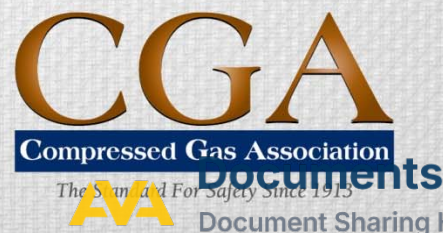


CGA TR-2—2004
REAFFIRMED 2018

HIGH PRESSURE STEEL CYLINDERS
IN-SERVICE PERFORMANCE

FIRST EDITION



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Work Item 14-018
Cylinder Specifications Committee

NOTE—No technical information has been changed from the 2004 edition. This reaffirmed edition may include minor editorial changes.

NOTE—Appendix A (Informative) is for information only.

REAFFIRMED: 2018
REAFFIRMED: 2008
FIRST EDITION: 2004

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Summary

Taylor-Wharton issued a report warning of the potential fragmentation hazard associated with “first generation” cylinders defined as carbon steel cylinders made from 1902 to approximately 1930. “First generation” cylinders are still in service and may be designated as 3A type cylinders.

This CGA technical report presents the results of extensive studies on fracture performance of DOT-3A type cylinders (including ICC-3 and 3A cylinders made since 1902). Data on service failures of DOT-3A type and DOT-3AA type cylinders are also compiled and analyzed.

The results of this study indicate that:

- Prevention of cylinder fragmentation during service has always been a consideration in cylinder design specifications. Design and testing acceptance criteria have been in place since the first specifications for high pressure seamless steel cylinders were written (before 1910).
- Regardless of age, there are few reported incidents of either DOT-3A or DOT-3AA cylinders in service that fail by fragmentation. All known incidents were associated with multiple flaws in the cylinders.
- If either DOT-3A or DOT-3AA cylinders fail in service due to a single flaw, they will *not* fragment. The failure mode at pressures higher than the test pressure is not considered in this report because industry standard operating practices limit cylinder pressure. Thus, cylinders are not expected to be pressurized in-service above the test pressure. The following table summarizes the failure modes of DOT-3A type and DOT-3AA type cylinders under pneumatic loading.

Failure pressure	Flaw	DOT-3A failure mode	DOT-3AA failure mode
Less than test pressure	Single crack	1 to 3 pieces	1 to 3 pieces
	Multiple cracks (SCC)	Many pieces	Many pieces
More than test pressure	Single crack	Many pieces	One or many pieces
	Multiple cracks (SCC)	Many pieces	Many pieces

- Both DOT-3A and DOT-3AA cylinders may fragment in service due to multiple cracks, e.g., stress corrosion cracking.
- Both DOT-3A and DOT-3AA cylinders have equivalent fracture initiation performance during service. This has been verified by extensive testing and analysis that is reported in the technical report ISO/TR 12391-2.
- The safety of DOT-3AA cylinders is obtained by stringent material property requirements that permit higher working stresses (thinner cylinder wall) than for DOT-3A cylinders. The equivalent safety of DOT-3A cylinders is obtained primarily by restricting the working stresses (thicker cylinder wall) to a lower level with less stringent material property requirements than for DOT-3AA cylinders.
- Carbon steel cylinders are currently being manufactured under established national (e.g., DOT-3A) and international (e.g., ISO 9809-3) cylinder specifications.
- DOT-3A cylinders are required to be requalified by periodic retesting in accordance with the rules specified in 49 CFR Part 180. In addition to the safety controls specified for the design and manufacture of the cylinders, the periodic requalification is required to ensure the safe use of DOT-3A type cylinders.
- From an evaluation of cylinders similar to DOT-3A type cylinders, the European Industrial Gas Association (EIGA) Position Paper 07-03, *Lifetime of pre 1930 Steel Cylinders* has concluded that such cylinders are suitable for continuous service and are currently in use today.

1 Introduction

In a letter entitled “A Century of Cylinders: An Open Letter to the Compressed Gas Industry (June 2002)” and the supporting test report “A Century of Cylinders-Test Program (June 28, 2002)” that were published by Taylor-Wharton, the compressed gas industry was warned of the potential fragmentation hazard associated with “first generation” cylinders defined as carbon steel cylinders made from 1902 to approximately 1930 [1, 2, 3].¹

This CGA technical report reviews the history of steel cylinder specifications and summarizes the procedures used for fracture and fragmentation control since steel cylinders were first manufactured. In addition, a summary and analysis of extensive studies of fracture control is presented to determine if DOT-3A cylinders are more likely to fracture and fragment in service than DOT-3AA specification cylinders [4]. Data on service failures of DOT-3A and DOT-3AA cylinder failures are also compiled and analyzed.

2 Scope

This report reviews the in-service performance of DOT-3A cylinders to determine their suitability for continued use.

3 Definitions

For the purpose of this publication, the following definitions apply.

3.1 Publication terminology

3.1.1 Shall

Indicates that the procedure is mandatory. It is used wherever the criterion for conformance to specific recommendations allows no deviation.

3.1.2 Should

Indicates that a procedure is recommended.

3.1.3 May

Indicates that the procedure is optional.

3.1.4 Will

Is used only to indicate the future, not a degree of requirement.

3.1.5 Can

Indicates a possibility or ability.

3.2 Technical definitions

3.2.1 3A type cylinder

Seamless steel cylinder having the material chemistry, tensile properties, and design wall stress similar to that of the DOT-3A specification cylinder [3]. For example, cylinders meeting the requirements of ISO 9809-3:2000 are considered to be 3A type cylinders [5].

3.2.2 3AA type cylinder

Seamless steel cylinder having the material chemistry, tensile properties, and wall stress similar to that of the DOT-3AA specification cylinder [4]. For example, cylinders meeting the requirements of ISO 9809-1:1999 are considered to be DOT-3AA type cylinders [6].

3.2.3 Brittle fracture

Separation of a metal that occurs with little or no plastic deformation and results in rapid crack propagation requiring little energy.

¹ References are shown by bracketed numbers and are listed in order of appearance in the reference section.

3.2.4 Burst pressure

Pressure at which a cylinder with no flaw fails when tested with increased pressure.

3.2.5 Charpy-V-notch (CVN) test

Impact test in which a specimen containing a V notch is struck with a pendulum to break the specimen. The energy absorbed to break the specimen is determined and is a measure of the resistance of the metal to fracturing.

3.2.6 Crack initiation

Onset of extension of a preexisting flaw.

3.2.7 Crack propagation

Increase in the length of a crack with little or no increasing load.

3.2.8 Ductility

Ability of a metal to deform plastically before failing, often measured by the elongation or reduction of area in a tensile test.

3.2.9 Failure pressure

Pressure at which a cylinder with a flaw fails when being loaded by increased pressure. This is the pressure at which the cylinder leaks or fractures.

3.2.10 Flawed cylinder burst test

Test conducted on a finished cylinder that has a prescribed flaw machined into the exterior and is internally pressurized to failure.

3.2.11 Fracture

Separation of a metal into two pieces caused by crack growth.

3.2.12 Fracture control

Combination of measures taken to prevent fracture during operation. This includes control of material properties requirements; design requirements; stress analysis; limits on applied stresses in the structure, inspection for cracks; and maintenance requirements.

3.2.13 Fracture performance

Type of crack growth at the instant of through-wall failure, by either stable crack arrest or a running crack rupture, i.e., leak or fracture.

3.2.14 Fracture toughness

Measure of a material's resistance to crack extension.

3.2.15 Fragmentation

Breaking into several pieces on fracturing. Each piece exhibits limited plastic deformation.

3.2.16 In-service condition

Normal conditions of a gas cylinder when it is filled, shipped, and used in accordance with the DOT regulations. This may include any pressure up to the designated test pressure.

3.2.17 Normalizing

Heat treatment process consisting of heating the steel above the critical transformation temperature range and cooling in still air at room temperature

3.2.18 Quenching and tempering

Heat treatment procedure for steel consisting of a process of rapid cooling from an elevated temperature above the critical transformation temperature range by contact with a liquid and subsequently reheating the steel to a temperature below the critical transformation temperature range and then cooling at any rate desired.

3.2.19 Service pressure

Maximum pressure to which a gas cylinder may be filled at 70 °F.

3.2.20 Test pressure

Pressure to which a gas cylinder must be subjected during the prescribed hydrostatic test.

4 Background information

4.1 Basic considerations of cylinder design

From the earliest days that compressed gas cylinders have been used, it has been recognized that the transportation of compressed gases could present potential serious safety problems. Therefore, extensive design studies, testing, inspection, manufacturing controls, requalification requirements, and operational controls have been imposed on the use of compressed gas cylinders. This has resulted in cylinders being designed, manufactured, and used to minimize any safety hazards. These requirements for the design, manufacturing, inspection, and requalification have been incorporated in various industry, national regulatory and international regulatory codes and specifications. From the earliest days of seamless steel cylinder manufacture, the specifications have always included requirements to prevent failure of the cylinders in service due to brittle fracture as well as failure due to overpressure, metal fatigue, and corrosion.

In the document entitled “CGA Basic Considerations of Cylinder Design,” the Cylinder Specification Committee of the Compressed Gas Association summarized the origin and the basic concepts for the requirements of the various cylinder specifications (see Appendix A). This document describes the origin of all of the present DOT (originally the Interstate Commerce Commission [ICC]) cylinder specification requirements. The following summary comments are largely quoted from this reference document. There are many requirements in the specifications that are intended to control brittle fracture in seamless steel cylinders.

The intent of DOT cylinder specifications was to provide containers for the transportation of compressed gases that are capable of containing the involved pressures and withstanding the handling to which such containers are subjected in transportation. The general basic concept of specifications for safely containing pressure is provided by the following strength considerations:

- pressure strength;
- structural strength; and
- corrosion strength.

Pressure strength is the strength required to safely withstand the gas pressure contained in the cylinder. Pressure strength is controlled by the yield strength of the cylinder material and the fatigue resistance of the cylinder. The yield strength must be sufficient to prevent permanent expansion, but must be low enough to ensure the maximum practical degree of ductility consistent with the minimum yield strength requirement. The fatigue resistance is controlled by limiting the stress at the test pressure to a safe percentage of the ultimate tensile strength of the cylinder material to prevent fatigue failure.

The structural strength is the strength required to safely withstand the handling to which the cylinder may normally be subjected. Adequate structural strength requires adequate impact ductility and deformation resistance. Adequate impact ductility ensures that cylinders have good resistance to brittle failure by being made of material that, when properly processed and inspected to eliminate any stress raising defects, will provide sufficient ductility and strength. Adequate deformation resistance ensures that the cylinder wall thickness is sufficient to resist deformation in handling.

The corrosion strength must be adequate to protect against loss of safety due to corrosion. Reasonable allowance should be provided to prevent loss of safety by the action of corrosive contents or environment.

To ensure that all cylinders specifications satisfy these strength requirements, the design factors for cylinders are controlled by:

- material control, which requires:
 - specific chemical analysis
 - specific melting process to consistently produce uniform and sound material

- inspection to ensure that test samples are representative of production materials and a uniformly high quality level is attained
- specific methods of fabrication to produce uniformly sound cylinders by the use of the permitted material
- limiting physical property requirements to those that have been proved by performance tests to meet the required relationship of ductility, yield, and ultimate tensile strength to the service pressure stress;
- the stress formula (to ensure that the stresses are elastic in service);
- the hydrostatic test; and
- safety factors.

