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A Novel Approach to Establishing Remaining Strength of Line Pipe and Fittings with Corrosion Type Defects

(DOT-PHMSA SBIR Phase 1 Project)

Kick-Off Meeting

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- ** Kiefner & Associates, Columbus, OH

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Acknowledgments & Disclaimer

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- The opinions expressed in this presentation are not necessarily those of the US Dept. of Transportation

- SBIR program is different than a normal R&D project!
  - End goal for SBIR efforts is to have a commercial product
  - IP developed in project is the property of Emc^2 and US government can use for own purposes

Presentation Outline

- Background & Objectives
- Proposed Project Tasks
  - Work Plans and status for tasks
- Schedule of Deliverables
- Plans for Phase 2

Background & Objectives

- ***Metal loss due to corrosion of gas pipelines has always been a major source of concern due to reduction in pressure-carrying capacity***
- ***Several simplified analytical models are currently available to assess remaining strength of corroded pipelines – based on specimen and full-scale experimental data, simplified empirical correlations and have been incorporated into ASME Codes and Federal Regulations***
- ***Most of the past work involved lower strength (< X65) steels; very little data exists on higher grades (X65 or higher) and almost no data on fittings***
- ***Critical need for a new approach for assessing remaining strength of higher grade (> X65) pipelines and fittings with blunt, areal type defects due to corrosion….***

Objective of Feasibility Study – SBIR Phase I

- Develop mathematical models and computational methods to assess the remaining strength of pipelines and fittings using a failure criterion for natural corrosion type areal defects that accounts for the transitional changes from very high notch acuity to generally thinned regions in old versus new linepipe steels

- Develop a Simulation of Natural Corrosion via Computation (SNC[2]) Software Code along with carefully selected laboratory experiments applicable for higher grade (> X65) steels
  - Includes failure criteria for old and new pipe and elbows
  - Includes eventual automated 3D FE modelling of complex corrosion to eliminate conservatisms in simplified approaches
  - Include hoop stress and longitudinal stresses – longitudinal stresses (tension or compressive) not included in B31G
  - This computer code will be a validated B31G – Level 3 assessment method, which can have impact to changes for Level 1 and 2 assessment procedures

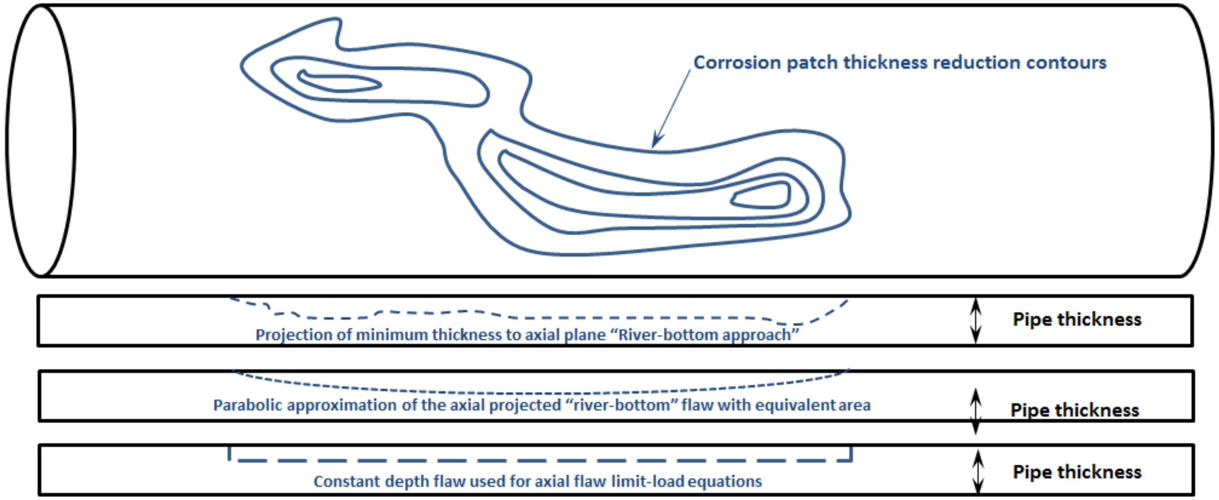
- Compare B31G & Mod B31G predictions to improved 3D FE criteria for complex corrosion flaw shape in identical X52 and X80 FE failure criterion (stress-based/strain based/acuity of surface contour profiles).
  - Possible that corrosion failure criterion needs to be more stringent for higher grade steels, but
  - 3D modelling eliminates potential conservatisms in simplified criteria.

Tasks Being Undertaken

- *Task 1 – Review of B31G for X65 and Higher Grade Pipe & Fittings*
- *Task 2 – Experiments for Preliminary Failure Criteria for Blunt Flaws*
- *Task 3 – Leak Versus Break Predictions*
- *Task 4 – Simulation of Natural Corrosion via Computation (SNC^2)*
- *Task 5 – Confirm Feasibility of SNC^2*
- *Task 6 – Program Management, Coordination, Reporting, and Travel*

Task 1 – Review of B31G for X65 – Objectives and Needs

- What failure criteria might be applicable?
  - Simplified criteria use geometric parameters
    - Effective bulging factors,
    - Shape factors for irregular shaped flaws,
    - Different approaches for irregular surface flaw transformation to simple shape, i.e.,
      - B31G/Mod B31G uses effective depth for the actual length,
      - For circumferential flaws the equivalent length is calculated for the maximum depth works better.



