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Failure and Repair of the Mach 5 Heater for Sandia's Hypersonic Wind Tunnel

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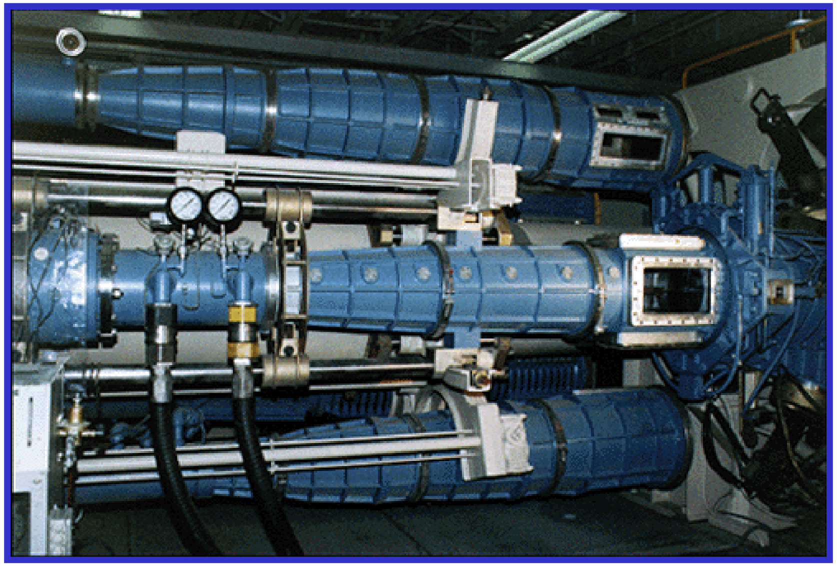
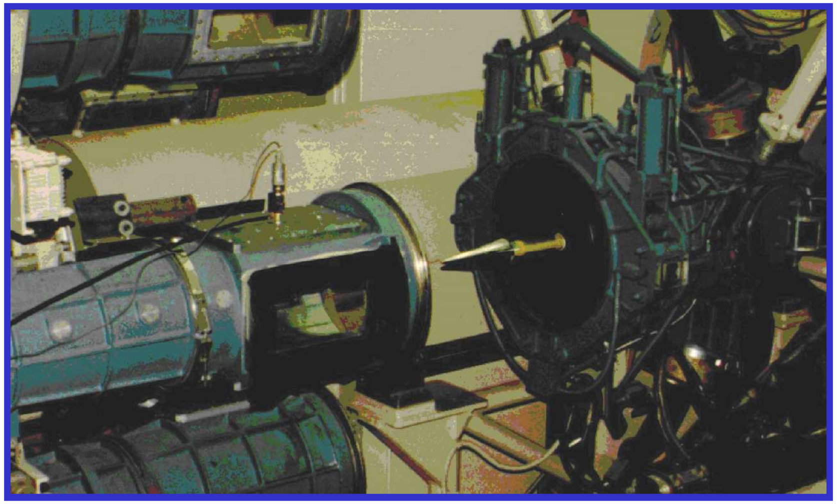
Hypersonic Wind Tunnel (HWT)

- Blowdown to vacuum
- M_∞ = 5, 8, 14
- Re = 0.2 - 10 x 10^6 /ft
- Run times: ~45 sec at 45 minute intervals
- Gases:
  - air at Mach 5
  - N_2 at Mach 8 and 14
- 18" diameter test section
- 4" - 5" maximum diameter model size
- Stagnation temperature to 1400 K (2500°R)





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HWT Subsystems

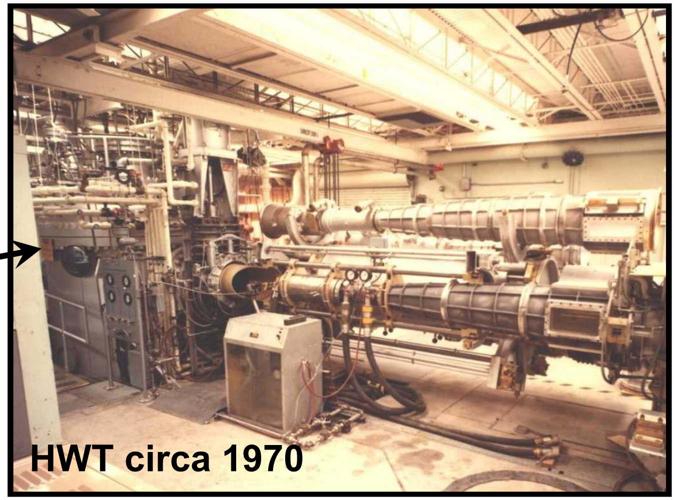
The Mach 5 test section is driven by 270 psia air from a compressor system.

