General Electric Advanced Technology Manual

Chapter 4.1

BWR Emergency Core Cooling System Evolution

TABLE OF CONTENTS

4.1 BWR ECCS EVOLUTION

4.1.1 Loss of Coolant Accident (LOCA)

The most severe accident (design basis accident) used for purposes of containment design, is the steam line break. Analyzing breaks in the main steam line covers the effects of all other steam type breaks.

The design basis accident used for the purposes of establishing core performance and cladding integrity is the instantaneous "guillotine" rupture of a recirculation line. Depending on plant design, a break in the suction or discharge line may be the worst case. Break size and location determines how fast pressure will decrease to allow the low pressure injection system to reflood the core. Spectrum analysis performed on a recirculation line break covers the effect of all other type liquid breaks such as the RHR suction and return lines, and recirculation riser lines.

For a given size break, the lower the elevation at which the broken line penetrates the reactor vessel, the greater will be the resultant peak clad temperature (PCT); i.e., PCT will be higher for those lines penetrating the vessel area that contain water than those penetrating the vessel steam space. Thus, to demonstrate the performance and capability of the Emergency Core Cooling System (ECCS), recirculation line breaks were analyzed since those resulted in the highest peak clad temperatures for a given break size.

4.1.2 Pre-LOCA Initial Conditions

In order to calculate the amount of potential fuel damage that could occur during and following a LOCA, a set of initial fuel and core conditions are specified. The values are conservatively chosen to be greater than those expected during normal full power operations. The resultant calculations are used to establish ECCS acceptance criteria. ECCS equipment is subsequently evaluated to determine if individually or collectively they are capable of preventing the plant from exceeding those criteria. Initial conditions include the following:

102% Reactor Power -

A calculated amount of stored heat that is possible to obtain due to the reactor power being at this level for an indefinite period of time. Even though this is unlikely to occur, this power level is used so as to include margins for instrument error.

600^0F Cladding Temperature -
At the time of the LOCA the cladding would be at a temperature near that of the adjacent coolant or approximately 600^0F.

2000^0F UO_2 Average Temperature and 4000^0F Peak Centerline Temperature -

The average temperature and peak centerline temperature are selected as calculated temperatures at the onset of the LOCA. Its realized that the hottest fuel pellets (hotspots) will be well above both of these values.

The excess heat that is contained in the fuel pellets is called stored heat and is approximately proportional to the power density and the thermal resistance of the pellet to clad gap. Stored heat is an important factor because it will significantly contribute to the cladding temperatures during the LOCA scenario.

4.1.3 LOCA Event Sequence

In order to emphasize the potential consequences of a LOCA, the expected sequence of events must be clearly understood. Although the DBA has not occurred at an operating commercial nuclear power plant, the core thermal and hydraulic responses to such an event are well known and predictable. Test facility experimentation was performed during the late 1950's and early 1960's which included the Boiling Water Reactor experiments (BORAX), Experimental Boiling Water Reactor (EBWR), and Special Power Excursion Reactor Test (SPERT).

Also, computer analysis and statistical models including the General Electric Thermal Analysis Basis (GETAB) and the General Electric Critical Quality (X)/Boiling Length (L),(GEXL correlation), provide conservative calculations of critical power and the occurrence of boiling transition within a fuel channel.

The early tests and experiments, and intricate computer codes, analysis, and models, provides credence to the expected reactor response to a LOCA. The sequence of events for such an accident is described as follows:

Fission heat drops rapidly - This occurs due to rapid void formation and the reactor scram

Clad cooling decreases - Core flow decreases suddenly when recirculation pumps trip. Also, moderator density is reduced as the bulk coolant flashes to steam and blankets the outside of the clad surface.

Pellet temperatures equalize - Fuel pellet centerline temperature initially decreases as fission heat production drops and stored heat is removed by the steam-water mixture produced during the blowdown phase.

Pellet temperatures begin increasing - Decay heat provides a continued source of heat which can no longer be removed when vessel blowdown is completed.

Zircaloy oxidation - If the cladding temperature exceeds 1800^{0}F, oxidation will occur. The chemical process adds additional heat to the cladding and also causes pellet temperatures to increase.

Pellet temperature increases until reflood begins - As vessel reflood commences, much of the water flashes to steam. It is the steam in combination with entrained water droplets that provides initial cooling of the core. As reflood continues, sufficient cooling is provided to overcome the heat inputs from the decay of fission products and cladding oxidation.

