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HEATUP OF STEAM GENERATOR TUBES DURING SEVERE ACCIDENTS

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Abstract

Rupture of steam generator tubes during severe accidents in pressurized water reactors (PWR's) can lead to direct release of radioactive materials into the environment, bypassing the containment. Using the computer code MAAP4.0, a number of accident sequences, all being variations of a station blackout accident with no recovery actions taken, have been investigated for a PWR with parameters similar to the Zion nuclear plant. These include cases with steam generator tube leak, with failure of pump seals shaft, with main steam isolation line break (MSLB), as well as with combinations of the above. It is shown in all cases that the hot leg pipe fails, precluding rupture of steam generator tubes. Increased heating of the tubes is noted in cases with tube leak, and is attributed to the effect of steam flow through the leak. MSLB with or without tube leak is also found to be conducive to increased tube heating because of reduced heat transfer to the steam generator shells. The margin for having hot leg to fail before the steam generator tubes is presented in terms of the temperature of the latter when hot leg fails and uncertainties in failure temperatures. A study of cesium iodide transport indicates no significant release to the environment in all realistic cases considered.

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1. Introduction

It has recently been suggested (Ref.1) within the Nuclear Regulatory Commission that leakage in steam generator tubes during normal operation of pressurized water reactors (PWR) can potentially increase during severe accidents. The resultant containment bypass can cause early release of large quantities of radionuclides into the environment. If true, Probabilistic Risk Assessments for PWR's might have to be revised.

The conclusion in Ref.1 is based on an analysis of steam flows through a hot leg pipe during a high pressure accident sequence such as a station blackout. Such steam flows are driven either by natural circulation or by forced convection through the leak in the steam generator tubes. Starting with the pipe at low temperature, high temperature steam is forced through the pipe at a constant rate, transfering heat to the pipe. The pipe heats up and the exit temperature of steam increases. It is shown that the exit temperature increases more rapidly in time when the flow rate is increased. The exit temperature is expected to be close to the temperature of the steam generator tubes, and the flow rate is expected to be increased by cracks in the steam generator tubes. The conclusion is thus made that tube leak can lead to increased tube heating and thus the potential for catastrophic tube failure. This potential is enhanced if the secondary side of the steam generator has depressurized, such as can occur when the relief valves are stuck-open, or a main steam line break (MSLB) has occurred. Earlier work (Ref.2) on station blackout in the Surry plant has predicted the surge line to be the first component of the reactor coolant system (RCS) to fail. By diverting steam flow away from the surge line and into the steam generator tubes, the leak can slow the temperature rise in the surge line and prevent its failure before that of the tubes.

The analysis in Ref.1 does not discuss failure of the hot leg pipes. It also relies on assumptions on the conditions of the superheated steam such as temperature, pressure and flow rates. Being a scoping study, it does not take into account the many complex thermal-hydraulic phenomena occuring in a realistic power plant. The present study is initiated by the desire to investigate the proposed mechanism through an integrated analysis.

As noted earlier, similar integrated analysis without tube leak has been performed in the past. The effect of steam flow on heatup of primary system pipings is also well-recognized. In fact, an early study on the Bellefonte nuclear plant (Ref.3) suggests that the temperature of the tubes can exceed that of the hot leg if the loop seals clear of water, so that hot gas from the core can flow into the tubes more easily. On the other hand, the same reference also shows that clearing of the loop seals does not occur if the reactor coolant pump shaft seals have failed. It is obvious that increased heating of steam generator tubes can occur under many different circumstances. Thus, the scope of the study is broadened to include such conceivable circumstances, even the ones with no tube leak.

The tool used for the present study is the computer code MAAP4.0 (Ref.4). Using this code, a number of accident sequences have been analyzed, all being variations of a basic station blackout accident with no recovery actions occuring in a fictitious plant with parameters similar to the Zion plant.

In the next section, the modeling capability of MAAP4.0 relevant to the present study is discussed. The results, preceded by an overview, are presented in section 3. Section 4 contains the conclusions and suggestions for future work.

2. Modeling

The calculations described in this report are performed using the computer code MAAP4.0. MAAP4.0 simulates severe accidents in light water reactors, modeling phenomena occuring in the core, primary system, containment, and engineered safeguard systems. It describes both the thermal-hydraulics of the system and the transport of fission products. In comparison with its predecessor MAAP3.0B, MAAP4.0 provides a more detailed description of core degradation, and incorporates mechanistic models for the failure of the RCS. This last capability is particularly pertinent to the present study, which addresses the manner by which the RCS is expected to fail during a high pressure accident sequence.

The basic approach of MAAP4.0 is to partition the reactor system into control volumes, or nodes, and solve the mass and energy equations in each node. The core is divided into a number of radial rings composed of fuel and control rod materials, which generate decay heat and undergo chemical reactions such as cladding oxidation. Core materials can also melt and relocate to various regions of the reactor system. Although the detailed behavior of the core has a large influence on the accident progression, only the early phase of core degradation, which terminates shortly after cladding oxidation, is of concern to the present study. This is because, for the cases considered, very large temperature rise in the structures leading to RCS failure takes place during this period in a station blackout sequence. To study the temperature rise during this period, when the core is fully uncovered, focus is on the mass and energy transfer carried out by the coolant vapor to various parts of the primary system as well as the steam generators and the containment.

For the computation of mass and energy transport by the coolant vapors and noncondensibles, the primary system of a PWR is nodalized into 14 volumes as shown in Fig.1, plus the quench tank. The reactor pressure vessel (RPV) is divided into the four regions consisting of the downcomer, core, upper plenum, and dome. For the particular reactor system being considered in this study, which is a Zion-like plant with four steam generator loops, the loop connected to the pressurizer is termed the "broken" loop, while the other three loops are lumped together and termed the "unbroken" loop. Each loop is divided into five regions, which are the hot leg, the steam generator hot tubes (the part of the U-tubes connected to the inlet plenum), the cold tubes (the other part of the U-tubes), the intermediate leg, and the cold leg.

From a fully uncovered core, decay and oxidation energies are transferred to the vapor by (1) upward steam flow from steaming in the bottom part of the core and the lower plenum and (2) natural circulation set up in the core region because of radial power peaking. Once in the vapor, energy is transferred to various regions of the primary system by flows driven by minute pressure gradients. Under the right circumstances, energy is also exchanged between (1) the upper plenum and the hot legs by counter-current flow in the hot legs, and (2) the hot legs and the steam generator tubes by natural circulation which goes out through one set of steam generator tubes and returns through another set. Energy is removed from the primary system gas by (1) flow through safety valves in the pressurizer, (2) breaks in the primary system such as from pump seal failure if applicable, and (3) heat transfer to various structures.

Structures in the primary system, such as walls and pipes, are modeled as two-dimensional heat sinks. Hot leg pipes are nodalized into an upper part and a lower part to allow for the occurrence of counter-current flow. Both the surge line and the steam generator hot tubes are described by single nodes. Within the structure, heat transfer is by conduction, while across the interface with gases, heat transfer is by natural or forced convection and radiation. An important heat sink for the primary system gas during this phase of the accident is represented by the heat transfer path connecting the gas to the steam generator tubes, the gas on the secondary side of the steam generators, and finally to the steam generator shells. The interface heat transfer for this path is natural convection, which increases with the pressure of the gas. Heat loss from exposed structures through insulation to the environment is minimal, but is modeled by the code.

At high temperatures, the hot leg pipes, the surge lines, and the steam generator tubes are subject to creep rupture. Creep rupture in MAAP4.0 is modeled using a modified Larson-Miller approach which also incorporates yield stress. The material for the hot leg pipes and the surge line is a type of carbon steel while that for the steam generator tubes is stainless steel. Creep rupture of RPV in the lower head region is also modeled, but it occurs much later in the accident sequence, and is not of concern in the present study.

Finally, MAAP4.0 has an integrated model of fission product transport that separates the fission products into twelve groups and allows them to exist as gases and aerosols. Fission products which settle on heat sinks can directly heat these structures.

3. Results

3 - 1. Overview

To study the possibility of rupture of steam generator tubes during high pressure accident sequences, eight accident scenarios have been investigated using MAAP4.0. As listed in Table 1, which gives a brief description of the scenarios and the timing of key events, these scenarios are all variations of the station blackout sequence. They are chosen either because their occurrence is likely, or because they are expected to cause high temperatures for the steam generator tubes. The eight sequences are composed of two equal groups, corresponding to having intact or leaky steam generator tubes.