DOT (ICC) specifications are performance specifications that were developed as a result of satisfactory test and service performance. Limitations imposed by the specifications are generally established to permit the fabrication of the cylinder proposed without going beyond the current need. This does not preclude the change of the specification to permit materials, designs, etc., other than covered by the original proposal, provided that substantiating data are furnished to prove satisfactory performance.

Some of the most significant information on the origin and development of the cylinder specifications is provided in the “Basic Considerations of Cylinder Design” provided in Appendix A. The CGA annual reports starting with the year 1918 are summarized in this appendix. The following is a summary of specific details from the annual reports that refer to cylinder fracture and fragmentation.

The first source of pertinent information was a paper entitled “Changes in Gas Cylinder Steels During Service” presented by K.G. Jobson in January 1927 at the Fourteenth Annual Meeting. This paper showed that a cylinder manufactured from sound, clean steel kept free from corrosion and properly handled should have a life of indefinite length. The fatigue limit, which is described as the maximum stress to which a product could be subjected at least 100 000 000 cycles, was a value equal to 45% to 55% of the ultimate tensile strength. The fatigue limit of a 0.50% plain carbon steel, which was evidently the material used for cylinders at that time, was from 50 000 psi to 53 000 psi. This meant that this steel had ultimate tensile strength from 91 000 psi to 118 000 psi, which was about the same as current steel for DOT-3A cylinders. For example, a 9-1/16 in OD oxygen cylinder had a stress of 34 856 psi using Barlow’s formula at 2000 psi service pressure. Since this stress was well under the fatigue limit, there was no need to be concerned with fatigue failure.

The Sixteenth Annual Report, dated 1928, contains a paper by Glen D. Bagley entitled “Principles of High Pressure Cylinder Testing.” The paper stated, “The fundamental properties desired in high pressure gas cylinders are:

- A sufficient wall thickness to limit the stress at the maximum working pressure to a safe percentage of the ultimate [tensile] strength of the steel.
- A proper value for the elastic limit, which is determined by the heat treatment of the steel so that it may be high enough to provide against the steel being excessively stretched during the acceptance test of the cylinder and low enough to secure the maximum possible degree of ductility consistent with the necessary minimum value of the elastic limit.”

The second statement emphasizes the basic concept that a seamless steel cylinder subjected to handling in service should be made of ductile material to minimize the danger of brittle failure.

The Nineteenth Annual Report, dated 1931, contains a very important historical paper by C.E. MacQuigg and J.J. Crowe entitled “Development of the Containers for the Transportation of Gases Under Pressure.” In giving the history of the development of cylinder specifications, the paper refers to the 1910 ICC regulations that were the first to include a reference to the manufacture of cylinders. The paper stated, “Compressed gas cylinders must be made of tough steel that will not break up into flying fragments when the cylinder explodes.”

This shows that one of the earliest considerations of cylinder design was the importance of using material that would withstand rough handling with a minimum risk of brittle failure. This concept has never changed from the original specifications through the present-day specifications.

Another basic consideration evident in this paper is the difference in containers intended for high pressure nonliquefied gases and those intended for low pressure liquefied gases. Quoting from the paper, "For the first type of cylinder the steel used must be placed in a condition, to give the maximum strength consistent with good shock resistance, while for the second class a steel with a lower ultimate [tensile] strength, higher ductility and higher safety factor can be used to advantage on account of the greater weight of gas which that type contains."

4.2 Basis for the DOT-3A cylinder specification

To comprehend the intent of any particular DOT cylinder specification, it is necessary to examine all preceding specifications beginning with the earliest one of that series. The first cylinder specification was for high pressure or low pressure cylinders and was designated ICC-3A. This has served as a basis for practically all other cylinder specifications and is currently specified as DOT-3A [3]. The basic considerations of cylinder design for the specification DOT-3A cylinders that are related to and control cylinder fracture are the:

- service pressure;
- steel;
- heat treatment; and
- physical and flattening tests.

No maximum service pressure is specified in the DOT-3A specification because the design criteria have been considered applicable regardless of the service pressure. Therefore, the service pressure is not considered a factor in controlling cylinder fracture.

The steel composition must be controlled to produce a satisfactory cylinder. A basic concept of DOT (ICC) cylinder design is that physical tests alone are not sufficient to ensure the quality required of the materials. To ensure the necessary quality for satisfactory cylinder performance, the maximum chemical limits are specified for certain elements, common to all steels, which can be detrimental to quality if in excess. In particular, the maximum carbon is specified to prevent the use of material that could behave in a brittle manner under allowable processes of manufacture. The maximum sulfur content is specified to prevent the use of material that will result in brittleness in cold deformation.

The basic considerations for heat treatment are:

- Cylinders must be heat treated by a method that will produce uniformity of physical properties in a "lot" of cylinders to ensure that the metallurgical structure of the cylinders selected for physical tests are representative of all cylinders in the lot;
- The heat treatment method is optional depending on the material and must have been determined by performance tests and experience to consistently produce cylinders that will pass all required tests and provide safe performance for the anticipated service conditions and life; and
- Heat treatment must be performed after all manufacturing operations that would significantly affect the metallurgical properties and before the hydrostatic test, which evaluates the heat treatment. The yield strength of the steel after heat treatment is limited to 73% of the ultimate tensile strength. This is to ensure that the cylinder has sufficient ductility to tolerate normal handling damage without failing by brittle fracture. The 73% ratio of yield strength to ultimate tensile strength combined with a test pressure of 5/3 of the service pressure ensures that the cylinder has a minimum theoretical safety factor for bursting of 2.25 based on the ultimate tensile strength.

The acceptable results for physical and flattening tests on cylinders from each production batch are required to provide the proper degree of strength and ductility.

The DOT (ICC) specifications with few exceptions are unique in that they do not specify ultimate tensile strength and yield strengths as numerical values. To permit a wide range of chemical analyses with corresponding wide variations in ultimate tensile strength and yield strength, the basic control resides in maintaining the yield strength at a level that will enable the cylinder to satisfactorily withstand the hydrostatic test, which determines the maximum stress that can be practically used and still meet the 10% limit on permanent expansion. The minimum value of ultimate tensile strength is specified by limiting the yield strength to 73% of the ultimate tensile strength.

The maximum stress under service pressure is limited to 3/5 of the stress at test pressure and is thus related to the yield and ultimate tensile strengths. This approach ensures that the stress formula is always correctly applied in the elastic range of the material.

The ductility of the cylinder is established in part by the ratio of the yield strength to ultimate tensile strength. The 73% yield strength to ultimate tensile strength ratio was established because it is characteristic of steels to be increasingly brittle with increasing yield strength-ultimate tensile strength ratio. Since gas cylinders are transported, handled, and stored with considerable human exposure, it is a basic concept that they be of tough and ductile material, well able to withstand such handling. Accordingly, maximum ductility commensurate with required strength is mandatory. These qualifications are ensured by specifying elongation in a tensile test and by a flattening test made on a finished cylinder. Empirical development of the cylinder specification proved that cylinders properly heat treated to pass the hydrostatic test and made of steel having minimum elongation of 20% in 2 in cylinders or 10% in 8 in cylinders can be consistently flattened to within six times the wall thickness without cracking. The added flattening test, which must be conducted on a finished cylinder, is a performance-oriented test and ensures more than adequate ductility to withstand extreme abuse.

4.3 Basis for the DOT-3AA cylinder specification

This specification was developed from specification DOT (ICC) -3A to take advantage of the strength and toughness of alloy steels. Except as indicated, the basic considerations are identical to those detailed in the DOT-3A specification.

The DOT-3AA specification permits the use of chromium-molybdenum alloy steels instead of only the carbon steel permitted by the DOT-3A specification. The alloy steels when heat treated to provide the required properties of strength and ductility usually have yield strength to ultimate tensile strength ratios too high to permit the use of this ratio as the control of safety factor. The basic consideration was to provide a safety factor and ensure ductility by specifying a maximum permitted wall stress at test pressure and a maximum ratio of wall stress at test pressure to the minimum ultimate tensile strength. The maximum stress at test pressure is limited to 70 000 psi to meet the same ductility requirements that are considered essential for DOT (ICC) -3A cylinders. The basic considerations for heat treatment are the same as for the DOT-3A specification. Specific methods of heat treatment are required that have been determined by performance tests and experience to consistently produce cylinders that will pass all required tests and provide safe performance for the anticipated service conditions and life.

4.4 Summary of the background of cylinder design specifications

It has been recognized from the very beginning of use of high pressure cylinders that the cylinders could fail by brittle fracture and fragmentation into many pieces. One of the primary provisions of all cylinder design specifications has been to ensure that cylinders do not fail by brittle fracture. This has been accomplished by:

- controlling the material composition;
- controlling the heat treatment;
- controlling the wall stress level;
- controlling the yield strength to ultimate tensile strength ratio; and
- elongation requirements and performance tests such as the flattening test.

Although none of these controls in themselves are specifically and explicitly aimed at controlling brittle fracture, these controls and the limits placed in the cylinder design specifications all work together to minimize or eliminate the potential for brittle fracture and fragmentation of the cylinders under normal operating conditions.

The need for ensuring that brittle fracture and fragmentation does not occur has been recognized since the earliest cylinder design specifications were published by the ICC as indicated by the following quote from the 1910 ICC regulations: "Compressed gas cylinders must be made of tough steel that will not break up into flying fragments when the cylinder explodes."

5 Review of existing cylinder specifications

The following is a summary of the primary provisions of the specifications that control the brittle fracture and fragmentation of seamless steel cylinders. All of the commonly used specifications that have been used or are presently used in the United States or worldwide for the manufacture of DOT-3A type or DOT-3AA type high pressure seamless steel cylinders are described.

The steel analyses and properties for DOT-3A and DOT-3AA cylinders are shown in the tabulations in 5.1.1 and 5.2.1. These tabulations show the key factors that control the ductility (toughness) of DOT-3A and DOT-3AA cylinders. The carbon steel and intermediate manganese steel cylinders referred to in this report were manufactured before the DOT-3AA specification was written. The high elongation (20% in 2-in gage length) and severe flattening test (flatten to 6t) requirements were specified to ensure a ductile material and thus prevent fragmentation if the cylinder ruptured under service pressure. When the DOT-3AA specification was written, the severe flattening test was continued, and the design stress was limited to 70 000 psi at test pressure so that heat treatment to a high ultimate tensile strength was not possible. These controls were selected to ensure a ductile (tough) material.

5.1 DOT-3A specification (49 CFR Part 178.36)

The DOT-3A specification (originally known as the ICC-3A specification) was the first specification used in the United States to manufacture high pressure seamless steel cylinders. This is the basic specification on which all later DOT specifications are based. There is no maximum service pressure or maximum cylinder size specified in this specification. No specific safety factor (burst pressure to service pressure ratio) is specified. For the chemical composition of the steel, only a maximum value for the carbon, sulfur, and phosphorus contents are specified. The carbon content is limited to 0.55% to minimize the tendency for brittle fracture. The sulfur content is limited to 0.050% as an additional control to ensure adequate ductility and toughness. Although no specific heat treatment is required, cylinders manufactured to this specification are universally heat treated by normalizing to obtain the required physical properties. No maximum values of ultimate tensile strength, yield strength, or wall stress are directly specified. However, the yield strength cannot exceed 73% of the ultimate tensile strength. The wall stress at test pressure must be below the yield strength to meet the required maximum of 10% permanent expansion at the test pressure. The test pressure is required to be at least 5/3 of the marked service pressure. These conditions result in a theoretical safety factor of at least 2.25. In practice, these requirements result in a maximum wall stress at service pressure that does not exceed 30 000 psi and an ultimate tensile strength that is less than 120 000 psi for all cylinders that have been manufactured under the DOT-3A specification.

