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Review of Methods for Assessing the Remaining Strength of Corroded Pipe

PHMSA Public Meeting, Anomaly Assessment and Repair Workshop

October 22 2008

Introductions

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- Vinod Chauhan – Principal Consultant and Principal Investigator
- Clive Ward – Principal Consultant, Integrity Management
- Bryan Lethcoe – Director, Integrity Management

Background

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- Advantica led a group sponsored project in the late 1990's to develop an updated method for assessing the remaining strength of corroded pipe
- Funded by 8 operators and 2 regulators
- A large database of burst test results on pipe with simulated corrosion defects was generated
- Outcome of the work led to development of the method now called LPC (Line Pipe Corrosion)
- Method embodied in British Standard BS 7910 and DNV RP-F101

Background

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- Advantica currently conducting a project for PRCI and PHMSA aimed at removing known gaps in current assessment methods
- Project #153 addresses assessment of:
  - Corroded high strength pipe (up to grade X100)
  - Corroded low toughness pipe
  - Corroded pipe subject to cyclic pressure loading
  - Corroded pipe subject to combined internal pressure and external loading

Background

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- PHMSA sponsored research with Advantica to investigate performance of methods used by the pipeline industry to predict the failure pressure of corroded pipe
- Methods investigated were
  - ASME B31G
  - Modified ASME B31G
  - RSTRENG
  - LPC-1
  - SHELL92
  - PCORRC
- Results of the work described in Advantica Report 6781 Issue 5.0 – "A Review of Methods for Assessing the Remaining Strength of Corroded Pipelines"

Burst Test Database - Sources

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- Predicted failure pressures compared against a database of burst tests
- AGA/PRCI Database – used to validate ASME B31G and RSTRENG
- Advantica Database
  - Corrosion Group Sponsored Project led by Advantica [completed]
  - Research Projects for pipeline operators – includes tests on grade X80 and X100 pipe [ongoing]
- Public Domain
  - ASME IPC/OMAE Proceedings
  - Petrobras/Korean Gas Corporation/University of Waterloo

Burst Test Database - Test Selection

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- Primary focus was to concentrate on tests with **isolated**, **axially oriented** defects in pipe subject only to **internal pressure loading**
- Tests excluded from the database
  - Tests with pressure reversals
  - Tests with closely spaced interacting defects or coincident with seam/girth welds
  - Tests on pipe subject to internal pressure and axial/bending loads
  - Test results suspect, e.g. early tests on grade B pipe conducted by Battelle (contained in the AGA/PRCI Database)
- To summarize the following test results were used
  - Pipe with real and machined metal loss defects
  - Pipe with isolated defects
  - Pipe subjected only to internal pressure loading
  - Vessel and Ring Expansion tests

Test Database - Overview

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- 313 test points listed in Appendix A of the report

INDEX	Source Reference	Grade	D/t	Defect Type	$\frac{L}{\sqrt{Dt}}$	$\frac{d}{t}$	$\frac{YS}{SMYS}$	$\frac{UTS}{SMTS}$	$\frac{YS}{UTS}$	Failure Mode	Failure Pressure (psi)
INDEX 1	PRCI-001	X52	78.5	Real	0.738	0.382	1.129	1.153	0.771	L	1623
INDEX 2	PRCI-002	X52	78.5	Real	0.665	0.382	1.129	1.153	0.771	L	1620
INDEX 3	PRCI-003	X52	78.5	Real	1.255	0.411	1.129	1.153	0.771	R	1700
INDEX 4	PRCI-004	X52	80.0	Real	1.640	0.640	1.227	1.221	0.792	R	1670
INDEX 5	PRCI-005	X52	78.9	Real	1.407	0.550	1.131	1.141	0.781	R	1525
INDEX 6	PRCI-006	B	63.7	Real	0.997	0.719	1.157	1.100	0.614	L	1100
INDEX 7	PRCI-007	B	63.7	Real	1.579	0.666	1.157	1.100	0.614	L	1165
INDEX 8	PRCI-008	B	63.7	Real	1.745	0.666	1.157	1.100	0.614	R	1220
INDEX 9	PRCI-009	B	64.9	Real	0.587	0.705	1.194	1.098	0.634	L	1040
INDEX 10	PRCI-010	B	64.0	Real	1.417	0.752	1.194	1.098	0.634	L	1165
INDEX 11	PRCI-011	B	65.8	Real	0.676	0.715	1.194	1.098	0.634	L	1020
INDEX 12	PRCI-012	B	65.8	Real	0.760	0.600	1.194	1.098	0.634	L	1215
INDEX 13	PRCI-013	B	65.8	Real	0.845	0.630	1.194	1.098	0.634	L	1320
INDEX 14	PRCI-014	B	65.8	Real	0.929	0.715	1.194	1.098	0.634	L	1320
INDEX 15	PRCI-015	B	63.2	Real	1.242	0.661	1.194	1.098	0.634	L	1335
INDEX 16	PRCI-016	B	64.9	Real	0.671	0.508	1.194	1.098	0.634	L	1350
INDEX 17	PRCI-017	B	64.9	Real	1.007	0.649	1.194	1.098	0.634	L	1375
INDEX 18	PRCI-018	B	64.0	Real	1.250	0.640	1.194	1.098	0.634	L	1438
INDEX 19	PRCI-019	B	65.8	Real	0.591	0.715	1.194	1.098	0.634	L	1450
INDEX 20	PRCI-020	B	64.0	Real	0.750	0.669	1.194	1.098	0.634	L	1200
INDEX 21	PRCI-021	B	64.0	Real	0.750	0.779	1.194	1.098	0.634	L	1490
INDEX 22	PRCI-022	B	64.0	Real	0.833	0.584	1.194	1.098	0.634	L	1520
INDEX 23	PRCI-023	B	64.0	Real	0.667	0.501	1.194	1.098	0.634	L	1520
INDEX 24	PRCI-024	B	64.0	Real	0.750	0.472	1.194	1.098	0.634	L	1520
INDEX 25	PRCI-025	B	64.0	Real	1.667	0.723	1.194	1.098	0.634	R	1510

Unique Number for each test

Data Source and Reference

Pipe Grade (API 5L)

Pipe Diameter / Wall Thickness

Real or Machined

Normalised Defect Length

Normalised Defect Depth

Recorded Failure Pressure

Leak or Rupture

Material Properties

Test Database – Material Grade Split

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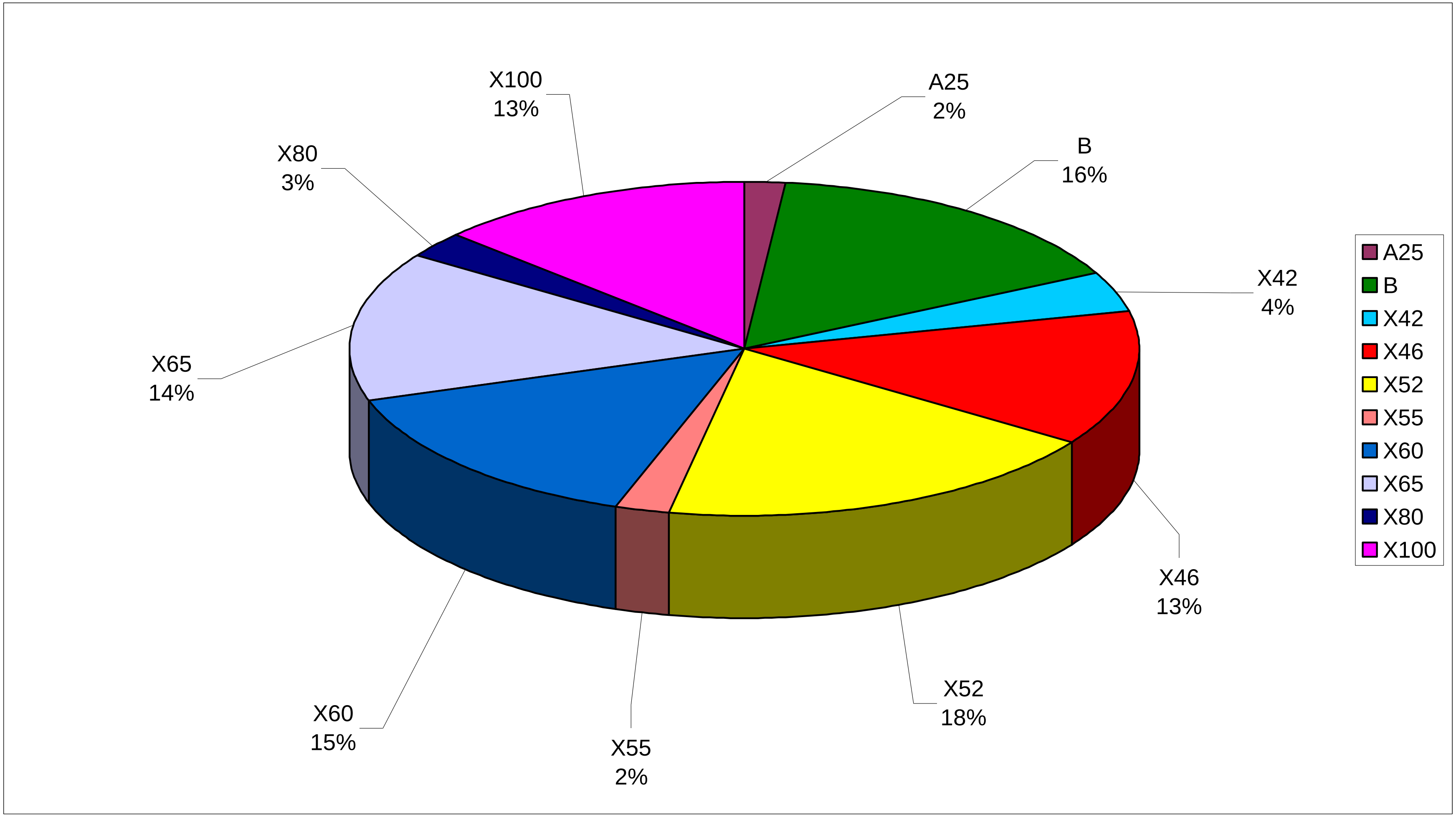
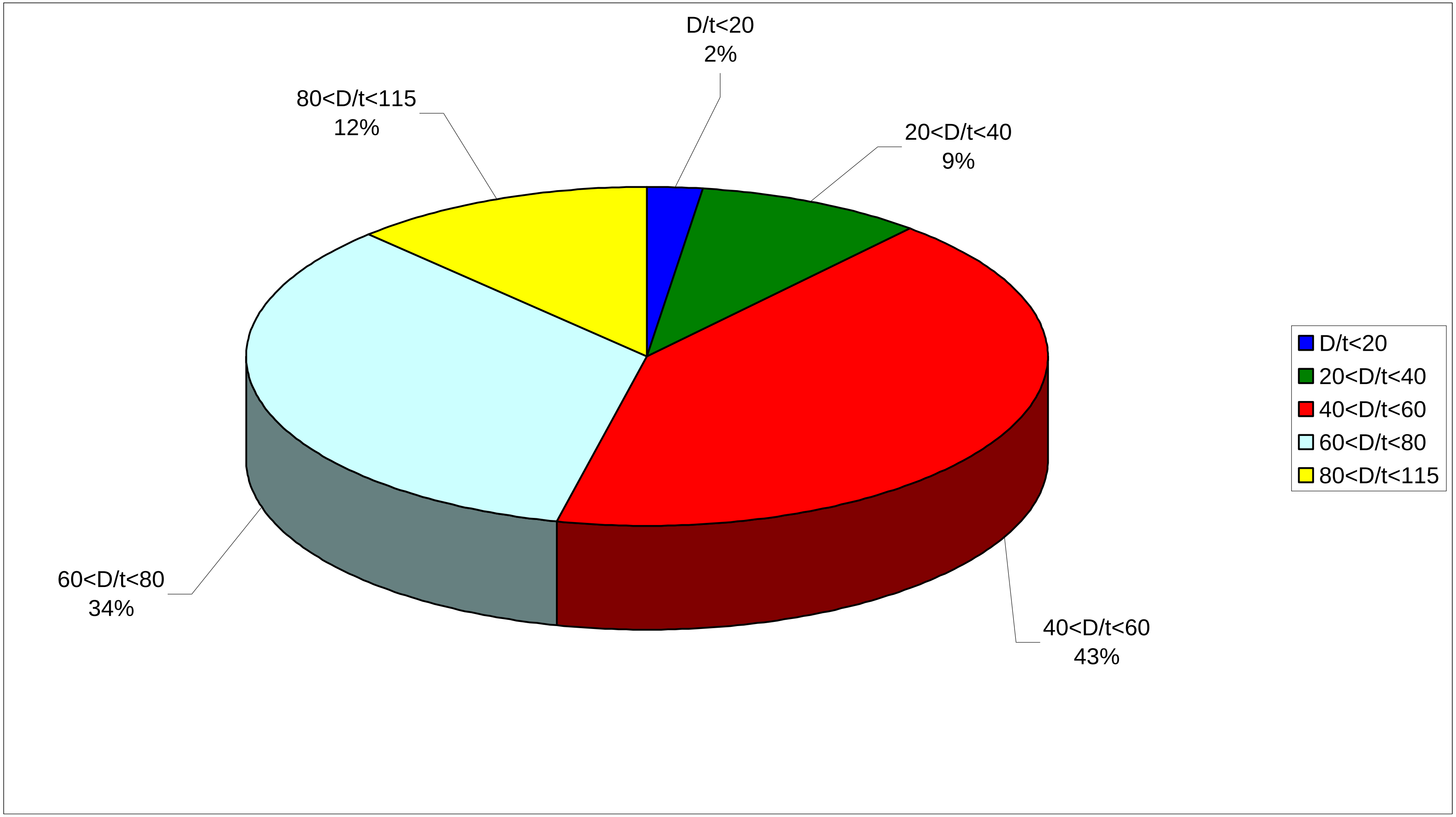


Test Database - Split by D/t Ratio



Test Database - Split by Defect Type

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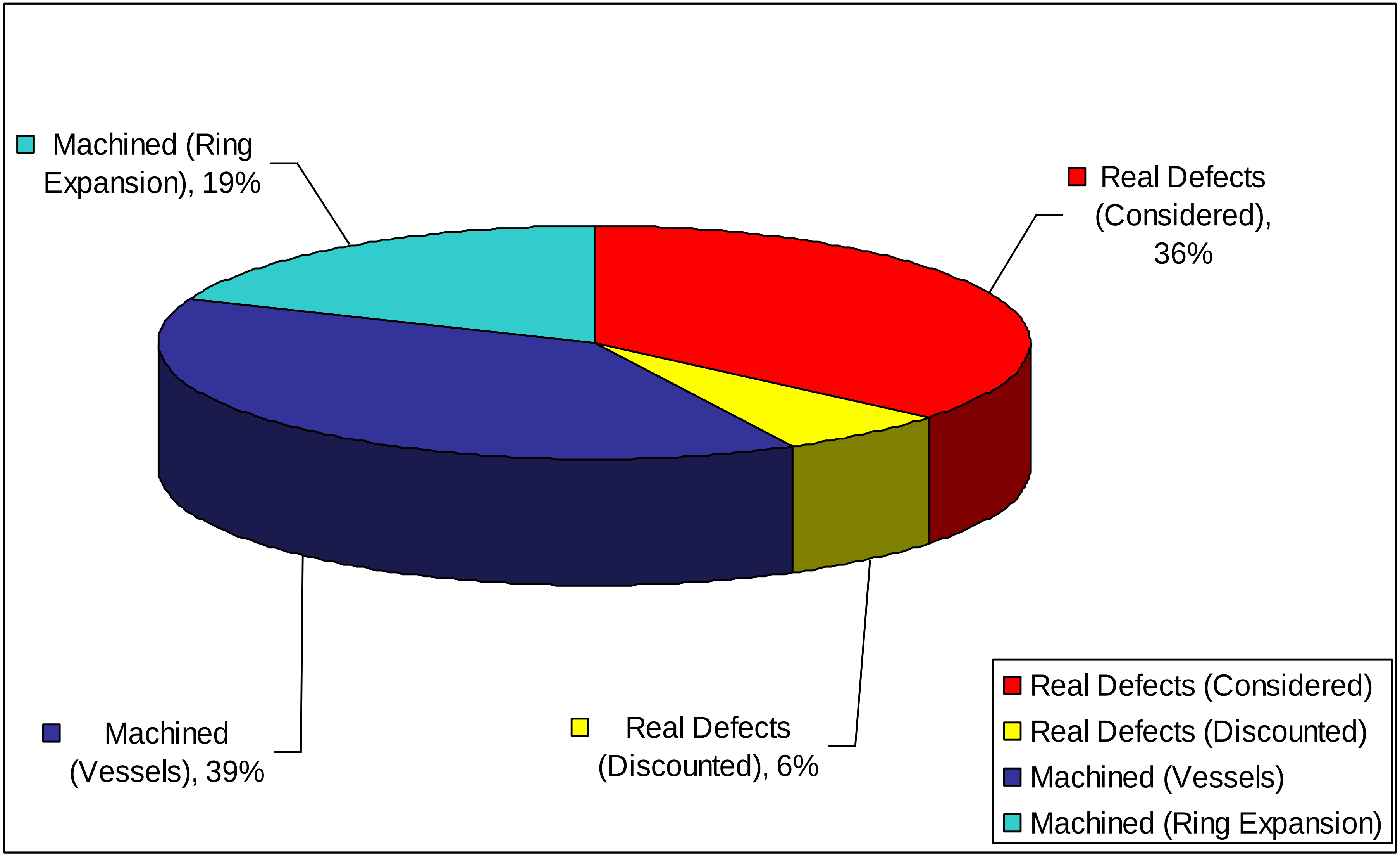

Test Database - Overview

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- 59 ring expansion tests
- 133 tests conducted on pipe with real corrosion defects
- 180 tests conducted on pipe with machined defects
- 79 recorded as leaks and 161 as ruptures (remainder not documented)

