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DESIGN RULES FOR VESSELS SUBJECT TO EXTREME DESIGN-BASIS INTERNAL DETONATION LOADS

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Introduction

ASME Code Case 2564 [1] for the design of vessels containing internal high-explosive (HE) detonations and other impulsive loadings is currently limited to internal impulsive loads that are both expected to occur and for which the owner's investment in the vessel is protected. This implies that the internal impulsive loadings are both within the design basis for the containment vessel being considered, and that sufficient margin has been provided by the design rules to assure that the vessel will continue to support that design basis following the designated event or events.

The Task Group on Impulsively Loaded Vessels of the Subcommittee on Pressure Vessels (SC VIII) has recently initiated an effort to modify Code Case 2564, in order to:

- Add design requirements for postulated internal impulsive loads for which the public health and safety continues to be protected, but for which the owner's investment in the vessel ***may*** be lost; and
- Adapt the current local strain limits for prevention of ductile tearing and material separation over to ductility exhaustion limits that have been adopted in the 2009 Addenda for our parent ASME Code Section VIII, Division 3, rules.

We will refer to internal impulsive loads for which the owner's investment in a vessel as ***extreme design-basis*** impulsive loads, as opposed to ***nominal design-basis*** impulsive loads. Such postulated impulsive loads continue to be within the design basis for the vessel being considered, and the vessel will continue to provide its containment function to protect the public health and safety, but the continued support of the design basis following the postulated event is ***not*** assured. The adaptation of the strain limits will include both the modification of the existing strain limits that apply to nominal design-basis impulsive loads ***and*** the extension of the ductility exhaustion concept to extreme design-basis impulsive loads.

In order to modify, adapt, and develop the additional requirements, the Task Group took a similar approach to that used in developing the original Code Case 2564 – with review of the current design margins against global plastic instability failure, local ductile material failure, localized brittle failure, and consideration of reduced margins for low-probability impulsive loading events.

In the process of developing these additional design requirements, the Task Group also considered an even more extreme set of internal impulsive loads – those that are ***beyond the design basis***, and for which the containment function of the vessel will likely be lost, but for which the vessel may continue to provide some continuing level of confinement for any hazardous material involved in the detonation. While such loadings were considered, and the margins necessary to provide continuing confinement were compared to those selected for extreme design-basis, any associated requirements are beyond the scope of the Task Group as an ASME Code body. Therefore, the effort to evaluate extreme, beyond-design-basis detonation loadings will not be discussed further.

In the following section, the change in the guiding principles governing protection against local ductile material failure will be described, as manifested by the latest revisions to the ASME Code Section VIII, Division 3 [2]. Instead of explicit limits on strain components and equivalent plastic strain, local ductile material failure will be governed by the principle of margin against ductility exhaustion. A subsequent section will justify the new design margins for extreme design-basis internal detonation loads, with an emphasis on relaxed margins on global plastic instability and local ductile material failure. Finally, the modified and adapted design limits will be demonstrated on a set of numerical example problems for a simple, cylindrical vessel geometry for which containment function and the vessel owner's investment are both protected, and for the case where the containment function continues to be protected but the vessel owner's investment may be lost.

Current Section VIII, Division 3, Elastic-Plastic Design Requirements

Sub-Paragraph KD-230 provides limits to be used when the design analysis is based upon elastic-plastic finite element or finite difference analysis. These limits include:

- Design margin of at least 1.732 against plastic collapse of the vessel under the worst combination of specified (nominal design-basis) loading;
- Design margin of at least 1.732 against accumulated strain damage (which will be referred to here as ductility exhaustion) for all of the loadings applied to the vessel;
- A requirement that no more than two cycles of the maximum ***operating*** load should be required to establish shakedown, except in small, local areas of strain concentrations;
- Consideration of component deformation and displacement where functions such as closure or sealing is specified; and
- Assessment of cyclic loading behavior, using either the classic fatigue rules of Sub-Article KD-3 or the fracture mechanics crack growth rules of Sub-Article KD-4.

The first of these limits – for protection against plastic collapse under worst-case combinations of nominal design-basis loading -- is analogous to the margin required in the current Code Case 2564 to prevent a plastic instability state under worst-case nominal design-basis impulsive loadings. Therefore, no further modification or adaptation of this limit is needed for Code Case 2564. However, there is a need to reduce the 1.732 margin to a much lower value for extreme design-basis impulsive loadings, in order to account for the much lower probability of occurrence of that loading and the risk that will be tolerated by the vessel owner.

The third, fourth, and fifth limits are beyond the scope of this paper, and will not be discussed further.

The second limit represents the item of greatest interest here, since this limit is based on a fundamentally different principle than that used for Code Case 2564. Currently, Code Case 2564 provides protection against local ductile material failure caused by nominal (as opposed to extreme) design-basis impulsive loads through local tearing strain limits. Plastic strain components are accumulated through the wall thickness of the vessel over strain cycles within a single detonation loading event, and for strain cycles within successive detonation loading events. These accumulated components of plastic strain are then used to calculate the maximum equivalent plastic strain, averaged through the wall thickness, which is then compared to a uniform plastic strain limit of 0.2%. In addition, the plastic strain components are linearized across the wall thickness and compared to a “bending” plastic strain limit of 2% (1% at welds). Finally, the maximum peak equivalent plastic strain is compared to a limit of 5% (2.5% at welds).

