Risks in High-Pressure Vessel Startup

Insights into the natures and hazards of brittle fracture and thermal fatigue failure, with recommended approaches in design and operation to minimize or eliminate risks.

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The safe design and construction of pressure vessels must consider all possible loading conditions which may determine the selection of materials, the thicknesses of the shells, and possibly some of the fabrication details.

The vessel startup period is part of the operational cycle and thus should be included. The rules of the ASME Pressure Vessel Code, Section VIII, specify this requirement, implicitly in Division 1 and explicitly in Division 2.

From a superficial point of view, concern for the startup period may seem paradoxical. After all, neither the pressure nor the temperature exceed the design values. However there are two special features related to the startup operation which may represent unsafe situations if some necessary precautions are ignored.

The first of these two special problems is the transformation which carbon and low-alloy steels undergo when the metal temperature falls below a critical temperature transition zone. In this transformed state the steel assumes a brittle characteristic (in contrast to its normal ductility), and its structural capacity is considerably reduced. Inasmuch as pressure vessels may be installed in very cold or frigid climates—well below the lower limit of the transition temperature zone—the application of the full load pressure during startup may represent an unsafe situation if the metal has not been heated up sufficiently

Although we have no first-hand knowledge of any such failures during vessel startup, there are records of brittle fracture failures occurring during hydrostatic test and a substantial number of in-service failures of field-erected, non-stress-relieved tanks at ambient temperatures. Photographs of a ruptured vessel and a two-ton fragment of this vessel are reproduced in Figures 1 and 2 respectively.

This failure occurred during a hydrostatic test. It can be assumed that had the vessel been filled with a compressible fluid such as air or synthesis gas, the rupture would have resulted in even greater fragmentation and missile energy. There was a complete absence of thinning or other evidence of local yielding. This is typical of brittle or cleavage fractures.

In addition to brittle fracture, the second potential hazard associated with a random startup is the possibility of failure or damage resulting from excessive transient thermal stresses. Whereas the danger of brittle fracture occurs in cold climates, transient thermal stresses can develop during startup in vessels located in moderate or warm climates; although the risks associated with this phenomenon are higher with lower ambient temperatures.

Very high thermal stresses can exist without any evidence of vessel failure. As a matter of fact, these stresses can be induced each time during several startups without visible signs of distress. The reason is that thermal stresses are primarily caused by strain incongruities and, in a ductile material, these differential strains can include relatively large increments of plastic strain without resulting in metal failure.

Although there may be no apparent failure after several

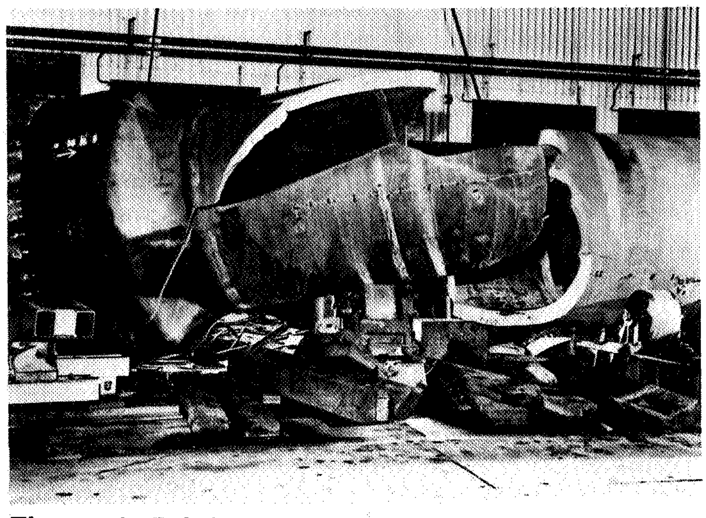


Figure 1. Brittle failure of an ammonia converter during shop hydrostatic test. Shell material is 5⅞-in. thick low alloy steel. Photo courtesy The Welding Institute (England).

Figure 2. Two-ton fragment of failed vessel in Figure 1, thrown 152 ft. Hydrostatic pressure at time of failure was 5,000 lb./sq.in. Photo courtesy The Welding Institute (England).

incidents of excessive thermal stress, the repeated plastic strain excursions cause cumulative damage to the metal such that its structural capacity diminishes after each event. This characteristic of failure, related to the number of stress or strain cycles, is known as fatigue.

