ABSTRACT

Long term asset management is a key issue in the high pressure industry, but only limited and somewhat fragmented guidelines exist in the form of various “New-Construction” Design Codes and Standards. The high pressure industry is a niche industry and many applications are not covered completely by existing codes and standards. The paper will cover an overview of various ASME and API documents and provide an overall methodology for the implementation of an effective and logical asset management protocol including Fitness for Service guidelines which can be referenced in lieu of a comprehensive document being available.

ASME discontinued publication and distribution of the High Pressure Systems Standard (HPS-2003) [6] in September 2009. One of the most common uses for this document was the section on vessel requalification. The paper here will discuss the application of this requalification methodology, and its use in an overall high pressure asset management plan.

API 510 [5] and the National Board Inspection Code (NBIC) [13] cover the in-service inspection, repair, alteration, and rerating activities for pressure vessels-including vessels constructed and approved as jurisdictional special based upon jurisdiction acceptance of particular design, fabrication, inspection, testing, and installation. However those documents reference most of the technical requirements in the ASME construction codes for design, welding, NDE, and materials as being applicable for in-service pressure vessels. Also, API 510 and NBIC recognize FFS assessments for evaluating the structural integrity of in-service damage of pressure-containing components. This paper will discuss the use of those construction codes for use in a Fitness for Service assessment and the development of a comprehensive strategy for long term asset management using these guidance documents in conjunction with the ASME/API Inspection Planning guidelines.

INTRODUCTION

Long term asset management is a key issue in the high pressure industry. The high pressure industry here is defined as equipment for pressures “generally above 10 ksi”.

The Standards specifically for pressures in these ranges and higher were first published in the 1985 to late 1990’s. ASME Section VIII Division 3 for High Pressure vessels was first published in 1997. Chapter IX of ASME B31.3 [11] was first published in 1985. There is a large amount of equipment that was designed and built prior to the publication of these documents to “good engineering practice” and as of the current date, there are still some jurisdictions that have not incorporated these Standards into their Boiler and Pressure Vessel laws.

The primary mode of failure for high pressure equipment is fractures caused by fatigue and thermal loadings. Other issues that may be experienced include stress corrosion cracking, cracking due to hydrogen embrittlement, and stress relaxation. Ongoing confusion as to the meaning of “cycle life” continues to this day. The definition of the design fatigue life or design life with regard to that calculated relative to the original Codes of construction such as ASME Section VIII Division 2 [3] and Division 3 [2] adds to the confusion.

There is a definitive need for a comprehensive document that deals with high pressure vessels in the same way that API 579-1 / ASME FFS-1 [4] deals with pressure equipment in general.
CURRENT INDUSTRY STANDARDS

Today there are various standards that can be used to assist in evaluating fitness for service of vessels under high pressure, however there is no single document exclusively committed to this task. These types of “Fitness for Service” evaluations then form the basis for the long term asset management plans for high pressure equipment.

Industry today is continually trying to apply “Recognized and Generally Accepted Good Engineering Practices (RAGAGEP)” to attempt to be compliant with OSHA regulations. OSHA 1910.119 [12] (j) specifies measures to be taken to assure that equipment used to process, store, or handle highly hazardous chemicals is designed, constructed, installed, and maintained to minimize the risk of release of such chemicals. It is required that a mechanical integrity program be in place to assure the continued integrity of process equipment. The elements of the program are to include:

- the identification and categorization of equipment and instrumentation
- development of written maintenance procedures
- training for process maintenance activities
- inspection and testing *
- identify deficiencies in equipment that are outside acceptable limits defined by the process safety information
- development of a quality assurance program

API 510 [5] and NBIC [13] currently cover in-service inspection, repair, alteration, and rerating activities for pressure vessels-including vessels constructed and approved as jurisdictional special based upon jurisdiction acceptance of particular design, fabrication, inspection, testing, and installation. It states that most of the technical requirements in the construction standards of the ASME Boiler and Pressure Vessel Codes for design, welding, NDE, and materials can be applied to in-service pressure vessels. Also, both API 510 [5] and NBIC recognize API 579-1 / ASME FFS-1 Fitness for Service Standard (FFS) [4] assessments for evaluating the structural integrity of in-service damage of pressure-containing components.

