Pressure-Dependent Fragilities for Piping Components

Pilot Study on Davis-Besse Nuclear Power Station

Manuscript Completed: September 1990
Date Published: October 1990

Prepared by
D. A. Wesley, T. R. Kipp*, D. K. Nakaki, H. Hadidi-Tamjed

ABB Impell Corporation
27401 Los Altos, Suite 480
Mission Viejo, CA 92691

Under Contract to:
Idaho National Engineering Laboratory
Managed by the U.S. Department of Energy

EG&G Idaho, Inc.
Idaho Falls, ID 83415

Prepared for
Division of Safety Issue Resolution
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555
NRC FIN B5699
Under DOE Contract No. DE-AC07-76ID01570

*EQE, Inc.
Costa Mesa, CA

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

ABSTRACT

The capacities of four, low-pressure fluid systems to withstand pressures and temperatures above the design levels were established for the Davis-Besse Nuclear Power Station. The results will be used in evaluating the probability of plant damage from Interfacing System Loss of Coolant Accidents (ISLOCA) as part of the probabilistic risk assessment of the Davis-Besse nuclear power station undertaken by EG&G Idaho, Inc. Included in this evaluation are the tanks, heat exchangers, filters, pumps, valves, and flanged connections for each system. The probabilities of failure, as a function of internal pressure, are evaluated as well as the variabilities associated with them. Leak rates or leak areas are estimated for the controlling modes of failure. The pressure capacities for the pipes and vessels are evaluated using limit-state analyses for the various failure modes considered. The capacities are dependent on several factors, including the material properties, modeling assumptions, and the postulated failure criteria. The failure modes for gasketed-flange connections, valves, and pumps do not lend themselves to evaluation by conventional structural mechanics techniques and evaluation must rely primarily on the results from ongoing gasket research test programs and available vendor information and test data.

EXECUTIVE SUMMARY

A loss of coolant accident resulting from the potential overpressurization by reactor coolant fluid of a system designed for low-pressure, low-temperature service has been shown to be a significant contributor to risk in several probabilistic risk assessments. In this report, the methodology developed to assess the probability of failure as a function of internal pressure is presented, and results developed for the controlling failure modes and locations of four fluid systems at the Davis-Besse Nuclear Power Station are shown. Included in this evaluation are the tanks, heat exchangers, filters, pumps, valves, and flanged connections for each system. The variability in the probability of failure is included, and the estimated leak rates or leak areas are given for the controlling modes of failure. For this evaluation, all failures are based on quasi-static pressures since the probability of dynamic effects resulting from such causes as water hammer have been initially judged to be negligible for the Davis-Besse plant ISLOCA.

The pressure capacities of the pipes and vessels are evaluated using limit state analyses for the various failure modes considered. The capacities are dependent on several factors, including the material properties, modeling assumptions, and the postulated failure criteria. A major source of uncertainty in the failure criteria is the expected strain resulting in failure. All welds are full penetration and the probability of failure at membrane strains below yield is considered to be quite low. On the other hand, biaxial strains and gage length effects, as well as strain concentrations and bending, significantly reduces the expected hoop strain at failure when compared to elongation data developed from standard specimen ultimate tests. Since test data from vessel tests are extremely limited, considerable variability is introduced not only in the failure criteria, but in analytical modeling and other assumptions. In particular, the limited data that do exist are related to finite length cylinders with internal pressure loading only, and no test results are available for such effects as thermal or bending strains in pipe, strain concentrations at branch connections, or nozzle loads on tanks. Since many of the base parameters are random and the methods used to evaluate the capacities are subject to some uncertainty, the pressure capacity for any failure mode is also considered to be a random variable.

Design stresses in piping systems and pressure vessels include provision for stresses resulting from deadweight, thermal expansion, nozzle loads, earthquake and other loads as well as internal pressure. Stresses from other than internal pressure may constitute a major or even the controlling portion of the design allowable stress. At overpressure conditions, however, the percentage of available strength required to resist the nonpressure loads may be expected to decrease (i.e., the deadweight stress in a piping system does not increase with an increase in pressure, and while thermal stresses may increase above the design case, they are not expected to be the controlling load). Thus, the failure criteria developed for pipe and pressure vessel burst is concentrated on the internal pressure effects, as reflected in the hoop stress in a cylinder, while still retaining some consideration for other loads such as bending or branch

connections in pipe, or nozzle loads in tanks. The goal was to develop criteria which could reasonably include these additional effects without requiring a detailed evaluation in order to obtain the actual magnitudes of the bending stresses, etc., at every location and temperature.

A different approach must be used to evaluate the pressure capacities for gasketed flange connections, valves, and pumps. Unlike the failure modes for piping, vessels, and heat exchangers, which lend themselves to evaluation by conventional structural mechanics techniques, the failure modes for gasketed flange connections, valves, and pumps are very complex and evaluation must rely primarily on the results from ongoing gasket research test programs and available vendor information and test data. The pressure capacity and the associated leak rate of gasketed flanges depend on a number of parameters including bolt material characteristics and bolt preload, flange flexibility, initial gasket stress and relaxation, and gasket stiffness characteristics.

It is assumed that the pressure capacities have a lognormal distribution. This assumption is made because a lognormal distribution has been shown to be a valid description of the variability in material strengths. In addition, for a random variable that can be expressed as the product and quotient of several random variables, the distribution of the dependent variable tends to be lognormal regardless of the distributions of the independent base variables.

Uncertainties will exist in the estimated pressure capacities due to differences between the analytical idealization of the structure and the real conditions. There are numerous possible sources of modeling uncertainties. Examples of the sources of modeling uncertainties include: assumptions used to develop the internal force distributions, failure criteria, and the use of empirical formulae. Moreover, since the uncertainties are dependent on the particular failure mode under consideration, they must be evaluated on a case-by-case basis.

ACKNOWLEDGMENTS

The authors wish to acknowledge the valuable assistance of Mr. John O'Brien of the US Nuclear Regulatory Commission who has provided direction and support for this evaluation. In addition, the authors wish to thank Mr. Jim Payne, who provided assistance in interpreting results from the PVRC Gasket Test Program, and Mr. Bill Galyean and the technical staff of EG&G Idaho, who provided insight into the system behavior to the ISLOCA event. Special thanks are also due Dr. Everett Rodabaugh and Dr. Robert Kennedy who reviewed the fragility methodology and provided valuable and insightful comments.

The authors also wish to note the helpful assistance of a number of people within vendor organizations who provided data, information, and insight related to components provided to the Davis-Besse Plant. These include:

Walt Stephan (Flexitallic Gasket Company)

John Ferrell (Velan Engineering)

Terry Stevens (Hayward-Tyler, formerly B&W Canada, Ltd.)

Roy Davie (Hayward-Tyler)

Jim Wasser (Crane Packing Company)

The time and assistance of each of those mentioned above have been an invaluable resource to this evaluation and are sincerely appreciated.

CONTENTS

ABSTRACT	iii
EXECUTIVE SUMMARY	iv
ACKNOWLEDGMENTS	vi
1. INTRODUCTION	1-1
2. TANKS, HEAT EXCHANGERS, AND PIPE	2-1
2.1 Median Cylinder and Pipe Failure Pressure Criteria	2-1
2.2 Cylinder and Pipe Failure Pressure Variability	2-3
2.3 Cylinder and Pipe Failure Stress and Variability	2-4
2.4 Pressure Vessel Head Failure	2-5
2.5 Pressure Vessel Head Variability	2-7
2.6 Pipe and Vessel Leak Areas	2-8
2.7 Vessel Pressure Capacities	2-8
2.7.1 T-4 Make-Up Tank	2-9
2.7.2 T-5 Purification Demineralizer Tank	2-9
2.7.3 T-9 Core Flood Tank	2-9
2.7.4 T-10 Borated Water Storage Tank	2-9
2.7.5 T-14 Reactor Coolant Drain Tank	2-10
2.7.6 E-25 Let-Down Heat Exchanger	2-10
2.7.7 E-26 Seal Return Cooler	2-10
2.7.8 E-27 Decay Heat Exchanger	2-11
2.7.9 F-12 and F-36 Filters	2-11
2.7.10 Pipe	2-11
3. GASKETED-FLANGE CONNECTIONS	3-1
3.1 Introduction Vessel Pressure Capacities	3-1
3.2 Variables Affecting Flanged Joint Leakage	3-1

3.2.1	Bolt/Stud Preload	3-2
3.2.2	Bolt/Stud Temperature	3-2
3.2.3	Bolt/Stud Yield Strength	3-3
3.2.4	Bolt/Stud Stress-Strain Relationship	3-3
3.2.5	Bolt Relaxation	3-3
3.2.6	Flange Flexibility	3-4
3.2.7	Initial Gasket Stress	3-5
3.2.8	Gasket Loading Stiffness	3-5
3.2.9	Gasket Unloading/Reloading Stiffness	3-6
3.2.10	Gasket Creep and Relaxation	3-6
3.2.11	Pipe Bending Moments	3-7
3.3	Flange Joint Behavior	3-7
3.4	Calculation of Leak Rate and Leak Area	3-8
3.5	Gasketed Flange Connection Capacities and Variabilities	3-12
3.5.1	150lb Flanges	3-12
3.5.2	300lb Flanges	3-15
3.5.3	600lb Flanges	3-16
3.6	Conservatism in Computed Leak Parameters	3-17
4.	VALVES	4-1
5.	PUMPS	5-1
	REFERENCES	R-1

TABLES

2-1	304 Stainless Steel Material Properties	2-12
2-2	316 Stainless Steel Material Properties	2-12
2-3	Carbon Steel Pipe Material Properties	2-13
2-4	Carbon Steel Plate Material Properties	2-13
2-5	Failure Stresses and Variability for 304 SS	2-14
2-6	Failure Stress and Variability for SA 106 B Pipe	2-14
2-7	Failure Stress and Variability for SA 516 Grade 70 Vessels	2-15
2-8	Lognormal Standard Deviations for Dished-Head Buckling	2-15
2-9	T-4 Make-Up Tank	2-16
2-10	T-5 Purification Demineralizer Tank	2-17
2-11	T-9 Core Flood Tank	2-18
2-12	T-10 Borated Water Storage Tank	2-19
2-13	T-14 Reactor Coolant Drain Tank	2-20
2-14	E-25 Let-Down Heat Exchanger	2-21
2-15	E-26 Seal Return Cooler	2-22
2-16	E-27 Decay Heat Exchanger	2-24
2-17	F-12 and F-35 Filters	2-26
2-18	304 Stainless Steel Pipe Failure Pressures - Corrosion Allowance = 0.000 in.	2-28
2-19	304 Stainless Steel Pipe Failure Pressures - Corrosion Allowance = 0.020 in.	2-30
2-20	304 Stainless Steel Pipe Failure Pressures - Corrosion Allowance = 0.040 in.	2-32
3-1	Stiffnesses for Asbestos-Filled Spiral Wound Gaskets	3-18
3-2	150# ANSI Flange and Gasket Data	3-19
3-3	150# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 15000 psi, JR = 0%)	3-20

3-4	150# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 20000 psi, JR = 0%)	3-21
3-5	150# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 25000 psi, JR = 0%)	3-22
3-6	150# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 30000 psi, JR = 0%)	3-23
3-7	150# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 25000 psi, JR = 15%)	3-24
3-8	150# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 25000 psi, JR = 25%)	3-25
3-9	150# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 25000 psi, JR = 33%)	3-26
3-10	150# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 25000 psi, JR = 50%)	3-27
3-11	150# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (Bolt Yield = 27500 psi)	3-28
3-12	300# ANSI Flange and Gasket Data	3-29
3-13	300# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 30000 psi, JR = 0%)	3-30
3-14	300# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 35000 psi, JR = 0%)	3-31
3-15	300# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 40000 psi, JR = 0%)	3-32
3-16	300# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 35000 psi, JR = 15%)	3-33
3-17	300# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 35000 psi, JR = 25%)	3-34
3-18	300# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 35000 psi, JR = 33%)	3-35
3-19	300# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 35000 psi, JR = 50%)	3-36
3-20	300# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 35000 psi, JR = 25%, BR = 10%)	3-37
3-21	300# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 35000 psi, JR = 25%, BR = 20%)	3-38

3-22	300# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (Bolt Yield = 27500 psi)	3-39
3-23	600# ANSI Flange and Gasket Data	3-40
3-24	600# Flange Gasket Stress, Gross Leak Pressure, and Leak Rate (IBS = 35000 psi, JR = 25%, BR = 10%)	3-41
3-25	2"-150# Flange Leak Rate and Leak Area for More Precise Evaluation	3-42
3-26	4"-150# Flange Leak Rate and Leak Area for More Precise Evaluation	3-43
3-27	8"-150# Flange Leak Rate and Leak Area for More Precise Evaluation	3-44
3-28	16"-150# Flange Leak Rate and Leak Area for More Precise Evaluation	3-45
3-29	24"-150# Flange Leak Rate and Leak Area for More Precise Evaluation	3-46
4-1	Bolted Bonnet Valve Gasket and Bonnet Bolting Data for 150lb to 600lb Valves	4-3
4-2	Bolted Bonnet Valve Gasket and Bonnet Bolting Data for 1500lb Valves	4-4
4-3	Bolted Bonnet Valve Gasket Stress, Gross Leak Pressure, and Leak Rate	4-5

FIGURES

3-1	Incremental Gasket Load to Total Pressure Load Ratio for 150 to 600 Lb. Rated Flanges	3-47
3-2	Typical Load-Deflection Diagram Showing A Standard Test Sequence	3-48
3-3	A Typical Mass-Leak-Rate Vs. Gasket Stress Plot	3-49
3-4	Gasket Stress Vs. Tightness Parameter for Two Spiral-Wound Asbestos Gaskets, Cyclic Tests with Water	3-50
3-5	Mass Leak Rate Versus Pressure for 8"-150# Flange	3-51
3-6	Leak Area Versus Pressure for 8"-150# Flange	3-52
3-7	Leak Area Versus Pressure for 8"-300# Flange	3-53

1. INTRODUCTION

The work presented in this report is described in Revision 4 of the Task Action Plan for Generic Issue 105, ***Interfacing System LOCA in LWRs***, dated February 13, 1990. It is anticipated that the results documented here will facilitate the resolution of this high priority generic issue in a timely manner as well as the effort being undertaken by EPRI/NUMARC.

A probabilistic risk assessment of the Davis-Besse nuclear power station is being conducted by EG&G Idaho, Inc., to evaluate the probability of plant damage from Interfacing System Loss of Coolant Accidents (ISLOCA). Impell Corporation is under subcontract to EG&G Idaho, Inc., to establish the pressure capacities of several low pressure systems to withstand pressures and temperatures above the design levels. The probability of failure as a function of internal pressure has been developed for the critical modes of failure of four fluid systems subject to potential overpressurization. The four systems identified by EG&G for the Davis-Besse nuclear power station are the core flood, high pressure injection, decay heat removal (low pressure injection), and make-up and purification systems. Included in this evaluation are the tanks, heat exchangers, filters, pumps, valves, and flanged connections for each system. The variability in the probability of failure is included, and the estimated leak rates or leak areas are given for the controlling modes of failure. For this evaluation, all failures are based on quasistatic pressures since the probability of dynamic effects resulting from such causes as water hammer have been initially judged to be negligible for the Davis-Besse nuclear power station ISLOCA.

The pressure capacities of the pipes and vessels are evaluated using limit state analyses for the various failure modes considered. The capacities are dependent on several factors, including the material properties, modeling assumptions, and the postulated failure criteria. A major source of uncertainty in the failure criteria is the expected strain resulting in failure. All welds are full penetration and the probability of failure at membrane strains below yield is considered to be quite low. On the other hand, biaxial strains and gage length effects as well as strain concentrations and bending significantly reduces the expected hoop strain at failure when compared to elongation data developed from standard specimen ultimate tests. Since test data from vessel tests are extremely limited, considerable variability is introduced, not only in the failure criteria but in analytical modeling and other assumptions. In particular the limited data that do exist are related to finite length cylinders with internal pressure loading only, and no test results are available for such effects as thermal or bending strains in pipe, strain concentrations at branch connections, or nozzle loads on tanks. Since many of the

base parameters are random and the methods used to evaluate the capacities are subject to some uncertainty, the pressure capacity for any failure mode is also considered to be a random variable.

A different approach must be used to evaluate the pressure capacities for gasketed flange connections, valves, and pumps. Unlike the failure modes for piping, vessels, and heat exchangers, which lend themselves to evaluation by general structural mechanics techniques, the failure modes for gasketed flange connections, valves, and pumps are very complex and evaluation must rely primarily on the results from ongoing gasket research test programs and available vendor information and test data.

It is assumed that the pressure capacities have a lognormal distribution. This assumption is made because a lognormal distribution has been shown to be a valid description of the variability in material strengths. In addition, for a random variable that can be expressed as the product and quotient of several random variables, the distribution of the dependent variable tends to be lognormal regardless of the distributions of the independent base variables.

With the pressure capacity assumed to be a lognormal random variable and denoting it as P , the probability of failure occurring at a pressure less than or equal to a specific value p is expressed as:

$$P_f = \text{Prob}(P \leq p) = \Phi \left[\frac{\ln(p/\hat{P})}{\beta_c} \right] \quad (1-1)$$

where: P_f = probability that failure occurs at a pressure $p \leq p$

P = random pressure capacity

β_c = logarithmic standard deviation of P

$\hat{P}$ = median pressure capacity

$\Phi(\cdot)$ = cumulative distribution function for a standard normal random variable

In equation (1-1), the pressure capacity for a given failure mode is probabilistically described by the following expression,

$$P = \hat{P} \cdot M \cdot S \quad (1-2)$$

in which $\hat{P}$ is the median pressure capacity, M is a lognormally distributed random variable having a unit median and a logarithmic standard deviation β_M representing the uncertainty in modeling, and S is also a lognormally distributed random variable with a unit median value and a logarithmic standard deviation β_S representing the uncertainty in the material properties. The overall uncertainty in the median capacity is obtained by taking the square root of the sum of the squares of β_M and β_S .

The median pressure capacity represents the internal pressure level for which there is a 50% probability of failure (leakage or burst) for a given failure mode. The median values are evaluated from limit state analyses for the different failure modes. The uncertainties, β_M and β_S , are associated with variability due to a lack of knowledge related to differences between the analytical model and the real structure. Modeling uncertainties are associated with the assumptions used to develop analytical models and their ability to properly represent the failure condition. The strength uncertainties are associated with variabilities related to the material resistance. Examples of the sources of strength uncertainties include: variability in steel yield and ultimate strengths, stress-strain relationships, and the influence of elevated temperatures on material strength.

Uncertainties will exist in the estimated pressure capacities due to differences between the analytical idealization of the structure and the real conditions. There are numerous possible sources of modeling uncertainties. Examples of the sources of modeling uncertainties include: assumptions used to develop the internal force distributions, failure criteria, and the use of empirical formulae. Moreover, since the uncertainties are dependent on the particular failure mode under consideration, they must be evaluated on a case-by-case basis. However, in many instances, the evaluation of these uncertainties would require very detailed analysis and/or extensive data which may not be available. As a result, it was necessary to use subjective evaluation and engineering judgment to estimate these uncertainties.

The evaluation of the median capacities and the associated variabilities for the postulated failure modes for tanks, heat exchangers and piping is discussed in Section 2 while the evaluation of median capacities and variabilities for flanged connections, valves, and pumps are discussed in Sections 3, 4, and 5, respectively.

2. TANKS, HEAT EXCHANGERS, AND PIPE

Virtually all the piping and many of the vessels of importance for ISLOCA consideration at Davis-Besse are fabricated from 304 Stainless Steel (i.e., SA 312, TP 304, and TP 304 H for pipe). The remaining vessels are fabricated from carbon steel. Ultimate strength values at room temperature up to 800°F (References 1 and 2) available in the literature were used to establish expected median strengths for the 304 SS. Table 2-1 shows the expected median ultimate strengths for room temperature, 400°F, 600°F, and 800°F, as well as the corresponding values for yield strength and elongation. Also shown for comparison are the corresponding ASME Code values. Tables 2-2 through 2-4 show similar expected median and code values for 316 SS (SA 312, TP 316, and TP 316 H for pipe), and Carbon steel (SA 106 Grade B for pipe and SA 516 Grade 70 for plate).

As is apparent from these tables, a significant margin of safety often exists when the median material properties are compared with the corresponding code (lower bound) values. In a few instances, however, the median values available in the literature are close to, or even slightly lower than, the Code value; particularly for the 800°F temperature range. In all cases, however, since the systems and components being evaluated here were designed, for the most part, for relatively low pressures and temperature, ultimate pressure capacities for these components, governed by stresses near median ultimate values rather than the code design stress intensity, S_m , or allowable stress, S , values, are expected to be well in excess of the system design pressures.

2.1 Median Cylinder and Pipe Failure Pressure Criteria

Design stresses in piping system pressure vessels include provision for stresses resulting from deadweight, thermal expansion, nozzle loads, earthquake and other loads as well as internal pressure. Stresses from other than internal pressure may constitute a major or even the controlling portion of the design allowable stress. At overpressure conditions, however, the percentage of available strength required to resist the nonpressure loads may be expected to decrease (i.e., the deadweight stress in a piping system does not increase with an increase in pressure, and while thermal stresses may increase above the design case, they are not expected to be the controlling load). Thus, the failure criteria developed for pipe and pressure vessel burst is concentrated on the internal pressure effects, as reflected in the hoop stress in a cylinder, while still retaining some consideration for other loads such as bending or branch connections in pipe, or nozzle loads in tanks. The goal was to develop

criteria which could reasonably include these additional effects without requiring a detailed evaluation in order to obtain the actual magnitudes of the bending stresses, etc., at every location and temperature.

Failure due to hoop stress in a basically unflawed cylinder can be expected when the failure strain is reached. Several factors influence the failure strain when compared to the elongation predicted from a simple uniaxial 2-inch gage specimen, however. First, an unrestrained cylinder is in a state of biaxial stress and it is known that failure strains are reduced for multiaxial stress states. Manjoine (Reference 3) suggests a triaxial reduction factor of the form:

$$T.F. = \frac{\sqrt{2}(\sigma_1 + \sigma_2 + \sigma_3)}{[(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2]^{1/2}} \quad (2-1)$$

where σ_i ($i = 1,2,3$) are the principal stresses.

For an unrestrained cylinder with no bending subjected to internal pressure, the hoop stress is twice the axial stress and the maximum radial stress equal to the internal pressure is small, compared to the hoop and axial stresses. For this condition,

$$\sigma_1 = 2\sigma_2 \quad \text{and} \quad \sigma_3 \approx 0$$

and $T.F. = 1.73$

Including provision for bending such that:

$$\sigma_1 = \sigma_2 \quad \text{and} \quad \sigma_3 \approx 0$$

results in $T.F. \approx 2$.

Thus, failure strain in a cylinder fabricated from a material with uniaxial elongation, ϵ , due to hoop stress could be expected in the range of:

$$\epsilon_{T.F.} = \frac{\epsilon}{1.73} \quad \text{to} \quad \frac{\epsilon}{2}$$

Another factor which can influence the failure strain in a pipe or vessel is the effective gage length. Part of the elongation reported for a 2-inch uniaxial test specimen results from necking. For longer specimens, the necking portion of the elongation remains essentially constant so that the total elongation for longer length specimen is less (i.e., the elongation for a uniaxial 8-inch test specimen is less than for a 2-inch specimen). For a segment of pipe, the effective gage length may be expected to be of the order of the pipe circumference, and a

further reduction on failure strain of the order of 1.5 to 2 is estimated. For pressure vessels with strain concentrations due to under- or over-reinforced nozzles and other discontinuities, failure is expected at somewhat lower average strains. Based on failure strain values which have been reduced to account for the triaxial and gage length effects and based on the typical stress-strain relationships for strain hardening carbon and austenitic steels, failure stresses can therefore be expected at about 0.9 and 0.85 of the ultimate uniaxial stress, respectively. Based on the limited available data, these ratios are assumed independent of temperature. Therefore, including the increased radius at failure and using the corrected stress, the median pressure for failure in a thin-walled circular cylinder can be found from the simple relationship:

$$\hat{p}_f = \frac{\hat{\sigma}_f t}{r(1 + \epsilon_f)} \quad (2-2)$$

where: $\hat{\sigma}_f$ is the median failure stress
 $\hat{p}_f$ is the median failure pressure
 t is the wall thickness (nominal)
 r is the initial inside radius
 and ϵ_f is the median hoop strain at failure

This approach defines the failure pressure in terms of hoop stress which is an easy parameter to quantify but includes some provision for the biaxial stress-state and strain concentration effects.

2.2 Cylinder and Pipe Failure Pressure Variability

The variability associated with the calculated cylinder failure pressure results from a number of sources including material strength wall thickness, variability in the stress-strain relationship, uncertainty related to the biaxial stress condition, necking and strain concentration effects on the failure strain and bending or discontinuity stresses. Most important, however, may be the existence, size, and orientation of partial through-wall flaws in the cylinder wall. To conduct a rigorous, probabilistic fracture mechanics evaluation of all the piping and vessels important for ISLOCA requires a knowledge of the crack depth, crack length, crack orientation, and fracture toughness including biaxial load and corrosion effects, both now and at end of plant life. In addition to a mean or median value of the above parameters, the statistical distribution and coefficient of variation would be required. Current evaluations are being

conducted to accumulate and evaluate this type of data, but a rigorous evaluation based on this type of data requires consideration of the stress-state at every pipe weld and component over the entire range of temperatures which is beyond the scope of the current program.