52-inch OD Grade X100 Vessel Test

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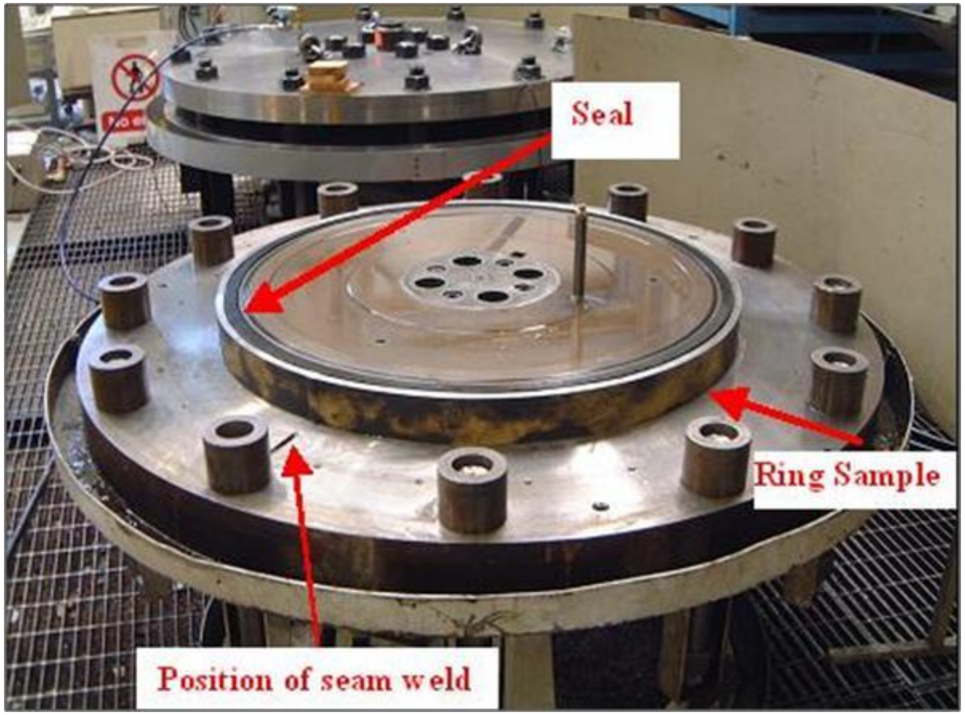
Fabricated Vessel with Machined Defect Located at Center of Vessel

Machined Axial Groove Defect

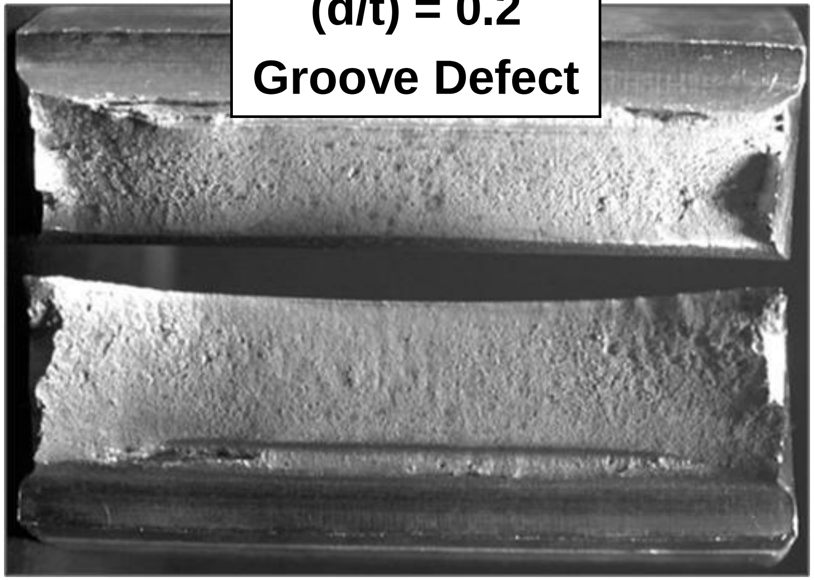
Vessel Rupture

Hydraulic Ring Expansion Test Set Up



Test Procedure Consistent with ASTM A370

Fracture Face
(d/t) = 0.2
Groove Defect



Seam Weld - 12 o’clock Position
Defect – 9 o’clock Position

Model Development

- ASME B31G developed by Battelle for PRCI/AGA NG-18 Project (1970's)
- Basic form of the toughness independent failure equation for axially orientated surface breaking defects

$$\sigma_f = \overline{\sigma}\left[\frac{1-\left(\frac{A}{A_o}\right)}{1-\frac{1}{M}\left(\frac{A}{A_o}\right)}\right]$$

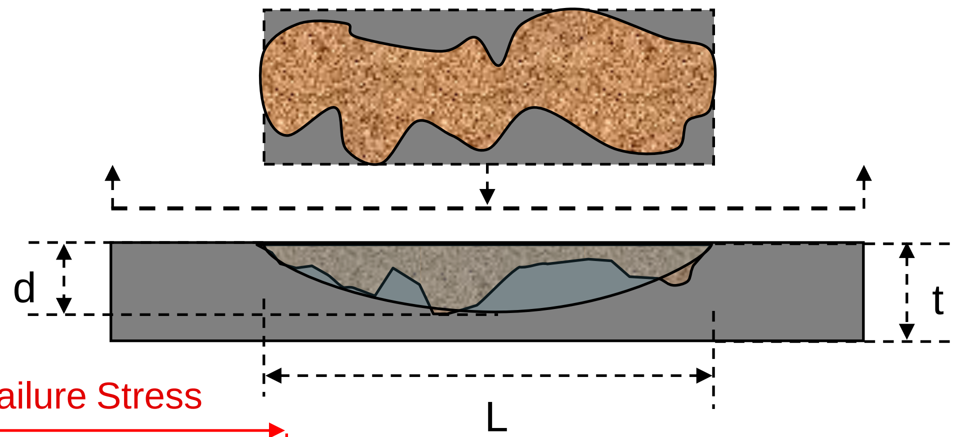
Failure Stress

Flow Stress

Ratio of the area of a part wall defect to a reference area

Folias (bulging) correction factor

ASME B31G



Failure Stress

Ratio of the area of a part wall defect to a reference area

Flow Stress

$$\frac{L}{\sqrt{Dt}} \le 4.479 \quad : \sigma_f = 1.1 * SMYS \left[\frac{1 - \left(\frac{A}{A_o} \right)}{1 - \frac{1}{M} \left(\frac{A}{A_o} \right)} \right]$$

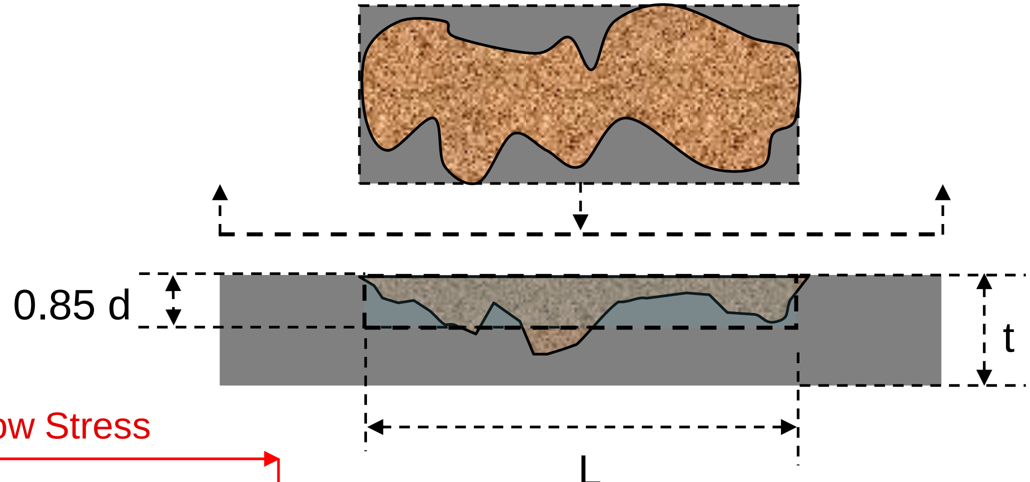
$$\frac{L}{\sqrt{Dt}} > 4.479 \quad : \sigma_f = 1.1 * SMYS \left[1 - \frac{d}{t} \right]$$

$$A = \frac{2}{3} L * d \qquad A_o = L * t$$

$$M = \sqrt{1 + 0.8 \left[\frac{L}{\sqrt{Dt}} \right]^2}$$

Folias (bulging) Factor

Modified ASME B31G



Ratio of the area of a part wall defect to a reference area

Flow Stress

Failure Stress

$$\sigma_f = \left(SMYS + 10{,}000\ psi\right)\left[\frac{1-\left(\frac{A}{A_o}\right)}{1-\frac{1}{M}\left(\frac{A}{A_o}\right)}\right]$$

$$A = 0.85\, L * d,\ \text{inch}^2 \qquad A_o = L * t,\ \text{inch}^2$$

$$\frac{L}{\sqrt{DT}} \le 7.071 : M = \sqrt{1 + 0.6275\left[\frac{L}{\sqrt{DT}}\right]^2 - 0.003375\left[\frac{L}{\sqrt{DT}}\right]^4}$$

$$\frac{L}{\sqrt{DT}} \succ 7.071 : M = 3.3 + 0.032\left[\frac{L}{\sqrt{DT}}\right]^2$$

Folias (bulging) Factor

RSTRENG

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Flow Stress

Failure Stress

Ratio of the area of a part wall defect to a reference area

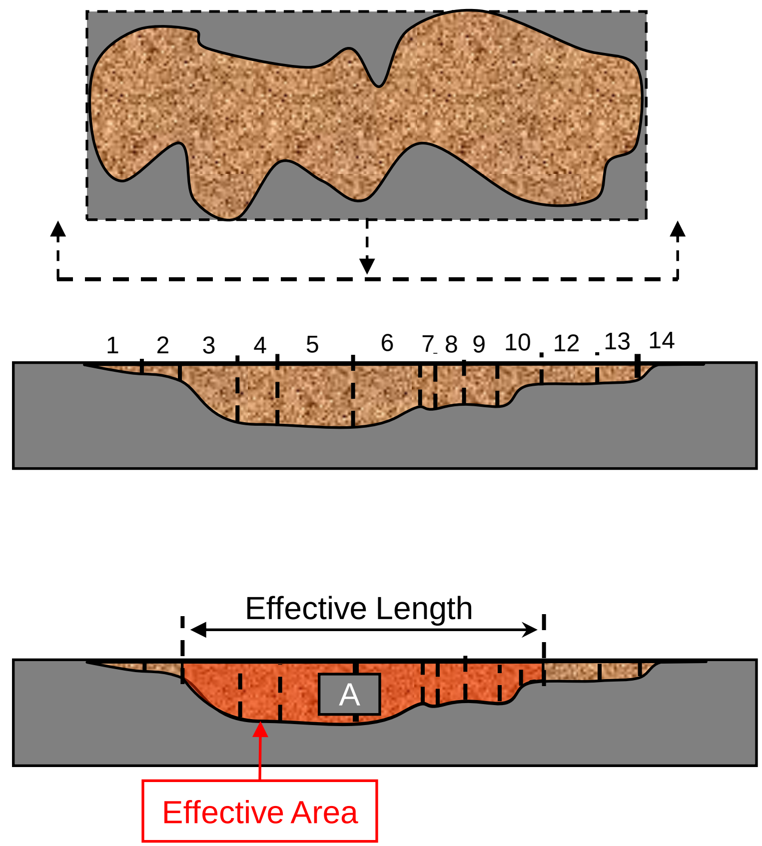
$$\sigma_f = (SMYS + 10{,}000psi)\left[\frac{1-\left(\frac{A}{A_o}\right)}{1-\frac{1}{M}\left(\frac{A}{A_o}\right)}\right]$$

$$A = L*d, \text{inch}^2 \qquad A_o = L*t, \text{inch}^2$$

$$\frac{L}{\sqrt{DT}} \le 7.071: M = \sqrt{1+0.6275\left[\frac{L}{\sqrt{DT}}\right]^2 - 0.003375\left[\frac{L}{\sqrt{DT}}\right]^4}$$

$$\frac{L}{\sqrt{DT}} > 7.071: M = 3.3+0.032\left[\frac{L}{\sqrt{DT}}\right]^2$$

Folias (bulging) Factor



Failure Pressure = Minimum Predicted Failure Pressure for all combinations of trapezoids

Defect Assessment Methods Studied

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Method	Origin of Basic Equation	Flow Stress, $\bar{\sigma}$, Definition	Defect Shape	Folias Factor (*M*)
NG-18	AGA NG-18 Toughness Independent Equation	σ_{SMYS}+10,000 psi	Rectangular	$\sqrt{1+0.6275\left(\frac{L}{\sqrt{Dt}}\right)^2-0.003375\left(\frac{L}{\sqrt{Dt}}\right)^4}$
ASME B31G	AGA NG-18 Toughness Independent Equation	1.1σ_{SMYS}	Parabolic (shape factor 0.67)	$\sqrt{1+0.8\left(\frac{L}{\sqrt{Dt}}\right)^2}$ for $\frac{L}{\sqrt{Dt}} \leq 4.479$
Modified ASME B31G	AGA NG-18 Toughness Independent Equation	σ_{SMYS}+10,000 psi	Arbitrary (shape factor 0.85)	$\sqrt{1+0.6275\left(\frac{L}{\sqrt{Dt}}\right)^2-0.003375\left(\frac{L}{\sqrt{Dt}}\right)^4}$ for $\frac{L}{\sqrt{Dt}} \leq 7.071$ $3.3+0.032\left(\frac{L}{\sqrt{Dt}}\right)^2$ for $\frac{L}{\sqrt{Dt}} > 7.071$
RSTRENG	AGA NG-18 Toughness Independent Equation	σ_{SMYS}+10,000 psi	Effective area and length (river bottom)	Consistent with Modified ASME B31G
LPC-1	AGA NG-18 Toughness Independent Equation	σ_{SMTS}	Rectangular	$\sqrt{1+0.31\left(\frac{L}{\sqrt{Dt}}\right)^2}$ for all defect lengths
SHELL92	AGA NG-18 Toughness Independent Equation	0.9σ_{SMTS}	Rectangular	$\sqrt{1+0.8\left(\frac{L}{\sqrt{Dt}}\right)^2}$ for all defect lengths
PCORRC	Battelle New Approach	σ_{SMTS}	Rectangular	Incorporated into PCORRC failure equation

Comparison of Methods

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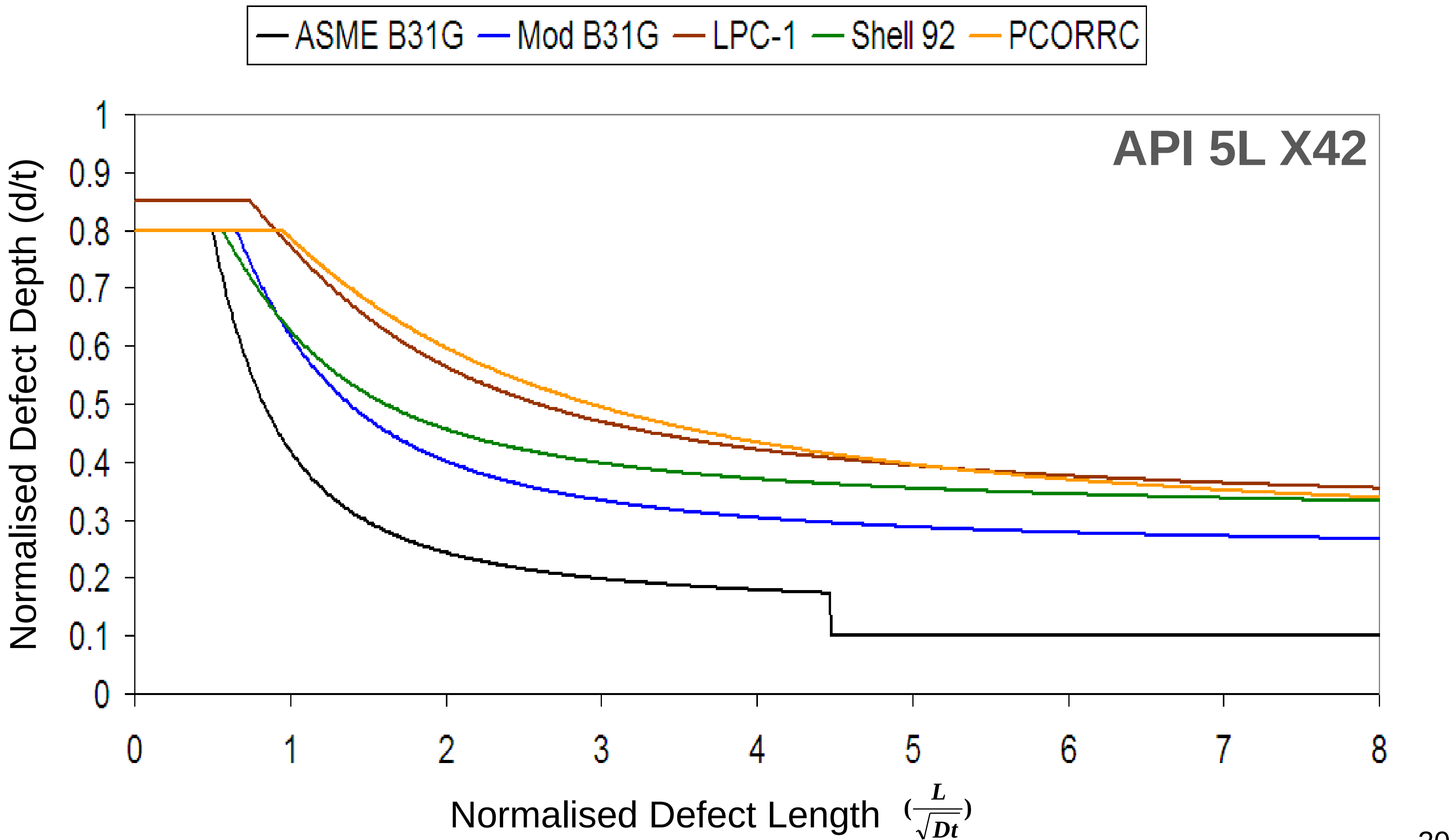

Sensitivity Studies

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- A number of studies were conducted to investigate the sensitivity of **predicted** failure pressure (P_f) to the **actual (recorded)** burst pressure (P_A)
- Sensitivity studies conducted by changing the flow stress for each assessment method

Case 1	Flow stress based on the recommendation given by each assessment method, but using actual material properties.
Case 2	Flow stress based on the recommendation given by each assessment method, using specified minimum material properties.
Case 3	Flow stress modified to equal the actual tensile strength of the pipe.
Case 4	Flow stress modified to equal the specified minimum tensile strength of the pipe.
Case 5	Flow stress modified to equal the mean of the actual yield strength and ultimate tensile strength.
Case 6	Flow stress modified to equal the mean of the specified minimum yield strength and ultimate tensile strength.

