TECHNICAL REPORT

THERMAL-HYDRAULIC PROCESSES INVOLVED IN LOSS OF RESIDUAL HEAT REMOVAL DURING REDUCED INVENTORY OPERATION

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SUMMARY

Recent plant experience has included many events occurring during outages at pressurized water reactors. A recent example is the loss of residual heat removal system event that occurred March 20, 1990 at the Vogtle-1 plant following refueling. Plant conditions during outages differ markedly from those prevailing at normal full-power operation on which most past research has concentrated. Specifically, during outages the core power is low, the coolant system may be in a drained state with air or nitrogen present, and various primary system closures may be unsecured. With the residual heat removal system operating, the core decay heat is readily removed. However, if the residual heat removal system capability is lost indefinitely and alternate heat removal systems are not utilized, heat up of the coolant could lead to core coolant boil-off, fuel rod heat up, and potential core damage.

This paper identifies the topics needed to understand pressurized water reactor response to an extended loss of residual heat removal event during refueling and maintenance outages. By identifying the possible plant conditions and cooling methods that would be used for each cooling mode, the controlling thermal-hydraulic processes and phenomena were identified. Controlling processes and phenomena include: gravity drain, core water boil-off, and reflux cooling processes. Important subcategories of the reflux cooling processes include: the initiation of reflux cooling from various plant conditions, the effects of air on reflux cooling, depression effects, issues regarding the steam generator secondaries, and the special case of boiler-condenser cooling with once-through steam generators.

Suggestions for assisting staff evaluation of industry capability to effectively respond to a loss of residual heat removal system include: evaluating the capability for using gravity-drain processes and other means of feeding the reactor coolant system without AC power, determining the best options for using secondary system vents and backup sources of
feedwater, and determining the capabilities of high point vents for removing air from the reactor coolant system. The primary area where research is needed regards initiation and continuation of reflux cooling in a reactor coolant system containing air. Specific issues are the primary pressure increase needed to start and maintain the reflux process, and the effects of steam and air migration.

These research actions will provide a better understanding of plant response to events occurring during outages. This understanding will be useful in achieving plant safety improvements in the following areas: operating procedures, training, instrumentation, equipment availability, and risk quantification.

This study has concentrated on loss-of-residual heat removal during reduced inventory operation in pressurized water reactors; studies may also be needed regarding analogous operations in boiling water reactors.

This, revision one, version of the report was modified from the original to reflect comments made by the NRC related to such areas as proper use of terms like "mid-loop operation" and "reduced inventory", and to contain the latest information on the subject.
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1. INTRODUCTION

The objective of this paper is to identify the important thermal-hydraulic phenomena in pressurized water reactors following loss of vital AC power and consequent loss of the residual heat removal system during reduced inventory operation, and to identify which of these phenomena require further study. The following steps were undertaken:

1. Plant configurations and alternative cooling modes were identified for the variety of potential plant conditions during such events.

2. Controlling phenomena were identified for each potential cooling mode.

3. The phenomena that are sufficiently well understood, such that they present no new issues requiring further study, were determined.

4. A recommended closure plan of action was developed to address the remaining phenomena judged not sufficiently understood.

The research indicated in the closure plan will provide a better understanding of plant response to events occurring during refueling and maintenance outages and will be useful in achieving plant safety improvements in the following areas: operating procedures, training, instrumentation, equipment availability, and risk quantification.

Events involving loss of residual heat removal during planned outages for maintenance or refueling with different initiators and plant conditions were reviewed, catalogued, and documented in References 1, 2, and 3. The primary emphasis was placed on the March 20, 1990 Vogtle event (LER42490006) and special attention also was given to the April 10, 1987 Diablo Canyon 2 event (LER32387005) and the Waterford 3 event which occurred on July 14, 1986 (LER38286015). Review of these events, each of which leads to
reactor coolant system heat up, was instrumental in understanding the various potential plant conditions and cooling modes. For brevity, only the Vogtle event is summarized here.

During a refueling outage, the Vogtle-1 plant (Westinghouse 4-loop design) experienced a loss of the residual heat removal (RHR) system on March 20, 1990. The incident occurred with Unit 1 shut down during a refueling outage. The water level had been lowered to the mid-loop level, and consequently air occupied the upper volume of the reactor coolant system. The event was initiated by an accident in the switchyard that interrupted the AC power supply to the RHR system. Diesel generator power was not immediately available; it required 36 minutes to achieve operation of one of the generators, restoring power to the RHR system. During this period, the reactor coolant temperature increased from 90°F to 136°F and the coolant level remained at mid-loop. The restoration of RHR cooling reversed the coolant heatup and the plant was recovered. A schematic of the Vogtle 1 plant, highlighting component elevations, is shown in Figure 1.

The NRC Incident Investigation Team's report on the Vogtle event is documented in Reference 1. Of particular interest is Section 8 of that document, entitled "Coping with the Loss of the Residual Heat Removal System," which studies the feasibility of alternate core cooling methods. The effect and response of non-boiling and boiling methods were discussed under various scenarios including: (1) whether the reactor coolant system is open or closed, (2) various operator actions are taken, and (3) different initial primary coolant levels. Alternate cooling mechanisms include reflux cooling and/or gravity feed of water from the Refueling Water Storage Tank. In most cases the reflux cooling option is available
Figure 1. Schematic of Vogtle 1 Plant.
(From Reference 1)
when core boiling cannot be prevented by gravity-feed cooling, and when
the reactor coolant system is closed (i.e. manways and reactor vessel
upper head are secured). The reflux cooling option has the advantage in
many cases of requiring no operator action.

This paper builds on the analysis provided in Reference 1 by exploring
in greater detail the thermal-hydraulic processes and phenomena expected
to occur during the various cooling modes potentially available following
a loss of AC power and RHR. The research support areas were defined in
Section III D of the appendix to the NRC's staff plan for evaluating
safety risks during shutdown and low power operation (memorandum from T.
E. Murley to J. M. Taylor, October 10, 1990). These are.

1. Systematically examine event sequences that might lead to a loss of
RHR cooling. These are addressed in Section 2 of this report.
2. Identify and assess sequences that can lead to recovery from loss of
RHR events, including natural circulation cooling in PWR's.
Controlling processes involved in these sequences and our ability to
model them are discussed in Section 3.
3. Evaluate the effectiveness of alternate cooling methods including:
   A. Initiation and promotion of convective core cooling using
      the refueling water storage tank and accumulators as coolant
      sources. Definition of example analyses for each vendor
      plant type which could be used for NRC staff assessment will
      be supplied by the research program as defined in Section 4.
   B. Maintenance of the inventory during core boiling using the
      refueling water storage tank and accumulators as cooling
      sources. The proposed research supporting this issue is
      also presented in Section 4.
   C. Initiation and promotion of reflux cooling. This is the
      subject of major research support described in Section 5.
In the event of loss of residual heat removal (RHR) during plant maintenance or refueling, the reactor has been shut down for many hours or days, the decay heat level is low (relative to power operation), and the plant is either in Mode 5 (cold shutdown) or Mode 6 (refueling) operation. A cold shutdown condition consists of an effective reactivity less than 0.99, no thermal power except decay heat and an average coolant temperature of 200°F or less. A refueling condition consists of fuel in the reactor vessel, vessel head closure bolts less than fully tensioned or with the upper head removed, an effective reactivity of 0.95 or less, no thermal power except decay heat, and an average coolant temperature of 140°F or less. Core decay heat generally is less than 20 MW, corresponding to approximately 1 day after reactor shutdown. These and, in general, other example data presented are for Vogtle-1, a "Vur-loop, 3411 MWt, pressurized water reactor of Westinghouse design. Notes are included indicating any classes of plants for which the presented data is not representative regarding response following a loss of residual heat removal event.

2.1 Plant Configuration

In the refueling mode, the reactor coolant system can be partially drained, and the high point (pressurizer, hot leg, reactor vessel head) vents, opened to promote draining, can have drawn nitrogen or air into the upper reactor coolant system. If the reactor coolant system water level is lower than three feet below the reactor vessel flange the condition is termed "reduced inventory" operation. Core decay heat is removed by the residual heat removal system that takes suction flow from one or two hot legs, cools the water with a heat exchanger, and returns it through the four cold legs to the core. The status of the containment may be open or closed; openings are possible at many locations.

During maintenance and refueling, the steam generator secondary systems are often in "wet layup" status and are essentially filled with
cold water and pressurized to about 5 psig with a nitrogen blanket. For steam generators undergoing maintenance operations, the secondaries may instead be drained.

In addition to vents opened for draining the reactor coolant system, other reactor coolant system openings often are present during maintenance and refueling outages. These additional openings may include one or more of the following: pressurizer relief valves or manways, steam generator manways, main coolant pump shaft seals, cold leg valves, or the reactor vessel upper head. Reduced inventory operations normally are performed with one or more openings in the reactor coolant system, however a closed system is possible under certain circumstances, as for example in the Vogtle event\(^1\). A refueling/maintenance outage generally requires about 40 to 80 days, depending on the maintenance required; the reactor vessel upper head is off for about half that time.

The actual reactor coolant system water level at reduced inventory operation may vary considerably. For steam generator maintenance operations, nozzle dams may be installed in the hot and cold legs near the steam generator plena. These dams, which can support a differential pressure of 50 psig\(^1\), may be in one or more coolant loops. There is no restriction on the number of loops with nozzle dams, however operations at Vogtle are generally performed with nozzle dams in no more than two of its four loops. The presence of nozzle dams reduces the volume of the reactor coolant system. This isolated volume typically will contain air and is in communication with the containment via open steam generator manways. Nozzle dam failure results in an effective increase in system volume and potential opening of a flow path to the containment.

2.2 Possible Scenarios Following Loss of AC Power and RHR

The process flow chart in Figure 2 shows plant behavior following a loss of residual heat removal event. The following discussion pertains to pressurized water reactors employing U-tube type steam generators (i.e.
plants of Westinghouse and Combustion Engineering design). The expected response of reactors employing once-through steam generators (i.e. plants of Babcock and Wilcox design) is also noted. The initiating event is assumed to be a station blackout (loss of all station AC power, offsite and onsite) which stops operation of the residual heat removal pumps.

Plant behavior is divided into the two main paths shown in Figure 2, one with an open reactor coolant system and the other with a closed reactor coolant system. If the system is open, early action may allow its closure (as depicted by the dashed line in the figure). This action would consist of securing any open manways or valves. If the reactor vessel head is off, it could potentially be secured, although 8 hours or more may be required for this operation. Closure of openings during an event appears unlikely because of increasing coolant temperatures and steam flow through the openings. A closed reactor coolant system provides the operators flexibility for maintaining core cooling and for maintaining it longer should an extended station blackout be experienced. Furthermore, if core cooling is lost a closed reactor coolant system provides an additional fission product barrier, increased time before core melt occurs if means for removing heat are not found, potential for heat removal methods that may not exist with an open system and the ability to work in the containment building for a longer time following loss of RHR systems.

2.2.1 Reactor Coolant System Open

First consider the upper main path in Figure 2; the reactor coolant system is open. The reactor coolant system is open to the containment (via upper head, manways, etc.) during about half of an average refueling and maintenance outage period. With no AC power available, two sources of borated water for the reactor coolant system may be available without offsite assistance: the accumulators, and gravity-drain of the refueling water storage tank (RWST). In addition, the makeup water storage tank is a potential source of non-borated water. Offsite assistance in the form of a pumper truck provides a possible additional source of coolant for
Figure 2. Potential plant conditions and cooling methods during loss of RHR and station blackout.
the reactor coolant system. Water may be added to the RWST and, with some reconfiguring of piping, it may be feasible to add water directly to the reactor coolant system in a timely manner. Generic plant capabilities in these regards have not been established.

The status of the accumulators can vary at reduced inventory operation. In general, the accumulators are expected to be depressurized with their isolation valves closed; however, accumulators could also be in a pressurized state. In a four loop plant, accumulator liquid volume is about 3000 ft$^3$ (22,000 gallons). Depressurized accumulators are potential gravity-drain water sources to the reactor coolant system in those plants where they are sufficiently elevated (accumulator elevations are plant specific). If fully-pressurized, discharging the accumulators by opening the isolation valves presents a control problem that has not yet been analyzed. Another possibility for advantageously using accumulators involves a gradual pressurization of the accumulator (using its nitrogen pressurization system) that would result in a controlled transfer of the accumulator water to the reactor coolant system. This possibility also has not yet been analyzed.

