Thermal Shock and Brittle Fracture of Material

Course No: T02-001

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Department of Energy
Fundamentals Handbook

MATERIAL SCIENCE
Module 3
Thermal Shock

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THERMAL STRESS

Thermal stresses arise in materials when they are heated or cooled. Thermal stresses effect the operation of facilities, both because of the large components subject to stress and because they are effected by the way in which the plant is operated. This chapter describes the concerns associated with thermal stress.

EO 1.1 **IDENTIFY the two stresses that are the result of thermal shock (stress) to plant materials.**

EO 1.2 **STATE the two causes of thermal stresses.**

EO 1.3 **Given the material's coefficient of Linear Thermal Expansion, CALCULATE the thermal stress on a material using Hooke's Law.**

EO 1.4 **DESCRIBE why thermal stress is a major concern in reactor systems when rapidly heating or cooling a thick-walled vessel.**

EO 1.5 **LIST the three operational limits that are specifically intended to reduce the severity of thermal shock.**

Thermal Shock

Thermal shock (stress) can lead to excessive thermal gradients on materials, which lead to excessive stresses. These stresses can be comprised of *tensile stress*, which is stress arising from forces acting in opposite directions tending to pull a material apart, and *compressive stress*, which is stress arising from forces acting in opposite directions tending to push a material together. These stresses, cyclic in nature, can lead to fatigue failure of the materials.

Thermal shock is caused by nonuniform heating or cooling of a uniform material, or uniform heating of nonuniform materials. Suppose a body is heated and constrained so that it cannot expand. When the temperature of the material increases, the increased activity of the molecules causes them to press against the constraining boundaries, thus setting up thermal stresses.

If the material is not constrained, it expands, and one or more of its dimensions increases. The thermal expansion coefficient (α) relates the fractional change in length $\frac{\Delta l}{l}$, called thermal strain, to the change in temperature per degree ΔT.

$$\alpha = \frac{\frac{\Delta l}{l}}{\Delta T} \tag{3-1}$$

$$\frac{\Delta l}{l} = \alpha \Delta T \tag{3-2}$$

where:

l = length (in.)
Δl = change in length (in.)
α = linear thermal expansion coefficient (°F^{-1})
ΔT = change in temperature (°F)

Table 1 lists the coefficients of linear thermal expansion for several commonly-encountered materials.

TABLE 1
Coefficients of Linear Thermal Expansion

Material	Coefficients of Linear Thermal Expansion (°F^{-1})
Carbon Steel	5.8×10^{-6}
Stainless Steel	9.6×10^{-6}
Aluminum	13.3×10^{-6}
Copper	9.3×10^{-6}
Lead	16.3×10^{-6}

In the simple case where two ends of a material are strictly constrained, the thermal stress can be calculated using Hooke's Law by equating values of $\frac{\Delta l}{l}$ from Equations (3-1), (3-2), and (3-3).

$$E = \frac{\text{stress}}{\text{strain}} = \frac{F/A}{\frac{\Delta l}{l}} \tag{3-3}$$

or

$$\frac{\Delta l}{l} = \frac{F/A}{E} \tag{3-4}$$

$$\alpha \Delta T = \frac{F/A}{E} \tag{3-5}$$

$$F/A = E\alpha\Delta T$$

where:

F/A = thermal stress (psi)

E = modulus of elasticity (psi)

α = linear thermal expansion coefficient (°F^{-1})

ΔT = change in temperature (°F)

Example: Given a carbon steel bar constrained at both ends, what is the thermal stress when heated from 60°F to 540°F?

Solution:

α = 5.8×10^{-6}/°F (from Table 1)

E = 3.0×10^{7} lb/in.^{2} (from Table 1, Module 2)

ΔT = 540°F - 60°F = 480°F

Stress = $F/A = E\alpha\Delta T = (3.0 \times 10^{7}$ lb/in.$^2) \times (5.8 \times 10^{-6}$/°F$) \times 480$°F

Thermal stress = 8.4×10^{4} lb/in.^{2} (which is higher than the yield point)

Thermal stresses are a major concern in reactor systems due to the magnitude of the stresses involved. With rapid heating (or cooling) of a thick-walled vessel such as the reactor pressure vessel, one part of the wall may try to expand (or contract) while the adjacent section, which has not yet been exposed to the temperature change, tries to restrain it. Thus, both sections are under stress. Figure 1 illustrates what takes place.

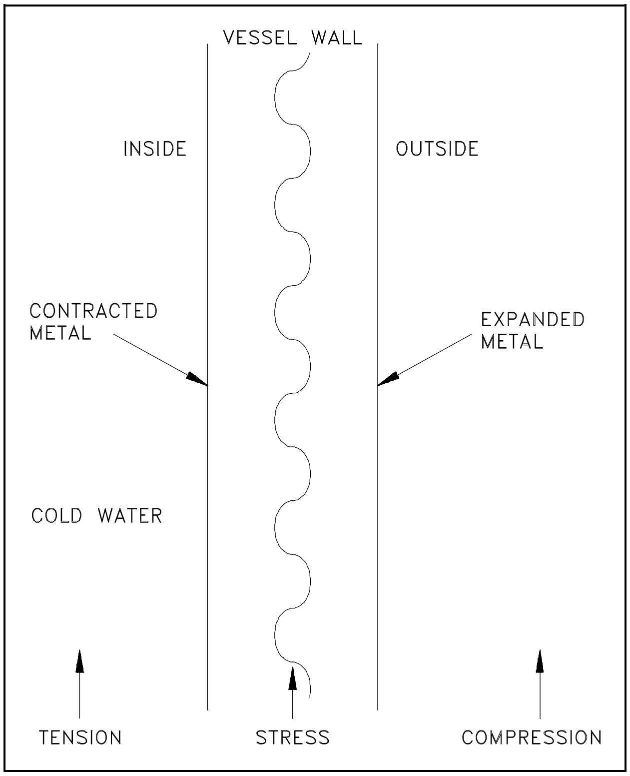

Figure 1 Stress on Reactor Vessel Wall

A vessel is considered to be thick-walled or thin-walled based on comparing the thickness of the vessel wall to the radius of the vessel. If the thickness of the vessel wall is less than about 1 percent of the vessel's radius, it is usually considered a thin-walled vessel. If the thickness of the vessel wall is more than 5 percent to 10 percent of the vessel's radius, it is considered a thick-walled vessel. Whether a vessel with wall thickness between 1 percent and 5 percent of radius is considered thin-walled or thick-walled depends on the exact design, construction, and application of the vessel.

