Preventative Measures to Ensure Against Fracture/Cracking of the Confinement Boundary welds in Carbon/Alloy Steel Casks

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Abstract

Most cask designs for storage and transportation of spent nuclear fuel use two lids, an inner shield lid and an outer structural lid. The structural lid may be attached to the cask body by either a full-penetration weld, a partial-penetration groove weld or bolts. Weld flaws, such as cracks, can occur in carbon and low alloy steels from several reasons. These reasons could result from defects in the cask shell material, improper fit-up of lid and backing ring, moisture contamination of the weld, or hydrogen induced cracking. Testing and evaluations have shown that weld flaws can be prevented if certain measures are implemented during weld fabrication. This paper will discuss improvement techniques that should be considered from accrued cask design and fabrication experiences. Additionally, a discussion is provided on how measured values of charpy tests and dynamic fracture toughness of welds, heat affected zone and base materials should be used as a basis to confirm weld integrity.

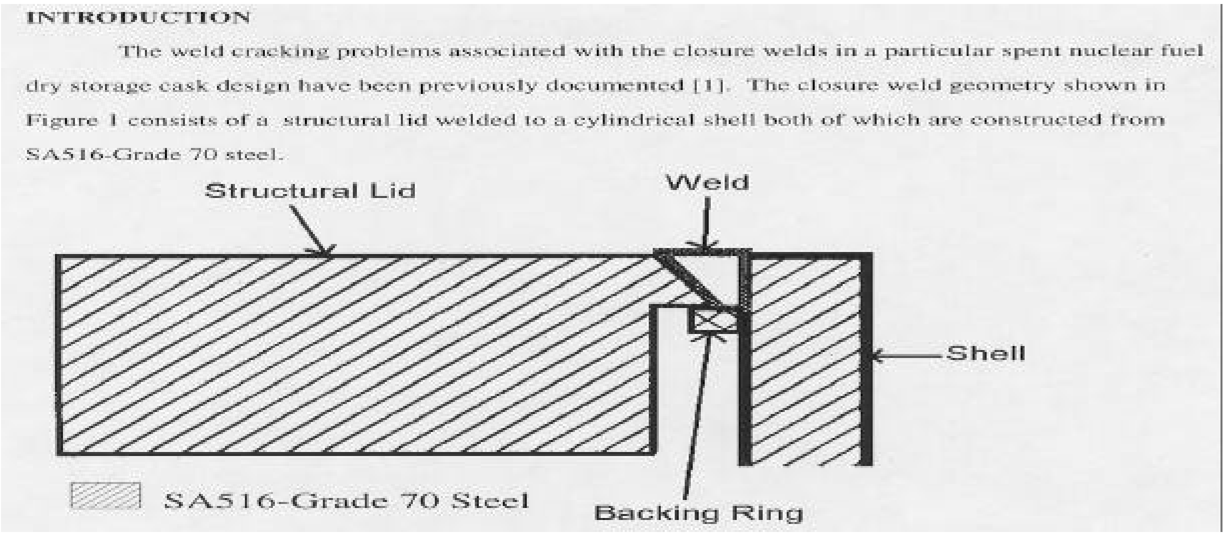
Introduction

One purpose of a dual-purpose dry cask storage system (DCSS) or transportation cask is to maintain the confinement of highly radioactive nuclear spent fuel under all anticipated and hypothetical accident conditions, including natural phenomena such as earthquakes, tornados, lightning, and floods. The design must adequately protect the spent fuel cladding against any potential gross rupture caused by degradation of the DCSS or transportation cask. The United States Nuclear Regulatory Commission's (NRC) regulatory guidance document, NUREG-1536[1], describes the need for an assessment of a brittle fracture for a DCSS or transportation cask confinement boundary fabricated from carbon steel. This confinement boundary typically consists of the cask body, the bottom head to cask body weld, and a lid closure system. The lid and bottom head are welded to the cask body by means of a full-penetration weld. The closure weld geometry of a typical carbon steel of a dual-purpose DCSS is shown schematically in Figure 1[2].

