EXHIBIT 2

EVALUATION OF PIPELINE DESIGN FACTORS

TASK REPORT

(August 1999 – January 2000)

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Prepared by:

Evangelos Michalopoulos and Sandy Babka

The Hartford Steam Boiler Inspection and Insurance Company
One State Street
Hartford, CT 06102

Prepared for:

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GRI Project Manager
K.G. Leewis
Pipeline Business Unit

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13. ABSTRACT

This report presents a summary and assessment of design margins used in major pipeline design codes of the U.S. and several other countries. The historical development of the design factors in the ASME B31.8 code is traced. The concept of the traditional historical factor of safety or design margin is related to the more recent developments in reliability-based or limit state design. These are compared to risk-based methods. Based on this review it is recommended that the B31.8 Code Committee begin an in-depth study of the current design practices used for pipelines to take advantage of major improvements in design, construction, materials, welding, and other quality related factors over the last 65 years. It is also recommended that the B31.8 Committee begin to incorporate some form of reliability based, limit states design or some specified risk assessment concepts in pipeline design in order to remain competitive in the international market. Such an undertaking will re-establish the historical leadership role of B31.8 and ASME in the development of international pipeline standards. More importantly, the incorporation of risk based principles should result in reduced risk, improved safety, reduced losses and more economic design, construction and operations of pipelines.

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Research Summary

TITLE:	Evaluation of pipeline design factors
CONTRACTOR:	The Hartford Steam Boiler Inspection and Insurance Co. GRI Contract No. 7094
PRINCIPAL INVESTIGATOR:	Evangelos Michalopoulos and Sandy Babka
REPORT PERIOD:	August 1999 through January 2000
OBJECTIVES:	To present a summary of design factors from major gas transmission pipeline codes and compare them to recent developments in reliability-based methods in order determine if a change in the design factors of B31.8 is feasible.
TECHNICAL PERSPECTIVE:	The design factors in the B31.8 Code have been in existence for several decades. Over the years there have been improvements in material manufacturing, fabrication, and examination. An examination of these improvements with respect to the existing design factors combined with risk based techniques should improve the design factors. Thus, the pipelines can be constructed more economically without compromising the long safety record.
RESULTS:	This report compiles several gas pipeline codes from the U.S. and other countries and compares the design factors. Risk based methods were also reviewed in an effort to validate their use to improve the existing design factors of B31.8.
TECHNICAL APPROACH:	A literature review was performed to establish the history of the B31.8 Code. Pipeline design codes from the U.S. and several other countries were researched to establish the design factors and the methods used in determining the factors. Risk based methods were examine to ascertain the validity of using them to improve upon the current factors.
PROJECT IMPLICATIONS:	
PROJECT MANAGERS:	GRI Project Manager Dr. Keith Leewis Pipeline Business Unit

EXECUTIVE SUMMARY

This report presents a summary and assessment of design margins used in major U.S. and international pipeline codes.

The historical development of the design factors in the ASME B31.8 code is traced. The major design factors and associated formulas in design codes from the U.S. and several other countries are summarized. The concept of the traditional historical factor of safety or design margin is related to the more recent developments in reliability-based or limit state design. These are compared to risk-based methods.

Based on this review it is recommended that the B31.8 Code Committee begin an in-depth study of the current design practices used for pipelines to take advantage of major improvements in the design, construction, testing, examination, material, welding, analytical techniques and other quality related factors over the last 65 years. The ASME Boiler and Pressure Vessel Code Committee has undertaken such a task in the past few years resulting in an improvement in the design margins for their respective Codes (Upitis and Mokhtarian, 1996 and 1997). This study, performed by the Pressure Vessel Research Council, resulted in a change in the design margin on tensile stress. The margins on yield stress for the Boiler and Pressure Vessel Codes remained unchanged. The design margins in the ASME B & PV Codes, several of the other ASME Piping Codes and the international pressure vessel codes take into consideration the complex configurations of many vessels and more types of loadings, such as thermal and cyclic stresses and areas of stress discontinuities. Transmission piping systems are "simpler" structures, which in most cases are not subject to the same complex design and loading issues as pressure vessels. The design factors in B31.8 are on the Specified Minimum Yield Stress (SMYS). It is believed that the improvements in quality related factors can be taken advantage of in order to improve on the existing design factors.

The potential design factors are summarized in the conclusions and recommendation section, Chapter 9 of this report. The changes in the design factors in B31.8 would result in increases of the design pressure (or maximum operating allowable pressure, MAOP) in the order of 0% to 15% depending on the class location along the pipeline route.

It is also recommended that DOT incorporate the current ASME B31.8 Code requirements in its Pipeline Safety Regulations, Code of Federal Regulations CFR Part 192. The recommended changes in the design factors would result in increases in the DOT allowable design pressure on the order of 6% to 15% depending on the class location.

An additional recommendation is that B31.8 Committee take a leadership role in the development and incorporation of rigorous risk-based design rules. A number of international codes have adopted some forms of reliability based or limit states design and some specified risk assessment concepts in pipeline design. To date, none of the international codes have begun to incorporate design rules based on rigorous risk principles. Such an undertaking will re-establish the historical leadership role of B31.8 and ASME in the development of international pipeline and pressure equipment standards. More importantly, the incorporation of risk based principles should result in reduced risk, improved safety, reduced losses and more economic design, construction and operations of pipelines.

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CHAPTER 1

INTRODUCTION

This report presents a summary and assessment of design margins used in domestic and international pipeline codes throughout the world. Potential changes to the design factors contained in the U.S. pipeline regulations and codes have been recommended as a result of this review. The recommendations allow an increase in the design pressure in many pipelines.

The historical development of the design factors in the ASME B31.8 code is traced in Chapter 2. Design formulas and design requirements in domestic and major international codes are summarized in Chapter 3. The basic design factors are summarized in Chapter 4. Chapter 5 gives an introduction to the traditional historical factor of safety used in various ASME boiler, pressure vessel and piping codes and its relationship to reliability. The concepts of safety factors, design margins and reliability are related in Chapter 6. Reliability and risk-based concepts are presented in Chapter 7. Chapter 8 presents an assessment of present pipeline design margins used as the basis for the recommendations presented in Chapter 9.

The recommended design factors are summarized in the conclusions and recommendations section, Chapter 9 of this report. The changes in the design factors in B31.8 would permit an increase in the design pressure (or maximum operating allowable pressure, MAOP) on the order of 0% to 15% depending on the class location along the pipeline route. Similar changes to DOT rules to make them consistent with recommended B31.8 rules would result in design pressure increases in the order of 6% to 15% depending on the class location.

CHAPTER 2

HISTORICAL REVIEW OF PIPELINE SAFETY MARGINS

Introduction

This chapter contains a historical summary of the safety or design margins in the ASME B31.8 pipeline code. The summary is liberally extracted from Reference 1, the forward of Reference 2 and Reference 8.

Background of B31.8

The code for natural gas pipelines began in the U.S. as a part of the American Standards Association Code for Pressure Piping, ASA B31.1. This code was originally published in 1935 as an American Tentative Standard Code for Pressure Piping covering Power, Gas, Air, Oil and District Boating. After adding Refrigeration to the scope, the ASA B31.1 was published as the American Standard Code for Pressure Piping in 1942. After this time there were additions and/or supplements published in 1944, 1947, and 1951. In all these publications the gas code was characterized under Section 2, Gas and Air Piping Systems. In 1952, the code was subdivided and the gas code became the Gas Transmission and Distribution Piping Systems issued as ASA B31.1.8. This document incorporated material from Sections 2, 6 and 7 of the 1951 Edition of the Pressure Piping Code making it a stand-alone code. In 1952 a new committee was organized to write code material for the new Section 8. The committee was charged with developing code requirements to reflect new materials and methods of construction and operations. The committee made many changes and introduced in the code the design philosophy and concept for the class location. These were incorporated and published in ASA B31.1.8 in 1955. In 1958 further revisions were published in ASA B31.8. Since that time the Section 8 Code Committee has published revisions in 1963, 1966, 1967, 1968, 1975, 1982, 1986, 1989, 1992, and 1995.

Origin of the 72 percent of the SMYS

The appropriate Maximum Allowable Operating Pressure (MAOP) for pipelines was one of the fundamental issues that had to be resolved. The committee had to find some basis for establishing the MAOP for pipelines. Many operators believed that the MAOP should be based on a test pressure. The problem was that pipeline operators were utilizing a wide variety of field pressure tests. Some operators were testing pipelines at 5 to 10 psig over operating pressure. One reason for these relatively low test pressures was that testing was done with gas. In order to establish a consistent rule, the committee thought that a good method would be to base the MAOP on the mill test. Customarily the mill test was 90 percent of the Specified Minimum Yield Strength (SMYS), which would apply to all pipes. The committees agreed that to be consistent, and based on current safe practice, the MAOP for cross-country pipelines should be

80 percent of the 90 percent of SMYS mill test, which is equivalent to 72 percent of the SMYS. The 72 percent of SMYS first appeared in 1935 in the American Standards Association Code for Pressure Piping, ASA B31.1.

The 1951 Edition of the B31.1 Code (ASA B31.1.8), for cross country pipelines included the 72 percent SMYS (80% of 90% mill test) and provided an equation (Barlow) to define wall thickness based on this maximum pressure and nominal wall thickness. Based on good engineering practice and a relatively safe record dating back to early last century, pipeline designs required thicker wall pipe in locations with higher population densities. The B31.1.8 code further identified a thicker wall pipe (or lower stress) for pipe in compressor stations which was limited to a percentage of the 80 percent of mill test as a function of diameter which was; 22% for 0.405 inch OD and smaller pipe; 49% for 3.5 inch OD pipe; 72% for 8.625 inch OD pipe and 90% for 24 inch OD and larger pipe. Therefore, for large diameter pipe in compressor stations percent of SMYS allowed would have been 90% x 80% x 90% hence 65% of SMYS. The only other limit on MAOP was 50 percent SMYS inside boundaries of cities and villages.

As mentioned previously the gas code was first issued as a stand-alone code in 1952 in ASA B31.1.8 Gas Transmission and Distribution Piping Systems. The Section 8 Code Committee was charged with the responsibility of maintaining and updating the code. Over a two and one half year period this Committee developed the ASA B31.1.8 – 1955 Gas Transmission and Distribution Piping Systems Code. During this time the MAOP was one of the items that was considered. Prior to the 1955 Edition of B31.1.8 time the gas transmission code limited the MAOP to 72 percent SMYS (80% of the mill test) in all locations except "inside incorporated limits of towns and cities" and certain limits in compressor stations. The MAOP in these areas were limited to 50% in towns and 63% in compressor stations.

Some committee members believed that MAOP should be based on the field test. Hydrostatic testing with a water column was performed by some operators at much higher pressures than had been performed in the past. However, other operators had done and were doing field pressure tests with gas at much lower pressures since hydrostatically testing at higher pressures was unacceptable to these operators. For this reason basing MAOP on testing was unacceptable. The consensus solution was finally found in adopting the long established practice of using 80 percent of 90 percent mill test pressure for MAOP in cross-country pipelines.

There was a realization by this Committee that there was a need to consider intermediate levels of pipeline stress levels (or wall thicknesses) based on population density and other special conditions.

Establishing Appropriate Wall Thickness (Stress Levels) for Class Locations

In 1955 the second edition of the American Standard Code for Pressure Piping, Section 8, ASA B31.1.8 – 1955 Gas Transmission and Distribution Piping Systems was published. This document was the first to designate four types of construction to be used based on population density. Prior to this, the old code generally permitted a maximum operating hoop stress of 72 % SMYS in all locations except those inside incorporated limits of cities and towns. In these areas a heavier wall thickness was required and operational history had shown that a maximum hoop stress of approximately 50% SMYS should be specified. By specifying maximum hoop stress the designs could be simplified and all diameters of pipe would be accounted for. Between 1952 and 1955 the Section 8 Subcommittee realized that there was a need to differentiate areas of population density and establish hoop stress limits below 72% SMYS that would be appropriate in each area to protect the public safety. Many operators were reducing the stress levels below 72% SMYS in certain areas although there was no code criteria to indicate what intermediate stress levels should be used for the various degrees of population density. These operators had adopted various lower stress levels for population density areas, as well as, road and railroad crossings but the criteria were not uniform among operators.

In order to study and evaluate how population densities could be classified and appropriate pipe hoop stress limits could be established, the Section 8 Committee formed a subgroup to address this problem. The subgroup elected to use a ½ mile corridor with the pipeline in the centerline and establish areas of population density within the corridor in running miles along the pipeline. An aerial survey of many miles of existing major pipelines was made to see what percentages of these pipelines would be impacted by areas of population density where lower stress levels should be applied to enhance public safety. A consulting engineering firm was engaged to evaluate the results. At the time of this study, it was found that about 5% of the total pipelines surveyed would be impacted by population density requiring stress levels below 72% SMYS. The subgroup determined that the population density in the ½ mile corridor traversed by the pipeline should be evaluated according to a building count along 1 mile and 10 mile sections to establish a population index to define hoop stress limits. From this study it was determined that the following class location categorization based on a population density index was needed:

Class 1, (72% SMYS) Sparsely Populated Areas
Class 2, (60% SMYS) Moderately Developed Areas
Class 3, (50% SMYS) Developed Residential and Commercial
Class 4, (40% SMYS) Heavy Traffic and Multistory Buildings

In addition, types of construction were established as follows:

Type A (72% SMYS)
Type B (60% SMYS)
Type C (50% SMYS)
Type D (40% SMYS)

The type of construction identified the wall thickness or hoop stress certain locations. For example uncased highways and railroad crossing in a Class 1 (72% SMYS) location would require a Type B (60% SMYS) construction in the crossing.

It is important to note that the ½ mile corridor width suggested establish the population density was not selected as one that would be a hazardous zone in the event of pipeline failure. The ½ mile corridor was conveniently the same as the width of typical aerial photographs of that time. The aerial photographs could be used to evaluate nearby activities that might threaten pipeline safety in the future.

Pipeline engineers assumed that the greater population density increased the chances of an incident which may cause damage to the pipeline. Some of these activities are trenching for water and sewer lines, terracing cutting for streets and other digging in the proximity of the pipeline. The lower stress levels are used so that in the event of outside damage to the pipeline from these activities the pipeline is less likely to fail and cause a hazard to the public.

The Federal Regulations 49 (CFR 192) were issued in 1970 as a result of the Pipeline Safety Act of 1968, by the Office of Pipeline Safety (OPS). Although OPS adopted much of the 1968 Edition of ASME B31.8, they reduced the corridor width from the arbitrary ½ mile to today's ¼ mile. This was done in a Notice of Proposed Rule Making (NPRM) which was as follows:

> "A recent study that included hundreds of miles of pipeline right-of-ways areas indicated that a zone of this width is not necessary to reflect the environment of the pipeline. A ¼ mile wide zone extending one-eighth of a mile on either side of the pipeline appears to be equally appropriate for this purpose. It would be an unusual instance in which a population change more than one-eighth of a mile away would have an impact on the pipeline. Conversely, an accident on the pipeline would rarely have an effect on people or buildings that were more than an eighth of a mile away. For these reasons it appears that the density zone can be reduced from one-half to one-quarter of a mile without any adverse effect on safety"

Development of 80 Percent SMYS MAOP

In the early 1950's, testing equipment, procedures and technology were developed to pressure test pipelines with gas. Some operators began at higher pressures with water in contrast to the more risky testing with gas. Some operators readily recognized the value of hydrostatic testing as a new tool to prove the integrity of the pipeline. Some operators were hydrostatically testing to 100% of the actual minimum yield strength as determined by the steel mill metallurgical test. One operator determined the actual minimum yield strength by hydrostatic test and plotted the internal pressure versus pump volume. The pressure-volume plot was a straight line confirming the elasticity of the steel. The actual minimum yield strength was defined when the slope of the line became one-half the slope of the straight line elastic portion of the plot as the pipe began to yield. By using actual minimum yield strength, MAOP's much greater than those based on the 72 % of SMYS were established. This allowed operators to set the MAOP to 80% of the actual strength of the structure rather than to 80% of what the pipe mills would guarantee (i.e. 90% of the specified yield). Hydrostatic testing to SMYS provided an additional level of safety. Essentially all defects that might result in failure near MAOP and were missed by prior inspections were discovered by pressure testing to actual minimum yield strength of the pipeline.