Therefore, for the current investigation, the variability was developed for a log-normal distribution by assuming a probability of failure of 0.001 corresponding to yield in the cylinder. This approach, in essence, assumes the possibility a large flaw may exist which would be required to fail the cylinder at yield but eliminates the need to determine how the flaw was developed. Since the controlling failure condition is based on hoop stress, the above assumption of failure at yield implies the controlling flaw is an axial crack although a larger circumferential crack could also lead to the same failure at yield. Whether the crack was present at fabrication or whether it was initiated and grew due to causes such as thermal fatigue, water hammer, or corrosion, is unknown and is not required with this assumption.

In essence then, the assumption of 0.001 probability of failure at yield implies a 0.001 probability of the existence of a very large flaw. This is believed to be a very conservative (probably overconservative) assumption. If it is found that a significant contribution to the total risk occurs due to pipe or vessel burst at pressures well below the median burst pressures, then this assumption should be reevaluated. This would require that burst, as opposed to flange leakage, is determined to be the dominant failure mode but could easily be evaluated by sensitivity studies where the variability is based on probability of failure at yield is assumed to be 10^{-4} or 10^{-5} , for instance, or by truncating the tails of the distribution in the range of .02 to .04. If the overall risk is found to be sensitive to these assumptions, further research into the probability of expected flaw size may be necessary.

2.3 Cylinder and Pipe Failure Stress and Variability

Using the methods described in Sections 2.1 and 2.2 above, median hoop failure stresses and variabilities were developed for the materials and temperature range for both pipes and vessels. Due to the possibility of strain concentrations due to nozzles and other discontinuity stresses in tanks, somewhat lower median failure stresses, along with decreased variabilities, were used for tanks and vessels compared to pipe. Tables 2-5 through 2-7 show the failure stresses and corresponding lognormal standard deviations for the materials used in Davis-Besse.

In general, the failure stresses decrease with temperature, but due primarily to change in the ratio of yield-to-ultimate with temperature, the lognormal standard deviation tends to increase with temperature. Note, however, the tendency of the failure stress for the

low carbon steels to increase in the 400° to 600°F range. This characteristic results from the corresponding increase in ultimate strength in same temperature range, although the yield strength of the same material shows essentially a monotonic decrease with temperature (c.f., Reference 4). The lognormal standard deviations shown in Tables 2-5 through 2-7 are considered to be representative (although probably conservative) for cylinders with median pressure determined essentially for unflawed vessels but admitting the possibility of the presence of very large flaws. As such, a lognormal distribution is considered reasonable for failure pressure of the order of plus one standard deviation and below. However, at failure pressures in the high end of the distribution, the use of the lognormal distribution is inappropriate and some upper bound cutoff is required. This occurs physically since the presence of flaws can significantly reduce the failure pressure below the median unflawed cylinder, but the absence of flaws cannot further strengthen the cylinder above the assumed median unflawed cylinder capacity. This upper bound cutoff is controlled essentially by the ultimate strength of the material without including the biaxial load and strain concentration reduction effects. In essence, the upper bound cutoff is expected to correspond more closely to the failure of a cylinder with no bending, nozzles, branch connections, or flaws, and is representative of the results obtained from finite length unflawed cylinder test results. The cutoff is also not a discrete value but has a median with associated uncertainty governed by the material strength properties. These values are shown for the individual vessels in a subsequent section.

2.4 Pressure Vessel Head Failure

Buckling of pressure vessel heads is also a potential mode of failure for several of the Davis-Besse tanks and heat exchangers. Both semi-ellipsoidal and torispherical heads are used for the safety-related Davis-Besse pressure vessels. Two modes of buckling have been identified for pressure vessels. The first is asymmetric buckling denoted by P_{cr} , and the second is plastic collapse denoted by P_o . Buckling pressure capacities for these modes of failure were calculated using the equations obtained by Galletly and his co-workers (References 5 through 8). These equations were developed from analyses results using the BOSOR-5 computer program (Reference 9). For 2:1 semi-ellipsoidal steel heads, these results may be summarized as:

$$P_{cr} = 10.4 \sigma_y \left(\frac{t}{2r} \right)^{1.25} \quad (2-3)$$

and

$$P_o = \frac{\sigma_y l (1 + 50 \epsilon_y)}{r} \quad (2-4)$$

where: σ_y is the yield stress

t is the head thickness
 r is the radius of the attached cylinder
 and ϵ_y is the yield point strain

The ranges of parameters investigated were:

$$200 < r/t < 750$$

$$30 \text{ ksi} < \sigma_y < 60 \text{ ksi}$$

and the strain hardening slope, S , = 0, 5, and 10 percent.

Similarly, for torispherical heads,

$$P_{cr} = \frac{285\sigma_y(1 - 125\epsilon_y)(r_t/2r)^{0.85}}{(2r/t)^{1.53}(R_s/2r)^{1.1}} \quad (2-5)$$

and

$$P_o = \frac{12.6\sigma_y(1 + 240\epsilon_y)(r_t/2r)^{1.04}}{(2r/t)^{1.09}(R_s/2r)^{0.79}} \quad (2-6)$$

where: r_t is the toroidal (knuckle) radius
 R_s is the radius of the spherical portion
 and the other terms are defined as for Equations 2-3 and 2-4.

The ranges of parameters investigated were:

$$250 < r/t < 750$$

$$1.5 < R_s/r < 3$$

$$0.12 < r_t/r < 0.36$$

$$20 \text{ ksi} < \sigma_y < 75 \text{ ksi}$$

and the strain hardening parameter, S , = 0 and 5 percent.

The above analysis results are sensitive to the analytical modeling assumptions. For instance, for strain hardening steel heads, buckling is predicted for semi-ellipsoidal heads only when deformation theory is used. No buckling is analytically predicted using flow theory (Reference 6). Similarly, no buckling of strain hardening steel torispherical shells was predicted for the lower r/t ratios. Equations 2-3 through 2-6 are also conservative by about 10 percent based on analysis results. Results of tests for steel head buckling pressure capacities are very limited. Reference 5 shows a ratio of experiment to theory pressures of 1.59 to 1.97. Thus, while the above equations are considered an adequate basis for design, they appear to be excessively conservative for use in establishing median-centered buckling capacity. For use in this investigation, the analytically predicted (Equations 2-3 through 2-6) buckling pressures were increased by a factor of 1.78 to determine the expected median capacities. In all cases, the P_0 plastic collapse capacity controls for steel heads.

2.5 Pressure Vessel Head Variability

The principal sources of uncertainty in determining the dished-head buckling capacities are the modeling uncertainty associated with the BOSOR-5 analyses, the variability in the yield strength over the temperature range of interest, and the expected variability in the actual buckling capacity compared to the analysis results. Reference 10 recommends a coefficient of variation 0.1 for plastic collapse of semi-ellipsoidal heads, and typical coefficients of variation on the yield strength of stainless steel at room temperature are about 0.12. From the limited test results for buckled heads, a coefficient of variation of about 0.11 was developed to account for the uncertainty in actual buckling capacity. Assuming a lognormal distribution, the overall lognormal standard deviation at room temperature was determined as:

$$(0.1^2 + 0.12^2 + 0.11^2)^{1/2} = 0.19$$

At higher temperatures, increased variability in the yield strength coefficient of variation (Reference 2) results in increased overall variability. Table 2-8 shows the lognormal standard deviations developed over the temperature range of interest.

It should be noted that buckling does not necessarily result in the formation of a leak in a ductile, thin shell. The dished-heads under consideration here are in a net compression membrane stress-state which tends to substantially reduce the probability of a leak occurring, even in the post-buckled condition. It is estimated that the conditional probability of crack formation is about 0.2, given buckling occurs.

2.6 Pipe and Vessel Leak Areas

Some conditions exist where the presence of large flaws could result in leaks rather than uncontrolled bursts at the failure pressures being considered here. For the most part, however, once the pressure exceeds yield, uncontrolled leaks are expected for tanks and pipes. Even if the flaw configuration is such that theoretically a "leak" occurs before "break", the leak area is large in the context of ISLOCA.

One exception is the asymmetric buckling of the dished-heads. As previously noted, the head is in a state of membrane compression such that crack formation is expected only in regions of high local bending in the post-buckled condition. To the writers' knowledge, there is essentially no experimental data on crack size for this mode of failure. Consequently, it was estimated that the crack width for this condition is expected to be in the range of ten times the computed crack opening displacement (COD) computed using methods such as those described in Reference 11. Crack lengths were estimated to range from a few inches up to about the radius of the cylinder to which the head is attached. Leak areas were taken as the product of the crack width and the crack length. As a result, the lower and upper bound leak areas corresponded to the estimated minimum and maximum crack lengths. The median leak area was evaluated based on the upper and lower bound leak areas representing a $\pm 3.09\beta$ variation. These assumptions lead to median crack leak areas of the order of a square inch or less for this mode of failure. It should be noted, however, that if the crack progresses to a region of net membrane tension such as the cylinder, large, uncontrolled leak areas may be expected to occur, even if the crack initiates in the knuckle region of the head. However, this effect was not included in the estimation of the leak areas associated with the asymmetric buckling of the dished heads.

2.7 Vessel Pressure Capacities

In this section, the pressure capacities of the individual Davis-Besse tanks and heat exchangers are presented for the important failure modes, together with the expected variabilities in terms of the lognormal standard deviations. Failure pressures are given for metal temperatures ranging from room temperature to 800°F. Interpolation may be used to determine failure pressure and variability at intermediate temperatures. Also shown are upper bound cutoffs and associated variabilities, as well as expected leak areas. In general, leak areas are considered independent of temperature except as noted. Both shell and tube side failure pressures are presented for heat exchangers, and where bolted flanges are used, the size and weight of the flange(s) is shown. Leak pressures and leak rates or leak areas are shown for various size and weight flanges in a subsequent section.

2.7.1 T-4 Make-Up Tank

The T-4 make-up tank is an 8'-0" diameter by about 8'-8" cylinder length tank fabricated from 304 SS. Both the 2:1 semi-ellipsoidal heads and the cylinder are 3/8-inch thick plate. One 18-inch, 150 pound blind flange is used. The tank was designed for 100 psig at 200°F with a 158 psig hydrotest specified. The median internal pressure capacities and expected variabilities for the temperature range of interest are shown in Table 2-9.

2.7.2 T-5 Purification Demineralizer Tank

The T-5 purification demineralizer tank is a 48-inch O.D. by 68-inch cylinder length tank fabricated from SA 240 TP 304 stainless steel. The cylinder is fabricated from 3/8-inch thick plate and the torispherical heads are 0.5-inch minimum. One 18-inch diameter, 150 pound blind flange is used. The tank was designed for 150 psig at 200°F with a 238 psig hydrotest specified. The median internal pressure capacities and expected variabilities are shown in Table 2-10.

2.7.3 T-9 Core Flood Tank

The T-9 core flood tank is a 9'-6-3/4" O.D. with approximately 17'-9" cylinder length tank located within the containment building. The tank cylinder and the 2:1 semi-ellipsoidal heads are fabricated from 2-3/8-inch thick SA 516 Grade 70 plate with a nominal 3/16-inch (1/4-inch minimum) stainless steel cladding. The tank was designed for 700 psig at 300°F. One 15-inch diameter flange is located on top of the tank. Burst pressures, for the most part, are above the range of interest for ISLOCA, and leakage of this tank is controlled by the 15-inch flange and gasket and therefore, leak areas for the cylinder and head were not calculated. The median failure capacities and associated variabilities for the cylinder and heads are shown in Table 2-11.

2.7.4 T-10 Borated Water Storage Tank

The T-10 borated water storage tank is a large, field-erected flat-bottomed storage tank. The tank is a nominal 47'-0" diameter, 44' high tank with a hemispherical 37'-7" radius dome. The cylinder is fabricated from six courses of SA 240 TP 304 stainless steel which vary from 0.57 to 3/16 inches thick. The dome thickness is 7/32 inches and the dome-cylinder connection is further strengthened by an angle iron ring girder. The tank is anchored by 48, 2-1/4-4 UNC A307 embedded anchor bolts. A manhole access is provided which consists of a 1/4-inch cover plate secured by 20, 5/8-inch diameter A193-B8 bolts on a 27-1/2-inch diameter bolt circle. The tank was designed for atmospheric pressure and 0 to 125°F. Test conditions consist of filling the tank to overflow. Failure modes evaluated included rupture of the cylinder

and dome, failure of the anchorage (tensile failure of the anchor bolts) with subsequent leak at the cylinder bottom plate junction, and leak at the manhole. Failure of the anchorage system may be confined to the room temperature condition, since elevated temperatures of the embedded anchor bolts is considered very unlikely. Due to the relatively shallow height of the dome and the presence of the ring girder at the dome-cylinder connection, buckling of the dome was not considered likely. The pressure capacities and variabilities of the controlling failure modes are shown in Table 2-12.

2.7.5 T-14 Reactor Coolant Drain Tank

The T-14 reactor coolant drain tank is a 4-foot outside diameter by 6'-7-1/2" cylinder length tank with torispherical heads. The tank and heads are fabricated from 1/4-inch 304 stainless steel. One 24-inch, 150 pound flange is used. The tank was designed for 50 psig at 300°F with a 75 psig hydrotest specified. Median failure pressure capacities and variabilities are shown in Table 2-13.

2.7.6 E-25 Let-Down Heat Exchanger

The E-25 let-down heat exchanger is a helical-coil compact heat exchanger with a 43-inch outside diameter by 22.7-inch length shell side cylinder fabricated from 1/2-inch SA 285 Grade C plate. The two flat end plates are 3-1/4 and 3-5/8 inch thick SA 515 Grade 65. The shell side was designed for 200 psig. Potential failure modes investigated included the shell side cylinder and end plates as well as tube buckling and rupture. The shell side cylinder pressure was found to govern with all other failure modes at much higher capacities. Since the tube side was designed for 2500 psig and tested to 4450 psig, the tube side failure modes were judged to have capacities much higher than the shell side. The median failure pressures and variabilities for the E-25 heat exchanger are shown in Table 2-14.

2.7.7 E-26 Seal Return Cooler

The E-26 seal return cooler is a long U-tube heat exchanger with the shell-side cylinder fabricated from 6-inch (6-5/8 inch O.D.) SA 53 B Schedule 40 pipe. Wall thickness is 0.28 inches. The test pressure of the shell side was 225 psig. Tubes are 5/8-inch O.D. No. 18 BWG 304 stainless steel with a nominal wall thickness of 0.049 inches. The tube-side outer cylindrical shell is 6-5/8 inch O.D. with a 0.134-inch wall thickness. Tube side test pressure was 238 psig. Two 1-1/2 inch, 150 pound flanges are located on the shell side and two 1-1/2 inch, 150 pound and one 6-inch, 150 pound flanges are located on the tube side. The tube sheet flange is a 6-inch, 150 pound flange. Tube buckling and rupture capacities are greater than the cylinder rupture pressure. The tube buckling capacity was evaluated by treating the

tube as a long, thin-walled cylinder subjected to an external pressure. The median pressure capacities and associated variabilities for both the tube and shell side cylinders are shown in Table 2-15.

2.7.8 E-27 Decay Heat Exchanger

The E-27 decay heat exchanger is a U-tube heat exchanger with 43-inch inside diameter. The shell side cylinder is fabricated from 1/2-inch SA 285 Grade C plate with a torispherical 1/2 inch thick head fabricated from SA 240 TP 304 stainless steel. The tube side cylinder is fabricated from 5/8-inch SA 285 Grade C plate and the head is 5/8-inch SA 240 TP 304. Two 20-inch, 150 pound flanges are located on the shell side together with a 44-inch tube sheet flange. Two 10-inch, 300 pound flanges are located on the tube side. Median pressure capacities and expected variabilities for both the shell and tube side cylinders and dished-heads are shown in Table 2-16.

2.7.9 F-12 and F-35 Filters

The F-12 and F-35 filters are nominal 14-inch O.D. cylinders with 0.156-inch wall thickness and 0.25-inch thick 2:1 semi-ellipsoidal bottom heads fabricated from 304 stainless steel. The top heads are 1-3/8 inch thick 304 flat plate secured by six 3/4-10 UNC, SA 193-B8M bolts on a 17-inch diameter bolt circle torqued to 45 ft/lb. An ethylene-propylene "o"-ring seal is employed. The filters were designed for 150 psig at 200°F with a 240 psig hydrotest specified. The filter leak pressure and area is governed by the bolted top head. Median cylinder and bottom head pressure capacities and variabilities are shown in Table 2-17, as is the top head leak area, as a function of pressure. The leak areas for the top head were based upon the flange gap opening due to bolt extension less the expected "o"-ring seal rebound. Leak areas for room temperature and higher temperatures are different due to the expected degradation of the ethylene-propylene "o"-ring seal at temperatures above about 400 to 450°F.

2.7.10 Pipe

All pipe of concern for the Davis-Besse ISLOCA investigation is fabricated from SA 312 TP 304 stainless steel. Median burst pressures for the temperature range of interest are presented for various assumed levels of corrosion in Tables 2-18 through 2-20. The associated variabilities at these temperatures are given in Table 2-5. Note that the variabilities given in Table 2-5 are for failure stress but can also be used for failure pressure since the contribution of other elements to the total variability is expected to be negligible.

Table 2-1. 304 Stainless Steel Material Properties

Temperature (°F)	Ultimate Strength (ksi)		Yield Strength (ksi)		Elongation (%) (2-inch gage)	
	Median	Code*	Median	Code	Median	Code
R.T.	86	75	37	30	60	35 (long.) 25 (trans.)
400	74	64.4	23	20.7	53	
600	70	63.5	19.5	18.2	49	
800	65.5	62.7	16.5	16.8	46	

* SA 312, TP 304, and TP 304 H

Table 2-2. 316 Stainless Steel Material Properties

Temperature (°F)	Ultimate Strength (ksi)		Yield Strength (ksi)		Elongation (%) (2-inch gage)	
	Median	Code*	Median	Code	Median	Code
R.T.	86.5	75	42	30	46	35 (long.) 25 (trans.)
400	81.5	71.8	35	21.4	43	
600	77.5	71.8	31	18.8	41.5	
800	73	70.9	28	17.6	40	

* SA 312, TP 316, and TP 316 H

Table 2-3. Carbon Steel Pipe Material Properties

Temperature (°F)	Ultimate Strength (ksi)		Yield Strength (ksi)		Elongation (%) (2-inch gage)	
	Median	Code*	Median	Code	Median	Code**
R.T.	68	60	36	35	36	22 (long.) 12 (trans.)
400	72	60	31	30	25	
600	69	60	27	25.9	33	
800	55	55.1	24	23.3	40	

* SA 106 Grade B

** Standard Specimen

Table 2-4. Carbon Steel Plate Material Properties

Temperature (°F)	Ultimate Strength (ksi)		Yield Strength (ksi)		Elongation (%) (2-inch gage)	
	Median	Code*	Median	Code	Median	Code
R.T.	84	70	46	38	27	21
400	87	70	40	32.6	16	
600	85	70	37	28.1	25	
800	71	64.3	34	25.3	34	

* SA 516 Grade 70

Table 2-5. Failure Stresses and Variability for 304 SS

Temperature (°F)	Pipe		Vessel	
	$\hat{\sigma}_f$ (ksi)	β	σ_f (ksi)	β
R.T.	74	0.22	67	0.19
400	62.9	0.33	57.9	0.30
600	59.5	0.36	54.6	0.33
800	55.7	0.39	51.2	0.37

where $\hat{\sigma}_f$ denotes the median hoop failure stress

Table 2-6. Failure Stress and Variability for SA 106 B Pipe

Temperature (°F)	$\hat{\sigma}_f$ (ksi)	β
R.T.	61.2	0.17
400	64.8	0.24
600	62.1	0.27
800	49.5	0.23

where $\hat{\sigma}_f$ denotes the median hoop failure stress

Table 2-7. Failure Stress and Variability for SA 516 Grade 70 Vessels

Temperature (°F)	$\bar{\sigma}_f$ (ksi)	β
R.T.	75.6	0.16
400	78.3	0.22
600	76.5	0.24
800	63.9	0.20

Table 2-8. Lognormal Standard Deviations for Dished-Head Buckling

Temperature (°F)	Lognormal Standard Deviation, β
R.T.	0.19
400	0.23
600	0.23
800	0.24

**Table 2-9. T-4 Make-up Tank
Median Failure Pressures and Variabilities**

TEMP.	CYLINDER				HEAD BUCKLING			
	$\hat{P}$	β	P_U	β	$\hat{P}_{CR}$	β	$\hat{P}_O$	β
R.T.	440	0.19	560	0.07	680	0.19	600	0.19
400°F	400	0.30	520	0.07	420	0.23	370	0.23
600°F	390	0.33	490	0.08	360	0.23	310	0.23
800°F	360	0.37	460	0.08	300	0.24	260	0.24

MEDIAN LEAK AREA (ALL TEMP. EXCEPT AS NOTED)

	$\hat{A}(\text{inch}^2)$	β
Cylinder	Uncontrolled	--
Head*, P_{CR}	1.0	0.65
Head*, P_O	Uncontrolled	--

where $\hat{P}$ is median cylinder rupture pressure (psig)
 P_U is upper bound cylinder rupture pressure (psig)
 $\hat{P}_{CR}$ is median asymmetric head buckling pressure (psig)
 $\hat{P}_O$ is median plastic collapse head buckling pressure (psig)

Flange: (1) 18"-150#

*Assume: 0.2 Probability of crack formation given head buckling occurs.

**Table 2-10. T-5 Purification Demineralizer Tank
Median Failure Pressures and Variabilities**

TEMP.	CYLINDER				HEAD BUCKLING			
	$\hat{P}$	β	P_U	β	$\hat{P}_{CR}$	β	$\hat{P}_O$	β
R.T.	890	0.19	1140	0.07	960	0.19	550	0.19
400°F	810	0.30	1040	0.07	660	0.23	320	0.23
600°F	780	0.33	990	0.08	570	0.23	270	0.23
800°F	730	0.37	930	0.08	490	0.24	230	0.24

MEDIAN LEAK AREA (ALL TEMP. EXCEPT AS NOTED)

	$\hat{A}(\text{inch}^2)$	β
Cylinder	Uncontrolled**	--
Head*, P_{CR}	0.4	0.5
Head*, P_O	Uncontrolled	--

where $\hat{P}$ is median cylinder rupture pressure (psig)
 P_U is upper bound cylinder rupture pressure (psig)
 $\hat{P}_{CR}$ is median asymmetric head buckling pressure (psig)
 $\hat{P}_O$ is median plastic collapse head buckling pressure (psig)

Flange: (1) 18"-150#

*Assume: 0.2 Probability of crack formation given head buckling occurs.

** Lea before break at low pressures, $\hat{A} = 30 \text{ inch}^2$ at yield pressure, $\beta = 0.6$ at yield

**Table 2-11. T-9 Core Flood Tank
Median Failure Pressures and Variabilities**

TEMP.	CYLINDER				HEAD BUCKLING			
	$\hat{P}$	β	P_U	β	$\hat{P}_{CR}$	β	$\hat{P}_O$	β
R.T.	3060	0.16	NA	NA	7060	0.22	4180	0.22
400°F	3270	0.22	NA	NA	6140	0.25	3600	0.25
600°F	3130	0.24	NA	NA	5680	0.27	3330	0.27
800°F	2560	0.20	NA	NA	5120	0.30	3060	0.30

MEDIAN LEAK AREA (ALL TEMP. EXCEPT AS NOTED)

	$\hat{A}(\text{inch}^2)$	β
Cylinder	NA	NA
Head*, P_{CR}	NA	NA
Head*, P_O	NA	NA

where $\hat{P}$ is median cylinder rupture pressure (psig)
 P_U is upper bound cylinder rupture pressure (psig)
 $\hat{P}_{CR}$ is median asymmetric head buckling pressure (psig)
 $\hat{P}_O$ is median plastic collapse head buckling pressure (psig)

Flange: (1) 15"- Special Flange

*Assume: 0.2 Probability of crack formation given head buckling occurs.

**Table 2-12. T-10 Borated Water Storage Tank
Median Failure Pressures and Variabilities**

TEMP.	CYLINDER				DOME		ANCHORAGE	
	$\bar{P}$	β	P_U	β	$\bar{P}_{CR}$	β	$\bar{P}_O$	β
R.T.	45	0.21	72	.07	52	0.12	53	.06
400°F	41	0.33	63	.07	47	0.24	NA	NA
600°F	37	0.35	60	.08	42	0.26	NA	NA
800°F	33	0.37	55	.08	38	0.28	NA	NA

MANHOLE: Initiation of leak = 104 psig
 Bolt Yield = 310 psig
 Bolt Fracture = 730 psig

Median Leak Area $\hat{A}(\text{inch}^2)$

Cylinder Uncontrolled

Dome Uncontrolled

Anchorage Uncontrolled

**Table 2-13. T-14 Reactor Coolant Drain Tank
Median Failure Pressures and Variabilities**

TEMP.	CYLINDER				HEAD BUCKLING			
	$\bar{P}$	β	P_U	β	$\bar{P}_{CR}$	β	$\bar{P}_O$	β
R.T.	590	0.19	750	0.07	330	0.19	260	0.19
400°F	540	0.30	690	0.07	230	0.23	150	0.23
600°F	510	0.33	650	0.08	200	0.23	130	0.23
800°F	480	0.37	620	0.08	170	0.24	110	0.24

MEDIAN LEAK AREA (ALL TEMP. EXCEPT AS NOTED)

	$\bar{A}(\text{inch}^2)$	β
Cylinder	Uncontrolled	--
Head*, P_{CR}	0.3	0.5
Head*, P_O	Uncontrolled	--

where $\bar{P}$ is median cylinder rupture pressure (psig)
 P_U is upper bound cylinder rupture pressure (psig)
 $\bar{P}_{CR}$ is median asymmetric head buckling pressure (psig)
 $\bar{P}_O$ is median plastic collapse head buckling pressure (psig)

Flange: (1) 24"-150#

*Assume: 0.2 Probability of crack formation given head buckling occurs.