When cold water enters the vessel, the cold water causes the metal on the inside wall (left side of Figure 1) to cool before the metal on the outside. When the metal on the inside wall cools, it contracts, while the hot metal on the outside wall is still expanded. This sets up a thermal stress, placing the cold side in tensile stress and the hot side in compressive stress, which can cause cracks in the cold side of the wall. These stresses are illustrated in Figure 2 and Figure 3 in the next chapter.

The heatup and cooldown of the reactor vessel and the addition of makeup water to the reactor coolant system can cause significant temperature changes and thereby induce sizable thermal stresses. Slow controlled heating and cooling of the reactor system and controlled makeup water addition rates are necessary to minimize cyclic thermal stress, thus decreasing the potential for fatigue failure of reactor system components.

Operating procedures are designed to reduce both the magnitude and the frequency of these stresses. Operational limitations include heatup and cooldown rate limits for components, temperature limits for placing systems in operation, and specific temperatures for specific pressures for system operations. These limitations permit material structures to change temperature at a more even rate, minimizing thermal stresses.

Summary

The important information in this chapter is summarized below.

Thermal Stress Summary

- Two types of stress that can be caused by thermal shock are:

  Tensile stress
  Compressive stress

- Causes of thermal shock include:

  Nonuniform heating (or cooling) of a uniform material

  Uniform heating (or cooling) of a nonuniform material

- Thermal shock (stress) on a material, can be calculated using Hooke's Law from the following equation. It can lead to the failure of a vessel.

  $F/A = E\alpha\Delta T$

- Thermal stress is a major concern due to the magnitude of the stresses involved with rapid heating (or cooling).

- Operational limits to reduce the severity of thermal shock include:

  Heatup and cooldown rate limits

  Temperature limits for placing systems into operation

  Specific temperatures for specific pressures for system operation

PRESSURIZED THERMAL SHOCK

Personnel need to be aware how pressure combined with thermal stress can cause failure of plant materials. This chapter addresses thermal shock (stress) with pressure excursions.

EO 1.6 **DEFINE the term pressurized thermal shock.**

EO 1.7 **STATE how the pressure in a closed system effects the severity of thermal shock.**

EO 1.8 **LIST the four plant transients that have the greatest potential for causing thermal shock.**

EO 1.9 **STATE the three locations in a reactor system that are of primary concern for thermal shock.**

Definition

One safety issue that is a long-term problem brought on by the aging of nuclear facilities is *pressurized thermal shock* (PTS). PTS is the shock experienced by a thick-walled vessel due to the combined stresses from a rapid temperature and/or pressure change. Nonuniform temperature distribution and subsequent differential expansion and contraction are the causes of the stresses involved. As the facilities get older in terms of full power operating years, the neutron radiation causes a change in the ductility of the vessel material, making it more susceptible to embrittlement. Thus, if an older reactor vessel is cooled rapidly at high pressure, the potential for failure by cracking increases greatly.

Evaluating Effects of PTS

Changes from one steady-state temperature or pressure to another are of interest for evaluating the effects of PTS on the reactor vessel integrity. This is especially true with the changes involved in a rapid cooldown of the reactor system, which causes thermal shock to the reactor vessel. These changes are called transients. Pressure in the reactor system raises the severity of the thermal shock due to the addition of stress from pressure. Transients, which combine high system pressure and a severe thermal shock, are potentially more dangerous due to the added effect of the tensile stresses on the inside of the reactor vessel wall. In addition, the material toughness of the reactor vessel is reduced as the temperature rapidly decreases.

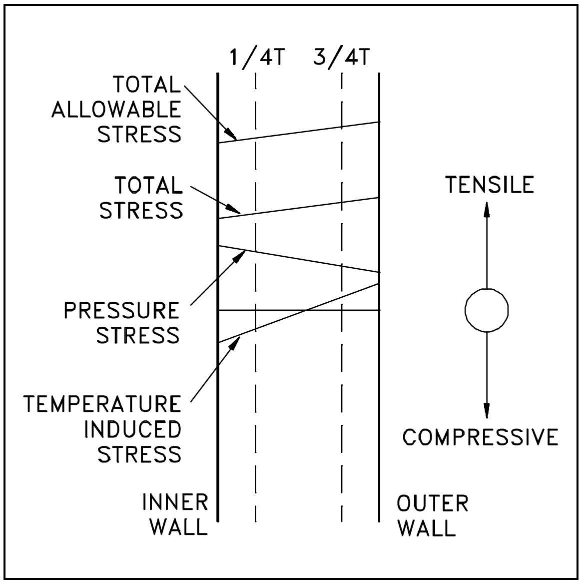

Figure 2 Heatup Stress Profile

Stresses arising from coolant system pressure exerted against the inside vessel wall (where neutron fluence is greatest) are always tensile in nature. Stresses arising from temperature gradients across the vessel wall can either be tensile or compressive. The type of stress is a function of the wall thickness and reverses from heatup to cooldown. During system heatup, the vessel outer wall temperature lags the inner wall temperature. The stresses produced by this temperature gradient and by system pressure will produce the profile shown in Figure 2.

