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T21b - Selected Examples of Natural Circulation for Small Break LOCA and Som Severe Accident Conditions

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SELECTED EXAMPLES OF NATURAL CIRCULATION FOR SMALL BREAK LOCA AND SOME SEVERE ACCIDENTS

Presented by

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COURSE ROADMAP

Opening Session

- INTRODUCTIONS
- ADMINISTRATION
- COURSE ROADMAP

Introduction

- GLOBAL NUCLEAR POWER
- ROLE OF N/C IN ADVANCED DESIGNS
- ADVANTAGES AND CHALLENGES

Local Transport Phenomena & Models

- LOCAL MASS, MOMENTUM AND ENERGY TRANSPORT PHENOMENA
- PREDICTIVE MODELS & CORRELATIONS

Integral System Phenomena & Models

- SYSTEMS MASS, MOMENTUM AND ENERGY TRANSPORT PHENOMENA
- N/C STABILITY AND NUMERICAL TECHNIQUES
- STABILITY ANALYSIS TOOLS
- PASSIVE SAFETY SYSTEM DESIGN

Natural Circulation Experiments

- INTEGRAL SYSTEMS TESTS
- SEPARATE EFFECTS TESTS
- TEST FACILITY SCALING METHODS

Reliability &Advanced Computational Methods

- PASSIVE SYSTEM RELIABILITY
- CFD FOR NATURAL CIRCULATION FLOWS

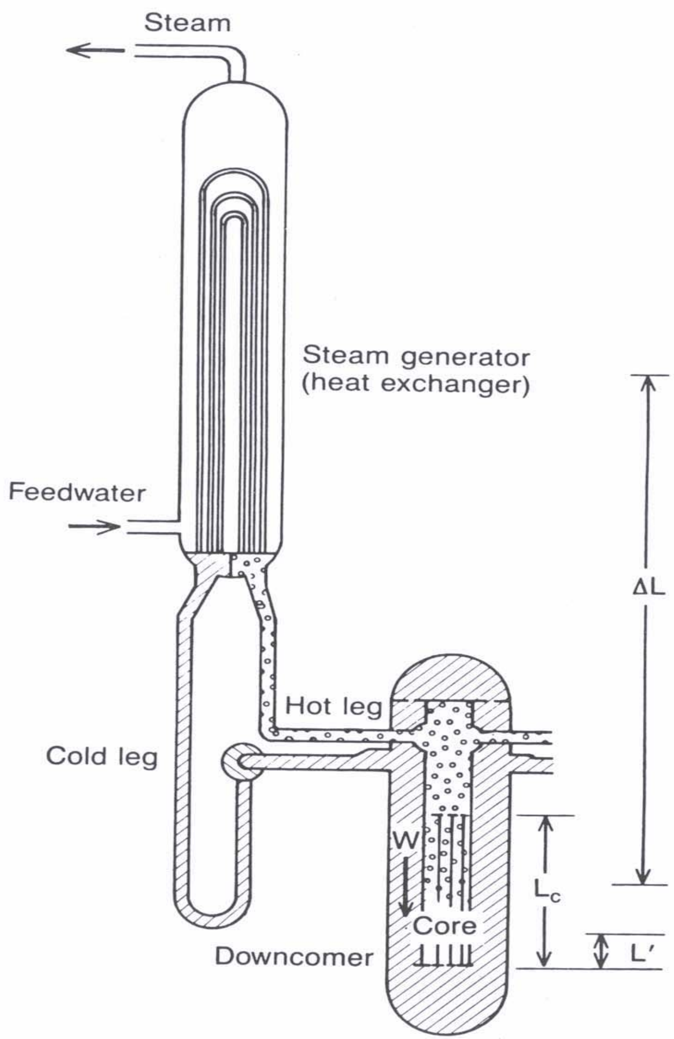
OVERVIEW

- Introduction
- Origin of small break LOCA issue (system thermal-hydraulics before and after TMI-2)
- Small break LOCA scenario in a PWR with relevance to nuclear reactor safety and main phenomena
- Natural circulation and its importance during SB LOCA
- Short description of severe accident scenario in PWR leading to natural circulation
- Description and importance of natural circulation during severe accidents
- Concluding remarks

INTRODUCTION

- The natural circulation cooling is an essential means of removing shutdown decay heat in PWRs following the loss of forced circulation by the reactor coolant pumps (RCPs) during operational transients or following accidents.
- Natural circulation in PWRs refers to primary coolant flow within the loops of a closed primary system and is driven by differences in the average coolant density within the loops of primary system.
- These density differences result from the heating of the reactor coolant in the core and the subsequent cooling of the reactor coolant in the steam generators, which are elevated relative to the core, resulting in a loop gravitational driving force.
- Provide overview on the importance of natural circulation for small break LOCA and severe accident cases with emphasize on natural circulation phenomena for PWRs utilizing U-tube steam generators.