All test sections exhaust to three vacuum spheres evacuated by a series of pumps.

The Mach 8 and 14 test sections are driven by nitrogen from a high-pressure evaporation of LN_2 and stored at 8600 psia.

HWT Heaters

Originally, the HWT used a pebble-bed heater.



HWT circa 1970

A series of upgrades through the 1970's produced the current HWT.

Each Mach number has its own electric resistance heater, based on the same design.

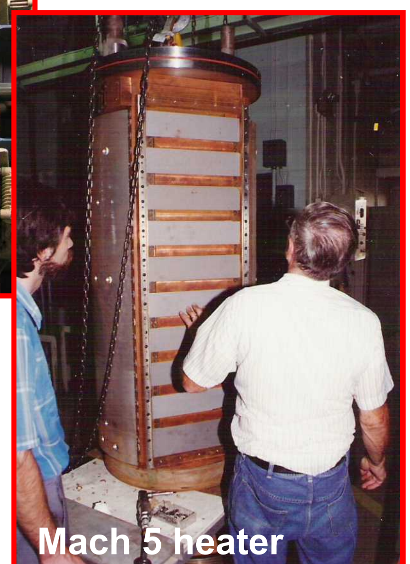
The heaters were designed and built by Fluidyne.

Mach 5 was the last to come on-line (1977) and is the largest.

No previous failures have occurred except for replacing damaged screens.

Mach 8 heater

Mach 14 heater



Mach 5 heater

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The Mach 5 Heater

- Powered by a 3 megawatt electrical transformer
- 3-phase system at 70 volts and 20,000+ amps
- Stagnation temperature established by voltage control
- Nichrome wire screens
  - 34 screens at 10 stations
- Energized components are principally copper
- Phases are separated by a variety of insulator types

partly disassemble

heater screens

The Failure

In December 2004, during a routine test at high stagnation temperature and high heater power, a failure occurred.

The first indications were from low readings on temperature and heat flux gages on the model.

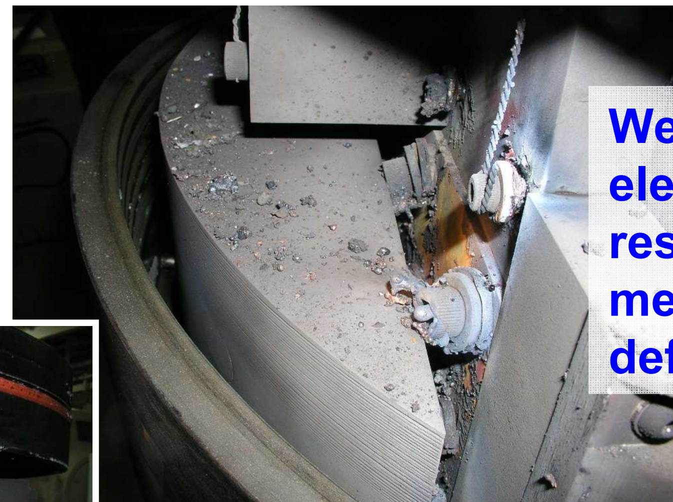
Subsequent examination showed a low stagnation temperature and a small change (<10%) in current balances between the three electrical phases.

We believed that we had ruptured one or more screens. This is a common failure at Mach 8 and 14 and had occurred once in 1993 at Mach 5.

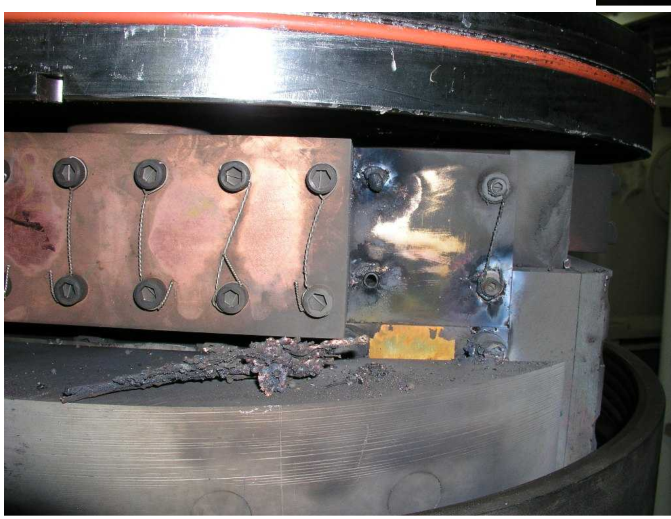
Upon removing the heater from its pressure vessel, we found a much more serious failure.

