The Nondestructive Testing Information Analysis Center
415A Crystal Creek Drive
Austin, TX 78746

Development of Accept Reject Criteria for Requalification of High Pressure Steel and Aluminum Cylinders

FINAL REPORT

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Mark Toughiry
Office of Hazardous Materials Technology
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1.0 INTRODUCTION

Objective - The objective of this study is to establish a sound technical basis for developing quantitative, "maximum allowable flaw sizes" and for setting acceptance/rejection limits for the cylinders at the time of retesting that are based on the performance of the cylinders.

Background - Seamless steel and aluminum cylinders that are used to transport high pressure gases, are required to meet safety regulation promulgated by the U.S. Department of Transportation (DOT) and other national authorities [1]. These safety regulations cover the design, materials, manufacturing, testing and retesting of the cylinders. As part of these safety regulations the cylinders are required to be periodically retested during their lifetime.

Retesting has traditionally been done by a combination of visual inspection (inside and outside), hydrostatic pressure testing, and volumetric expansion during pressurization. Using these traditional methods of retesting, the cylinders were rejected due to: leaking, bursting, excessive volumetric expansion, or excessively large surface flaws detected by visual examination [2], [3]. Excessive volumetric expansion was attributed to large areas of the cylinder wall being reduced in thickness due to general corrosion and or softening of the material due to exposure to heat. The maximum allowable size of surface flaws to cause rejection of the cylinders was essentially qualitative and was established from past service experience. None of the rejection criteria were based on quantitative assessments of the cylinder performance.

More recently, methods of retesting the cylinders by ultrasonic methods have been developed. These new retesting methods permit the quantitative determination of the cylinder wall thickness and the size of flaws that are detected in the cylinders. The U.S. DOT safety regulations permits the use of ultrasonic examination under exemption for retesting steel and aluminum cylinders. These ultrasonic test methods permit the quantitative determination of the size of any flaws that are present in the cylinders. However, to use these ultrasonic test methods it is required that quantitative, "maximum allowable flaw sizes" be established to set acceptance/rejection limits for the cylinders at the time of retesting.

1.1 **Technical Approach**

In this study, the performance of selected cylinders was evaluated based on the principle of structural integrity analysis. The effect of various types and sizes of flaws on the performance of seamless steel cylinders was evaluated by analytical modeling that was verified by using data from other studies that involved extensive testing of steel cylinders containing flaws. It should be noted that comparable data from extensive testing of aluminum cylinders is not currently available. Therefore this study is limited to an assessment of flaws in steel cylinders.

The periodic inspection of seamless cylinders requires that "maximum allowable flaw sizes" be established for each type of flaw. Typical flaws that can occur in high-pressure seamless gas cylinders during service are: corrosion pits, line corrosion, gouge, local thin areas of corrosion, and cracks. To establish "maximum allowable flaw sizes," an assessment of typical flaws that occur in seamless cylinders was carried out using the analytical procedures described in the API Recommended Practice 579 Fitness-for-Service" (API 579) [4].

In using these procedures, first the "critical flaw sizes" are determined. The "critical flaw size" is defined as the size (ex. depth and length or area) of the flaw that will cause the cylinders to fail at either the designated test pressure or at the marked service pressure. In this study, the API Recommended Practice 579 "Fitness-for-service" was used to calculate the "critical flaw sizes" for a range of cylinder sizes and strength levels. Next, the "maximum allowable flaw sizes" are determined by adjusting the "critical flaw sizes" to account for any time-dependent degradation that can occur in service, such as crack growth.

To first determine the "critical flaw sizes" the procedures described in the API 579 were used in this study to predict, by analysis, the effect of various sizes of local thin areas, pits, notches, and cracks on the calculated cylinder burst pressure for selected sizes and strengths levels of cylinders. Then, to verify the API 579 analysis procedures, data from a number of hydrostatic burst tests on selected cylinders with various sizes of flaws were compared with the analytical results. These results showed that the analysis conducted according to API 579 reliably estimated the actual measured burst pressure of the cylinders for all flaw sizes and types.

"Critical flaw sizes" were determined for various types of flaws at (1) the designated service pressure and (2) at the hydrostatic test pressure of the cylinder. This establishes "critical flaw sizes" (depth versus area or length) for each type of flaw in any cylinder. The "critical flaw sizes," calculated at the service pressure, predict the size of flaws that could be expected to cause the cylinder to fail in service. The "critical flaw sizes" calculated at the hydrostatic test pressure, predict the size of flaws that could be expected to cause the cylinder to fail during the traditional hydrostatic pressure test.

After the "critical flaw sizes" to cause failure of the cylinders at both the test pressure and the service pressure were established, the "maximum allowable flaw sizes" that are to be used to establish acceptance or rejection criteria during retesting were established for a wide range of cylinder types and strength levels. This was done by modifying (reducing) the size of the "critical flaw sizes" for each cylinder by adjusting for time dependent degradation, such as fatigue crack growth, stress corrosion, or corrosion that may occur during the use of the cylinder. In this study, only the effects of fatigue crack growth were evaluated. The fatigue cycle that was used in this study to make this adjustment was 3500 cycles (once a day filling for the 10 year retest interval) at the designated test pressure. This results in the "allowable flaw size" criteria that may be used to establish the acceptance or rejection of the cylinders during retesting. The final acceptance or rejection criteria that are used during retesting may also take into account other factors, for example, the capability of the inspection instruments and procedures.

2.0 DEFINITIONS AND NOMENCLATURE

2.1 Cylinder Description

OD = outside cylinder diameter

ID = inside cylinder diameter

a = flaw depth

a_i = initial flaw depth, determined by the allowable flaw size analysis

L = flaw length (Longitudinal dimension of flaw).

A = flaw area

C = circumferential dimension of the flaw

t = minimum wall thickness, in.
t_{mm} = minimum ligament (material below the flaw) thickness, in.

td = design wall thickness

ta = actual wall thickness at the flaw

P_S = cylinder service pressure

P_T = cylinder test pressure

P_b = burst pressure for a cylinder without a flaw

P_f = burst pressure for a cylinder with a flaw

P_f/P_b= burst pressure ratio

2.2 Fitness-for-Service Assessment

Types of flaws:

LTA = Local thin area (may be circular or rectangular area of reduced wall thickness, the length and width are approximately equal)

Crack = two dimensional flaw (length and depth only)

Notch = long, narrow flaw (the width is much smaller than the depth)

Pit = small approximately round flaw

Failure modes:

Leak = release of gas pressure from the cylinder without extension of the flaw
(May occur due the internal pressure or due to corrosion)

Burst = opening of the cylinder due to the internal gas pressure without substantial extension of the flaw

Fracture = opening of the cylinder due to the internal gas pressure with substantial, unstable extension of the flaw

Critical flaw size – the flaw size that causes the cylinder to fail at a designated pressure

Allowable flaw size – the flaw size that will not grow to the critical flaw size at service pressure and before next retest interval

Calculated parameter

RSF = Remaining strength factor = P_f/P_b

Fatigue crack growth (da/dN) = flaw growth amount for each cycle of pressure loading

Failure by Plastic Collapse = failure of the cylinder containing a flaw due to internal pressure in the cylinder by failure of the remaining ligament below the flaw without substantial extension of the flaw

2.3 Cylinder Material Properties

UTS = Ultimate tensile strength

YS = Yield stress

Flow strength = (UTS + Y'S)/2

Fracture toughness = $K_{IC}(J)$ = Fracture toughness from J integral tests, ksi $in^{0.5}$

3.0 MODELING AND ANALYSIS OF FLAW SIZES

Basis and Theory - The approach that was used in this study to define "maximum allowable flaw sizes" for seamless cylinders, was to determine the effect of various types and sizes of flaws on the performance of the cylinders. In particular, the reduction in the failure pressure of the cylinders containing flaws was determined by analytical modeling. These analytical results were then verified by using data from other studies involving the experimental testing of selected cylinders.

To evaluate the significance of flaws in cylinders, the principals of structural integrity analysis are used. Several general theoretical, empirical, or semi-empirical methods of analysis have been developed to model flaws in pressure vessels, such as cylinders, and to evaluate the significance of the flaws[4],[5],and [6]. The purpose of these methods of analysis is to determine how much the failure pressure (p_f) of a cylinder containing a flaw is reduced compared to a similar cylinder that does not contain any flaws (l). Failure of the cylinder may occur by bursting, by fracture, by leaking or other failure modes. These methods of analysis can be used to make an assessment of the current state of the cylinder, that is, the current failure pressure of the cylinder. These methods of analysis can also be used to determine a projected future state of the cylinder due to increases in the size of the flaws over time by such mechanisms as fatigue, corrosion, stress corrosion, or other time dependent degradation.

After reviewing the methods of analysis that have been developed to evaluate the significance of flaws in pressure vessels, the methods of analysis described in the API Recommended Practice 579 "Fitness-for-Service" [4] were chosen to evaluate the cylinders used in this study and to develop "critical flaw sizes" and "maximum allowable flaw sizes" for seamless cylinders. The "Fitness-for-Service" method of analysis provides a quantitative evaluations of cylinders containing flaws to determine their suitability for continued use.

The "Fitness-for-Service" method of analysis can be used to evaluate all types of flaws commonly found in cylinders.

Summary of the "Fitness-for-Service" Method of Analysis - The application of the API 579 "Fitness-for-Service" method of analysis requires the following steps:

(1) identification of the type of flaw (i.e., crack, local thin area, pit, etc.) and the type of damage that caused the flaw (i.e., corrosion, fatigue cracking, cuts, gouges, etc.)

(2) identification of the failure mode (i.e., brittle fracture, burst, leak, etc.)

(3) selection of the specific method of analysis (i.e., fracture analysis, burst analysis, leak analysis, etc.)

(4) obtaining the necessary data (i.e., material properties, applied stresses, flaw characterization and size, etc.)

(5) selection of the level of assessment

(6) selection of the appropriate acceptance criteria

(7) evaluation of the remaining life of cylinder due to enlargement of the flaws.

Each of these steps is briefly described next.

Step 1: The types of flaws that can occur in seamless cylinders have been identified in the Compressed Gas Association (CGA) pamphlet C-6 [3] and in the ISO 6406 standard [7]. The types of flaws that have been identified are:

- Cracks
- Notches
- Gouges
- General Corrosion

- Local corrosion (Local Thin Area – LTA)
- Pitting Corrosion – isolated pits, multiple pits (i.e., line corrosion)
- Arc Burns
- Fire Damage

In this study, the only flaws that will be evaluated are cracks, notches, general and local corrosion.

The types of damage that occur in seamless cylinders to cause the flaws that have been identified are: corrosion (general and local), fatigue cracking, stress corrosion cracking, cuts, gouges, deformation, and fire. In this study, the only types of damage that will be evaluated are corrosion and fatigue cracking.

Step 2: The failure modes that may cause seamless cylinders to fail in service are bursting, leaking, and fracture. Cylinders may fail by bursting when (1) the cylinder wall is reduced by corrosion so that internal pressure causes the wall stress to exceed the strength of the material or (2) a flaw of sufficient size is present in the wall of the cylinder to cause the wall to fail by plastic collapse. In cylinders that fail by bursting, the cylinder generally remains in one piece and the initiating flaw does not extend extensively. Cylinders may fail by leaking when a flaw is present that is sufficiently deep that the remaining wall ruptures or the remaining wall thickness below the flaw fails by corrosion. Cylinders may fail in service by fracturing when the combination of a sufficiently large flaw and a high enough wall stress exceeds the fracture toughness of the cylinder. In cylinders that fail by fracturing, the cylinder may break into many pieces or the initiating flaw may extend greatly in length.

Step 3: Each of the different failure modes can be reliably evaluated by the “Fitness-for-Service” analysis procedures. However, each failure mode (burst, leak, or fracture) must be analyzed by a different analytical model. The selection of which failure mode is most likely to occur depends on the cylinder design, the material properties, and the size of the flaws in the cylinder. In this study, the primary failure mode that was evaluated was failure by bursting due to the internal pressure in the cylinders.

Step 4: The data required to conduct the “Fitness-for-Service” analysis of flaws in cylinders are: (1) the material properties (i.e., yield strength, tensile strength, fracture toughness, etc.), (2) the applied stress due to the pressure in the cylinder, and (3) the size, shape, location of the flaws to be evaluated. In this study, only applied stresses caused by the internal pressure in the cylinders are considered. When exact values of some of the necessary values are not available, the necessary data may have to be assumed or generic data for a typical cylinder may have to be used. The completeness and quality of the available data determines what level of assessment can be carried out.

Step 5: Selection of the level of assessment depends on the available data, on the accuracy of the evaluation that is required, and on the uncertainty in the results that is required. The API 579 methods of analysis permit three levels of assessment depending on the available data and on the accuracy of the evaluation that is required.

The Level 1 assessment requires a minimum amount of data on the flaw size, the applied stress, and the material properties. This level of assessment is the easiest to use but gives the most conservative prediction of the failure pressure of the cylinder. That is, the predicted failure pressure of a cylinder with a specified flaw size is significantly less than the actual measured failure pressure of the flawed cylinder.

The Level 2 assessment requires additional, more detailed data than the Level 1 assessment for the flaw size, the applied stress, and the material properties. This level of assessment uses more complex calculations and gives a more exact (less conservative) prediction of the failure pressure of the cylinder. That is, the predicted failure pressure of a cylinder with a specified flaw size is closer to the actual measured failure pressure of the flawed cylinder.

The flaw size analysis used in this study of seamless cylinders used the Level 2 assessment procedures for all of the cylinders that were analyzed.

The Level 3 assessment requires the use of advanced stress analysis and material modeling procedures and exact measurements of the flaw size. This level of assessment generally results in a precise prediction of the failure pressure of the cylinder. That is, the predicted failure pressure of a cylinder with a specified flaw size is very close to the actual measured failure pressure of the flawed cylinder. However, because of the increased demands for additional data and the increased complexity of the calculations, the Level 3 assessment is only used in very demanding and specialized applications (e.g. nuclear facilities).

Step 6: The next step in using the “Fitness-for-Service” assessment procedures is the choice of the “acceptance criteria.” The “acceptance criteria” is chosen for each specific case that is analyzed. The “acceptance criteria” may be (1) the “maximum allowable stress” (2) the “remaining strength factor,” or (3) the “failure assessment diagram.”