  - Material property changes with vintage and grade:
    - Margins on actual yield to SMYS changes,
    - Effect of yield-to-ultimate strength (Y/T) ratios,
    - Actual tensile-to-SMYS (T/SMYS) ratio change,
    - Definition of flow stress and strain-hardening exponent when available,
    - Maximum strain at uniform elongation (strain at ultimate), and
    - Influence of toughness of the grade of steels.

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Task 1 – Review of B31G for X65 – Plans and Progress

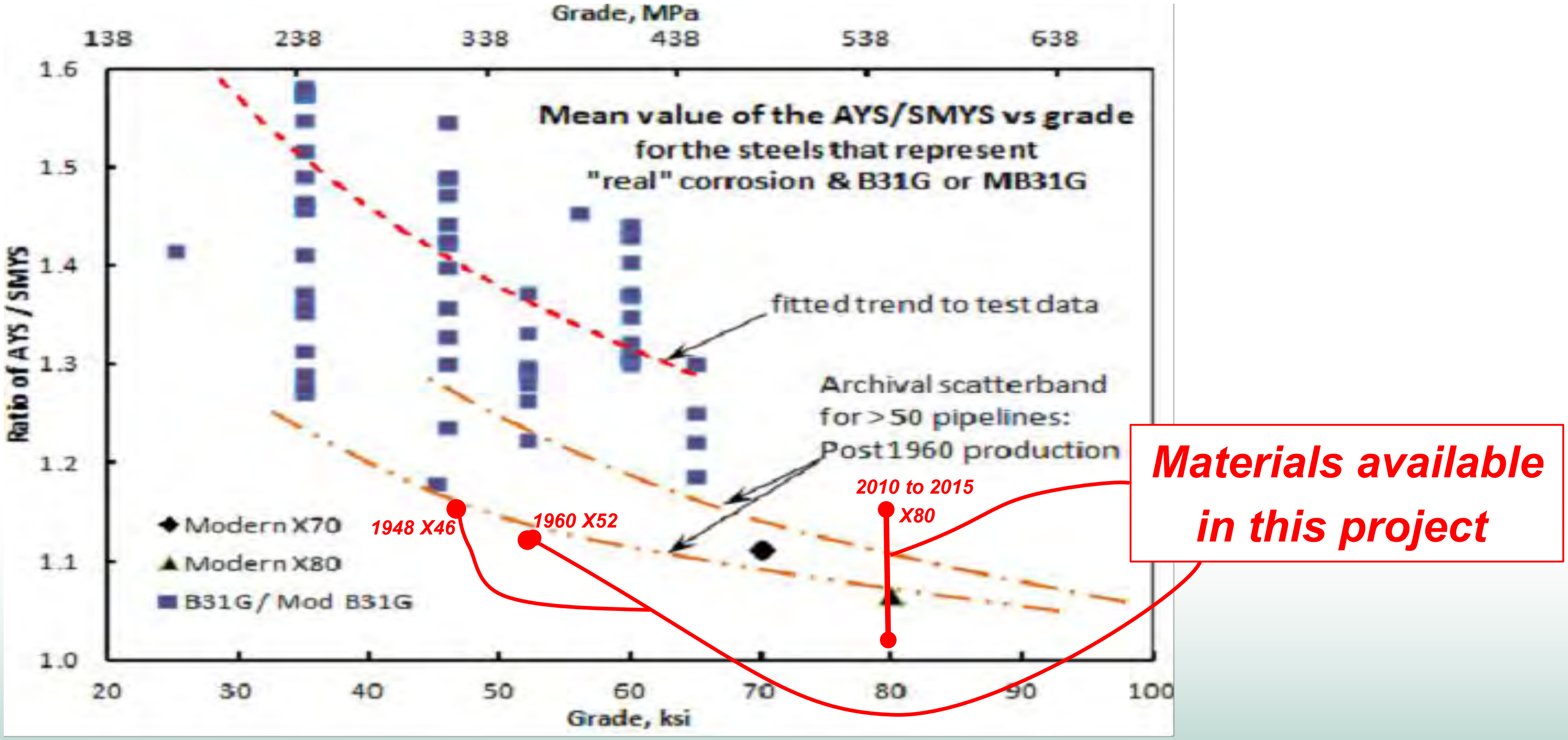
- ***Review of past criteria – Skill Sets for Project Team Members***
  - ***John Kiefner involved with initial development of B31***
  - ***Mike Rosenfeld involved with B31G/B31.8 and recent changes***
  - ***Brian Leis reviewed past corrosion work as part of PRCI past efforts***
  - ***Gery Wilkowski conducted transition temperature fracture tests for flaws with different notch acuities in old linepipe***
  - ***Do-Jun Shim showed lower bulging factor than Battelle equation for axial surface cracks in PRCI project***
  - ***Gery Wilkowski & Prabhat Krishnaswamy co-authored ASME BPV Section XI Code Case N597 for evaluation of blunt, erosion-corrosion type of defects in safety-related nuclear piping***

Task 1 – Review of B31G for X65 – Plans and Progress

- ***Some specific needs for other tasks***
  - ***Material selection criteria for Task 2***
    - ***Is the ~1960 vintage X52 pipe available for Task 2 testing comparable to pipe from the older corroded pipe tests? (AYS/SMYS comparable to a 1948 pipe used in past PRCI SENT testing)***
  - ***Selection of a few cases of low-grade corroded pipe burst tests for Task 4***
    - ***Need very good documentation of corrosion contours, material strength, and burst test failure pressure***
    - ***Cases where B31G/Mod B31G are overly conservative or nonconservative good to have***