After approximately 16 years of research, study and testing to prove the value of pressure testing to actual minimum yield strength the practice was documented and published in the AGA REPORT L 30050 (Duffy et. al 1968). Many in the pipeline industry realized the merits of hydrostatic testing to actual minimum yield to:

1) Increase the known safety margin between MAOP and test pressure
2) Prove the feasibility of operating safely above 72% SMYS with a greater known safety factor
3) Remove defects that might fail in service
4) Improve the integrity of the pipe

Based on this experience, a proposal was made around 1966 to ASME B31.8 Code Committee to allow operation the of pipelines above 72% SMYS. Unfortunately the proposal to allow the operation of pipelines at 80% SMYS received some unresolved negative votes which precluded inclusion in the 1968 Edition of ASME B31.8 (the Code). However, before the B31.8 Code Committee could resolve the negatives votes and finalize Code material to allow the operation of pipeline at 80% SMYS, the Pipeline Safety Act of 1968 was enacted. In 1968, the Office of Pipeline Safety (OPS) adopted the 1968 Edition of ASME B31.8 as an interim safety standard until 1970 at which time OPS issued the final rules, Title 49 Code of Federal Regulations Part 192 (49 CFR 192, the regulations). Title 49 CFR 192 was taken almost verbatim from the 1968 Edition of ASME B31.8, hence, the MAOP in Class 1 locations for pipelines installed after November 11, 1970 required 72% SMYS. Those pipelines built before November 11, 1970 operating above 72% SMYS could continue operating at these pressures if they qualified under the "grandfather clause" in the Federal Regulations. The "grandfather clause" essentially said not withstanding all other requirements for establishing MAOP for new pipeline that:

"...an operator may operate a segment of pipeline found to be in satisfactory condition, considering its operating and maintenance history, at the highest actual operating pressure to which the segment was subjected during the 5 years preceding July 1, 1970...",

subject to the requirements of change in class location.

The "grandfather clause" is for pipelines built before the Federal Regulations were issued. When a class location change occurs, that portion of the pipeline within the new class location must meet the requirements of a new pipeline, i.e., a pipeline under the "grandfather clause" that operates over 72% SMYS would no longer be able to operate above 72% SMYS. New pipelines constructed after the Federal Regulations were issued, could not be qualified above 72 % SMYS in the United States.

After the Federal Regulations became effective many operators failed to see a role for the ASME B31.8 in the regulatory environment. At this time the B31.8 essentially disbanded. However, in 1974 operators realized that unless the code was updated or reaffirmed by 1975 the code would be withdrawn in accordance with ASME policy. It was realized that the code was essential for bid purposes and guidance internationally. In addition, American valve manufacturers and fabricators would be forced to build to foreign specifications in the absence of the ASME B31.8 Code, which references U.S. specifications and standards for valves. It became apparent that unless the B31.8 Code was maintained that American manufacturers would be required to use foreign standards and specifications. The B31.8 Code is presently utilized in the Middle East, North and South America and many other areas internationally. Consequently, the Code Committee was reorganized in 1974 and published the 1975 Edition to preserve the Code.

In the latter part of the 1970's, the proposal to allow pipelines to operate up to 80% SMYS was again submitted to the ASME B31.8 Code Committee. The Committee worked several years to develop criteria and requirements for the design, hydrostatic testing and ductile fracture control for pipelines to be operated up to 80% SMYS. The greatest opposition came from pipe manufacturing members who were on the Committee. The pipeline operator Committee members realized that transporting gas at 80% SMYS would be a great economic advantage, however, the pipe manufacturing members envisioned reduced profits from the sale of thinner wall. The Committee finally resolved all the issues involved in design, hydrostatic testing, and ductile fracture control and approved provisions for pipelines to operate up to 80% SMYS. The allowance to operate pipelines to maximum limit in onshore Class 1 locations was published in the ASME B31.8a – 1990 Addenda to the B31.8 1989 Edition.

Conclusions

The code for natural gas pipelines originated as an American Standards Association code for pressure piping. Committee members believed that the MAOP should be based on a pressure test, however, the operators were using a wide variety of maximum field test pressures. For consistency, the Committee decided to use 80% of the pipe mill manufacturer's guarantees which were 90% minimum specified yield strength. Thus, the MAOP for rural cross country pipelines was established as 72% SMYS and was published in the 1935 Edition of the American Standards Association Code for Pressure Piping ASA B31.1.

The ASME B31.1.8 – 1955 Gas Transmission and Distribution Piping Systems was the first to designate class locations based on population density. Prior to this the code had generally allowed 72% SMYS for cross country pipelines and 50% SMYS for pipelines inside incorporated limits of town and cities. The Committee had a study done that indicated only 5% of the pipeline would require lower stress levels due to population density. The original corridor was set at ½ mile with the pipeline in the centerline. The corridor was later reduced to ¼ mile in the 1970 49 CFR 192 followed by ASME B31.8 in the 1982 Edition. As a result of a detailed study it was determined that four stress levels would be the simplest method to categorize the design factors. These four were Class 1 (72% SMYS), Class 2 (60% SMYS), Class 3 (50% SMYS), and Class 4 (40% SMYS).

Beginning in the early 1950's hydrostatic testing developed as a major tool to prove the integrity of the pipe. After many years of research and development operators realized the value of testing pipe to actual yield strength. Some operators were using the actual minimum yield strength to determine MAOP. One operator established MAOP's at 80% of the actual hydrostatic yield strength which in some cases was over 80% SMYS. Based on almost 40 years of research, testing, and operational experience, the ASME B31.8 Committee developed code requirements for establishing an 80% SMYS MAOP. This provision was published in ASME B31.8a – 1990 Addenda to the B31.8 – 1989 Edition.

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CHAPTER 3

SUMMARY OF DESIGN FORMULAS FROM VARIOUS CODES

This chapter summarizes the basic design formulas and requirements of major domestic and international pipeline codes. The main objective of this summary is to assess the design factors used in the various codes for the purpose of making recommendations to B31.8 for possible code improvements. All Codes used in this summary are current as of the date of this report.

ASME B31.4 Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids (Ref. 1)

Pressure Design of Straight Pipe (Par. 404.1.2)

The internal pressure design wall thickness, t, of steel pipe shall be calculated by the following equation

$$t = \frac{P_i D}{2S} \qquad t = \frac{P_i D}{20S} \text{ in metric units}$$

The nominal wall thickness of straight sections of steel pipe shall be equal to or greater than t_n determined in accordance with the following formula

$$t_n = t + A$$

where,

t	=	pressure design wall thickness, in. (mm)
t_n	=	nominal wall thickness satisfying requirements for pressure and tolerances, in. (mm)
A	=	sum of allowances for threading, grooving, corrosion, etc., in. (mm)
P_i	=	internal design gage pressure, psi (bar)
D	=	outside diameter, in. (mm)
S	=	applicable allowable stress value, psi (MPa)

Allowable Stress Value (Par. 402.3.1)

The allowable stress value, *S*, to be used in the calculations shall be established as follows:

$S = 0.72 \times E \times$ Specified Minimum Yield Strength of pipe, psi (MPa)

where

0.72	=	design factor on nominal wall thickness
E	=	weld joint factor

Limits of Calculated Stresses Due to Occasional Loads (Par. 402.3.3)

The sum of longitudinal stresses produced by pressure, live and dead loads, and those produced by occasional loads, such as wind and earthquake, shall not exceed 80% of the specified minimum yield strength of the pipe. It is not necessary to consider wind and earthquake as occurring concurrently.

Expansion and Flexibility (Par. 419)

The maximum computed expansion stress range, S_E , without regard to fluid pressure stress, based on 100% of the expansion, with modulus of elasticity for the cold condition – shall not exceed the allowable stress range, S_A , where S_A=0.72 SMYS.

The sum of longitudinal stresses due to pressure, weight and other external loadings shall not exceed $0.75S_A$ or 0.54 SMYS.

The sum of the longitudinal stresses produced by pressure, live and dead loads, and those produced by occasional loads, such as wind and earthquake, shall not exceed 80% of the specified minimum yield strength of the pipe (0.8 SMYS). It is not necessary to consider wind and earthquake occurring concurrently.

ASME B31.8 Gas Transmission and Distribution Piping Systems

Steel Pipe Design Formula (Par. 841.11)

The design pressure for steel gas piping systems or the nominal wall thickness for a given design pressure shall be determined by the following formula:

$$P = \frac{2St}{D} FET \qquad t = \frac{PD}{2SFET}$$

where

P	=	design pressure, psi
S	=	specified minimum yield strength, psi
D	=	nominal outside diameter of pipe, in.
t	=	nominal wall thickness, in.
F	=	design factor. In setting the design factor due consideration has been given and allowance has been made for the various underthickness tolerances provided for in the pipe specifications listed and approved for usage in this Code.
E	=	longitudinal joint factor
T	=	temperature derating factor

Design Factor F (Par. 841.114)

The design factor is a function of location class. The basic design factor is given in Table 841.111A in the Code and is reproduced below:

TABLE 841.111A
BASIC DESIGN FACTOR F

Location Class	**Design Factor F**
Location Class 1, Division 1	0.80
Location Class 1, Division 2	0.72
Location Class 2	0.60
Location Class 3	0.50
Location Class 4	0.40

The above basic design factors are used for pipelines, mains and service lines. There are exceptions (modification to the design factor) that apply to crossings of roads, railroads, parallel encroachment of pipelines and mains on roads and railroads, fabricated assemblies, pipelines on bridges, compressor station piping and near concentration of people in Location Classes 1 and 2. The values range from the basic design factor to a lower value of 0.50, except for Location Class 4 which is always 0.40. The complete Table 841.114B is reproduced below.

TABLE 841.114B
DESIGN FACTORS FOR STEEL PIPE CONSTRUCTION

	Location Class				
	1				
Facility	Div. 1	Div. 2	2	3	4
Pipelines, mains, and service lines [see para. 840-2(b)]	0.80	0.72	0.60	0.50	0.40
Crossings of roads, railroads without casing:					
(a) Private roads	0.80	0.72	0.60	0.50	0.40
(b) Unimproved public roads	0.60	0.60	0.60	0.50	0.40
(c) Roads, highways, or public streets, with hard surface and railroads	0.60	0.60	0.50	0.50	0.40
Crossings of roads, railroads with casing:					
(a) Private roads	0.80	0.72	0.60	0.50	0.40
(b) Unimproved public roads	0.72	0.72	0.60	0.50	0.40
(c) Roads, highways, or public streets, with hard surface and railroads	0.72	0.72	0.60	0.50	0.40
Parallel encroachment of pipelines and mains on roads and railroads:					
(a) Private roads	0.80	0.72	0.60	0.50	0.40
(b) Unimproved public roads	0.80	0.72	0.60	0.50	0.40
(c) Roads, highways, or public streets, with hard surface and railroads	0.60	0.60	0.60	0.50	0.40
Fabricated assemblies (see para. 841-121)	0.60	0.60	0.60	0.50	0.40
Pipelines on bridges (see para. 841-122)	0.60	0.60	0.60	0.50	0.40
Compressor station piping	0.50	0.50	0.50	0.50	0.40
Near concentration of people in Location Classes 1 and 2 [See para. 840.3(b)]	0.50	0.50	0.50	0.50	0.40

Location Class (Par. 840.2)

The location class is a function of the number of buildings intended for human occupancy near the pipeline. An area ¼ mile wide along the route of the pipeline and 1 mile in length is used to determine the number of buildings for location class categorization. The location classes are defined as follows:

<u>Location Class 1</u>
A Location Class 1 is any 1 mile section that has 10 or fewer buildings intended for human occupancy. It is intended to cover areas such as wasteland, deserts, mountains, grazing land, farmland, and sparsely populated areas.

<u>Location Class 1, Division 1</u>
A location where the design factor is greater than 0.72 but equal or less than 0.80 and has been hydrostatically tested to 1.25 the maximum operating pressure.

Location Class 1, Division 2
A location where the design factor is equal or less than 0.72 and the pipe has been hydrostatically tested to 1.1 times the maximum operating pressure.

Location Class 2
A location in any 1 mile section that has more than 10 but fewer than 46 buildings intended for human occupancy. It is intended for fringe areas around cities and towns, industrial areas, ranch or country estates, etc.

Location Class 3
A location in any 1 mile section that has 46 or more buildings intended for human occupancy. It is intended to reflect areas such as suburban housing developments, shopping centers, residential areas, industrial areas and other populated areas not in Location Class 4.

Location Class 4
This location class includes areas where multistory buildings are prevalent, and where traffic is heavy or dense and where there may be numerous other utilities underground.

Temperature Derating Factor T for Steel Pipe (Par. 841.116)

The effects of temperature on the allowable stress is included through the temperature derating factor shown below:

TABLE 841.116A TEMPERATURE DERATING FACTOR T FOR STEEL PIPE	
Temperature, °F	Temperature Derating Factor T
250 or less	1.000
300	0.967
350	0.933
400	0.900
450	0.867

From the above table it is seen that the maximum temperature that the Code covers is 450 °F.

Expansion and Flexibility and Longitudinal Stresses (Par. 832)

The maximum combined (bending and torsional) expansion stress, S_E , shall not exceed 0.72S, where S is the specified minimum yield strength, psi.

In addition the total of the following shall not exceed the specified minimum yield strength, S:

a) the combined stress due to expansion, S_E
b) the longitudinal pressure stress
c) the longitudinal bending stress due to external loads, such as weight of pipe and contents, wind, etc.

The sum of (b) and (c) above shall not exceed 0.75S.

Canadian Standard: CSA Z662-99 Oil and Gas Pipeline Systems (Clause 4.3.3)

The Canadian Standards Association Standard Z662 gives the following equation for the design pressure for a straight pipe:

$$P = \frac{2St}{D} x 10^3 x F x L x J x T$$

where

P	=	design pressure, kPa
S	=	specified minimum yield strength, MPa
t	=	design wall thickness, mm
D	=	outside diameter of pipe, mm
F	=	design factor
L	=	location factor
J	=	joint factor
T	=	temperature factor

Design Factor F

The design factor to be used in the formula above is 0.8.

Location Factor (L) for Steel Pipe

The location factor is given in the Table 4.1 in the Standard and is included in this report for convenience.

Table 4.1
Location Factor for Steel Pipe
(See Clauses 4.3.3.3 and 15.4.1.3)

Application	Location factor (L)			
	Class 1 location	**Class 2 location**	**Class 3 location**	**Class 4 location**
Gas (Non-sour service)				
General and cased crossings	1.00	0.90	0.70	0.55
Roads*	0.75	0.625	0.625	0.50
Railways	0.625	0.625	0.625	0.50
Stations	0.625	0.625	0.625	0.50
Other	0.75	0.75	0.625	0.50
Gas (Sour service)				
General and cased crossings	0.90	0.75	0.625	0.50
Roads*	0.75	0.625	0.625	0.50
Railways	0.625	0.625	0.625	0.50
Stations	0.625	0.625	0.625	0.50
Other	0.75	0.75	0.625	0.50
HVP and CO_2				
General and cased crossings	1.00	0.80	0.80	0.80
Roads*	0.80	0.80	0.80	0.80
Railways	0.625	0.625	0.625	0.625
Stations	0.80	0.80	0.80	0.80
Other	0.80	0.80	0.80	0.80
LVP				
All except uncased railway crossings	1.00	1.00	1.00	1.00
Uncased railway crossings	0.625	0.625	0.625	0.625

*For gas pipelines, it shall be permissible to use a location factor higher than the given value, but not higher than the applicable value given for "general and cased crossings," provided that the designer can demonstrate that the surface loading effects on the pipeline are within acceptable limits (see Clause 4.6).

Notes:

(1) Roads: Pipe, in parallel alignment or in uncased crossings, under the travelled surface of the road or within 7 m of the edge of the travelled surface of the road, measured at right angles to the centreline of the travelled surface.

(2) Railways: Pipe, in parallel alignment or in uncased crossings, under the railway tracks or within 7 m of the centreline of the outside track, measured at right angles to the centreline of the track.

(3) Stations: Pipe in, or associated with, compressor stations, pump stations, regulating stations, or measuring stations, including the pipe that connects such stations to their isolating valves.

(4) Other: Pipe that is

(a) supported by a vehicular, pedestrian, railway, or pipeline bridge;

(b) used in a fabricated assembly; or

(c) within five pipe diameters in any direction of the last component in a fabricated assembly, other than a transition piece or an elbow used in place of a pipe bend that is not associated with the fabricated assembly.

