What Killed the First MiniBooNE Horn?

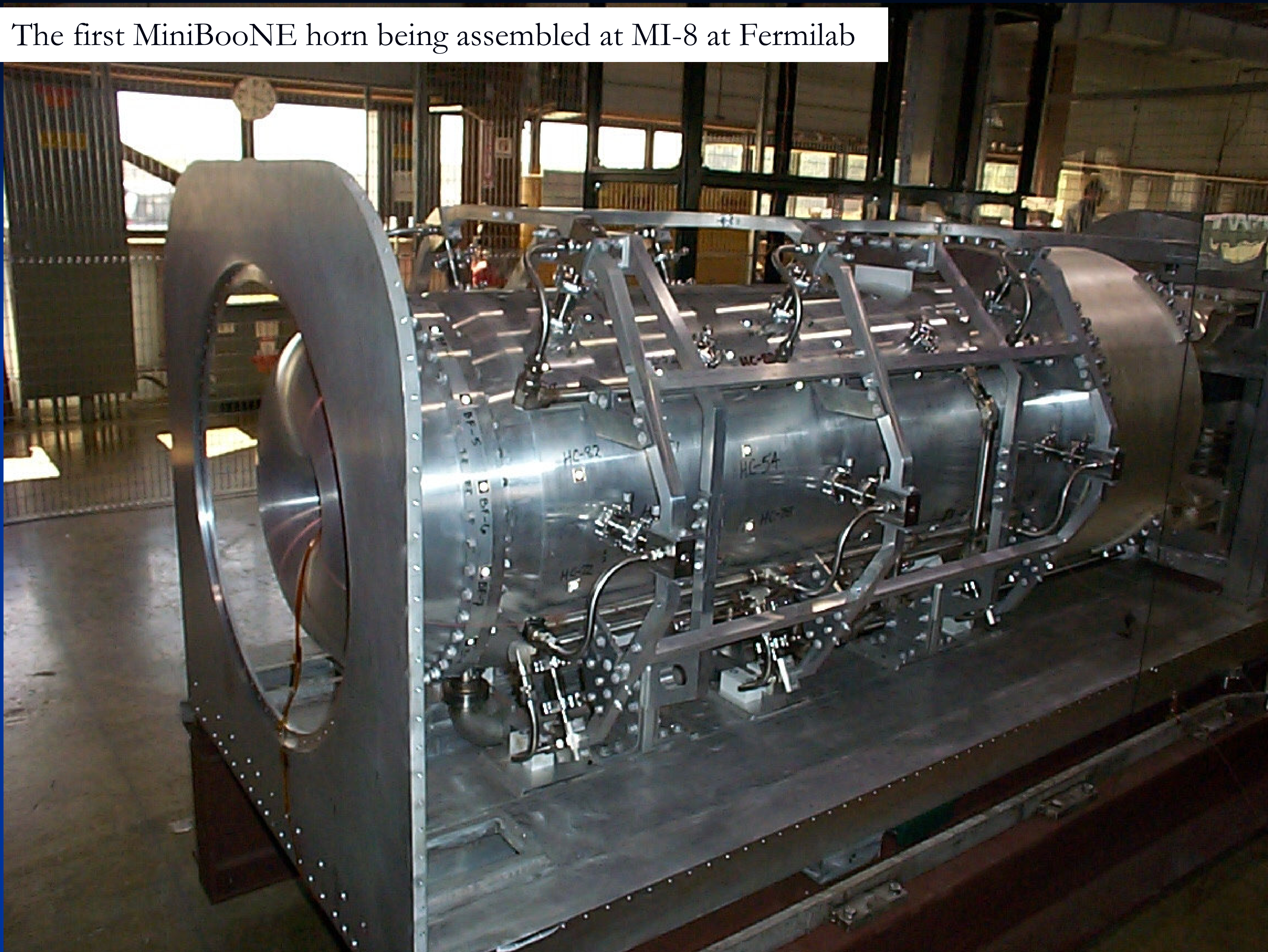
L. Bartoszek
BARTOSZEK ENGINEERING

Presentation for NBI2005

Originally presented 7/9/05

Updated 9/16/08

The first MiniBooNE horn being assembled at MI-8 at Fermilab



The sequence of events:

- Water leak discovered sometime between October, 2003 and March, 2004
- March, 2004: We install new hardware to collect leaking water
- April, 2004: Tunnel dehumidification system installed
- July, 2004: Stripline corrosion discovered, system has a ground fault
- Run plan for August is to reduce current if the ground fault gets worse, or run with the horn off

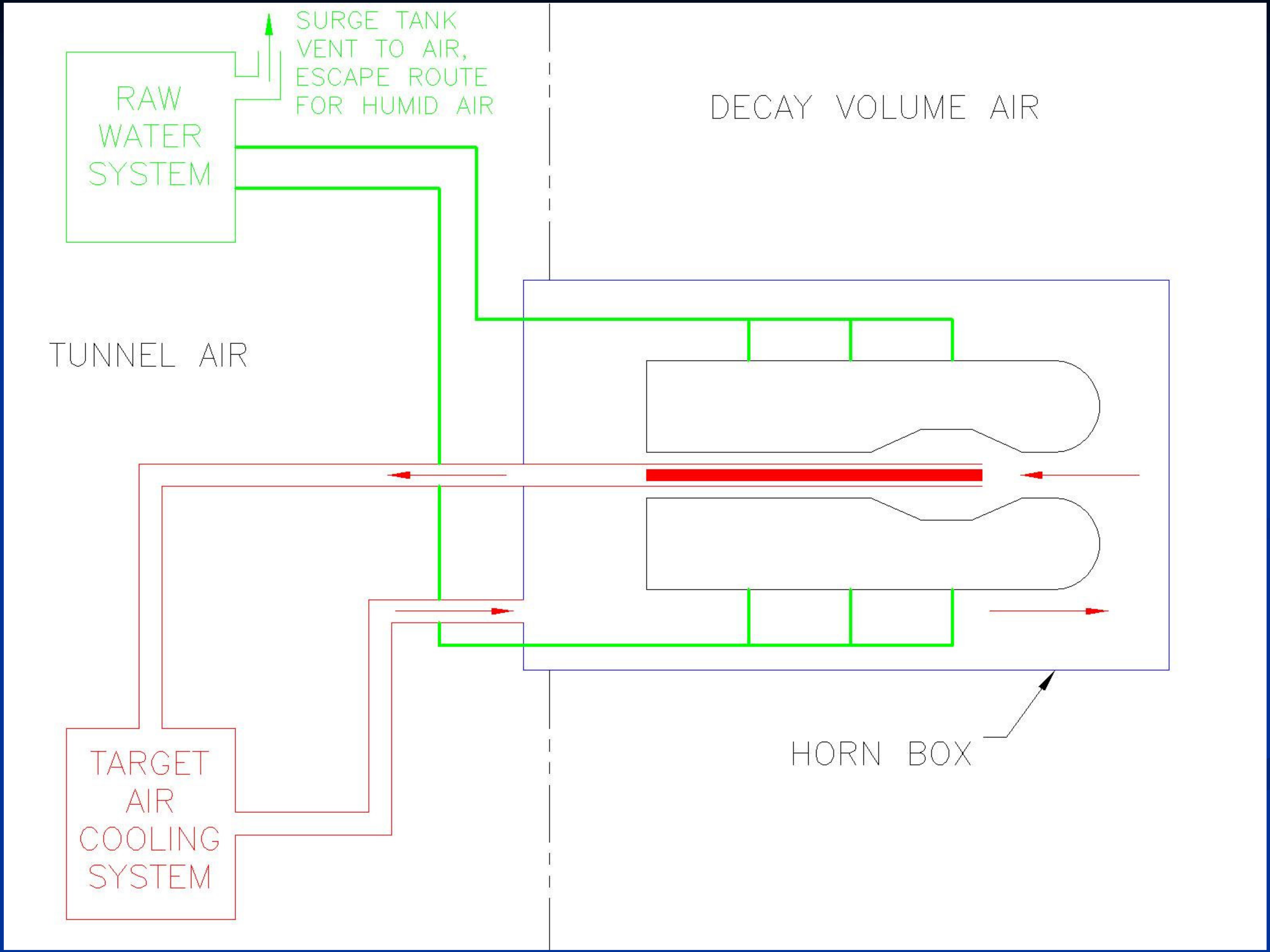
Sequence cont'd:

