Pipeline Research Council International

Hard Spots Susceptibility

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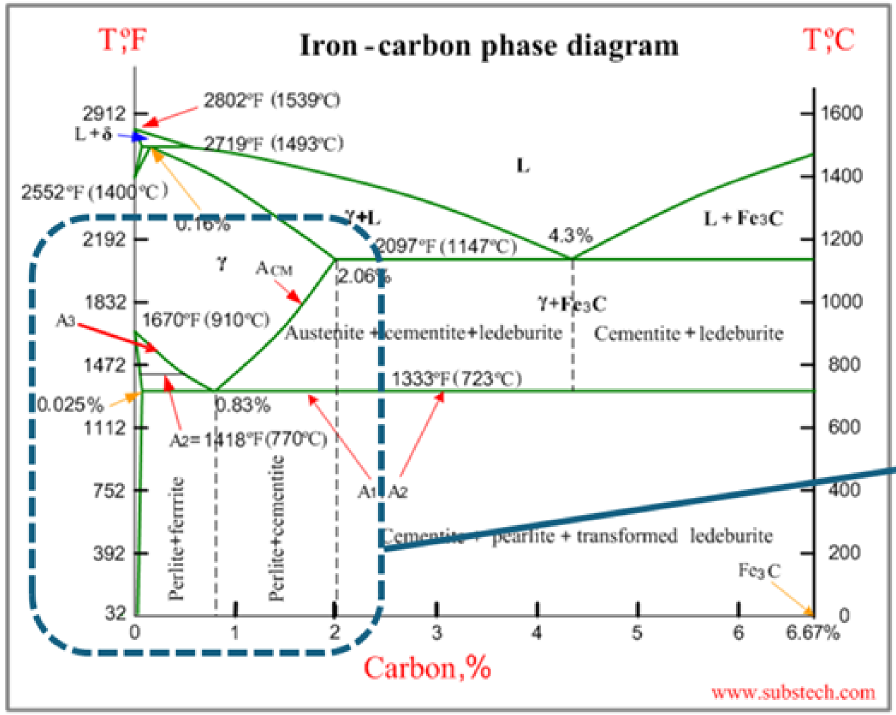
Aspects of Hard Spots Susceptibility

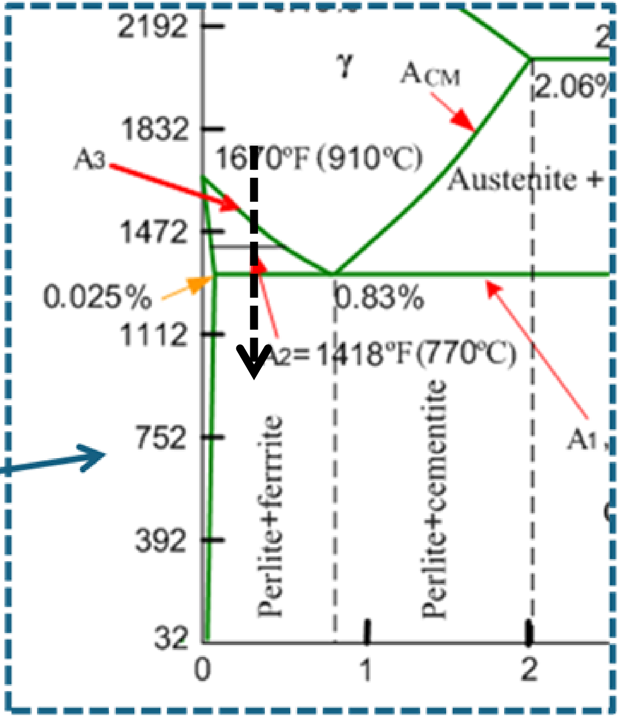
1. **Susceptibility to *hard spots in the pipe***
   - Metallurgical factors
   - Pipe manufacturing process
   - High susceptibility pipe
   - Low susceptibility pipe
2. **Susceptibility to *hard spots failing***
   - Hardness level
   - Hard spot size
   - Pipeline stress
   - Sources of hydrogen
   - Changes in conditions

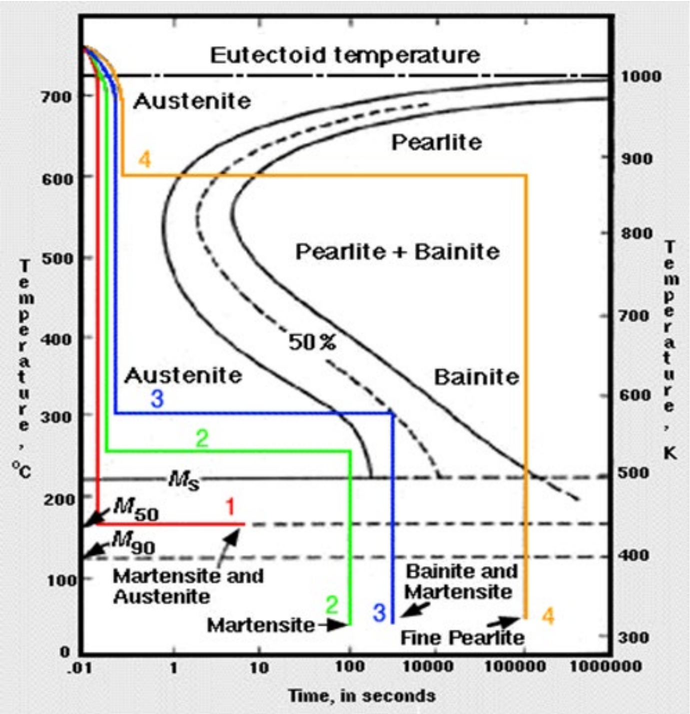
1. Susceptibility to hard spots in the pipe

Metallurgical factors

- **Factors that contribute to metallurgical hard spots**
  - Steel composition, especially C, Mn
  - Cooling rate from above A_3 temperature (~1570 F or 854 C at 0.25%C)



