The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

SMR/1848-T03

Course on Natural Circulation Phenomena and Modelling in Water-Cooled Nuclear Reactors

25 - 29 June 2007

Applications of Natural Circulation Systems

N. Aksan
Paul Scherrer Institut (PSI), Villingen, Switzerland

IAEA Course on Natural Circulation in Water-Cooled Nuclear Power Plants,
International Centre for Theoretical Physics (ICTP), Trieste, Italy,
25th to 29th, June 2007, Paper ID. T3

APPLICATION OF NATURAL CIRCULATION SYSTEMS: ADVANTAGES AND CHALLENGES-II

Presented by

Nusret Aksan
Paul Scherrer Institut (PSI),
5232 Villigen PSI,
Switzerland
Tel. +41-56-310-2710,
Fax. +41-56-310-4481,
E-mail: nusret.aksan@psi.ch

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
- Heat removal from intact primary system
- Heat removal from the primary system of the reactor in case of accidents
- Passive removal of heat from containment
- Example of HPLWR
- Concluding remarks

INTRODUCTION (I)

- Advance plant design: A design of current interest for which improvement over its predecessors and /or existing designs is expected
- Two groups of advanced designs:

  - Evolutionary design
  - Innovative design
- Evolutionary design: achieves improvements over existing designs through small to moderate modifications, with a strong emphasis on maintaining proven design features to minimize technological risks. E.g., ABWR, EPR. Designs, which are developed with a great emphasis on **utilization of passive safety systems and inherent safety features,** belong to this category. E.g., AP 600, AP 1000, ESBWR, SWR 1000, HPLWR, etc.

INTRODUCTION (II)

- Innovative design: An advanced design which incorporates radical conceptual changes in design approaches or system configuration with existing practice. E.g., PIRUS, IRIS, etc.
- Increased safety requirements, the aim to introducing effective and transparent safety functions, expanded considerations of severe accidents lead to **growing consideration of passive safety systems for ALWRs**
- To reduce the complexity of the emergency core cooling and of the long-term decay heat removal systems by increased use of **passive systems**

DEFINITIONS

- **A Passive component** is a component which does not need any external input to operate
- **A passive system** is either a system which is composed entirely of passive components ar a system which uses active ones in a very limited way to initiate subsequent passive operation
- Passive safety systems are characterized by their full reliance upon natural forces, such as natural circulation, gravity, to accomplish their designated safety functions.

PASSIVE SAFETY PRINCIPLES OF NEXT GENERATION ALWR DESIGNS

- Low volumetric heat generation rates,
- Reliance solely on natural forces, such as gravity and gas pressurization, for safety system operation
- Dependence on natural phenomena, such as natural convection and condensation, for safety system performance.