Our First Sign of Serious Trouble

As the heater was hoisted out of its pressure vessel, it was quickly obvious that this was not simply a screen rupture.



We found marks from electrical scorching, residue of slagged metals, and melted and deformed bolt heads.



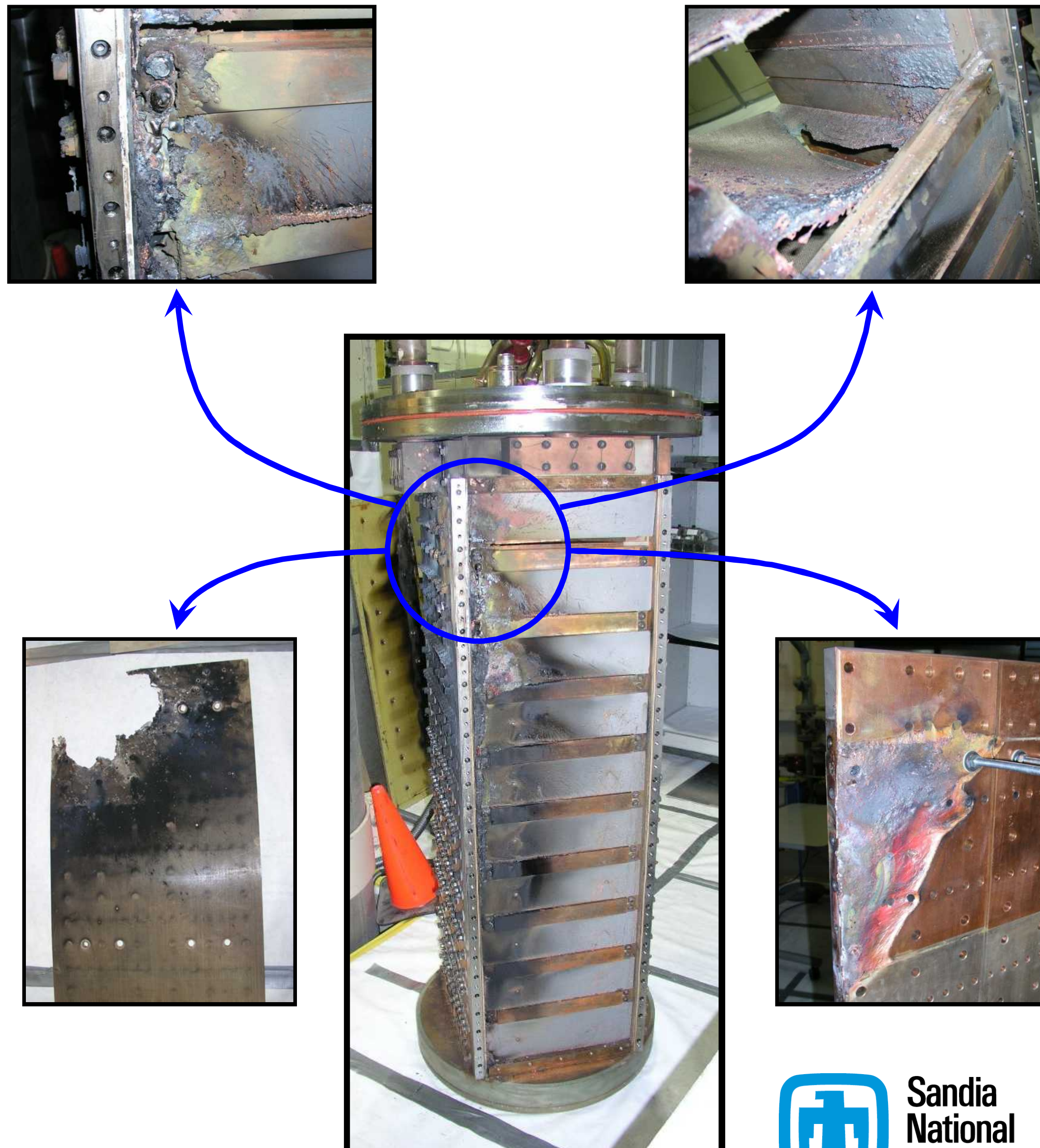
Safety concerns immediately placed us on hold due to the possibility of inhalation of heavy metal particulates.