This plastic strain limit approach must now be adapted in order to reflect the ductility exhaustion principle. At any location within the vessel, and at any time during the elastic-plastic structural response of the vessel, the calculation of an ***increment*** of equivalent plastic strain triggers an assessment of ductility exhaustion. That ***increment*** of equivalent plastic strain must then be compared to a maximum measure of material ductility for the stress conditions that exist at that time, at that point. The ratio of that increment to the maximum ductility measure is the increment of ductility exhaustion that must be accumulated and compared to a ductility exhaustion limit of 1.0, reduced by a margin that depends upon the likelihood of the loading event. For nominal design-basis loading events, the margin is 1.732. The only conceptual changes needed to apply this ductility exhaustion principle to nominal design-basis impulsive loading events are:

- An increment of equivalent plastic strain may be calculated at some time during any one of several strain cycles during a single impulsive loading event, or at some time during a subsequent impulsive loading event; and
- The stress states that govern the maximum measure of material ductility may change significantly during the vessel dynamic structural response.

In order to accumulate the strain damage and to determine whether sufficient residual ductility will be available to provide safe operation throughout all of the vessel duty cycles, the stresses and deformations must be calculated elastic-plastically at a sufficient number of points in the vessel, including through the wall thickness. With modern computational methods, there is no reason not to accumulate the strain damage at every possible point of interest, which means at every integration point in a finite element elastic-plastic analysis. For the special case of impulsive loading on a vessel, time histories of stress/strain are generated at every integration point, and time histories of displacement at every nodal point.

Local Ductility Measures and Accumulated Strain Limit Damage

Any ***increment*** of equivalent plastic strain at a particular location in the vessel and at the k^{th} load step (or the k^{th} time step), $\Delta\varepsilon_{peq,k}$, must be compared to the maximum ductility measure for the current stress state at that point and at that time. The maximum ductility measure is determined from three possible ductility measures:

- The ratio, R, of the material yield strength, S_y, at the analysis temperature, to the material tensile strength, S_u, at the analysis temperature;

- The minimum specified elongation, El, in percent, which is understood to mean the uniform strain at maximum load in a uniaxial tensile test, readily obtained from a plot of the engineering stress versus engineering strain from a tensile test (see Figure 1); and
- The minimum specified reduction of area, RA, in percent, which is understood to be related to the true fracture strain found in a uniaxial tensile test. Note that the fracture strain from the engineering stress-strain curve in Figure 1 is not the same as the fracture strain from the true stress-strain curve in Figure 2. The true strain at fracture is equal to the natural logarithm of the quantity 1/(1-RA).

Knowing R, El, and RA, Table KD-230 contains formulas for calculating three parameters, m_2, m_3, and m_4, for ferritic steel, austenitic stainless steel and nickel-based alloys, duplex stainless steel, precipitation hardening nickel-based steel, and aluminum. Then, the maximum of these three potential local ductility measures is designated ε_{Lu}, the uniaxial strain limit. Then, the maximum permitted local total equivalent plastic strain, $\varepsilon_{L,k}$, at any point at the k^{th} load step (or the k^{th} time step) is found from ε_{Lu} by taking the local stress state at that location and at that time step into account through a triaxiality factor:

$$TR = (\sigma_{1,k} + \sigma_{2,k} + \sigma_{3,k})/\sigma_{e,k} ,$$

where $\sigma_{1,k}$, $\sigma_{2,k}$, and $\sigma_{3,k}$ are the three principal stresses at that location and at that time, while $\sigma_{e,k}$ is the von Mises equivalent stress at that location and at that time. The equation for $\varepsilon_{L,k}$ that takes the local state of stress into account is given by:

$$\varepsilon_{L,k} = \varepsilon_{Lu} \ \exp\{-1/3\ [m_5/(1+m_2)]\ (TR - 1)]\},$$

where m_5 is a constant from Table KD-230 that is equal to 2.2 for ferritic steel.

The calculated increment of equivalent plastic strain, $\Delta\varepsilon_{peq,k}$, at a particular location in the vessel and at the k^{th} load step (or the k^{th} time step), is then divided by the maximum permitted local total equivalent plastic strain, $\varepsilon_{L,k}$, at that point and time to derive the increment of strain limit damage, $D_{\varepsilon,k}$, and that increment is added to any previously calculated increments to determine whether the ductility at that point has been exhausted. The total strain limit damage at that point, $D_{\varepsilon t}$, accumulated over all of the loading cycles, must be less than 1.0, with a design margin for nominal design-basis loads of 1.732.

No margin is currently specified in KD-230 for extreme design-basis loads. However, for extreme design-basis impulsive loads, the Task Group on Impulsively Loaded Vessels proposes a margin of 1.25, which reflects the lower probability of occurrence.

Example of Maximum Permitted Local Ductility

For example, suppose we examine the case of the high-strength, low-alloy ferritic steel SA-517/SA-517M, which has a minimum yield strength at room temperature of 100 ksi (690 Mpa), a tensile strength range of 115-135 ksi (795-930 Mpa), a minimum elongation of 14% over a 2-inch (50-mm) gauge length (for wall thicknesses of interest), and a reduction in area for round bar tensile specimens) of 45%. However, the reduction in area for rectangular specimens appears to be much lower, of the order of 35%. From Table KD-230, using the lowest tensile strength for conservatism,

$$m_2 = 0.60\ (1.00\ R) = 0.078;$$

$m_3 = 2 \ln[1.00 + (El/100)] = 0.262$; and

$m_4 = \ln[100/(100\text{-}RA)] = 0.431$.

The three parameters – m_2, m_3, and m_4 – can be interpreted as a strain hardening exponent corresponding to power law hardening behavior, the strain corresponding to uniform elongation, and the fracture strain corresponding to reduction in area, respectively. Therefore, ε_{Lu} is the maximum of the three, or 0.431.

As an example, consider two stress state cases that are generally applicable to conditions in a cylindrical vessel under internal detonation loads – the first where the longitudinal and circumferential principal stresses are very nearly equal and positive, with the third (through-the-wall-thickness) principal stress essentially zero, and the second where the longitudinal and circumferential principal stresses are very nearly equal but of opposite sign, with the third principal stress very nearly zero.

