forging—upstream flange and inner conductor made as one piece

Straightness after machining

- Measurement showed that the part was not straight by ~.5 inches
- Graphing the distortion showed that all of the deflection happened in the first 15 inches of the upstream end, the rest of the part was straight
  - This is the transition where the geometry of the part changes most
- Calculation showed that the force required to deflect the part was very large, ~300 pounds

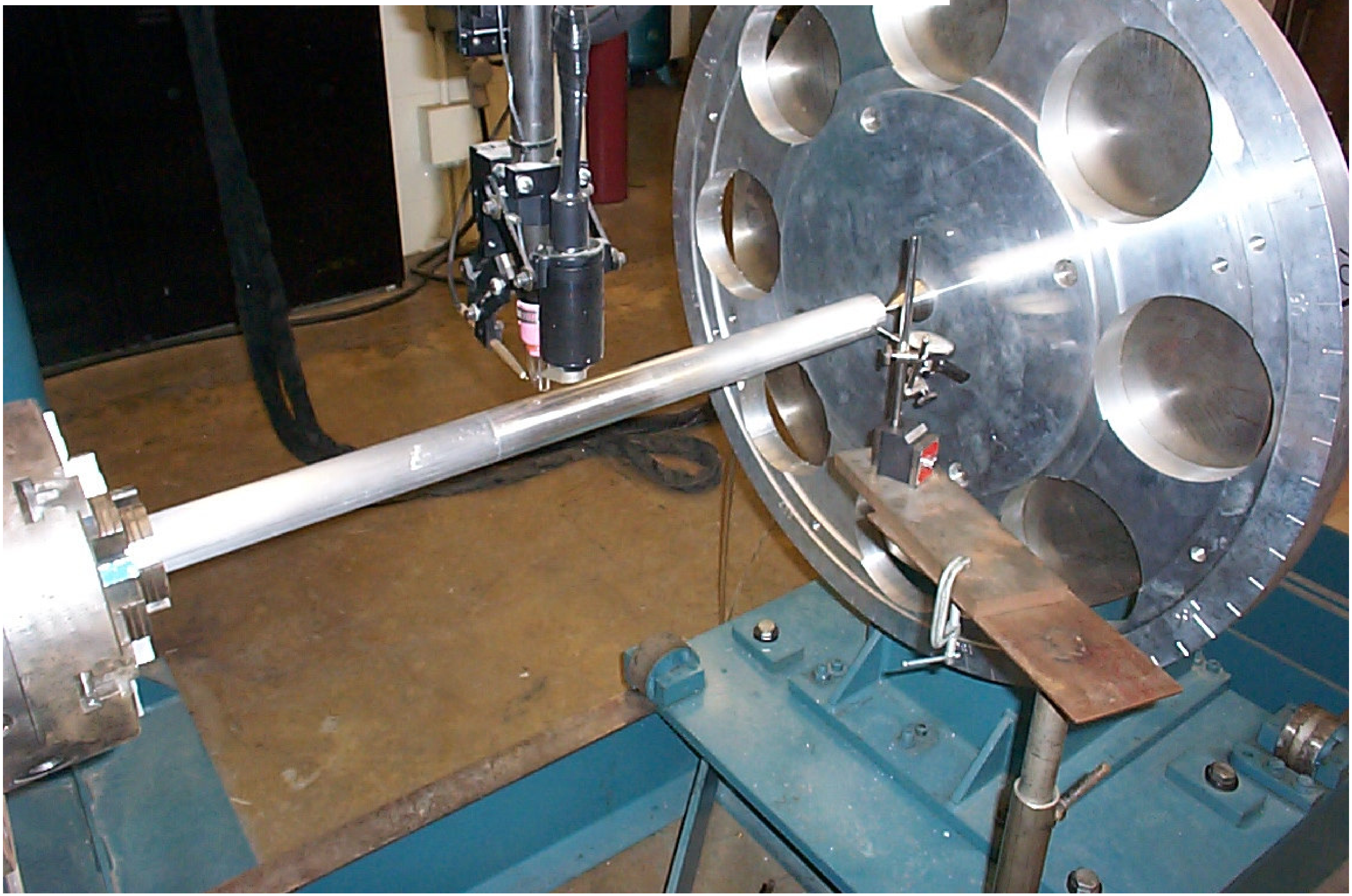


Graph of deflection of center of inner conductor from ideal straight line perpendicular to upstream flange

