BR (Basic Rupture Risk) A Framework to Improve the Likelihood of the Failure Consequence

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Abstract

This paper is a summary/review of "Review the Intent and Safety Impact of Hoop Stress and Percentage of Specified Minimum Yield Stress Boundaries on Natural Gas Transmission and Distribution Pipelines" a PHMSA and GTI OTD R&D project. This summary represents the culmination of a comprehensive effort to provide a simple set of criteria for use by operators and regulators for systems governed by US Department of Transportation regulations DOT/PHMSA 49CFR Part 192 Subpart O and Subpart P code requirements. The approach leverages systematic processes, an extensive range of failure calculations, underpinned by deep, rigorous statistical analyses, to achieve and confirm the project results. This paper summarizes the scope undertaken, highlighting the major activities executed. The large detailed report can be found at: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=845

Overview

SMYS – Specified Minimum Yield Stress

The practice of limiting operating stress to a fraction of the specified minimum yield stress (SMYS) remains a good engineering "historical rule of thumb" to maintain safety as an integral part of the regulations. Engineers are taught to produce designs such that the maximum stress due to internal pressure never exceeds some fraction the elastic range for steel (SMYS), defined as the % stress ratio. This practice ensures pipelines always behave elastically without permanent deformation.

The class 1 division 2 maximum stress ratio of 72% SMYS was based on limiting designs to 80% of the old mill test pressures which at that time were 90% SMYS. When more people are present (class 2, 3 & 4), engineers increase wall thicknesses to reduce the possibility of failure from time-dependent deterioration like corrosion or fatigue and mechanical damage such as dig-ins.

Design practice requires increasing the wall thickness from class 1 (72% SMYS) to class 2 (60% SMYS) to address surcharge loads at crossings. In class 3 (50% SMYS) requires a further wall thickness increase to address station fatigue and extend corrosion penetration time in populated suburban areas. In class 4 (40% SMYS), there are 4-story apartments, and even thicker pipe wall helps prevent dig-in damage and further extends the time for corrosion penetration. Finally, distribution systems (<20% SMYS) in urban areas require even thicker pipe wall to provide additional protection from dig-ins and to extend the time for corrosion penetration. These engineered safety improvements were added to B31.8 in 1955 before the invention of modern inspection tools to locate, size, and assess corrosion and cracking damage.

The stress ratio is found in ASME B31.8S, where the failure pressure over MAOP is defined as the pressure safety factor. The reinspection intervals for stress ratio categories are provided in this

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standard and require a range of responses from immediate to scheduled, with the later having a magnitude related to the magnitude of the stress ratio.

Operating Pressure / Failure Pressure

This report introduces a failure pressure ratio defined as the operating pressure (P) / failure pressure (Pf). The predicted failure pressure is based on the use of fracture equations given the geometry of the flaw and the material properties of the steel pipe. This can include the properties of the weld and heat affected zones as well.

Low ratios of P/Pf, (like MAOP/SMYS), indicate an increased level of safety. As the P/Pf ratio approaches unity, failure is expected. The P/Pf ratio is shown as the x-axis of the project Baseline Risk of rupture (BR) diagram and is an improved alternative to the % SMYS approach because the defect geometry is calculated and incorporated explicitly instead of by applying a simple safety factor. Stated another way, each calculation in the full report accounted for defect size directly – relying on the fracture equations instead of a safety factor "rule of thumb."

Pipeline Impact Radius

To improve the usefulness of the project Baseline Risk of rupture diagram, the Y-axis is defined as the Potential Impact Radius (PIR) equation from 192 Part O. The inputs of diameter and operating pressure estimate the size of the high consequence screening area (HCA) where people and other receptors could be exposed to a significant, possibly lethal, dosage of thermal radiation from burning natural gas.

The safety of the system decreases or damage potential increases as increasing failure pressure and diameter, increase the area impacted. As any plotted point (X, Y) moves farther away from the origin, both the P/Pf ratio increases as the HCA size also increases. Failure by leak or rupture is highly dependent on material properties and the defect geometry, and this is addressed by the Failure Mode analysis found in Chapter 5 of the report, falling in one of three categories:

1. All defects of a given size are expected to fail as a leak,
2. There is a mixture of cracks that leak and corrosion (non-crack like) that rupture for a given defect size, and
3. All defects of a given size are expected to fail as a rupture.