When austenitic stainless steel materials are used to create the containment boundary of the DCSS or transportation cask, they are exempt from fracture toughness testing requirements of the ASME Code. Ferritic steels used to create the confinement boundary are required to meet the requirements of NB-2300 and beyond. Consequently, the nil-ductility transition (NDT) temperature, and measured fracture toughness for the base metal, weld metal, and heat affected zone (HAZ) metal must be evaluated.

Figure 1 Closure Weld Geometry For a Carbon Steel Cask

Critical flaw size calculations for both normal and accident conditions for the most conservative stress states should be evaluated and compared to acceptance criteria for detected flaws during pre-service examination. Since a particular material can exist in many different grades and classes, it is crucial that the exact class and grade of material to be used to fabricate a DCSS be properly tested and evaluated for regulatory requirements.



INTRODUCTION

The weld cracking problems associated with the closure welds in a particular spent nuclear fuel dry storage cask design have been previously documented [1]. The closure weld geometry shown in Figure 1 consists of a structural lid welded to a cylindrical shell both of which are constructed from SA516-Grade 70 steel.

Weld Design and Specifications

There are two nationally recognized welding codes: ASME^3 and AWS D1.1^4. The ASME Code governs welded pressure vessels, from domestic hot water heaters to nuclear reactors. The AWS D1.1 “Structural Welding Code” is the applicable code for welding structural steel, such as the steel used for bridges and steel-framed skyscrapers. The NRC staff recommends the ASME Code, Section III, Division 3 ^{5} and associated ASME Code, Section IX, as the preferred design Code for a DCSS. Some older DCSS designs used the AWS Code. It should be noted that the various construction Codes differ from one another in their requirements for materials and welding procedures due to the fact that each construction Code is specialized with particular applications in mind.

Weldability of Carbon and Alloy Steels

In general, weldability of steel decreases as hardenability increases, because higher hardenability promotes the formation of microstuctures more susceptible to cracking. Hardenability is defined as the relative ability of a steel to form martensite when quenched from a temperature above the upper critical temperature. In controlling hardenability, the carbon equivalent (CE) of the base metal governs. The CE is the sum of the alloying effects of the alloying elements.
One frequently encountered CE formula (there are several) is as follows:

$$CE = C\% + Mn\% / 6 + Ni\% / 20 + (Cr\% + Mo\%) / 10 + Cu\% / 40$$ [6]

When this CE formula is applied, the following table is used to interpret the results.

	Table 1. Carbon Equivalency
Carbon Equivalency	Comment
≤ 0.40%	Weldability is good
> 0.4%	Special precautions required, Low hydrogen practices, high preheat and high heat input required.
> 0.6%	Difficult to weld. Low hydrogen practices, high preheat, maintenance of interpass temperature, and pre-heat after welding until Post Weld Heat Treatment (PWHT) are all recommended. Note - PWHT generally required.

As illustrated in Table 1, investigators have categorized steels into different groups depending on their calculated carbon equivalent value. The three regions shown in Figure 2 exhibit different hardenability curves (Figure 3). For example, HY-80 is an alloy steel-which is used by the Navy for ship construction. HY-80 is a Zone III material. Characteristics of Zone III materials are moderately high carbon and CE values which result in hard HAZ microstructures after welding[7].

Various techniques are employed to weld steels of greater hardenability. The most common are the use of preheat and PWHT. However, it should be noted that a full temperature PWHT of a closure lid weld may not be feasible due to the potential for overheating the fuel cladding, thereby precluding welded closure for some designs.

Hydrogen Cracking in Welds of Carbon and Alloy Steel

Hydrogen Cracking in weldments is an insidious problem which may not manifest itself until days after the weld is completed. More costly fabrication controls such as minimum preheat and interpass temperature and stringent electrode handling may be imposed to assure that hydrogen cracking will not occur. The problem is typically more serious with quenched and tempered high strength low alloy steels, i.e., HY-80 and SA-508, Class 4N. Hydrogen cracking has been observed in carbon steel DCSS. Although the material susceptibility is not regarded as being high, in the highly constrained joint situation of a lid closure weld, the phenomenon has created considerable problems.