A failure resulting from thermal stress fatigue may not be as spectacular as a brittle fracture but it is in fact a more sinister mode of failure, because it may finally occur during normal operation and be completely unanticipated.

Another result can be bowing of the vessel

There is one other possible consequence of a high thermal circumferential gradient which, although not as dramatic as brittle fracture, has been the cause of much consternation. This is the phenomenon of bowing of a vessel caused by an uneven temperature variation around the vessel girth. There have been observations of an 80-ft. high vertical coke drum bowing to an 18-in. offset at the top during the steam-quench decoking operation. Another observed case was the bowing of a horizontal ammonia converter during startup, in which the degree of bowing was amplified by a long interchanger overhanging one end.

In both these cases, fortunately, the gross strains were elastic and the vessels returned to their initial positions after the transient thermal loads were removed. However, if the thermal gradient is severe enough, plastic straining can result in a permanent vessel bow.

Brittle fracture is a term used to describe a mode of failure in normally ductile material, characterized by practically no measurable stretching or deformation. Although this type of failure may result from a number of contributing factors, the single most important external variable influencing the brittle fracture behavior of steels is temperature.

This relationship is illustrated in Figure 3, which depicts an idealized transition temperature curve (Charpy impact energy vs. temperature) for ferritic materials such as carbon and low-alloy steels. Actual numbers are deliberately omitted because they depend very significantly on the kind of steel and a variety of metallurgical factors. It is to be noted that exposure to low temperatures does not cause permanent impairment of metal properties. The drastic reduction of

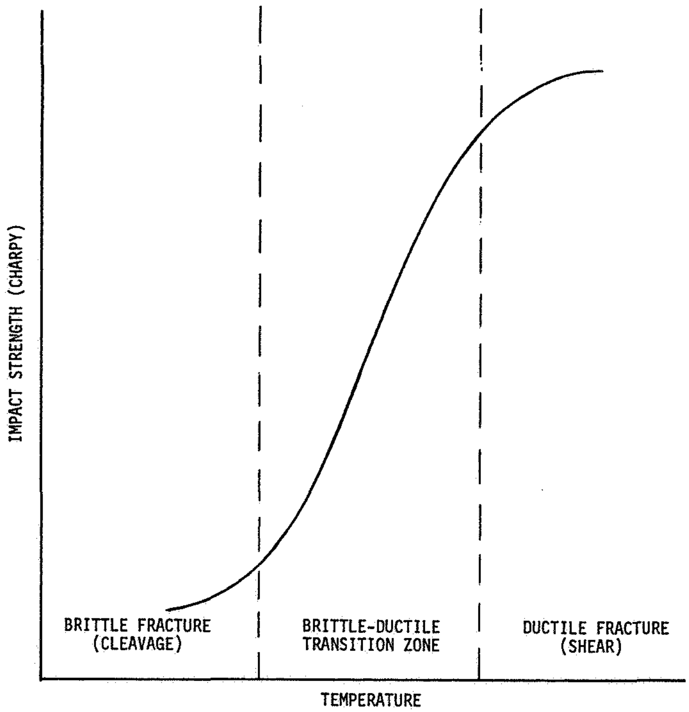


Figure 3. Impact strength/temperature curve for ferritic steels.

ductility and impact strength is fully recoverable by warming the steel above its transition temperature range.

The typical impact-temperature curve may be divided into three broad, arbitrarily demarcated zones. The center one is defined as the transition temperature zone because it marks the transition from predominantly ductile to predominantly brittle type fracture. For pressure vessel carbon steels not intended for low-temperature service, transition temperature zones generally fall within the range from −20°F to +100°F. Impact test strength levels for these steels may vary between approximately 1 and 5 ft. lb. for 100% brittle fracture and 40 to 100 ft.lb. for 100% ductile failure.

Note that the test for brittle fracture relates metal temperature with a quantity of energy required to cause failure. The rationale for this relationship is apparent by examining an idealized tensile stress-strain diagram for a typical carbon steel, as shown in Figure 4. The energy required to cause failure is substantially equal to the strain energy absorbed by the structure at the time of failure. The unit volume strain energy is equal to the area under the stress-strain curve.

It can be seen from Figure 4 that the area under the ductile carbon steel curve, *OAA'* which has a large component of plastic strain energy, is an order of magnitude greater than the area under the brittle characteristic curve, *OBB'*, which is limited to elastic strain energy. This is consistent with the 100 ft.lb. to 5 ft.lb. ratio indicated above.