Schematic of a typical PWR system and elevations



ORIGIN OF SMALL BREAK LOCA ISSUE (I)

- Public hearings by former U.S. Atomic Energy Commission, in early 1970's
- Resulting in ECCS Rule 10 CFR 50.46 and associated Appendix K
- The safety criteria prescribed in 10 CFR 50.46 are applicable to both large and small break LOCA
- Conservative prescriptions of Appendix K resulted in the large break LOCA generally being the most limiting accident
- Major safety research program to support code development for large break LOCA in mid-70's

ORIGIN OF SMALL BREAK LOCA ISSUE (II)

- TMI-2 accident in March 1979; extensive reorientation of LWR safety research programs and also regulatory changes
- Consequent to TMI-2 small break LOCA and plant operational transients received major attention
- Phenomena are significantly dependent on facility scale and geometry
- Operational facilities were modified to carry small break LOCA experiments and new facilities designed and constructed

SB-LOCA SCENARIO IN A PWR WITH RELEVANCE TO NUCLEAR REACTOR SAFETY AND MAIN PHENOMENA (I)

- **Rates of coolant discharge and pressure variations with time are major characteristic difference between a small break and a large break LOCA.**
- **Another principal difference is the domination of gravity effects in small breaks versus inertial effects in the large breaks.**
- **Small break LOCA's are characterized by an extended period after the occurrence of the break, during which the primary system remains at a relatively high pressure and the core remains covered**
- **As soon as the pumps are tripped (automatically or manually), gravity controlled phase separation occurs and gravitational forces dominate the flow and distribution of coolant inside the primary system.**

SB-LOCA SCENARIO IN A PWR (II)

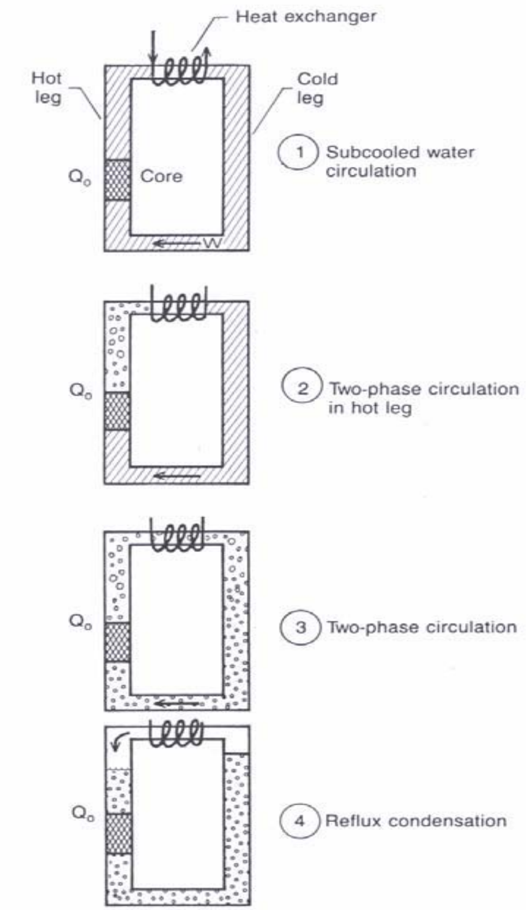
- **Unlike large break LOCA, the sequence of events following a small break LOCA in PWRs can evolve in a variety of ways, no unique path**
- **Some factors effecting how the scenario unfolds:**
  - **Operator actions** (e.g., pumps on or off)
  - **Reactor design** (e.g., U-tube or once-through SGs
  - **ECCS set points,**
  - **Size of core by-pass,**
  - **Break size and location,**
  - **Etc.**
- **Consequently, a best-estimate code must have sufficient modelling capabilities to take these factors into account**
- **An adequate set of modelling capabilities for any of the plausible scenarios will be equally adequate for all other scenarios**

SB-LOCA SCENARIO IN A PWR (III)