This approach solves the leak-before-rupture quandary that the % SMYS stress ratio was roughly or anecdotally trying to approximate, but unable to define quantitative boundaries due to a lack of a sound technical basis. Additionally, the BR plot allows collapsing three separate plots for crack failures, wall loss failures, and the leak rupture boundary into a single plot. Detailed discussion is provided in the Sensitivity Study, Chapter 5 of the report. Capable engineers who have all the TVC

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information and can use API 579/ASME FFS and the Maxey/Folias equation can repeat what has been done in this report from first principles. For those lines that are missing information, this project will predict the leak/rupture failures and established these boundaries having the full range of pipe diameter, wall thickness, yield strength or grade, Cvn toughness, defect length and depth, and with typical operating pressures found in the PHMSA incident data report.

Engineers lacking data no longer need to guess at the leak or rupture outcome. Historically the rule of thumb was that ruptures generally occur above 30% SMYS, rarely below; while many failures actually leaked rather than ruptured at much higher stress ratio values, some even above 40% SMYS. With the body of work methodology presented in this report, we now have tools to calculate the actual boundary and determine if the pipe will fail as a leak or not. The diagram can be conservatively used knowing just the pipeline diameter, MAOP, and SMYS. Ruptures use the full PIR, while leaks use a simple process to derate the PIR area.

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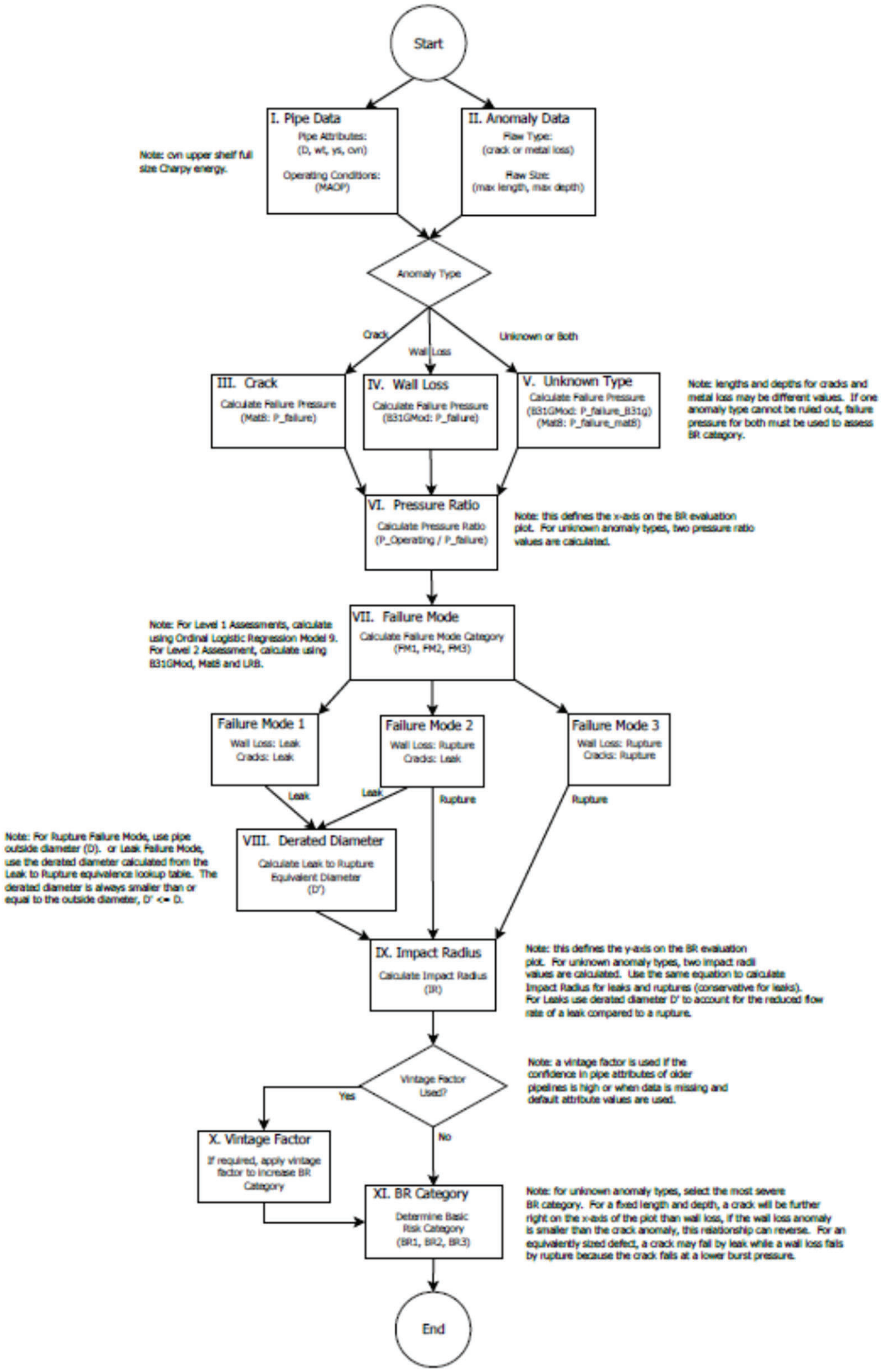