The “maximum allowable stress” criteria are used where the design is based on a specified fraction of the yield strength or tensile strength. This is the criteria used to specify the wall thickness in the design of new cylinders. This criteria has limited use in the “Fitness-for-Service” analysis because suitable maximum allowable stress levels can not easily be established for cylinders containing flaws. The only place where this criterion can be used in cylinders is to evaluate areas of general corrosion where the stress in the remaining wall can be calculated and related to the maximum allowable wall stress.

The “remaining strength factor” (RSF) can be used for the analysis of most types of flaws in cylinders. The RSF is defined as the ratio of the limit load or plastic collapse load of a cylinder containing a flaw to the limit load or plastic collapse load of a cylinder that does not contain flaw. Another way of defining the RSF is the ratio of the failure pressure of a cylinder containing a flaw and the failure pressure of the same cylinder without a flaw. The acceptance criteria are then specified as a fixed value of RSF This was the criteria that was primarily used in this study.

For crack like flaws, it is necessary to use the “failure assessment diagram” criteria. In this criterion, cylinders containing crack like flaws may fail either by unstable fracture or by plastic collapse. Unstable fracture occurs for cylinders with relatively small flaws in cylinders made from brittle materials. Plastic collapse occurs in cylinders with relatively large flaws that are made from high toughness materials. For the cylinders analyzed in this study, any cylinders containing crack like flaws failed by the plastic collapse mechanisms.

Step 7: After an assessment is made of the present state of the cylinder (i.e., the predicted failure pressure of the cylinder) containing a flaw, the “Fitness-for-Service” method of analysis may also be used to make an assessment of the remaining life of the cylinder, if required.

The remaining life assessment is used to account for any increase in the size of existing flaws during the anticipated service, for example by corrosion, fatigue, or stress corrosion. This assessment is used (1) to establish presently “maximum allowable flaw sizes” and (2) to define appropriate retest intervals. An assessment of the effect of fatigue and corrosion on the size of existing flaws in cylinders was made in this study to establish “allowable flaws sizes” for setting retest requirements.

4.0 EXPERIMENTAL RESULTS

As part of a program being conducted by the International Standards Organization (ISO), Technical Committee 58 (TC 58) /Subcommittee 4 (SC 4)/ Working Group 1 (WG 1) on “Rejection Criteria for Metal Cylinders,” steel cylinders containing machined flaws were tested by monotonic or cyclical pressurization until failure occurred by bursting [8]. The results of these tests are shown in Table A-1 of the Appendix to this report.

Most of the cylinders that were tested by monotonic pressurization contained machined flaws on the exterior of the cylinder (OD flaws). A few of the cylinders that were tested by monotonic pressurization had flaws machined on the inside of the cylinder wall (ID flaws). The cylinders that contained OD machined flaws had flaws that simulated notches, round local thin area (LTA), rectangular LTA, and pits (small round flaws). All of the ID machined flaws simulated round LTA type of flaws. The simulated flaws in the cylinders that were tested by cyclical pressurization all had ID notch type flaws. The results of these tests were used (1) to verify that the API 579 methods of analysis can be reliably used to predict the failure pressure of cylinders containing flaws, (2) to verify the calculated “critical flaw sizes” for cylinders, and (3) to verify the calculated “maximum allowable flaw sizes” for cylinders.

As part of a program that was conducted by ISO Technical Committee 58 (TC 58) /Subcommittee 3 (SC 3)/Working Group 14 (WG 14) on “Toughness and acceptance levels of steels of strength levels above 1100 N/mm^2 several hundred monotonic hydrostatic, flawed-cylinder burst tests were conducted to evaluate the fracture performance of a wide range of steel cylinders [9].Each test cylinder had a longitudinal notch type of flaw machined in the exterior wall (OD) of the cylinder. The cylinders tested ranged in tensile strength from 700 MPa to 1400 MPa. The cylinders that were tested were divided into five groups of materials (A through F) based on the tensile strength range of the material. The cylinders ranged in diameter (D) from 140 mm to 240 mm, in wall thickness (t) from 3.8 mm to 14.4 mm, and had flaw sizes (longitudinal machined notches) that ranged in depth from 20% to 90% of the wall thickness and in length from 4 times the cylinder wall thickness to 20 times the cylinder wall thickness.

In the WG-14 test program, all of the cylinders were tested to failure by monotonic pressurization. Selected results of these tests were also used in this study to verify that the API 579 methods of analysis can be reliably used to predict the failure pressure of cylinders containing flaws for a wide range of cylinder sizes and strength levels. The only tests results from the WG-14 program that were selected for this study were tests in which the measured failure pressure was either near the test pressure or near the service pressure of the cylinders. The flaw sizes for the selected test results were compared with the calculated flaw size for failure at either the test pressure or the service pressure. The selected test results of this program that were used are shown in Table A-2 of the appendix of this report.

5.0 VERIFICATION OF THE FLAW SIZE ANALYSIS

The API 579 “Fitness-for-service” method of analysis provides a sound technical basis for evaluating the significance of flaws in any type of pressure vessel. To demonstrate that these methods of analysis could be reliably applied to evaluating flaws in seamless cylinders, a limited number of seamless steel cylinders containing flaws of different types and sizes were tested in another study by hydrostatically testing the cylinders to failure by bursting. To verify that the API 579 method of analysis reliable predicts the performance of cylinders containing flaws, the results of these burst tests were compared in this study with the burst pressure predicted by the API 579 analysis results.

The preliminary analysis showed that the failure of the steel cylinders that were tested could be evaluated by the calculating the remaining strength factor (RSF) for the cylinders containing flaws. For these cylinders, the fracture toughness was sufficiently high that failure of the cylinders containing flaws failed by bursting when the stress in the cylinder wall causes failure by plastic collapse as the internal pressure was increased.

For this verification analysis, both local thin area (LTA) types of flaws and notch type flaws were evaluated. A local thin area type of flaw is one in which the length and width of the flaw are approximately equal. This type of flaw represents a typical area of wall thickness reduction due to corrosion in the cylinder. A notch type of flaw is one, which is V shaped and in which the length of the flaw is many times greater than the width of the flaw. This type of flaw represents a crack like flaw in the cylinder. For the examples analyzed here, the API 579 level 1 assessment method was found to be adequate. The stress in the cylinder wall at the location of the flaw was only caused by the internal pressure in the cylinder.

To verify the use of the API 579 procedures, the remaining strength factor (RSF) was calculated for each of the cylinders that was tested. The remaining strength factor (RSF) defined by API 579 may also be defined as the failure pressure ratio of $P_f/P_{b,}$ where P_f is the failure pressure of the cylinder containing the flaw and P_b is the failure pressure of the same type and size of cylinder that does not contain a flaw.

The RSF or P_f/P_b ratio is calculated as:

$$RSF = \frac{R_t}{1-(\frac{1}{M_t})(1-R_t)} \qquad (1)$$

Where:

M_t = Folias stress magnification factor = $(1 + 0.48\ \lambda^2)$ (2)

$$l = \frac{1.285S}{(Dxt)^{1/2}} \qquad (3)$$

R_t = remaining thickness ratio = t_{mm}/t (4)

The following provides a theoretical background for the above Equation 1.

The failure hoop stress in the presence of a flaw is given by the following Equation 5.

$$\sigma_f = \sigma_{flow/}Mp \quad (5)$$

Where M_p is the stress magnification factor for part through flaw. M_p is given by the following Equation 6.

$$M_P = \frac{1-\frac{a}{tM_t}}{1-\frac{a}{t}} \qquad (6)$$

Where M_t is the stress magnification factor for through wall flaw of length S. M_t can be obtained from Equation 2 given above.

The ratio, σ_f / σ_{flow} is defined as RSF (or P_f/P_b).

Therefore from Equation 5,

$$RSF = \frac{1}{M_p} = \frac{1-\frac{a}{t}}{1-\frac{a}{tM_t}} \qquad (7)$$

$$R_t = t_{mm}/t = (t - a)/t = 1\text{-}a/t \qquad (8)$$

$$\therefore\ a/t = 1 - R_t \quad (9)$$

Substituting a/t in terms of R_t in Equation 7, results in Equation 1

The cylinders used in the verification test program were designed and fabricated in accordance with the rules given in US DOT Exemption 9421[10]. The following provides the Exemption E-9421 cylinder specifications:

Size: ID = 8.75 in.
Design Min. wall thickness = 0.26 in.
Height = 51 in.
Service Pressure (P_s) = 4500 psi
Test Pressure (P_T) = 6750 psi

Material: modified AISI 4130 quenched and tempered steel.

Mechanical Properties:

UTS = 155 – 175 ksi (Typical)
Yield strength = 140 – 160 ksi (Typical)
Elongation (2 in. G.L.) = 12 %
K_{IC} (J) $\geq$ 85 ksi $in^{0.5}$ (@RT in TL Direction)

The test cylinders tested in the verification program were made according to DOT Exemption E-9421; test results are shown in Table 1.

Table 1. Results of Cylinder Tests with Flaws

Cylinder **No. (See Note 1)**	**Flaw Description**	**Measured Min Wall t** in.	**Flaw Length L in.**	**Flaw Width C in.**	**Flaw Depth a in.**	**Burst Pressure Psi**	**Measured RSF (See Note 2)**	**Calculated RSF (See Note 3)**
1	Unflawed burst	0.248	---	---	---	10,050	---	---
2	Unflawed burst	0.278	---	---	---	11,350	---	---
3	Longitudinal notch	0.253	2.53	---	0.026	9,750	0.91	0.95
4	Longitudinal notch	0.271	2.71	---	0.052	9,300	0.87	0.90
5	Longitudinal notch	0.261	2.61	---	0.078	8,850	0.83	0.84
6	Longitudinal notch	0.253	2.53	---	0.104	8,350	0.78	0.77
7	Longitudinal notch	0.269	2.69	---	0.130	8,300	0.78	0.68
8	Longitudinal notch	0.271	2.71	---	0.013	10,700	1.00	0.98
9	Longitudinal notch	0.277	2.77	---	0.026	10,800	1.01	0.95
10	Longitudinal notch	0.267	2.67	---	0.039	10,500	0.98	0.93
11	Rectangular LTA	0.273	2.25	1.75	0.013	10,100	0.94	0.98
12	Rectangular LTA	0.291	2.25	1.75	0.026	10,700	1.00	0.96
13	Rectangular LTA	0.285	2.25	1.75	0.039	10,100	0.94	0.94
14	Rectangular LTA	0.281	2.25	1.75	0.052	9,900	0.93	0.91
15	Rectangular LTA	0.291	2.25	1.75	0.078	10,400	0.97	0.86
16	Rectangular LTA	0.290	2.25	1.75	0.104	9,400	0.88	0.80
17	Rectangular LTA	0.277	2.25	1.75	0.130	8,100	0.76	0.72

Note 1: Cylinder ID = 8.75” Nominal
Note 2: Measured burst pressure with flaw/avg. burst pressure w/o flaw (10700 psi)
Note 3: Calculated RSF using Equation 1

Two cylinders (No. 1 and 2) without flaws were hydrostatically pressurized to burst to establish the burst pressure (P_b) to be used to calculate the measured RSF (or P_f/P_b). Cylinder 1 burst at 10,050 psi pressure and cylinder 2 burst at 11,350 psi pressure. This gives an average burst pressure for an unflawed cylinder of 10,700 ± 350 psi. This value will be used as the denominator to calculate the ratio P_f/P_b which is the measured RSF for the tested cylinders.

Test cylinders numbered 3 through 10 (Table 1) had longitudinal notches machined on the outside surfaces of cylinder. Table 1 shows the length “S” and depth “a” dimensions of the machined notches. The cylinders were hydrostatically pressurized to burst. The measured burst pressure and ratio of the failure pressure of the flawed cylinder to the failure pressure of the unflawed cylinder (P_f/P_b), which is the measured RSF value, are also shown in Table 1. It should be noted that all of the cylinders burst at the machined notches.

Test cylinders numbered 11 through 17 had rectangular LTA’s machined on the outside surfaces of the test cylinders. Table 1 shows the LTA dimensions of the tested cylinders. The cylinders were hydrostatically pressurized to burst. The measured burst pressure and ratio of the failure pressure of the flawed cylinder to the failure pressure of the unflawed cylinder (P_f/P_b), which is the measured RSF value, are also shown in Table 1. It should be noted that all of the cylinders burst at the machined LTA.

The RSF values of each tested cylinder were calculated using Equation 1. The ratio of the measured failure pressure (P_f) of a cylinder with a flaw to the measured failure pressure of a cylinder without a flaw ($P_b = 10{,}700$ psi), that is (P_f/P_b) is defined as the “measured RSF” for the tested cylinders. These results are shown in Table 1. A comparison of the measured RSF to the calculated RSF is shown in Figure 1 for all of the cylinders that were tested. Figure 1, shows that the measured and calculated values lie along a 45^o line. This indicates that the API 579 analytical procedures can be used to reliably calculate the RSF and therefore to calculate the failure pressure of cylinders containing flaws. The agreement between the calculated and measured RSF values confirms that for seamless steel cylinders, the remaining strength factor (RSF) analysis reliably predicts the pressure at which the cylinders will fail by bursting. This analysis is suitable for use to evaluate the effects of notches, cracks, local thin area, and general wall thinning due to corrosion. Therefore, the API 579 methods of analysis can be used to calculate the “critical flaw sizes” for these types of flaws in seamless steel cylinders.

6.0 CRITICAL FLAW SIZE ANALYSIS AND VERIFICATION

The development of “critical flaw size” requirements that can be used for the inspection of cylinders requires that the length or area and the depth of flaws that will cause the cylinder to fail at a designated pressure must be established. These requirements are most conveniently shown as curves of the flaw depth (defined as a/t ratio) versus the length or diameter of the flaw for designated failure pressures.

As shown above, the API 579 method of analysis can reliably be used to calculate the failure pressure of seamless steel cylinders containing various types and sizes of flaws. These methods can be used to predict, by analysis, the effect of various sizes of local thin areas, pits, notches, and cracks on the failure pressure of selected sizes and strength levels of steel cylinders.