The second potential source of water for the reactor coolant system is gravity-draining from the RWST, which typically contains about 53,300 ft$^3$ (400,000 gallons) of borated water. The elevation of the RWST with respect to the reactor coolant system varies, so in some plants gravity drain may not be possible. For the Vogtle plant, only a portion of the RWST is above the top of the pressurizer, therefore the quantity of water available for gravity feed without a reactor coolant system heatup depends on the elevation of the lowest opening in the reactor coolant system. For example, if the only opening is the manway on the top of the pressurizer, then the RWST would drain to that elevation and flow would stop. After that time, the remaining RWST fluid could flow into the reactor coolant system: (1) as a result of an altered hydrostatic balance as the reactor system fluid is heated, and (2) to replace any core steam
expeled through the pressurizer manway. Depending on the situation and plant, it may be possible to open alternate drain paths, thus increasing the RWST liquid available for delivery without primary system heatup, or control the drain rate, thus delaying RWST depletion. The desirability of employing drain paths in this manner has not been established. It may be possible to control the RWST drain rate to the minimum flow needed to prevent core boiling (thus conserving RWST inventory while eliminating concerns regarding boron precipitation from solution). However, the desirability of using this control method has not been established.

As an alternate source of coolant, a pumper truck could be employed to inject fluid into the cold legs. The time required to align the necessary plant systems for such operation is not known. The water injected would not be borated. If during pumper truck injection core coolant boiling was the only sink for removing water, then the average core boron concentration would remain constant. If a sufficiently large water drain was opened, however, the core boron concentration would decrease due to flushing with the non-borated water. This concern is greatest when new fuel is present because the initial boron concentration is the highest then. For new fuel, it is likely the control rod worth is insufficient to maintain a subcritical core in this situation.

If no water is available to replenish inventory (or if an established source is lost or depleted), then boiling of the core coolant will ensue. With the reactor system open, the size and location of the opening determines whether steam condenses and remains in the system, escapes through the openings, or partially condenses and partially escapes. The boil-off of the core coolant could lead to core uncovering and damage. If the core is damaged and the containment open, fission products will be released to the environment; with it closed, the release to the environment will not be as likely.
2.2.2 Reactor Coolant System Closed

The closed reactor coolant system condition is represented by the lower main logic paths in Figure 2. With the manways and reactor vessel head closed, core cooling may still be accomplished by gravity-draining the RWST into the cold legs. Eventually, when core boiling occurs, a drain line from the hot leg is required to be opened in order to continue feeding from the RWST. This cooling mode is comparable to that described in Section 2.2.1. If the reactor coolant system drain paths are small, the onset of core boiling could rapidly increase system pressure and stop the injection flow. As with the open system, RWST draining will continue until its level reaches the drain path vent elevation when the gravity-driven flow will stop. The necessary operator response will then be to close the hot leg drain paths to completely close the reactor coolant system in anticipation of a switch to reflux cooling decay heat removal.

In the reflux cooling mode, core decay heat is removed by boiling; steam flows to the steam generators where it is condensed on the inner surfaces of the steam generator tubes. The condensate from the upflow side of the U-tubes flows downward, against the upward flowing steam, into the steam generator inlet plenum, hot leg, reactor vessel upper plenum, and back to the core. The condensate from the downflow side of the U-tubes is returned to the cold leg where, due to manometric flow, it is available for core cooling. To work, the reflux cooling mode requires that one or more steam generators be operational. In other words, at least one steam generator secondary must contain cold water and nozzle dams must not be present in the hot and cold leg piping of the loop with that steam generator. If one or more steam generators are not operational, then boil-off and core damage might occur.

In Babcock and Wilcox plants (with once-through steam generators), the cooling mode analogous to reflux cooling is the "boiler-condenser" mode, the condensate is returned to the cold leg and need not flow against the
steam flow. Boiler-condenser mode requires that the primary and secondary side coolant levels be situated such that an adequate condensing surface is available on the inside of the tubes. The secondary side level must be sufficiently elevated, and the primary side level sufficiently depressed, so that both a cooling sink and steam path to the tubes at its elevation are available. At reduced inventory operation, air will reside in the upper regions of the tubes. Boiler-condenser cooling thus requires this air to be compressed, allowing steam to find a condensing surface inside the upper tube region. The reactor vessel vent valves present in Babcock and Wilcox plants preclude core coolant level depression, relative to coolant levels in the rest of the system, due to system pressurization and static head effects.

Reflux cooling results in the transfer of the decay heat to the steam generator secondary sides. Since the secondary systems are generally isolated and nitrogen-pressurized, continual reflux cooling will result in a heating and pressurizing of the secondary liquid. Although normally intervention would be expected; however if valves could not be opened, a closed secondary system would be expected to continue heating (in the extreme, its temperature would reach saturation at the secondary relief valve opening setpoint pressure). To continue condensation, the primary system temperature must exceed the secondary system temperature, and thus the primary system pressure will rise along with the secondary. The primary system pressure increase has the potential to jeopardize the integrity of the reactor coolant system (for example, the Tygon tubing used for level instrumentation during outages). With an elevated secondary pressure, operation of the turbine-driven auxiliary feedwater pump is possible. If this pump is started, it can provide feedwater from the condensate storage tank to the steam generators, allowing the reflux process to continue indefinitely. If the turbine driven auxiliary feedwater pump is not started, the secondary inventory would be boiled off at the steam generator relief valve setpoint pressure. When the secondary inventory was depleted, the reflux process would cease and core boil-off and damage would occur.
Another procedure is to vent the steam generator secondary systems to the atmosphere by manually opening the atmospheric dump valves. This action would limit the heating and pressurization of the primary and secondary systems. More importantly, however, depressurized secondary systems could allow offsite assistance (for example a pumper truck) to be used for indefinitely replenishing the secondary inventory and continuing the reflux process.

In order to establish reflux cooling, the core boiling must sufficiently pressurize the reactor coolant system to compress the nitrogen or air in the upper regions of the reactor coolant system to expose a tube condensing surface to the steam flow. The reactor coolant system pressure increase needed for this to occur is not known. Furthermore, the required pressure increase will be a function of various plant conditions such as the decay heat and initial reactor vessel water level. The magnitude of the required pressure rise is significant because the integrity of the nozzle dams, temporary instrument tube thimble seals, and temporary level instrumentation may be challenged. If these plant features fail, then the event sequence is made more complex by the resulting loss of coolant.
3. CONTROLLING PROCESSES AND THERMAL-HYDRAULIC PHENOMENA

This section discusses the processes and thermal-hydraulic phenomena that control the cooling methods presented in Section 2, with the intent of indicating the current understanding regarding them. The discussion is separated into three subjects: (1) gravity-drain processes, (2) core boil-off processes, and (3) reflux cooling processes. The specific areas evaluated for each of these processes are shown in Table 1.

3.1 Gravity-Drain Processes

As described in Section 2, for a station blackout, loss-of-residual heat removal event, gravity-drain of the refueling water storage tank (RWST) is a process with potential to delay core boil-off and damage. RWST gravity drain may deliver core coolant either when the reactor coolant system is open (pressurizer PORV, manways, pump shaft seals, or reactor vessel upper head) or when it is closed (in which case a reactor coolant system drain path eventually needs to be opened). To be effective, it is necessary that all or part of the RWST be at an elevation above the lowest opening in the reactor coolant system. The static head of the RWST water forces borated coolant into the cold legs and reactor vessel downcomer, making it available for core cooling. Water heated by the core flows out reactor coolant system openings (pressurizer or steam generator manways, reactor coolant pump seals, or reactor vessel upper head) or drain valves and falls to the containment sump. In the Vogtle event, the RWST water level was 76 ft above the hot leg centerline and 16 ft above the pressurizer manway elevation, which is within the normal operating range. Reference 1 indicates that the Vogtle RWST water available above the pressurizer manway is 216,600 gallons. Therefore the RWST is available for gravity-feed in the Vogtle-1 plant. However, RWST elevations relative to the reactor coolant system vary from plant to plant. A generic plant survey regarding the capability for RWST draining does not exist.
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<tr>
<th>Process</th>
<th>Factors</th>
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<tr>
<td>Gravity Drain</td>
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<td></td>
<td>Rate Needed to Avoid Boiling</td>
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<td>Actual Rates Attainable</td>
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<td>If Boiling Occurs, Boron Overconcentration</td>
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<td>Control of Drain Rate</td>
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<td>Instrumentation Available</td>
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<td>Drains Available</td>
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<td>Core Boil-Off</td>
<td>Time to Uncovery and Damage</td>
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<td>Heat Losses</td>
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<td>Reflux Cooling</td>
<td>Initiation Process</td>
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<td>Horizontal Stratification in Hot Leg</td>
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<td>Two-Phase Natural Circulation</td>
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<td>Effect of Air on All Processes</td>
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<td>Steam/Air Mixing</td>
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<td>Buoyancy, Turbulent Mixing, Diffusion</td>
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<td>Conservatism of &quot;No-Mixing&quot;</td>
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<td>Air Absorption in Condensate</td>
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<td>Humidity Within the Air</td>
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<td>Core Level Depression</td>
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<td>Tube Flooding</td>
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<td>Hot Leg Flooding</td>
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<td>Applicable CCFL Models</td>
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<td>Loop Seal Depression</td>
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<td>Primary Pressure Required</td>
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<td>Temporary Thimble Tube Seals</td>
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<td>Temporary Level Instrumentation</td>
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<td>Steam Generator Secondary Effects</td>
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<td>Vent Availability and Effect</td>
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<td>Viability of Feedwater Processes</td>
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<td>Heatup and Boil-Off Times</td>
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<td>Babcock and Wilcox Plants</td>
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<td>Vent Availability/Effectiveness</td>
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<td>Adequate Condensing Surface</td>
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<td>Heating at Top of Tubes</td>
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The drain rate required to prevent net core boiling may be readily calculated, given the core decay heat. For the Vogtle event, that rate was 130 GPM. A plant-specific analysis for Vogtle indicates the RWST is capable of providing this drain rate with a small driving head of only 0.8 ft. However, no generic studies have been performed to determine if the no-boiling drain rate is attainable. The drain rate is determined by the driving head and the resistance of the flow path through the injection lines and fittings, reactor core, and leakage paths to the containment. The drain rate therefore will be totally dependent on the elevations of the particular plant and on the losses and flow areas of openings in the reactor coolant system. Generic information regarding the period of time that RWST gravity-drain might delay core boil-off similarly is not known. For Vogtle, analysis indicates this period will be 25 hours with the pressurizer manway open. The capabilities, control, and observation of the drain rates were referenced in the Vogtle report. These quantitative results were not incorporated in the Vogtle procedures, although when questioned, the operators were aware of multiple modes of RWST draining (via the chemical volume and control, safety injection, and residual heat removal systems). If the reactor coolant system is closed, which suitable drain paths may be opened under blackout conditions is not known (a hot leg drain path is preferred since the RWST injection would flow through the core to the reactor coolant system opening). Ability to open hot leg drains appears to be limited to the residual heat removal suction piping. If only cold leg drains are available, the RWST fluid will maintain core coverage but will not flow through the core. Instead the RWST fluid will be bypassed out the drain. Therefore, water boiling is more likely with a cold leg drain than with a hot leg drain.

When the drain rate is sufficient to avoid boiling, then the core boron concentration approaches that in the RWST. However, if the water boils, then the steam produced does not carry off boron and the core boron concentration increases, providing the potential for boron precipitation. This precipitation could, in the extreme, partially block the core flow or cover fuel and result in core damage. The Vogtle report estimates that
precipitation would not occur until after 10 days of core boiling, based on an initial core decay heat of 2.5 MW, but this was only an approximation and more detailed calculations should be performed for this and other scenarios. Also, this concern would arise sooner if the loss-of-residual heat removal event occurred sooner after reactor shutdown. Conversely, if the RWST is refilled with non-borated water, or some other source of non-borated water is used, the reactivity effect of diluting the core boron concentration must be considered.

If the reactor coolant system is closed and the core coolant boils, the rise in system pressure will reduce the flow from the RWST. Some or all of the core steam may be condensed in the steam generators in the presence of air (see discussion of reflux cooling in Section 3.3), however the interaction between a gravity-driven injection system and a reflux cooling process is not well understood.

In summary, gravity-drain injection involves relatively simple thermal-hydraulic phenomena. However, the significant process variables (elevations, piping lengths, etc.) vary considerably from plant to plant, or are dependent on specific event assumptions (system configuration, status of openings, etc.). The interaction of a gravity-drain RWST system with steam generator reflux boiling involves more complex phenomena (unique plant features, coupled manometer considerations, low system pressures) that are not well understood analytically or experimentally.

3.2 Core Boil-Off Processes

As indicated in Section 2, core water boil-off is a controlling process in situations where: (1) feed to the reactor coolant system is not available or has been lost, (2) where steam generators are unavailable for reflux cooling, and (3) where reflux cooling is established but later lost. The boil-off may occur near atmospheric pressure when the reactor coolant system is open, or at elevated pressures when it is closed.
The starting point for a loss-of-residual heat removal event is subcooled water in the reactor coolant system. Before boiling occurs, the water must be heated to saturation. Reference 1 estimates this would have required 109 minutes for the Vogtle event; however this time could be much shorter for some events.