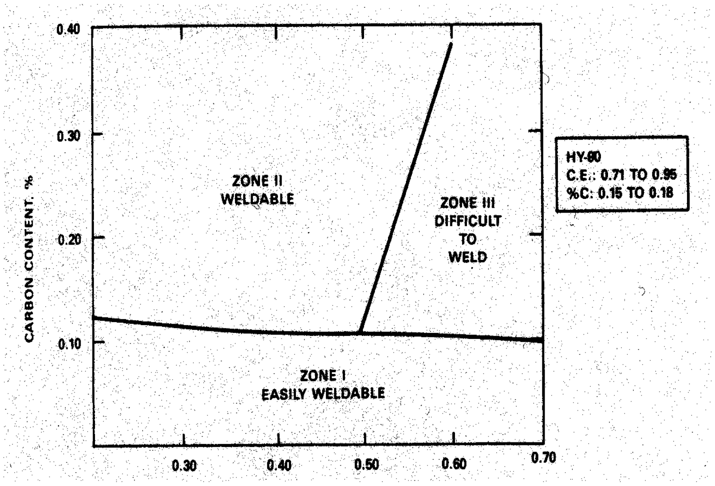
Figure 2
Hardenabilty Curve For HY-80

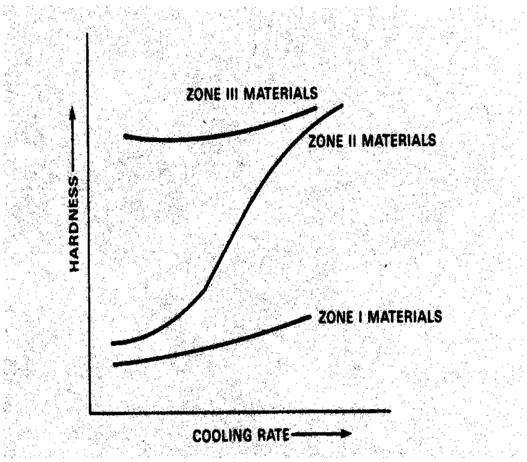
Figure 3
Zone Hardness Curve

CE

Electrode and Filler Metal Requirements

For any weld, the specified weld metal strength must equal or exceed the specified base metal strength. The selected filler metal should closely match the composition of the alloy steel. The AWS filler metal specification for covered electrodes, bare solid wire electrodes, and flux-cored electrode wires provide data to select filler metals that meet specific strength levels and provide desired alloy composition. All weld filler metals should be specified by the ASME Section II, Part C, specification and an associated AWS classification.





Problems with Welding Carbon or Alloy Steel Cask Lids

Less than optimum joint design, weakness of plate material due to metallurgical reasons; and over-reliance upon the ASME Code instead of welding/metallurgy knowledge, are all contributors to the problems that have been encountered with lid cask welds. These three contributors to cask lid weld problems have been identified by NRC and industry through several years of experience.

Constraint of the Weld Joint Design

As the weld material cools, it shrinks. The amount of shrinkage can be considerable since it is cooling from a solidification temperature of roughly 2400 degrees Fahrenheit. The larger the weld, the greater the propensity for shrinkage problems. The shrinkage must be accommodated. Frequently, the joint is designed so that the shrinkage can occur without external restraint. An example of this is a circumferential butt joint in a pipe. The weld shrinkage in this case is accommodated by the two pipe spools being drawn together (assuming they are not restrained).

In the case of the welded cask lid (See Figure 1), the lid is a heavy section plate that is thick enough to resist highly compressive bending or buckling loads. It would not be easy to crush or distort the lid with a load applied across its diameter since it would be compressing solid steel. However, it would be a lot easier to deform a piece of pipe since the load would result in bending stresses, thereby bending the steel, not compressing or crushing it.

This is effectively what the weld is doing to the lid as it cools. Therefore, given the massiveness of the lid plate, and the relatively small size of the weld and the situation just described, it is noted that the lid plate is not going to yield to accommodate weld shrinkage. What happens is that the weld yields and plastically deforms. Although many welds have sufficient strain capacity to yield upon cooling without cracking, experience with ferritic cask lids has demonstrated that this capacity is often marginal in cask closure welds. Consequently, the propensity for cracking is relatively high. This propensity must be alleviated by other means, the most common being welding technique and/or heat treatments.