**Table 2-14. E-25 Let-Down Heat Exchanger
Median Failure Pressures and Variabilities**

TEMP.	SHELL SIDE CYLINDER			
	$\hat{P}$	β	P_u	β
R.T.	1300	0.17	1440	0.07
400°F	1420	0.24	1580	0.07
600°F	1330	0.27	1480	0.08
800°F	1010	0.23	1120	0.08

MEDIAN LEAK AREA (ALL TEMP. EXCEPT AS NOTED)

	$\hat{A}(\text{inch}^2)$	β
Cylinder (Shell Side)	30	1.0

Head Failure Pressure (Shell Side) >> Cylinder Failure

Tube Buckling Pressure (Shell Side) >> Cylinder Failure

Tube Rupture Pressure (Tube Side) > 4500 psig

**Table 2-15. E-26 Seal Return Cooler
Median Failure Pressures and Variabilities**

TEMP.	SHELL SIDE CYLINDER			
	$\hat{P}$	β	P_u	β
R.T.	5050	0.17	5610	0.07
400°F	5540	0.24	6160	0.07
600°F	5160	0.27	5730	0.08
800°F	3940	0.23	4380	0.08

MEDIAN LEAK AREA (ALL TEMP. EXCEPT AS NOTED)

$\hat{A}(\text{inch}^2)$

β

Cylinder (Shell Side)

Uncontrolled

--

Shell Side Flanges (2) 1-1/2" - 150#

Tube Sheet Flange, 6" - 150#

Tube Buckling Pressure >> Cylinder Rupture Pressure

Table 2-15. E-26 Seal Return Cooler (Continued)
Median Failure Pressures and Variabilities

TEMP.	TUBE SIDE CYLINDER			
	$\hat{P}$	β	P_U	β
R.T.	2400	0.22	2670	0.07
400°F	2250	0.33	2500	0.07
600°F	2150	0.36	2390	0.08
800°F	2020	0.39	2240	0.08

MEDIAN LEAK AREA (ALL TEMP. EXCEPT AS NOTED)

	$\hat{A}(\text{inch}^2)$	β
Cylinder	4.0	1.0
Tube Side Flanges	(2) 1-1/2" - 150# (1) 6" - 150#	
Tube Sheet Flange	6" - 150#	
Tube Rupture Pressure > Cylinder Rupture Pressure		

**Table 2-16. E-27 Decay Heat Exchanger
Median Failure Pressures and Variabilities**

TEMP.	SHELL SIDE CYLINDER				SHELL SIDE HEAD BUCKLING			
	$\hat{P}$	β	P_U	β	$\hat{P}_{CR}$	β	$\hat{P}_O$	β
R.T.	1270	0.17	1410	0.07	2490	0.19	1670	0.19
400°F	1390	0.24	1540	0.07	1710	0.23	980	0.23
600°F	1300	0.27	1440	0.08	1460	0.23	820	0.23
800°F	990	0.23	1100	0.08	1260	0.24	680	0.24

MEDIAN LEAK AREA (ALL TEMP. EXCEPT AS NOTED)

	$\hat{A}(\text{inch}^2)$	β
Cylinder	Uncontrolled	--
Head*, P_{CR}	0.4	0.5
Head*, P_O	Uncontrolled	--

where $\hat{P}$ is median cylinder rupture pressure (psig)
 P_U is upper bound cylinder rupture pressure (psig)
 $\hat{P}_{CR}$ is median asymmetric head buckling pressure (psig)
 $\hat{P}_O$ is median plastic collapse head buckling pressure (psig)

Shell Side Flanges (2) 20" - 150#

Tube Sheet Flange 44" Dia. Flange

*Assume: 0.2 Probability of crack formation given head buckling occurs.

Table 2-16. E-27 Decay Heat Exchanger (Continued)
Median Failure Pressures and Variabilities

TEMP.	TUBE SIDE CYLINDER				TUBE SIDE HEAD BUCKLING			
	$\bar{P}$	β	P_U	β	$\bar{P}_{CR}$	β	$\bar{P}_O$	β
R.T.	1590	0.17	1770	0.07	3460	0.19	2100	0.19
400°F	1740	0.24	1930	0.07	2360	0.23	1230	0.23
600°F	1630	0.27	1810	0.08	2030	0.23	1030	0.23
800°F	1240	0.23	1380	0.08	1750	0.24	850	0.24

MEDIAN LEAK AREA (ALL TEMP. EXCEPT AS NOTED)

	$\bar{A} (inch^2)$	β
Cylinder	Uncontrolled	--
Head*, P_{CR}	0.4	0.5
Head*, P_O	Uncontrolled	--

where $\bar{P}$ is median cylinder rupture pressure (psig)
 P_U is upper bound cylinder rupture pressure (psig)
 $\bar{P}_{CR}$ is median asymmetric head buckling pressure (psig)
 $\bar{P}_O$ is median plastic collapse head buckling pressure (psig)

Tube Side Flanges (2) 10" - 300#

Tube Sheet Flange 44" Dia. Flange

*Assume: 0.2 Probability of crack formation given head buckling occurs.

**Table 2-17. F-12 and F-35 Filters
Median Failure Pressures and Variabilities**

TEMP.	CYLINDER				HEAD BUCKLING			
	$\hat{P}$	β	P_U	β	$\hat{P}_{CR}$	β	$\hat{P}_O$	β
R.T.	1270	0.19	1630	0.07	4660	0.19	2830	0.19
400°F	1160	0.30	1490	0.07	2900	0.23	1730	0.23
600°F	1110	0.33	1420	0.08	2460	0.23	1460	0.23
800°F	1040	0.37	1330	0.08	2080	0.24	1230	0.24

MEDIAN LEAK AREA (ALL TEMP. EXCEPT AS NOTED)

	$\hat{A}(\text{inch}^2)$	β
Cylinder	--	--
Bottom Head*, P_{CR} Top Head Controls	--	--
Bottom Head*, P_O		
Top Head - (See Attached Table)		

where $\hat{P}$ is median cylinder rupture pressure (psig)
 P_U is upper bound cylinder rupture pressure (psig)
 $\hat{P}_{CR}$ is median asymmetric head buckling pressure (psig)
 $\hat{P}_O$ is median plastic collapse head buckling pressure (psig)

*Assume: 0.2 Probability of crack formation given head buckling occurs.

Table 2-17. F-12 and F-35 Top Plate Leak Area (Continued)

Room Temperature

P (psig)	A (in. ²)
550	Initiation of Leak
600	0.8
650	2.5
880	2.5
900	13.0
1100	32.0
1300	73
> 1300	140

400° and Greater

160	Initiation of Leak
300	.05
450	.10
500	1.25
600	2.5
860	2.5
900	16.0
1100	41.0
> 1100	140.0

Table 2-18. 304 Stainless Steel Pipe Failure Pressures

CORROSION ALLOWANCE = 0.000

Pipe Size (in)	Schedule	OD (in)	ID (in)	FAILURE PRESSURES			
				70°F	400°F	600°F	800°F
1-1/2	40S	1.900	1.610	9968	8556	7963	7525
	80	1.900	1.500	14757	12666	11788	11140
	160	1.900	1.337	23303	20001	18615	17591
2	40S	2.375	2.067	8246	7078	6587	6225
	80	2.375	1.939	12443	10680	9940	9393
	160	2.375	1.689	22476	19292	17955	16967
3	10S	3.500	3.260	4074	3497	3254	3075
	40S	3.500	3.068	7792	6688	6225	5882
	80	3.500	2.900	11449	9827	9146	8643
	160	3.500	2.624	18474	15857	14758	13946
4	10S	4.500	4.260	3118	2676	2490	2353
	40S	4.500	4.026	6515	5592	5205	4918
	80	4.500	3.826	9749	8367	7787	7359
	160	4.500	3.438	17094	14672	13655	12904
6	10S	6.625	6.357	2333	2002	1864	1761
	40S	6.625	6.065	5110	4386	4082	3857
	80	6.625	5.761	8299	7123	6630	6265
	120	6.625	5.501	11307	9705	9032	8536
	160	6.625	5.189	15314	13145	12234	11561
8	10S	8.625	8.329	1967	1688	1571	1485
	20	8.625	8.125	3405	2923	2720	2571
	40S	8.625	7.981	4465	3833	3567	3371
	80	8.625	7.625	7258	6229	5798	5479
	120	8.625	7.189	11054	9488	8830	8344
	140	8.625	7.001	12837	11018	10254	9690
	160	8.625	6.813	14718	12633	11757	11110
10	10S	10.750	10.420	1753	1504	1400	1323
	20	10.750	10.250	2699	2317	2156	2038
	40S	10.750	10.020	4032	3460	3221	3043
	80	10.750	9.564	6862	5890	5482	5180
	120	10.750	9.064	10294	8835	8223	7770
	140	10.750	8.750	12649	10857	10104	9548
	160	10.750	8.500	14649	12573	11702	11058
12	10S	12.750	12.390	1608	1380	1284	1214
	20	12.750	12.250	2259	1939	1804	1705
	Std	12.750	12.000	3459	2969	2763	2611
	40	12.750	11.938	3764	3231	3007	2841
	80	12.750	11.376	6684	5737	5339	5046
	120	12.750	10.750	10296	8837	8224	7772
	140	12.750	10.500	11858	10178	9473	8952
	160	12.750	10.126	14340	12308	11455	10825
14	10S	14.000	13.624	1527	1311	1220	1153
	20	14.000	13.375	2586	2220	2066	1952
	Std	14.000	13.250	3132	2689	2502	2365
	40	14.000	13.125	3689	3167	2947	2785
	80	14.000	12.500	6641	5700	5305	5013
	120	14.000	11.814	10240	8789	8180	7730
	140	14.000	11.500	12030	10326	9610	9081
	160	14.000	11.188	13909	11938	11111	10500

Calculation 304P000

Table 2-18. 304 Stainless Steel Pipe Failure Pressures (Continued)

CORROSION ALLOWANCE = 0.000

Pipe Size (in)	Schedule	OD (in)	ID (in)	70°F	FAILURE PRESSURES		
					400°F	600°F	800°F
16	10S	16.000	15.624	1332	1143	1064	1005
	20	16.000	15.375	2250	1931	1797	1698
	Std	16.000	15.250	2722	2336	2174	2054
	40	16.000	15.000	3689	3167	2947	2785
	80	16.000	14.314	6518	5595	5207	4920
	120	16.000	13.564	9939	8530	7939	7502
	140	16.000	13.124	12127	10409	9687	9154
	160	16.000	12.814	13759	11810	10991	10387
18	10S	18.000	17.624	1131	1013	943	891
	20	18.000	17.375	1991	1709	1590	1503
	Std	18.000	17.250	2406	2065	1922	1816
	40	18.000	16.876	3686	3164	2944	2782
	80	18.000	16.126	6431	5520	5137	4855
	120	18.000	15.250	9979	8565	7972	7533
	140	18.000	14.876	11621	9975	9283	8773
	160	18.000	14.433	13677	11739	10925	10324
20	10S	20.000	19.564	1233	1059	985	931
	20S	20.000	19.250	2156	1851	1722	1628
	40	20.000	18.814	3488	2994	2787	2633
	80	20.000	17.938	6361	5460	5082	4802
	120	20.000	17.000	9766	8382	7801	7372
	140	20.000	16.500	11739	10075	9377	8861
	160	20.000	16.064	13559	11638	10831	10236
24	10S	24.000	23.500	1177	1011	941	889
	20S	24.000	23.250	1785	1532	1426	1348
	40	24.000	22.626	3361	2884	2684	2537
	80	24.000	21.564	6251	5366	4994	4719
	120	24.000	20.376	9842	8448	7862	7430
	140	24.000	19.876	11482	9855	9172	8658
	160	24.000	19.314	13426	11524	10725	10135

Calculation 304P000

Table 2-19. 304 Stainless Steel Pipe Failure Pressures

CORROSION ALLOWANCE = 0.020

Pipe Size (in)	Schedule	OD (in)	ID (in)	FAILURE PRESSURES			
				70°F	400°F	600°F	800°F
1-1/2	40S	1.900	1.610	8593	7375	6864	6487
	80	1.900	1.500	13281	11399	10609	10026
	160	1.900	1.337	21647	18580	17292	16341
2	40S	2.375	2.067	7175	6158	5732	5416
	80	2.375	1.939	11302	9700	9028	8532
	160	2.375	1.689	21166	18167	16908	15978
3	10S	3.500	3.260	3395	2914	2712	2563
	40S	3.500	3.068	7071	6069	5648	5338
	80	3.500	2.900	10686	9172	8536	8067
	160	3.500	2.624	17631	15133	14084	13309
4	10S	4.500	4.260	2598	2230	2075	1961
	40S	4.500	4.026	5966	5120	4765	4503
	80	4.500	3.826	9170	7871	7325	6922
	160	4.500	3.438	16450	14119	13141	12418
6	10S	6.625	6.357	1985	1704	1585	1498
	40S	6.625	6.065	4745	4072	3790	3582
	80	6.625	5.761	7915	6794	6323	5975
	120	6.625	5.501	10905	9360	8711	8232
	160	6.625	5.189	14888	12778	11893	11239
8	10S	8.625	8.329	1701	1460	1359	1284
	20	8.625	8.125	3133	2689	2503	2365
	40S	8.625	7.981	4188	3595	3345	3161
	80	8.625	7.625	6967	5980	5566	5259
	120	8.625	7.189	10746	9223	8584	8112
	140	8.625	7.001	12521	10747	10002	9452
	160	8.625	6.813	14393	12354	11498	10865
10	10S	10.750	10.420	1540	1322	1230	1163
	20	10.750	10.250	2484	2132	1984	1875
	40S	10.750	10.020	3811	3271	3044	2877
	80	10.750	9.564	6631	5691	5297	5006
	120	10.750	9.064	10049	8625	8028	7586
	140	10.750	8.750	12396	10640	9902	9357
	160	10.750	8.500	14388	12349	11494	10861
12	10S	12.750	12.390	1429	1227	1142	1079
	20	12.750	12.250	2078	1784	1660	1569
	Std	12.750	12.000	3274	2810	2616	2472
	40	12.750	11.938	3579	3072	2859	2701
	80	12.750	11.376	6489	5570	5184	4899
	120	12.750	10.750	10090	8660	8060	7617
	140	12.750	10.500	11648	9997	9304	8793
	160	12.750	10.126	14122	12121	11281	10660
14	10S	14.000	13.624	1365	1171	1090	1030
	20	14.000	13.375	2420	2077	1933	1827
	Std	14.000	13.250	2965	2545	2369	2238
	40	14.000	13.125	3521	3022	2812	2658
	80	14.000	12.500	6464	5548	5163	4879
	120	14.000	11.814	10052	8628	8030	7588
	140	14.000	11.500	11838	10160	9456	8936
	160	14.000	11.188	13711	11768	10953	10350

Calculation 304P020

Table 2-19. 304 Stainless Steel Pipe Failure Pressures (Continued)

CORROSION ALLOWANCE = 0.020

Pipe Size (in)	Schedule	OD (in)	ID (in)	70°F	FAILURE PRESSURES		
					400°F	600°F	800°F
16	10S	16.000	15.624	1190	1021	951	898
	20	16.000	15.375	2106	1807	1682	1589
	Std	16.000	15.250	2576	2211	2058	1945
	40	16.000	15.000	3542	3040	2829	2674
	80	16.000	14.314	6364	5462	5083	4804
	120	16.000	13.564	9775	8390	7809	7379
	140	16.000	13.124	11958	10264	9553	9027
	160	16.000	12.814	13586	11661	10853	10256
18	10S	18.000	17.624	1055	906	843	796
	20	18.000	17.375	1863	1599	1488	1407
	Std	18.000	17.250	2278	1955	1819	1719
	40	18.000	16.876	3555	3051	2839	2683
	80	18.000	16.126	6294	5402	5028	4751
	120	18.000	15.250	9834	8441	7856	7424
	140	18.000	14.876	11473	9847	9165	8660
	160	18.000	14.433	13523	11607	10803	10208
20	10S	20.000	19.564	1120	961	895	846
	20S	20.000	19.250	2041	1752	1630	1541
	40	20.000	18.814	3371	2893	2693	2545
	80	20.000	17.938	6238	5354	4983	4709
	120	20.000	17.000	9636	8270	7697	7274
	140	20.000	16.500	11604	9960	9270	8760
	160	20.000	16.064	13421	11520	10721	10132
24	10S	24.000	23.500	1083	930	865	818
	20S	24.000	23.250	1690	1450	1350	1276
	40	24.000	22.626	3263	2800	2606	2463
	80	24.000	21.564	6149	5278	4912	4642
	120	24.000	20.376	9734	8355	7776	7348
	140	24.000	19.876	11371	9760	9083	8584
	160	24.000	19.314	13312	11426	10634	10049

Calculation 304P020

Table 2-20. 304 Stainless Steel Pipe Failure Pressures

CORROSION ALLOWANCE = 0.040

Pipe Size (in)	Schedule	OD (in)	ID (in)	FAILURE PRESSURES			
				70°F	400°F	600°F	800°F
1-1/2	40S	1.900	1.610	7218	6195	5766	5449
	80	1.900	1.500	11806	10133	9431	8912
	160	1.900	1.337	19992	17159	15970	15091
2	40S	2.375	2.067	6104	5239	4876	4608
	80	2.375	1.939	10160	8721	8116	7670
	160	2.375	1.689	19855	17042	15861	14988
3	10S	3.500	3.260	2716	2331	2170	2050
	40S	3.500	3.068	6349	5450	5072	4793
	80	3.500	2.900	9923	8517	7927	7491
	160	3.500	2.624	16787	14409	13410	12672
4	10S	4.500	4.260	2078	1784	1660	1569
	40S	4.500	4.026	5416	4648	4326	4088
	80	4.500	3.826	8592	7374	6863	6486
	160	4.500	3.438	15807	13567	12627	11932
6	10S	6.625	6.357	1637	1405	1307	1235
	40S	6.625	6.065	4380	3759	3499	3306
	80	6.625	5.761	7531	6464	6016	5685
	120	6.625	5.501	10502	9014	8390	7928
	160	6.625	5.189	14461	12412	11552	10917
8	10S	8.625	8.329	1435	1232	1146	1083
	20	8.625	8.125	2861	2455	2285	2159
	40S	8.625	7.981	3911	3357	3124	2952
	80	8.625	7.625	6677	5731	5334	5040
	120	8.625	7.189	10438	8959	8338	7880
	140	8.625	7.001	12204	10475	9749	9213
	160	8.625	6.813	14068	12075	11238	10620
10	10S	10.750	10.420	1328	1140	1061	1002
	20	10.750	10.250	2268	1946	1811	1712
	40S	10.750	10.020	3590	3081	2868	2710
	80	10.750	9.564	6400	5493	5112	4831
	120	10.750	9.064	9805	8416	7833	7402
	140	10.750	8.750	12143	10422	9700	9166
	160	10.750	8.500	14128	12126	11286	10665
12	10S	12.750	12.390	1251	1073	999	944
	20	12.750	12.250	1897	1628	1516	1432
	Std	12.750	12.000	3090	2652	2468	2332
	40	12.750	11.938	3393	2912	2711	2561
	80	12.750	11.376	6295	5403	5028	4752
	120	12.750	10.750	9884	8483	7895	7461
	140	12.750	10.500	11437	9816	9136	8633
	160	12.750	10.126	13903	11933	11106	10495
14	10S	14.000	13.624	1202	1032	960	908
	20	14.000	13.375	2255	1935	1801	1702
	Std	14.000	13.250	2798	2402	2235	2112
	40	14.000	13.125	3352	2877	2678	2530
	80	14.000	12.500	6287	5396	5022	4746
	120	14.000	11.814	9865	8467	7880	7447
	140	14.000	11.500	11645	9995	9302	8791
	160	14.000	11.188	13513	11599	10795	10201

Calculation 304P040

Table 2-20. 304 Stainless Steel Pipe Failure Pressures (Continued)

CORROSION ALLOWANCE = 0.040

Pipe Size (in)	Schedule	OD (in)	ID (in)	FAILURE PRESSURES			
				70°F	400°F	600°F	800°F
16	10S	16.000	15.624	1048	900	837	791
	20	16.000	15.375	1962	1684	1567	1481
	Std	16.000	15.250	2431	2087	1942	1835
	40	16.000	15.000	3394	2913	2711	2562
	80	16.000	14.314	6209	5329	4960	4687
	120	16.000	13.564	9612	8250	7678	7256
	140	16.000	13.124	11790	10119	9418	8900
	160	16.000	12.814	13414	11513	10715	10126
18	10S	18.000	17.624	929	798	742	702
	20	18.000	17.375	1736	1490	1387	1310
	Std	18.000	17.250	2149	1845	1717	1623
	40	18.000	16.876	3423	2938	2735	2584
	80	18.000	16.126	6156	5284	4918	4647
	120	18.000	15.250	9689	8316	7740	7314
	140	18.000	14.876	11324	9719	9046	8548
	160	18.000	14.433	13370	11475	10580	10093
20	10S	20.000	19.564	1007	864	804	760
	20S	20.000	19.250	1926	1653	1539	1454
	40	20.000	18.814	3253	2792	2599	2456
	80	20.000	17.938	6115	5248	4884	4616
	120	20.000	17.000	9505	8158	7593	7175
	140	20.000	16.500	11470	9845	9163	8659
	160	20.000	16.064	13284	11401	10611	10028
24	10S	24.000	23.500	989	849	790	747
	20S	24.000	23.250	1595	1369	1274	1204
	40	24.000	22.626	3165	2716	2528	2389
	80	24.000	21.564	6146	5189	4830	4564
	120	24.000	20.376	9625	8261	7689	7266
	140	24.000	19.876	11259	9664	8994	8499
	160	24.000	19.314	13197	11327	10542	9962

Calculation 304P040

3. GASKETED FLANGE CONNECTIONS

3.1 Introduction

Although most of the piping joints in the four safety systems under investigation are full penetration butt welds, a number of gasketed flange connections are required for the installation and maintenance of flow restricting orifices, flow elements, and major equipment components. The elements of the flanged joints are defined in References 12 and 13 and include standard ANSI B16.5 flanges with asbestos-filled, spiral-wound gaskets.

The gaskets are specified in Reference 12 to be Flexitallic or equal using Type 304 stainless steel winding material. Style CG gaskets (with outer compression gauge ring) are used in combination with raised face flanges and Style R gaskets are used in combination with tongue and groove flanges. The lines designated for 150, 300, and 600lb rated service employ raised face flanges for virtually all cases. The flanges for these lower rated systems are fabricated from Type 304 stainless steel and are secured by means of SA193-B8 Class 1 bolts or studs which are of a Type 304 stainless steel material with minimum room temperature yield and ultimate strengths of 30,000 and 75,000 psi, respectively.

The piping fabrication and installation specification for the Davis-Besse plant (Reference 14) stipulates that 150lb rated flanges should normally have bolts prestressed in the range of 15,000 to 30,000 psi (based on minimum thread root area) while 300 to 900lb rated flanges should normally have bolts prestressed in the range of 30,000 to 40,000 psi. The specification goes on to state that the gasketed flange joint bolts/studs and nuts should be torqued to the minimum value which prevents leaks during the preservice hydrotest without exceeding the above ranges.

3.2 Variables Affecting Flanged Joint Leakage

The behavior of gasketed flanges under pressure and temperature conditions is quite complex. The propensity for leakage under a given pressure loading is as much or more dependent upon the previous history of the joint than it is on its state at the time the pressure is applied. As a result, numerous variables are introduced. These include:

- Bolt/Stud Preload
- Bolt/Stud Temperature
- Bolt/Stud Yield Strength
- Bolt/Stud Stress-Strain Relationship
- Bolt Relaxation
- Flange Flexibility

- Initial Gasket Stress
- Gasket Loading Stiffness
- Gasket Unloading/Reloading Stiffness
- Gasket Creep and Relaxation
- Pipe Bending Moments

3.2.1 Bolt/Stud Preload

As noted above there are a range of preload stress values which satisfy the requirements of the installation specification for the various flange pressure ratings. For 150lb rated flanges the range is 15,000 to 30,000 psi based on area at the thread root. However, it will be shown in results presented later that a bolt preload of 15,000 psi provides an insufficient load to properly seat the gasket for the system operating conditions. In addition, a bolt preload of 20,000 psi provides a sufficient gasket seating load for only small flanges less than about 2-1/2 inches in diameter. For larger flanges, leakage would be observable at the operating and hydrotest conditions. Thus, for 150lb flanges, a bolt preload stress of 25,000 psi was taken as a median value with the range from 25,000 to 30,000 psi taken to represent a $+2.33\sigma$ variation.