Joint Factor (J) for Steel Pipe

The joint factor to be used in the design formula shall not exceed the applicable value given in Table 4.2. For welded pipe, Table 4.2 applies to pipe having a longitudinal seam or a helical seam.

Table 4.2 Joint Factor for Steel Pipe	
Pipe Type	Joint Factor (J)
Seamless	1.00
Electric Welded	1.00
Submerged arc welded	1.00
Continuous welded	0.60

Temperature Factor (T) for Steel Pipe

The temperature factor for steel pipe is given below:

Table 4.3 Temperature Factor for Steel Pipe		
Temperature, °F	Temperature, °C	Temperature Factor (T)
Up to 248	Up to 120	1.00
302	150	0.97
356	180	0.93
392	200	0.91
446	230	0.87

Wall Thickness Allowances

The nominal wall shall not be less than the design wall thickness, *t*, plus allowances for corrosion, threading and for grooved pipe. In determining the nominal wall thickness, the consideration of manufacturing tolerances is not required.

Flexibility and Stress Analysis

Hoop Stress

The hoop stress used in the stress analysis for any location on the pipeline shall be calculated using the following formula:

$$S_h = \frac{PD}{2t_n} x\, 10^{-3}$$

where

S_h	=	hoop stress, MPa
t_n	=	pipe nominal wall thickness, less allowances, mm
P	=	design pressure, kPa
D	=	outside diameter of pipe, mm

Combined Hoop and Longitudinal Stresses

The hoop stress due to design pressure combined with the net longitudinal stress due to the combined effects of pipe temperature changes and internal fluid pressure shall be limited in accordance with the following formula:

$$S_h - S_L \leq 0.90\, S \text{ x } T$$

Note that this formula does not apply if S_L is positive (i.e. tension.)

The longitudinal compression stress is calculated using the following formula:

$$S_L = \nu S_h - E_c\, \alpha\, (T_2 - T_1)$$

where

S_h	=	hoop stress due to design pressure, MPa
S_L	=	longitudinal compression stress, MPa
ν	=	Poisson's ratio
α	=	linear coefficient of thermal expansion, $^oC^{-1}$
E_c	=	modulus of elasticity of steel, MPa
T_2	=	maximum operating temperature, ^oC
T_1	=	ambient temperature at time of restraint, ^oC
S	=	specified minimum yield strength, MPa
T	=	temperature factor

Combined Stresses for Restrained Spans

For those portions of restrained pipelines that are freely spanning or supported aboveground, the combined stress shall be limited in accordance with the following formula:

$$S_h - S_L + S_B \leq S \times T$$

where symbols are defined above, except for

S_B	=	absolute value of beam bending compression stress resulting from live and dead loads, MPa

Stresses Design for Unrestrained Portions of Pipeline Systems

The thermal expansion stress range, based on 100% of the expansion, shall be limited in accordance with the following formula:

$$S_E \leq 0.72\, S \times T$$

where,

S_E	=	thermal expansion stress, MPa
S	=	specified minimum yield strength, MPa
T	=	temperature factor

The sum of the longitudinal pressure stress and the total bending stress due to sustained force and wind loading shall be limited in accordance with the following formula:

$$0.5\, S_h + S_B \leq S \times F \times L \times T$$

where symbols have been defined previously above.

Guidelines for Risk Assessment of Pipelines

This standard contains a non-mandatory appendix which provides guidelines on the application of risk assessment to pipelines. These guidelines identify the role of risk assessment within the context of an overall risk management process, provide a standard terminology, identify the components of the risk assessment process and provide reference to methodological guidelines for risk assessment.

Limit States Design

The standard also provides a non-mandatory appendix for limit states design. Limit states as defined in this standard means a reliability-based design method that uses factored loads (nominal or specified loads multiplied by a load factor) and factored resistances (calculated strength, based on nominal dimensions and specified material properties multiplied by a resistance factor).

This type of design in the U.S. is also referred to as the partial safety factor approach. It should not be confused with limit load or plastic analysis.

British Standard: BS 8010 Section 2.8 Steel for Oil and Gas

This section of the British Standard BS 8010: Part 2 provides guidance on the design, construction and installation of steel pipelines on land for oil, gas and toxic fluids.

The design equations cover the calculation of hoop stress and the calculation of expansion and flexibility stress and their appropriate allowable stress limits.

Hoop Stress (Clause 2.9.2)

The hoop stress can be calculated by using either the thin wall or thick wall design equation:

Thin wall

$$S_h = \frac{pD}{20t}$$

Thick Wall

$$S_h = \frac{p(D^2 + D_i^2)}{10(D^2 - D_i^2)}$$

where

S_h	=	hoop stress (N/mm^2)
p	=	internal design pressure (bar)
D	=	outside diameter (mm)
t	=	design thickness (mm)
D_i	=	inside diameter (D-2t) (mm)

The thick wall design equation gives more accurate calculation of hoop stress and always gives the smallest value of maximum stress. Where the D/t ratio is greater than 20, the difference between the stresses calculated between the two formulae is less than 5%.

Longitudinal Stress

The total longitudinal stress should be the sum of the longitudinal stress arising from pressure, bending, temperature, weight, other sustained loadings and occasional loadings.

For totally restrained sections of a pipeline, the longitudinal tensile stress resulting from the combined effects of temperature and pressure change alone should be calculated as follows:

Thin Wall

$$S_{L1} = \nu S_h - E\alpha(T_2 - T_1)$$

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Thick Wall

$$S_{L1} = v(S_h - \frac{p}{10}) - E\alpha(T_2 - T_1)$$

where

S_{L1}	=	longitudinal tensile stress (N/mm^2)
v	=	Poisson's ratio (0.3 for steel)
p	=	internal design pressure (bar)
S_h	=	hoop stress using the nominal pipe wall thickness (N/mm^2)
E	=	modulus of elasticity (N/mm^2) (2.0 x 10^5 at ambient temperature for carbon steel)
α	=	linear coefficient of thermal expansion (per °C) (11.7x10^6 per °C, up to 120 °C for Carbon Steel)
T_1	=	installation temperature (°C)
T_2	=	maximum or minimum temperature (°C)

For unrestrained section of a pipeline, the longitudinal tensile stress resulting from the combined effects of temperature and pressure change alone should be calculated as follows:

Thin Wall

use $k = 1$ in the following thick wall formula

Thick Wall

$$S_{L2} = \frac{S_h}{k^2 + 1} + \frac{1000 M_b i}{Z}$$

where

S_{L2}	=	longitudinal tensile stress (N/mm^2)
M_b	=	bending moment applied to the pipeline (N•m)
i	=	stress intensification factor
k	=	ratio of D/D_i
Z	=	pipe section modulus (mm^3)

Shear Stress

The shear stress should be calculated from the torque and shear force applied to the pipeline as follows:

$$\tau = \frac{1000T}{2Z} + \frac{2S_F}{A}$$

where

τ	=	shear stress (N/mm^2)
T	=	torque applied to the pipeline (N•m)
S_F	=	shear force applied to the pipeline (N)
A	=	cross sectional area of the pipe wall (mm^2)
Z	=	pipe section modulus (mm^3)

Equivalent Stress

The equivalent stress should be calculated using the von Mises equivalent stress criteria as follows:

$$S_e = (S_h^2 + S_L^2 - S_h S_L + 3\tau^2)^{1/2}$$

where

S_h	=	hoop stress using the nominal pipe wall thickness (N/mm^2)
S_L	=	total longitudinal stress (N/mm^2)
τ	=	shear stress (N/mm^2)

Limits of Calculated Stress

Allowable Hoop Stress

The allowable hoop stress (S_{ah}) should be calculated as follows:

$$S_{ah} = a\, e\, S_y$$

where

S_{ah}	=	allowable hoop stress (N/mm^2)
a	=	design factor
e	=	weld joint factor
S_y	=	specified minimum yield strength of pipe (N/mm^2)

Allowable Equivalent Stress

The allowable equivalent stress should be calculated as follows:

$$S_{ae} = 0.9\ S_y$$

where

S_{ae}	=	allowable equivalent stress (N/mm^2)
S_y	=	specified minimum yield strength of the pipe (N/mm^2)

Design Factor

The maximum design factor a to be used in the calculation of allowable stress for pipelines should be :

Category B substances
The design factor a should not exceed 0.72 in any location. In high population density areas consideration for extra protection should be given. Code provides typical examples of extra protection measures.

Category C and Category D substances
The design factor a should not exceed 0.72 in class 1 and 0.30 in class 2 and class 3 locations. However, the design factor may be raised to a maximum of 0.72 in class 2 locations providing it can be justified to a statutory authority by a risk analysis carried out as part of a safety evaluation for the pipeline.

Pipelines designed to convey Category D substances in class 2 locations should be given either a nominal wall thickness of 9.52 mm (0.375 in.) or be provided with impact protection to reduce the likelihood of penetration from mechanical interference.

It is essential than pipelines designed to operate in class 3 locations be limited to a maximum operating pressure of 7 bar (101.5 psi).

Categorization of Substances

Substances should be placed in one of the following four categories according to the hazard potential of the substance.

Category A
Typically water based fluids

Category B
Flammable and toxic substances which are liquids at ambient temperature and atmospheric pressure conditions. Typical examples would be oil, petroleum products, toxic liquids and other liquids which could have an adverse effect on the environment if released.

Category C
Non flammable substances which are gases at ambient temperature and atmospheric pressure conditions. Typical examples would be oxygen, nitrogen, carbon dioxide, argon and air.

Category D
Flammable and toxic substances which are gases at ambient temperature and atmospheric pressure condition and are conveyed as gases or liquids. Typical examples would be hydrogen, methane, ethane, ethylene, propane, butane, liquefied petroleum gas, natural gas liquids, ammonia and chlorine.

Classification of Location

The location of Category C and D substance pipelines should be classified in relation to population density along the route of the pipeline to determine the operating stress levels and the proximity distances from normally occupied buildings.

The location of Category B substance pipelines need not be classified in relation to population density but may require extra protection or be subject to safety evaluation.

Class 1 Location
Areas with population density less than 2.5 persons per hectare

Class 2 Location
Areas with population density greater than or equal to 2.5 persons per hectare and which may be extensively developed with residential properties, schools and shops, etc.

Class 3 Location
Central areas of towns and cities with a high population and building density, multi-story buildings, dense traffic and numerous underground services.

The code also contains requirements for the proximity to occupied buildings and requirements for the calculation of population densities.

Safety Evaluation

The pipeline designer should give consideration to the preparation of a safety evaluation. The evaluation should include the following:

a) critical review of pipeline route;
b) description of technical design including potential hazards of the substance to be conveyed and design and construction aspects of the pipeline system;
c) details of pressure control, monitoring and communication systems, emergency shutdown facilities and leak detection (where incorporated);
d) proposals for pipeline monitoring and inspection during operation together with emergency procedures.

Risk Analysis

Where a risk analysis is required as part of the safety evaluation it should include the following:

a) the identification of all potential failure modes;
b) a statistically based assessment of failure mode and frequency;
c) a detailed evaluation of the consequences of failure from small holes up to full bore rupture including reference to population density;
d) prevailing weather conditions;
e) time taken to initiate a pipeline shutdown.

The risk analysis should culminate in an evaluation of risk along the pipeline.

German Standard: DIN 2413 Part 1 Design of Steel Pressure Pipes

The German Standard DIN 2413 Part 1 covers the design of steel pressure pipes with circular cross-sectional shape and ratio of outside to inside diameter, d_a / d_i, up to 2.0, for the following service conditions (referred to load cases I through III).

I. Pipes subjected to predominantly static loading and rated for a temperature up to 120 °C.
II. Pipes subjected to predominantly static loading and rated for temperature over 120 °C.
III. Pipes subjected to fatigue loading and rated for a temperature up to 120 °C.

For loading case I, which is referenced by DIN 2470 Part 2, the design wall thickness is given by the following equation:

$$s_v = \frac{d_a\, p}{2\sigma_{zul}\, v_N} \quad and \quad \sigma_{zul} = K / S = Y\, K$$

where

s_v	=	Design wall thickness of pipe, not including relevant design factors, N/mm^2
d_a	=	Pipe outside diameter, mm
p	=	Design pressure, mm
σ_{zul}	=	Maximum permissible stress under static loading, N/mm^2
v_N	=	Degree of utilization of the design stress in the weld
K	=	Characteristic strength value, N/mm^2
S	=	Safety factor for fatigue strength
Y	=	Degree of utilization = $1/S$

The characteristic strength, K, is the yield strength or 0.2% proof strength or 0.5% proof strength (specified minimum values at 20 °C).

The required thickness shall be calculated from the following equation:

$$s = s_v + c_1 + c_2$$

where

s	=	Required wall thickness of pipe, including relevant design factors, mm
c_1	=	Factor to allow for the lower limit deviation for wall thickness, mm
c_2	=	Factor to allow for corrosion or wear, mm

DIN 2470 Part 2 Steel Gas Pipelines

The German Standard DIN 2470 Part 2: Steel Gas Pipelines for Permissible Working Pressures exceeding 16 bar Pipes and Fittings, provides requirements for steel pipes and fittings used for public gas supply lines rated for permissible working pressures exceeding 16 bar (232 psi). Part 1 applies to pressures up to 16 bar.

The pipe wall thickness shall be designed as specified in DIN 2413, Category I. The factor of safety S to be used in the design of buried gas pipelines varies from 1.50 to 1.60 for the steel grades covered in this standard. The small variation is associated with the minimum elongation after fracture of the steels.

The above factors cover normal stressing imposed by laying under ground. If additional stressing of a special nature exists (e.g. in the case of lines above ground or an earth cover more than 3 m when the ratio s/d_a is not greater than 1%) additional verification of the stress conditions shall be carried out. s and d_a are the nominal thickness and the outside diameter of the pipe, respectively.

European Standard: PrEN 1594 Pipelines for Gas Transmission

The European draft Standard PrEN 1594 Pipelines for Gas Transmission applies to pipelines for on land gas supply systems with Maximum Operating Pressure (MOP) greater than 16 bar (232 psi). The design temperature of the system is equal to or greater than –40 ^{0}C and lower than 120 ^{o}C.

Design

For the determination of the wall thickness, a distinction is made between standard and non standard cases. Most cases can be treated as standard.

Hoop Stress Due to Internal Pressure

For standard cases it is sufficient to calculate the hoop stress due to internal pressure:

$$\frac{DP \; x \; D}{20T_{min}} \leq f_o \; x \; R_{t\,0.5}$$

where

DP	=	design pressure, bar
D	=	outside diameter of pipe, mm
	=	$D_i + 2T_{min}$ if D_i is preset
D_i	=	is the inside diameter, mm
T_{min}	=	minimum wall thickness, mm
f_o	=	design factor
$R_{t\,0.5}$	=	specified minimum yield strength, N/mm^2

Design Factor (f_o)

The design factor (f_o) for the internal pressure to be used for the pipeline section in question is as follows:

- underground sections, except stations ≤ 0.72
- pipelines in tunnels continuously supported ≤ 0.72
- stations ≤ 0.67

Criteria for Nonstandard Cases

Nonstandard cases involve the following areas;

- settlement areas;
- mining subsidence areas;
- frost heave areas;
- landslide areas;
- earthquake areas;
- areas of future planned increase in soil cover, local embankments etc.

The standard provides a number of annexes (appendices) that provide calculation methods and requirements for the above cases.

In addition, the designer shall take into account all other circumstances that may require calculation as nonstandard case, such as;

- higher pipe temperature and/or large temperature differences in relation to special pipe configurations;
- any circumstances that may lead to excessive construction settlement differences as a result of the construction techniques employed;
- aboveground pipelines locally supported.

Wall Thickness Determination for Nonstandard Cases

In the nonstandard case the wall thickness determination comprises of an analysis of the loads and displacements and an analysis of the stresses and strains which may occur.

The PrEN 1594 Standard provides requirements for buried pipelines, pipe/soil interaction analysis methods, above ground pipeline sections and structural models for pipelines.

Analysis Based on Elastic Theory

When axial and tangential stresses have been determined they are combined to give the stress resultant σ_v

The stress resultant is a parameter which is considered to be characteristic of the state of stress at a point. The state of stress at any point is completely described by the normal stress σ_x , σ_y , σ_z , and by the shear stress τ_x , τ_y , and τ_z , in a tri-axial system with mutually perpendicular axes x, y and z or by the principal stress σ_1 , σ_2 and σ_3 and their directions. The stress resultant may be calculated either by the shear stress hypothesis or the yield criterion.