A number of welding techniques have been developed to cope with the problem of weld shrinkage. The techniques include the use of preheat, stringer instead of weave weld bead placement and, as an after the fact measure, PWHT. Of the three, stringer bead technique may well have the greatest efficacy. It works simply because the individual weld beads are kept small enough to avoid a wide area of concurrent shrinkage. Placement of the stringer bead also has the effect of tempering or annealing the adjacent weld bead and thus enhancing the ductility of the adjacent weld bead. An illustration of stringer weld bead versus weave weld bead are shown in Figure 4.

Pre-heat is desirable because it slows the cooling rate of the weld. By slowing the cooling rate, certain metallurgical processes are changed (or even avoided) and the ductility is maintained. PWHT is a tempering heat treatment. It causes certain metallurgical changes in the material that result in greater ductility, with a minimal loss of strength. However, this is only viable when weld cracking during the initial cooling does not occur.

For welding cask lids, stringer beads and preheat have been successfully employed. PWHT, a process that is very desirable from ductility gains, cannot be employed for some cask closure weld. The reason is the potential for overheating the spent fuel cladding.

Plate material problems

Several instances of lamellar tearing of the cask shell plate have been reported. Lamellar tearing is the failure (cracking) of the plate material when tensile forces are applied in a direction normal to the surface of the plate. Generally, the plate material face experiences only compressive or minimal loads applied in a direction normal to the surface. The failures that result from such tensile loads are somewhat similar to the splitting of wood along its grain. The causes of this problem are related to the amount, size and shape of sulfur or phosphorous inclusions within the steel. The method for manufacturing a plate material result in a plate that does not have uniform properties in three orthogonal directions. The through-the-thickness direction is normally the weakest direction in a typical plate material. Usually, this is of little concern to the designer or user, unless a surface tensile load is applied in the normal direction to the plate face. Modern steel industry practice has largely alleviated the severity of the problem. A great amount of research was performed in the late 60's or early 70's after the total loss of a North Sea oil platform due to lamellar tearing of welds.

Bearing in mind the stresses resulting from the weld shrinkage, it becomes immediately obvious that a very large (at yield strength) tensile load is applied normally to the cask shell plate surface. Thus the opportunity for failure due to lamellar tearing exists. Lamellar tearing of the cask shell plate is shown schematically in Figure 5.

Figure 4 Stringer Bead and Weave Bead weld

Figure 5 Lamellar Tearing of the Cask Shell Plate

This problem is alleviated by a combination of several methods. Most importantly, low sulfur, low phosphorous, controlled-inclusion-shape steel must be specified and procured. Prior to use, the intended weld area of the plate must be ultrasonically examined to detect any lamella. Any plates containing lamella (over a certain size) must be rejected, or, the defects ground out and weld repaired.

Another solution is a weld joint redesign. The joint design follows normal heavy section weld joint design practices that have been employed for generations (on much more inferior material than today's) to avoid lamellar tearing.

Over-reliance upon the ASME Code/under-reliance upon Good Engineering

Any construction Code is a guide. The forward of the ASME Code so states that reliance upon the Code must be tempered with good engineering judgement and practice. This may be viewed by some as just a legal buy-off, but it should be obvious (although frequently overlooked or ignored) that the real intent is to say that the Code cannot possibly anticipate situation. Generally, the ASME Code serves well. The risk that is created is "cookbook engineering", where the ASME Code is followed with no thought given to the consequences of deviations from proven previous designs and practices.

Additionally, no Code is infallible. A major contention amongst many welding and materials engineers is the manner in which ASME Code addresses welds. One of the weakness with the Code is the manner in which pre-heat and PWHT are merely suggested for certain applications rather than requiring them in an unambiguous manner. This contrasts starkly with certain sections of ANSI B31.1, Power Piping[8], which unambiguously provides "MANDATORY MINIMUM VALUES" for each.

This example is not to imply that the ASME Code should be abandoned, but to raise the issue for awareness. However, there are certainly cases where the Code can be supplemented by adopting the more stringent requirements that treat the materials in a less ambiguous (metallurgically sound) fashion. In regards with regard to pre-heat and PWHT, the NRC staff frequently refers to ANSI B31.1 for guidance when a new question on welding is encountered, due to its more conservative approach to welding requirements.