Widespread misconception is cited

The use of the energy parameter is responsible for a widespread misconception concerning the hazard of brittle failure. One may be led to assume that if the load is applied carefully and gradually, avoiding any shock or dynamic effects, then the reduced ductility due to passing through the

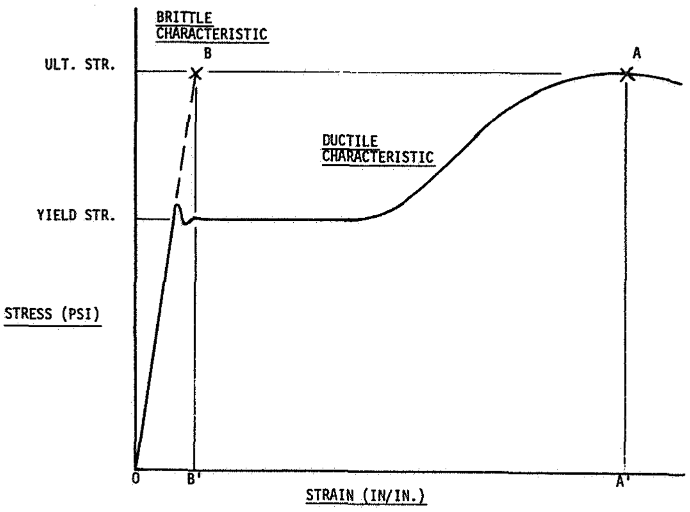


Figure 4. Idealized stress/strain diagram.

transition temperature zone can be ignored.

The flaw in this reasoning can be clearly pointed out by considering the transformation to be from the ductile carbon steel to a brittle material such as cast iron. One can quickly appreciate the limited capacity of cast iron to withstand tensile stress. A quantitative comparison of the allowable design strengths of ductile carbon steel vs. cast iron (or carbon steel beyond the nil ductility temperature limit) can be determined by comparing the allowable design stresses of the two materials using the ASME Pressure Vessel Code as the authoritative source. Section VIII, Division 1 of this Code lists an allowable design stress of 15,000 lb./sq.in. for carbon steel plate SA-515 Grade 60 (minimum tensile strength = 60,000 lb./sq.in. The same Code specifies an allowable design stress in tension for Class 60 cast iron (minimum tensile strength = 60,000 lb./sq.in.) as 6,000 lb./sq.in.

These values yield a ratio of 2.5/1 and this can be expressed as a reduction of safe load capacity of 40% of the original design load capacity. The implication of increased risk is very clear if the design load is applied to a vessel in this vulnerable condition. As a matter of fact, the Code covers this increased risk situation by requiring that vessels intended for low-temperature operation and constructed of non-impact tested carbon steel, be designed to 2½ times the maximum operating pressure.

The concept of a transformation from carbon steel to cast iron when the metal temperature reduces below the transformation zone is not far fetched from a structural point of view. In fact, a cast iron vessel may have several advantages over an equivalent fabricated carbon steel vessel in the nil--ductility state. As stated above, the unit volume strain energy associated with fracture is equal to the area under the stress-strain curve. For a purely elastic and brittle material this can be expressed as $u = S^2(fracture)/2E$; where $S(fracture)$ is the ultimate strength and E is the modulus of elasticity.

Since $E(carbon\ steel) = 30 \times 10^6$lb./sq.in. and $E(cast\ iron) = 14 \times 10^6$lb./sq.in., the energy-absorbing capacity of cast iron is more than twice that for brittle carbon steel having the same ultimate strength.

Another disadvantage of a brittle carbon steel fabricated vessel over a cast iron vessel is that the latter is designed for a low shock capacity material by including large fillet radii and generous transitions to minimize stress concentrations. Needless to say, a welded carbon steel vessel may have many sharp corners, mechanical notches, incipient cracks at weld connections, etc. Although these are of small concern in a ductile material structure they may act as initiation poins for fracture in a brittle material.

The analogy of a cast iron vessel in this instance is very deliberate. All engineers have a respect for the limitations of cast iron pressure equipment. This is generally based on first-hand experiences and early design training indoctrination. A ductile carbon steel vessel which is shut down and exposed to a very cold or frigid climate should be thought of as a poorly constructed cast iron vessel during the startup operation. Retain all the fears and prejudices that go along with that concept; and treat the vessel, piping, and equipment accordingly.