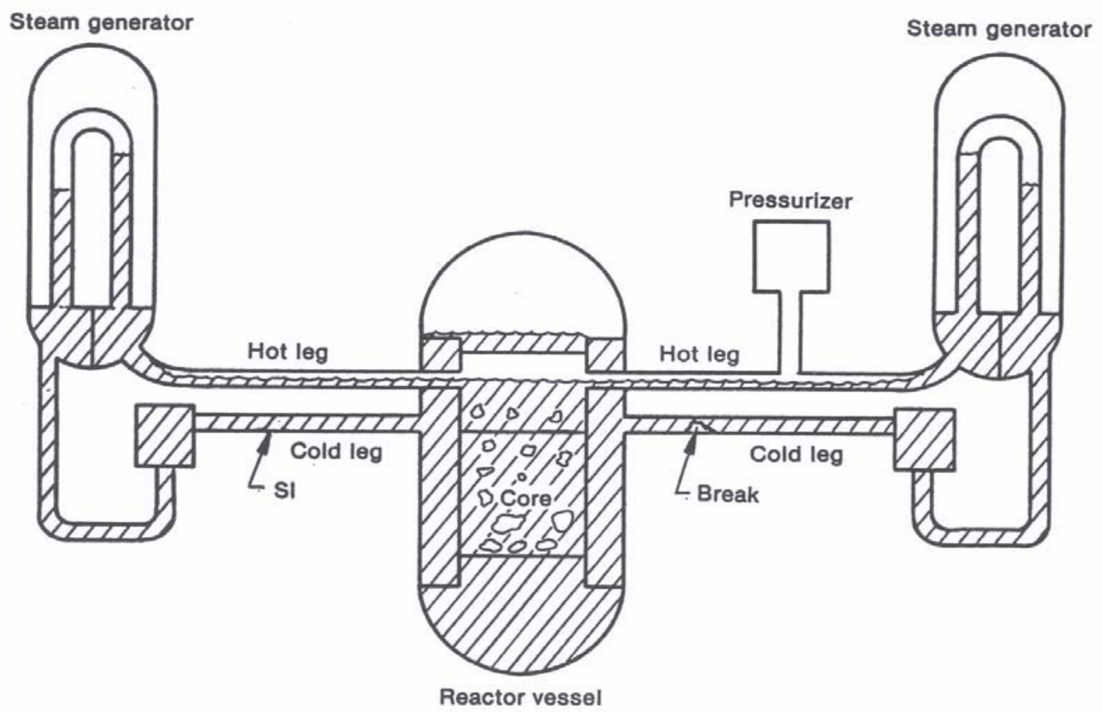
- **The phenomena and processes are the same but their interactions and timing of various developments changes in different operations**
- **During a PWR small break LOCA, three distinct core heat-ups can occur:**

  - The first heat up is caused by loop seal formation and the manometric core liquid level depression.
  - The second heat up occurs following the core quench caused by loop seal clearing and is caused by a simple core boil-off.
  - The third possible heat up can occur following depletion of the accumulator tanks and before LPIS injection begins.
  - Various factors affect the magnitudes of the three potential core heat ups. Although the magnitudes of the core heat ups may vary, ECCS performance must be such that the criteria (e.g., 10. CFR 50.46) is not exceeded.