Figure 1. IMP process flow diagram.

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Basic Risk of Rupture Framework

The report summarizes the results of our calculations as a set of "clean sheet", two-dimensional plots, that we call a Basic Risk of rupture (BR) plot. This new plot shows the progression from safer to less safe areas. Each progression away from the origin requires better knowledge of the materials and defect geometry: moving from the simpler (BR 1) to the larger (BR 3) consequence outcome.

The Integrity Management Process Flow diagram for those that can calculate the leak/rupture for their pipe is found in Figure 1 and provides the BR Framework. Chapter 6 of the full report contains the vast amount of validation and calibration (as multidimensional calculations) demonstrating that leaks or ruptures are correctly represented in this two-dimensional BR Framework of Figure 2.
The Basic Risk Framework proposed in this report requires calculating and plotting each specific case on:

1. The Y-axis: The potential impact radius increases with increasing diameter and line pressure.
    a. As the pressure and/or diameter increase, the number of receptors impacted within the PIR circle is likely to increase.
2. The X-axis: The operating pressure divided by the predicted failure pressure, the closer the operating pressure is to the failure pressure the farther the ratio moves away from the origin.
    a. As the damage progresses with time it reduces the failure pressure, and the pressure ratio moves to the right decreasing the safety ratio.
    b. As the operating pressure is lowered the safety ratio increases, moving the pressure ratio to the left increasing safety. (i.e. lowering operating pressures during repair.)
    c. As the analysis progresses from BR 1 through BR 3 increasing knowledge is required. (i.e. 192, from P to O)

The BR framework combines into a single point representation the:

- pressure ratio (akin to the reducing safety margin and/or surrogate for prospect of failure)
- impact area of a rupture failure (akin to bigger damage extent of an ignited rupture).
- leak or rupture failure mode categories (akin to 2nd severity consequence of failure),

all to identify the level of integrity management required (considering the overall vector (length and angle) as defined by the BR categories.

The framework is plotted in Figure 2. The PIR model that defines the y-axis is a single-point vertical jet fire model that defines a boundary based on a 1% mortality radiation intensity threshold for a 30-second exposure. As the impact radius increases, the BR level and the associated integrity management requirements increase. Horizontal thresholds are defined at 100-foot and 330-foot impact radii - commensurate with current thresholds in the regulations and based on sound historical risk principles. The specific boundaries between the three BR zones are very deliberately set and each boundary and each cross over point is explained in detail in the report.

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Examples of Leak vs. Rupture Boundary Considerations

The leak/rupture boundary calculation is built into the solutions in the report; the BR framework plots beginning with Figure 111 provide examples of the how failure modes, leak and rupture, interrelate with the BR regions which are themselves each separately colored. The failure mode plotted as a hollow marker, will leak for both cracks (triangle marker) and wall loss by corrosion (circle marker). A filled in triangle or filled in circle will rupture for both cracks and wall loss, respectively. These solutions plotted as the triangles or the circles are overlaid on top of the Basic Risk zones, where BR 1 is green, BR 2 is blue, and BR 3 is orange.

The movement away from the origin into a higher BR region suggests increasingly higher levels of system knowledge and effort in managing asset integrity. Conversely, the closer the plotted point is to the origin, the safer the system, and the required analysis simplifies.