Variables other than temperature also related

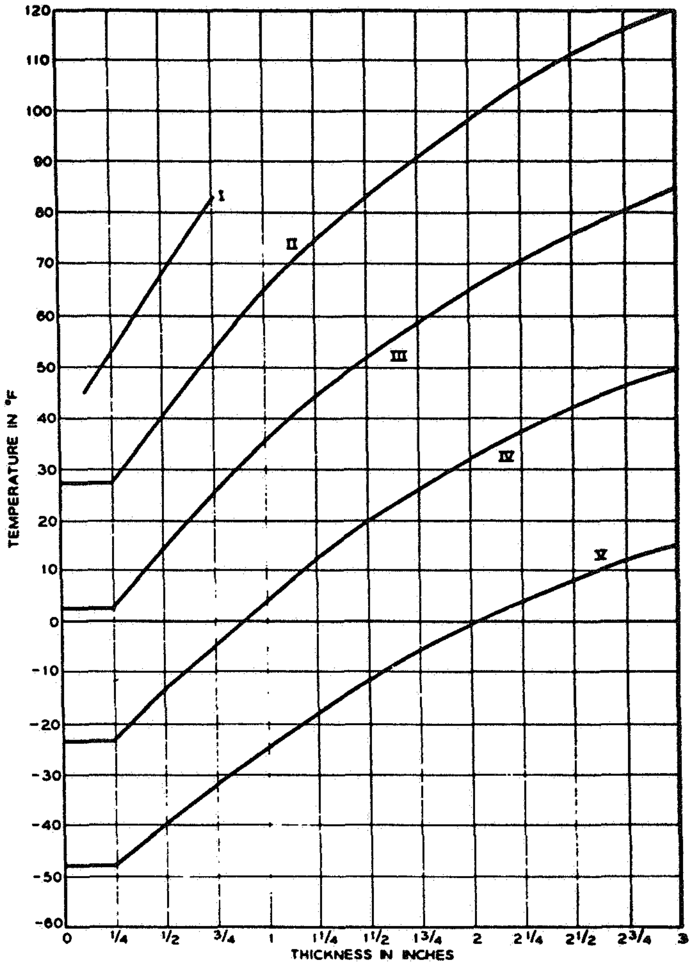
Although temperature is the single most important variable influencing the brittle fracture behavior of steels, there are other contributing factors. Generally, these factors are related to the metallurgy, manufacture, and fabrication of the as-built vessel. However it is erroneous to assume that no changes in the brittle-fracture-toughness characteristic can occur after the vessel is installed and in service.

Cold deformation or straining, and the strain aging that normally follows, generally raises the transition temperature of steel. This means that local areas of high stress (occurring during normal operation) will be vulnerable to brittle fracture at higher temperatures than previously. These local areas are at supports, attachment welds, welded baffles, inadvertent stress raisers caused by design or fabrication, etc. Therefore, a vessel subjected to a prematurely high pressure during startup cannot be presumed safe for future startups at that same overpressure. Ignorance of this adverse effect of strain aging can result in a false sense of security for operating personnel.

Plant operating instructions generally include startup procedures which are intended to control the heatup rate of a vessel and to maintain a reduced fluid pressure until a metal temperature is reached which is considered safe from brittle fracture. Only then may the full operating pressure be applied.

For pressure vessels constructed from carbon steels not intended for low-temperature service, the reduced fluid pressure at startup, and the safe metal temperature for normal operating pressure, should be based on the rules established in the ASME Pressure Vessel Code Section VIII, Division 2.

Figure 5 (from Figure AM-218.1 of the Code) specifies the safe temperature limits for various grades of carbon steel as a function of plate thickness. Vessels operating below these safe temperatures, and constructed of non-impact tested materials, are limited by the Code to a maximum pressure equal to 40% of the allowable pressure at room temperature. The minimum temperature at which this 40% reduced



GROUP I: Includes only SA-36 plate up to ¾ in. in thickness when welded to primary pressure components.

GROUP II: (a) Plate steels: SA-36 over ¾ in. in thickness when welded to primary pressure components; SA-285 and SA-515; (b) all other product forms of carbon steel conforming to specifications listed in Table ACS-1, unless assigned by these notes to another group.