During heatup, it can be seen that while the pressure stresses are always tensile, at the 1/4 thickness (1/4 T), the temperature stresses are compressive. Thus, the stresses at the 1/4 T location tend to cancel during system heatup. At the 3/4 T location, however, the stresses from both temperature and pressure are tensile and thus, reinforce each other during system heatup. For this reason the 3/4 T location is limiting during system heatup.

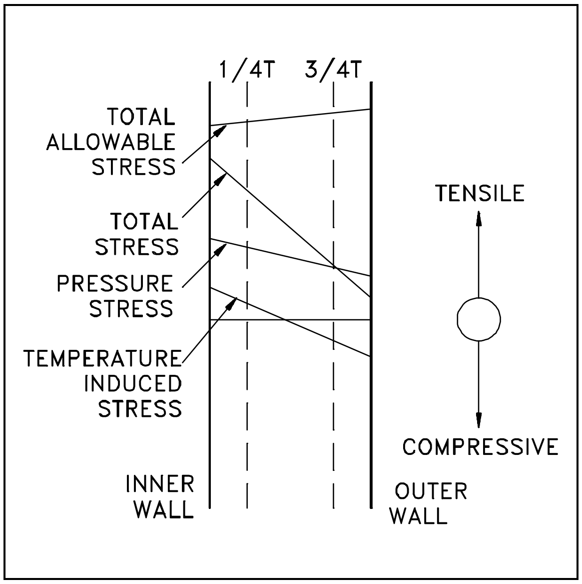

Figure 3 Cooldown Stress Profile

During system cooldown, the stress profile of Figure 3 is obtained. During cooldown, the outer wall lags the temperature drop of the inner wall and is at a higher temperature. It can be seen that during cooldown, the stresses at the 3/4 T location are tensile due to system pressure and compressive due to the temperature gradient. Thus during cooldown, the stresses at the 3/4 T location tend to cancel. At the 1/4 T location, however, the pressure and temperature stresses are both tensile and reinforce each other. Thus, the 1/4 T location is limiting during system cooldown.

Plant temperature transients that have the greatest potential for causing thermal shock include excessive plant heatup and cooldown, plant scrams, plant pressure excursions outside of normal pressure bands, and loss of coolant accidents (LOCAs). In pressurized water reactors (PWRs), the two transients that can cause the most severe thermal shock to the reactor pressure vessel are the LOCA with subsequent injection of emergency core cooling system (ECCS) water and a severe increase in the primary-to-secondary heat transfer.

Locations of Primary Concern

Locations in the reactor system, in addition to the reactor pressure vessel, that are primary concerns for thermal shock include the pressurizer spray line and the purification system.

Summary

The important information in this chapter is summarized below.

Pressurized Thermal Shock Summary

- Definition of pressurized thermal shock (PTS)

  Shock experienced by a thick-walled vessel due to the combined stresses from a rapid temperature and/or pressure change.

- Pressure in closed system raises the severity of thermal shock due to the additive effect of thermal and pressure tensile stresses on the inside reactor vessel wall.

- Plant transients with greatest potential to cause PTS include:

  Excessive heatup and cooldown

  Plant scrams

  Plant pressure excursions outside of normal pressure bands

  Loss of coolant accident

- Locations of primary concern for thermal shock are:

  Reactor Vessel

  Pressurizer spray line

  Purification system

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BRITTLE FRACTURE MECHANISM

Personnel need to understand brittle fracture. This type of fracture occurs under specific conditions without warning and can cause major damage to plant materials.

EO 1.1 **DEFINE the following terms:**

- **a. Ductile fracture**
- **b. Brittle fracture**
- **c. Nil-ductility Transition (NDT) Temperature**

EO 1.2 **DESCRIBE the two changes made to reactor pressure vessels to decrease NDT.**

EO 1.3 **STATE the effect grain size and irradiation have on a material's NDT.**

EO 1.4 **LIST the three conditions necessary for brittle fracture to occur.**

EO 1.5 **STATE the three conditions that tend to mitigate crack initiation.**

EO 1.6 **LIST the five factors that determine the fracture toughness of a material.**

EO 1.7 **Given a stress-temperature diagram, IDENTIFY the following points:**

- **a. NDT (with no flaw)**
- **b. NDT (with flaw)**
- **c. Fracture transition elastic point**
- **d. Fracture transition plastic point**

Brittle Fracture Mechanism

Metals can fail by ductile or brittle fracture. Metals that can sustain substantial plastic strain or deformation before fracturing exhibit *ductile fracture*. Usually a large part of the plastic flow is concentrated near the fracture faces.

Metals that fracture with a relatively small or negligible amount of plastic strain exhibit *brittle fracture*. Cracks propagate rapidly. Brittle failure results from *cleavage* (splitting along definite planes). Ductile fracture is better than brittle fracture, because ductile fracture occurs over a period of time, where as brittle fracture is fast, and can occur (with flaws) at lower stress levels than a ductile fracture. Figure 1 shows the basic types of fracture.

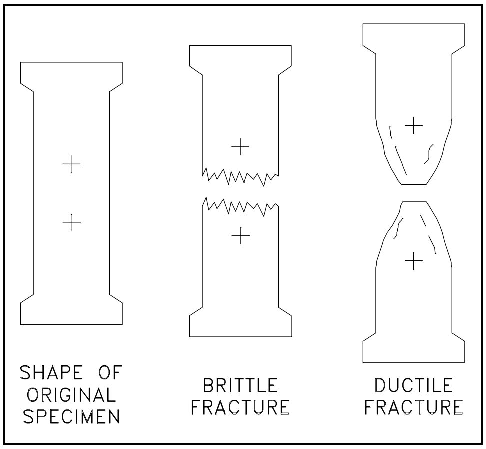

Figure 1 Basic Fracture Types

Brittle cleavage fracture is of the most concern in this module. *Brittle cleavage fracture* occurs in materials with a high strain-hardening rate and relatively low cleavage strength or great sensitivity to multi-axial stress.