} Specified minimum material properties used in assessments

Case 1 – ASME B31G

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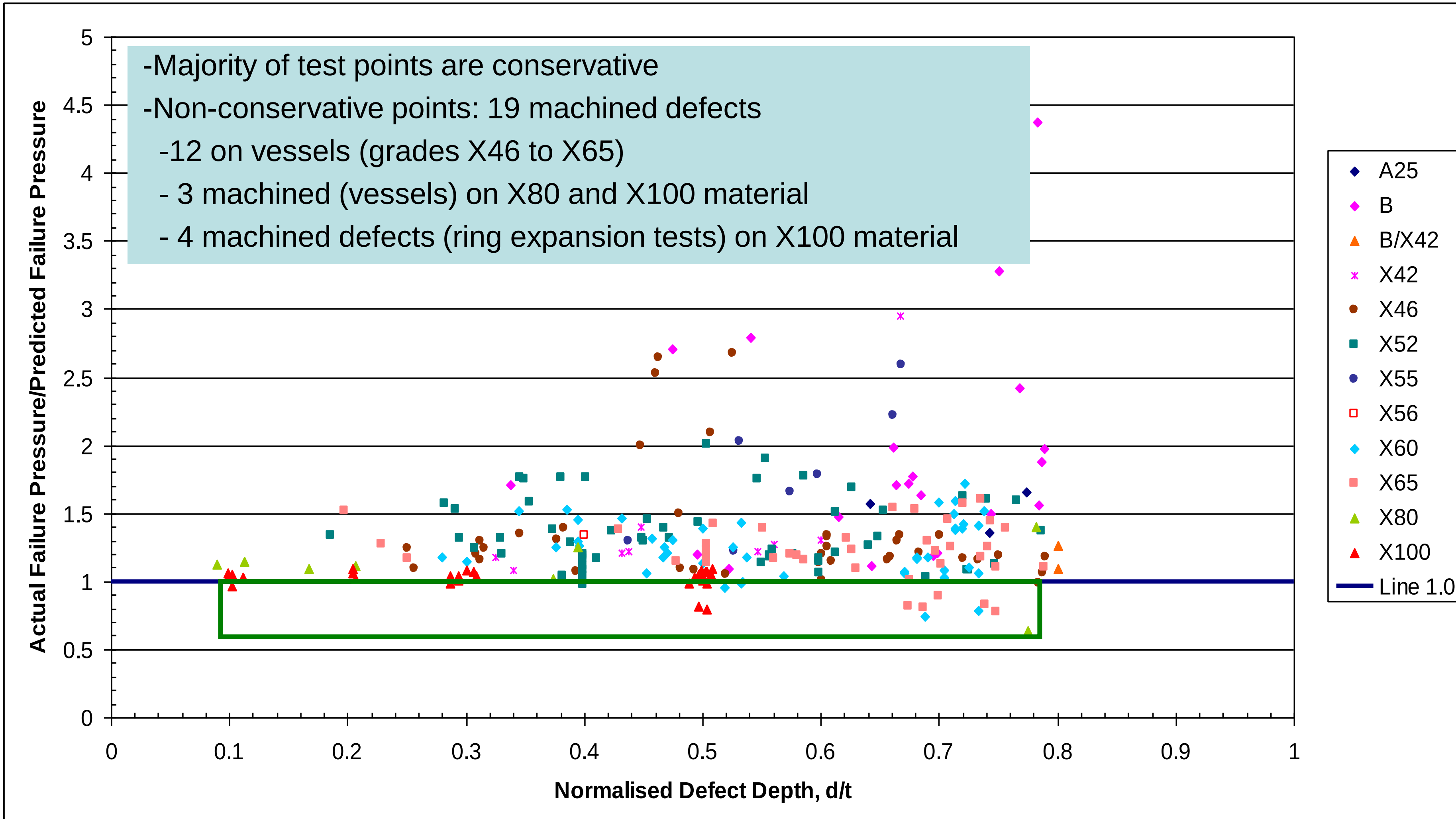
Case 1 – Actual Material Properties



Case 1 – Mod ASME B31G

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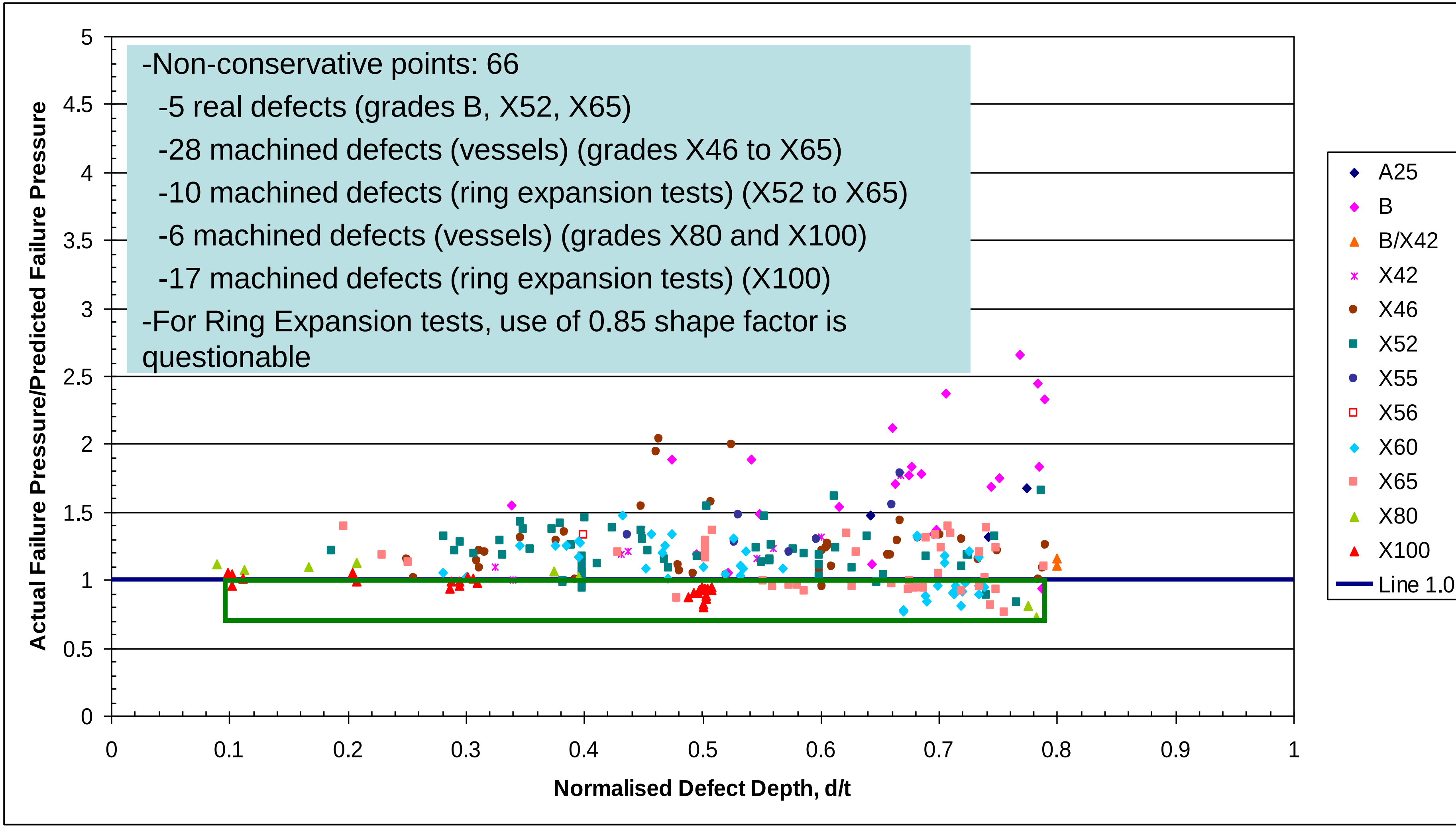
Case 1 – Actual Material Properties



Case 1 – RSTRENG

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Case 1 – Actual Material Properties

-Marked reduction in the scatter compared to ASME B31G and Mod ASME B31G

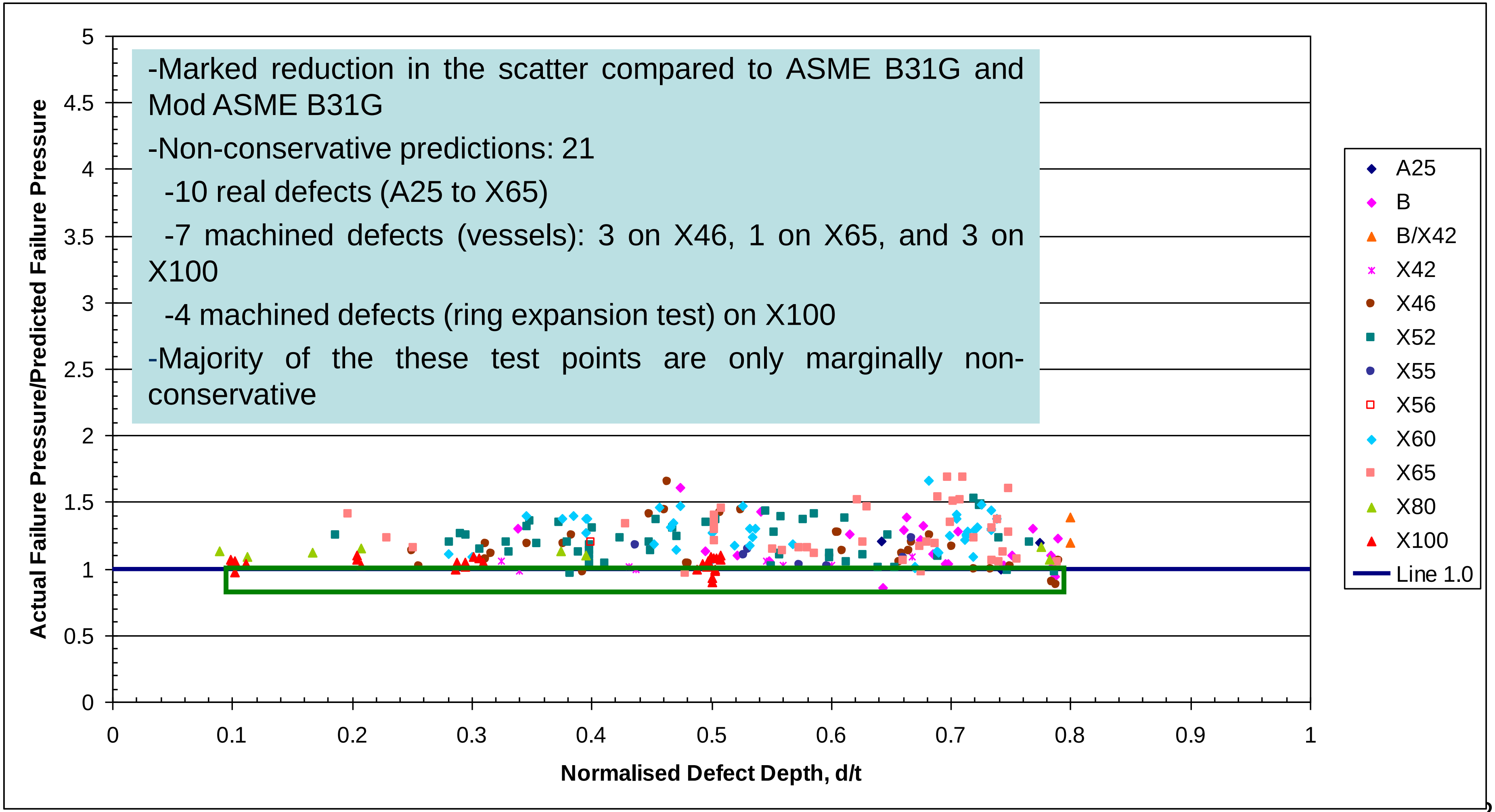
-Non-conservative predictions: 21

-10 real defects (A25 to X65)

-7 machined defects (vessels): 3 on X46, 1 on X65, and 3 on X100

-4 machined defects (ring expansion test) on X100

-Majority of the these test points are only marginally non-conservative



Case 1 – SHELL92

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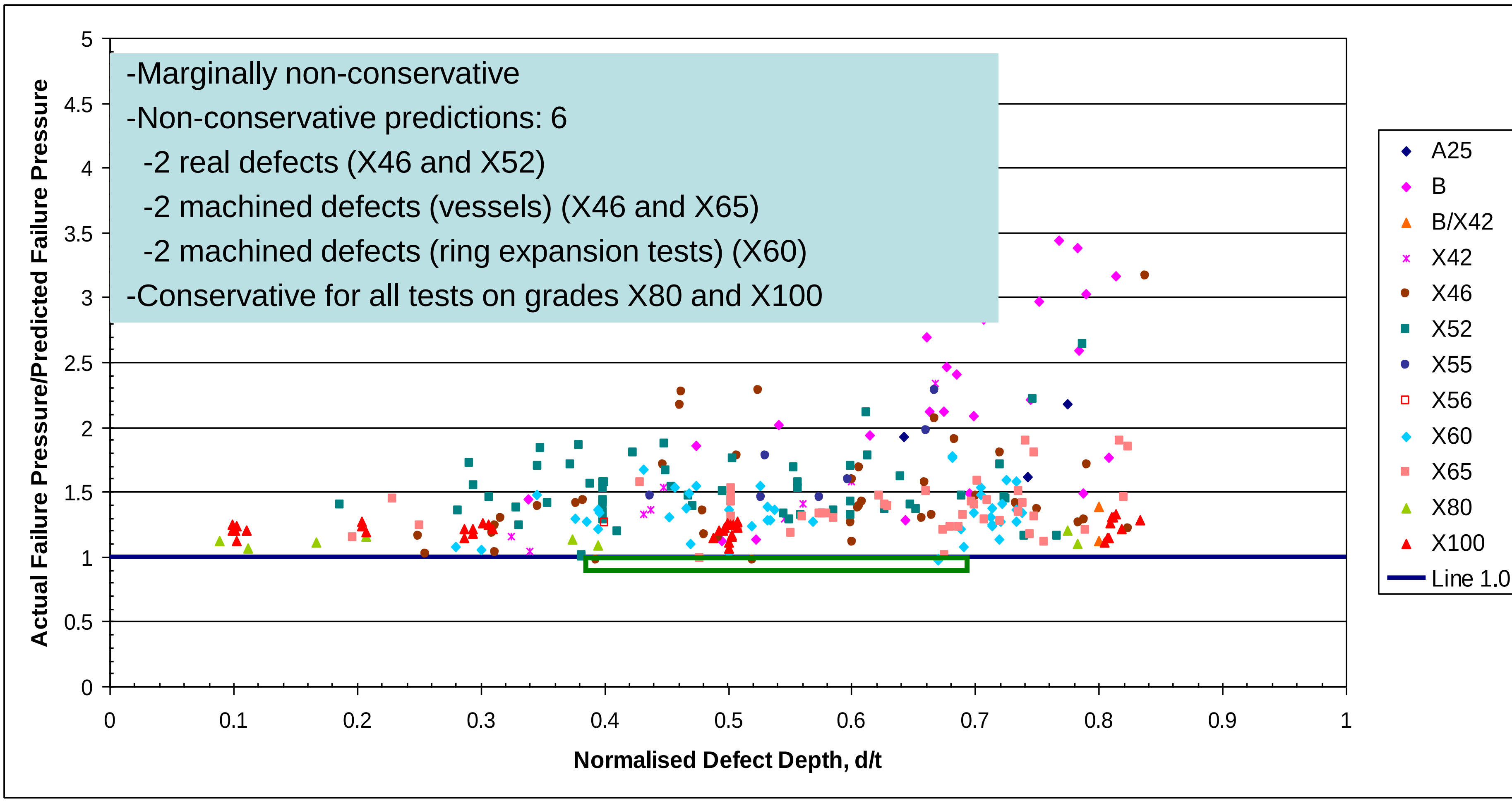
Case 1 – Actual Material Properties