GROUP III: Plate steels: SA-442 up to 1 in. in thickness, inclusive.

GROUP IV: Plate steels: SA-442 over 1 in. in thickness when not normalized; SA-516 up to 1½ in. in thickness, inclusive comparable thicknesses and strength grades.

GROUP V: (a). Pipe Steel: SA-524, Grades I & II; (b) Plate Steels: normalized SA-442 over 1 inch in thickness and normalized SA-516 and SA-662.

Figure 5. Upper limits of temperature transition zones for carbon steels.

pressure can be increased to full load may then be considered to be the temperature indicated on the applicable curve of Figure 5.

The logic of adhering to a prescribed startup procedure should be apparent from the foregoing discussion. Operating personnel should not view these startup precautions as trivial. The risk can be as great as overloading a poorly designed cast iron vessel 2½ times the allowable stress.

Transient thermal stresses

Thermal stresses are self-balancing stresses produced by nonuniform distributions of temperature, T, or by differing thermal coefficients of expansion, α. They develop in a solid body whenever a volume of material is prevented from assuming the size and shape that it normally should under a change in temperature.

When related to pressure vessels, which are composed chiefly of cylindrical elements and other shells-of-revolution, thermal stresses are dependent on the αT gradient. If the gradient is in the plane of the shell (meridional or circumferential), the stresses are related to changes in the slope of the gradient.

For transverse gradients (radial, across the plate thickness) the stress intensity is dependent on the slope change of the gradient and also the difference in temperature, ΔT, across the plate thickness.

In the case of a circumferential gradient, the deformation associated with the thermal stress is non-axisymmetric and this results in gross distortion effects which can sometimes arouse apprehension although they may not necessarily represent unsafe conditions. Vessel bowing is one of the more common phenomena resulting from the existence of a circumferential temperature gradient.

When thermal stresses are inherent in the nature of a process and/or the construction of a pressure vessel, the designer is obliged to include these stresses in the design and construction of the vessel. Both Divisions 1 and 2 of Section VIII of the ASME Pressure Vessel Code include this requirement. On the other hand, if the normal or steady state operation of a vessel does not cause thermal stresses then they are not usually considered in the design. However, all vessels operating at metal temperatures higher than ambient must pass through a transition state during startup, from an idle condition to normal full-load operation.

During this transient period, temperature gradients will develop in the vessel shell. These transient gradients vary with time and are dependent on the temperature, the flow, and the physical properties of the fluid being introduced into the vessel. The geometry of the fluid inlet nozzle and the flow mechanics of the fluid entering the vessel also affect the temperature gradient patterns. The transient temperature gradients thus formed result in transient thermal stresses which also vary with time until the vessel reaches steady state conditions at normal operation.

There are two obvious means of controlling startup transient thermal stresses: 1) *special design features* — use of thermal barriers, sleeves, shrouds, baffles, etc.; and 2) *Adherence to startup operating procedures* — to control the temperature and flow rate of the ingoing fluid at startup by incrementally bringing them up to normal operation.

The first alternative is used when transients are an inherent part of normal operation such as in cyclic processes or for temperature-control steam quenching. Needless to say, this alternate increases the cost of the vessel by including construction features which are not ncessary for normal operation.

The second alternative is, by far, the more common practice followed, although it will increase the duration of the startup period. The vessel designer does not normally consider a startup transient as a vessel operating load condition and usually relies instead on a controlled startup procedure being followed.

Pressure Vessel Code contains useful guide

Although the safe rate of heatup should depend on a study of the particular vessel in question, a good guide might be the restrictive measures specified by the ASME Pressure Vessel Code Section VIII, Division 1, in the paragraphs related to postweld heat treatment of carbon and low-alloy steel vessels. The Code specifies that the rate of heating need not be less than 100°F/hr., for reasonably simple structures, and need not be more than 400°F/hr. divided by the maximum metal thickness of the shell or had plate in inches, but in no case more than 400°F/hr. The Code also limits the temperature gradient to 250°F/15 ft. interval of length. This represents a gradient of about 17°F/ft. and is conservative.

The evaluation of transient thermal stresses is an involved procedure which does not lend itself to a generalized solution in explicit form. However, as mentioned above, the αT gradient and the ΔT across the shell can be used as indicators of the intensity of thermal stress.

