FORENSIC ENGINEERING INVESTIGATIONS

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HALES & GOOCH LTD.

Chicago USA and Christchurch NZ

www.halesgooch.com

FORENSIC ENGINEERING

- What happened? Evidence?
- Why did it happen? Analysis?
- Who was responsible? Basis?
- Who should have done what?

- Opinions/Interrogatories
- Depositions/Reports
- Mediation/Arbitration
- Settlement
- Trial (Last resort)

PROGRESSIVE ROLES REQUIRE GREAT CARE

- Specialist investigator
- Consulting expert
- Expert witness

FORENSIC ENGINEERING TASKS

- Inspect & document
- Review evidence
- Measure & test
- Apply theory
- Analyze & calculate
- Communicate opinions

INVESTIGATION GUIDELINES

1. **Bring all the pieces together again**

    Case Example: Process Boiler Explosion

2. **Question all assumptions**

    Case Example: Supermarket Bag Stand

3. **Think through the logic**

    Case Example: Electric Motor Fire

4. **Explain the unusual**

    Case Example: Black Liquor Tank Collapse

5. **Demonstrate findings clearly**

    Case Example: Pressure Washer

1

BRING ALL THE PIECES TOGETHER AGAIN!

4 March 1993, 9:46pm

Boiler Explosion In La Porte Kills 2

By Phillip J. O'Connor
Staff Writer

Investigators combed through debris on Friday seeking the cause of a boiler explosion in a La Porte, Ind., factory that killed two workers and injured 11, five of them seriously.

Inspectors from the U.S. Occupational Safety and Health Administration and the Indiana Boiler and Pressure Vessel Division were also questioning witnesses at American Rubber Products Corp.

The force of the blast sent the boiler, which was 10 feet in circumference, flying through the rear of the building about 10 p.m. Thursday, knocking a 15-square-foot hole in a brick-and-cinder-block wall, investigators said.

Alden Taylor, a spokeman for the state office that inspects boilers, said no violations were found when the boiler underwent its last annual inspection, on July 29. He said it was built in 1975 and used natural gas.

Kenneth Haselwander, an OSHA spokesman, said the plant underwent a major inspection in February, 1992, and no violations of workplace standards were found.

Killed were Joan Erickson, 18, of La Porte, and Linda White, 38, of Michigan City, Ind. They were working in a room containing the boiler.

The injured—all but one were women—were working in the same room as Erickson and White but were farther away from the boiler, said La Porte County Coroner Barbara Huston.

Christopher Cunningham, 20, of La Porte, who suffered burns over 75 percent of his body and whose legs were broken, was in critical condition at the University of Chicago Hospitals.

Denise Preston, 29, of Kingsford Heights, Ind., who suffered burns over 95 percent of her body, and Sue Ellen Johnson, 37, of La Porte, who suffered burns over 80 percent of her body, were in critical condition at St. Joseph Medical Center's burn unit in Fort Wayne, Ind.

At La Porte Hospital, Vicki Dirks, 36, of La Porte, was in serious condition with multiple trauma and Bernadine Pinks, 56, of Knox, Ind., was in fair condition with multiple trauma and burns. Five other workers suffered smoke inhalation.

The plant, which employs about 390 people, makes rubber gaskets for the automotive industry.

SUN-TIMES/Jack Jordan

6 March 1993, 8:30am

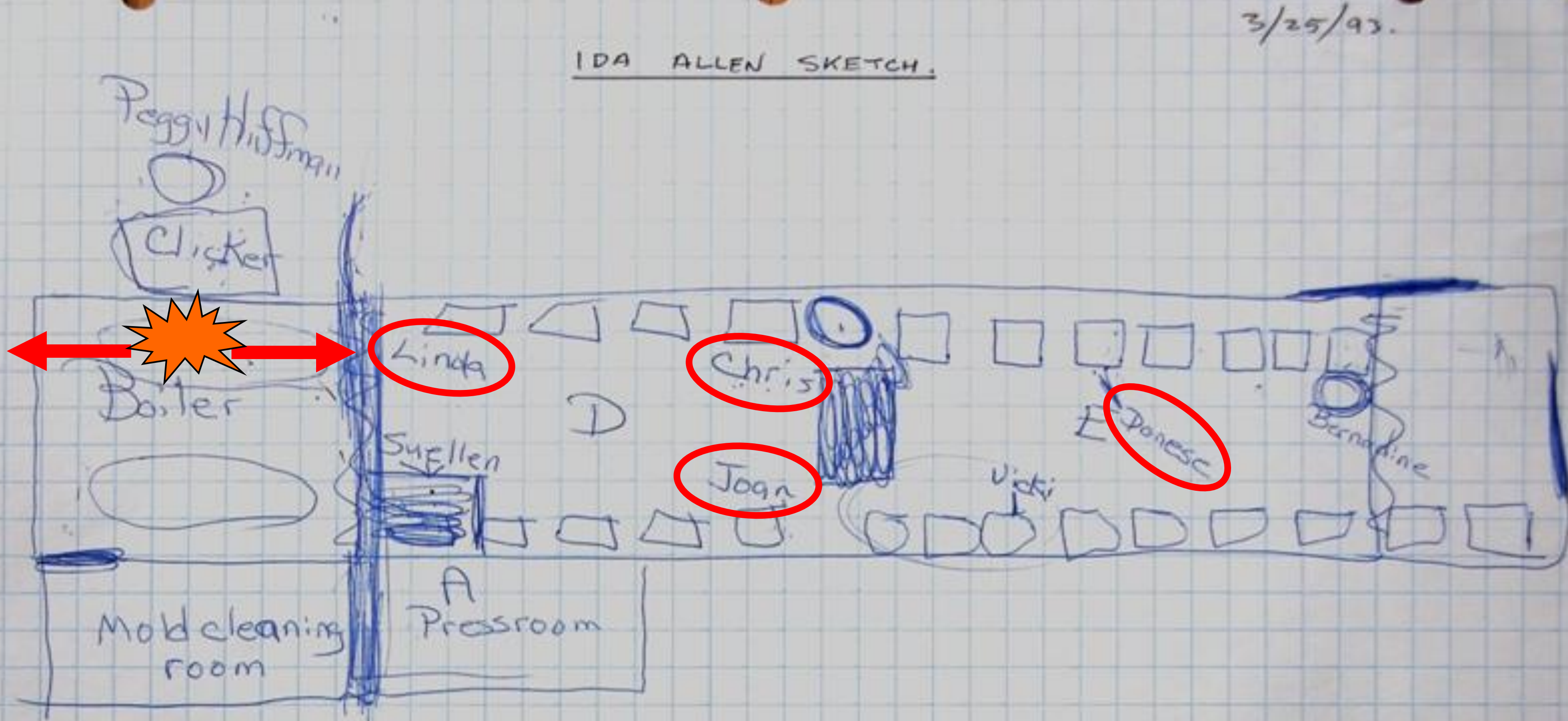
Boiler went end-over-end through wall of building

Took everything with it – skid, pumps, pipes and all

Burner went other way – straight through machines

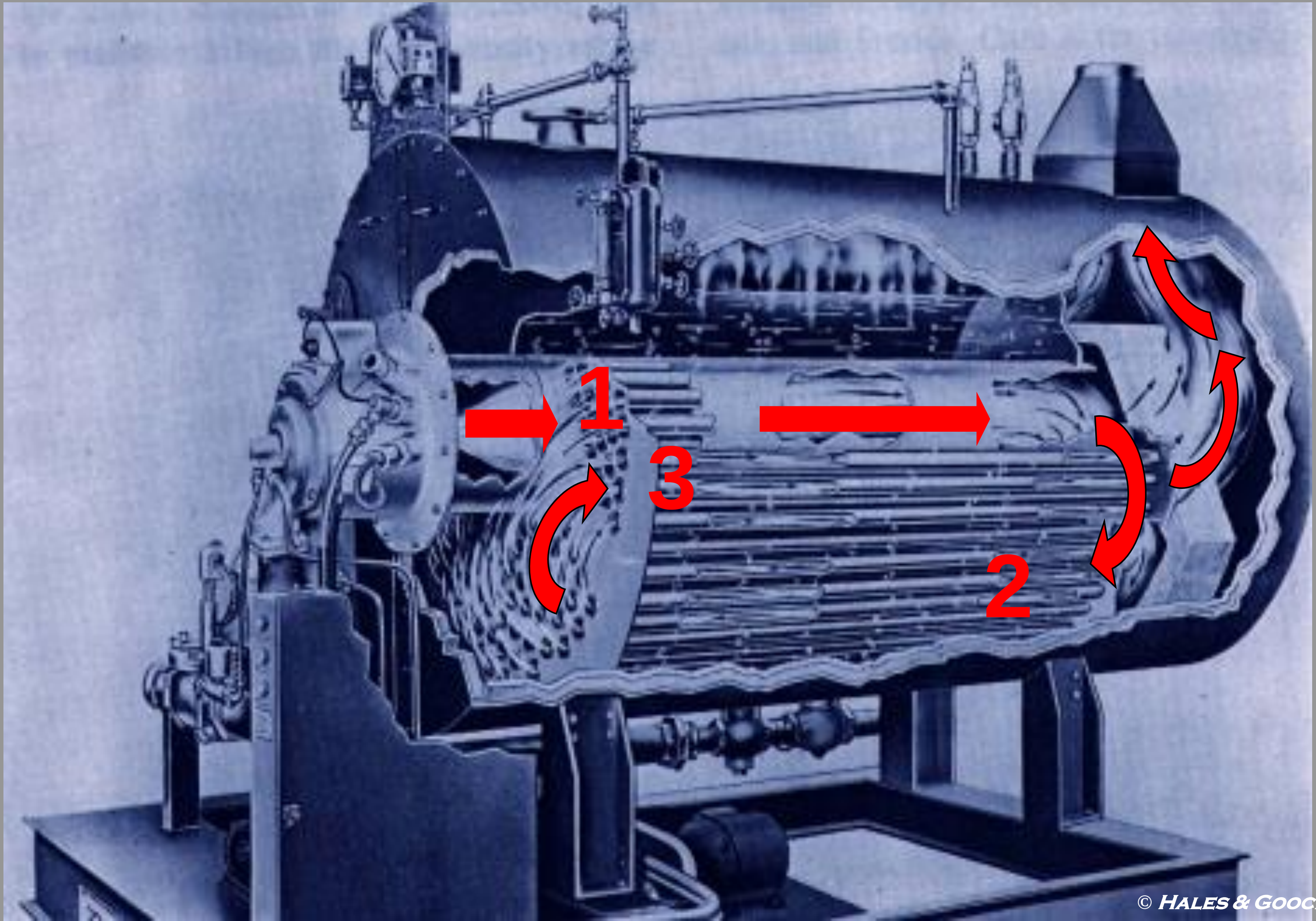
GAS BURNER and FRONT COVER

- Weighed over 500 Kg
- Propelled by steam
- Smashed to pieces
- Killed 2 workers
- Injured 11 more
- 2 died in hospital
- Everyone scalded

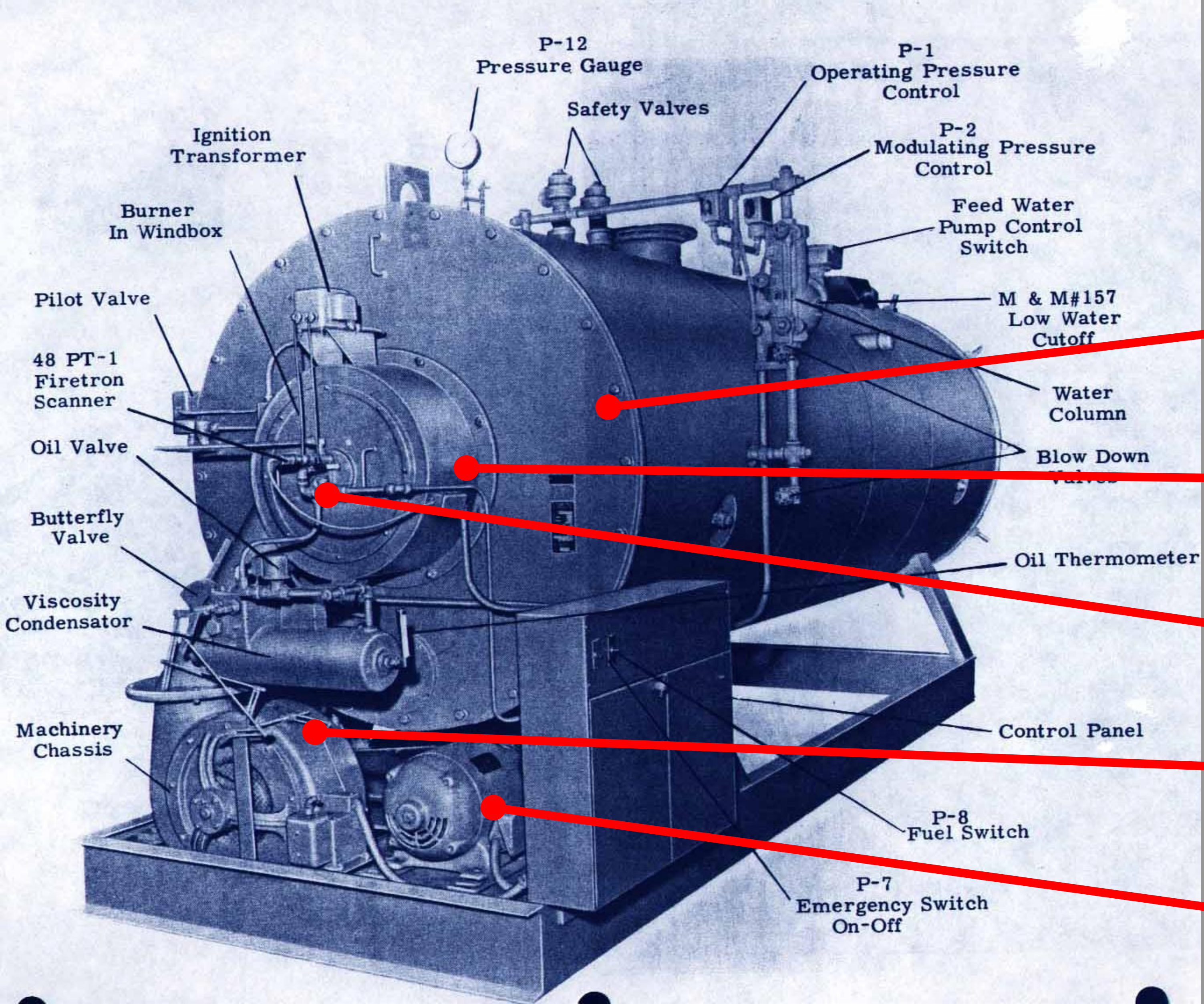


- Company in shock – like a family
- Gentle interviews – piecing together the story
- All loved the boiler – pressure gauge at 120 psi
- Operating normally – no forewarning of explosion
- Wave of steam, mica and water smashed everything

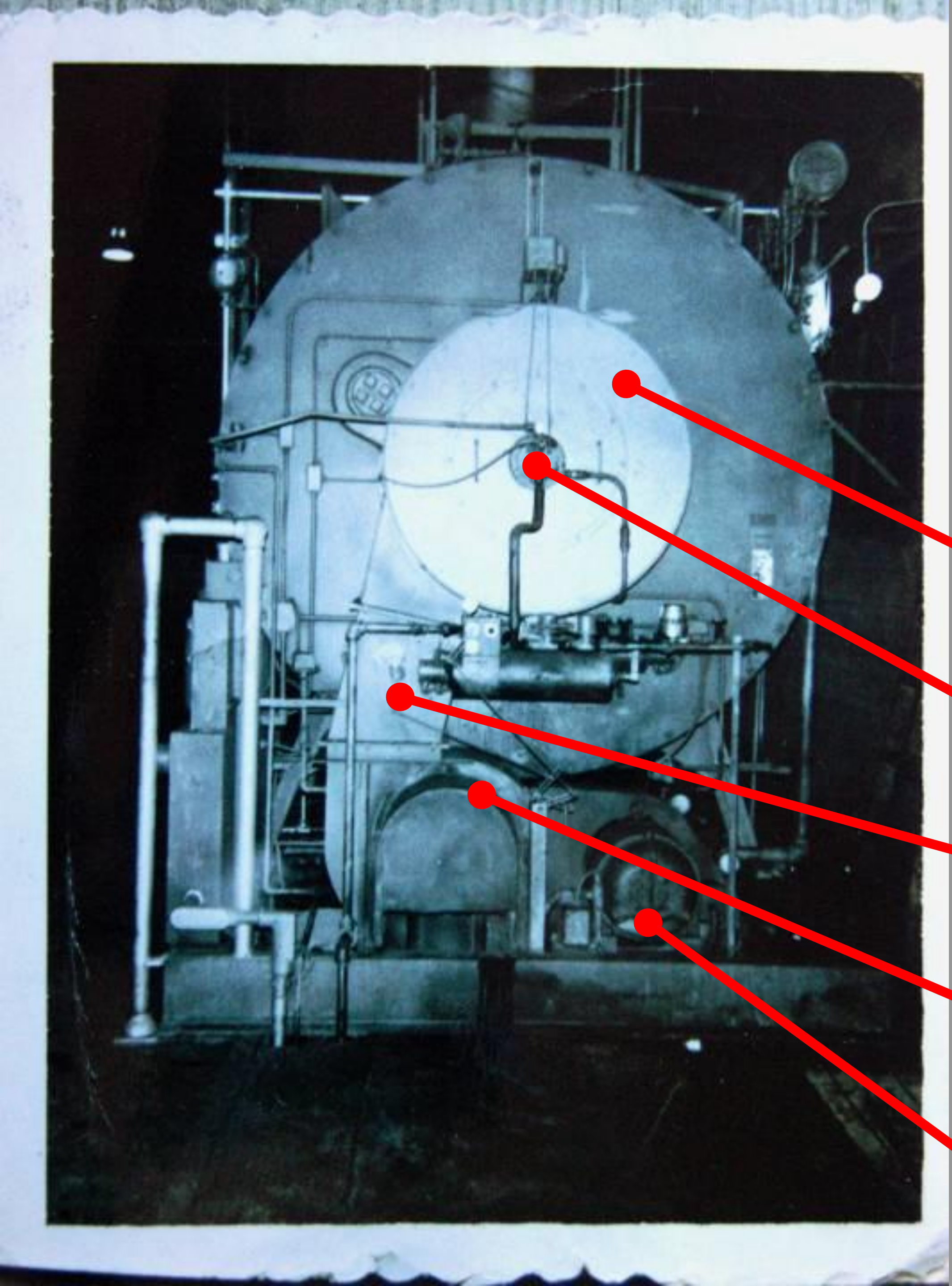
Typical “3-pass” boiler



1958 York-Shipley – Installed 1959



1959
PHOTO TAKEN WHEN BOILER INSTALLED



Lightweight wind box

Oil burner in centre

Air duct on top of blower

Blower mounted on skid

Motor mounted on skid

30 years later – 1988
New Gas-fired Burner Installed

Installation of an I.C. Conversion Burner on your York Shipley or Leffel Boiler which includes the following:

1. I.C. DG2525 gas only burner
   a. I.R.I. gas train and controls
   b. E series flame monitor
   c. Full modulation, manual pot

2. Remove old burner

3. Fabricate and install adapter plate

4. Ram new cone

5. Hook to existing gas and electrical

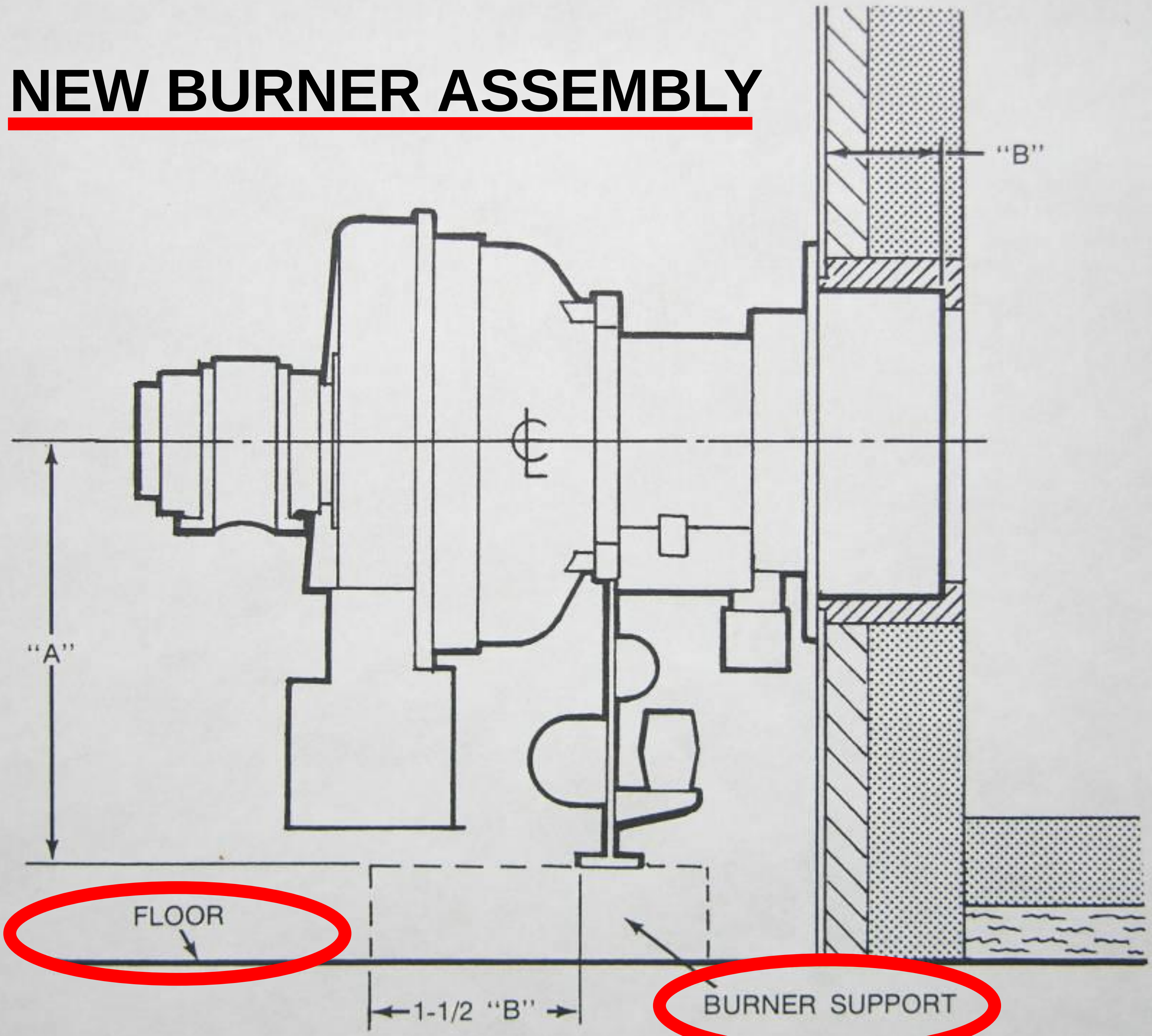
6. Fire and tune for max. eff.