- August, 2004: Ground fault gets worse, decision taken to remove the horn
- Auxiliary drain system added to spare horn
- October, 2004: First horn is removed (after surviving 96 million pulses) and entombed, spare installed

- The ground fault was the ultimate reason to remove the horn.
  - A worsening water leak would have forced horn replacement eventually

Important note about the horn/target system:

- The air cooling system of the target and the volume of "stagnant" air surrounding the horn inside the horn box are coupled together
- If the water pipes outside the horn but inside the horn box leak, that water can get into the target cooling system
- Also, the target cooling air can create flows inside the horn box that stratify humid air
  - We learned this later

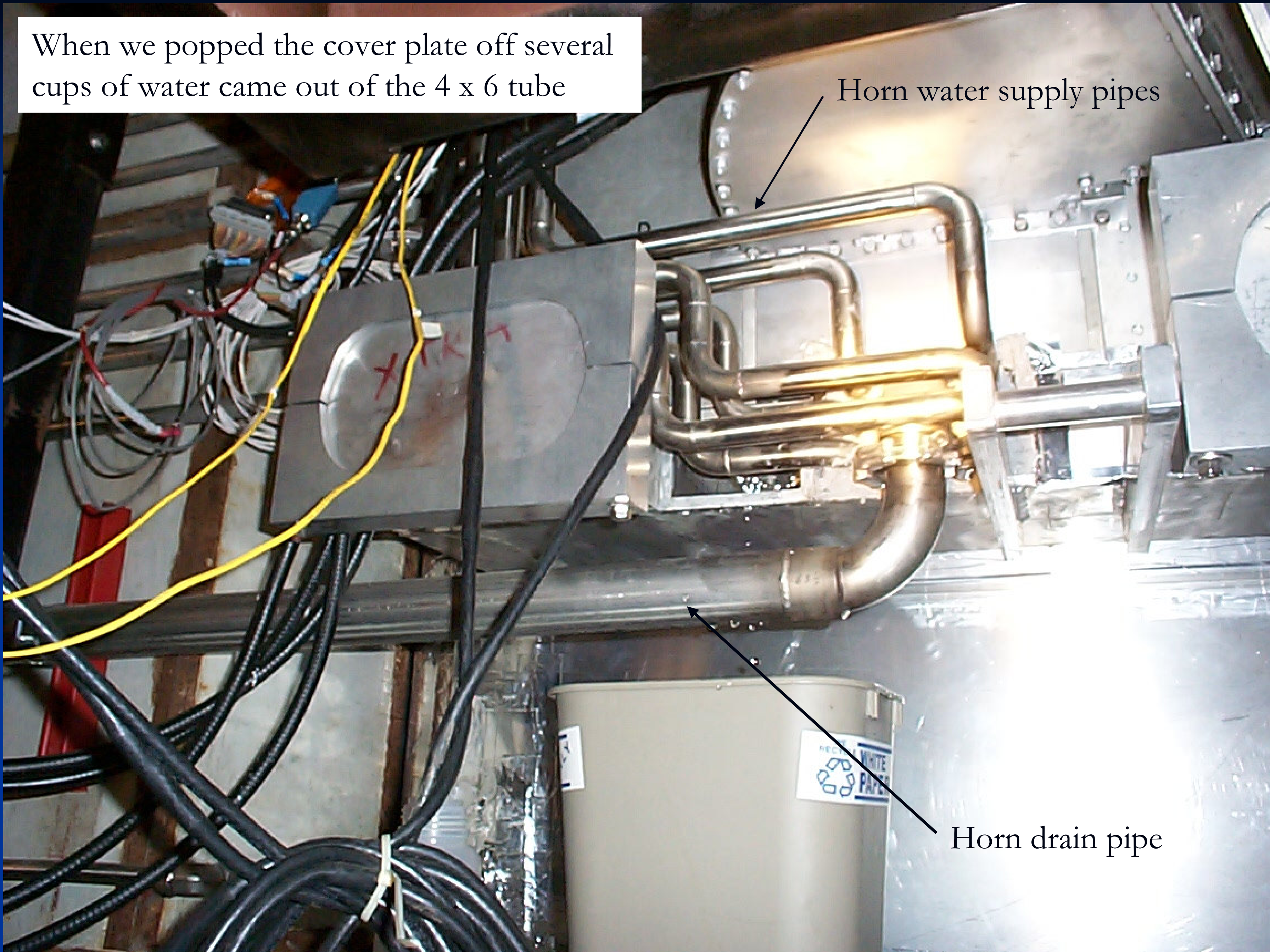

SURGE TANK
VENT TO AIR,
ESCAPE ROUTE
FOR HUMID AIR
RAW
WATER
SYSTEM
DECAY VOLUME AIR
TUNNEL AIR
HORN BOX
TARGET
AIR
COOLING
SYSTEM

The evidence for a leak

- We saw water dripping from the upstream end of the horn box
- The RAW (RadioActive Water) system had to be refilled more frequently since October, 2003
- Tritium activation of the leak water matched that of the RAW system water

The leak as we first saw it

When we popped the cover plate off several cups of water came out of the 4 x 6 tube



Steps we took to investigate 1

- Drilled holes in other members of the horn box to see if there was water anywhere else
  - We did not find any other water
- Drilled holes in the air barrier to look under the horn box for water not making it to the upstream end of the horn box
  - We did not find any under, but search was incomplete
- Opened up the target air cooling system