Case 1 – LPC-1

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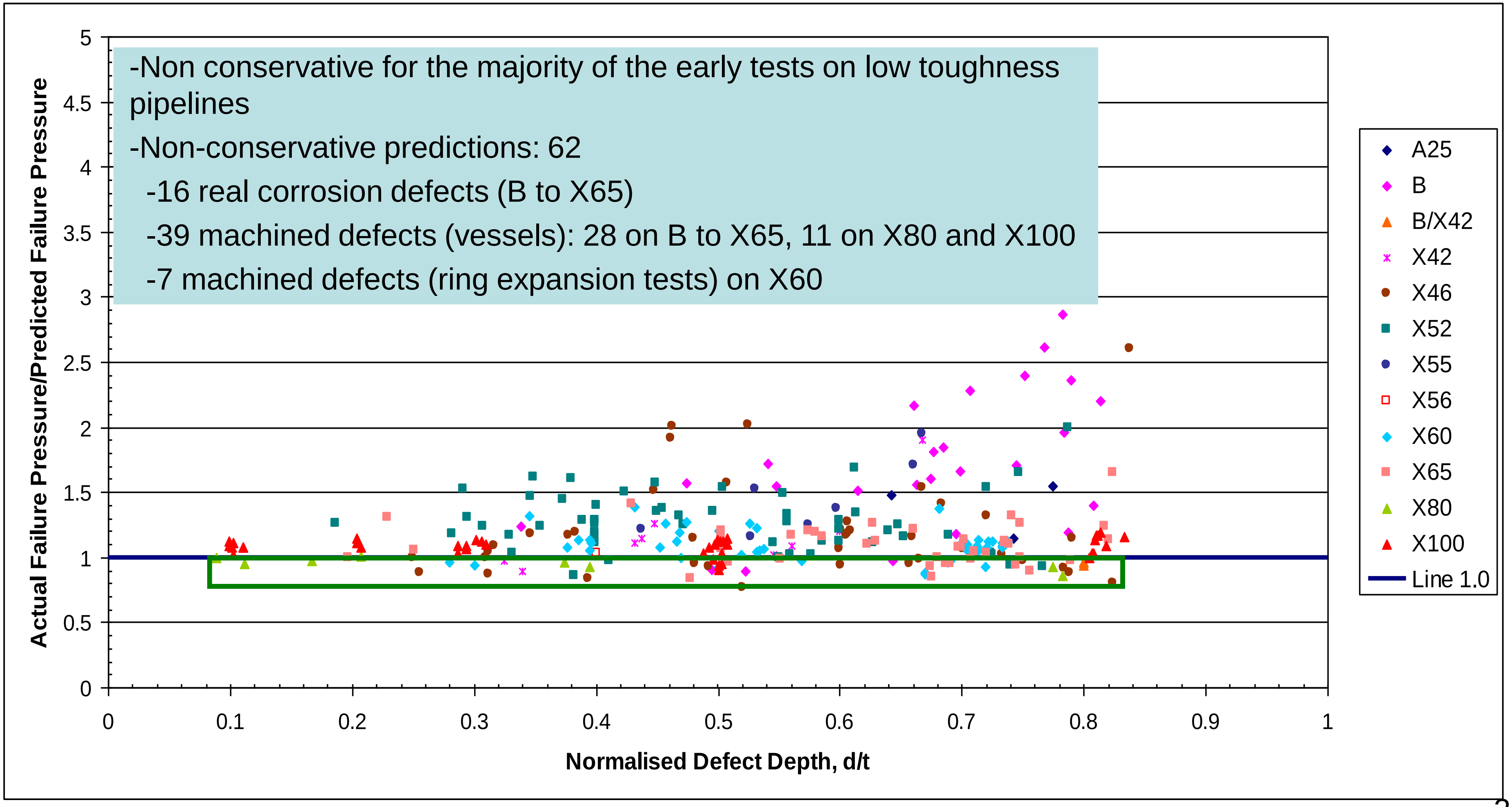
Case 1 – Actual Material Properties



Case 1 – PCORRC

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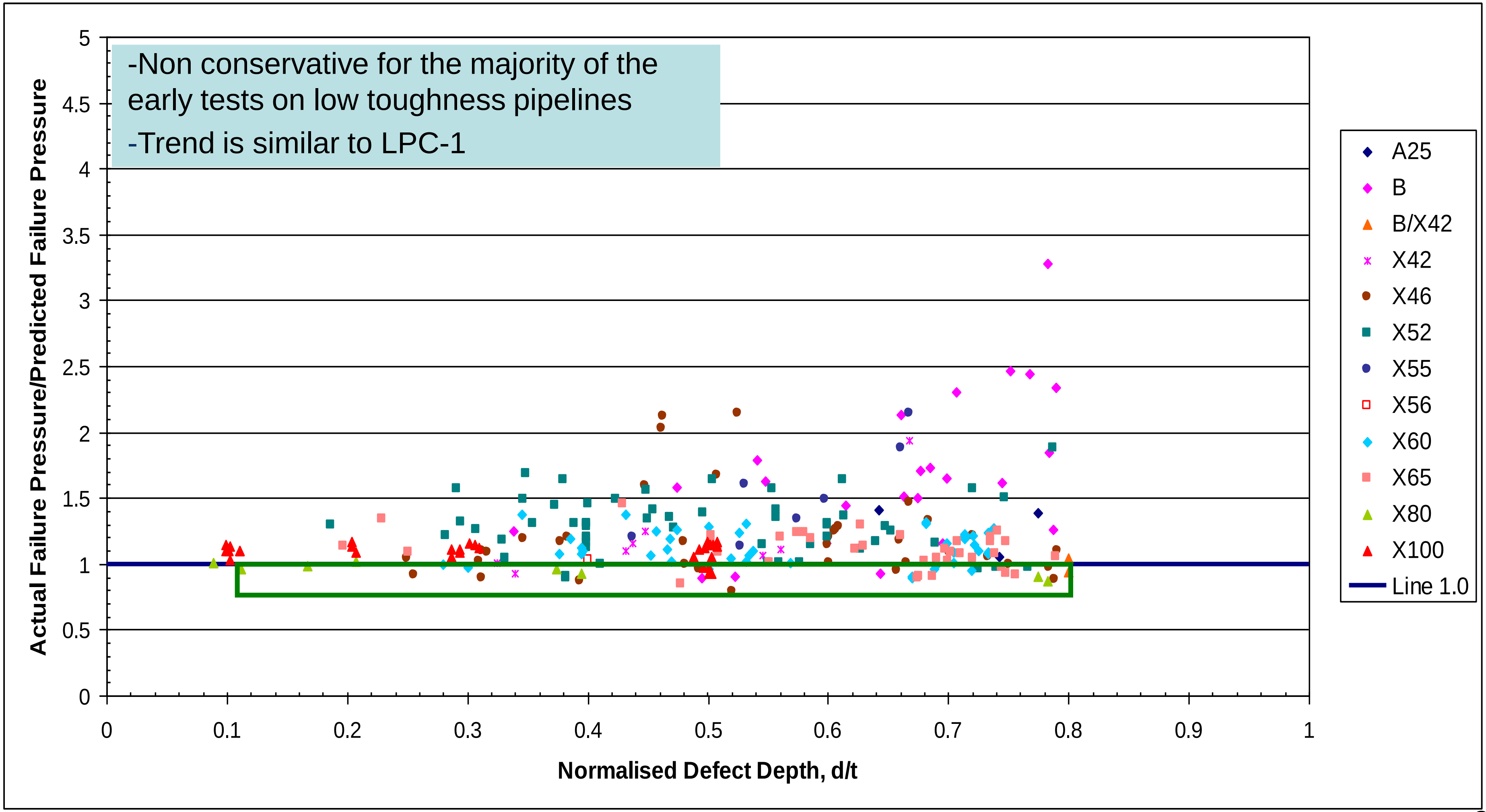
Case 1 – Actual Material Properties



Case 1 – ASME B31G

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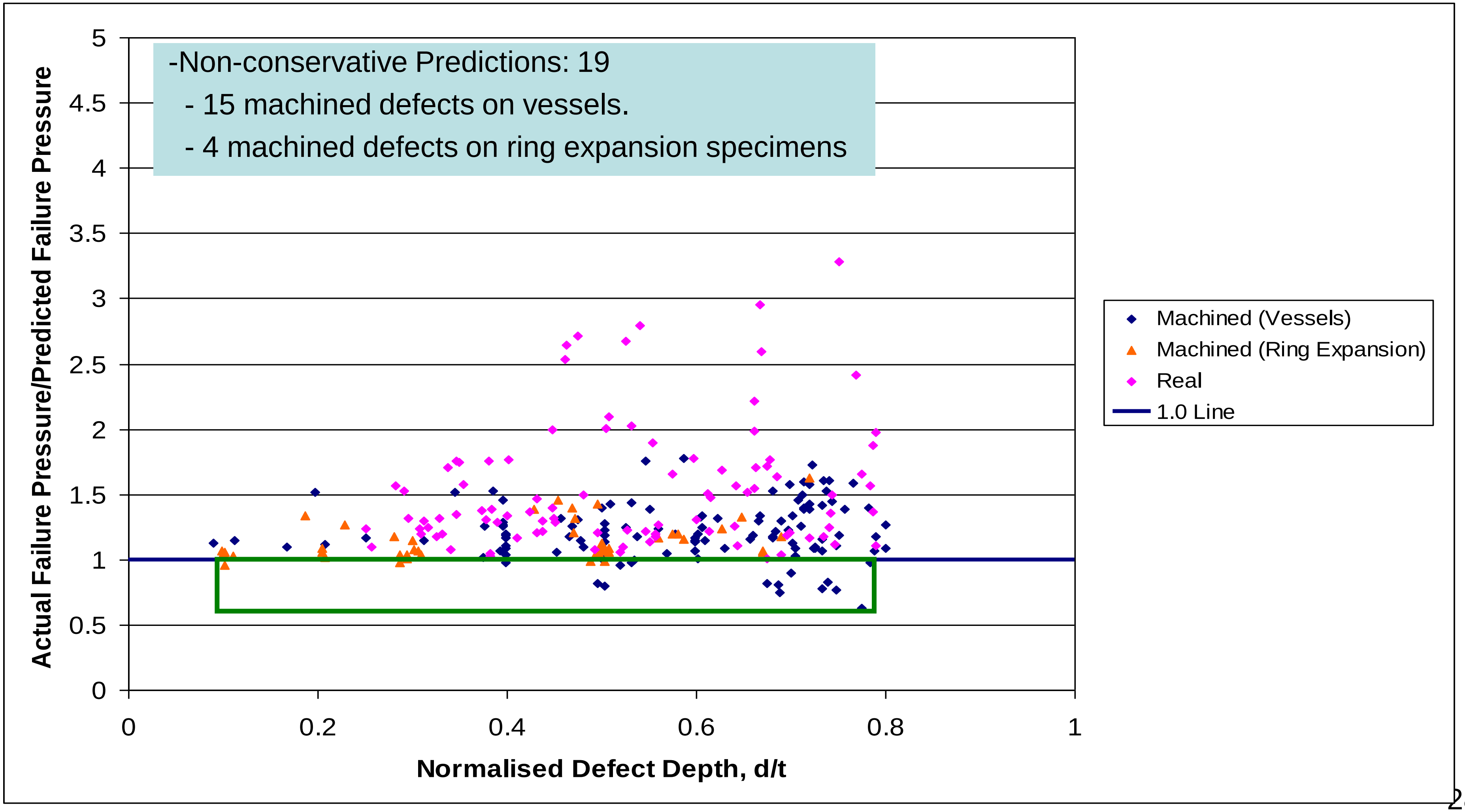
Machined vs. Real Corrosion Defects



Case 1 – Modified ASME B31G

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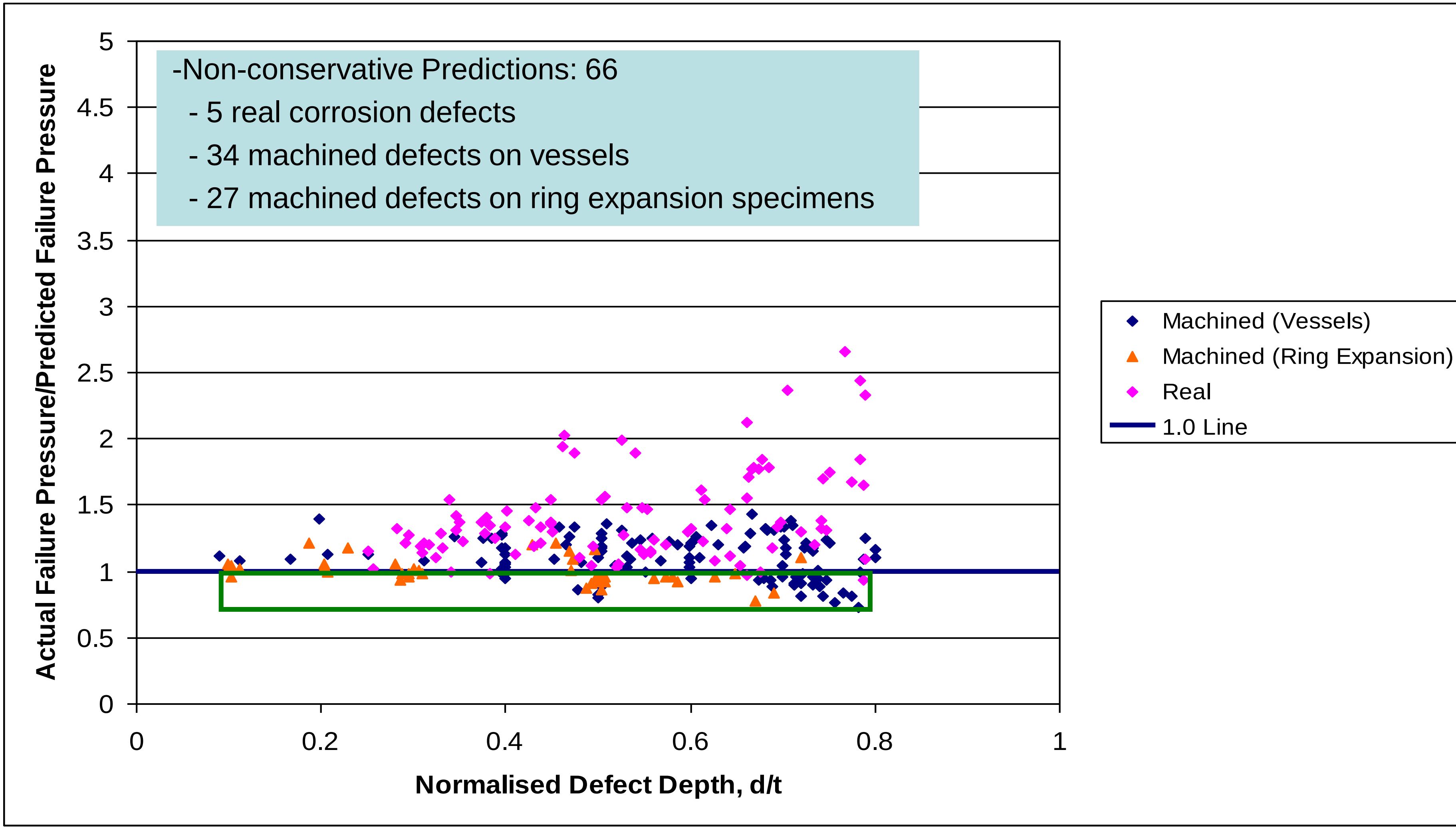
Machined vs. Real Corrosion Defects



Case 1 – RSTRENG

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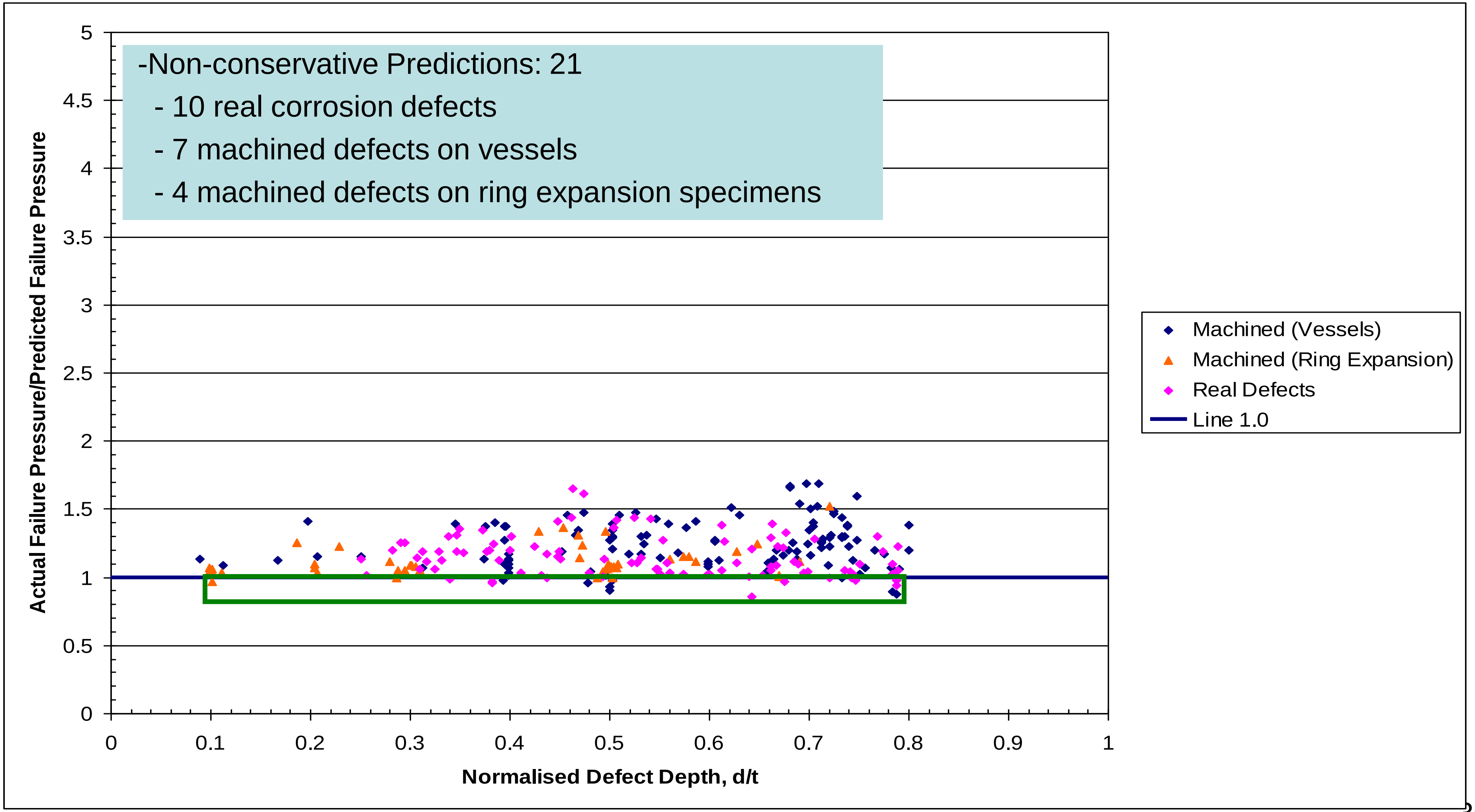
Machined vs. Real Corrosion Defects