However, the API 579 method has not previously been used to develop “critical flaw size” requirements for cylinders. The basis for using the API 579 to establish the “critical flaw sizes” for seamless steel cylinders has been described in detail by Smith, Rana, and Clark [11]. The “remaining strength factor” (RSF) which is defined by API 579 may also be defined as the failure pressure ratio of (P_f/P_b), where P_f is the failure pressure of the cylinder containing the flaw and P_b is the failure pressure of the same type and size of cylinder that does not contain a flaw.

To establish “critical flaw size” requirements for cylinders, the failure (burst) pressure (P_f) of the cylinders containing a flaw is specified. The ratio (P_f/P_b) is then calculated. This ratio (P_f/P_b) which is now defined as the as the “residual strength factor”(RSF) as shown in Equation 1 above. An inverted form of Equation 1 is then used to back calculate the flaw depth and length or area that is expected to cause the cylinder to fail at the designated pressure. In the present study, the failure pressure (P_f) of the cylinder was specified as (1) the designated service pressure (MAWP) and (2) the hydrostatic test pressure of the cylinder. The “critical flaw size” curve (depth versus area or length) for each type of flaw in any cylinder was then calculated. The “critical flaw size” curves for failure at the designated service pressure of the cylinder shows the size of flaws that would cause the cylinder to fail in service. The “critical flaw size” curves for failure at the hydrostatic test pressure of the cylinder shows the size of flaws that would cause the cylinder to fail during the traditional hydrostatic pressure test. This shows the size of flaws that could be expected to have been left in the cylinder after performing the traditional hydrostatic pressure test.

In this study, the analysis was carried out using Equation 1 for each size of flaw at two values of (P_f/P_b) or RSF. The values of (P_f/P_b) used in the analysis were 0.67 and 0.44. The (P_f/P_b) equal to 0.67 is used to calculate the size of flaws that would be expected to reduce the burst pressure of a cylinder with a flaw to 67 % of the burst pressure of a cylinder without a flaw. This value was chosen because the US DOT exemption E-9421 for the type of cylinders tested [10] requires that the test pressure used in the hydrostatic test must be approximately 67% of the minimum burst pressure of a cylinder without a flaw. The size of flaws calculated at this pressure represent the size of flaws that could be expected to cause the cylinder to fail (burst) at the test pressure in the hydrostatic test.

Similarly the (P_f/P_b) equal to 0.44 is used to calculate the size of flaws that would be expected to reduce the burst pressure of a cylinder with a flaw to 44 % of the burst pressure of a cylinder without a flaw. This value was chosen because the US DOT exemption E-9421 for the type of cylinders tested requires that the burst pressure of a cylinder without a flaw, (P_b), should be at least 5/4 (2.25) times the service pressure (Ps). Therefore, for a cylinder which contains a flaw and that fails at the maximum service pressure, the failure pressure must be not be greater than 44% (1 /2.25) of the minimum burst pressure of a cylinder without a flaw. The size of flaws calculated at this pressure represent the size of flaws that could be expected to cause the cylinder to fail (burst) in service. An example of these calculations is shown in Figure 2 for a cylinder that was used in this test program, which is: 4500 psi service pressure, 8.75 in. ID and 0.26 in. wall. This analysis method can be used to determine “critical flaw sizes” at a specified (P_f/P_b) ratio for any specific cylinder size.

To demonstrate that the API method of analysis reliably predicts the critical flaw sizes for cylinders, a comparison was made between the analytical predictions and experimental test results obtained from the ISO TC 58 /SC 4/WG 1 on “Rejection Criteria for Metal Cylinders” [8] and from the ISO TC 58/SC 3/WG 14 on “Toughness and acceptance levels of steels of strength levels above 1100 N/mm^2 “ [9]. Selected results from the WG1 test program are shown in Figures 3 and 4. Figure 3 shows that the measured flaw sizes for a local thin area type of flaw are all equal to or larger than the calculated “critical flaw sizes” for a failure pressure of 99 % of the failure pressure of an unflawed cylinder. Figures 4 shows that for a longitudinal notch type of flaw that is 10 times the cylinder wall thickness long (a 10t flaw), the measured and calculated flaw depth are in good agreement for flawed cylinders that failed at pressures of 66% to 91% of the failure pressure of an unflawed cylinder.

In the WG 14 test program, several hundred monotonic hydrostatic, flawed-cylinder burst tests were conducted. The flaw type in all of these test was a longitudinal notch type of flaw. The cylinders tested ranged in tensile strength from less than 750 MPA to more than 1250 MPA. The cylinders tested represent the full range of strength levels and sizes of cylinders currently used in the world. From this test data, the results of tests in which the measured failure pressure was near the marked service pressure were selected. The measured flaw sizes from these tests that caused failure at the marked service pressure were compared with the calculated “critical flaw sizes” for failure at the marked service pressure as shown in Figure 5.

In addition, the test data from the WG 14 test program in which the measured failure pressure was near the cylinder test pressure were selected. The measured flaw sizes from these tests that caused failure at the test pressure were compared with the calculated “critical flaw sizes” for failure at the marked test pressure as shown in Figure 6.

These results show that for failure at both the marked service pressure and the test pressure, the measured flaw sizes were larger than the calculated “critical flaw sizes.” Therefore, critical flaw sizes can be reliably calculated using the API 579 assessment procedure and used to establish “critical flaw sizes “ for all steel cylinders currently in use.

7.0 ALLOWABLE FLAW SIZE ANALYSIS AND VERIFICATION

The “critical flaw size: requirements define the size of flaws that will cause the cylinder to fail immediately when the cylinder is pressurized to the specified pressure. The “maximum allowable flaw sizes” are defined as the initial size of flaws that will grow during service to the critical size to cause failure. Flaws in cylinders are known to grow during service by fatigue and by stress corrosion.

For this study, only fatigue crack growth will be considered. To develop “maximum allowable flaw sizes” for the steel cylinders, the fatigue life cycle is defined as 3500 pressure cycles from 0 pressure to the service pressure. This fatigue life cycle was chosen to represent the most extreme case of the cylinder use which is a daily filling of the cylinder to the service pressure for 10 years, which is the normally required retest cycle.

To develop the allowable flaw size requirements, the “critical flaw sizes” that are expected to cause failure at both the service pressure and at the test pressure are then carried out to determine the “initial” flaw sizes that will grow to the critical flaw size after 3500 pressure cycles to a maximum pressure equal to the service pressure. These “initial” flaw sizes are then defined as the “maximum allowable flaw sizes” for the cylinder.

The following example shows the procedure used to calculate the “maximum allowable flaw sizes” for a typical steel cylinder The fatigue crack growth rate analysis used in this study is based on the Paris fatigue crack growth rate equation [12].

The crack growth rate is calculated as:

$$da/dN = C\,(\Delta K)^m$$

Where (for steel cylinders):

$C = 4.7\text{x}10^{-10}$
$m = 2.8$
da/dN = crack growth per unit cycle, in/cycle
ΔK = cyclic stress- intensity range, ksi√in

For a surface crack in a cylinder the stress-intensity is defined as:

$$\sqrt{\Pi a / Q}\ \Delta K = M_F\ M_{RN}\Delta\sigma$$

Where:

M_F = Folias stress-intensity magnification factor
M_{RN} = Raju-Newman factor
$\Delta\sigma$ = cyclic stress; ksi
a = crack depth, in.
Q = crack shape factor, is a function of crack depth and crack length

The example cylinder had a service pressure (P_s) of 4500 psi and a test pressure (P_t) of 6750 psi. Critical-flaw-sizes were first calculated using the API 579 Level 2 methods of analysis described above. The maximum allowable flaw sizes were then calculated using the fatigue crack analysis equations described above. For this analysis the computer software program “Fracture Graphics” was used [13].

For this example, the cyclical stress used was 76.1 ksi. This represents a nominal hoop stress at the 4500 psi service pressure calculated using the mean diameter formula $PD_m/2t$.
The final flaw dimensions are known from the calculation of the critical flaw sizes at each of the specified failure pressures. The fatigue crack growth analysis program is then used to calculate the initial flaw sizes that will grow to these critical sizes after 3500 cycles. The results of the “allowable flaw size “calculations are shown in Tables 2 and Table 3, and in Figures 7 and 8. Table 2 shows the maximum allowable flaw sizes that will become critical size at service

pressure. Similarly, Table 3 shows the maximum allowable flaw sizes for the test pressure case. The difference in the allowable flaw size for the analyzed two cases (i.e.,, allowable flaw size for failure at service pressure and at test pressure) is very small.

TABLE 2
Calculated Initial Flaw Size to Become Critical Size at Ps Subjected to 3500 Cycles at Zero to 4500 Psi Ps

Flaw Length In.	Critical Flaw Depth at Ps a In.	Initial Flaw Depth ai In.	Flaw Depth Ratio ai/t
0.5	0.252	0.0880	0.34
1.0	0.234	0.0480	0.18
2.0	0.203	0.0338	0.13
3.9	0.176	0.0279	0.11
7.9	0.160	0.0253	0.10
11.8	0.155	0.0245	0.09

TABLE 3
Calculated Initial Flaw Size to Become Critical Size at Pt Subjected to 3500 Cycles at Zero to 4500 Psi Ps

Flaw Length In.	Critical Flaw Depth At Pt a In.	Initial Flaw Depth ai In.	Flaw Depth Ratio ai/t
0.5	0.240	0.0875	0.34
1.0	0.203	0.0472	0.18
2.0	0.151	0.0333	0.13
3.9	0.116	0.0275	0.11
7.9	0.100	0.0250	0.10
11.8	0.095	0.0242	0.09

8.0 EVALUATION OF CORROSION PITTING

Cylinders can fail when the gas environment permits pitting (highly localized) corrosion to occur either (1) by bursting or (2) by leaking. Although pitting may occur as an isolated individual pit, generally when pitting corrosion occurs, it will result in a failure due to a cluster or line of corrosion pits.

When pitting corrosion is significant enough for failure to occur by bursting, the API 579 analysis described above can be used to calculate the “critical flaw sizes.” However, for failure to occur by bursting from an isolated pit, the pit must be sufficiently large in diameter and sufficiently deep. The API 579 methods of analysis show that a cylinder would not be expected to fail by bursting from an isolated pit unless the pit has a diameter equal to about twice the wall thickness of the cylinder and has a depth of approximately 80 % through the cylinder wall. Smaller or shallower pits would not be expected to fail by bursting but could fail by leaking if the corrosion continues for a sufficient period of time.

An isolated pit may cause the cylinder to fail by leaking if the corrosion continues for a sufficient period of time. The rate of pitting corrosion is dependent on the particular gas being transported in the cylinder, on the specific moisture content of the gas, and on the average temperature of service for the cylinders. These conditions are highly dependent on the operating conditions under which the cylinder is used. Very dry gas (for example, less than 5 ppm moisture) will be essentially inert and no pitting would be expected to occur and existing pits would not be expected to grow in depth. Therefore, leaking as a result of pitting corrosion would never be expected to occur. For gases containing moderate amounts of moisture (100 to 500 ppm, pitting corrosion rates of 10 to 50 mils per year (0.010 to 0.050 in./year) can occur. Pitting corrosion rates at this level could cause the cylinder to fail by leaking in a period of several years. For gases containing significant amounts of moisture (> 1000 ppm), pitting corrosion rates exceeding 100 mils per year (0.100 in./year) can occur so that the cylinders may fail by leaking in time intervals shorter than the retest interval. Reliable quantitative experimental data on pitting corrosion rates for various gases, cylinder materials, moisture levels, and pressures is not readily available.

Pitting is very localized and is particularly difficult to detect visually or by any known nondestructive technique because the pits are very small in area and are often covered by corrosion products. The rate of pitting is very unpredictable and the time for the cylinder to fail by leaking due to pitting can not be reliably predicted because (1) the pitting may require a long initiation (incubation) period to start the pit and (2) once initiated, the pit may grow very rapidly and quickly lead to leaking. That is, even for a specified gas composition, the pitting corrosion rate is very not linear with time and highly variable for apparently identical conditions. For example, an extended period of time, month or years, may be required to initiate a pit and then the pit will increase in depth at an accelerating rate until failure occurs [14] [154].

As the pit develops, the chemical environment in the pit changes from that of the bulk environment in the cylinders and this may significantly increase the rate of pitting. In steel cylinders, the chemical environment in the pit will generally become significantly acidic even when the general environment is neutral. For pitting corrosion to occur in steel gas cylinders, oxygen must be present as one of the environmental components to which steel is exposed. The oxygen may come from moisture in the gas or from other oxygen containing chemical species such as carbon monoxide or carbon dioxide. The rate of pitting may be increased if acid forming chemicals, such as hydrogen chloride or hydrogen sulfide are present in the gas.

Reliable data for pitting corrosion rates for various gases in steel cylinders have not been found in the technical literature. However, if reliable pitting corrosion rates can be found in the technical literature or obtained from experimental tests, the time to failure (peroration of the cylinder wall and leaking to occur) can be estimated by the following analysis:

(Time to failure) = (original wall thickness, t_d)/(average pitting rate, mils/year)

If it is known that a specific gas and cylinder steel has a minimum initiation time before pit growth can occur, then the time to failure may be estimated as:

(Time to failure) = [minimum initiation time, in hours] - [(original wall thickness, t_d)/(average pitting rate, mils/year)]

For example, for a steel cylinder with an initial wall thickness of 0.250-inch that contains wet gas which causes pitting corrosion at an average rate (initiation plus rapid growth rate) of 500 mils per year (0.500-inch), the cylinder could be expected to fail by leaking in:

t_f = (0.250)/(0.500) = ½ year

This is an extreme case, but such short times to failure and leaking have occasionally been observed.

A more typical example, is for a steel cylinder with an initial wall thickness of 0.250-inch that contains a generally dry gas which causes pitting corrosion at an average rate (initiation plus rapid growth rate) of 5 mils per year (0.005-inch/year), the cylinder could be expected to fail by leaking in:

t_f = (0.250)/(0.005) = 50 years

This is expected to be a more realistic case for general purpose cylinders without specific high purity gas requirements, but such short times to failure and leaking have occasionally been observed.