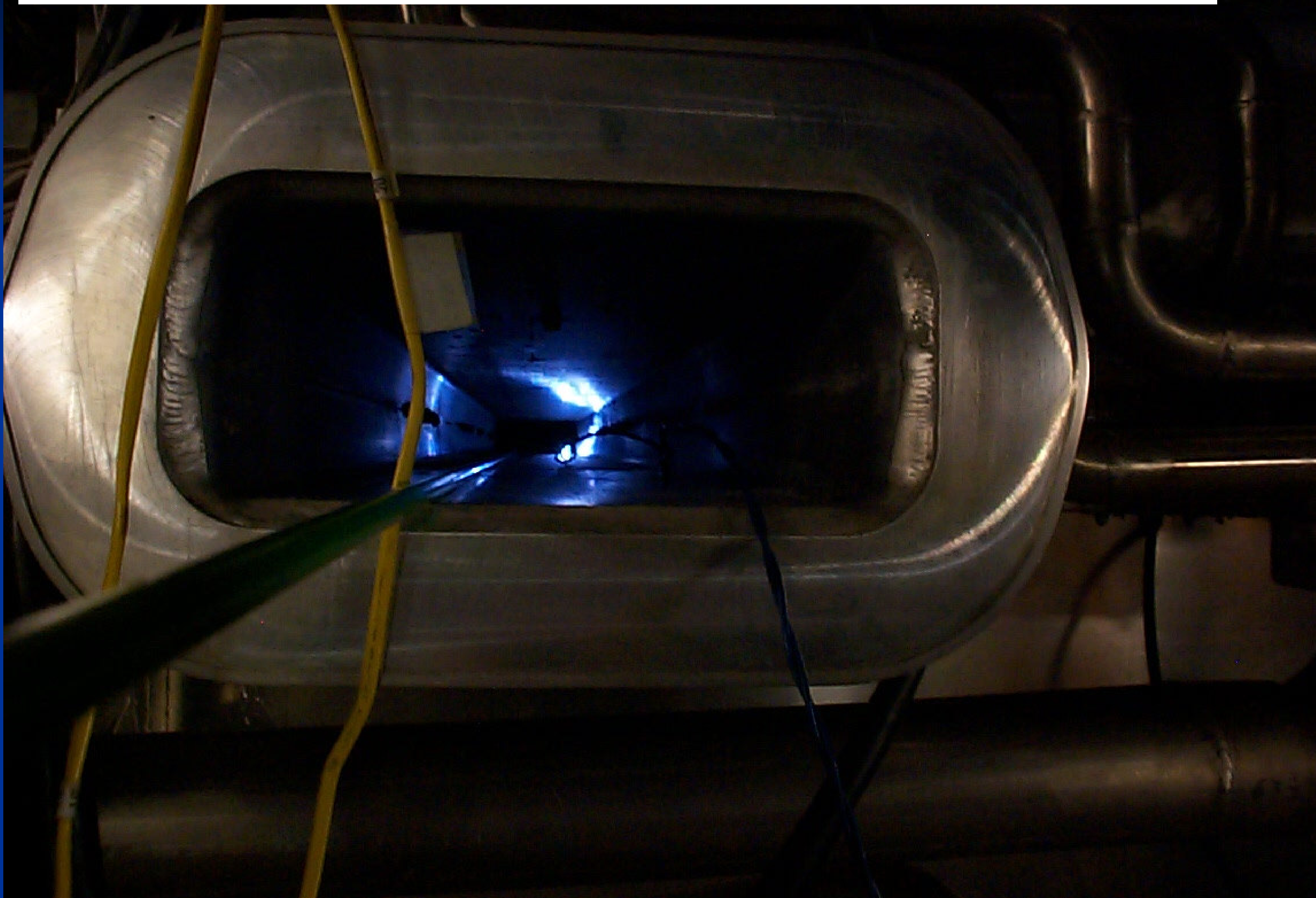
Results from target air system

- Droplets of water were seen in one of the air cooling pipes
- The high efficiency air filter drain was opened
  - No water dripped out
  - Swabbing revealed dampness inside the bottom of the filter can
- No additional build-up of aluminum oxide in the tubing was found.
  - Looked same as before

Steps we took to investigate 2

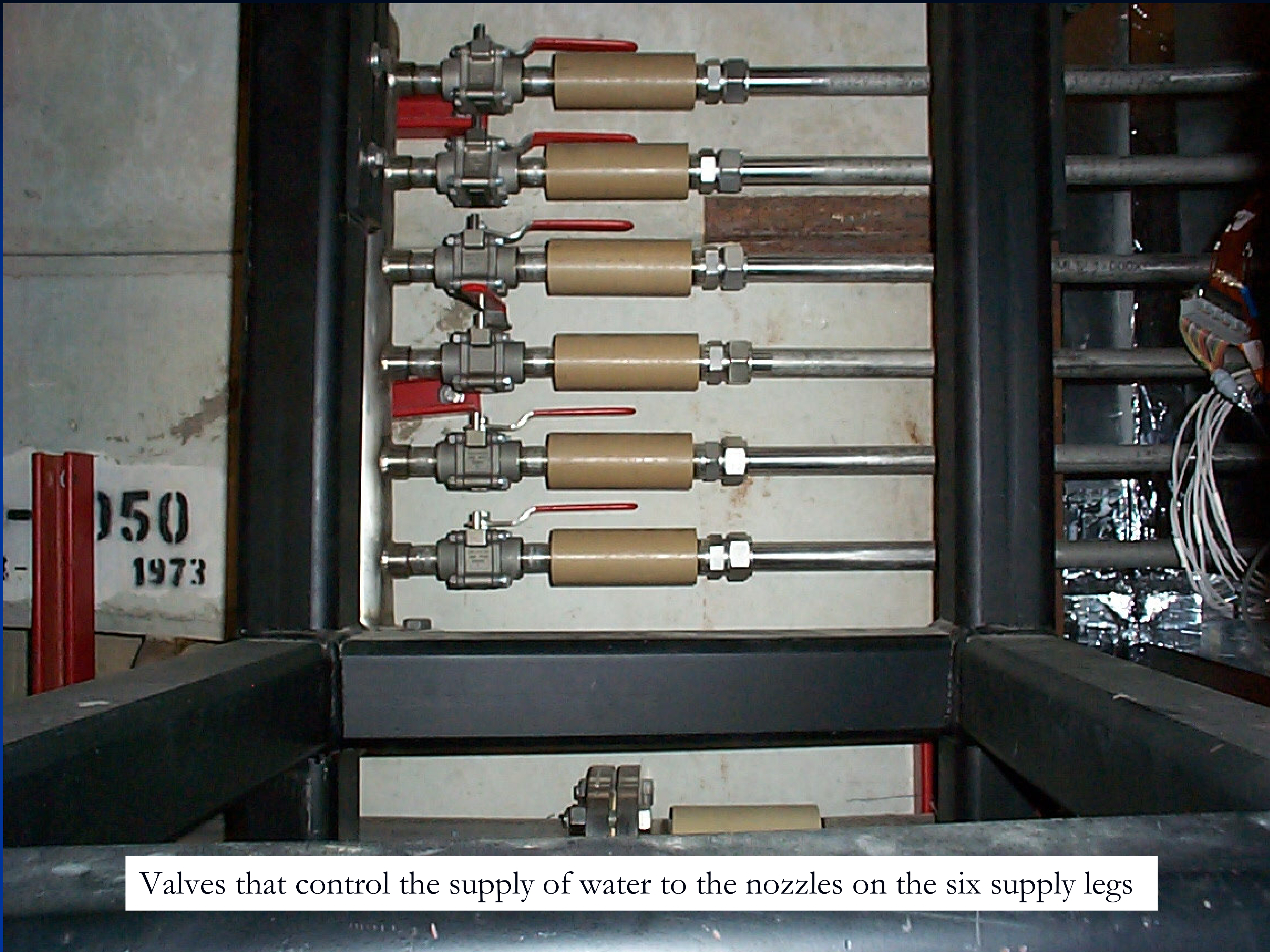
- We used a camera and a borescope to see into the dark areas inside and under the horn box
  - Observations were hampered by lack of good tools to view inside the horn box
  - We were fortunate to have ports to see into the horn box
    - They were originally designed as stripline air cooling ducts but were not used for that purpose finally
- We were trying to see whether the leak was on the supply piping or the drain piping

The camera on a stick that could see into the horn box through a hole in the support platform. The hole it looks through is the mirror of the target air return port.



Steps we took to investigate 3

- We turned off the supply legs one by one to see if the leak would stop
- The leak rate did not change when any of the legs on the left (same side as the leak) were turned off—stayed 35 mL/hr
- The leak rate dropped to 1/3 of the original when any of the right legs were turned off
- The leak only went away when the entire system was shut off