For 300 and 600lb flanges, the range of allowable bolt preload stress is 30,000 to 40,000 psi, again based on thread root area. Since SA193-B8 bolts with a minimum yield stress of 30,000 psi are used in the lower pressure safety systems under investigation, it is possible or even likely that the bolts in these flanges are stressed beyond yield. Thus, any additional load carried by the bolt will result in relatively large bolt deflections with corresponding unloading of the gasket. Since bolt preload stresses in the specified range all provide sufficient load to properly seat the gasket, a preload stress of 35,000 psi was taken as a median value with the range from 30,000 to 35,000 psi taken to represent a -2.33σ variation.

It should be remembered that the uncertainty variability is related to the parameter of interest such as leak rate or leak area. Thus, the variability is calculated from the variation in say, leak rate resulting from the variations in initial bolt stress noted above.

3.2.2 Bolt/Stud Temperature

The maximum operating temperatures for the low pressure portions of the safety systems under consideration range from 150 to 280°F. As a result, the bolt temperature is likely less than 200°F during normal operation. However, during the ISLOCA event, the reactor coolant system pressure and temperature conditions of 2250 psi and 650°F can propagate back through the initially cold, non-operating systems. Based on preliminary analyses of the

system, it is our understanding that the pressure propagates much more rapidly than the fluid temperature. Specifically, a relatively large leak at or downstream (reverse flow condition) of the flange connection must occur in order for the flange or flange bolting temperatures to rise substantially. In addition, the higher temperature conditions in the pipe must continue to flow for a relatively long period of time before the bolting temperature will rise substantially. Thus, it was judged that potential flange leakage will most likely occur under high pressure-low temperature conditions and that leak rates and leak areas will increase somewhat as the flange and bolt temperatures increase. Based on these considerations, a bolt temperature of approximately 140°F was taken to represent the median case and the effect of higher bolt temperatures was not considered. Evaluation of higher bolt temperatures, should they occur, can be modeled employing lower elastic modulus, yield strength, and ultimate strength values.

3.2.3 Bolt/Stud Yield Strength

The material properties of Type 304 stainless steel are given in Table 2-1 of this report. Consistent with the selected 140°F median value for the flange bolt/stud temperature, a value of 33,000 psi was taken as the median bolt yield strength. The ASME Code minimum value of 27,500 psi was taken to represent a -2.33σ variation.

3.2.4 Bolt/Stud Stress-Strain Relationship

References 1 and 2 provide limited data on the stress-strain curve to failure for Type 304 stainless steel at room and elevated temperatures. These data were interpolated to estimate the strain at failure for a bolt temperature of 140°F and were scaled to median material property values. The resulting curve was approximated in a piecewise linear fashion. Increase in the assumed median bolt temperature could have a substantial effect on the stress-strain relationship which would affect the calculation of leak areas for pressures where the bolt stress exceeds the yield strength.

3.2.5 Bolt Relaxation

For stainless steel bolts which are initially torqued to prestress levels exceeding the material yield strength, some relaxation will occur. This relaxation requires substantial time, particularly at the relatively low bolt temperatures experienced during normal plant operation. Relaxation during the course of the ISLOCA event is judged to be negligible. Relaxation of the bolting in joints which have required little or no maintenance since the beginning of plant operation may be on the order of 10 to 20%. For purposes of this study, 10% bolt relaxation was taken to be a median value for those bolts prestressed beyond material yield strength with 20% relaxation taken to represent a -2.33σ variation. Since bolt relaxation only applies

to 300 and 600lb flanges which exhibit relatively high pressure capacity, this variable, which is judged to be conservatively biased, is expected to have a very small effect on overall plant risk.

3.2.6 Flange Flexibility

The flanged joint consists of the flange, the flange bolting, and the gasket. To study specific variables most test programs isolate one or more of the joint elements, such as the flexibility of the flange. However, to properly characterize the overall joint behavior, all three elements must function as part of an integral unit. In order to evaluate the joint behavior, three axisymmetric elastic finite element joint models (Reference 21) were developed. The models were for a 4"-300# flange, a 12"-300# flange, and a 4"-150# flange and included the flange and pipe structure, bolt stiffness, and gasket unloading stiffness. Material properties were taken at 200°F. As expected, it was found that flange flexibility affects the way that the pressure load is carried by the gasket and bolting. As the relative flange stiffness increases, a greater portion of the pressure load goes to loading the bolting and a lesser portion goes to unloading the gasket. Thus, for larger flanges or more flexible flanges (lower pressure rating), the portion of the pressure load going to the unloading of the gasket increases. This can be seen in Figure 3-1 which plots the results of the three analyses. In this figure, the ratio of the load removed from the gasket to the total pressure load is plotted versus nominal flange size. For the elastic case of the 4"-300# flange about 43% of the total pressure load goes to unloading the gasket while the remaining 57% is carried by increased bolt load. The ratio for the larger 12"-300# flange is approximately 86% and the ratio for the lighter weight 4"-150# flange is about 59%. One additional computer run using the 4"-300# analysis model showed that if the bolt stress exceeds the material yield stress, the ratio increases to 97% reflecting the much lower bolt inelastic modulus. It is likely that the variation of the ratio with flange size is more complex than the linear variation shown but project time constraints limited the scope of this supporting study. Due to the lack of specific data, the maximum value of the incremental gasket load to total pressure load ratio was set at 1.0. However, for flanges which are flexible relative to the gasket, experience has shown that the ratio can be greater than 1.0 such that an increase in pressure results in a decrease in flange bolt tension.

Relatively low strength 304 stainless steel (SA193-B8) flange bolts are used for the gasketed flange connections at the Davis Besse plant. As a result, leak areas at higher pressures are primarily governed by the inelastic distortion of the bolts with the flange remaining essentially elastic. In contrast, for plants using high strength flange bolting (e.g., SA193-B7), the flange is stressed to higher levels and some inelastic behavior can be expected at higher

pressures. For such cases, the inelastic distortion of the flange at the gasket is expected to be a substantial contributor to calculated leak area. It is recommended that further study of the effect of flange flexibility be undertaken and incorporated if leakage through gasketed flange connections is found to be a major contributor to overall plant risk for the ISLOCA initiating event.

3.2.7 Initial Gasket Stress

Over the past several years, the Pressure Vessel Research Committee (PVRC) of the Welding Research Council has sponsored a major ongoing gasket test program as part of its Long Range Flanged Joint Improvement Program. Most of the tests have been conducted with nitrogen or helium as the test fluid; however, a limited data set exists for tests using water. Some of the results of the test program are reported in References 15 through 18. These results clearly indicate that the leak resistance of a gasketed flange joint is a function of the initial level to which the gasket is stressed during the preloading of the flange bolting. The higher the initial gasket stress, the greater the leak resistance. The gasket stress versus deflection curve (Figure 3-2) and the mass leak rate versus gasket stress curve (Figure 3-3) for a typical spiral-wound gasket are both characterized by the presence of a "knee" at a gasket stress of approximately 5,000 psi. Above 5,000 psi the leak rate drops more rapidly with increasing stress indicating improved sealing performance. Thus, although the controlled variable in assembling a flanged connection is bolt preload, it is the resulting gasket stress which determines the leak resistance of the joint for the pressure loading.

3.2.8 Gasket Loading Stiffness

The loading stiffness parameter is of importance since it determines whether or not the flange raised face bottoms out on the 0.125" thick compression gauge ring due to the bolt preload. Spiral-wound gaskets used for virtually all applications are fabricated to the requirements of Military Specification MIL-G-21032E, including Amendment 2 (Reference 19). This standard specifies the test load and corresponding deflection for each gasket size and service rating. Gaskets with an initial nominal thickness of 0.175" are to be compressed to a thickness of 0.130 ± 0.005 " under the specified test load while gaskets with an initial nominal thickness of 0.125" are to be compressed to a thickness of 0.100 ± 0.005 ". Figure 3-2 shows the gasket stress versus deflection for the loading sequence of a typical spiral-wound gasket and Table 3-1 presents the range of gasket stiffness (expressed as gasket stress per inch of deflection) which meet the specification. All of the gaskets used in the Davis Besse flange connections have a nominal thickness of 0.175" except the 44" Decay Heat Cooler tubesheet gasket which is nominally 0.125" thick. The Reference 19 specified test load is shown together

with the resulting bolt stress (based on bolt stress area). Test loads greater than 557000 lbs are not specified since this load is judged to be the practical limit of testing facilities. However, since the specified test load corresponds to the load resulting from prestressing the flange bolts to approximately 30,000 psi (based on bolt thread root area), the stiffness for larger size gaskets can also be computed. 300 and 600lb rated gaskets are interchangeable for sizes 3" and smaller and therefore, the stiffness are identical. The stiffness associated with the nominal compressed thickness ($T_g=0.130$) were taken to be median centered and the range from a compressed thickness of 0.125 to 0.135" was considered to represent a $\pm 2.33\sigma$ variation.

Based upon the definition of the gasket test load noted above, prestressing the flange bolts to less than 30,000 psi will not result in a lock-up between the flange and the compression gauge ring. However, prestressing the bolts to 30,000 psi or greater may or may not result in lock-up depending on the gasket loading stiffness.

3.2.9 Gasket Unloading/Reloading Stiffness

The unloading stiffness characterizes the recovery of the gasket as the gasket stress is reduced due to increase in pressure, bolt relaxation, or other means. Figure 3-2 depicts the loading and unloading/reloading behavior of a typical spiral-wound gasket. Review of the available test data indicates that the recovery behavior for all spiral wound gaskets is quite similar and can reasonably be expressed as an unloading/reloading stiffness of about 1,000,000 psi/inch. This appears to be a reasonable value for new gaskets such as those used in the test program. However, hardening due to gasket aging may substantially increase the gasket unloading/reloading stiffness, resulting in a decrease of the Gross Leak Pressure and an increase in the joint leak rate. It is important to note that reloading of the gasket due to removal of the pressure load, for example, follows the unloading stiffness curve.

3.2.10 Gasket Creep and Relaxation

It is understood from experience that gaskets behave nonlinearly and that they creep, even at room temperature. Until recently, information available on the creep and relaxation of commonly-used fabricated gaskets was scarce. Such information is vital for the proper understanding of the behavior of bolted flange joints. The previously mentioned PVRC-sponsored test program provided a vehicle for gathering creep and relaxation data for spiral-wound gaskets which is reported in Reference 18. The results indicate that maximum creep occurs at the lower stress levels and is particularly extensive at about 5,000 psi which coincides with the yield plateau in the stress-deflection diagram. For constant stress, most of

the creep occurs in the first 10 to 15 minutes, while for cyclic stress, 20 to 25 stress cycles are required. Cyclic creep exhibits nearly the same overall behavior as constant stress creep, but is more extensive. In contrast, gasket relaxation is greatest at a higher initial stress level but is reasonably constant in terms of percent relaxation. Most of the gasket relaxation also occurs in the first 10 to 15 minutes after initial prestressing of the bolts. It is also of interest to note that lock-up of the flange and compression gauge ring significantly limits the gasket relaxation.

In a real life gasketed bolted flange connection, the gasket is subjected to neither pure creep or pure relaxation, even under steady-state operating conditions, since gasket creep causes the bolt load and deflection to change when there is no lock-up between the flange and the compression gauge ring. It is expected that, in many cases, the flange bolting was initially tightened and then retightened some minutes or hours later or possibly during or after the preservice hydrostatic pressure test. Retightening eliminates much of the effect of initial short term creep and relaxation. Thus to account for relaxation and cyclic creep for those cases where lock-up between the flange and compression gauge ring does not occur (all 150# flanges and 300 and 600# flanges with low bolt stress and high gasket loading stiffness), a joint relaxation of 25% was taken to be median-centered while the range from 0 to 25% was taken to represent a $+3.0\beta$ variation.

3.2.11 Pipe Bending Moments

Bending moments in the piping at the flange connection due to deadweight or thermal loads are carried by tension in the bolting. Based on normal practice, the piping supports are placed such that deadweight pipe stresses are relatively low and thus, the additional bolt stress is small. If the flange bolting is elastic, it was felt that the reduced gasket stress on the one side is balanced by an increased gasket stress on the other such that the joint mass leak rate will be about the same whether or not the bending moment is considered. On the other hand, if the flange bolting is inelastic, the bending moment could result in some increase in the calculated leak area but the increase would be limited by redistribution of the bending moment. Thus, pipe bending stress was not considered specifically in the evaluation of the flange joint. It is judged that the variabilities from other sources and conservatisms introduced into the approach cover the potential effect of pipe bending moments.

3.3 Flange Joint Behavior

The behavior of gasketed flange connections due to increasing pressure of the ISLOCA event is characterized in the manner described in the following steps.

1. The flange bolts are initially torqued and retightened to prestress levels satisfying the requirements of Reference 14 resulting in an initial gasket stress.
2. Over the course of normal operation, gaskets sustain cyclic creep and relaxation. If Step 1 produced lock-up between the flange and compression gauge ring, the relaxation reduces the gasket stress with a corresponding increase in the lock-up stress and negligible change in the bolt stress. If Step 1 did not produce lock-up, the creep and relaxation reduces the gasket stress with a corresponding reduction in the bolt stress.
3. Over the course of normal operation, bolts prestressed above the material yield stress in Step 1 relax. Since Step 1 produced lock-up, the relaxation reduces the bolt stress with a corresponding reduction of the lock-up stress and possibly a reduction of the gasket stress if the lock-up stress was small.
4. At the initiation of the ISLOCA event, the increasing pressure must first overcome the lock-up load, if any, with no reduction of the gasket stress or increase in bolt stress.
5. Further increase in pressure to the Gross Leak Pressure, defined as the point at which the gasket stress and the pressure are equal, is shared by the gasket and bolts in accordance with Figure 3-1 resulting in a decrease in the gasket stress and an increase in the bolt stress. If the bolt yield stress is reached at a pressure less than the Gross Leak Pressure, 97% of the pressure load above the bolt yield pressure contributes to a reduction of the gasket stress while the remaining 3% contributes to an increase in the bolt stress.
6. Further increase in pressure above the Gross Leak Pressure results in a corresponding increase in the bolt stress accompanied by increases in bolt length up to the bolt failure strain in accordance with the bolt stress-strain diagram.

These steps were used consistently in the evaluation of the myriad of cases covering the sizes, pressure ratings, and ranges of the variables affecting leakage.

3.4 Calculation Of Leak Rate And Leak Area

The definition of the onset of gross leakage, or the Gross Leak Pressure, as the point at which the gasket stress is equal to the pressure being retained, is used quite generally throughout the gasket industry. This definition has come about, it appears, from gasket tests

where some "O"-ring and flat face gaskets have suffered blowout. Although it is doubtful that spiral-wound gaskets are on the verge of catastrophic failure when the gasket stress is reduced to the point that it equals the pressure, the potential certainly exists. For pressures less than the Gross Leak Pressure, the mass leak rate is calculated from the results of the gasket leakage test with water reported in Reference 17. Leakage of this form is related to the presence of seams and crevasses in the flange/seal joint rather than any apparent leak area. In this test, 4"-600# rated gaskets were subjected to both standard and cyclic load pressure sequences. The results are presented in Figure 3-4 which is a plot of Gasket Stress versus the Tightness Parameter (T_p). T_p is equated as:

$$T_p = \frac{P}{P^*} \left[\frac{L_{RM}^*}{L_{RM}} \right]^\alpha \quad (3-1)$$

where P = Internal Fluid Gauge Pressure (psig)

P^* = Reference Atmospheric Pressure (14.7 psia)

L_{RM}^* = Reference Mass Leak Rate (1 mg/sec)

L_{RM} = Total Mass Leak Rate through the Gasket (mg/sec)

and α = Tightness Parameter Exponent (1.0 for solid water)

Thus, the total mass leak rate for the water case is computed as:

$$L_{RM} = \frac{P}{(14.7 \cdot T_p)} \quad (3-2)$$

Since the leak rate data correspond to the total mass leakage from the 4"-600# rated gasket and not, for example, the leakage per unit mean circumference, a correction must be made to the calculated mass leak rate to account for the various gasket sizes. Since the probability of leakage increases with gasket perimeter, it is reasonable to assume that leakage through a larger diameter gasket will increase in proportion to the gasket diameter. In addition, a correction factor must be introduced to account for variations in the gasket width. It should be noted that the calculation of gasket width and gasket area should not include the outer 1/8" which is ineffective in the sealing process. The leak rate at the Gross Leak Pressure is then equated as:

$$LR_{GLP} = \frac{(D_o + D_i)(p)}{348.6 W_G} \left[\frac{1}{e^{(6.1872 - 6.2361(9.2103 - \ln SG_o) - .791311(\ln SG_o - \ln SG))}} \right] \quad (3-3)$$

where D_o = Gasket Outside Diameter (in)

D_i = Gasket Inside Diameter (in)

W_G = Gasket Width (in)

SG_o = Initial Gasket Stress (psi) = Actual Gasket Stress/(1 - $JR/100$)

SG = Current Gasket Stress (psi)

and JR = Joint Relaxation expressed in percent of SG_o .

Note that in Equation 3-3 the quantity, 348.6, is the product of 14.7 from Equation 3-2 and 23.714 which is the value of $(D_o + D_i)/W_G$ for a 4" - 600# rated gasket. The quantity in the denominator of the term within the brackets in Equation 3-3 represents the Tightness Parameter (T_p) which is obtained by curve-fitting using the curves shown in Figure 3-4.

It is difficult to get a handle on the significance of a leak rate in milligrams per second. However, if a drop of water is idealized as a 1/8 inch diameter solid sphere, a leak rate of 1 mg/sec would correspond to 3.5 drops per minute or about one drop every 17 seconds. By the time the leak rate increased to 17 mg/sec, the joint leakage would be about 1 drop per second which would certainly be of concern for nuclear operation. Leak rates of 200 to 500 mg/sec would constitute a spray of water which could possibly inhibit some operator actions in the vicinity.

For pressures above the Gross Leak Pressure, it was judged that the leakage is no longer due to seams and crevasses in the flange/seal joint but due to actual separation of the flange and gasket. Thus, a leak area is calculated which is intended to be in addition to the leak rate calculated at Gross Leak Pressure. The leak area is calculated as the mean gasket perimeter times the separation distance at the gasket. The separation distance is affected by bolt extension, gasket recovery, and flange flexibility. Of these, the contribution of bolt extension is by far the most dominant one. Therefore, the separation distance calculated in this study includes the effect of bolt extension only. Note that excluding the effect of gasket recovery from the leak area calculation is conservative and leads to slightly higher leak area values. The leak area at pressures above the Gross Leak Pressure is equated as shown in

Equations 3-4 and 3-5, respectively, for the case where the bolt stress is less than or equal to the bolt material yield stress and for the case where the bolt stress exceeds the material yield. The term, $f(p_{GL}, JR, SG_o, SG_{pGL}, K_C)$, represents the remaining recoverable gasket deflection beyond GLP. It should be noted that some gasket recovery occurs prior to GLP. Due to the difficulties involved in arriving at a reasonably accurate estimate of the term, $f(p_{GL}, JR, SG_o, SG_{pGL}, K_C)$, and recognizing the fact that the effect of bolt extension on the leak area far exceeds that of the gasket recovery, this term was conservatively neglected.

For bolt stress $\leq$ yield

$$A_L = \frac{\pi(D_o + D_i)}{2} \left[L_B \left\{ \frac{(P - P_{GL})(A_p)}{N_B(A_B)(E_B)} \right\} - f(p_{GL}, JR, SG_o, SG_{pGL}, K_C) \right] \quad (3-4)$$

For bolt stress $>$ yield

$$A_L = \frac{\pi(D_o + D_i)}{2} \left[L_B \left\{ \frac{(S_{By} - S_{So})}{E_B} + \left[S_{So} + \frac{(P - P_{GL})(A_p)}{N_B(A_B)} - S_{By} \right] / E'_B \right\} - f(p_{GL}, JR, SG_o, SG_{pGL}, K_C) \right] \quad (3-5)$$

where L_B = Bolt/Stud Length (in)

P_{GL} = Gross Leak Pressure (psi)

A_p = Pressure Area (in²) - based on gasket inside diameter

N_B = Number of Flange Bolts

A_B = Bolt Tensile Stress Area (in²) - per bolt

E_B = Bolt Material Elastic Modulus (psi)

SG_{pGL} = Gasket Stress at Gross Leak Pressure (psi)

$f(p_{GL}, JR, SG_o, SG_{pGL}, K_C)$ = Recoverable Gasket Deflection (in)

K_C = Gasket Unloading/Reloading Stiffness (psi/in)

S_{By} = Bolt Material Yield Stress (psi)

$$S_{Ba} = \text{Actual Bolt Stress (psi)} = (1 - JR / 100) S_{Bo} \text{ for no lockup case} \\ = S_{Bo} \text{ for lockup case}$$

$$S_{Bo} = \text{Initial Bolt Stress (psi)}$$

and $E'_B = \text{Bolt Modulus for appropriate inelastic portion of the stress-strain diagram (psi)}$

3.5 Gasketed Flange Connection Capacities and Variabilities

Program schedule and time constraints required submittal of bolted flange pressure capacities and variabilities to the risk analysis group prior to the arrival of the data related to the actual gasket loading stiffness and the effective gasket sealing surface area. Thus, the flange capacities reported below and used in the probabilistic risk analysis were based upon assumed values of gasket stiffness taken from the gasket stress-deflection data reported in References 15 through 17. These stiffness ranged from 170,000 to 230,000 psi/in and are identified for each calculation. In addition, it was conservatively assumed that the gasket load to total load ratio (Figure 3-1) was equal to 1.0 for all flanges. In Section 3.6, selected samples of the more precise calculations are presented and it will be shown that these simplifying assumptions result in a lower calculated Gross Leak Pressure and an overprediction of the leak rate and leak area on the order of 20 to 30 percent. Since flange connections other than the 44" Decay Heat Cooler tubesheet appear to be a small contributor to plant risk from the ISLOCA event, this overprediction is expected to have a negligible impact on the level of overall plant risk.

3.5.1 150lb Flanges

The results of the analyses for the 150lb rated flanges are presented in Tables 3-2 through 3-11. Table 3-2 shows the dimensional data for the gaskets and flange bolting which are standard for 150lb ANSI flanges while Tables 3-3 through 3-11 present the calculated leak rates (pressure $\leq$ Gross Leak Pressure) and leak areas (pressure $>$ Gross Leak Pressure) for the various cases studied. The cases include variation in initial bolt/stud stress (Tables 3-3 through 3-6), variation in joint relaxation (Tables 3-4 and 3-7 through 3-10), and variation in bolt yield strength (Tables 3-4 and 3-11).

Each table includes the effective gasket stress, defined here as the gasket stress due to bolt preload unaffected by the presence of the compression gauge ring, the actual gasket stress, limited by the presence of the compression gauge ring, and the resulting gasket loading deflection. For the 150lb flanges, the effective and actual gasket stress values are

equal indicating that the bolt preload is insufficient to bottom out the flange on the compression ring and thus the gasket deflection is less than the maximum deflection of the nominal 0.175" gasket. As noted above, the Gross Leak Pressure (GLP) is computed assuming that the pressure load results in a direct and corresponding reduction in the gasket load. As expected, the computed Gross Leak Pressure is greater for small flanges and trends lower as flange size increases. The mass leak rates and leak areas are calculated as described above. In Table 3-3, which presents the results for an initial bolt stress of 15,000 psi, it can be seen that the mass leak rate at the Gross Leak Pressure and even at low fractions of the GLP are high indicating that the preload is insufficient to properly seat the gasket. It can also be seen that the gasket stress is well below the 5000 psi "knee" of the stress-deflection and stress-leak rate curves for typical spiral wound gaskets (Figures 3-2 and 3-3). Thus, an initial bolt stress of 15,000 psi was not considered a realistic plant condition even though it is within the allowable range stipulated in the fabrication specification (Reference 14).

Comparing Tables 3-3 through 3-6, the Gross Leak Pressure increases and the mass leak rate decreases with increasing initial bolt stress. The leak area also increases somewhat with increase in initial bolt stress due to the fact that the increased bolt stress is approaching the material yield strength. It should be noted, however, that the leak areas are reported in terms of multiples of the Gross Leak Pressure and not constant pressures. Comparing Tables 3-7 through 3-10, it can be seen that Gross Leak Pressure decreases and leak rate increases slightly with increase in joint relaxation. It was also found that the leak area decreases slightly with increasing joint relaxation. The effect of variation in bolt yield stress can be seen by comparing Tables 3-4 and 3-11. Due to the use of a gasket load to total load ratio of 1.0 in the calculations, variation in the bolt yield stress has no effect on the computed Gross Leak Pressure or the mass leak rate. However, a reduced bolt yield stress results in a substantial increase in the leak area. Bolt yield stress is by far the most dominant variable in terms of large leaks for 150lb flange connections.