Many metals that are ductile under some conditions become brittle if the conditions are altered. The effect of temperature on the nature of the fracture is of considerable importance. Many steels exhibit ductile fracture at elevated temperatures and brittle fracture at low temperatures. The temperature above which a material is ductile and below which it is brittle is known as the *Nil-Ductility Transition (NDT) temperature*. This temperature is not precise, but varies according to prior mechanical and heat treatment and the nature and amounts of impurity elements. It is determined by some form of drop-weight test (for example, the Izod or Charpy tests).

Ductility is an essential requirement for steels used in the construction of reactor vessels; therefore, the NDT temperature is of significance in the operation of these vessels. Small grain size tends to increase ductility and results in a decrease in NDT temperature. Grain size is controlled by heat treatment in the specifications and manufacturing of reactor vessels. The NDT temperature can also be lowered by small additions of selected alloying elements such as nickel and manganese to low-carbon steels.

Of particular importance is the shifting of the NDT temperature to the right (Figure 2), when the reactor vessel is exposed to fast neutrons. The reactor vessel is continuously exposed to fast neutrons that escape from the core. Consequently, during operation the reactor vessel is subjected to an increasing fluence (flux) of fast neutrons, and as a result the NDT temperature increases steadily. It is not likely that the NDT temperature will approach the normal operating temperature of the steel. However, there is a possibility that when the reactor is being shut down or during an abnormal cooldown, the temperature may fall below the NDT value while the internal pressure is still high. The reactor vessel is susceptible to brittle fracture at this point. Therefore, special attention must be given to the effect of neutron irradiation on the NDT temperature of the steels used in fabricating reactor pressure vessels. The Nuclear Regulatory Commission requires that a reactor vessel material surveillance program be conducted in water-cooled power reactors in accordance with ASTM Standards (designation E 185-73).

Pressure vessels are also subject to cyclic stress. *Cyclic stress* arises from pressure and/or temperature cycles on the metal. Cyclic stress can lead to fatigue failure. Fatigue failure, discussed in more detail in Module 5, can be initiated by microscopic cracks and notches and even by grinding and machining marks on the surface. The same (or similar) defects also favor brittle fracture.

Stress-Temperature Curves

One of the biggest concerns with brittle fracture is that it can occur at stresses well below the yield strength (stress corresponding to the transition from elastic to plastic behavior) of the material, provided certain conditions are present. These conditions are: a flaw such as a crack; a stress of sufficient intensity to develop a small deformation at the crack tip; and a temperature low enough to promote brittle fracture. The relationship between these conditions is best described using a generalized stress-temperature diagram for crack initiation and arrest as shown in Figure 2.