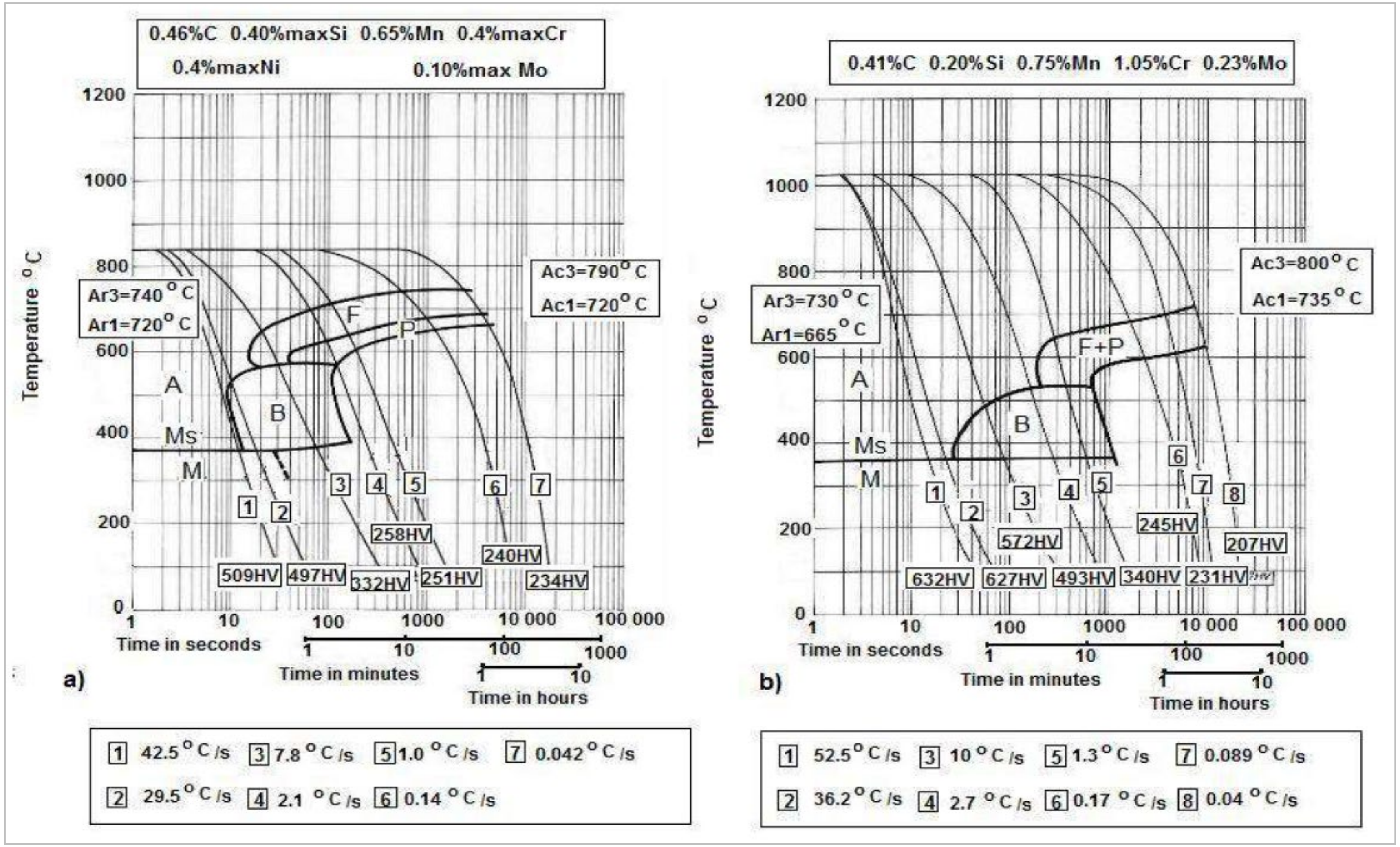




Effect of steel composition and cooling rate

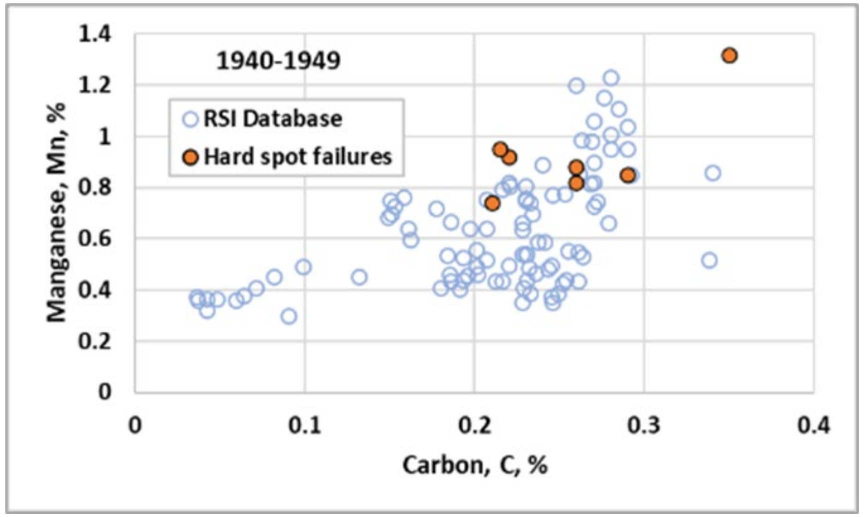
1045 plain carbon steel

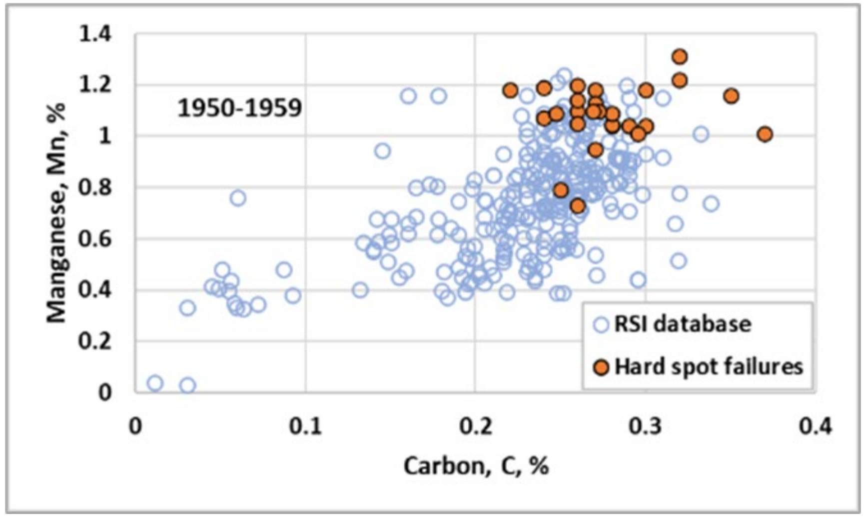
4340 Ni-Cr-Mo alloy steel



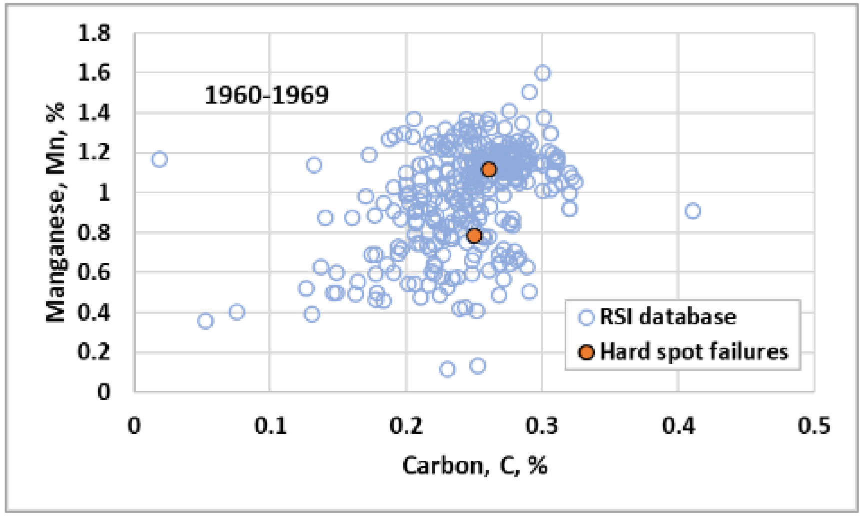
- C, Mn, Mo, Cr, Ni, Si, V, B increase hardenability
- Higher hardenability steels attain much higher hardness with rapid cooling rates than lower hardenability steels
- No significant difference with slow cooling rates

Influence of steel composition





Steel composition of pipe affected by HS failures tends to be high C and Mn but within bounds for decade of origin