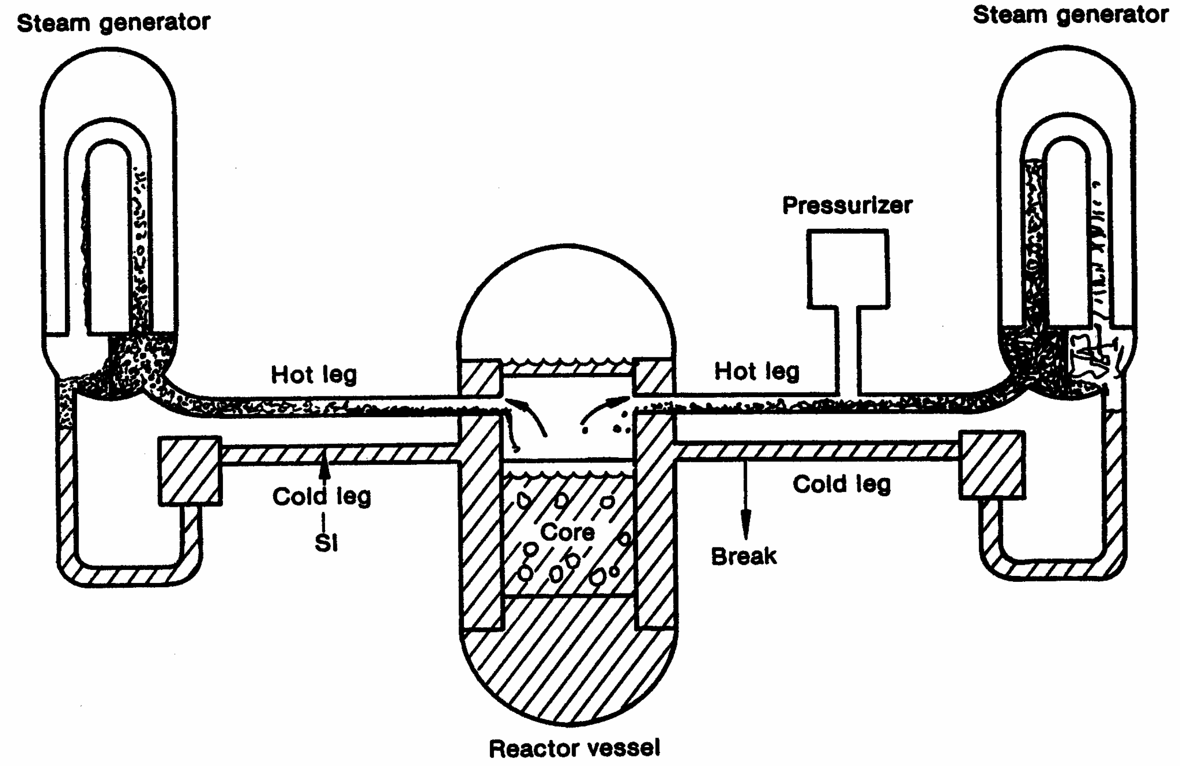
Different modes of natural circulation cooling in a PWR



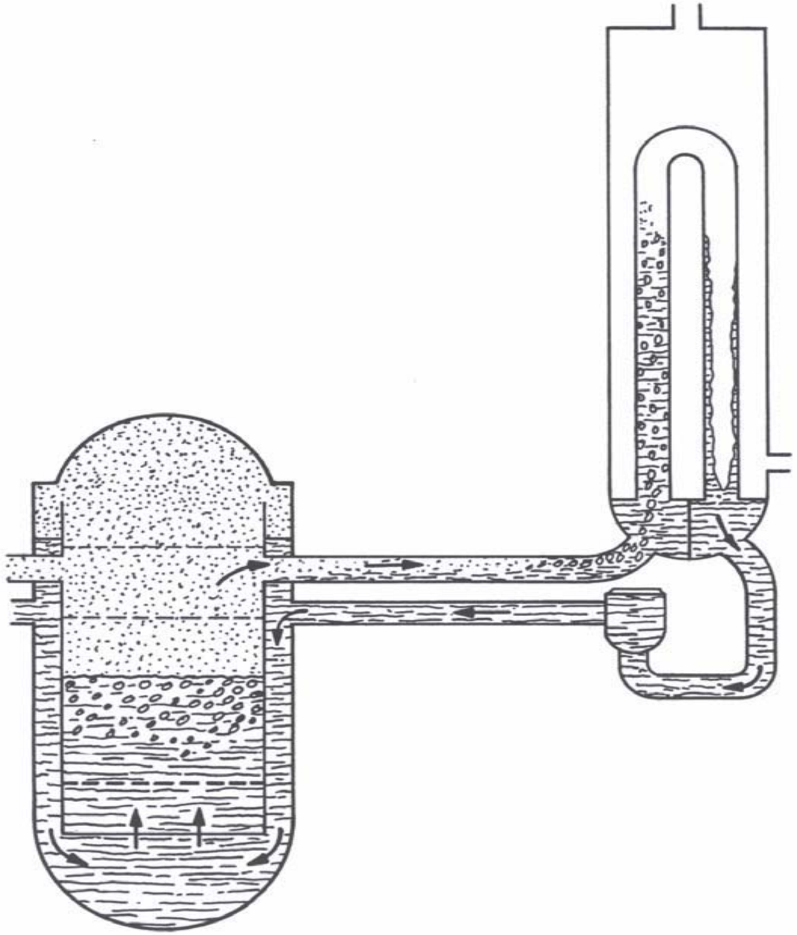
Formation of a continuous vapor phase at the top of the steam generator U-tube and vessel during a small break LOCA in PWR