Figure 6 illustrates a simple physical model subjected to a thermal impulse load (temperature-time step function). Temperature response curves are shown depicting the temperature-time history of the model. This figure is representative of the very common situation in which an externally insulated cylinder, soaked at the ambient temperature, T_O, is suddenly exposed to a higher temperature, T_I, on the inside surface.

Immediately after TI is applied ($t \cong 0$), the transient temperature gradient will have a sharp knee close to the inside surface indicating a very limited and local thermal stress at this instant. This is shown in Figure 6. With the lapse of time, also shown in Figure 6, the gradient tends to straighten out (the change in the slope is reducing) and the temperature differential ΔT ($= T_i - T_j$) tends to reduce to the steady state condition, $T_I - T_S$. Both of these effects result in reduced intensity of the thermal stress.

Note that the inside metal skin temperature, T_i, is not shown equal to the applied temperature, T_I, during the early transients. This temperature lag is the result of an inside surface film which constitutes a thermal barrier. The effectiveness of this barrier depends on the properties and dynamic state of the contacting fluid.

If the fluid is boiling water/steam then the film barrier can be ignored and T_i will be equal to T_I for all gradients. If the fluid is hot air or synthesis gas, a film with some heat-flux resistance will be formed and the transients will resemble those shown in Figure 6. In the absence of a rigorous heat transfer analysis it may be judicious to evaluate the transient thermal stress based on the conservative assumption that $T_i = T_I$.

Determining maximum stress

The maximum stress (longitudinal or circumferential) of a cylindrical shell caused by a radial temperature gradient may be expressed as $\sigma max = K \cdot E\alpha \cdot \Delta T/(1-v)$ in which v is Poisson's ratio, and K is a factor which varies from 0.5 to 1.0, depending on the general shape of the gradient.

For a steady-state gradient the value of K closely approximates the lower limit of 0.5. On the other hand, K approaches the upper limit of 1.0 for a first-instant ($@ t \approx 0$) transient gradient having a very sharp knee at the inner surface. Both of these extreme gradients are illustrated in Figure 6. If no inside surface film exists, the curvature of the knee will be at its sharpest and ΔT will equal its maximum value of $T_I - T_O$. This latter condition, which results in the maximum thermal stress localized at the inside surface of the shell, is commonly called thermal shock.

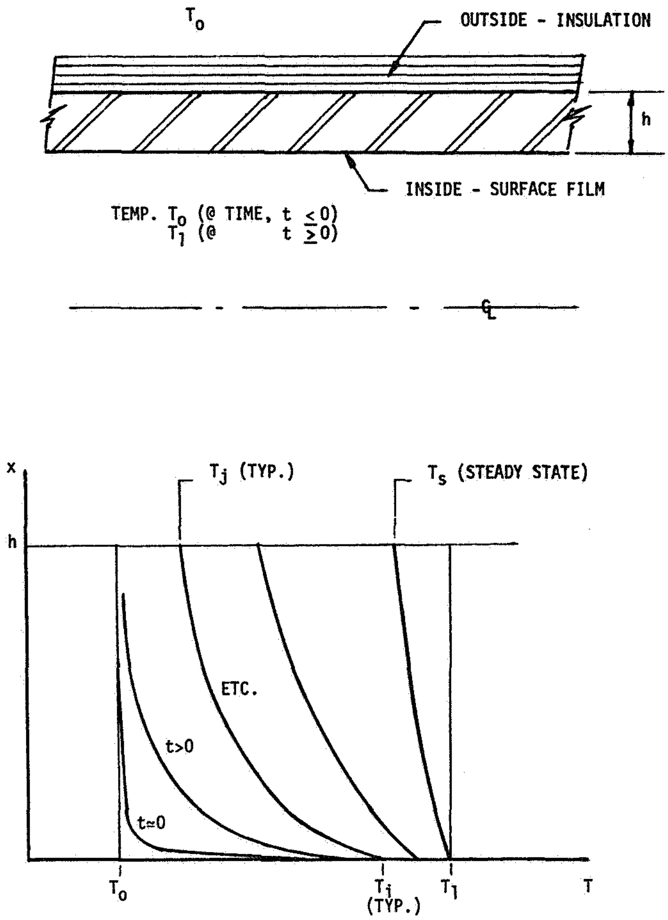


Figure 6. Transient radial temperature gradients.