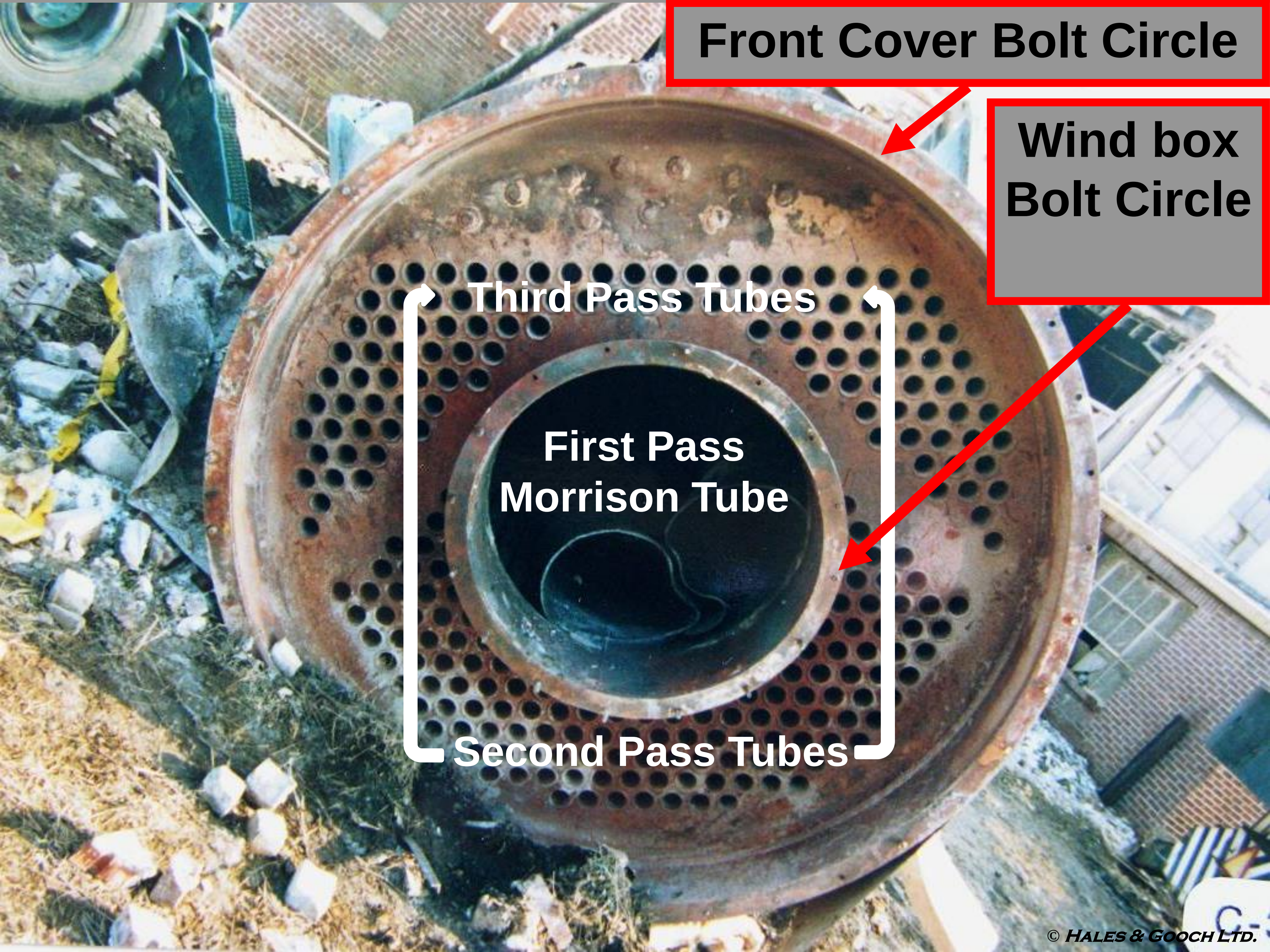
Price......................$21,950.00

New Burner:

- Replaced wind box
- One big assembly
- Cantilever mounted
- On boiler, not skid
- Smaller bolt circle

NEW BURNER ASSEMBLY



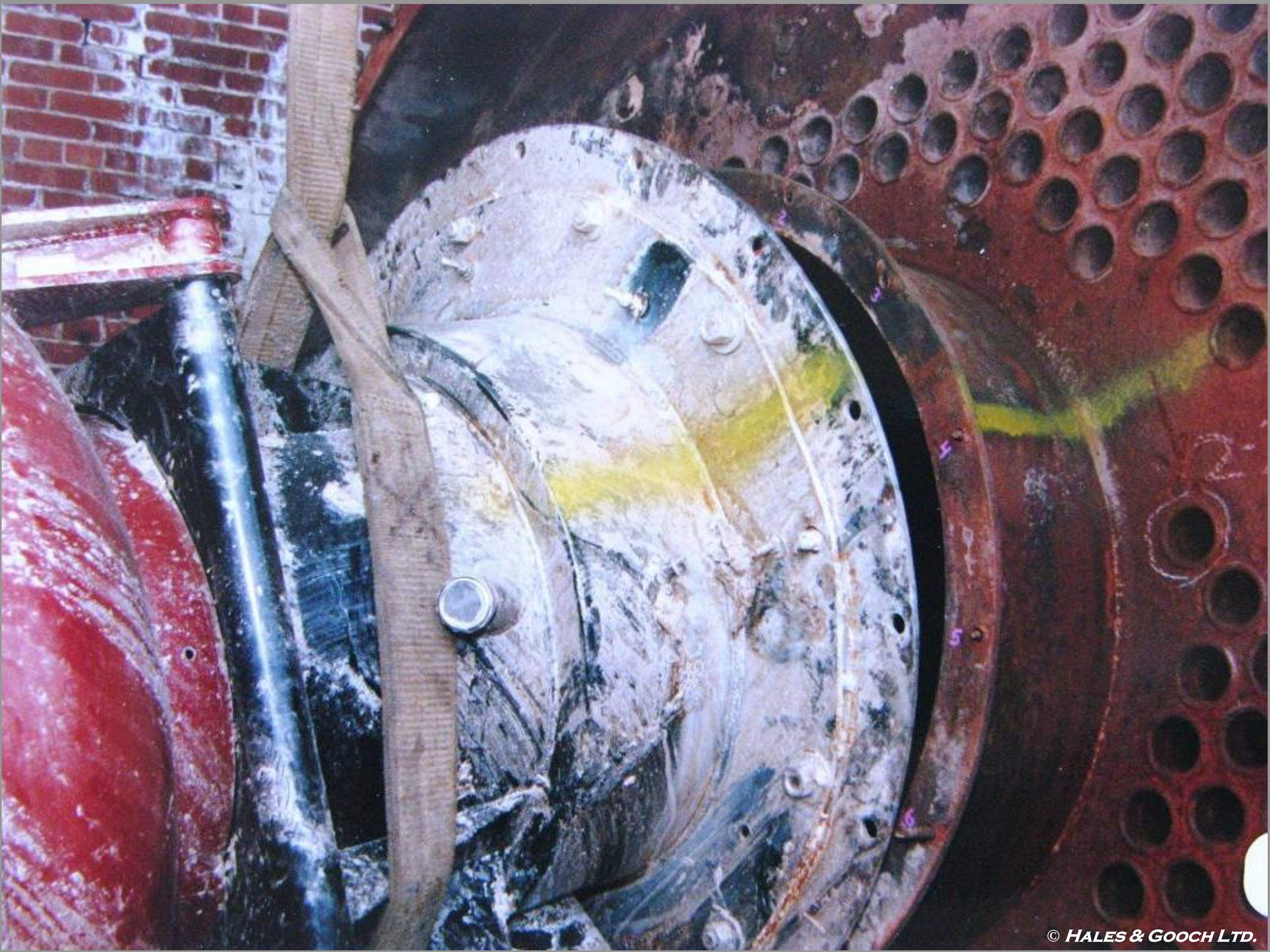

Front Cover Bolt Circle
Wind box
Bolt Circle
Third Pass Tubes
First Pass
Morrison Tube
Second Pass Tubes
© Hales & Gooch Ltd.


C-6

Morrison tube collapse – Low water?

Not so fast – put it back together!


F-10




1

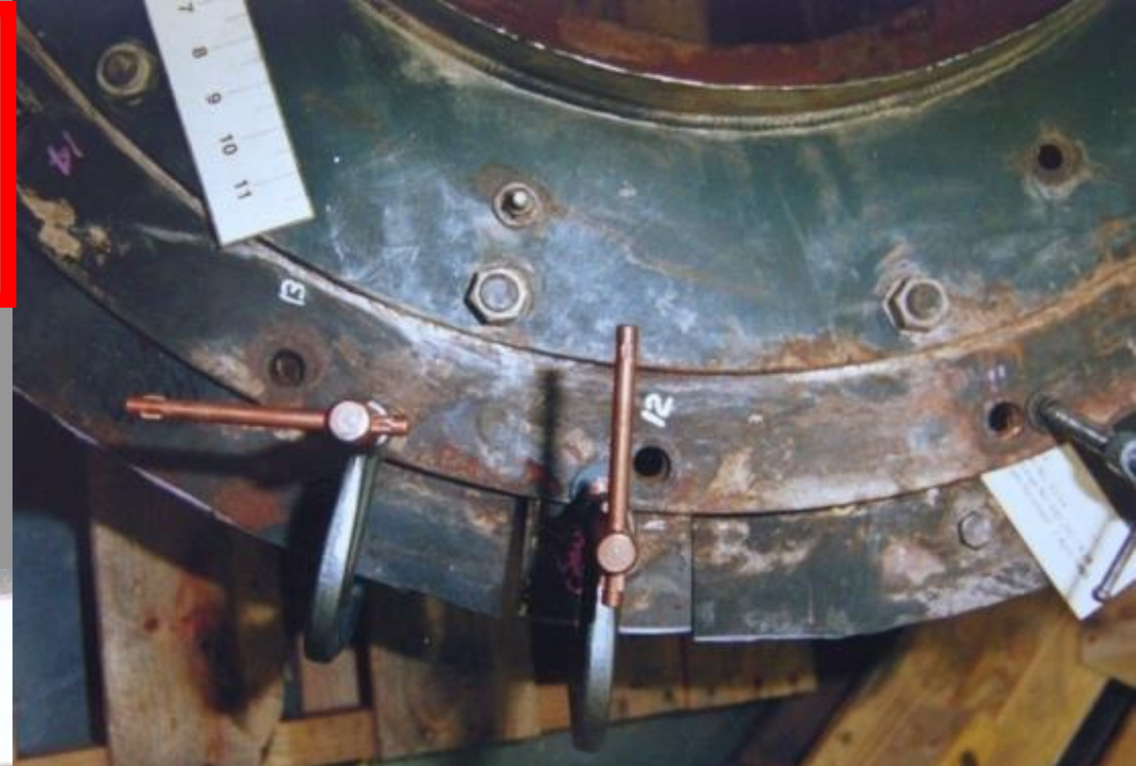

2


13


12

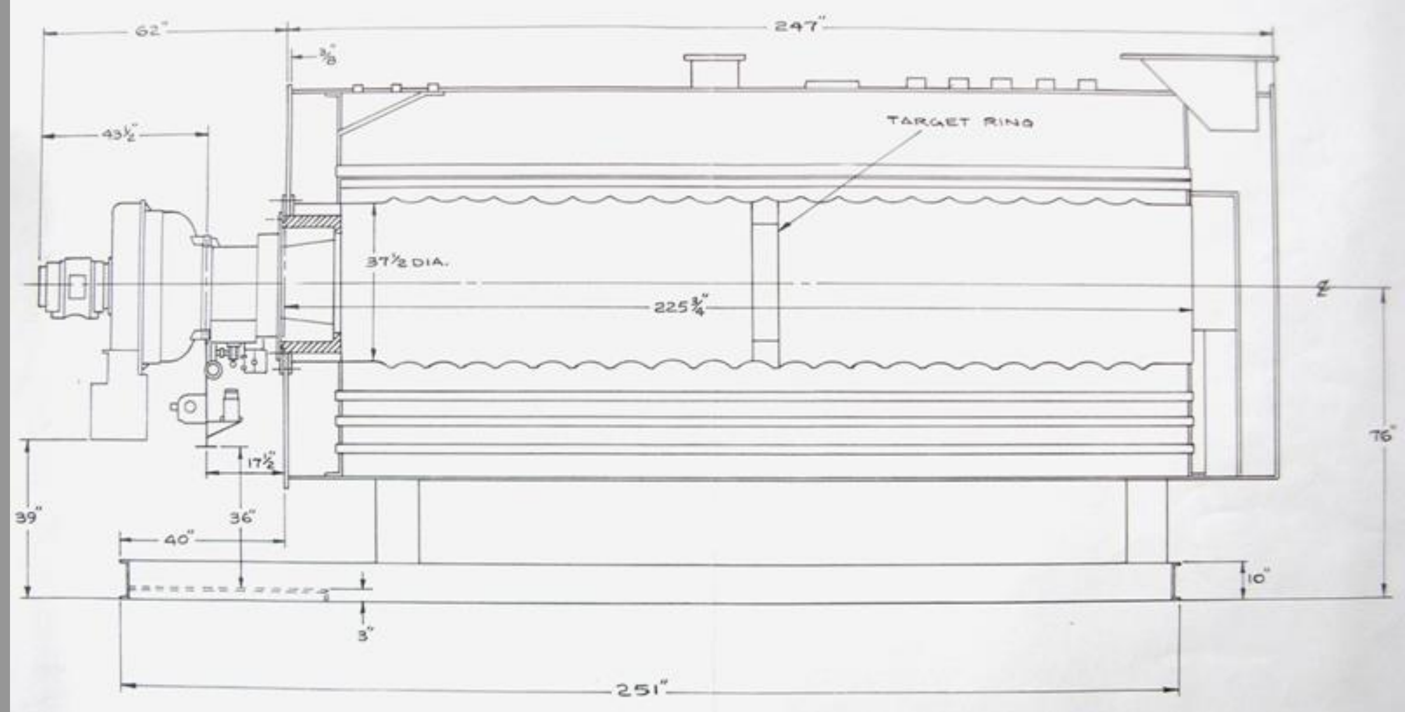

14

Reconstruction of adapter plate bolting at a lab in Texas

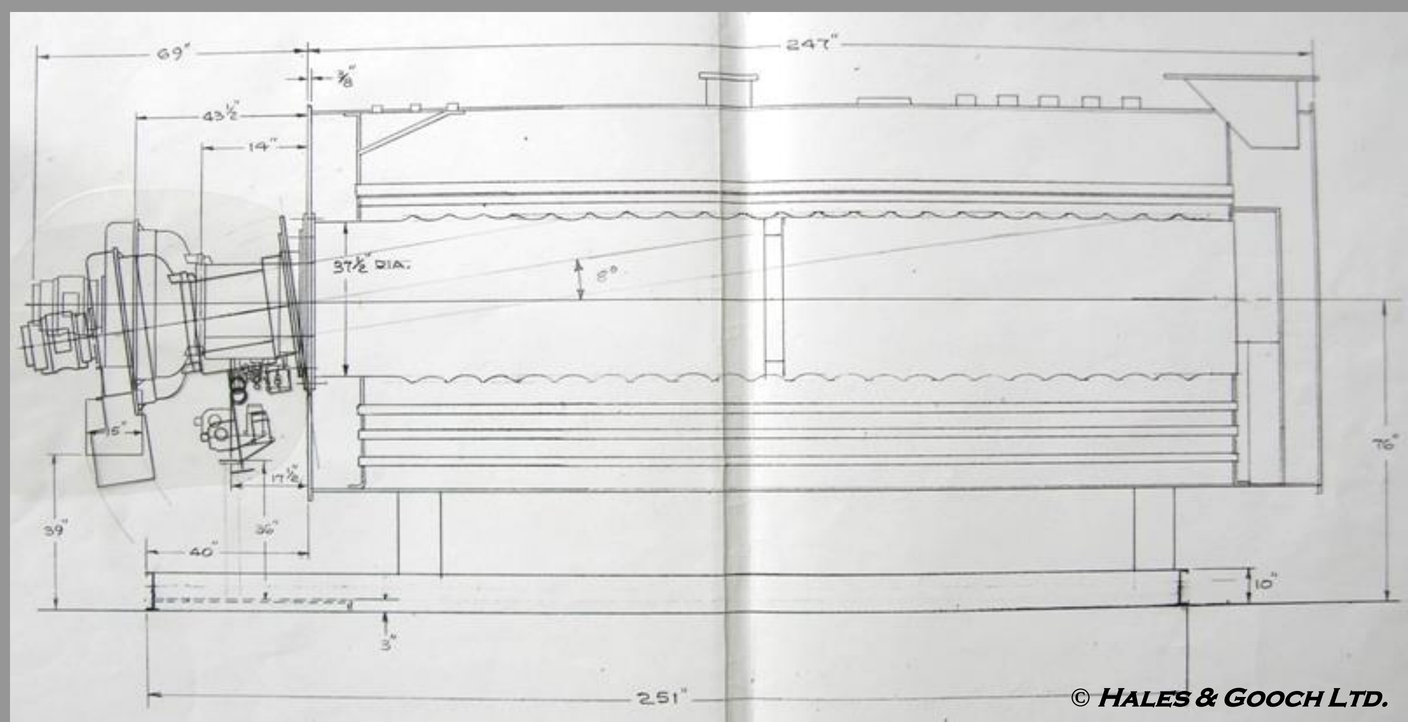


Each bolt told its own story – during the five years each one failed, but in a different way!