During boiling, steam pressurizes the reactor coolant system and escapes through any openings. In equilibrium, the pressure rise is that required to force the steam out the vent; the smaller the vent the higher the resulting pressure. If the system is unvented, the pressure will continue to rise. The limit of the pressurization is the opening setpoint pressure of the pressurizer code safety valves, typically about 2500 psia.

As the core water boil-off progresses, the mixture level will fall into the core. For the Vogtle event, boil-off of the mixture level to the top of the core is estimated to require about 11 hours, but could occur much sooner under some other conditions. Steam cooling of the upper core region will prove effective in limiting the fuel temperature rise for some time thereafter. Eventually, however the core uncovering becomes deeper, the steam production rate declines, and the steam cooling is ineffective in preventing fuel heatup and damage.

Phenomena involved in the core water boil-off appear to be relatively well understood. Timing will be determined by the initial water inventory, system pressure, core power (the time after shutdown), the core axial power shape, and the openings in the reactor coolant system. One uncertainty regards the "best" correlation to use to determine the two-phase mixture level, however this affects only the sequence timing.

Because the decay heats are low, there is a potential for ambient heat loss to be a significant effect during the late stages of a boil-off. During normal operation (with an average coolant temperature of 570°F), typical reactor coolant heat loss is about 8 MW. The thermal driving potentials and heat transfer mechanisms for heat loss in a boil-off situation are different than for normal operation, are not well understood, but could represent a significant mitigating effect.
3.3 Reflux Cooling Processes

As described in Section 2, reflux cooling processes are important for delaying core boil-off following a loss-of-residual heat removal system event. The following sections describe various aspects of the reflux cooling process in a closed reactor coolant system as it pertains to this event. Section 3.3.1 describes initiation of reflux cooling and Section 3.3.2 describes possible effects of noncondensable gas (air) in the upper portion of the reactor coolant system. Section 3.3.3 describes the possibility for core level depression effects. Section 3.3.4 discusses steam generator secondary issues affecting reflux cooling and Section 3.3.5 discusses boiler-condenser considerations unique to the once-through steam generators of Babcock and Wilcox plants.

3.3.1 Initiation of Reflux Cooling

Initiation of reflux condensation cooling depends on the ability of steam, produced by core boiling, to reach condensing surfaces in the steam generator U-tubes. During a plant shutdown condition the reactor coolant level may be near reduced inventory with air or nitrogen occupying the upper volumes of the primary system. This air inhibits steam flow from the reactor vessel to the steam generator U-tubes. Important aspects of reflux initiation are: (1) the initial reactor coolant water level, (2) the need to establish and preserve horizontal stratification of the liquid in the hot legs, (3) the primary system pressure requirements/limitations, and (4) the possible need for draining or venting of the primary system in order to obtain a stable reflux cooling mode at an acceptable pressure.
Until very recently, initiating reflux from a shutdown, reduced inventory operating condition has not yet been thoroughly examined in reflux experiments with noncondensable gases present. Most existing experiments investigating reflux with noncondensables were initiated from a stable reflux condition by injecting noncondensible gas into the reactor system. A recent experiment in the PKL-III facility, investigating reflux starting from mid-loop operation with noncondensables, showed that refluxing is readily initiated from such conditions with only one steam generator available and a decay heat of 0.7 and 1.0% of full power. Analytical studies with thermal hydraulic systems codes also have not addressed this issue. These codes have been used to calculate some reflux phenomena in steam-water systems, but they do not have the models capable of simulating the phenomena associated with mixing or stratification of two gas phases (air and steam) that are relevant to this situation.

The Vogtle report evaluated the effect of four different primary water levels on the initiation of reflux: top of core, mid-pipe with an uncovered pressurizer surge line, hot and cold legs filled with liquid and air in the upper reactor vessel, and a filled reactor vessel. The first two cases are expected to result in stable reflux cooling modes at relatively low system pressures. It was noted that these cases would be similar to the reflux conditions experienced at Diablo Canyon in April 1987. Hand calculations for the last two cases determined that an intermittent or cyclic refluxing mode was possible as water was forced into and out of the pressurizer, the U-tubes drained, and condensation occurred in the steam generator U-tubes. Draining or venting may be necessary to control reactor system pressure and/or to obtain a stable refluxing mode similar to the first two cases.

Reference 1 noted that none of these initial water levels leads to a core heat-up as long as the reactor coolant system remains intact (i.e. pressurization or dynamic effects do not affect the integrity of temporary thimble tube seals). Not identified in the Vogtle report is the potential for establishing two-phase net loop natural circulation flow. The initiation
of boiling in the core when the vessel is filled with water results in a liquid swell and pressurization that forces two-phase mixture into the pressurizer and steam generator U-tubes. If the liquid in the steam generator tubes reaches the elevation of the steam generator tube U-bends, a buoyancy driven two-phase natural circulation flow over the U-bends will result. Uncertainties or variables associated with the initiation of two-phase net loop natural circulation include: the decay heat level, the pressure, the behavior of the flow into and out of the pressurizer, and the flow of noncondensable gas both before and after the initiation of two-phase natural circulation.

Reflex includes horizontal stratification of the liquid in the hot legs. If the steam flow is too high, horizontal stratification cannot be sustained, and steam may still be able to reach the steam generators via slug or bubbly flow regimes. Scoping calculations were performed using the Taitel-Dukler criteria to determine the threshold for horizontal stratification. Figure 3 presents the results of the calculations at atmospheric pressure for a hot leg water level at mid-pipe and for differing numbers of active steam generators. In practice, a higher hot leg water level will be present most often. Calculations for lower water levels indicate that horizontal stratification exists for all decay heats of interest even if only one steam generator is active, while for higher water levels and fewer active steam generators the likelihood for loss of horizontal stratification increases. Results for these other cases appear in Appendix B.

The presence of noncondensable gases in the steam generator U-tubes reduces the condensation of steam. Primary system pressure increases as necessary to: (1) compress the noncondensable gas so that a condensing surface is exposed in the steam generator U-tubes, and (2) provide the primary-to-secondary temperature difference. Reference 3 indicated that if all the noncondensable gas in the primary system during the Diablo Canyon event was isothermally compressed into the steam generator U-tubes, the resulting pressure would be 20 psig. A more reasonable estimate was obtained by considering only those noncondensable gas volumes that must be
Figure 3. Horizontal stratification behavior in hot leg.
compressed into the steam generator U-tubes to initiate reflux cooling. One calculation assumed that most of the gas in the pressurizer and pressurizer surge line remained there, while another calculation assumed that these gases also had to be compressed into the steam generator U-tubes. The pressure estimates assumed a two-foot condensation region was available in the lower part of the upflow sides of the tubes. A best estimate for the pressure rise needed to initiate reflux, obtained by averaging the results of the above two calculations, is 10 psid with an uncertainty of 5 psid. This value agrees well with the rise in pressure experienced in the Diablo Canyon incident which was roughly estimated to have been 7 to 10 psid\textsuperscript{3}.

However, the presence of nozzle dams in one or more primary loops significantly increases the pressure required to initiate reflux (assuming no openings in the pressurizer). The nozzle dams effectively reduce the volume into which noncondensable gases from locations outside the steam generator U-tubes must be compressed. Based on an isothermal compression of Diablo Canyon volumes, a rough estimate for the pressure rise necessary to initiate reflux when nozzle dams isolate two primary loops is 18 psig. This value is much closer to the design pressure (25 psig) of the temporary thimble tube seals\textsuperscript{1} and therefore their integrity may be challenged.

Investigation of the different primary water levels\textsuperscript{1} indicated the potential need for sufficient vent paths from the primary system that may be used to control primary system pressure or to remove noncondensable gas from the system. Draining might be beneficial if steam flow to the steam generator U-tubes is impeded by a reactor liquid level above the top of the hot leg piping. In this situation, an accurate vessel level indication is needed to interpret plant response. References 1 and 3 discuss problems associated with the reactor vessel level instrumentation system.

In summary, initiation of reflux from mid-loop operation with significant amounts of noncondensable gas in the upper elevations of the primary system requires further investigation. The effects of different
primary water levels on the initiation of reflux were discussed in Reference 1. Verification of these postulated initiation phenomena is necessary, as well as the consideration of other phenomena such as the initiation of two-phase loop natural circulation under certain conditions. Additional study is needed to determine the pressure rise necessary to start reflux, as a function of initial water level and noncondensable gas concentration. The effects of primary system venting and/or draining with regard to reflux initiation are also not well understood.

3.3.2 Noncondensable Effects

The primary concern regarding noncondensable gases in plants with U-tube steam generators (UTSGs) is gas accumulation in the steam generator tubes that could prevent steam from reaching a condensing surface. The effects of noncondensables on reflux cooling have been investigated in the high pressure (\(-1000\) psia) Semiscale facility\(^{11,12}\), and the reduced pressure (\(-100\) psia) PKL\(^6,13,14\), FLECHT-SEASET\(^7\), and EPRI/SRI\(^8\) facilities. Integral test facility data at atmospheric pressure has not been found in the literature. Local or separate effects experiments at atmospheric pressure have been performed\(^{15,16,17}\). The noncondensable/reflux experiments in the integral facilities mentioned above were initiated by discrete injections of noncondensable gases after a steady refluxing mode had been established. The problems associated with initiating reflux from a mid-loop operating condition with significant amounts of noncondensables in the upper elevations of the primary loop have not yet been investigated, except for the recent, as yet unpublished PKL-III experiment.\(^9\)

Experiments indicate that noncondensable gases in the steam generator U-tubes tend to shift the steam condensation region to the lower portions of the upflow sides of the U-tubes. Consequently, the steam generator is divided into "active" and "passive" zones, active meaning steam
condensation occurs in that zone. This effectively reduces the primary-to-secondary heat transfer area and therefore a larger primary-to-secondary temperature difference is needed to remove the core decay heat. For a given steam generator secondary temperature, the primary temperature and pressure must rise to provide this temperature difference.

Reflux cooling is not possible if noncondensables occupy all of the steam generator U-tubes and prevent steam from reaching a condensing surface. For a situation like the Vogt event, the pressure increase initially required to start reflux may not be sufficient to maintain the condensing surface. Additional noncondensable gas from the reactor vessel may be swept along with the steam to the steam generator U-tubes. Steam is condensed and drained from the tubes leaving the noncondensable gas behind to further impede the condensation process. This accumulation of additional noncondensable gas in the steam generator U-tubes requires an added pressurization to compress the added gas volume and maintain an adequate condensing surface. Reduced-pressure experiments (less than 75 psia) by EPRI/SRI demonstrated that significant amounts of noncondensables may be accommodated by the reactor system in this manner without jeopardizing adequate core cooling. Due to buoyancy, thermal mixing, and diffusion effects, some mixing of steam and air is to be expected in this situation.

Challenges to the integrity of the reactor coolant system (for example the temporary thimble tube seals and nozzle dams) could alter the reflux cooling mechanism and limit its effectiveness if openings are sufficiently large.

The noncondensable gas migration and mixing tendencies within the primary loop are important issues that have not been fully investigated. Basic phenomena that are not well understood include the tendency for air to accumulate at the condensation site and for air to be returned to the reactor vessel via absorption into the condensate. Additional uncertainty
regards the split of the steam-gas mixture flow among the three paths from the core. The first path is into the reactor vessel upper head where venting may be possible through the reactor vessel upper head vent valve and the core bypass flow paths. The second flow path is into the hot leg piping and pressurizer via the surge line. Venting from the pressurizer may be accomplished with the power operated relief valves (some plants do not have these valves, and in others opening them may not be possible at low pressures). The third path is into the hot leg piping and to the steam generator U-tubes. During reflux condensation in a closed reactor coolant system, a vent path does not exist in the U-tube steam generators (i.e., the steam generator manways are closed).

The steam-gas mixture flow split among these paths is an important variable for determining the thermal hydraulic response of the system and the potential for vents to remove gas from the system. Note that the first two paths allow venting, while the third path does not. The third steam-gas path provides cooling through reflux condensation, but it may also transport additional noncondensable gas to the steam generator U-tubes and therefore may be self-limiting if tube condensation is impeded.

Buoyancy effects may also play a role in determining the effectiveness of reflux cooling. Air is heavier than steam so the buoyancy effect will tend to promote mixing of steam upward into the air-filled steam generator tubes. The significance of this effect is not well understood.

