DETERMINISTIC AND PROBABILISTIC ANALYSIS OF PWR PRESSURE VESSEL INTEGRITY FOR DIFFERENT TRANSIENT CONDITIONS

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Abstract

In this study, nuclear reactor pressure vessel analysis is performed via deterministic and probabilistic methods for six different transient conditions which may cause pressurized thermal shock. A classical four loop PWR with SA533B type ferritic steel pressure vessel is analyzed. Deterministic analysis is performed for obtaining change in material properties and mechanical state of vessel against temperature and pressure changes. In probabilistic analysis, failure probabilities for vessel beltline region welds are calculated. VISA II computer code is employed for both deterministic and probabilistic analysis.

1. Introduction

Pressure vessel is the most critical component of a nuclear reactor since it contains core, its internals and control mechanisms at high temperature and pressure. Neutron fluence, high pressure, temperature, and stresses arising from these loads are important points concerned in pressure vessel integrity analysis. It is of special importance for pressurized water reactors since they operate at higher pressures and neutron fluxes when compared to boiling water reactors [1,2]. Pressure vessel contains the primary side of the coolant loop. It prevents the release of radioactive substances to environment.

Reactor vessels are designed and manufactured according to strict regulations including the safety margins. The reactor vessel steels are chosen among steels of high fracture toughness, high yield strength and low radiation embrittlement. Therefore, change in material properties must be taken into account in design of vessel.

Since there is no actual failure of pressure vessels, there is no real data for pressure vessel failure, therefore, the probabilistic methods play an important role in analysis as well as deterministic approaches.

There are two types of events which endanger the integrity of pressure vessel; overcooling transients and cold repressurization. Cold repressurization occurs when system pressure is increased significantly at startup. Overcooling transients happen by the injection of cold emergency core cooling system due to break or leak at the primary system. In this study, six overcooling transients are analyzed. These events are; large main steam line break (LMSLB), small main steam line break (SMSLB), loss of heat sink (LOHS), small break LOCA (SBLOCA), large break LOCA of 50 cm^2 (LBLOCA50) and large break LOCA of 200 cm^2 (LBLOCA200) break. Vessel Integrity Simulation Analysis (VISA II) code is employed deterministic and probabilistic calculations.

2. Description of Vessels and Transients

2.1. Reactor Pressure Vessel and Materials

A classical four loop PWR is subjected to our study. Reactor pressure vessel characteristics are presented in Table 1.

Overall hight	13 660 mm
Inside diameter	4394 mm
Wall thickness opposite core	215 mm
Dry weight of pressure vessel	434 800 kg
Normal operating pressure	15.98 MPa
Design pressure	17.13 MPa
Normal operation coolant inlet temperature	288 °C
Normal operation coolant outlet temperature	327 °C

Table 1. Characteristic of PWR reactor pressure vessel

Reactor pressure vessel steels are chosen among high fracture toughness materials. Two common ferritic steels employed in light water reactor vessels are SA508 and SA533B. In this study, SA533B type steel, which is commonly used in newer vessels is employed. The copper, nickel and phosphorus constitutients of SA533B and its weld material are presented in Table 2.

Constitutient (w/o)	*base*	*weld*
Cu	0.14	0.055
Ni	0.58	0.97
P	0.013	0.022

Table 2. Constitutient of PWR base and weld steel

Weld material is important in pressure vessel failure analysis since pressure vessel welds are the most susceptible parts which may lead to vessel rupture. SA508 type vessel steel is composed of circumferentially oriented welds while SA533B type is composed of three circumferential and six axially oriented welds.

Copper, nickel, and phosphorus are the most important elements in pressure vessel steel analysis. Since copper precipitation under irradiation is the most well known embrittlement mechanism, it is of prime importance in fracture toughness and nil ductility temperature prediction. Nickel was added to improve the hardenability of ferritic steels. Moreover, phosphorus content is important in most cases and phosphorus embrittlement mechanism must be analyzed and understood in detail.

2.2. Neutron Fluence

Fast neutron fluence used in the analysis includes neutrons with energies greater than 1 MeV. Neutron fluence in pressurized water reactor is in the 1-10$\times 10^{19}$ neutrons / cm^2 range. In this study, the neutron fluence at inner vessel wall is chosen to be an average value of 4×10^{19} neutrons / cm^2.