It should be noted that ASME PTB-2, “Guide to Life Cycle Management of Pressure Equipment Integrity” [9] has section 12 for High Pressure Vessels. Specifically, this document notes the use of National Board documents for pressure vessels in general terms, the use of PCC-3 Risk Based Inspection Planning for development of in-service inspection plans, and BPV Section V & RP SNT-TC-1A for the inspection itself. API 579-1 is referenced for any fitness for service evaluations that may be required.

On that basis, the document many would turn to regarding “Fitness for Service Assessment” of pressure equipment is the API 579-1 / ASME FFS-1 Fitness for Service Standard (FFS)[4]. Though this Standard focuses on components with in-service damage, Part 4 of this Standard contains guidelines for evaluating static strength of a vessel. A Level 3 evaluation can be performed for an in-service vessel. The assessment technique for Level 3 recommends the use of Annex B1 (4.4.1.2, 4.4.4, 5.2.5.2 & 5.4.4). Additionally, Part 9 of this Standard deals with the issue of growth of cracks and crack-like flaws in cyclic service.

Several issues exist in the direct application of the criteria in the FFS document. The first is the limitation of the fracture mechanics solutions to low wall ratios. Presently, the solutions for flaws in walls of a diameter ratio over 2.0 are not available. The second is that the “Load Case Combinations” for performing a Load and Resistance Factor Design (LRFD) analysis of the vessel use different design factors than are found in ASME Section VIII Division 3 which are specifically determined for use with high pressure equipment. In lieu of this, the requirements in ASME Section VIII, Division 3 can be applied, but as this is a “new construction Standard” its applicability is implicit to the subject.

Several other Standards are either presently available in industry regarding the subject of high pressure equipment evaluation or have recently been available. These include Chapter IX of the ASME B31.3 Pressure Piping Standard [11] that deal specifically with the issues of high pressure piping, fittings and tubing.

ASME discontinued sales of the High Pressure Systems Standard (HPS-2003) [6]. The most recent edition was the High pressure Systems Standard 2003. The material in this book is presently being reviewed and certain key parts are under consideration for inclusion in other standards. One of the most commonly used parts of this Standard was the information on High Pressure Vessel Requalification including the requirements in Appendix A of that Standard. The Boiler and Pressure Vessels Committee on Pressure Vessels (Section VIII) and its Sub-Group High Pressure Vessels have taken action to incorporate that information into a non-mandatory appendix which is expected to be in the 2013 edition of Section VIII, Division 3. The Subcommittee on Inspection Planning of the ASME Post Construction Standards Committee also has formed a task group, aimed at addressing many of the issues, including vessel requalification, risk assessment in high pressure equipment, and mitigation of risk in operation of high pressure equipment through barricading.

PROGRAMMATIC METHODOLOGY

Industry is looking for methods today to manage key assets in a world of ever decreasing maintenance budgets and in environments where operating plants technical engineering staff is being considered “overhead expenses” and continually being reduced. In addition, with the “baby boomers” heading for retirement, there is continued turnover in technical expertise in operating plants that once handled all high pressure issues internally.

In some cases, this leads to asset management plans that have little if any technical engineering basis for maintenance
and management of these key assets. The range of approaches varies widely.

In some cases, equipment was specifically designed for high pressure applications to be below the “six inch rule”. In jurisdictions where this rule is in place, pressure vessels below 6 inch inside diameter are exempt from the pressure vessel regulations. This can include extremely high pressure experimental reactors which may have been designed to no particular standard or vessels that have been in operation for a long period of time and not have any type of long term inspection program associated with them. The alternative at times is for the owners of this equipment or their local AI to require repeated hydrostatic testing of the equipment to 1.5 times design pressure which for high pressure equipment, can lead to doing more harm than good because it can initiate in or cause the failure of fatigue cracks.