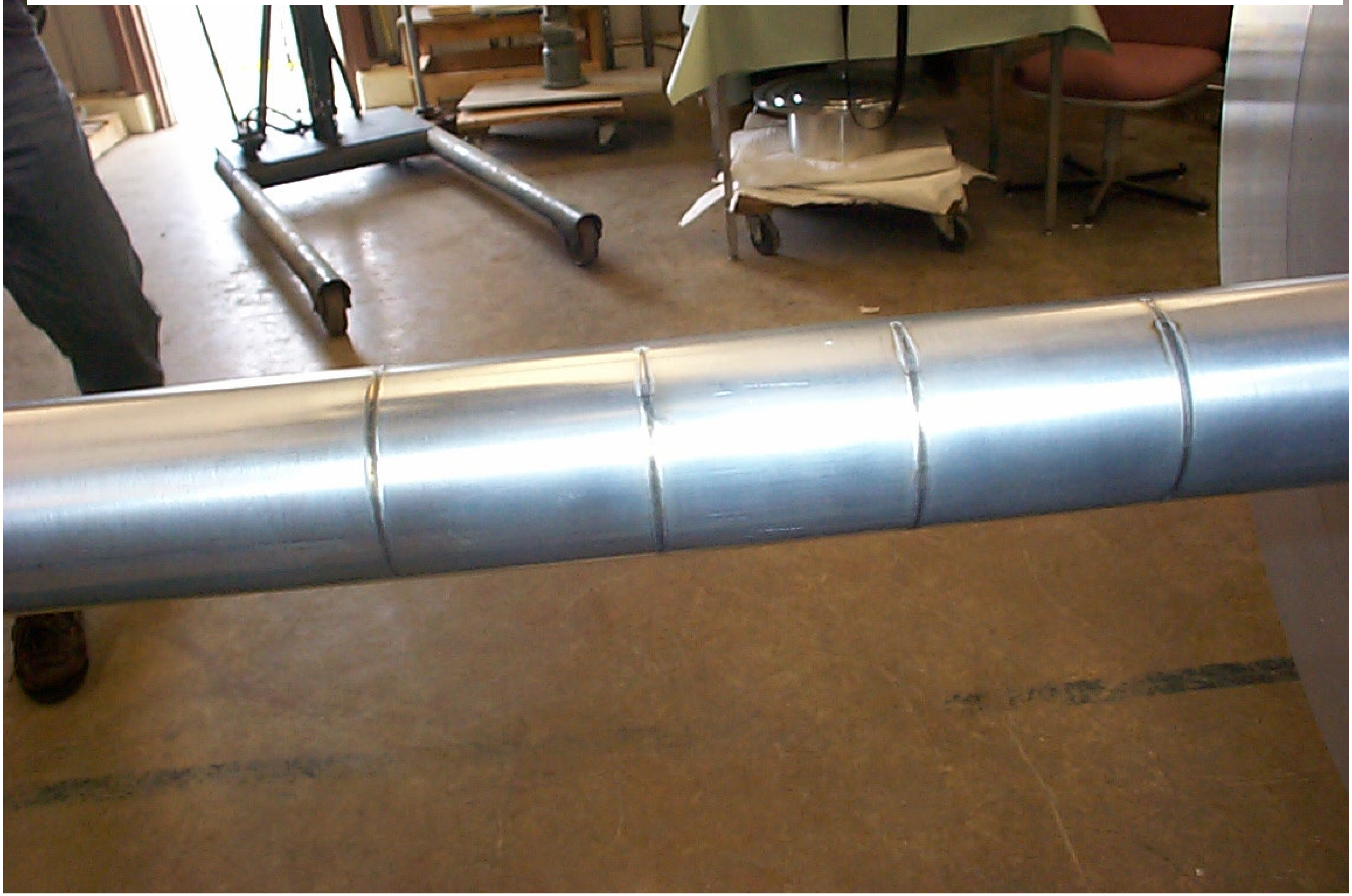


Expanded vertical axis scale of same chart showing the straightness of the inner conductor after wash pass welding—straight line is fit to indicator measurements

Setup of tube to warm up welding machine prior to straightening the inner conductor



These are "wash" pass welds used to straighten a bent tube. They do not fully penetrate the tube wall.



Conclusion from welding experience

- We were able to straighten the inner conductor to better than .010 inches, ~.25 mm after wash pass welding
- We do not know how the fatigue life of the material in the spare horn inner conductor has been affected
  - Welding of the prototype horn has not adversely affected the fatigue life as far as we can tell after 50 million pulses