Fluence distribution in the vessel wall is modelled by the relation;

$$\phi = \phi_o \times \exp(-0.0945\, x)$$

where x is the depth in centimeters from the inner vessel surface.

2.3 Description of Transients

Small main steam line break transient is characterized by a break of 3.2 cm^2. All component operations and operator actions were assumed to be taken properly to deal with the accident after cold emergency cooling water was injected. Because of the isolation of auxiliary feedwater, the cooling rate becomes lower, and eventually the temperature starts to increase gradually. Large main steam line break transient is similar to small main steam line break at event sequence. The size of the break is 33.6 cm^2. both of the transients occur at full power. Both transients last at the end of 8000 seconds.

Loss of heat sink at full power is characterized as the simultaneous loss main feedwater and auxiliary feedwater. Because of cold emergency cooling water injection, coolant temperature decreased rapidly, but pressure decreased simultaneously by opening the pressurizer relief valve. Transient takes 5500 seconds.

In small break LOCA, the transient happens at full power and transent time is 8000 seconds. The temperature starts to decrease with cold emergency cooling water injection. System pressure decreases rapidly because the coolant flow rate through the break was greater than the charging and emergency cooling water flow rate.

Large break LOCA occurs in the hot leg of primary coolant loop when the reactor is at full power. The size of the break is 50 cm^2. Temperature starts to decrease with cold emergency core cooling water injection. Accumulator tank is employed since pressure decreases to 1 MPa. No significant increase in pressure or temperature is observed since the break is greater than the charging. Transient lasts at the end of 5000 seconds.

In large break LOCA, the size of the break is 200 cm^2. Since discharge rate of coolant is higher, system introduces a sharper decrease in pressure and temperature. Total transient time is 3000 seconds.

Figures 1 and 2 present temperature and pressure histories for main steam line break transients. Figure 3 and 4 presents temperature and pressure histories for loss of heat sink transient. Figure 5 and 6 represents temperature and pressure history of large break LOCA of 50 cm^2 transient. Figure 7 and 8 represents temperature and pressure history of large break LOCA of 200 cm^2 transient.

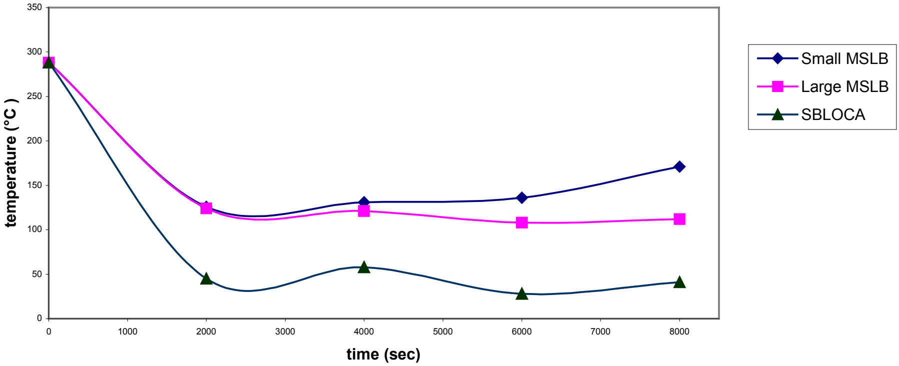

Figure 1 Temperature Histories for Main Steam Line Break and Small Break LOCA Transients