The estimation of the leak rate and leak area variabilities were based upon the results of the 8"-150# flange cases. It was judged that calculated uncertainties would not vary substantially with flange size and therefore a constant uncertainty variability was used for all flanges. Mass leak rate is plotted versus pressure in Figure 3-5 for each of the 8"-150# flange cases investigated. It can be seen that the variation of leak rate due to variation in the initial bolt stress is greater than that due to variation in percent joint relaxation. The uncertainty variability for joint relaxation was computed judging the range from 25% to 0% relaxation to reasonably represent a -3β variation. Although there was a slight difference in the variability

calculated for each pressure, an uncertainty variability of $\beta_{JR} = 0.18$ was selected to model the variation over the entire pressure range. Similarly, the uncertainty variability due to variation in initial bolt preload stress was computed judging the range from 25,000 to 30,000 psi to reasonably represent a $+2.33\beta$ variation. Accordingly, an uncertainty variability of $\beta_{BP} = 0.48$ was selected to model the variation over the entire pressure range. As noted above, there was no variation in leak rate due to variation in bolt yield stress and therefore, the combined mass leak rate uncertainty variability for 150lb rated flanges is:

$$\beta_{LR} = (0.18^2 + 0.48^2)^{1/2} = 0.51 \quad (3-6)$$

The variability in leak area is treated somewhat differently than leak rate. Figure 3-6 shows the initial portion of the leak area versus pressure curves for an 8"-150# flange for each of the cases studied. It can be seen that the leak area increases slowly until the bolt stress reaches the material yield, at which point the leak area begins to increase more rapidly in accordance with the piecewise linear representation of the material stress-strain diagram. As a result, the leak area versus pressure curves are essentially a set of parallel lines varying as to the pressure at which the bolt stress reaches material yield. Thus, the range of possible leak areas at any given pressure can be determined by Monte Carlo simulation using the median curve shape adjusted for the possible range of pressures corresponding to bolt yield. The uncertainty variabilities associated with variation in initial bolt preload stress, joint relaxation, and bolt yield stress were computed to be 0.02, 0.02, and 0.10, respectively. Thus, the combined bolt yield pressure uncertainty variability is:

$$\beta_{YP} = (0.02^2 + 0.02^2 + 0.10^2)^{1/2} = 0.11 \quad (3-7)$$

Therefore, using the median yield pressure of 1160 psi (see Figure 3-6, the median case curve for initial bolt stress of 25,000 psi and joint relaxation of 25%) and β_{YP} of 0.11, a set of bolt yield pressure values can be sampled using Monte Carlo simulation. Then, shifting the median curve as parallel lines determined by the above yield pressure values, a set of leak area versus pressure curves are obtained from which leak area variability can be estimated at a given pressure.

3.5.2 300lb Flanges

The results of the analyses for the 300lb rated flanges are presented in Tables 3-12 through 3-22. Table 3-12 shows the dimensional data for the gaskets and flange bolting which are standard for 300lb ANSI flanges while Tables 3-13 through 3-22 present the calculated leak rates (pressure $\leq$ Gross Leak Pressure) and leak areas (pressure $>$ Gross Leak Pressure) for the various cases studied. The cases include variation in initial bolt/stud stress (Tables 3-13 through 3-15), variation in joint relaxation (Tables 3-14 and 3-16 through 3-19), variation in bolt relaxation (Tables 3-17, 3-20, and 3-21), and variation in bolt yield strength (Tables 3-14 and 3-22).

Except for the 44" Decay Heat Cooler tubesheet, the effective gasket stress exceeds the actual gasket stress for the 300lb rated flanges indicating that the bolt preload is sufficient to bottom out the flange on the compression ring. Thus, the gasket deflection is equal to the maximum deflection of the nominal 0.175" gasket. The tubesheet flange uses a nominal 0.125" thick Style R gasket which has no compression gauge ring. The dimensional characteristics of the tubesheet and tubesheet flange preclude the tubesheet from bottoming out on the flange but would allow the gasket to be severely crushed unless care was taken during assembly. The Gross Leak Pressure (GLP) is again computed assuming that the pressure load results in a direct and corresponding reduction in the gasket load.

Comparing Tables 3-13 through 3-15, it can be seen that the 300lb rated flanges behave similar to the 150lb rated flanges with regard to the effect of the initial bolt preload stress; the Gross Leak Pressure increases and the mass leak rate decreases with increasing initial bolt stress. The leak area, however, decreases somewhat with increase in initial bolt stress due to the fact that the increased bolt stress creates a greater lock-up force which must be overcome before the gasket begins to unload. Comparing Tables 3-16 through 3-19, it can be seen that joint relaxation has no effect whatever on the flange leak resistance. This is again due to the lock-up between the flange and the compression gauge ring. As the gasket relaxes, the reduced gasket force results in a corresponding increase in the lock-up force with negligible change in the bolt force. Because the bolt preload stress levels for the 300lb rated flanges exceed the material yield strength, some relaxation is expected, even at the relatively low system operating temperatures. Thus the bolt relaxation variable was introduced. Tables 3-17, 3-20, and 3-21 allow a comparison of the leak resistance of the flanges considering 0, 10, and 20 percent relaxation. As expected, the Gross Leak Pressure decreases and the leak rate and leak area increase with increasing bolt relaxation. The effect of variation in bolt yield stress can be seen by comparing Tables 3-14 and 3-22. Again due to the use of a gasket load

to total load ratio of 1.0 in the calculations, variation in the bolt yield stress only effects the leak area. However, since the initial bolt preload is already above yield for the 300lb flange median case, a reduction of the bolt yield stress has a much lesser effect than seen for the 150lb rated flanges and the effect is only present for pressures outside the range of interest (i.e., >2500 psi).

The mass leak rates for pressures less than the Gross Leak Pressure are quite low for the 300lb rated flanges and the Gross Leak Pressures are relatively high for the median case (Table 3-20). Thus, the specific value for the uncertainty variability related to leak rate is of little importance. Therefore the combined uncertainty variability of 0.51 computed for the 150lb rated flanges was also used to represent the combined variability for the 300lb rated flanges accounting for variation in initial bolt preload stress and bolt relaxation.

The variability in leak area for the 300lb flanges is treated identical to that for the 150lb flanges. Figure 3-7 shows the initial portion of the leak area versus pressure curves for an 8"-300# flange for each of the cases studied. The leak area versus pressure curves are again essentially a set of parallel lines varying as to the pressure at which the bolt stress reaches material yield. Thus, the range of possible leak areas at any given pressure can be determined by Monte Carlo simulation using the median curve shape adjusted for the possible range of pressures corresponding to bolt yield. The uncertainty variabilities associated with variation in initial bolt preload stress, joint relaxation, bolt relaxation, and bolt yield stress were computed to be 0.02, 0.00, 0.05, and 0.00, respectively. Thus, the combined bolt yield pressure uncertainty variability is:

$$\beta_{y_p} = (0.02^2 + 0.05^2)^{1/2} = 0.06 \quad (3-8)$$

The leak area variability can then be estimated as described in Section 3.5.1.

3.5.3 600lb Flanges

The results of the analyses for the 600lb rated flanges are presented in Tables 3-23 and 3-24. Table 3-23 shows the dimensional data for the gaskets and flange bolting which are standard for 600lb ANSI flanges. Table 3-24 presents the calculated leak rates and leak areas for the median case. It can be seen from Table 3-24 that the Gross Leak Pressures for

all sizes of 600lb rated flanges are very high and greater than the range of interest. Thus, 600lb flanges are not expected to leak when subjected to pressures as high as the Reactor Coolant System operating pressure.

3.6 Conservatism in Computed Leak Parameters

As noted earlier, the Gross Leak Pressures, mass leak rates, and leak areas reported above are somewhat conservative due to the values used for the gasket loading stiffnesses and the gasket load to total load ratio early in the program. After receipt of the gasket stiffness information provided by the manufacturer, more precise calculations were made using the stiffness data presented in Table 3-1, the gasket load to total load ratios shown in Figure 3-1, and a smoother representation of the bolt material stress-strain diagram. A sample of the results of these more precise calculations are included in Tables 3-25 through 3-29 which present the 150lb rated flange median case analysis for the 2", 4", 8", 16", and 24" flanges, respectively. These calculations trace the increase in bolt stress, decrease in gasket stress, and corresponding mass leak rate and leak area with increasing pressure up to 3000 psi. The Gross Leak Pressure and pressure corresponding to bolt yield are also identified. Comparing these results with the appropriate row in Table 3-8 shows the differences between the analyses. For the smaller flanges, the apparent difference is larger, reflecting the effect of the gasket load to total load ratio while for the larger flanges (greater than about 12"), the load ratio was equal to one for both analyses and thus, the differences are small.

As an example, by comparing the pressure and gasket stress columns in Table 3-25, it can be seen that as the pressure increases the gasket stress decreases and that the Gross Leak Pressure, defined as the pressure at which the two are equal, will occur at about 3200 psi for the 2" flange as opposed to 1891 psi from Table 3-8. However, the leak rate of 4 mg/sec and leak area of 0.02 sq-in at 1.5GLP (approximately 2800 psi) from Table 3-8 overstate the corresponding values of 1 mg/sec and 0.00 sq-in from the more precise analysis. Since the absolute magnitude of the differences for the 2" flange are small, the effect on overall plant risk is negligible. In contrast, the Gross Leak Pressure from Table 3-29 for the 24" flange is 640 psi compared with 634 psi from Table 3-8. The leak rate of 49 mg/sec and leak area of 2.83 sq-in at 2.0GLP (approximately 1270 psi) overstate the corresponding values of 37 mg/sec and about 2.3 sq-in by approximately 25 percent. Again, it is judged that these differences will have a negligible effect on the calculated plant risk from the postulated ISLOCA event.

TABLE 3-1
STIFFNESSES FOR ASBESTOS-FILLED SPIRAL WOUND GASKETS

Flange Diameter (in)	Pressure Rating (#)	*-----GASKET-----*				*-----BOLTS-----*			Gasket Test Load (lbs)	Bolt Stress at GTL (psi)	*-----GASKET STIFFNESS-----*		
		OD (in)	ID (in)	Width (in)	Area (sq in)	Number	Diameter (in)	Length (in)			T _g =0.125 (psi/in)	T _g =0.130 (psi/in)	T _g =0.135 (psi/in)
1-1/2	150	2.750	2.125	0.2500	1.865	4	1/2	1.625	15100	26660	161902	179892	202378
	300	2.750	2.125	0.2500	1.865	4	3/4	1.875	36200	27096	388137	431263	485171
	600	2.750	2.125	0.2500	1.865	4	3/4	2.375	36200	27096	388137	431263	485171
2	150	3.375	2.750	0.2500	2.356	4	5/8	1.750	24200	26817	205416	228240	256770
	300	3.375	2.750	0.2500	2.356	4	5/8	2.000	48400	26817	410832	456480	513540
	600	3.375	2.750	0.2500	2.356	8	5/8	2.625	48400	26817	410832	456480	513540
2-1/2	150	3.875	3.250	0.2500	2.749	4	5/8	2.000	24200	26817	176071	195634	220089
	300	3.875	3.250	0.2500	2.749	8	3/4	2.250	72500	27133	527485	586094	659356
	600	3.875	3.250	0.2500	2.749	8	3/4	2.875	72500	27133	527485	586094	659356
3	150	4.750	4.000	0.3125	4.234	4	5/8	2.125	24200	26817	114318	127021	142898
	300	4.750	4.000	0.3125	4.234	8	3/4	2.500	72500	27133	342483	380537	428104
	600	4.750	4.000	0.3125	4.234	8	3/4	3.125	72500	27133	342483	380537	428104
4	150	5.875	5.000	0.3750	6.332	8	5/8	2.125	48500	26873	153184	170204	191479
	300	5.875	5.000	0.3750	6.332	8	3/4	2.250	72500	27133	228986	254429	286232
	600	5.875	5.000	0.3750	6.332	8	3/4	3.625	101000	27374	244947	272163	306184
6	150	8.250	7.188	0.4688	11.275	8	7/8	3.625	72500	27133	128606	142895	160757
	300	8.250	7.188	0.4688	11.275	8	3/4	3.125	100700	25125	178629	198477	223286
	600	8.250	7.188	0.4688	11.275	12	3/4	3.125	190000	26166	258043	286715	322554
8	150	10.375	9.188	0.5313	16.220	8	3/4	3.500	72500	27133	89394	99327	111743
	300	10.375	9.188	0.5313	16.220	12	7/8	3.500	150800	27248	185940	206600	232425
	600	10.375	9.188	0.5313	16.220	12	7/8	5.000	262000	28626	253710	281900	317137
10	150	12.500	11.313	0.5313	19.767	12	7/8	2.625	151000	27284	152781	169756	190976
	300	12.500	11.313	0.5313	19.767	16	1	4.000	264400	27310	267518	297242	334398
	600	12.500	11.313	0.5313	19.767	16	1-1/4	5.625	446000	28785	313474	348304	391842
12	150	14.750	13.375	0.6250	27.489	12	7/8	5.625	151000	27284	109862	122069	137328
	300	14.750	13.375	0.6250	27.489	16	1-1/8	4.250	349400	28632	254211	282457	317764
	600	14.750	13.375	0.6250	27.489	20	1-1/4	5.875	557000	28759	294730	327478	368413
14	150	16.000	14.625	0.6250	29.943	12	1	3.000	198000	27268	132250	146944	165312
	300	16.000	14.625	0.6250	29.943	20	1-1/8	4.500	436000	28583	291217	323574	364021
	600	16.000	14.625	0.6250	29.943	20	1-3/8	6.125	264000	27408	328998	365553	411247
16	150	18.250	16.625	0.7500	40.939	16	1	3.125	264000	27268	128973	143303	161216
	300	18.250	16.625	0.7500	40.939	20	1-1/4	4.750	557000	28759	272113	302348	340141
	600	18.250	16.625	0.7500	40.939	20	1-1/2	6.625	27643	27643	306701	340778	383376
18	150	20.750	18.688	0.9688	59.822	16	1-1/8	5.000	27262	27262	111226	123584	139032
	300	20.750	18.688	0.9688	59.822	24	1-1/4	7.125	27565	27565	214187	237985	267733
	600	20.750	18.688	0.9688	59.822	24	1-5/8	7.125	28439	28439	308754	343060	385943
20	150	22.750	20.688	0.9688	65.909	20	1-1/8	3.625	27262	27262	126192	140213	157740
	300	22.750	20.688	0.9688	65.909	24	1-1/4	5.250	27565	27565	194406	216007	243008
	600	22.750	20.688	0.9688	65.909	24	1-5/8	7.625	28439	28439	336140	373488	420175
24	150	27.000	24.750	1.0625	86.161	20	1-1/4	4.000	27565	27565	123927	137696	154908
	300	27.000	24.750	1.0625	86.161	24	1-1/2	5.750	27643	27643	216232	240258	270290
	600	27.000	24.750	1.0625	86.161	24	1-7/8	8.625	28667	28667	385000	427778	481250
44	300	47.625	45.625	0.9375	137.138	40	1-3/8	10.215	---	27408	307457	368948	461185

Reference: MIL-G-21032E, Amendment 2
Calculation GASSTIF

GTL = Gasket Test Load
T_g = Compressed Gasket Thickness

TABLE 3-2
150# ANSI FLANGE AND GASKET DATA

Flange Diameter (in)	*-----GASKET-----*					*-----BOLTS-----*			
	OD (in)	ID (in)	Width (in)	Area (sq in)	Pressure Area (sq in)	Number	Diameter (in)	Area (sq in)	Length (in)
Flanges									
1-1/2	2.750	2.125	0.3125	2.393	3.547	4	1/2	0.1416	1.625
2	3.375	2.750	0.3125	3.007	5.940	4	5/8	0.2256	1.750
2-1/2	3.875	3.250	0.3125	3.497	8.296	4	5/8	0.2256	2.000
3	4.750	4.000	0.3750	5.154	12.566	4	5/8	0.2256	2.125
4	5.875	5.000	0.4375	7.474	19.635	8	5/8	0.2256	2.125
6	8.250	7.188	0.5313	12.882	40.574	8	3/4	0.3340	2.250
8	10.375	9.188	0.5938	18.245	66.296	8	3/4	0.3340	2.500
10	12.500	11.313	0.5938	22.209	100.509	12	7/8	0.4612	2.625
12	14.750	13.375	0.6875	30.373	140.500	12	7/8	0.4612	2.750
14	16.000	14.625	0.6875	33.073	167.989	12	1	0.6051	3.000
16	18.250	16.625	0.8125	44.510	217.077	16	1	0.6051	3.125
18	20.750	18.688	1.0313	63.884	274.279	16	1-1/8	0.7627	3.375
20	22.750	20.688	1.0313	70.364	336.129	20	1-1/8	0.7627	3.625
24	27.000	24.750	1.1250	91.450	481.105	20	1-1/4	0.9684	4.000
Tubesheet									
6	8.250	7.250	0.5000	12.174	41.282	8	3/4	0.3340	3.500

Bolt areas correspond to tensile stress area and not thread root area which is the basis for the bolt torque values
(Reference 14)

TABLE 3-3
150# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 15000 psi
JOINT RELAXATION = 0%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at .25GLP (mg/sec)	Leak Rate at .50GLP (mg/sec)	Leak Rate at .75GLP (mg/sec)	Leak Area at 1.25GLP (sq in)	Leak Area at 1.5GLP (sq in)	Leak Area at 1.75GLP (sq in)	Leak Area at 2.0GLP (sq in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	3550	3550	0.015	1430	172	24	56	101	0.00	0.00	0.00	0.00	23957
2	4502	4502	0.020	1513	60	7	17	33	0.00	0.00	0.00	0.01	24959
2-1/2	3870	3870	0.017	1148	150	17	40	78	0.00	0.00	0.01	0.01	25552
3	2626	2626	0.011	764	1167	128	310	600	0.00	0.01	0.01	0.01	25637
4	3622	3622	0.021	999	228	24	59	115	0.00	0.01	0.01	0.01	25865
6	3111	3111	0.018	750	575	55	136	272	0.01	0.01	0.02	0.02	26385
8	2197	2197	0.013	474	3943	348	869	1773	0.01	0.02	0.02	0.03	26763
10	3738	3738	0.022	676	286	22	56	118	0.01	0.02	0.03	0.04	27285
12	2733	2733	0.016	486	1498	114	290	611	0.01	0.03	0.04	0.05	27334
14	3293	3293	0.019	542	605	44	111	237	0.02	0.03	0.05	0.07	27533
16	3263	3263	0.019	555	616	46	116	246	0.02	0.04	0.06	0.08	27448
18	2865	2865	0.017	541	1107	89	224	466	0.02	0.05	0.07	0.09	27166
20	3252	3252	0.019	563	617	46	118	249	0.03	0.06	0.08	0.11	27404
24	3177	3177	0.019	507	749	53	135	289	0.04	0.07	0.11	0.15	27604
Tubesheet													
6	3292	3292	0.019	750	451	41	103	208	0.01	0.02	0.03	0.04	26584

Bolt Yield Stress = 33,000 psi (SA193-B8 Class 1)
Kgasket = 230,000 psi/in (Flanges 3" and less)
Kgasket = 170,000 psi/in (Flanges greater than 3")
DGmax = 0.050 in
Calculation 1501500

TABLE 3-4
150# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 20000 psi
JOINT RELAXATION = 0%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at 25GLP (mg/sec)	Leak Rate at 50GLP (mg/sec)	Leak Rate at 75GLP (mg/sec)	Leak Area at 1.25GLP (sq in)	Leak Area at 1.5GLP (sq in)	Leak Area at 1.75GLP (sq in)	Leak Area at 2.0GLP (sq in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	4734	4734	0.021	1907	38	5	12	22	0.00	0.00	0.00	0.01	31942
2	6003	6003	0.026	2017	13	2	4	7	0.00	0.00	0.01	0.03	33278
2-1/2	5160	5160	0.022	1530	33	4	9	17	0.00	0.01	0.01	0.13	34069
3	3502	3502	0.015	1018	259	28	69	133	0.00	0.01	0.01	0.18	34183
4	4830	4830	0.028	1332	51	5	13	25	0.00	0.01	0.01	0.28	34486
6	4148	4148	0.024	1000	128	12	30	60	0.01	0.02	0.02	0.61	35180
8	2929	2929	0.017	632	874	77	193	393	0.01	0.02	0.03	1.04	35684
10	4984	4984	0.029	902	63	5	12	26	0.01	0.03	0.04	1.67	36381
12	3644	3644	0.021	648	332	25	64	136	0.02	0.04	0.05	2.10	36445
14	4391	4391	0.026	722	134	10	25	53	0.02	0.04	0.07	2.68	36710
16	4350	4350	0.026	740	137	10	26	55	0.03	0.05	0.08	3.08	36597
18	3820	3820	0.022	722	246	20	50	103	0.03	0.06	0.09	3.38	36222
20	4336	4336	0.026	751	137	10	26	55	0.04	0.07	0.11	4.39	36538
24	4236	4236	0.025	677	166	12	30	64	0.05	0.10	0.15	6.19	36806
Tubesheet													
6	4390	4390	0.026	1000	100	9	23	46	0.01	0.02	0.04	1.06	35445

Bolt Yield Stress = 33,000 psi (SA193-B8 Class 1)
Kgasket = 230,000 psi/in (Flanges 3" and less)
Kgasket = 170,000 psi/in (Flanges greater than 3")
DGmax = 0.050 in
Calculation 1502000

TABLE 3-5
150# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 25000 psi

JOINT RELAXATION = 0%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at .25GLP (mg/sec)	Leak Rate at .50GLP (mg/sec)	Leak Rate at .75GLP (mg/sec)	Leak Area at 1.25GLP (sq in)	Leak Area at 1.5GLP (sq in)	Leak Area at 1.75GLP (sq in)	Leak Area at 2.0GLP (sq in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	5917	5917	0.026	2384	12	2	4	7	0.00	0.00	0.20	0.42	39928
2	7503	7503	0.033	1913	4	1	1	2	0.00	0.03	0.37	0.71	41598
2-1/2	6450	6450	0.028	1273	10	1	3	5	0.00	0.09	0.57	1.05	42586
3	4377	4377	0.019	1273	80	9	21	41	0.00	0.13	0.76	1.39	42729
4	6037	6037	0.036	1664	16	2	4	8	0.01	0.20	1.00	1.80	43108
6	5185	5185	0.031	1250	40	4	9	19	0.01	0.41	1.67	2.94	43975
8	3661	3661	0.022	790	272	24	50	122	0.01	0.70	2.53	4.37	44605
10	6230	6230	0.037	1127	20	2	4	8	0.02	1.10	3.55	6.00	45476
12	4555	4555	0.027	810	103	8	20	42	0.02	1.39	4.43	7.48	45556
14	5489	5489	0.032	903	42	3	8	16	0.03	1.76	5.44	9.11	45898
16	5438	5438	0.032	925	42	3	8	17	0.03	2.03	6.36	10.69	45746
18	4776	4776	0.028	902	76	6	15	32	0.04	2.24	7.41	12.58	45277
20	5420	5420	0.032	938	43	3	8	17	0.05	2.89	9.13	15.36	45673
24	5295	5295	0.031	846	52	4	9	20	0.06	4.07	12.39	20.72	46007
Tubesheet													
6	5487	5487	0.032	1250	31	3	7	14	0.01	0.71	2.72	4.72	44307

Bolt Yield Stress = 33,000 psi (SA193-B8 Class 1)

Gasket = 230,000 psi/in (Flanges 3" and less)

Gasket = 170,000 psi/in (Flanges greater than 3")

DGmax = 0.050 in

Calculation 1502500

TABLE 3-6
150# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 30000 psi
JOINT RELAXATION = 0%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at .25GLP (mg/sec)	Leak Rate at .50GLP (mg/sec)	Leak Rate at .75GLP (mg/sec)	Leak Area at 1.25GLP (sq in)	Leak Area at 1.5GLP (sq in)	Leak Area at 1.75GLP (sq in)	Leak Area at 2.0GLP (sq in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	7101	7101	0.031	2861	5	1	1	3	0.09	0.36	0.63	0.91	47913
2	9004	9004	0.039	3026	2	0	0	1	0.16	0.57	0.98	1.39	49918
2-1/2	7740	7740	0.034	2296	4	0	1	2	0.25	0.83	1.40	1.98	51103
3	5252	5252	0.023	1528	31	3	8	16	0.33	1.09	1.85	2.61	51274
4	7245	7245	0.043	1997	6	1	2	3	0.43	1.40	2.36	3.32	51729
6	6222	6222	0.037	1500	15	1	4	7	0.72	2.24	3.75	5.59	52770
8	4393	4393	0.026	948	105	9	23	47	1.09	3.29	5.50	8.51	53526
10	7476	7476	0.044	1353	8	1	1	3	1.52	4.76	7.40	12.01	54571
12	5466	5466	0.032	972	40	3	8	16	1.89	5.54	9.20	14.99	54667
14	6587	6587	0.039	1083	16	1	3	6	2.32	6.73	11.14	18.44	55065
16	6525	6525	0.038	1110	16	1	3	7	2.71	7.91	13.11	21.56	54895
18	5731	5731	0.034	1083	29	2	6	12	3.17	9.37	15.58	25.03	54333
20	6504	6504	0.038	1126	16	1	3	7	3.64	11.37	18.86	30.91	54807
24	6354	6354	0.037	1015	20	1	4	8	5.27	15.27	25.26	42.07	55208
Tubesheet													
6	6585	6585	0.039	1500	12	1	3	6	1.17	3.58	5.99	9.11	53168