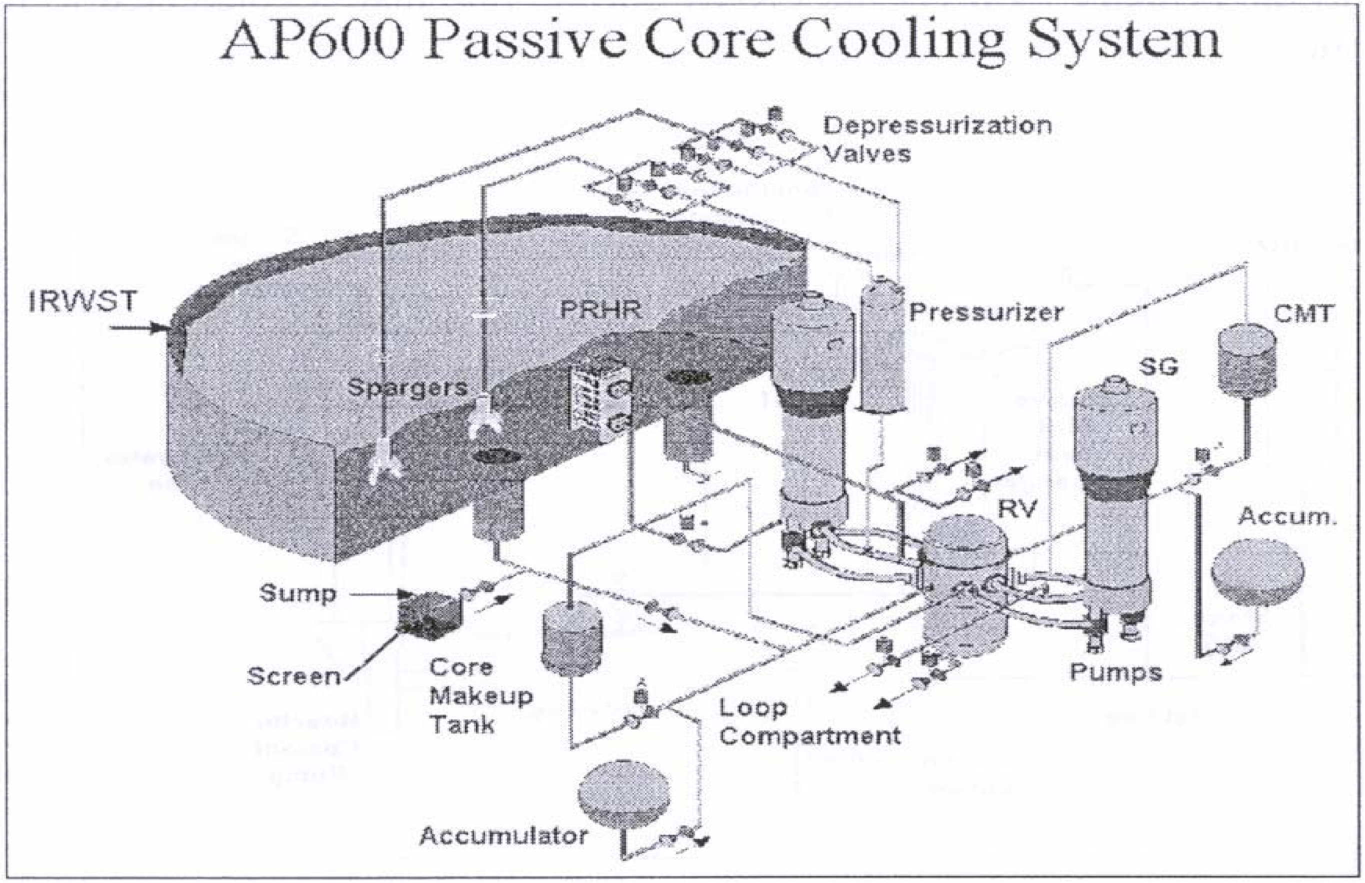
HEAT REMOVAL FROM INTACT PRIMARY SYSTEM (I)

- The engineered safety features, which incorporate these passive safety principles, achieve increased reliability by means of system redundancy, minimization of system components, non-reliance on external power sources, and integral long term decay heat removal and containment cooling systems.
- Decay heat can be removed by circulating the primary coolant in heat exchangers or condensers typically immersed in pools inside the containment