Prevention Measures to Ensure Against Cracking in Carbon and Alloy Steel Welds

Several material and operational factors can cause incomplete weld closure on carbon and alloy steels used for DCSS. These could potentially include: the high degree of weld joint constraint, propensity for hardenability, preclusion of PWHT, and the presence of hydrogen (from water in the DCSS and residual moisture in the weld material). NRC staff/industry experience has demonstrated that a combination of preventative or compensatory measures are necessary for successful weld closure, as discussed below.

Additionally, as previously discussed, the geometry of the typical lid closure weld (Figure 1) favors the possibility of lamellar tearing on the cask shell side of the joint. The propensity of lamellar tearing (caused by high stresses in the thru-the-thickness direction of the shell plate and the presence of lamellar inclusions in the steel) can be alleviated by certain steel-making practices.

Listed below are several preventative or compensatory measures that are necessary for successful weld closure:

1. Use of low-hydrogen welding procedures, process, and filler metals.
2. Use low C E base metals and weld metals.
3. Perform NDE examination.
4. Maintain preheat for a minimum of one hour after welding is complete (hydrogen bake-out).

An experienced welding engineer and a materials engineer should be an integral part of the design team from the conceptual stages through production of the DCSS.

Fracture Toughness Analysis and Data for the Cask Confinement Boundary Flaws

Dynamic fracture toughness and NDT or fracture appearance transition temperature test data of the actual material should be evaluated for samples of weld metal, HAZ, and base materials that have been taken from weldments that use the same materials of construction and welding procedures as used for production. During cask fabrication (as opposed to lid welding), the importance of preheat and PWHT is paramount. Adherence to PWHT Table WB-4622.1-1 of ASME Section III, Division 3 (1998), is recommended. Staff experience has shown that the Code option of a lower temperature PWHT for a longer time is generally undesirable. It is especially detrimental when fracture toughness is important to the design. Therefore, Table WB-4622.4(c)-1, or similar, is generally unacceptable[9].

To demonstrate the weld-HAZ-BM (base metal) properties for carbon steels, it is necessary to perform full-size weld mock-ups using the same base and weld metals as intended for the construction of DCSS. The welding process, parameters, and any associated pre-heat, etc., must be identical to those proposed for production. Fracture toughness samples for the weld metal, HAZ, and adjacent base metal must be machined from the completed welds. A statistical number of samples must be produced and tested to ensure repeatability of results. The effects of welding pre-heat, PWHT, temper bead technique, etc., upon the fracture properties and NDT must be demonstrated by test, not reference, to similar materials from the literature.

Attempts have been made to use a correlation equation to calculate fracture toughness, K_{Ic}, from upper shelf Charpy V-notch (CVN) energy. NRC staff experience has shown that CVN to K_{Ic} correlations are unreliable and therefore unacceptable[10]. Actual fracture toughness test data[11] and analysis must be provided on confinement boundary material before staff review can proceed in the material and structural disciplines. It is noted that the use of data for similar materials is a good indication of potential success. However, it is not a substitute for tests using the actual material(s) of construction. If test data (e.g., Charpy and NDT) from literature are used to support potential success concerning the toughness of the welds and confinement boundary material, the compared reference material(s) should be of the same class and grade. Likewise the compared referenced material(s) should have the same chemical composition and mechanical properties of the actual material of construction. A common mistake is to assume that if the actual material of construction for the confinement boundary has the same weld “P-Number” as the compared reference material, the fracture toughness properties are the same. It is incorrect to assume that two different materials having the same P-Number have equivalent fracture toughness. P-Numbers were developed to associate base materials with similar welding properties and thus reduce the number of welding procedure qualifications required[12].

Conclusions

Carbon and alloy steels used as materials of construction of DCSS or transportation cask have favorable design attributes from the standpoint of heat transfer and low cost. However, the potential short-coming of lower fracture toughness (relative to the stainless steels) and the added care required for fabrication practices must be considered integral with the design, or success will likely not be achieved. Adoption of the above outlined practices and experience have demonstrated that a successful design of a DCSS or transportation cask can be achievable using ferritic steel for the construction of DCSS or transportation cask.

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