There are no specific requirements in this specification that directly control the fracture toughness of the cylinder steel. However, there are several test requirements that ensure that the ductility of the cylinders is adequate to minimize the probability of brittle fracture and fragmentation. There is a requirement that the elongation in the tensile test must exceed 20% in 2-in gage length and that the finished cylinder be flattened to a minimum of 6 times the wall thickness. These requirements combined with the maximum yield strength to ultimate tensile strength ratio of 73% ensure that the cylinders have adequate ductility and toughness to minimize brittle fracture and fragmentation in service. These requirements have proven to be adequate for the manufacture of safe cylinders during the entire time that DOT-3A cylinders have been in use.

5.1.1 Carbon steel—DOT-3A cylinders

Steel specification (chemical composition):

Carbon	0.55% max.
Sulfur	0.050% max.
Phosphorus	0.045% max.

Heat Treatment:

Completed cylinder shall be uniformly and properly heat treated before tests.

Specified properties:

Yield strength – not over 73% of the ultimate tensile strength

Elongation – 20% in 2-in gage length, 10% in other cases

Flattening test – 6t without cracking

Hydrostatic test – test pressure = 5/3 service pressure

Permanent expansion at hydrostatic test pressure shall not exceed 10%.

Measure permanent expansion using the water jacket method.

5.2 DOT-3AA specification (49 CFR Part 178.37)

The DOT-3AA specification was developed during the 1940s to permit the use of alloy steels, which had a desirable combination of high strength and improved ductility and toughness compared with the carbon steels permitted by the DOT-3A specification. Like the DOT-3A specification, there is no maximum service pressure specified in this specification. Likewise, no specific safety factor (burst pressure to service pressure ratio) is specified.

The chemical composition of the specific steels that are permitted is specified. The DOT-3AA cylinders may be made of carbon-manganese (intermediate manganese) steel or of a chromium-molybdenum (AISI 4130X steel). Additional alloy steels such as NE-8930, AISI 9115 and 9125, and a carbon boron steel have been permitted but have only been used in very limited amounts. The chemical composition of the steels requires that the primary alloying elements such as carbon, manganese, molybdenum, and chromium be controlled within specified limits and that the impurities such as sulfur and phosphorous be limited to specified maximum values. These controls on the chemical composition ensure adequate ductility and toughness when the cylinders are properly heat treated.

All cylinders manufactured to this specification must be heat treated by quenching and tempering with the exception of cylinders made from AISI 4130X steel, which may alternately be heat treated by normalizing only. Cylinders manufactured since about 1950 have been universally manufactured from AISI 4130X steel and have all been heat treated by quenching and tempering to obtain the required physical properties. No maximum values of ultimate tensile strength or yield stress are directly specified. In contrast to the DOT-3A specification, a maximum for the ratio of yield strength to ultimate tensile strength is not specified. Instead, a maximum permitted wall stress at test pressure of 70 000 psi is specified, and the wall stress at test pressure must not exceed 67% of the minimum ultimate tensile strength.

There are no specific requirements in the DOT-3AA specification that directly control the fracture toughness of the cylinder steel. However, similar to the DOT-3A specification, the DOT-3AA specification includes several test requirements that ensure the ductility of the cylinders is adequate to minimize the probability of brittle fracture and fragmentation. There is a requirement that the elongation in the tensile test must be at least 20% in 2-in gage length and that the finished cylinder be flattened to a minimum of six times the wall thickness. These requirements combined with the wall stress requirement of 70 000 psi at test pressure ensure that the cylinders have adequate ductility and toughness to minimize brittle fracture in service. These requirements have proven to be adequate for manufacture of safe cylinders during the entire time that DOT-3AA type cylinders have been in use.

5.2.1 Intermediate manganese steel—DOT-3AA cylinders

Steel specification (chemical composition):

Carbon	0.40% max.
Manganese	1.35% to 1.65%
Silicon	0.10% to 0.30%
Sulfur	0.050% max.
Phosphorus	0.040% max.

Heat treatment:

Quench and temper
Quench in oil or other suitable medium
Temper at not less than 1150 °F
Each cylinder shall be magnetic particle inspected

Specified Properties:

Design wall stress—less than 67% of minimum ultimate tensile strength and not more than 70 000 psi
Elongation—20% in 2-in gage length, 10% in 8-in gage length
Flattening test—6t without cracking
Hydrostatic test—test pressure = 5/3 service pressure
Permanent expansion not to exceed 10%
Measure permanent expansion using water jacket method

5.2.2 Chromium-molybdenum steel—DOT-3AA cylinders

Steel specification (chemical composition):

Carbon	0.25% to 0.35%
Manganese	0.40% to 0.90%
Silicon	0.15% to 0.35%
Sulfur	0.050% max.
Phosphorus	0.040% max.
Chromium	0.80% to 1.10%
Molybdenum	0.15% to 0.25%

Heat Treatment:

Quench and temper
Quench in oil or other suitable medium
Temper as suitable

Specified Properties:

Design wall stress— less than 67% of minimum ultimate tensile strength and not more than 70 000 psi
Elongation—20% in 2-in gage length, 10% in 8-in gage length
Flattening test—6t without cracking
Hydrostatic test—test pressure = 5/3 service pressure
Permanent expansion not to exceed 10%
Measure permanent expansion using water jacket method

5.3 ISO 9809-3:2000, Gas cylinders—Refillable seamless steel gas cylinders—Design, construction, and testing—Part 3: Normalized steel cylinders

ISO 9809-3:2000 is for the construction of seamless steel cylinders made from carbon, carbon-manganese, or carbon-manganese-molybdenum steels that are heat treated by normalizing or normalizing and tempering [5]. These cylinders are similar in size, materials of construction, and properties to DOT-3A cylinders that are produced from carbon or carbon-manganese steel.

Like the DOT-3A specification, there is no absolute maximum service pressure specified for these cylinders. There are controls on the chemical composition of the steel and on the required mechanical properties of the finished cylinder to ensure that the finished cylinders are tough, ductile, and of uniform quality. ISO 9809-3:2000 includes some additional requirements for the required mechanical properties that are not included in the DOT-3A specification.

The chemical composition of the steel must not exceed the following values:

Carbon	0.45% max.
Manganese	1.70% max.
Chromium	0.20% max.
Nickel	0.20% max.
Copper	0.20% max.
Micro alloying elements	0.15% max.
Sulfur	0.020% max.
Phosphorus	0.020% max.

The chemical composition of the steels requires that the primary alloying elements, such as carbon and manganese, and the impurities, such as sulfur and phosphorous, be limited to specified maximum values. These controls on the chemical composition ensure adequate ductility and toughness when the cylinders are properly heat treated.

The cylinder design permits the maximum ratio of the yield strength to ultimate tensile strength to be 75%. The burst pressure of the cylinder must be greater than 1.6 times the test pressure. The test pressure normally is set at 1.5 times the service pressure. Thus the safety factor at service pressure is 2.4.

Prototype design qualification tests must include a hydraulic burst test and a hydraulic pressure cycling test. The cylinder must show a ductile fracture mode in the hydraulic burst test. In the pressure cycling test, the cylinders must exceed 12 000 cycles at test pressure without leaking.

Tests to evaluate the mechanical properties of the finished cylinders are required on samples from each production batch. The required mechanical properties of the steel are specified to ensure that the cylinders have the appropriate toughness and ductility. The maximum ultimate tensile strength permitted in the finished cylinder must not exceed 800 MPa (116 000 psi). The elongation measured in the tensile test must not be less than 20%. A flattening test is required on one cylinder from each production batch, and the cylinder must not crack when flattened to a value of 6t. Alternately, ring flattening tests may be carried out on one cylinder from each production batch. CVN impact tests must be carried out on one cylinder from each production batch. The average energy value for three transverse CVN specimens must be greater than 20 J/cm² at the lowest operating temperature of either -20 °C or -50 °C.

Although there are no specific requirements in ISO 9809-3:2000 that directly control the fracture toughness of the cylinder steel, the standard has several test requirements that ensure that the ductility and fracture toughness of the cylinders is adequate to minimize the probability of brittle fracture and fragmentation.

5.4 ISO 9809-1:1999, Gas cylinders—Refillable seamless steel gas cylinders—Design, construction, and testing—Part 1: Quenched and tempered steel cylinders with tensile strength less than 1100 MPa

ISO 9809-1:1999 is for the construction of seamless steel cylinders made from carbon-manganese and alloy steels that are heat treated by quenching and tempering [6]. These cylinders are similar in size, materials of construction, and mechanical properties to DOT-3AA cylinders that are produced from carbon-manganese and alloy steels. The maximum ultimate tensile strength permitted is 1100 MPa (159 500 psi.)

Like the DOT-3AA specification, there is no absolute maximum service pressure specified for these cylinders. There are controls on the chemical composition of the steel and on the required mechanical properties of the finished cylinder to ensure that the finished cylinders are tough and ductile and of uniform quality.

ISO 9809-1:1999 includes some additional requirements for the required mechanical properties that are not included in the DOT-3AA specification.

The chemical composition of the steel must not exceed the following values:

	C-Mn Steel	Cr-Mo Steel
Carbon	0.038% max.	0.025% to 0.38%
Silicon	0.10% to 0.35%	0.10% to 0.40%
Manganese	1.35% to 1.75%	0.40% to 1.00%
Sulfur	0.020% max.	0.020% max.
Phosphorus	0.020% max.	0.020% max.
Chromium	-----	0.80% to 1.20%
Molybdenum	-----	0.15% to 0.40%

The chemical composition of the steels requires that the primary alloying elements such as carbon, manganese, chromium, and molybdenum, and the impurities such as sulfur and phosphorous be limited to specified maximum or range of values. These controls on the chemical composition ensure adequate ductility and toughness when the cylinders are properly heat treated.

The cylinder design permits the maximum ratio of the yield strength to ultimate tensile strength to be 90%. The burst pressure of the cylinder shall be greater than 1.6 times the test pressure. The test pressure is normally set at 1.5 times the service pressure. The ultimate tensile strength is limited to 1100 MPa (159 500 psi) for the chromium-molybdenum steels and to 1030 MPa (149 300 psi) for the carbon-manganese steels.

Prototype design qualification tests must include a hydraulic burst test and a hydraulic pressure cycling test. The cylinders must show a ductile fracture mode in the hydraulic burst test. In the pressure cycling test, the cylinders must exceed 12 000 cycles at test pressure without leaking.