The establishment of reflux cooling during a loss of residual heat removal with the reactor coolant system in a mid-loop operating condition was demonstrated at Diablo Canyon on April 10, 1987. It is believed that the steam generators provided cooling in the reflux mode for approximately three quarters of an hour. The primary system pressure increase was estimated at 7 to 10 psi. Most of the steam produced in the core is believed to have been condensed and returned to the reactor vessel. Initially, condensation occurred on the cool walls of the upper reactor vessel. Eventually, the steam reached a condensing surface in the steam generator U-tubes and reflux condensation removed the core decay heat.
The use of thermal-hydraulic system codes to simulate the complex phenomena associated with condensation in the presence of significant amounts of noncondensable gases is not presently defensible because the area of application is well beyond its assessment base. The problem is that there are no models capable of simulating the mixing and/or stratification of two gas phases that may occur. The mass transfer model in the presence of noncondensable gases also needs to be improved. Development of new models or code modifications may be needed. Alternately, simplified but reasonable analysis methods may need to be developed.

The reflux condensation process is described in detail in Section B2.1 of Appendix B. The effects of noncondensable gases on the reflux cooling mode are discussed in greater detail in Section B2.4 of Appendix B.

In summary, the effect of large amounts of noncondensable gases in the upper elevations of the primary loop with regard to initiating reflux from a reduced inventory operating condition has not been studied. There is much uncertainty in the use of systems codes to simulate the transient phenomena of interest. The migration and mixing tendencies of air and steam in the primary loop at low pressures are not well understood. Additional study in this area may lead to a better understanding of the following: the required pressure rise for reflux, when and how vent and/or drain operations might be effective in controlling pressure or removing noncondensables, and the significance of buoyancy effects.

3.3.3 Core Level Depression Effects

Three effects that can potentially lead to core level depression are discussed below: steam generator tube flooding, hot leg flooding, and pressurizer surge line flooding.
3.3.3.1 Steam Generator Tube Flooding

The countercurrent flow of steam into the U-tubes and condensate return during reflux cooling has the potential to cause a depression of the core level. On the upflow side of the U-tubes, the upward flowing steam opposes the return of condensate, thus "holding up" liquid within the tubes. On the downflow side of the U-tubes, the steam flow assists the draining of condensate. Any resulting differential liquid inventory between the U-tube upflow and downflow sides provides a hydrostatic head that depresses the core level. This issue is of concern since if the core level depression is sufficient, then the upper regions of the core may be uncovered. Flooding has been observed in a number of reflux condensation experiments. Section 2.2 of Appendix B summarizes the various modes of tube flooding and applicable experiments. Large thermal-hydraulic systems codes generally have the capability of simulating tube flooding phenomena during reflux condensation in steam/water systems. However, current code capability for simulating flooding in reflux processes with air present is believed to be inadequate.

Previous evaluations of steam generator tube flooding phenomena have regarded system performance following a small break loss-of-coolant accident (LOCA). Plant conditions following a loss-of-residual heat removal event during reduced inventory operation differ in two significant respects. First, for reduced inventory operation the primary system pressure is much lower than is the case for the LOCA (near atmospheric vs. about 1000 psia). The steam density at atmospheric pressure is much smaller than at the elevated pressure; therefore, for a given steam mass flow its velocity is much higher at atmospheric pressure. This steam density effect tends to promote tube flooding. Second, the core decay heats of interest for reduced inventory operation are much lower than for post-LOCA operation. This decay heat effect tends to reduce the likelihood of tube flooding.
To evaluate the net result of the effects of low steam density and low core decay heat at mid-loop operation on steam generator tube flooding, a calculation was performed. Assuming atmospheric pressure, the Wallis non-dimensional vapor velocity in the steam generator U-tubes was calculated as a function of the core decay heat. A parametric study was added to evaluate the effect of one or more steam generators being unusable for reflux cooling. Details of this calculation are found in Appendix A. The results of the calculation (shown in Figure 4) are significant because they show the non-dimensional tube steam velocities to be much lower than the threshold value of 0.5 needed for tube flooding (based on a Wallis-type flooding correlation) for virtually all decay heats of interest. The figure shows that core level depression due to steam generator tube flooding is only of concern when one steam generator is refluxing, and then only for decay heats greater than about 15 MW (approximately 2 days after shutdown).

3.3.3.2 Hot Leg Flooding

There is a potential for flooding in the vertically-inclined portion of the hot leg. Typically the hot leg rises about 3 ft from its horizontal elevation to the steam generator. If flooding occurs at this location, then there is a potential to accumulate water in the steam generator inlet plenum as well. The diameter of the hot leg is large and a Kutateladze-type correlation is more applicable than a Wallis-type flooding correlation for hot leg applications. Because the diameter of the hot legs is much larger than that of the steam generator tubes, hot leg flooding would at first appear to be less likely than tube flooding. However, because the steam generator tube flow area is about 3 times that in the hot leg; the hot leg velocity is higher than the tube velocity, increasing the likelihood of hot leg flooding.
Figure 4. Steam generator tube flooding behavior
To evaluate the net result of the effects of low steam density and low core decay heat at mid-loop operation (as compared with a post-LOCA situation) on hot leg flooding, a calculation was performed. Assuming atmospheric pressure, the Kutateladze non-dimensional vapor velocity in the hot legs was calculated as a function of the core decay heat. A parametric study was added to evaluate the effect of one or more steam generators being unusable for reflux cooling. Details of this calculation are found in Appendix A. The results of the calculation (shown in Figure 5) are significant because they show the non-dimensional hot leg velocities to be much lower than the threshold value of 3.2 needed for liquid holdup (based on a Kutateladze-type flooding correlation) for virtually all decay heats of interest. The figure shows that hot leg flooding is only of concern when one steam generator is refluxing, and then only for decay heats greater than about 10 MW (approximately seven days after shutdown). The potential for hot leg liquid holdup due to flooding therefore appears to be only slightly greater than for steam generator tube flooding discussed in the previous section. Because this potential is even less at higher primary system pressures, core level depression effects due to liquid holdup caused by flooding in the hot legs are not a concern for a loss-of-residual heat removal event as long as two or more steam generators are active.

3.3.3.3 Pressurizer Surge Line Flooding

Flooding in the vertical section of the pressurizer surge line could allow retention of liquid within the line itself and within the pressurizer, an effect that has the potential to depress the core level. Since the pressurizer is air-filled during mid-loop operation, this issue appears limited to situations when there is an opening on the top of the pressurizer, allowing convection of liquid into the pressurizer through the surge line.
Kg Versus Decay Heat and Number of Active Steam Generators at Atmospheric Pressure

Figure 5. Hot leg vertical section flooding behavior.
To evaluate the possibilities for pressurizer surge line flooding, a calculation was performed. Assuming atmospheric pressure, the Kutateladze non-dimensional velocity in the 14-in diameter surge line was calculated as a function of the core decay heat. A parametric study was added to evaluate the effect of only a portion of the steam production passing to the pressurizer, as might occur in the presence of reflux cooling. Details of the calculation appear in Appendix A. Figure 6 shows the results of these calculations indicating pressurizer surge line flooding is generally to be expected over the decay heat range of interest. Pressurizer surge line flooding is indicated at decay heats above about 3 MW (corresponding to 100 days after shutdown) if all steam passes to the pressurizer and at decay heats above about 10 MW (corresponding to about 9 days after shutdown) if only 25% of the steam passes to the pressurizer.

3.3.4 Steam Generator Secondary Issues

Experiments performed during the late 1970's in the low-pressure PKL facility investigated the effects of reduced steam generator secondary inventory on the effectiveness of reflux cooling. The results indicated that the primary-to-secondary differential temperature increased significantly when either: (1) the secondary level was lowered, or (2) when noncondensable gases were present within the tubes.

For the loss-of-residual heat removal/station blackout event, reflux condensation is expected to occur in the lower portion of the steam generator tubes, near the tubesheet. This is the location where steam is most likely to be present, regardless of steam/air mixing concerns. On the secondary side, water will be warmed at the bottom and, due to buoyancy, the secondary side will be well-mixed. Therefore, for this event with steam generators in "wet layup": (1) the reflux process will be insensitive to the secondary level, and (2) virtually all the secondary-side liquid will be available as a reflux cooling heat sink.
Kg vs. Decay Heat and and Fraction of Steam Entering Pressurizer Surge Line

![Graph showing Kg vs. Decay Heat and Steam Fraction]

Figure 6. Pressurizer surge line flooding behavior.
Calculations indicate that for the Vogtle event (core decay heat of 2.5 MW), approximately 4 hours is required to heat up the steam generator secondaries from 90°F to 212°F. At a decay heat rate of 17.1 MW, this time is reduced to 34 minutes. The time required to boil-off all secondary water at atmospheric pressure is 120 hours at a decay heat of 2.5 MW and 18 hours at a decay heat of 17.1 MW. These calculations place into perspective the worth (with respect to delaying core boil-off) of the steam generators as a reflux cooling heat sink.

The venting of steam generators was discussed in Section 2.2.2. If no operator action is taken, reflux cooling heat transfer will heat the secondary fluid, increasing its pressure. The pressure increase raises the saturation temperature and therefore delays the onset of secondary-side boiling. If the secondary system remains sealed, then its pressure could increase to a limiting condition of the secondary safety valve opening setpoint pressure, about 1100 psia. If the secondary side is vented to atmosphere, by manually opening the atmospheric dump valves, then the secondary side pressure will be lower and secondary side boiling will occur sooner.

Based on a limited review, it appears that plant procedures currently do not address secondary-side venting for a Vogtle-like event. Discussions with operators indicate they likely would choose to vent the secondaries early in the event sequence. Vented secondaries allow the use of low pressure backup feedwater sources to replace any secondary fluid lost through boiling. Candidate sources for this feedwater include the plant fire protection system and pumper trucks. If such a backup feedwater source is available, the core reflux cooling process could be continued indefinitely. Unvented secondaries would likely preclude use of these low-pressure backup feedwater sources. The higher secondary pressures associated with unvented secondaries would, however, provide a possibility of starting the turbine-driven auxiliary feedwater pump. Secondary side pressures of as low as 100 psia may be sufficient to drive the pump. However, control of this pump could be critical, because of the
low core decay heat. If the secondary side is fed too rapidly, its steaming rate and pressure would fall, perhaps leading to a loss of the pumping capability. Additionally, there are unknowns regarding venting of the secondaries: the ability to open and control valves, and appropriate timing for venting operations.

In summary, operators would likely vent the secondary system if possible. Options for providing feedwater to either vented or unvented secondaries have not been fully evaluated.

3.3.5 Boiler-Condenser Cooling In Babcock and Wilcox Plants

The discussion provided here addresses the differences between the reflux cooling processes described for plants with U-tube steam generators and the analogous boiler-condenser cooling processes present in Babcock and Wilcox designed plants with once-through steam generators (OTSGs). With OTSGs, condensate is returned to the cold leg and need not flow against the steam flow. Boiler-condenser cooling during a loss-of-residual heat removal/station blackout event requires the primary and secondary side levels to be situated such that an adequate condensing surface is available on the inside of the tubes. The secondary side level must therefore be sufficiently elevated and the primary side level must be sufficiently depressed so that both a cooling sink and steam path to the tubes at the elevation of that sink are available. The effectiveness of pool (i.e. to a pool of secondary liquid) boiler condensing heat removal has been demonstrated experimentally. 23,24,25

The secondary-side level requirement would generally be met for the loss-of-residual heat removal event because the steam generators are in wet-layup and are filled with cold liquid virtually up to the upper tube sheet. The primary-side level requirement is also met because the upper regions of the reactor coolant system have been drained.
The primary question regarding the effectiveness of boiler-condenser cooling for the event studied here is the ability of core steam to reach the condensing surface in the steam generators. Experimental data for this issue is very limited. High-pressure tests were conducted in the MIST facility to determine the effects of noncondensable gases, but these tests also included a cold leg break. Low-pressure noncondensable gas experiments were conducted by EPRI/SRI in a facility modeling a Babcock and Wilcox plant. These experiments indicated that noncondensable gas in the steam generator tubes dictated the elevation where the condensation process occurred. Because the steam had been condensed out of a steam/air mixture that flowed into the tubes, high concentrations of noncondensable gas accumulated within the tubes. Since the presence of noncondensables impedes the condensation process, the condensing region may be forced to a higher elevation in the steam generator. Note this is the opposite effect observed for the U-tube steam generators where the condensing process tends to occur in the lower regions of the tube bundle.

If, due to accumulation of noncondensables, the condensation process is unable to remove the core decay heat, the reactor coolant system pressures and temperatures will increase and expose more condensing surface. These observations led to the conclusion that the pressure limits of the facility determine the amount of noncondensable gas that may be accommodated. This pressure limit is important, especially as it affects integrity of nozzle dams, or temporary liquid level instruments.