Among the group with intact tubes, Case 1 is a base case. The accident is initiated by failure of off-site and on-site power, and none of the ECCS components requiring power to operate can function. This case is used to illustrate the basic phenomena which are encountered in all other cases, and to provide results against which other cases can be compared. In Case 2, a pump seal failure is assumed to occur early in a station blackout sequence, leading to a loss of coolant. Pump seal failure is considered likely as piping temperature increases for lack of coolant circulation during station blackout. In Case 3, MSLB is assumed to occur in the steam generator loop containing the pressurizer at the beginning of the station blackout sequence. This case is considered because it has been suggested that depressurization of the secondary side of the steam generator might be conducive to rupture of steam generator tubes. In Case 4, pump seal LOCA and MSLB are combined together to see if there is any enhancement of individual effects.

Cases 5 through 8 pertain to plants with leaky steam generator tubes. Concern has been expressed that small leaks in steam generator tubes might be enlarged due to increased heating of the tubes during a high pressure accident sequence. The increased heating is supposed to result from the diversion of superheated steam in the hot leg region from the surge line to the leaking steam generator tubes. This can be called a flow diversion effect. Cases 5 and 6 are variations of Case 1 with tube leaks of different sizes. In reality, leaks are in the form of small cracks in the steam generator tubes which can number in the hundreds. In using MAAP4.0 to simulate tube leak, a single break area is specified. The significance of the area lies in the water and steam flows predicted by the code according to the break flow model. Thus, in Case 5, in which the break area is about a quarter of the area of a single tube, the predicted steam flow during the period when the primary system pipings heat up by an uncovered core amounts to 355 GPM, which is in the middle of the range considered in Reference 1. In Case 6, the leak size is increased to that of the cross-section of a single tube for the purpose of studying size dependence. Case 7 combines a " -tube" leak with pump seal LOCA, while Case 8 combines it with MSLB.

The primary objective of the study is to determine if the steam generator tubes would fail catastrophically in the sequences being considered. This objective is straightforwardly achieved because the code incorporates failure models of the RCS which indicates which component of the RCS would fail as the accident progresses. The result is that steam generator tubes are not predicted to fail in all cases. In fact, the hot leg pipe in one of the loops is always predicted to be the first component of the RCS to fail, and its failure precludes that of the steam generator tubes because the primary system is then depressurized. Table 1, which will again be referred to later, gives the time when hot leg rupture occurs. Table 2 gives the temperature of the upper part of the hot leg and the primary system pressure at the time of hot leg rupture. It can be seen that high temperature correlates with low pressure. This can be explained by the fact that the strength of materials, both in terms of yield stress and resistance to creep, is a decreasing function of temperature. Table 2 also gives the temperature of the hot tubes at the time of hot leg rupture, as an indication of the margin for tube failure to occur before hot leg failure.

The second objective is to determine which scenario comes closest to rupturing the steam generator tubes before the hot leg and to understand the underlying thermal-hydraulic reasons. Achieving such an understanding leads to more confidence in the predictions of the code. More importantly, the identification of contributing mechanisms suggests areas to which future work should be directed for improving the predictions.

The methodology used to achieve the second objective is to deduce causal relations through examination of the timing of important events, temperature histories of various components, and steam flows within and out of the primary system, etc. Structure heating is significant only after the core has uncovered, and is intimately connected to the circulation of superheated steam within the primary system. As the accident progresses to the point where core melting and relocation occur, code prediction becomes less reliable owing to the complexity of the phenomena. Attention is therefore focused on the period of time when the core is largely uncovered while cladding oxidation remains insignificant so that little core damage has occurred. This period, which will be referred to as the period of preoxidation heatup, is taken to begin when of the active fuel rods become uncovered and to end when the maximum cladding temperature reaches . Heating rates of structures and distribution of steam flows are examined in this period to uncover the responsible mechanisms. The main results of these heating rates are contained in Table 3, which will be referred to as the individual cases are discussed in the following. The table gives the rate of temperature rise of the hottest part of the core and the upper part of the "broken" hot leg. It also gives the ratios of the heating rates of the surge line and the steam generator hot tubes in the " broken" loop to the heating rate of the hot leg in the same loop. With the base case as a reference, the last ratio is a measure of the increased heating of the hot tubes relative to the hot leg in the various scenarios.

Large uncertainties are incurred in predicting catastrophic failure of RCS components such as hot leg, surge line and steam generator tubes, not only because of intrinsic modeling difficulties but also because of variations from plant to plant in the physical conditions of the components. To address these uncertainties, in doing calculations for the eight cases with MAAP4.0, the failure model in the code is intentionally suppressed by assigning zero area to the primary system break when component failure is predicted. Next, the observation is made that both the hot leg and the steam generator tubes are predicted to fail at about . This value then represents a reasonable average failure temperature predicted by the code for the accident sequences being considered. Then, an uncertainty value is defined such that, if the hot leg were to fail at this value above and the steam generator tubes were to fail at the same value below , the two components would fail at the same time. This temperature value, which is listed in Table 4, is a measure of the tolerance which allows the conclusion of hot leg failure to remain valid. It also provides a measure of the margin available to compensate for modeling errors or neglected effects such as tube corrosion. The other temperature difference listed Table 4 will be discussed in the subsection dealing with uncertainties.

The release of fission products might be considered to be the ultimate goal of an analysis of severe accidents. The concern which drives the present work is whether release directly into the environment might be large as a result of steam generator tube leaks and their enlargement. The conclusion that a hot leg is always the first RCS component to fail indicates that most of the release is into the containment. This fact is verified by rerunning the accident sequences of Cases 1 and 8, and allowing the hot leg to rupture when it is predicted to occur. The distribution of cesium iodide among the primary system, the containment, and the environment is determined until the time of vessel failure. As a variation, a hypothetical case is also considered in which hot leg rupture is suppressed in Case 8 but steam generator tube rupture is allowed to happen when it is predicted. The resulting release to the environment is large. Non-negligible release to the environment also occurs through the steam generator leak alone without catastrophic failure if the leak is as large as the one assumed in Case 6 and a MSLB has occurred.

3 - 2. Cases with Intact Steam Generator Tubes

3 - 2 - 1. Case 1: Base Case

A station blackout sequence in a PWR is initiated by a complete loss of off-site power and a failure of the diesel generators to supply on-site power. For simplicity, an immediate failure of the turbine-driven auxiliary feedwater pump is also assumed. As a result, the main coolant pumps and the feedwater pumps coast down, and auxiliary feedwater pumps cannot be operated. In addition, the main steam isolation valve (MSIV) is assumed to be closed and reactor scram is assumed to occur. Almost immediately, the stored heat in the core is transferred to the coolant, which in turn delivers it to the saturated water on the secondary side of the steam generators. The boiling of the steam generator water with the MSIV closed raises the pressure in the steam generator to the setpoint of the relief valves in about minutes. From this time on, the pressure stays near the setpoint of MPa as shown in Fig.2, with water inventory in the steam generators depleting through the relief valves as it absorbs decay heat from the core. The steam generators become dry at min. into the accident as shown by the water level plotted in Fig.3.

In the RPV, the temperature of water rises under the influence of decay heat from the core as shown in Fig.4. Expanding into the pressurizer, the primary system water pushes up the water level and compresses the gas in the pressurizer. Water level in the pressurizer is shown in Fig. 5. With no pressurizer spray available, the compression causes the primary system pressure to increase as shown in Fig.2. The process of heating and pressurization accelerates as heat transfer to the secondary side of the steam generator is reduced by the falling water level in the steam generator. At min., the safety valves in the pressurizer open and continue to cycle at their setpoint pressure of MPa.

Primary system water inventory begins to deplete through the safety valves. At first, only steam in the pressurizer is forced through the safety valves. Then at min., as can be seen from the pressurizer water level in Fig.5, the pressurizer becomes filled with water, which then flows out of the safety valves. The flow rates of water and steam through the safety valves are shown in Figures 6 and 7, respectively. Note that when the valves are closed, there is no flow. For a period of about minutes, when the pressurizer is filled with water, the primary system water inventory is gradually depleted as shown in Fig. 8. The primary system water starts boiling at min., when its temperature reaches (Fig.4). The resulting steam flow through the safety valves causes very rapid depletion of the primary system water inventory. The boiled up water level in the RPV falls, uncovering the core at minutes. As shown by the boiled-up water level in Fig.9, after the core uncovers, it takes only minutes for the water level to fall to a level of m. At this point, less than of the active fuel rods remain submerged.