Tests to evaluate the mechanical properties of the finished cylinders are required on samples from each production batch. The required mechanical properties of the steel are specified to ensure that the cylinders have the appropriate toughness and ductility. The maximum ultimate tensile strength permitted in the finished cylinder must not exceed 1100 MPa (159 500 psi). The elongation measured in the ultimate tensile test must not be less than 14%. A flattening test is required on one cylinder from each production batch, and the cylinder must not crack when flattened to a value of 9t. Alternately, ring flattening tests may be carried out on one cylinder from each production batch. CVN impact tests must be carried out on one cylinder from each production batch. The average energy value for three transverse CVN specimens must be greater than 40 J/cm² at -50 °C.

ISO 9809-1:1999 has several test requirements that ensure that the ductility and fracture toughness of the cylinders is adequate to minimize the probability of brittle fracture and fragmentation.

5.5 Present worldwide use of DOT-3A type cylinder

5.5.1 Introduction

Title 49 of the U.S. *Code of Federal Regulations* (49 CFR) Part 178.36 authorizes the continual use of DOT-3A specification cylinders provided they pass the prefill inspection and the periodic hydrostatic test or ultrasonic examination. The DOT regulations do not place a life limit on either DOT-3A or DOT-3AA cylinders. Worldwide standards for the design, manufacture, and use of these types of cylinders are specified by standards written by ISO Technical Committee 58 (ISO/TC 58), Subcommittees 3 (SC 3) and 4 (SC 4). These standards are prepared and finally approved through the ISO Central Secretariat, Geneva, Switzerland for worldwide use. SC 3, which writes the cylinder design standards, has a membership of 33 nations. SC 4, which writes the cylinder use and retest standards, has a membership of 31 nations. Thus, they represent worldwide practice. These standards authorize the continued use of DOT-3A type cylinders provided they pass a prefill inspection and a periodic requalification by either a hydrostatic test or ultrasonic examination. The United States is an active member of the ISO committees.

The ISO standards have been incorporated into the United Nations regulations covering gas receptacles (cylinders) and, when agreed, they will become a mandatory part of the DOT regulations. Thus, there are no plans worldwide to place a mandatory life limit in statute years on high pressure seamless steel cylinders of DOT-3A or DOT-3AA type cylinders or to remove DOT-3A type cylinders from service.

5.5.2 Survey of current practices for the use of DOT-3A type cylinders

To compare current practices outside the United States, inquiries were made to European and Japanese cylinder users and manufacturers to determine whether specific company or national regulations impose a mandatory life limit on high pressure seamless steel cylinders. The European industrial gas companies operate high pressure seamless steel cylinder filling plants both in Europe and in various countries around the world. The Japanese response represents their national practice, which includes a number of cylinder filling plants and cylinder manufacturers.

These inquiry responses stated that they:

- do not impose a life limit on high pressure steel cylinders because of age;
- continue to use high pressure steel cylinders made before 1950; and
- remove high pressure steel cylinders from service only because of rejection in the routine prefill visual inspection or the periodic hydrostatic or ultrasonic inspection.

EIGA has recently issued the following statement: "Evidently, technological developments and innovations in the manufacturing process have greatly contributed to the production of high performance, lightweight "third and fourth" generation cylinders without compromising safety. It should be noted however that safety was not the driving force behind the development of "third and fourth" generation cylinders. The equivalence of safety between the generations of cylinders has been maintained. This is due to these older cylinders being manufactured from low strength steels (higher ductility), are used under less demanding wall stresses and are more resistant to corrosion, (e.g. thicker wall). Provided the cylinders are re-tested at the appropriate, specified intervals and maintained in a satisfactory condition between the re-test intervals, the cylinders can continue to be used without any lifetime restrictions" [7].

5.5.3 Survey of current manufacturers of DOT-3A type cylinders

An inquiry was made to four U.S. cylinder manufacturers, the largest European manufacturer of such cylinders and Japanese authorities. These inquiries were to determine whether or not the DOT-3A specification represents a current viable cylinder specification. In response to this inquiry:

- the largest manufacturer of DOT-3A type cylinders in Europe replied that they manufacture approximately 30 000 such cylinders per year; i.e., intermediate manganese steel-normalized heat treatment;
- Japanese authorities responded that the KANTO High Pressure Cylinder Manufacturing Company, Ltd of Japan produces DOT-3A type cylinders in water capacity sizes of 0.5 L to 10 L from intermediate manganese steel-normalized heat treatment; and
- four U.S. manufacturers of DOT-3A and DOT-3AA cylinders each stated that they no longer produce DOT-3A cylinders. All production has shifted to DOT-3AA chromium-molybdenum steel cylinders. However, one U.S. manufacturer has recently applied to DOT for an exemption to permit production of steel cylinders based on ISO 9809-3:2000 for the manufacture of carbon steel cylinders that are heat treated by normalizing.

5.5.4 Summary of the survey of current use of DOT-3A type cylinders

The survey of current use of DOT-3A type cylinders showed that:

- age is not a logical or necessary reason to reject and discontinue the use of DOT-3A type cylinders;
- DOT-3A type cylinders are still manufactured in substantial quantities;
- no evidence was uncovered that would justify removing all DOT-3A type cylinders from service in the United States;

- none of the four major U.S. manufacturers currently make DOT-3A cylinders because demand has switched to the more efficient chromium-molybdenum DOT-3AA steel cylinders;
- European manufacturers make DOT-3A type cylinders to ISO 9809-3. These cylinders are mainly made from intermediate manganese steel;
- DOT-3A type cylinders are currently manufactured in Japan; and
- major European and U.S. industrial gas companies continue to use DOT-3A type cylinders that are often well over 50 years old.

6 Discussion

This section presents an assessment of the Taylor-Wharton letter and report and additional data considered by the experts working group of the Docket 02-37 Task Force [1, 2].

For this report, fracture performance of a cylinder is divided into two phases. One is the fracture initiation phase, and the second is the fracture propagation phase. The fracture initiation phase is defined as the process when a new crack initiates from a pre-existing crack. The amount of the crack growth required to define an onset of crack propagation is usually very small (approximately 0.2 mm). Once the fracture initiates, high toughness, ductile materials require an increase in the applied stresses to further increase the crack extension to result in a final fracture. However, if the material is brittle (low toughness), the final fracture occurs with a slight or no increase in the applied stress after the fracture initiation. The primary controlling parameters for the fracture initiation are crack size, applied stress, and toughness.

The fracture propagation phase deals with what happens to the crack once it initiates. Specific issues with a propagating crack are how far it travels, how many crack branches are developed, and eventually how many pieces of a cylinder are produced. The controlling parameters for fracture propagation are hydrostatic or pneumatic loading, stress level, pressure energy, geometry, and material toughness.

It is well known that hydrostatic loading is considered to be a stiff-spring system. For ductile, high toughness materials, the crack travels a short distance and gets arrested quickly due to loss of the fluid.

Pneumatic loading features a soft-spring system, which provides a continuing crack driving force to extend the crack. Unlike hydrostatic loading, the pneumatic loading results in a slower depressuring rate; thus, the loading has more time to cause crack extension. The factors that determine the rate of depressurization after the initial rupture of the cylinder are energy, density, gas volume, rate of enlargement of the rupture area, and cylinder diameter, etc. Thus for a given fracture, the crack propagation by pneumatic pressure is much more extensive than that by hydrostatic pressure.

6.1 Review and summary of the Taylor-Wharton letter and report

The Taylor-Wharton letter and report recommends that “only seamless steel high-pressure cylinders employing state-of-the-art technology (third and fourth generations) be used.” From the test results provided in the Taylor-Wharton report, this CGA technical report concludes that the technical reasons for the preceding recommendations are as follows:

- Fragmentation of “first generation” carbon steel cylinders occurs when tested under hydro-pneumatic pressure and at applied pressure equal to the normal burst pressure of an unflawed cylinder; and
- The CVN test impact energy values of “first generation” carbon steel cylinder material are relatively low.

The hydro-pneumatic burst test used in Taylor-Wharton report is not recognized as an appropriate method to evaluate cylinder fitness for use in normal and adverse service conditions. The discussion in this section (all sections of Section 6) indicates why this cylinder test method (where the failure pressure is above test pressure) is not appropriate and which methods are appropriate.

There have been no documented records that show that DOT-3A cylinders have a higher failure rate than DOT-3AA or newer cylinders. In the rare cases where there have been cylinder failures of DOT-3A and 3AA cylinders, there have been no documented records that show that DOT-3A cylinders cause more significant damage, injury,

or destruction than DOT-3AA cylinders. The Taylor-Wharton letter and report does not provide any information that the DOT-3A cylinders have had a higher failure rate in service than the DOT-3AA or newer cylinders. This is true even though the DOT-3A cylinders have been in service for a much longer period of time than the DOT-3AA or newer cylinders. There are no documented records that show that the failure rate of DOT-3A cylinders increases with age.

The Taylor-Wharton letter states that “each advance from carbon steel to intermediate manganese steel to the modern chrome moly alloy steel has resulted in the enhanced toughness of seamless steel cylinder products. In addition to allowing thinner walls, the increased toughness equates to cylinders that exhibit improved flaw tolerance and fracture performance. For example, an antiquated carbon steel cylinder may fragment on failure as opposed to the predictable, “leak before break” attribute of a modern chrome moly cylinder. Decades of advancements in cylinder design, manufacturing technology, and inspection expertise have also contributed to a modern cylinder population with improved fracture performance.” The assessment made in this CGA technical report indicates that the above conclusions are not technically correct in all situations.

Over the last 15 years, there has been an extensive study of the fracture of steel cylinders conducted under a program carried out by the ISO/TC 58/SC 3/Working Group 14 (WG 14). WG 14 is entitled “Toughness and Acceptance Levels of Steels of Strength Levels above 1100 MPa.” Several hundred flawed cylinder burst tests on old as well as new cylinders were conducted as part of the WG 14 program to evaluate the overall “fracture performance” of all types of cylinders currently used or manufactured in the world. This program included some of the oldest DOT-3A cylinders as well as DOT-3AA cylinders and some of newest high strength steel cylinders. The results of the WG 14 test programs are reported in ISO/TR 12391 parts 1, 2, 3, and 4 [8, 9, 10, 11].

The results of the ISO WG 14 program showed that all seamless steel cylinders currently made or used in the world have equivalent overall fracture performance (see 6.6). All types of cylinders tested exhibited the desirable leak-before-break fracture behavior with very substantial flaws in the cylinders. Both the DOT-3A cylinders and the DOT-3AA cylinders have essentially the same leak-before-break performance. The new cylinders do not have improved flaw tolerance defined as the size of a flaw that will cause failure at a specified failure pressure (for example, the maximum allowed working pressure).

The WG 14 program showed both experimentally and by analysis that the old cylinders were no more likely to fracture than the new cylinders. The reason for this is although the fracture toughness of the old cylinders is lower than the fracture toughness of the new cylinders, the working wall stress in the old cylinders is lower than in the new cylinders. It is the combination of fracture toughness and wall stress that determines if the cylinders will fracture. The WG 14 program showed that even for very large flaws in the cylinders, the failure of the cylinders was controlled, not by the fracture toughness alone, but a combination of the fracture toughness and the wall stress. This was true for both the oldest DOT-3A cylinders tested and the newest DOT-3AA and DOT exemption E-9421 cylinders. These tests showed that the overall fracture performance of steel cylinders is not controlled by the fracture toughness alone, but is primarily controlled by the strength of the cylinder. The WG 14 program emphasized “total cylinder fracture performance” not just fracture toughness.