9.0 DISCUSSION

Significance of the analysis - For steel cylinders at all strength levels, the API 579 method of analysis has been shown to be reliable for calculating “critical flaw sizes” for failure of the cylinders at all pressures. The flaw types that were analyzed were: local thin areas, holes/pits, notches, and crack -like flaws. The predicted failure pressures and the predicted flaw sizes that were obtained by the analysis were in good agreement with extensive experimental test results.

For the steel cylinders that were evaluated, it was shown that the failure mode due to the internal pressure in the cylinder was by bursting due to ductile, plastic collapse of the cylinder wall in the region of the flaw. Other failure modes that could result from the pressure in the cylinder, such as fracture, were shown to not be significant for the steel cylinders evaluated in this study. It was found to be sufficient to analyze the flaws in the cylinders using only a two dimensional model. That is, the circumferential dimension of the flaws did not significantly affect the predicted failure pressure of the cylinder.

The flaw size analysis conducted in this study and the experimental verification of the analysis shows that for steel cylinders the “critical flaw sizes” and the “maximum allowable flaw sizes” can be reliably determined by the analytical modeling alone. The verification of the analysis is sufficient so that it should not be necessary to conduct additional experimental tests to determine “maximum allowable flaw sizes” to be used for setting acceptance/rejection criteria for use at the time of retesting.

Significance of “critical flaw size” - The “critical flaw size” evaluation is the starting point to be used for setting acceptance/rejection criteria for use at the time of retesting. The “critical flaw sizes” are the flaw sizes that are expected to actually cause failure at the specified pressure. The “critical flaw sizes” at the service pressure show the flaw size that would be expected to cause a failure of the cylinder while in service. Once this flaw size is established, “maximum allowable flaw sizes” can be established to ensure that no flaw actually reaches the critical size while the cylinder is in service.

The “critical flaw sizes” at test pressure determine the flaw size that is expected to cause failure of the cylinder during the traditionally used hydrostatic pressure test. The significance of the “critical flaw sizes” at test pressure is that flaws of these sizes could have been left in the cylinder at the end of hydrostatic testing. Because cylinders that have been in service after only being retested by hydrostatic testing have not been found to fail in service in significant numbers, it can be concluded that cylinders that contain flaws that are as large as the “critical flaw sizes” have an adequate safety margin.

Significance of “maximum allowable flaw sizes” – The “maximum allowable flaw sizes” are established by reducing the size of the “critical flaw sizes” to account for flaw growth during service due to such phenomena as fatigue, corrosion, or stress-corrosion. The analysis and experimental verification conducted in this study was limited to and evaluation of fatigue crack growth. The “maximum allowable flaw sizes” are used to establish the size of flaws that cause the cylinders to be rejected at the time of retesting. The analysis of the “maximum allowable flaw sizes” may also be used to define the required retest interval.

Significance of other failure modes - In this study, only failure by bursting due to the internal pressure in the cylinder was evaluated. However, other failure modes may occur in cylinders and may need to be evaluated before establishing final acceptance/rejection criteria. Some cylinder applications may require an evaluation of fracture, stress-corrosion cracking or corrosion.

For some types of cylinders, it may be necessary to evaluate the probability of failure by fracture. For the cylinders tested in this study, the ductility and fracture toughness are sufficiently high that the flow strength of the steel is the appropriate material parameter that controls the failure of the cylinder. By this flow strength criterion, failure occurs when the local stress in the presence of a flaw reaches the material’s flow strength, and failure by burst occurs at the flaw. The extensive testing that was done as part of the ISO WG 14 program showed that the flow strength criterion was appropriate for all presently used steel cylinders and that fracture analysis is not required to evaluate the cylinders.

In this study, only fatigue crack growth was considered in establishing “maximum allowable flaw sizes” . However, in cylinders used to transport some gases, it may be necessary to also evaluate stress-corrosion cracking to properly establish “maximum allowable flaw sizes” The occurrence of stress-corrosion cracking is highly dependent on the specific gas being transported in the cylinder and the specific operating conditions, such as the moisture content of the gas. When stress-corrosion cracking needs to be considered, the “maximum allowable flaw sizes” can be established by adjusting the “critical flaw sizes” in a manner analogous to that used for the fatigue crack growth analysis. Instead of the crack growth rate per cycle that is used in the fatigue analysis, the stress-corrosion cracking rate per unit of time is used to adjust the “critical flaw sizes” and to establish the “maximum allowable flaw sizes”. However, the stress-corrosion cracking rate is so specific to the particular gas being transported that the analysis can only be done on a case by case basis.

In this study, general corrosion and corrosion leading to local thin areas in the cylinder wall that cause failure of the cylinder by bursting can be adequately analyzed using the “fitness-for-service” procedures and “critical flaw sizes” can be established. However, for highly localized corrosion that results in isolated pitting, that causes the cylinder to fail by leaking, adequate procedures to estimate “critical flaw sizes” not available. Reliable analytical models to estimate the size of isolated corrosion pits and the rate of growth of the pits and that have been experimentally verified are not available. Reliable data for pitting corrosion rates for various gases in steel cylinders are not available. The rate of pitting is highly dependent on the specific gas in the cylinder and on the specific operating conditions. Therefore, the “critical flaw sizes” for isolated pits can not be estimated for general types of cylinders but must be estimated for each specific type of cylinder, gas composition and operating conditions.

Considerations for establishing acceptance/rejection criteria – Although a sound technical basis has been established for developing “maximum allowable flaw sizes” that accounts for fatigue cracking and stress-corrosion cracking (if appropriate), other factors may be taken into account before establishing the final acceptance/rejection criteria for retesting cylinders. It may be necessary to consider all the expected operating conditions that the cylinder will see. In addition, it may be necessary to take into account the reliability and sensitivity of the specific inspection equipment and to adjust the “maximum allowable flaw sizes” to provide an additional margin of safety.

10.0 SUMMARY AND CONCLUSIONS

1. The API 579 Recommended Practice 579 “Fitness-for-Service” methods of analysis have been shown to reliably define the “critical flaw sizes” for most types of flaws that occur in seamless steel cylinders.

2. Extensive hydrostatic, flawed-cylinder burst test data were used to verify the use of the API 579 methods of analysis for defining “critical flaw sizes” in seamless steel cylinders.

3. For the cylinders tested in the ISO WG-1 and WG-14 program, the ductility and fracture toughness are sufficiently high that the flow strength criterion is the appropriate failure criterion. to predict the burst pressure and therefore to develop “critical flaw size” requirements for seamless steel cylinders of all strength ranges.

4. “Maximum allowable flaw sizes” can be established by calculating the amount of fatigue crack growth during the use of the cylinder using established fatigue crack growth data and analysis.

5. The “maximum allowable flaw sizes” can be used to set the acceptance levels for flaws at the time of inspection or retesting the cylinders.

6. The “critical flaw sizes” for highly localized corrosion types of flaws (isolated pits) can not be reliably estimated, in general for cylinders because the rate of pitting corrosion is highly dependent on the operating conditions under which the cylinder is used and reliable quantitative experimental data on pitting corrosion rates for various gases, cylinder materials, moisture levels, and pressures is not readily available.

11.0 RECOMMENDED FUTURE WORK

1. Additional experimental and analytical studies should be conducted on specific cylinder materials, gases, and environments to establish quantitative acceptance/rejection requirements for cylinders that may fail by leaking due to pitting corrosion.

2. “Maximum allowable flaw sizes” should be established for application s where stress-corrosion cracking is significant.

3. Acceptance/rejection criteria based on the API 579 method of analysis should be established and verified by experimental testing for aluminum alloys cylinders.

12.0 ACKNOWLEDGMENTS

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Technical advice and consultation was provided by Mr. Mahendra Rana of Praxair, Inc.

Extensive testing of some of the flawed cylinders that were conducted under the ISO WG 14 program and that are reported here was conducted by:

H Barthelemy, L' Air Liquide, France

C. Duren, Mannesmann, Germany

C. Hall, Taylor Wharton Cylinders, USA

G. Konul, Joseph Heiser, Inc., Austria

M. Rana, Praxair, USA

R Shafkey, Norris Cylinders, USA

J. Walters, Chesterfield Cylinders, UK

J. Wedding, Coyne Cylinder, USA

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14.0 FIGURES

FIG. 1 VERIFICATION OF API 579 ANALYSIS FOR SEAMLESS STEEL CYLINDERS

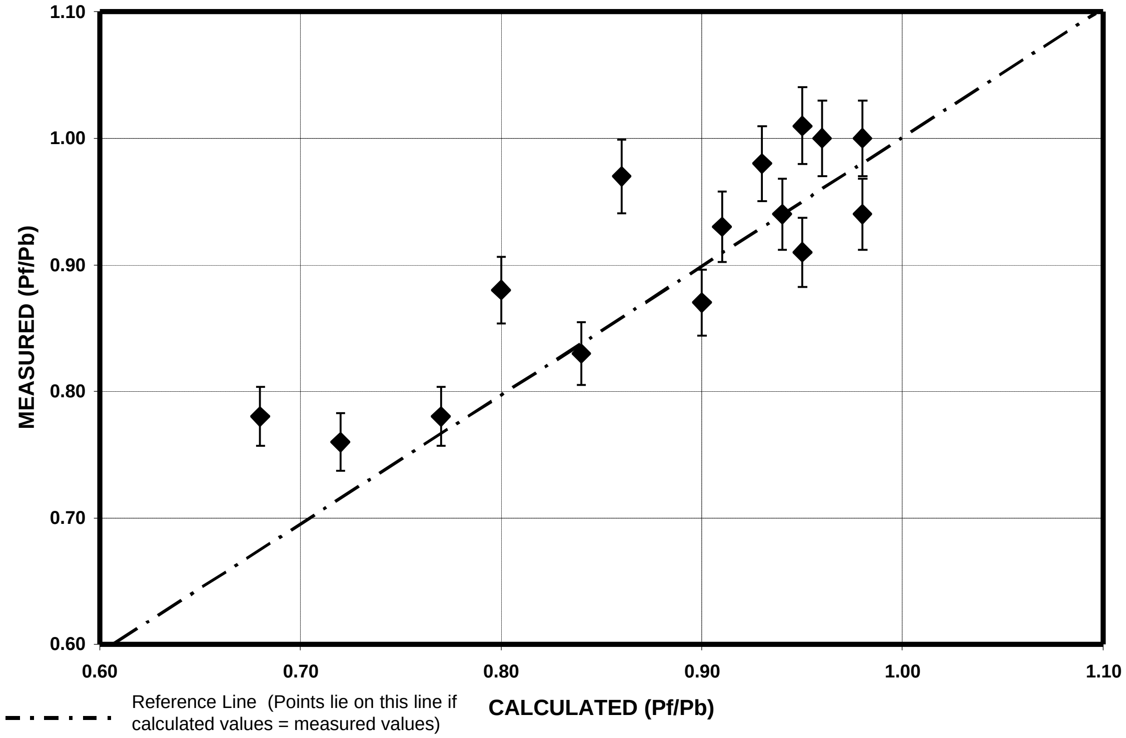

FIG 2 CRITICAL FLAW SIZE FOR STEEL CYLINDERS

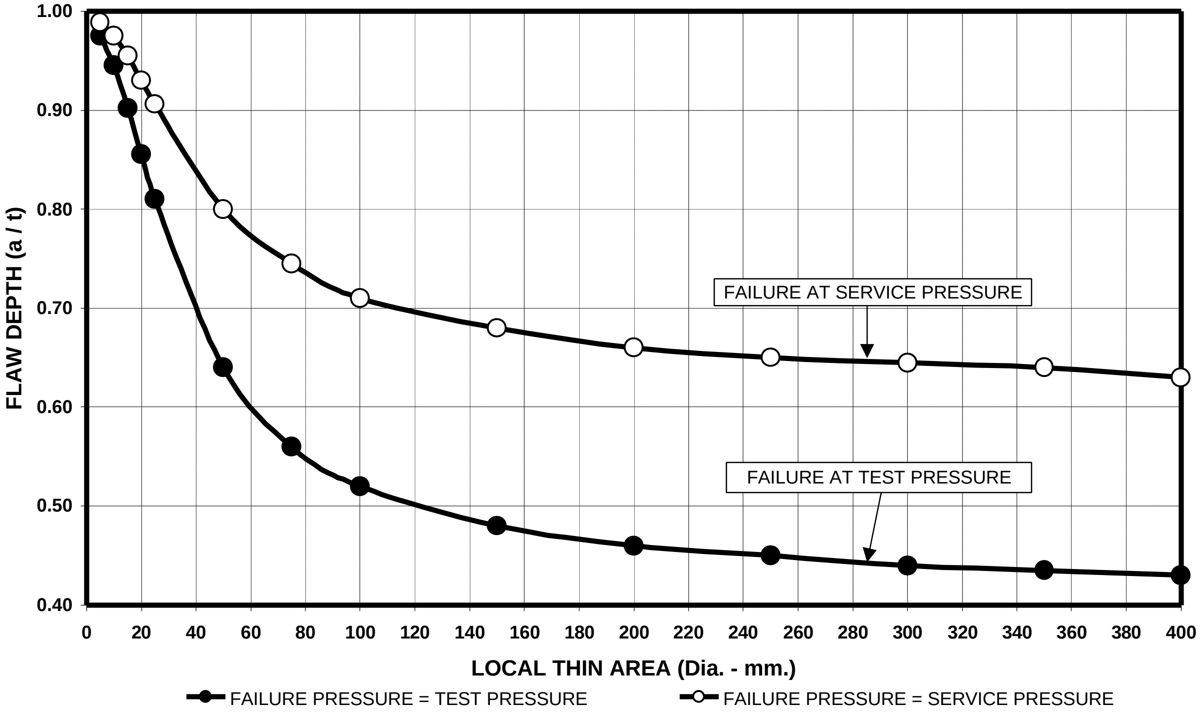

FIG. 3 CRITICAL FLAW DEPTH AND AREA
FOR Pf / Pb = 0.99

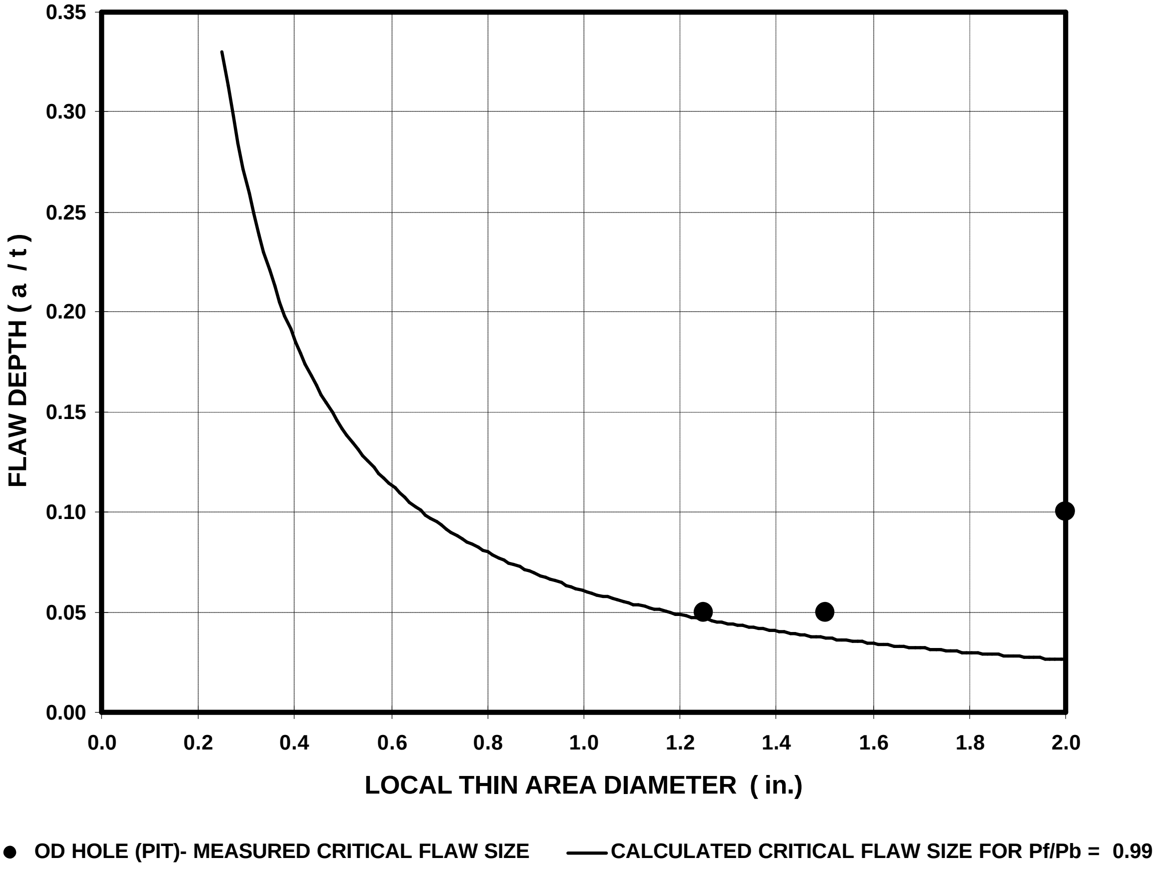

FIG. 4 FLAW DEPTH COMPARISON
FOR 10 t LONG LONGITUDINAL NOTCH FLAW

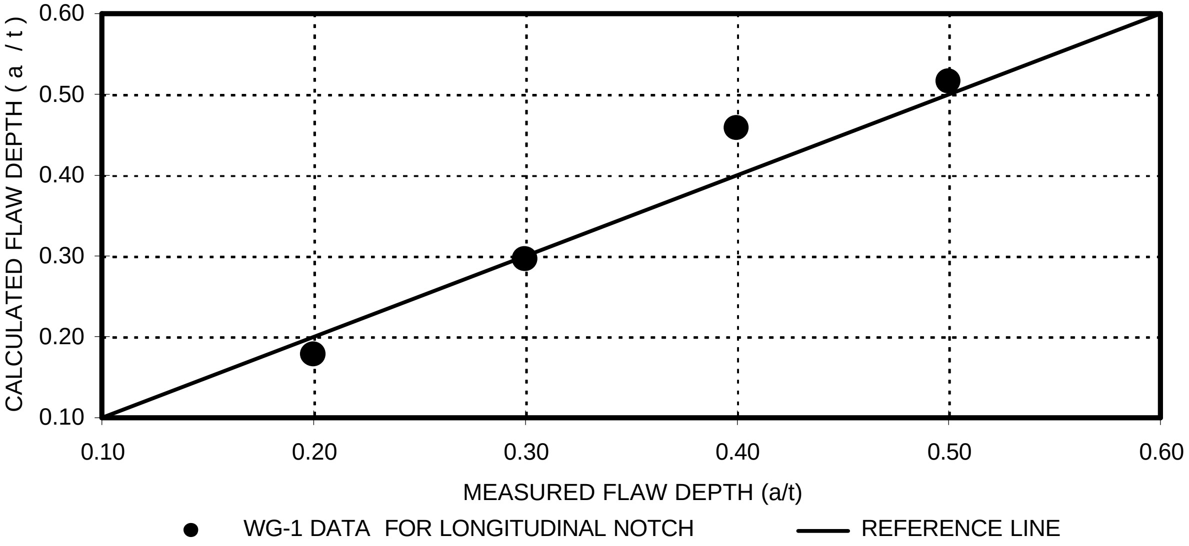

FIG. 5 CRITICAL FLAW DEPTH AND LENGTH
FOR FAILURE PRESSURE (Pf) = SERVICE PRESSURE (Ps)

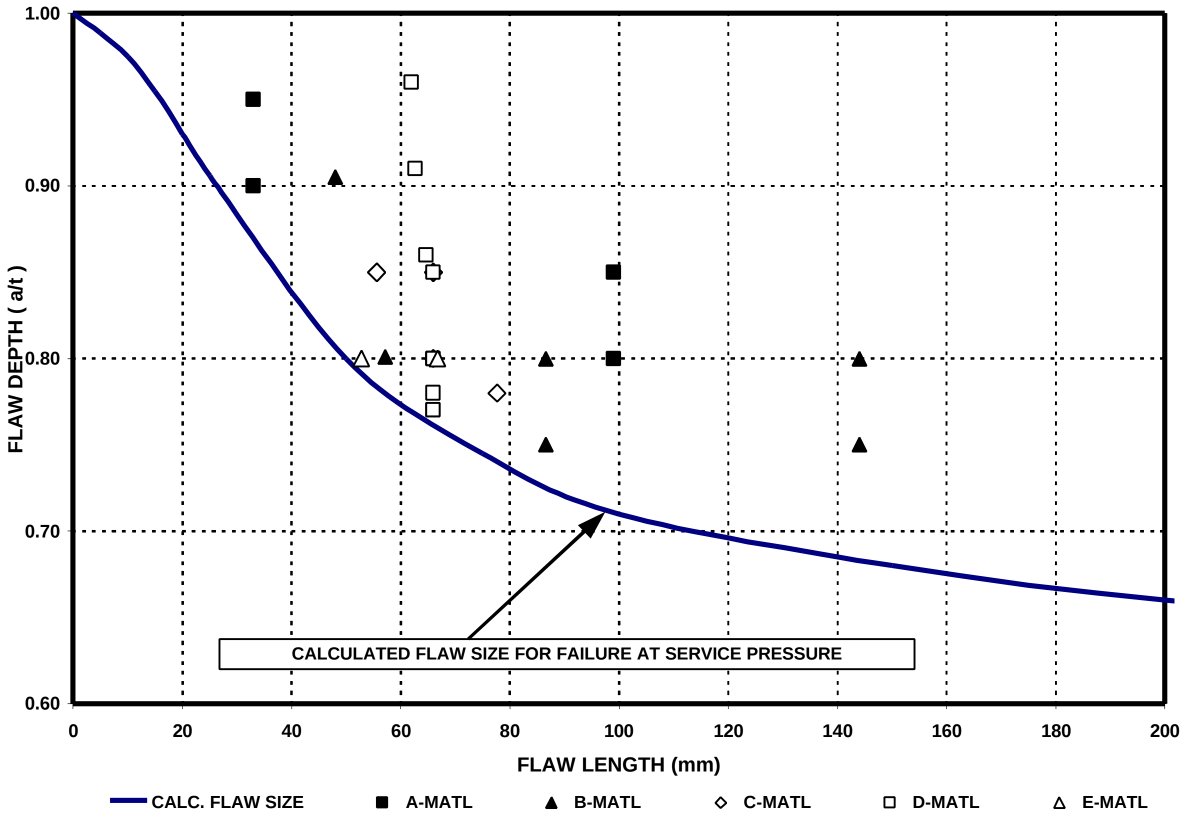

FIG. 6 CRITICAL FLAW DEPTH AND LENGTH FOR FAILURE PRESSURE (Pf) = TEST PRESSURE (Pt)