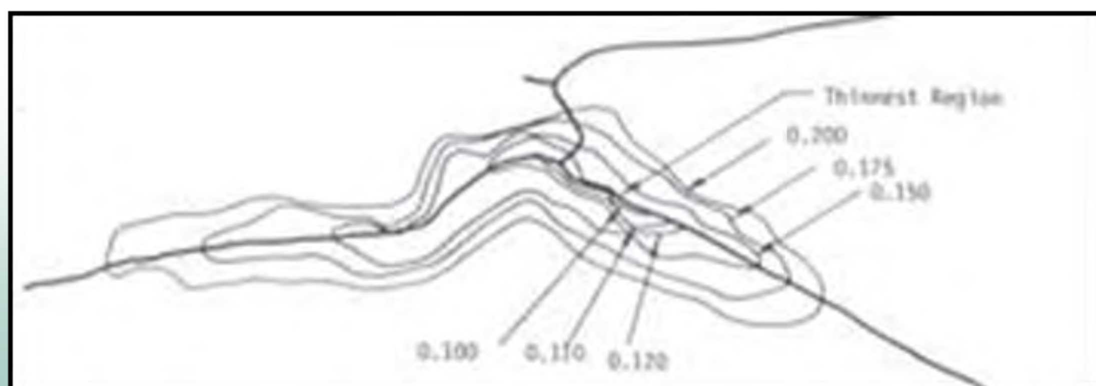
Task 1 – Review of B31G for X65 – Trends and Pipe Available

- ***Trend in the ratio of Actual Yield Strength (AYS) to SMYS for various grades of steel representing existing B31G or ModB31G criteria changes significantly for X65 or higher-grade pipe.***



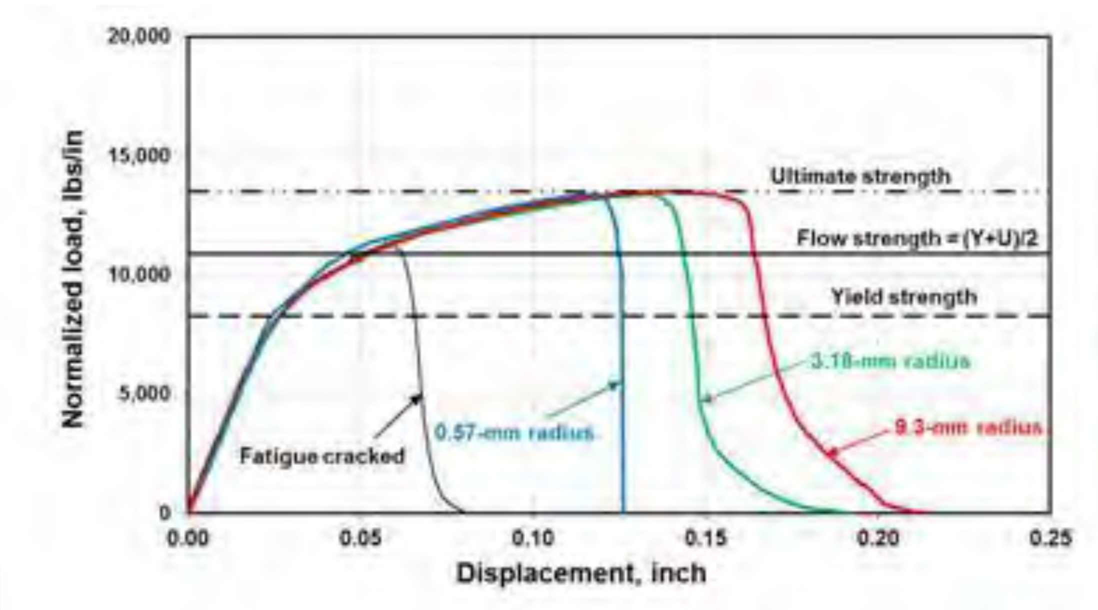
Task 2 – Preliminary Failure Criteria Expts - Objective

- *Actual flaws will have different roughnesses/contours in the corroded area.*
- *Can these surface morphology aspects affect the failure stress/strain?*



Task 2 – Preliminary Failure Criteria Expts – Plans and Progress

- ***Past Emc^2 data showed that sharp flaws failed at flow stress while blunt flaws fail at ultimate strength.***
  - ***There is a transition of failure stress criteria with notch acuity!***
    - ***Is the transition different for X80 materials than X52?***



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Task 2 – Preliminary Failure Criteria Expts – Plans and Progress

- ***Led by Emc[2] using past blunt flaw SENT testing approach***
  - ***Guidance from Leis and Rosenfeld/Kiefner***
  - ***Kiefner & Associates to assist is specimen fabrication***
  - ***SENT testing at Emc[2]***

- ***Have currently selected one typical X52 pipe (~1960 vintage) and 4 optional X80 pipes with extremes in properties from two pipe manufacturers (2010 to 2015 pipes).***