Because the active condensing region is at the top of the OTSG secondary, warming of the secondary fluid occurs at the top of the boiler region as compared to the bottom of the secondary side in U-tube generators. This difference is significant because thermal stratification is likely in the OTSG secondary side. This stratification effectively reduces the liquid available for use as a secondary heat sink, accelerates the onset of secondary-side boiling, and may aggravate pressurization of the primary system.
A feature of the Babcock and Wilcox plants not available in all plants of other design is the high point vents. These vents are located on the reactor vessel upper head and at the top of each hot leg U-bend (most Westinghouse and Combustion Engineering plants have reactor vessel head vents but none have vents comparable to those on the Babcock and Wilcox hot leg U-bends). These vent paths provide a potential for removing air from the upper regions of the reactor cooling system. Note, however, that the effectiveness of the high point vents for purging air from the upper regions of the reactor coolant system has not been demonstrated. The vents are opened by solenoid-activated valves that are powered through inverters by the station batteries. The valves therefore could be opened during the early stages of a station blackout event. It is envisioned that the vents would be opened, allowing core steam production to flush air out of the upper regions of the reactor coolant system. The vents would then be closed, allowing the initiation of a boiler-condenser heat removal using a pure steam flow to the steam generators. Appropriate timing for these valve operations has not yet been addressed. The vent configuration varies from plant to plant; in some plants the vents lead to the containment and in others they lead to the pressurizer relief tank.

In summary, OTSG boiler-condenser cooling will likely be established following a loss-of-residual heat removal/station blackout event. The high secondary and low primary levels provide a large condensing surface. Continuation of the condensation process appears to be jeopardized, however, by accumulation of air within the tubes. This phenomena forces the condensation process higher into the tubes. In the limit, the primary system pressure must rise to expose more condensing surface. This pressure rise may challenge the integrity of temporary closures such as level instruments, and nozzle dams for cases where they are installed in one steam generator and the other is relied on for condensation. The localization of heat removal at the tops of the steam generators effectively limits the secondary heat sink and accelerates the onset of secondary boiling. Generally the effects of air on the condensation process are not well understood. There appears to be potential for using the high point vents to purge air from the reactor coolant system, however their use in this application has not yet been demonstrated.
4. SUGGESTIONS FOR EVALUATING INDUSTRY CAPABILITIES

This section suggests areas where, based on the discussions in Section 3, additional plant-specific analyses should prove useful for determining industry capability to effectively respond to a loss of the residual heat removal system. A report providing examples of these analyses is being prepared.

4.1 RWST Gravity-Drain Potential

The capability for establishing RWST gravity drain needs to be determined for each plant. The major process variables for RWST gravity drain include RWST elevations, geometries, and normal water levels, elevations and sizes of maintenance and refueling primary coolant system openings. These parameters differ significantly from plant to plant.

4.2 RWST Gravity-Drain Without Core Boiling

The capability of the flow from the RWST to prevent core boiling should be evaluated. Process variables evaluated should include (1) the driving head between the lowest permitted level in the RWST and the highest reactor coolant vent location, (2) the minimum achievable coolant flow rate from the RWST considering flow resistances throughout the system, and (3) a realistic convective heat transfer rate which exceeds decay heat levels based on coolant temperatures and flow rates.
4.3 **Secondary Venting and Options for Replenishing Inventory**

It is suggested the usefulness of venting the steam generator secondary system be considered. Venting appears to be desirable, however, the capability to do so, proper timing, and appropriate cooldown rates should be ascertained. The capability for replenishing secondary inventory via low pressure sources (if the secondary is vented) or via turbine-driven auxiliary feedwater (if the secondary is unvented) should be confirmed.

4.4 **Use of High-Point Vents for Venting Air**

Babcock and Wilcox plants include high-point vents on the hot legs and reactor vessel upper head. Most plants of other designs include reactor vessel upper head vents. Since the presence of air impedes the reflux process, the use of high-point vents to flush air from the primary coolant system should be evaluated.

4.5 **Ambient Heat Loss Effects During Core Boil-Off**

The ambient heat loss from the reactor system to containment at normal operation is about 8 MW and is within the decay heat range of interest. It is recommended that the limits of core cooling by ambient heat loss during a core boil-off be considered. Ambient heat losses may provide a lower limit on the range of core decay heats for which a loss-of-residual heat removal event requires appropriate action.
5. RECOMMENDED RESEARCH

Additional NRC-sponsored research appears to be needed regarding reflux cooling in the presence of noncondensable gas. The concern is that the pressure increase required to initiate and/or continue reflux cooling in a closed system may challenge the integrity of the primary coolant system (the temporary thimble tube seals, temporary level instrumentation, or nozzle dams). If feed-and-bleed is initiated in conjunction with refluxing, the concern is the effect the inflow from the RWST and the outflow through the openings may have on the reflux process. The objectives of this recommended research are to confirm the initiation and continuation of reflux cooling in the presence of air or nitrogen and to provide data against which the performance of the calculational tools may be assessed. Most importantly, the improved understanding should be useful for generation of operating procedures and training programs.

Existing system code (RELAP5 and TRAC-PFL) capabilities in this area appear to be limited because noncondensable gases are tracked with, and are in thermal equilibrium with, the steam phase. The system code models are therefore not capable of simulating separate migration behavior for steam and noncondensable gas. The significance of this behavior to the overall simulation of a loss-of-residual heat removal event needs to be determined.

Low pressure integral scale testing in existing experimental facilities would prove to be useful to verify the reflux initiation and continuation phenomena postulated in the Vogtle report. A review of the pertinent PKL-III data should be made when it becomes available to determine if it is sufficient to address this issue. Since the one experiment performed was at a fairly high power (0.7 and 1.0% of full power) and with only one steam generator operational, additional data are likely needed. Candidate facilities include PKL (Germany), ROSA-IV (Japan), and BETHSY (France). If steam and noncondensable gas migration and mixing are not sufficiently understood from the integral experiments, then these
effects should be independently studied using additional separate effects experiments. This separate effects data would answer questions regarding steam migration to the U-tubes.

The experimental data should then be used to assess the appropriate calculational tools. The pressure rise needed to initiate reflux should be quantified, possible interactions between the reflux, RWST feed, and drain/vent processes should be studied, and the data used for model assessment and development, if necessary. The calculational tools could then be used for a complete analysis of system behavior following a loss-of-residual heat removal event.

The product of this research would be a sufficient understanding of the phenomena involved with reflux cooling in the presence of noncondensable gas; this understanding would lead to an improvement in plant operations, procedures, and operator training.
6. REFERENCES


9. PKL Experiment IIIB4.5 - to be published.


Appendix A

Scoping Calculations

Contents

A1.) Steam Generator U-tube Flooding Calculations................................. A-1

A2.) Horizontal Stratification in the Hot Legs................................................ A-5

A3.) Flooding at the Hot Leg Bend............................................................ A-11

A4.) Flooding in the Pressurizer Surge Line............................................. A-14

A5.) References......................................................................................... A-16
A1.) Steam Generator U-tube Flooding Calculations

This section discusses the Wallis-typeflooding correlation calculations used to investigate the possibility of flooding in steam generator U-tubes [1]. Flooding has been shown in a number of experiments [2,3,4,5,6] to occur when the value of the non-dimensional superficial vapor velocity,$\dot{J}_g$, was greater than 0.5. Wallis defined $\dot{J}_g$ as

$$\dot{J}_g = \frac{J_g \sqrt{\rho_g}}{\sqrt{gD(\rho_f - \rho_g)}}$$

where,

- $D$ = Tube diameter.
- $g$ = Acceleration due to gravity
- $J_g$ = Superficial vapor velocity
- $\rho_g$ = Density of steam
- $\rho_f$ = Density of water

A mass and energy balance in the primary loop is used to obtain the following expression for the superficial vapor velocity

$$J_g = \frac{Q}{\rho_g h_{fg} A}$$

where,

- $A$ = Cross sectional area of the U-tubes in one steam generator times the number of active steam generators.
- $h_{fg}$ = Latent heat of vaporization
- $Q$ = Core decay heat.

An active steam generator in this context means one which is capable of removing heat from the primary system. For simplicity, it is assumed that there is no flow through inactive loops, i.e., through loops with inactive steam generators. This convention will be used throughout this appendix.
Calculations of $j_g$ were performed by varying the decay heat and the number of active loops for pressures of both 1.0 atm and 2.0 atm. The results of these calculations are given in Figures A1.1 and A1.2. Relevant data used are given below:

- Rated plant power = 3411 MW
- Number of U-tubes/steam generator = 5626
- SG U-tube piping inner diameter = .688 inches
- Number of primary loops = 4

Note that at atmospheric pressure, flooding is possible only when 15 MW of decay heat must be removed by one active steam generator. When the pressure is increased to 2.0 atm, this decay heat value is increased to approximately 20 MW. These calculations demonstrate that flooding in the steam generator U-tubes is not likely under reduced inventory conditions.
**Jg* VERSUS DECAY HEAT AND NUMBER OF ACTIVE STEAM GENERATORS AT ATMOSHPERIC PRESSURE**

![Graph showing Jg* versus decay heat and number of active steam generators.](image)

- **Legend:**
  - 4 SGs
  - 3 SGs
  - 2 SGs
  - 1 SGs
  - Jg* Critical

- **Key Points:**
  - Liquid hold-up in steam generator U-tubes
  - No liquid hold-up

- **Axes:**
  - Y-axis: Jg*
  - X-axis: Power (MW) Days After Shutdown

**Figure A1.1**
$Jg^*$ VERSUS DECAY HEAT AND NUMBER OF ACTIVE STEAM GENERATORS AT A PRESSURE OF 2 atm

![Graph showing $Jg^*$ versus decay heat and number of active steam generators at a pressure of 2 atm.](image)

Liquid hold-up in steam generator U-tubes

- $Jg^*$ crit.
- 4 SGs
- 3 SGs
- 2 SGs
- 1 SG

No Liquid hold-up

Power (MW)

Days After Shutdown

Figure A1.2
A2.) Horizontal Stratification in the hot legs

This section addresses the possibility of loss of horizontal stratification in the hot legs, which subsequently signals the loss of classical reflux condensation. These calculations are used to determine the range of decay heat over which classical reflux is possible.

Three different hot leg liquid levels were considered in these calculations. These levels, measured from the bottom of the hot leg pipe (see Figure A2.1), were: one quarter of the pipe diameter, mid-pipe, and three-quarters of the pipe diameter. The results of the calculations are shown in Figures A2.2 through A2.4, which demonstrate the behavior of the hot leg velocity as a function of the decay heat and the number of active loops. Figure A2.2 shows that for \( h/D = 0.25 \), the loss of horizontal stratification is not a concern. When the hot leg liquid level is at mid-pipe (\( h/D = 0.5 \)), the loss of horizontal stratification is possible with one active loop for decay heat levels greater than 9 MW, and with two active loops for decay heat levels greater than 19 MW (Figure A2.3). The results for \( h/D = 0.75 \) indicate that loss of horizontal stratification is possible for almost all cases considered, except when four loops are active and the decay heat is less than 5 MW (Figure A2.4).

The loss of horizontal stratification is assumed to occur if the hot leg vapor velocity is greater than the critical velocity defined by Taitel-Dukler [7,8]. This critical velocity is defined as

\[
V_{cr} = \frac{1}{2} (1 - \cos \theta) \sqrt{\frac{(\rho_f - \rho_g) g \alpha}{\rho_g D \sin \theta}}
\]

where,

- \( A \) = Cross sectional area of the hot leg piping
- \( D \) = Tube diameter
- \( g \) = Acceleration due to gravity
- \( \alpha \) = Hot leg void fraction
- \( \rho_g \) = Density of steam
- \( \rho_f \) = Density of water
\( \theta \) = Angle between a vertical line through the pipe center and the stratified liquid level at the pipe inner wall (see Figure A2.1).

Figure A2.1, below, illustrates the hot leg cross sectional geometry [3].

\[ \begin{align*} 
V_g &= \frac{Q}{\rho_g h_{fg} A^*}, \\
\mbox{where} \\
A^* &= \mbox{Cross sectional steam flow area in the hot leg.} \\
h_{fg} &= \mbox{Latent heat of vaporization} \\
Q &= \mbox{Core decay heat removed by each active steam generator.} \\
\end{align*} \]
assumed that there is no flow through an inactive loop. Relevant data used in these calculations are given below:

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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<td>Rated plant power</td>
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<td>Hot leg piping inner diameter</td>
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<tr>
<td>Number of primary loops</td>
<td>4</td>
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Hot Leg Steam Velocity vs. Decay Heat and No. of Active Loops (Pipe Level = .25D)

Figure A2.2
Hot Leg Steam Velocities vs. Decay Heat and No. of Active Loops (Pipe Level at Mid-Pipe)

![Graph showing steam velocities vs. power and days after shutdown for different loop configurations.]