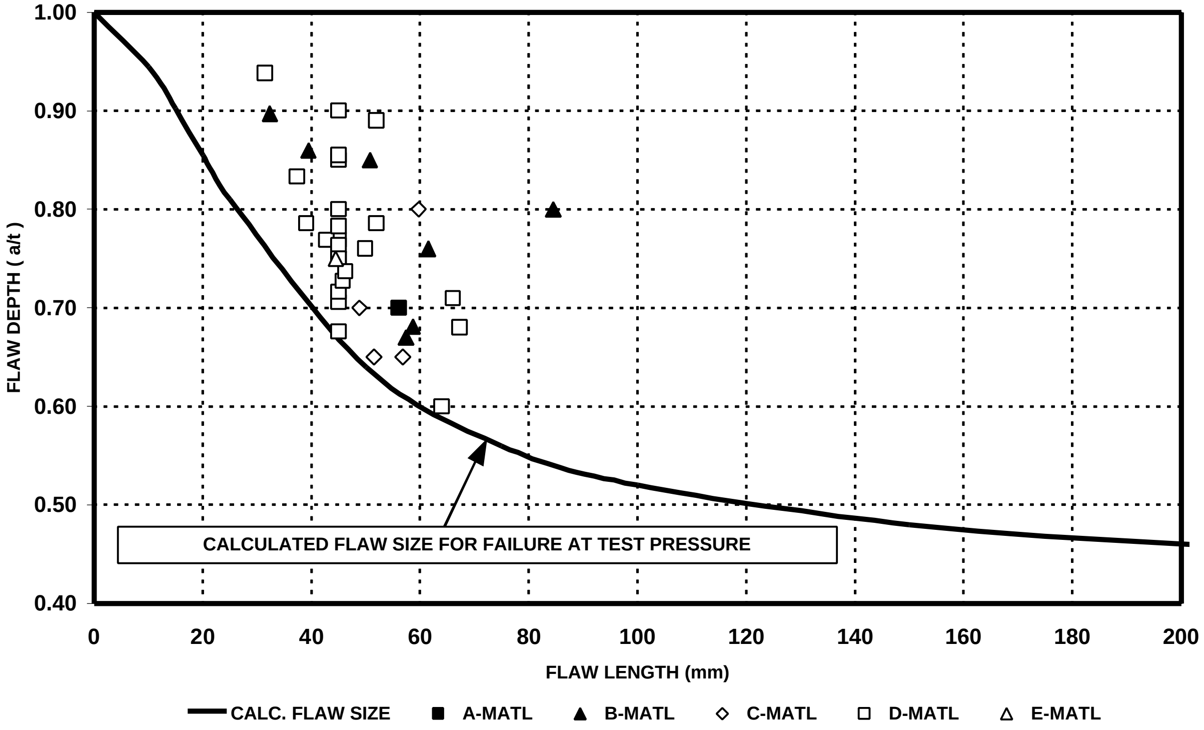

FIG. 7 ALLOWABLE FLAW SIZES
FOR FAILURE AT SERVICE PRESSURE

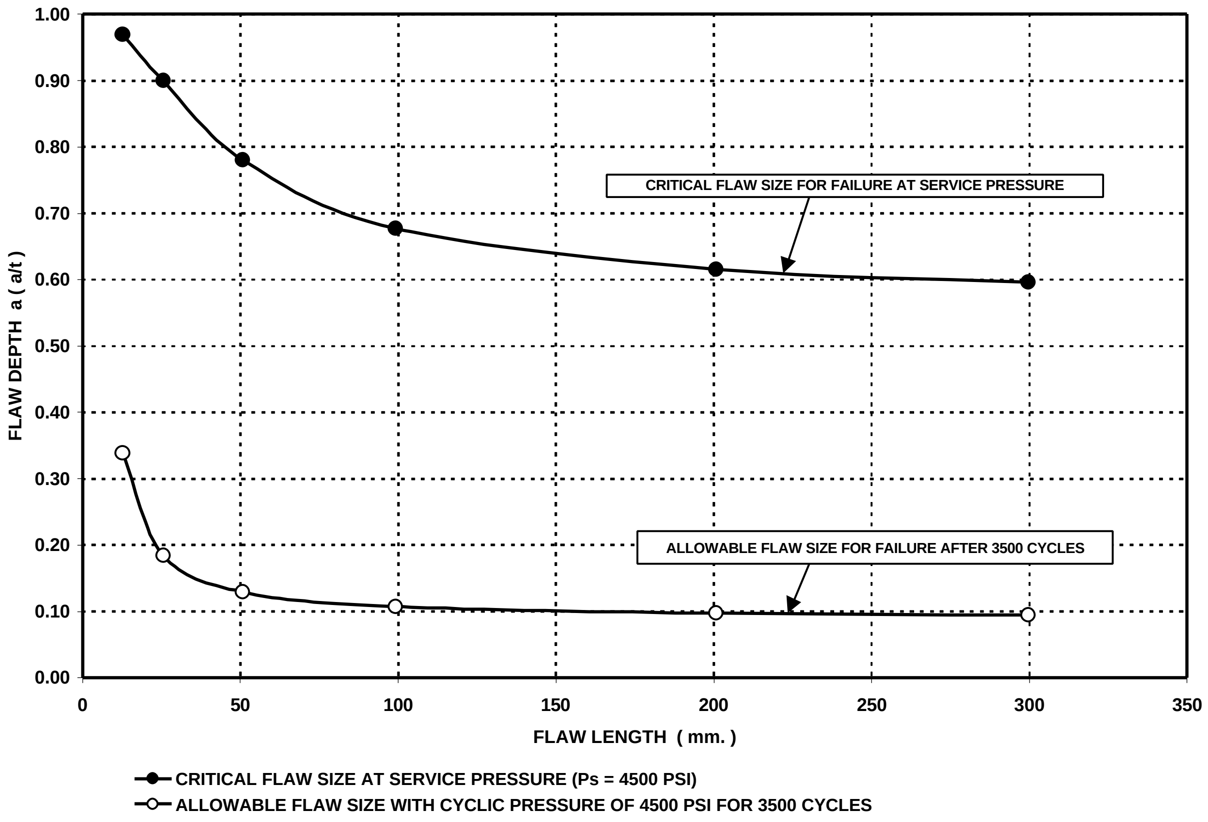

FIG. 8 ALLOWABLE FLAW SIZES
FOR FAILURE AT TEST PRESSURE

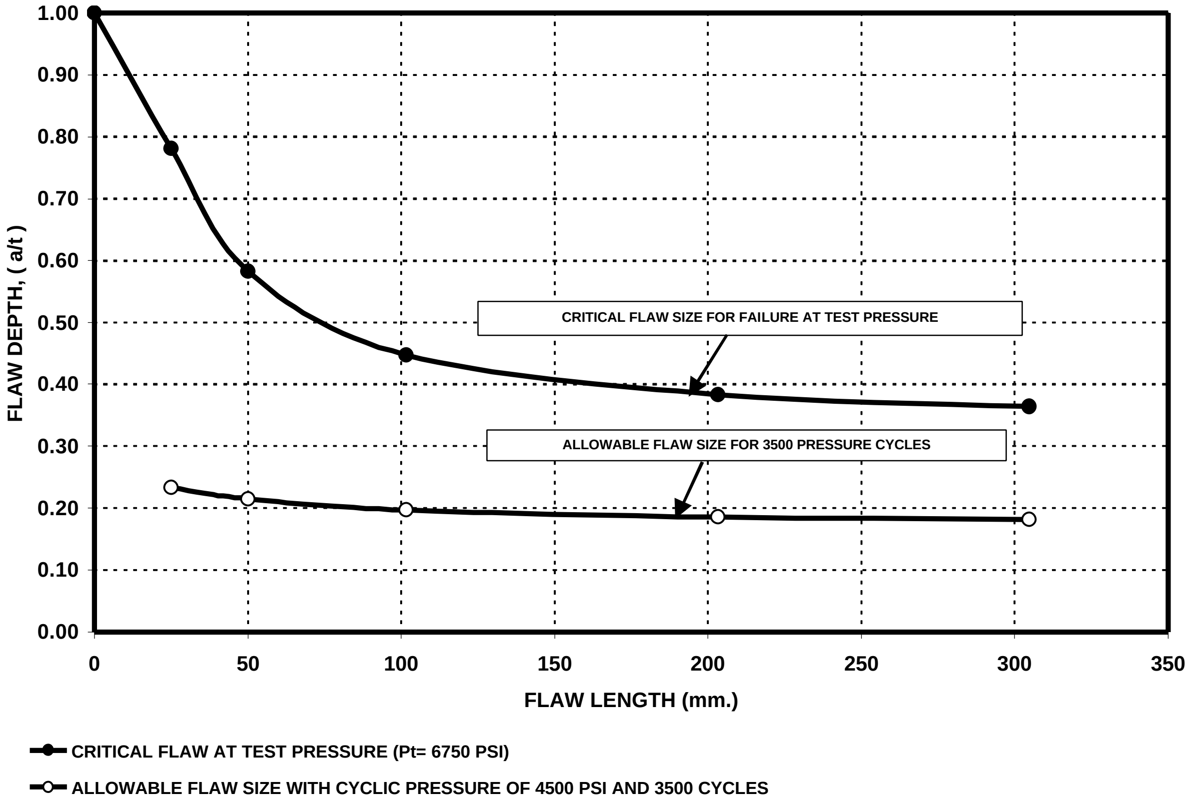

TABLE A -1 TESTS CONDUCTED BY WG-1 ON STEEL CYLINDERS FOR FITNESS-FOR-SERVICE ANALYSIS

	TENSILE					WALL THICKNESS (in.)															
CYLINDER TYPE	STRENGTH MINIMUM (psi.)	INSIDE DIAMETER (in.)	DESIGN THICKNESS (in.)	SERVICE PRESSURE (psi.)	TEST PRESSURE (psi.)			WALL	WALL	FLAW	FLAW TYPE	FLAW DESCRIPTION	FLAW SIZE						BURST PRESSURE (psi.)	FAILURE AT FLAW	CYCLES TO FAIL
						MIN. WALL	AVG. WALL	UNDER FLAW	AT FLAW	AT			DEPTH (% X td)	LENGTH (n X td)	LENGTH (in.)	WIDTH (in.)	DIA. (in.)	AREA (sq. in.)			
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.224	-----	-----	-----	-----	**DESIGN**	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
											UNFLAWED										
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.238	0.266	-----	-----	-----	NONE	-----	-----	-----	-----	-----	-----	-----	8550	-----	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.233	0.259	-----	-----	-----	NONE	-----	-----	-----	-----	-----	-----	-----	8550	-----	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.233	0.265	-----	-----	-----	NONE	-----	-----	-----	-----	-----	-----	-----	8475	-----	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.245	0.262	-----	-----	-----	NONE	-----	-----	-----	-----	-----	-----	-----	8650	-----	-----
											ROUND-LTA										
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.232	0.261	0.202	-----	avg	OD-LTA-ROUND	**LTA 1 1/2" Ø (1.767 in2) @ 0.90t**	10	-----	-----	-----	1.50	1.767	8350	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.230	0.259	0.202	-----	avg	OD-LTA-ROUND	**LTA 1 1/2" Ø (1.767 in2) @ 0.90t**	10	-----	-----	-----	1.50	1.767	7950	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.238	0.265	0.213	-----	avg	OD-LTA-ROUND	**LTA 1 1/2" Ø (1.767 in2) @ 0.95t**	5	-----	-----	-----	1.50	1.767	8200	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.229	0.261	0.213	-----	avg	OD-LTA-ROUND	**LTA 1 1/2" Ø (1.767 in2) @ 0.95t**	5	-----	-----	-----	1.50	1.767	8000	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.240	0.263	0.179	-----	min	OD-LTA-ROUND	**LTA 1 1/2" Ø @ 0.80t**	20	-----	-----	-----	1.50	1.767	8250	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.236	0.267	0.202	-----	min	OD-LTA-ROUND	**LTA 1 1/2" Ø @ 0.90t**	10	-----	-----	-----	1.50	1.767	8150	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.229	0.256	0.202	-----	avg	OD-LTA-ROUND	**LTA 1 1/4" Ø (1.227 in2) @ 0.90t**	10	-----	-----	-----	1.25	1.227	7950	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.239	0.260	0.202	-----	avg	OD-LTA-ROUND	**LTA 1 1/4" Ø (1.227 in2) @ 0.90t**	10	-----	-----	-----	1.25	1.227	8000	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.235	0.262	0.213	-----	avg	OD-LTA-ROUND	**LTA 1 1/4" Ø (1.227 in2) @ 0.95t**	5	-----	-----	-----	1.25	1.227	8250	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.228	0.260	0.213	-----	avg	OD-LTA-ROUND	**LTA 1 1/4" Ø (1.227 in2) @ 0.95t**	5	-----	-----	-----	1.25	1.227	7850	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.250	0.272	0.202	-----	avg	OD-LTA-ROUND	**LTA 1" Ø (0.785 in2) @ 0.90t**	10	-----	-----	-----	1.00	0.785	8750	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.234	0.263	0.202	-----	avg	OD-LTA-ROUND	**LTA 1" Ø (0.785 in2) @ 0.90t**	10	-----	-----	-----	1.00	0.785	8250	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.240	0.263	0.213	-----	avg	OD-LTA-ROUND	**LTA 1" Ø (0.785 in2) @ 0.95t**	5	-----	-----	-----	1.00	0.785	8450	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.229	0.262	0.213	-----	avg	OD-LTA-ROUND	**LTA 1" Ø (0.785 in2) @ 0.95t**	5	-----	-----	-----	1.00	0.785	8050	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.236	0.262	0.179	-----	min	OD-LTA-ROUND	**LTA 1" Ø @ 0.80t**	20	-----	-----	-----	1.00	0.785	8150	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.238	0.265	0.202	-----	min	OD-LTA-ROUND	**LTA 1" Ø @ 0.90t**	10	-----	-----	-----	1.00	0.785	8150	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.235	0.263	0.179	-----	min	OD-LTA-ROUND	**LTA 2" Ø @ 0.80t**	20	-----	-----	-----	2.00	3.142	8700	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.242	0.264	0.202	-----	min	OD-LTA-ROUND	**LTA 2" Ø @ 0.90t**	10	-----	-----	-----	2.00	3.142	8450	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.228	0.258	0.150	-----	avg	OD-LTA-ROUND	**LTA 3/4" Ø (0.442 in2) @ 0.67t**	33	-----	-----	-----	0.75	0.442	8150	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.235	0.259	0.202	-----	avg	OD-LTA-ROUND	**LTA 3/4" Ø (0.442 in2) @ 0.90t**	10	-----	-----	-----	0.75	0.442	8000	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.236	0.264	0.202	-----	avg	OD-LTA-ROUND	**LTA 3/4" Ø (0.442 in2) @ 0.90t**	10	-----	-----	-----	0.75	0.442	8550	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.239	0.261	0.213	-----	avg	OD-LTA-ROUND	**LTA 3/4" Ø (0.442 in2) @ 0.95t**	5	-----	-----	-----	0.75	0.442	8200	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.234	0.265	0.202	-----	avg	OD-LTA-ROUND	**LTA 3/4" Ø (0.442 in2) @ 0.95t**	5	-----	-----	-----	0.75	0.442	8200	no	-----
											RECTANGULAR-LTA										
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.234	0.256	0.212	-----	min	D-LTA-RECTANGULA	**LTA 2.25" (10t) long x 1.75" x 10%t deep**	10	-----	2.25	1.75	-----	3.938	8250	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.238	0.269	0.193	-----	min	D-LTA-RECTANGULA	**LTA 2.25" (10t) long x 1.75" x 20%t deep**	20	-----	2.25	1.75	-----	3.938	7700	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.230	0.252	0.163	-----	min	D-LTA-RECTANGULA	**LTA 2.25" (10t) long x 1.75" x 30%t deep**	30	-----	2.25	1.75	-----	3.938	7300	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.232	0.264	0.142	-----	min	D-LTA-RECTANGULA	**LTA 2.25" (10t) long x 1.75" x 40%t deep**	40	-----	2.25	1.75	-----	3.938	7400	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.241	0.264	0.129	-----	min	D-LTA-RECTANGULA	**LTA 2.25" (10t) long x 1.75" x 50%t deep**	50	-----	2.25	1.75	-----	3.938	7100	yes	-----
											LONGITUDINAL NOTCH										
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.235	0.265	0.213	-----	min	OD-NOTCH	**longitudinal notch 10%t deep x 10t long**	10	10	2.25	-----	-----		8250	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.225	0.260	0.238	-----	avg	OD-NOTCH	**longitudinal notch 10%t deep x 5t long**	10	5	1.13	-----	-----		8450	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.225	0.255	0.233	-----	avg	OD-NOTCH	**longitudinal notch 10%t deep x 5t long**	10	5	1.13	-----	-----		8050	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.233	0.263	0.199	-----	min	OD-NOTCH	**longitudinal notch 15%t deep x 5t long**	15	5	1.13	-----	-----		7950	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.241	0.264	0.230	-----	avg	OD-NOTCH	**longitudinal notch 15%t deep x 5t long**	15	5	1.13	-----	-----		8600	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.232	0.261	0.227	-----	avg	OD-NOTCH	**longitudinal notch 15%t deep x 5t long**	15	5	1.13	-----	-----		8000	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.236	0.259	0.191	-----	min	OD-NOTCH	**longitudinal notch 20%t deep x 10t long**	15	10	2.25	-----	-----		7550	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.236	0.268	0.223	-----	avg	OD-NOTCH	**longitudinal notch 20%t deep x 5t long**	20	5	1.13	-----	-----		8450	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.233	0.261	0.188	-----	min	OD-NOTCH	**longitudinal notch 20%t deep x 5t long**	20	5	1.13	-----	-----	-----	8000	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.243	0.265	0.220	-----	avg	OD-NOTCH	**longitudinal notch 20%t deep x 5t long**	20	5	1.13	-----	-----	-----	8400	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.248	0.265	0.192	-----	min	OD-NOTCH	**longitudinal notch 25%t deep x 5t long**	25	5	1.13	-----	-----	-----	8150	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.227	0.261	0.160	-----	min	OD-NOTCH	**longitudinal notch 30%t deep x 10t long**	30	10	2.25	-----	-----	-----	7250	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.243	0.265	0.176	-----	min	OD-NOTCH	**longitudinal notch 30%t deep x 5t long**	30	5	1.13	-----	-----	-----	8200	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.235	0.260	0.145	-----	min	OD-NOTCH	**longitudinal notch 40%t deep x 10t long**	40	10	2.25	-----	-----	-----	7150	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.236	0.259	0.248	-----	avg	OD-NOTCH	**longitudinal notch 5%t deep x 5t long**	5	5	1.13	-----	-----	-----	8500	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.240	0.261	0.250	-----	avg	OD-NOTCH	**longitudinal notch 5%t deep x 5t long**	5	5	1.13	-----	-----	-----	8500	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.227	0.262	0.115	-----	min	OD-NOTCH	**longitudinal notch 50%t deep x 10t long**	50	10	2.25	-----	-----	-----	7000	yes	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.256	0.269	0.077	-----	min	OD-NOTCH	**longitudinal notch 80%t deep x 13t long**	80	13	2.91	-----	-----	-----	3900	yes	-----