				Round-bar transverse tensile test average values							
Grade (ksi)	Pipe #	Diameter, inch	Thickness, inch	0.2% offset yield, ksi	Y/SMYS	Ultimate strength, ksi	Y/T	T/SMYS	T/(Y+10ksi)	Uniform strain, %	Max strain, %
X52	52	36	0.390	58.06	1.12	76.06	0.763	1.46	1.23	16.01%	30.2%
[redacted]											
X80	2015-L	48	0.734	82.09	1.03	97.82	0.839	1.22	1.09	Not available yet	28.0%
X80	2015-H	48	0.734	94.78	1.18	100.15	0.946	1.25	1.11	Not available yet	23.5%
[redacted]											
X80	2010-L	48	1.005	81.65	1.02	98.69	0.827	1.23	1.10	9.69%	14.8%
X80	2010-H	48	1.005	92.15	1.15	103.15	0.893	1.29	1.15	6.44%	15.0%

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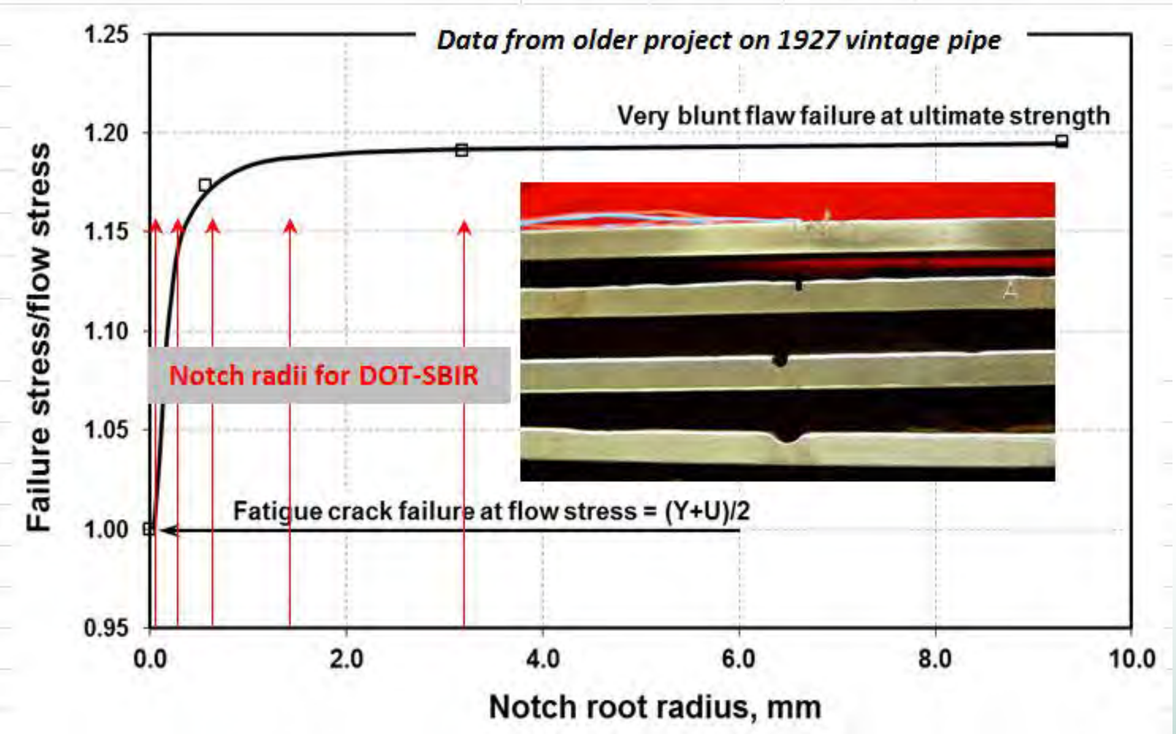
Task 2 – Preliminary Failure Criteria Expts – Plans and Progress

- ***Conduct SENT tests with 6 different notch acuities (see below table)***
  - ***Sharper notches made by EDM wire, blunter flaws made by milling***
  - ***Unnotched full-thickness strap and round-bar tensile tests***
  - ***SENT specimens ~16” long***
  - ***Width = 1.5T***
  - ***a/t = 0.5***

Specimen ID	Diameter, in	Radius, mm
A	0.006	0.076
B	0.015625	0.198
C	0.03125	0.397
D	0.0625	0.794
E	0.125	1.588
F	0.25	3.175
G	Spare	
H	Unnotched strap tensile and round bar	