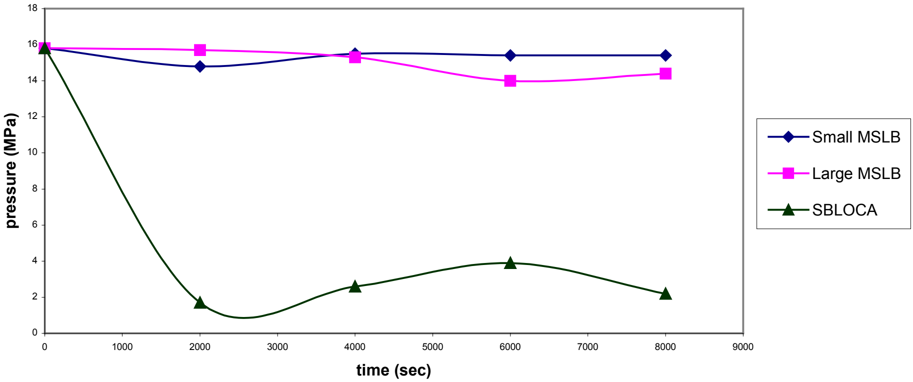

Figure 2 Pressure Histories for Main Steam Line Break Transients

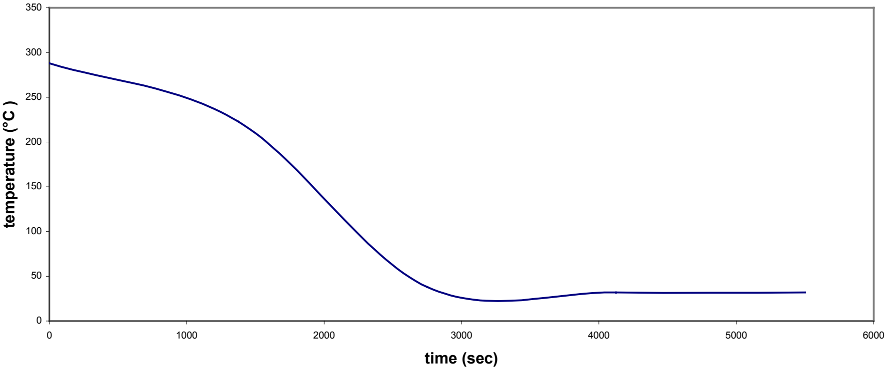

Figure 3 Temperature History for Loss of Heat Sink Transient

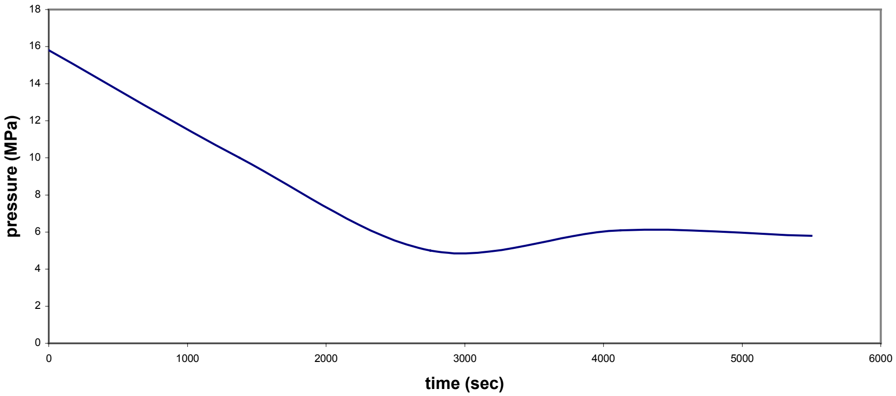

Figure 4 Pressure History for Loss of Heat Sink Transient

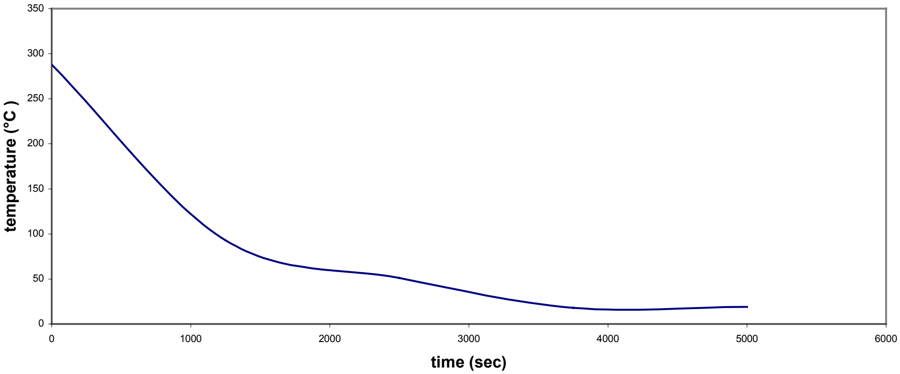

Figure 5 Temperature History for Large Break LOCA Transient (50 cm^2)