TABLE A -1 (CON'T) TESTS CONDUCTED BY WG-1 ON STEEL CYLINDERS FOR FITNESS FOR PURPOSE ANALYSIS

	TENSILE					WALL THICKNESS (in.)															
CYLINDER TYPE	STRENGTH MINIMUM	INSIDE DIAMETER	DESIGN THICKNESS	SERVICE PRESSURE	TEST PRESSURE			WALL	WALL	FLAW	FLAW TYPE	FLAW DESCRIPTION	FLAW SIZE						BURST PRESSURE	FAILURE AT	CYCLES TO
						MIN.	AVG.	UNDER	AT	AT			DEPTH	LENGTH	LENGTH	WIDTH	DIA.	AREA			

	(psi.)	(in.)	(in.)	(psi.)	(psi.)	WALL	WALL	FLAW	FLAW				(% X td)	(n X td)	(in.)	(in.)	(in.)	(sq. in.)	(psi.)	FLAW	FAIL
											OD-HOLE (PIT)										
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.236	0.260	0.161	-----	min	HOLE	OD hole 1/2" dia x 1/3t deep	1/3 X td	-----	-----	-----	0.5000	0.196	8100	-----	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.236	0.261	0.186	-----	avg	HOLE	OD hole 1/4" dia x 1/3t deep	1/3 X td	-----	-----	-----	0.2500	0.049	8450	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.252	0.265	0.190	-----	avg	HOLE	OD hole 1/4" dia x 1/3t deep	1/3 X td	-----	-----	-----	0.2500	0.049	8600	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.233	0.260	0.185	-----	avg	HOLE	OD hole 1/8" dia x 1/3t deep	1/3 X td	-----	-----	-----	0.1250	0.012	8500	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.248	0.266	0.191	-----	avg	HOLE	OD hole 1/8" dia x 1/3t deep	1/3 X td	-----	-----	-----	0.1250	0.012	8500	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.238	0.264	0.189	-----	avg	HOLE	OD hole 3/16" dia x 1/3t deep	1/3 X td	-----	-----	-----	0.1875	0.028	8250	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.245	0.270	0.195	-----	avg	HOLE	OD hole 3/16" dia x 1/3t deep	1/3 X td	-----	-----	-----	0.1875	0.028	9050	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.233	0.261	0.158	-----	min	HOLE	OD hole 3/4" dia x 1/3t deep	1/3 X td	-----	-----	-----	0.7500	0.442	8050	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.247	0.270	0.195	-----	avg	HOLE	OD hole 3/8" dia x 1/3t deep	1/3 X td	-----	-----	-----	0.3750	0.110	8200	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.236	0.260	0.185	-----	avg	HOLE	OD hole 3/8" dia x 1/3t deep	1/3 X td	-----	-----	-----	0.3750	0.110	8350	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.241	0.266	0.191	-----	avg	HOLE	OD hole 5/16" dia x 1/3t deep	1/3 X td	-----	-----	-----	0.3125	0.077	8650	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.230	0.258	0.183	-----	avg	HOLE	OD hole 5/16" dia x 1/3t deep	1/3 X td	-----	-----	-----	0.3125	0.077	8050	no	-----
DOT 3F/9809-1	130,000	8.75	0.224	3300	4950	0.222	0.259	0.147	-----	min	HOLE	OD hole 5/8" dia x 1/3t deep	1/3 X td	-----	-----	-----	0.6250	0.307	8100	no	-----
HC4500	155,000	8.75	0.260	4500	6750	0.260	0.300	-----	-----	-----	**DESIGN**	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
											UNFLAWED										
HC4500	155,000	8.75	0.260	4500	6750	0.248	0.300	-----	-----	-----	NONE	-----	-----	-----	-----	-----	-----	-----	10050	-----	-----
HC4500	155,000	8.75	0.260	4500	6750	0.278	0.303	-----	-----	-----	NONE	-----	-----	-----	-----	-----	-----	-----	11350	-----	-----
			0.260								**LONGITUDINAL NOTCH**										
HC4500	155,000	8.75	0.260	4500	6750	0.253	0.299	0.227	-----	-----	OD-NOTCH	longitudinal notch 10 %t deep x 10t long	10	10	2.60	-----	-----	-----	9750	yes	-----
HC4500	155,000	8.75	0.260	4500	6750	0.271	0.296	0.219	-----	-----	OD-NOTCH	longitudinal notch 20 %t deep x 10t long	20	10	2.60	-----	-----	-----	9300	yes	-----
HC4500	155,000	8.75	0.260	4500	6750	0.261	0.304	0.183	-----	-----	OD-NOTCH	longitudinal notch 30 %t deep x 10t long	30	10	2.60	-----	-----	-----	8850	yes	-----
HC4500	155,000	8.75	0.260	4500	6750	0.253	0.304	0.149	-----	-----	OD-NOTCH	longitudinal notch 40 %t deep x 10t long	40	10	2.60	-----	-----	-----	8350	yes	-----
HC4500	155,000	8.75	0.260	4500	6750	0.269	0.308	0.139	-----	-----	OD-NOTCH	longitudinal notch 50 %t deep x 10t long	50	10	2.60	-----	-----	-----	8300	yes	-----
HC4500	155,000	8.75	0.260	4500	6750	0.271	0.285	0.141	-----	-----	OD-NOTCH	longitudinal notch 5 %t deep x 10t long	5	10	2.60	-----	-----	-----	10700	yes	-----
HC4500	155,000	8.75	0.260	4500	6750	0.277	0.297	0.147	-----	-----	OD-NOTCH	longitudinal notch 10 %t deep x 10t long	10	10	2.60	-----	-----	-----	10800	yes	-----
HC4500	155,000	8.75	0.260	4500	6750	0.267	0.317	0.157	-----	-----	OD-NOTCH	longitudinal notch 15 %t deep x 10t long	15	10	2.60	-----	-----	-----	10500	yes	-----
			0.260								**RECTANGULAR-LTA**										
HC4500	155,000	8.75	0.260	4500	6750	0.273	-----	0.260	-----	-----	D-LTA-RECTANGULA	LTA 2.25" long x 1.75" x 5%t deep	5	8.65	2.25	1.75	-----	3.938	10100	yes	-----
HC4500	155,000	8.75	0.260	4500	6750	0.291	-----	0.200	-----	-----	D-LTA-RECTANGULA	LTA 2.25" long x 1.75" x 10%t deep	10	8.65	2.25	1.75	-----	3.938	10700	yes	-----
HC4500	155,000	8.75	0.260	4500	6750	0.285	-----	0.265	-----	-----	D-LTA-RECTANGULA	LTA 2.25" long x 1.75" x 15%t deep	15	8.65	2.25	1.75	-----	3.938	10100	yes	-----
HC4500	155,000	8.75	0.260	4500	6750	0.281	-----	0.229	-----	-----	D-LTA-RECTANGULA	LTA 2.25" long x 1.75" x 20%t deep	20	8.65	2.25	1.75	-----	3.938	9900	yes	-----
HC4500	155,000	8.75	0.260	4500	6750	0.291	-----	0.213	-----	-----	D-LTA-RECTANGULA	LTA 2.25" long x 1.75" x 30%t deep	30	8.65	2.25	1.75	-----	3.938	10400	yes	-----
HC4500	155,000	8.75	0.260	4500	6750	0.290	-----	0.186	-----	-----	D-LTA-RECTANGULA	LTA 2.25" long x 1.75" x 40%t deep	40	8.65	2.25	1.75	-----	3.938	9400	yes	-----
HC4500	155,000	8.75	0.260	4500	6750	0.277	-----	0.147	-----	-----	D-LTA-RECTANGULA	LTA 2.25" long x 1.75" x 50%t deep	50	8.65	2.25	1.75	-----	3.938	8100	yes	-----
											OD-HOLE (PIT)										
HC4500	155,000	8.75	0.260	4500	6750	0.270	-----	0.183	-----	-----	OD-HOLE	-----	33	-----	-----	-----	0.500	0.196	10600	yes	-----
HC4500	155,000	8.75	0.260	4500	6750	0.275	-----	0.188	-----	-----	OD-HOLE	-----	33	-----	-----	-----	0.750	0.442	10600	no	-----
											ID-HOLE (PIT)										
HC4500	155,000	8.75	0.260	4500	6750	-----	-----	0.223	-----	-----	ID-HOLE	ID hole 1/2" dia x 1/3t (0.093") deep	33	-----	-----	-----	0.500	0.196	10900	no	-----
HC4500	155,000	8.75	0.260	4500	6750	-----	-----	0.225	0.316	-----	ID-HOLE	ID hole 3/4" dia x 1/3t (0.097") deep	33	-----	-----	-----	0.750	0.442	10450	no	-----
HC4500	155,000	8.75	0.260	4500	6750	-----	-----	0.170	0.322	-----	ID-HOLE	ID hole 1/2" dia x (0.150") deep	58	-----	-----	-----	0.500	0.196	10600	no	-----
HC4500	155,000	8.75	0.260	4500	6750	-----	-----	0.179	0.320	-----	ID-HOLE	ID hole 1/2" dia x (0.150") deep	58	-----	-----	-----	0.500	0.196	10300	no	-----
HC4500	155,000	8.75	0.260	4500	6750	-----	-----	0.208	0.329	-----	ID-HOLE	ID hole 1/2" dia x (0.081") deep	31	-----	-----	-----	0.500	0.196	6750	yes	4904
HC4500	155,000	8.75	0.260	4500	6750	-----	-----	-----	0.289	-----	ID-HOLE	ID hole 3/4" dia x (0.121") deep	47	-----	-----	-----	0.750	0.442	6750	yes	6594

TABLE A -1 (CON'T) TESTS CONDUCTED BY WG-1 ON STEEL CYLINDERS FOR FITNESS FOR PURPOSE ANALYSIS

	TENSILE					WALL THICKNESS (in.)															
CYLINDER	STRENGTH	INSIDE	DESIGN	SERVICE	TEST			WALL	WALL	FLAW	FLAW TYPE	FLAW DESCRIPTION	FLAW SIZE						BURST	FAILURE	CYCLES
TYPE	MINIMUM	DIAMETER	THICKNESS	PRESSURE	PRESSURE	MIN.	AVG.	UNDER	AT	AT			DEPTH	LENGTH	LENGTH	WIDTH	DIA.	AREA	PRESSURE	AT	TO
	(psi.)	(in.)	(in.)	(psi.)	(psi.)	WALL	WALL	FLAW	FLAW				(% X td)	(n X td)	(in.)	(in.)	(in.)	(sq. in.)	(psi.)	FLAW	FAIL
											DESIGN										
HC6000	155,000	8.75	0.339	6000	9000	0.339	0.380	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
											UNFLAWED										
HC6000	155,000	8.75	0.339	6000	9000	0.331	0.374	-----	-----	-----	NONE	-----	-----	-----	-----	-----	-----	-----	13400	-----	-----
HC6000	155,000	8.75	0.339	6000	9000	0.332	0.373	-----	-----	-----	NONE	-----	-----	-----	-----	-----	-----	-----	13700	-----	-----
											LONGITUDINAL NOTCH										
HC6000	155,000	8.75	0.339	6000	9000	0.340	0.379	0.314	-----	-----	OD-NOTCH	longitudinal notch 10 %t deep x 10t long	10	10	3.39	-----	-----	-----	13600	no	-----

HC6000	155,000	8.75	0.339	6000	9000	0.328	0.382	0.276	-----	-----	OD-NOTCH	**longitudinal notch 20 %t deep x 10t long**	10	10	3.39	-----	-----	-----	12350	yes	-----
HC6000	155,000	8.75	0.339	6000	9000	0.331	0.382	0.253	-----	-----	OD-NOTCH	**longitudinal notch 30 %t deep x 10t long**	30	10	3.39	-----	-----	-----	11000	yes	-----
HC6000	155,000	8.75	0.339	6000	9000	0.317	0.378	0.213	-----	-----	OD-NOTCH	**longitudinal notch 40 %t deep x 10t long**	40	10	3.39	-----	-----	-----	9850	yes	-----
HC6000	155,000	8.75	0.339	6000	9000	0.345	0.380	0.215	-----	-----	OD-NOTCH	**longitudinal notch 50 %t deep x 10t long**	50	10	3.39	-----	-----	-----	9000	yes	-----
HC6000	155,000	8.75	0.339	6000	9000	0.344	0.372	0.214	-----	-----	OD-NOTCH	**longitudinal notch 5 %t deep x 10t long**	5	10	3.39	-----	-----	-----	13500	yes	-----
HC6000	155,000	8.75	0.339	6000	9000	0.366	0.397	0.236	-----	-----	OD-NOTCH	**longitudinal notch 15 %t deep x 10t long**	15	10	3.39	-----	-----	-----	13600	yes	-----