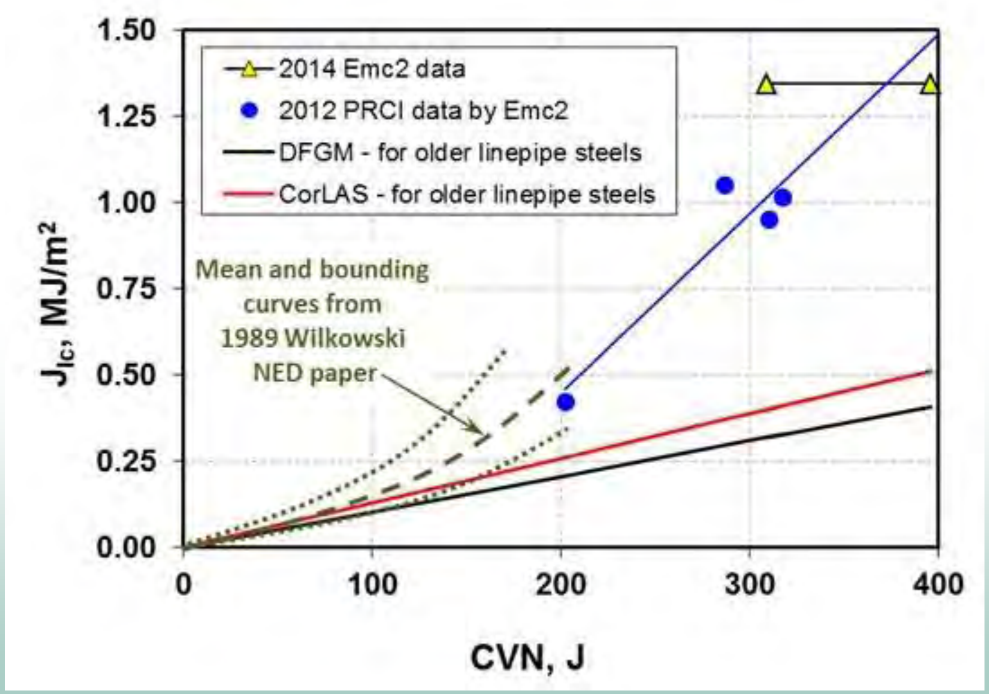


Task 2 – Preliminary Failure Criteria Expts – Plans and Progress

- *Testing at Room Temp (RT) to ensure upper-shelf behavior*
- *Data to be obtained during experiments:*
  - *Load,*
  - *Load-line displacement (cross-head displacement),*
  - *Crack-mouth-opening displacement (for FE analyses of SENT tests), and*
  - *d-c EP in some cases to document start of ductile tearing.*
- *SENT FE analyses*
  - *Determine if failure is controlled by strain in ligament reaching uniform elongation in tensile tests – regardless of notch acuity*
  - *2D FE analyses using actual stress-strain curve and load-CMOD data for validation of FE model (ABAQUS with refined mesh)*

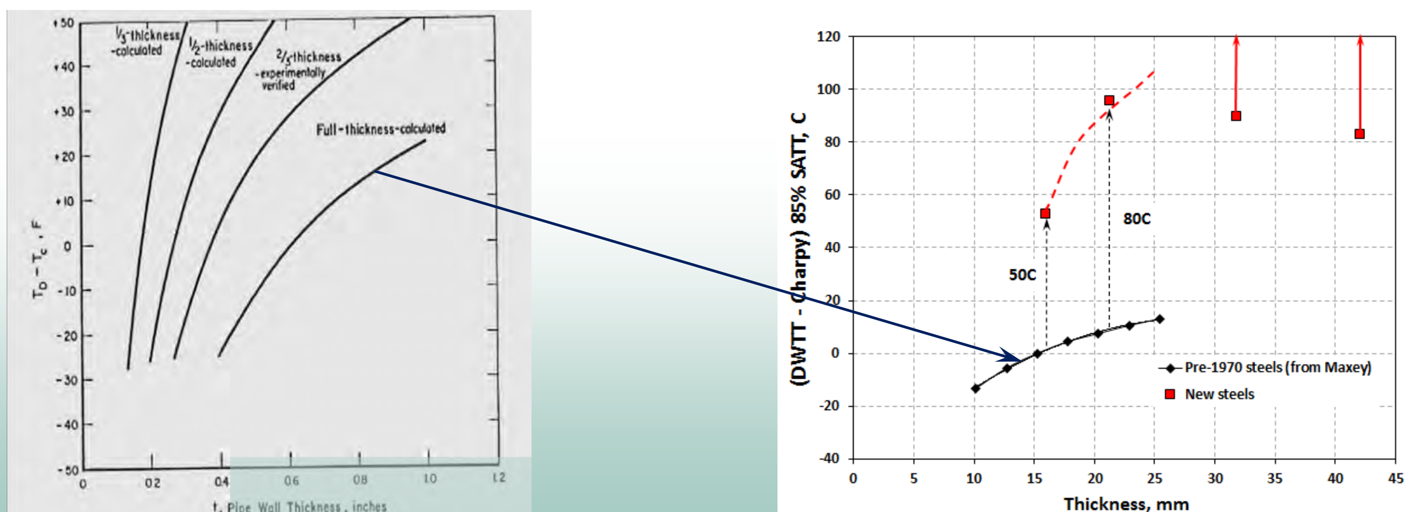
Task 3 – Leak Versus Break Predictions - Objectives

- ***Minor effort in Phase I program***
  - ***Newer high-grade steels frequently have very low sulphur content, and so have very high Charpy upper-shelf energy values.***
  - ***Correlation between Charpy energy and the material fracture initiation toughness for a sharp crack is quite different than older linepipe.***
  - ***Corrosion flaw failure criterion based may be based on ultimate strength, but critical TWC for leak/break consideration based on flow stress.***



Task 3 – Leak Versus Break Predictions - Objectives

- ***Minor effort in Phase I program***
  - ***B31G – 2012 Paragraph 1.7(e) says "(e) Pipe body material may be considered to have adequate ductile fracture initiation properties for purposes of this Standard if the material operates at a temperature no colder than 100°F (55°C) below the temperature at which 85% shear appearance is observed in a Charpy V-notched impact test.***
    - ***True for older line-pipe steels with less than 200J of Charpy energy – PRCI project conducted at Emc^2. (Blunt-notch SENT data shown in prior figures showed that.)***
    - ***However, new low-sulfur, high-Charpy-energy, line-pipe steels (X60-X80), are susceptible to brittle fracture propagation at lower temperature than from API 5L3 DWTT testing and Charpy results – other R&D efforts underway.***
      - ***Fracture initiation temperature for surface flaw related to DWTT transition temperature***
      - ***Can't trust Charpy transition temperature for new line-pipe steels!!!***