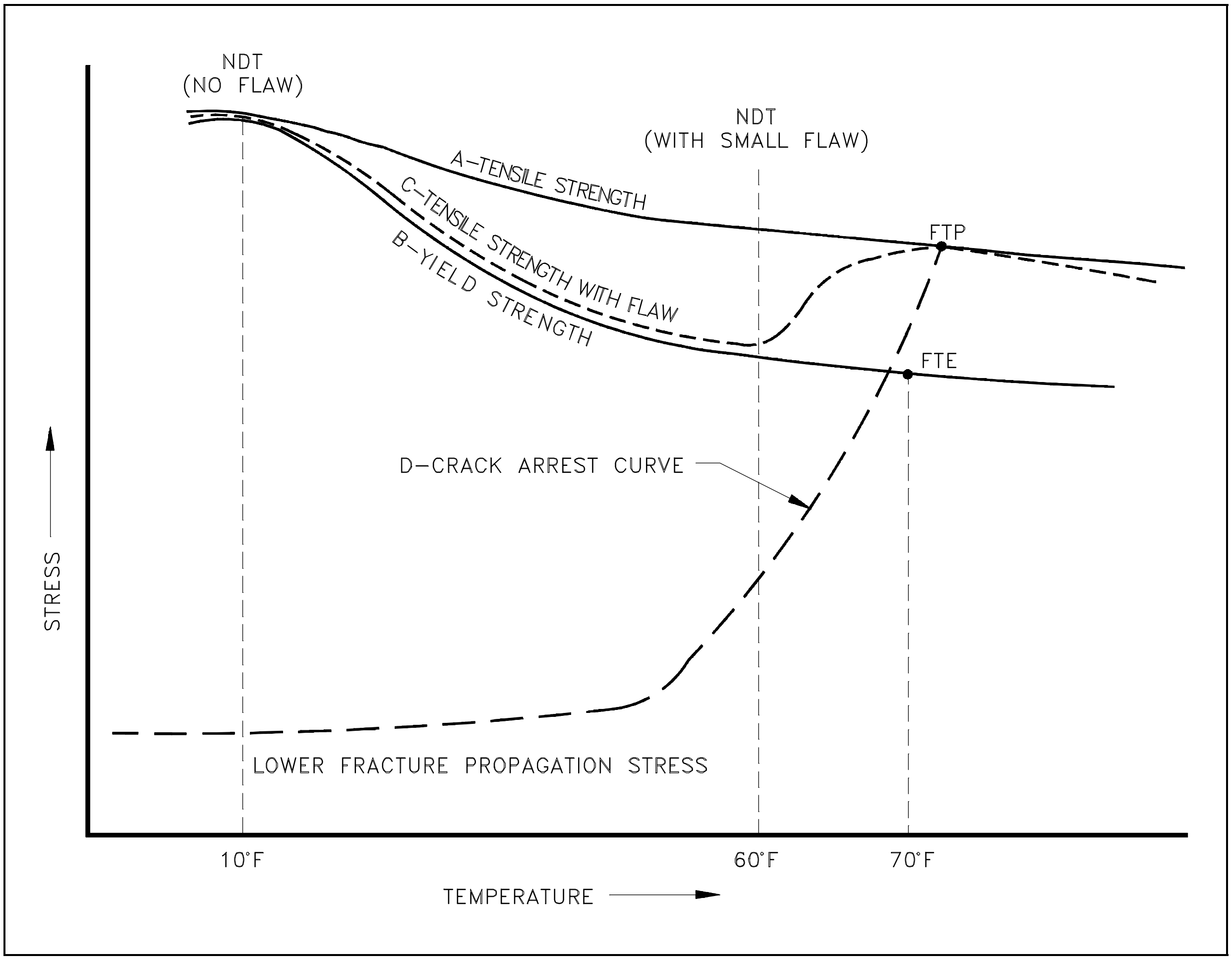

Figure 2 Stress-Temperature Diagram for Crack Initiation and Arrest

Figure 2 illustrates that as the temperature goes down, the tensile strength (Curve A) and the yield strength (Curve B) increase. The increase in tensile strength, sometimes known as the ultimate strength (a maximum of increasing strain on the stress-strain curve), is less than the increase in the yield point. At some low temperature, on the order of 10°F for carbon steel, the yield strength and tensile strength coincide. At this temperature and below, there is no yielding when a failure occurs. Hence, the failure is brittle. The temperature at which the yield and tensile strength coincide is the NDT temperature.

When a small flaw is present, the tensile strength follows the dashed Curve C. At elevated temperatures, Curves A and C are identical. At lower temperatures, approximately 50°F above the NDT temperature for material with no flaws, the tensile strength curve drops to the yield curve and then follows the yield curve to lower temperatures. At the point where Curves C and B meet, there is a new NDT temperature. Therefore, if a flaw exists, any failure at a temperature equal or below the NDT temperature for flawed material will be brittle.

Crack Initiation and Propagation

As discussed earlier in this chapter, brittle failure generally occurs because a flaw or crack propagates throughout the material. The start of a fracture at low stresses is determined by the cracking tendencies at the tip of the crack. If a plastic flaw exists at the tip, the structure is not endangered because the metal mass surrounding the crack will support the stress. When brittle fracture occurs (under the conditions for brittle fracture stated above), the crack will initiate and propagate through the material at great speeds (speed of sound). It should be noted that smaller grain size, higher temperature, and lower stress tend to mitigate crack initiation. Larger grain size, lower temperatures, and higher stress tend to favor crack propagation. There is a stress level below which a crack will not propagate at any temperature. This is called the lower fracture propagation stress. As the temperature increases, a higher stress is required for a crack to propagate. The relationship between the temperature and the stress required for a crack to propagate is called the crack arrest curve, which is shown on Figure 2 as Curve D. At temperatures above that indicated on this curve, crack propagation will not occur.

Fracture Toughness

Fracture toughness is an indication of the amount of stress required to propagate a preexisting flaw. The fracture toughness of a metal depends on the following factors.

a. Metal composition
b. Metal temperature
c. Extent of deformations to the crystal structure
d. Metal grain size
e. Metal crystalline form

The intersection of the crack arrest curve with the yield curve (Curve B) is called the *fracture transition elastic* (FTE) *point*. The temperature corresponding to this point is normally about 60°F above the NDT temperature. This temperature is also known as the Reference Temperature - Nil-ductility Transition (RT_{NDT}) and is determined in accordance with ASME Section III (1974 edition), NB 2300. The FTE is the temperature above which plastic deformation accompanies all fractures or the highest temperature at which fracture propagation can occur under purely elastic loads. The intersection of the crack arrest curve (Curve D) and the tensile strength or ultimate strength, curve (Curve A) is called the *fracture transition plastic* (FTP) *point*. The temperature corresponding with this point is normally about 120°F above the NDT temperature. Above this temperature, only ductile fractures occur.

Figure 3 is a graph of stress versus temperature, showing fracture initiation curves for various flaw sizes.