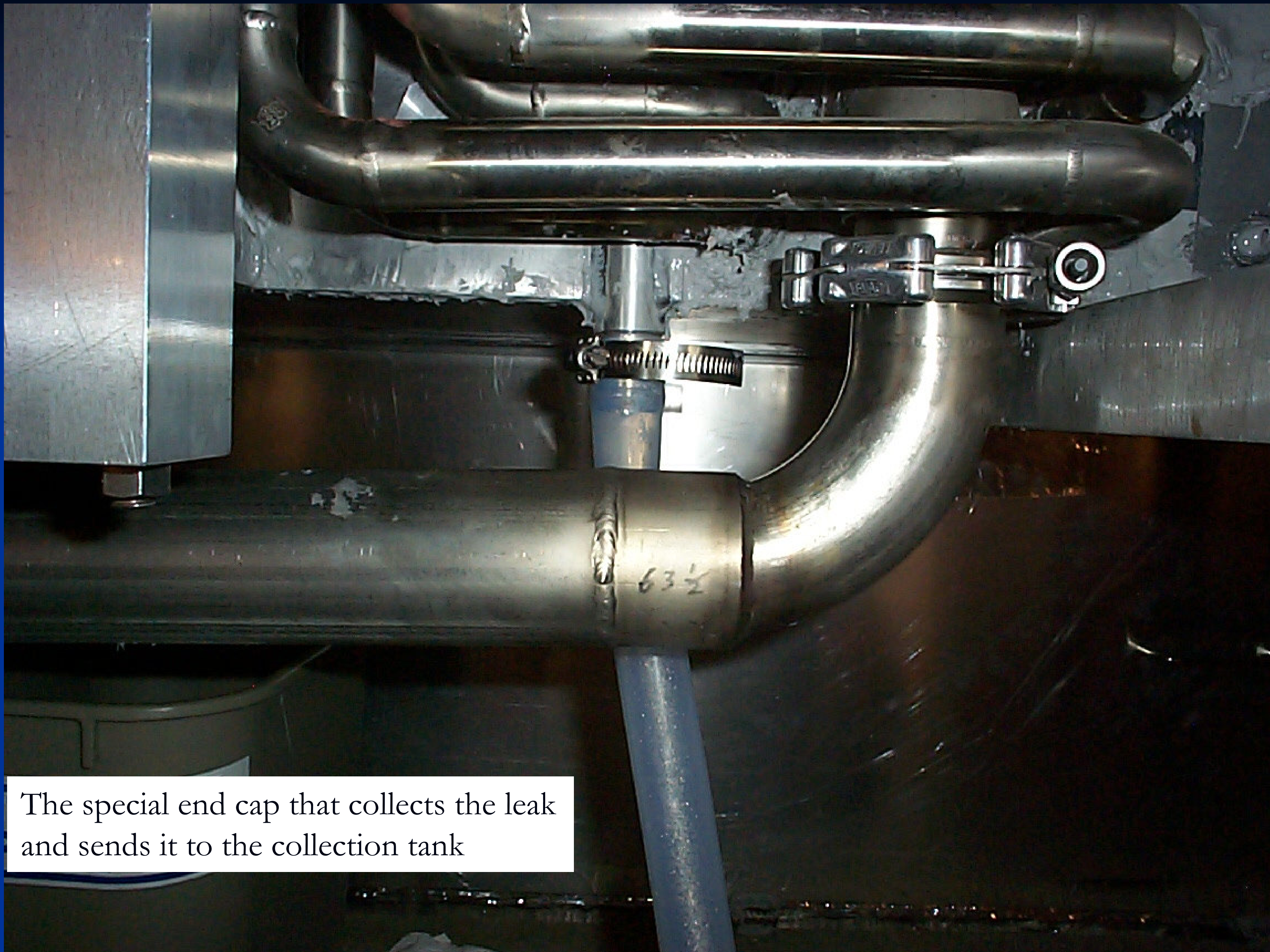


Valves that control the supply of water to the nozzles on the six supply legs

The Temporary Fix

- We added a leak collection system with a liquid level sensor to monitor the amount leaking out
- We added a 5 gallon calibrated bucket to the top of the RAW system surge tank
  - The only measurement of water added to the tank before was an uncalibrated non-linear sight glass
  - Now there is an electronic readout sight glass for continuous monitoring of the level in the surge tank

The leak collection tank and the level sensor



The special end cap that collects the leak
and sends it to the collection tank

The leak collection system fully assembled

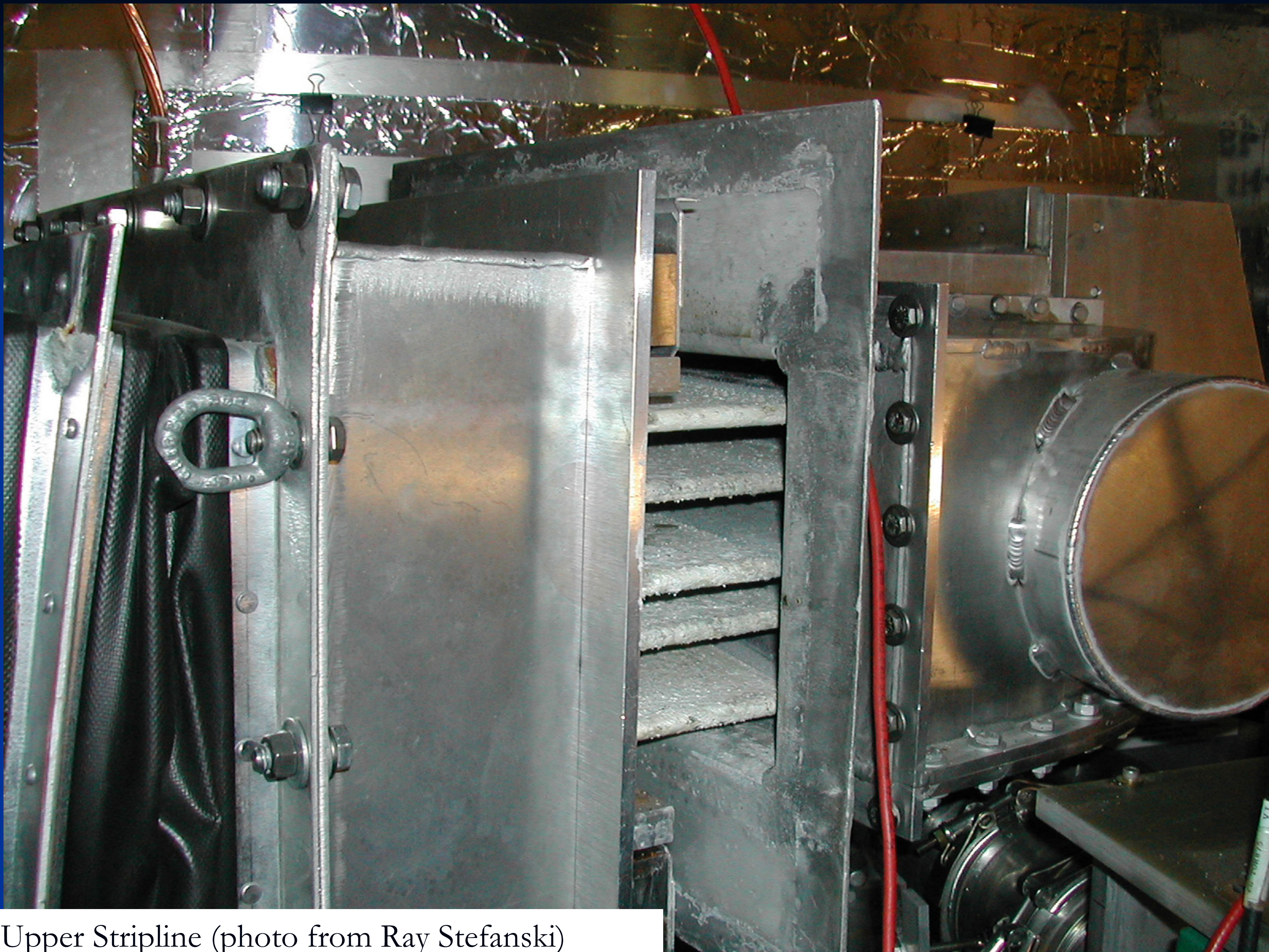
The calibrated 5 gallon bucket to add water to the surge tank of the RAW system

Pictures taken just before horn removal

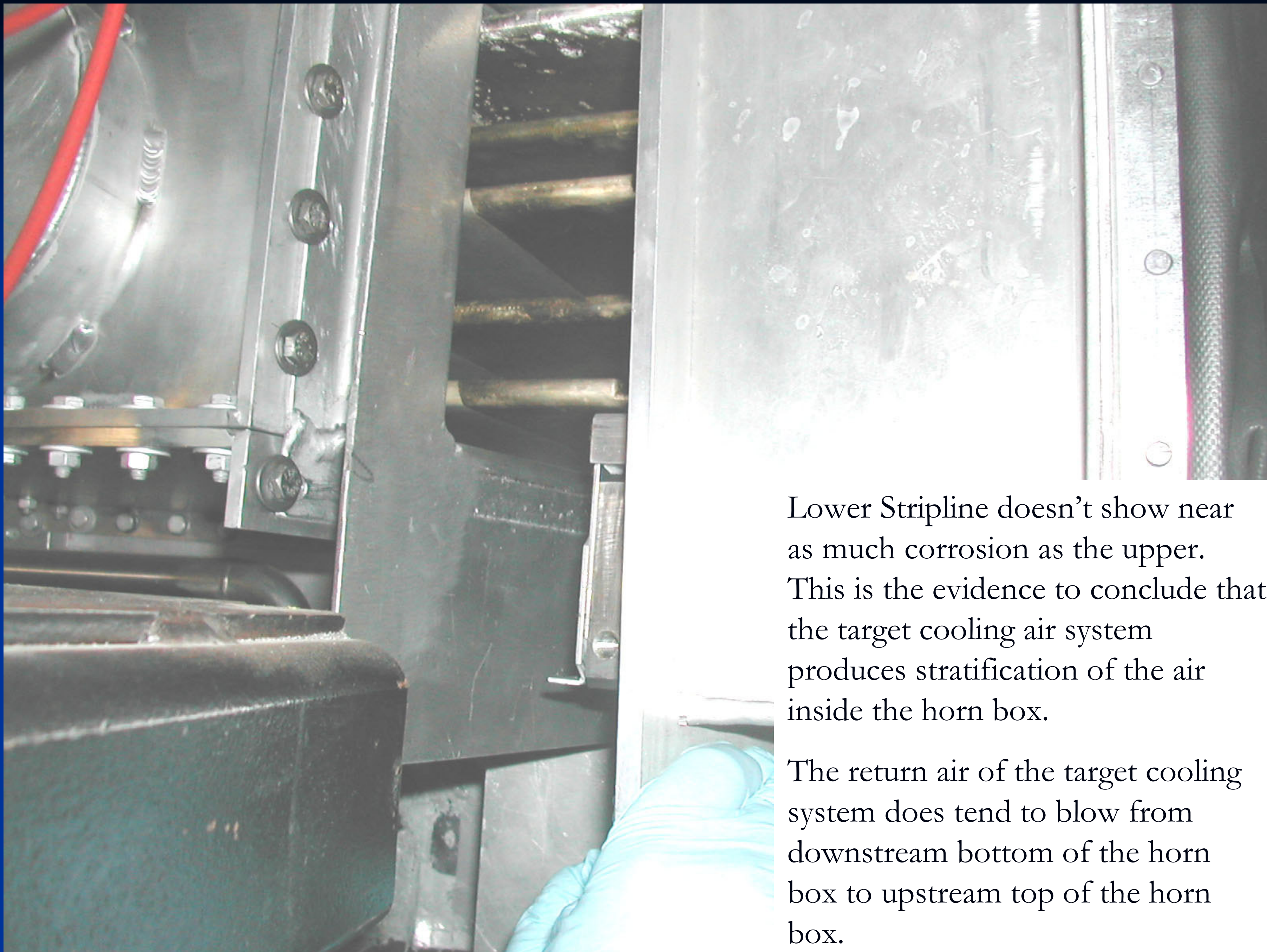
- The next few pictures show where we saw stripline corrosion—and where we didn’t
- The corrosion ended right at the air barrier on the stripline
- The parts inside the horn box are covered with a white powder that is mostly aluminum oxide and makes the pictures look like those from sunken ships