OEM’s programs vary in complexity and technical basis. Some include a program with a basis on the actual life of the vessel. Others may include periodic inspection of the equipment which is based on their own internal program with no particular tie to the specific equipment.

In some cases, operators or “User’s” of high pressure equipment, with little basis for long term management and a desire to be conservative, will retire equipment at the end of the “ASME Life” of the equipment. This is a quite conservative approach and the equipment is often times able to continue in service for up to an order of magnitude longer [6].

A programmatic integrated engineering approach to managing these assets is desired to allow the best management of these assets. This type of approach uses a truly technical basis for evaluating the life of the equipment, utilizes “state-of-the-art” technology for the examination of the equipment and optimizes the inspection frequency.

This type of program would include:
- Confirmation of design integrity of the equipment to known modern Standards
- Evaluation of the life of the equipment using “state-of-the-art methods in current published Standards
- Development of “state-of-the-art” Non-Destructive Evaluation” techniques to get the most complete / accurate assessment of equipment condition
- Performance of a complete baseline inspection of all critical areas of the equipment
- Establishment of a long term inspection and monitoring plan for the equipment including
  - Techniques to be used
  - Methods of implementation
  - Acceptance criteria that form the basis for life analysis
- Criteria for the long term “retirement” of the equipment

DESIGN CONFORMITY ASSESSMENT

One of the principal issues when setting up long term management programs is to be sure of the basis on which the equipment is being evaluated. The recommended practice for this is to ensure, as a minimum that it meets the minimum design margins found in published Standards. In some cases, the equipment may not meet these margins, even though it has been in-service many years. Lower toughness materials were sometimes used in the past and may not meet the criteria found in the Standards published today. Also, in some cases, the design requirements of past materials do not meet the requirements that are accepted today. This includes design margins that may have been common practice either in some industries or company design books for this type of equipment.

When performing an evaluation of a piece of equipment, the first step is to determine the proper Standard with which to evaluate it that is available today. The options would commonly be either Appendix B of API 579-1, ASME Section VIII Division 2 Part 5, or ASME Section VIII Division 3. This may involve either linear elastic analysis methods or elastic-plastic analysis methods to show conformity of the entire design. The most significant difference between Div. 2 and Div. 3 is the design margin. Div 3 uses a margin of 1.8 while the margin for Div. 2 is 2.4. ASME Section VIII Division 3 is recommended to provide the most modern evaluation of high pressure equipment.

NDE TECHNIQUES

One of the key components to the calculation of life of a component using the fracture mechanics philosophy of either ASME Section VIII Division 3 or API 579-1 is the determination of the initial flaw size. The life of a component when considered on a crack growth basis is largely determined while the flaw is small. The larger a flaw is the more rapidly it tends to grow in general terms.

Therefore, detectability and accurate sizing of flaws in a vessel can be of utmost importance in optimizing the frequency with which the equipment must be inspected and maximizing the interval between inspections.

ASME Section VIII Division 3 typically uses a flaw size of 3/16 inch long x 1/16 inch deep as a basic initial assumption. This is largely based on criteria from wet fluorescent magnetic particle testing (WFMT) and other similar surface examination techniques. It also presently has an apparent discrepancy between this size flaw and the “acceptable flaw sizes” which are incorporated into KE-3 for the evaluation of welds using ultrasonic (UT) techniques in lieu of radiographic (RT) techniques. For an 8 inch wall thickness with a surface connected flaw, the current acceptance criteria would be a flaw that is on the order of 0.332 inch deep and 0.998 inch long. This is a size that is readily detectible using modern methods.

Modern NDE protocol for inspection of this type of equipment includes a complete baseline inspection of the equipment at the time of manufacture. The intent would be to
include both a surface examination and volumetric examination of the vessel.

Surface examination in the manufacture of equipment today includes use of traditional methods such as visual examination (VT) including the use of bore scopes, methods of liquid penetrant examination (PT) and magnetic particle examination, both wet (WFMT) and dry (MT).