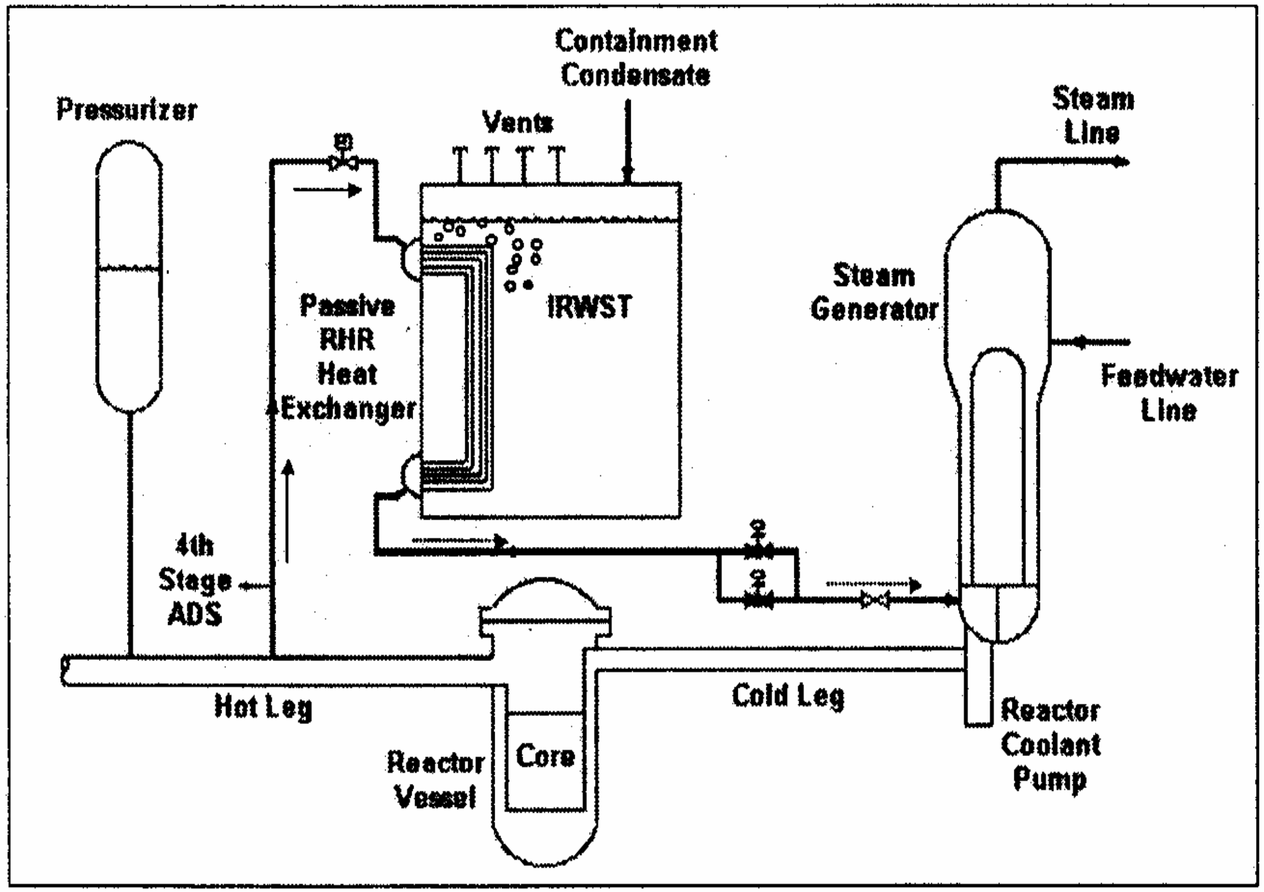
HEAT REMOVAL FROM INTACT PRIMARY SYSTEM (II)

- Heat exchangers connected to the primary system and immersed in a water pool inside the containment, e.g., AP600/AP1000 where Passive Residual Heat Removal (PRHR) heat exchanger is immersed in IRWST, SWR 1000 has emergency condensers permanently connected to the core and located in Core Flooding Pool
- Another solution is the use of Isolation Condensers connected to the Reactor Pressure Vessel and immersed in external pools, as in ESBWR