For the first case, with two of the principal stresses equal and positive (tensile), the triaxiality factor is 2, which is moderately high, so that $\varepsilon_{L,k}$ is reduced to about one-half of ε_{Lu}. That is, the maximum permitted local total equivalent plastic strain at any point at the k^{th} load step (or the k^{th} time step) is about 0.22 or 22%.

For the second case, with two of the principal stresses equal but of opposite sign, the triaxiality factor is zero. However, the minimum triaxiality factor should be assumed to be unity, so that $\varepsilon_{L,k} = \varepsilon_{Lu} = 0.43$ or 43%.

Plastic Instability Margin Requirements

The current plastic collapse load margin requirement in KD-230 for nominal design-basis loads is 1.732, which is identical to the plastic instability state margin requirement for nominal design-basis impulsive loads in the current Code Case 2564. In order to justify reducing that margin for extreme design-basis impulsive loads, the Task Group has reviewed the existing procedures, to the extent applicable, of Section III [2] and Section XI [3] of the ASME Boiler & Pressure Vessel Code that provide rules for the design and inservice requirements for nuclear power plant components, respectively. The Section III and Section XI rules are based on the classification (by the owner of the power plant) of design-basis loadings into four categories, with the classification dependent on the likelihood of occurrence of the loadings and on the need to protect the owner's investment should such unlikely loadings actually occur. The categories are referred to as Level A, Level B, Level C, and Level D Service Loadings, with the first two categories comprising loadings that are ***expected*** to occur, while the last two categories represent loadings that are ***not expected*** to occur, but for which the public health and safety must be protected regardless of likelihood. The difference between Level C and Level D Service Conditions depends on the degree to which the owner's investment in the power plant is to be protected for the unexpected loading event.

For Level C Service Conditions, the design limits are set so that – while power plant components may experience relatively severe damage – the owner should be able to return those components to service through inspection (to identify the degree of damage) and repair (to restore the component to serviceability). For Level D Service Conditions, the design limits are set so that the public health and safety is protected, but the owner's investment in the power plant ***may*** be lost. The process of classification of unexpected loadings into Level C Service Conditions is intended to permit the owner to balance the benefits of protecting the investment through more rugged design for unexpected loadings against the costs of providing such a rugged design. Level D Service Conditions and their Service Limits tend to be set by regulation so that adequate protection is provided for public health and safety. Probabilistic risk estimates are usually considered to be the basis for establishing and/or modifying the Level D requirements.

Guidance for Level C and Level D Service Limits can be found in both Section III and Section XI. In particular, the non-mandatory Appendix F (Rules for Evaluation of Service Loadings with Level D Service Limits) [4] contains limits for design by analysis of severe, design-basis loadings, depending upon whether the system/component analysis is carried out using linear elastic or non-linear elastic-plastic or plastic analysis. Only the limits based on non-linear elastic-plastic analysis are considered here.

Paragraphs F-1341.2 through F-1341.4 of Appendix F provide three alternative sets of design limits for unexpected Level D Service Loadings. The most relevant of the three is the limit on plastic instability load in F-1341.4, which is 70 % of the calculated or measured plastic instability load, depending on whether the method used is plastic analysis or experimental analysis. In other words, the component or system is subjected to the unexpected load through either analysis or experiment (often a scale-model experiment), with the loading increased to the point of plastic instability, and the limiting load permitted is 70 % of that ***demonstrated*** plastic instability load.

For the case of extreme design-basis impulsive loading, the loading will typically end before the component or system reaches the point of plastic instability, so the terminology used here is ***plastic instability state***, rather than ***plastic instability load***. Since it is the impulse that governs this plastic instability state, not the pressure loading, this limit can be translated as "the severe, design-basis impulse is limited to 70 % of the impulse that leads to the plastic instability state." Another way to state this limit is that the component or system must be able to withstand 1.0/0.7 = 140 % of the ***extreme design-basis*** impulsive loading without reaching the plastic instability state. While a plastic instability state margin of 1.4 is readily justified, the Task Group proposes that an even more reduced margin of 1.25 be used for extreme design-basis impulsive loadings, which would correspond to limiting the loading to 80% of the impulsive lading that would lead to a plastic instability state. The lower margin proposal, again, is consistent with the lower probability of event occurrence.

Application to the DAVINCH Controlled Detonation System

Kobe Steel, Ltd. designs, fabricates, and operates systems, referred to as **D**etonation of **A**mmunition in **V**acuum **IN**tegrated **CH**amber (DAVINCH) systems, for the purpose of providing containment during the destruction by detonation of chemical weapons and other munitions. The essential design characteristics of the DAVINCH detonation containment system are:

- Two relatively close-fitting vessels, one referred to as the inner vessel and the second is referred to as the outer vessel (see Figure 3);
- Removable inner vessel with monolithic wall construction fabricated from high-strength, low alloy steel (see Figure 4);
- Fixed outer vessel with laminated carbon alloy steel cylindrical wall fabrication welded to monolithic carbon steel top and bottom ellipsoidal heads;

- Narrow circumferential detonation gas transmission path through the inner vessel into the cavity between the inner and outer vessels;
- Internal system vacuum capability, enabling the detonation pressures to be substantially reduced; and
- Absence of any expansion chamber.