According to the shear stress hypothesis, the stress resultant is

$$\sigma_v = \sigma_{max} - \sigma_{min}$$

According to the von Mises / Huber Hencky yield criterion the resultant stress is given by:

$$\sigma_y = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \sigma_x\sigma_y - \sigma_y\sigma_z - \sigma_z\sigma_x + 3(\tau_x^2 + \tau_y^2 + \tau_z^2)}$$

In a bi-axial system;

$$\sigma_y = \sqrt{\sigma_x^2 + \sigma_y^2 - \sigma_x\sigma_y + 3\tau^2}$$

Allowable Stress

If the analysis is based on elasticity theory where all stresses are considered as primary stresses, the analysis may be carried out using characteristic values for the loads. In that case the maximum stress resultant shall not exceed the allowable stress.

The allowable stress is 0.72 $R_{t\,0.5}$ (θ)

Up to 60 °C	$R_{t\,0.5}$ (θ) = $R_{t\,0.5}$
Over 60 °C	$R_{t\,0.5}$ (θ) may be interpolated linearly between values at room temperature ($R_{t\,0.5}$) and the values for $R_{t\,0.5}$(θ) at 100 °C or 150 °C.

where $R_{t\,0.5}$ (θ) indicates the value of the minimum yield strength at temperature (θ).

Elasto-Plastic and Plastic Analysis

A more sophisticated analysis may be carried out using elasto-plastic or plastic analysis. The standard provides an Annex (Appendix) where the procedure to be followed, the relevant limit states, the contingency factors for the soil mechanics parameters, the load factors and stress concentration factors (for elasto-plastic analysis) are described.

The elasto-plastic and plastic analysis procedure is based on the method of (partial) load factors and calculation loads. The calculation loads are obtained by multiplying the relevant (characteristic) loads.

The load factors take into account the uncertainty for the magnitude of the loads, the strength of the material and the construction.

The effect of the calculation loads should not exceed the limit values associated with the relevant limit states.

Characteristic values for the loads (internal pressure, soil loads, differential settlement, thermal loads, etc.) are values for which the probability of their values being less than about 5%.

Characteristic values for the material properties of the pipeline (yield strength, tensile strength etc.) are values for which the probability of the actual values being less than the characteristic values is less than about 5%.

Characteristic values for soil engineering parameters are obtained by multiplying or dividing the average values by the contingency factors given in Table G.1 in the standard, reproduced below for convenience.

The characteristic loads then should be multiplied by the factors given in Table G.2 in the standard, reproduced below for convenience.

Table G.1

Contingency factors for soil engineering parameters referred to mean value

Parameter	**Factors**
Neutral earth pressure	1.1
Passive earth pressure	1.1
Lateral bending constant (k_l) - for sand and clay - for peat	 1.3 1.4
Ultimate bearing capacity - for sand and clay - for peat	 1.2 1.5
Horizontally passive earth pressure (contact angle =180°) and horizontal neutral soil resistance (contact angle =120°) - for sand - for clay - for peat	 1.2* 1.4 1.5
Soil friction	1.4
Relative displacement required for maximum soil friction (frictional elasticity)	1.4
Frictional bending constant (k_w)	1.7**

NOTES

* These contingency factors are partly based on current pipelaying practice

** Soil friction (w) and displacement δ together give the frictional bending constant $k_w = w/\delta$ for which the contingency factor is 1.7.

Table G.2

Loads, partial load factors

Load components	Load factors		
(Characteristic loads)	Operational phase		Construction phase
	Station	Pipeline	
Design pressure	1.50	1.39	1.10
Soil parameters	1.50	1.50	1.50
Traffic loads	1.50	1.50	1.50
Meteorological loads (wind, snow)	1.50	1.20	1.10
Marine loads (wave currents)	1.50	1.20	1.39
Incidental loads	1.50	1.39	1.10
Installation loads	1.50	1.50	1.10
Deadweight	1.50	1.50	1.10
Settlement / subsistence	1.50	1.50	1.10
Forced deformation	1.50	1.50	1.10
Temperature differences	1.25	1.25	1.25
Elastic bends	1.50	1.50	1.10

AS 2885.1 Australian Standard Pipelines – Gas and Liquid Petroleum

Australian Standard AS 2885.1 specifies requirements for the design and construction of steel pipelines and associated piping and components that are used to transmit single phase and multiphase hydrocarbon fluids, such as natural and manufactured gas, liquefied petroleum gas, natural gasoline, crude oil, natural gas liquids and liquid petroleum products. The standard applies when:

a) the temperatures of the fluid are not warmer than 200 °C nor colder than –30 °C; and
b) either the maximum allowable operating pressure (MAOP) of the pipeline is more than 1050 kPa, or at one or more positions in the pipeline the hoop stress exceeds 20% of the SMYS.

Wall Thickness for Design Internal Pressure (Clause 4.3.4.2)

The Australian pipeline standard gives the following wall thickness equation for the design internal pressure:

$$\delta_{dp} = \frac{p_d D}{2 F_d \sigma_y}$$

where

δ_{dp}	=	wall thickness for internal design pressure, mm
p_d	=	design pressure, MPa
D	=	nominal outside diameter, mm
F_d	=	design factor
σ_y	=	yield stress, MPa

The required wall thickness is determined by the following equation:

$$\delta_w = \delta_{dp} + G$$

where

δ_w	=	required wall thickness, mm
δ_{dp}	=	wall thickness for design internal pressure, mm
G	=	allowance due to manufacturing tolerances, corrosion, erosion, threading, machining and other necessary conditions, mm.

Design Factor

The design factor (F_d) shall not be more than 0.72, except for the following for which the design factor shall not be more than 0.60:

(a) Fabricated assemblies.
(b) Any section of a telescoped pipeline for which the MAOP is based on a test pressure factor of less than 1.25.
(c) Pipelines on bridges or other structures.

Occasional Loads

Occasional loads are those which are unusual, or which occur with a very low or unpredictable frequency. Occasional loads include wind, flood, earthquake, and some traffic loads and surge pressure-induced load.

When occasional loads act in combination with other defined loads (excluding traffic or vehicular) the maximum limit may be increased to 110% of the stress limit allowed for the original load or load combination, unless a separate specific limit is defined for occasional loads. Occasional loads from two or more independent sources (such as wind and earthquake) need not be considered as acting simultaneously.

Axial Loads – Restrained Pipe

Whenever a pipeline or segment of a pipeline is of fixed length in service, it shall be considered to be restrained and stresses in service shall be calculated. Limit stresses shall be calculated in accordance with the maximum shear stress (Tresca) theory. Stresses from normal loads shall not exceed the following:

(1) Hoop stress .... Yield stress times design factor.
(2) Longitudinal stress .... Yield stress times design factor.
(3) Combined stress .... Yield stress times 0.90.

Strains from diametral deflections caused by normal loads or occasional loads shall not exceed 0.5%.

For pipe subject to bending stresses, the net longitudinal stress due to the combined effects of changes in temperature, imposed displacements and internal pressure shall be calculated from the equation:

$$\sigma_L = \mu\, \sigma_C - E\alpha(T_2 - T_1)$$

where

T_1	=	mean temperature of pipeline during hydrostatic testing, °C.
T_2	=	maximum or minimum operating temperature of pipeline, °C.
E	=	Young's Modulus, MPa
σ_L	=	longitudinal stress, MPa
σ_C	=	circumferential stress, MPa
α	=	linear coefficient of thermal expansion, $°K^{-1}$
μ	=	Poisson's ratio (0.3 for steel)

Axial Loads – Unrestrained Pipe

Whenever a pipeline or segment of a pipeline is not of fixed length in service, it shall be considered to be wholly or partially unrestrained and stresses, strains, deflections and displacements shall be assessed. The expansion stress range shall not exceed 72% of the yield strength. The expansion stress range, S_E, represents the variation in stress resulting from variations in temperature and associated imposed displacements. It is not a total stress.

Strains from diametral deflections caused by normal loads or occasional loads shall not exceed 0.5%.

Safety and Risk Assessment

The Australian standard contains a section on safety which is addressed through a formal risk assessment procedure. The risk assessment procedure is designed to ensure that each threat to a pipeline and each risk from loss of integrity of a pipeline are systematically identified and evaluated, while action to reduce threats and risks from loss of integrity is implemented so that risks are reduced to As Low As Reasonably Practical (ALARP). Further, the procedures are designed to ensure that identification of threats and risks from loss of integrity and their evaluation is an ongoing process over the life of the pipeline.

The risk assessment procedure consists of:

1) Risk identification
2) Risk evaluation
3) Management of risk

The risk identification step identifies the hazardous events through a location and location class analysis, a threat analysis which could result in hazardous events (such as external interference, corrosion, natural events, operations and maintenance activities), and an external interference protection design program, and a failure analysis that combines the design features of the pipeline with the identified threats to determine the failure mode.

The risk evaluation step contains a frequency and consequence analysis for each defined hazardous event. A frequency of occurrence of each hazardous event shall be assigned for each location where risk estimation is required. The frequency of occurrence shall be selected from

Table 2.4.2 in the standard. Table 2.4.2 is included in this report for convenience. The contribution of operations and maintenance practices and procedures to the occurrence of or prevention of hazardous events may be considered in assigning the frequency of occurrence to each hazardous event at each location.

For each hazardous event the consequence analysis assesses the consequences for:

(a) human injury or fatality;
(b) interruption to continuity of supply and economic impact; and
(c) environmental damage.

A risk matrix similar to Table 2.4.4(A) is used to combine the results of frequency analysis and consequence analysis. The severity classes used in the risk matrix are established for each pipeline project using severity classes. Table 2.4.4(B) provides typical severity classes for pipelines.

The management of risks addresses actions to be taken in order to reduce the risk when the derived risk parameters exceed regulatory requirements. Actions intended to reduce risk may be taken at the design stage or the operating pipeline stage. The actions to be taken for each risk class shall be in accordance with Table 2.5.1

The design stage actions may include the following:

a) Relocation of the pipeline route.
b) Modification of the design for any one or more of the following:
    i) Pipeline isolation.
    ii) External interference protection.
    iii) Corrosion.
    iv) Operation
c) Establishment of specific procedural measures for prevention of external interference.
d) Establishment of specific operation measures.

The operating stage actions may include one or more of the following:

a) Installation of modified physical external interference protection measures.
b) Modification of procedural external interference protection measures in operation.
c) Specific actions in relation to identified activities; e.g. presence of operating authority personnel during activities on the easement.
d) Modification to pipeline marking.

TABLE 2.4.2
FREQUENCY OF OCCURRENCE FOR HAZARDOUS EVENTS

Frequency of occurrence	Description
Frequent	Expected to occur typically once per year or more.
Occasional	Expected to occur several times in the life of the pipeline.
Unlikely	Not likely to occur within the life of the pipeline, but possible.
Remote	Very unlikely to occur within the life of the pipeline.
Improbable	Examples of this type of event have historically occurred, but not anticipated for the pipeline in this location.
Hypothetical	Theoretically possible, but has never occurred on a similar pipeline.

TABLE 2.4.4(A)
RISK MATRIX

Frequency of occurrence	Risk class			
	Severity class			
	Catastrophic	Major	Severe	Minor
Frequent	H	H	H	I
Occasional	H	H	I	L
Unlikely	H	H	L	L
Remote	H	I	L	L
Improbable	H	I	L	N
Hypothetical	I	L	N	N

LEGEND:
H = High risk
I = Intermediate risk
L = Low risk
N = Negligible

TABLE 2.4.4(B)

TYPICAL SEVERITY CLASSES FOR PIPELINES FOR USE IN RISK MATRIX

Severity class	Description
Catastrophic	Applicable only in location classes T1 and T2 where the number of humans within the range of influence of the pipeline would result in many fatalities.
Major	Event causes few fatalities or loss of continuity of supply or major environmental damage.
Severe	Event causes hospitalizing injuries or restriction of supply.
Minor	Event causes no injuries and no loss of or restriction of supply.

TABLE 2.5.1

RISK MANAGEMENT ACTIONS

Risk class	Action required
High	Modify the hazardous event, the frequency or the consequence to ensure the risk class is reduced to intermediate or lower.
Intermediate	Repeat the risk identification and risk evaluation processes to verify and, where possible to quantify, the risk estimation. Determine the accuracy and uncertainty of the estimation. Where the risk class is confirmed to be intermediate, modify the hazardous event, the frequency or the consequence to ensure the risk class is reduced to low or negligible.
Low	Determine the management plan for the hazardous event to prevent occurrence and to monitor changes which could affect the classification.
Negligible	Review at the next review interval.

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CHAPTER 5

SUMMARY OF DESIGN MARGINS

This chapter contains a summary of design margins or safety factors of major pipeline and pressure vessel codes. This is used in the assessment of the design margins of existing codes and to develop the recommendations for changes to the design margins in B31.8 made in this report.

A summary of design factors on the yield strength and tensile strength margins is presented in Table 5.1.

Design factors (sometimes called factors of safety) are applied to the resistance capability of materials (strength) in order to provide a margin for uncertainties in the material, design, construction, operation of equipment and other factors.

Design factors summarized here are typically only used to address the most common mode of failure of bursting or plastic collapse due to internal design pressure. There are other modes of failure such as buckling, creep, cracking, fatigue, brittle low temperature fracture, expansion, thermal effects etc. that are addressed in codes. Such factors are not summarized in this report.

The design margins in the ASME B & PV Codes, several of the other ASME Piping Codes and the international pressure vessel codes take into consideration the complex configurations of many vessels and more types of loadings, such as thermal and cyclic stresses and areas of stress discontinuities. Transmission piping systems are "simpler" structures, which in most cases are not subject to the same complex design and loading issues as pressure vessels. The design factors in B31.8 are on the Specified Minimum Yield Stress (SMYS).

A summary of the methodologies used to determine the design margins for each of the piping codes is presented in Table 5.2.

Table 5.1 - Summary of Design Margins

	CODE	CONDITION	FACTOR[1] ON YIELD STRENGTH	FACTOR[1] ON TENSILE STRENGTH	COMMENTS
Transmission Pipeline Codes	B31.4 Pipeline Transportation Systems for Liquids	Pressure hoop stress	0.72		
	B31.8 Gas Transmission and Distribution Systems	Pressure hoop stress Location Class 1, Div 1 Location Class 1, Div 2 Location Class 2 Location Class 3 Location Class 4	 0.80 0.72 0.60 0.50 0.40		Code includes numerous modifications for types of facilities, crossings, encroachment, etc.
	British BS 8010 Section 2.8 Pipelines on Land: Steel for Oil and Gas	Pressure hoop stress Category B substances Category C & D Class 1 Category C & D Class 2 Category C & D Class 3	 0.72 0.72 0.30 0.30		Categories are related to hazard potential of substances and location class to population densities.
	Canadian CSA Z662 Oil and Gas Pipeline Systems	Pressure hoop stress Basic design factor Depending on location and type of facility	 0.80 0.50 to 0.80		Canadian code is similar to B31.8. Limit States Design (LSD) non-mandatory appendix
	Dutch NEN 3650 Requirements for Steel Pipeline Transportation	Pressure hoop stress Simplified analysis procedure	 0.55 to 0.72		Code is sophisticated with plastic, reliability, and probabilistic and complete risk analysis procedures.
	European DRAFT CEN PrEN 1594 Pipelines for Gas Transmission	Pressure hoop stress Basic design method Alternative design method	 0.67 0.67	 0.42 0.53	The alternative design route requires more controls. Has LSD option.
	German DIN 2470 Part 2: Steel Gas Pipelines	Pressure hoop stress	0.62 to 0.67		Variation is associated with material minimum elongation and fracture properties.