Case 2 – ASME B31G

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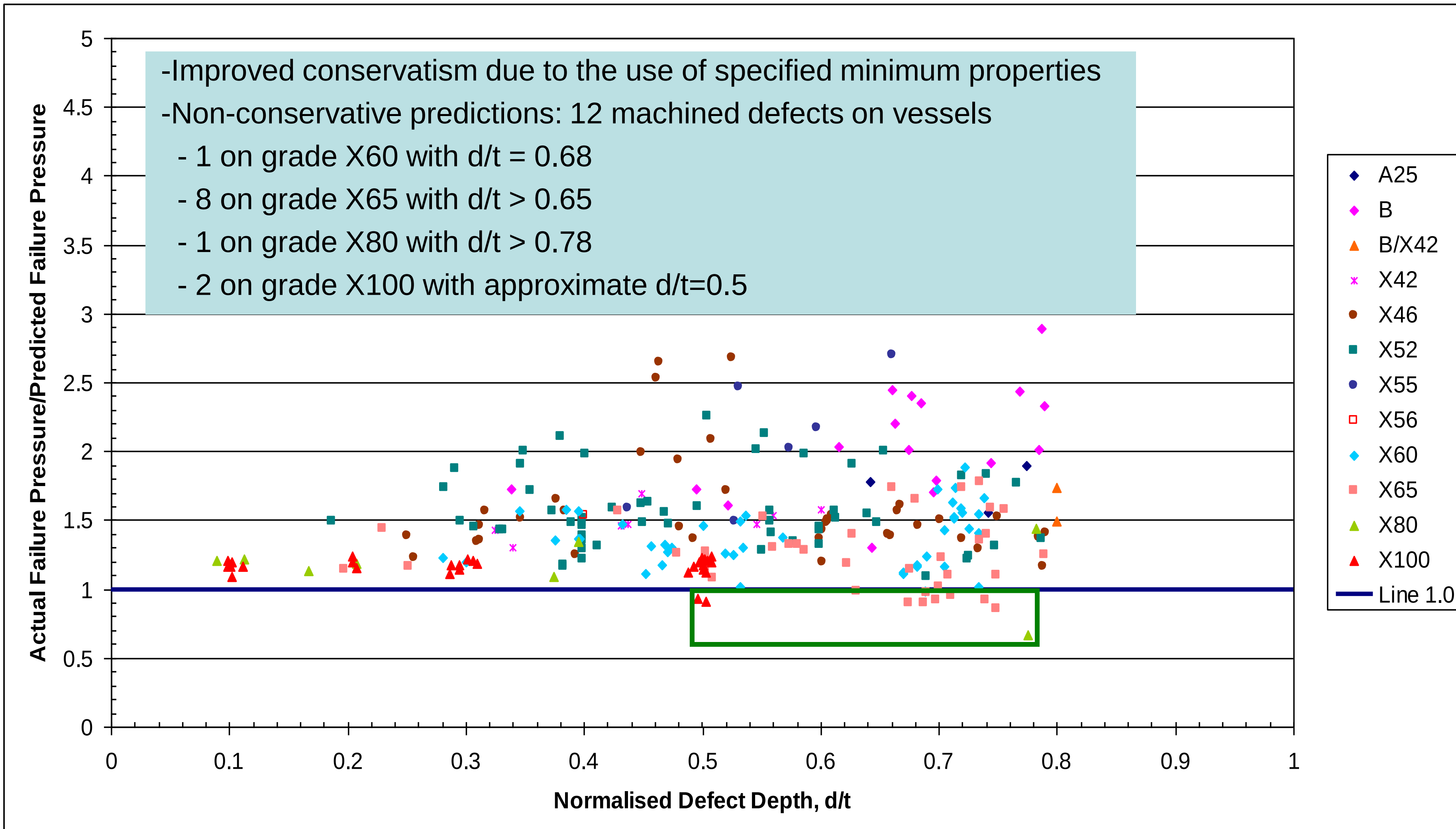
Case 2 – Specified Minimum Material Properties



Case 2 – Modified ASME B31G

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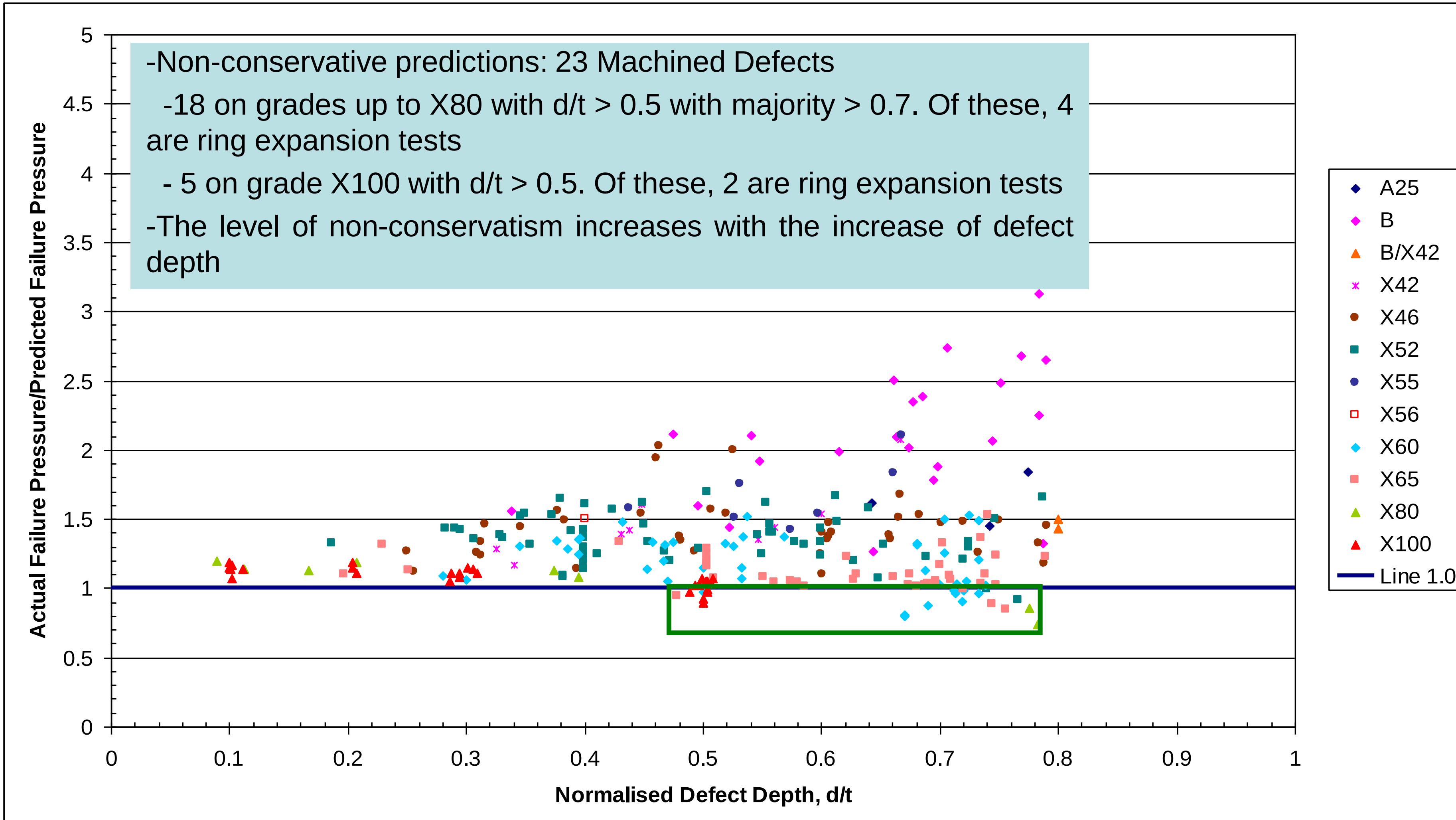
Case 2 – Specified Minimum Material Properties



Case 2 – RSTRENG

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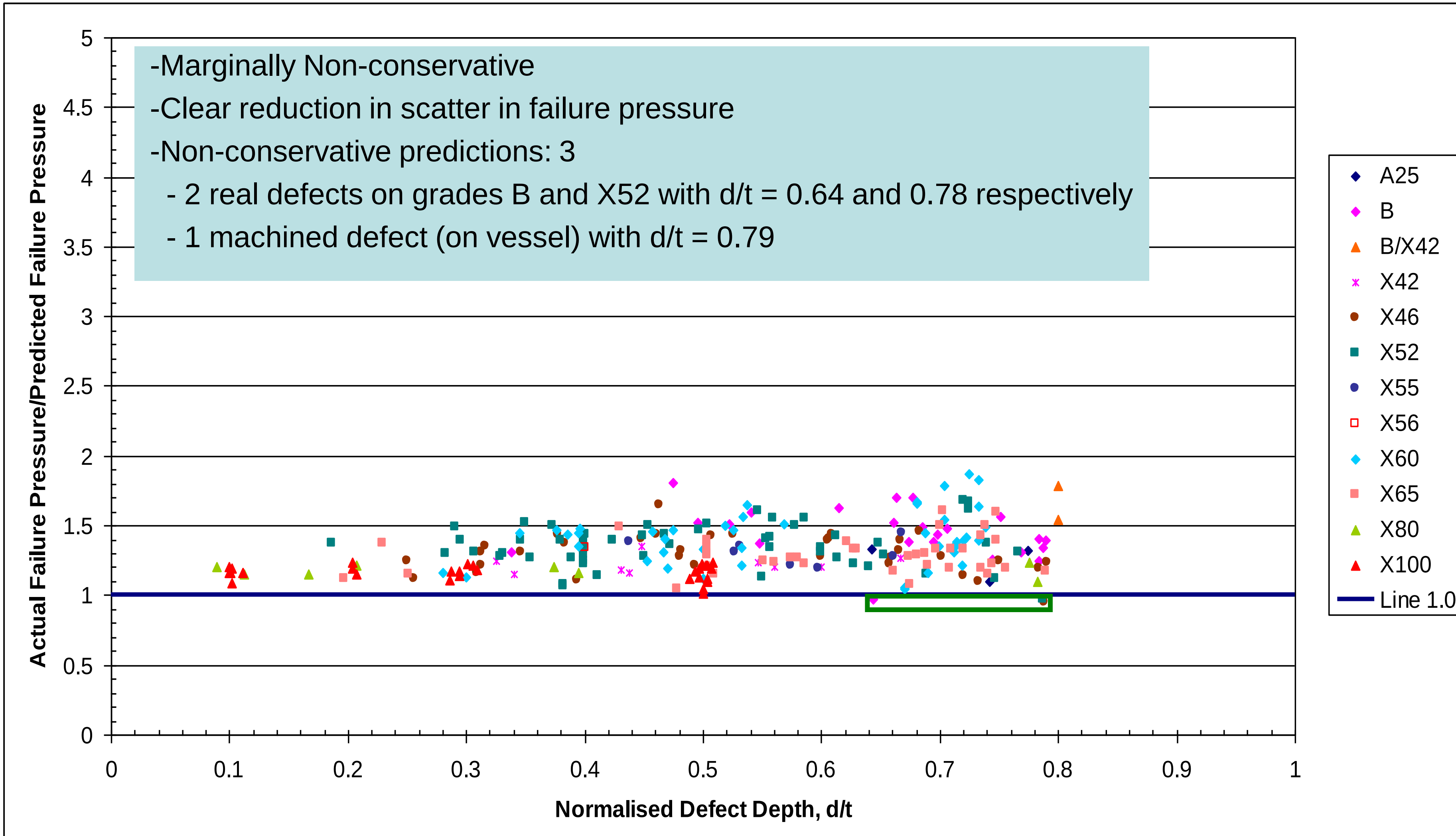
Case 2 – Specified Minimum Material Properties



Case 2 – SHELL92

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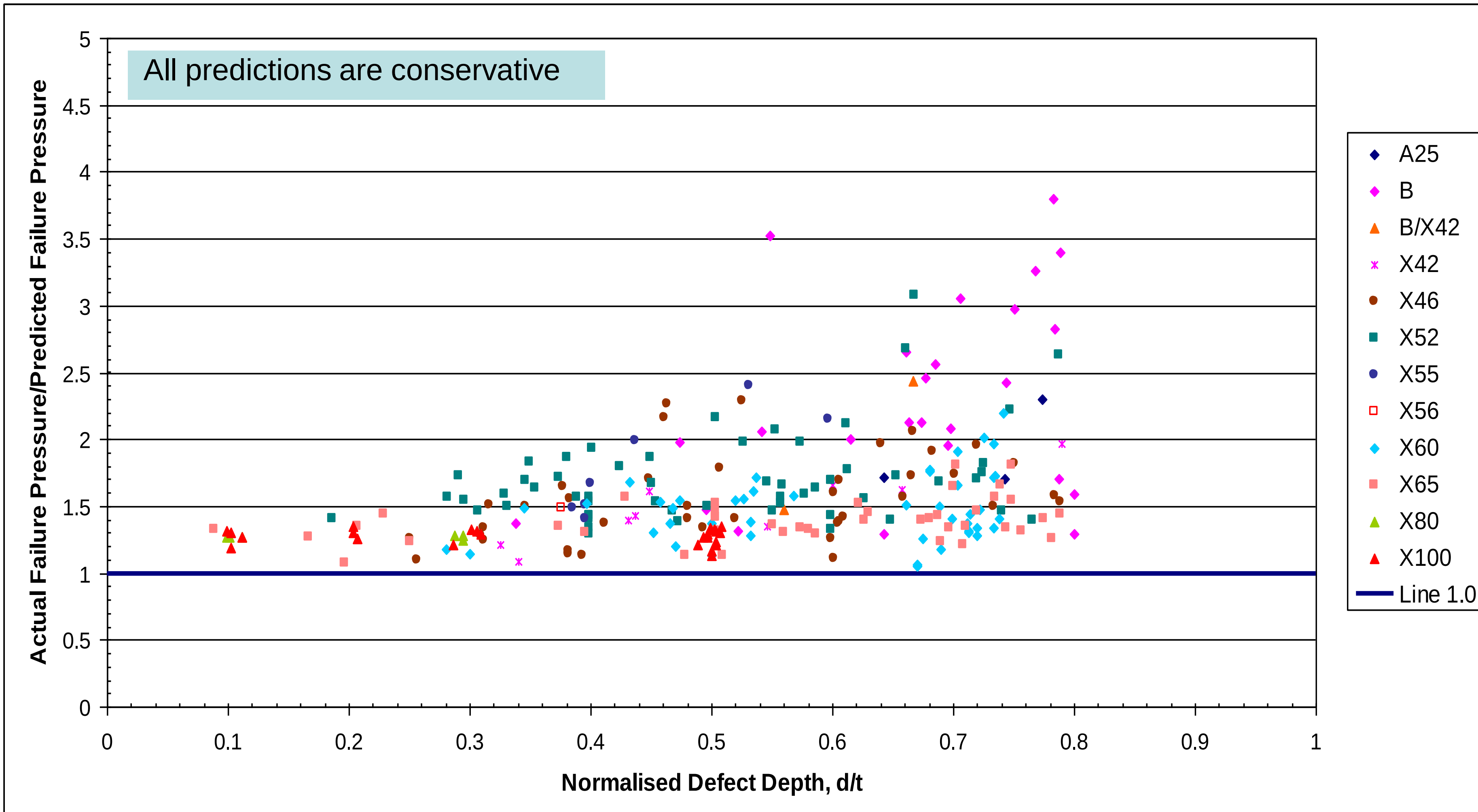
Case 2 – Specified Minimum Material Properties