Initial Damage Assessment

After protracted discussions concerning hazard mitigation, we fully opened the heater.

We found a real mess:

- **Copper blocks eroded to ½" depth**
- **Shattered glass insulators**
- **Multiple torn screens**
- **Insulation breach**
- **Metal debris, molten copper, and carbon dust deposited on components**

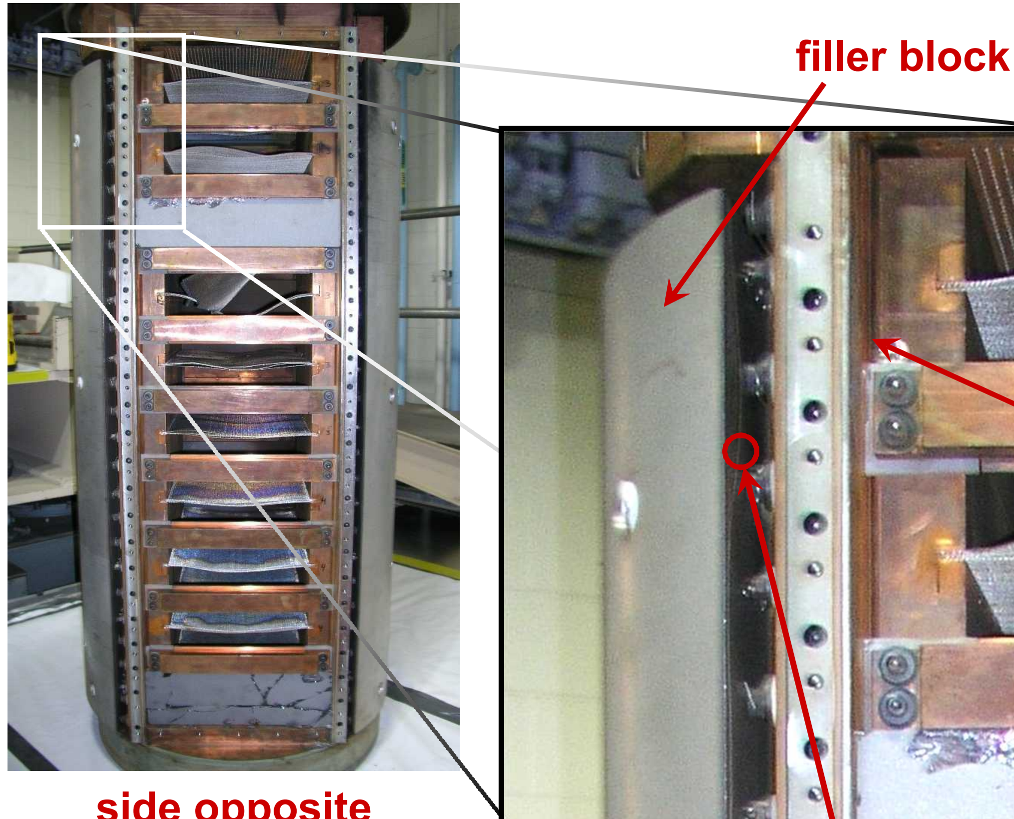


What Happened?

A sheet of teflon fiberglass laminate insulates between bolts through the bus bars and a filler block at floating potential.

The insulation has a small degree of freedom to flutter in this gap.

Our leading theory is that the insulation wore through after years of cycling. This allowed the filler block to make contact with two phases.



side opposite from failure

When 20,000 amps flow someplace you don't want, you will have a bad day.