The first of these systems, called DAVINCH 10 (DV10) was rated for 10 kg (22 lb) of TNT explosive equivalent, and was deployed for the Lake Kussyaro chemical weapons destruction project in Northern Japan. This simplified version of the system had both inner and outer vessels fabricated from SA283 carbon steel plate material. The second and third systems, referred to as DV45 and DV65, were rated for 45 kg (100 lb) and 65 kg (140 lb) of TNT equivalent explosive, respectively. Both of these systems have been deployed at the Kanda Port chemical weapons destruction project in Southern Japan. In both cases, the inner vessels are fabricated from high-strength, low-alloy steels, with the designation HT590 used for the top and bottom heads of the inner vessel and the designation HT780 for the cylindrical side walls. The designation implies HT refers to heat treatment and the numbers following HT denote the nominal ultimate tensile of the material in Mpa units. A fourth system, referred to as DV50, is rated for 50 kg (110 lb) of TNT equivalent explosive, is currently operating at Poelkapelle in Belgium. The DAVINCH design is under consideration for application to destruction of chemical weapons by detonation in other countries.

DAVINCH Ductility Exhaustion Application

An analysis of a DAVINCH vessel was conducted several years ago, with one purpose of the analysis to demonstrate the satisfaction of leak-before-burst criteria in KD-140 of the ASME Code Section VIII, Division 3. The results of this analysis were reported, in part, at the CWD 2007 conference [5]. Some of these same results will be used here to evaluate the potential for ductility exhaustion following multiple detonations of a 29.1 kg (64 lb) TNT equivalent charge. As a simplified example, Figures 5 and 6 show the circumferential strain histories at the inner and outer surfaces of the DAVINCH inner vessel. The analysis showed that the peak values of the calculated strains are in phase at the inner and outer surfaces because the of a “beating” phenomenon. The lower frequency (about an order of magnitude lower) of the longitudinal motion of the inner cylindrical shell periodically “beats” with the much higher radial expansion frequency of the shell. At the times when the longitudinal motion is pushing the cylindrical shell into axial compression, with a Poisson ratio tensile effect on the circumferential strain, and with the radial expansion circumferential tensile strains at their maximum, the local circumferential principal strain can reach values very near to 1800 μstrain. This beating phenomenon has been observed by Duffey and Romero [7] to cause strain growth when the two frequencies are closely spaced.

The 1800 μstrain is about one-half of the strain necessary to cause yielding at the worst-case point (about 3600 μstrain). For the DV60 system, the 29.1 kg TNT equivalent charge that was analyzed is about one-half of the maximum nominal design-basis charge of 60 kg TNT equivalent. Therefore, it would be expected that a small amount of equivalent plastic strain will be generated at only one of the cycles within the individual detonation cyclic response, at around 18 msec, while the other “beats” at around 8 or 9 msec and at around 27 msec are below yield.

The HT780 high strength, low-alloy ferritic steel has similar material properties to SA-517, with a minimum elongation of 22%. The ratio of yield to ultimate strength is essentially the same, and informant on reduction in area is not known. We will conclude that a reasonable maximum for m_2, m_3, and m_4 is between 0.25 and 0.30. We note that axial compression in the cylindrical shell combined with radial expansion gives the highest effective shear stress, but we also note that – at that same time – the triaxiality factor is fairly low. For conservatism, we will use a triaxiality factor of 2. This implies that the maximum permitted local total equivalent plastic strain will be approximately one half of 0.25 to 0.30. For conservatism, the maximum permitted local total equivalent plastic strain will be chosen as 12.5%.

The total equivalent plastic strain increment at the single point within each maximum nominal design-basis detonation will be less than 100 μstrain, so that the strain limit damage increment will be about one part in 1250. Another way of expressing this is that about 1250 maximum 60 kg TNT equivalent detonations would be required to exhaust the ductility at the one point in the DAVINCH inner vessel wall. When the margin of 1.732 is applied, some 720 detonations would be required to reach the design limit for local ductile failure. With all of the conservatism embedded in this simplified assessment, many more detonation cycles could be tolerated.

DAVINCH Extreme Design-Basis Ductility Exhaustion and Global Plastic Instability

For the case of extreme design-basis impulsive loading, the example of a 500 kg (1100 pound) explosive detonated unintentionally within the DV60 system has been assessed, in order to estimate the margin for protection of the public health and safety, including worker safety, under such unlikely conditions. Note that the detonation loading is between eight and nine times the level of the nominal design-basis detonation loading. The results of this analysis were reported, in part, at the CWD 2008 conference [6]. Some of these same results will be used here to evaluate the potential for ductility exhaustion following a single extreme design-basis detonation event.

The first step in the evaluation of the unlikely detonation loading analytical results is the estimation of the detonation pressure loading that is applied to both the inner and outer vessels of the DAVINCH DV 60 system by the 500 kg (1100 lb) TNT equivalent explosive charge. The next step was the assessment of the inner vessel structural response to the extreme design-basis detonation, which gave elastic-plastic principal strains (see Figure 7 for the principal circumferential strains) and the effective plastic strains (see Figure 8). These strains appear to have been calculated at mid-wall or averaged across the wall thickness of the inner shell. The maximum circumferential elastic-plastic strains are located at or near the longitudinal mid-point for the inner vessel and at or near the point of maximum specific impulse. The elastic-plastic strains at these gauge locations are above 3 % and below 6 %. The effective plastic strains at these same points are between 4 % and 6 %, reaching these values after 1 to 1.5 msec and remaining at these levels thereafter.

The assessment of ductility exhaustion in this case is trivial, since the maximum permitted local total equivalent plastic strain, $\varepsilon_{L,k}$, will be essentially the same during the short period of equivalent plastic strain accumulation. For this example, the total strain limit damage at the worst location will be slightly less than 0.5 so that, even with a required margin of 1.732, no ductility exhaustion is expected. However, for this very unlikely detonation loading, a more appropriate margin against local ductile failure would be 1.25. For this margin, considerable residual ductility remains.

In addition, no evidence of potential plastic instability can be observed in either the principal circumferential strain or the equivalent plastic strain histories. Based upon a margin against global plastic instability from extreme design-basis detonation loadings of 1.25, the analysis shows that resistance to a 400 kg (880 pound) extreme design-basis detonation load has been demonstrated.