Volumetric examination of the equipment includes radiographic techniques (RT) including both traditional and digital radiography, ultrasonic testing (UT) including traditional straight beam and shear wave exams.

A number of other modern and advanced techniques are also becoming more readily available in industry to provide a much more comprehensive assessment of high pressure equipment, including eddy current array (ECA) for surface examination, and ultrasonic linear phased array (LPA), time of flight diffraction (TOFD), and ultrasonic guided wave technologies (GWT) for volumetric examinations. A review of the paper by Milligan, et al. [10] is recommended in lieu of a detailed discussion in this paper.

**NDE TECHNIQUES OF EQUIPMENT MONITORING TO EVALUATE EXTENSION OF SERVICE LIFE**

As stated previously, in older equipment it is common that a complete baseline inspection may never have occurred or been documented at the time of manufacture or after placed in service.

In service monitoring during operation is used for tracking in-service condition of high pressure equipment. Design of this equipment is generally based on predicted or assumed loading cycles that the equipment is expected to undergo during its lifetime. Much of this equipment is used for many years and often in services that were not able to be predicted at the time of design. Also, many times, it is desirable to lengthen the time between inspection cycles without doing actual physical inspection, which can take critical assets out of service for significant periods.

There are several monitoring methods for tracking the condition of equipment in-service, both implicitly and explicitly.

There are software packages on the market today that utilize operational data, including loading fluctuations such as pressure and temperature transients that then use that data with life prediction models to determine the “actual” remaining life of the equipment in service. These can be useful in equipment with long service cycles which are designed such that disassembly can be labor and cost intensive.

One other method available on the market today is acoustic emission monitoring of equipment. This technique places sensors on the equipment in-service to detect acoustic disturbances in the material of the equipment to detect when cracks are active. This technique cannot determine the size of flaws, but, in some cases can detect when a flaw reaches a level that is active enough to be detected and should then be further evaluated with direct measurement and sizing techniques. There are several limitations to acoustic emission. It is not able to be used on many types of high pressure construction, specifically on equipment with multiple layers where movement of the layers can result in “noise” that will obscure the signals that are typically able to be detected by the sensors. An example of this would be wire wound construction.

**LIFE ASSESSMENT**

There are several methods of evaluation of life assessment published in Standards today. ASME Section VIII alone has four methods for performing this type of evaluation. These include both fatigue and fracture mechanics.

ASME Section VIII Division 2[3] has a method for performing a fatigue assessment using traditional S-N approach to fatigue. The method was changed slightly in the 2007 to current editions of the Code to use a Von Mises based stress as input in lieu of the Tresca based stress criteria that was in the previous editions. ASME Section VIII Division 2 and 3 also includes what is called the “Structural Stress Method” for calculation of the fatigue life of welded components. ASME Section VIII Division 3 also has a fatigue assessment procedure similar to the procedure from Div. 2 prior to the 2007 edition. This methodology however, allows a designer to account for calculated residual stresses in the analysis in lieu of using “mean stress corrected” fatigue curves as is the case in Div. 2. It should also be noted that the “S-N” and “Structural Stress” fatigue methods of Division 3 are limited to vessels that can be proven to be “leak before break”.

In each of these methods, the test data were fit with a “best fit” curve and then reduced by design margins. The “S-N” approach factors of 2:1 on stress and 20:1 on life to place the design curve at the lower bound of the test data. Margins in the “Structural Stress” method are based on a statistical approach.

Division 3 requires the use of fracture mechanics for vessels where “leak before break” cannot be demonstrated. In the most recent editions, the fracture mechanics solutions of API 579-1 are recommended where applicable. The solutions are limited to wall ratios of 2.0 (OD/ID). Appendix D of Div. 3 also has a fairly complete set of solutions where API 579-1 is limited. In addition, the failure assessment diagram (FAD) is required for determination of the critical flaw size in Div 3. The 2011 addenda of Div 3 has margins on monowall vessels of ½ of the number of cycles from the initial flaw size to critical flaw size and the number of cycles for a crack to reach ¼ of the critical flaw size.