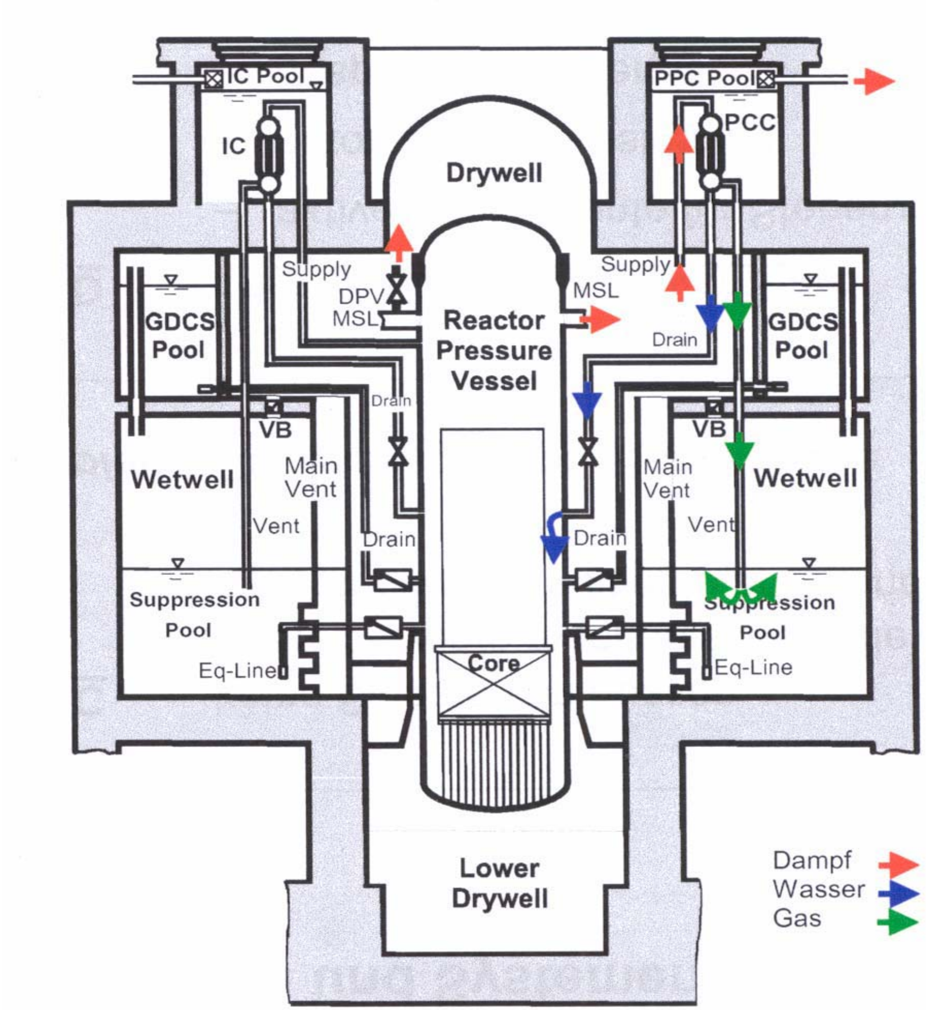
AP600 Passive Core Cooling System



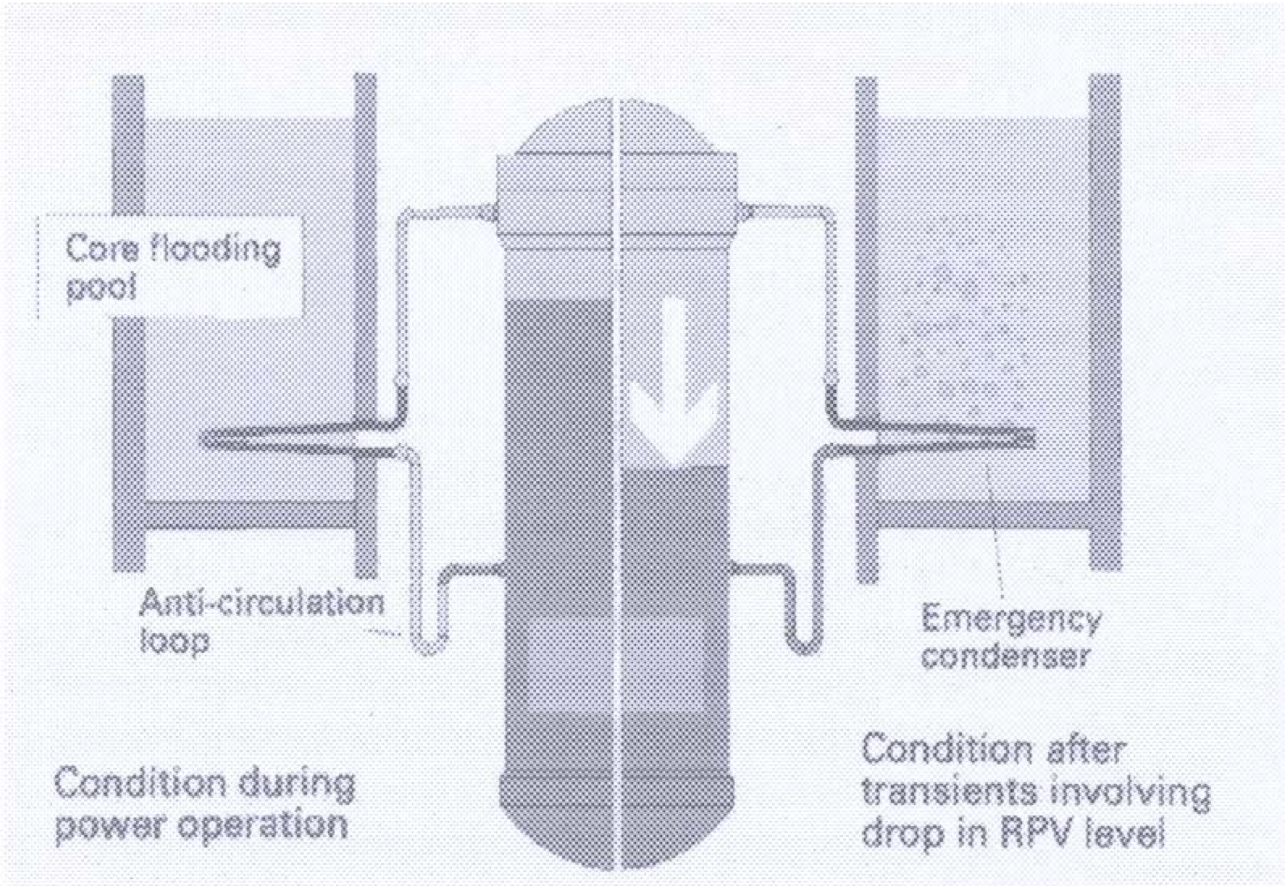
AP-600/ AP 1000 Passive Residual Heat Removal