						WALL THICKNESS (in.)							**FLAW SIZE**								
CYLINDER TYPE	**TENSILE STRENGTH MINIMUM (psi.)**	**INSIDE DIAMETER (in.)**	**DESIGN THICKNESS (in.)**	**SERVICE PRESSURE (psi.)**	**TEST PRESSURE (psi.)**	**MIN. WALL**	**AVG. WALL**	**WALL UNDER FLAW**	**WALL AT FLAW**	**FLAW AT**	**FLAW TYPE**	**FLAW DESCRIPTION**	**DEPTH (% X td)**	**DEPTH (in.)**	**LENGTH (n X td)**	**LENGTH (in.)**	**FATIGUE CRACK GROWTH (in.)**	**LIGAMENT AFTER CYCLING (in.)**	**CYCLES AT 6750 PSI**	**CYCLED TO FAILURE**	**BURST PRESSURE (psi.)**
HC4500	155,000	8.75	0.260	3300	4950	0.260	-----	-----	-----	-----	**DESIGN**	-----	-----	-----	-----	-----	-----	-----	-----	-----	-----
											ID LONGITUDINAL NOTCH										
HC4500	155,000	8.75	0.260	4500	6750	0.260	-----	-----	0.300	-----	ID-NOTCH	**longitudinal notch 5 %t deep x 10t long**	5	0.013	10	2.60	0.215	0.072	6556	-----	6750
HC4500	155,000	8.75	0.260	4500	6750	0.260	-----	-----	0.270	-----	ID-NOTCH	**longitudinal notch 10 %t deep x 10t long**	10	0.026	10	2.60	0.175	0.690	3512	-----	6750
HC4500	155,000	8.75	0.260	4500	6750	0.260	-----	-----	0.290	-----	ID-NOTCH	**longitudinal notch 15 %t deep x 10t long**	15	0.038	10	2.60	0.180	0.071	1260	-----	6750
HC4500	155,000	8.75	0.260	4500	6750	0.260	-----	-----	0.300	-----	ID-NOTCH	**longitudinal notch 20 %t deep x 10t long**	20	0.052	10	2.60	0.180	0.068	1339	-----	6750
HC4500	155,000	8.75	0.260	4500	6750	0.260	-----	-----	0.310	-----	ID-NOTCH	**longitudinal notch 25 %t deep x 10t long**	25	0.065	10	2.60	0.200	0.045	2038	-----	6750
HC4500	155,000	8.75	0.260	4500	6750	0.260	-----	-----	0.295	-----	ID-NOTCH	**longitudinal notch 5 %t deep x 3.85t long**	5	0.013	3.85	1.00	0.235	0.047	3081	-----	6750
HC4500	155,000	8.75	0.260	4500	6750	0.260	-----	-----	0.295	-----	ID-NOTCH	**longitudinal notch 10 %t deep x 3.85t long**	10	0.026	3.85	1.00	0.220	0.049	4244	-----	6750
HC4500	155,000	8.75	0.260	4500	6750	0.260	-----	-----	0.265	-----	ID-NOTCH	**longitudinal notch 15 %t deep x 3.85t long**	15	0.038	3.85	1.00	0.185	0.041	1511	-----	6750
HC4500	155,000	8.75	0.260	4500	6750	0.260	-----	-----	0.305	-----	ID-NOTCH	**longitudinal notch 20 %t deep x 3.85t long**	20	0.052	3.85	1.00	0.210	0.043	3190	-----	6750
HC4500	155,000	8.75	0.260	4500	6750	0.260	-----	-----	0.305	-----	ID-NOTCH	**longitudinal notch 25 %t deep x 3.85t long**	25	0.065	3.85	1.00	0.195	0.045	3055	-----	6750

TABLE A - 2 TESTS CONDUCTED BY WG-14 ON STEEL CYLINDERS

FOR FAILURE PRESSURE (Pf) APPROXIMATELY = SERVICE PRESSURE (Ps)

	CYLINDER DESCRIPTION						FLAW DESCRIPTION				TEST RESULTS			
								FLAW SIZE						
CYLINDER TEST NO.	DIA. (mm.)	DESIGN THICK. (td) (mm.)	SPECIFIED YIELD MINIMUM (MPa)	SPECIFIED TENSILE MINIMUM (MPa)	DESIGN TEST PRESSURE (bar)	DESIGN SERVICE PRESSURE (bar)	FLAW TYPE	DEPTH (a/ t)	LENGTH [n = l / t]	LENGTH (mm.)	FAILURE PRESSURE (bar)	FAILURE MODE	Pf/Pb MEASURED	CALC. (Pf/Pb) (RSF)
GROUP A MATERIAL (MEASURED TENSILE STRENGTH < 750 MPa)														
A-1-1	230	6.6	640	----	232	155	OD-LONGITUDUINAL NOTCH	0.95	5	33.0	166	LEAK	O.48	0.21
"	230	6.6	640	----	232	155	OD-LONGITUDUINAL NOTCH	0.90	5	33.0	162	LEAK	0.44	O.27
A-1-2	230	6.6	640	----	232	155	OD-LONGITUDUINAL NOTCH	0.85	15	99.0	169	LEAK	0.49	0.24
"	230	6.6	640	----	232	155	OD-LONGITUDUINAL NOTCH	0.80	15	99.0	172	FRACTURE	0.50	0.21
GROUP B MATERIAL (MEASURED TENSILE STRENGTH 750 TO 950 MPa)														
B-7-1	237	8.7	724	897	414	276	OD-LONGITUDUINAL NOTCH	0.80	10	86.6	283	FRACTURE	0.46	0.35
B-7-2	237	8.7	724	897	414	276	OD-LONGITUDUINAL NOTCH	0.75	10	86.6	269	LEAK	0.43	0.42
B-8-1	238	14.4	724	897	690	460	OD-LONGITUDUINAL NOTCH	0.80	10	144.0	462	LEAK	0.45	0.31
B-8-2	238	14.4	724	897	690	460	OD-LONGITUDUINAL NOTCH	0.75	10	144.0	441	LEAK	0.43	0.37
B-9-20	178	3.8	687	862	232	156	OD-LONGITUDUINAL NOTCH	0.91	13	48.0	152	LEAK	0.44	0.19
B-9-21	178	3.8	687	862	232	156	OD-LONGITUDUINAL NOTCH	0.80	15	57.2	159	FRACTURE	0.46	0.33
GROUP C MATERIAL (MEASURED TENSILE STRENGTH 950 TO 1080 MPa)														
C-4-1	236	6.6	1069	1207	466	310	OD-LONGITUDUINAL NOTCH	0.85	10	66.0	303	LEAK	0.43	0.3
C-4-1	236	6.6	1069	1207	466	310	OD-LONGITUDUINAL NOTCH	0.80	10	66.0	310	LEAK	0.44	0.37
C-5-16	229	6.0	880	1030	300	200	OD-LONGITUDUINAL NOTCH	0.78	13	77.6	217	LEAK	0.44	0.36
C-10-1	235	5.6	930	1068	345	230	OD-LONGITUDUINAL NOTCH	0.85	10	55.6	228	LEAK	0.44	0.31
C-10-5	235	5.6	930	1068	345	230	OD-LONGITUDUINAL NOTCH	0.85	10	55.6	228	LEAK	0.44	0.31
C-10-6	235	5.6	930	1068	345	230	OD-LONGITUDUINAL NOTCH	0.85	10	55.6	245	LEAK	0.47	0.31
C-12-1	191	6.6	950	1100	476	317	OD-LONGITUDUINAL NOTCH	0.85	10	66.0	333	LEAK	0.47	0.28
GROUP D MATERIAL (MEASURED TENSILE STRENGTH 1080 TO 1210 MPa)														
D-5-11	237	6.6	1068	1207	465	310	OD-LONGITUDUINAL NOTCH	0.86	10	64.7	324	LEAK	0.46	0.28
D-5-12	237	6.6	1068	1207	465	310	OD-LONGITUDUINAL NOTCH	0.91	10	62.7	316	LEAK	0.45	0.2
D-10-1	236	6.6	1068	1207	465	310	OD-LONGITUDUINAL NOTCH	0.80	10	66.0	331	FRACTURE	0.47	0.37
D-10-4	236	6.6	1068	1207	465	310	OD-LONGITUDUINAL NOTCH	0.85	10	66.0	307	LEAK	0.44	0.3
D-10-7	236	6.6	1068	1207	465	310	OD-LONGITUDUINAL NOTCH	0.80	10	66.0	328	LEAK	0.47	0.37
D-14-2	236	6.6	1068	1207	465	310	OD-LONGITUDUINAL NOTCH	0.80	10	66.0	297	LEAK	0.43	0.37
D-14-4	236	6.6	1068	1207	465	310	OD-LONGITUDUINAL NOTCH	0.78	10	66.0	324	FRACTURE	0.46	0.4
GROUP E MATERIAL (MEASURED TENSILE STRENGTH > 1250 MPa)														
E-1-9	235	5.6	----	----	345	230	OD-LONGITUDUINAL NOTCH	0.80	12	66.7	219	LEAK	0.42	0.36
E-2-3	234	6.6	----	----	466	311	OD-LONGITUDUINAL NOTCH	0.80	8	52.8	310	FRACTURE	0.44	0.43

TABLE A - 3 TESTS CONDUCTED BY WG-14 ON STEEL CYLINDERS

FOR FAILURE PRESSURE (Pf) APPROXIMATELY = TEST PRESSURE (Pt)

	CYLINDER DESCRIPTION						FLAW DESCRIPTION				TEST RESULTS			
								FLAW SIZE						
CYLINDER TEST NO.	DIA. (mm.)	DESIGN THICK. (td) (mm.)	SPECIFIED YIELD MINIMUM (MPa)	SPECIFIED TENSILE MINIMUM (MPa)	DESIGN TEST PRESSURE (bar)	DESIGN SERVICE PRESSURE (bar)	FLAW TYPE	DEPTH (a/t)	LENGTH (n = l / t)	LENGTH (mm.)	FAILURE PRESSURE (bar)	FAILURE MODE	Pf/Pb MEASURED	CALC. (Pf/Pb) (RSF)
GROUP A MATERIAL (MEASURED TENSILE STRENGTH < 750 MPa)														
A-1-2	230	6.6	640	----	232	155	OD-LONGITUDUINAL NOTCH	0.70	9	56.1	234	FRACTURE	0.67	0.54
GROUP B MATERIAL (MEASURED TENSILE STRENGTH 750 TO 950 MPa)														
B-3-6	235	5.8	724	----	276	184	OD-LONGITUDUINAL NOTCH	0.86	7	39.4	276	LEAK	0.67	0.39
B-3-7	235	5.8	724	----	276	184	OD-LONGITUDUINAL NOTCH	0.67	10	57.4	270	FRACTURE	0.65	0.57
B-3-11	235	5.8	724	----	276	184	OD-LONGITUDUINAL NOTCH	0.76	11	61.5	268	FRACTURE	0.65	0.43
B-4-1	230	6.5	724	----	221	147	OD-LONGITUDUINAL NOTCH	0.80	13	84.5	212	LEAK	0.65	0.33
B-6-5	230	6.4	724	----	276	184	OD-LONGITUDUINAL NOTCH	0.85	8	50.8	269	LEAK	0.65	0.35
B-9-10	175	3.8	687	862	232	156	OD-LONGITUDUINAL NOTCH	0.90	9	32.4	234	LEAK	0.67	0.27
B-9-23	175	3.8	687	862	232	156	OD-LONGITUDUINAL NOTCH	0.68	15	56.1	224	FRACTURE	0.64	0.48
GROUP C MATERIAL (MEASURED TENSILE STRENGTH 950 TO 1080 MPa)														
C-3-3	235	6.1	724	----	276	184	OD-LONGITUDUINAL NOTCH	0.85	8	48.8	290	FRACTURE	0,70	0,57
C-5-20	229	6.0	880	1030	300	200	OD-LONGITUDUINAL NOTCH	0.80	10	59.7	305	LEAK	0.68	0.38
C-15-1	191	5.8	950	1050	420	280	OD-LONGITUDUINAL NOTCH	0.78	10	56.8	436	FRACTURE	0.66	0.56
C-18-1	232	5.2	950	1050	309	206	OD-LONGITUDUINAL NOTCH	0.85	10	51.5	317	FRACTURE	0.68	0.59
GROUP D MATERIAL (MEASURED TENSILE STRENGTH 1080 TO 1210 MPa)														
D-2-1	230	4.5	1100	1160	300	200	OD-LONGITUDUINAL NOTCH	0.83	8	37.4	300	LEAK	0.67	0.41
D-2-2	230	4.5	1100	1160	300	200	OD-LONGITUDUINAL NOTCH	0.94	7	31.5	300	LEAK	0.67	0.22
D-2-3	230	4.5	1100	1160	300	200	OD-LONGITUDUINAL NOTCH	0.90	10	45.0	300	LEAK	0.67	0.24
D-2-4	230	4.5	1100	1160	300	200	OD-LONGITUDUINAL NOTCH	0.85	10	45.0	300	LEAK	0.67	0.34
D-2-5	230	4.5	1100	1160	300	200	OD-LONGITUDUINAL NOTCH	0.80	10	45.0	300	LEAK	0.67	0.42
D-2-6	230	4.5	1100	1160	300	200	OD-LONGITUDUINAL NOTCH	0.75	10	45.0	300	FRACTURE	0.67	0.49
D-2-7	230	4.5	1100	1160	300	200	OD-LONGITUDUINAL NOTCH	0.71	10	45.0	300	FRACTURE	0.67	0.54
D-2-8	230	4.5	1100	1160	300	200	OD-LONGITUDUINAL NOTCH	0.77	10	45.0	300	FRACTURE	0.67	0.46
D-2-9	230	4.5	1100	1160	300	200	OD-LONGITUDUINAL NOTCH	0.72	10	45.0	300	FRACTURE	0.67	0.53
D-2-10	230	4.5	1100	1160	300	200	OD-LONGITUDUINAL NOTCH	0.68	10	45.0	300	FRACTURE	0.67	0.58
D-2-11	230	4.5	1100	1160	300	200	OD-LONGITUDUINAL NOTCH	0.77	10	42.8	285	LEAK	0.63	0.48
D-2-13	230	4.5	1100	1160	300	200	OD-LONGITUDUINAL NOTCH	0.76	10	45.0	290	LEAK	0.64	0.47
D-2-14	230	4.5	1100	1160	300	200	OD-LONGITUDUINAL NOTCH	0.75	10	45.0	310	LEAK	0.69	0.49
D-3-5	230	5.2	934	----	300	200	OD-LONGITUDUINAL NOTCH	0.89	10	52.0	295	LEAK	0.66	0.50
D-3-5	230	5.2	934	----	300	200	OD-LONGITUDUINAL NOTCH	0.79	8	39.1	310	FRACTURE	0.69	0.47

D-3-6	230	5.2	934	----	300	200	OD-LONGITUDUINAL NOTCH	0.76	10	49.9	295	FRACTURE	0.63	0.43
D-5-7	230	6.6	1069	1207	465	310	OD-LONGITUDUINAL NOTCH	0.68	10	67.3	457	LEAK	0.65	0.44
D-11-8	230	6.4	1069	1207	450	300	OD-LONGITUDUINAL NOTCH	0.60	10	64.0	465	FRACTURE	0.69	0.62
D-14-32	236	6.6	1069	1207	465	310	OD-LONGITUDUINAL NOTCH	0.71	10	66.0	459	FRACTURE	0.66	0.49
GROUP E MATERIAL (MEASURED TENSILE STRENGTH > 1250 MPa)														
E-1-4	236	5.6	----	----	345	230	OD-LONGITUDUINAL NOTCH	0.75	8	44.5	334	FRACTURE	0.65	0.52