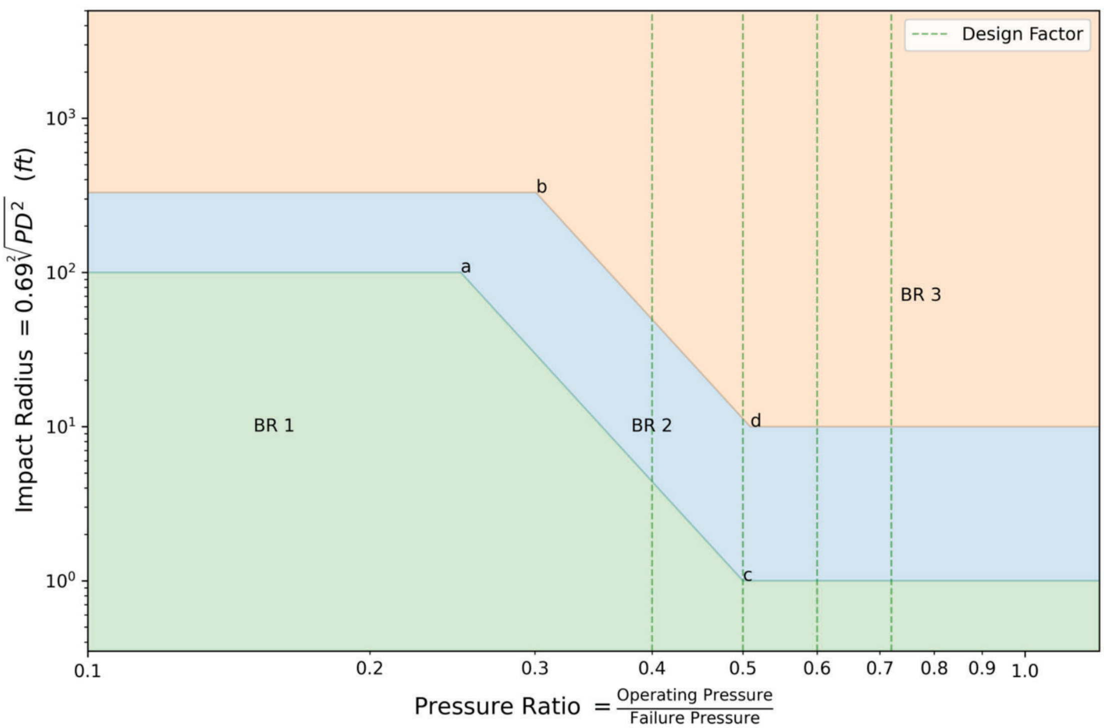

Figure 2. BR Boundaries for actual rupture or leak-equivalent rupture

Risk and Integrity Management Considerations

This simplified two-dimensional safety methodology is fully discussed in Chapter 6.1 of the report. It requires the use of the well-established fracture/failure equations interrelated in Chapter 5 to calculate the failure pressure. The operating pressure is defined by the company.

The ratio of these two define the X value, instead of % SMYS it becomes % failure pressure. The new Y-axis is established by the PIR equation which assumes rupture. The larger the value of

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0.69√PD2 the larger the area enclosing thermal radiation receptors such as people or property. If the failure solutions predict a leak for a crack and/or wall loss, then the defined process based on the defect length is used to estimate an equivalent leak hole size. This hole size is used to adjust the diameter value as directed, reducing the size of the PIR area and allows replotting of the Y-Axis value on the same BR plot. This makes comparisons straightforward and provides a consistent way to compare basic consequence magnitude.

In general, distribution systems represent a lower P/Pf ratio and are expected to leak generating even smaller PIRs. Distribution lines, because they plot close to the origin, fall into the simpler monitoring and knowledge effort region (BR1). The larger diameter interstate pipelines are expected to have higher P/Pf ratios due to the higher design factor. These Class 1 pipes are more likely to rupture having the largest PIRs. The X & Y plotted points for large diameter high pressure pipes vector furthest from the origin and typically will fall into the highest effort region (BR3) expecting the most knowledge and monitoring effort.

Chapter 6.2 defines the precise method to determine if a failure will be a stable leak or a rupture. There are two "Levels" of analysis to calculate the core physical/material models. Level 1 which is a high confidence ordinal logistic model developed and explained in Chapter 5. Adding vintage adjustment factors; Level 2, employs the three failure/fracture model equations directly with a range of input factors - to also appropriately account for uncertainty in the pipeline input attributes to the calculation.