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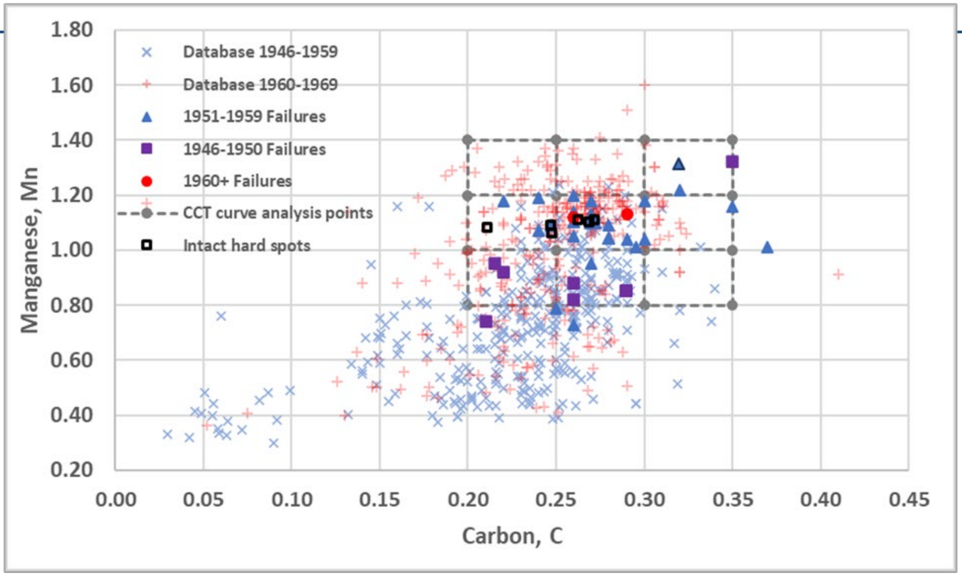
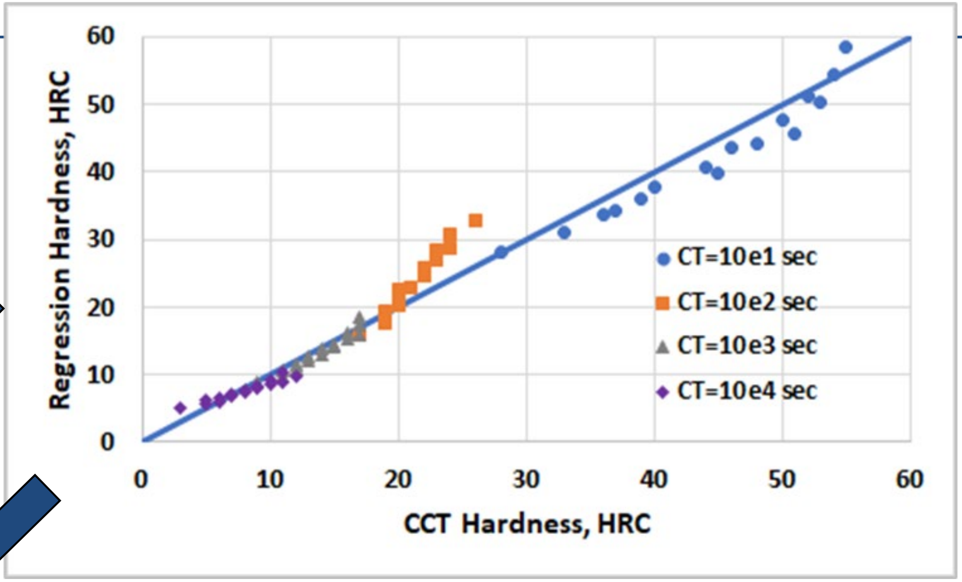
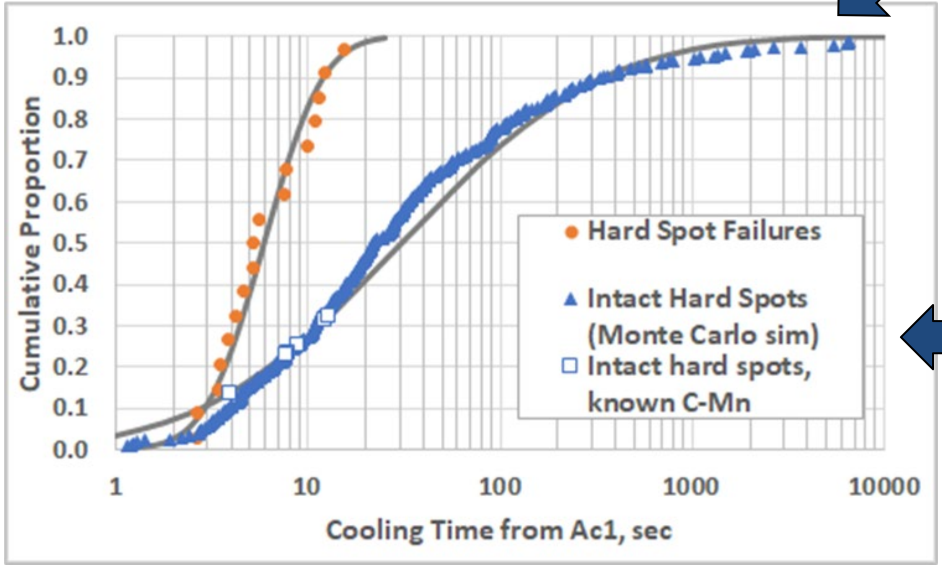
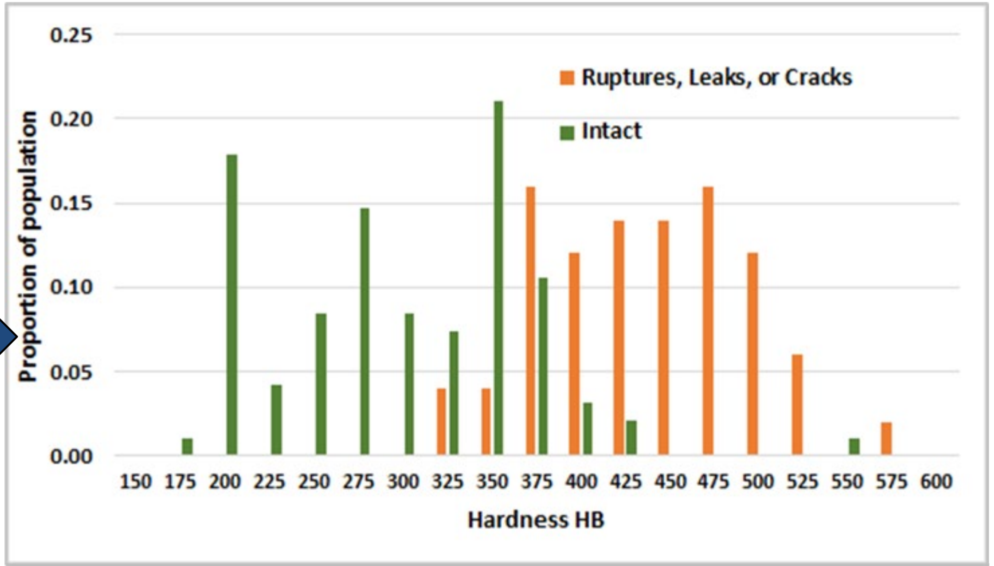
Effect of steel composition and cooling rate

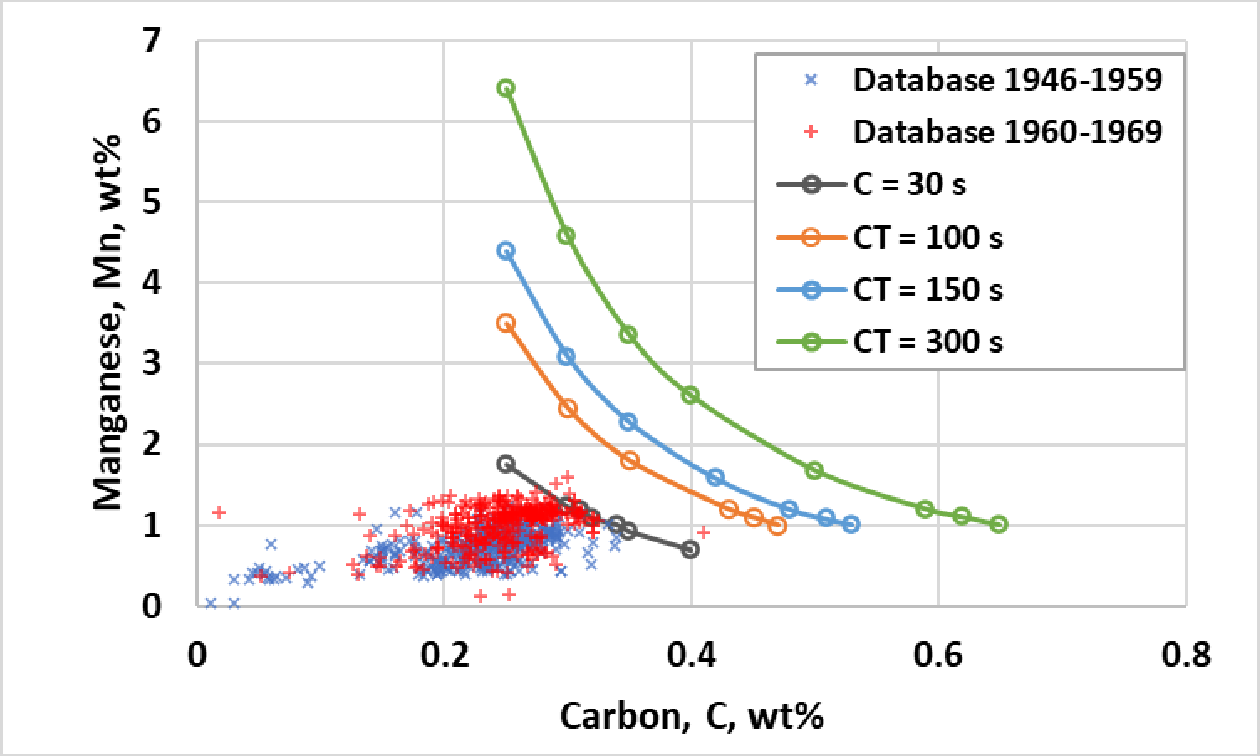








Could locally enrich composition explain hard spots?



- C-Mn content necessary to attain 425 BHN at 50th percentile "normal" cooling rate (30 sec from Ac1) is at upper edge of line pipe composition
- C-Mn content to attain 425 BHN at 70th, 80th, 90th percentile cooling rates (>100 sec) are extreme
  - Cannot attain high hardness on composition alone – must have high cooling rates
- No evidence of enriched composition reported in metallurgical investigations
  - But no investigations actually checked for enriched composition

Pipe manufacturing process factors

Pipe Type	No. Incid.	% Incid.
SAW	19	21.6%
FW	58	65.9%
YS&T ERW	5	5.7%
Other ERW	2	2.3%
SMLS	2	2.3%
Not reported	2	2.3%
TOTAL	88	100%

← Discrete plates (SAW, FW, YS&T ERW)

← Continuous coil (Other ERW)

← Hot finished (SMLS)

← Likely 1 ERW, 1 SMLS (Not reported)

How does accidental quenching occur?