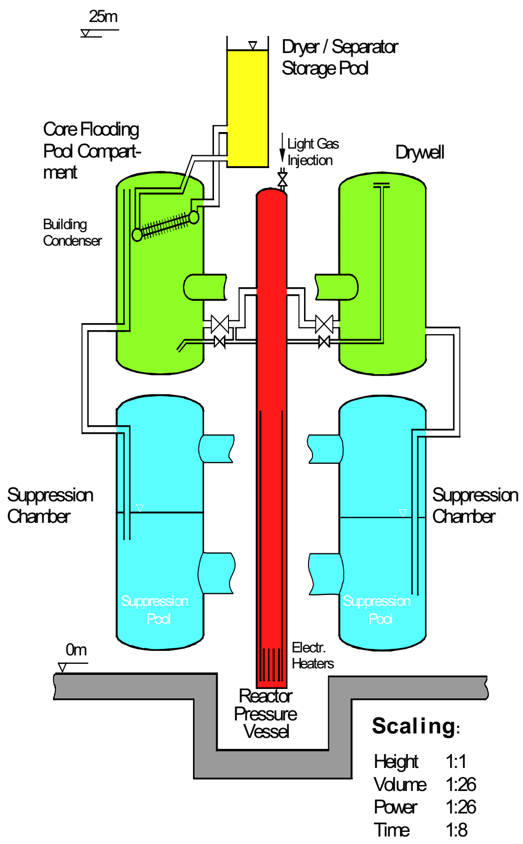
ESBWR PASSIVE SAFETY SYSTEMS

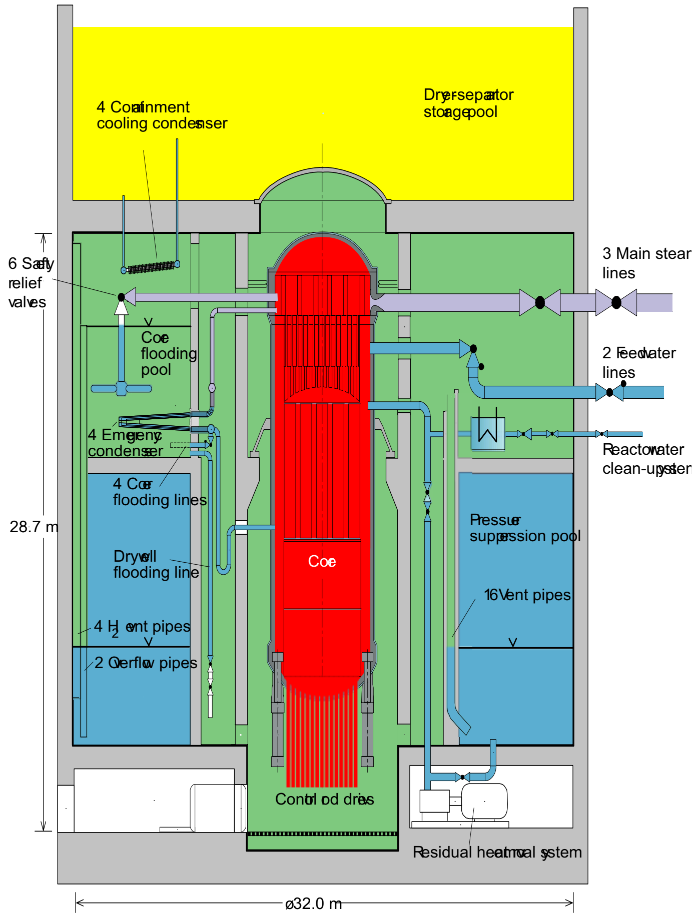


SWR-1000 Emergency Condenser for removing heat from the primary system



PASSIVE HEAT REMOVAL IN SWR 1000





HEAT REMOVAL FROM INTACT PRIMARY SYSTEM OF THE REACTOR IN CASE OF ACCIDENTS (I)