The above formula can be used to determine a conservative limit for ΔT for any specific material by applying it with the allowable stress criterion of the ASME Pressure Vessel Code Section VIII, Division 2. This authority allows the total of the primary stress (due to pressure in this instance) plus the secondary thermal stress to be equal to, or less than, three times the basic allowable tensile stress.

If the assumptions are made that the pressure stress is equal to the basic allowable tensile stress and that $K = 1.0$, then the equation may be transposed and reduced to $\Delta T = 2S(1-v)/(E\alpha)$, in which S represents the basic allowable tensile stress for the material.

As an example, the safe ΔT for *SA* 515 Gr.60 operating above the temperature transition zone and below 650°F will be $\Delta T = 2 \times 15{,}000(1-0.3)/(30 \times 10^6 \times 6 \times 10^{-6}) = 117$°F.

The safe longitudinal temperature gradient that may be tolerated during the heatup of a cylindrical shell may be approximated by the use of a simple formula which applies to the longitudinal bending stress resulting from a sharp change in gradient from zero (no change in temperature with length) to a linear gradient of T' °F/in. of cylinder length.

The formula is $\sigma x(max.) = 1.41\ E\alpha T'\sqrt{ah}$, in which ah is the product of the thickness and radius of the cylindrical shell. Applying this formula and the above Code criterion for primary plus secondary stresses, the safe longitudinal gradient for a 12-ft. diameter by 3-in. wall thickness, SA515 Gr.60 vessel is:

$$T' = 2.5\times 15{,}000/(1.41\times 30\times 10^{6}\times 6\times 10^{-6}\sqrt{72\times 3}) =$$
$$10°F/in. \equiv 120°F/ft.$$

$2.5S$ is used in this calculation (instead of the $2S$ used previously), because the significant pressure stress in this instance is the longitudinal stress, which is equal to ½ the maximum (circumferential) pressure stress. Consequently, $3S - 0.5S = 2.5S$. This value of T' should be considered an upper limit for the safe longitudinal temperature gradient during startup.

As described above, vessel bowing is symptomatic of a circumferential temperature gradient. Consequently, this effect can be minimized by avoiding fluid flow patterns which tend to cause an uneven heatup around the circumference of the vessel. Typical of problems involving deflections in structures, it is the stress intensity, rather than the strain, which is the index of safe design and construction.

As a general rule, it would be prudent for operating personnel to be wary of vessel bowing during the startup sequence. In such an event, the cause of the circumferential temperature gradient should be determined; and it must be established whether the bowing is inherent in the operation or whether it represents a maloperation in the startup sequence.

If the former applies, the anticipated bowing must be checked for safety by the engineering department. If maloperation is the culprit, it stands to reason that the operating procedures should be reviewed and appropriately modified.

Conclusion

A discourse was presented on the potential safety hazards related to two aspects of vessel startup: 1) the pressure build-up procedure; and 2) the rate of metal heatup. The first is concerned with the application of a primary load (pressure) on a vessel constructed of a metal sensitive to low temperature when the metal temperature is at or below the transition temperature zone.

The second is concerned with transient temperature gradients and their corresponding thermal stresses.

In either aspect, conditions of stress and strain may be produced which can be beyond the limits of safety, as specified by the Code or as acceptable to good engineering practice. Consequently the designer is obliged to design and construct the vessel such that it can structurally withstand rapid startup practices or else he must specify a startup procedure for controlling these load variables.

The latter course is the one generally followed — especially if low capital investment is a strong economic incentive. In this instance, the designer expects the operating personnel to follow specified procedures. The owner/operator has an option, during the design stage, to spend additional funds for materials with improved low temperature impact properties in the event that there is an economic advantage to accelerate plant startup.

This article has also outlined some general guidelines from which startup procedures can be established. However, it should be kept in mind that startup procedures should be applied selectively, to suit the individual vessel and circumstances. The load conditions (pressure and temperature) during this operation are as significant to safety as are the design load conditions during normal operation. #

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DISCUSSION

GENE COMEAU, Farmland Industries: I have two questions. The first question involves the graph that you put up showing the upper limit of the transition temperature for various materials. Now the last time I looked at this situation, as I recall there wasn't any real upper limit or lower limit. The allowables were based on statistical averages, and that you could get a given mill run of material that had a very low or a very high transition temperature. Is that correct?

EAGLE: You could get variations in transition temperature depending on how you handled the material.