- High pressure (1500-4000 psig) water sprays are encountered by hot plate and strip
  - At the roughing mill
  - To cool rollers at successive roll stands
  - On runout table
- Plate/skelp rolling speeds can be high. When hot plate or strip maintains travel speed, hard spots don’t occur
- Failure of a roller to properly engage a plate (“bite”) or guide plate motion could impede forward motion, result in a mill wreck from momentum of incoming material (“cobble”)
- Spray heads are supposed to swing away or shut off, but if that doesn’t happen the immobile hot plate or strip can be quenched locally

Why do hard spots occur in plate but not strip?

- **ERW hot strip coils weight 20-50T, moving 200-4000 fpm.**
  - Few opportunities for sudden stops
  - Skelp is coiled at >1300 F, thermal mass takes 1-3 days to cool, tempers any residual hard spots
  - Salvaged skelp from mill cobble that is coiled below a tempering temperature could explain the few ERW hard spots observed
- **Discrete plate used with SAW, FW, and YS&T ERW**
  - Each plate weighs 3-6T → much lower momentum, more easily stopped
  - Each leading edge is an opportunity for rollers to fail to engage plate
  - Interrupted plate motion and accidental quench is more likely than with hot strip
- **What about seamless?**
  - Cooling sprays are encountered multiple time in SMLS forging process
  - Tube is furnace reheated between most forming stages, annealing hard spots
  - Finished SMLS pipe is generally cooled slowly

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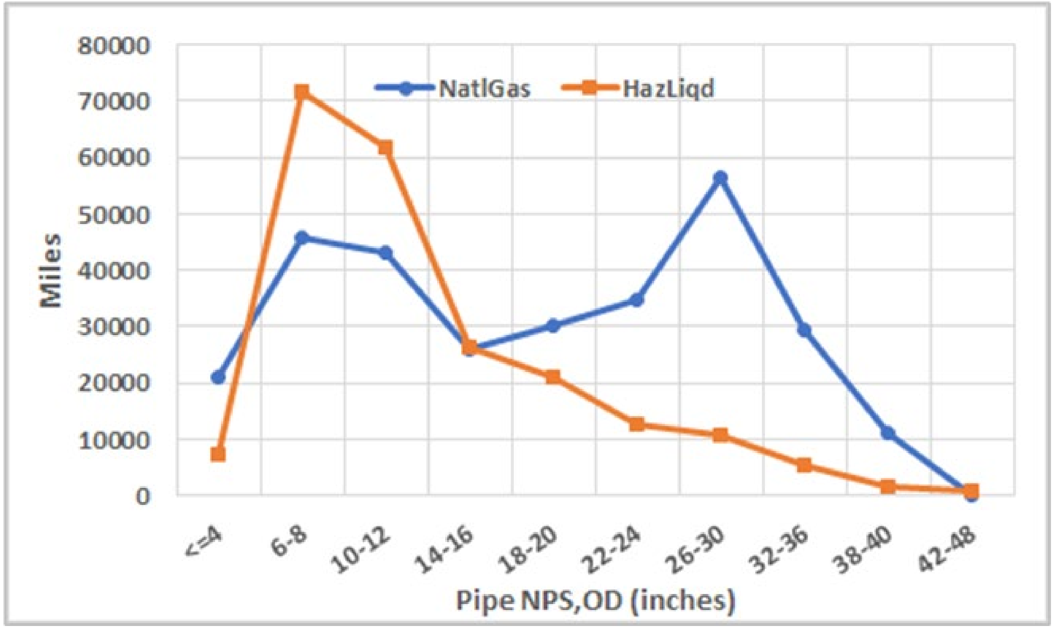
Why mostly large OD gas lines, not liquid lines?

Category	No. Incid.	% Incid.
Natural gas	83	94.3%
Size <=16" / >16"	*1 / 82*	--
Hazardous liquids	5	5.7%
Size <=16" / >16"	*2 / 3*	--



- **HL sizes biased toward pipe NPS 8"-12", mostly ERW**
- **NG size distribution is bimodal:**
  - NPS 6-12 ERW but fewer miles than HL
  - 24-36" OD, SAW, FW, YS&T ERW, 2-3X mileage as HL
- **Hydraulic gradient effects**
  - Larger gradient in HL
  - NG lines operate at 40% higher length averaged hoop stress (18% SMYS) than HL

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High susceptibility to hard spots in pipe

Category	Justification
Manufactured 1944-1960	Era of high C-Mn content for YS, most observed incidents
Pipe > 16”OD manufactured from discrete plate (SAW, FW, YS&T ERW)	Plate rolling process susceptible to accidental quenches, most observed incidents
Pipe in above categories manufactured by • < 1960 Bethlehem • < 1960 AO Smith • < 1960 Youngstown • “Unknown”, any year	Observed incident rate

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Low susceptibility to hard spots in pipe

Category	Justification
SMLS, LW	Hot finished, mild steel composition, low incident rate
Most ERW	Continuous skelp has limited opportunities for accidental quench, warm coil is self-tempering, low incident rate
Pipe manufactured after 1970	Trend toward lean C composition, low incident rate
FBE, XPE factory coating	Resists disbondment, less likely to be exposed to H from corrosion, low incident rate, XPE shields pipe from CP

2. Susceptibility to hard spots failing

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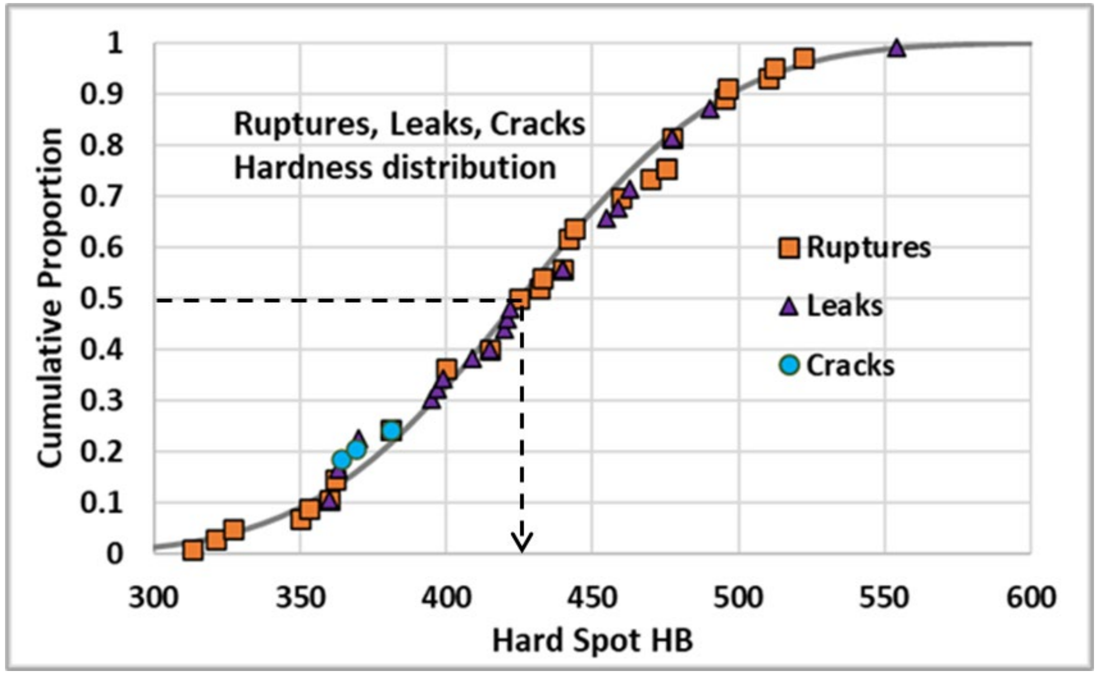
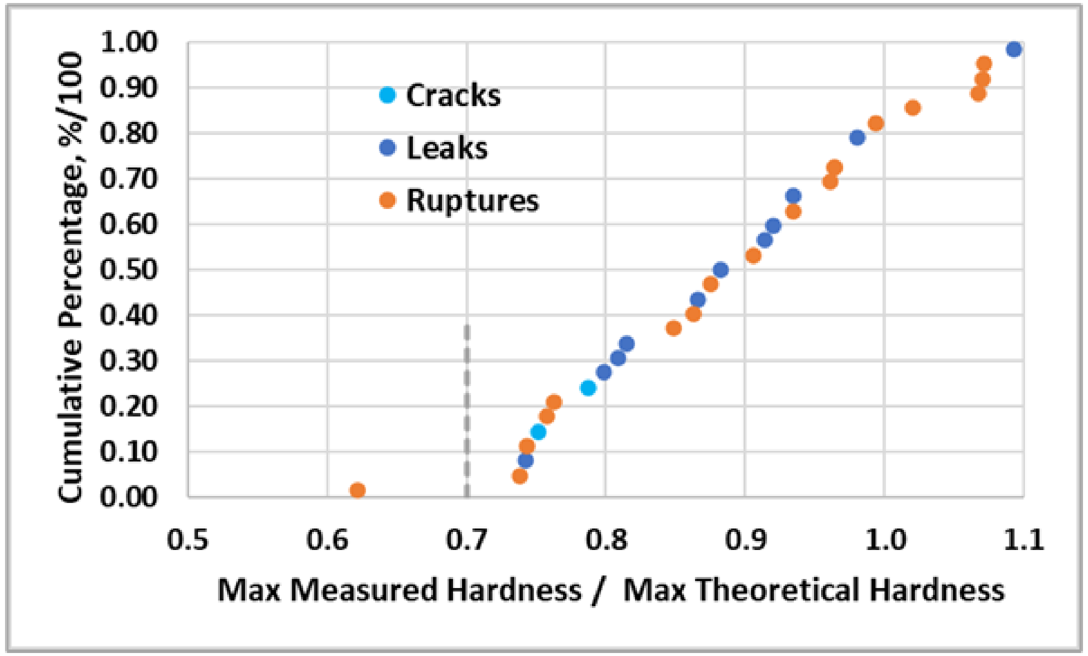
Influence of hardness level