Bolt Yield Stress = 33,000 psi (SA193-B8 Class 1)
Kgasket = 230,000 psi/in (Flanges 3" and less)
Kgasket = 170,000 psi/in (Flanges greater than 3")
DGmax = 0.050 in
Calculation 1503000

TABLE 3-7
150# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 25000 psi
JOINT RELAXATION = 15%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at .25GLP (mg/sec)	Leak Rate at .50GLP (mg/sec)	Leak Rate at .75GLP (mg/sec)	Leak Area at 1.25GLP (sq in)	Leak Area at 1.5GLP (sq in)	Leak Area at 1.75GLP (sq in)	Leak Area at 2.0GLP (sq in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	5030	5030	0.026	2026	11	2	4	7	0.00	0.00	0.00	0.06	33939
2	6378	6378	0.033	2143	4	0	1	2	0.00	0.00	0.01	0.20	35358
2-1/2	5483	5483	0.028	1626	10	1	3	5	0.00	0.01	0.01	0.36	36198
3	3720	3720	0.019	1082	78	9	21	40	0.00	0.01	0.01	0.49	36319
4	5132	5132	0.036	1415	15	2	4	8	0.01	0.01	0.02	0.66	36642
6	4408	4408	0.031	1062	38	4	9	18	0.01	0.02	0.12	1.19	37379
8	3112	3112	0.022	672	263	23	58	118	0.01	0.02	0.31	1.87	37914
10	5295	5295	0.037	958	19	1	4	8	0.02	0.03	0.67	2.75	38654
12	3872	3872	0.027	688	100	8	19	41	0.02	0.04	0.85	3.44	38723
14	4666	4666	0.032	767	40	3	7	16	0.02	0.05	1.16	4.29	39005
16	4622	4622	0.032	786	41	3	8	16	0.03	0.05	1.31	4.99	38884
18	4059	4059	0.028	767	74	6	15	31	0.03	0.07	1.29	5.68	38486
20	4607	4607	0.032	797	41	3	8	17	0.04	0.08	1.83	7.13	38822
24	4501	4501	0.031	719	50	4	9	19	0.05	0.11	2.74	9.82	39106
Tubesheet													
6	4664	4664	0.032	1062	30	3	7	14	0.01	0.03	0.27	1.97	37661

Bolt Yield Stress = 33,000 psi (SA193-B8 Class 1)
Kgasket = 230,000 psi/in (Flanges 3" and less)
Kgasket = 170,000 psi/in (Flanges greater than 3")
DGmax = 0.050 in
Calculation 1502515

TABLE 3-8
150# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 25000 psi
JOINT RELAXATION = 25%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at .25GLP (mg/sec)	Leak Rate at .50GLP (mg/sec)	Leak Rate at .75GLP (mg/sec)	Leak Area at 1.25GLP (sq in)	Leak Area at 1.5GLP (sq in)	Leak Area at 1.75GLP (sq in)	Leak Area at 2.0GLP (sq in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	4438	4438	0.026	1788	11	2	4	7	0.00	0.00	0.00	0.01	29946
2	5628	5628	0.033	1891	4	0	1	2	0.00	0.00	0.01	0.01	31199
2-1/2	4838	4838	0.028	1435	10	1	3	5	0.00	0.01	0.01	0.01	31939
3	3283	3283	0.019	955	76	8	20	39	0.00	0.01	0.01	0.01	32046
4	4528	4528	0.036	1248	15	2	4	7	0.00	0.01	0.01	0.02	32331
6	3889	3889	0.031	937	37	4	9	18	0.01	0.01	0.02	0.03	32981
8	2746	2746	0.022	593	256	23	56	115	0.01	0.02	0.03	0.21	33453
10	4672	4672	0.037	846	19	1	4	8	0.01	0.03	0.04	0.58	34107
12	3417	3417	0.027	607	97	7	19	40	0.02	0.03	0.05	0.75	34167
14	4117	4117	0.032	677	39	3	7	15	0.02	0.04	0.06	1.07	34416
16	4078	4078	0.032	694	40	3	8	16	0.02	0.05	0.07	1.18	34310
18	3582	3582	0.028	677	72	6	15	30	0.03	0.06	0.09	1.08	33958
20	4065	4065	0.032	704	40	3	8	16	0.03	0.07	0.10	1.64	34254
24	3971	3971	0.031	634	49	3	9	19	0.05	0.09	0.14	2.56	34505
Tubesheet													
6	4115	4115	0.032	937	29	3	7	14	0.01	0.02	0.03	0.14	33230

Bolt Yield Stress = 33,000 psi (SA193-B8 Class 1)
Gasket = 230,000 psi/in (Flanges 3" and less)
Gasket = 170,000 psi/in (Flanges greater than 3")
DGmax = 0.050 in
Calculation 1502525

TABLE 3-9
150# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 25000 psi
JOINT RELAXATION = 33%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at 25GLP (mg/sec)	Leak Rate at .50GLP (mg/sec)	Leak Rate at .75GLP (mg/sec)	Leak Area at 1.25GLP (sq in)	Leak Area at 1.5GLP (sq in)	Leak Area at 1.75GLP (sq in)	Leak Area at 2.0GLP (sq in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	3965	3965	0.026	1597	11	2	4	6	0.00	0.00	0.00	0.00	26752
2	5027	5027	0.033	1690	4	0	1	2	0.00	0.00	0.01	0.01	27871
2-1/2	4322	4322	0.028	1282	10	1	3	5	0.00	0.00	0.01	0.01	28533
3	2933	2933	0.019	853	74	8	20	38	0.00	0.01	0.01	0.01	28628
4	4045	4045	0.036	1115	14	2	4	7	0.00	0.01	0.01	0.02	28882
6	3474	3474	0.031	837	36	3	9	17	0.01	0.01	0.02	0.03	29463
8	2453	2453	0.022	529	250	22	55	112	0.01	0.02	0.03	0.04	29885
10	4174	4174	0.037	755	18	1	4	7	0.01	0.02	0.04	0.05	30469
12	3052	3052	0.027	543	95	7	18	39	0.02	0.03	0.05	0.06	30523
14	3678	3678	0.032	605	38	3	7	15	0.02	0.04	0.05	0.07	30745
16	3643	3643	0.032	620	39	3	7	16	0.02	0.04	0.06	0.09	30650
18	3200	3200	0.028	604	70	6	14	30	0.03	0.05	0.08	0.10	30336
20	3631	3631	0.032	629	39	3	7	16	0.03	0.06	0.09	0.12	30601
24	3547	3547	0.031	567	48	3	9	18	0.04	0.08	0.12	0.17	30825
Tubesheet													
6	3676	3676	0.032	837	29	3	7	13	0.01	0.02	0.03	0.04	29685

Bolt Yield Stress = 33,000 psi (SA193-B8 Class 1)
K_{gasket} = 230,000 psi/in (Flanges 3" and less)
K_{gasket} = 170,000 psi/in (Flanges greater than 3")
D/G_{max} = 0.050 in
Calculation 1502533

TABLE 3-10
150# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 25000 psi
JOINT RELAXATION = 50%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at .25GLP (mg/sec)	Leak Rate at .50GLP (mg/sec)	Leak Rate at .75GLP (mg/sec)	Leak Area at 1.25GLP (sq in)	Leak Area at 1.5GLP (sq in)	Leak Area at 1.75GLP (sq in)	Leak Area at 2.0GLP (sq in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	2959	2959	0.026	1192	10	1	3	6	0.00	0.00	0.00	0.00	19964
2	3752	3752	0.033	1261	4	0	1	2	0.00	0.00	0.00	0.01	20799
2-1/2	3225	3225	0.028	956	9	1	2	5	0.00	0.00	0.01	0.01	21293
3	2189	2189	0.019	637	70	8	19	36	0.00	0.00	0.01	0.01	21364
4	3019	3019	0.036	832	14	1	4	7	0.00	0.01	0.01	0.01	21554
6	2593	2593	0.031	625	34	3	8	16	0.00	0.01	0.01	0.02	21988
8	1831	1831	0.022	395	235	21	52	106	0.01	0.01	0.02	0.03	22302
10	3115	3115	0.037	564	17	1	3	7	0.01	0.02	0.03	0.04	22738
12	2278	2278	0.027	405	89	7	17	36	0.01	0.02	0.03	0.05	22778
14	2744	2744	0.032	451	36	3	7	14	0.01	0.03	0.04	0.05	22944
16	2719	2719	0.032	463	37	3	7	15	0.02	0.03	0.05	0.06	22873
18	2388	2388	0.028	451	66	5	13	28	0.02	0.04	0.06	0.08	22639
20	2710	2710	0.032	469	37	3	7	15	0.02	0.05	0.07	0.09	22836
24	2647	2647	0.031	423	45	3	8	17	0.03	0.05	0.09	0.12	23003
Tubesheet													
6	2744	2744	0.032	625	27	2	6	12	0.01	0.01	0.02	0.03	22153

Bolt Yield Stress = 33,000 psi (SA193-B8 Class 1)
Kgasket = 230,000 psi/in (Flanges 3" and less)
Kgasket = 170,000 psi/in (Flanges greater than 3")
D/Gmax = 0.050 in
Calculation 1502550

TABLE 3-11
150# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 25000 psi
JOINT RELAXATION = 0%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at .25GLP (mg/sec)	Leak Rate at .50GLP (mg/sec)	Leak Rate at .75GLP (mg/sec)	Leak Area at 1.25GLP (sq in)	Leak Area at 1.5GLP (sq in)	Leak Area at 1.75GLP (sq in)	Leak Area at 2.0GLP (sq in)	Bolt Stress at 2.0GLP (psi)
Fanges													
1-1/2	5917	5917	0.026	2384	12	2	4	7	0.08	0.30	0.53	0.76	39928
2	7503	7503	0.033	2522	4	1	1	2	0.14	0.48	0.82	1.16	41598
2-1/2	6450	6450	0.028	1913	10	1	3	5	0.21	0.69	1.17	1.65	42586
3	4377	4377	0.019	1273	80	9	21	41	0.28	0.91	1.54	2.17	42729
4	6037	6037	0.036	1664	16	2	4	8	0.36	1.16	1.97	2.77	43108
6	5185	5185	0.031	1250	40	4	9	19	0.60	1.86	3.13	4.39	43975
8	3661	3661	0.022	790	272	24	60	122	0.91	2.74	4.58	6.42	44605
10	6230	6230	0.037	1127	20	2	4	8	1.26	3.72	6.17	8.62	45476
12	4555	4555	0.027	810	103	8	20	42	1.58	4.62	7.67	10.71	45556
14	5489	5489	0.032	903	42	3	8	16	1.93	5.61	9.28	12.96	45888
16	5438	5438	0.032	925	42	3	8	17	2.26	6.59	10.92	15.25	45746
18	4776	4776	0.028	902	76	6	15	32	2.64	7.81	12.98	18.15	45277
20	5420	5420	0.032	938	43	3	8	17	3.24	9.48	15.71	21.95	45673
24	5295	5295	0.031	846	52	4	9	20	4.39	12.72	21.05	29.38	46007
Tubesheet													
6	5487	5487	0.032	1250	31	3	7	14	0.97	2.98	4.99	6.99	44307

Bolt Yield Stress = 27,500 psi (SA193-B8 Class 1)

Gasket = 230,000 psi/in (Flanges 3" and less)

Gasket = 170,000 psi/in (Flanges greater than 3")

Gmax = 0.050 in

Calculation 1502500Y

TABLE 3-12
300# ANSI FLANGE AND GASKET DATA

Flange Diameter (in)	*-----GASKET-----*				Pressure Area (sq in)	*-----BOLTS-----*			
	OD (in)	ID (in)	Width (in)	Area (sq in)		Number	Diameter (in)	Area (sq in)	Length (in)
Flanges									
1-1/2	2.750	2.125	0.3125	2.393	3.547	4	3/4	0.3340	1.875
2	3.375	2.750	0.3125	3.007	5.940	8	5/8	0.2256	2.000
2-1/2	3.875	3.250	0.3125	3.497	8.296	8	3/4	0.3340	2.250
3	4.750	4.000	0.3750	5.154	12.566	8	3/4	0.3340	2.500
4	5.875	5.000	0.4375	7.474	19.635	8	3/4	0.3340	2.750
6	8.250	7.188	0.5313	12.882	40.574	12	3/4	0.3340	3.125
8	10.375	9.188	0.5938	18.245	66.296	12	7/8	0.4612	3.500
10	12.500	11.313	0.5938	22.209	100.509	16	1	0.6051	4.000
12	14.750	13.375	0.6875	30.373	140.500	16	1-1/8	0.7896	4.250
14	16.000	14.625	0.6875	33.073	167.989	20	1-1/8	0.7896	4.500
16	18.250	16.625	0.8125	44.510	217.077	20	1-1/4	0.9985	4.750
18	20.750	18.688	1.0313	63.884	274.279	24	1-1/4	0.9985	5.000
20	22.750	20.688	1.0313	70.364	336.129	24	1-1/4	0.9985	5.250
24	27.000	24.750	1.1250	91.450	481.105	24	1-1/2	1.4899	5.750
Tubesheet									
44	47.625	45.625	1.0000	146.48	1634.92	40	1-3/8	1.2319	10.215

Bolt areas correspond to tensile stress area and not thread root area which is the basis for the bolt torque values
(Reference 14)

TABLE 3-13
300# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 30000 psi
JOINT RELAXATION = 0%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at .25GLP (mg/sec)	Leak Rate at .50GLP (mg/sec)	Leak Rate at .75GLP (mg/sec)	Leak Area at 1.25GLP (sq-in)	Leak Area at 1.50GLP (sq-in)	Leak Area at 1.75GLP (sq-in)	Leak Area at 2.0GLP (sq-in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	16749	11500	0.050	6748	0	0	0	0	0.11	0.42	0.73	1.05	47913
2	18008	11500	0.050	6052	0	0	0	0	0.19	0.66	1.12	1.59	49918
2-1/2	22919	11500	0.050	6797	1	0	0	0	0.28	0.93	1.58	2.23	51103
3	15552	11500	0.050	4524	1	0	0	0	0.39	1.28	2.18	3.07	51274
4	10726	10000	0.050	2957	1	0	0	1	0.56	1.81	3.05	4.30	51729
6	9334	9334	0.047	2249	2	0	0	1	1.00	3.11	5.21	7.77	52770
8	9100	9100	0.046	1964	2	0	1	1	1.52	4.61	7.69	11.92	53526
10	13078	10000	0.050	2367	2	0	0	1	2.31	6.79	11.28	18.31	54571
12	12479	10000	0.050	2218	2	0	0	1	2.92	8.57	14.22	23.17	54667
14	14325	10000	0.050	2356	2	0	0	1	3.47	10.09	16.71	27.66	55065
16	13450	10000	0.050	2290	2	0	0	1	4.12	12.02	19.92	32.77	54895
18	11253	10000	0.050	2126	2	0	0	1	4.69	13.88	23.07	37.08	54333
20	10217	10000	0.050	1769	2	0	0	1	5.63	16.47	27.31	44.76	54807
24	11730	10000	0.050	1874	2	0	0	1	7.58	21.95	36.32	60.47	55208
Tubesheet													
44	10092	6000	0.030	493	47	2	5	12	0.22	0.44	0.67	18.36	35412

Bolt Yield Stress = 33000 psi (SA193-B8 Class 1)
 Gasket = 230,000 psi/in (Flanges 3" and less)
 Gasket = 200,000 psi/in (Flanges greater than 3")
 DGmax = 0.050 in (Flanges)
 DGmax = 0.035 in (44" Tubesheet)
 Calculation 3003000

TABLE 3-14
300# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 35000 psi
JOINT RELAXATION = 0%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at 25GLP (mg/sec)	Leak Rate at 50GLP (mg/sec)	Leak Rate at 75GLP (mg/sec)	Leak Area at 1.25GLP (sq-in)	Leak Area at 1.50GLP (sq-in)	Leak Area at 1.75GLP (sq-in)	Leak Area at 2.0GLP (sq-in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	19540	11500	0.050	7873	0	0	0	0	0.37	0.73	1.10	1.83	55899
2	21010	11500	0.050	7061	1	0	0	0	0.55	1.09	1.71	2.94	58237
2-1/2	26739	11500	0.050	7930	1	0	0	0	0.76	1.51	2.53	4.23	59620
3	18145	11500	0.050	5277	1	0	0	0	1.04	2.08	3.50	5.85	59820
4	12513	10000	0.050	3450	1	0	0	1	1.45	2.90	5.00	8.28	60351
6	10889	10000	0.050	2624	1	0	0	1	2.45	4.91	8.82	14.68	61565
8	10617	10000	0.050	2291	1	0	0	1	3.60	7.20	13.30	22.44	62446
10	15258	10000	0.050	2761	2	0	0	1	5.23	10.46	20.01	34.31	63666
12	14558	10000	0.050	2588	2	0	0	1	6.59	13.18	25.29	43.41	63779
14	16712	10000	0.050	2749	2	0	0	1	7.72	15.44	29.98	51.75	64243
16	15703	10000	0.050	2672	2	0	0	1	9.22	18.43	35.61	61.33	64045
18	13129	10000	0.050	2480	2	0	0	1	10.72	21.45	40.71	69.57	63388
20	11920	10000	0.050	2063	2	0	0	1	12.64	25.29	48.72	83.81	63942
24	13685	10000	0.050	2186	2	0	0	1	16.76	33.53	65.38	113.06	64410
Tubesheet													
44	11774	7000	0.035	576	21	1	2	6	0.26	0.52	26.42	61.27	41314

Bolt Yield Stress = 33000 psi (SA193-B8 Class 1)
Kgasket = 230,000 psi/in (Flanges 3" and less)
Kgasket = 200,000 psi/in (Flanges greater than 3")
DGmax = 0.050 in (Flanges)
DGmax = 0.035 in (44" Tubesheet)
Calculation 3003500

TABLE 3-15
300# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 40000 psi
JOINT RELAXATION = 0%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at .25GLP (mg/sec)	Leak Rate at .50GLP (mg/sec)	Leak Rate at .75GLP (mg/sec)	Leak Area at 1.25GLP (sq-in)	Leak Area at 1.50GLP (sq-in)	Leak Area at 1.75GLP (sq-in)	Leak Area at 2.0GLP (sq-in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	22332	11500	0.050	8997	0	0	0	0	0.42	0.85	1.79	3.00	63884
2	24011	11500	0.050	8070	1	0	0	0	0.62	1.42	2.83	4.89	66557
2-1/2	30559	11500	0.050	9063	1	0	0	0	0.86	2.08	4.07	7.62	68137
3	20737	11500	0.050	6031	1	0	0	0	1.19	2.88	5.65	10.64	68366
4	14301	10000	0.050	3943	1	0	0	1	1.66	4.09	8.09	15.42	68972
6	12445	10000	0.050	2999	1	0	0	1	2.81	7.18	14.38	28.11	70360
8	12133	10000	0.050	2619	1	0	0	1	4.11	10.79	21.78	43.23	71367
10	17437	10000	0.050	3156	2	0	0	1	5.98	16.16	32.95	66.55	72761
12	16638	10000	0.050	2957	2	0	0	1	7.53	20.42	41.65	84.26	72890
14	19100	10000	0.050	3142	2	0	0	1	8.82	24.17	49.48	100.68	73420
16	17947	10000	0.050	3054	2	0	0	1	10.53	28.73	58.73	119.21	73194
18	15005	10000	0.050	2835	2	0	0	1	12.25	32.92	66.96	134.75	72443
20	13623	10000	0.050	2358	2	0	0	1	14.45	39.32	80.32	162.81	73076
24	15640	10000	0.050	2498	2	0	0	1	19.16	52.69	107.97	220.13	73611
Tubesheet													
44	13456	8000	0.040	658	10	0	1	3	0.30	24.52	64.35	104.17	47216

Bolt Yield Stress = 33000 psi (SA193-B8 Class 1)
Kgasket = 230,000 psi/in (Flanges 3" and less)
Kgasket = 200,000 psi/in (Flanges greater than 3")
DGmax = 0.050 in (Flanges)
DGmax = 0.035 in (44" Tubesheet)
Calculation 3004000

TABLE 3-16
300# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 35000 psi
BOLT RELAXATION = 0%
JOINT RELAXATION = 15%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at 25GLP (mg/sec)	Leak Rate at 50GLP (mg/sec)	Leak Rate at 75GLP (mg/sec)	Leak Area at 1.25GLP (sq-in)	Leak Area at 1.50GLP (sq-in)	Leak Area at 1.75GLP (sq-in)	Leak Area at 2.0GLP (sq-in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	19540	9775	0.050	7873	0	0	0	0	0.37	0.73	1.10	1.83	55899
2	21010	9775	0.050	7061	1	0	0	0	0.55	1.09	1.71	2.94	58237
2-1/2	26739	9775	0.050	7930	1	0	0	0	0.76	1.51	2.53	4.23	59620
3	18145	9775	0.050	5277	1	0	0	0	1.04	2.08	3.50	5.85	59820
4	12513	8500	0.050	3450	1	0	0	1	1.45	2.90	5.00	8.28	60351
6	10889	8500	0.050	2624	1	0	0	1	2.45	4.91	8.82	14.68	61565
8	10617	8500	0.050	2291	1	0	0	1	3.60	7.20	13.30	22.44	62446
10	15258	8500	0.050	2761	2	0	0	1	5.23	10.46	20.01	34.31	63666
12	14558	8500	0.050	2588	2	0	0	1	6.59	13.18	25.29	43.41	63779
14	16712	8500	0.050	2749	2	0	0	1	7.72	15.44	29.98	51.75	64243
16	15703	8500	0.050	2672	2	0	0	1	9.22	18.43	35.61	61.33	64045
18	13129	8500	0.050	2480	2	0	0	1	10.72	21.45	40.71	69.57	63388
20	11920	8500	0.050	2063	2	0	0	1	12.64	25.29	48.72	83.81	63942
24	13685	8500	0.050	2186	2	0	0	1	16.76	33.53	65.38	113.06	64410
Tubesheet													
44	11774	5950	0.035	489	20	1	2	5	0.22	0.44	0.66	16.22	35117

Bolt Yield Stress = 33000 psi (SA193-B8 Class 1)
Kgasket = 230,000 psi/in (Flanges 3" and less)
Kgasket = 200,000 psi/in (Flanges greater than 3")
DGmax = 0.050 in (Flanges)
DGmax = 0.035 in (44" Tubesheet)
Calculation 3003515

TABLE 3-17
300# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 35000 psi
BOLT RELAXATION = 0%
JOINT RELAXATION = 25%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at .25GLP (mg/sec)	Leak Rate at .50GLP (mg/sec)	Leak Rate at .75GLP (mg/sec)	Leak Area at 1.25GLP (sq-in)	Leak Area at 1.50GLP (sq-in)	Leak Area at 1.75GLP (sq-in)	Leak Area at 2.0GLP (sq-in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	19540	8625	0.050	7873	0	0	0	0	0.37	0.73	1.10	1.83	55899
2	21010	8625	0.050	7061	1	0	0	0	0.55	1.09	1.71	2.94	58237
2-1/2	26739	8625	0.050	7930	1	0	0	0	0.76	1.51	2.53	4.23	59620
3	18145	8625	0.050	5277	1	0	0	0	1.04	2.08	3.50	5.85	59820
4	12513	7500	0.050	3450	1	0	0	1	1.45	2.90	5.00	8.28	60351
6	10889	7500	0.050	2624	1	0	0	1	2.45	4.91	8.82	14.68	61565
8	10617	7500	0.050	2291	1	0	0	1	3.60	7.20	13.30	22.44	62446
10	15258	7500	0.050	2761	2	0	0	1	5.23	10.46	20.01	34.31	63666
12	14558	7500	0.050	2588	2	0	0	1	6.59	13.18	25.29	43.41	63779
14	16712	7500	0.050	2749	2	0	0	1	7.72	15.44	29.98	51.75	64243
16	15703	7500	0.050	2672	2	0	0	1	9.22	18.43	35.61	61.33	64045
18	13129	7500	0.050	2480	2	0	0	1	10.72	21.45	40.71	69.57	63388
20	11920	7500	0.050	2063	2	0	0	1	12.64	25.29	48.72	83.81	63942
24	13685	7500	0.050	2186	2	0	0	1	16.76	33.53	65.38	113.06	64410
Tubesheet													
44	11774	5250	0.035	432	20	1	2	5	0.02	0.04	0.05	0.07	30986

Bolt Yield Stress = 33000 psi (SA193-B8 Class 1)
Kgasket = 230,000 psi/in (Flanges 3" and less)
Kgasket = 200,000 psi/in (Flanges greater than 3")
DGmax = 0.050 in (Flanges)
DGmax = 0.035 in (44" Tubesheet)
Calculation 3003525