BURNER AS INSTALLED



BURNER 5 YEARS LATER



Last question: was the leg supported?

C. INSTALLATION

Locate the burner properly. The burner signed for operation with the blast tube le slightly downward. Do not tilt burner up or sively downward. Installation of the refractory oven, or combustion cone, shipped with the burner is shown in Figure 2-2. Securely support the burner pedestal on the floor or foundation. Allow enough clearance at the rear of the burner to allow the housing to swing open for service and maintenance. Figure 2-3 shows an installation with typical burner support. D63 and smaller burners may be completely supported by the firing head flange if the boiler front plate is strong enough. Many boilers, including some Scotch Marine types, do not have sufficiently rigid front plates and require additional support under the burner base. All D84 and larger burners must have leg support, but it is recommended that *all* series D burners be installed with such support. Bases under the


Here is the leg!

CHECKING BURNER LEG HEIGHT/SUPPORT

- Flange already cut out
- Positioning difficult
- Luckily skid all there
- Boiler refitted on skid
- Leg was bent but intact
- Measured accurately
- No support had ever been fitted under leg!

NO BOLTING – NO SUPPORT!

(i.e. Burner was hanging from flange bolts)

SUMMARY OF PRELIMINARY CONCLUSIONS

5.1 The primary cause of the explosion was flame impingement on the inner surface of the furnace (Morrison) tube, leading to a catastrophic collapse of the tube with rapid depressurization and ejection of steam and water.

5.2 The flame impingement resulted from angular displacement of the retrofitted burner assembly, during otherwise normal operation of the boiler.

5.3 The angular displacement of the burner was the trigger event in a progressive sequence of failures caused by faulty design and manufacture of the support system used to connect the replacement burner to the boiler.

NEW BOILER INSTALLED

BUT THAT WAS NOT ALL!

- **Aug 1993 – Hales Report submitted to client**
  Burner installer tendered policy limit, approx $1 million
- **Oct 1993 – Lawsuits filed against other companies**
  Total claim in range of $8 – 15 million
- **Jul 1994 – Negotiations over Hales file and report**
  Client insurance "sold" it to plaintiffs for $41,433.81
- **Sep 1994 – Plaintiff lawyers asked to retain Hales**
  Declined due to conflict and "low-water cutoff" theory
- **Mar 1998 – New plaintiff lawyers in Washington DC**
  Low-water cutoff theory failed at trial – plaintiffs lost
- **May 2001 – New Indiana trial & Hales subpoenaed**
  New theory "improper inspection" – plaintiffs won

Hales testified at trial, as per report

2

QUESTION ASSUMPTIONS!


THE FOOD STORE
Apples
Pears
Citrus
where everything is put into plastic bags
© Hales & Gooch Ltd.

PLASTIC BAG DISPENSER

- Supermarket wanted bag stands with 4 rolls
- Went to a fabrication shop with a drawing
- Discussed overall concept and dimensions
- Welded steel construction with hollow base
- No geometric (or dimensional) tolerances
- Verbal agreement on details and finish
- About 20 delivered and put into service.


4-Roll Bag Stand
BANANAS
What Food Should Cost.-
What Food Should Cost.-
3/98
Spook
Guess My Weight

HELP! AMBULANCE!

BAG STAND HIT 3-YR OLD GIRL

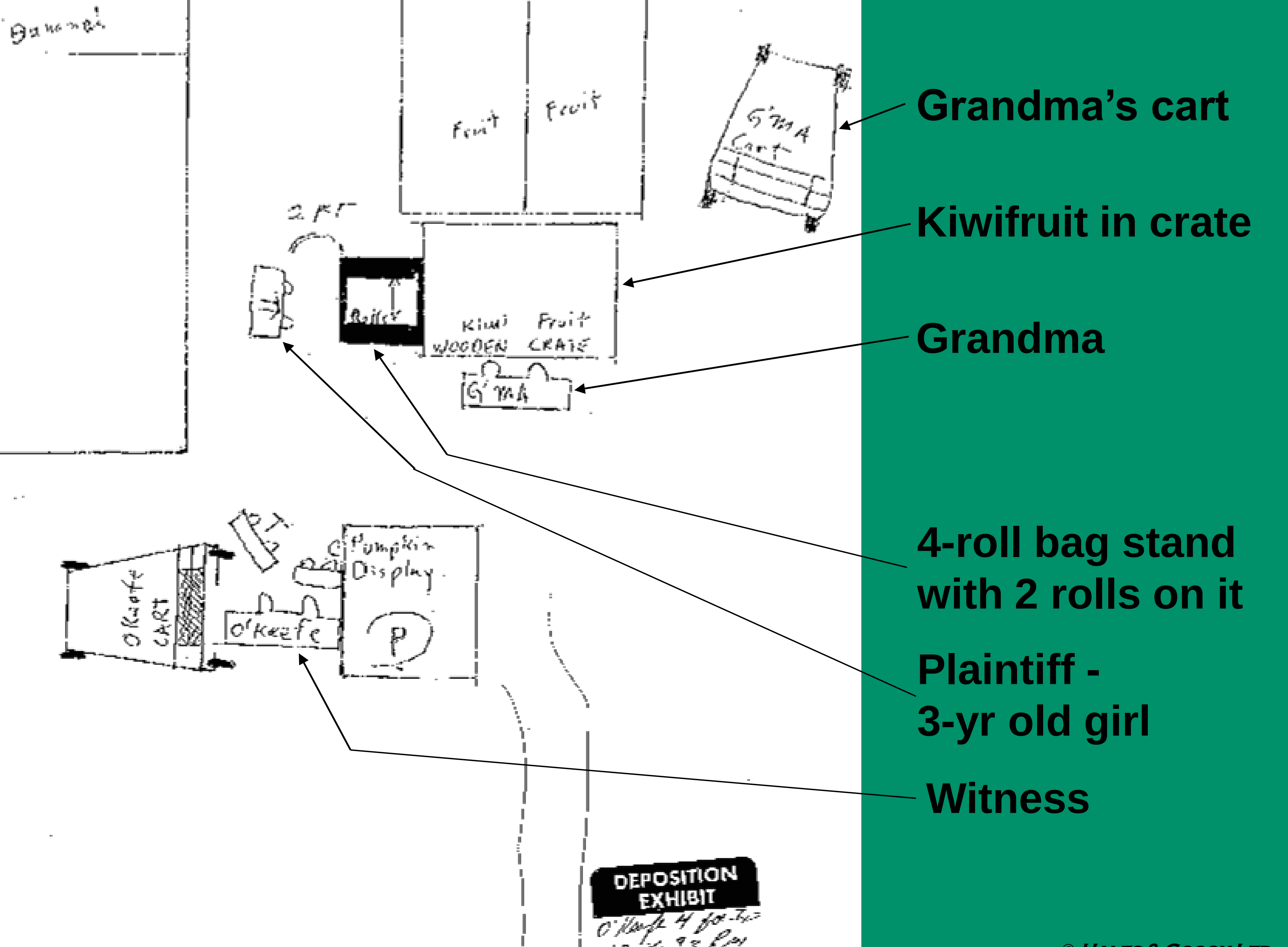
At Approx 11:50 Am R/a was called to the produce dept. Upon arrival R/a was informed that a bagstand (next to the Kiwi). fell on a 3yr old girl. The top of the bagstand hit her 1 in over her left eye, cutting it approx 2 inches. Her Grandmother pulled the bagstand off the girl and held the cut to stop the bleeding. An Ambulance was called and the little girl was transported to christ Hospital.

Assumption:

She must have pulled it over on herself – or Grandma must have done something

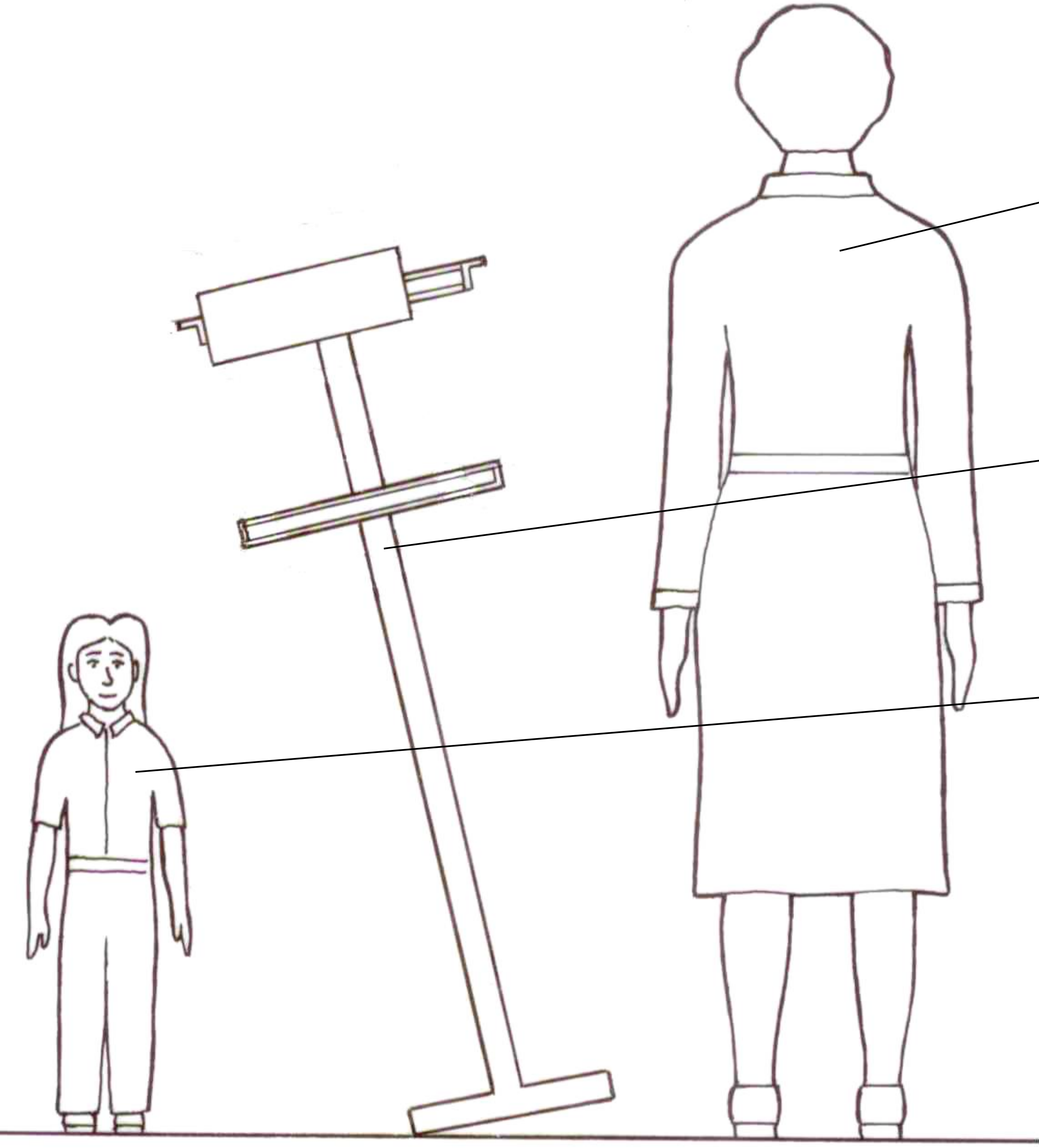
Q. The stand was embedded in her skull?
A. It was embedded in her skull. When she lifted it off, there was blood everywhere.
Q. Where was the blood coming from?
A. From her head, her forehead, across the eye.
Q. You said the stand just fell over on her?
A. It fell over.
Q. And as it fell down and struck her in the head, what happened to the little girl?
A. She was knocked down with this across her head, into her head, and I didn't know if she was alive or dead.
She just -- I mean, she just spread out, everything just spread out. She didn't move.

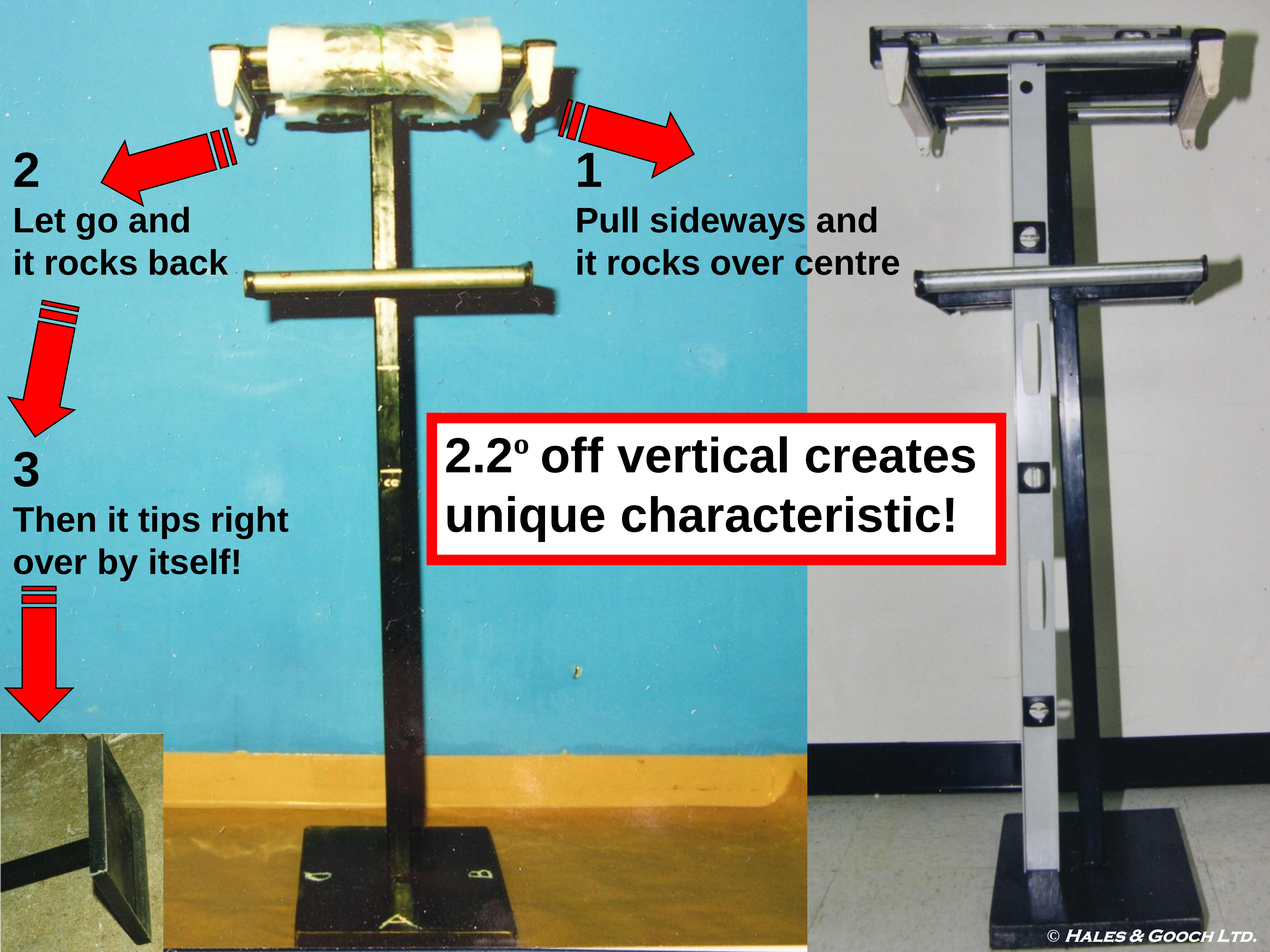

What Food Should Cost.
398
298
What Food Should Cost.
Kiwi Fruit
3/98
198
148
248
228
98
119
Child
Grandma


Grandma's cart
Kiwifruit in crate
Grandma
4-roll bag stand
with 2 rolls on it
Plaintiff -
3-yr old girl
Witness
Fruit
Fruit
G'MA
Cart
2 FT
Kiwi Fruit
WOODEN CRATE
G'MA
Pumpkin
Display
P
O'Keefe
CART
O'Keefe
DEPOSITION
EXHIBIT


What Food Should Cost.
198
68
178
Recipe Center
Recipes
What Food Should Cost.
Kiwi Fruit
3/98
each
What Food Should Cost.
Sugar Cane
149
Child
Grandma
© Hales & Gooch Ltd.

RELATIVE SIZES




2
Let go and
it rocks back
1
Pull sideways and
it rocks over centre
3
Then it tips right
over by itself!
2.2º off vertical creates
unique characteristic!
© Hales & Gooch Ltd.

HOW VERTICAL IS VERTICAL?

(when no geometric tolerances are used)

- Welder said he made stands vertical
- Store manager said they looked OK to him
- Weber's Law: "Just noticeable difference"
- Grandma just pulled until a bag came off
- Child did nothing, but is now brain-injured
- **So, who should pay the $2 million claim?**
- Lawsuit took 5 years – store + fabricator paid
- **Key issue - lack of stability in design**


Now they have a heavy circular stable base!
© Hales & Gooch Ltd.

3

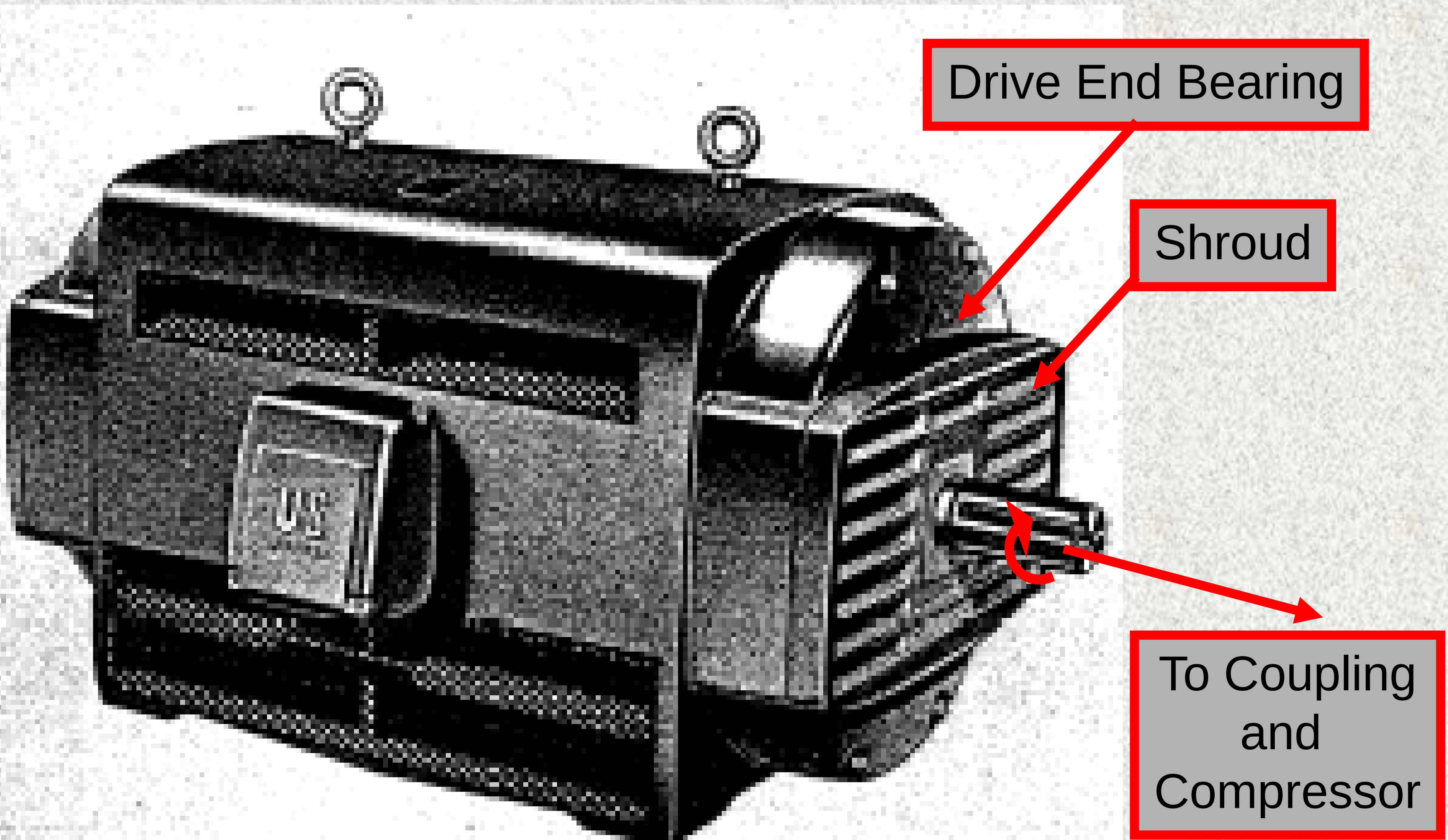
THINK THROUGH THE LOGIC!