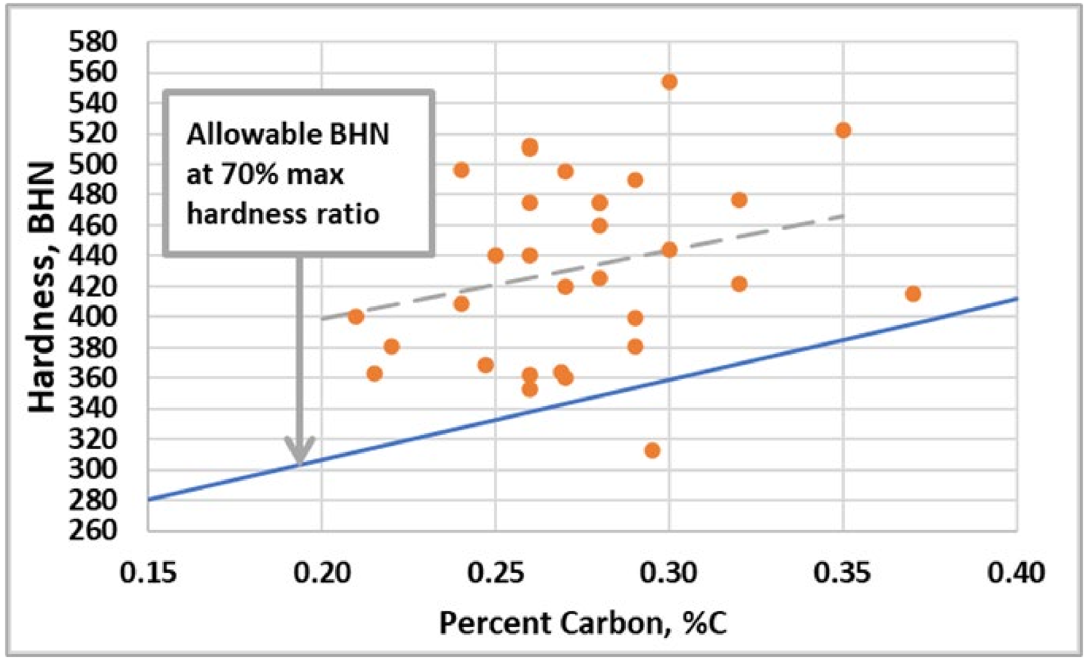


- 50th pct hardness in failures = 425 BHN
- 5th pct hardness in failures = 325 BHN

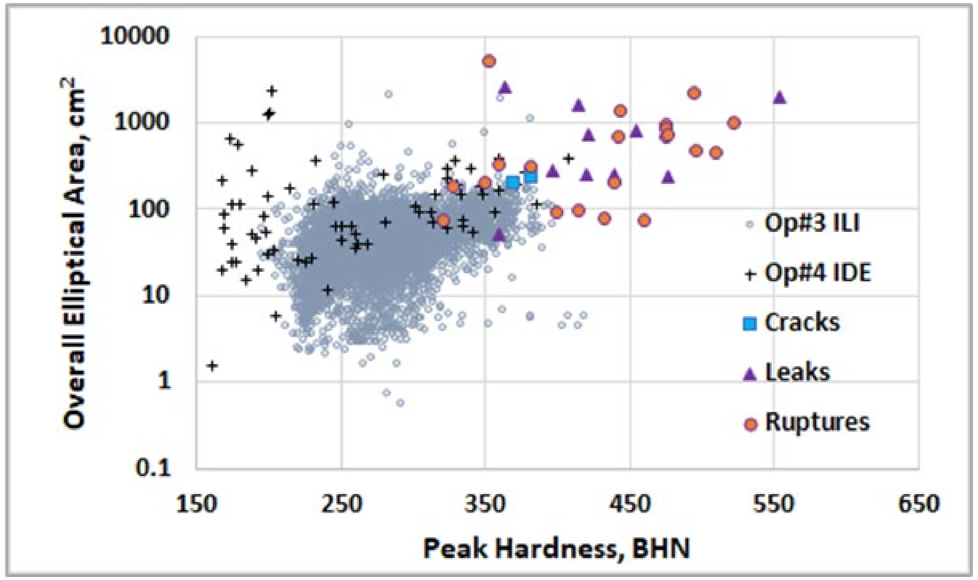
The meaning of hardness differs by %C

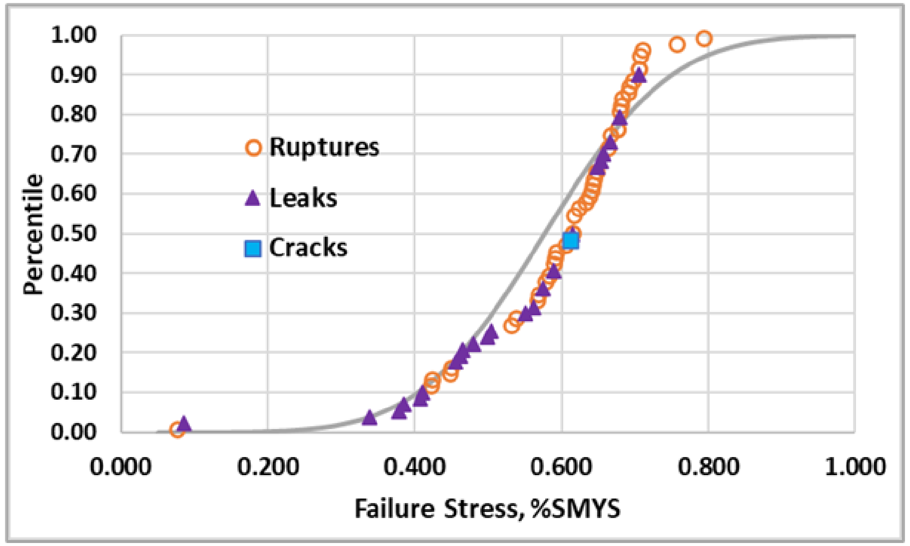
- **Max theoretical hardness is a function of %C:**
  - $BHN_{MAX} = 747.9 \times \%C + 288.7$
- **Only 1 incident (outlier) at BHN < 70% BHN_{MAX}**
  - $BHN_{Allow} = 0.7 \times BHN_{MAX} = 523.5 \times \%C + 202.1$
- **425 BHN means more in 0.23%C steel than 0.36%C steel**