Large temperature increases in the core, the gas, and the structure of the primary system take place with the core exposed. The cladding temperatures at four elevations along the central axis of the core are plotted in Fig. 10, showing higher temperatures for the higher elevations. These temperatures all exhibit a rapid increase following a more gentle rise. The rapid increase for the upper elevations results from the heat released during cladding oxidation, which becomes important when the temperature approaches . The rapid increase of the lower elevations is the result of heat transfer from the upper elevations, either through conduction or natural circulation. The subsequent cooling and stabilization of the temperatures are the consequences of the termination of cladding oxidation in the upper part of the core caused by zirconium relocation, the blockage of steam flow from the covered part of the core as a result of melt relocation and freezing, and the release of volatile fission products together with their associated decay power, etc. However, details of core degradation are not the concerns for the present work, because focus is on the period leading to failure of the RCS, which turns out to be always by hot leg rupture. In most cases studied, hot leg rupture occurs before extensive oxidation has taken place. In the present case, the time for hot leg rupture is min. Breaching of the RCS by hot leg failure is suppressed in the present case, although failure is predicted by the code. The plant behavior would be different if failure would have been allowed, as will be demonstrated in a later section.

The temperature histories of vapors in the core, the upper plenum, the hot leg pipe, and the steam generator hot tubes are shown in Fig.11. The latter two are shown for the "broken loop", but the values for the "unbroken loops" are similar. Vapor temperature in the core remains close to the highest cladding temperature, and is substantially above the vapor temperature in the upper plenum. The latter is almost the same as the vapor temperature in the upper half of the hot leg. However, a large temperature difference exists between vapor temperatures in the hot leg and the hottest regions of the steam generator tubes.

Temperatures for the upper part of the hot leg pipe, the surge line, and the hot tubes are shown in Fig.12. Differences between the "broken" and "unbroken" loops are scarcely noticeable, in part due to the fact that the flow to and from the pressurizer is small during the heatup phase. In Fig.13, a comparison is made between the hot leg piping temperature and the vapor temperature inside the hot leg. A similar comparison is made in the hot tube region in Fig.14. A much smaller temperature difference exists between the vapor and the structure in the hot tube region than in the hot leg region, a result which is explained by the much smaller heat capacity of the hot tubes. As seen from Fig.12, of the three structures, the hot leg has the highest temperature at all times, except for a brief period after core uncovery, when it is exceeded by the surge line. As mentioned before, hot leg is predicted to fail at 198.8 minutes, at which time the hot leg temperature is K, and the primary system pressure is MPa, the setpoint of the safety valves. It appears that yield stress is the limiting factor for hot leg rupture in the present case. With a thickness of cm and a radius of cm, the hoop stress in the pipe amounts to MPa at the time of rupture. Refering to the plot for carbon steel in Fig. 15 the yield stress at is close to MPa. On the other hand, according to the plot for carbon steel in Fig.16, which gives the time to rupture, without consideration of yield stress, as a function of temperature when the material is subject to a tensile stress of MPa, it would require a lapse of approximately min. before the hot leg would fail. However, since creep rupture is modeled as a cumulative effect which depends on how long the material stays at elevated temperatures, ten minutes does not represent enough margin to completely discount the importance of creep rupture as a failure mechanism for the hot legs.

Temperatures of some structures inside the RPV are plotted in Fig. 17. These include the lower and upper core barrel, the internal structures in the upper plenum, and the dome plate. Of all structures inside the RPV, the upper plenum internals suffer the largest temperature rise, because they are in the direct path of natural circulation from the core. Even so, at the time of hot leg rupture, their temperature is only K, which is not high enough to cause melting or oxidation.

The sources of heating are decay power and oxidation power in the core. These are plotted in Fig.18. During the period between core uncovery and hot leg failure, decay power is fairly constant at a level of MW, while oxidation power shows a sharp peak near min. Cladding in the top part of the core is oxidized during the oxidation peak. The resulting rapid core heating initiates melting and relocation. Refreezing of the melt in the colder lower elevation forms blockages for steam flow which limit subsequent oxidation. After the oxidation peak is over, about kg of hydrogen is produced, corresponding to approximately of the total zircaloy in the core being oxidized. However, hot leg rupture occurs before the oxidation peak is reached. At the time of hot leg rupture, oxidation power is about two-thirds of decay power.

A closer examination of structure heating has been made during the period of preoxidation heatup defined in the last section. Table 1 lists the beginning and end times of the period, while Table 3 gives the rate of increase of the highest temperature in the core, the heatup rates of the upper part of the hot leg, the surge line, and the hot tubes of the steam generator in the "broken" loop. The latter two heating rates are expressed as fractions of the the hot leg rate. All rates are obtained by performing a linear fit to the respective temperature curves. The use of Table 2 is mainly for the intercomparison of the eight cases considered. With respect to the base case, it is noted that surge line heats up at of the rate of the hot leg, while steam generator tubes heat up at only of the same.

An accounting of the energy flows during this period shows that on the average, fission products in the core generate heat at the rate of MW, of which is retained by the core and is absorbed by primary system structures and steam generator shells. The rest goes to the containment. Of the amount absorbed by the primary system structures and steam generator shells, large fractions are accounted for by the % going to the upper plenum internals and % to the steam generator shells. Each hot leg absorbs %.

The manner by which energy is transported to various parts of the system can be eludicated by an examination of steam flows. Fig.19 shows the magnitudes of the three natural circulations which occur after core uncovery. The natural circulations for the hot leg and steam generator refer to the "broken loop". The flow rates in each of the "unbroken" loops are similar. The core-upper plenum circulation is much greater than steaming rate from the bottom of the core, and is therefore the dominant mechanism for removing heat from the core. The oscillatory behavior reflects the opening and closing of the safety valves, which affects the flows through its influence on the primary system pressure. Figures 20 shows the flow rates of steam through the surge lines, with the positive sign indicating flows to the pressurizer. The spikes occur whenever the safety valves are open, but there is a small positive flow even when the valves are closed. The small flow is sufficient to flood the surge line so that there is no water flowing down the surge line, except immediately after the closing of the valves, wher steam flow has not built up to a large enough value. Then water flows down for a brief period of time from the pressurizer as shown in Fig.21. Net flows of steam from the upper plenum to the "broken" hot leg and from the "broken" hot leg to the steam generator hot tubes are shown in Figs. 22 and 23 respectively. These figures show that steady flows from the RPV are modified by the opening of the safety valves, which draw steam from all regions of the primary system.

The pattern of steam flow within the primary system is depicted in Fig. 24, which is a schematic representation of the average flow rates (kg/s) among the primary system regions during the period of pre-oxidation heatup. The direction of these average flows clearly demonstrate the prevalence of the suction effect of the safety valves. The direction of flow indicates that most of the primary system regions are losing steam mass. This is possible in the face of a steady pressure (at the safety valve setpoint only because temperature is everywhere increasing. The requisite delivery of energy to cause temperature increase is achieved either during the time intervals when the safety valves are closed or by means of natural circulation. It is worth noting that a large throughput exists in the "broken" hot leg.

3 - 2 - 2. Case 2: Pump Seal LOCA

In Case 2, pump seals in both the "broken" and the "unbroken" loops are assumed to fail at min. after the start of the station blackout accident, since cooling water is no longer being supplied to the pumps. The break size of the ensuing LOCA is adjusted so that the initial water flow is 150 GPM out of the break in each loop.

It is expected that timing of key events might be affected by the presence of the breaks, and that the different steam flow patterns in the primary system after core uncovery might lead to differences in structure heatup. Specifically, the early loss of coolant through the breaks should lead to earlier core uncovery. This appears to be borne out by Table 1, which shows a slight decrease of core uncovery time for the present case in comparison with the base case. However, detailed investigation to be discussed later shows that the time histories leading up to core uncovery are rather different in these two cases, so that simple arguments based on loss of coolant inventory alone cannot account for the timing.