Power (MW)
Days After Shutdown

Figure A2.3
Hot Leg Steam Velocity vs. Decay Heat and No. of Active Loops
(Liquid Level in pipe = .75D)

Figure A2.4
A3.) Flooding at the Hot Leg Bend

The calculations of hot leg flooding characteristics were based on the Kutateladze Correlation [8]. Hot leg flooding can affect core level depression and reflux efficiency.

The Kutateladze correlation chosen, is given by,

$$\sqrt{K_g} + \sqrt{K_1} = \sqrt{3.2}.$$  \hspace{1cm} (5)

Flooding occurs when there is no liquid downflow ($K_1 = 0$) or when $K_g = 3.2$. $K_g$ is defined by

$$K_g = \alpha \sqrt{\frac{(\rho_f - \rho_g) \sigma g}{\rho_g}} \times \frac{1}{4}.$$  \hspace{1cm} (6)

where

$g$ = Acceleration due to gravity

$\alpha$ = Void fraction

$\rho_g$ = Density of steam

$\rho_f$ = Density of water

$\sigma$ = Surface tension.

A mass and energy balance in the primary loop is used to obtain an expression for the superficial vapor velocity

$$j_g = \frac{Q}{\rho_g h_{fg} A}.$$  \hspace{1cm} (7)

where,

$A$ = Cross sectional area of the hot legs

$h_{fg}$ = Latent heat of vaporization
\[ Q = \text{Core decay heat.} \]

Calculations of \( K_g \), at atmospheric pressure, were performed by varying the decay heat and the number of active loops. The results are given in Figure A3.1. Relevant data used in the calculations are:

- Rated plant power: \( 3411 \text{ MW} \)
- Hot leg piping inner diameter: \( 29 \text{ inches} \)
- Number of primary loops: \( 4 \)

The results show that at atmospheric pressure, flooding would occur only when one active steam generator is required to remove approximately 10 MW or more of decay heat.
Kg Versus Decay Heat and Number of Active Steam Generators at Atmospheric Pressure

Figure A3.1
A4.) Flooding in the Pressurizer Surge-Line

The calculations of flooding characteristics in the pressurizer surge line are also based on the Kutateladze Correlation [8]. Flooding in the vertical section of the pressurizer surge line can cause core level depression due to liquid hold-up in the pressurizer. NUREG 1410 indicated that a column of water in the pressurizer can also cause erroneous reactor coolant system level indications when the temporary reactor vessel level indication system (RVLIS) is used during reduced inventory operation [9]. Equations (5), (6), and (7) in the previous section are used to determine flooding characteristics in the pressurizer surge-line.

Calculations of $K_g$ were performed at atmospheric pressure. The fraction of the core generated steam entering the pressurizer surge line and the decay heat were varied to determine flooding tendencies. The results of these calculations are shown in Figure A4.1. Relevant data used in the calculations are:

- Rated plant power = 3411 MW
- Surge line piping inner diameter = 14 inches

Figure A4.1 demonstrates that if all the steam generated in the core enters the pressurizer surge line, flooding is possible at all decay heats considered. If one quarter of the steam produced in the core enters the pressurizer surge line, flooding is possible only if the decay heat is greater than 11 MW.
Kg vs. Decay Heat and and Fraction of Steam Entering Pressurizer Surge Line

Figure A4.1
A5.) References


**APPENDIX B**

LOW PRESSURE REFLUX/BOILING CONDENSATION WITH NONCONDENSABLES IN PRESSURIZED WATER REACTORS

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</table>
B1.) Introduction

The Vogtle Electric Generating Plant experienced a loss of the Residual Heat Removal (RHR) system on March 10, 1990. The incident occurred with Unit 1 shut down during a refueling outage. The water level in the reactor vessel had been lowered to the mid-loop level, and consequently a significant amount of air occupied the upper elevations of the primary system. The emergency diesel generator was manually restarted in the emergency mode 36 min. after the loss of power. It was able to provide sustained power to the RHR system, eliminating the necessity for non-routine actions to maintain adequate core cooling.

This appendix is concerned with the situation where restoration of power to the RHR system is not possible, and an alternative method of core cooling is necessary. In particular, the effectiveness of reflux/boiling condensation as an alternative cooling mechanism is of primary interest. The goal of this appendix is to synthesize the results of relevant experiments and analysis, in order to improve the understanding of the plant thermodynamic behavior associated with reflux/boiling condensation cooling during reduced inventory operation with significant amounts of non-condensable gases present.

On March 23, 1990 an Incident Investigation Team was sent to Vogtle by the Executive Director for Operations of the U.S. Nuclear Regulatory Commission. The results of the team's investigation are documented in NUREG-1410 [1]. Of particular interest to this discussion is Section 8.3 of that document, entitled "Reflux Cooling and Effect of Reactor Coolant System Water Level", which studies the feasibility of reflux cooling in the situation mentioned above. The reflux cooling option is desirable when boiling cannot be prevented by gravity-feed cooling, and when the Reactor Coolant System (RCS) is closed (i.e., the steam generator and pressurizer manways, and the reactor vessel head are sealed).

NUREG-1410 identified the need for additional analysis of the reactor coolant system following the loss of the RHR system. It was noted that the plant thermodynamic behavior associated with reflux cooling is not well
understood during a plant shutdown situation. It was stated that little work has been done to provide guidance with regard to preventing core boiling, reasonably setting up for reflux cooling, and how to minimize risk if electrical power is lost. The Incident Investigation Team envisioned the following problems with regard to reflux condensation:

- If the hot leg water level is too high, the steam flow is impeded and reflux condensation may be disrupted.
- If the steam generator tubes are liquid full, drainage of the tubes must occur before steam can reach the tube surfaces and condense.
- Air may prevent steam from entering the steam generator tubes.

The calculations performed by the Incident Investigation Team indicated that reflux cooling is effective regardless of the initial reactor system water level as long as the following requirements are satisfied:

- The initial vessel liquid level is above the top of the core.
- Steam generators are operable.
- Uncontrolled loss of reactor coolant does not occur.

It was also noted that stable modes of reflux cooling can be reached with operator adjustments to the reactor coolant system inventory. Thus, the need for accurate water level indication was identified [1]. This need was apparent after the Diablo Canyon incident in April of 1987 [29]. Considerable uncertainty was associated with the Reactor Vessel Refueling Level Instrumentation System (RVRLIS).

Experiments in integral test facilities such as SEMISCALE [2,3,4,5], LOFT [6], PKL [7,8,9], FLECHT-SEASET [10,11], EPRI/SRI [12], LSTF [13,14], and BETHSY [15] have demonstrated that reflux cooling is an effective means of decay heat removal in plants with U-tube Steam Generators (UTSGs). Local or separate effects experiments, such as those performed at the University of California at Santa Barbara [16,17], M.I.T. [18], by Hein et. al. [19], and the at University of California at Berkley [20], have discovered unstable U-tube flow characteristics during the reflux condensation mode of natural circulation.
Several of the above references address potential adverse effects associated with flooding and steam generator liquid hold-up, and loop liquid seal formation which may occur during reflux cooling. The situation during the Vogtle incident was further complicated by the low system pressure and the presence of large amounts of air in the steam generator U-tubes. The experiments conducted by FLECHT-SEASET, PKL, EPRI/SRI, and the University of California at Santa Barbara considered the effects of noncondensables on reflux cooling at low pressure. Thus, these tests are considered more relevant to the Vogtle incident than the high pressure (~ 1000 psi) experiments performed in SEMISCALE, LOFT, LSTF, and BETHSY, or the work by M.I.T. and Hein, et. al which did not examine the effects of significant amounts of noncondensible gases on boiling condensation.

Experiments in integral test facilities such as MIST [24], OTIS [26], and those at EPRI/SRI [25] and the University of Maryland at College Park (UMCP) [27] have demonstrated the effectiveness of boiling condensation as a heat removal mechanism in plants with Once Through Steam Generators (OTSGs). MIST and EPRI/SRI experiments investigated the effects of noncondensable gases, but the MIST experiments were conducted at high pressure and with a cold leg break so that the primary system was not closed. OTIS and UMCP experiments did not consider the effects of noncondensables.

The results of these experiments were examined to determine the effects of noncondensable gases, flooding, loop seal formation/clearing, degraded secondary conditions, and low pressure. This appendix is organized into four major sections. The following section describes the phenomena associated with reflux condensation cooling in plants with a UTSG type design. Section 3 addresses the phenomena associated with boiling condensation in plants with OTSGs. Section 4 discusses RELAP5 simulation of the transient phenomena, and the last section consists of summary and conclusions.
B2.) Reflux Condensation Phenomena in Plants with UTSGs

B2.1) Introduction

In the reflux condensation mode of natural circulation, single-phase vapor generated in the core flows through the hot leg piping, is condensed in the steam generators, and flows back to the core as a liquid. Experiments have demonstrated that, in the absence of noncondensables, an approximately equal condensation split exists between the upflow and downflow sides of the steam generator U-tubes [2,4,21]. In the upflow sides of the steam generator U-tubes a counter-current flow of vapor and condensate is established. Condensate drains back to the core via the hot leg while vapor continues to flow over the U-tube upper bend. In the downflow sides of the steam generator U-tubes vapor and condensate flow co-currently into the cold leg suction piping. Figure B2.1 illustrates this phenomena in a single U-tube. Since the primary heat transfer mechanism during reflux cooling is condensation, small primary-to-secondary temperature differences and mass flow rates are characteristic of this mode of natural circulation [2,7,15,25].

NUREG-1269, which investigates the loss of RHR at Diablo Canyon in April of 1987 during reduced inventory operation with noncondensables, describes the following three possible directions the steam-gas mixture can flow from the vessel [29]:

1.) The vessel upper head, and as the pressure increases the steam-gas mixture may be vented through the reactor vessel upper head vent (RVUHV) or through the vessel bypass paths. However, the vent flow is much smaller than the steam generation rate so that this path will not relieve the reactor coolant system pressure.

2.) The hot leg and into the pressurizer via the pressurizer surge line. A vent path exists in the pressurizer through the power operated relief valve (PORV).

3.) The hot leg and into the steam generator U-tubes. No vent path is available unless a steam generator manway is open.
Figure B2.1. Liquid distribution in a single U-tube during reflux condensation.
Note that the steam-gas mixture will most likely follow the first two paths until the pressure increases sufficiently to expose a condensation surface in the steam generator U-tubes.

B2.2) Flooding Effects (Non-Uniform U-tube Flow)

During reflux condensation, flooding is possible in the counter-current flow regions in the upflow sides of the steam generator U-tubes, and the stratified counter-current flow regions in the hot legs. The tendency for flooding may be enhanced by a low system pressure and the presence of non-condensible gases. Low system pressure results in lower steam densities and hence, higher steam velocities. Noncondensable gases in the steam generator U-tubes cause a greater fraction of the condensation to occur in the upflow sides of the U-tubes. As a result, more condensate must drain from these tubes and the likelihood of liquid holdup is increased. Flooding has been observed in a number of reflux condensation experiments [5,13,14,15,16,17,18].

In order to describe the flooding effects upon the reflux flow behavior, the terminology of Nguyen et. al. will be adopted [16]. They identified three distinct U-tube flow modes associated with reflux condensation. At low vapor velocities the classical reflux condensation phenomena was observed. At the onset of flooding at the steam generator inlet, there is a transition from the classical reflux mode to what Nguyen et. al. labeled the oscillatory mode [16]. This mode is characterized by the formation of liquid columns in the riser sections of the steam generator U-tubes. The transition to the oscillatory mode begins when portions of the liquid condensate are carried upwards by the vapor flow. This phenomena can be quantified with a Wallis-type flooding correlation. Liquid hold-up was observed when the non-dimensional superficial vapor velocity, \( j_g^* \), was 0.50. This result is supported by high pressure LSTF data in which liquid hold-up occurred for \( j_g^* = 0.4 \) and \( j_g^* = 0.56 \) corresponding to core powers of 5% and 7%, respectively [13]. Flooding also occurred in the FLECHT-SEASET facility for \( j_g^* \sim 0.50 \) which correspond to core power levels of about 2.5% at a pressure of 140 psia. Thus, in the FLECHT-SEASET facility there were no stable reflux modes for decay heat levels greater than 2.5% core power.
The carry-over mode occurs when sufficiently high vapor velocities are able to carry the condensate over the upper U-bends of the U-tubes. In this situation, a co-current flow of liquid and vapor exists in both the upflow and downflow sides of the steam generator U-tubes and a transition to two-phase natural circulation may occur. The transition to the carry-over mode was observed by Nguyen et. al. to occur when $j^* = 0.9$ [16], while LSTF experiments observed this flow mode when $j^* = 0.8$ (10% core power).

Flow modes similar to those described above have also been observed by Calia and Griffith [18], BETHSY [15], Hein et. al. [19], Semiscale [2], and in PKL [7]. The three modes of U-tube behavior described above are illustrated in Figure B2.2.