Fracture performance (initiation) depends on a combination of both fracture toughness and the wall stress, not just on fracture toughness alone. Although the older carbon steels used in cylinders can obtain the same strength levels as the newer chromium-molybdenum steels used in newer cylinders, the older carbon steel cylinders cannot be used at higher strength (and higher wall stress) levels, i.e., higher gas service pressures, because the carbon steels do not have adequate fracture toughness. Therefore, the older carbon steel cylinders can only be used at lower design pressures because their strength and wall stress levels necessitate much higher wall thickness for the same pressure. Only because the newer chromium-molybdenum steels have higher fracture toughness in combination with the higher strength is it possible to use higher wall stress levels and take full advantage of the strength of the metal allowing much lighter high pressure seamless steel cylinders.

The differences noted between the DOT-3A cylinders and the DOT-3AA cylinders (as shown in the test report “A Century of Cylinders-Test Program”) refer to the ultimate failure condition when an unflawed cylinder fails at a pressure of at least 2-1/2 times the maximum allowed working pressure of the cylinder [2]. In this case, DOT-3A cylinders may sometimes fail in more pieces than the DOT-3AA cylinders. For the tests reported, the failure pressure to marked service pressure ratio was essentially the same for DOT-3A cylinders and DOT-3AA cylinders. However, because the cylinder will not see such a high pressure in service, this ultimate failure condition is not relevant to any service failures.

For tests of cylinders containing 3 in long x 0.140 in deep flaws, the test results reported in the Taylor-Wharton report show that the failure pressure of the 3A type cylinders was less than the test pressure of the cylinders in three of the six cylinders tested [2]. In the only example shown of a pre-1930 carbon steel cylinder tested under hydro-pneumatic pressure with a 3 in long x 0.140 in deep flaw, a 3A type cylinder failed in more than one piece, but this was only after being pressurized in excess of twice the marked service pressure of the cylinder.

In summary, if older cylinders are more likely to fracture and fragment than newer cylinders, there should be a record of service failures, and the rate of failures should increase as the age of the cylinders increases. However, failed cylinders of any age are so rare that there are few examples to investigate. No reason has been shown that would cause the older cylinders to fail at this time and that suddenly “old” cylinders are no longer safe for continued use.

6.2 Occurrence and control of cylinder fragmentation

6.2.1 Description of cylinder failure modes

The cylinder failure modes that are discussed here refer only to whether the cylinder stays in one piece or breaks into several pieces when the cylinder fails.

Cylinders will fail by fracturing either at a pressure well above test pressure or at a pressure below the test pressure due to the presence of a crack or of cracks in the cylinder. When no cracks are present in the cylinder, the cylinder will only fail by fracturing at the normal burst pressure (which is well above the service and test pressures required for the cylinder). The design criteria for DOT-3A and 3AA type seamless steel cylinders has always required that the burst pressure for a cylinder not containing cracks must be at least 2.25 times the service pressure.

When the cylinders that do not contain cracks fail at the normal burst pressure, both the DOT-3A or 3AA type seamless steel cylinders will deform substantially before failing and may break into several pieces upon failing or may remain in one piece. The burst pressure is determined and controlled by the:

- ultimate tensile strength of the steel;
- cylinder wall thickness;
- cylinder diameter; and
- distribution of the stresses in the cylinder wall at the time of failure.

When the cylinder fails at the burst pressure, whether the cylinder stays in one piece or breaks into several pieces is determined and controlled by the:

- stresses in the cylinder wall at that pressure;
- size of the cylinder (length and diameter);
- stiffness of the cylinder (as estimated by the diameter to thickness ratio);
- type of loading (hydraulic or pneumatic); and
- ductility and or toughness of the cylinder steel.

All of these factors work together in a complex and not completely understood way to determine and control whether the cylinder stays in one piece or breaks into several pieces when it fails at the burst pressure.

The particular failure mode when the cylinder fails at the normal burst pressure, i.e., whether the cylinder stays in one piece or breaks into several pieces, is not related to the failure mode that occurs when the cylinder fails at a pressure below the test pressure because of the presence of cracks in the cylinder. That is, a cylinder may break into several pieces (fragment) when it fails at the normal burst pressure, but may stay in one piece when it fails at a pressure below the test pressure. This occurs because at the normal burst pressure, the cylinder undergoes extensive plastic deformation before failure that changes the distribution of the stresses in the cylinder wall, and the stresses throughout cylinder wall are highly plastic. By contrast when a cylinder fails at a pressure

below the test pressure because of the presence of cracks in the cylinder, the cylinder is not significantly deformed even in the presence of cracks and the stresses in the cylinder wall are well within the elastic range.

6.2.2 Cylinder failure modes under service conditions

For purposes of this discussion, failure under service conditions is defined as failure of the cylinder at any pressure below the normal test pressure required for the cylinder. For the cylinders to fail under these conditions, the cylinder must contain significant flaws such as cracks so the failure pressure is reduced from the normal burst pressure to a pressure level below the test pressure. The choice of limiting the concern for failure of the cylinder to any pressure up to the test pressure is that in actual service the cylinder can be expected to be pressurized, on occasion, only up to the test pressure. The failure mode at pressures higher than the test pressure is not considered in this report because industry standard operating practices limit cylinder pressure. Thus cylinders are not expected to be pressurized in-service above the test pressure.

Failure of any cylinder at a pressure above the test pressure represents a significant potential safety hazard. The failure modes that a cylinder may experience if it is pressurized to a pressure above the test pressure are not considered in this discussion because such failures can occur only due to exceptional operational upset conditions and are not due to the cylinder design, material, material's properties, or age.

The most common reason for cylinders to fail at a pressure below the test pressure is due to the presence of cracks in the cylinder that cause the cylinder to fail by fracturing. Fracture is normally considered to consist of distinct steps that are:

- a) fracture initiation;
- b) fracture propagation; and
- c) fracture arrest.

Fracture of pressure vessels such as cylinders has been extensively studied, and the factors that control the fracture process are well understood.

6.2.2.1 Fracture initiation

Fracture initiation in a cylinder is controlled by:

- stress level, which is determined by the pressure, diameter, and wall thickness;
- size (length and depth), shape, and number of cracks in the cylinder; and
- fracture initiation toughness of the cylinder material.

As the crack size and/or the number of cracks in the cylinder increases, the pressure to initiate fracture is decreased and may be reduced from the normal burst pressure of the cylinder to a pressure at or below the service pressure. When fracture initiation occurs, the cylinder may just leak or the crack may extend by fracture propagation. Fracture initiation was studied extensively in the WG 14 test programs [8, 9]. These test programs have shown the pressure to initiate fracture in seamless steel cylinders will only be reduced to below the test pressure if either a very large single crack (deeper than 50% of the cylinder wall and a few inches long) is present in the cylinder or many smaller cracks that may link up are present in the cylinder.

The tests in the WG 14 test program have shown that for cylinders containing a single crack, the fracture initiation is controlled by a combination of both the wall stress and fracture toughness of the steel (not just the fracture toughness alone), and the fracture initiation performance of both DOT-3A and 3AA type cylinders is equivalent. DOT-3A type cylinders have lower fracture toughness than DOT-3AA type cylinders. However, since DOT-3A type cylinders have much lower wall stress, the fracture performance of the two cylinder types is equivalent.

Fewer tests and analysis have been conducted to determine the fracture initiation performance of cylinders that contain many smaller cracks (such as those caused by stress corrosion cracking) instead of a single large crack (such as those caused by fatigue cracking). The individual small cracks may not be large enough to cause the cylinder to fail even at the test pressure. However, when many small cracks that are relatively close together are present in the cylinder, the small cracks generally link up as the pressure in the cylinder is increased and form a

single large crack when the ligament of metal between them fails. This creates a single large crack that will then either leak or fracture depending on the crack size and pressure.

The fracture initiation performance of steel cylinders is not affected by whether the cylinders are pressurized hydrostatically or pneumatically. Both hydrostatic and pneumatic tests produce equivalent results. The fracture initiation tests for the cylinders are used to determine the failure pressure when specified sizes of cracks are present in the cylinders and whether the cylinder just leaks or fractures at this pressure. These types of tests do not directly determine if the cylinder will break into many pieces (fragments) or will stay in one piece when it fails.

6.2.2.2 Fracture propagation

Once fracture is initiated in a cylinder, the fracture may

- not propagate (i.e., the crack length may not become much longer than the initial crack length);
- propagate a limited distance in a relatively straight line and stop (arrest) before reaching the ends of the cylinder, or
- propagate to the ends of the cylinder and leave the cylinder in one piece or in many pieces.

The extent of fracture propagation in a cylinder is controlled by:

- pressurizing medium (hydrostatic or pneumatic);
- stress level and the stress distribution in the cylinder when the fracture initiates;
- presence of other cracks in the cylinder;
- location of the crack in the cylinder and the length size of the cylinder;
- stiffness of the cylinder (as estimated by the diameter to thickness ratio); and
- fracture toughness of the cylinder material.

Once fracture initiates in the cylinder, the extent of the fracture propagation is strongly controlled by the pressurizing medium. If the cylinder is pressurized hydrostatically, the crack may propagate a relatively short distance and stop or arrest because the pressure in the cylinder that drives the crack propagation drops quickly when the cylinder opens up and the stress to propagate the crack becomes insufficient to continue to propagate the crack. If the cylinder is pressurized pneumatically, the crack may propagate for a longer distance and may not stop before reaching the ends of the cylinder because the pressure in the cylinder that drives the crack propagation does not drop quickly when the cylinder opens up and the stress to propagate the crack remains sufficient to continue to propagate the crack.

The extent of the fracture propagation depends on the level of the stress (i.e., whether the stresses are elastic or plastic) and the stress distribution (i.e., whether the stresses are predominantly hoop stresses or are biaxial stresses). If the stresses in the cylinder are in the elastic range when the crack is initiated, the crack may propagate a short distance and arrest when the stress level drops slightly and the stress is no longer sufficient to continue the crack propagation. However, if the stresses in the cylinder are in the plastic range when fracture is initiated, the crack may propagate for an extended distance before the stress level drops enough so the stress is no longer sufficient to continue the crack propagation. If the stresses in the cylinder wall are predominantly hoop stresses when the fracture initiates, the crack will tend to propagate in a straight direction and extend for a relatively long distance. However, if the stresses are predominantly biaxial when the fracture initiates, the cracks may extend only a short distance in a straight line and then turn and run circumferentially around the cylinder and arrest.

Once fracture initiates in the cylinder, the extent of the fracture propagation may depend on the presence of other cracks in the cylinder. As a crack propagates, it may intersect other cracks and cause the crack to change its direction of propagation. This may cause the crack to arrest and stop before it propagates extensively.

The location of the crack in the cylinder and the length of the cylinder affect the extent of the fracture propagation because if the crack approaches the end of a cylinder after propagating a short distance, the crack will arrest

and/or turn, and the crack propagation will end. This occurs because the ends of the cylinder are thicker and stiffer than the main body of the cylinder. Therefore, the stress level is lower, the stress distribution is altered near the ends of the cylinder, and fracture propagation cannot continue.

The stiffness of the cylinder, which is estimated by the diameter to thickness ratio of the cylinder, affects the extent of the crack propagation. In a relatively thick cylinder that has a high stiffness (i.e., a low diameter to thickness ratio), the crack may propagate in a straight line for a relatively long distance without stopping. By comparison, as the crack starts to propagate in a relatively thin cylinder that has a low stiffness (i.e., a high diameter to thickness ratio), the shape of the cylinder may change sufficiently to cause the crack to turn and arrest.