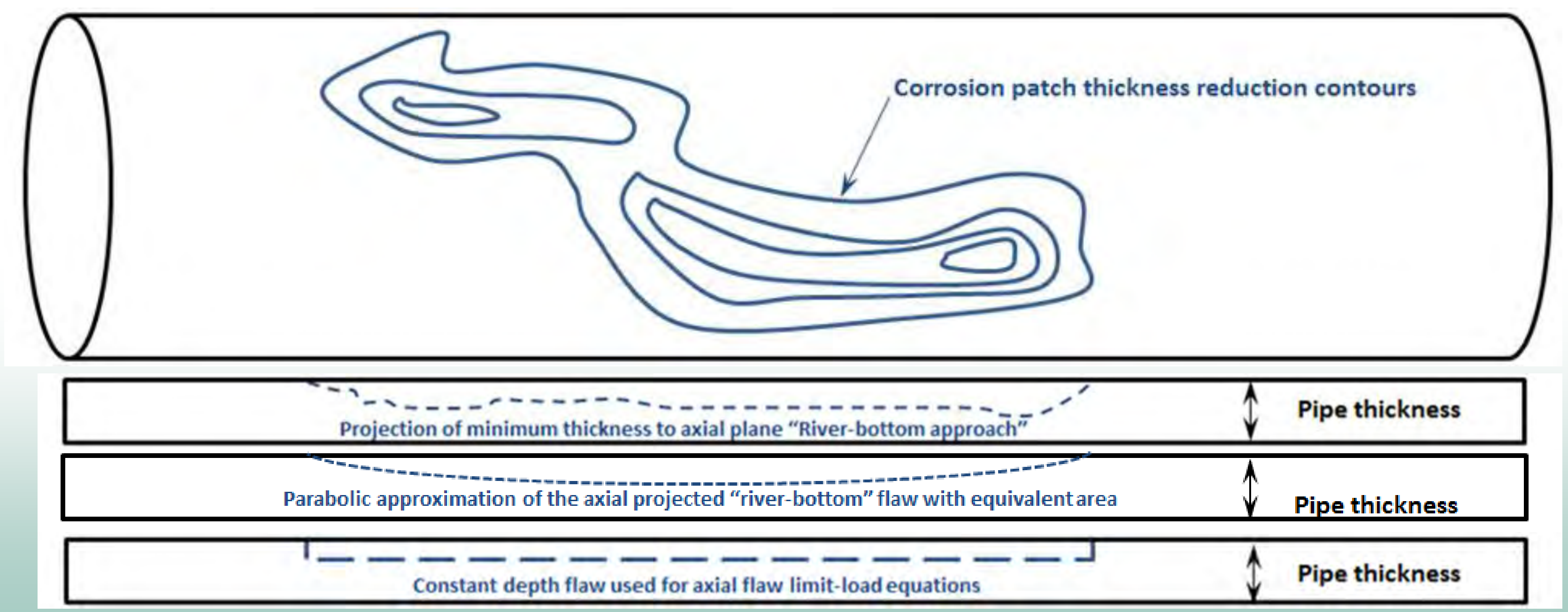
Task 3 – Leak Versus Break Predictions - Plans

- **Minor effort in Phase I program – Experience available**
  - John Kiefner involved with initial development of axial surface cracked pipe failure criterion
  - Mike Rosenfeld involved with B31G/B31.8 and recent changes
  - Brian Leis reviewed past corrosion and planar flawed pipe work as part of PRCI past efforts
  - Gery Wilkowski conducted many past pipe tests with axial flaws, very familiar with brittle-to-ductile transition temperature problems with DWTT for high Charpy energy steels
  - Do-Jun Shim showed lower axial surface crack bulging factor than Battelle equation for in PRCI project, and also examined axial through-wall-crack failure in new X70-X80 steels