Clad heatup is terminated - Continued injection of coolant by the ECCS will eventually cover the core with water.

4.1.4 Cladding Failure Mechanisms

In order to maintain the integrity of the fuel rods, cladding ductility must be maintained. Metallurgical and chemical changes will affect ductility.

Zirconium has two different metallurgical crystal structures including the alpha phase and the beta phase. At room temperatures zirconium is in the alpha phase which is a brittle crystal structure. When heated above 1150^{0}F, the crystal structure undergoes a change and is transformed into the beta phase which is ductile. However, if the zirconium cladding oxidizes, even though its temperature is above 1150^{0}F, the crystal structure is in the alpha phase and becomes brittle.

Oxidation of the cladding is a chemical event that occurs due to a steam oxidation process and is normally referred to as a metal-water reaction. Water molecules are absorbed on the surface of the cladding and disassociate to hydrogen and hydroxyl radicals at high temperatures. Within the surface of the cladding the hydroxyl radicals, after several chemical steps, are converted into oxygen ions and hydrogen atoms. The hydrogen atoms, wherever formed, will combine into hydrogen molecules and escape from the surface of the cladding. The oxygen ions however, diffuse further into the surface and are dissolved into the metal. As this reaction continues and if the concentration of oxygen is high enough, zirconium dioxide is formed. This oxidation process takes place between 2060 and 2960^{0}F. The formation of zirconium dioxide causes this area of the cladding to become brittle and the loss of ductility of this metal may cause the fuel rods to burst upon quenching. The thickness and the rate of oxidation is temperature dependent.

4.1.5 ECCS Criteria Development

4.1.5.1 Initial ECCS Criteria

The original standard for the BWR ECCS was developed as a result of lengthy discussions and agreements between the General Electric Company (GE), Westinghouse (W) and the Atomic Energy Commission (AEC). That standard established the first ECCS criteria listed below:

- Peak cladding temperature - 2700^{0}F

- Two independent and separate physical means for ensuring adequate core cooling following a LOCA (e.g. spray and flooding)

4.1.5.2 Interim ECCS Criteria

On June 29, 1971, the AEC published the interim criteria for immediate implementation. The vendors were allowed a reasonable amount of time to compile data and comments concerning those criteria prior to commencing public hearings which would establish the final ECCS acceptance criteria. Those interim criteria provided the basis for reasonable assurance that the ECCS would effectively limit core damage in the highly unlikely event of a LOCA. The interim criteria consisted of the following:

- Peak Cladding Temperature - 2300^{0}F

- Maximum hydrogen generation - The calculated total amount of hydrogen generated from the chemical reaction of the cladding with water or steam shall not exceed .01 times the hypothetical amount that would be generated if all the cladding were to react.

- Coolable geometry - The calculated changes in core geometry shall be such that the core remains amenable to cooling.

- Long Term Cooling - After any calculated initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and the decay heat shall be removed for an extended period of time.

Additionally, single failures resulting in complete loss of the Low Pressure Coolant Injection (LPCI) System was required to be considered in the accident sequence and analyses.

4.1.5.3 Final ECCS Acceptance Criteria

Public hearings commenced early in 1972 for the purpose of assisting the AEC in its determination as to whether or not the Interim Criteria should be retained as issued or if those criteria should be adopted in some other form. Participation in the hearings was extensive. In attendance were members of the AEC, three states, four reactor vendors, a consolidated group of electric utility companies, interveners, and other interested parties and individuals. The hearings lasted a total of 125 days and generated more than 22,000 pages of transcript.

After all documentation was submitted and testimonies heard, the AEC made its decisions and the final acceptance criteria were published December 28, 1973. Some of the criteria were highly contested by the vendors and utility groups. Those arguments and the basis for the criteria will be discussed later. In 1974, the final criteria were added as paragraph 50.46 of 10 CFR 50.

Interim criterion number one, specifying that the temperature of the Zircaloy cladding should not exceed 2300^0F, was replaced by the first two criteria listed below. The other three criteria were retained with some modification of the wording. Single failure consideration continued to be required. The final criterion and the basis of each are as follows:

Peak Cladding Temperature - 2200^0F Basis

This criteria and the one which follows (17% clad oxidation) are closely interrelated and together ensure that the zircaloy cladding will remain sufficiently intact to retain the UO_2 fuel pellets in their separate fuel rods and therefore remain in an easily coolable array. Conservative calculations indicate that the cladding will swell and burst in a longitudinal split but will retain the fuel pellets provided that the cladding is not too heavily oxidized.