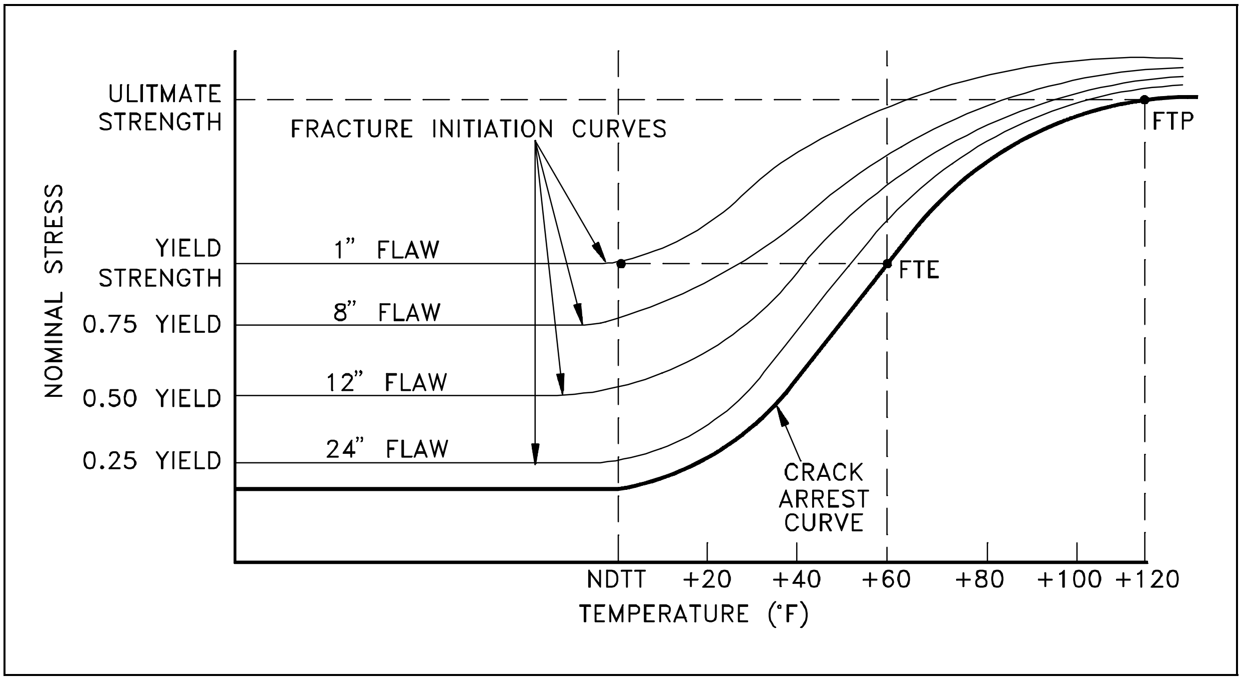

Figure 3 Fracture Diagram

It is clear from the above discussion that we must operate above the NDT temperature to be certain that no brittle fracture can occur. For greater safety, it is desirable that operation be limited above the FTE temperature, or NDT + 60°F. Under such conditions, no brittle fracture can occur for purely elastic loads.

As previously discussed, irradiation of the pressure vessel can raise the NDT temperature over the lifetime of the reactor pressure vessel, restricting the operating temperatures and stress on the vessel. It should be clear that this increase in NDT can lead to significant operating restrictions, especially after 25 years to 30 years of operation where the NDT can raise 200°F to 300°F. Thus, if the FTE was 60°F at the beginning of vessel life and a change in the NDT of 300°F occurred over a period of time, the reactor coolant would have to be raised to more than 360°F before full system pressure could be applied.

Summary

The important information in this chapter is summarized below.

Brittle Fracture Summary

- Ductile fracture is exhibited when metals can sustain substantial plastic strain or deformation before fracturing.
- Brittle fracture is exhibited when metals fracture with a relatively small or negligible amount of plastic strain.
- Nil-Ductility Transition (NDT) temperature is the temperature above which a material is ductile and below which it is brittle.
- Changes made to decrease NDT include:

  Use of smaller grain size in metals

  Small additions of selected alloying elements such as nickel and manganese to low-carbon steels
- NDT decreases due to smaller grain size and increases due to irradiation
- Brittle fracture requires three conditions:

  Flaw such as a crack
  Stress sufficient to develop a small deformation at the crack tip
  Temperature at or below NDT
- Conditions to mitigate crack initiation:

  Smaller grain size
  Higher temperature
  Lower stress levels
- Factors determining fracture toughness of a metal include:

  Metal composition
  Metal temperature
  Extent of deformations to the crystal structure
  Metal grain size
  Metal crystalline form

MINIMUM PRESSURIZATION-TEMPERATURE CURVES

Plant operations are effected by the minimum pressurization-temperature curves. Personnel need to understand the information that is associated with the curves to better operate the plant.

EO 1.8 STATE the two bases used for developing a minimum pressurization-temperature curve.

EO 1.9 EXPLAIN a typical minimum pressure-temperature curve including:

a. Location of safe operating region
b. The way the curve will shift due to irradiation

EO 1.10 LIST the normal actions taken, in sequence, if the minimum pressurization-temperature curve is exceeded during critical operations.

EO 1.11 STATE the precaution for hydrostatic testing.

MPT Definition and Basis

Minimum pressurization-temperature (MPT) *curves* specify the temperature and pressure limitations for reactor plant operation. They are based on reactor vessel and head stress limitations and the need to preclude reactor vessel and head brittle fracture. Figure 4 shows some pressure-temperature operating curves for a pressurized water reactor (PWR) Primary Coolant System (PCS).

Note that the safe operating region is to the right of the reactor vessel MPT curve. The reactor vessel MPT curve ensures adequate operating margin away from the crack arrest curve discussed above. The curves used by operations also incorporate instrument error to ensure adequate safety margin. Because of the embrittling effects of neutron irradiation, the MPT curve will shift to the right over core life to account for the increased brittleness or decreased ductility. Figure 4 also contains pressurizer and steam generator operating curves. Operating curves may also include surge line and primary coolant pump operating limitations. The MPT relief valve setting prevents exceeding the NDT limit for pressure when the PCS is cold and is set below the lowest limit of the reactor vessel MPT curve.