Of particular concern with regard to nuclear reactor safety analysis is the oscillatory U-tube flow mode. A positive hydrostatic head in the steam generator U-tubes exerts a back pressure on the core liquid level; and, while core cooling remains effective, core liquid level depression is possible [17]. This effect was first observed in Semiscale, where it was discovered that core coolant level depression during pump suction liquid seal formation can be aggravated by the existence of a positive hydrostatic head in the steam generator U-tubes [5].

The oscillatory mode was so named due to the observed periodic fill and dump behavior in the U-tubes. As the liquid column in a U-tube reached the top of the U-tube bend, spillover would occur. After spillover, a siphoning effect would pull the liquid column over the U-tube bend. Steam flow in this cleared tube would then increase significantly, allowing the remaining tubes to partially drain until the pressure drops in all tubes were equal. A liquid column would again form in the cleared tube and the pattern would repeat. The spillover event appeared to occur randomly in any one of the U-tubes. It is believed that the random nature of the fluctuations of the liquid columns is the cause of the randomness in the spillover event [17]. In the presence of noncondensable gases, spillover events may act to redistribute the noncondensables to other non-cleared U-tubes or to other locations in the primary loop. The distribution of the noncondensables in the primary loop is very important in determining the thermal hydraulic behavior of the system.
Reflux condensation  Oscillatory  Carryover

Figure B2.2. Two-phase flow patterns in an inverted U-tube [17].
A redistribution of gases due to U-tube spillover events should be considered when determining the system thermal hydraulic response.

It should be pointed out that calculations of steam velocities in the Vogtle steam generators as a function of decay heat, when compared with criteria for the onset of flooding, indicate that flooding would be unlikely to occur under conditions occurring during reduced inventory operation. At decay heat levels as high as 30 MW, flooding would not occur as long as two or more steam generators are active. With only one steam steam generator available, flooding would not be expected at decay heats below 15 MW. Decay heat levels would be below this value two days after shutdown. The results of the flooding calculations are shown in Figure B2.3.

Several additional comments should be made with regard to U-tube flow phenomena during reflux cooling. First, it is noted that the experimental results cited above are based on a limited number of U-tubes in the steam generators. In this situation, individual tube behavior has a greater affect on the system thermal hydraulic response than it would in an actual PWR steam generator with a much larger number of U-tubes [4] (thousands of tubes). In addition, the tube-to-tube interactions which may occur through the steam generator inlet and exit plena are not understood. Finally, the University of California at Santa Barbara research indicated that the common advanced thermal-hydraulic analysis systems codes, RELAP5 and TRAC-PF1, have difficulty predicting the onset of the oscillatory U-tube flow mode and the growth of the liquid column [17].

B2.3.) Loop Seal Formation/Clearing Phenomena

During mid-loop operation, a liquid seal exists in the loop cold leg suction piping. During reflux cooling, the liquid seal impedes the flow of vapor through the loop piping. An experiment conducted in the Semiscale facility demonstrated that the effect of the loop seal is more complicated than a simple manometric balance between the reactor vessel and downflow leg of the loop seals [5]. The important parameters were identified as the core vapor
Figure B2.3. \( J_{g^*} \) vs. decay heat levels and number of active steam generators at atmospheric pressure.
generation rate, the core coolant bypass flow, the U-tube condensation rate, and flooding.

If the core vapor generation rate is sufficiently high, a differential pressure may develop between the reactor vessel (hot leg) and the downcomer (cold leg) [2]. Consequently, the vessel coolant level may be depressed relative to the downcomer. In addition, this core liquid level depression may be intensified by liquid hold-up in the steam generator U-tubes resulting from flooding at the steam generator inlet.

There are often two sets of bypass paths in plants with UTSGs capable of removing steam from the upper vessel plenum to the downcomer. One set is the downcomer inlet annulus-to-upper head flow path, and the second set is leakages through the gaps at each hot leg penetration by the slip fit between the core barrel assembly and the reactor vessel [28]. The flow behavior through these core bypass paths during this type of transient is not well understood.

The Semiscale experiment, mentioned above, demonstrated that core voiding was possible prior to the blowout of the the pump suction liquid seals [2,5]. Figure B2.4 demonstrates the hydrostatic heads in the primary system which lead to the core liquid level depression phenomena [2].

Loop seal blowout during the high pressure Semiscale experiments was observed to be a steady process. However, in experiments conducted in the low pressure FLECHT-SEASET facility, the clearing of the loop seal was not steady. It was observed that steady state reflux condensation was periodically interrupted by venting of steam through the intact loop seal [10]. The core vapor generation rate was greater than the steam generator condensation rate and consequently, uncondensed vapor flowed into steam generator exit plenum and cold leg, displacing the liquid in those locations. The vapor depressed the liquid level in the downside of the cold leg suction piping until steam eventually vented through the loop seal. The differential pressure between the loop hot and cold leg nozzles was temporarily relieved, and the liquid seal re-formed. This process is illustrated in Figure B2.5. The following effects resulted from the venting of steam through the loop seal [10,11]:

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Figure B2.4. Demonstrations of hydrostatic heads in the primary system which can lead to core level depression [2].
Figure B2.5. Loop seal liquid distributions [11].
Fluid from the downcomer was forced into the rod bundle by the vented steam. This liquid replaced the two-phase mixture in the lower elevations of the vessel and temporarily stopped vapor generation in the lower vessel elevations. The liquid from the downcomer also forced the two-phase froth level well above the hot leg nozzle elevation.

A two-phase mixture was forced into the steam generator inlet plenum.

The flow in the steam generator U-tubes changed from a countercurrent to co-current two-phase flow.

It is believed that the periodic venting of steam through the loop seal during reflux condensation is a low pressure effect. This phenomena has also been observed in the low pressure PKL facility [11].

B2.4.) Effect of Noncondensable Gas on Reflux Cooling

Calia and Griffith [18] noted that at low pressure a small mass fraction of noncondensable gas may become a significant volume fraction in the primary system. At low pressures the influence of noncondensable gases on reflux cooling is more pronounced than at high pressures. The primary concern regarding noncondensable gases during reflux cooling is that they will accumulate in the steam generator U-tubes and disrupt the condensation of steam from the core. The following general effects of noncondensables on reflux condensation have been observed in SEMISCALE [2,4], PKL [7,8,9], FLECHT-SEASET [11], and EPRI/SRI [12]:

- The condensation of vapor from the core is shifted to the upflow side of the steam generator U-tubes while noncondensable gas is deposited in the downflow sides of the steam generator U-tubes, the steam generator exit plenum, and above the loop seal liquid vapor interface.
- The steam generator is divided into active and passive zones thereby reducing the total condensing surface area. In the case of large amounts of noncondensable gases in the primary system,
the condensing surface will be confined to a short distance above the tube sheet along the upflow sides of the steam generator U-tubes.

• If steam is unable to reach the steam generator U-tubes because of noncondensable gas blockages, the system pressure will increase until the noncondensable gas volume has been sufficiently compressed to allow condensation in the lower portions of the upflow sides of the steam generator U-tubes.

• An increase in the primary-to-secondary temperature difference is necessary to remove the core decay heat because of the reduced heat transfer area. An increase in the primary pressure also results.

Tests conducted by EPRI/SRI concluded that the amount of noncondensable gases which could be accommodated by the primary system is limited only by the design pressure of the system as long as secondary cooling is available [12]. In this low pressure (< 75 psi) experiment, Helium gas was injected into the primary system in increments which amounted to 60% of the total system volume. It was observed that reflux condensation is highly tolerant of significant amounts of noncondensable gases. When noncondensable gases prevented steam condensation, the system pressure would increase to compress the noncondensable gas volume, thereby exposing a condensing surface in the lower portions of the steam generator U-tubes. In this experiment adequate core cooling was possible with reflux cooling even with significant amounts of noncondensable gases. However, this experiment was conducted at approximately 1% core power and problems associated with flooding did not occur.

Experiments in the low pressure FLECHT-SEASET (approximately 140 psi) facility indicated that flooding is a potential problem during reflux cooling [11]. Low system pressures yield higher steam velocities and consequently, the flooding characteristics differ from those of high pressure systems. Flooding problems are also complicated by the presence of noncondensable gases, which tend to shift the condensation to the upflow sides of the steam generator U-tubes. This results in more condensate trying to drain from the upflow sides of the U-tubes. Hence, the noncondensables
increase the probability for liquid column formation in the steam generator U-tubes. The combined effects of low pressure, noncondensable gases (Helium), and flooding in experiments performed in the FLECHT-SEASET facility are discussed below.

Noncondensable gas would collect above the liquid-gas interface above the loop seal and extend upwards into the steam generator exit plenum and the steam generator U-tubes. This noncondensable gas exerted a back pressure on the vessel liquid forcing core liquid level depression. Periodic venting of the noncondensable gas through the loop seal temporarily relieved this pressure difference. However, the flooding tendency of the uphill sides of the steam generator U-tubes added to the pressure exerted on the vessel liquid level. The liquid level in the vessel was depressed to approximately two-feet below the bottom of the loop seal elevation [11]. By comparing the tests with and without noncondensable gases, it was discovered that the frequency with which steam vents through the loop seal was greater than the frequency of the noncondensable gas vents. Core uncovering did not occur in the test where noncondensable gases were not present [11]. The longer venting period in the noncondensable gas test may be due to the fact that Helium is lighter than steam. Recall that air is heavier than steam, so similar behavior might not occur when air is the noncondensable gas present in the downflow side of the loop suction. Note also that the velocity of the vapor generated in the core exceeded the steam generator U-tube flooding limit in both these tests.

B2.5) Secondary Side Effects

Experiments performed at the low pressure PKL test facility investigated the effects of reduced secondary inventory on the effectiveness of reflux cooling [9]. The results indicated that the primary-to-secondary temperature difference increased due to the reduced heat exchanger area. A halving of the primary-to-secondary heat transfer area occurred when the secondary level was lowered to uncover half of the U-tubes, and this resulted in a doubling of the temperature difference when no noncondensable gases were present. When noncondensable gases were present, this temperature difference increased by a factor of four (from 2K to 8K).
NUREG 1410 stated that at a core power of 2.5 MW, 5 days would be required to boil-off the secondary liquid [1]. However, it was also stated that if the Vogtle incident had occurred earlier in the refueling process the core power could have been as high as 17.1 MW and the time to secondary boil-off would be significantly reduced.

The presence of significant amounts of noncondensible gases in the steam generator U-tubes reduces much of the heat transfer area in the higher elevations of the steam generator tubes. Therefore, one would expect that the effects of reduced secondary inventory would become significant only when the secondary liquid level drops to the lower elevations of the steam generator U-tubes where the majority of the heat transfer occurs.

B2.6.) Vent Operation

Many Plants with UTSGs have reactor vessel upper head vent valves and pressurizer power operated relief valves. Vent operation may be used to control the primary pressure or to remove noncondensible gases. Plants equipped with these system vents have backup systems to insure operation if a loss of power event occurs. However, if these backup systems fail, it is unclear whether the environment in containment would allow for manual operation of the vent valves. In addition, effectiveness of vent operation is not well understood.

B2.7.) Summary

Reflux condensation can be an effective means of heat removal in PWRs with UTSGs even in the presence of significant amounts of noncondensible gases. Numerous experiments have demonstrated this fact [2,6,7,15,21]. Problems would arise if the decay heat level was high enough to cause flooding, and/or to generate steam faster than it can be condensed in the steam generators. However, calculations indicate this is unlikely at decay heat levels typical during reduced inventory operation.

Under shutdown conditions, special equipment such as temporary thimble tube seals, nozzle dams, and liquid level instruments may be in place.
These devices are vulnerable to failure at elevated pressures [1,29]. This equipment may impose pressure limitations on the primary system. These limitations could subsequently remove the capability of the system to compress the noncondensable gas volumes to insure a condensation surface in the steam generators.

The Diablo Canyon incident demonstrated that reflux cooling can occur during mid-loop operation upon the loss of the RHR system [29]. An order of magnitude estimate for the pressure increase necessary to initiate reflux was given in NUREG-1269 as 10psig ± 5psig. Note that this pressure is capable of causing Tygon tube rupture (failure at 2.5psig-5psig), and in fact Tygon tube rupture did occur in the Diablo Canyon Incident [29].
B3.) Boiling Condensation Phenomena in Plants with OTSGs

B3.1.) Introduction

In the case of plants with Once Through Steam Generators (OTSGs) the natural circulation behavior with a partially filled Reactor Coolant System (RCS) is quite different from the behavior encountered in plants with U-Tube Steam Generators (UTSGs). In the OTSG type plant design the hot legs consist of long vertical sections which lead to inverted U-bends ('candy cane' regions) and then drop into the top the steam generators. The steam generators themselves consist of a very large number of vertical tubes connecting the candy cane regions and steam generator outlet plenum. Steam from the core flows through the hot leg to the steam generator where it is condensed. The condensate then drains to the liquid level in the cold side of the primary loop. This mode of cooling is normally called boiling condensation.