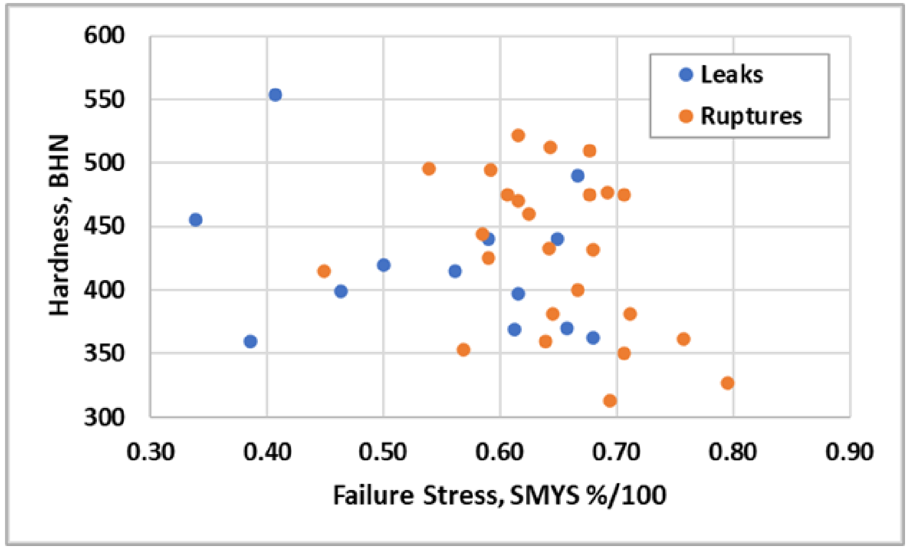




Influences of hard spot size & pipe stress



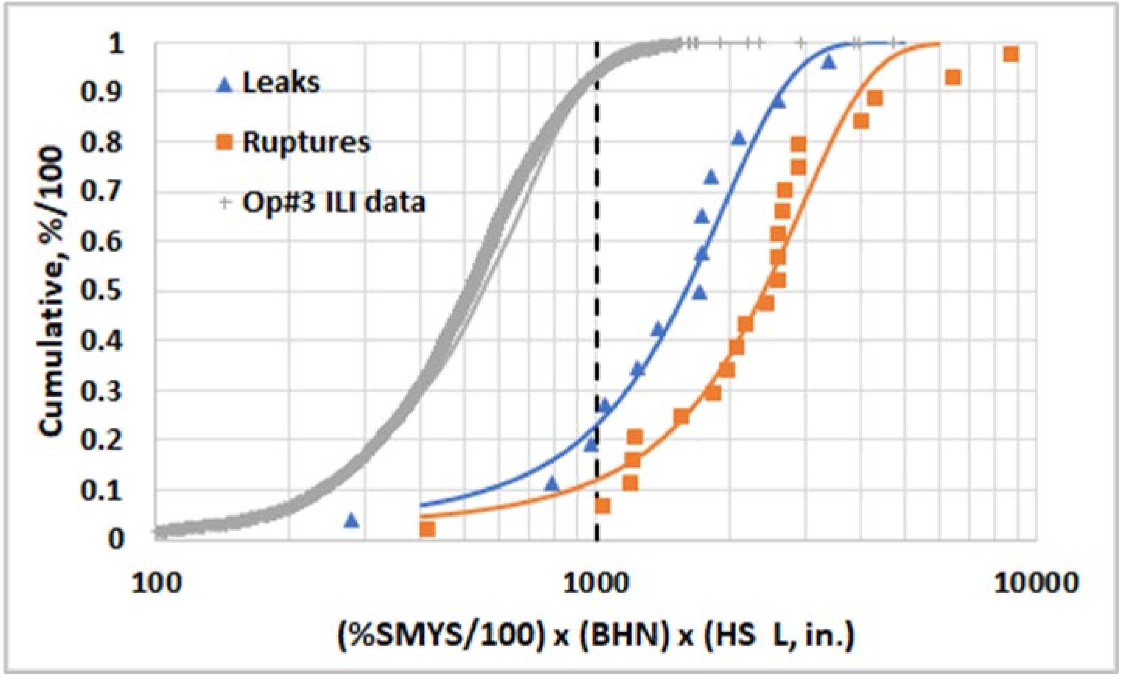


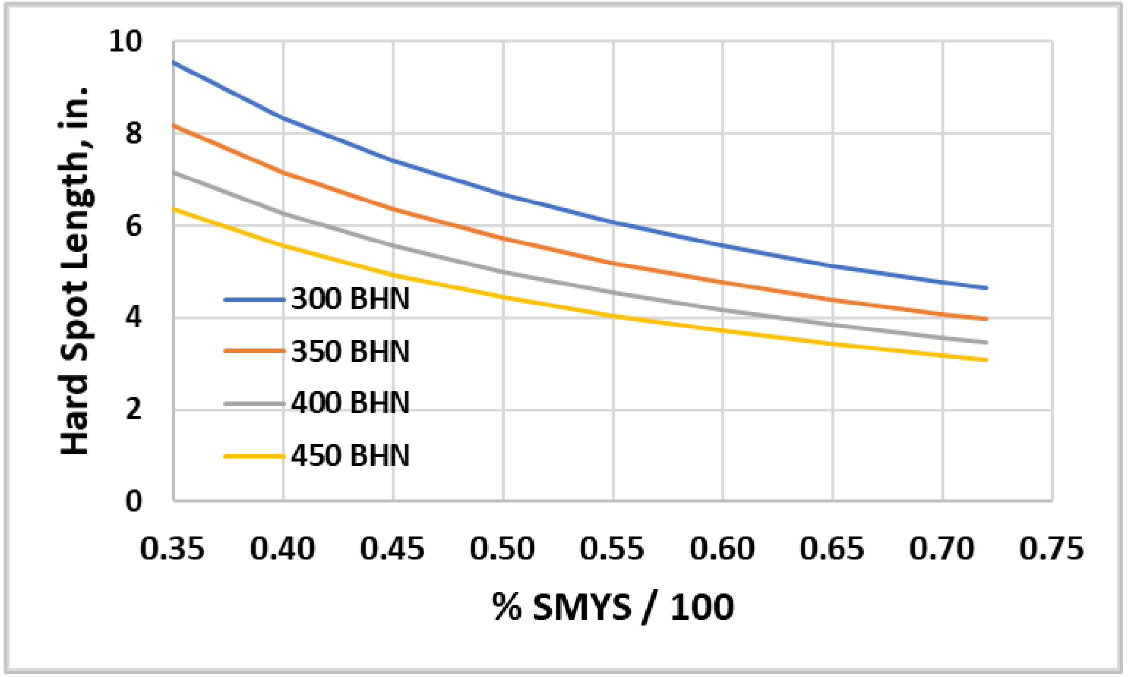


- Hardness correlates loosely with hard spot size (area) – but not predictive
- Mean failure stress ~60% SMYS, 90% were at stress > 40% SMYS
- Failure stress loosely correlates inversely with BHN

Combined influence of BHN, %SMYS, and HS size

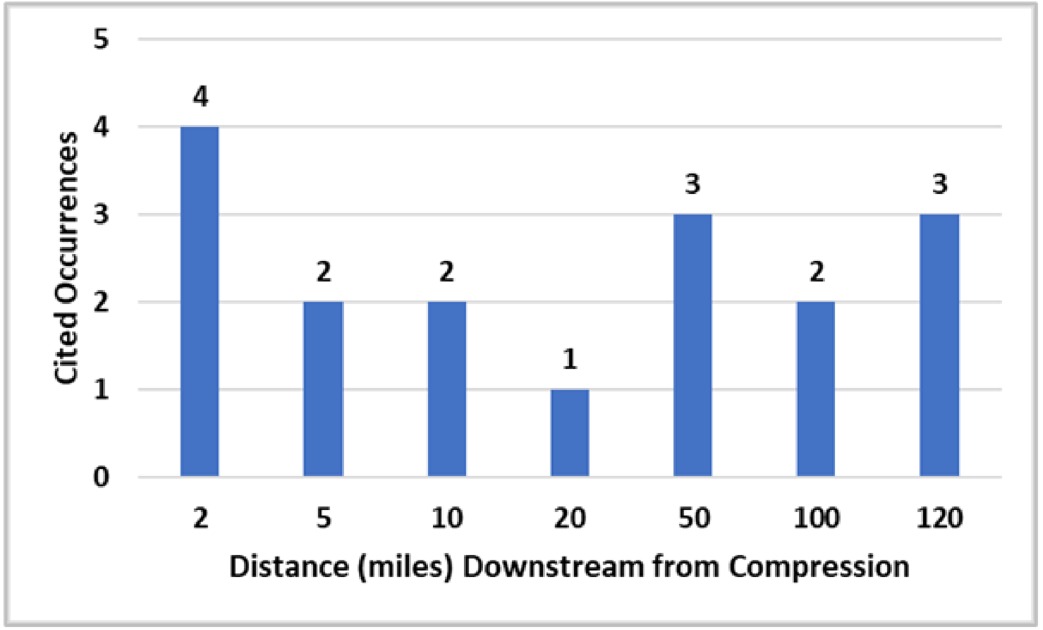
- **No single attribute governs, need to consider a combined effect:**
  - Hard spot severity index HSSI = (% SMYS) × (BHN) × (L [in.])
  - Requires no software or information about an existing crack, if any