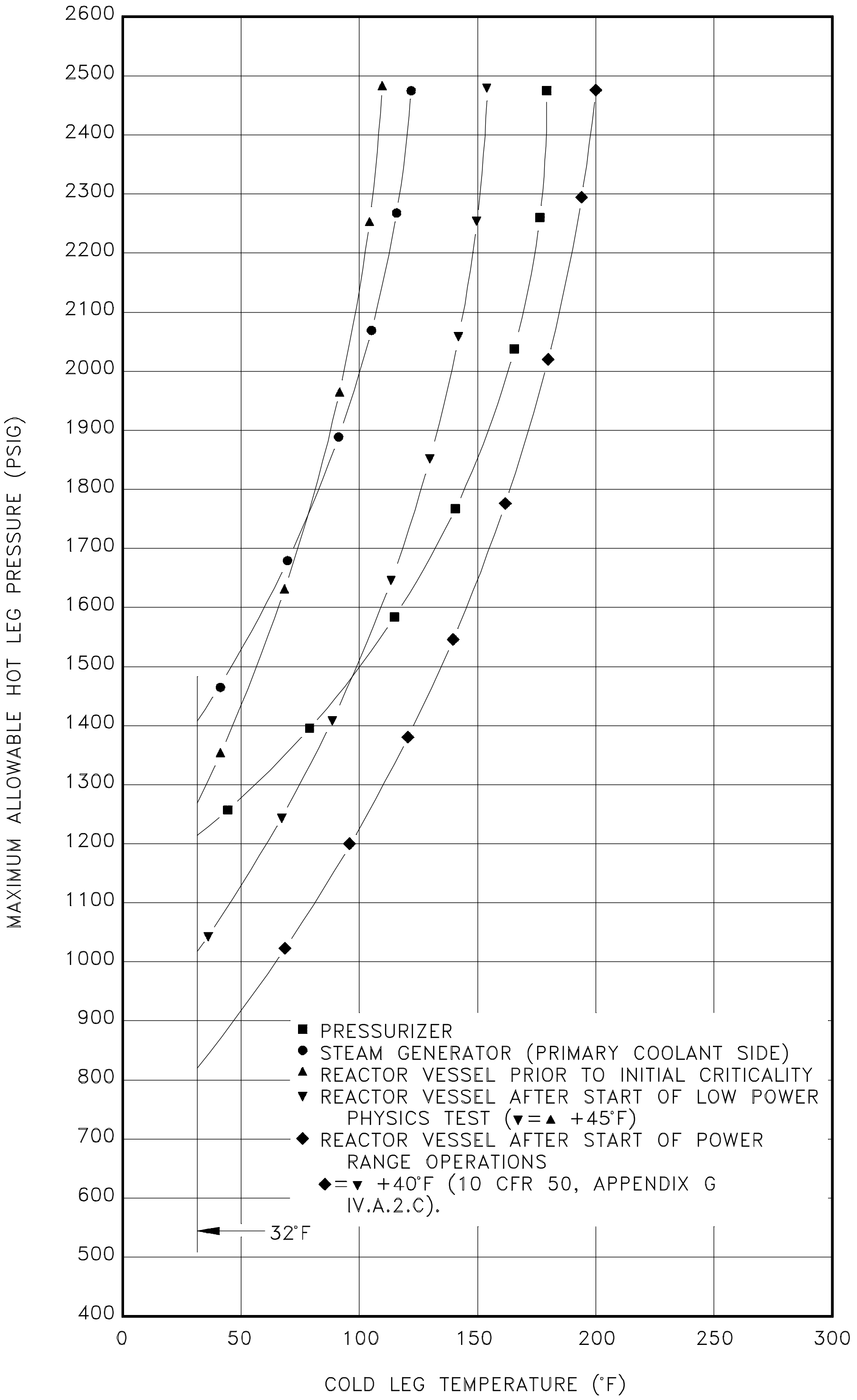

Figure 4 PCS Temperature vs. Pressure for Normal Operation

If the limit of the MPT curve is exceeded during critical operation, the usual action is to scram the reactor, cool down and depressurize the PCS, and conduct an engineering evaluation prior to further plant operation.

During hydrostatic testing, minimum pressurization temperature precautions include making sure that desired hydrostatic pressure is consistent with plant temperatures so that excessive stress does not occur. Figure 5 shows MPT curves for hydrostatic testing of a PWR PCS. The safe operating region is to the right of the MPT curves. Other special hydrostatic limits may also apply during testing.

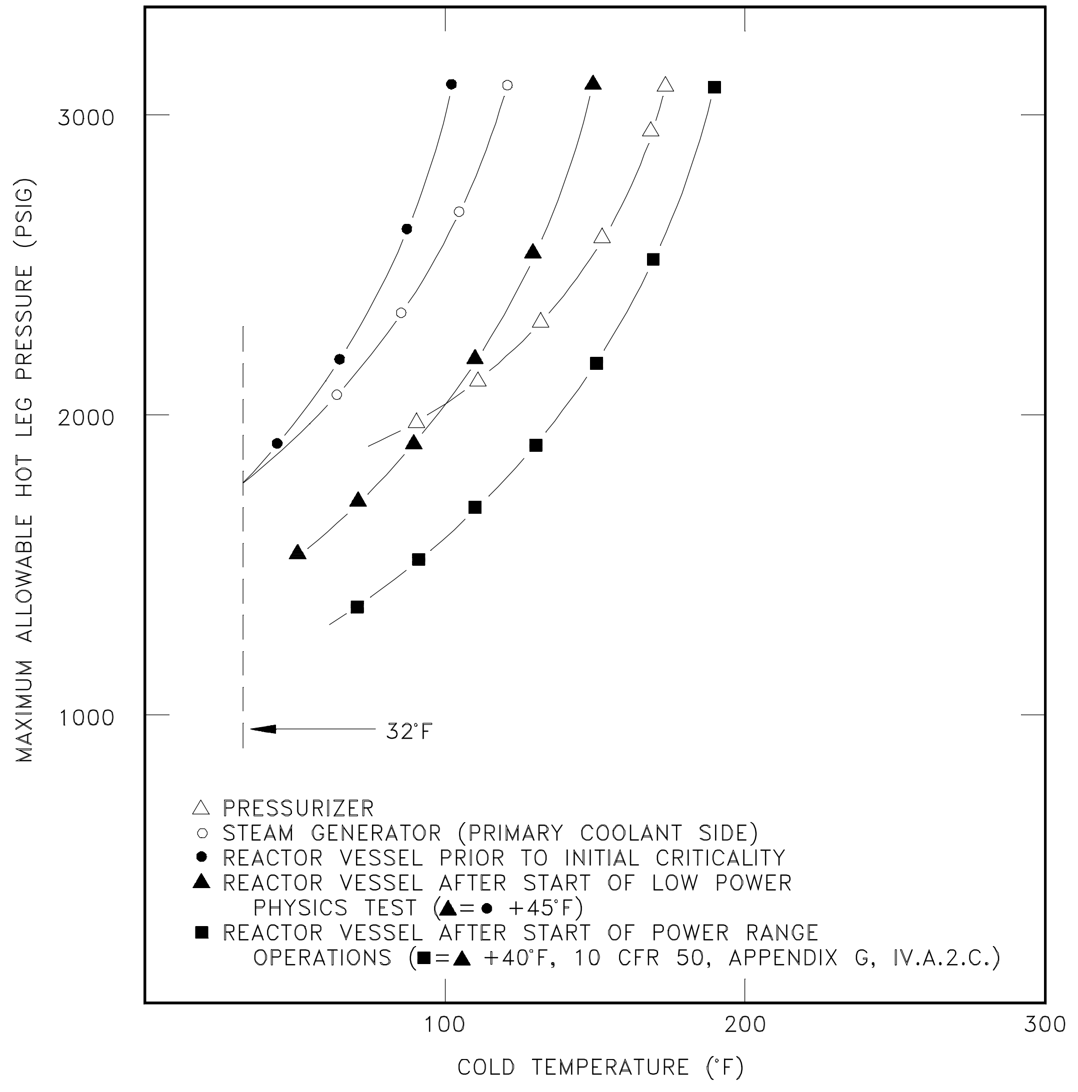

Figure 5 PCS Temperature vs. Hydrotest Pressure

Summary

The important information in this chapter is summarized below.