Example:

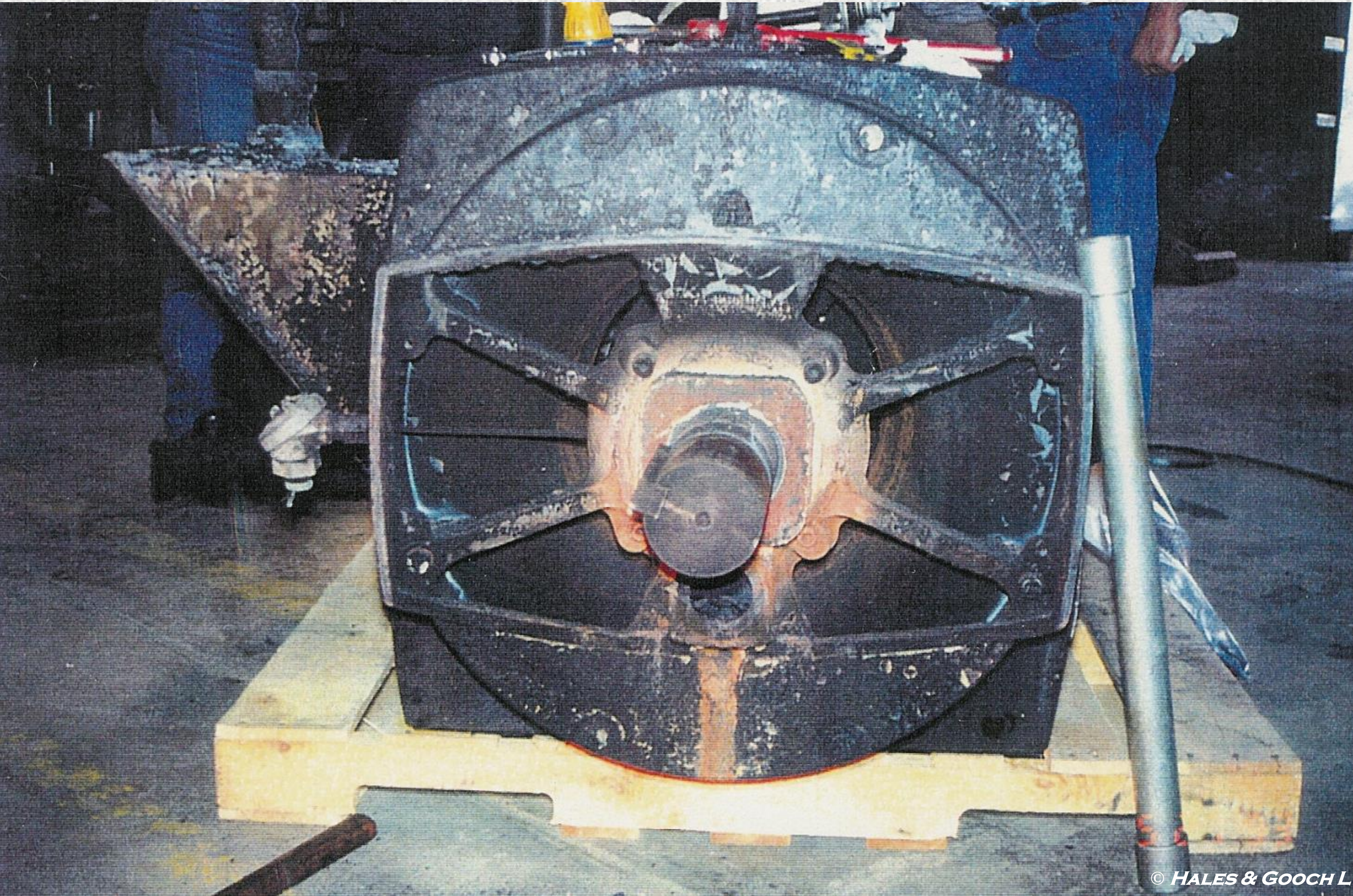
THE DRY-RUNNING BEARING

fire in a large meat-packing refrigeration system

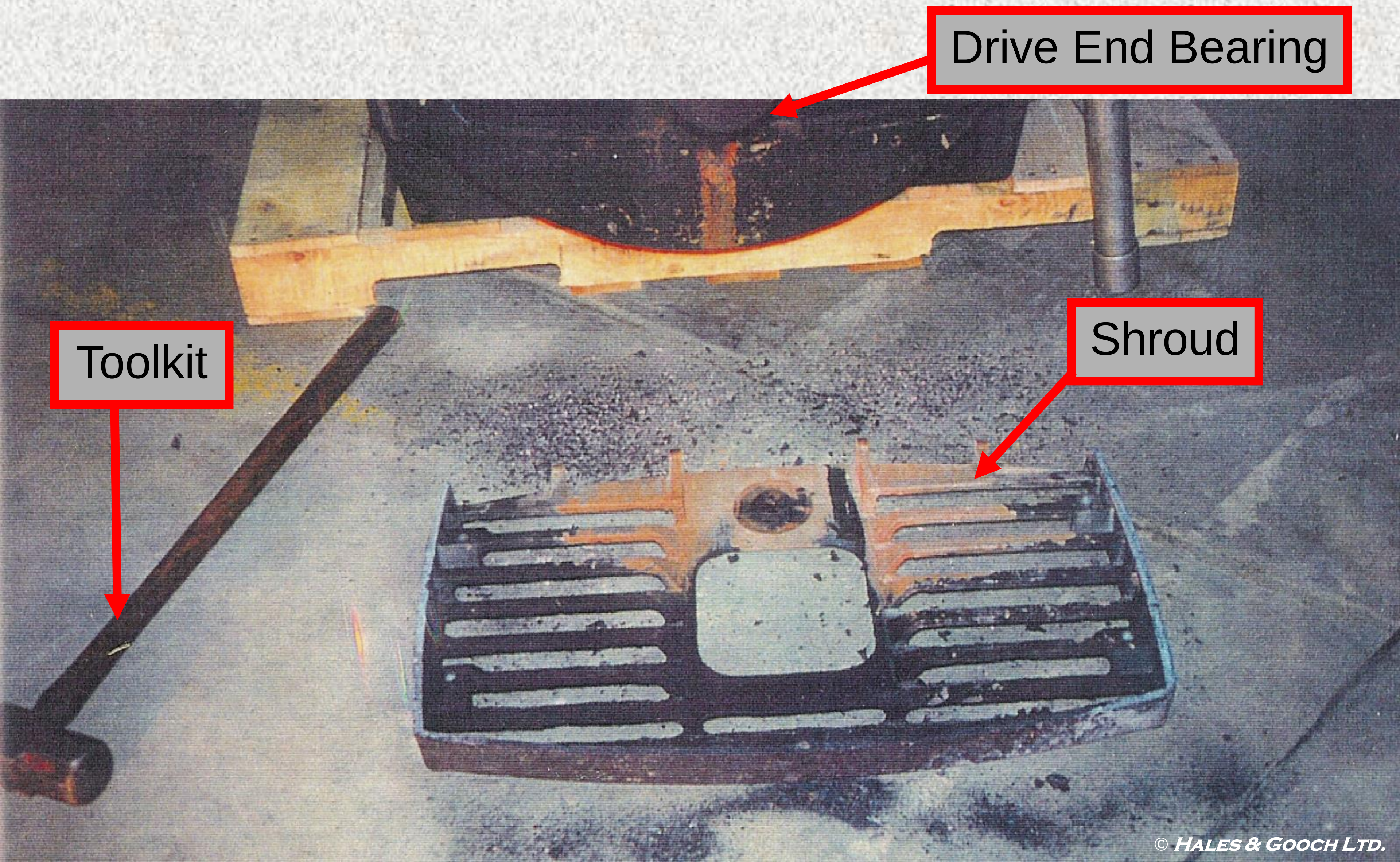
800 Horsepower Electric Motors



... all burned up!



Lots of testimony + lots of bits!



Lots of different noises!

First came the rattling …

It was a noise created by – upon startup of the machine of the motor it would rotate at some harmonic that the shroud would vibrate and was causing the sound.

The noise that we heard was a thin metal noise. That's the only part in the motor that is made out of thin metal that would make that noise.

Basically, it sounded like a rapidly shaking something that's thin made of metal. It wasn't a solid noise. I guess that's the best way I can describe it.

so they contacted the manufacturer:

Re: Start-up Resonance

Dear Mr. G[redacted]:

You have described a noise on a motor at [redacted] associated with start-up. This is a common occurrence in motors due to system or component resonances. Typically, a component in the motor, such as an air baffle, will have a natural frequency at some point below the operating speed of the motor. When the motor is started, it will pass through this frequency as it accelerates causing the component to resonate. No harm is done to the motor by this passing resonance.

Please let us know if we can help further.

Sincerely,

Sr. Product Service Engineer

Then came a surging noise …

And at that time I did a vibration analysis of the motor, took various readings on opposite drive end and drive end bearings and listened to it with a stethoscope

A I've used a screwdriver before as a stethoscope.
Q Tell me how you do that.
A Stick a screwdriver in your ear and put the sharp point against the body of the machine.
Q See, I'd never do that, because I'd use the wrong end. Did you use a screwdriver to listen to the motor?
A No.
Q And where did you learn to use a screwdriver as a crude stethoscope to listen in on a motor?
A Just watching the other mechanics.

but it wasn't like a failing bearing:

Q How does it sound when bearings are going out?
A It's rough and it's like gravel, gravelly.
Q Sort of a grinding?
A Yes.
Q Continuous?
A Continuous.
Q Not a surging?
A No.

So what did happen?

Many Expert Opinions!

1

The following opinions are based on my 55 years experience, training and engineering education, particlarly applied to the design, development, construction, testing, installation and operation of heavy duty rotating equipment.

6. The noise reported in Unit #3 was most probably foreign-object-contact (established during the motor overhaul) and noted during the initial and subsequent start-ups of the unit.

2

This catastrophic motor failure was caused by improper alignment of the motor shaft to the compressor shaft. Misalignment of the motor to the compressor caused excessive vibration in the motor, extreme overheating, lock-up of the drive-end bearing, and malformation of the shaft.

During the failure process, the motor vibrated, causing vibration in the entire Compressor Unit. Vibration caused the oil circulating under pressure inside the compressor unit to spew out, contact the extremely hot motor, and ignite a fire that eventually spread to other combustibles.

3

Based on nearly 30 years of designing and testing Thomas and competitive flexible disc ... thrust loads on the motor shaft. Therefore, coupling misalignment was not a contributor to the motor bearing failure.

4

negligent for failing to properly align the motor to the compressor;

5

Not having written emergency operations instructions contributed to this fire.

6

The 800 horsepower motor is not a likely primary cause of the surge noise reported

... surge was most likely a change in motor speed as a result of a change in torque

7

The noise emanating from Compressor No. 3 for many hours immediately prior to the fire was not associated/correlated with the fact that Compressor No. 3 required additional work on the coupling connecting motor and compressor.

8

review of this information, and my more than thirty years experience in the field of refrigeration, I have arrived at opinions regarding the behavior and performance of the parties

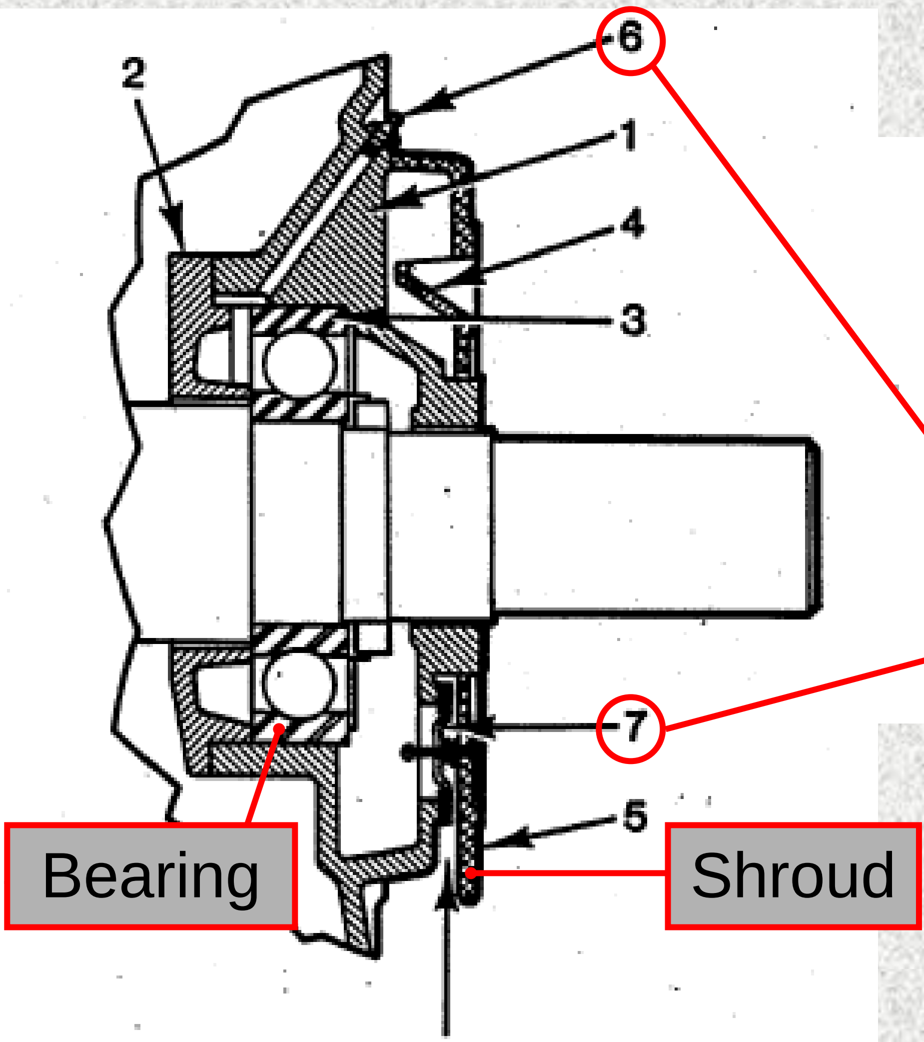
9

motor protection system on Compressor Unit 3 failed to function as intended

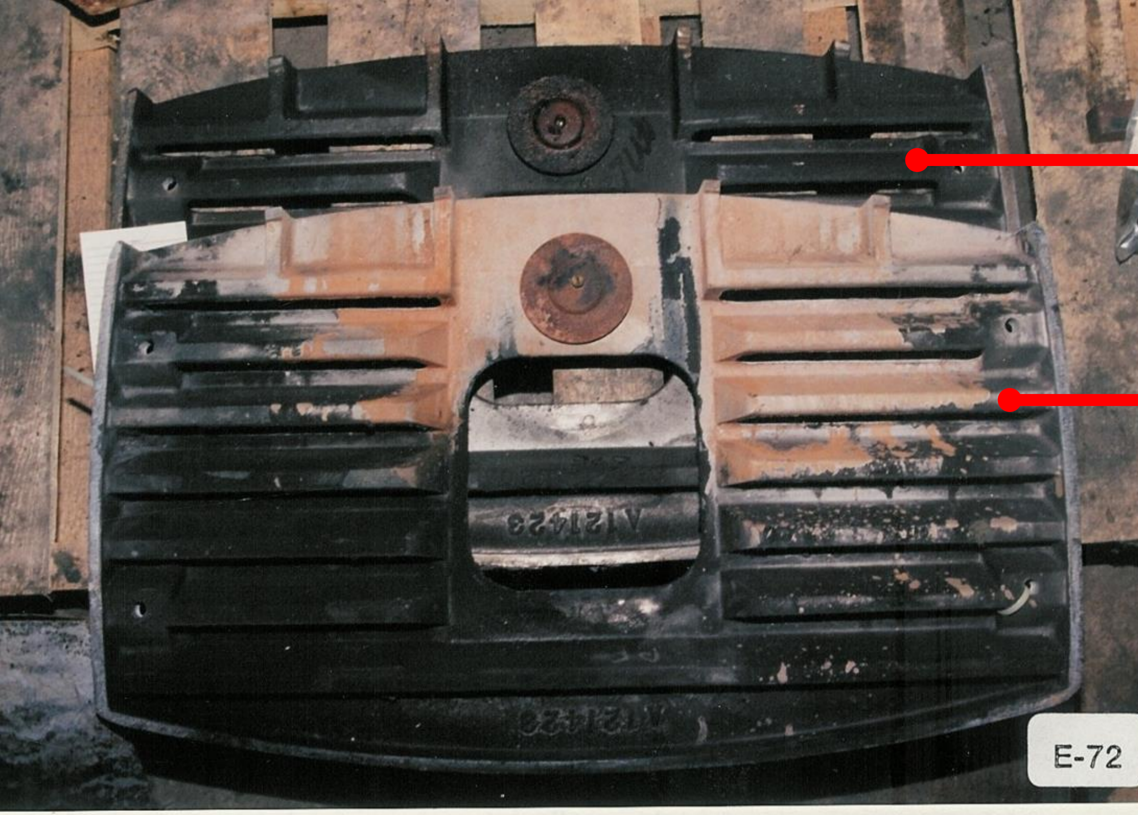
None correct!

B. Motors with Automatic Grease Drain

To relubricate bearings, add new grease until clean grease flows from the drain (drain is behind the grill and is automatically activated by the regreasing operation). Grease accumulations at drain should be removed to prevent grease entering the motor. Excess grease in bracket reservoir will be automatically purged while motor is running.