Summary

The ASME Code Case 2564 that provides design rules for vessel subject to internal impulsive loads, such as those from controlled detonations inside steel containment vessels, is being modified and adapted, in order to:

- Convert the existing local ductile failure prevention strain limits to more robust strain limit damage design criterion to be used when performing elastic-plastic design analysis of nominal design-basis impulsive loads;
- Extend the local strain limit damage criterion from nominal design-basis impulsive loads to extreme design-basis impulsive loads, where the public health and safety continues to be protected, but where the owner's investment in the containment vessel may be lost;
- Rationalize the margins required to prevent both local ductile failure and global plastic instability for extreme design-basis impulsive loads; and
- Demonstrate the proposed changes to Code Case 2564 through application to an existing controlled detonation containment vessel – in this case, the DAVINCH DV60 system.

The strain limit damage, or ductility exhaustion, approach was described and applied, showing that typical high-strength, low-alloy ferritic steels have considerable margin against local ductile failure. In addition, reduced design margins for low probability, extreme design-basis impulsive loading events have been developed, justified and applied.

References

[1]. Case 2564, "Impulsively Loaded Pressure Vessels," 2008 Addenda, ASME Boiler & Pressure Vessel Code, Code Cases: Boilers and Pressure Vessels, American Society of Mechanical Engineers, New York, NY, 2008.

[2]. ASME Boiler & Pressure Vessel Code, Section VIII, Division 3, Alternative Rules for the Construction of High Pressure Vessels, American Society of Mechanical Engineers, New York, NY, 2007 Edition Plus 2008 Addenda.

[3]. ASME Boiler & Pressure Vessel Code, Section XI, Rules for Inservice Inspection of Nuclear Power Plant Components, American Society of Mechanical Engineers, New York, NY, 2007 Edition.

[4]. ASME Boiler & Pressure Vessel Code, Section III, Division 1: Appendices, Rules for Construction of Nuclear Facility Components, American Society of Mechanical Engineers, New York, NY, 2007 Edition.

[5]. Nickell, R. E., “ASME Code Rules for Vessels Subject to Detonation Loads and Their Application to the DA VINCH Chemical Weapons Destruction System,” **Proceedings,** 10^{th} International Chemical Weapons Demilitarization Conference, Brussels, Belgium, May 2007.

[6]. Clayton, A. M. and Nickell, R. E., “New ASME Code Case for CWD Detonation Vessels, “ **Proceedings,** 11^{th} International Chemical Weapons Demilitarization Conference, Interlaken, Switzerland, May 2008.

[7]. Duffey, T. A. and Romero, C., “Strain Growth in Spherical Explosive Chambers Subjected to Internal Blast Loading,” International Journal of Impact Engineering, Vol. 28, No.9, pp. 967-983, October 2003.

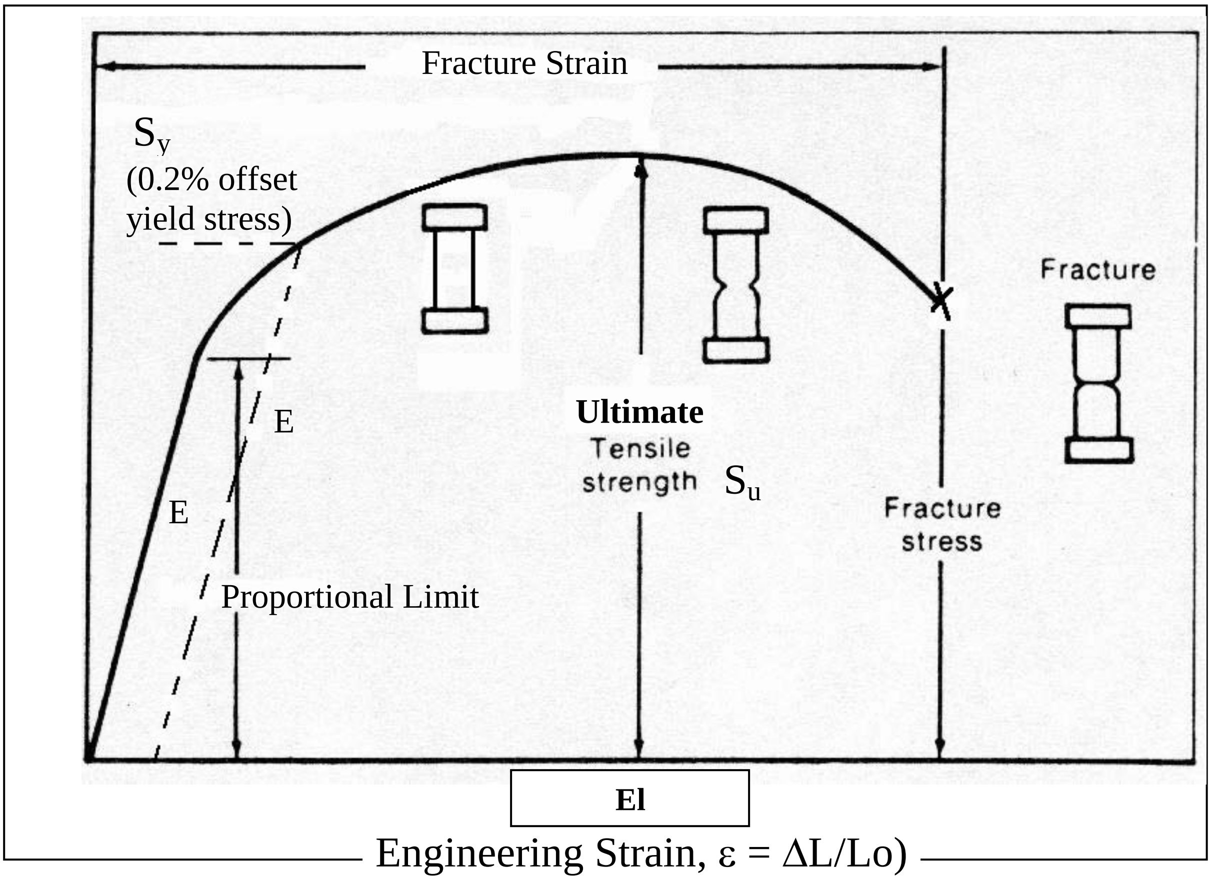

Figure 1. Uniaxial Tension Engineering Stress Versus Engineering Strain Curve. (El, minimum specified elongation is the strain at maximum load)