Minimum Pressurization-Temperature Curves Summary

- MPT curves are based on reactor vessel and head stress limitations, and the need to prevent reactor vessel and head brittle fracture.
- MPT curve safe operating region is to the right of the curve.
- MPT curve will shift to the right due to irradiation.
- Normal actions if MPT curves are exceeded during critical operation are:

  Scram reactor

  Cool down and depressurize

  Conduct engineering evaluation prior to further plant operation

- The precaution to be observed when performing a hydrostatic test is to make sure the pressure is consistent with plant temperatures.

HEATUP AND COOLDOWN RATE LIMITS

Personnel operating a reactor plant must be aware of the heatup and cooldown rates for the system. If personnel exceed these rates, major damage could occur under certain conditions.

EO 1.12 **IDENTIFY the basis used for determining heatup and cooldown rate limits.**

EO 1.13 **IDENTIFY the three components that will set limits on the heatup and cooldown rates.**

EO 1.14 **STATE the action typically taken upon discovering the heatup or cooldown rate has been exceeded.**

EO 1.15 **STATE the reason for using soak times.**

EO 1.16 **STATE when soak times become very significant.**

Basis

Heatup and cooldown rate limits, as shown in Figure 6, are based upon the impact on the future fatigue life of the plant. The heatup and cooldown limits ensure that the plant's fatigue life is equal to or greater than the plant's operational life. Large components such as flanges, the reactor vessel head, and even the reactor vessel itself are the limiting components. Usually the most limiting component will set the heatup and cooldown rates.

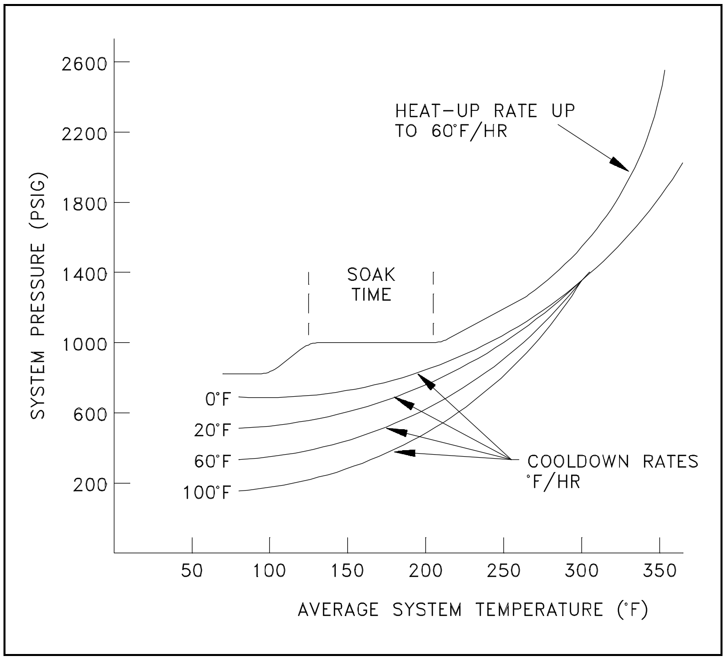

Figure 6 Heatup and Cooldown Rate Limits

Thermal stress imposed by a rapid temperature change (a fast ramp or even a step change) of approximately 20°F (depending upon the plant) is insignificant (10^6 cycles allowed depending upon component) and has no effect on the design life of the plant.

Exceeding Heatup and Cooldown Rates

Usually, exceeding heatup or cooldown limits or other potential operational thermal transient limitations is not an immediate hazard to continued operation and only requires an assessment of the impact on the future fatigue life of the plant. However, this may depend upon the individual plant and its limiting components.

Individual components, such as the pressurizer, may have specific heatup and cooldown limitations that, in most cases, are less restrictive than for the PCS.

Because of the cooldown transient limitations of the PCS, the reactor should be shut down in an orderly manner. Cooldown of the PCS from full operating temperature to 200°F or less requires approximately 24 hours (depending upon cooldown limit rates) as a minimum. Requirements may vary from plant to plant.

Soak Times

Soak times may be required when heating up the PCS, especially when large limiting components are involved in the heatup. Soak times are used so that heating can be carefully controlled. In this manner thermal stresses are minimized. An example of a soak time is to heat the reactor coolant to a specified temperature and to stay at that temperature for a specific time period. This allows the metal in a large component, such as the reactor pressure vessel head, to heat more evenly from the hot side to the cold side, thus limiting the thermal stress across the head. Soak time becomes very significant when the PCS is at room temperature or below and very close to its RT_{NDT} temperature limitations.

Summary

The important information in this chapter is summarized below.

Heatup-Cooldown Rate Limits Summary

- Heatup and cooldown rate limits are based upon impact on the future fatigue life of the plant. The heatup and cooldown rate limits ensure that the plant's fatigue life is equal to or greater than the plant's operational life.
- Large components such as flanges, reactor vessel head, and the vessel itself are the limiting components.
- Usually exceeding the heatup or cooldown rate limits requires only an assessment of the impact on the future fatigue life of the plant.
- Soak times:

  May be required when heating large components

  Used to minimize thermal stresses by controlling the heating rate

  Become very significant if system is at room temperature or below and very close to RT_{NDT} temperature limitations