Photo courtesy of Ray Stefanski

Air barrier



Upper Stripline (photo from Ray Stefanski)



Lower Stripline doesn't show near as much corrosion as the upper. This is the evidence to conclude that the target cooling air system produces stratification of the air inside the horn box.

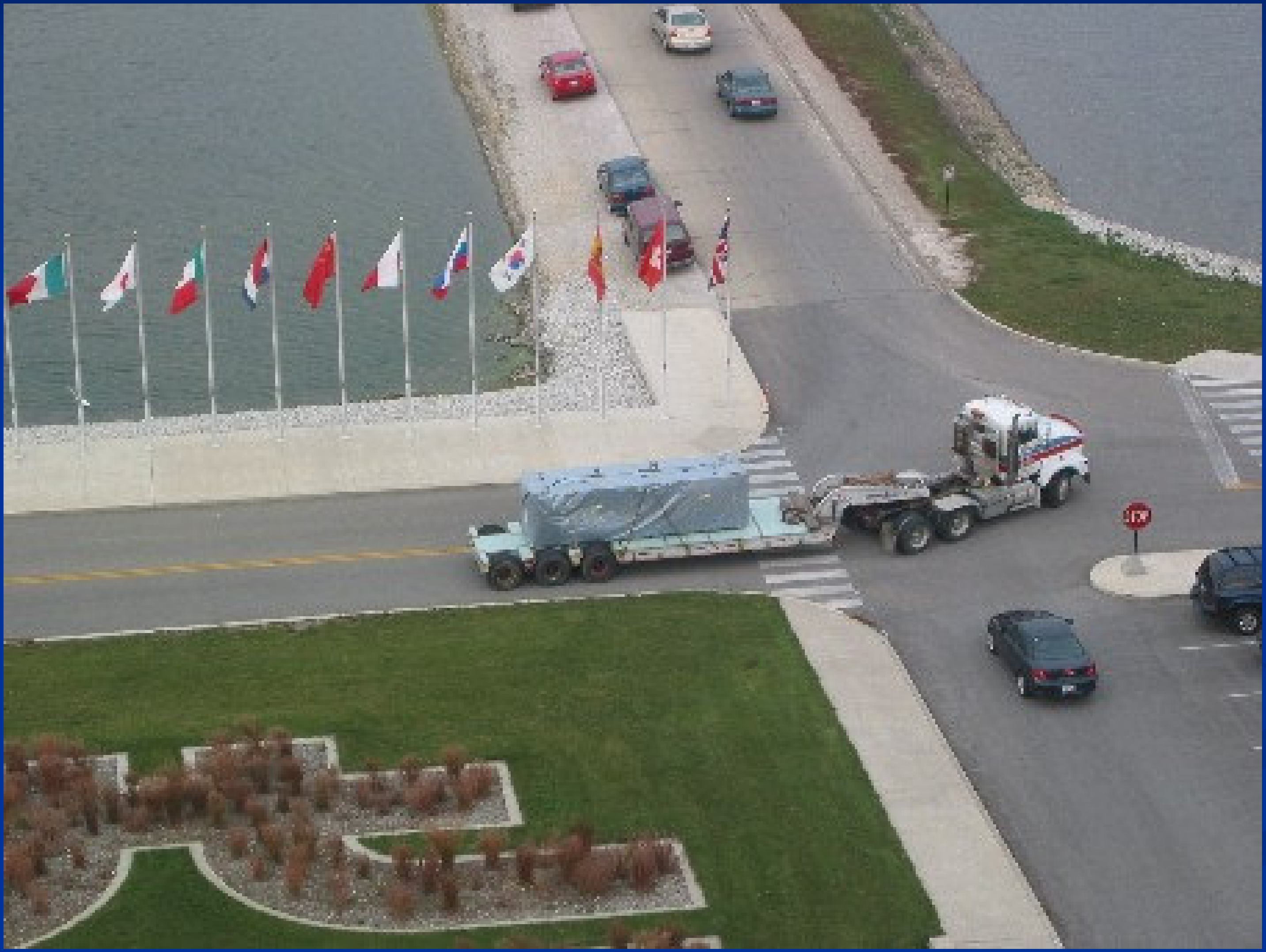
The return air of the target cooling system does tend to blow from downstream bottom of the horn box to upstream top of the horn box.

Borescope pictures of the connection between the stripline and horn


11
02
AL
[2]
[2]
[Y]
C

AL
[2]
[2]
[Y]
03

Burial of the horn



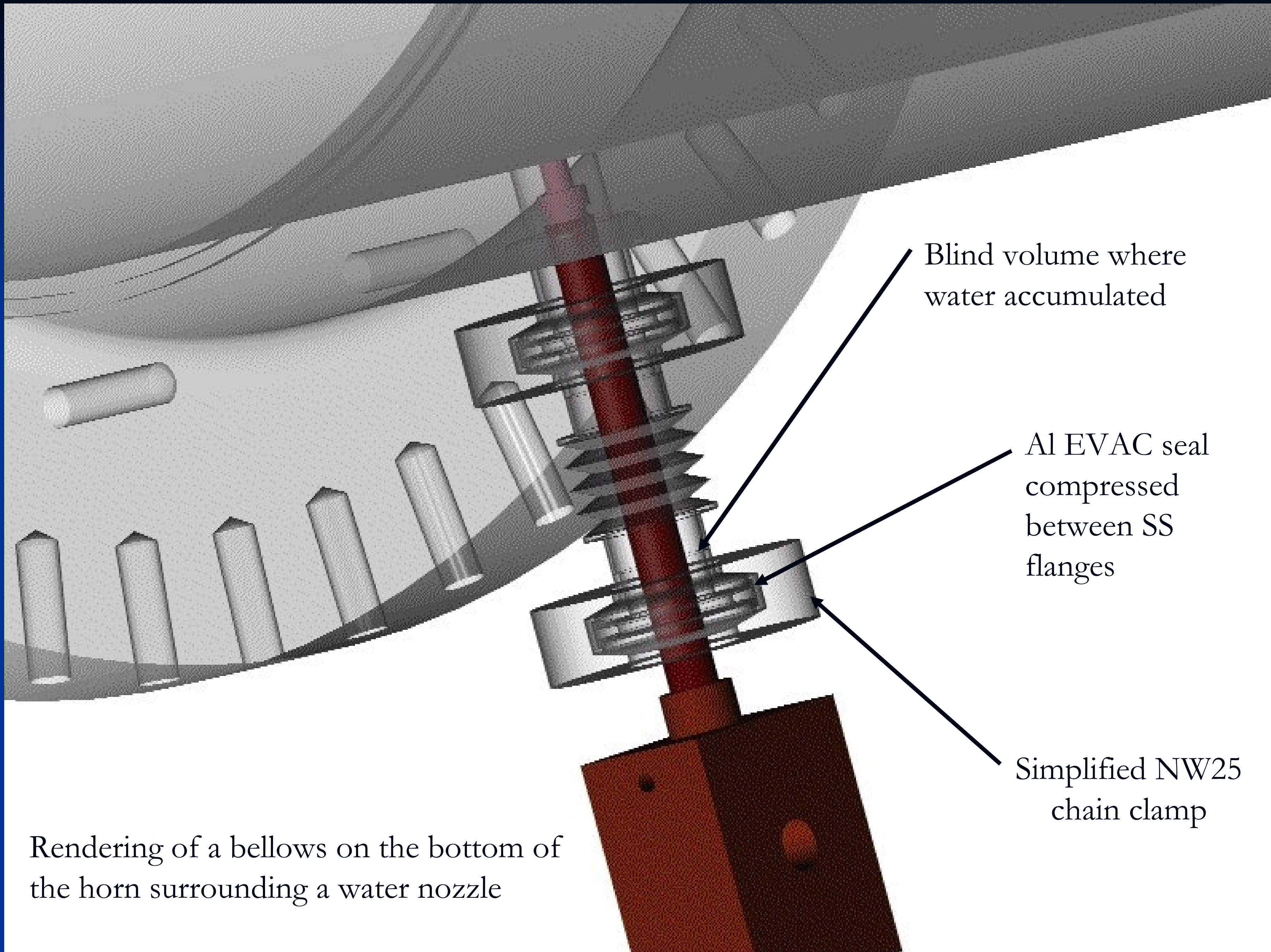
The horn in its coffin on the drive from MI-12 to the TSB tomb