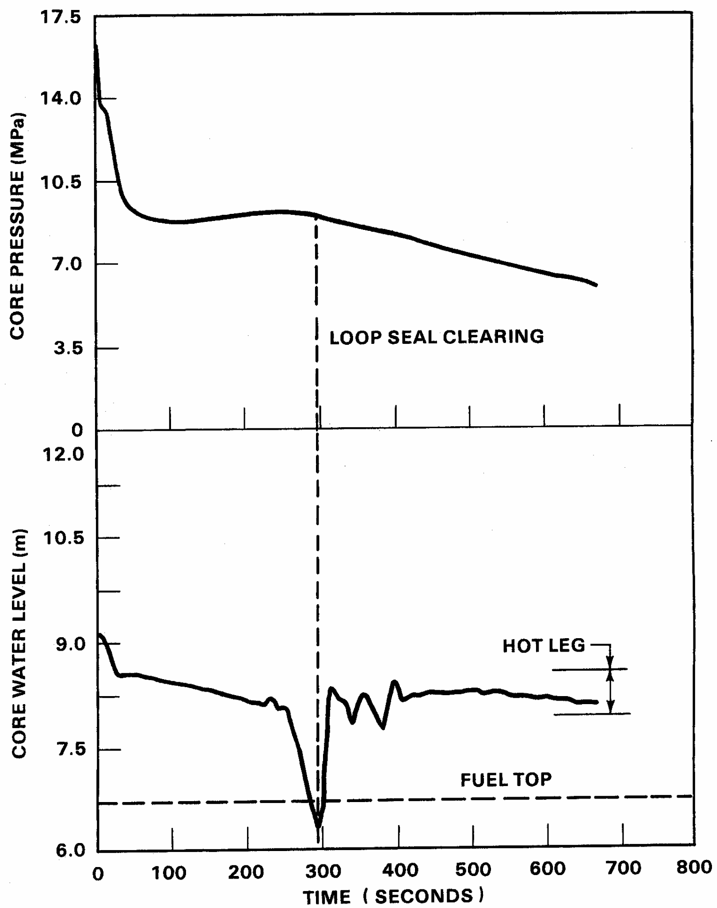
Initiation of core uncovery during a small break LOCA in PWR



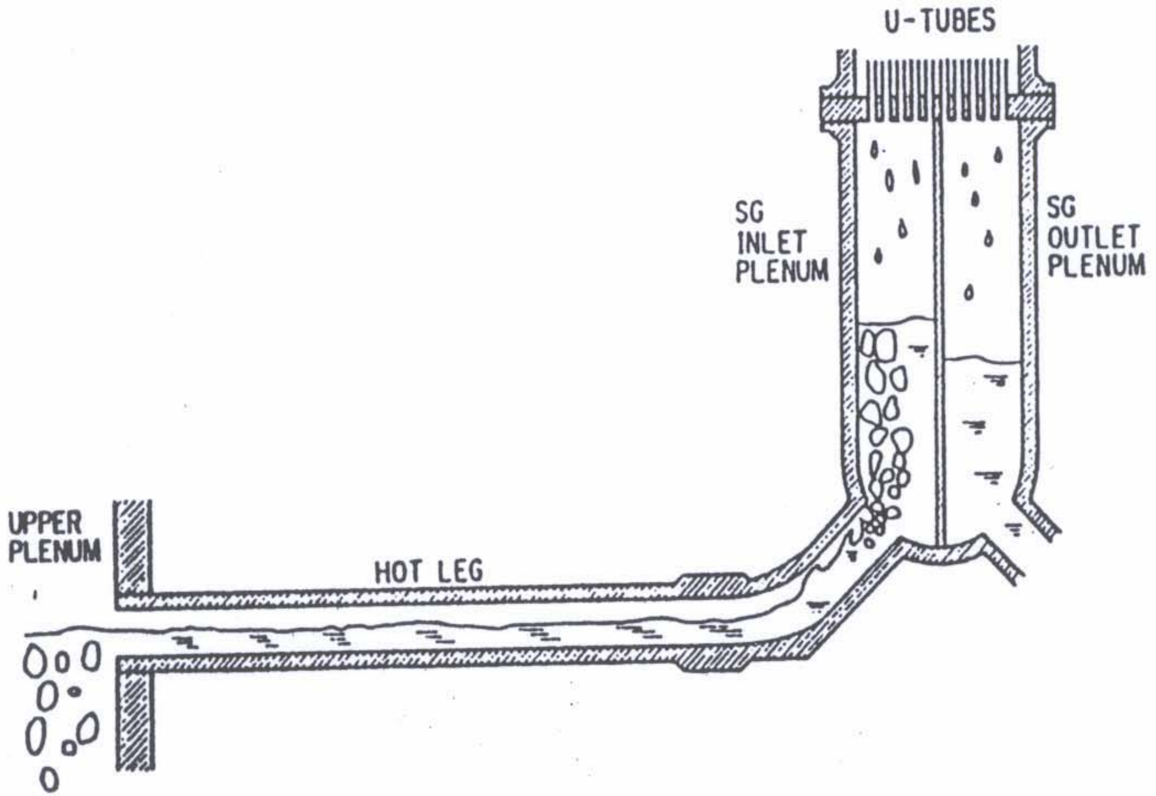
Liquid inventory trapped outside of the reactor vessel due to a loop seal