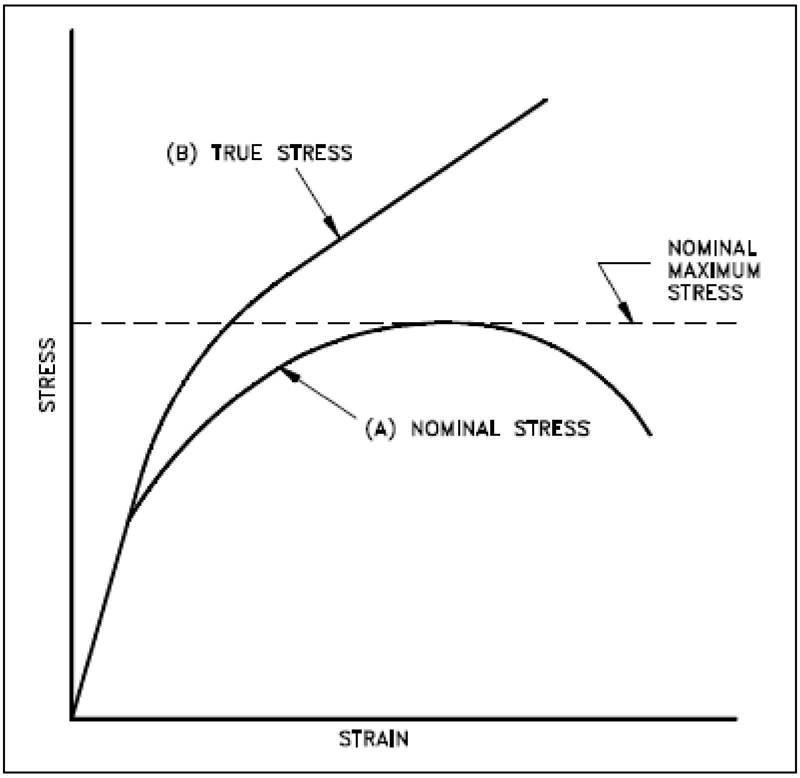

Figure 2. Engineering Stress-Strain Curve and True Stress-Strain Curve

Figure 3. View of DAVINCH with top heads of both the inner and outer vessels removed.

Figure 4. External surface of DAVINCH inner vessel after removal from the outer vessel.