Case 2 – LPC-1

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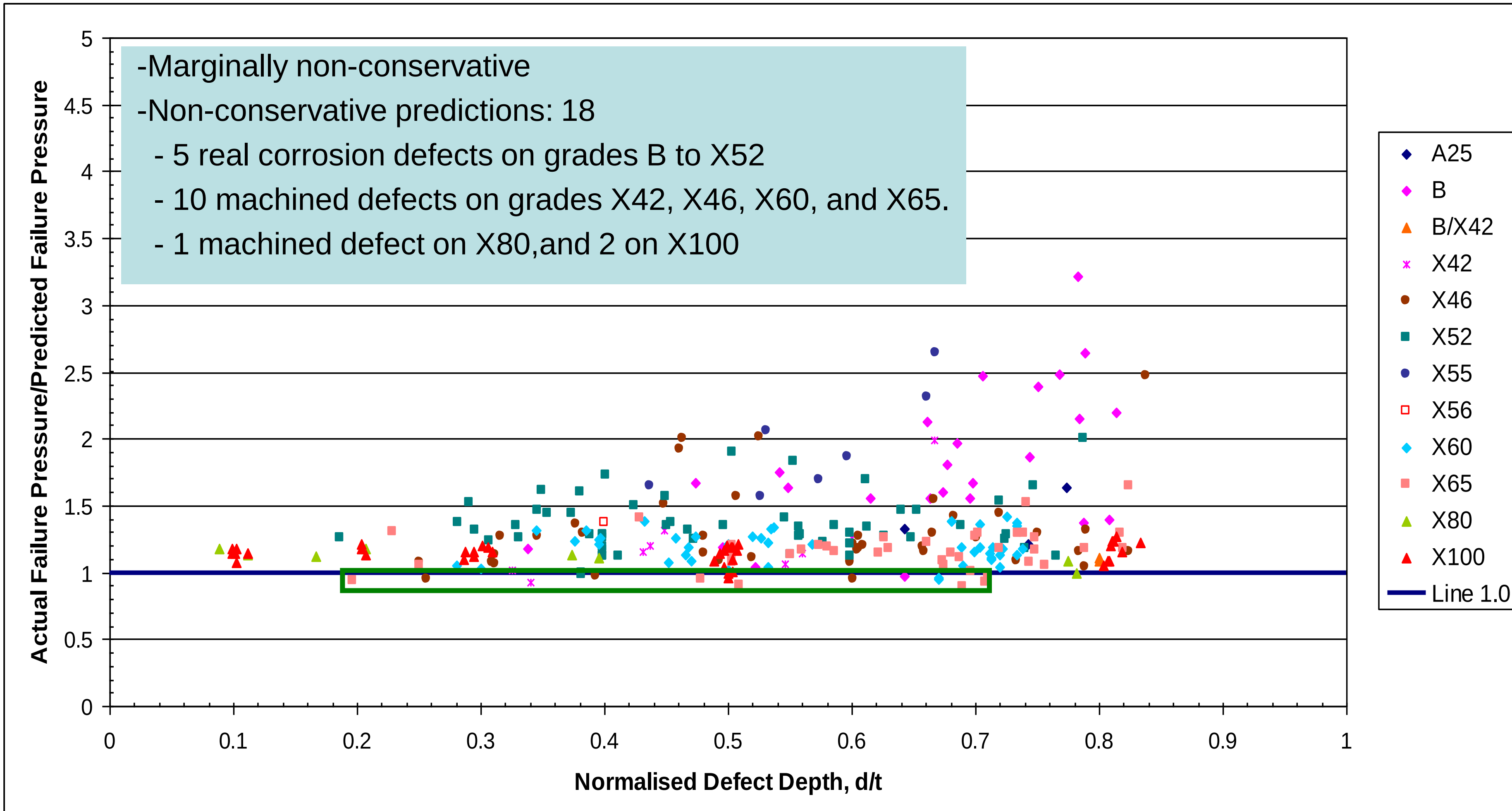
Case 2 – Specified Minimum Material Properties



Case 2 – PCORRC

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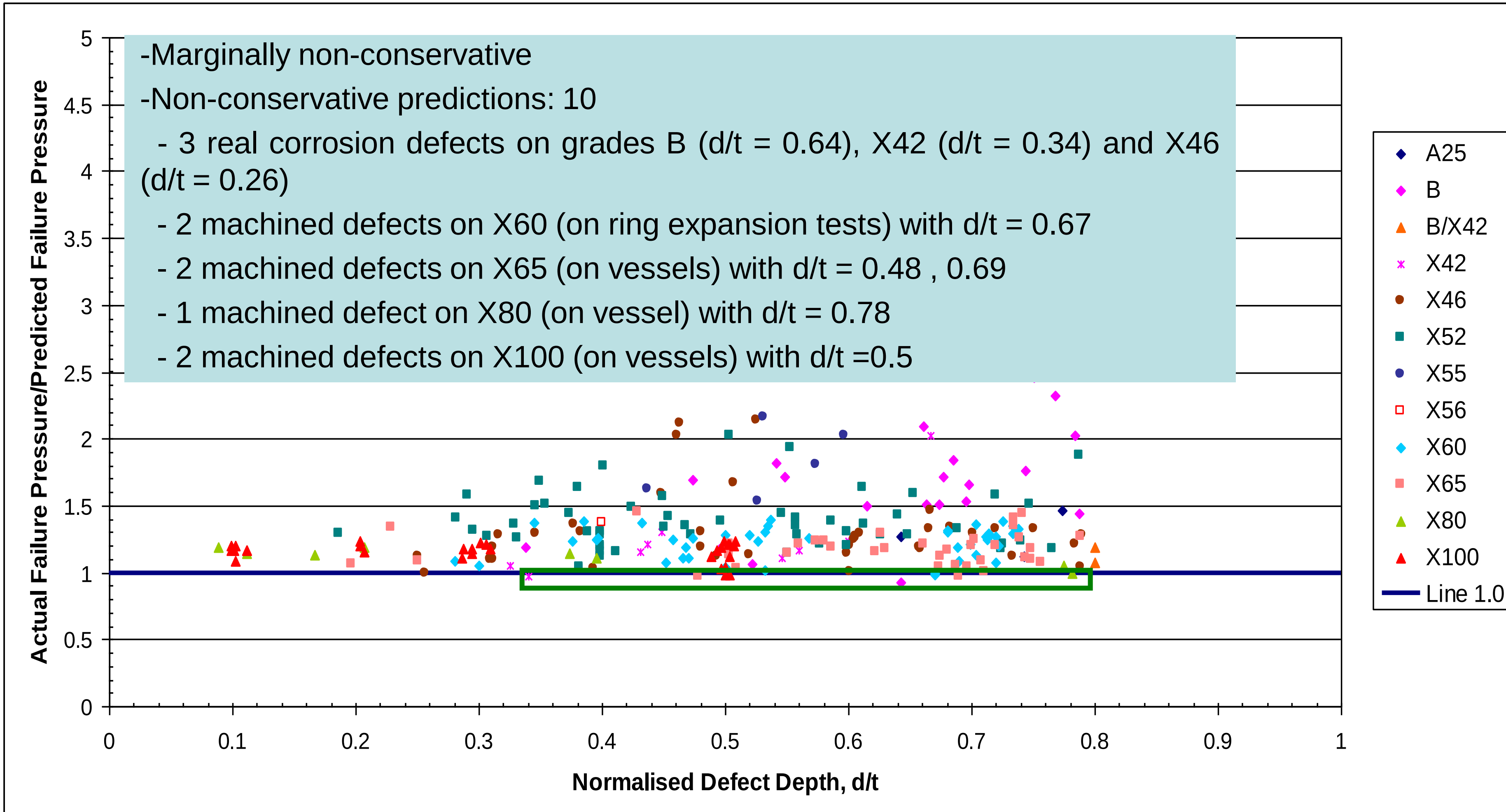
Case 2 – Specified Minimum Material Properties

-Marginally non-conservative

-Non-conservative predictions: 10

- 3 real corrosion defects on grades B (d/t = 0.64), X42 (d/t = 0.34) and X46 (d/t = 0.26)
- 2 machined defects on X60 (on ring expansion tests) with d/t = 0.67
- 2 machined defects on X65 (on vessels) with d/t = 0.48 , 0.69
- 1 machined defect on X80 (on vessel) with d/t = 0.78
- 2 machined defects on X100 (on vessels) with d/t =0.5



Case 2 – ASME B31G

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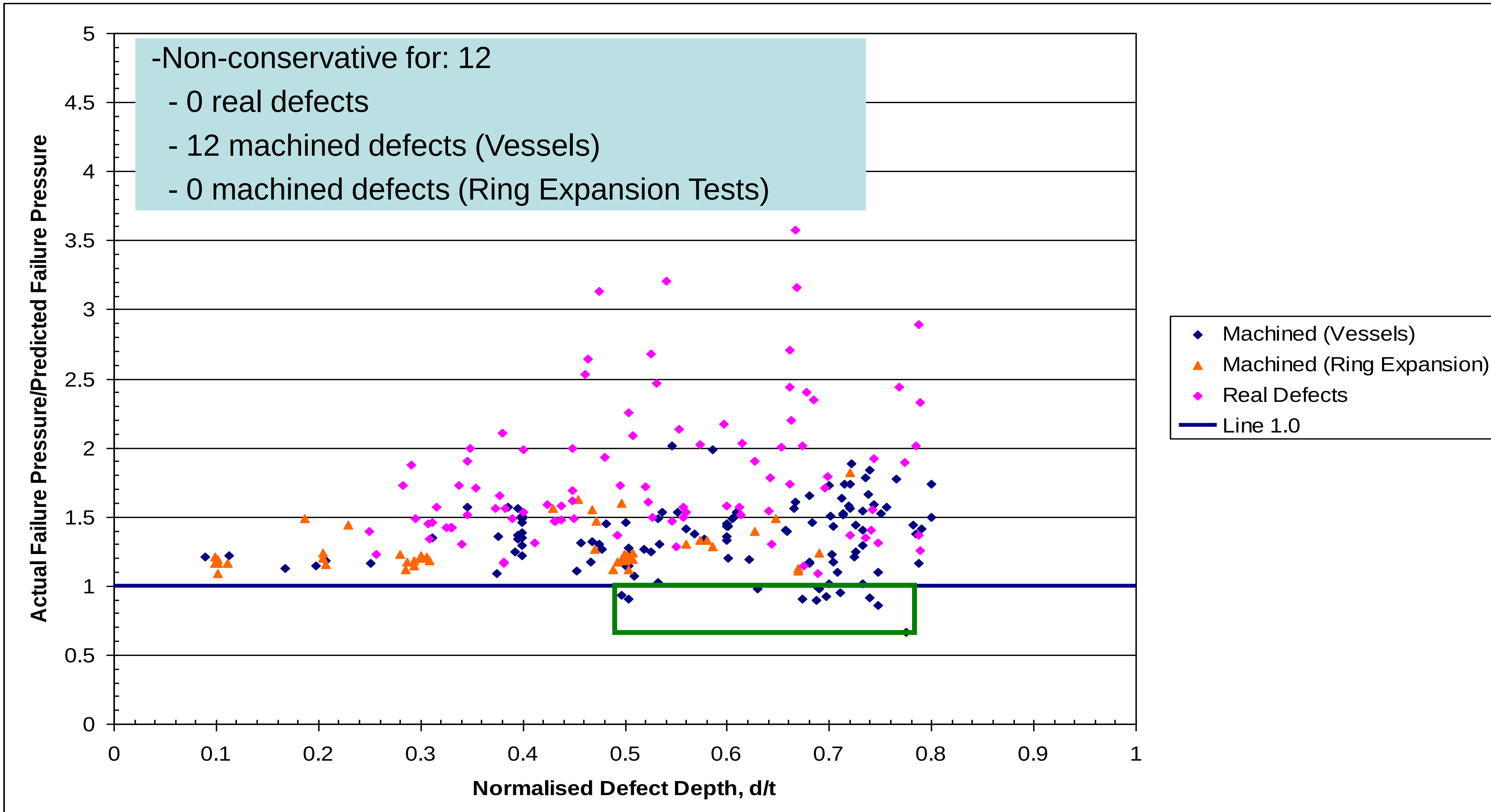
Machined vs. Real Corrosion Defects



Case 2 – Modified ASME B31G

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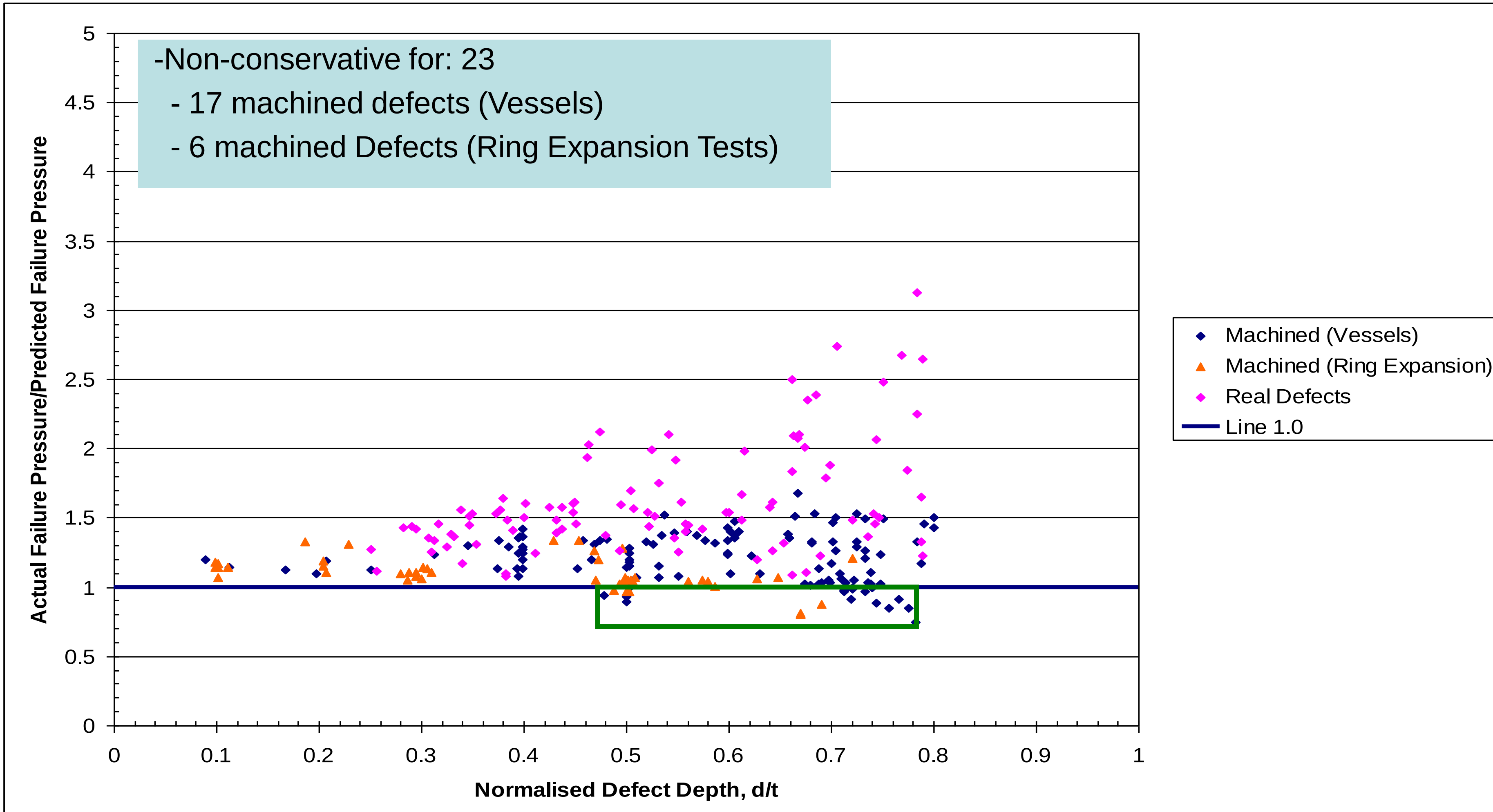
Case 2 – Specified Minimum Material Properties



Statistical Analysis – Case 1 & 2

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Assessment Method	P_A/P_f Case 1		P_A/P_f Case 2	
	Mean	Standard Deviation	Mean	Standard Deviation
ASME B31G	1.347	0.479	1.550	0.642
Modified ASME B31G	1.194	0.289	1.340	0.356
RSTRENG	1.188	0.168	1.322	0.168
LPC-1	1.205	0.309	1.306	0.326
PCORRC	1.220	0.301	1.325	0.334
SHELL92	1.465	0.403	1.592	0.432

Case 6 – ASME B31G

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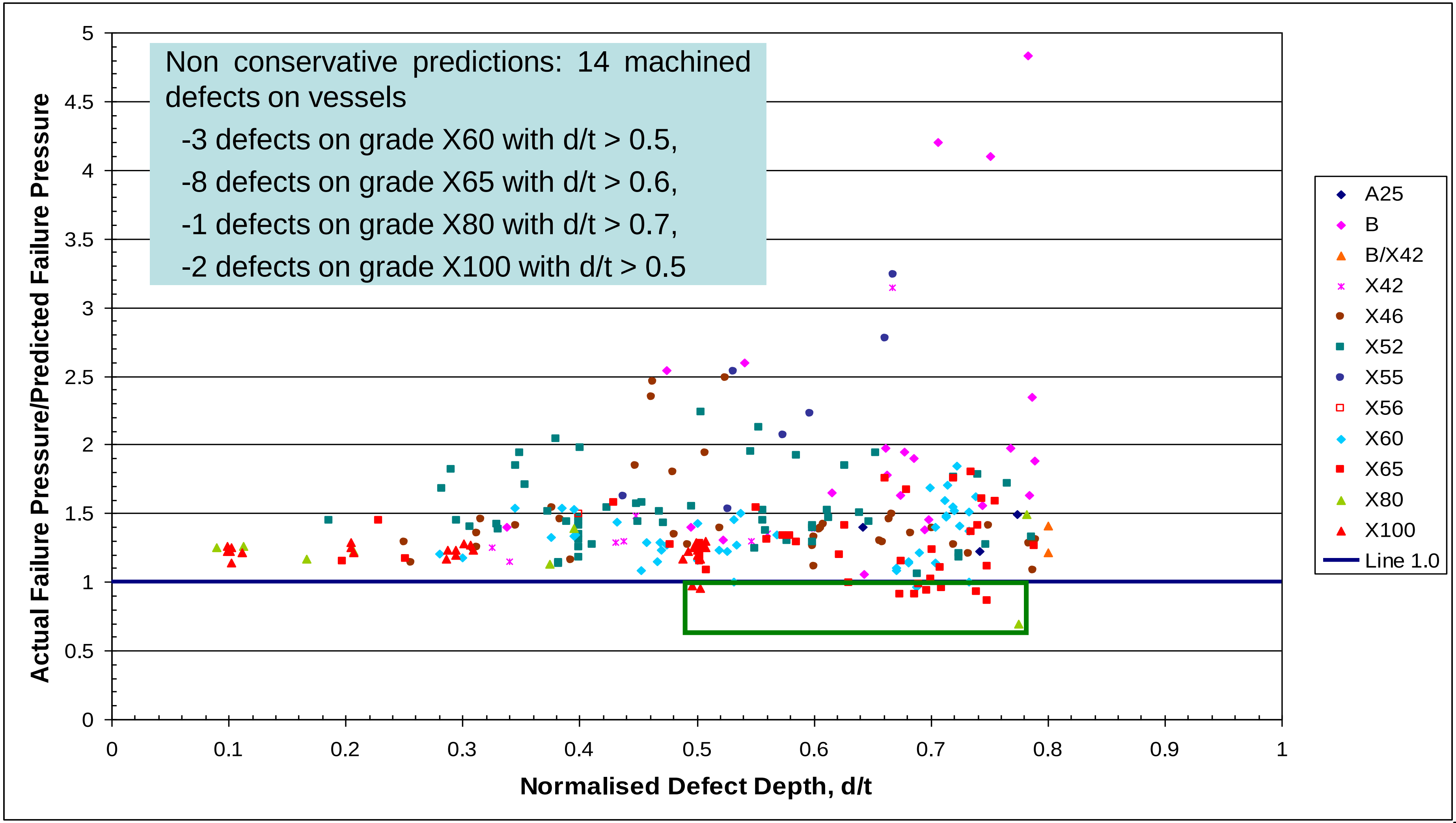
Case 6 – Average of Specified Minimum Material Properties