1 Factors presented as a multiple of S_y and S_u.

Table 5.1 - Summary of Design Margins (continued)

	CODE	CONDITION	FACTOR[1] ON YIELD STRENGTH	FACTOR[1] ON TENSILE STRENGTH	COMMENTS
Other Pipeline Codes	B31.1 Power Piping	Pressure hoop stress	0.67	0.25	
	B31.3 Process Piping	Pressure hoop stress	0.67	0.33	
	B31.5 Refrigeration Piping	Pressure hoop stress	0.625	0.25	
	B31.9 Building Systems Piping	Pressure hoop stress	0.67	0.25	
	B31.11 Slurry Transportation Systems	Pressure hoop stress	0.80		

1 Factors presented as a multiple of S_y and S_u.

Table 5.1 - Summary of Design Margins (continued)

	CODE	CONDITION	FACTOR[1] ON YIELD STRENGTH	FACTOR[1] ON TENSILE STRENGTH	COMMENTS
Boiler and Pressure Vessel Codes	Section I Power Boilers	Pressure hoop stress Prior to 1999 Addenda 1999 Addenda	 0.67 0.67	 0.25 0.285	Recently this Division reduced the margin on tensile from 4 to 3.5. First change since WW II.
	Section VIII Division 1 Pressure Vessels	Pressure hoop stress Prior to 1999 Addenda 1999 Addenda	 0.67 0.67	 0.25 0.285	Recently this Division reduced the margin on tensile from 4 to 3.5. First change since WW II.
	Section VIII Division 2 Alternative Rules for PVs	Pressure hoop stress i.e. primary general membrane stress	0.67	0.33	
	Section VIII Division 3 High Pressure Vessels	Pressure hoop stress i.e. primary general membrane stress	0.67 or 0.577		Factor 0.577 is based on fully plastic flow using maximum shear theory.
	British BS 5500 Unfired Pressure Vessels	Pressure hoop stress Carbon Steels Austenitic Steels	 0.67 0.67	 0.42 0.40	
	Dutch Stoomwezen Pressure Vessels	Pressure hoop stress Material with elongation > 10% Material with elongation < 3%	 0.67 ...	 0.44 0.25	Gas Limit State Design option
	German AD Merkblätt Pressure Vessels	Pressure hoop stress Rolled and forged steel and aluminum alloys Cast steels	 0.67 0.50		

1 Factors presented as a multiple of S_y and S_u.

Table 5.2 –Design Margin Determination

CODE	PLASTIC ANALYSIS	LIMIT STATE OR RELIABILITY	SOME RISK ASSESSMENT REQUIREMENTS	FULL RISK BASED REQUIREMENT
B31.1	NO	NO	NO	NO
B31.3	NO	NO	NO	NO
B31.4	NO	NO	NO	NO
B31.5	NO	NO	NO	NO
B31.8	NO	NO	NO	NO
B31.9	NO	NO	NO	NO
B31.11	NO	NO	NO	NO
AS 2885.1	NO	NO	YES	NO
BS 8010 – 2.8	NO	NO	YES	NO
CSA Z662	NO	YES	YES	NO
NEN 3650	YES	YES	YES	NO
PrEN 1594 DRAFT	YES	YES	YES	NO
DIN 2413 Part 1	YES	NO	NO	NO

References

1. ASME B31.1, Power Piping, ASME, New York, NY, 1998 Edition with addenda.

2. ASME B31.3, Process Piping, ASME, New York, NY, 1999 Edition with addenda.

3. ASME B31.4, Pipeline Transportation Systems for Liquid Hydrocarbons and Other Liquids, ASME, New York, NY, 1998 Edition with Addenda.

4. ASME B31.8, Gas Transmission and Distribution Piping Systems, ASME, New York, NY, 1995 Edition with Addenda.

5. ASME Section VIII, Division 1, Rules for the Construction of Pressure Vessels, ASME, New York, NY, 1998 Edition with 1999 Addenda.

6. ASME Section VIII, Division 2, Alternative Rules for the Construction of Pressure Vessels, ASME, New York, NY, 1998 Edition with 1999 Addenda.

7. ASME Section VIII, Division 3, Alternative Rules for High Pressure Vessels, ASME, New York, NY, 1998 Edition with 1999 Addenda.

8. AS 2885.1, Australian Standard, Pipelines –Gas and Liquid Petroleum; Part 1 Design and Construction, Standard of Australia, Homebush, Australia, 1997.

9. BS 8010 Section 2.8, Code of Practice for Pipelines, Section 2.8 Steel for Oil and Gas, British Standard Institute, 1992.

10. CFR Part 192, Code of Federal Regulations, Pipeline Safety Regulations, U.S. Department of Transportation, October 1996.

11. CSA Z662-99, Oil and Gas Pipeline Systems, Canadian Standards Association, Etobicoke, Ontario, Canada, April 1999.

12. DIN 2413 Part 1, Design of Steel Pressure Pipes, German Standard, English Version by British Standards Institute, London, England, October 1993

13. DIN 2470 Part 2, Steel Gas Pipelines, German Standard, English Version by British Standards Institute, London, England, May 1983.

14. NEN 3650, Requirements for Steel Pipeline Transportation Systems, Dutch Standard, Nederlands Normalisatie-Instituut, 1st Edition, March 1998.

15. PrEN 1594, Pipelines for Gas Transmission, draft European Standard by Technical Committee CEN/TC 234, available from British Standards Institute, November 1994.

CHAPTER 6

CONCEPTS OF SAFETY FACTORS, DESIGN MARGINS AND RELIABILITY

Traditional Factor of Safety and Design Margin

When a component is subjected to a set of loads, Q, and the component has a capacity or resistance, R, then the concepts of safety factor and safety margin can be used to describe their relationship to reliability. The terms loads and resistance are used widely in structural and mechanical engineering, where the load is usually referred to as stress and the resistance as strength. In the traditional design approach, such as that adopted by the ASME Codes, the safety factor or safety margin is made large enough to more than compensate for uncertainties in the values of both the load and the resistance of the system. Although the load and resistance involve uncertainties, the design calculations are deterministic, using for the most part the best estimates of load or resistance. The probabilistic analysis of load and resistance can be used to estimate the reliability and also rationalize the determination and use of safety factors or design margins.

The safety factor or design margin is defined as

$$v = \frac{R}{Q} \quad \text{and} \quad R = v\,Q$$

where

R = resistance (strength)
Q = load (applied stress)

and the safety margin or margin of safety is defined as

$$M = R - Q \quad \text{or} \quad M = (v-1)\,Q$$

Failure then occurs if the factor of safety is less than one **or** if the safety margin becomes negative. The concept of reliability comes from the notion that there is always some small probability of failure that decreases as the safety factor or safety margin increases.

If we define the failure probability as

$$p = P(Q > R)$$

then in this context the reliability is defined as the probability of non-failure or probability of success

$r = 1 - p$ or $r = 1 - P(R < Q)$

When the load and resistance are associated with probability distributions, the mean values of the load and the mean value of the resistance can be expressed as

$$Q_m = \int_{-\infty}^{\infty} x \, f_Q(x) \, dx$$

$$R_m = \int_{-\infty}^{\infty} x \, f_R(x) \, dx$$

Thus the traditional safety factor is associated with the mean or average quantities and is expressed as

$$v = \frac{R_m}{Q_m}$$

As a second alternative the factor of safety can be expressed as the most probable value Q_o and R_o at the load and resistance distribution. Then the safety factor becomes

$$v = \frac{R_o}{Q_o}$$

The above definitions are associated with loads and resistances, which can be characterized in terms of normal or lognormal distributions.

Reliability Based Design

In general the expression for reliability can be obtained by integrating the probability distributions for load and resistance. The complete expression for reliability is given by (adopted from Lewis, 1987) [3]

$$r = \int_0^{\infty} \left[\int_0^{x} f_Q(q) dq \right] f_R(x) dx$$

The failure probability also can be determined as follows

$p = 1 - r$

or

$$p=\int_0^\infty\left[\int_x^\infty f_Q(q)dq\right]f_R(x)dx$$

Thus the failure probability is loosely associated with the overlap of the probability density function for the load and resistance in the sense that if there is no overlap, the failure probability is zero and r = 1.

A graphical interpretation of reliability is provided in the AISC Load and Resistance Factor Design Specification (LFRD) Specification (AISC 1986). This is illustrated in Figure 6.1. It can be seen that because the resistance, R, and load, Q, are random variables, there is some small probability that R may be less than Q, (R < Q). This is portrayed by the shaded area in this figure where the distribution curves crossing the upper diagram of Figure 6.1 (Merkle and Ellingwood, 1990).

An equivalent situation is expressed if the expression R < Q is divided by Q and the result is expressed logarithmically. This results in a single frequency distribution curve which combines the uncertainties for both Q and R. The probability of attaining a limit state (R< Q) is equal to the probability that ln(R/Q) < 0 and is represented by the shaded area in the lower diagram of Figure 1. The probability of failure may be decreased, or conversely the reliability increased, by moving the mean of ln(R/Q) to the right or by reducing the spread of the curve about the mean relative to the origin. A convenient way is to express the mean using the standard deviation of the curve as a unit of measure. Thus the mean of the curve can be expressed as (AISC 1986)[1]:

$$[\ln(R/Q)]_m=\beta\,\sigma_{\ln(R/Q)}$$

The factor β is called the "reliability index".

If the actual probability distribution function for ln(R/Q) is known then a complete probabilistic analysis can be performed. In actual practice only the means and standard deviations of the many variables that make resistance and load functions can be estimated. This information can be used to derive the following design condition

$$\beta\,\sigma_{\ln(R/Q)}\approx\beta\sqrt{V_R^{\,2}+V_Q^{\,2}}\le\lambda v(R/Q)_m\approx\ln(R_m/Q_m)$$

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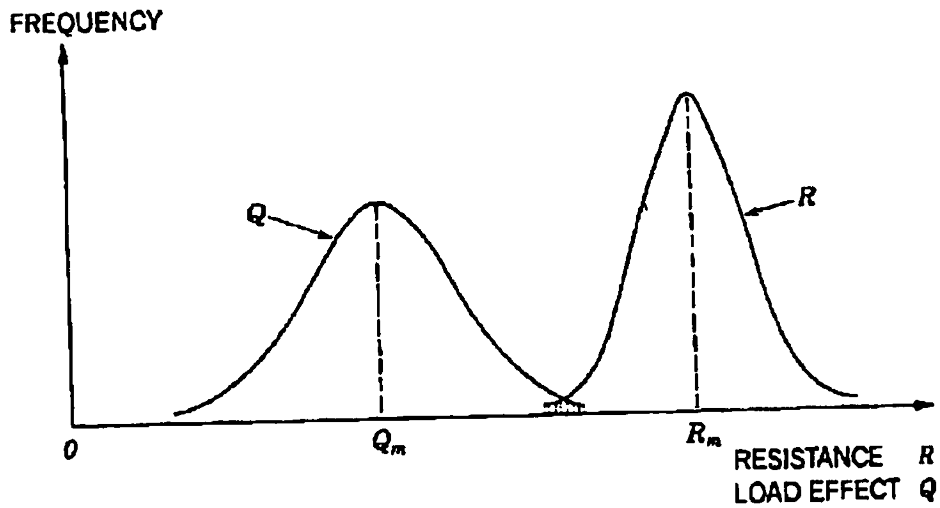
In the above formula, $V_R = \sigma_R/R_m$ and $V_Q = \sigma_Q/Q_m$, are the coefficients of variation for the resistance and load respectively. Similarly σ_R and σ_Q are the standard deviations and R_m and Q_m are the mean values.

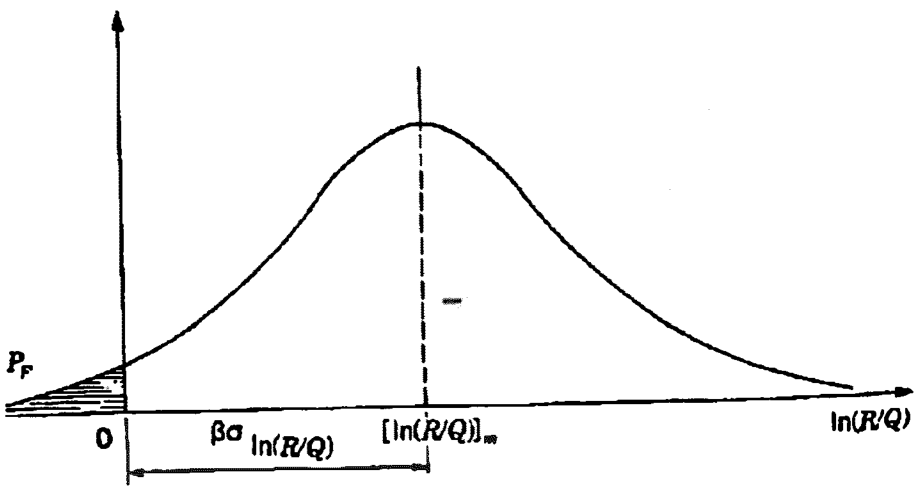
The above approximation provides a convenient way to calculate the reliability index, β, in terms of the means and coefficients of variations of the resistance and the load

$$\beta = \frac{\ln(R_m / Q_m)}{\sqrt{V_R^{\,2} + V_Q^{\,2}}}$$

The above concepts of reliability have been used in the development of the AISC LRFD (Load Resistance Factor Design). Similar applications can be adapted for ASME Code type applications.



Frequency distribution of load effect Q and resistance R



Definition of reliability index

Figure 6.1 Load, Resistance and Reliability Index Relationship (Ref. AISC LRFD Manual)

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Example - Structural Reliability of Corroded Cylinder Subjected to Internal Pressure

The concepts of reliability can be used to obtain a probabilistic solution of a corroded cylinder subjected to internal pressure. In this case all essential variables, such as geometry, material properties, effects of corrosion etc., can be investigated in terms of their impact on safety. A literature search did not produce any available solutions to this problem. For the purposes of the present study the general solution for this problem is developed below. The probability and reliability concepts discussed previously are used in this development.

The margin of safety, M, or level of performance of the system, can be defined in terms of design variables vector, x, the resistance (strength or capacity), R, which is treated as a random constant, and the load or stress, Q, which is a function the random design variables. In mathematical terms this is expressed as

$$M(x) = M(x_1, x_2, x_3, \ldots\ldots, x_n) = R/Q$$

The limiting design condition or limit state may be defined as

$$M(x) = 0$$

Similarly the safe state may be defined as

$$M(x) \geq 0$$

and the failure state as

$$M(x) \leq 0$$

To get a complete description of the reliability of the system, the joint density function of M(x) needs to be known. Generally this is not the case, and an approximate solution is obtained from the knowledge of the moments of the random variables, i.e., mean, standard deviation, etc..

Given a random function f(x) the mean or the expectation is represented as

$$\mu_f = \Sigma\, [f(x)]$$

and the standard deviation as

$$\sigma_f^2 = \Sigma\, [f^2(x)] - \mu_f^2$$

Expanding the function in terms of Taylor's series about the mean and neglecting high order terms, the second order approximation to the mean is given by (Zibdeh, 1990)

$$\mu_f = f(\mu_1, \mu_2, \ldots, \mu_n) + \frac{1}{2}\sum_{j=1}^{n} \frac{\partial^2 f}{\partial x_i} \Big|_{\mu} \sigma_{xj}^{\ 2}$$

and the standard deviation is

$$\sigma_f \approx \sum_{j=1}^{n} \frac{\partial^2 f}{\partial x_i} \Big|_{\mu} \sigma_{xj}^{\ 2}$$

where σ_{xj} is the standard deviation of the design variable x_j and can be written as

$$\sigma_{xj} = V_j \mu_j$$

where V_j is the coefficient of variation of x_j.

The probability of failure is obtained by assuming appropriate forms for the distributions for the stress (load) as well as the strength (resistance).

For normally distributed stress and strength, the probability of failure is written as

$$p_f = \Phi\left(-\frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^{\ 2} + \sigma_Q^{\ 2}}} \right)$$

where Φ is the normal probability function and the remaining quantities are associated with the mean and standard deviation and have been defined previously.

The reliability can be calculated from

$$r_f = 1 - p_f$$

For a lognormally distributed stress and strength, the probability of failure

$$p_f = \Phi\left(-\frac{\lambda_R - \lambda_Q}{\sqrt{\zeta_R^{\ 2} + \zeta_Q^{\ 2}}} \right)$$

where

$$\lambda_R = \ln \mu_R - \frac{1}{2}\zeta_R^{\ 2}$$

$$\lambda_Q = \ln \mu_Q - \frac{1}{2}\zeta_Q^2$$

$$\zeta_R = \ln(1 + V_R^2)$$

$$\zeta_Q = \ln(1 + V_Q^2)$$

Similarly the reliability for the lognormal distribution can be obtained from the relationship

$$r_f = 1 - p_f$$

The above expressions can be used to obtain numerical solutions of the probabilities of failure for any corroded component with a given design equation or analytical solution for the stress. It can be used to study the sensitivity of any design variable on the reliability of the system. What is required is an analytical expression of the function f(x), i.e the load function Q(x).