Figure B3.1 demonstrates the liquid distribution in the primary loop during boiling condensation. Boiler Condensation operation requires the primary level to be lower than the secondary liquid pool. Consequently, this particular heat transfer process is commonly termed pool boiling condensation. A second type of boiling condensation, called EFW (Emergency Feedwater) boiling condensation, occurs when the primary liquid level is above the secondary pool within the steam generator, but a primary condensing surface exists below the EFW injection elevation. Figure B3.2 presents the loop liquid distribution during this mode of natural circulation. Experiments have demonstrated that both types of boiling condensation are effective means of heat removal [24,25,26].

B3.2.) Effect of Noncondensable Gas on Boiling Condensation

The primary question regarding boiling condensation in a OTSG with noncondensables present, is the ability of the steam generated in the core to reach a condensing surface in the steam generators. Experimental data regarding this issue is very limited. High pressure tests were performed at the MIST facility to determine the effects of noncondensible gases, but these tests also included a cold leg break [24]. Consequently, MIST data may not be
Figure B3.1. OTSG liquid levels during pool boiling condensation.
Figure B3.2. OTSG liquid levels during auxiliary feedwater (EFW) boiling condensation.
directly related to the situation discussed in this report. Additional low pressure noncondensable gas experiments were conducted by EPRI/SRI in a facility modeled after TMI-2 [25]. The EPRI/SRI results will be discussed below.

It was discovered in the EPRI/SRI experiment that the noncondensable gas in the steam generators dictated the elevation of the condensation region in OTSGs. High concentrations of noncondensable gas (Nitrogen) accumulated above the primary steam generator liquid level due to the removal of steam from the gas mixture by condensation. Since the presence of noncondensables impedes condensation, the condensing region may be forced to a higher elevation in the steam generator. If this elevation is above the secondary pool level and EFW is not available, the heat removal ability of the steam generator may be lost. A loss of the heat sink results in increases in both primary pressure and temperature. Pressure increases were observed to compress the noncondensable gas volume sufficiently to expose a condensing surface. These observations led to the conclusion that the pressure limits of the facility determine the amount of noncondensable gas which may be accommodated by the system [25]. This pressure limit is very important, especially if it is determined by the vulnerability of equipment such as nozzle dams, or temporary liquid level instruments.

B3.3.) Secondary Side Effects

The availability of EFW is an important issue, since the EFW availability guarantees the existence of a condensing surface high in the steam generators. If EFW is not operable due to loss of power, the secondary pool level must be high enough to provide a condensing surface in the steam generator or boiling condensation is not possible.

It appears that in the case of plants with OTSGs, the effect of noncondensable gas is to drive the condensing surface towards the top of the steam generator. Note that the opposite is true in the case of plants with UTSGs, where the condensing surface is driven towards the lower portions of the upflow sides of the steam generator U-tubes. Another adverse effect in the case of OTSGs is that stratification tends to place the hotter water at the top of the secondary, thus reducing the primary-to-secondary temperature.
difference in the region where condensation must occur. Therefore, the boil-off of the secondary liquid (without EFW) is a much greater concern in the case of a OTSG.

B3.4.) Vent Operation

In plants with OTSGs, reactor vessel vent valves (RVVVs) may be used to vent steam from the core into the downcomer region where condensation may occur. In addition, vents exist at the top of the hot leg U-bend region (hot leg upper head vent, HLUHV). These vents may be useful in removing noncondensable gas from the primary system.

The effectiveness of vent operation in plants with OTSGs under conditions similar to the Vogtle incident, are not well understood. Questions regarding the operability of these valves in the scenario of the Vogtle incident also exist.

B3.5.) Summary

The feasibility and effectiveness of boiling condensation in plants with OTSGs under conditions similar to the Vogtle incident is not clearly understood. Pressure limitations resulting from the vulnerability of nozzle dams or level instruments may render boiling condensation an inappropriate option.
B4.) Feasibility of RELAP5 Simulation of the Transient Phenomena

The use of RELAP5 to simulate the complex phenomena associated with condensation in the presence of significant amounts of noncondensable gases is not presently defensible because the area of application is well beyond its assessment base. Therefore care must be taken in the interpretation of results. If RELAP5 is used to model the phenomena associated with this transient, large uncertainties should be expected in the results until additional assessment and/or code improvements are made. The primary concern is that there is no model in the code capable of addressing the mixing and/or stratification of two gas phases which may occur in this situation.

Improvements and modifications have been implemented in the MOD3 version of the code, but considerable testing and code assessment is required to validate the models. Modeling of the coupled complex phenomena associated with low pressure, noncondensables, condensation, flooding, liquid holdup, and core liquid depression may not be feasible with RELAP5. Several specific deficiencies in RELAP5/MOD2 are discussed below.

One primary issue of concern is the noncondensable model in RELAP5/MOD2. An improved model has been implemented in MOD3 which enables calculations with pure noncondensible gas as a working fluid [21]. However, this improvement does not solve the problems associated with the mixing and/or stratification of steam and noncondensable gas. The code assumes perfect mixing of the gas and steam within a control volume. The mass transfer model in the presence of noncondensable gas also needs improvement.

Deficiencies in the RELAP5/MOD2 CCFL and interface drag models were identified in the assessment of the code. Developmental assessments of the modifications in the MOD3 version have shown good results, but further assessment is necessary [22,23].

Additional problems regarding the correlations used by RELAP5 in calculating the wall and interfacial shear stresses in the condensation region of a UTSG were identified by Nguyen [17]. Modifications were made to the
existing RELAP5/MOD2 interfacial shear stress model by Nguyen to improve the accuracy of the RELAP5 prediction of the interfacial shear stress. These modifications included changes in the flow regime map and the corresponding drag coefficients in the condensation region. A need for improvements in the wall shear stress model in the condensation region was also identified, but it was noted that additional experimental data may be needed before these improvements can be made [17]. Note that the modifications described above are not currently implemented in RELAP5/MOD2 or RELAP5/MOD3. The ability of RELAP5/MOD3 to predict reflux condensation, natural circulation, and the oscillatory mode was tested against the experimental data base of Nguyen et. al. [32,33]. The code had difficulty simulating the data when noncondensable gases (air) were present in the system [32].

Simulation of this type of transient also raises questions with regard to nodalization. For example, Sections B2.4 and B3.2 noted that noncondensable gases during reflux/boiling condensation can force condensation to occur in relatively small regions in the steam generators. Consequently, finer nodalization in these regions may be necessary to simulate the condensation phenomena. In short, additional investigation is necessary to identify and resolve the problems associated with nodalization during reflux/boiling condensation with noncondensables present under reduced inventory operating conditions.
B5.) Summary and Conclusions

B5.1.) Plant Initial Conditions

This report discusses the important issues related to reflux (UTSGs) or boiling (OTSGs) condensation under the following conditions:

• Primary water level near mid-loop.
• Presence of large amounts of noncondensable gases in the upper elevations of the primary loop.
• Complete loss of the Residual Heat Removal (RHR) system.
• A closed primary system, but with the possibility of reactor coolant system draining and vent operation.
• Low primary system pressure (near atmospheric).
• Possible pressure limitations due to vulnerability of shutdown equipment such as temporary thimble tube seals or level instruments.
• Wide range of decay heat levels.

Issues associated with plants with both UTSGs and OTSGs were considered. Since the behavior of these plants differ significantly in this situation, the important issues related to each type will be addressed separately.

B5.2.) Plants with UTSGs

Plants with UTSGs are capable of using the reflux condensation mode of natural circulation cooling under partial liquid inventory conditions. Experiments in many integral test facilities have investigated this mode of natural circulation cooling. Several of these include FLECHT-SEASET [10,11], PKL [7,8,9], Semiscale [2,3,4,5], LSTF [13,14], and an EPRI/SRI facility. Semiscale and LSTF are high pressure facilities, while the others listed are low pressure facilities. In addition, many local or separate effects experiments have also been performed. Several of these include University of California at Santa Barbara tests [16,17], M.I.T. tests [18], and tests conducted by Hein, et. al. [19].
Flooding and steam generator liquid hold-up are issues of concern with regard to reflux cooling. Low system pressures result in low steam densities, and high steam velocities which increases the possibility of flooding. However, calculations indicate that during reduced inventory operation decay heat levels will probably be sufficiently low to preclude flooding. Uncertainties with regard to this issue include core vessel by-pass flow, spillover effects if the liquid columns reach the tops of the U-tubes, and loop seal behavior. Evidence of flooding and steam generator liquid hold-up can be found in the results of several experiments [2,5,13,14,17].

The formation of loop seals in the cold leg suction piping impedes the flow of vapor during reflux cooling [5,10,11,29]. If the vapor generation rate is greater than the condensation rate, the liquid levels in the core and in the downflow side of the loop seal may be depressed. Liquid hold-up in the steam generator U-tubes will aggravate this effect and may result in a core liquid level depression to an elevation below the bottom of the loop seal elevation. Low pressure experiments also observed the periodic venting of steam or noncondensable gases through the loop seal to relieve the loop differential pressure [10,11]. Uncertainties with regard to loop seal behavior include core by-pass flow, steam generator liquid hold-up due to flooding, and steam generation/condensation rates.

The presence of noncondensable gases in the steam generator U-tubes of the primary loop raises the question of whether the steam produced in the core can reach a condensing surface in the steam generators. Experiments have discovered that if a condensing surface does not exist, pressure increases will compress the noncondensable gas volume sufficiently to expose a condensing surface in the lower portions of the steam generator U-tubes [2,4,7,8,9,11,12]. The shift in the condensation region to this location due to the presence of the noncondensable gases increases the possibility of liquid hold-up in the steam generator U-tubes. Other experimental observations include the accumulation of noncondensable gases above the gas-liquid interface of the loop seal. The venting period of noncondensables through the loop seal was found to be greater than the period observed for pure steam. Thus, the potential for core liquid level depression due to the loop seal formation is greater when noncondensable gases are present. Uncertainties with regard to
noncondensables include noncondensable gas-steam mixing, the potential for removing noncondensables through venting, and the redistribution or migration of noncondensables if a spillover events occur in the steam generator U-tubes.

Primary system pressure limitations due to the presence of shutdown equipment such as temporary thimble tube seals nozzle dams, and liquid level instruments could restrict the use of reflux cooling. If noncondensables prevent steam from reaching a condensing surface in the steam generators, reflux cooling is not possible unless primary pressure increases compress the noncondensable gas volume sufficiently to expose a condensing surface. Pressure and temperature increases will also occur due to the reduced heat transfer area in the steam generator U-tubes because of the noncondensables present in the tubes.

B5.3.) Plants with OTSGs

Plants with OTSGs are capable of using boiling condensation to remove core decay heat. Two types of boiling condensation are possible in the OTSG. Pool boiling condensation occurs when the primary level is below the secondary pool level within the steam generator. Auxiliary feedwater (AFW) boiling condensation normally occurs when pool boiling is not possible, but a condensing surface exists below the AFW sparger spray elevation. Experiments investigating boiling condensation include those performed at MIST [24], EPRI/SRI [25], OTIS [26], and the University of Maryland at College Park (UMCP) [27]. Low pressure integral tests investigating the effects of noncondensables are limited to the work done by EPRI/SRI [25].

In the presence of large amounts of noncondensable gases, the primary concern is the ability of steam to reach the steam generators. Observations at EPRI/SRI [25] indicated that the amount of noncondensable gases in a steam generator dictated the elevation of the condensation region. High concentrations of noncondensable gases accumulate above the primary liquid level in the steam generator since most of the steam has been condensed from the gas mixture. Condensation was impeded by these high concentrations of noncondensable gases and the condensation region was driven to a higher
elevation in the steam generator. If the condensation region is driven above the top of the steam generator tube sheet or above the secondary liquid level, a pressure increase is necessary to compress the noncondensable gas volume and regain a heat sink. Uncertainties with regard to the effectiveness of boiling condensation with large amounts of noncondensables include the availability of AFW, limits on the primary pressure (level instruments, etc.), secondary liquid level, operation of vents to control pressure and/or to remove noncondensable gases.

B5.4.) Use of RELAP5 to Simulate the Transient Phenomena

The use of RELAP5 to simulate the complex phenomena associated with condensation in the presence of significant amounts of noncondensable gases, is not presently defensible. The models used by the code cannot simulate all of the complex phenomena associated with this type of transient. The primary concern is that there is no model in the code capable of addressing the mixing and/or stratification of two gas phases. Additional investigation is necessary to determine if other codes exist, which can effectively model the phenomena described above. Development of new models or code modifications may be needed if there are no existing codes with this modeling capability.
REFERENCES


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