After core uncovery, steam can flow from the RPV through the hot leg pipes, the steam generator tubes, the intermediate legs, and the breaks in pump seals out to the containment. This flow might be expected to cause more uniform heating of the structures encountered in the path. In particular, the hot tubes of the steam generator might show increased heating relative to the hot leg. However, reference to Table 3 indicates that this effect is minimal. By contrast, the table shows a dramatic change in the heating of the surge line. The surge line is in fact being cooled during the period of pre-oxidation heatup. As will be shown in the following, the surge line cools because the primary system pressure is not high enough to cause the safety valves to open, so that there is no flow of hot steam through the surge line into the pressurizer. In fact, referring to Table 2, at the time of hot leg rupture, the primary system pressure is only MPa. The corresponding failure temperature of the hot leg is higher than that for the base case, because a smaller pressure difference between the primary system and the containment now drives the hoop stress to the yield stress.

Examining the phenomena in the present case in more detail, Fig.25 presents the time history of the primary system pressure. The pressure drops precipitously at the time of pump seal failure because of loss of coolant through the breaks. The loss of coolant lowers the level in the pressurizer, and the consequent expansion of gas volume in the pressurizer lowers the pressure. The flow of coolant through the break in the "broken" loop is shown in Fig.26, and represents one-quarter of the total flow out of the breaks considering that there are four loops. The observed maximum mass flow rate of kg/s per loop is equivalent to a volumetric flow of GPM per loop.

The drop in pressure is suddenly arrested when a value of MPa is reached, and a slow repressurization follows. This is because at MPa, the primary system water becomes saturated, as evidenced by the appearance of non-zero void fraction in the primary system as shown in Fig.27. Continued steaming from decay heat as the steam generators gradually dry out causes the pressure to rise. Two-phased flow through the breaks (Fig.26) during this period causes primary system water inventory to gradually deplete as shown in Fig.28. At min., the safety valves open, leading to a rapid loss of inventory and core uncovery at min.

The time when saturated water first appears at the safety valves in the base case is min., which is remarkably close to that of the present case. However, the routes taken to reach this stage are quite different in the two cases. In the base case, this stage is reached by bringing to saturation almost the full amount of the original water in the primary system at the pressure of the safety valves setpoint. In the present case, this stage is reached by increasing the pressure of a saturated system of water and steam, with the inventory depleting all the while. While it takes less time to bring a smaller mass of water to saturation under identical pressure, more time (energy) is consumed in pressurizing the system in the presence of breaks. The near equality of the times for saturated water to reach the safety valves in the two cases, when rapid coolant loss will ensue, can only be coincidental in view of these opposing influences. But the somewhat earlier core uncovery time in the present case can be accounted for by the smaller water inventory at this stage.

From the time (min.) of core uncovery up to the time (min.) when the water level reaches m, signalling the beginning of the period of pre-oxidation heatup, the primary system pressure remains near MPa. At the end of the period of pre-oxidation heatup at min., when the highest temperature in the core reaches K, the pressure has fallen to MPa. The cause for the falling pressure is the inability of steam generation in the primary system to keep pace with steam loss through the breaks. Steam generation in the primary system is mainly from the core region, and is plotted in Fig. 29. Because the fraction of active fuel immersed in water is slowly decreasing, steaming rate decreases from approximately kg/s from min. A similar reduction occurs also in the base case. However, in that case, there is no break in the primary system. A reduction in steaming rate is compensated for by less frequent opening of the safety valves, maintaining the primary system pressure near the setpoints.

As discussed above, structure heatup in case 2 takes place while the primary system is depressurizing through the breaks in the pump seals. This should influence the manner of heatup. Because of reduced pressure, the primary system natural circulation flow rates are somewhat smaller, as shown in Fig.30. This should reduce the rate of energy exchange between the core and primary system piping. With essentially the same decay power in the core, a faster heating rate of the core for the present case than for the base case is expected. However, there exists now a much stronger unidirectional steam flow from the core to other regions of the primary system, as shown by Fig.31, which is a schematic representation of the flow pattern during the period of pre-oxidation heatup. Averaging kg/s as compared with kg/s in the base case, this flow results from the suction effect created by the breaks in the intermediate legs in all four loops. The flow removes heat from the core, and is responsible for the somewhat slower heating of the core as seen from Table 3. For similar reasons, this flow and its continuation in other primary system regions as evidenced in Fig.31 should cause more rapid heating of other structures. Thus, as seen from Table 3, the hot leg heats up at K/s instead of K/s. At the same time, the relative heating of the steam generator tubes to the hot leg remains essentially unchanged. Fig.31 also shows little flow through the surge line, because the safety valves are closed. In fact, water is draining from the pressurizer as shown in Fig.32. Thus, the surge line, which heats up briefly during the period when the safety valves are open and steam from the RPV is flowing into the pressurizer, is now cooling down as is noted in Table 3.

A composite plot of the temperatures of the hot leg, the surge line and the steam generator hot tubes is given by Fig.33. Table 1 gives the time of hot leg rupture as min. At this time, the temperature of the upper part of the hot leg is K and the pressure is MPa.

During the period of preoxidation heatup, the decay power is about MW, similar to the base case. The core retains and the primary system structures absorbs . Compared with the base case, these results are consistent with more uniform heating due to the larger steam flow in the primary system.

3 - 2 - 3. Cases 3 and 4: MSLB with or without Pump Seal LOCA

In Case 3 a main steam line break is assumed to occur in the loop containing the pressurizer (the "broken" loop) at the beginning of the station blackout accident. The break is chosen to be large enough so that depressurization of the secondary side of the steam generator to atmospheric pressure takes place within minutes. Thus, cases with MSLB also exhibit the behavior that would be expected from stuck-open relief valves in the steam generator.

The heat removal capability of a depressurized steam generator is much reduced because coolant is rapidly lost. On this basis, it is expected that core uncovery and other events that depend on the absorption of decay energy will take place sooner. However, a counter-acting influence comes from the rapid heat removal because of flashing in the "broken" steam generator, which lasts about 20 minutes. As a result, the timing of key events for this case is similar to the base case, as can be seen in Table 1.

The massive steam generator shells are important heat sinks. After dryout of the steam generators, heat transfer from the tubes to the shells is by natural convection through the vapor in the intervening space. The heat transfer coefficient for natural convection is smaller when gas pressure is low. Thus, as structures heat up after core uncovery, those in the "broken" loop would be expected to show more rapid temperature increase than the "unbroken" loop because of reduced heat transfer to the steam generator shells. In particular, the steam generator tubes would be affected to a greater extent. Referring to Table 3, the somewhat higher heating rate of the hot leg in the "broken" loop and the higher relative heating rate of the hot tubes of the steam generator appear to confirm the expectation.

To examine the sequence in more detail, Fig.34 presents plots of the pressures in the primary system and the steam generators in the "broken" and "unbroken' loops. The rapid depressurization of the "broken" steam generator is apparent. Coolant is also lost at the same rate through flashing as shown in Fig.35, which plots water levels in the steam generators. In connection with Fig.35, it is interesting to note that water level of the "unbroken" loop does not fall immediately as in the base case (Fig.3). This is because, for a brief period of time, the "broken" loop is removing more heat compared with the base case, owing to the sudden decrease of the secondary water temperature from flashing. Later on, when coolant inventory in the "broken" steam generator is essentially depleted, a reduction of the heat removal capability of the steam generators occurs, causing more rapid increase of the primary system pressure compared with the base case. As shown in Fig.34, the pressure setpoint of the safety valves is reached much earlier. Nevertheless, the times for onset of boiling of the primary system water are not too different between the two cases, being min. and min. for case 3 and case 1, respectively. As a result, the difference between core uncovery times is also small, as shown in Table 1.

During the period of preoxidation heatup, which lasts from min. to min., all steam generators have dried out, and are removing heat from the primary system by natural convection. The steam generator in the "broken" loop , which is at atmospheric pressure, is much less efficient in removing heat compared with the others, since the heat transfer coefficient is proportional to the second power of density at the same temperature according to the correlation used in MAAP4.0. The overall reduction in heat transfer capability means that core and structures heat up at a more rapid rate in comparison with the base case, as can be seen from the heating rates of the core and the hot leg in Table 3. The asymmetry of heat transfer among the different loops should also show up in the structure temperatures. It can be seen from Fig.36, which plots the temperatures of the surge line, and of the hot legs and hot tubes of the "broken" and "unbroken" loops, that the hot tubes in the "broken" loop heat up at a higher rate than in the other loops. In fact, as shown in Table 3, the relative heating rate of the hot tubes to the hot leg is , which is close to twice that of the base case.