Case 6 – Modified ASME B31G

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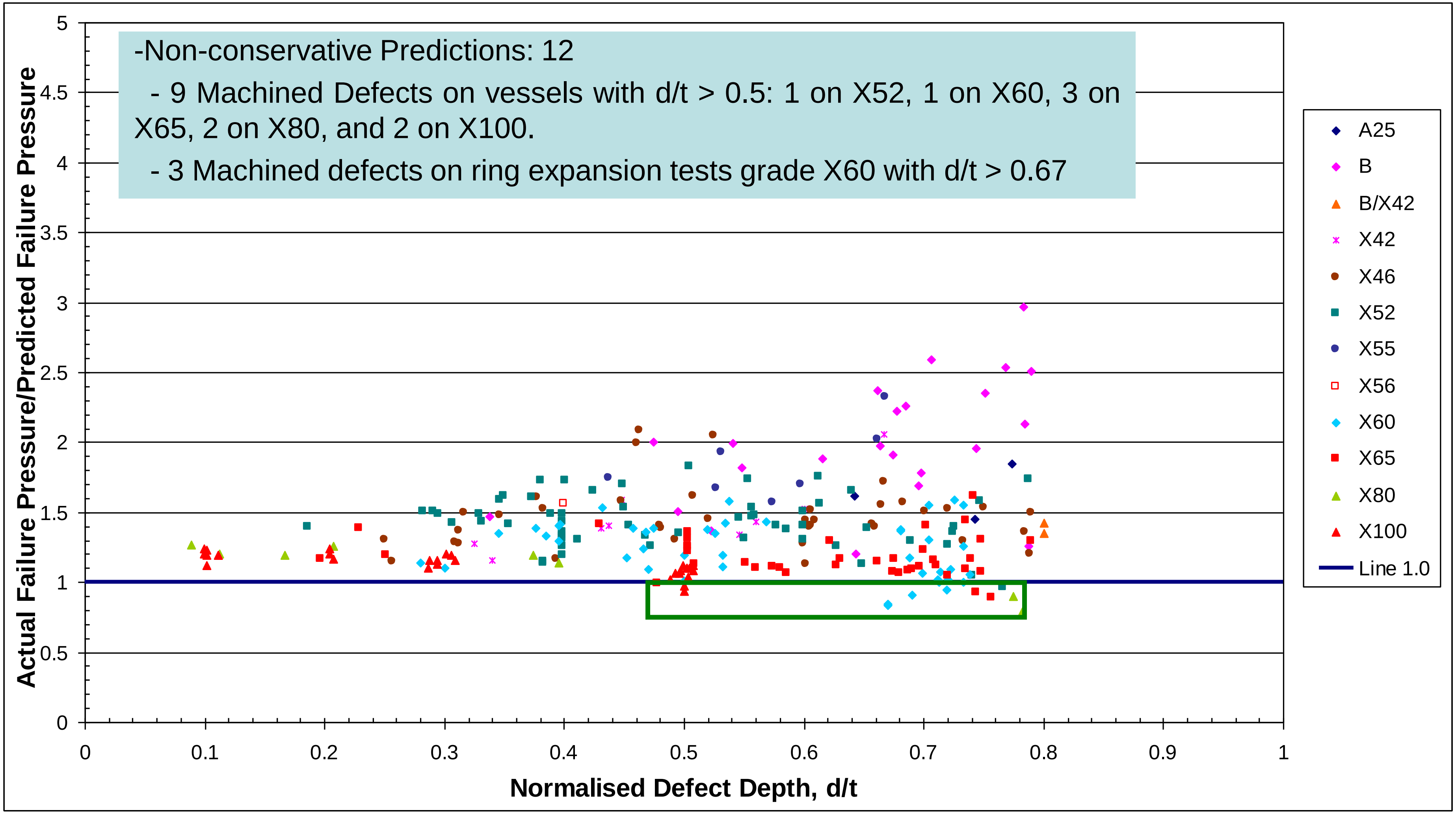
Case 6 – Average of Specified Minimum Material Properties



Case 6 – RSTRENG

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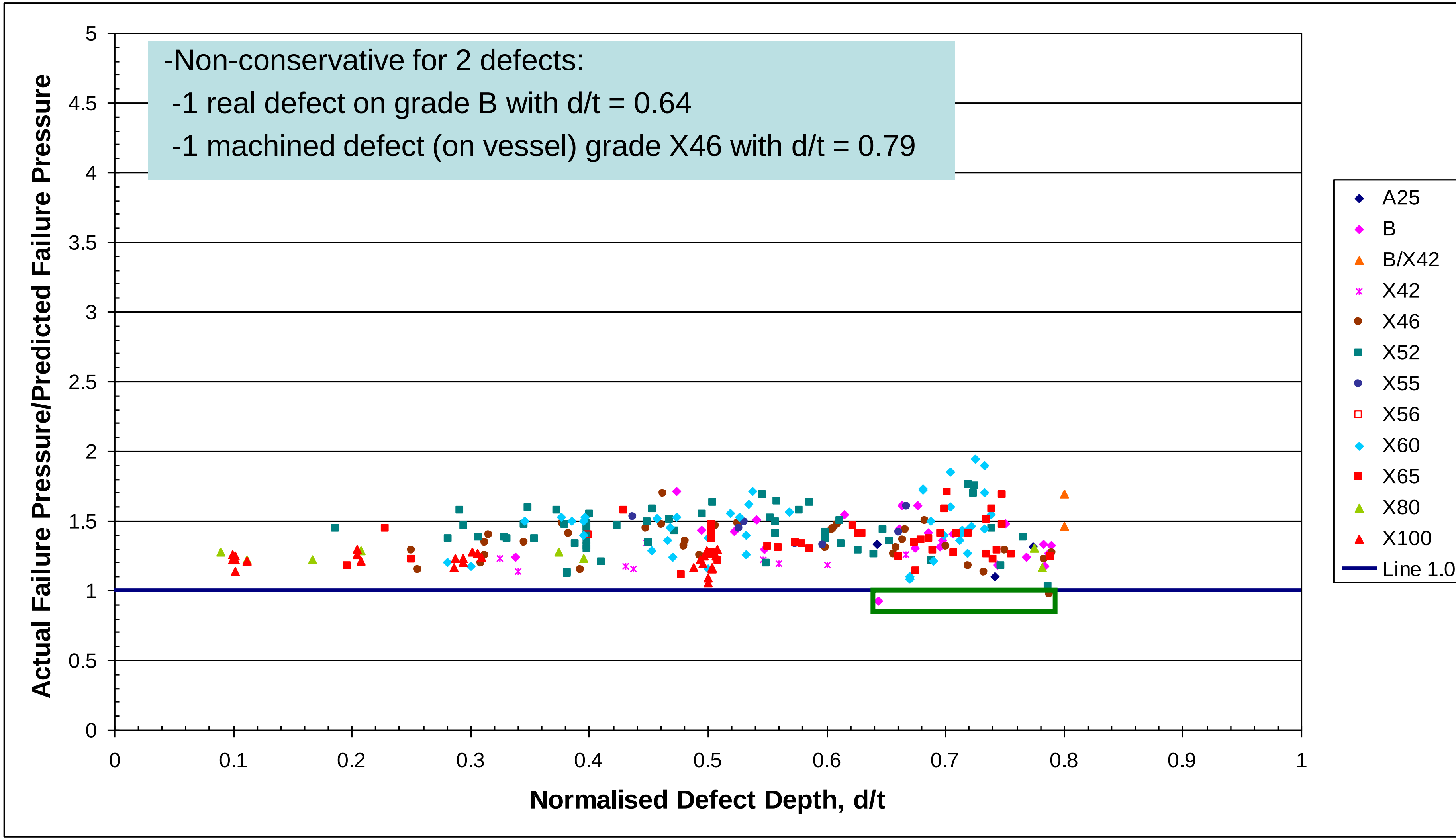
Case 6 – Average of Specified Minimum Material Properties



Case 6 – SHELL 92

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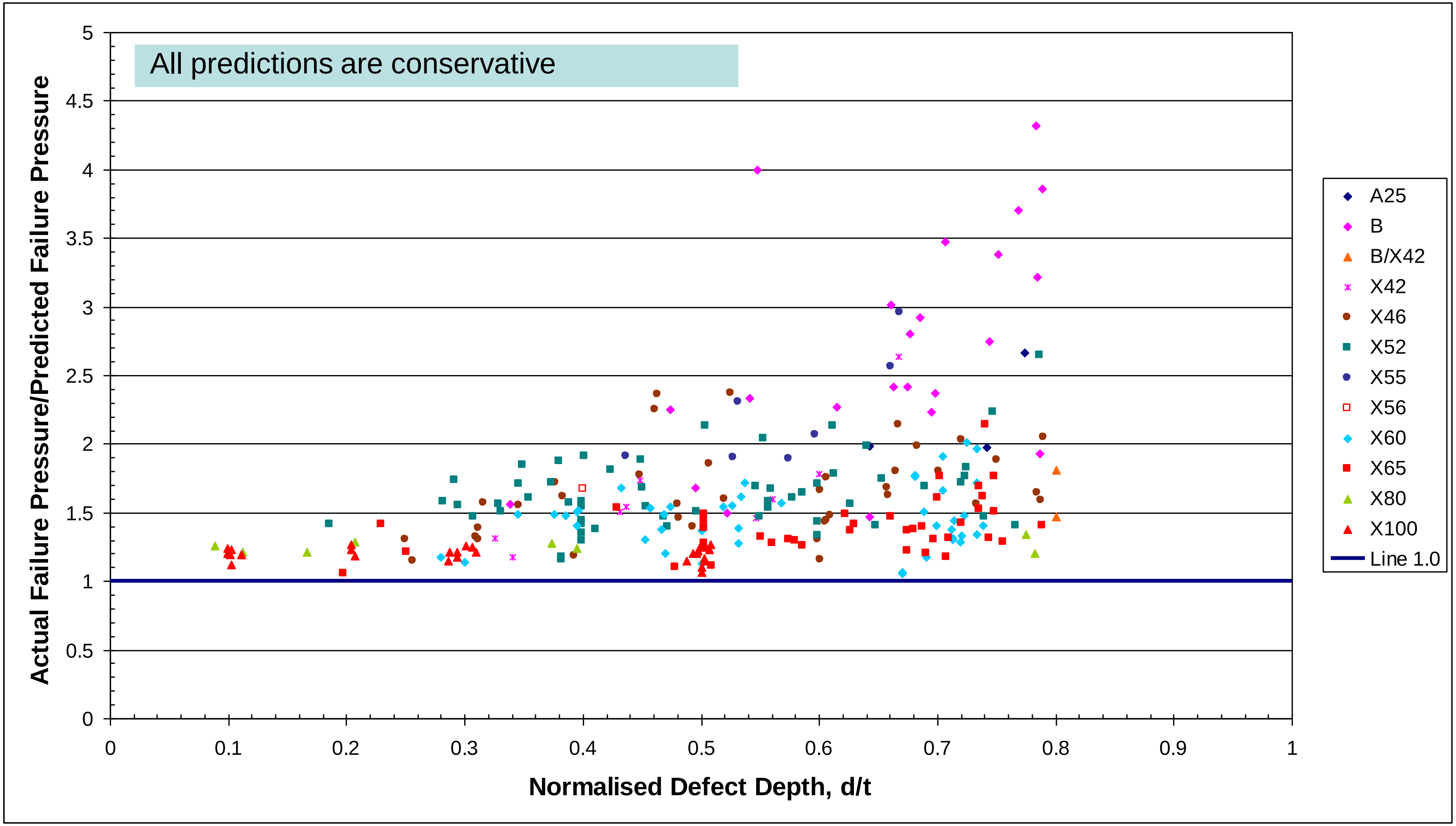
Case 6 – Average of Specified Minimum Material Properties



Case 6 – LPC-1

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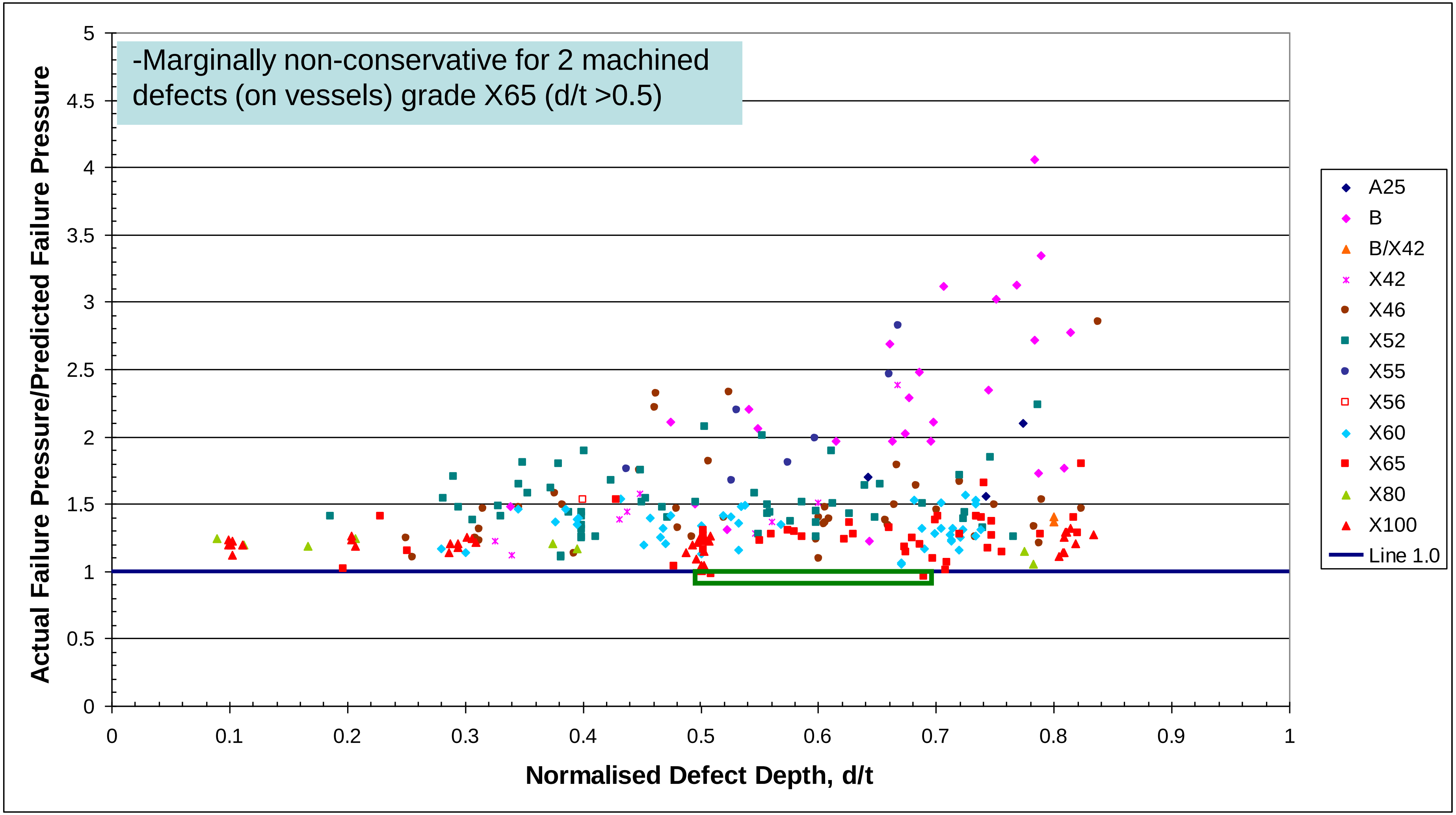
Case 6 – Average of Specified Minimum Material Properties