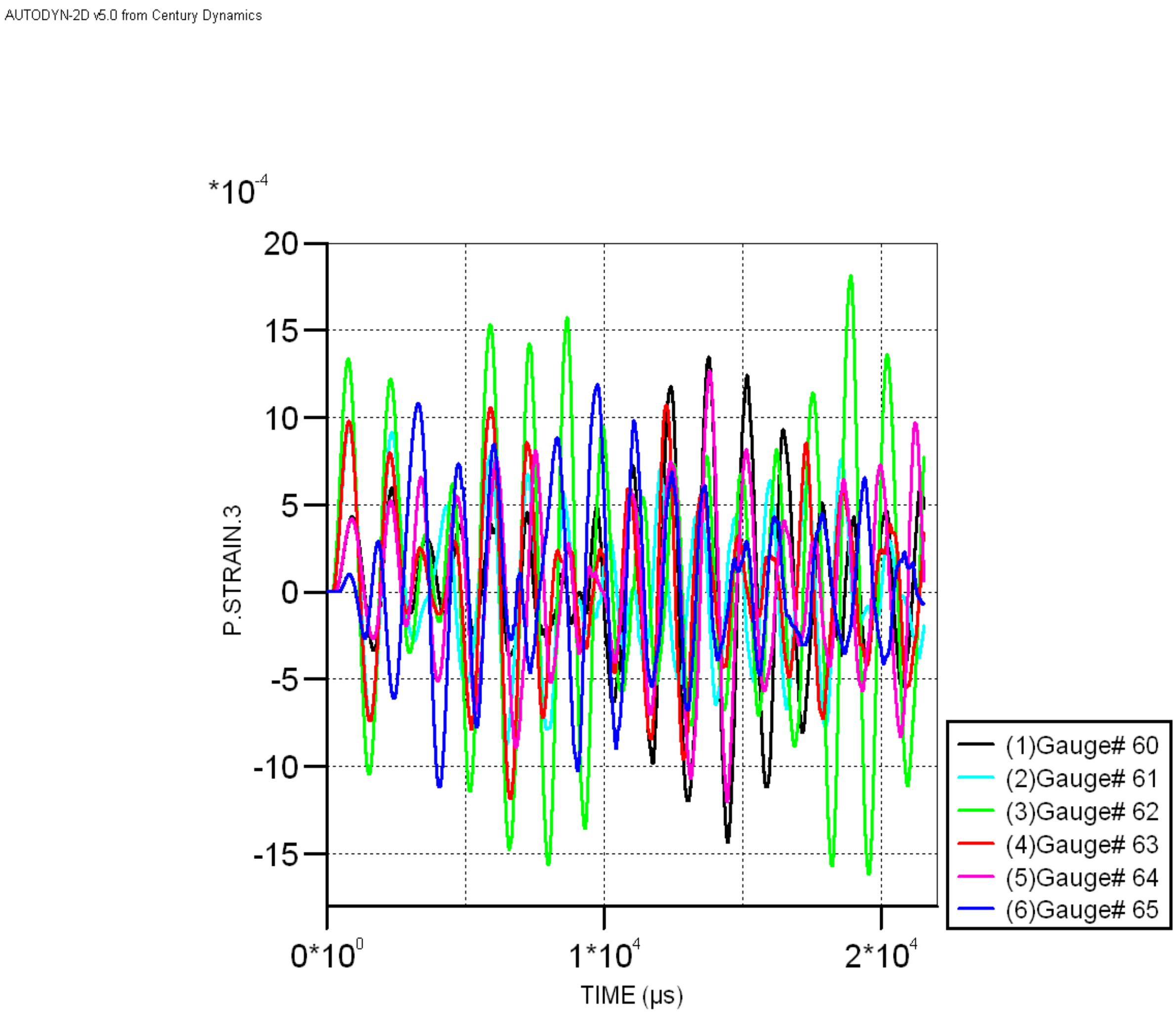

Figure 5. Circumferential Strain Histories Along Inner Surface of DAVINCH Inner Vessel.

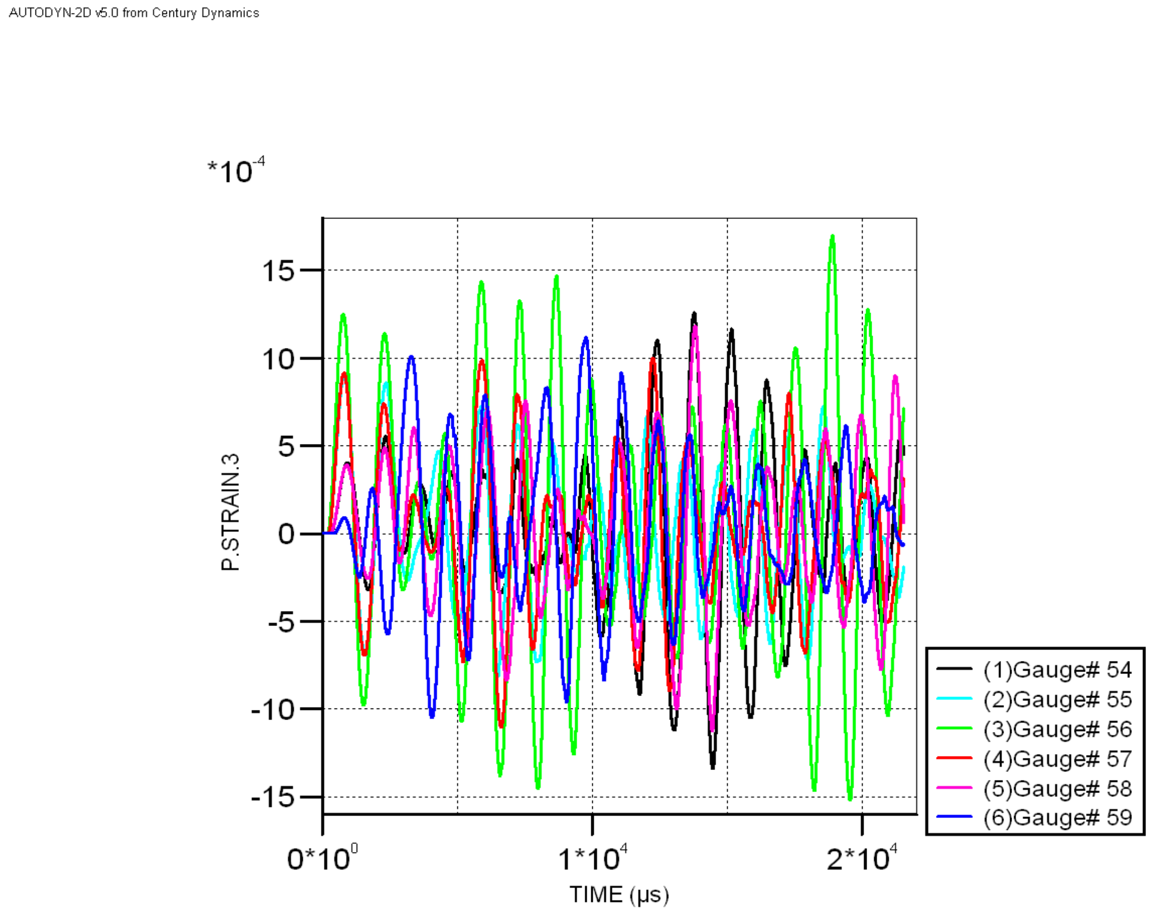

Figure 6. Circumferential Strain Histories Along Outer Surface of DAVINCH Inner Vessel.