Once fracture initiates in the cylinder, the extent of fracture propagation has not been shown to be directly and strongly dependent on the fracture toughness of the cylinder material. This is because once the crack has initiated and extended even a short distance, the crack is sufficiently long so the crack can continue to extend even if the wall stresses are relatively low and the fracture toughness is relatively high.

6.2.3 Control of cylinder fragmentation

When fracture initiation and fracture propagation occur in a cylinder, the cylinder may stay in one piece or may break into several pieces (fragment). The factors that control fragmentation are not as well documented as the factors that control fracture initiation and fracture propagation. In general fragmentation is controlled by the:

- presence of multiple cracks in the cylinder;
- stress level and the stress distribution in the cylinder when the fracture propagates;
- cylinder stiffness; and
- ductility and/or toughness of the cylinder material.

Seamless steel cylinders that fail at pressures below test pressure have not been found to fragment when the fracture initiates from a single dominant crack such as a fatigue crack. These cylinders either just leak or if the crack propagates, the cylinder will open up but stay in one piece. By comparison, when similar seamless steel cylinders contain multiple cracks such as stress corrosion cracks (SCC), failure at pressures below the test pressure can result in fragmentation, and the cylinder can break into many pieces. When there are multiple cracks in the cylinder, the primary propagating crack intersects the other cracks, and the direction of propagation may change so that pieces of cylinder may break off (fragment).

Whether seamless steel cylinders fragment when crack propagation occurs depends on the level of the stresses in the cylinder wall (i.e., whether the stresses are elastic or plastic) and on the stress distribution (i.e., whether the stresses are predominantly hoop stresses or are biaxial stresses) present in the cylinder wall. If the stresses in the cylinder are in the elastic range when a single crack propagates, the crack will generally run in a straight line, the cylinder will open up, and the cylinder will not fragment. This is what happens when the cylinder fails at a pressure below the test pressure. However, if the stresses in the cylinder wall are in the plastic range when a single crack propagates, the crack will propagate for an extended distance and the cylinder can fragment. This is what happens when a cylinder fails at the normal burst pressure (i.e., well above the test pressure). If the stresses in the cylinder wall are predominantly hoop stresses when the fracture propagates, a single crack will propagate predominantly in a straight direction, and the cylinder will not fragment. However, if the stresses are predominantly biaxial, such as occurs when any bulging takes place before the fracture initiates, a single crack may turn and run circumferentially around the cylinder, and the cylinder can fragment. This is what happens when a cylinder fails at the normal burst pressure.

The tendency for a cylinder to fragment can be affected by the stiffness of the cylinder. In a relatively thick cylinder that has a high stiffness, the cylinder will maintain its general shape and will not bend or twist as it opens up when a crack propagates, and the cylinder is likely to break into several pieces. This is most likely to happen for a thick-walled higher pressure cylinder. By comparison, in a relatively thin cylinder that has a low stiffness, the cylinder will be able to bend and twist as it opens up when a crack propagates, and the cylinder is likely to stay in one piece.

The ductility and/or toughness of the cylinder material has not been shown to be a dominant controlling factor in determining whether a cylinder will remain in one piece or will fragment when it fails. The effect of the level of toughness or ductility on the tendency to stay in one piece or to break into many pieces has not been directly established. Low levels of toughness or ductility do not mean that the cylinder is more likely to fragment than to remain in one piece when the cylinder fails. Whether the cylinder stays in one piece or breaks into many pieces is controlled more by the other factors described previously rather than the specific level of toughness or ductility.

6.3 Service experience with DOT-3A type cylinders

The service experience of DOT-3A type (and DOT-3AA type) cylinders indicates that there are few reported incidents of fragmentation type failures in service. The following section describes the service experience on DOT-3A type cylinders.

6.3.1 Carbon steel, 3A cylinders

Typical 3A cylinders manufactured in early 1900s were 9-1/16 in OD x 51 in long and were marked ICC-3A 2015 and contained 220 ft³ oxygen at service pressure. On January 31, 1942, the ICC authorized filling ICC-3A 2015 cylinders to a pressure 10% in excess of their marked service pressure, commonly known as plus rated cylinders. This plus (+) rating has been continued to date. In the 1970s the regulatory responsibility was transferred from the ICC to the DOT, and such cylinders were marked DOT-3A-2015. Before 1914, the primary sizes of cylinders were made of AISI 1025 mild carbon steel, and the 9 in size had a wall thickness of 0.375 in, was over 6 ft tall, and weighed in excess of 200 lb. Manual handling of such cylinders was very difficult, and the new cylinders were designed to be much more weight efficient.

These new cylinders were manufactured from 1-in thick plate by a hot drawing process and were heat treated by a quench and temper process. The heat treatment was designed to produce a ultimate tensile strength in the range of 90 000 psi to 105 000 psi and a relatively high ductility specified as 40% tensile elongation in 2-in gage length or 20% tensile elongation in 8-in gage length. The high ductility was specified to prevent excessively "hard" steel. To further preclude the hard steel, a permanent expansion requirement of 1% minimum was specified at hydrostatic test pressure. The steel composition specified in ICC-3A was a plain carbon steel with chemical analysis limited at 0.55% max. carbon, 0.050% max. sulfur, and 0.045% max. phosphorous; however, manganese was a nominal 0.70% max. and silicon was a nominal 0.35% max.

The specified minimum wall thickness for the 220 ft³ cylinder was 0.260 in, which produced 49 500 psi design stress at the 3360 psi test pressure and the 29 700 psi stress at 2015 psi service pressure. The stress at 2215 psi (plus rated) was 32 700 psi. These give a calculated safety factor for ultimate tensile strength to service stress of about 3.1.

The ICC-3A specification required that the cylinders be inspected during manufacture by an independent inspection agency and that the agency prepare a manufacturing report covering each cylinder. These reports are basically the same as issued today for DOT requirements.

These reports include such items as

- minimum wall thickness;
- chemical analysis of each heat of steel;
- results of tensile tests from each lot or 200 cylinders;
- results of flattening tests;
- results of hydrostatic test on each cylinder; and
- certification statement signed by the independent inspector.

An attempt was made to find reported fracture type failures of 3A cylinders in the open literature as well from the DOT. Reports on two failures were found and are described in 6.3.3.1 and 6.3.3.2.

A group high carbon 3A type cylinders were subjected to the flawed cylinder burst test as part of the ISO/TC 58 WG 14 test program conducted in the 1990s. Those cylinders had an acceptable leak-before-break performance with about 3.5 in (>10t) long flaw.

6.3.2 Intermediate manganese-normalized steel 3A cylinders

The use of high carbon steel for manufacture was discontinued when the industry developed a new design of intermediate manganese-normalized steel. The normalizing heat treatment consists of heating the cylinders above the transformation temperature for a specific time and then cooling in still air.

The steel analysis was carbon-0.40% max; manganese-1.35% to 1.65%; silicon-0.30% max.; sulfur 0.050% max.; phosphorous-0.04% max. The steels were aluminum killed to provide a fine-grained deoxidation practice. Grain size was ASTM 8 or finer.

The cylinder was the same size as the typical high carbon type and had a minimum design wall thickness of 0.260 in. The design stress was the same 49 500 psi at test pressure, thus providing a service stress of 29 700 psi at 2025 psi service pressure or 32 700 psi at 2215 psi plus rated service pressure.

The ultimate tensile strength was approximately 89 000 psi minimum, which would provide a safety factor of 2.7 (burst pressure to service pressure ratio). The other manufacturing limits such as elongation, flattening test, etc. previously listed were applicable for all ICC-3A types. The normalizing heat treatment produces a “soft” steel with low hardness and high ductility and wall stress at test pressure near the yield point.

6.3.3 Reported failures Incidents

An attempt was made to find reported failures of DOT-3A and DOT-3AA cylinders in the open literature as well as from the files of the DOT. Reported incidents of in-service cylinder ruptures are very few. The description of two incidents, one on 3A and one on 3AA follows.

6.3.3.1 Linde Union Carbide oxygen DOT-3A type cylinder explosion

On October 23, 1963, an oxygen cylinder shattered into more than 200 fragments at a plant in Corpus Christi, Texas. The failure investigation indicated that the cylinder failure was caused by an internal explosion involving a mixture of fuel gas and oxygen. The source of the fuel gas as well as the ignition for the explosion has not been established. The cylinder was manufactured in 1924, thus it is believed that it was a DOT-3A type specification cylinder.

6.3.3.2 Failure of DOT-3AA cylinder

In July 1975, a seamless steel cylinder ruptured while it was being filled with oxygen gas. The rupture occurred at a pressure of about 2500 psi. The cylinder had a DOT-3AA 2265 marking, and it was manufactured in 1975. The material of construction was quenched and tempered intermediate manganese steel. The failure occurred from 3-in long and 0.232-in deep flaw located on the outside wall of the cylinder. The cylinder ruptured in one piece. Figure 1 shows the photograph of the cylinder.



Figure 1—DOT-3AA cylinder in-service ruptured

6.4 Single flaw fracture propagation mode

This section presents the expected fracture propagation mode under pneumatic loading when the fracture initiates from a single flaw. Fracture propagation mode deals with what happens to the crack once it initiates from a flaw. Specific issues with a propagating crack are how long it travels, how many branches are developed, and eventually how many pieces of a cylinder are produced.

Two sets of data are presented. One is from Praxair's test program, and the other is from a service failure of a DOT-3AA cylinder.

6.4.1 Praxair data

Test results on four flawed cylinders are presented to show the fracture propagation mode of DOT-3A cylinders under pneumatic loading. Figure 2 shows the geometry of the flaw machined on the outside surface of the cylindrical wall. The cylinders were pressurized to failure with nitrogen gas. Two cylinders were manufactured from intermediate manganese steel, and two were manufactured from high carbon steel. The cylinder data and results are presented in Table 1.

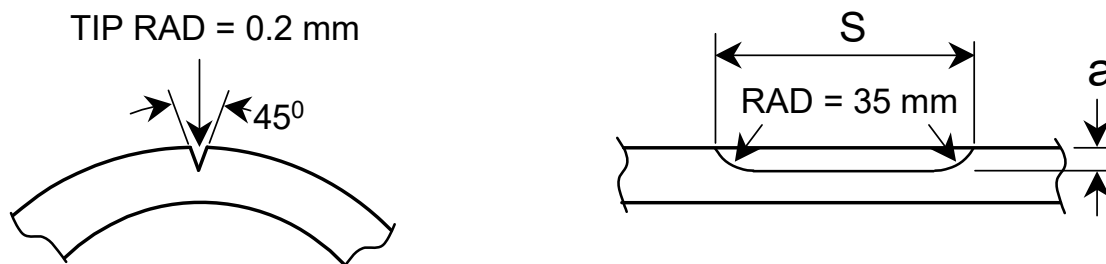


Figure 2—Notch geometry

Table 1—Results of fracture mode of flawed 3A cylinder tests

Cylinder no.	Material	Year built	Service pressure	OD	Wall	Flaw length	Flaw depth	Failure Pressure	No. of pieces
			psi	in	in	in	in	psi	
1	IM	1937	2215	9.13	0.279	12	0.150	2625	1
2	IM	1944	2215	9.13	0.274	14	0.175	2390	1
3	HC	1917	2215	9.14	0.286	10	0.125	2680	1
4	HC	1916	2215	9.17	0.303	12	0.150	2605	2
Notes 1 IM = intermediate manganese. 2 HC = high carbon.									

