Low cycle fatigue is associated with significant plastic strains. High cycle fatigue occurs at stresses below the elastic limit (refs. [1] and [2]).

Thermal fatigue cracking has occurred in boiling water reactor (BWR) and pressurized water reactor (PWR) feedwater nozzles. Thermal fatigue cracks have formed in BWR feedwater nozzles due to relatively low-temperature feedwater bypassing the thermal sleeve/sparger configuration in the nozzle to mix with the higher temperature reactor water and cause thermal cycling at the nozzle corner and bore locations (refs. [3] and [4]). Stainless steel cladding on the low alloy steel nozzles amplified this effect due to differences in the coefficient of thermal expansion for the two metals (ref. [4]). In many cases, these small cracks did not penetrate the clad on the reactor vessel nozzles; however, thermal stresses due to start-up, shutdown, and scram cycles could cause these cracks to grow to significant depths (refs. [3] and [4]).

PWR feedwater line cracks have occurred at the pipe-to-nozzle weld counterebore discontinuity, due to the thermal stratification of feedwater flow at low-flow conditions (ref. [5]). Generally, in such cases of incomplete mixing or turbulent flow producing temperature changes (and stresses), higher frequency cycling is effective at crack initiation, as it is more of a surface effect than low-frequency thermal cycling, which is more of a gross wall thickness effect and can grow cracks to more significant depths (ref. [4]). Also, there are a high number of thermal cycles on PWR charging line nozzles with temperature step changes from 100°F to 500°F (38°C to 260°C) and simultaneous pressure transients.

Low-cycle thermal fatigue can be categorized as a series of large temperature changes with significant plastic strains. High-cycle (higher frequency) fatigue is sometimes known as thermal shock, which is associated with rapid temperature changes, such as heat-up followed quickly by cooldown. Thermal striping is an example of this phenomenon (ref. [6]). Fast breeder reactor components are subject to thermal striping as incompletely mixed streams of sodium at different temperatures impinge on a metal surface, as in a liquid sodium mixing tee (refs. [7] and [8]). Thermal striping can also occur in LWR mixing tees with hot and cold water where complete fluid mixing does not occur.

Pressurized thermal shock of PWR reactor vessels, caused by the introduction of cold safety injection water into a relatively hot reactor vessel, is a low-cycle event that can cause fatigue cracking in some postulated cases (refs. [9] and [10]). Large diameter steel pipe, reinforced by stiffening rings and saddle supports, can be subject to thermal fatigue due to system start-up and shutdown. Thermal lag between the pipe and stiffeners and supports can lead to constraint and cracking (ref. [11]). Normal piping expansion and contraction can also lead to an accumulation of thermal stress cycles, when constrained by pipe supports, etc., and should be considered in design.

Thermal stratification within a pipe or in a branch pipe with a closed end can result in temperature differences between the top and bottom of the pipe. Thermal stratification can also lead to thermal fatigue.

In all cases, fatigue damage most often occurs at locations of stress concentration, generally at locations with a change of stiffness. In high cyclic areas, weld caps provide a stress concentration and are often removed for better stress concentration management.

**W-4220 MATERIALS**

Nonbrittle materials are selected to minimize the potential for fatigue cracking in vessels and piping components. Grades of carbon steel, low alloy steel, stainless steel, and nickel-based alloys that are not notch sensitive minimize the potential for crack initiation and propagation.

Fabrication practices should minimize surface roughness, notches, cold work, forming stresses, and weld residual stresses to reduce possible material heterogeneities and “mean stress” effects in fatigue. Avoid discontinuities or crevices, which can act to initiate fatigue cracks. In low alloy steel, sulfur content should be controlled.

**W-4230 DESIGN**

The fatigue analysis design procedure for vessel, piping, and bolting is described in NB-3200, NB-3600, NC-3200, and Mandatory Appendices XIII and XIV. For each alternating stress intensity, $S_{alt}$, the corresponding number of allowable cycles, $N$, is determined from the fatigue curves for the material under consideration (Mandatory Appendix I). The number of cycles specified, $n$, for the design life of the component divided by $N$ is the partial usage factor for each specified load-pair alternating stress. The total cumulative usage factor (CUF) is the sum of the partial usage factors, and this must be less than 1 according to Miner’s rule (ref. [23]). When the material is exposed to an LWR environment, W-2700 also applies.

Design specifications must quantify the bounding thermal, pressure, vibration, and seismic cycles, including consideration of on-off flow cycling of feedwater during hot standby, start-up and cooldown rates, reactor scrams, and stratification in piping (ref. [12]). Heavy-walled flanges and valves may also be susceptible to such thermal gradients when subjected to rapid temperature changes. Usually, components must be on the order of at least 1-in. to 2-in. (25-mm to 50-mm) thick for through-wall stresses to be significant, but stiffening rings and saddles on piping can add constraint and cause significant thermal stresses in even thinner pipes and tees (refs. [1] and [11]). See Nonmandatory Appendix N for cyclic criteria for earthquakes.