To corroborate the conclusion that reduced heat transfer coefficient is responsible for the higher tube heating rate in the "broken" loop, Fig.37 shows the temperatures of the hot tubes, the vapor on the secondary side of the steam generator, and the steam generator shells for the "broken" and the "unbroken" loops. The differences between the temperatures of these components yield information about the heat transfer coefficient due to natural convection, with a large difference indicative of a small heat transfer coefficient. It is observed that the differences are much larger, particularly between the vapor and the shells, for the "broken" loop than for the "unbroken" loop.

Despite the increased heating of the hot tubes in the "broken" loop when the secondary side of the steam generator is depressurized, the hot leg still attains its failure temperature before the surge line and the hot tubes. As shown in Tables 1 and 2, failure occurs at min., when the hot leg temperature reaches K. At that time, the hot tube temperature is K, considerably higher than its value for the base case.

In case 4, both pump seal LOCA and MSLB are allowed to occur in a station blackout sequence, with parameters such as break sizes and opening time identical to those used in cases 2 and 3. The results indicate that individual effects observed in cases 2 and 3 are duplicated and enhanced. Thus, the times for both core uncovery and hot leg rupture are even earlier than for cases 2 and 3, as shown in Table 1. Hot leg heating rate in the preoxidation period as well as relative (to hot leg) heating rate of hot tubes are both more rapid than for cases 2 and 3, as shown in Table 3. Just as for case 2, the surge line is cooling during this period, because the safety valves are closed. Hot leg failure occurs at a primary system pressure of MPa, when the temperature of the upper part of the hot leg pipe reaches K (Table 2). At this time, the hot tube temperature is K, and is the highest among all eight cases considered. Fig. 38 shows the structure temperatures for the "broken" and the "unbroken" loops for this case.

3 - 3. Cases with Steam Generator Tube Leak

3 - 3 - 1. Case 5: " -tube" Leak

In the first case with a steam generator tube leak, a leak size of cm^2 is assumed to be present in the hot tubes of the steam generator in the loop containing the pressurizer at the beginning of a station blackout accident. The significance of the leak size, which is approximately equal to one-quarter of the cross-sectional area of a single tube, lies in its control over the coolant leak rate. Results from the code run indicate that at the beginning of the accident, water leaks out at a rate of kg/s, or GPM (See Fig.40). During the period of preoxidation heatup, the average flow rate of steam out of the leak is kg/s, corresponding to a volumetric flow rate of GPM, at the prevailing temperature of and pressure of MPa. This flow rate is in the mid-range of the volumetric flow rate considered in Ref.1. The leak size in case 5 has been chosen with this in mind.

The concern expressed in Ref.1 that the increased steam flow through the leak might cause steam generator tube to rupture before the hot leg fails to materialize: the hot leg is still the first component to fail. As shown in Table 2, at the time of failure, the hot leg temperature is and the primary system pressure is MPa, just as for the base case. However, the tubes are now at K, somewhat higher than the K for the base case, showing evidence for increased heating of the tubes. More evidence is displayed in Table 3, which shows higher relative heating for the tubes and lower for the surge line in comparison with the base case.

It is observed from Table 1 that core uncovery and hot leg rupture times are much later than the base case. The delay amounts to more than thirty minutes. This contradicts the expectation that the core should uncover sooner because coolant is lost through the leak. Indeed, the expectation is borne out in the case of coolant loss through pump seal failure, for which calculations show that core uncovery time becomes progressively shorter as the size of the LOCA break increases. On the other hand, for coolant loss through steam generator leaks, the opposite is true, as can be seen in Table 1 for cases 5 and 6. There is thus a basic difference between losing coolant to the containment and to the secondary side of the steam generator. Explanation of this difference has been found by examining in more detail the heat removal by steam generators from the primary system.

The primary system pressure shown in Fig.39 exhibits the expected early depressurization because of the leak. The leak rate is shown in Fig.40. For the first min., only water goes through the leak. Judging from the plots of primary system water masses for the present and the base case in Fig.41, the leak is too small to have much influence on the inventories at the beginning, although it does have large influence on the water level in the pressurizer as can be seen by a comparison of Fig.42 with Fig.5. The decrease of water level, as shown in Fig.42, and the accompanying expansion of the vapor volume in the pressurizer causes the primary system pressure to decrease.

At min., the primary system pressure starts to increase. The cause can be traced to heat transfer to the steam generators. The pressure is influenced by both temperature and mass of the primary system water. Increase in temperature forces water into the pressurizer because of thermal expansion, while decrease in water mass lowers water level in the pressurizer. Primary system pressure goes up and down with the water level in the pressurizer. The temperature is determined from a competition between the energy input from core fission product decay on the one hand, and energy lost through boiling off steam generator water on the other. At first, water levels in the steam generators are high and heat removal is rapid. The resultant small increase in temperature cannot compensate for the loss of inventory, and the pressure goes down. As the steam generators gradually boil dry, they remove less and less heat from the primary system as shown in Fig. 43, which plots the decay power and the power removed by the steam generators. The more rapid rise in temperature eventually overcompensates for the effect of coolant loss, and the trend of pressure decrease is reversed.

The pressure increase causes the safety valves to open at min., which is much later than the min. obtained for the base case. However, the temperature of water in the primary system is considerably higher at this juncture than the base case. Consequently, it takes only a few more minutes, at min., for water to reach saturation. Before this time, the loss of coolant inventory in the primary system has been insignificant, as can be seen from Fig.41. Boiling leads to rapid coolant loss, mainly through the safety valves, leading to core uncovery at min.

The much longer time it takes to reach core uncovery in the present case in comparison with the base case would be puzzling had a purely energetic consideration been invoked to predict the core uncovery time. Such a consideration would start from the premise that it would take a fixed amount of energy absorbed by a fixed mass of the primary system water to reach the setpoint. In the face of inventory loss through the leak, it would therefore take less energy, and thus less time, to reach core uncovery in the present case. In reality, when the leak is not too large, core uncovery occurs after the rapid coolant loss through boiling when pressure has reached the safety valve setpoint. The rate of pressurization therefore controls the time of core uncovery. Pressurization in turn is determined by an interplay between temperature rise and inventory depletion of primary system water, as discussed in subsection 3-2-2. Finally, temperature rise is determined by the net power into the coolant, with input taken from decay heat and removal largely from heat transfer to the steam generator coolant. It has been shown in case 2 that pressurization in the presence of a break to the containment is still rapid enough as the steam generators gradually boil dry, that core uncovery occurs sooner than the base case. In the present case, the primary system water which leak into the secondary side of the steam generator will partly flash to steam and partly join the inventory of saturated water (at the secondary pressure) on the secondary side. It has been estimated that about half of the leaked primary system water will end up in the latter, and will continue to remove heat from the primary system through boiling. The net result is an increase in the heat removal capability of the "broken" steam generator, as shown in Fig. 43, where the heat removal rates by the steam generators in cases 5 and 1 can be compared. Consequently, less power goes into heating the primary system water in the present case, resulting in a slower pressurization. This slowing down of pressurization causes delayed core uncovery.

The onset of the period of preoxidation heatup is also delayed until min. It can be seen from Table 3 that the heating rates of both the core and the hot leg are smaller than those of the base case during the same period. These lower rates stem from a lower decay power that occurs later in an accident sequence. Indeed, the average decay power during this period is MW for the present case, which is to be compared with MW for the base case.

Table 3 also reveals that the relative (to the hot leg) heating rates of the hot tubes and of the surge line in the "broken" loop are respectively somewhat higher and lower when compared with the base case. Also, temperature histories of the surge line and the hot leg and hot tubes of the "broken" and "unbroken" loops shown in Fig.44 indicate that while there is no difference between the temperatures of the hot legs in the two loops, the hot tubes in the "broken" loop where the leak exists heat up at a slightly higher rate. This is apparently a manifestation of the effect noted in Ref.1 that the diversion of steam flow from the surge line into the hot tubes and through the leak can cause increased heating of the hot tubes at the expense of the surge line.