Section VIII, Division 1 (ASME B & PV Code) Pressure Design Equation

For example the load function, or the design stress equation in the circumferential direction for a shell subjected under internal pressure, in ASME Code, Section VIII, Division 1. Par. UG-27, can be written as

$$s = \frac{1}{E}\left(\frac{PR}{t-c} + kP\right)$$

Where

s	=	stress, in.
E	=	joint efficiency
P	=	internal pressure, psi
R	=	inside radius, in.
t	=	thickness, in.
c	=	corrosion allowance, in.
k	=	constant = 0.6

B31.8 Pressure Design Equation

It should be recognized that the various sections of the B31 Piping Code use a similar equation to that in Section VIII Division 1 . The above equation can be adopted to represent the B31 pressure design formulas. In particular, B31.8 uses the thin wall cylinder equation for the design equation which is equivalent to setting k=0 in the above equation. The B31.8 formula for design pressure for steel gas piping can be written as

$s = PD/2tE$

where

D = outside diameter = 2 x outside radius

Code design rules for pressure equipment put a limit on the stress, s, which is typically referred to as an allowable stress, S. The allowable stress, S, is determined typically from the material tensile and yield strength and applying an appropriate design factor or factor of safety.

$S = v F_l$

where

F_l = Tensile Strength (F_u) or Yield Strength (F_y)

Note: For > X70 pipe $F_y \approx F_u - 10$ ksi. F_y and F_u converge as you exceed X70 pipe (X80, X90, X100, etc.)

Design rules require the following condition to be satisfied

$S \leq s$

For the above formulation, the relative importance of each of the above design variables can be examined against the reliability or safety of the component. Nominal or average values of the quantities together with an estimate of the coefficients of variation are required. Alternatively, any quantity of interest can be treated as a variable and its effect over a range of values can be examined.

The mean and standard deviation of the hoop stress can be obtained from the above equations by taking the appropriate partial derivatives of the above formula for the hoop stress.

After lengthy mathematical manipulations the following mean value of the hoop stress (load) is obtained using the above design formula

$$\mu_Q = \frac{1}{E}\left[\frac{PR}{t-c} + kP\right] + \left[\frac{PR}{E^3(t-c)} + \frac{kP}{E^3}\right]\sigma_E^2 + \left[\frac{PR}{E(t-c)^3}\right]\sigma_t^2 + \left[\frac{PR}{E(t-c)^3}\right]\sigma_c^2$$

Similarly, the expression for the standard deviation for the hoop stress (load) is

$$\sigma_Q^2 = \left[\frac{Q}{P}\right]^2 \sigma_P^2 + \left[\frac{P}{E(t-c)}\right]^2 \sigma_R^R + \left[-\frac{PR}{E^2(t-c)} - \frac{kP}{E^2}\right]\sigma_E^2 + \left[-\frac{PR}{E(t-c)^2}\right]^2 \sigma_t^2 + \left[\frac{PR}{E(t-c)^2}\right]\sigma_c^2$$

Knowing the mean and standard deviations, the reliability or probability for failure can be obtained for normal distribution. For other types of distributions similar closed formed solutions can be obtained. In cases where the variables have different distributions or for complex problems, Monte Carlo simulations can be used to obtain numerical rather than closed formed solutions

Numerical Example

The following numerical example is presented below to illustrate the above reliability principles. The example does not represent an actual pipeline situation or typical conditions, but it is presented here for the sole purpose of illustrating the concepts discussed above.

Design Information

A NPS 10" pipe schedule 40 is constructed with ASTM A 53 Grade ERW material. The design temperature is 250 ^{o}F. There is no corrosion allowance. The Specified Minimum Yield Strength (SMYS) of the material specification is 35,000 psi. The actual mean yield strength measured from a number of pipe samples is 40,000 psi and the coefficient of variation of the data is 0.07. The coefficient of variation of the pressure is 0.015, of the thickness is 0.04 and the diameter is 0.0015. The remaining variables are constant and not varied in this example. The design factor, F, for B31.8 applications is 0.8, which produces the highest allowable stress in any of the ASME codes. Determine the allowable design pressure and the reliability. Normal distributions are assumed for all probabilistic variables.

Solution

The complete design parameters and design pressure solution is summarized in Table 6.1. Using the B31.8 equation presented above, the design pressure is 1901 psi.

Figure 6.2 shows the probability distribution function of the yield strength and the applied stress. The distance between the mean values (peak values) is an indication of the safety margin or design factor. The broadness of the curve is an indication of the standard deviation or variation of the yield strength data and the applied stress. The area of the overlapping curve is associated with the probability of failure but in magnitude is not equal to the probability of failure. Figure 6.3 shows the cumulative distribution functions, which is another form of the probability distributions.

Figure 6.4 shows the histogram or probability distribution of the applied stress obtained by running Monte Carlo simulations. The mean value of the applied stress is 28,000 psi and the standard deviation is 1204 psi.

The probability of failure of this example is 4.12E-5 and the reliability is 0.99995876. It can be seen that the reliability is extremely high in this example even with the high design factor of 0.8.

This is typical because of the high design margins used in codes of construction. For lower design factors used in other class locations the reliability approaches 1. It should be noted that this example only addresses internal pressure and the overall reliability is affected by other load conditions and other construction and operation factors.

References

1. AISC (1986), AISC Load and Resistance Factor Design Specification for Structural Steel Buildings, American Institute of Steel Construction, First Edition, September 1, 1986.

2. Dai, Shu-Ho and Wang Ming-O (1992), Reliability Analysis in Engineering Applications, Van Nostrand Reinhold, New York.

3. Lewis, E.E. (1987), Introduction to Reliability Engineering, John Wiley and Sons, New York, 1987.

4. Merkle, D.H., and Ellingwood, B. (1990), LFRD Loads, Modern Steel Construction, July-August 1990, pp. 15.

5. Zibdeh, H.S., (1990), Reliability of Thermally Loaded Cylinders, Journal of Pressure Vessel Technology, Vol. 112, August 1990, pp. 303-308.

Table 6.1

EXAMPLE OF RELIABILITY ANALYSIS OF PIPE UNDER INTERNAL PRESSURE

Design pressure	P	1901 Psi
Design temperature	T	250 F
Material ASTM A 53 Grade B ERW		
Pipe is 10 NPS Schedule 40		
Yield Strength, psi	Fy	35,000 Psi
Design Factor	F	0.8
Nominal Outside Diameter	D	10.75 In
Longitudinal joint factor	E	1
Temperature derating factor	T	1
Corrosion	c	0 In
Nominal thickness	t	0.365 In
Outside radius	Ro	5.375 In
Inside radius	Ri	5.01 In
B31.8 Design Pressure (calculated)	P	1901 Psi
Constant	k	0
Mean Yield Strength	S	40,000 Psi
Coefficient of variation of Yield Strength	V_S	0.07
Standard deviation of yield strength	s_strength	2800 Psi
Coefficient of variation of Pressure	Vp	0.015
Standard deviation of pressure	s_p	28.52 Psi
Coefficient of variation of thickness	V_t	0.04
Standard deviation of thickness	s_t	0.0146 In
Coefficient of variation of diameter	V_D	0.0015
Standard deviation of diameter	s_D	0.016125 In
Calculated stress (B31.8)	stress	28000.00 Psi
Standard deviation of applied stress	s_applied	1204.00 Psi
Normal distribution variable	z	-4
Probability of failure	Pf	4.12E-05
Reliability	Rf	9.9995876E-01

PROBABILISTIC VARIABLES

Design pressure	P	1901 Psi
Thickness	t	0.365 In
Outside diameter	D	10.75 In
Calculated B31.8 stress	stress	28000 In

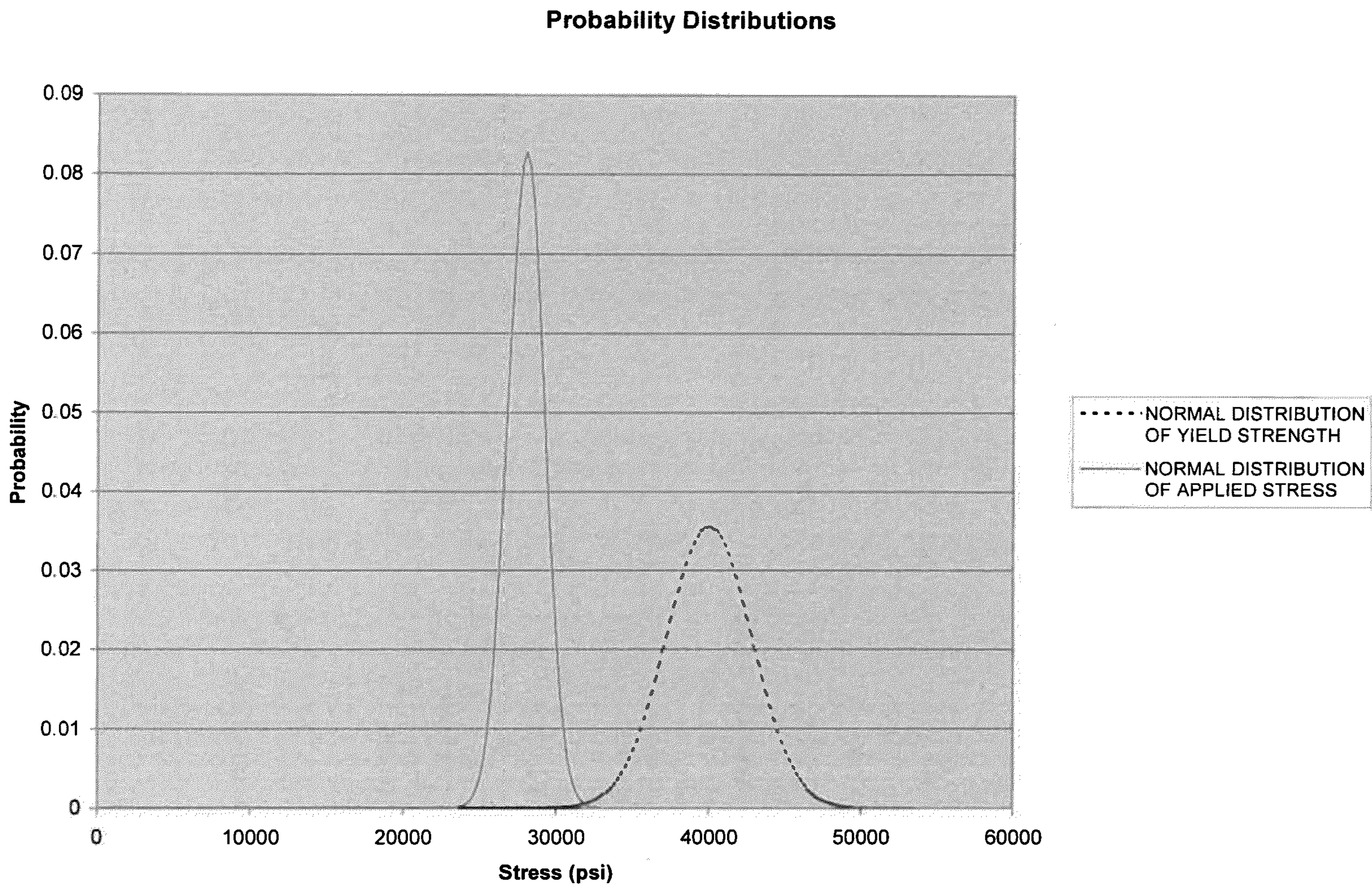

Figure 6.2 - Probability Distribution Function of the Yield Strength and the Applied Stress of Example

CHAPTER 7

RELIABILITY, PROBABILITY AND RISK METHODS

ASME pressure vessel, boiler and piping codes use the concept of the factor of safety in the development of design formulas. This approach began with the first ASME code in 1914, which addressed boilers, using a single factor as a particular mode of failure to provide an adequate protection against failure. Typically, separate factors are used for various modes of failure such a bursting, plastic deformation, plastic failure, buckling, creep, fatigue and other mode of failure that are considered significant for a particular application.

This single factor, also referred to as design margin, design factor or by other terms, is typically a conservative factor developed to address the various uncertainties in the quality of design, fabrication, examination, testing, material manufacture and handling, design analytical methods, applied loads, strength or resistance of the material and other factors that might affect the quality and performance of the pressure equipment.

The concepts presented in Chapter 6 are related to the development of reliability based design methods. These methods attempt to develop separate design factors to be applied to individual load or resistance terms. The objective is to provide a uniform design margin or factor of safety against the numerous load and resistance variables that are use to model a particular mode of failure.

In discussing risk based methods and to understand better the limitations of present codes it is useful to present the basic definitions of probability of failure, reliability and risk.

Risk

Risk is a term that accounts for both the probability of failure and the consequence of failure. In mathematical terms risk is expressed as :

Risk = probability x consequence

or

$$Q = P \times C$$

where

Q	=	risk
P	=	probability, frequency or likelihood of failure
C	=	consequence or severity of failure

The terms probability, frequency or likelihood of failure are used interchangeably and represent the same quantity. Typically the differentiation of these three terms is the method of quantification, i.e. a descriptive term (such as high, average, low, category A, B, etc), a single value estimate which is the frequency or number of failures in a given period or, a complete probabilistic description represented by a probability distribution function. The same applies to the terms consequence or severity. The consequences might involve, fatalities, injury or health implications to workers and the public, environmental damage or economic losses. When consequences involve fatalities, injury or health implications to people then the term safety is often used. The term factor of safety used in design codes is associated with the reduction or minimization of risk to humans.

Risk is synonymous with the expected consequences over a period of time. The term risk as used here should not be confused by common uses by the public at large. Often people use the term risk to refer to potential hazards, threats, events, perils or cause that might result in some risk. Examples are smoking, health, dietary, driving, natural events and other factors or causes. These factors might result in a probability of failure or a consequence of failure and thus some risk. Therefore, the public interchanges the terms risk and risk factors. In a strict sense, risk involves both the probability of failure and the consequence of failure in qualitative or quantitative terms.

Reliability

Reliability is a term associated with the probability that particular equipment will perform its intended function. Reliability is the complement of the probability of failure. Thus, reliability is related to the probability of failure by

$$R = 1 - P$$

where

R = reliability = probability of success
P = probability of failure

therefore, risk can be expressed as

$$Q = P \times C = (1\text{-}R) \times C$$

Risk Change, Benefit

The change in the risk is given by

$$dQ = dP \times C + P \times dC = -dR \times C + (1\text{-}R) \times dC$$

where, the letter d is used to indicate change or the derivative function. The change in the risk can be used reduce or minimize risk and compare against various decision alternatives. The commonly used term of benefit is the decrease (negative change) in risk. The risk cost is increase or positive change in risk. Mathematically, benefit and risk cost can be expressed as