Case 6 – PCORRC

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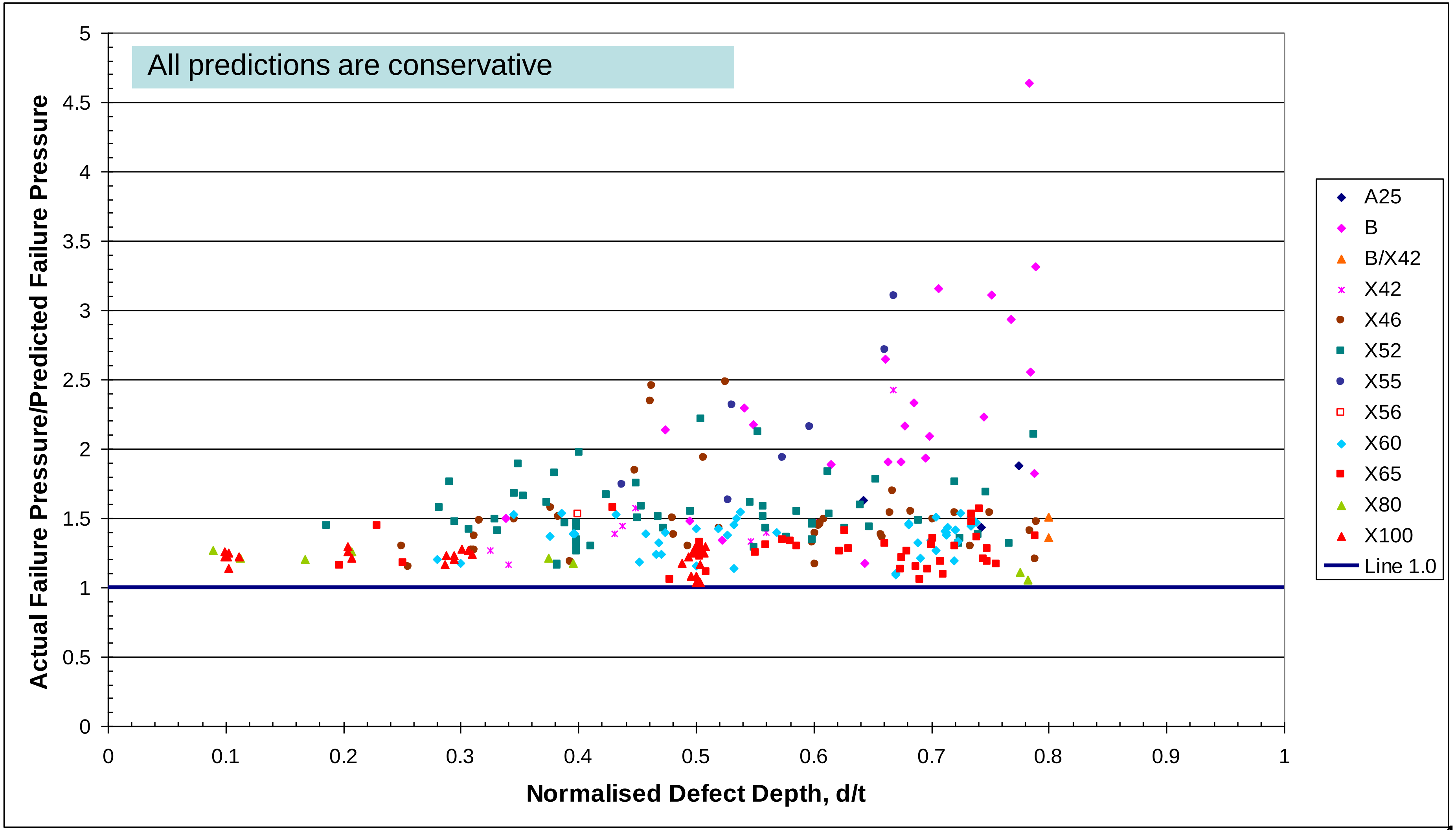
Case 6 – Average of Specified Minimum Material Properties



Case 1 – Non-Conservative Results

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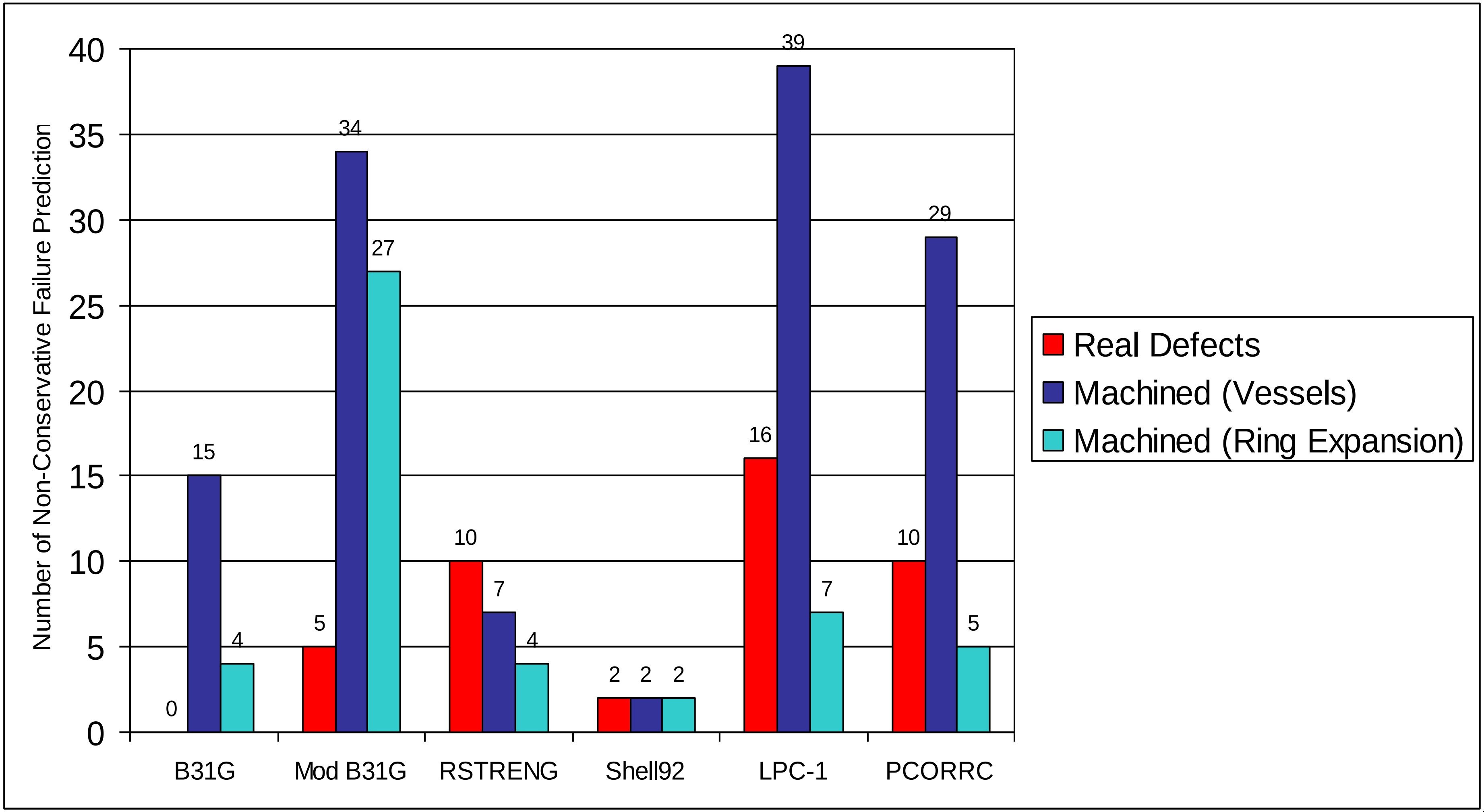
Case 1 – Actual Material Properties



Case 2 – Non-Conservative Results

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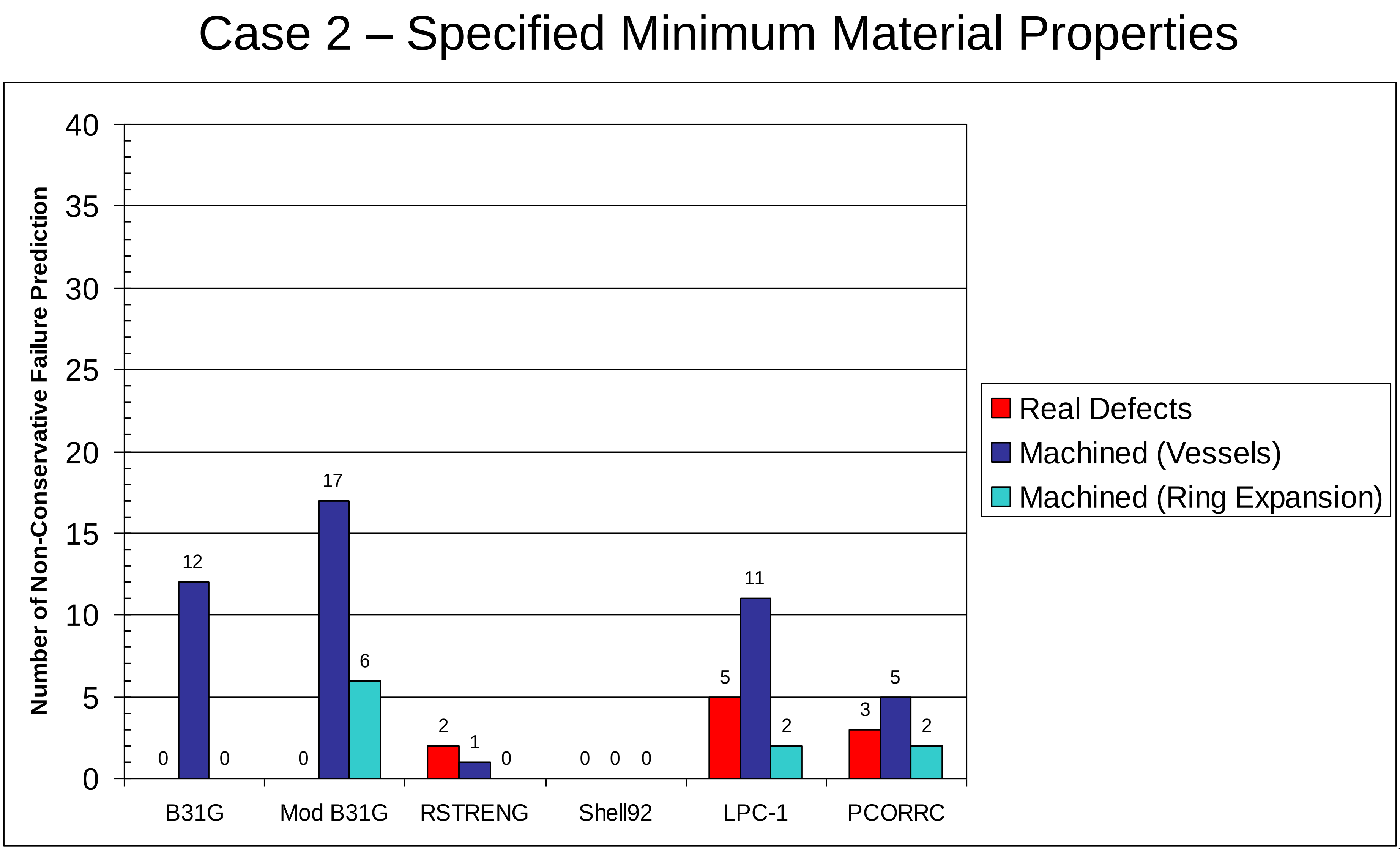

Case 6 – Non-Conservative Results

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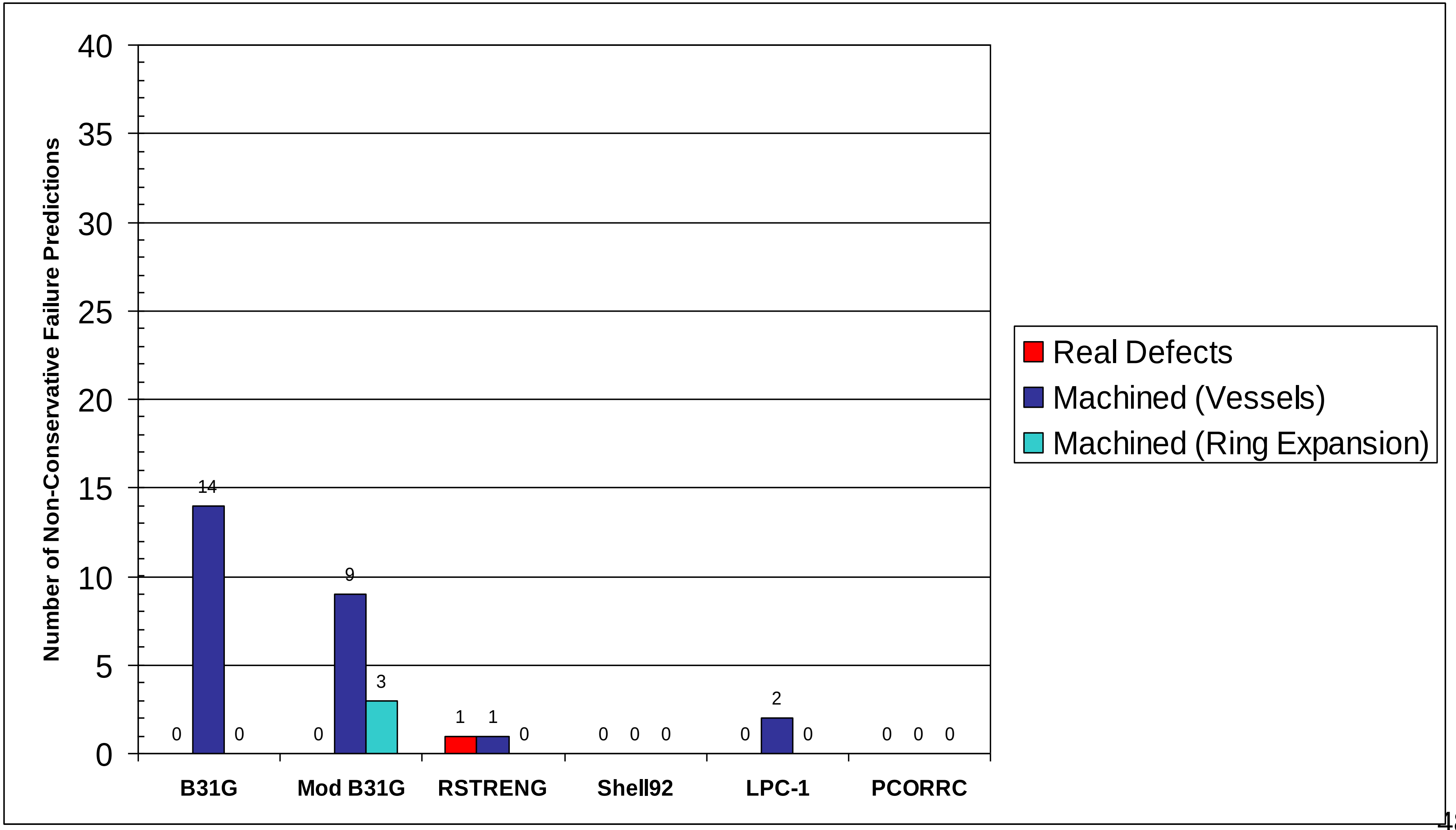
Case 6 – Average of Specified Minimum Material Properties



Confidence Levels of Predicted Failure Pressures

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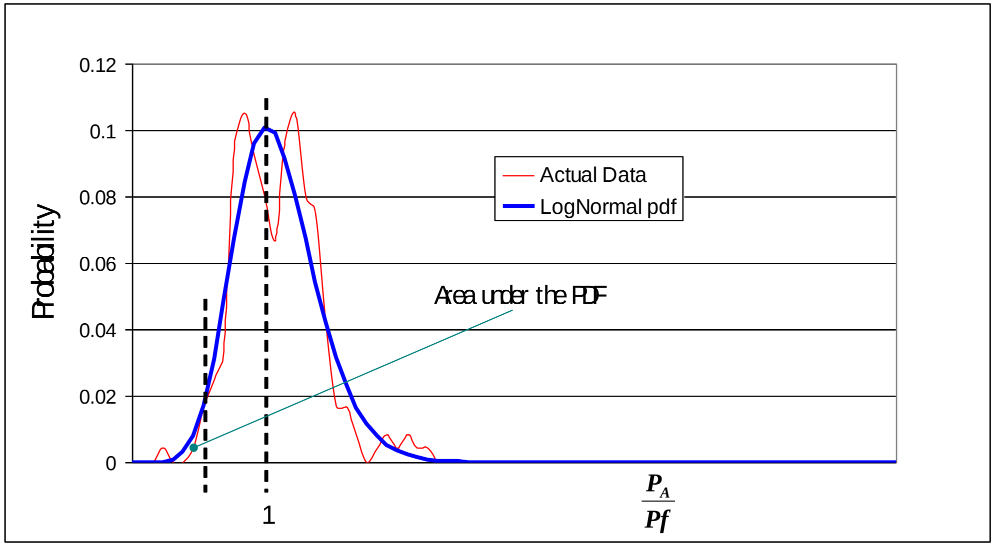
- Using the results obtained from the assessments, the question was asked "*What is the likelihood of predicting a non-conservative failure pressure by more than 5%, 10%, 15% and 20%?"*
- Where sufficient test data is available a probability density function (PDF) of the ratio P_A/P_f can be created



Confidence Levels of Predicted Failure Pressures

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- Full discussion and results of assessments given in section 7 of 6781 Issue 5
- Example results shown below for Case 1 (Grade X60 and X80/X100)

		ASME B31G (Case 1)		Modified ASME (Case 1)		SHELL92 (Case 1)		RSTRENG (Case 1)	
		d/t<60	d/t>60	d/t<60	d/t>60	d/t<60	d/t>60	d/t<60	d/t>60
X60	No.Tests	24	21	24	21	24	21	23	21
	>20%	0.10%	2.70%	0.00%	11.00%	0.00%	0.10%	0.00%	0.00%
	>15%	0.30%	4.90%	0.30%	19.70%	0.00%	0.30%	0.00%	0.10%
	>10%	1.10%	8.10%	1.10%	30.90%	0.10%	0.90%	0.00%	0.40%
	>5%	2.90%	12.50%	3.40%	43.50%	0.40%	2.00%	0.10%	1.30%
	None	93.60%	82.20%	91.40%	43.90%	98.60%	95.90%	99.40%	96.80%
X80/X100	No.Tests	37	3	37	3	37	3	37	3
	>20%	0.00%	38.70%	0.70%	78.00%	0.00%	0.40%	0.00%	9.30%
	>15%	0.50%	44.50%	4.20%	86.00%	0.00%	1.80%	0.00%	16.20%
	>10%	3.10%	50.10%	15.50%	91.50%	0.00%	5.50%	0.20%	25.30%
	>5%	12.40%	55.40%	36.60%	95.10%	0.00%	12.90%	2.80%	36.00%
	None	68.80%	39.70%	38.40%	2.80%	100.00%	75.30%	82.80%	52.90%

Discussion & Questions

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- Thank you for your attention