TABLE 3-18
300# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 35000 psi
BOLT RELAXATION = 0%
JOINT RELAXATION = 33%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at .25GLP (mg/sec)	Leak Rate at .50GLP (mg/sec)	Leak Rate at .75GLP (mg/sec)	Leak Area at 1.25GLP (sq-in)	Leak Area at 1.50GLP (sq-in)	Leak Area at 1.75GLP (sq-in)	Leak Area at 2.0GLP (sq-in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	19540	7705	0.050	7873	0	0	0	0	0.37	0.73	1.10	1.83	55899
2	21010	7705	0.050	7061	1	0	0	0	0.55	1.09	1.71	2.94	58237
2-1/2	26739	7705	0.050	7930	1	0	0	0	0.76	1.51	2.53	4.23	59620
3	18145	7705	0.050	5277	1	0	0	0	1.04	2.08	3.50	5.85	59820
4	12513	6700	0.050	3450	1	0	0	1	1.45	2.90	5.00	8.28	60351
6	10889	6700	0.050	2624	1	0	0	1	2.45	4.91	8.82	14.68	61565
8	10617	6700	0.050	2291	1	0	0	1	3.60	7.20	13.30	22.44	62446
10	15258	6700	0.050	2761	2	0	0	1	5.23	10.46	20.01	34.31	63666
12	14558	6700	0.050	2588	2	0	0	1	6.59	13.18	25.29	43.41	63779
14	16712	6700	0.050	2749	2	0	0	1	7.72	15.44	29.98	51.75	64243
16	15703	6700	0.050	2672	2	0	0	1	9.22	18.43	35.61	61.33	64045
18	13129	6700	0.050	2480	2	0	0	1	10.72	21.45	40.71	69.57	63388
20	11920	6700	0.050	2063	2	0	0	1	12.64	25.29	48.72	83.81	63942
24	13685	6700	0.050	2186	2	0	0	1	16.76	33.53	65.38	113.06	64410
Tubesheet													
44	11774	4690	0.035	386	19	1	2	5	0.33	0.66	0.99	1.32	27680

Bolt Yield Stress = 33000 psi (SA193-B8 Class 1)
Kgasket = 230,000 psi/in (Flanges 3" and less)
Kgasket = 200,000 psi/in (Flanges greater than 3")
DGmax = 0.050 in (Flanges)
DGmax = 0.035 in (44" Tubesheet)
Calculation 3003533

TABLE 3-19
300# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 35000 psi
BOLT RELAXATION = 0%
JOINT RELAXATION = 50%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at .25GLP (mg/sec)	Leak Rate at 50GLP (mg/sec)	Leak Rate at .75GLP (mg/sec)	Leak Area at 1.25GLP (sq-in)	Leak Area at 1.50GLP (sq-in)	Leak Area at 1.75GLP (sq-in)	Leak Area at 2.0GLP (sq-in)	Bolt Stress at 2.0GLP (psi)
Flanges:													
1-1/2	19540	5750	0.050	7873	0	0	0	0	0.37	0.73	1.10	1.83	55899
2	21010	5750	0.050	7061	1	0	0	0	0.55	1.09	1.71	2.94	58237
2-1/2	26739	5750	0.050	7930	1	0	0	1	0.76	1.51	2.53	4.23	59620
3	18145	5750	0.050	5277	1	0	0	0	1.04	2.08	3.50	5.85	59820
4	12513	5000	0.050	3450	1	0	0	1	1.45	2.90	5.00	8.28	60351
6	10889	5000	0.050	2624	1	0	0	1	2.45	4.91	8.82	14.68	61565
8	10617	5000	0.050	2291	1	0	0	1	3.60	7.20	13.30	22.44	62446
10	15258	5000	0.050	2761	2	0	1	1	5.23	10.46	20.01	34.31	63666
12	14558	5000	0.050	2588	2	0	1	1	6.59	13.18	25.29	43.41	63779
14	16712	5000	0.050	2749	2	0	1	1	7.72	15.44	29.98	51.75	64243
16	15703	5000	0.050	2672	2	0	1	1	9.22	18.43	35.61	61.33	64045
18	13129	5000	0.050	2480	2	0	0	1	10.72	21.45	40.71	69.57	63388
20	11920	5000	0.050	2063	2	0	0	1	12.64	25.29	48.72	83.81	63942
24	13685	5000	0.050	2186	2	0	1	1	16.76	33.53	65.38	113.06	64410
Tubesheet:													
44	11774	35000	0.035	288	18	1	2	5	0.25	0.49	0.74	0.99	20657

Bolt Yield Stress = 33000 psi (SA193-B8 Class 1)
Kgasket = 230,000 psi/in (Flanges 3" and less)
Kgasket = 200,000 psi/in (Flanges greater than 3")
DGmax = 0.050 in (Flanges)
DGmax = 0.035 in (44" Tubesheet)
Calculation 3003550

TABLE 3-20
300# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 35000 psi
BOLT RELAXATION = 10%
JOINT RELAXATION = 25%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at 25GLP (mg/sec)	Leak Rate at 50GLP (mg/sec)	Leak Rate at 75GLP (mg/sec)	Leak Area at 1.25GLP (sq-in)	Leak Area at 1.50GLP (sq-in)	Leak Area at 1.75GLP (sq-in)	Leak Area at 2.0GLP (sq-in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	17586	8625	0.050	7085	0	0	0	0	0.33	0.66	0.99	1.49	53809
2	18909	8625	0.050	6355	0	0	0	0	0.49	0.98	1.47	2.45	55914
2-1/2	24065	8625	0.050	7137	1	0	0	0	0.68	1.36	2.04	3.55	57158
3	16330	8625	0.050	4750	1	0	0	0	0.94	1.87	2.81	4.91	57338
4	11262	7500	0.050	3105	1	0	0	1	1.31	2.61	4.01	6.96	57816
5	9800	7500	0.050	2362	1	0	0	1	2.21	4.42	7.16	12.15	58909
6	9555	7500	0.050	2062	1	0	0	1	3.24	6.48	10.86	18.18	59702
10	13732	7500	0.050	2485	2	0	0	1	4.71	9.41	16.46	27.10	60799
12	13102	7500	0.050	2329	2	0	0	1	5.93	11.86	20.82	34.27	60901
14	15041	7500	0.050	2474	2	0	0	1	6.95	13.90	24.75	41.04	61319
16	14133	7500	0.050	2405	2	0	0	1	8.30	16.59	29.37	48.55	61140
18	11816	7500	0.050	2232	2	0	0	1	9.65	19.30	33.45	55.25	60549
20	10728	7500	0.050	1857	2	0	0	1	11.38	22.76	40.15	66.27	61047
24	12317	7500	0.050	1967	2	0	0	1	15.09	30.18	54.02	89.81	61469
Tubesheet													
44	10597	5250	0.035	432	20	1	2	5	0.19	0.39	0.58	0.78	30986

Bolt Yield Stress = 33000 psi (SA193-B8 Class 1)
Kgasket = 230,000 psi/in (Flanges 3" and less)
Kgasket = 200,000 psi/in (Flanges greater than 3")
DGmax = 0.050 in (Flanges)
DGmax = 0.035 in (44" Tubesheet)
Calculation 30035251

TABLE 3-21
300# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 35000 psi
BOLT RELAXATION = 20%
JOINT RELAXATION = 25%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at .25GLP (mg/sec)	Leak Rate at .50GLP (mg/sec)	Leak Rate at .75GLP (mg/sec)	Leak Area at 1.25GLP (sq-in)	Leak Area at 1.50GLP (sq-in)	Leak Area at 1.75GLP (sq-in)	Leak Area at 2.0GLP (sq-in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	15632	8625	0.050	6298	0	0	0	0	0.29	0.59	0.83	1.17	51719
2	16808	8625	0.050	5649	0	0	0	0	0.44	0.87	1.31	1.96	53590
2-1/2	21391	8625	0.050	6344	1	0	0	0	0.60	1.21	1.81	2.87	54696
3	14516	8625	0.050	4222	1	0	0	0	0.83	1.66	2.50	3.97	54856
4	10011	7500	0.050	2760	1	0	0	1	1.16	2.32	3.49	5.65	55261
6	8711	7500	0.050	2099	1	0	0	1	1.96	3.93	5.89	9.93	56252
8	8493	7500	0.050	1833	1	0	0	1	2.88	5.76	8.64	14.93	56957
10	12206	7500	0.050	2209	2	0	0	1	4.18	8.37	12.92	22.37	57933
12	11647	7500	0.050	2070	2	0	0	1	5.27	10.54	16.35	28.26	58023
14	13370	7500	0.050	2199	2	0	0	1	6.18	12.35	19.52	33.47	58394
16	12563	7500	0.050	2138	2	0	0	1	7.37	14.75	23.12	39.78	58236
18	10503	7500	0.050	1984	2	0	0	1	8.58	17.16	26.18	45.56	57710
20	9536	7500	0.050	1651	2	0	0	1	10.11	20.23	31.59	54.43	58153
24	10948	7500	0.050	1749	2	0	0	1	13.41	26.82	42.66	72.96	58528
Tubesheet													
44	9419	5250	0.035	432	20	1	2	5	0.19	0.39	0.58	0.78	30986

Bolt Yield Stress = 33000 psi (SA193-B8 Class 1)
Kgasket = 230,000 psi/in (Flanges 3" and less)
Kgasket = 200,000 psi/in (Flanges greater than 3")
DGmax = 0.050 in (Flanges)
DGmax = 0.035 in (44" Tubesheet)
Calculation 30035252

TABLE 3-22
300# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 35000 psi
JOINT RELAXATION = 0%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at .25GLP (mg/sec)	Leak Rate at .50GLP (mg/sec)	Leak Rate at .75GLP (mg/sec)	Leak Area at 1.25GLP (sq-in)	Leak Area at 1.50GLP (sq-in)	Leak Area at 1.75GLP (sq-in)	Leak Area at 2.0GLP (sq-in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	19540	11500	0.050	7873	0	0	0	0	0.37	0.73	1.48	2.36	55899
2	21010	11500	0.050	7061	1	0	0	0	0.55	1.13	2.36	3.92	58237
2-1/2	26739	11500	0.050	7930	1	0	0	0	0.76	1.67	3.38	5.72	59820
3	18145	11500	0.050	5277	1	0	0	0	1.04	2.31	4.66	7.92	59820
4	12513	10000	0.050	3450	1	0	0	1	1.45	3.30	6.58	11.25	60351
6	10889	10000	0.050	2624	1	0	0	1	2.45	5.83	11.38	20.24	61565
8	10617	10000	0.050	2291	1	0	0	1	3.60	8.80	17.08	31.64	62446
10	15258	10000	0.050	2761	2	0	0	1	5.23	13.25	26.08	49.63	63666
12	14558	10000	0.050	2588	2	0	0	1	6.59	16.74	32.99	62.94	63779
14	16712	10000	0.050	2749	2	0	0	1	7.72	19.86	39.31	75.66	64243
16	15703	10000	0.050	2672	2	0	0	1	9.22	23.58	46.60	89.36	64045
18	13129	10000	0.050	2480	2	0	0	1	10.72	26.95	52.89	100.11	63388
20	11920	10000	0.050	2063	2	0	0	1	12.64	32.26	63.68	121.87	63942
24	13685	10000	0.050	2186	2	0	0	1	16.76	43.30	85.87	165.76	64410
Tubesheet													
44	11774	7000	0.035	576	21	1	2	6	0.26	31.42	66.27	101.11	41314

Bolt Yield Stress = 27500 psi (SA193-B8 Class 1)
 Gasket = 230,000 psi/in (Flanges 3" and less)
 Gasket = 200,000 psi/in (Flanges greater than 3")
 DGmax = 0.050 in (Flanges)
 DGmax = 0.035 in (44" Tubesheet)
 Calculation 3003500Y

TABLE 3-23
600# ANSI FLANGE AND GASKET DATA

Flange Diameter (in)	*-----GASKET-----*				Pressure Area (sq in)	*-----BOLTS-----*			
	OD (in)	ID (in)	Width (in)	Area (sq in)		Number	Diameter (in)	Area (sq in)	Length (in)
Flanges									
1-1/2	2.750	2.125	0.3125	2.393	3.547	4	3/4	0.3340	2.375
2	3.375	2.750	0.3125	3.007	5.940	8	5/8	0.2256	2.625
2-1/2	3.875	3.250	0.3125	3.497	8.296	8	3/4	0.3340	2.875
3	4.750	4.000	0.3750	5.154	12.566	8	3/4	0.3340	3.125
4	5.875	4.750	0.5625	9.388	17.721	8	7/8	0.4612	3.625
6	8.250	6.875	0.6875	16.334	37.122	12	1	0.6051	4.375
8	10.375	8.875	0.7500	22.678	61.862	12	1-1/8	0.7896	5.000
10	12.500	10.813	0.8438	30.897	91.821	16	1-1/4	0.9985	5.625
12	14.750	12.875	0.9375	40.681	130.192	20	1-1/4	0.9985	5.875
14	16.000	14.250	0.8750	41.577	159.485	20	1-3/8	1.2319	6.125
16	18.250	16.250	1.0000	54.192	207.394	20	1-1/2	1.4899	6.625
18	20.750	18.500	1.1250	69.360	268.803	20	1-5/8	1.7723	7.125
20	22.750	20.500	1.1250	76.429	330.064	24	1-5/8	1.7723	7.625
24	27.000	24.750	1.1250	91.450	481.105	24	1-7/8	2.4107	8.625

Bolt areas correspond to tensile stress area and not thread root area which is the basis for the bolt torque values
(Reference 14)

TABLE 3-24
600# FLANGE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

INITIAL BOLT STRESS = 35000 psi

BOLT RELAXATION = 10%

JOINT RELAXATION = 25%

Flange Diameter (in)	Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Rate at .25GLP (mg/sec)	Leak Rate at .50GLP (mg/sec)	Leak Rate at .75GLP (mg/sec)	Leak Area at 1.25GLP (sq-in)	Leak Area at 1.50GLP (sq-in)	Leak Area at 1.75GLP (sq-in)	Leak Area at 2.0GLP (sq-in)	Bolt Stress at 2.0GLP (psi)
Flanges													
1-1/2	17586	8625	0.050	7085	0	0	0	0	0.42	0.83	1.25	1.89	53809
2	18909	8625	0.050	6355	0	0	0	0	0.64	1.29	1.93	3.21	55914
2-1/2	24065	8625	0.050	7137	1	0	0	0	0.87	1.74	2.61	4.54	57158
3	16330	8625	0.050	4750	1	0	0	0	1.17	2.34	3.51	6.14	57338
4	12380	8625	0.050	4287	0	0	0	0	1.52	3.04	4.56	7.49	55591
6	14003	8625	0.050	4279	1	0	0	0	2.77	5.55	8.32	14.33	56875
8	13161	8625	0.050	3530	1	0	0	0	4.25	8.50	13.20	22.80	58050
10	16288	8625	0.050	4101	1	0	0	0	5.92	11.84	18.87	32.24	58569
12	15463	8625	0.050	3681	1	0	0	0	7.46	14.92	24.26	41.12	59001
14	18666	8625	0.050	3860	1	0	0	0	8.87	17.74	30.07	50.10	59986
16	17320	8625	0.050	3588	1	0	0	0	10.93	21.87	37.06	61.76	59974
18	16098	8625	0.050	3302	1	0	0	0	13.41	26.83	45.58	75.88	60039
20	17531	8625	0.050	3296	1	0	0	0	16.16	32.32	56.05	92.56	60577
24	19929	8625	0.050	3183	1	0	0	0	22.63	45.26	81.03	132.16	61469

Bolt Yield Stress = 33000 psi (SA193-B8 Class 1)

Kgasket = 230,000 psi/in

DGrax = 0.050 in

Calculation 60035251

TABLE 3-25
2"-150# FLANGE LEAK RATE AND LEAK AREA FOR MORE PRECISE EVALUATION

FLANGE DIAMETER = 2 in
INITIAL BOLT STRESS = 25000 psi
JOINT RELAXATION = 25%

Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Pressure (psi)	Bolt Stress (psi)	Bolt Delta L (in)	Gasket Stress (psi)	Leak Rate (mg/sec)	Leak Area (sq in)
7181	7181	0.040	100	19086	0.000021	7058	0	0.00
7181	7181	0.040	200	19421	0.000043	6934	0	0.00
7181	7181	0.040	300	19757	0.000064	6811	0	0.00
7181	7181	0.040	400	20093	0.000085	6687	0	0.00
7181	7181	0.040	500	20428	0.000106	6563	0	0.00
7181	7181	0.040	600	20764	0.000128	6440	0	0.00
7181	7181	0.040	700	21100	0.000149	6316	0	0.00
7181	7181	0.040	800	21435	0.000170	6193	0	0.00
7181	7181	0.040	900	21771	0.000192	6069	0	0.00
7181	7181	0.040	1000	22107	0.000213	5946	0	0.00
7181	7181	0.040	1100	22442	0.000234	5822	0	0.00
7181	7181	0.040	1200	22778	0.000255	5699	0	0.00
7181	7181	0.040	1300	23114	0.000277	5575	0	0.00
7181	7181	0.040	1400	23450	0.000298	5452	0	0.00
7181	7181	0.040	1500	23785	0.000319	5328	0	0.00
7181	7181	0.040	1600	24121	0.000341	5205	0	0.00
7181	7181	0.040	1700	24457	0.000362	5081	1	0.00
7181	7181	0.040	1800	24792	0.000383	4958	1	0.00
7181	7181	0.040	1900	25128	0.000404	4834	1	0.00
7181	7181	0.040	2000	25464	0.000426	4711	1	0.00
7181	7181	0.040	2100	25799	0.000447	4587	1	0.00
7181	7181	0.040	2200	26135	0.000468	4464	1	0.00
7181	7181	0.040	2300	26471	0.000490	4340	1	0.00
7181	7181	0.040	2400	26806	0.000511	4217	1	0.00
7181	7181	0.040	2500	27142	0.000532	4093	1	0.00
7181	7181	0.040	2600	27478	0.000553	3970	1	0.00
7181	7181	0.040	2700	27813	0.000575	3846	1	0.00
7181	7181	0.040	2800	28149	0.000596	3722	1	0.00
7181	7181	0.040	2900	28485	0.000617	3599	1	0.00
7181	7181	0.040	3000	28820	0.000639	3475	1	0.00

Bolt Yield Stress = 33,000 psi (SA193-B8 Class 1)

Kgasket = 228,000 psi/in

DGmax = 0.050 in

Calculation 1502525B

TABLE 3-26
4"-150# FLANGE LEAK RATE AND LEAK AREA FOR MORE PRECISE EVALUATION

FLANGE DIAMETER = 4 in
INITIAL BOLT STRESS = 25000 psi
JOINT RELAXATION = 25%

Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Pressure (psi)	Bolt Stress (psi)	Bolt Delta L (in)	Gasket Stress (psi)	Leak Rate (mg/sec)	Leak Area (sq in)
5344	5344	0.040	100	19196	0.000034	5161	0	0.00
5344	5344	0.040	200	19642	0.000069	4978	0	0.00
5344	5344	0.040	300	20088	0.000103	4795	1	0.00
5344	5344	0.040	400	20534	0.000137	4612	1	0.00
5344	5344	0.040	500	20980	0.000172	4429	1	0.00
5344	5344	0.040	600	21426	0.000206	4246	1	0.00
5344	5344	0.040	700	21872	0.000240	4063	2	0.00
5344	5344	0.040	800	22318	0.000275	3880	2	0.00
5344	5344	0.040	900	22764	0.000309	3698	2	0.00
5344	5344	0.040	1000	23211	0.000343	3515	2	0.00
5344	5344	0.040	1100	23657	0.000378	3332	3	0.00
5344	5344	0.040	1200	24103	0.000412	3149	3	0.00
5344	5344	0.040	1300	24549	0.000446	2966	4	0.00
5344	5344	0.040	1400	24995	0.000481	2783	4	0.00
5344	5344	0.040	1500	25441	0.000515	2600	5	0.00
5344	5344	0.040	1600	25887	0.000549	2417	5	0.00
5344	5344	0.040	1700	26333	0.000584	2234	6	0.00
5344	5344	0.040	1800	26779	0.000618	2051	7	0.00
5344	5344	0.040	1888.7	27175	0.000649	1888.7	8	0.00
5344	5344	0.040	1900	27298	0.000658	—	8	0.00
5344	5344	0.040	2000	28386	0.000742	—	8	0.00
5344	5344	0.040	2100	29474	0.000826	—	8	0.00
5344	5344	0.040	2200	30562	0.000909	—	8	0.00
5344	5344	0.040	2300	31649	0.000993	—	8	0.01
5344	5344	0.040	2400	32737	0.001077	—	8	0.01
5344	5344	0.040	2424.1	33000	0.001097	—	8	0.01
5344	5344	0.040	2500	33825	0.006590	—	8	0.10
5344	5344	0.040	2600	34913	0.013830	—	8	0.22
5344	5344	0.040	2700	36001	0.021070	—	8	0.34
5344	5344	0.040	2800	37089	0.028311	—	8	0.47
5344	5344	0.040	2900	38177	0.035551	—	8	0.59
5344	5344	0.040	3000	39265	0.042791	—	8	0.71

Bolt Yield Stress = 33,000 psi (SA 193-B8 Class 1)

Gasket = 170,000 psi/in

DGmax = 0.050 in

Calculation 1502525E

TABLE 3-27

8"-150# FLANGE LEAK RATE AND LEAK AREA FOR MORE PRECISE EVALUATION

FLANGE DIAMETER = 8 in

INITIAL BOLT STRESS = 25000 psi

JOINT RELAXATION = 25%

Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Pressure (psi)	Bolt Stress (psi)	Bolt Delta L (in)	Gasket Stress (psi)	Leak Rate (mg/sec)	Leak Area (sq in)
3089	3089	0.031	100	19197	0.000040	2754	7	0.03
3089	3089	0.031	200	19643	0.000081	2418	17	0.00
3089	3089	0.031	300	20090	0.000121	2083	28	0.00
3089	3089	0.031	400	20536	0.000162	1748	43	0.00
3089	3089	0.031	500	20983	0.000202	1413	64	0.00
3089	3089	0.031	600	21430	0.000243	1078	94	0.00
3089	3089	0.031	700	21876	0.000283	743	148	0.00
3089	3089	0.031	709.8	21920	0.000287	709.808	156	0.00
3089	3089	0.031	800	24158	0.000490	—	156	0.01
3089	3089	0.031	900	26639	0.000715	—	156	0.01
3089	3089	0.031	1000	29120	0.000939	—	156	0.02
3089	3089	0.031	1100	31601	0.001164	—	156	0.03
3089	3089	0.031	1156.4	33000	0.001291	—	156	0.03
3089	3089	0.031	1200	34082	0.003764	—	156	0.29
3089	3089	0.031	1300	36563	0.029190	—	156	0.88
3089	3089	0.031	1400	39044	0.048617	—	156	1.48
3089	3089	0.031	1500	41526	0.073836	—	156	2.25
3089	3089	0.031	1600	44007	0.104990	—	156	3.20
3089	3089	0.031	1700	46488	0.138827	—	156	4.23
3089	3089	0.031	1800	48969	0.182355	—	156	5.56
3089	3089	0.031	1900	51450	0.225884	—	156	6.89
3089	3089	0.031	2000	53931	0.270916	—	156	8.26
3089	3089	0.031	2100	56412	0.327719	—	156	10.00
3089	3089	0.031	2200	58893	0.384521	—	156	11.73
3089	3089	0.031	2300	61375	0.441323	—	156	13.47
3089	3089	0.031	2400	63856	0.510466	—	156	15.58
3089	3089	0.031	2500	66337	0.586949	—	156	17.91
3089	3089	0.031	2600	68818	0.663433	—	156	20.25
3089	3089	0.031	2700	71299	0.739916	—	156	22.58
3089	3089	0.031	2800	73780	0.834971	—	156	25.48
3089	3089	0.031	2900	76261	0.952226	—	156	29.06
3089	3089	0.031	3000	78742	1.096642	—	156	33.47

Bolt Yield Stress = 33,000 psi (SA193-B8 Class 1)

Kgasket = 99,300 psi/in

DGmax = 0.050 in

Calculation 1502525G

TABLE 3-28
16"-150# FLANGE LEAK RATE AND LEAK AREA FOR MORE PRECISE EVALUATION

FLANGE DIAMETER = 16 in
INITIAL BOLT STRESS = 25000 psi
JOINT RELAXATION = 25%

Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Pressure (psi)	Bolt Stress (psi)	Bolt Delta L (in)	Gasket Stress (psi)	Leak Rate (mg/sec)	Leak Area (sq in)
4434	4434	0.031	100	18750	0.000000	3904	1	0.00
4434	4434	0.031	200	18750	0.000000	3374	2	0.00
4434	4434	0.031	300	18750	0.000000	2843	4	0.00
4434	4434	0.031	400	18750	0.000000	2313	6	0.00
4434	4434	0.031	500	18750	0.000000	1783	9	0.00
4434	4434	0.031	600	18750	0.000000	1253	15	0.00
4434	4434	0.031	700	18750	0.000000	722	27	0.00
4434	4434	0.031	703.6	18750	0.000000	703.6	27	0.00
4434	4434	0.031	800	20912	0.000245	—	27	0.01
4434	4434	0.031	900	23154	0.000499	—	27	0.03
4434	4434	0.031	1000	25397	0.000753	—	27	0.04
4434	4434	0.031	1100	27639	0.001006	—	27	0.05
4434	4434	0.031	1200	29881	0.001260	—	27	0.07
4434	4434	0.031	1300	32123	0.001514	—	27	0.08
4434	4434	0.031	1339.1	33000	0.001613	—	27	0.09
4434	4434	0.031	1400	34365	0.014975	—	27	0.82
4434	4434	0.031	1500	36607	0.036920	—	27	2.02
4434	4434	0.031	1600	38850	0.058964	—	27	3.21
4434	4434	0.031	1700	41092	0.085486	—	27	4.67
4434	4434	0.031	1800	43334	0.120678	—	27	6.59
4434	4434	0.031	1900	45576	0.155870	—	27	8.51
4434	4434	0.031	2000	47818	0.202709	—	27	11.06
4434	4434	0.031	2100	50060	0.251879	—	27	13.75
4434	4434	0.031	2200	52303	0.301049	—	27	16.43
4434	4434	0.031	2300	54545	0.356202	—	27	19.44
4434	4434	0.031	2400	56787	0.420367	—	27	22.95
4434	4434	0.031	2500	59029	0.484531	—	27	26.45
4434	4434	0.031	2600	61271	0.548695	—	27	29.95
4434	4434	0.031	2700	63513	0.624890	—	27	34.11
4434	4434	0.031	2800	65755	0.711287	—	27	38.83
4434	4434	0.031	2900	67998	0.797683	—	27	43.54
4434	4434	0.031	3000	70240	0.884079	—	27	48.26