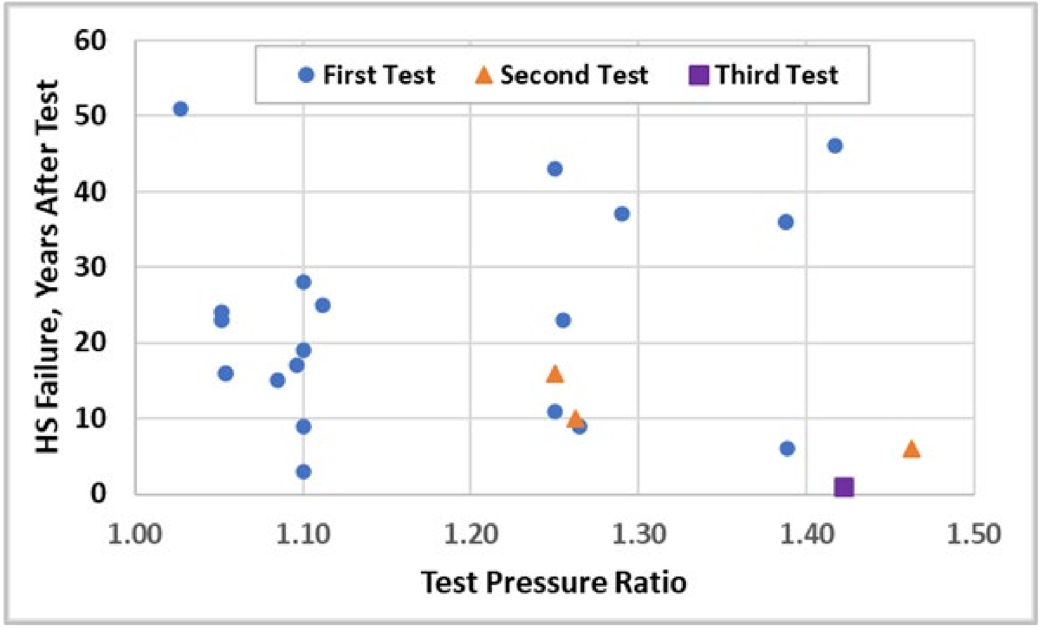


Other influences on susceptibility to HS failure

No trend with location downstream from compression



No trend with hydrotest level and time to failure



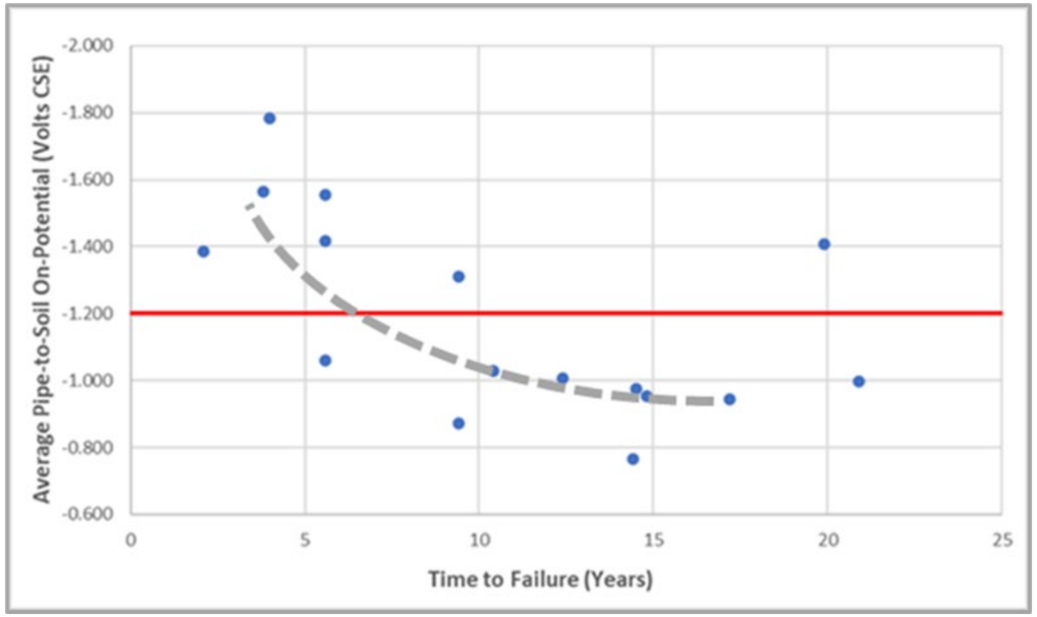
Sources of hydrogen

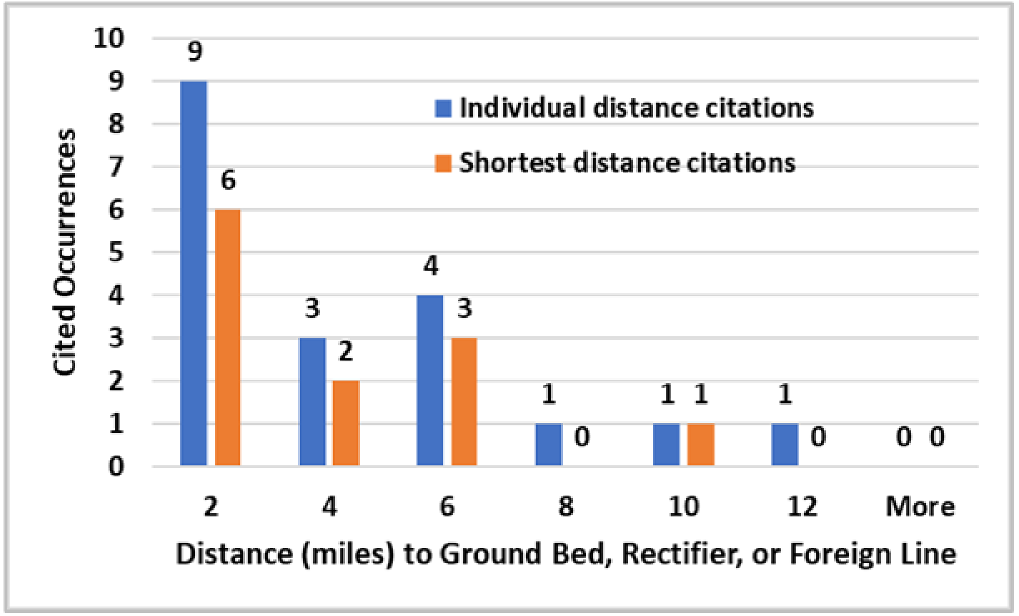
- Mode of cracking is a clue to the source of hydrogen:
  - 81% of 42 confirmed HSC → suggests CP or corrosion
  - 19% of 42 confirmed SCC → suggests corrosion

Metric	All met reports	Undet. or NR crack type	Known crack type	HSC	SCC
Incident count	51	9	42	34	8
Average BHN	425.2	426.3	422.0	427.8	397.4

CP as source of hydrogen

- Time to failure trends inversely with level of CP overprotection
- HSC failures trend inversely with proximity to source of CP current
- Proximity to CP can be a risk factor for prioritizing post-ILI response



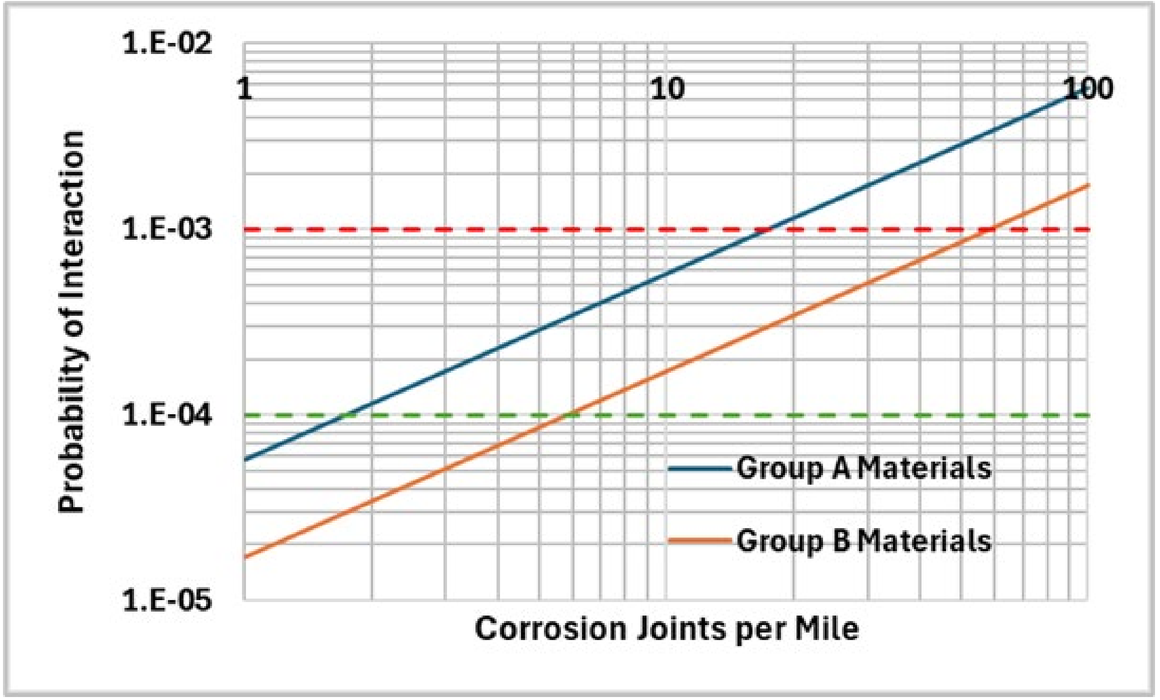


Garrity, K., PRCI REX-2023-060

Probability of corrosion interaction

Susceptibility to hydrogen from corrosion interacting with an unknown hard spot is implied by probability of corrosion coexisting with hard spots on *same joint of pipe*:

- Groups A and B materials based on high or low hard spot failure rates and ILI indications
- Interaction probability criteria:
  - >1e-3, >20/mile Group A, >50/mile Group B
  - <1e-4, <2/mile Group A, <5/mile Group B



Group A (high): <1960 AO Smith, Bethlehem, Welland, YS&T, and "Unknown" of any year

Group B (low): <1970 Kaiser, <1960 Republic, and all others (USS, Natl Tube, ConsWest, etc)

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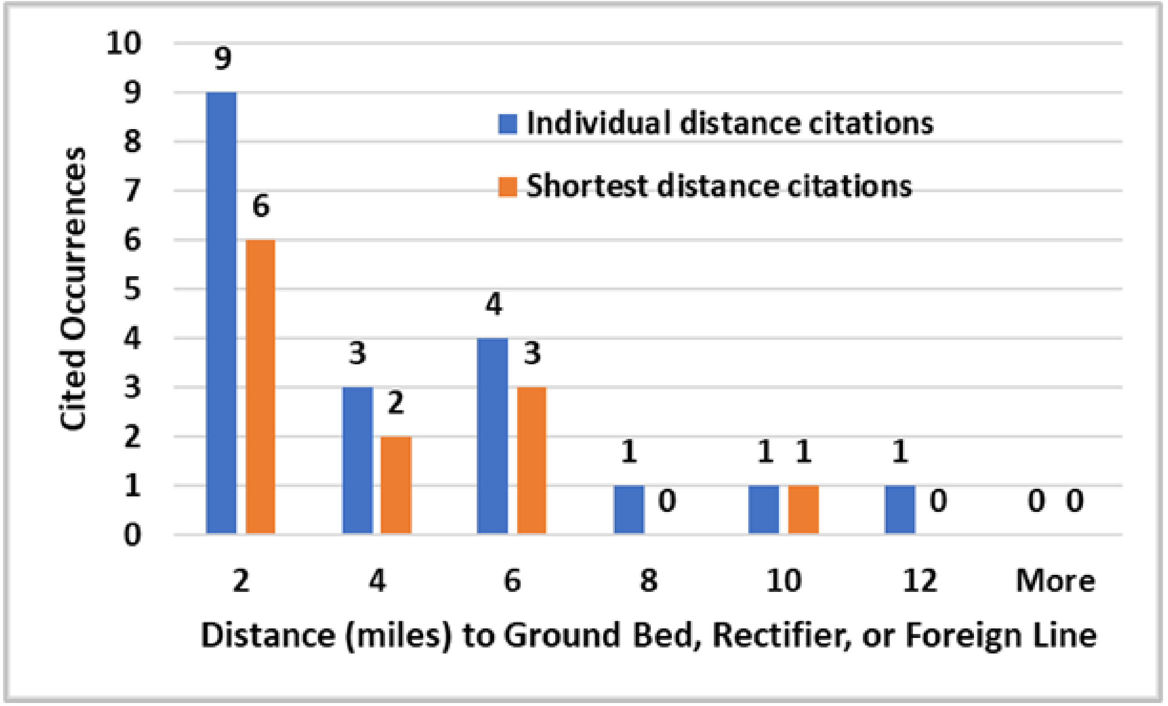
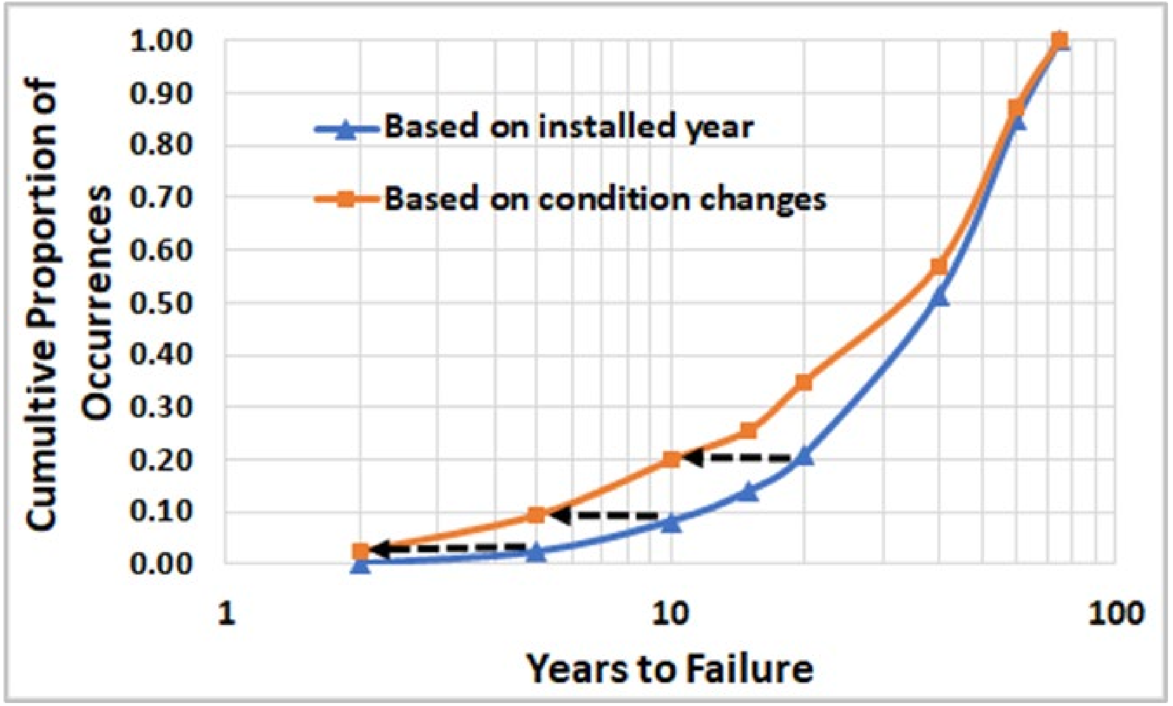
Changes in conditions

Evidence points to *changes in conditions* that introduce hydrogen as causal:

- Added anode ground beds, increased CP rectifier output, change in flow
- Reported changes accounted for shorter time to failure in 50% of incidents
- Time to failure reduced by half or 10 yrs (whichever was less)





Prioritizing baseline assessment

Risk Category	Incidents/Mile, 1e-3	Includes
High	> 1.50	< 1960 AOS, Bethlehem, Welland
Moderately high	1.0-1.50	< 1960 Youngstown, Unknown of any year
Moderate	0.5-1.0	<1970 Kaiser, <1960 Republic
Low	< 0.50	All others

- Threat level screening criterion considered *only what could be known before ILI*
- Focused on whether hard spots and cracks could be present and could fail
- Exceptions carved out for SMLS and non-YS&T ERW pipe, and FBE and XPE coatings

Threat Level	Percentile	Threat Score	Recommended Baseline ILI
Not a Threat	< 10th percentile	< 35	None
Low Threat	10th-50th percentile	35-47	Reevaluate threat in 10 years
Moderate Threat	50th-90th percentile	48-60	Plan ILI within 7 years
Meaningful Threat	> 90th percentile	> 60	Advanced response, see discussion

Other aspects

Managing hard spots can fit within an IM template:

- Considerations for response to ILI
  - Hard spot dimensions and BHN
  - Proximity to sites of CP overprotection or under-protection
  - Other risk factors
- Validation of ILI performance
  - Apply API 1163 or other sound statistical method
  - Be aware that *field NDE today cannot verify an indicated hard spot on ID surface*
- Need for reassessment
  - Prior assessment results and tool performance
  - Changes in tool capabilities
- Mitigations
  - How many and which indications to investigate over time
  - Managing CP – may be harder than just dig, examine, and repair hard spots
  - What is an appropriate repair?

thank you

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