$$B = dQ \quad \text{when } dQ < 0$$

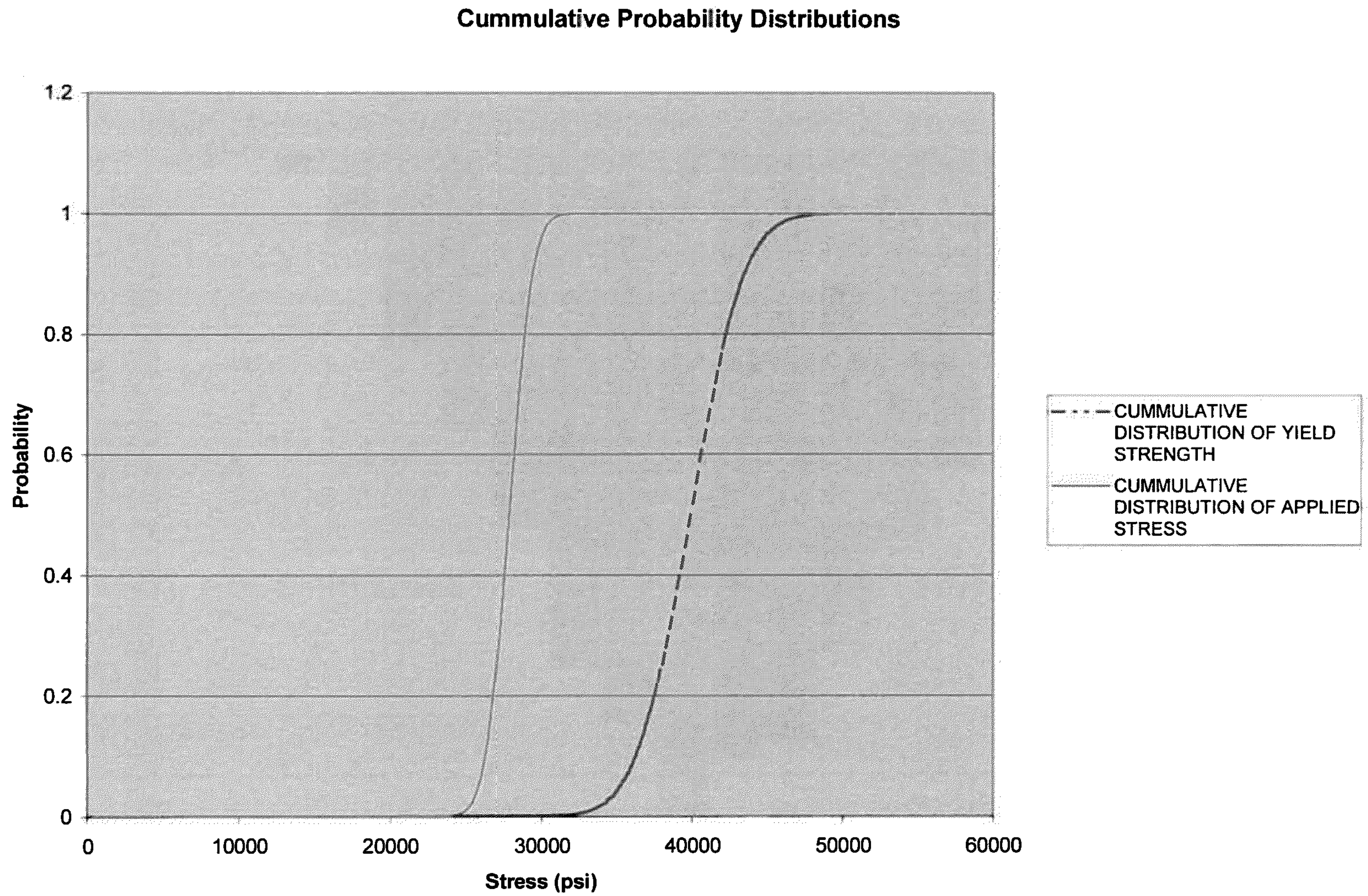

Figure 6.3 Cumulative Distributions of Example

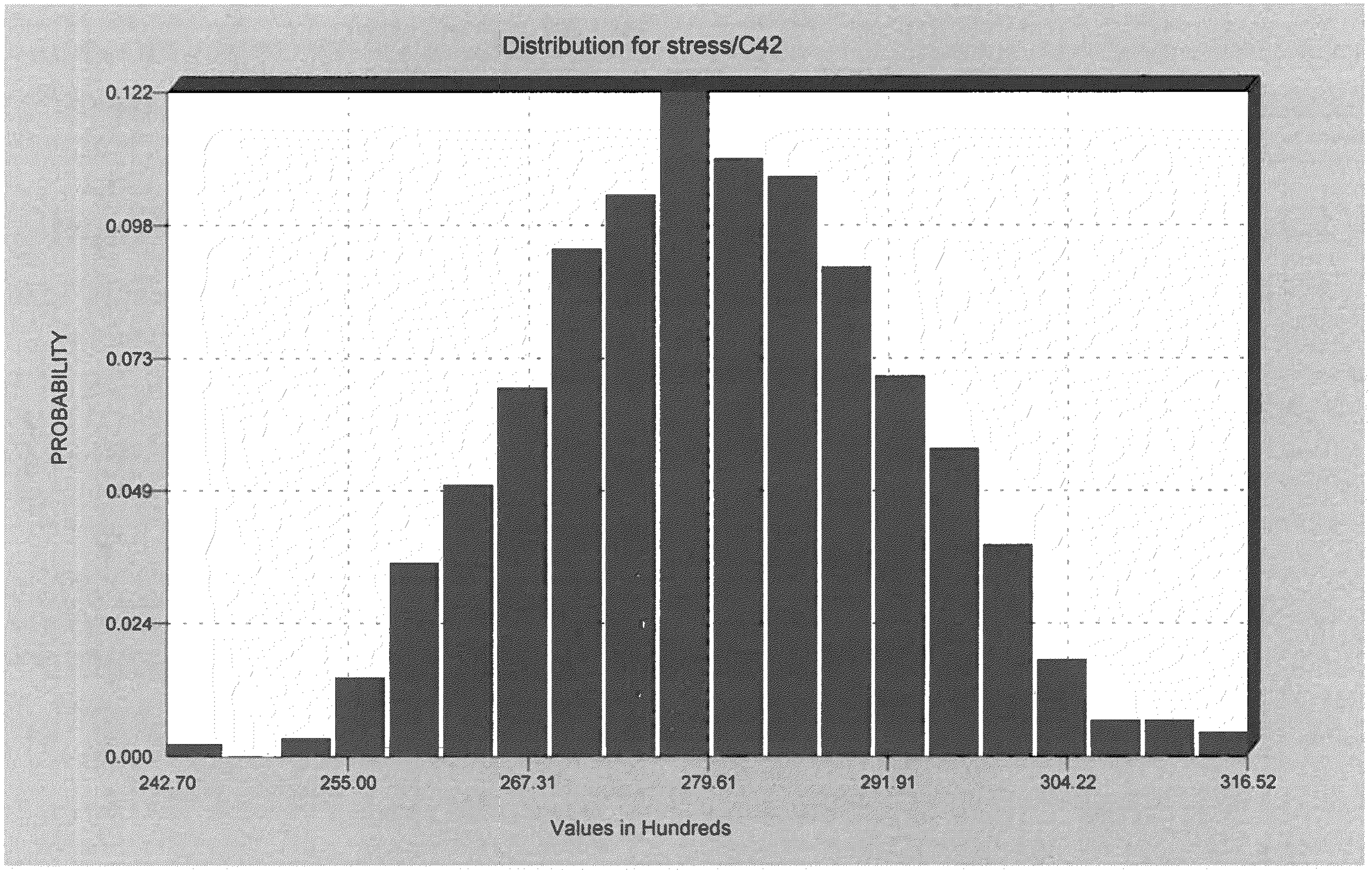

Figure 6.4 Probability Distribution of Applied Stress in Example

$D = dQ$ when $dQ > 0$

where

B = benefit

D = risk cost

Benefit / Cost Analysis

Various decisions such as design and code requirements have an associated cost of implementation or investment to achieve a risk reduction. Traditional benefit/cost analysis can be used to rank, justify and select code requirements by calculating the benefit cost ratio, i.e.

$$\frac{B}{I} = \frac{dQ}{I} = \frac{benefit}{implementation\ Cost}$$

Uses of Risk Concepts in Existing Codes

There are numerous examples where risk concepts have been used indirectly in the development of existing codes over the years. The design rules in boiler, pressure vessel and piping codes can be related to the above risk concepts. Existing rules use the concept of the factor of safety (design margin or design factor) to provide an adequate margin of safety. ASME codes are commonly referred to as safety codes and are not performance codes. It can be seen that in terms of consequence they are concerned with safety, meaning the rules have been developed to avoid or minimize fatalities, injury or health implications to the public. Economic or other types of consequences are not considered directly, although Code Committee members in their decision-making and judgments sometimes consider such factors.

Neglecting differences in consequences or addressing only safety and not economic losses is equivalent to making all consequences to be the same. Thus, the consequence term in the risk change equation drops out. For a constant consequence, the change in risk is proportional to the change in the probability of failure or proportional to the change in the reliability, i.e.

$$dQ \sim dP \sim -dR$$

Therefore, ASME codes are simple conservative reliability based codes where a single design factor is used for all factors that affect a particular mode of failure.

Sometimes Code Committee members through judgments (not through rigorous risk analysis) have developed code rules that address varying consequences. Examples are the lethal service rules in Section VIII, Division 1 where more restrictive fabrication and examination requirements are stipulated. The increase in the allowable stress limits for wind and earthquake is a recognition of the reduced probability of occurrence of such unlikely events in relation to other design loads. Section III, the nuclear code differentiates its requirements in terms of class 1, class 2 and class 3 components. These components are obviously indirectly related in their importance to the potential consequence or severity of failure.

The B31.3 process piping code uses the fluid service classifications of normal service, category D and high pressure to address differences in consequences of failure. The increases in the allowable stresses for occasional loads , such as wind and earthquake loads, in comparison to sustained loads such as pressure and dead weight loads reflect the different probability of occurrence.

The ASME B31.8 is one of the most sophisticated ASME codes in its adoption of risk concepts. B31.8 has adopted location classifications to specify different design factors. Most ASME codes use the same design factor for a particular mode of failure. In B31.8, Class locations are defined in terms of population densities in a specified region along a pipeline. The main reasoning of B31.8 committee members in adopting class location was the recognition of the potential of damage to a pipeline as a function of the population density. This is associated with the probability of occurrence of an event which effects the probability of failure of the pipeline. Similarly, the population density also effects the severity or consequence if a failure occurs.

The civil engineering industry for many years has incorporated requirements in building codes that have different requirements for various types of facilities such as structures, homes, hospitals, fire stations etc.. Building codes developed by the American Institute of Steel Construction (AISC), the American Concrete Institute (ACI) , national codes such as UBC, BOCA etc, took a leading role in their development and incorporation of design rules based on rigorous reliability based methods. The main objective has been more economical designs with improved and consistent factors of safety to cover various types of load conditions and other uncertainties. All these codes do not address the consequences with the same mathematical rigor as they do for the reliability or probability of failure.

Recently a number of ASME code committees have been examining similar type of reliability-based requirements; commonly referred to as partial design factors, limit state analysis etc. Some foreign pipeline codes, such as the Canadian code have already codified such requirements. Some foreign codes such as the Canadian, Australian, British, European, Dutch etc. have incorporated various levels of risk-based concepts. However, none of the codes have as yet developed rigorous risk based design rules and requirements that treat the probability of failure and the consequence of failure with the same importance and rigor. From a risk point of view both are equal in importance since risk is equal to the probability of failure and consequence of failure.

It is recommended that B31.8 first undertake an effort to review in detail other foreign pipeline codes that have incorporated reliability and risk based concepts. However, it is strongly recommended that B31.8 take the lead in the development and implementation of code requirements that are based on complete risk based methods and not on reliability or quasi-risk based methods. This should result in improved safety and improved reliability, by reducing risk, increased design pressures, and more economical design, construction and operation of pipelines. In addition it will allow B31.8 to retain its leadership role among the international pipeline codes. The historic leadership of B31.8 is evident in reviewing the various foreign codes that are obviously based on the requirements and philosophy of B31.8. The incorporation of different design factors as a function of class location by B31.8 (a forerunner to reliability concepts) has influenced foreign codes to incorporate reliability or risk-based concepts.

CHAPTER 8

ASSESSMENT OF PRESENT PIPELINE CODE RULES

In this report a review of design factors in American and major international pipeline standards and codes was conducted. In addition, recent on going and planned changes in design margins in codes covering pressure vessels, boilers and piping have been examined and assessed.

The major design factors in the present B31.8 code such as the 0.72 factor, which is applied against the Specified Minimum Yield Strength for the design of internal pressure, first appear in the 1935 American Standards Association Code for Pressure Piping, ASA B31.1 for the cross-country pipeline rules. In the last 65 years major quality improvements have been made in all areas, which have significantly reduced the uncertainties covered by the design factors. Consequently changes in the design factors are overdue for economical operation, optimization of resources, to address international competition for the American pipeline industry while maintaining or still increasing the historical margins of safety and risk to the industry and the public.

The various foreign codes have basically adopted the B31.8 design factors but have made a number of refinements and improvements in their code rules. Major enhancements in foreign codes are associated with their incorporation of reliability based, limit state, plastic analysis and risk-based concepts.

Historically, design margins have been reduced to reflect technological improvements in all areas, such as fabrication, examination, testing, materials, welding, design, analytical methods, load characterization and specification, and many other factors that affect the quality of pressure equipment and safety performance. In the first ASME code adopted in 1914 that covered boilers, a design factor of 5 was applied to the tensile strength to establish the allowable tensile stress for internal pressure design. The same factor had also been adopted by the pressure vessel code and piping code developed in the 1920's. Reflecting the improvements in high strength materials, codes have also specified design factors on the yield strength as 5/8 or 2/3.

The dominant design factor of 5 against the tensile strength was reduced to 4 in the 1940's to reflect improvements in the technology. In the 60's and 70's a design factor of 3 was adopted in the Section III nuclear code for class 1 components, Section VIII, Division 2 of the pressure vessel code and B31.3, Process Piping, (formerly petroleum and refinery piping) based on improvements in the analytical techniques and other factors.

Recently the ASME undertook an effort to assess the design factors used in its boiler, pressure vessel, and nuclear component codes. This study was driven by international competition and current international standards, many of which employ lower design margins. Two major studies, References 1 and 2, have resulted in a reduction of the design margin from 4 to 3.5 in Section VIII, Division 1 of the pressure vessel code. Section I, Power Boilers, and Section III Class 2 & 3, Nuclear Components, soon followed and have also reduced the design margins from 4 to 3.5.

The same reduction is being considered by B31.1, Power Piping, which uses the same basic design margins as Section I.

By reducing the design factor from 4 to 3.5, ASME recognized that since its inception in the early 1900's, the Code has undergone major improvements and revisions as new and improved materials and methods of fabrication have been instituted in the pressure vessel industry over time. The allowable stresses used in the design formulae were determined by multiplying the ultimate tensile strength listed in the material specification by a factor, or design margin, set by the Code Committee. This factor was 5 until the 1940's when it was reduced to 4.

Other factors were also considered besides the ultimate tensile strength when determining the allowable stresses. For temperatures below the range where creep and stress rupture govern the stresses, the maximum allowable stresses are the lowest of the following:

1) 1/4 of the minimum tensile strength at room temperature;
2) 1/4 of the tensile strength at temperature;
3) 2/3 of the minimum yield strength at room temperature;
4) 2/3 of the yield strength at temperature.

With new toughness and design rules implemented in Division 1, improved material manufacturing processes and fabrication techniques, and successful experience with Division 2 vessels, which use higher stress values with similar toughness rules, the ASME B & PV Committee began researching the possibility of reducing the design margin to 3.5 on ultimate tensile strength. The Committee assigned the task to the Pressure Vessel Research Council (PVRC), which began researching the methods used to determine the allowable stresses and the existing Code rules for construction.

The PVRC investigated documented pressure vessel failures and determined that the majority of failures fell into one or more of the following categories:

1) Failures from design faults or inadequate details
2) Process or operation related failures of pressure vessels
3) Service related degradation
4) Poor notch toughness, material or fabrication defects, welding or repairs

The occurrence of failures in vessels due to inadequate design rules is very low. Most of these occurred during the hydrostatic test because the test medium temperature was too low. The research showed that the majority of failures that have been documented were related to poor notch toughness, normal service degradation and operating conditions. Recent revisions to the Code in the areas of notch toughness, fabrication and hydrostatic/pneumatic testing requirements were made to reinforce the existing requirements. The PVRC concluded, citing the advances in the Code and manufacturing capabilities, that the design margin could be justifiably reduced to 3.5 on the ultimate tensile strength at temperature below the creep range.

With the implementation of the 1999 Addenda to the 1998 Edition the maximum allowable stresses listed in Section II, Part D, Tables 1A and 1B have changed as a result of this design margin reduction.

Based on the recent changes on the design factor to ASME Section VIII, Division 1 and other codes that use the same design factors, it may be possible to improve the design factors used in B31.8 without reducing the historical safety built into the pipeline design. Design factors have been used historically to address uncertainties such as in the design and operating loads, material manufacture, fabrication of components, examination, testing, analytical techniques, modes of failure, failure causes and other quality related factors

The B31.8 design factors have not changed for many years and do not reflect the improvements in the technology in the design, manufacture and operation of pipelines. The same improvements discussed in References 1 and 2 may be applicable to pipelines.

It is recommended that the B31.8 Code Committee undertake a similar effort, to that of the ASME Boiler and Pressure Vessel Code Committee, to examine the improvements in materials and fabrication techniques. As a result of this comprehensive study it may be possible to improve the existing design factors in B31.8 comparable to the recent change of the design factor from 4 to 3.5 in Section I, Section III, Section VIII, Division 1. This results in an approximate increase of 4/3.5 or approximately 15% in the design pressure.

Since B31.8 specifies different design factors that vary from 0.4 to 0.8 depending on the class location an appropriate adjustment is required for each location class before the above increase is implemented. The maximum design factor is 0.8 for Location Class 1 Division 1 pipeline segments. A number of foreign codes use the same factor but none exceed this factor. In addition, the pipeline codes have specified design factors only on the yield strength and not on the tensile strength (due to the nature of the imposed loads). Table 8.1 summarizes the yield and tensile strength properties for all B31.8 pipeline materials.