The intent of the tests was to compare the flaw tolerance capability at or near service pressure as well the resultant fracture propagation mode. As shown in Table 1, the failure of the cylinders occurred at about 8% to 21% higher than the marked service pressure. Figures 3, 4, 5, and 6 show the overall view of the tested cylinders. As indicated in Table 1, the intermediate manganese cylinders ruptured in one piece, while one high carbon cylinder (No. 3) ruptured in one piece, and the other (No. 4) in two pieces. The data also indicate that the 3A cylinders do not fracture in many pieces when fracture occurs at or near the marked service pressure. It can also be observed from the photographs that both materials exhibited a considerable amount of plasticity.

**Figure 3—Flawed tested 3A cylinder (no. 1)**



Figure 4—Flawed tested 3A cylinder (no. 2)



Figure 5—Flawed tested 3A cylinder (no. 3)



Figure 6—Flawed tested 3A cylinder (no. 4)

6.4.2 In-service failure of a DOT-3AA cylinder

The cylinder failure described in 6.3.3.2 indicates one piece fracture when fracture initiates from a single flaw at failure pressures less than or equal to test pressure. This failure mode further confirms the expected failure mode under pneumatic loading and is in agreement with the test data presented in 6.4.1.

6.5 Multiple flaw fracture propagation mode

The data presented in 6.4 indicate that if a fracture initiates from a single longitudinal flaw, the crack usually runs in the longitudinal direction, then it turns in the hoop direction at the head area and at the bottom area, and that results in one or two-piece fracture. If a cylinder contains multiple flaws such as SCC and if these cracks are of equal size, then the fracture can initiate at several of these cracks. The fracture surface from a cylinder that failed with multiple cracks is shown in Figure 7. In this situation, the cylinder will have many propagating cracks and may break up the cylinder in several pieces. The other scenario postulated with multiple flaws is that, if a fracture initiates from a single critical flaw during the propagation, the crack may develop into several branches as it propagates through the least resistance provided by the companion flaws. This is shown in Figure 8 in which the propagating crack shows a step where the crack turns 90 degrees before continuing to propagate. This type of crack propagation will lead to fragmentation. Fracture mechanics procedures exist to handle the effect of multiple flaws on fracture initiation mode; however, no procedure or data could be found on the effect of multiple flaws on the fracture propagation.

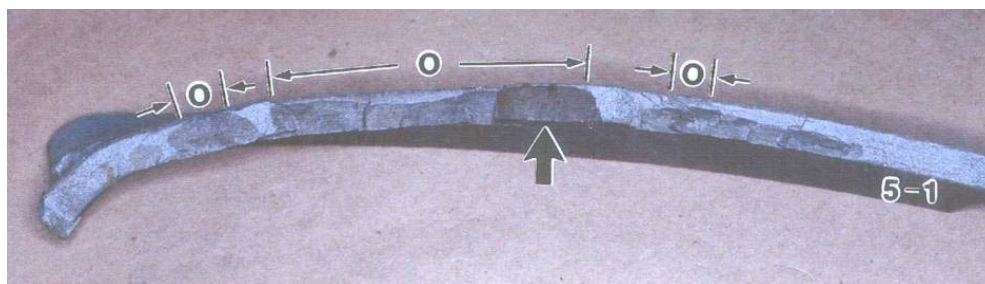


Figure 7—Fracture surface where multiple cracks exist

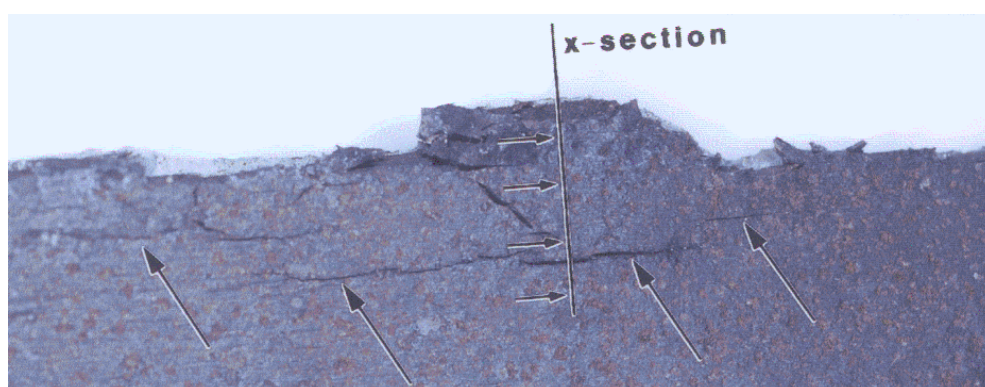


Figure 8—Cylinder surface showing multiple cracks

6.6 Fracture initiation

Test data from ISO/TR 12391 Part 2 and Praxair are presented to compare the fracture initiation strength of DOT-3A and DOT-3AA cylinders in the presence of crack-like flaws [9].

6.6.1 ISO data

In ISO/TR 12391 Part 2, the tested 3A cylinders had a design service pressure of 155 bar (2248 psi), 9 in OD, 0.236 in design wall. The 3AA cylinders had design service pressure in the range of 155 bar (2248 psi) to 440 bar (6670 psi). The diameters and thicknesses of 3AA cylinders were in the range of 7 in to 9.4 in, and 0.15 in to 0.57 in respectively.

Longitudinal notches were machined on the outside surface of the test cylinders (see Figure 2). The cylinders were pressurized to failure. The failure pressure and failure mode (leak-before-break or fracture) was recorded. Figures 9 and 10 show the results on 3A cylinders, and Figures 11, 12, and 13 show the results on 3AA cylinders. Figure 14 shows the comparison of the data compiled from Figures 9 through 13.

In Figures 9, 10, 11, 12, 13, and 14, P_f/P_s means the ratio of the measured failure pressure (P_f) and marked service pressure (P_s) and "n" means a flaw length multiplier, which is a number (n) equal to flaw length (l_o) divided by design wall thickness (t). For example, $n = 10$ means 10t long flaw.

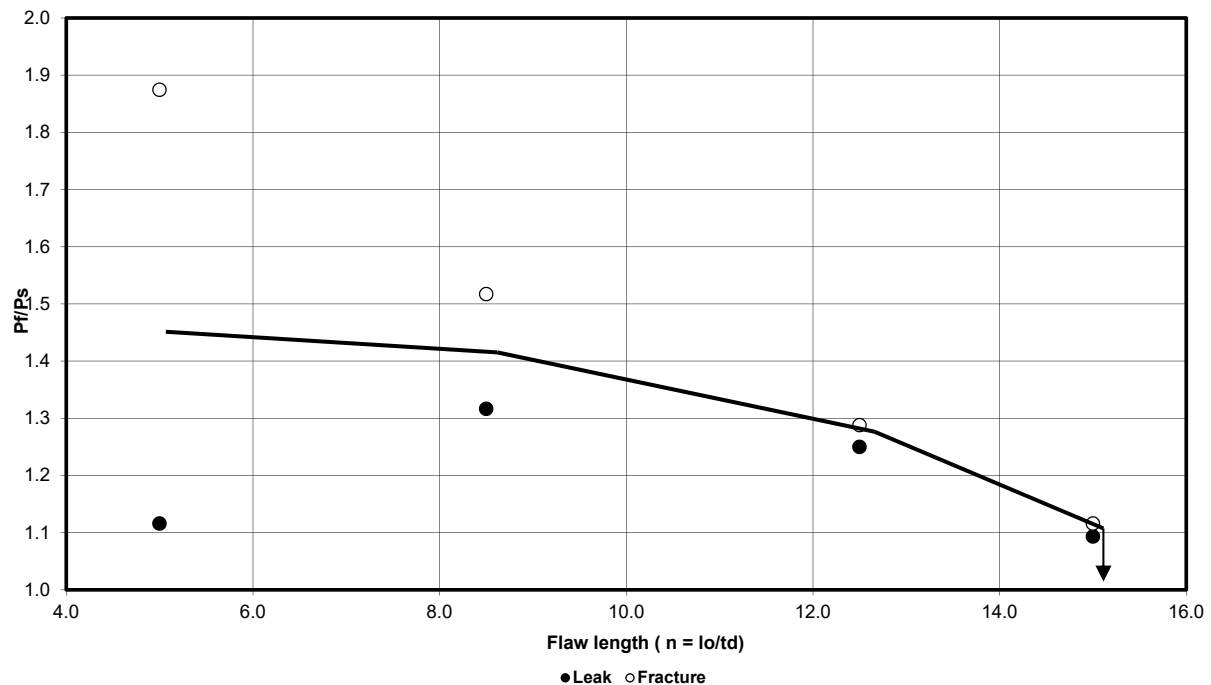


Figure 9— Flawed cylinder burst test results for A-1 material²

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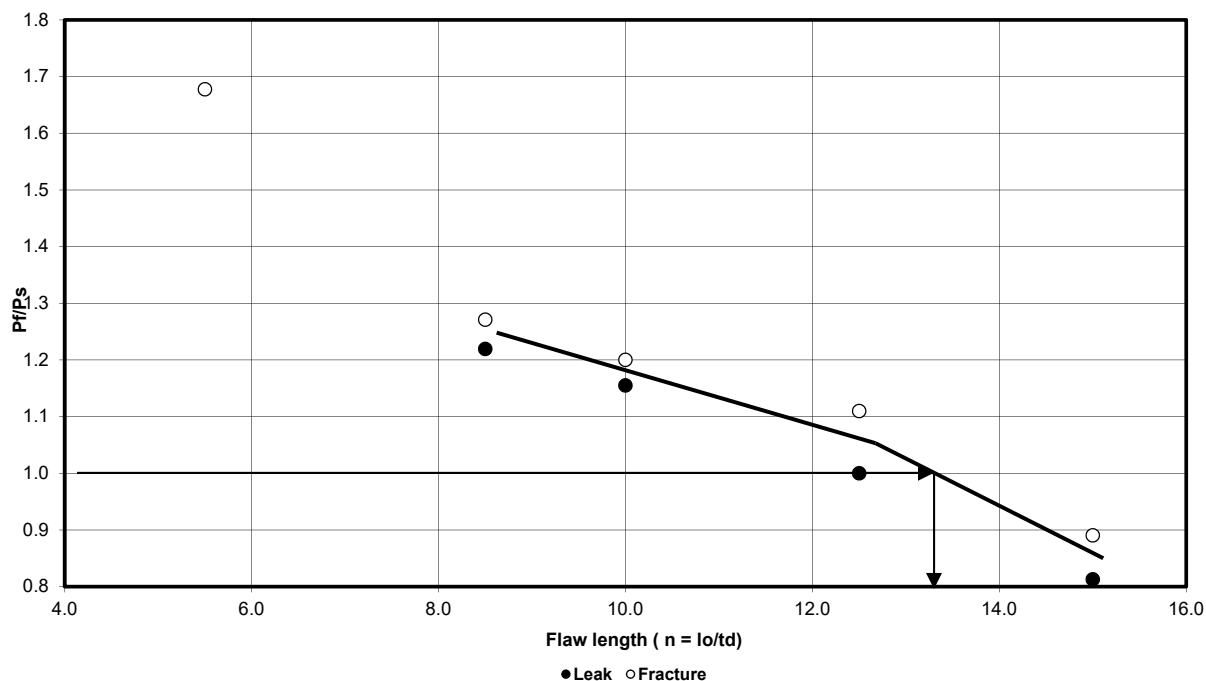