The pattern of steam flow during the period of preoxidation heatup is shown in Fig.45. When compared with the pattern for the base case in Fig.24, the most obvious difference is that both the pressurizer and the steam generator in the "broken" loop provide suction to the primary system in the present case. The total average flow to the pressurizer and the steam generator is almost equal to the flow to the pressurizer alone in the base case. There is now a net flow from the hot leg in the "broken" loop to the hot tubes. To examine the flows in more detail, Figs.46 and 47 give the temporal variation of the flows from upper plenum to the hot leg and from the hot leg to the hot tubes, respectively. Comparing with the corresponding flows in the base case given by Figs. 22 and 23, the safety valves are open less often, which is a consequence of the longer intervals for repressurizarion in the presence of the leaks. Also, a steady background of positive flow is visible in Fig.47, whereas it is not noticeable in Fig.23. This steady background is responsible for the net positive flow from the hot leg to the hot tubes, despite being interrupted by periodic flow reversals due to the suction from the pressurizer. By contrast, such background flow is absent in the flow from the hot tubes to the cold tubes shown in Fig.48. This indicates that the background flow into the hot tubes is due to the suction effect of the leak. Thus, the flow diversion by steam generator tube leak noted in Ref.1 is reproduced.

As indicated in Fig.45, the average steam flow rate through the leak during the period of preoxidation heatup is kg/s. The average temperature of steam in the hot tubes is K during this period, and the pressure is MPa. Under these conditions, the corresponding volumetric flow rate is GPM. Similarly, with an average temperature of K for steam in the upper plenum, the volumetric flow rate into the hot leg that corresponds to the mass flow rate of kg/s indicated in Fig.45 is GPM. These figures are to be compared with GPM of steam at K and MPa flowing through the hot leg assumed in Ref.1. Thus, while the observed volumetric flow rates are comparable to those of Ref.1, the temperature, which is self-consistently obtained in the present case, falls far below the assumed value in that reference. Even at the time of hot leg rupture at min., the vapor temperature in the upper plenum is only K.

It should be pointed out that besides the flow diversion effect, there is another potential contributing factor to a relative heating of the hot tubes. This comes from the observation that the leak is delivering pressurized steam at high temperature to the secondary side of the steam generator. In the ideal gas approximation, steam suffers no change in temperature upon emerging on the secondary side. Thus, steam on the secondary side is maintained by the leak at a higher temperature than the case with no leak. This in turn leads to higher temperature for the tubes.

3 - 3 - 2. Case 6: " Tube" Leak

To enhance the flow diversion effect, in case 6 the size of the steam generator tube leak is taken to be cm^2, which is about equal to the cross-section of a single tube. Flow rates of water and steam through the leak in this case is shown in Fig. 49, where it is seen that the water flow rate quickly stabilizes to a value near kg/s for a long period of time. Compared with the kg/s flow rate observed for the pump seal LOCA break in one loop as shown in Fig. 26 fo. case 2, it is concluded that coolant is lost at slightly more than one half of the rate in case 2. Also, the volumetric flow rate of steam (at MPa and K) out of the break is GPM during the period of preoxidation heatup, and is much higher than the rates assumed in Ref.1.

As seen from Table 3, the flow diversion effect is indeed enhanced: during the period of preoxidation heatup, temperature of the hot tubes increases at % of the rate of the hot leg as compared with % for case 4 and % for the base case. The surge line is even cooling down, because there is no flow into the pressurizer as the pressure is below the setpoint of the safety valves. In fact, as indicated in Table 2, by the time of hot leg rupture, the primary system pressure has decreased to MPa. Temperatures of the surge line and the hot leg and hot tubes in the "broken" and "unbroken" loops after core uncovery are shown in Fig.50. The flow pattern in Fig.51 also clearly indicates the large flow through the leak and the negligible flow in the surge line during the preoxidation heatup period.

Timing of key events is delayed even more than case 4. Thus, as shown in Table 1, core uncovers at min., and hot leg fails at min. This delay correlates with the slower heating rates of the core and the hot leg shown in Table 3 for the preoxidation period, because decay power is less. It results from the same slowing down of pressurization due to the leak into the secondary side of the steam generator noted in case 4.

To examine the sequence in more detail, the primary system pressure is plotted in Fig.52. The early depresssurization is much more rapid than for case 4 because coolant is lost at a greater rate. The pressure abruptly turns around when reaching MPa. At this pressure, the primary system water becomes saturated. The subsequent flashing and continued generation of decay heat cause the pressure to increase. The increase is very slow. In fact, it is much slower than the repressurization observed in Fig.25 for case 2 after saturation of primary system water, even though coolant loss rate is only half of the rate for case 2. As discussed in subsection 3-3-1, the cause for this is the replenishment of water on the secondary side of the steam generator. This is shown clearly by the water levels in the "broken" and the "unbroken" steam generators in Fig.53 The plots of energy removal rates by the steam generators for the present case and case 2 in Fig.54 also show the prolonged effectiveness of the steam generators in the present case.

Primary system water inventory decreases at the rate of kg/s for more than min. as shown by Figs. 55 and 49. At min., the leak becomes uncovered, and the two-phased flow out of the leak is replaced by steam flow (Fig.49). This leads to a slight decrease of pressure as can be seen in Fig. 52, which in turn causes flashing of the primary system water. The resultant increased steam flow through the core carries more of the decay power in the core to the higher elevations of the pressurizer and the steam generator U-tubes. In the U-tubes, the steam comes into contact with the colder tube wall, and condenses thereupon, with the latent heat removed to the secondary side of the steam generator. There is therefore a sudden increase in the power removed from the steam generator as can be seen in Fig.54. (In fact the same phenomena to a lesser extent occur also in case 5, as is evidenced by the peaking of the power removed by the steam generator at min. in Fig.43.) With no replenishment from the leak, this power increase causes the water on the secondary side of the steam generator to boil away rapidly, as shown in Fig. 53. The consequent reduction in heat removal rate from the primary system causes the pressure to increase, thereby stopping flashing of the primary system water and steam condensation in the U-tubes. As the pressure continues to rise, steam flow through the leak maintains the reduction of primary water inventory at essentially the same rate as before. The core uncovers while this reduction is taking place, before the setpoint of the safety valves is reached.

Upon reaching a maximum close to the setpoint, the pressure decreases again. This is because steaming rate fails to keep up with loss rate through the leak. The period of preoxidation heatup occurs during this second depressurization. As noted earlier, hot leg failure occurs not long after the end of this period at min. At this time, the pressure is . MPa, and the temperature of the hot leg is K, while that for the hot tubes is K.

3 - 3 - 3. Cases 7 and 8: " -tube" Leak with Pump Seal LOCA or MSLB

In case 7, pump seal LOCA with the same parameters as case 2 is assumed to occur in a station blackout accident with a cm^2 leak in the hot tubes of the steam generator in the "broken" loop as in case 5. Examination of heating rates in Table 3 shows that the present case shares with case 2 the attribute that surge line is cooling in the preoxidation heatup period and with case 5 the attribute that increased relative heating of the hot tubes occurs, as is to be expected. The rate of rise of core temperature in the preoxidation heatup period at K/s is the smallest of all eight cases considered. As shown in Table 2, this case requires the highest hot leg temperature for failure, because the pressure at failure time is the lowest. According to Table 1, timing of key events is similar to case 2.

The fact that timing of key events bears more resemblance to case 2 rather than case 5 can be explained by the observation that the leak rates of water in the early part of the accident for case 2 is many times that for case 5 (See Figs.26 and 40, bearing in mind that the result in Fig.26 has to be multiplied by four to obtain the total). Thus the total leak rate, which controls event timing, is closer to that in case 2. The similarity is clearly brought out in Figs. 56 and 57, which compare the primary system pressure and water inventory respectively for the two cases.

The steam flow pattern during the period of preoxidation heatup is shown in Fig.58. Flows in the "unbroken" loop are essentially the same as in case 2, and are dominated by the suction effect of the break in this loop. However, in the "broken" loop, a stronger flow now exits from the upper plenum into the hot leg region. The flow continues into the hot tubes, where it splits into a part going through the tube leak and a part going into the cold tubes. Flows from the cold tubes on are again similar to case 2. The leak flow is kg/s, close to the kg/s in case 5. The similarity of the flows into the hot tubes and through the leak in the present case and case 5 correlates with the equality of the relative heating of the hot tubes observed in Table 3. Both are either manifestation of the flow diversion effect or steam leakage into the steam generator noted earlier. The flow from the core to the upper plenum is the strongest in the present case. The rapid energy convection by this flow explains the low core heating rate seen in Table 3.