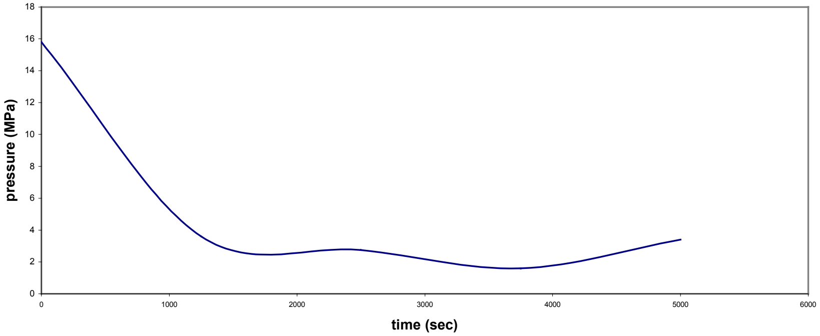

Figure 6 Pressure History for Large Break LOCA (50 cm^2)

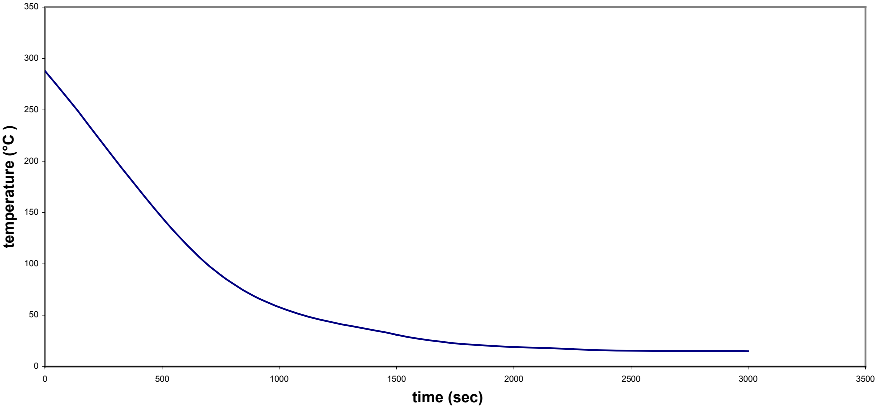

Figure 7 Temperature History for Large Break LOCA Transient (200 cm^2)

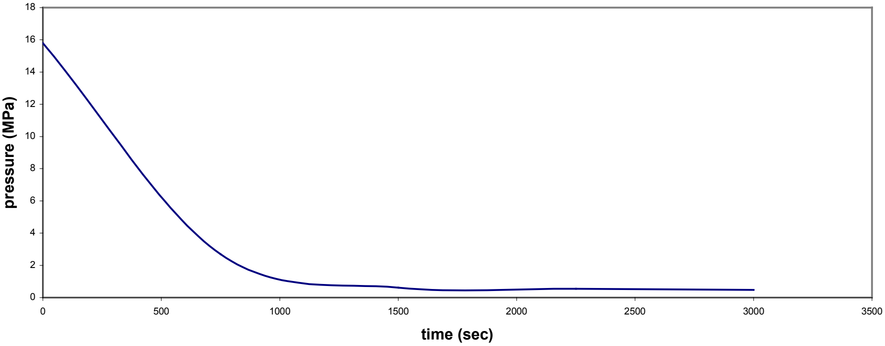

Figure 8 Pressure History for Large Break LOCA Transient (200 cm^2)

3. Analysis

Pressure vessel integrity analysis is composed of deterministic and probabilistic parts.

3.1 Deterministic Analysis

Deterministic analysis is composed of heat transfer analysis and stress analysis. The term ‘fracture mechanics analysis’ includes stress and heat transfer analyses as well as the calculation of crack tip stress intensity factors.

VISA II code calculates crack tip stress intensity factors and the corresponding values of crack tip temperatures, initiation, and arrest toughness values for various crack depths. Stainless steel vessel clad is taken into consideration in calculations. Deterministic analysis provides an input to probabilistic analysis.

In fracture mechanical analysis, linear elastic material behavior is assumed. Linear elastic fracture mechanics (LEFM) is the base approach for calculations. The fracture toughness values are calculated based on copper and nickel content, neutron fluence, and initial value of nil ductility temperature, RT_{NDTO}. The radiation induced shift in RT_{NDT} is calculated employing the USNRC Regulatory Guide 1.99 Revision 2.