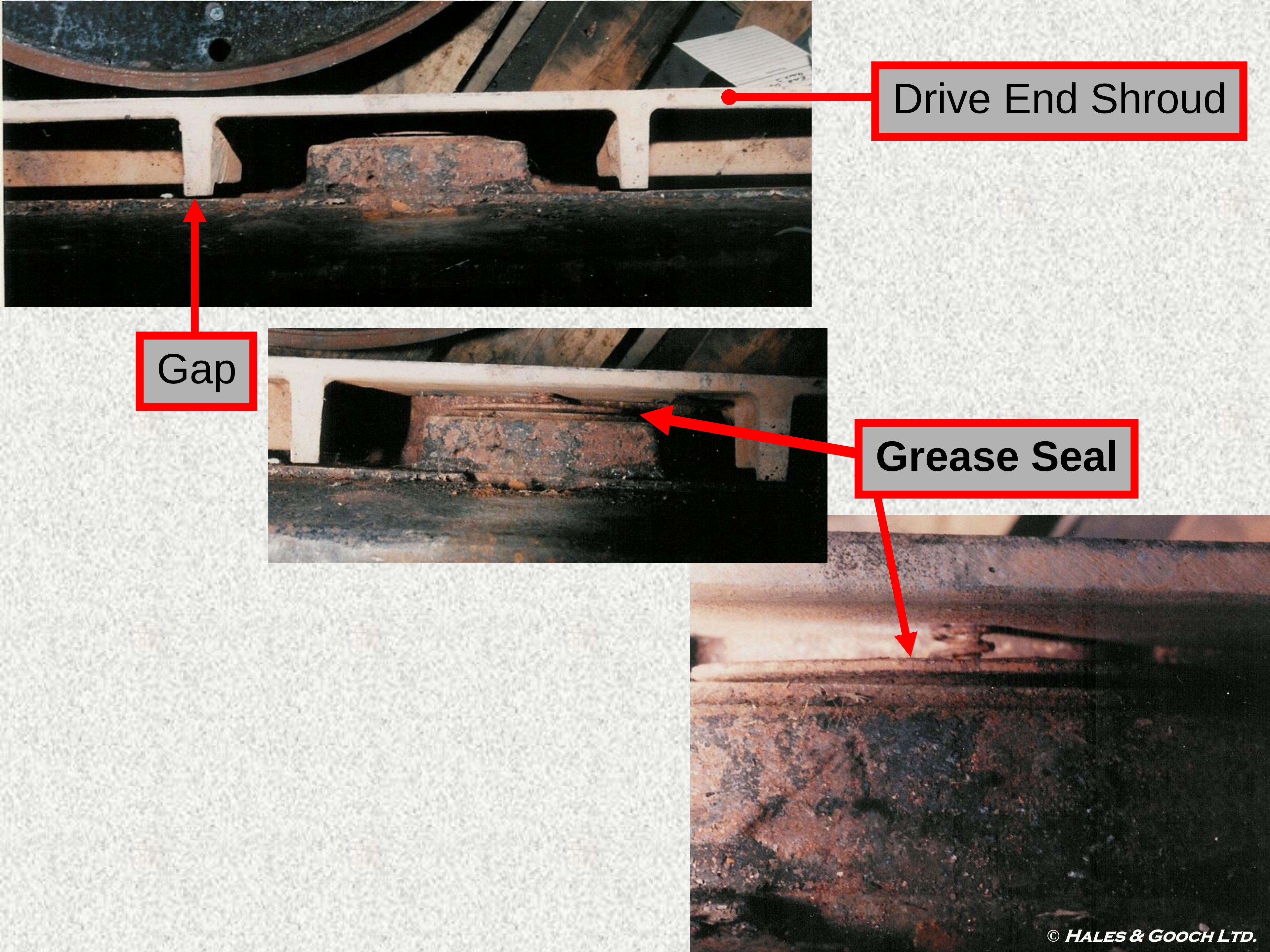
1. MOTOR BRACKET
2. BEARING CAP
3. BEARING
4. UPPER GRILL
5. LOWER GRILL
6. GREASE FILL
7. GREASE DRAIN

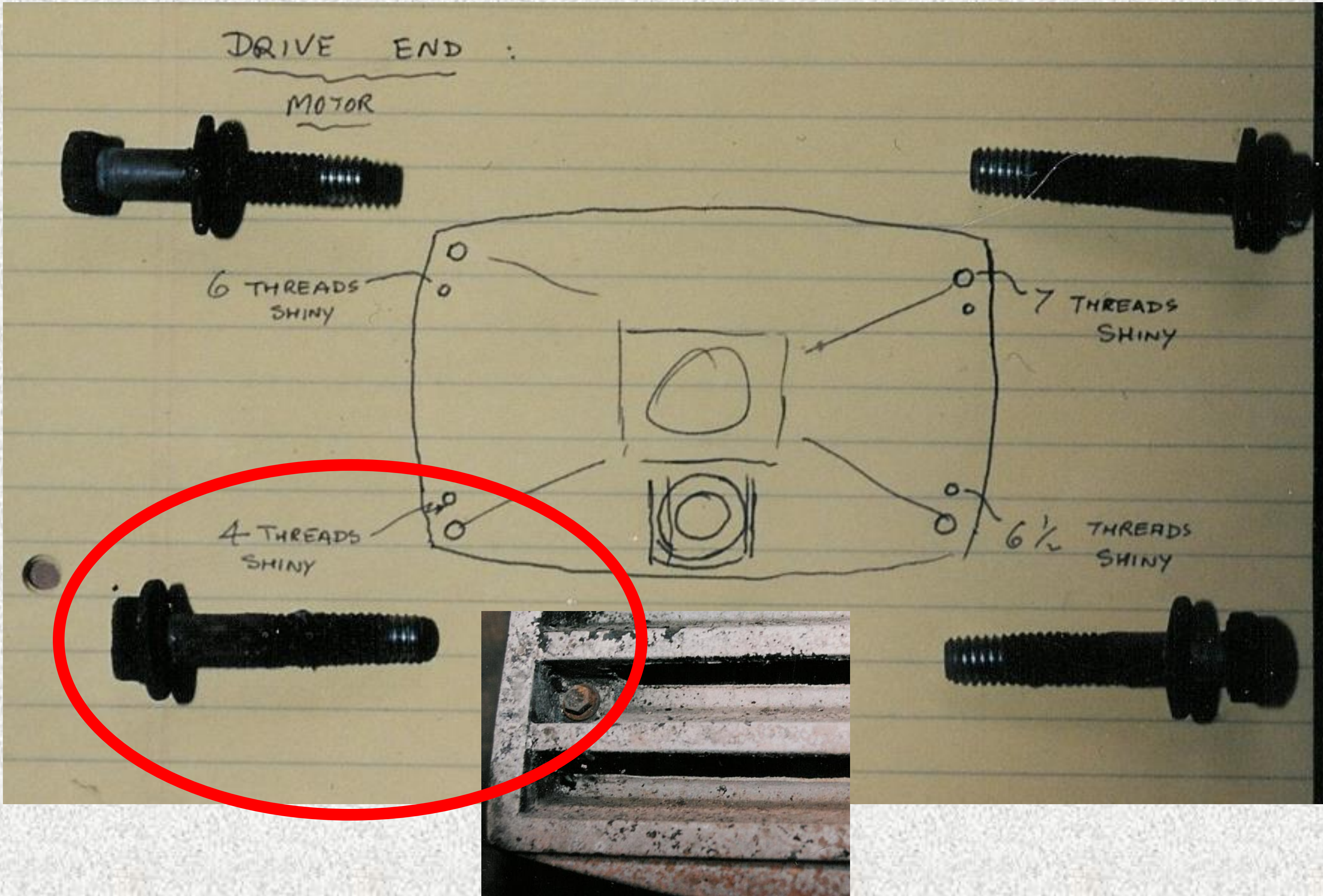


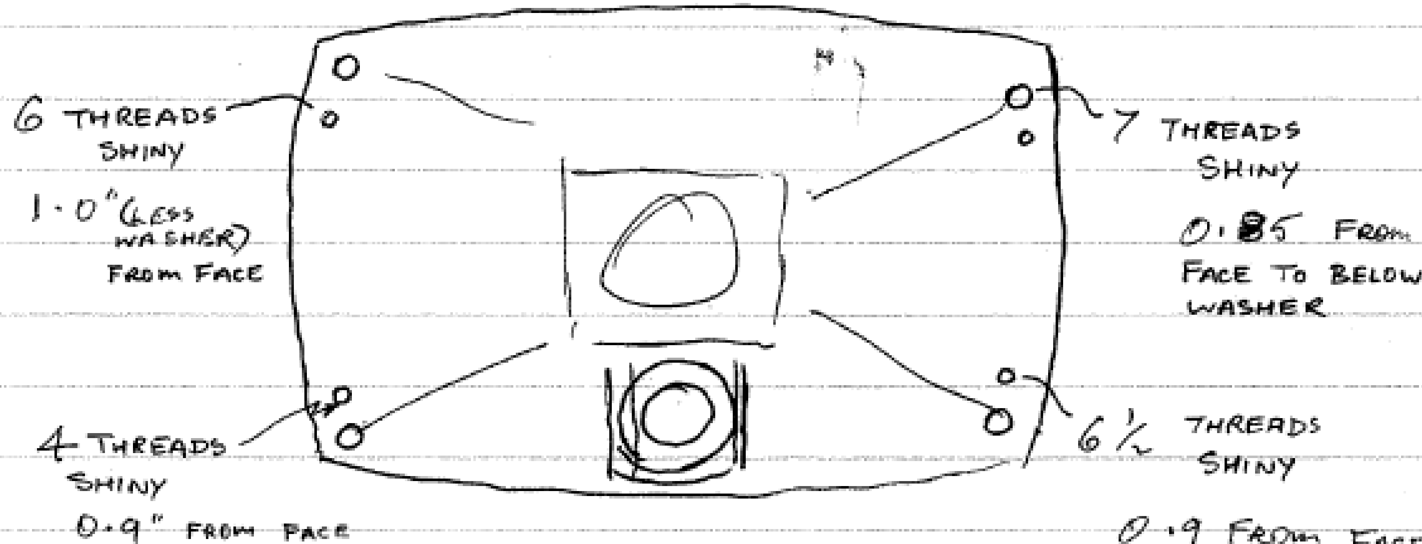
Non-Drive End Shroud

Drive End Shroud

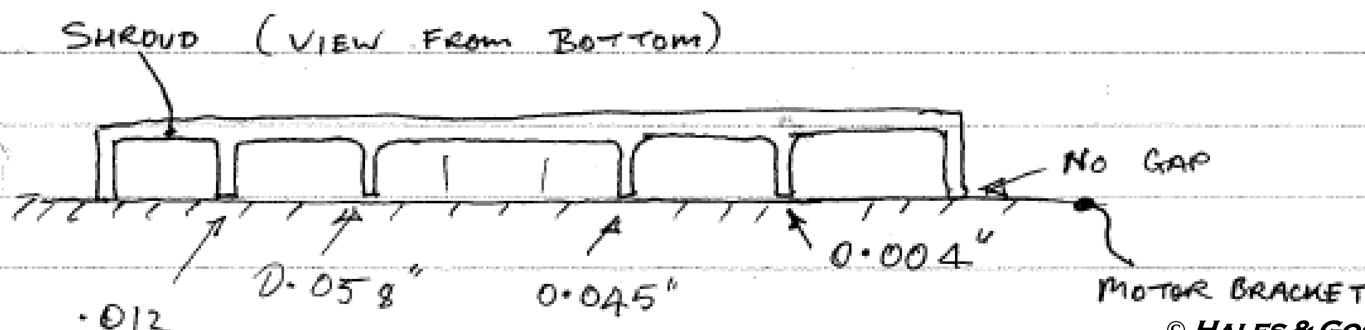
Drive End Shroud

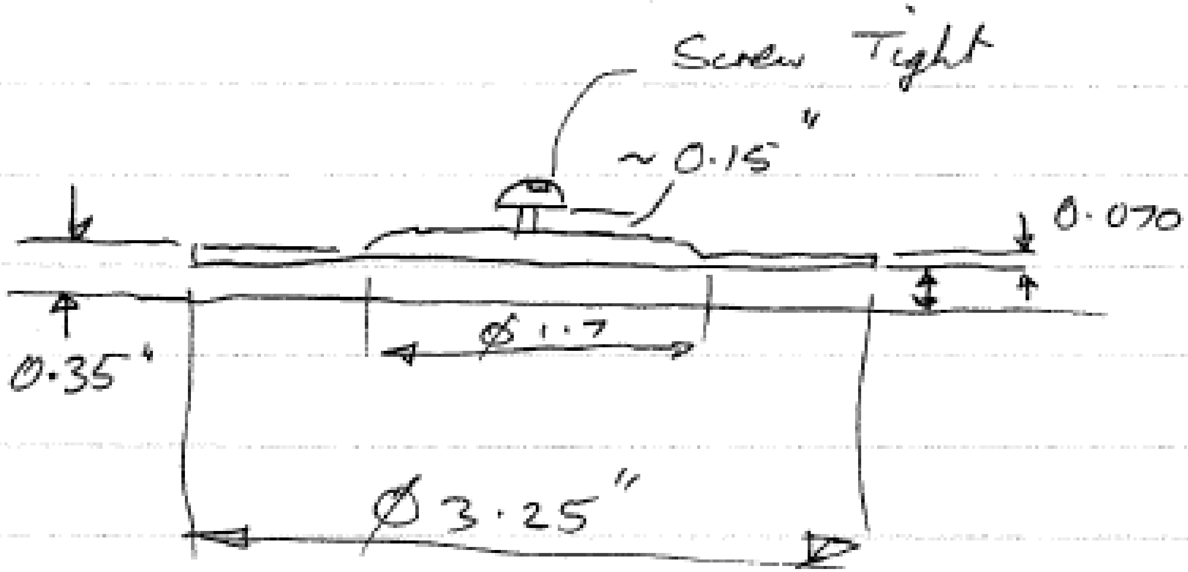

Drive End Shroud
Gap
Grease Seal


DRIVE END :
MOTOR
6 THREADS SHINY
7 THREADS SHINY
4 THREADS SHINY
6 ½ THREADS SHINY



- 16 THREADS / INCH
- Ø 5/16" BOLTS × 1 ¾" LG.
- WASHERS: 0·075" THICK
- LOOSE FIT THREADS
- IMPACT MARKS AROUND PERIMETER OF SHROUD.
- METALLIC RATTLING IF BOLTS LOOSE





CLOSED END - NO. 3 - SEAL ON SHROUD.

- Cork washer 0.055"
- Spring force about same as drive end.
- On non-drive end screw loose.
- Washer stuck on but peels off.

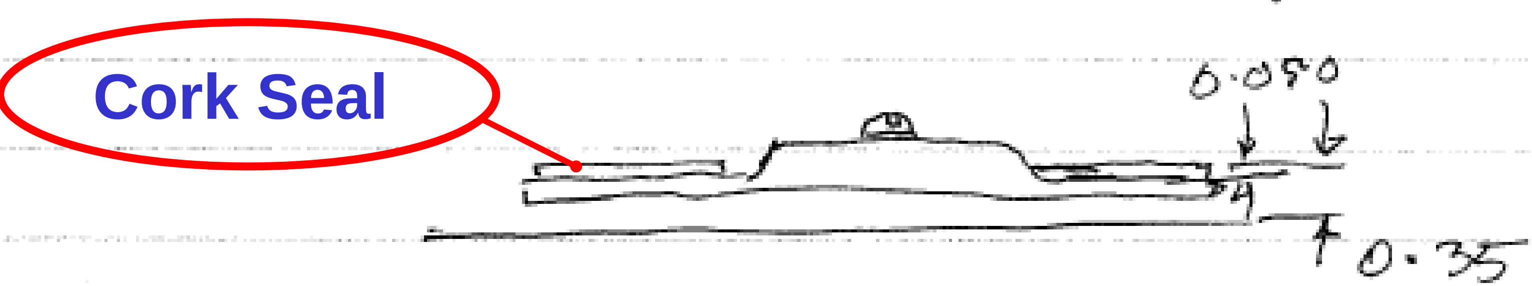
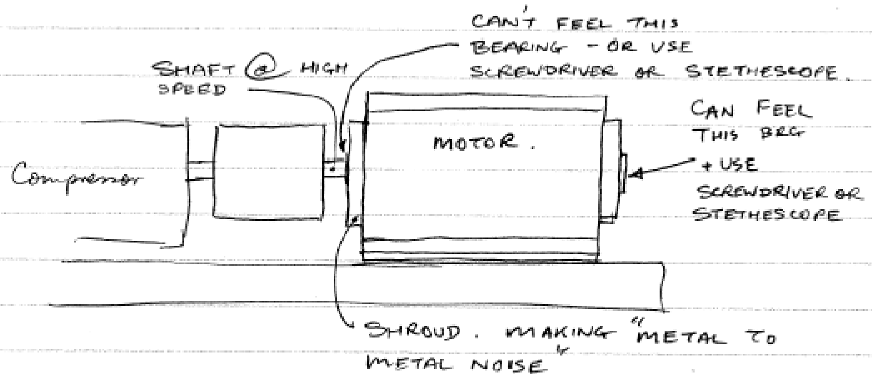


EXHIBIT
Hales
253
8-7-97 SS
PENGAD-Bayonne, NJ

-1-

POINTS OF INTEREST ON FAILURE

1.



2. VIBRATING SHROUD + NOISE @ START-UP :
- LOOSE ?
- NOT FITTED CORRECTLY ?
- BENT ?
- DISTORTED ?
- SEAL SPRING BROKEN ?
  ⇒ RATTLE
- CRACKED ?

3. AUTOMATIC DRAIN FOR BEARING DEPENDS ON SHROUD + SEAL TOGETHER

ie. Bearing depends on
→ Grease which depends on
→ Seal which depends on
→ Spring - loaded subassembly (?)
→ which depends on shroud
→ which depends on shroud stiffness/damping
→ which depends on 4 bolts

See Hales P.131
Embod design.
Separate function - crit
Combine - economy

Logic Sequence Diagram

Grease seal depends on casing + shroud + 4 bolts + cork washer + spring-loaded plate

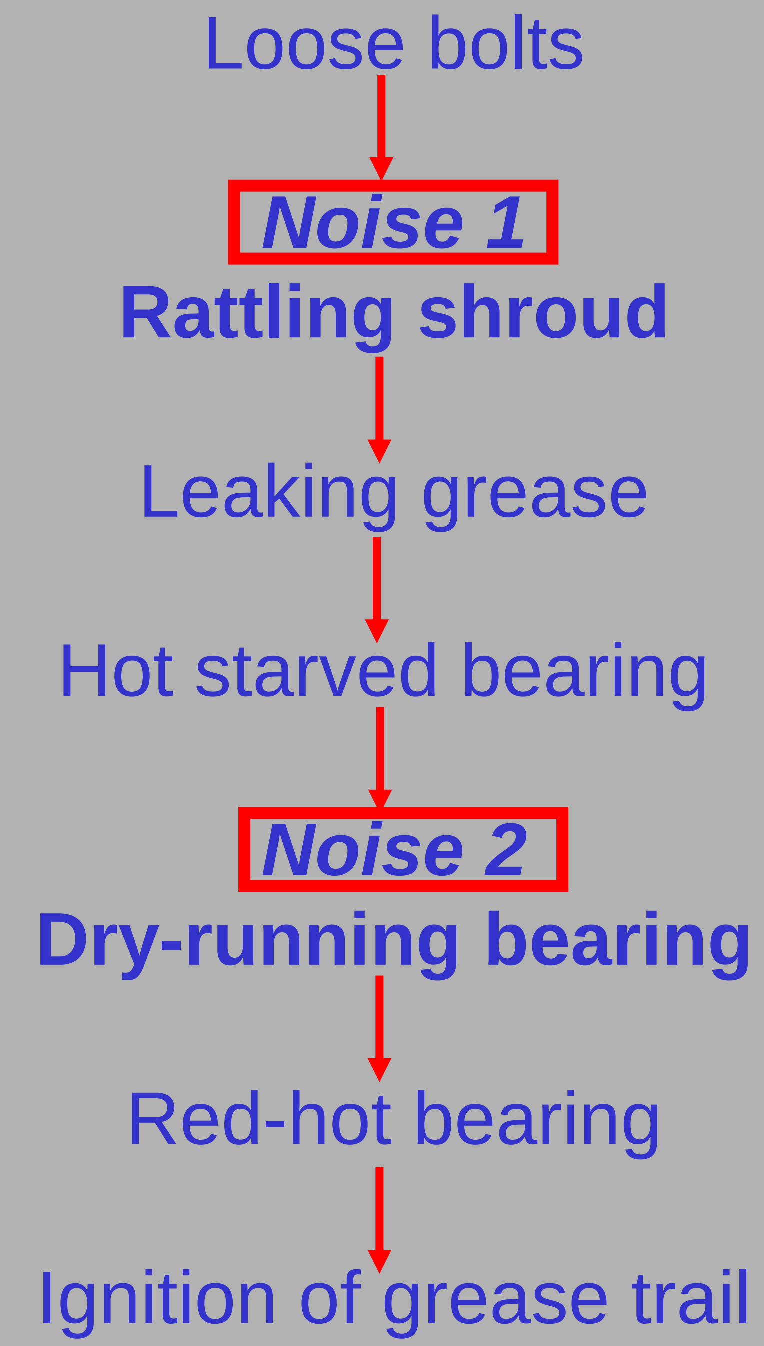
Managing Engineering Design:
Separate functions – criticality
Combine functions – economy
per Pahl & Beitz guidelines
for Embodiment Design

4. NOISE 1
(Cowling movement)

Comes from shroud,
→ Which indicates movement,
→ Which indicates not clamped against housing,
→ Which indicates problem with drain seal,
→ Which means grease will leak out, (but US Electric says OK)
→ Which means grease will go below level of bearing,
→ Which means heat & grease runs more freely which means
→ level goes down faster,
→ Which starves bearing,

NOISE 2
(Bearing wear)

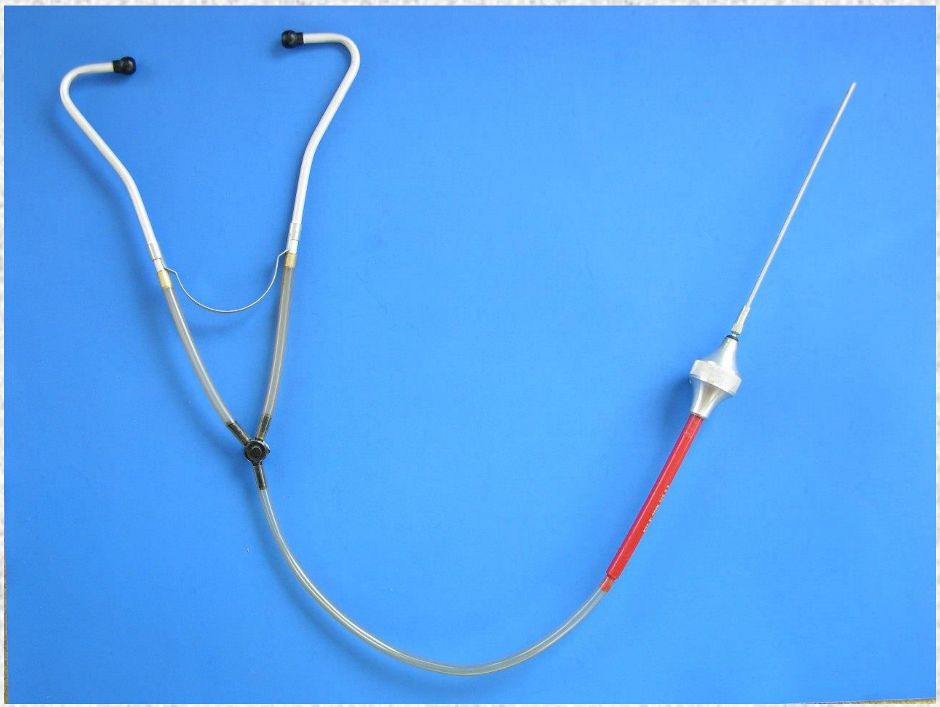
→ Which generates bearing wear,
→ Which gives different noise in addition to shroud noise and consistent w/ brgs.
→ Heat → ignition of grease trail (burning down) ? to oil on floor → (oil from seal leak)
→ oil fire to No. 4.
→ burns up on No. 4. to brg. ?
→ more cowling damage from upward heat.