Bolt Yield Stress = 33,000 psi (SA193-B8 Class 1)
Kgasket = 143,000 psi/in
DGimax = 0.050 in
Calculation 1502525K

TABLE 3-29

24"-150# FLANGE LEAK RATE AND LEAK AREA FOR MORE PRECISE EVALUATION

FLANGE DIAMETER = 24 in

INITIAL BOLT STRESS = 25000 psi

JOINT RELAXATION = 25%

Eff Gasket Stress (psi)	Act Gasket Stress (psi)	Gasket Deflect. (in)	Pressure (psi)	Bolt Stress (psi)	Bolt Delta L (in)	Gasket Stress (psi)	Leak Rate (mg/sec)	Leak Area (sq in)
4215	4215	0.031	100	18750	0.000000	3656	1	0.00
4215	4215	0.031	200	18750	0.000000	3098	3	0.00
4215	4215	0.031	300	18750	0.000000	2540	6	0.00
4215	4215	0.031	400	18750	0.000000	1981	10	0.00
4215	4215	0.031	500	18750	0.000000	1423	15	0.00
4215	4215	0.031	600	18750	0.000000	865	27	0.00
4215	4215	0.031	640.2	18750	0.000000	640.2	37	0.00
4215	4215	0.031	700	20236	0.000215	—	37	0.02
4215	4215	0.031	800	22720	0.000575	—	37	0.05
4215	4215	0.031	900	25204	0.000935	—	37	0.08
4215	4215	0.031	1000	27688	0.001295	—	37	0.11
4215	4215	0.031	1100	30172	0.001655	—	37	0.13
4215	4215	0.031	1200	32656	0.002015	—	37	0.16
4215	4215	0.031	1213.8	33000	0.002065	—	37	0.17
4215	4215	0.031	1300	35140	0.028875	—	37	2.34
4215	4215	0.031	1400	37624	0.059993	—	37	4.86
4215	4215	0.031	1500	40108	0.091112	—	37	7.39
4215	4215	0.031	1600	42592	0.139565	—	37	11.32
4215	4215	0.031	1700	45076	0.189470	—	37	15.36
4215	4215	0.031	1800	47560	0.252224	—	37	20.45
4215	4215	0.031	1900	50044	0.321951	—	37	26.11
4215	4215	0.031	2000	52528	0.391678	—	37	31.76
4215	4215	0.031	2100	55012	0.473066	—	37	38.36
4215	4215	0.031	2200	57496	0.564056	—	37	45.74
4215	4215	0.031	2300	59980	0.655046	—	37	53.12
4215	4215	0.031	2400	62464	0.748121	—	37	60.67
4215	4215	0.031	2500	64948	0.870637	—	37	70.60
4215	4215	0.031	2600	67432	0.933154	—	37	80.94
4215	4215	0.031	2700	69916	1.115671	—	37	90.47
4215	4215	0.031	2800	72400	1.238187	—	37	100.41
4215	4215	0.031	2900	74884	1.419453	—	37	113.50
4215	4215	0.031	3000	77368	1.607280	—	37	128.69

Bolt Yield Stress = 33,000 psi (SA193-B8 Class 1)

Kgasket = 138,000 psi/in

DGmax = 0.050 in

Calculation 1502525N

FIGURE 3-1
INCREMENTAL GASKET LOAD TO TOTAL PRESSURE LOAD RATIO
FOR 150 TO 600 LB. RATED FLANGES

FIGURE 3-2

TYPICAL LOAD-DEFLECTION DIAGRAM SHOWING A STANDARD TEST SEQUENCE

FIGURE 3-3
A TYPICAL MASS-LEAK-RATE VS. GASKET STRESS PLOT

FIGURE 3-4

GASKET STRESS VS. TIGHTNESS PARAMETER FOR TWO SPIRAL-WOUND ASBESTOS GASKETS,
CYCLIC TESTS WITH WATER

FIGURE 3-5
MASS LEAK RATE VERSUS PRESSURE FOR 8"-150# FLANGE

FIGURE 3-6
LEAK AREA VS. PRESSURE FOR 8"-150# FLANGE

FIGURE 3-7
LEAK AREA VS. PRESSURE FOR 8"-300# FLANGE

4. VALVES

Three failure modes are postulated for the various valves present in the Davis Besse safety systems under consideration. These include failure of the valve body, failure of the stem packing, and failure of the bolted bonnet. Since the valve body thickness is typically greater than that of the adjacent piping (one supplier used 600lb bodies for all valves rated for 600lb service and less), it was judged that failure of the adjacent piping will occur prior to failure of the valve body. Also the types of valve stem packing currently used in most nuclear plants tends to compress under high pressure conditions providing a greater resistance to leakage. Although it is certainly possible that the stem packing for some valves could deteriorate in response to service conditions, it was judged that any resulting leak rate or leak area would be quite small and have a negligible effect on both the valve and system operation. Thus, it was felt that the only credible failure mode for the system valves pertains to failure of the bolted bonnet seal.

The bolted bonnet valves are sealed using Style R spiral wound gaskets compressed between the bonnet and the valve body which are machined in a tongue and groove configuration. According to the valve instruction manual (Reference 20), the valves are to be fitted with high tensile bolts with yield strengths of 100,000 psi or greater. In addition, the bonnet bolts are to be torqued to specified levels which prestress the bolt in the range of 35,000 to 45,000 psi. Preloading of the bolt to the specified levels results in a substantial lock-up force between the bonnet and valve body. Frequently a seal weld is applied to the lip at this junction. The bolted bonnet valves were analyzed in a manner identical to that for the gasketed flange connections with no credit being taken for the seal weld. Table 4-1 provides a list of the typical 150, 300, and 600lb rated valves used in the safety systems under consideration including specific valve details and dimensional data pertaining to the valve gasket and bonnet bolting. Table 4-2 provides a list of typical 1500lb rated valves used in the various systems. All such valves were subjected to hydrostatic test pressure levels above the pressure range of interest. Thus, 1500lb valves were not considered further in the evaluation. Table 4-2 also lists several bonnetless valves which were not considered further.

The calculation of Gross Leak Pressure, mass leak rate, and leak area for important valves is presented in Table 4-3. During extensive discussions with the manufacturer of the 150lb rated diaphragm valves it was found that the manufacturer had conducted failure pressure tests on similar valves with failure occurring at pressures in excess of 8000 psi. Thus,

the gross leak pressure for these valves is simply listed as >3000 psi. The leak areas are calculated for all valves with Gross Leak Pressures less than 2500 psi. The resulting areas are generally small.

TABLE 4-1

BOLTED BONNET VALVE GASKET AND BONNET BOLTING DATA FOR 150LB - 600LB VALVES

Valve Number	Valve Size (in)	Valve Operator	Valve Type	Hydro Test Pressure (psi)	*-----GASKET-----*				*-----BOLTS-----*						
					OD (in)	ID (in)	Width (in)	Area (sq in)	DGI (in)	Number	Diameter (in)	Area (sq in)	Length (in)	Torque (ft-lbs)	Stress (psi)
150# Valves															
RC-115 (G)	3	HW	Diaphragm	338	8.674	6.605	1.035	24.828	--	4	0.625	0.2555	1.500	35.0	15029
RC-118 (G)	3	HW	Diaphragm	338	8.674	6.605	1.035	24.828	--	4	0.625	0.2555	1.500	35.0	15029
RC-1773A(G)	3	AO	Diaphragm	336	8.674	6.605	1.035	24.828	--	4	0.625	0.2555	1.500	35.0	15029
DH-81 (N)	14		Sw. Check	97	15.234	14.563	0.336	15.723	0.050	12	1.000	0.6051	6.750	320.0	36263
MU-10A (N)	3	MO	Gate	213	3.250	2.750	0.250	2.356	0.035	8	0.625	0.2256		74.0	35988
MU-12A (N)	2-1/2	MO	Gate	213	3.250	2.750	0.250	2.356	0.035	8	0.625	0.2256		74.0	35988
MU-91 (G)	3	HW	Diaphragm	213	8.674	6.605	1.035	24.828	--	4	0.625	0.2555	1.500	35.0	15029
MU-95 (N)	3		Sw. Check	213	3.875	3.250	0.313	3.497	0.035	8	0.625	0.2256		74.0	35988
MU-268 (G)	1-1/2	HW	Diaphragm	213	4.750	3.625	0.563	7.400	--	4	0.375	0.0876	1.000	5.0	10437
MU-270 (G)	2-1/2	HW	Diaphragm	213	6.604	5.092	0.756	13.889	--	4	0.500	0.1597	1.313	20.0	17175
MU-3971 (X)	4	MO	3-Way	645	4.250	3.625	0.313	3.866	--	4	0.625	0.2555	1.500	35.0	15029
300# Valves															
HP-10 (N)	6		Sw. Check	645	7.750	7.125	0.313	7.302	0.050	8	0.750	0.3340	4.500	130.0	35586
HP-12 (N)	6	HW	Gate	645	7.469	6.969	0.250	5.670	0.050	8	0.750	0.3340	4.500	130.0	35586
DH-43 (N)	6		Sw. Check	645	7.750	7.125	0.313	7.302	0.050	8	0.750	0.3340	4.500	130.0	35586
DH-45 (N)	6	HW	Gate	645	7.469	6.969	0.250	5.670	0.050	8	0.750	0.3340	4.500	130.0	35586
DH-61 (N)	2-1/2	HW	Globe	645	3.250	2.750	0.250	2.356	0.035	8	0.625	0.2256	2.375	95.0	46201
DH-64 (N)	4	MO	Gate	645	5.656	5.156	0.250	4.246	0.035	8	0.625	0.2256	3.000	95.0	46201
DH-66 (N)	6	HW	Gate	645	7.469	6.969	0.250	5.670	0.050	8	0.750	0.3340	4.500	130.0	35586
DH-68 (N)	6	HW	Gate	645	7.469	6.969	0.250	5.670	0.050	8	0.750	0.3340	4.500	130.0	35586
DH-127 (N)	8	HW	St. Check	645	9.719	9.094	0.313	9.235	0.050	12	0.750	0.3340	5.500	130.0	35586
DH-128 (N)	8		Sw. Check	645	9.875	9.250	0.313	9.388	0.050	8	0.750	0.3340	5.500	130.0	35586
DH-1517 (N)	12	MO	Gate	430	13.940	13.190	0.375	15.981	0.050	12	1.000	0.6051	6.250	316.0	35810
DH-2733 (N)	18	MO	Gate	430	21.875	20.875	0.500	33.576	0.035	24	1.250	0.9985	7.500	650.0	35711
600# Valves															
MU-11 (F)	2-1/2	MO	3-Way	213	3.875	3.250	0.313	3.497	0.035	8	0.750	0.3340		130.0	35586

(G) = Grinnell; (N) = Valen; (X) = Xonox; (F) = Fisher

TABLE 4-2
BOLTED BONNET VALVE GASKET AND BONNET BOLTING DATA
FOR 1500LB VALVES

Valve Number	Valve Size (in)	Valve Operator	Valve Type	Hydro Test Pressure (psi)
1500# Valves				
RC-74 (V)	3	HW	Globe	3550
CF-1B (V)	14	MO	Gate	3187
CF-31 (V)	14		Sw. Check	3125
HP-2D (V)	2-1/2	MO	Globe	2550
HP-22 (V)	4		Sw. Check	2550
HP-24 (V)	4	HW	Gate	2550
HP-32 (R)	1-1/2	MO	St. Check	2550
HP-49 (V)	2-1/2	HW	St. Check	3125
HP-51 (V)	2-1/2		Sw. Check	3125
DH-77 (V)	10	MO	St. Check	3125
MU-2A (V)	2-1/2	MO	Gate	3453
MU-3 (V)	2-1/2	AO	Gate	3453
MU-6 (C)	2	AO	Globe	3187
MU-85 (V)	2-1/2	HW	Gate	3187
Bonnetless Valves				
DH-13B (F)	6	MO	Butterfly	645
DH-14B (F)	10	MO	Butterfly	645
DH-55 (V)	2	HW	Gate	645

(V) = Velan; (R) = Rockwell; (C) = Copes-Vulcan; (F) = Fisher

TABLE 4-3

BOLTED BONNET VALVE GASKET STRESS, GROSS LEAK PRESSURE, AND LEAK RATE

Valve Number	Valve Size (in)	Valve Operator	Valve Type	Eff. Gasket Stress (psi)	Act. Gasket Stress (psi)	Pressure Area (sq in)	Preload Pressure (psi)	Gross Leak Pressure (psi)	Leak Rate at GLP (mg/sec)	Leak Area at 1.25GLP (sq-in)	Leak Area at 1.5GLP (sq-in)	Leak Area at 1.75GLP (sq-in)	Leak Area at 2.0GLP (sq-in)
150# Valves													
RC-115 (G)	3	HW	Diaphragm	619	619	34,264	0	>3000	0				
RC-118 (G)	3	HW	Diaphragm	619	619	34,264	0	>3000	0				
RC-1773A (G)	3	AO	Diaphragm	619	619	34,264	0	>3000	0				
DH-81 (V)	14		Sw. Check	16747	11500	166,557	495	1445	2	0.57	0.66	0.76	0.85
MU-10A (V)	3	MO	Gate	27566	8050	5,940	7742	7829	4				
MU-12A (V)	2-1/2	MO	Gate	27566	8050	5,940	7742	7829	4				
MU-91 (G)	3	HW	Diaphragm	619	619	34,264	0	>3000	0				
MU-95 (V)	3		Sw. Check	18571	8050	8,296	4436	5507	4				
MU-268 (G)	1-1/2	HW	Diaphragm	494	494	10,321	0	>3000	0				
MU-270 (G)	1-1/2	HW	Diaphragm	790	790	20,364	0	>3000	0				
MU-3971 (X)	4	MO	3-Way	3973	3973	10,321	0	2278	0	0.02	0.03	0.03	0.04
300# Valves													
HP-10 (V)	6		Sw. Check	13022	11500	39,871	279	2016	1	0.25	0.28	0.31	0.34
HP-12 (V)	6	HW	Gate	16771	11500	38,142	784	2170	1	0.24	0.27	0.30	0.33
DH-43 (V)	6		Sw. Check	13022	11500	39,871	279	2016	1	0.25	0.28	0.31	0.34
DH-45 (V)	6	HW	Gate	16771	11500	38,142	784	2170	1	0.24	0.27	0.30	0.33
DH-61 (V)	2-1/2	HW	Globe	35389	8050	5,940	10845	8050	4				
DH-64 (V)	4	MO	Gate	19638	8050	20,881	2356	3318	7				
DH-66 (V)	6	HW	Gate	16771	11500	38,142	784	2170	1	0.24	0.27	0.30	0.33
DH-68 (V)	6	HW	Gate	16771	11500	38,142	784	2170	0	0.24	0.27	0.30	0.33
DH-127 (V)	8	HW	St. Check	15445	11500	64,950	561	1923	1	0.33	0.37	0.42	0.47
DH-128 (V)	8	HW	Sw. Check	10128	10128	67,201	0	1242	2	0.31	0.36	0.41	0.45
DH-1517 (V)	12	MO	Gate	16271	11500	136,641	558	1704	1	0.49	0.57	0.65	0.73
DH-2733 (V)	18	MO	Gate	25488	8050	342,250	1711	2277	12	0.54	0.68	0.83	0.98
600# Valves													
MU-11 (F)	2-1/2	MO	3-Way	27187	8050	8,296	8068	8050	4				

(G) = Grinnell; (V) = Velan; (X) = Xonox; (F) = Fisher

Calculation BBVALVES

5. PUMPS

There are three pumps of interest in this analysis; the High Pressure Injection Pump, the Makeup and Seal Water Injection Pump, and the Decay Heat Removal Pump. The first two are multistage high pressure pumps with design pressures of 2000 and 3050 psi, respectively. Both were subjected to hydrostatic test pressures equal to 1.5 times the design pressure. However, the low pressure suction end seal assemblies were only hydrostatically tested to 850 psi. The Decay Heat Removal Pump has a design pressure of 450 psi and the entire pump assembly, including the seals, was subjected to hydrostatic test pressures of 900 psi. A review of the bolted joints and end plate connections indicates that all three pumps are able to withstand pressures of 2500 psi without leakage through any of the bolted connections or "O"-ring seals. Thus, the failure for the pumps is related to leakage through the spring loaded mechanical shaft seals. The main elements of the mechanical seals are a rotating face usually made of carbon and a stationary face usually made of tungsten carbide or ceramic. Based on extensive discussions with the seal manufacturer, it was found that the rotating seal would maintain its structural integrity to pressures in excess of 2500 psi. In addition, the seal face loading spring has sufficient stiffness and strength to maintain contact between the two face elements for pressures in excess of 2500 psi. The mechanical seals are designed to withstand a pressure of 1200 to 1250 psi without leaking. At greater pressures, the rotating face begins to distort creating a rotation at the contact surface. At 2500 psi the rotation is three times the maximum allowable value. Thus, it is recommended that the potential for leakage through the pump seals be characterized assuming a nominal leak rate of 100 to 200 mg/sec together with an uncertainty variability of about 0.20.

REFERENCES

1. Harvey, P. D. Ed., **Engineering Properties of Steel**, American Society for Metals, Metals Park, Ohio, 1985.
2. Weiss, V. and J. G. Sessler, Eds., **Aerospace Structural Metals Handbook, Vol. I: Ferrous Alloys**, ASD-TDR-67-741, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, March 1963.
3. Manjoine, M. H., **Ductility Indices at Elevated Temperature**, J. Engineering Materials and Technology, Trans. ASME, Vol. 97, Series H, No. 2, 1975 pp. 156-161.
4. **Metals Handbook, Vol. 1, Properties and Selection: Iron and Steel**, 8th Ed., American Society for Metals, Metals Park, Ohio, 1961.
5. Galletly, G. D., **Elastic and Elastic-Plastic Buckling of Internally Pressurized 2:1 Ellipsoidal Shells**, Trans. of the ASME, Journal of Pressure Vessel Technology, Vol. 100, November 1978, pp. 335-343.
6. Galletly, G. D. and R. W. Aylward, **Plastic Collapse and Controlling Failure Pressures of Thin 2:1 Ellipsoidal Shells Subjected to Internal Pressure**, Trans. of the ASME, Journal of Pressure Vessel Technology, Vol. 101, February 1979, pp. 64-71.
7. Galletly, G. D. and S. K. Radhamohan, **Elastic-Plastic Buckling of Internally Pressurized Thin Torispherical Shells**, Trans. of the ASME, Journal of Pressure Vessel Technology, Vol. 101, August 1979, pp. 216-225.
8. Radhamohan, S. K., and G. D. Galletly, **Plastic Collapse of Thin Internally Pressurized Torispherical Shells**, Trans. of the ASME, Journal of Pressure Vessel Technology, Vol. 101, November 1979, pp. 311-320.
9. Bushnell, D., **BOSOR 5 - Program for Buckling of Elastic-Plastic Shells of Revolution Including Large Deflections and Creep**, Computers and Structures, Vol. 6, 1976, pp. 221-239.
10. Greimann, L. G., F. Fanous, A. Wold-Tinsae, D. Kelalaar, T. Lin, and D. Bluhn, **Reliability Analysis of Steel Containment Strength**, USNRC NUREG/CR-2442, June 1982.
11. Kumar, V., M. D. German, and C. F. Shih, **An Engineering Approach for Elastic-Plastic Fracture Analysis**, prepared for Electric Power Research Institute, NP-1931, Research Project 1237-1, July 1981.
12. Piping Class Sheets, Davis-Besse Plant Design Standard 12501-M-601, Rev. 16, Bechtel Associates Professional Corporation.
13. Piping Class Summary, Davis-Besse Plant Design Standard 12501-M-602, Rev. 25, Bechtel Associates Professional Corporation.

14. Technical Specification for Field Fabrication and Installation of ASME Section III and Safety-Related B31.1 Piping, Davis-Besse Technical Specification 12501-M-453Q, Rev. 2, Bechtel Associates Professional Corporation.
15. Bazergui, A. and L. Marchand, **PVRC Milestone Gasket Tests - First Results, Bulletin 292**, Welding Research Council, New York, NY, February 1984.
16. Bazergui, A., L. Marchand, and H. Raut, **Development of A Production Test Procedure for Gaskets Bulletin 309**, Welding Research Council, New York, NY, November 1985.
17. Bazergui, A., L. Marchand, and H. Raut, **Further Gasket Leakage Behavior Trends, Bulletin 325**, Welding Research Council, New York, NY, July 1987.
18. Bazergui, A., **Short Term Creep and Relaxation Behavior of Gaskets, Bulletin 294**, Welding Research Council, New York, NY, May 1984.
19. MIL-G-21032E, **Military Specification for Metallic-Asbestos, Spiral Wound Gaskets**, through Amendment 2, 18 May 1979.
20. **Instruction Manual for Installation, Operation, and Maintenance of VELAN Manual Operated Bolted Bonnet Gate, Globe, Stop Check, and Check Valves**, Manual VEL-HO-1, Velan Engineering Companies, Montreal, Quebec, Canada.
21. **Algor Finite Element System**, Algor Interactive Systems, Inc., Pittsburgh, PA, 1989.

BIBLIOGRAPHIC DATA SHEET

(See instructions on the reverse)

1. REPORT NUMBER
(Assigned by NRC. Add Vol., Supp., Rev.,
and Addendum Numbers, if any.)

NUREG/CR-5603
EGG-2607

2. TITLE AND SUBTITLE

Pressure-Dependent Fragilities for Piping Components:
Pilot Study on Davis-Besse Nuclear Power Station

3. DATE REPORT PUBLISHED

MONTH YEAR

October 1990

4. FIN OR GRANT NUMBER

B5699

5. AUTHOR(S)

D.A. Wesley, T.R. Kipp, D.K. Nakaki, H. Hadidi-Tamjed

6. TYPE OF REPORT

Technical

7. PERIOD COVERED (Inclusive Dates)

8. PERFORMING ORGANIZATION - NAME AND ADDRESS (If NRC, provide Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address; if contractor, provide name and mailing address.)

ABB Impell Corporation
27401 Los Altos, Suite 480
Mission Viejo, CA 92691

Under contract to:
Idaho National Engineering Laboratory
EG&G Idaho, Inc.
Idaho Falls, ID 83415

9. SPONSORING ORGANIZATION - NAME AND ADDRESS (If NRC, type "Same as above"; if contractor, provide NRC Division, Office or Region, U.S. Nuclear Regulatory Commission, and mailing address.)

Division of Safety Issue Resolution
Office of Nuclear Regulatory Research
U.S. Regulatory Commission
Washington, D.C. 20555

10. SUPPLEMENTARY NOTES

11. ABSTRACT (200 words or less)

The capacities of four, low-pressure fluid systems to withstand pressures and temperatures above the design levels were established for the Davis-Besse Nuclear Power Station. The results will be used in evaluating the probability of plant damage from Interfacing System Loss of Coolant Accidents (ISLOCA) as part of the probabilistic risk assessment of the Davis-Besse nuclear power station undertaken by EG&G Idaho, Inc. Included in this evaluation are the tanks, heat exchangers, filters, pumps, valves, and flanged connections for each system. The probabilities of failure, as a function of internal pressure, are evaluated as well as the variabilities associated with them. Leak rates or leak areas are estimated for the controlling modes of failure. The pressure capacities for the pipes and vessels are evaluated using limit-state analyses for the various failure modes considered. The capacities are dependent on several factors, including the material properties, modeling assumptions, and the postulated failure criteria. The failure modes for gasketed-flange connections, valves, and pumps do not lend themselves to evaluation by conventional structural mechanics techniques and evaluation must rely primarily on the results from ongoing gasket research test programs and available vendor information and test data.

12. KEY WORDS/DESCRIPTORS (List words or phrases that will assist researchers in locating the report.)

pressure-dependent fragilities
piping components
Interfacing System Loss of Coolant Accidents (ISLOCA)
probabilistic risk assessment
Davis-Besse Nuclear Power Station

13. AVAILABILITY STATEMENT

Unlimited

14. SECURITY CLASSIFICATION

(This Page)

Unclassified

(This Report)

Unclassified

15. NUMBER OF PAGES

16. PRICE

-END-

DATE FILMED

11 / 28 / 90