DEVELOPMENT OF ACCEPTANCE/REJECTION CRITERIA FOR REQUALIFICATION OF HIGH PRESSURE GAS CYLINDERS.

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ABSTRACT

The objective of this study is to establish a sound technical basis for developing acceptance/rejection limits for seamless, high pressure gas cylinders that can be used at the time of prequalification the cylinders. The development of acceptance/rejection limits for cylinders is done in three steps. First, the "critical flaw sizes" (e.g. depth and length or area) for selected types of flaws are established by analysis that has been verified by experimental tests. Next the "allowable flaw sizes" are calculated by modifying (reducing) the size of the "critical flaw sizes" for each cylinder by adjusting for fatigue crack growth that may occur during the use of the cylinder. Finally the acceptance/rejection limits are established to take into account other factors such as all the expected operating conditions that the cylinders may see in service and as well as the reliability and detectability of the specific inspection equipment to be used to provide as acceptable and to adjust the "allowable flaw sizes" to provide an additional margin of safety.

In this study, the API Recommended Practice 579 "Fitness-for-Service" was used to calculate the "critical flaw sizes"a variety of flaws in a range of cylinder sizes and strength levels. For this study the "critical flaw size" defined as the size of the flaw that will cause the cylinders to fail at the marked service pressure of the cylinder. Flawed-cylinder burst tests were conducted to verify the calculated "critical flaw sizes. The "allowable flaw sizes" were then calculated by using well established fatigue crack growth rate data to allow for the expected amount of fatigue crack growth that could occur during established prequalification internals. A limited number of tests were conducted to verify the "allowable flaw size" calculations. Further adjustments are made to the "allowable flaw sizes" to define the acceptance/rejection limits to be used during cylinder prequalification.

1 INTRODUCTION

Seamless steel 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]. As part of these safety regulations the cylinders are required to be periodically requalified during their lifetime. Recently, methods of requaliying the cylinders by ultrasonic methods have been developed that permit the quantitative determination of the cylinder wall thickness and the size of flaws that are detected in the cylinders. To use these ultrasonic test methods it is necessary to establish "allowable flaw sizes" and to develop "acceptance/rejection limits" for the cylinders at the time of prequalification.

2 ANALYSIS AND EXPERIMENTAL RESULTS

2.1 TECHNICAL APPROACH

In this study, the “critical flaw sizes” are first established by analysis for seamless cylinders by determining the effect of various types and sizes of flaws on the performance (i.e. burst pressure) of the cylinders. The “critical flaw size” is defined as the size (ex. depth and length or area) of a flaw that will cause the cylinders to fail at the marked service pressure (MAWP). 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 [2]. This method of analysis, determines how much the failure pressure of a cylinder containing a flaw is reduced compared to the failure pressure of a similar cylinder that does not contain a flaws. The calculated “critical flaw sizes” were verified by hydrostatic burst tests on cylinders containing a variety of flaw sizes as described in reference [3].

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 “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. For this study, only fatigue crack growth will be considered. To develop “allowable flaw sizes” for the steel cylinders, the fatigue life cycle is defined as 3500 pressure cycles from 0 psi 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 prequalification interval.

To develop the “allowable flaw size” requirements, fatigue crack growth rate calculations are carried out to adjust the “critical flaw sizes” that are expected to cause failure at the MAWP 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 MAWP. These “initial” flaw sizes are then defined as the “allowable flaw sizes” for the cylinder.

2.2 ANALYSIS OF FLAW SIZES

For the seamless steel cylinders evaluated here, the “remaining strength factor” (RSF) defined in the API 579 methods of analysis was found to be the suitable failure criteria. 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. The RSF may also be defined as the ratio of the failure pressure of a cylinder containing a flaw and the failure pressure of the same cylinder without a flaw, that is: RSF = $(P_f)/(P_b)$. The RSF is calculated as:

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

Where: M_t is the Folias stress magnification factor

R_t is the remaining thickness ration = t_{mm}/t

To develop the allowable flaw size” requirements, the “critical flaw sizes” that are expected to cause failure at the MAWP are then carried out to determine the “initial” flaw sizes that will grow to the critical flaw size after a designated use cycle. For this study, only fatigue crack growth was considered to calculate the “allowable flaw sizes”. To develop “allowable flaw sizes”. For this study, 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 prequalification interval.

The following example shows the procedure used to calculate the “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 [4].

The crack growth rate is calculated as:

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

Where (for steel cylinders):

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

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

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

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 methods of analysis described above. The allowable flaw sizes were then calculated using the fatigue crack analysis equations described above. 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 Figures 1.