Demonstration of surging noise from dry-running bearing:

1972 Jaguar E-Type alternator idler pulley

(mounted on stick and spun by hand – “wow, wow, wow!”)



Attorneys heard it in deposition!

Summary

- Lots of parties already had done inspections
- Lots of theories - none explained all evidence
- Lots of testimony on noises - not analyzed
- Lots of bits kept in storage - shrouds ignored
- **Noises told the whole story**
- Shrouds and bolts provided evidence
- Logic sequence provided explanation
- Case settlement shortly after deposition

Flawed Embodiment Design

4

EXPLAIN THE UNUSUAL!

Example:

ONE SINGLE DATA POINT

Woomf … and over she goes!

Plant Problems

Black liquor used as fuel for boilers:

- Hot black liquor by-passing flash tanks
- Flashing steam in storage tank
- Tank not a pressure vessel
- Rapid corrosion – thickness below min.
- Stirrer not working – stratified liquid

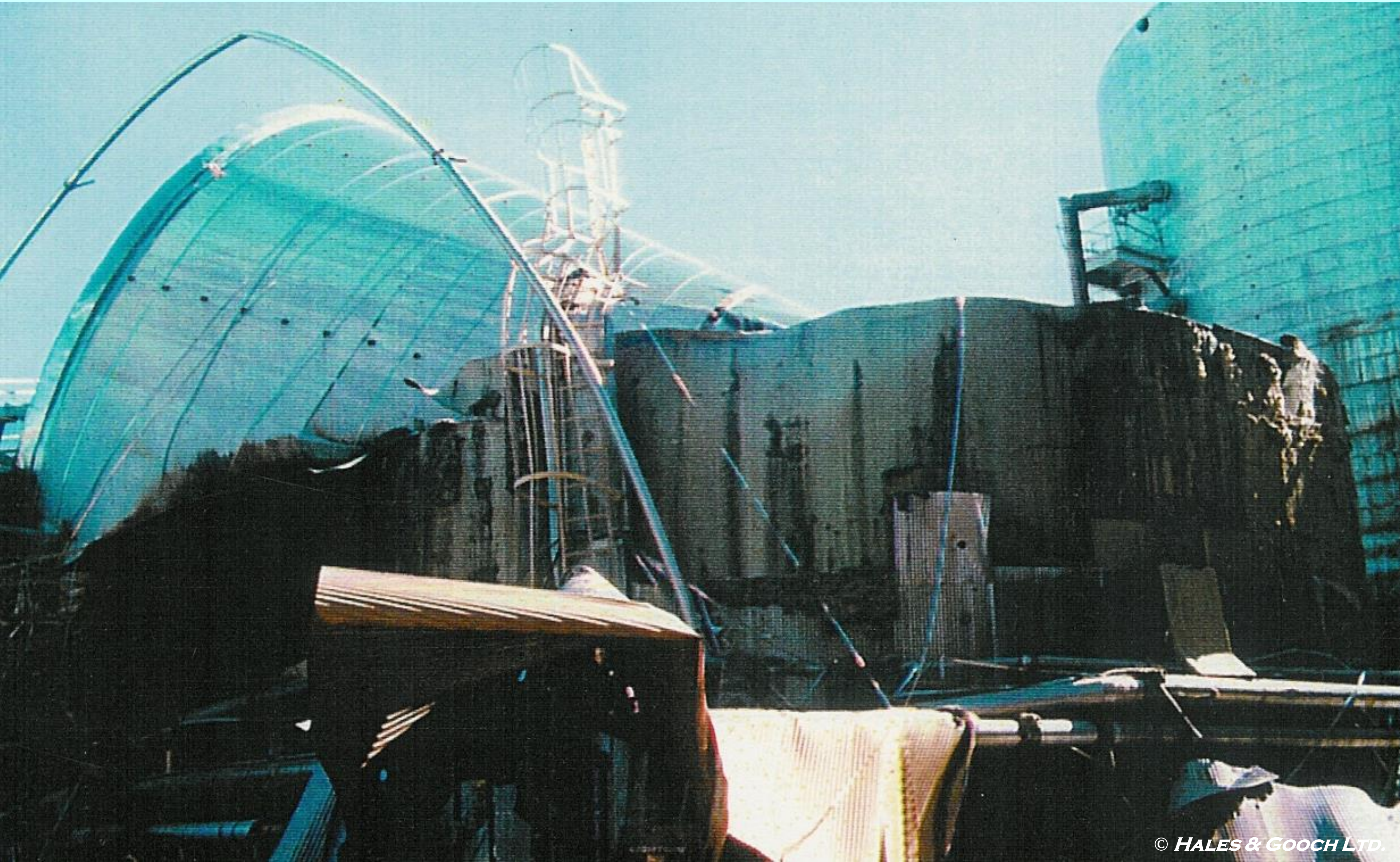
Maintenance Approach

- Keep patching until next budget
- Check wall thickness - ultrasonics
- Calculate life on “average” thickness
- Weld patches over failing areas

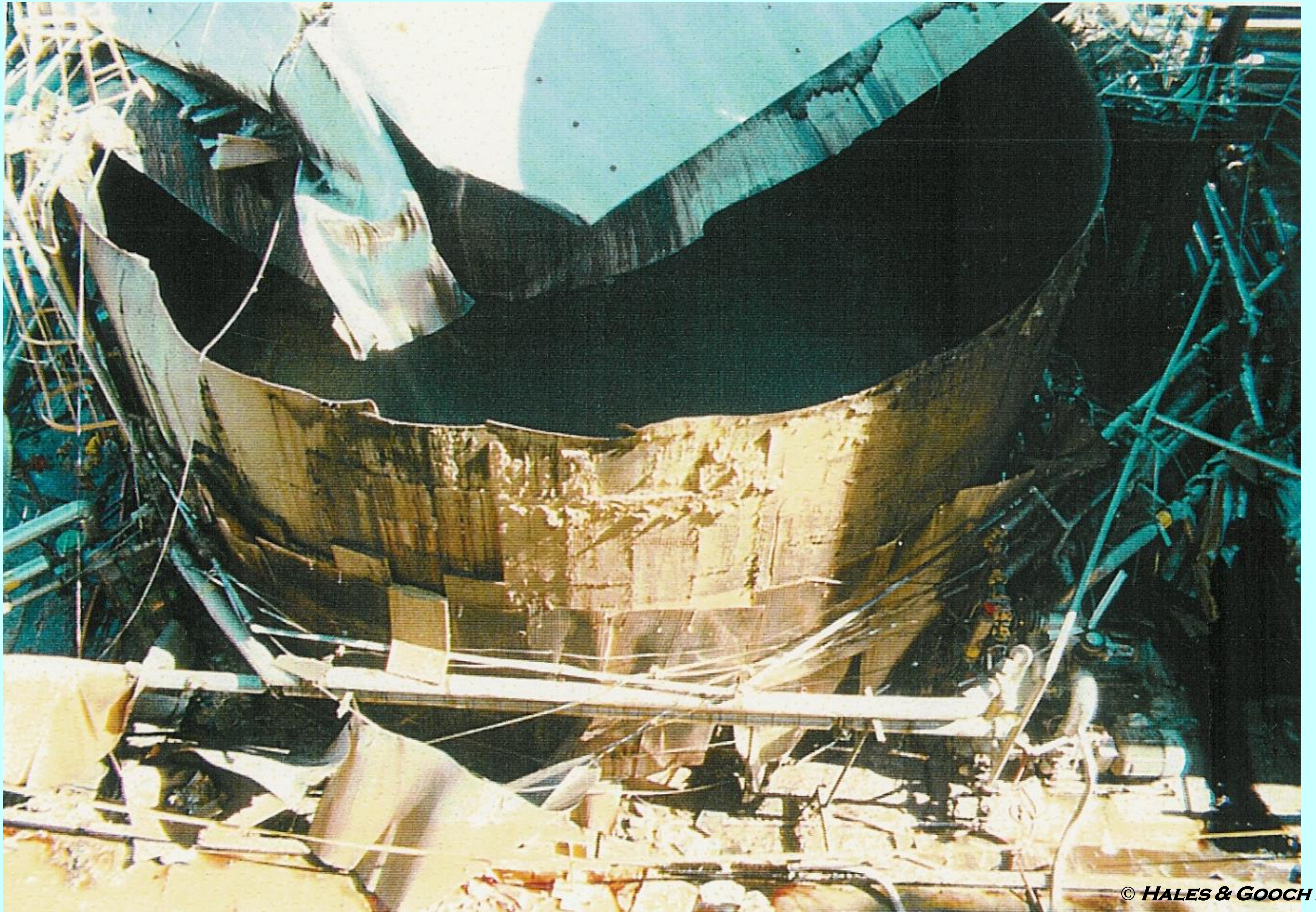
Tank gave way:

workers engulfed by hot black liquor

Top half fell into bottom half

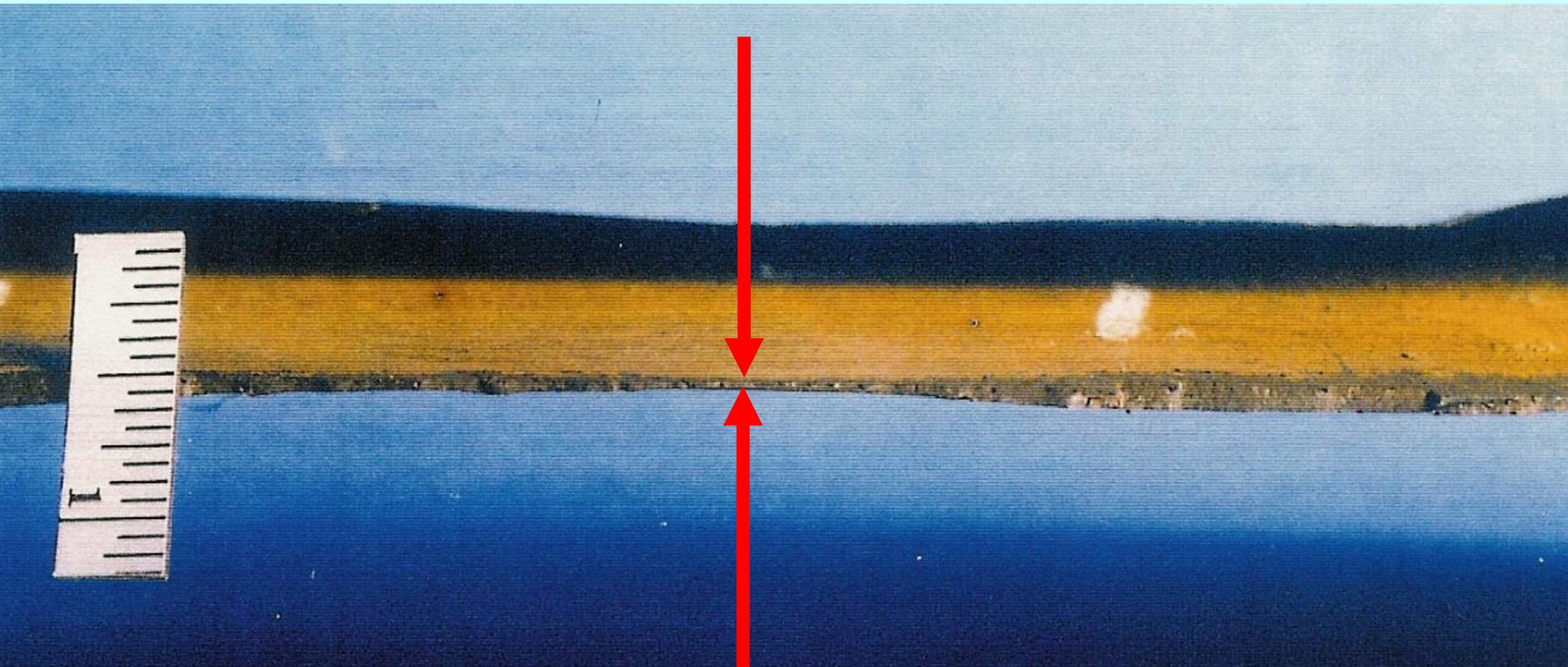


Torn off all the way around



Cut it all up!

Wow, look at that!



Wall thickness corroded from 0.500" to 0.020" here!!

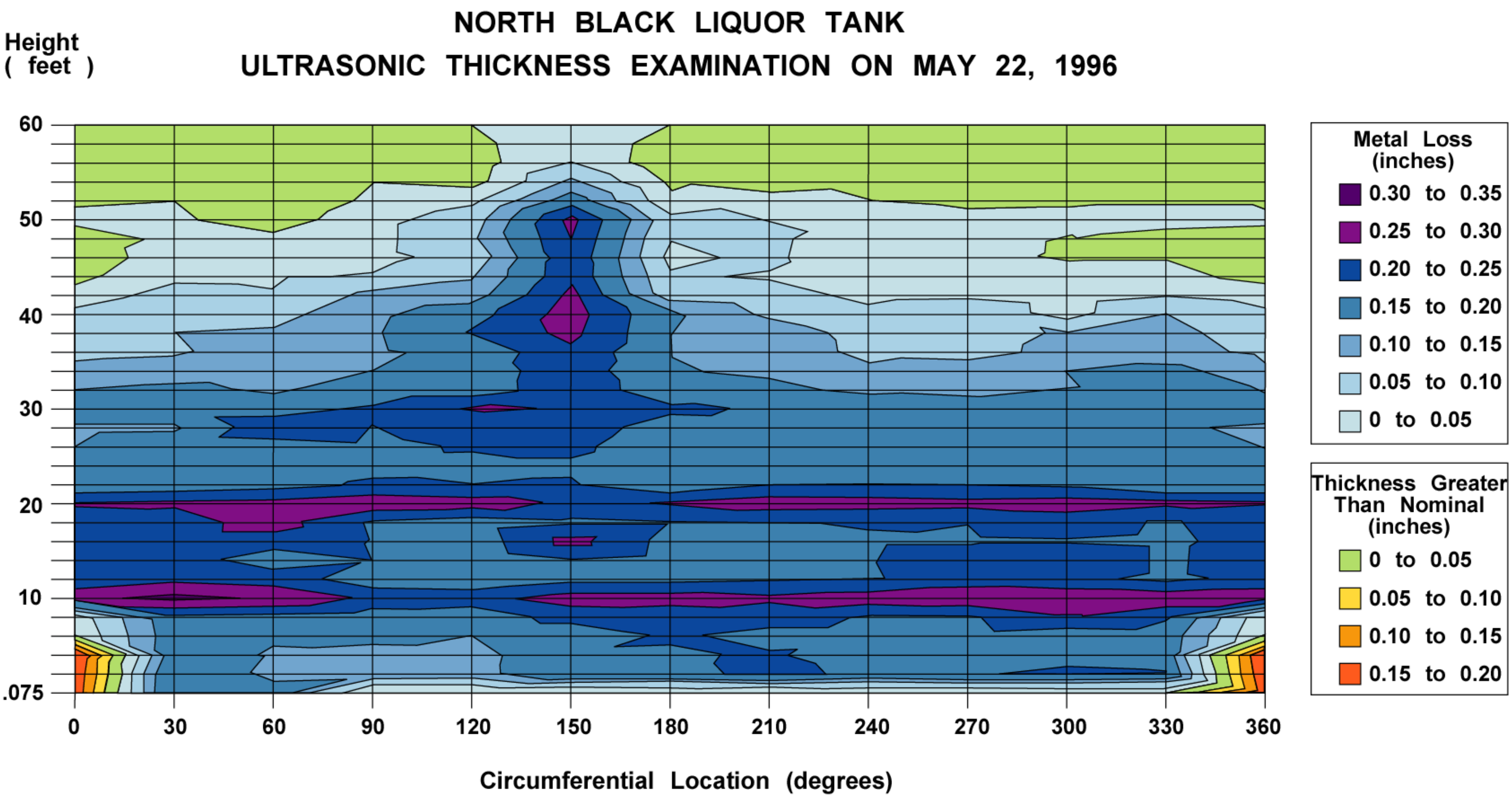
Hey, look at that!