Electrical Damage

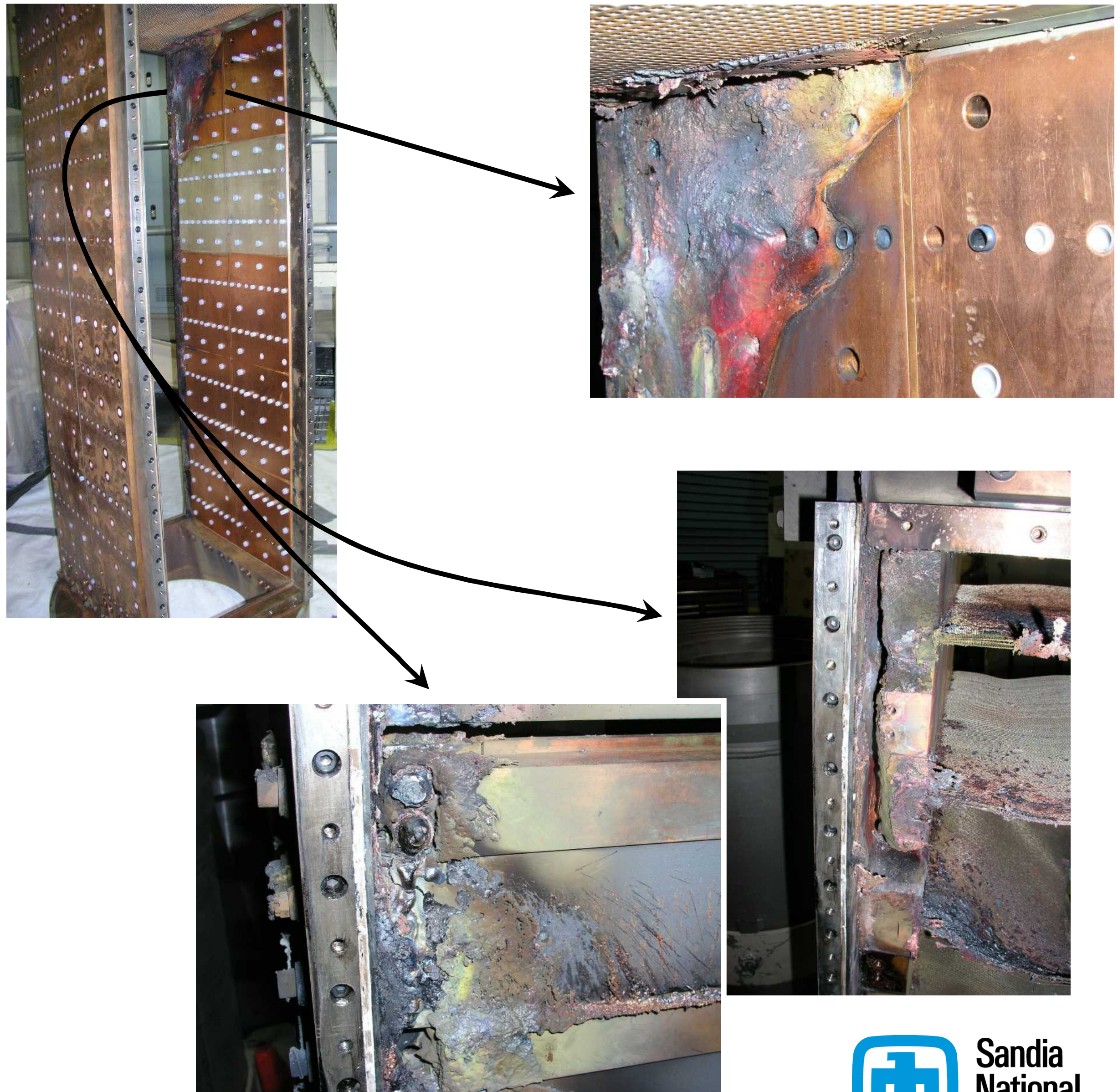
Contact between electrical phases created I^2R heating.

This melted portions of the copper bus bar and the adjacent screen blocks.

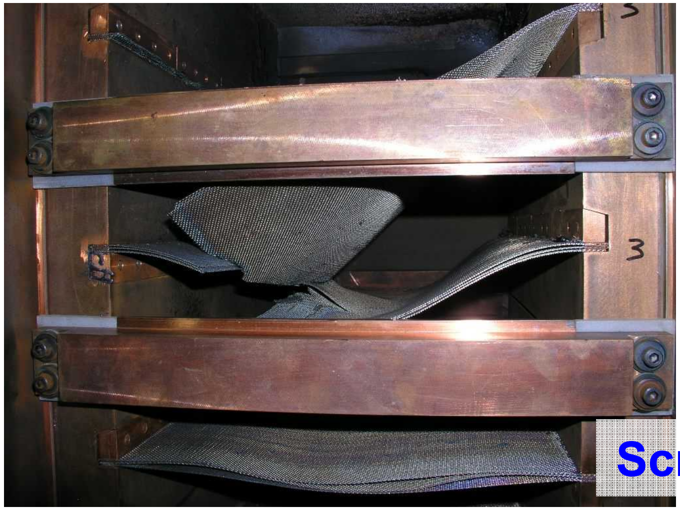
Erosion depths reached 0.5 inch.