In case 8, a cm^2 leak is combined with MSLB in the same "broken" loop. Reference to Table 1 shows that timing of key events is similar to case 5. This is understandable because it has been shown that coolant loss rate controls timing while MSLB by itself has relatively little effect on timing. The heating rate of the hot tubes as a fraction of the heating rate of the hot leg during the period of preoxidation heatup is the highest in the present case, being equal to %. This is due to a combination of the effect of reduction of heat transfer in a depressurized steam generator and the flow diversion effect, with stronger influence from the former. Temperatures of the surge line and the hot legs and hot tubes in the "broken" and the "unbroken" loops are shown in Fig.59. At the time of hot leg rupture, the upper part of the hot leg pipe is at K, while the hot tubes are at K. The margin of K is the smallest among the eight cases.

The hot tubes are predicted to fail at min. This of course is possible only because hot leg failure has been suppressed. The temperature of the hot tubes at the time of failure is K, when the primary system pressure is MPa. At this pressure, the hoop stress in the tubes, which are of radius cm and thickness cm, amounts to MPa, and is considerably below the yield stress of stainless steel at K, as can be seen from Fig.15. On the other hand, examination of the curve for time to rupture versus temperature for stainless steel at MPa in Fig.16 shows that it would take only a few minutes for rupture to occur if the temperature and pressure were to persist. Thus, the mechanism for tube failure in this case is by creep rupture rather than yield stress.

3-4 Uncertainties

The above calculations predict that hot leg is the first component of the RCS to fail, and its failure precludes the failure of surge line and steam generator tubes, because the primary system is then depressurized. Since large uncertainties can be associated with failure modeling, the temperatures at which structures would fail might vary over a wide range. It is natural to ask with what confidence is the hot leg predicted to fail first. This subsection provides an approximate gauge for this confidence.

The observation is first made that K is a convenient estimate for the temperature of the upper part of the hot leg at the time of rupture (Table 2). In some of the eight cases considered where steam generator tube rupture is predicted (only when hot leg failure has been suppressed), the tube temperature is also close to K at the time of rupture (K for case 8, for example). In view of the fact that different materials are used for the hot leg and the steam generator tubes, and that the failure mechanisms are also different as discussed in subsection 3-2-3, the closeness of the failure temperatures can only be considered coincidental. Assuming K to be the mean temperature for failure of both components, an indication of the impact of the uncertainty in failure temperatures on the precedence of hot leg versus steam generator tube failures can be gauged from the quantity ΔT, defined so that the hot leg temperature of $+ \Delta T$ occurs at the same time as the steam generator tube temperature of $- \Delta T$. Thus, if steam generator tubes were to fail at $- \Delta T$ and hot leg at $+ \Delta T$, the two RCS components would fail at the same time. The second column of Table 4 gives values of ΔT for the sequences considered earlier. A small value indicates less confidence in the prediction that hot leg would fail before steam generator tubes. It is seen that of the cases considered, a station blackout accident with intact steam generator tubes, in which pump seal LOCA and main steam line break are assumed to have occurred (case 4) presents the least error margin for the prediction.

If the case numbers are arranged in ascending order of ΔT, the sequence 4,8,6,3,5,2,1,7 is obtained. Another indication of the likelihood of reversal of failure order can be obtained from the relative heating rates of the hot tubes to the hot leg given in Table 3. The sequence thus obtained is 8,4,6,3,5,7,2,1. Comparing these two sequence, the order of case 7 in the first sequence appears to be most out of place. The value of ΔT obtained for this case also appears to be at odds with the rest. Since this value depends on phenomena which occur later in the accident when significant core damage has occurred and the modeling becomes less reliable, more credence should be given to the sequence obtained with the latter method.

In the above calculations, a single temperature is used for the steam generator tubes. This does not take into account the fact that the locations where the tubes join the tube sheets have the highest temperature and are more likely to fail than elsewhere in the tubes. A reasonable estimate of the temperature at these locations can be obtained by averaging the gas temperatures at the inlet plenum and on the secondary side of the steam generator. (In MAAP4.0, the temperature at the inlet plenum is obtained as a by-product of the calculation of steam generator natural circulation.) This temperature for case 1 is plotted in Fig. 60 and compared with the hot leg (upper part) and hot tube temperatures, as an illustration of how much difference can be caused by its use. Using this temperature in lieu of the hot tube temperature, a quantity for failure uncertainty similar to ΔT can be defined. Denoted by $\Delta T'$, this quantity can be found in the last column of Table 4 . While it narrows the margin for the prediction, the conclusions on the relative effectiveness of the various scenarios for tube heating remain unchanged.

3 - 5. Release of Cesium Iodide

The ultimate goal for considering various accident scenarios is to determine how the release of fission products would be influenced by them. In particular, it is important to determine how much is released directly into the environment as compared with release into the containment, as the consequence of the former to publc health cannot be mitigated. Usually, this requires detailed information on the plant layout. However, one common feature of PWR plants is that the secondary side of steam generators is vented to the atmosphere. As a result, tube leak in a vented steam generator allows for a direct pathway for fission products to the environment. On the other hand, other modes of RCS failure such as hot leg rupture, pump seal LOCA, and surge line rupture, tend to release into the containment. Results from the preceding subsection are therfore reassuring in that they indicate hot leg is the first component to fail and its failure precludes massive failure of the steam generator tubes. Nevertheless, it is useful to gain some quantitative information on the behavior of fission product and to assess the impact of leaks in the steam generator tubes. In the following, cesium iodide is chosen as a representative fission product species to be studied in a number of accident sequences.

The base case is considered again, with RCS failure models enabled. The sequence is followed to the time of reactor vessel failure, which happens at min., and is due to creep rupture of the lower head vessel wall. The primary system pressure is plotted in Fig.61. It decreases precip. ously to atmospheric pressure at min., when hot leg rupture occurs in the "unbroken" loop. The decrease triggers injection of accumulator water into the primary system, which rapidly lowers the temperatures of all components, and covers the core again with water. The temperature of the hottest part of the core shown in Fig.62 exhibits this rapid decrease. As water gradually boils off, the core is uncovered for the second time at min. Heating of all primary system components resume. With aid from oxidation, the core eventually reaches more than K. Very severe core damage in the form of melting and relocation takes place. With core support plate failing at min., molten core materials are relocated into the lower plenum. After boil-off of water in the lower plenum, thermal attack from the molten debris fails the vessel wall at min.

Fig.63 plots the distributions of CsI released to the primary system, and to the containment. They are expressed as fractions of the total inventory in the core at the beginning of the accident, which is kg. There is no release to the environment in this case. Release from the core starts soon after the first core uncovery, and the cesium iodide at first stays in the primary system as vapor. The release stops for about min. after hot leg rupture, because the core is recovered by injection from the accumulator. At the time of hot leg rupture, some of the cesium iodide is transported to the containment through the hot leg break. Release resumes after the core is again uncovered. The ensuing heatup and meltdown of the core lead to ve rapid release of the total inventory in the core. Since the RCS is breached by the hot leg break, there is release into the containment as well as into the primary system. Some amount of cesium iodide are retained in the primary system as deposits on the vessel wall and piping. At first, the masses of cesium iodide in the primary system and in the containment are comparable. As temperatures in the primary system increase, revaporization of the deposited cesium iodide occurs, which causes rapid decrease of the inventory in the primary system as the vapor is driven to the containment. At the time of reactor vessel failure, % of the core inventory of cesium iodide exists in the containment and % remains in the primary system.

The second case considered is the case of " -tube" steam generator leak with MSLB in subsection 3-3-3. In this case, failure of reactor vessel occurs at min. As shown in Fig.64, the distribution of cesium iodide among the primary system and the containment do not differ much from the base case. There is a small amount released to the steam generator through the leak after the initial core uncovery. Releases to both the steam generator and from there to the environment increase during the second core heatup. However, they remain very small. At the time vessel failure, only % of the original inventory of cesium iode has been released to the environment.

If the leak size is increased to cm^2 ("single tube"), similar cesium iodide distribution is obtained as shown in Fig.65. The amounts retained in the steam generator and released to the environment are now somewhat larger, being % and % respectively at the time of vessel failure.