Chapter 6.3 outlines the Basic Framework with requirements within the zones. Hundreds of thousands of realistic case calculations were used to confirm line placements and inflections. It shows how the intersection points on the X and Y-axis agree with historical observations, and it discusses and reviews the effect of ignition probability on the PIR which always assumed no ignition delay.

Chapter 6.4 addresses the Leak Derating Factor. Leaks release a smaller rate of product because the hole can be considerably small in cross section compared to full bore ruptures. The methodology used to down-rate leaks to an equivalent percentage of the pipeline diameter is addressed in 6.4. The leak is then reduced to an equivalent diameter to be used in the PIR or Y-axis calculation. The leak derating reduces the diameter value moving the Y-axis lower, therefore moving the calculation to a lower BR category. Examples are given in 6.7.

Chapter 6.5 addresses historical Vintage Pipe Derating Factor is used when there are TVC gaps. It is based on a standard methodology to address pipe attributes for different decades as the technology evolved and improved. Vintage pipe generally lacks some attribute details such as seam type, toughness, or another property, which makes calculations less certain.

The derating method can be adjusted by the operator for their unique system based on the systematic approach in this report to address their range of manufacturing, and construction practices across

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decades, such as evolving standards, different steel making processes, changing pipe mill test levels and gradually improving inspection expectations, plus the variety of construction practices, girth welding techniques, inspection quality and levels of preservice pressure testing.
Pipeline history was discussed in detail in chapter 2 Regulatory Review, Chapter 3 Literature Search, and past pipe performance based on the PHMSA Incident records in Chapter 4 Incident Databases. Together these chapters support both the ranges of each design of experiment (DOE) inputs to the calculations and the vintage pipe derating methodology outlined in 6.5.

The vintage pipe derating is used to lower the Pf which in turn moves the ratio to the right along the X-axis, decreasing the safety ratio, and can move an outcome from the BR1 area all the way into the BR3 field. Similarly, the use of the suggested vintage adjustment requires collecting additional anomaly data in the pipe segment to support moving away from derating and possible rupture. These steps result in increasing engineering rigor and may require a higher priority to complete the analysis and address extra mitigation responses for the inspection findings. These extra efforts help justify filling gaps in historical traceable, verifiable, and complete (TVC) records to minimize an extra-ordinary effort to complete all the missing data and ensure a proper quantitative engineering analysis before an incident may happen. Examples are presented.

Chapter 6.6 discusses considerations for the Prevention and Mitigation activities such as the response activity(s) following integrity assessments.

Section 6.7 provides the process flow diagram to conduct this improved integrity analysis giving much more information beyond a MAOP/SMYS ratio. This Chapter also contains worked examples showing how pressure, diameter, and wall thickness changes can help or hinder rupture.

Chapter 7: Gap Analysis - locates the gaps between the current US DOT/PHMSA CFR 49 Part 192 code requirements for integrity management programs and the framework defined in this project.

Chapter 8: Recommendations - provide recommendations to extend the work and to make better use of this report.

The recommendations were as follows:

1. **Consequence Receptors:** In this project, incorporation of specific consequence receptors was out of the project scope. To develop the Basic Risk levels into a Quantitative Risk, the consequence receptors and consequence models must be layered into the basic risk structure defined here.
2. **Probability of Failure:** The basic risk levels defined here are intended to categorize levels of integrity practice to help define regulatory leak/rupture boundaries for operation. To enhance this, the uncertainties in independent variables should be quantified and combined with recommendation 1 to produce a quantitative risk measure.

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3. **Basic Risk Categories:** The basic risk of rupture categories defined in this project may be used to inform when a more rigorous approach is needed. It is recommended that evaluated cases resulting in a Basic Risk Category 3 use a more rigorous risk evaluation.
4. **IMP Levels:** The Basic Risk Categories do not define requirements for an integrity management program. It is recommended that the basic risk categories be used to develop integrity management levels and that the process consider the appropriate stakeholder input.
5. **Regulatory Workflow:** To make this process practical and repeatable, it is recommended that the necessary regulatory language needed to implement the concepts described in this report be developed. This should include an FAQ, audit checklist, and identification of practices and regulator code language that reduces ambiguity and misinterpretation before enforcement.

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    - Public project web page at: https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=845
- Operations Technology Development, under project OTD 4.20.a.
    - Further information available at: https://www.otd-co.org

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