Steel bolts melted and deformed.

Molten copper flowed downstream.

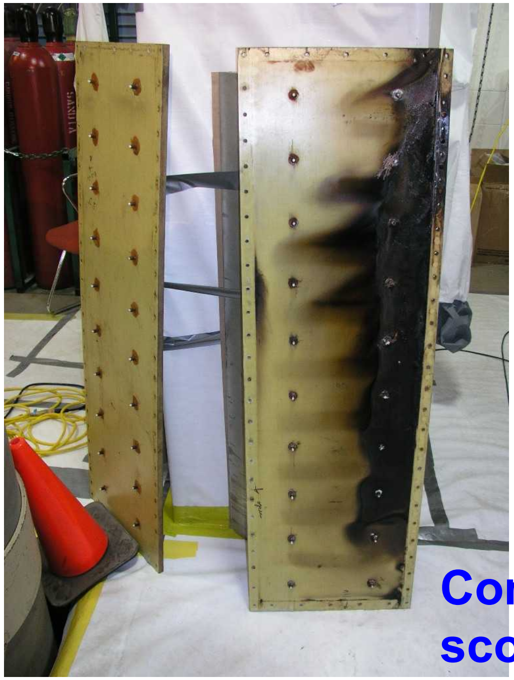


Subsidiary Damage



Screens were torn.

Glass cracked.



Components were scorched.

Residue was deposited throughout the heater.

How Do We Fix It?

This failure is well outside our experience.

Examine the documentation:

- No final report on the heater installation was written; only a preliminary design report
- No as-built drawings; numerous discrepancies found with the existing hardware

Contact ASE (formerly Fluidyne) for guidance

- They had not built more heaters like ours and did not have substantial experience with such a failure.
- We concluded that we were probably the best experts on our own heaters.
- We received advice from several ASE engineers, including a visit by Dave DeCoursin, now retired, who helped design the heater.

Constraints on the Repair

Financial Limits

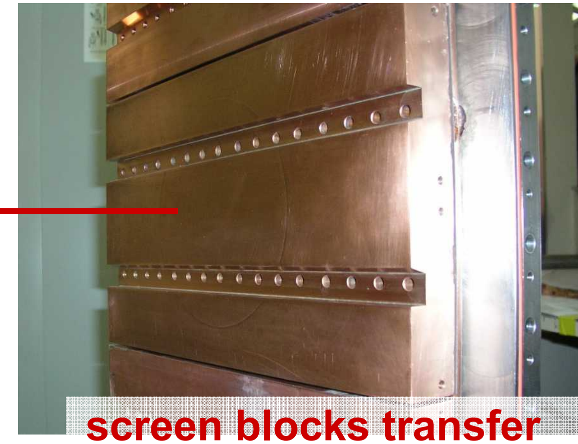
- We received only $70k in new money for the repair.
- The rest was unofficially redirected from existing maintenance budgets and aerodynamics research projects.
- We did not have the resources to re-engineer the heater.

Personnel Limits

- Sandia's wind tunnels were once operated and maintained by a team of 10-15 engineers and technicians.
- We now have 1.5 engineers and 2 technicians.
- Time spent on the repair was time not spent on "real work."

No use in complaining…. Find a way to get it done!

Material Selection



screen blocks transfer power from the bus bars to the nichrome screens

Many of the materials used in the 1970's are not available today.

We must select appropriate replacement materials.

New materials are not one-for-one substitutes and have different properties.

Lacking adequate documentation, we do not know why materials were chosen.

- i.e., electrical conductivity? thermal expansion? yield strength?