Where was the ground fault?

- We were never able to localize the ground fault
- Disconnecting the horn from the power supply showed it to be somewhere in the horn box
- Looking at the pulse shape in the ground, it was concluded that it was between the HV of the inner conductor and building ground
- With all the corrosion, it could have been anywhere along the stripline in the horn box

Where was the water leaking?

- **We finally opened up the horn box and looked at the horn in January, 2007**
- My guess of galvanic corrosion of an aluminum seal between two stainless flanges on a bellows on the bottom left side of the horn was confirmed.
- The bellows on the bottom of the first horn trapped water that never got exchanged and cleaned
  - Radiation induced chemistry accumulated in these
  - Aluminum acts as a sacrificial anode for stainless



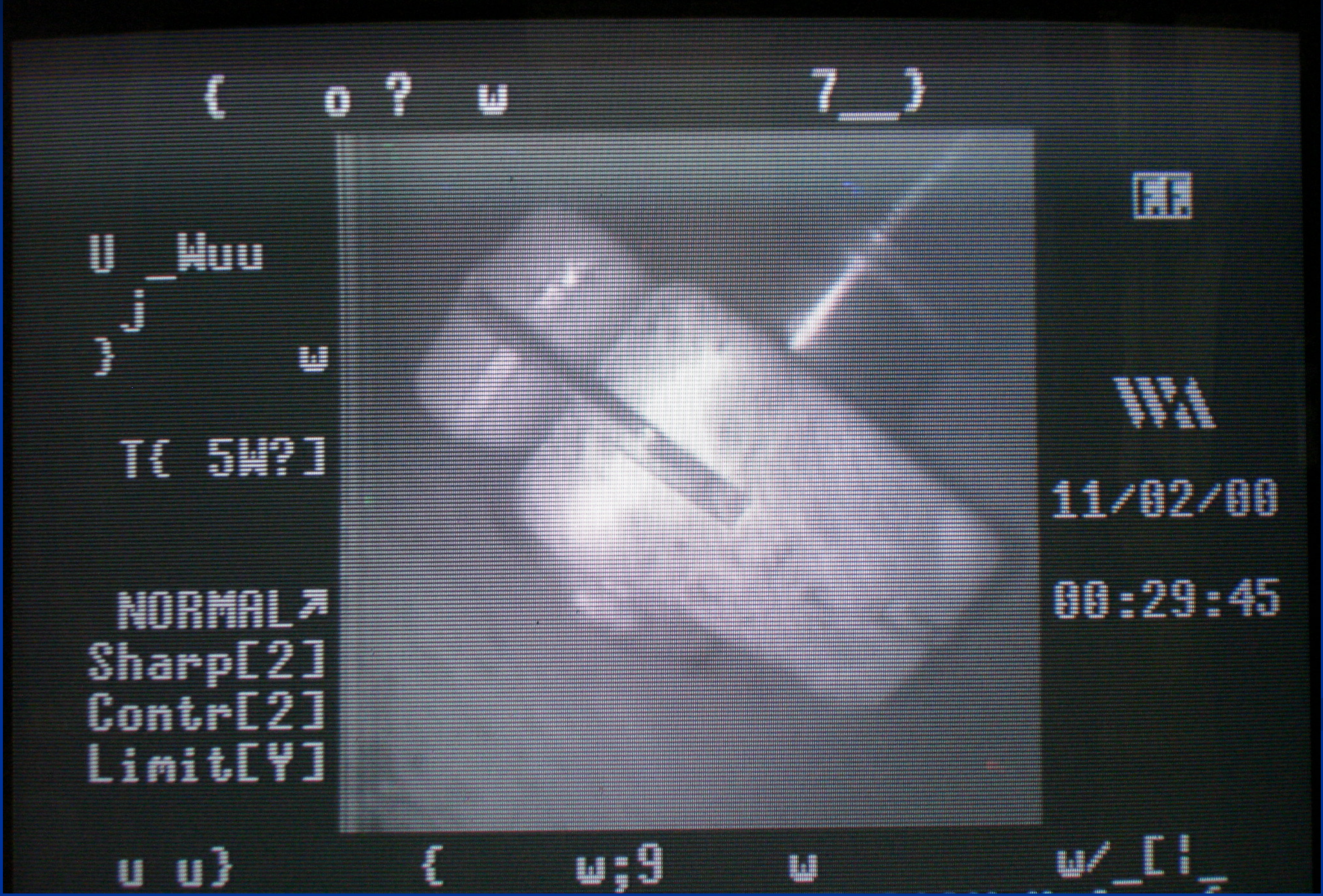
Rendering of a bellows on the bottom of the horn surrounding a water nozzle