In transient analysis, the temperature difference between the inner and outer walls is calculated. During an overcooling transient, the stainless steel cladding at vessel inner wall tends to increase the thermal stresses since thermal expansion coefficient of clad metal is higher than thermal expansion coefficient of vessel base metal. Also thermal conductivity of cladding is lower than that for base metal which intensifies the temperature difference between vessel inner and outer surfaces. Table 3 and Table 4 represent the temperature differences between inner and outer walls at different times of the transient.

As can be seen from Tables 3 and 4, the temperature difference between inner and outer walls reaches the maximum value at the first half of the transient. The vessel wall faces the maximum difference of 176 °C among the other transients. This means that the temperature stress on vessel wall is maximum for loss of heat sink transient. Temperature gradients tend to decrease after the first half of the transient after the ECCS is activated.

Another point to be observed s the positive gradient of fracture toughness due to rapid cooling of the vessel wall. The stress intensity factors for longitudinally and axially oriented flaws are also modelled in this study. Especially longitudinally oriented flaws are of prime concern for pressure vessel analysis since they have a greater contribution to vessel failure.

time	ΔT (°X)	time	ΔT (°X)	time	ΔT (°X)
0.1 T_{SMSLB}	83	0.1 T_{LMSLB}	83	0.1 T_{SBLOCA}	130
0.2 T_{SMSLB}	104	0.2 T_{LMSLB}	105	0.2 T_{SBLOCA}	158
0.3 T_{SMSLB}	88	0.3 T_{LMSLB}	90	0.3 T_{SBLOCA}	127
0.4 T_{SMSLB}	60	0.4 T_{LMSLB}	65	0.4 T_{SBLOCA}	84
0.5 T_{SMSLB}	37	0.5 T_{LMSLB}	43	0.5 T_{SBLOCA}	52
0.6 T_{SMSLB}	21	0.6 T_{LMSLB}	30	0.6 T_{SBLOCA}	38

Table 3. Temperature Difference Between Inner and Outer Vessel Walls for Main Steam Line Break and Small Break LOCA Transients

time	ΔT (°X)	time	ΔT (°X)	time	ΔT (°X)
0.1 T_{LOHS}	-24	0.1 $T_{LBLOCA50}$	91	0.1 $T_{LBLOCA200}$	83
0.2 T_{LOHS}	21	0.2 $T_{LBLOCA50}$	137	0.2 $T_{LBLOCA200}$	142
0.3 T_{LOHS}	92	0.3 $T_{LBLOCA50}$	145	0.3 $T_{LBLOCA200}$	172
0.4 T_{LOHS}	150	0.4 $T_{LBLOCA50}$	134	0.4 $T_{LBLOCA200}$	180
0.5 T_{LOHS}	176	0.5 $T_{LBLOCA50}$	119	0.5 $T_{LBLOCA200}$	163
0.6 T_{LOHS}	165	0.6 $T_{LBLOCA50}$	57	0.6 $T_{LBLOCA200}$	148

Table 4. Temperature Difference Between Inner and Outer Vessel Walls for Large Break LOCA and Loss of Heat Sink Transients

3.2 Probabilistic Analysis

The probabilistic analysis employs Monte Carlo techniques to assess the probability of vessel failure. Generally, Monte Carlo methods are used to determine the probability distribution of a function of random variables. This is accomplished by making a large number of evaluations using different sets of sampled values of the random variables. The sample values are obtained by generating random variables.