Investigation of Cause

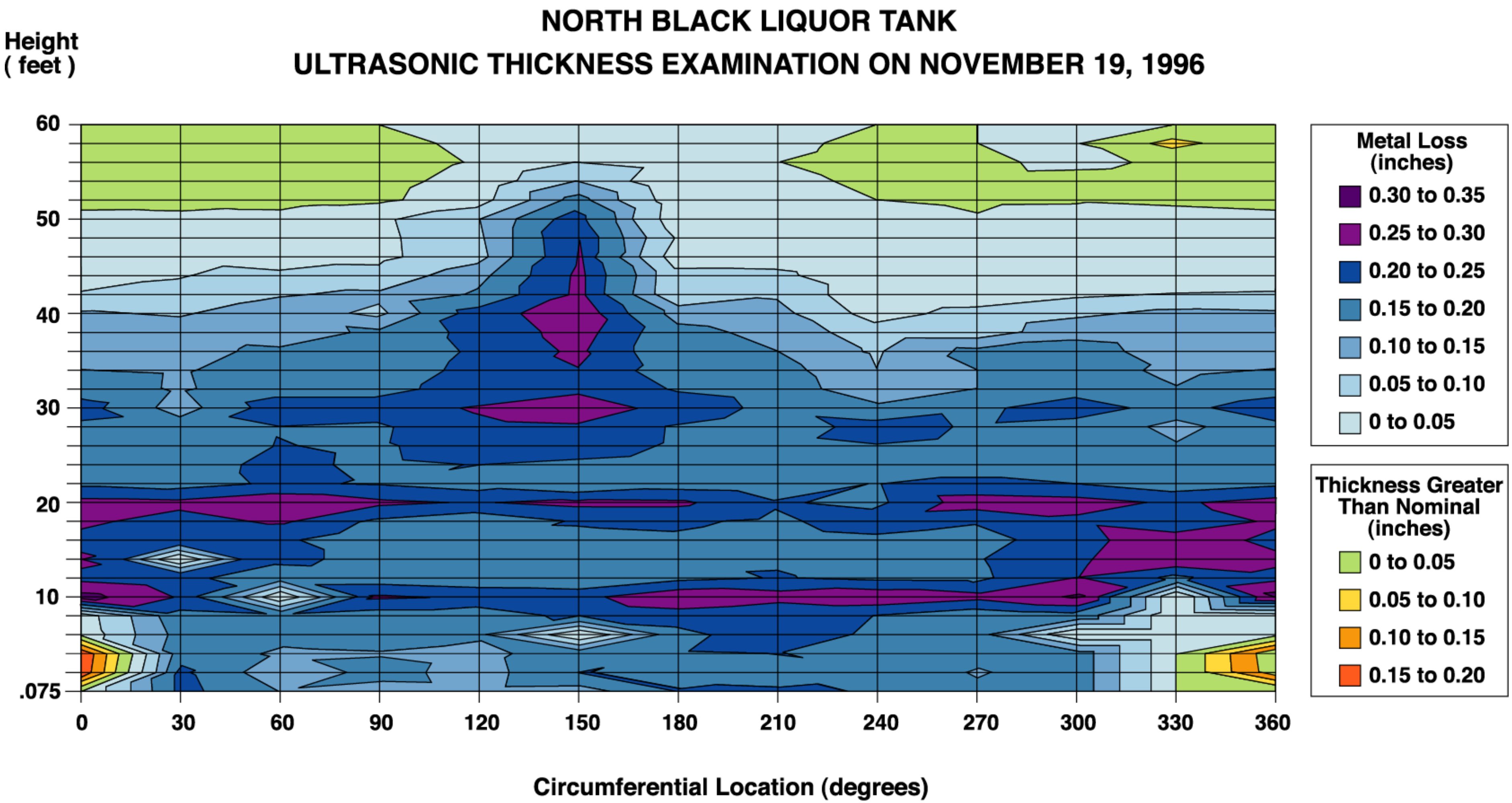
- Plaintiff focused on thickness measurements
- Metallurgical samples taken as evidence

But, analysis of measurements showed:

- Plant did not analyze data in detail
- “Averaging” calculations not to API Standard
- Data showed consistent pattern
- Pattern showed accelerating corrosion



NORTH BLACK LIQUOR TANK
ULTRASONIC THICKNESS EXAMINATION ON MAY 22, 1996
Height (feet)
60
50
40
30
20
10
.075
0
30
60
90
120
150
180
210
240
270
300
330
360
Circumferential Location (degrees)
Metal Loss (inches)
0.30 to 0.35
0.25 to 0.30
0.20 to 0.25
0.15 to 0.20
0.10 to 0.15
0.05 to 0.10
0 to 0.05
Thickness Greater Than Nominal (inches)
0 to 0.05
0.05 to 0.10
0.10 to 0.15
0.15 to 0.20



NORTH BLACK LIQUOR TANK
ULTRASONIC THICKNESS EXAMINATION ON NOVEMBER 19, 1996
Height
(feet)
60
50
40
30
20
10
.075
0
30
60
90
120
150
180
210
240
270
300
330
360
Circumferential Location (degrees)
Metal Loss
(inches)
0.30 to 0.35
0.25 to 0.30
0.20 to 0.25
0.15 to 0.20
0.10 to 0.15
0.05 to 0.10
0 to 0.05
Thickness Greater
Than Nominal
(inches)
0 to 0.05
0.05 to 0.10
0.10 to 0.15
0.15 to 0.20

Analysis of Evidence

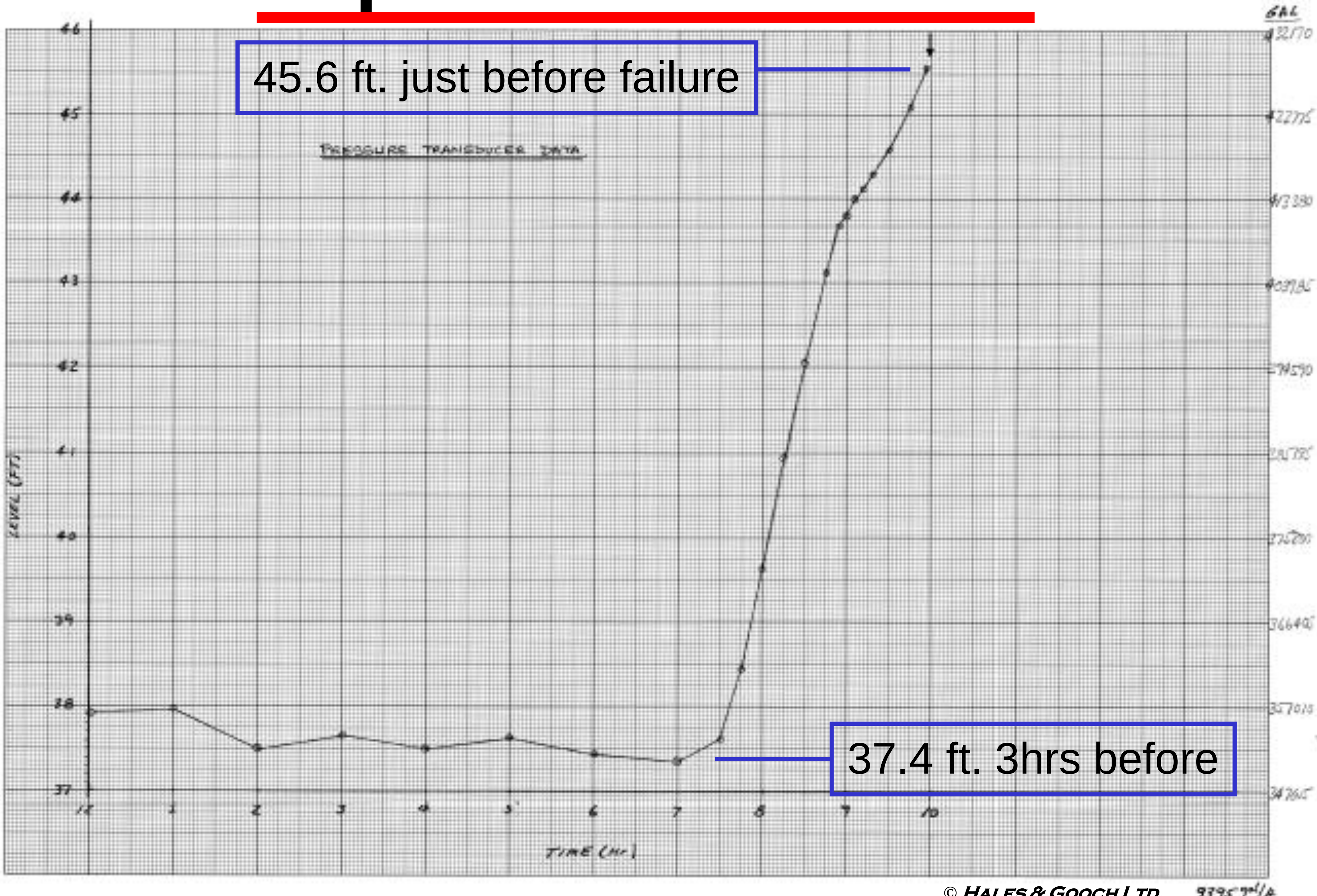
- Accident reports
- Tank drawings
- Photographs
- Pressure transducer data
- Wall thickness measurements
- Demolition map
- Deposition transcripts

Analysis of Data

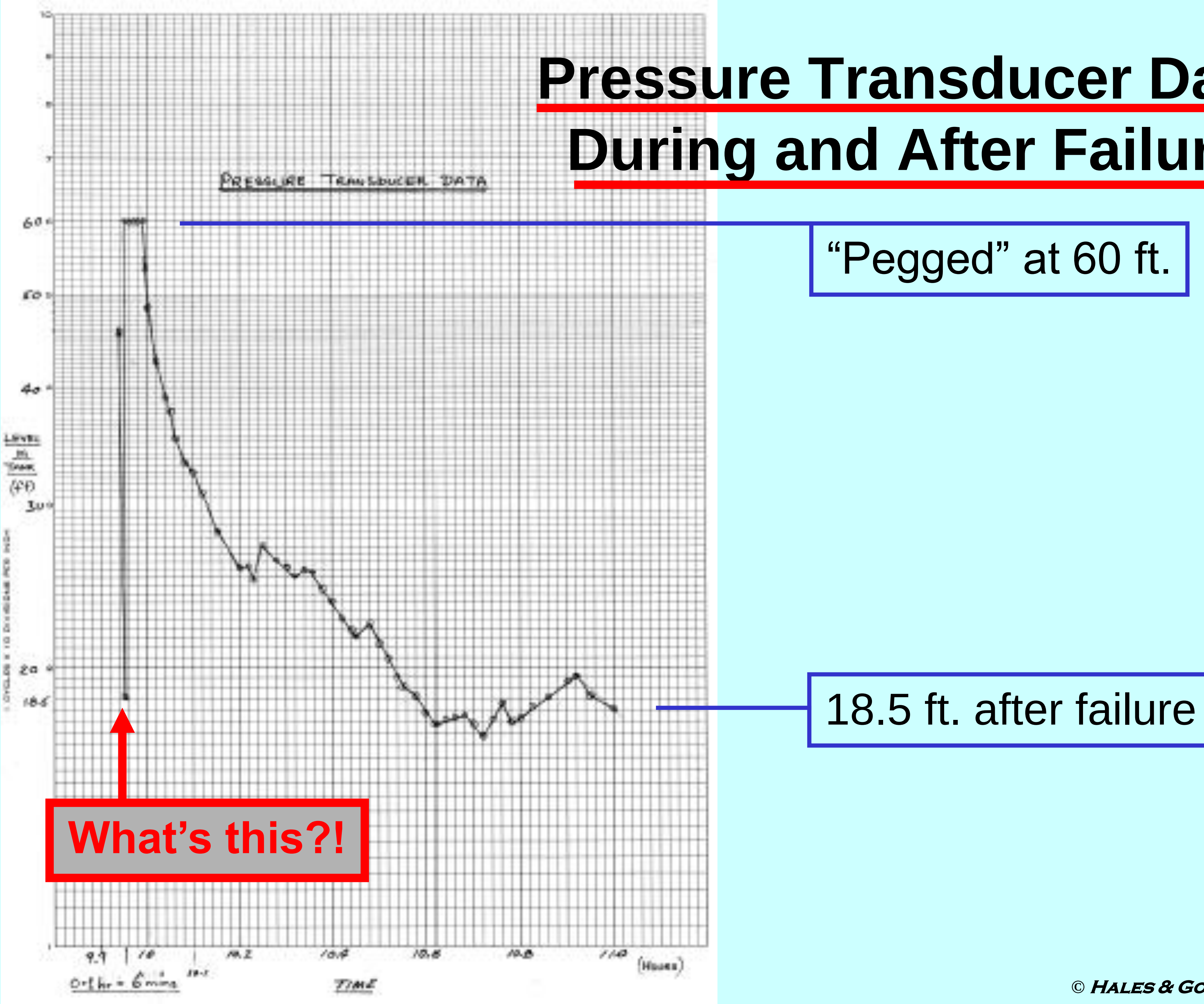
- Black liquor flow history – pressure transducer
- Rapid swings in flow rate – pressure transducer
- Flows during tank failure – pressure transducer
- Mass and energy balance – pressure transducer

- API Standard 650 compliance – wall thickness
- API Standard 653 compliance – wall thickness
- Calculations of stress in wall – wall thickness

Liquid Level in Tank



Pressure Transducer Data During and After Failure



9.504	44.59
9.508	44.61
9.512	44.61
9.517	44.63
9.521	44.63
9.525	44.64
9.529	44.64
9.533	44.66
9.538	44.66
9.542	44.68
9.546	44.68
9.550	44.68
9.554	44.70
9.558	44.71
9.563	44.73
9.567	44.71
9.571	44.73
9.575	44.73
9.579	44.75
9.583	44.77
9.587	44.75
9.592	44.77
9.596	44.79
9.600	44.81
9.604	44.81
9.608	44.81
9.613	44.81
9.617	44.85
9.621	44.85
9.625	44.85
9.629	44.85
9.633	44.87
9.637	44.87
9.642	44.89
9.646	44.89
9.650	44.90
9.654	44.90
9.658	44.89
9.663	44.90
9.667	44.90
9.671	44.92
9.675	44.94
9.679	44.94
9.683	44.94
9.688	44.96
9.692	44.96
9.696	44.96
9.700	44.98
9.704	44.98
9.708	45.00
9.712	44.98
9.717	45.02
9.721	45.02
9.725	45.04
9.729	45.05
9.733	45.05
9.738	45.07

PRESSURE TRANSDUCER DATA

Show tank filling to 45.6 ft then a sudden drop to 18.56 ft followed by a max spike to 60 ft

Pressure transducer operating correctly - confirmed by data on liquid level in tank after failure.

9.742	45.07
9.746	45.09
9.750	45.11
9.754	45.11
9.758	45.11
9.762	45.11
9.767	45.13
9.771	45.17
9.775	45.13
9.779	45.15
9.783	45.18
9.788	45.18
9.792	45.18
9.796	45.18
9.800	45.20
9.804	45.20
9.808	45.20
9.813	45.22
9.817	45.24
9.821	45.22
9.825	45.24
9.829	45.26
9.833	45.26
9.837	45.28
9.842	45.28
9.846	45.30
9.850	45.30
9.854	45.32
9.858	45.34
9.863	45.34
9.867	45.36
9.871	45.36
9.875	45.36
9.879	45.37
9.883	45.41
9.887	45.4[illegible]
9.892	45.41
9.896	45.4[illegible]
9.900	45.4[illegible]
9.904	45.4[illegible]
9.908	45.47
9.913	45.48
9.917	45.48
9.921	45.50
9.925	45.50
9.929	45.52
9.933	45.52
9.938	45.5[illegible]
9.942	[illegible]
9.946	18.56
9.950	[illegible]
9.954	60.00
9.958	60.00
9.962	60.00
9.967	60.00
9.971	60.00
9.975	60.00

The Key!

9.946   18.56

Results of Analysis

- Tank did not fail from overpressure
- Three unusual things identified:
  - Black liquor in tank at time was superheated
  - Rapid pressure **drop** followed by pressure spike
  - Pressure trace matched time constant of event

WAS IT A "BLEVE"?

(Boiling Liquid Expanding Vapor Explosion)

Characteristics of a BLEVE:

- Confined liquid in tank engulfed by fire
- Liquid gets superheated and pressure rises
- Pressure relief too slow to match increase
- Tank weakened by heat, can't take pressure
- First failure in tank sets off "rarefaction wave"
- Instant vaporization of superheated liquid
- Instant pressure spike and shock wave
- Explosion!

TANK BLEVE RESULTS

These experiments repeated those done by McDevitt *et al* (ref. 10) with the addition of the dynamic response pressure transducer. Consequently, the outcome was predictable. This allowed collection of pressure data under conditions where in which a BLEVE was assured.

The temperatures at which the tanks were punctured were somewhat inaccurate due to the nature of the test. It was not possible to have a temperature indication at a remote location, so it was necessary for someone to remain near the tank (but behind the blast wall) to read the temperature. Once the desired temperature was reached, that person moved to a "safe" area. The Protective Services person then fired into the tank. Due to the time between the last temperature reading and the rupture of the tank, the exact temperature at the time of rupture is estimated.

Figure 2 shows the pressure-time history as recorded by the transducer at the end of the tank. The fluid inside the tank was 879 g (88 v%) or R22, which was heated to approximately 65 C. The pressure inside the tank at this temperature would be 2700 kPa. As can be seen from the figure, the pressure dropped slightly, then rose to a maximum of 3500 kPa. This result shows that the

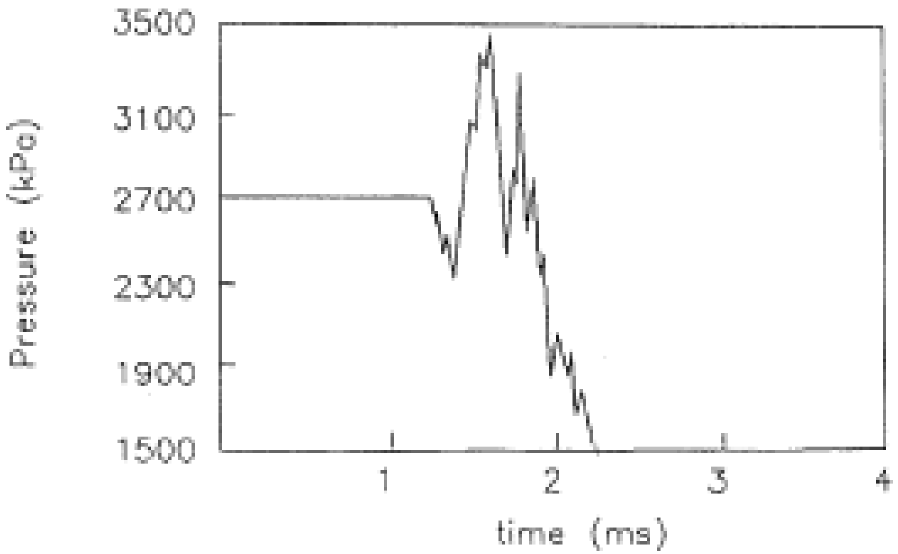


Figure 2: Pressure Response during a BLEVE of R22 in a 1 Litre Tank

REVIEW OF REPORTED RESEARCH DATA

Critical Factors

TEST ① Temperature: Need a confined liquid at a temperature which is higher than its normal boiling point at atmospheric pressure. (not boiling). Superheated liquid

Our liquid is at ≈ 246°F

Boiling pt at atm pressure is ≈ 224°F (solids raise B.Pt.)

Average	211°F + 10°F ⇒ 221°F	PADD	+ 1P0001061 (1st P)
max.	212 + 11 ⇒ 223°F.		+ 1P0001068 (mono)

TEST ② Characteristic pressure trace

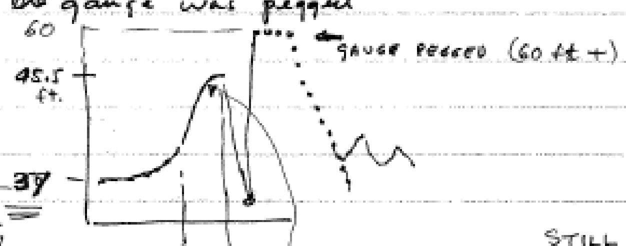
Rapid Depressurization followed by Rapid pressure rise i.e. initial drop in pressure is followed by rapid pressure rise

Ref: ① Ben Hanchey dep. BLEVE ② Journal Haz. mat 1990 Prediction Step of Boiling Liquid Expanding Vapour Explosions

We have the characteristic curve

We show a pressure drop followed by a rapid pressure rise i.e. Pressure gauge shows Height 45.5 ft → 18.5 ft → 60 ft

we don't know how high pressure actually reached because the gauge was pegged



Midnight to 7 am Steady @ 38-37 Then took off.

Rate 6829 gal/min (1.5 hr)

280 gal/min (1 hr)

Started with 353,252 gal End 428,036 gal at failure (22% increase over ~2 hrs)

What we have here:

1 SUPERHEATED LIQUID

2 PRESSURE DROP, THEN SPIKE

(2

TEST 3) Time Constant

Events of pressure drops & rise have been reported to be rapid i.e. short time constant events.

For example - experiments on 1 liter container show that these events can occur on a time scale of about 2 miliseconds (2×10^{-3} sec)

Our container at the 45.5 ft level contained 428,036 gal which is about 1.7×10^{6} larger than the 1 l system

Our pressure drops & rise occurred in 30 - 36 sec

The slow elevated time  ≈ 2 - 2.5 MIN = 150 sec

12 MIN ⇒ 720 sec

— 12 MINS WHOLE EVENT → Tank @ 35 ft.

If direct scaling was used (which would not likely be appropriate because of dissimilar geometry, fluids, initiation source etc.) the time constant would be ≈ $(1.7 \times 10^{6})(2 \times 10^{-3}) \approx 3420$ sec

i.e. ⇒ May be on the order of $10^{2} - 10^{3}$ sec

Our time constant in fact is on the order of $10^{1} - 10^{2}$ maybe 10^{3} sec

Consistent with the phenomena.