Pictures from the autopsy of Horn 1

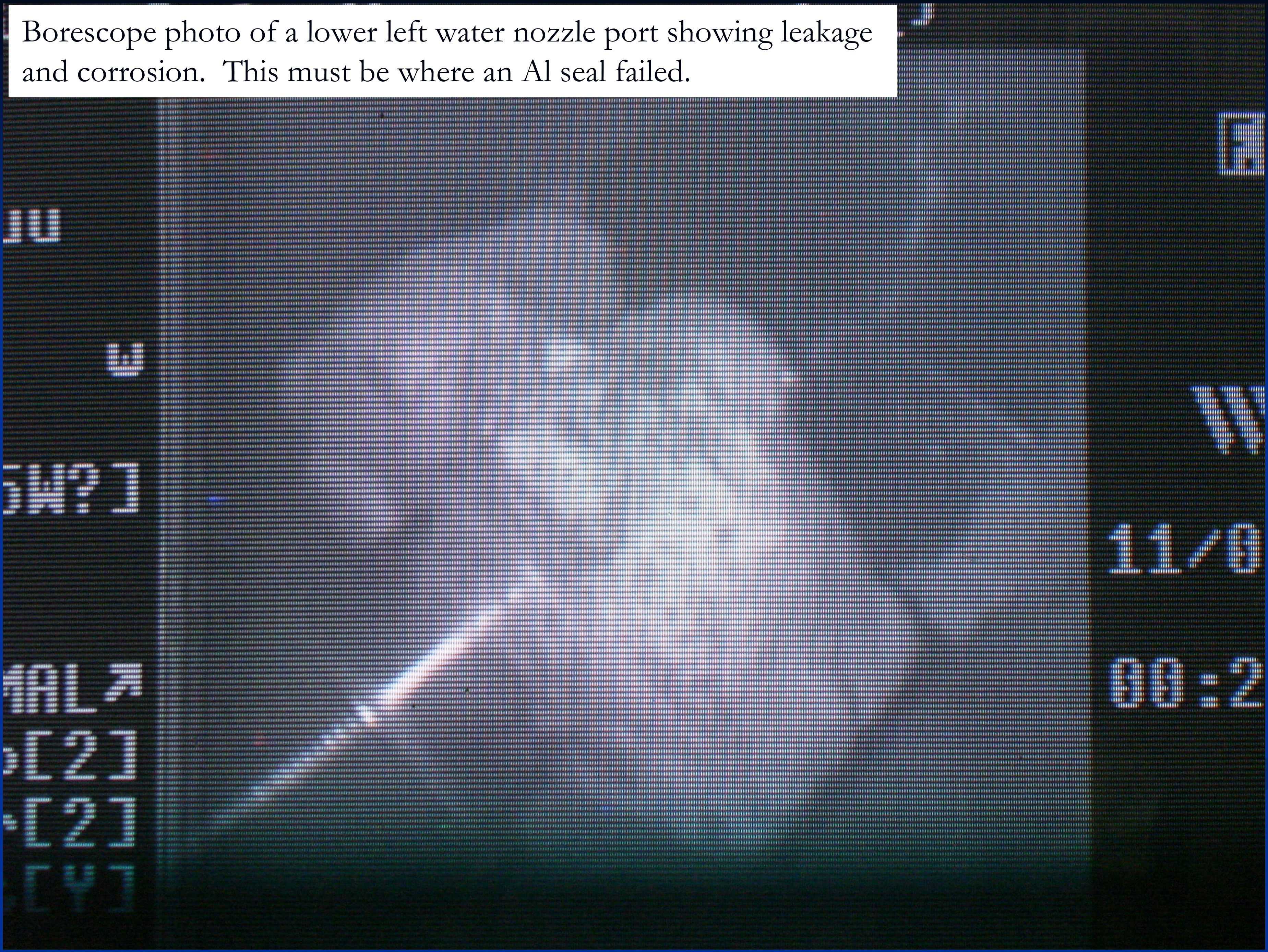
- The next pictures were taken at the Target Service Building at FNAL where the broken Horn 1 is entombed
- A hole was punctured into the thin downstream window of the horn box allowing a borescope to enter the horn box
  - Note that borescope pictures are arbitrarily rotated because it's hard to orient the probe to indicate up and down

This is a picture of the DS end of horn 1

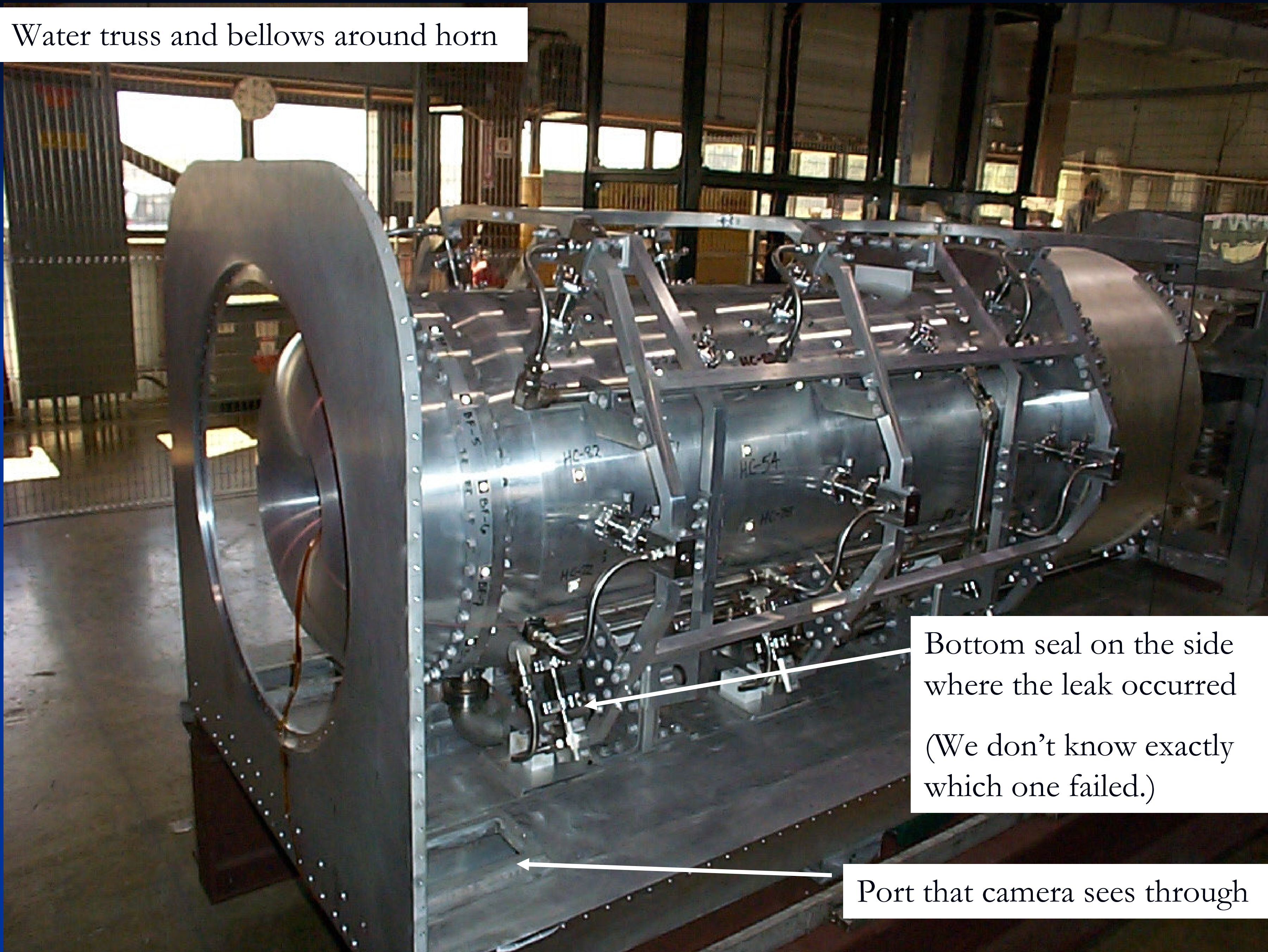
Borescope photo of an EVAC chain clamp around a lower right water nozzle port. No sign of leakage and corrosion.



Borescope photo of a lower left water nozzle port showing leakage and corrosion. This must be where an Al seal failed.