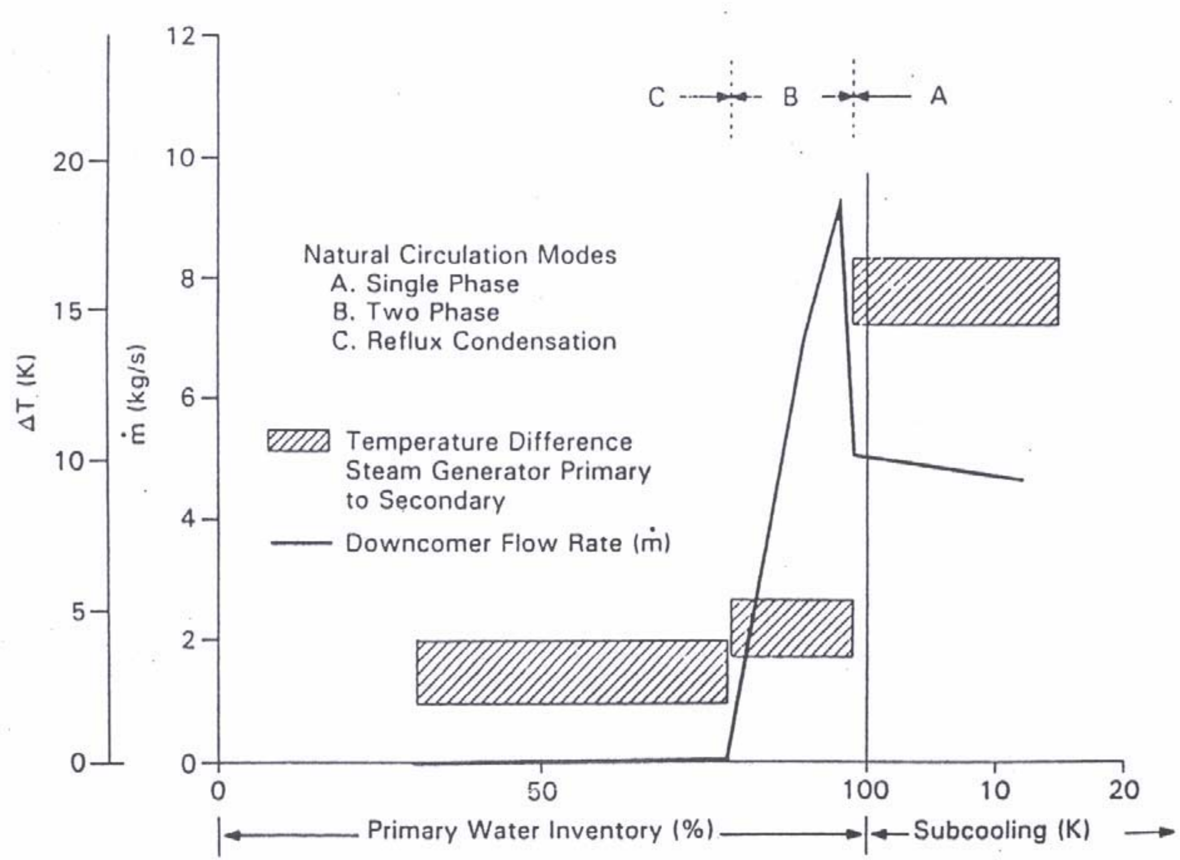
Typical transients of the primary system pressure and reactor vessel water level following a small break LOCA at the cold leg in a PWR