COMEAU: But can you also, from the mill get a material that is very brittle?

EAGLE: Yes we can.

COMEAU: What I'm trying to point out is that in spite of the code saying that you can use this particular material, let's say at minus 20 degrees, that's not really the case, is it? If it's not impact tested, you don't know what you've got.

ANSWER: That - that is a pretty good statement. You don't know what you've got if it's not impact tested but the code curves are based on presumably

a safe range, if you stay within them.
COMEAU: Do you believe that the codes are based on a safe range?
EAGLE: Let me consult our company metallurgist, Larry Zeis. I don't believe we've had any problems with that, have we Larry?
LARRY ZEIS, Pullman Kellogg: He showed two curves, the first was just a schematic which showed an upper shelf dropping off to a lower shelf. That was just a typical curve for all ferritic and low alloy steels. The second group of curves, which came from ASME Section VIII, Division 2, show temperature - thickness combinations at which you do not need to run impact tests. Tha Code says that if you use material below the limiting thickness, above the limiting temperature, you will be safe from brittle fracture. There have been very few failures in pressure vessels constructed in accordance with ASME Section VIII, Division 1 and this Division is much less conservative than Division 2 in this respect. I think the answer to your second question is that you can believe that second set of curves.

The second set of curves is from Division 2, Section VIII, which is much more conservative than Division 1.
COMEAU: I guess my question is, if you use the codes will you be safe all of the time?
ZEIS: No, if you were to design to ASME Section VIII, Division 1, that says that you can use a four inch thick A515 plate down to minus 20, and I think most of us believe that that is not true - that that will not be safe.
COMEAU: I'm thinking of a tank car that I was familiar with that was brittle at 100 degrees F.
ZEIS: Well the same thing would apply to these thicker materials. The ASME Section VIII, Division 1, would say you could use this down to minus 20°F. Division 2, with its set of curves, would say you cannot. You have to impact test if design temperature is 130 degrees.
COMEAU: So the Division 1 vs Division 2 - you are saying, Division 2 is safe at all times.
ZEIS: As far as brittle fracture is concerned.
COMEAU: You don't have to think - that's what I mean.
ZEIS: You just follow that code and you would be safe against brittle fracture. It says either use this material at this temperature, or if you want it use it at a lower temperature you must impact test it. Whereas Division 1 says, only if it's below minus 20, then you must impact test. So with Division 1, you have to apply some judgment.
COMEAU: This is not my second question. This is question 1A. Why does it cost so much to impact test?
EAGLE: Because of the possibility of not meeting impact values there may be some rejected plates. In other words, when the impact test is not within the range specified, what can the mill do with that plate since you won't buy it?
COMEAU: Well doesn't that say something pretty bad about the quality of the material?
EAGLE: Sure, that's just about what it amounts to.
COMEAU: Yes but the reason it costs so much is because a lot of material fails? Correct?
EAGLE: It fails under a particular load test that you apply to it, but if you want to use a material that has a relatively low transition temperature, and you want it impact tested to a high value, obviously a lot of failures are going to occur until sufficient plates are located that will meet the requirements. It depends on the property of the material itself. The easier it is to meet the impact test, the less the premium will be for the possibility of failure.
COMEAU: I'm just trying to make a point. The reason it costs so much is not because of the test, but because so much of it fails.
EAGLE: It's not the cost of the test. It's the cost of the possibility of failure and what can then be done with that plate which fails the impact test.
COMEAU: The cost of paper work is there too.
EAGLE: Yes
COMEAU: My second question refers to strain ageing?
EAGLE: Yes.
COMEAU: Would you explain that in more detail?
EAGLE: Well every time you put something through a stress that goes beyond the elastic limit, you do a little bit of damage to it. It's kind of like creep - where you are changing the properties every time the elastic limit is exceeded. A rubber band, if you keep stretching it, sooner or later will break.
ZEIS: The stretching of the steel causes instability which causes internal precipitation and hardening and lower ductility.
COMEAU: These are not normal stresses, is that correct? These are unusual stresses -
ZEIS: That's right. If you stay below the safe thermal gradients that you calculate, then you should not get into these difficulties; but if you take excursions that go beyond them, then there is a possibility of causing some damage. It's not a failure caused by any one cycle at any particular time, but an accumulation.
COMEAU: Thank you very much.
EAGLE: Thanks for your help Larry.