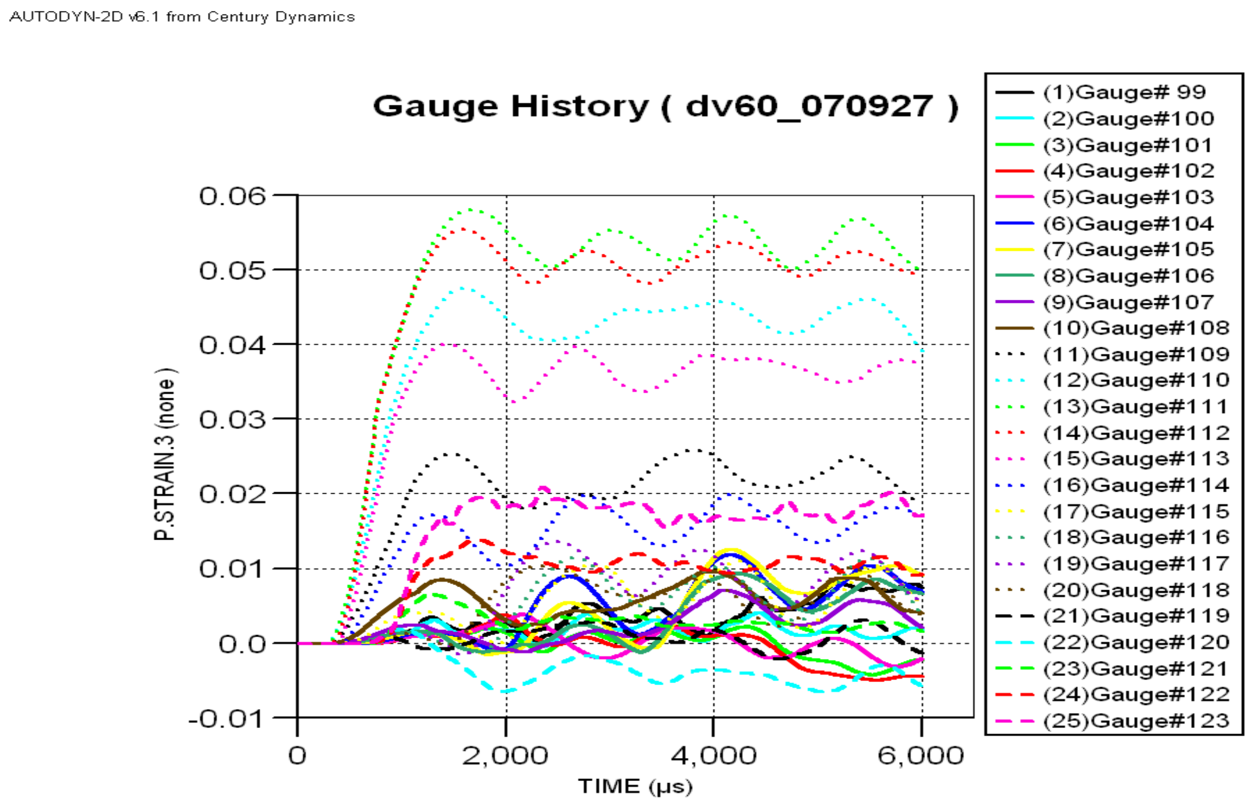

Figure 7. Circumferential Strain Histories in DAVINCH Inner Vessel Wall.

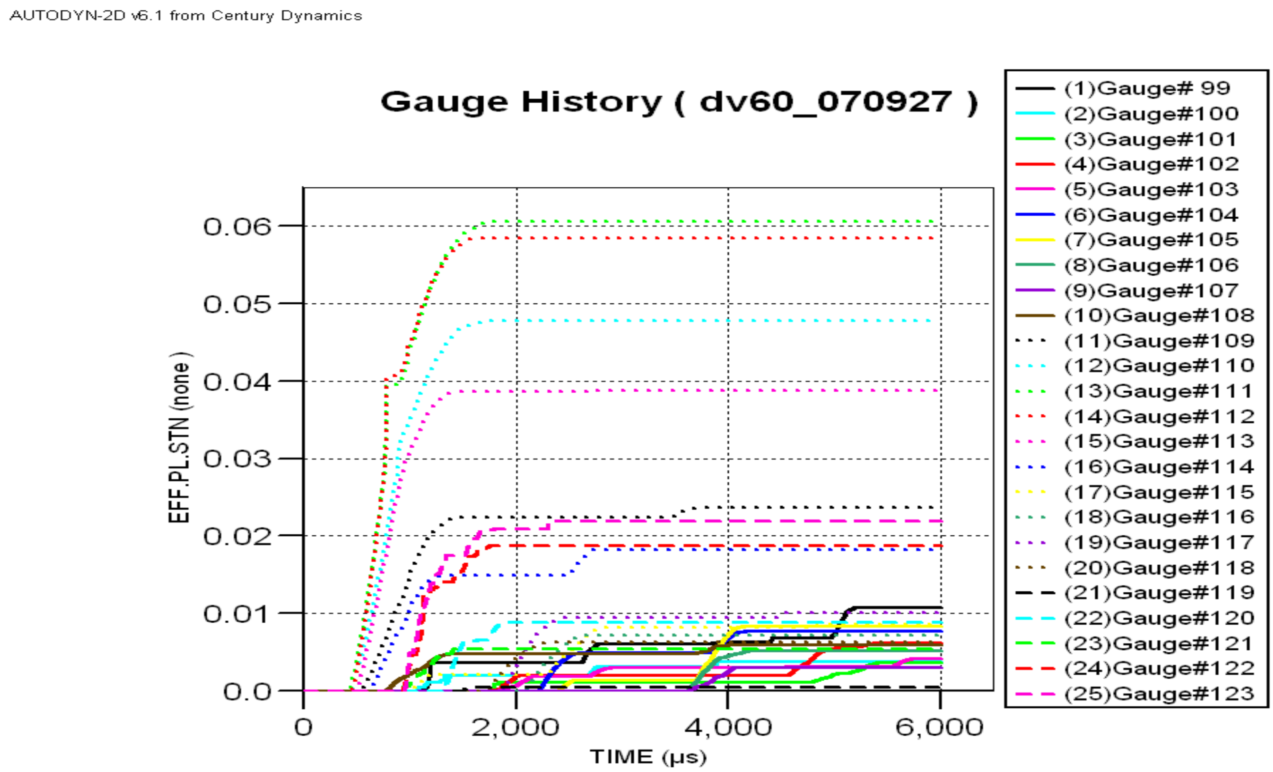

Figure 8. Equivalent Plastic Strain Histories in DAVINCH Inner Vessel Wall.