Schematic of liquid distribution during reflux condensation in PWRs



Mass flow rates and primary to secondary temperature differences as functions of primary mass inventory for PKL test facility



NATURAL CIRCULATION AND ITS' IMPORTANCE DURING SB LOCA (I)

- **Natural circulation is expected to be an essential core heat rejection mechanism during certain kinds of accidents or transients in a PWR** (e.g., small break LOCAs or operational transients involving loss of pumped circulation)
- **Characterization of the natural circulation cooling processes requires:**
  - **Identifying conditions under which natural circulation will occur,**
  - **Determining the effectiveness of natural circulation in removing core decay heat and recovering the plant (i.e., what are natural circulation cooling limitations)**
  - **Identifying how changing plant conditions affect natural circulation cooling.**

NATURAL CIRCULATION AND ITS' IMPORTANCE DURING SB LOCA (II)

- The buoyant forces resulting from density differences cause fluid to circulate through the primary loops, providing a means of removing the core decay heat.
- Depending on the primary loop fluid inventory, natural circulation consists of three distinct modes of cooling:
  - Single-phase
  - Two-phase (liquid continuous)
  - Reflux condensation (or boiler condenser mode)
- In both single-phase and two-phase natural circulation, the mass flow rate is the most important heat removal parameter. In contrary, the primary mechanism of heat removal is vapor condensation during reflux condensation.

NATURAL CIRCULATION AND ITS' IMPORTANCE DURING SB LOCA (III)

- **The amount of heat removed from the core through single-phase natural circulation cooling is normally the amount produced by decay heat power levels (about 5% core power).**
- **Characterization of natural circulation has been focused in several areas, including effects of both primary and secondary liquid inventory and distribution on natural circulation effectiveness, the stability of the various natural circulation modes and transitions between modes, the possibilities of natural circulation flow interruption due to instabilities, countercurrent-flow limiting in the hot leg and steam generator tubes, and the effects of noncondensables on natural circulation process.**

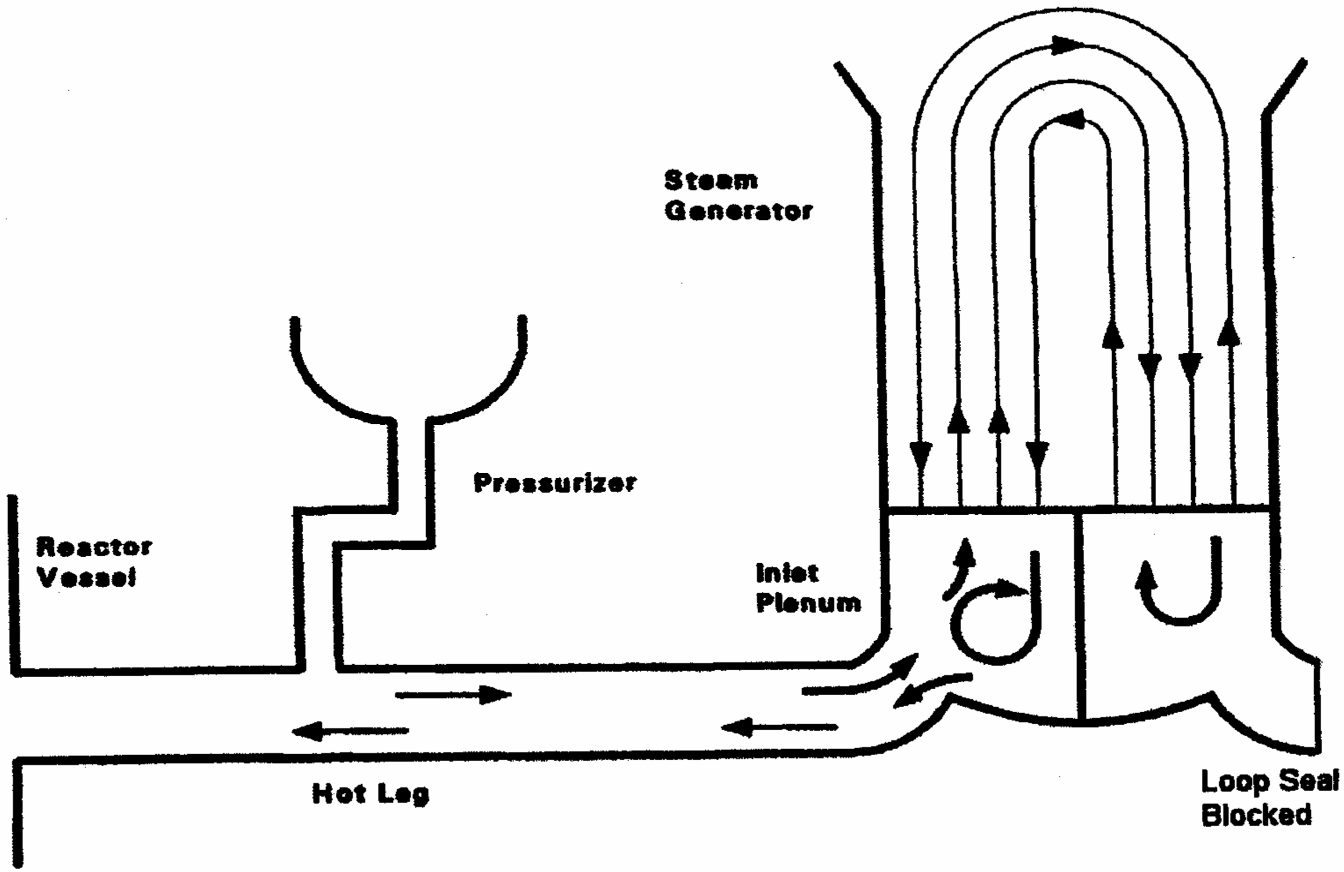
SHORT DESCRIPTION OF SEVERE ACCIDENT SCENARIO IN PWR LEADING TO NATURAL CIRCULATION