To illustrate the potential serious consequence of an enlargement of a steam generator leak before hot leg rupture occurs, the case of " -tube" leak with MSLB is recalculated by suppressing hot leg and surge line failures while allowing steam generator tube rupture to occur when it is predicted. This happens at min. At this time, the leak size is arbitrarily increased to an area corresponding to the cross-sectional area of tubes. The distribution of cesium iodide is shown in Fig. 66. Substantial release takes place before tube rupture as higher temperature is now reached by the core, but the released cesium iodide is almost completely retained in the primary system, with a small amount in the containment and even smaller amount in the steam generators and the environment. Immediately after tube rupture, a good fraction (% of orginal core inventory) of cesium iodide is transported into the environment, partly from existing inventory in the primary system, and partly through continued release from the core. By way of comparison, the fraction in the containment has reached only % at this stage, and remains constant until reactor vessel failure. As accumulator injection begins upon depressurization of the primary system, the mass distribution is stabilized for about min. as a lull in the release persists. When the core is again uncovered, release is almost all directly into the environment through the tube break, with some amount retained in the steam generator. At the time of reactor vessel failure, which happens at min., % of the total initial inventory, has been released into the environment. It is fortunate that because of hot leg rupture, this scenario is not predicted to happen.

4. Conclusions

A number of high pressure accident sequences for PWRs initiated by a station blackout have been studied, including those with likely component failures such as pump seal LOCA and MSLB, and those with steam generator tube leaks. It is predicted in all cases for a plant with Zion-like parameters that hot leg rupture occurs, precluding the occurrence of surge line and steam generator tube ruptures. As a result, cesium iodide is mostly released to the containment or confined to the primary system, with little release to the environment.

The sequences have been examined with a view to identify circumstances that might exhibit increased tendency for steam generator tubes to reach failure temperature before the hot legs do. An artificial calculation in which hot leg failure is suppressed shows that massive steam generator tube break coupled with an assumed main steam line break can cause large release of cesium iodide to the environment.

One of the circumstances identified is first discussed in Ref.1, in which the diversion of superheated steam from the surge line by leaks in steam generator tubes has the consequence of lowering the heating rate of the surge line and increasing the same for the tubes themselves in relation the the hot leg. It is found that for leak sizes leading to flow rates in the range considered in Ref.1, the former effect is reproduced while the latter effect is weak. The latter effect becomes significant only for much larger leak sizes whose occurrence is inconceivable in practice. Integrated analysis also gives a much lower temperature for steam exiting the reactor vessel into the the hot leg than is assumed in Ref.1. It is also found that the surge line cooling effect can be produced when pump seal LOCA occurs during accident progression with no tube leak.

A circumstance with a strong tendency for increased tube heating is found in the occurrence of main steam line break, or steam generator relief valves sticking open, during a station blackout sequence. The reduced heat transfer coefficient for the depressurized steam on the secondary side of the steam generator leads to higher heating rates for the tubes. The difference between having or not having leak in the steam generator tubes of a size consistent with flow rates in Ref.1 is slight under the circumstance. During the initial heatup period when oxidation remains insignificant, the heating rate of steam generator tubes can increase to % of the heating rate of the hot leg from the % characteristic of cases with no MSLB.

It is not meaningful to accurately model component failure in a generic plant configuration. To provide insight into the reliability of the conclusion of early hot leg failure, estimates are made of the changes in failure temperatures of hot legs and steam generator tubes that would lead to earlier failure of the latter. In the worst scenario, which is a combination of tube leak with MSLB, the hot leg failure temperature has to be increased by from and the tube failure temperature lowered by the same amount from in order for the tubes to be the first to rupture.

Future improvements can be suggested in several areas that will increase the reliability of the conclusions. The first is in the modeling of the failure of RCS components. Improvements in this area include use of better material data at high temperatures, assessment of material strength as actually occuring in power plants, and use of finer nodalization for thermal hydraulic calculations. The second is to refine the model for energy flow through steam generator breaks such as MSLB. Currently, the flow used in MAAP4.0 is that of an ideal fluid and does not include turbulent heat transfer. As a result, gases on the secondary side of the steam generator do not reach the temperature of the environment even when the break is very large. The third is to examine in more detail the role played by water in the loop seals. Whether or not the water clears in the loop seals influences gas flow in the primary system and therefore temperature distribution among the primary system components. In MAAP4.0, gas flow is apparently allowed through the water in the loop seals as steam flow has been predicted from the steam generator tubes to the intermediate leg through the break in a pump seal

LOCA, even though the location of the break is on the other side of the loop seal as the tubes. Finally, sensitivity study needs to be conducted by varying model parameters expected to have important impact on heatup of the RCS components.

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TABLE 1: Case description and timing of key events

TABLE 2: Conditions at time of hot leg rupture

TABLE 3: Heating rates during period of preoxidation heatup

TABLE 4: Uncertainty parameters for steam generator tube failure

Figure 1

PWR primary system nodalizations (Westinghouse 4-loop design)

Figure 2

Primary system and steam generator pressures in case 1

Figure 3

Steam generator water level in case 1

Figure 4

Core region water temperature in case 1

Figure 5
Pressurizer water level in case 1

Figure 6

Water flow through safety valves in case 1

Figure 7

Steam flow through safety valves in case 1

Figure 8

Primary system water inventory in case 1

Figure 9

Core boiled-up water level in case 1

Figure 10

Core temperatures in case 1

Figure 11

Gas temperatures in primary system regions in case 1

Figure 12

Structure temperatures in case 1

Figure 13

Temperatures in hot leg region in case 1

Figure 14

Temperatures in hot tube region in case 1

Figure 15

Yield stress for carbon steel and stainless steel

Figure 16 Time to rupture versus temperature for carbon steel and stainless steel

Figure 17

Structure temperatures in case 1

Figure 18

Decay and oxidation power in case 1

Figure 19

Primary system natural circulations in case 1

Figure 20
Steam flow through surge line in case 1

Figure 21
Water flow through surge line in case 1

Figure 22

Steam flow from upper plenum to "broken" hot leg in case 1

Figure 23

Steam flow from "broken" hot leg to hot tubes in case 1

Figure 24

Steam flow pattern in case 1

Figure 25

Primary system pressure in case 2

Figure 26

Flow rates of water and steam through primary system break in case 1

Figure 27

Primary system void fraction in case 2

Figure 28

Primary system water inventory in cases 1 and 2

Figure 29
Steam generation from core in case 2

Figure 30

Primary system natural circulations in case 2

Figure 31
Steam flow pattern in case 2

Figure 32

Water flow in surge line in case 2

Figure 33
Structure temperatures in case 2

Figure 34

Primary system and steam generator pressures in case 3

Figure 35
Steam generator water levels in case 3

Figure 36

Structure temperatures in case 3

Figure 37

Temperatures in steam generator region in case 3

Figure 38

Structure temperatures in case 4

Figure 39

Primary system pressure in case 5

Figure 40

Water and steam flows through steam generator tube leak in case 5

Figure 41 Primary system water inventories in cases 1 and 5

Figure 42

Pressurizer water level in case 5

Figure 43

Decay power and power removed by steam generators in case 5

Figure 44

Structure temperatures in case 5

Figure 45

Steam flow pattern in case 5

Figure 46

Steam flow from upper plenum to "broken" hot leg in case 5

Figure 47

Steam flow from "broken" hot leg to hot tubes in case 5

Figure 48

Steam flow from "broken" hot tubes to cold tubes in case 5

Figure 49

Water and steam flows through steam generator tube leak in case 6

Figure 50

Structure temperatures in case 6

Figure 51

Steam flow pattern in case 6

Figure 52

Primary system pressure in case 6

Figure 53
Steam generator water levels in case 6

Figure 54

Decay power and power removed by steam generators in case 6

Figure 55
Primary system water inventory in case 6

Figure 56
Primary system pressure in cases 7 and 2

Figure 57 Primary system water inventory in cases 7 and 2

Figure 58

Steam flow pattern in case 7

Figure 59 Structure temperature in case 7

Figure 60
Average of inlet plenum and secondary-side steam temperature, hot leg temperature, and SG tube temperature in case 1

Figure 61

Primary system pressure in case 1 allowing hot leg rupture

Figure 62

Temperature of hottest part of core in case 1 allowing hot leg rupture

Figure 63

CsI distribution in case 1 allowing hot leg rupture

Figure 64

CsI distribution for " -tube" leak with MSLB, allowing hot leg rupture

Figure 65

CsI distribution for " -tube" leak with MSLB, allowing hot leg rupture

Figure 66

CsI distribution for " -tube" leak with MSLB, suppressing hot leg rupture