Maximum Cladding Oxidation - 17% of the total cladding thickness before oxidation.

Same as Basis given above.

Maximum Hydrogen Generation - 1% of the hypothetical amount that would be generated if all the cladding were to undergo a zirconium-water reaction. Basis

This criteria ensures that hydrogen will not be generated in amounts that could lead to explosive concentrations. This criteria is the same as the interim acceptance criteria with the exception that it is more explicit in detailing how much of the

Zircaloy is to be used as the bases for the 1% hydrogen calculation.

Coolable Geometry Basis

Calculated changes in core geometry shall be such that the core remains amenable to cooling.

Long Term Cooling Basis

After any calculated initial operation of the ECCS, the calculated core temperature shall be maintained at an acceptably low value and the decay heat shall be removed for an extended period of time.

The long term maintenance of cooling is considered from the time the cladding is cooled to 300^0F or less. The intent of this criteria is self-evident.

4.1.5.4 Appendix K

In 1974, a new Appendix K titled "Appendix K- ECCS Evaluation Models," was added to 10 CFR Part 50. Appendix K provides guidelines for the ECCS evaluation models. Some highlights of this appendix include:

- Gives the terms and assumed values that are to be used in the ECCS design evaluations. When computer calculations are performed to evaluate the effectiveness of the ECCS and maximum temperatures in the core, the following conservative values are used:

    - Stored heat - assumes that the reactor was at 102% for an indefinite period of time with the highest peaking factors.

    - Blow down - heat transfer during blowdown is made in the conservative direction. It is probable that this factor has a conservatism of several hundred degrees Fahrenheit.

    - Heat generation rate - it is assumed that the heat generation rate from the decay of fission products is 20% greater than proposed by ANS standards. This figure is used due to operating at 102% of rated power for an infinite time which represents an improbable situation.

    - Peak temperature criteria - limitation of the peak calculated temperature of the cladding (2200^0F) is applied to the hottest-region of the hottest fuel rods. This provides a substantial degree of conservatism to ensure that the core will suffer a very limited amount of core damage due to a LOCA.

- ECCS single failure criteria. These calculations also have to assume the most damaging single failure of the ECCS component or subsystem.

- Addresses reflood and refill rates of less than 1 inch per second i.e., if the reflood/refill rate drops to less than 1 inch per second, then the calculations must assume that the cooling of the core is by steam alone. This is very conservative because the water splatter carryover that will be entrained in the steam will remove heat from the cladding but is not used in the calculations.

Many years have passed since Appendix K was implemented. Calculations have been revised as a direct result of obtaining better data through research and development programs performed by NRC and private industry. Recent calculations have established that the maximum fuel clad temperatures reached during a LOCA will be approximately 900^0F less than the older calculated value of 2200^0F. This added margin of safety has resulted in the reduction of many restrictions in the areas of fuel operating temperatures, surveillance testing frequencies, and permissible "down times" for safety-related equipment for testing and maintenance. These changes should result in increased reactor availability and more efficient fuel burn up.

4.1.6 Meeting Changing ECCS Criteria

The initial criteria was met by an ECCS consisting of two 100% core spray (C.S.) systems and one low pressure coolant injection (LPCI) System. Original data and calculations proved that the C.S. System could by itself, terminate post accident heatup by spray action alone. Core spray or LPCI could successfully meet the peak cladding temperatures (PCT) for all large line breaks.

When the interim criteria were established, initial calculations indicated that PCT could not be maintained less than 2300^0F. Several factors contributing to the inadequacy of the ECCS included:

- Establishment of the single failure criteria - the single worst failure was determined to be a failure within the LPCI system. The LPCI system included a LPCI loop selection logic that prevented opening of the injection valve supplying the "broken" recirculation loop and opened the injection valve which supplied the "good" loop thus supplying water from both divisions of LPCI. Failure of the injection valve supplying the "good" recirculation loop to open would render inoperable the entire LPCI System.