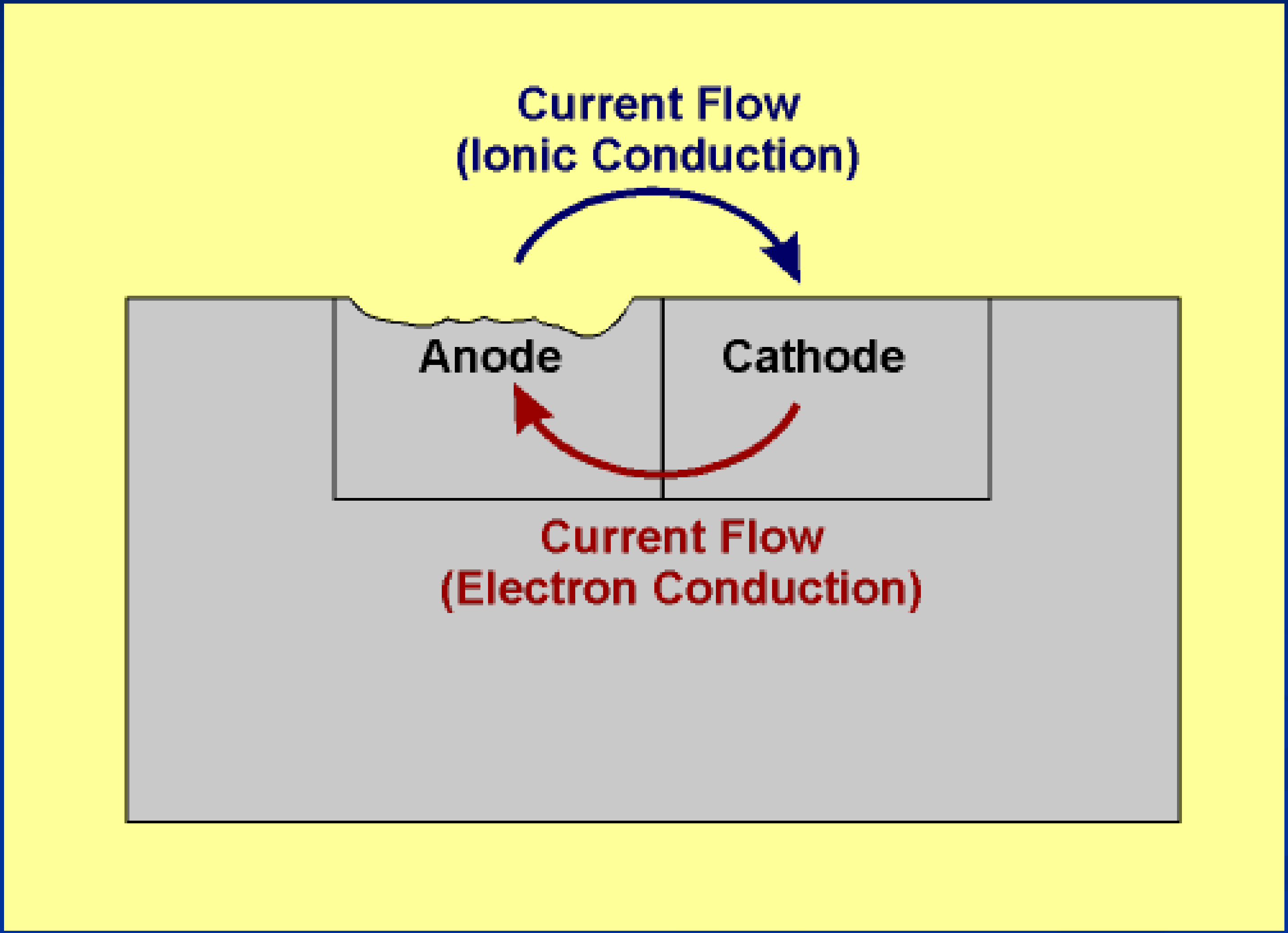
Water truss and bellows around horn



Three conditions necessary for galvanic corrosion to occur:

1. There must be two electrochemically dissimilar metals present
   - Stainless 304 and Aluminum are far apart in the galvanic corrosion series
2. There must be an electrically conductive path between the two metals
   - They are squeezed together in a seal
3. There must be a conductive path for the metal ions to move from the more anodic metal to the more cathodic metal
   - The RAW water

A simple corrosion cell

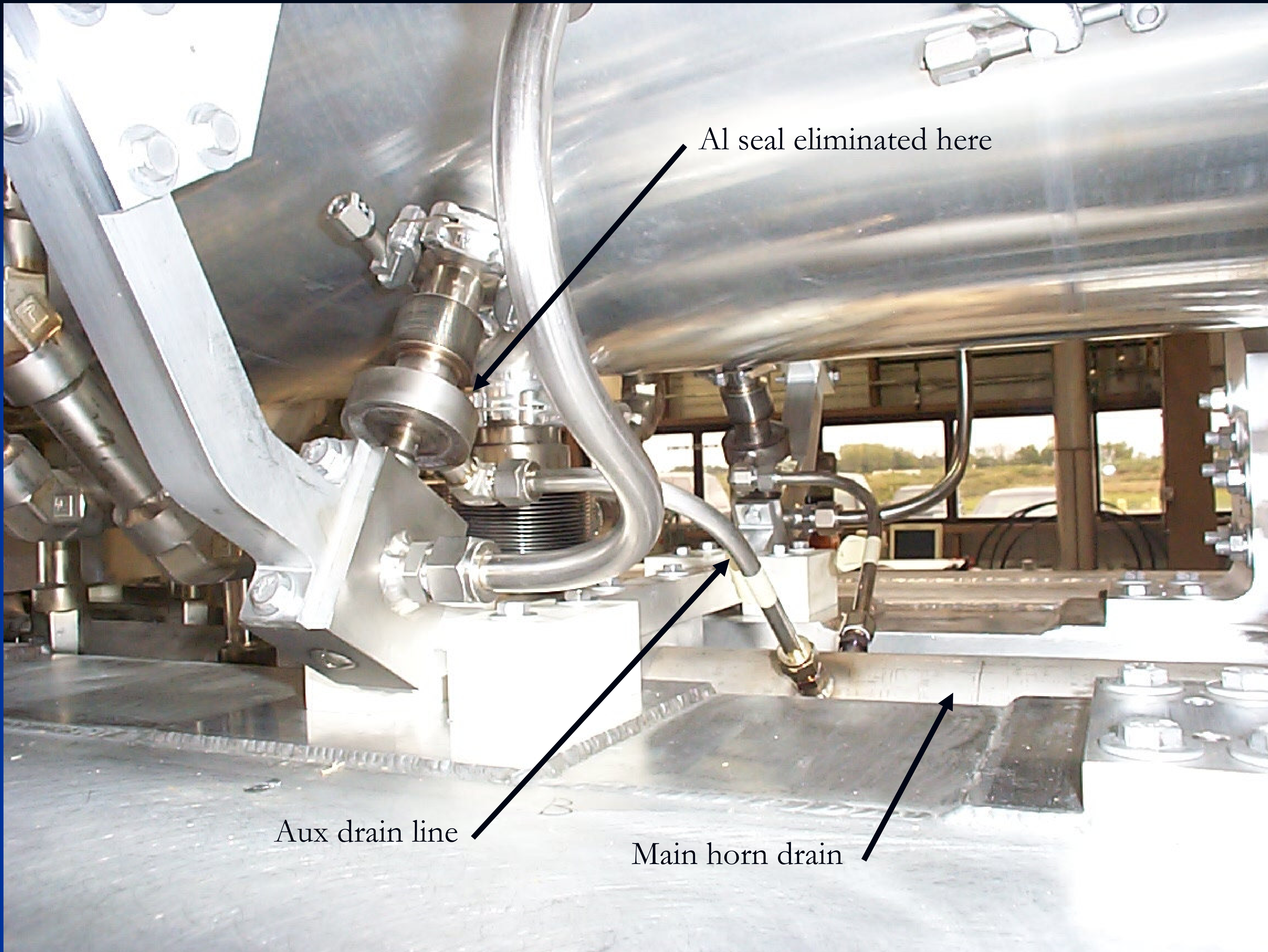


If any of the three necessary conditions are not met, galvanic corrosion cannot take place. The horn satisfies all three conditions and because of the water sealing requirement, it is hard to break one of the conditions

Picture courtesy of: http://www.corrosion-club.com/

Fixing the Second Horn

- We welded the flanges on the bottom six bellows eliminating one aluminum seal
- We added an auxiliary drain to prevent water from collecting in the bottom six bellows
- The leak collection tank became a permanent part of the RAW system
- We improved the ability of the spare horn platform to route water to the leak tank
- We added a new dehumidification system to the horn box


Al seal eliminated here
Aux drain line
Main horn drain

Failure Modes: Fatigue vs. Corrosion

- Continued research on the fatigue of Al indicates that Al 6061-T6 can survive much longer than I thought before
  - ASM Metals Handbook reports cycle life up to 5E8 cycles—everybody else was at 5E7
  - New ultrasonic gigacycle fatigue testing machines extend the range of the material data
  - The material is not limited, it is the fatigue data that is limited
- Conclusion: If a horn is designed to survive fatigue, corrosion will probably be what kills it

Positive conclusions:

- We built the world's longest lived horn that survived 96 million pulses at the fastest pulse rate ever (5 Hz average, 15 Hz instantaneous)
- There was no sign of fatigue failure anywhere
- The first horn lasted just over two years
- The improvements to the spare horns have allowed the second horn to accumulate ~200 million pulses by September of 2008, and it is still going

Other Conclusions:

- If horns are made out of aluminum and water systems out of stainless, corrosion will probably be the death of the horn
- Diagnosing the MiniBooNE horn is complicated by the interconnected-ness of the air systems
- We could use better tools to analyze failed horns, but we are glad that we were able to dissect horn 1 to learn what killed it
  - The only way to improve horns is to learn what kills them