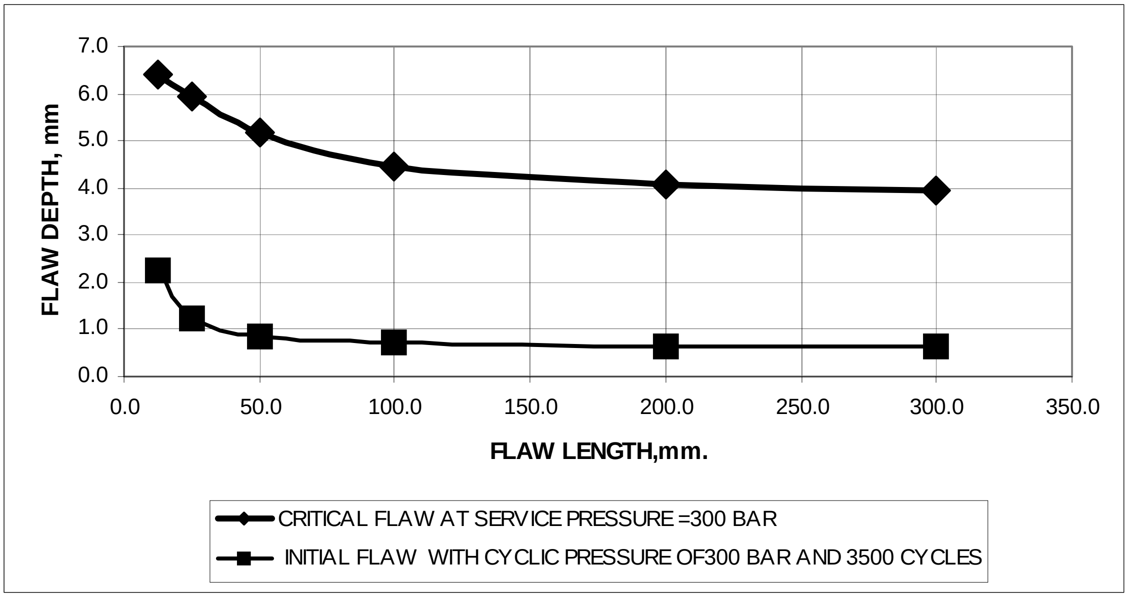

Figure 1: LTA Analysis of 300 Bar, 230 mm OD, 6.6 mm Wall Cylinder

2.3 Establishing acceptance/rejection criteria – Although a sound technical basis has been established for developing "allowable flaw sizes" that take accounts fatigue cracking, 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. It may be necessary to take into account the reliability and detect ability of the specific inspection equipment and to adjust the "allowable flaw sizes" to provide an additional margin of safety. In addition, it is necessary to provide a "user friendly" form to present the "acceptance/rejection" limits for use by the prequalification tester. An example of the "acceptance/rejection" criteria is shown in Figure 2.

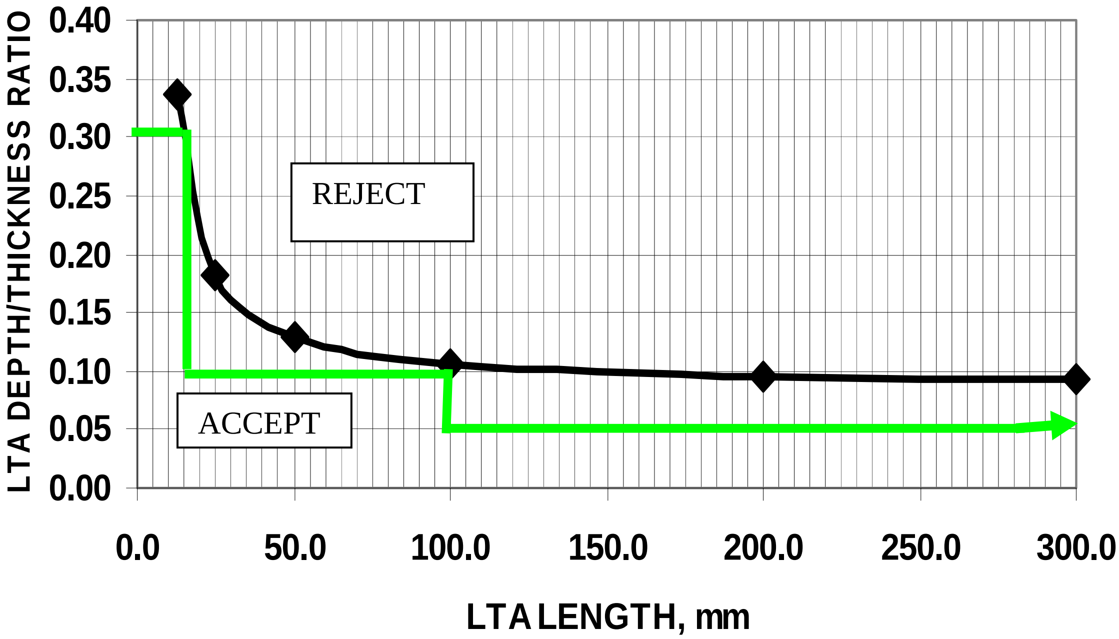

Figure 2 Allowable Flaw Size Criteria for HP Steel Cylinders

3 DISCUSSION

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.

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 “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 “allowable flaw sizes” to be used for setting acceptance/rejection criteria for use at the time of retesting.

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 MAWP show the flaw size that would be expected to cause a failure of the cylinder while in service. Once this flaw size is established, “allowable flaw sizes” can be established to ensure that no flaw actually reaches the critical size while the cylinder is in service.

The “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. The analysis and experimental verification conducted in this study was limited to and evaluation of fatigue crack growth. The "allowable flaw sizes" are used to establish the size of flaws that cause the cylinders to be rejected at the time of prequalification.

Although a sound technical basis has been established for developing "allowable flaw sizes" that take accounts 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 detect ability of the specific inspection equipment and to adjust the "allowable flaw sizes" to provide an additional margin of safety.

4 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 flaws in seamless steel cylinders.

2. "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.

3. The "allowable flaw sizes" are then used to set the "acceptance/rejection" levels for flaws at the time of inspection or requalification of the cylinders.

5 REFERENCES

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