There is a philosophical difference between the fatigue methods of Div. 2 and Div. 3 and the fracture mechanics approach. The fatigue methods determine the time for failure in a standard test specimen. Most high pressure vessels are significantly thicker than the dimension of a standard fatigue specimen and typically have a significant stress gradient through the wall. This is typically considered the “initiation” life. The fracture mechanics method preferred in most cases in Div. 3 is
considered to determine the “propagation” life. The margins are significantly different between the two approaches [2,3].

RISK VS PRESCRIPTIVE BASED INSPECTION PLANNING

Once the structural integrity is verified for the equipment, and the life is determined, the most important component of asset management for high pressure equipment is a complete in-service inspection plan. A complete plan should include each of the components discussed previously: complete NDE inspection plan utilizing the latest detection and sizing techniques, the life assessment for determination of the period between inspections, either based on time or on number of operational cycles, and the detectable and allowable flaw sizes for each failure mode being examined during an in-service inspection. The preceding portions of this paper show the complete interrelationship among each of the components of this inspection plan.

One of the most significant maintenance costs associated with many types of high pressure equipment is the costs associated with performing in-service inspections, including lost production time. Therefore, lengthening the time between those inspections can greatly reduce maintenance costs and increase operational profitability.

The state-of-the-art NDE methods are likely not what was considered at the time of the manufacture of the equipment. Often these methods can be more expensive than more traditional methods. However, lengthening the time between inspections can greatly reduce overall costs. The high pressure equipment life will be evaluated with the fracture mechanics approaches found in ASME Section VIII Division 3. The rate of crack growth is very slow when the flaws are small and therefore the majority of the components life is during the period when the flaws are small. Any reduction in the size of flaw that can be found can exponentially increase the time between inspections.

One of the most commonly used parts of the ASME High Pressure Systems Standard [6] is the information on vessel requalification. This standard had a simple methodology based on experienced base criteria that has been successfully implemented in many industries as a basis for their in-service inspection plans. This used the acceptance criteria / initial flaw sizes from ASME Section VIII for the detection criteria and based the period between inspections on the life calculated by those methods.

Since that time, the use of Risk Based Inspection Planning based on ASME PCC-3 [7,8] has come into use. This standard, while not common in all industries is effectively used in some industries, and provides a more technically based approach to determining the period for inspections.

CONCLUSIONS AND RECOMMENDATIONS

A comprehensive plan regarding the “Fitness for Service” of high pressure equipment is essential to safe long term operation of the equipment and proper management of key assets. This type of asset management plan should includes:

- Complete documentation of design integrity of the component
- Complete life assessment coupled with
- Inspection plan which includes the most modern NDE methods for evaluation of potential flaws
- Optimized inspection interval based on the life cycle predictions and the NDE methods employed
- Upfront evaluation of long term criteria for the repair, replacement, or retirement of equipment.

Many of the significant gaps in the Codes and Standards available to the high pressure industry were pointed out in the late 1970’s and 1980’s through the efforts of what was then part of the Operations, Applications, and Components Technical Committee of the ASME Pressure Vessels and Piping division which is now known as the High Pressure Technology Committee. This lead to the creation of ASME Section VIII Division 3[2], Chapter IX of B31.3 [11], and the former High Pressure Systems Standard [6]. These efforts need to continue. Specifically with the expansion of the API 579-1 / ASME FFS-1 Fitness for Service Document, the Post Construction Inspection Planning documents (possibly PCC-3 on Risk Based Inspection Planning) and others to consider this niche industry called high pressure.

Finally, industry needs to become more familiar with the Codes, Standards and technology presently available in industry today regarding the management of key assets including high pressure equipment. Merely relying on OEM’s conservative recommendations which may or may not have a firm technical basis in the management and maintenance of these key business assets in some situations is not in the best interests of the “User’s”. “User’s” charged with the responsibility of managing these assets should have a firm understanding of the technical basis of all of the decisions being made relative to these often key pieces of equipment.
REFERENCES
12. OSHA 1910.119, Process Safety Management of Highly Hazardous Chemicals