For each iteration, the simulated values of initial nil ductility temperature, fluence at the inner vessel wall, flaw size, flaw location, copper content and nickel content are selected from their respective distributions. The simulation of the flaw location includes determination of 1) specific weld, of the many welds in vessel, in which flaw is located, and 2) location of the flaw within the vessel wall thickness. With these results fixed for one iteration, the code steps through the time history of transient. For each time step, the applied stress intensity factor at the crack tip is taken from the stored values from the deterministic portion of the code. The fluence at the crack tip is calculated and the sampled value of fluence at the inner vessel wall of the RPV. The value of the shift in nil ductility temperature is calculated using the sampled copper and nickel values and the attenuated neutron fluence. The value of the shift is added to the sampled initial nil ductility temperature to obtain the adjusted RT_{NDT}. The value of fracture toughness, K_{IC}, is sampled and compared to the applied stress intensity factor at this point. Crack growth initiates if K_{IC} is less than the applied stress intensity factor. I f crack initiation does not occur, the simulation moves to the next time step. If initiation occurs, the crack is extended 0.25 inch and the crack arrest toughness, K_{Ia} is simulated. The mean value of K_{Ia} is calculated using the values of RT_{NDT}, fluence and temperature at the crack tip. If crack arrest occurs, the simulation moves to the next time step; if not, the crack is extended another 0.25 inch and a new value of K_{Ia} is simulated. This process continues until either the vessel fails or transient is completed. Table 5 shows the results of probabilistic analysis.

Transient	P_i	P_f	P_o
SMSLB	1×10^{-4}	1×10^{-4}	1×10^{-8}
LMSLB	1×10^{-4}	1×10^{-4}	1×10^{-8}
LOHS	9.7×10^{-1}	2×10^{-2}	1.9×10^{-3}
SBLOCA	1.8×10^{-1}	4.7×10^{-2}	8.4×10^{-3}
LBLOCA50	5.9×10^{-1}	1.4×10^{-1}	8.2×10^{-2}
LBLOCA200	9×10^{-1}	1.2×10^{-1}	1×10^{-2}

Table 5. Results of Probabilistic Analysis

P_i represents the probability of initiation of a flaw in vessel beltline region weld material where P_f represents the probability of failure of that flaw. The overeall probability, P_O is the failure probability of a vessel weld due to a flaw initiated, which is the product of Pi and P_f. Another point to be considered is that circumferentially and axially oriented flaws on circumerentially and axially oriented welds are modelled in analysis. But the flaws which lead to failure are axially oriented on axial welds of pressure vessel beltline region. Large break LOCA of 50 cm^2 pipe break is the most critical of the transients analyzed for pressure vessel integrity. Large break LOCA of 200 cm^2 and small break LOCA comes after the transient. Since the discharge rate of coolant and addition of cold water from emergency core cooling system is high especially for LOCA transients, the result is not surprising.

Another screening criterion applied in pressure vessel integrity analysis is the shift in nil ductility temperature due to transient. Large Break LOCA of 50 cm^2 causes the highest shift in pressure vessel with 84°C. The shift nil ductility temperature values for four transients are similar. Table 6 presents the shift in nil ductility temperatures for transients analyzed.

Transient	Δ RT$_{NDT}$ (°C)
SMSLB	51
LMSLB	75
LOHS	83
SBLOCA	68
LBLOCA50	84
LBLOCA200	82

Table 6. Shift in Nil Ductility Temperatures due to Transients Analyzed

4. Conclusions

In this study, pressure vessel integrity analysis is carried for a Westinghouse design PWR. The most limiting conditions for pressure vessel are resulted from overcooling of vessel and overpressurization. Six overcooling transients are analyzed in this study, these are; small main steam line break, large main steam line break, loss of heat sink, small break loca, large break loca of 50 cm^2 and large break loca of 200 cm^2 pipe break.

The most susceptible part of pressure vessel against failure is the beltline region where the core is located. In a SA533B forged steel pressure vessel, there exists circumferential and axial welds on the beltline region. The study analyzed the cracks located longitudinally and axially on those welds. The results showed that crack initiation and failure only occurred on axially oriented welds and the cracks were longitudinally oriented.

Pressure vessel integrity analysis is performed by the calculation of shift in nil ductility temperature, the stress distribution on vessel wall, and the probability of initiation of a crack located on vessel beltline region welds to predict the probability of vessel failure. USNRC Reegulatory Guide 1.99 Revision 2 is employed in predicting the shift in RT_{NDT}. The vessel faces the highest shift of 84°C in large break loca transient of 50 cm^2 pipe break. According to the current US regulatory practice, 10 CFR 50.61 Regulatory Guide 1.154, the screening criteria for shift in nil ductility temperature is 149°C for circumferential welds and 132°C for plates and forgins. These temperatures for the pressure vessel analyzed in this study remains below the specified limits in all transient cases.

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