- **There are innumerable accident sequences that lead to core damage, but not all of them can or will result in natural circulation playing an important role in the accident progression**
- **Accident sequences, in which natural circulation will be significant, do have several characteristics in common:**
  - **The reactor coolant pumps can not be running.**
  - **There should be no pumped emergency core coolant injection.**
  - **There should be no large breaks in the system.**
- **As examples, two transients that would result in significant natural circulation flows are designated:**
  - **The TMLB station blackout sequence:** All AC power is lost and no steam-driven auxiliary feedwater is supplied to SGs. High-pressure **boil-off** with relief valves cycling. The **loop seals remain filled** with water
  - **The S_2D sequence is a small break LOCA with no high-pressure coolant injection: High pressure boil-off**

DESCRIPTION AND IMPORTANCE OF NATURAL CIRCULATION DURING SEVERE ACCIDENTS

- Three natural circulation flows can be important during severe accidents:
  - In-vessel natural circulation
  - Hot leg countercurrent flow
  - Flow through the coolant loops
  - Coolant loop flow
- The primary effect of the natural circulation flows is to redistribute the energy being generated in the core. This energy redistribution will slow the heat-up of the core, delaying fuel damage and increase the temperature of structures elsewhere in the RCS, so that they may get hot enough to melt or fail (e.g., surge line or hot leg failures).
- Slowing the core heat-up provides additional time for system recovery or operator actions, either of which could terminate the transient by returning the core to a covered, cooled state.

Overview of natural circulation flow pattern in a hot leg of a PWR during severe accident conditions



CONCLUDING REMARKS (I)

- **Natural circulation plays an important role in the accident progression during small break LOCA.**
- **Single-phase natural circulation is generally an affective and dependable means for removing decay heat in PWRs.** Nonuniform flow, noncondensable gases, and secondary side conditions can significantly influence the single-phase mode of natural circulation.
- **The two-phase natural circulation can provide an adequate method for removing decay heat from the core.** Two-phase flow is more tolerant for noncondensable gases than is single-phase natural circulation.
- **The reflux condensation is also very efficient way of heat removal mechanism.**
- **In all modes of natural circulation, the heat sink must remain active.**

CONCLUDING REMARKS (II)

- Natural circulation in severe accidents redistributes energy from the core to structures in the upper plenum and coolant loops. This energy transfer not only slows the heat-up of the core, it also contributes to potential failure of the RCS piping.

- Information from separate effects tests and integral test facilities, operating plant data and analysis have made significant contributions to the knowledge base concerning natural circulation cooling in PWRs.

- It is extremely important that the commonly used thermal-hydraulic system codes together with the CFD codes are able to simulate natural circulation during transients and accidents, because they will be relied upon to predict full-scale plant behavior.