3

SHORT TIME CONSTANT

CAUSE OF FAILURE

Boiling Liquid Expanding Vapor Induced Shock *
(BLEVIS)

***** New term, coined to describe phenomenon

BLEVIS

(Boiling Liquid Expanding Vapor Induced Shock)

Characteristics identified:

- Liquid enters tank at fast rate and boiling
- Superheated liquid trapped in tank
- Tank weakened from corrosion, not from heat
- First failure in tank initiates “rarefaction wave”
- Boiling causes instant vaporization, pressure rise and shock wave
- Tank collapses immediately, without explosion.

Supporting Evidence

- Meets the 3 criteria for this type of failure:
  - Liquid above boiling point in confined space
  - Triggering event with shock wave
  - Weakened structure unable to take shock load
- Big leak just prior to failure → slower fill rate
- Defined pattern of liquor on roof
- Tank collapsed inwards first, not outwards
- Failure of anchor bolts and agitator drive
- No eye witnesses (rapid time-constant)

Summary

- Claim of poor measurements proved false
- Plant side-stepped warnings given by data
- High risk operation dependent on failing tank

- Thickness issues switched to process issues
- Single data point was key to what happened
- Metallurgical analysis irrelevant
- Case settled after presentation to attorneys

5

DEMONSTRATE IT CLEARLY!

Example:

THE HIGH PRESSURE WASHER

LAB TECHNICIAN LOSES EYE

- Water/Sewage Company - Indiana
- New pressure washer – 3700psi
- Operator using it to clean clarifiers
- Turned off and put in back of truck
- Driver went to unload at building
- Asked lab technician to help
- She helped him lift unit out of truck
- Spray gun shot her in the eye

THE ACCIDENT - Plaintiff

"When we set it down, there is a hose attached to the unit that goes to the wand, the machine was not on, the machine was not hooked up to any hydrant. It was just by itself. And as I was starting to stand up, the wand - -the hose was beneath my feet, and I was still bent over and Jimmy was still bent over. And to get out of my way, he moved the wand and the next thing I know it fired. I didn't see anything. It just went off."

THE ACCIDENT - Driver

"We were pulling it out of the back of the tailgate. We set it down, the wand had fallen off. I went to pick it up, and when I picked it up, I picked it up by the handle, and boom, it just went off and got her right above the eye."

Question: "How high did you lift it off the ground before water discharged?"
Answer: "I want to say maybe two or three feet maybe."

Question: **"And in what direction at that point was the nozzle end, the end that the water comes out of, of the wand facing?"**
Answer: **"Away from me. It was up towards the air."**
Question: **"At the time the incident happened, you had gotten the wand two or three feet above the ground?"**
Answer: **"Well, the back part, yes. The handle part."**
Question: **"So you're talking about it being oriented in an upward pointing way?"**
Answer: **"Yes."**

THE ACCIDENT - Manufacturer

Question: **"When our pressure washer, when it is operated and then the engine's shut off and the water hose disconnected, there remains residual pressure, until you squeeze the trigger?**
Answer: **"Yeah. Until you purge the gun, there is trapped pressure in the hose, correct."**
Question: **"If you had a flow-actuated unloader that would not be the case though, would it?"**
Answer: **"That's correct."**

MANUFACTURER'S DESIGN PROCESS

- Structured on series of design reviews
- Specialty items purchased complete
- Use of industry-proven components
- Prototype testing against specification
- Testing to meet applicable standards
- Records kept on all testing
- Flow-actuated unloaders found unreliable

GOOD, BUT PLAINTIFF'S EXPERT OPINION:
"Should have had a flow-actuated unloader"

INSPECTION OF EXEMPLAR UNIT

TRIGGER TESTS WITH POWER OFF

- 4lbs to squeeze trigger without water pressure or pump
- 5lbs to squeeze trigger with water pressure on but no pump
- 25lbs to squeeze trigger when operating with water & pump
- 25lbs to squeeze trigger first time pulled after motor shut off
- 4lbs again once water pressure released from hose when off

SQUIRTING TESTS WITH POWER OFF

1. Machine operating under full pressure
2. Machine shut off
3. Nozzle inserted into container
4. Squeeze trigger to release pressure
5. Measure volume of water released

Results: 56ml = 3.42 cu. ins.

HOSE TESTS WITH POWER OFF

- High pressure hose – heavy duty wall thickness
- Difficult to coil even with pressure off – “springs back”
- Lot easier to coil when disconnected from machine & gun
- When pressurized near impossible to coil on hooks
- Hose twists to form “figure-of-eight” when pressurized
- Hose has to be rotated to continue coiling
- Easiest way to overcome problem is to squeeze trigger
- When pressure released then much easier to coil

INSPECTION OF ARTIFACT UNIT

HOSE & GUN

High Pressure Hose — Connect one end to the water pump and the other end to the spray gun.

Spray Gun — Controls the application of water onto cleaning surface with trigger device. Includes safety latch.

SAFETY HIERARCHY

1. Eliminate the hazard and/or risk
2. Apply safeguarding technology
3. Use warning signs
4. Train and instruct
5. Prescribe personal protection

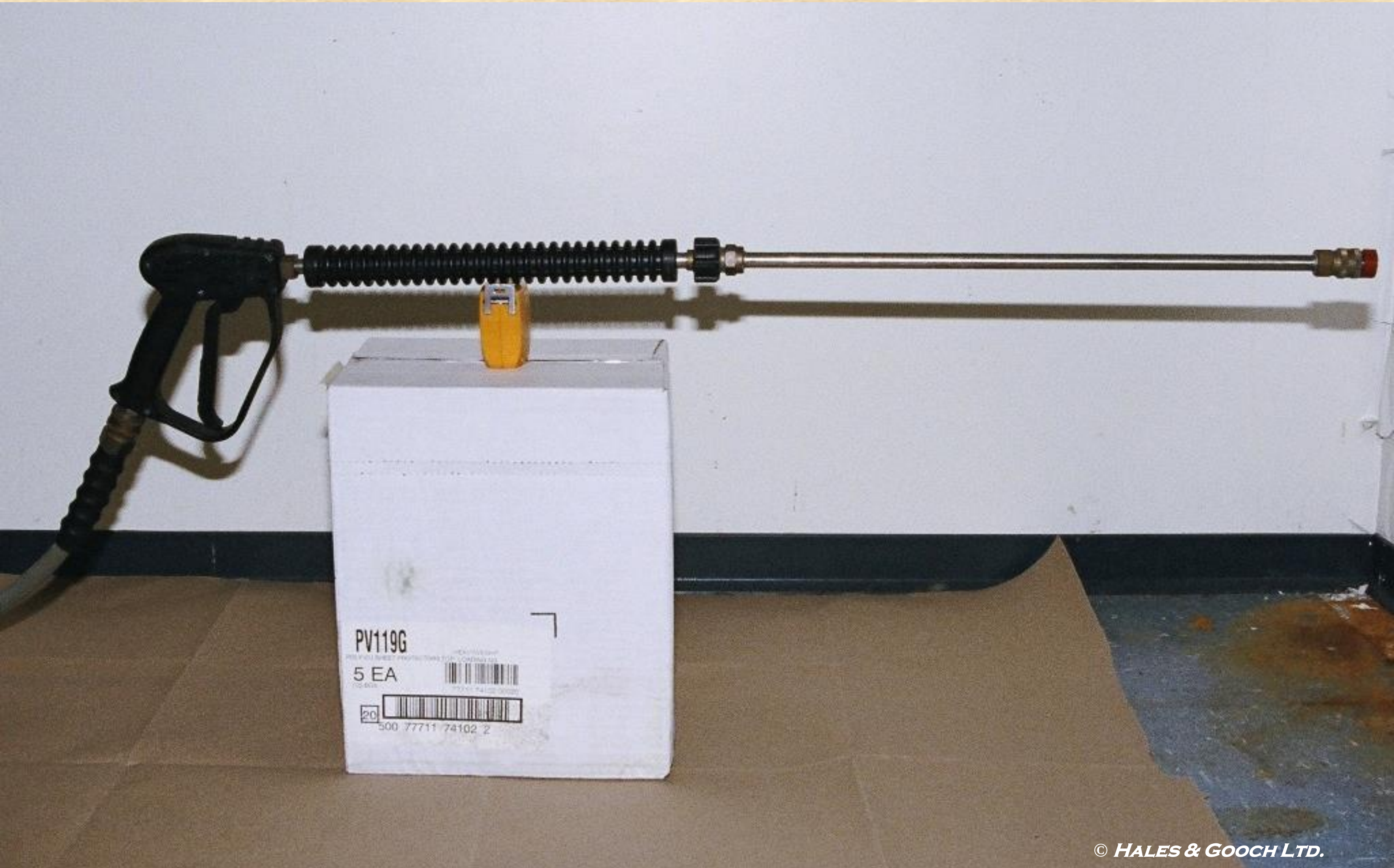
CHECK ON PRESSURE WASHER DESIGN:

SAFETY HIERARCHY – LEVEL 1

Eliminated hazard and/or risk by design? ✓

- Hose twists up and can't be coiled under pressure
- Gun points to ground when picked up by handle
- Trigger guard prevents hitting trigger
- Trigger hard to squeeze when hose pressurized
- Additional force required to point gun upwards

CENTER OF GRAVITY – GUN + HOSE



CHECK ON PRESSURE WASHER DESIGN:

SAFETY HIERARCHY – LEVEL 2

Applied safeguarding technology? ✓

- Trigger guard geometry protects trigger
- Trigger lock placed in natural position
- Projections on lock assist easy use
- Over-center geometry with detent action
- Hose couplings locked when pressurized

TRIGGER LOCK – STOWED POSITION

TRIGGER LOCK – USING PROJECTIONS

TRIGGER LOCK – LOCKED POSITION

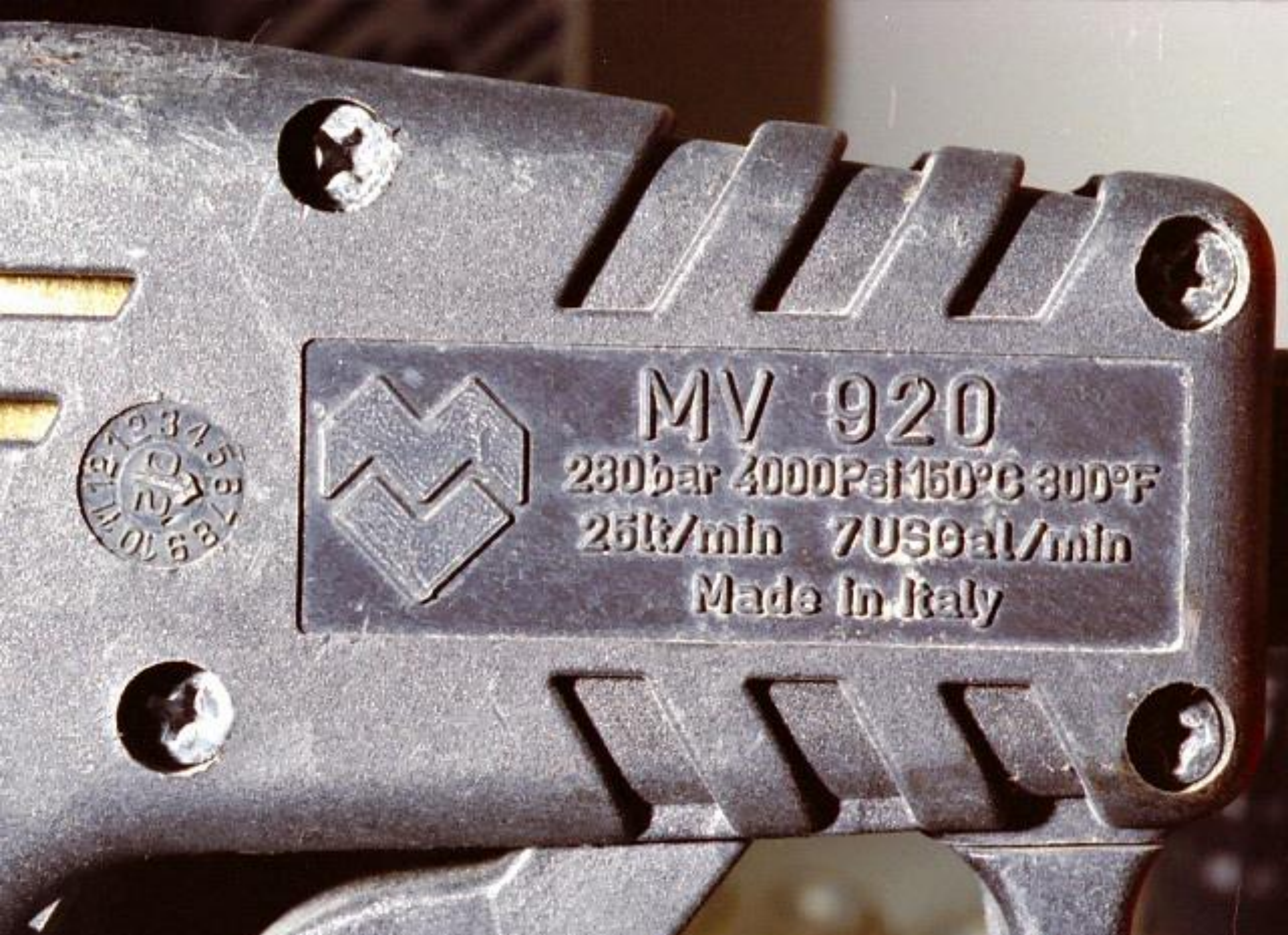
CHECK ON PRESSURE WASHER DESIGN:

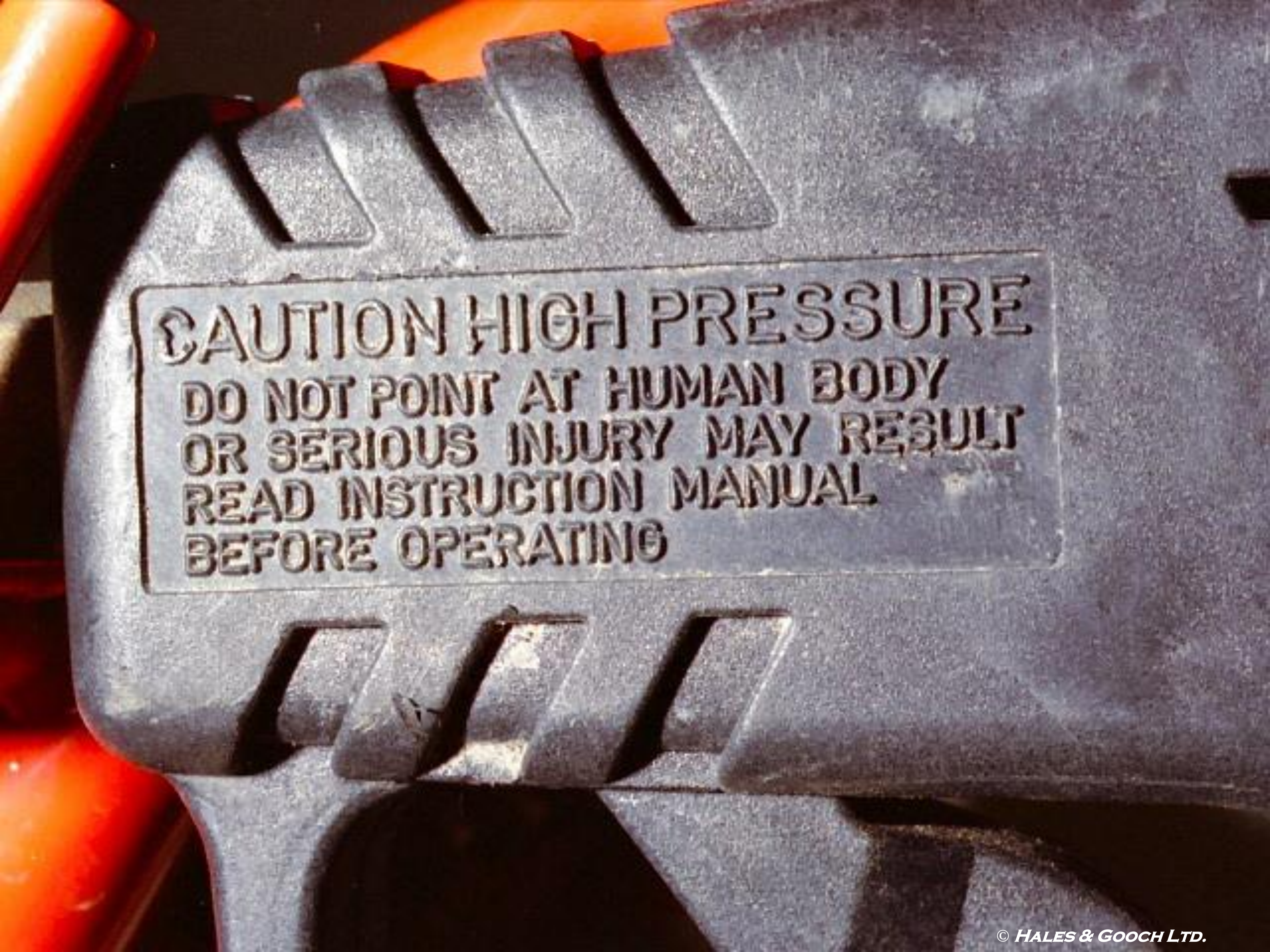
SAFETY HIERARCHY – LEVEL 3

Warnings provided? ✓

- Hose won't coil when pressurized
- Spray gun won't stay in hooks when pressurized
- Hose connections locked when pressurized
- First notice on box is "3700psi"!
- Hose couplings locked when pressurized
- Warning tag on machine
- Embossed warning on the handle of the gun


HIGH PRESSURE


MV 920
280bar 4000Psi 150°C 300°F
25lt/min 7USGal/min
Made in Italy


CAUTION HIGH PRESSURE
DO NOT POINT AT HUMAN BODY
OR SERIOUS INJURY MAY RESULT
READ INSTRUCTION MANUAL
BEFORE OPERATING

WARNING TAG ON MACHINE

WARNING TAG ON MACHINE

CHECK ON PRESSURE WASHER DESIGN:

SAFETY HIERARCHY – LEVEL 4

Training and Instruction? ✓

- Warning on gun tells operator to read manual
- Manual instructs operator to read manual!
- Manual instructs use of trigger to release pressure
- Warns user never to aim spray gun at people
- It adds a caution regarding the trigger lock
- Relieve pressure in hose after turning off engine
- Trigger must be squeezed to relieve pressure
- etc., etc.

MANUAL – Instructions & Warnings

⚠ WARNING

The high pressure stream of water that this equipment produces can pierce skin and its underlying tissues, leading to serious injury and possible amputation.

- NEVER aim spray gun at people, animals or plants.
- DO NOT allow CHILDREN to operate pressure washer.
- NEVER repair high-pressure hose. Replace it with an equivalent rated hose.
- Keep high pressure hose connected to pump and spray gun while system is pressurized.

⚠ ADVERTENCIA

La corriente de agua de alta presión que produce este equipo pueden perforar la piel y sus tejidos profundos, ocasionando lesiones serias y posible amputación.

- NUNCA apunte la pistola a la gente, animales o plantas.
- NO permita en ningún momento que NIÑOS operen la máquina lavadora a presión.
- NUNCA repare la manguera de alta presión. Remplacela.
- Mantenga conectada la manguera a la máquina o a la pistola de rociado cuando el sistema esté presurizado.

Check Gun and Nozzle Extension

Examine the hose connection to the spray gun and make sure it is secure. Test the trigger by pressing it and making sure it springs back into place when you release it. Put the safety latch in the on position and test the trigger. You should not be able to press the trigger.

CHECK ON PRESSURE WASHER DESIGN:

SAFETY HIERARCHY – LEVEL 5

Personal Protection Equipment? ✓

- **Goggles supplied with machine**
- **Manual recommends wearing goggles**

PRESSURE WASHER DESIGN

Company hardly realized it but in fact design followed Safety Hierarchy:

- **Eliminate hazard and/or risk by design** ✓
- **Apply safeguarding technology** ✓
- **Provide warnings** ✓
- **Train and instruct** ✓
- **Prescribe personal protection** ✓

Case settled quickly as design not at fault

FORENSIC INVESTIGATION GUIDELINES

1. Bring all the bits together again
2. Question all assumptions
3. Think through the logic
4. Explain the unusual
5. Demonstrate findings clearly