The Department of Transportation (DOT) pipeline safety rules (CFR Part 192) impose a maximum limit of 0.72 on the design factor for its Class 1 pipelines. The DOT rules have not changed since the 1970's and do not reflect the 0.8 maximum design factor and the distinction of Division 1 and Division 2 of Class 1 locations adopted by B31.8. A number of foreign codes have successfully adopted and implemented the 0.8 design factor. With successful past experience domestically and internationally with the 0.8 design factor, it is recommended the pipeline industry work with the U.S. DOT to adopt the maximum limit of B31.8.

Consistent with the application of the 15% increase in the design pressure for Class 4 pipelines and the 0% increase in the Class 1, Division 1 pipelines, appropriate increases in other location classes have been developed. These are presented and summarized in the Conclusions and Recommendation Chapter of this report.

References

1. Upitis, E., and Mokhtarian, K. (1996) Evaluation of Design Margins for ASME Code, Section VIII, Division 1, Prepared for the Pressure Vessel Research Council, May 1996, Revision 1.

2. Upitis, E., Mokhtarian, K., (1997) Evaluation of Design Margins for ASME Code Section VIII, Divisions 1 and 2 – Phase 2 Studies, Prepared for the Pressure Vessel Research Council, PVRC Project No 97-2, October 1997.

Table 8.1 – Summary of B31.8 Material Stresses

Material Spec.	Grade	Type	SMYS (Fy)	SMTS (Fu)	Ratio of Fu to Fy
API 5L	A25	BW, ERW, S	25.0	45.0	1.80
API 5L	A	ERW, S, DSA	30.0	48.0	1.60
API 5L	B	ERW, S, DSA	35.0	60.0	1.71
API 5L	X42	ERW, S, DSA	42.0	60.0	1.43
API 5L	X46	ERW, S, DSA	46.0	63.0	1.37
API 5L	X52	ERW, S, DSA	52.0	66.0	1.27
API 5L	X56	ERW, S, DSA	56.0	71.0	1.27
API 5L	X60	ERW, S, DSA	60.0	75.0	1.25
API 5L	X65	ERW, S, DSA	65.0	77.0	1.18
API 5L	X70	ERW, S, DSA	70.0	82.0	1.17
API 5L	X80	ERW, S, DSA	80.0	90.0	1.13
ASTM A 53	Type F	BW	30.0	48.0	1.60
ASTM A 53	A	ERW, S	30.0	48.0	1.60
ASTM A 53	B	ERW, S	35.0	60.0	1.71
ASTM A 106	A	S	30.0	48.0	1.60
ASTM A 106	B	S	35.5	60.0	1.69
ASTM A 106	C	S	40.0	70.0	1.75
ASTM A 134	A283A	EFW	24.0	45.0	1.88
ASTM A 134	A283B		27.0	50.0	1.85
ASTM A 134	A283C		30.0	55.0	1.83
ASTM A 134	A283D		33.0	60.0	1.82
ASTM A 135	A	ERW	30.0	48.0	1.60
ASTM A 135	B	ERW	35.0	60.0	1.71
ASTM A 139	A	EFW	30.0	48.0	1.60
ASTM A 139	B	EFW	35.0	60.0	1.71
ASTM A 139	C	EFW	42.0	60.0	1.43
ASTM A 139	D	EFW	46.0	60.0	1.30
ASTM A 139	E	EFW	52.0	66.0	1.27
ASTM A 333	1	S, ERW	30.0	55.0	1.83
ASTM A 333	3	S, ERW	35.0	65.0	1.86
ASTM A 333	4	S	35.0	60.0	1.71
ASTM A 333	6	S, ERW	35.0	60.0	1.71
ASTM A 333	7	S, ERW	35.0	65.0	1.86
ASTM A 333	8	S, ERW	75.0	100.0	1.33
ASTM A 333	9	S, ERW	46.0	63.0	1.37
ASTM A 381	Class Y-35	DSA	35.0	60.0	1.71
ASTM A 381	Class Y-42	DSA	42.0	60.0	1.43
ASTM A 381	Class Y-46	DSA	46.0	63.0	1.37
ASTM A 381	Class Y-48	DSA	48.0	62.0	1.29
ASTM A 381	Class Y-50	DSA	50.0	64.0	1.28
ASTM A 381	Class Y-52	DSA	52.0	66.0	1.27
ASTM A 381	Class Y-56	DSA	56.0	71.0	1.27
ASTM A 381	Class Y-60	DSA	60.0	75.0	1.25
ASTM A 381	Class Y-65	DSA	65.0	77.0	1.18

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A review of design factors in American and major pipeline standards and codes from other countries was conducted. In addition, recent on going and planned changes in design margins in codes covering pressure vessels, boilers and piping have been examined and assessed.

Based on this review it has been concluded that it may be possible to improve the design factors used in B31.8 without reducing the historical safety built into the pipeline design. Design factors have been used historically to address uncertainties such as in the design and operating loads, material manufacture, fabrication of components, examination, testing, analytical techniques, modes of failure, failure causes and other quality related factors.

The major design factors in the present B31.8 Code, which are applied against the Specified Minimum Yield Strength for the design of internal pressure, first appear in the 1935 American Standards Association Code for Pressure Piping, ASA B31.1, in the cross-country pipeline rules. In the last 65 years major quality improvements have been made in all areas which have significantly reduced the uncertainties and the need for conservative design factors. Consequently, changes in the design factors are appropriate at this time. This will lead to more economical operation of pipelines, better optimization of resources, and will address international competition for the American pipeline industry, while preserving and improving upon the same historical margins of safety and risk to the industry and the public.

Recommendations

It is recommended that the B31.8 Code Committee begin an in-depth study of the current design practices used for pipelines in relation to the improvements in materials, design and fabrication techniques that have been made over the past several decades. Such a study could provide the technical justification to revise the design factors as presented in Table 9.1. The ASME Boiler and Pressure Vessel Code Committee has undertaken such a task in the past few years resulting in an improvement in the design margins for their respective Codes (Upitis and Mokhtarian, 1996 and 1997).

Table 9.1 summarizes the design factors that are recommended for consideration and adoption in the B31.8 and U.S. Department of Transportation design rules. Appropriate changes in the design factors in other areas of the code can be made consistent with the above recommendations.

A comparison of existing and recommended design factors is presented in Figure 9.1. The resulting ratio increases in the design factors are illustrated in Figure 9.2. The increases in the design pressures for B31.8 range from 0% to 15% depending on the class location. For DOT rules the increases range from 6% to 15% depending on the class location.

In addition, it is recommended that the B31.8 Code Committee undertake a major effort to fully incorporate risk-based principles in the code so that pipeline companies, which are now using risk management for their pipeline operations, can optimize the pipeline designs and improve safety margins as well. A number of pipeline standards from other countries have incorporated some aspects of reliability or risk-based principles. These are referenced in Chapter 4 of this report. In particular the Canadian, Australian, British and Dutch standards have incorporated risk based principles which B31.8 should consider as a minimum. Presently, various ASME Code Committees are assessing development of risk-based design codes under the names of partial safety factors, limit state design etc. However, presently all on-going efforts are in reality reliability based using concepts introduced in Chapters 7 and 8. They are similar to the AISC LRDF approach, which address only half of the risk term, namely the probability of failure or its complement, reliability. Some codes try to address consequences using various categories or classes to differentiate some requirements

It is also recommended that B31.8 take a leadership role towards developing a fully risk-based design approach where both the probability of failure and the consequence are treated with the same level of importance and mathematical rigor. Such an approach will lead to improved and consistent safety in pipelines, increased maximum allowable operating pressures, provide more economical designs and operations and overcome the limits imposed by the present single design factor approach where all uncertainties are combined into a conservative single design factor. In addition, it will bring back to B31.8 its recognized leadership in its international use by having the most advanced, sophisticated and economical design rules. The historical leadership of B31.8 is clearly evident in other foreign standards, which are based on past B31.8 design philosophy and rules. The incorporation of different design factors as a function of location class by B31.8 (a forerunner to reliability concepts) has influenced foreign codes to incorporate reliability or risk-based concepts.

In order to have the safest, best pipeline operations in the world, the B31.8 Code must make the best technical methods and the best design codes available to pipeline operators.

Table 9.1 Recommended Design Factors

CLASS LOCATION	EXISTING B31.8 DESIGN FACTOR	RECOMMENDED DESIGN FACTOR
Class 1, Division 1	0.80	0.80
Class 1, Division 2	0.72	0.76
Class 2	0.60	0.68
Class 3	0.50	0.57
Class 4	0.40	0.46

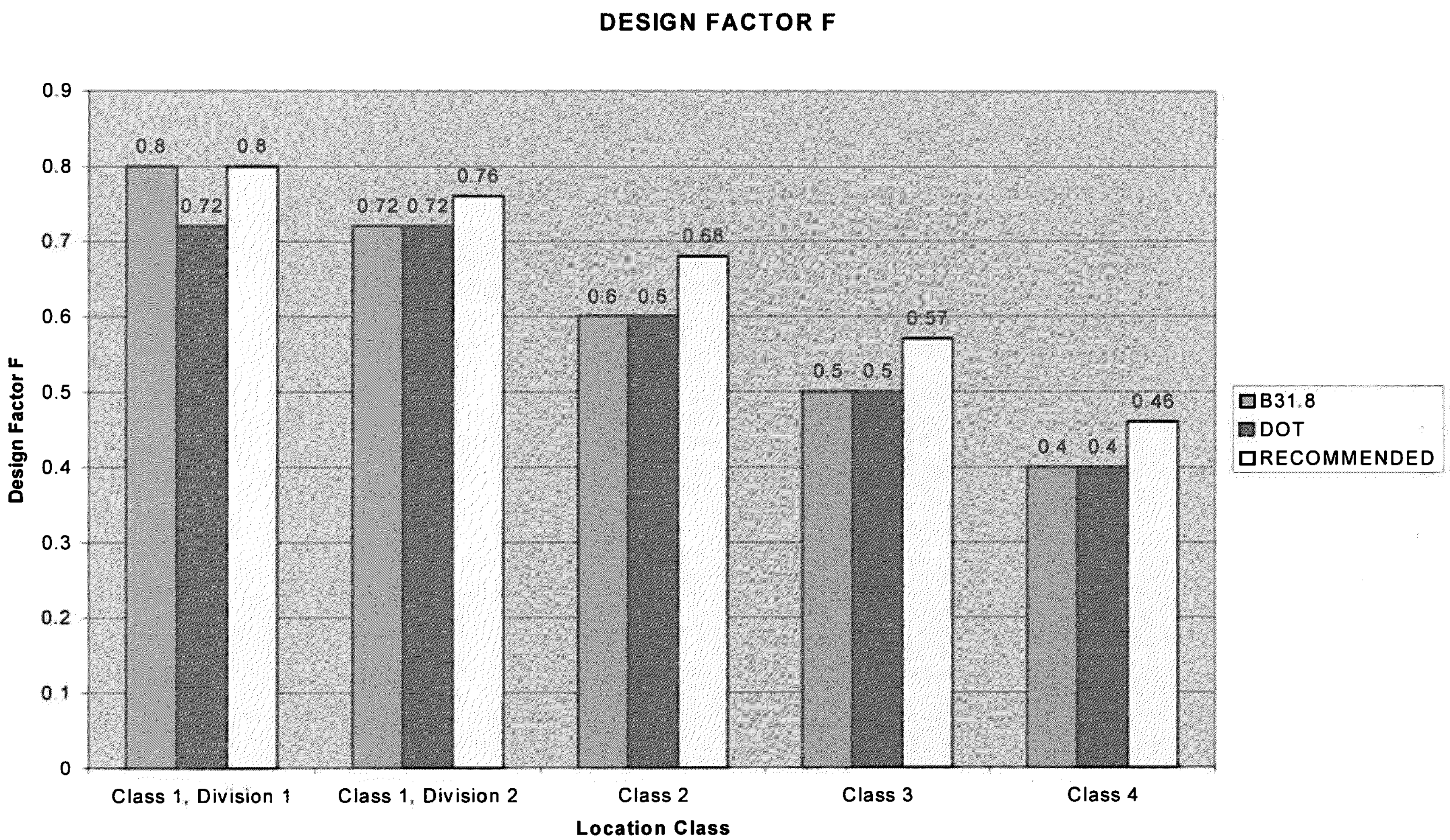

Figure 9.1 Comparison of Design Factors

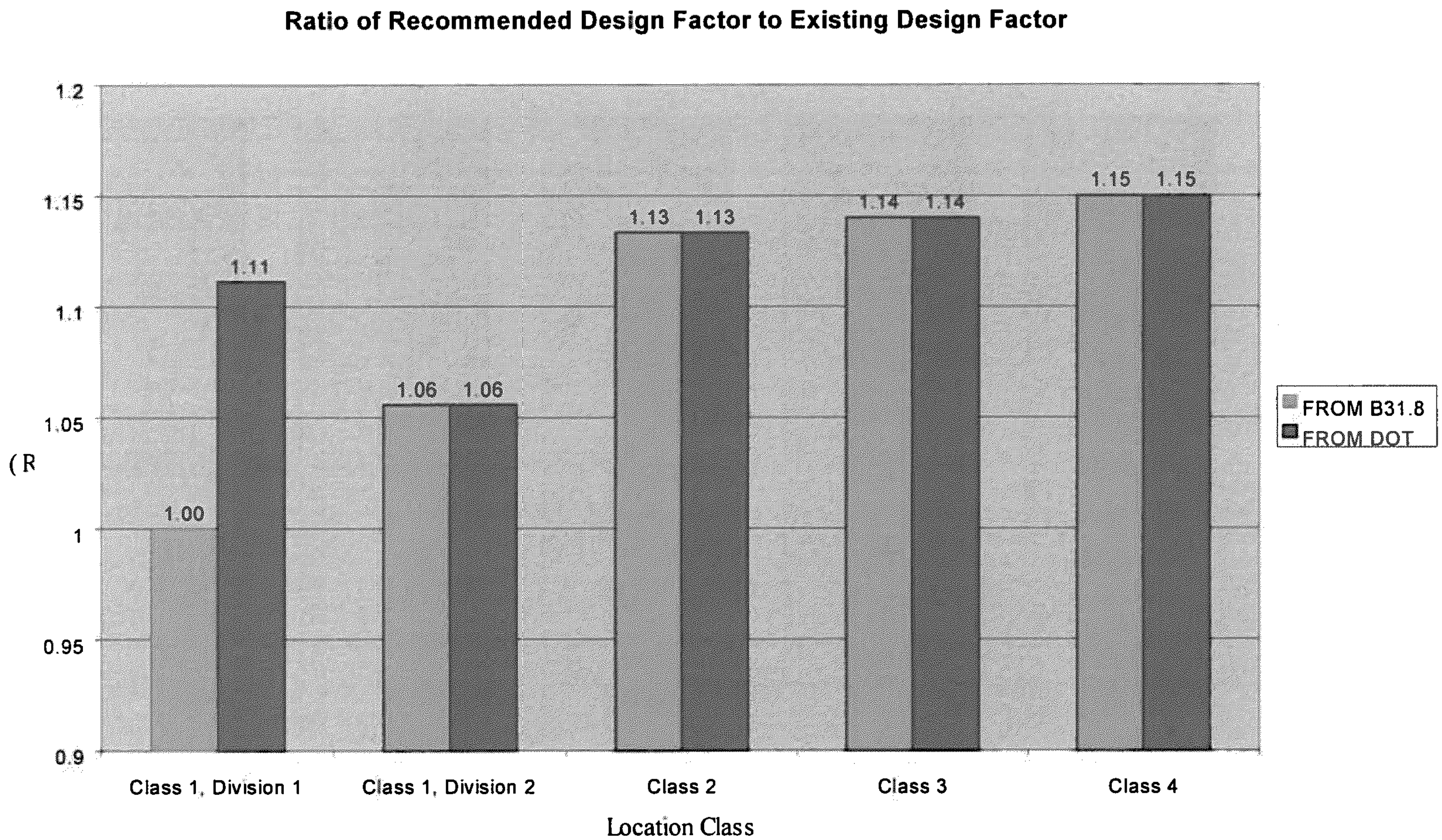

Figure 9.2 Recommended Design Pressure Increases