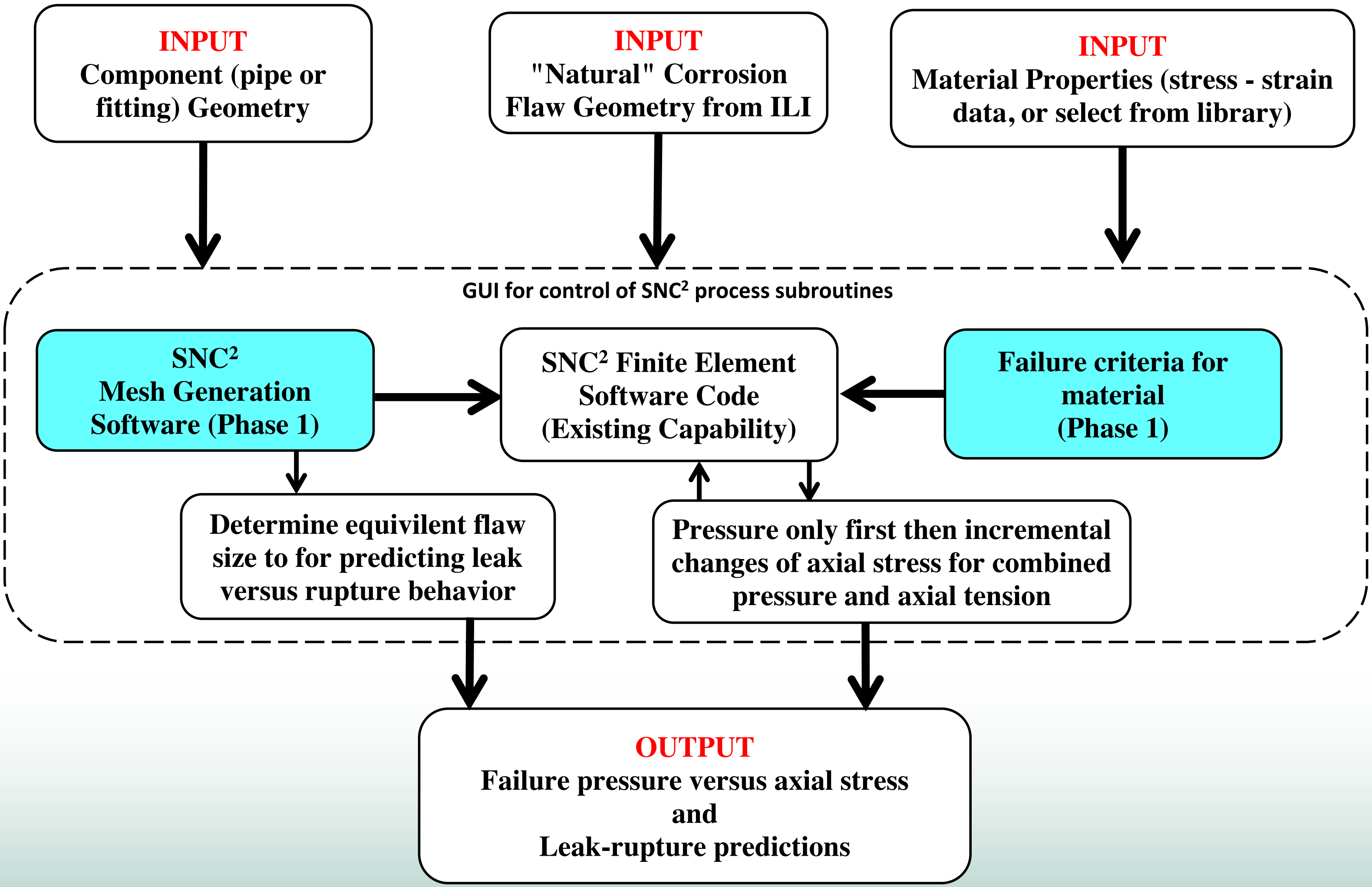
- **Plans**
  - Show potential differences in leak/break behavior for corrosion flaws than for planar flaws

Task 4 – SNC^2 Methodology - Objectives

- ***Corrosion criteria such as B31G require many simplifying assumptions to make predictions of failure pressure for complex corrosion flaw geometries.***
  - ***Develop corrosion contours plot for case of interest***
  - ***Determine river-bottom contour and project to axial plane***
  - ***Calculate area loss***
  - ***Calculate equivalent flaw depth (originally parabolic shape) to get a constant depth flaw for axial surface flaw limit-load equation***



Task 4 – SNC^2 Methodology



Two highlighted Items will be the critical focus of Phase 1 feasibility effort

Task 4 – SNC^2 Methodology - Objectives

- Establish method to allow any user to get refined solution by automated procedure on the Cloud at trivial cost – B31G Level 3 approach
  - Construct automated FE meshing software for complicated corrosion profiles from any user input – matrix of flaw depth measurements is corroded area is input along with general pipe geometry
  - This is trivial FE meshing software compared to other Emc^2 automatic meshing programs for complicated shapes or cracked plates, pipes, elbows
  - User to define material property input – guidance from this program what is needed for failure criteria
  - WARP3D FE solver to be used on Cloud for calculating failure pressure versus longitudinal stress in straight pipe (in Phase I) or elbows
  - More precise margins on failure pressure possible to assist in repair/replacement decisions and operating intervals for next inspection.

- Emc^2 already working with OSU Super Computer Center for hosting other FE-based software for Cloud computing
  - Virtual Fabrication Technology (VFT) for weld residual stress and manufacturing distortion control – DOE SBIR Phase II project

Task 4 – SNC^2 Methodology - Plans

- **Task conducted by Emc^2 staff**
  - Drs. Ed Punch, Bud Brust, and Do-Jun Shim familiar with automated FE meshing and use of WARP3D and ABAQUS FE solvers
- **Develop general mesh generator for corroded pipe**
  - Conduct trial cases on Emc^2 computer system at this time
  - Sample cases supplied by Kiefner & Associates from past corroded pipe tests
  - Mesh size needs to be sensitive enough to pick up notch acuity influences
- **Solve some initial problems with ABAQUS and WARP3D for validation of software solutions before validation against experiments in Task 5**
  - Mesh refinement requirements,
  - Hoop stress and axial tension loading (axial stress not in B31G),
  - Use actual stress-strain curves (not Ramberg-Osgood approximations)

Task 5 – Confirm Feasibility of SNC^2 – Objectives and Plans

- **First level of verification of SNC^2 is to predict the pipe burst test data for older X52 pipe with a complex corrosion shape for a key burst test (data from Task 1)**
  - Need very good documentation of corrosion contours, corrosion morphology (any roughness or notch radii information), material strength, and burst test failure pressure
  - Cases where B31G/Mod B31G are overly conservative or nonconservative to choose from
  - Accuracy of predicting this older pipe burst behavior is validation of failure criterion
- **Failure criterion to be developed based on Task 2 results and FE analyses of SENT tests**
- **Repeat the pipe/corrosion FE model analysis, using material properties for X80 pipe data from Task 2**
  - Compare failure predictions to B31G/Modified B31G

Task 6 – Program Management, Deliverables, Schedule, etc.