- The C.S. System was judged incapable of meeting the new PCT requirements by itself. This was due to the existing 7X7 fuel design and C.S. system test results that indicated counter current flow limiting effects and questionable spray behavior in a steam environment.

The reactor vendor and owners groups established several possible methods for meeting the interim criteria. Possible alternatives included:

- Redesign the LPCI and C.S. Systems in order to take credit for both spray and flooding.
- Redesign the fuel to limit power production by the fuel pellets.
- Take credit for water accumulation and the eventual flooding capability of the C.S. System.
- Limit PCT by limiting MAPLHGR.

A reanalysis was performed using the last two alternatives listed above and the results indicated that either the C.S. or LPCI systems could prevent PCT from exceeding 2300°F for all large pipe breaks. However, with LPCI unavailable, the C.S. System would be required to provide both spray and flooding. The flooding capability was accomplished by drilling holes in the lower core plates.

In core instrument tube vibrations on BWR/4 plants required plugging of the bypass flow holes in the lower core plate. Those holes provided part of the design core bypass flow (10%). The bypass holes also allowed the core spray water to accumulate in the bypass region to reflood the bottom head volume and then the fuel. Plugging the holes resulted in a reduction in the core sprays ability to reflood the core and maintain PCT below the specified limit. This new problem meant that on high power density cores the core spray system could not meet the final 2200°F criteria without severe MAPLHGR restrictions. This prompted General Electric to restore the bypass flow by drilling holes in the lower tie plate of the fuel assemblies.

The final acceptance criteria further restricted the maximum PCT to 2200°F. This limit made discharge pipe breaks more severe for certain vessel geometries. Also, because the LPCI System was assumed to be unavailable for those breaks, it was determined that the C.S. System may not prevent exceeding the PCT criteria in high power density cores even with combined spray and flooding capability.

Rather than placing further limits on MAPLHGR, the final acceptance criteria was met by a combination of design and physical plant changes. Those changes involved substantial changes to the LPCI System including removal of the LPCI Loop Selection Logic, permanent closure or removal of the LPCI pumps discharge lines Division I and II crossconnect valve, and total separation and independency of the two divisions.

Completing the modifications to the LPCI System provided assurance that the C.S. System in combination with all or one of the two divisions of LPCI would meet all of the new ECCS criteria for all size pipe breaks. Later development of the 8 X 8 fuel assemblies reduced MAPLHGR, thus also contributing to the margin of safety during the LOCA.

4.1.7 Vendors Response to the Final Acceptance Criteria

None of the reactor manufacturers or owners groups agreed with the Staffs proposal of 2200^0F maximum cladding temperature. Westinghouse proposed a calculated temperature of 2700^0F. Combustion Engineering and the utility group agreed on a calculated temperature of 2500^0F because much of the data on oxidation and its effects stops at less than 2500^0F. B&W suggested a more conservative figure of 2400^0F because excessive metal- water reaction rates would be precluded below 2400^0F. GE disagreed with the staff's position of 2200^0F and stated that 2700^0F was acceptable as far as embrittlement of the cladding was concerned and suggested that the interim criteria of 2300^0F be retained to ensure that the core never gets into regions of metal-water reactions. Since the owners groups did not agree with each other and all had different calculated temperatures, the staff chose to retain its proposed value of 2200^0F.

All owner groups essentially agreed on the oxidation limit of 17%. However, they had recommended that a more conservative limit of 12% be used to avoid brittle behavior of the cladding. It should be understood that the 12% value was to be used with a calculated higher cladding temperature than that proposed by the AEC staff.

The maximum hydrogen generation criteria was misunderstood by some of the vendors and their analysis. This criteria has nothing to do with oxidation or the need to retain the strength of the cladding.

Combustion Engineering and Babcock & Wilcox argued that a coolable geometry criteria was no longer necessary because the peak cladding temperature and oxidation criterion would ensure adequate fuel rod integrity. The AEC agreed with the vendors. However, the Commission felt that in view of the fundamental and historical importance of maintaining core coolability, they desired to retain this criteria as a basic objective.

The long term cooling criteria is the same as the interim criteria. No arguments were presented by the vendors in this area.

4.1.8 Summary

The Commission believes the implementation of the new regulations will ensure an adequate margin of performance of the ECCS should a design LOCA ever occur. This margin is provided by conservative features of the evaluation models and by the criteria themselves.