A straightforward example is the replacement of the screen blocks

- Made from zirconium copper
  - Not available in large sizes from a credible vendor
- Modern equivalent is GlidCop
  - High electrical and thermal conductivity
  - Good high-temperature strength
  - Also high cost

Material Selection

Locating a substitute for the side panels was not straightforward

- Made from Scotchply 1007, a glass fiber composite
- Once made by 3M, but now discontinued
- Portions of Scotchply product line sold to Cytec corporation
- Neither 3M nor Cytec have material information on the 1007 product
- Eventually, we found a retired 3M engineer with the relevant information in his basement
- Many potential replacements do not have known flexural strength properties at elevated temperatures

A reasonable substitute for our application is G11 glass-epoxy resin

- Temperature rating and strength properties lower than Scotchply 1007
- However, the heater was designed for use with a Mach 3.5 nozzle that was never constructed
  - We can de-rate the necessary strength

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Other Steps to Recovery

Many other components to locate or fabricate

- Bus bars, steel support beams
- Numerous insulators, glass panels, etc.
- Replacement screens

Material testing showed the copper bus bars had softened over years of operation

- Probably due to an annealing effect from thermal cycling
- Believed to retain sufficient strength for continued use

Lots of trouble making it all fit together

- Deformation of hardware over ~30 years
- Undetected discrepancies between drawings and hardware

Other Steps to Recovery

An awful lot of tedium….

- More than 2000 bolts
  - Most with insulating washers and sleeves and safety-wire
- Paranoia about any possibility of contact between electrical phases

Replace the thin insulation whose breach is believed to have initiated the failure

- Use a thicker sheet of G10 fiberglass laminate
- Plane the filler block to create space

A whole lot of cleaning!

- Stray bits of metal punctured thin sheets of glass-fiber insulation and created shorts

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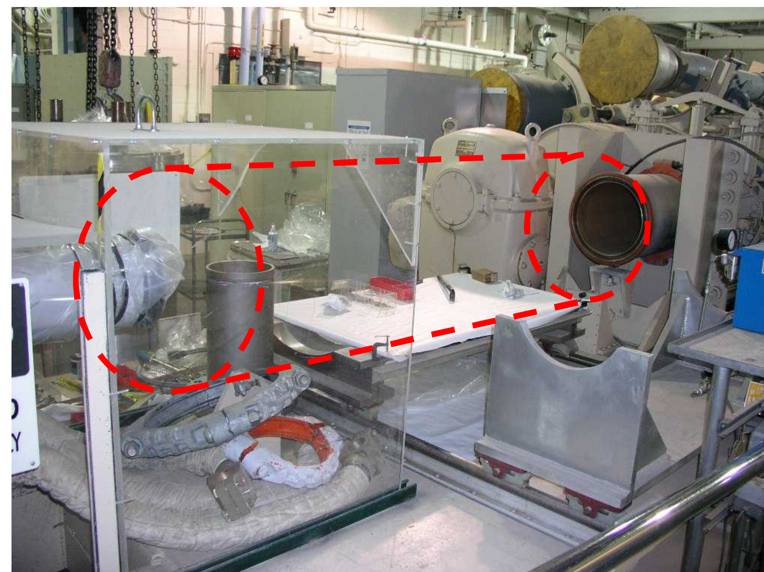
Final Assembly

Lower the heater back into its pressure vessel.

Return it to its position upstream of the nozzle and reconnect the power cables.



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Return to Operation

Various delays have slowed the heater assembly.

- Expect re-start in mid- to late-May

Initial Operation Plan

- Check resistance values on each phase for evidence of a short
- Begin with several cold runs
  - Check hardware for proper operation
  - Blow out dust
- Short low-heat runs at higher pressure
  - Best mass flow rate for cooling heater
  - Examine stagnation temperature
- Move to hotter conditions

We believe if the heater works once, it will work for many times.

- If something is wrong in our rebuild, we'll learn about it quickly.

Performance Monitoring

Unfortunately, we have few methods to monitor the heater performance.

- Current monitors to examine ratios between currents
  - We expect somewhat different values than before the rebuild
- Tunnel stagnation temperature
- We are unaware of any internal fault sensors likely to be useful without risking the health of the heater
- Can we develop a ground-fault or current-fault detector?

Heater Inspection

- After a series of successful runs, we will open the heater and inspect it for damage or flaws
- We will conduct periodic future inspections
- We will inspect the Mach 8 and 14 heaters for degradation

Lessons to Learn

Despite this serious failure, the heater did operate successfully for 27 years.

The most serious failures likely will occur from an unexpected source.

Just because it ran great yesterday doesn't mean it will tomorrow.

Reductions in funding and personnel have consequences for maintenance and failure recovery.

Unfortunately, fiscal realities mean we can expect unpleasant surprises in the future.

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