			DOT Phase 1 SBIR Program			
TASK	**Months**					
	1	**2**	**3**	**4**	**5**	**6**
Task 1	█					
Task 2		█	█			
Task 3		█	█	█		
Task 4				█	█	
Task 5		█	█	█		
Task 6	––––Δ		––––Δ		––––Δ	
Final Report						█

- ***Tasks 2, 3 and 5 will be on-going simultaneously during Phase 1 effort***

Deliverables and Schedule

Deliverable	Original Schedule	Updated Schedule
Technical Brief	Feb 28, 2015	Completed
Interim Progress Report 1	March 31, 2015	April 15, 2015
Interim Progress Report 2	May 31, 2015	May 31, 2015
Final Report	July 31, 2015	July 31, 2015
Documentation Media	July 31, 2016	July 31, 2016

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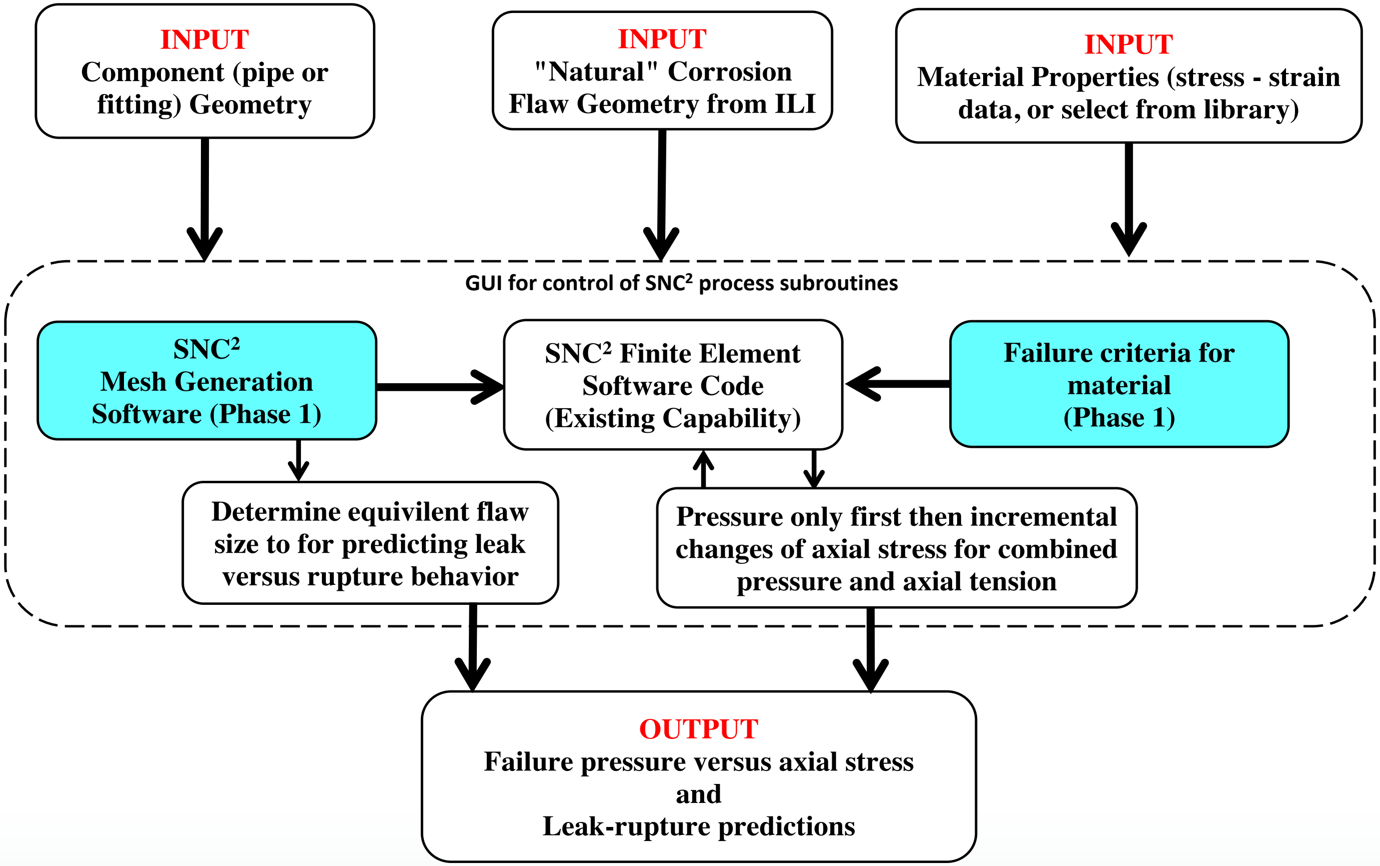
Phase 2 – Plans [GET FEEDBACK DURING MEETING]



- ***Full-Scale Burst Test Experiments for Verification***
- ***Complete the Development of SNC² Code for B31G Level 3***
  - ***Potential improvements to B31G Level 1 and 2 approaches***
  - ***Applicable to longitudinal stress considerations – not in B31G***
  - ***Applicable to circumferential/helical corrosion – not necessarily in B31G***

Questions ???