Figure 10—Flawed cylinder burst test results for A-2 material³

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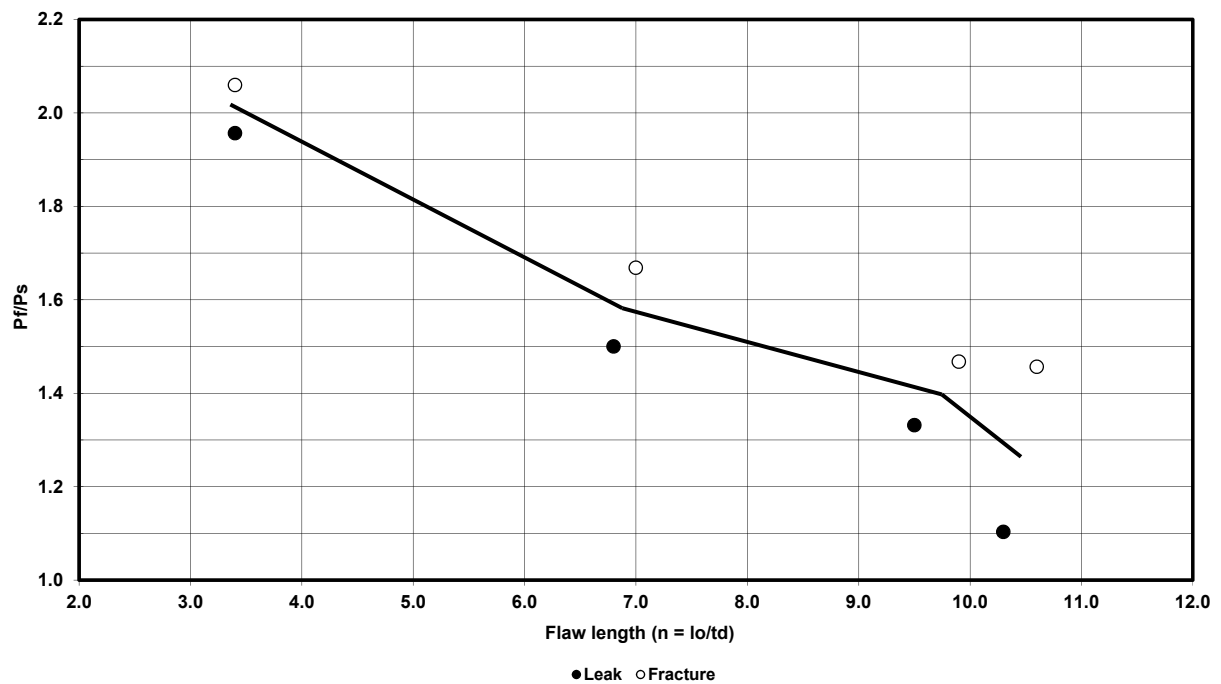


Figure 11—Flawed cylinder burst test results for B-3 material⁴

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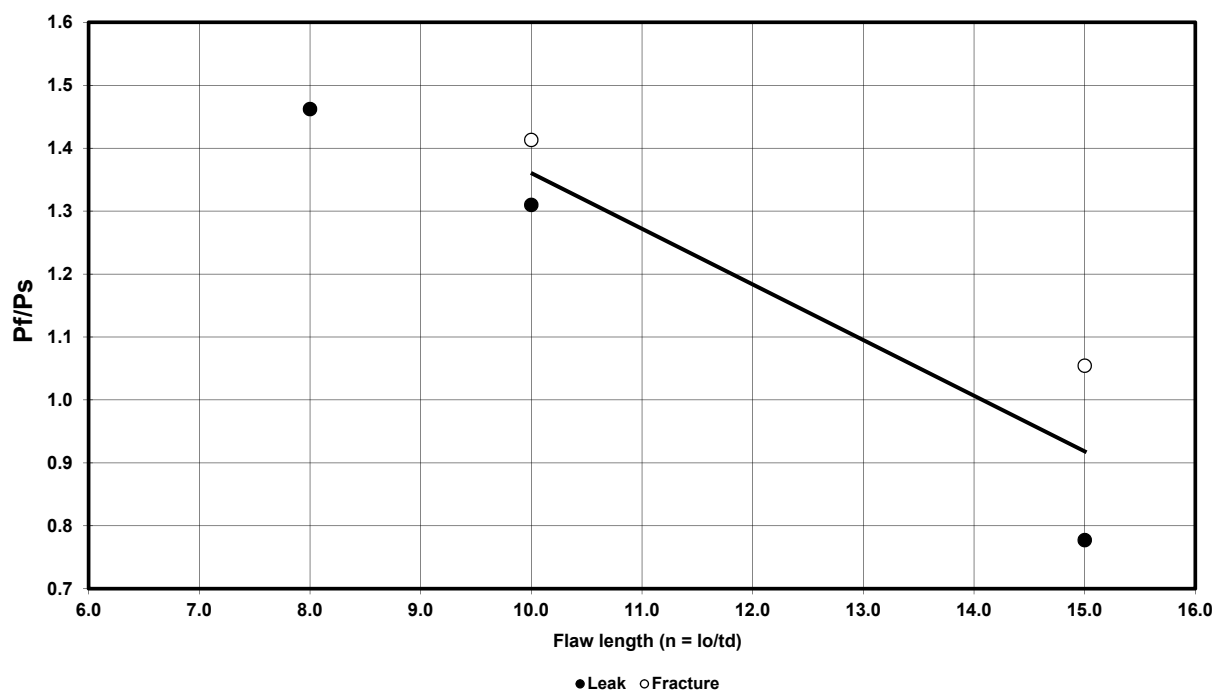


Figure 12—Flawed cylinder burst test results for B-6 material⁵

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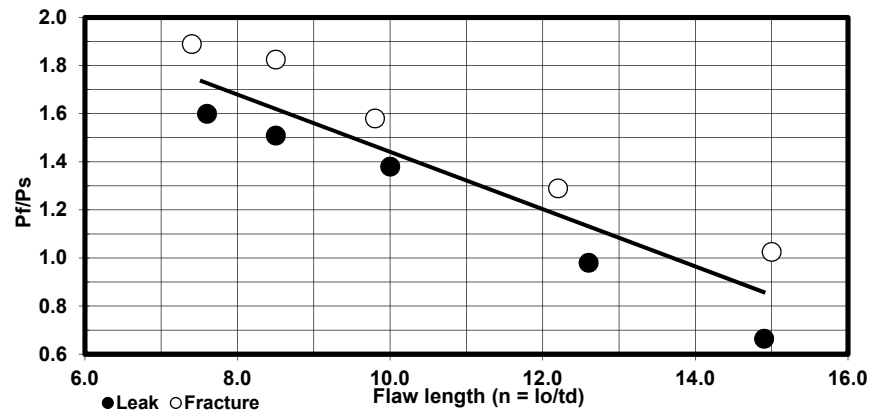


Figure 13—Flawed cylinder burst test results for B-9 material⁶

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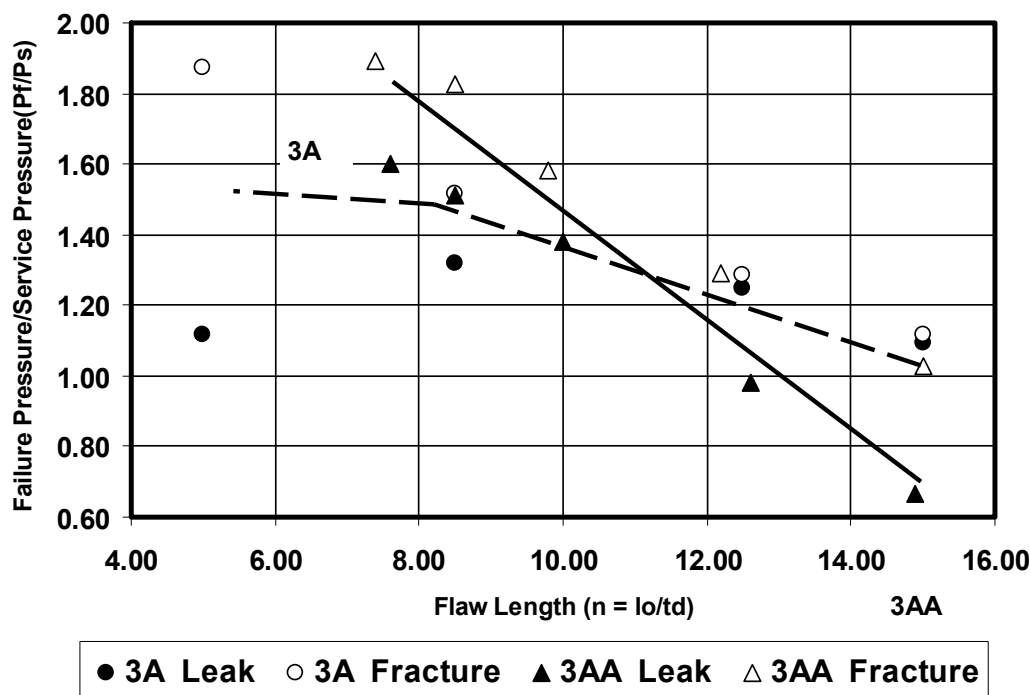


Figure 14—Fracture performances of 3A and 3AA cylinders

Figure 14 indicates that at P_f/P_s ratio of one, a 3A cylinder will exhibit leak-before-break performance for a flaw length of approximately 15t. For 3AA cylinders, Figure 14 shows the leak-before-break performance at 13t long flaw.

These results show that the fracture resistance of both 3A and 3AA cylinders is equivalent.

In conclusion, flawed cylinder test results on 3A and 3AA cylinders were evaluated from ISO/TR 12391. The data indicated that both types of cylinders could exhibit leak-before-break performance for 12t to 15t long flaws at applied pressure equal to service pressure. Thus, it can be concluded that both 3A and 3AA cylinders have equivalent fracture resistance characteristics.

6.6.2 Praxair flawed cylinder data

Cylinders of three different steels were obtained to investigate burst characteristics with dimensionally varying longitudinally machined sidewall notches (see Figure 2). The steels were chromium molybdenum, intermediate manganese, and high carbon; and they were representative of the cylinder steels in service. The service pressure of chromium molybdenum cylinders was 2640 psi and 2215 psi for intermediate manganese and high carbon cylinders.

The project plan was to produce known size artificial flaws (i.e., machined notches) in the cylinder sidewalls and pressurize the cylinders with water or gas until they burst. The objective was to correlate the burst pressure with the flaw size. Test results are given in Table 2.

The measured failure pressure versus flaw depth is plotted in Figure 15. Figure 15 shows that the failure pressure is almost directly proportional to the flaw depth. This behavior is exhibited by both 3AA and 3A cylinders indicating that the fracture initiation strength is the equivalent for DOT-3A and 3AA type cylinders.