- In case of LOCA, passive solutions for decay heat removal from the core rely on:

  - High-pressure gravity driven water tanks connected at their top to the primary system, e.g., Core make-up tanks (CMT) at any pressure, High-pressure accumulators at about 50 bar,

  - Flooding of the core after depressurization of the primary system by ADS operation, e.g., lower-pressure Core reflood tanks (CRT) at about 15 bar, In-Containment Refueling Water Storage Tank (IRWST),Gravity driven cooling system (GDCS)

HEAT REMOVAL FROM INTACT PRIMARY SYSTEM OF THE REACTOR IN CASE OF ACCIDENTS (I)

- The primary system of ALWRs is designed such that the core can be kept covered in spite of breaches in the primary system
- In addition, elimination of primary system piping contributes to the elimination of certain LOCA scenarios, e.g. large break LOCA as in PWRs or BWRs
- Passive plants rely on **automatic depressurization** of the primary system and actuation of low-pressure gravity driven core make-up tanks.

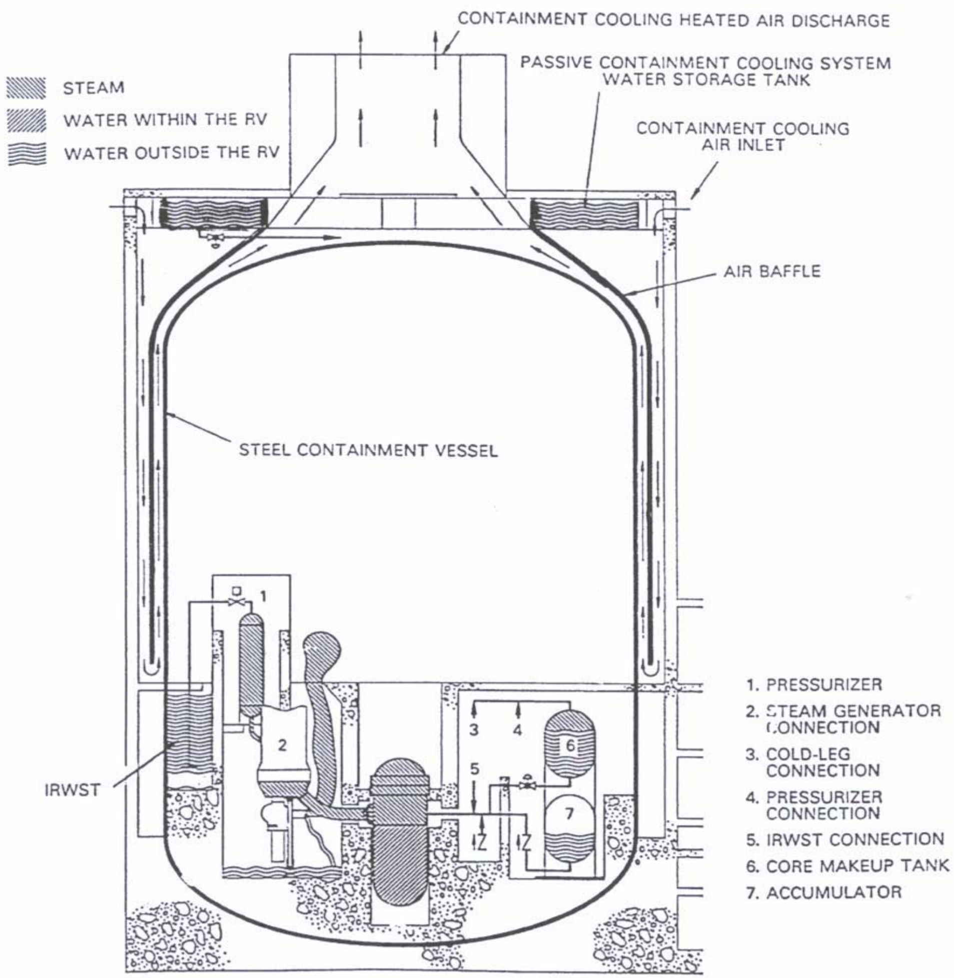
PASSIVE REMOVAL OF HEAT FROM CONTAINMENT (I)

- All containment systems profit from the **passive heat sink** provided by the **structures** inside the containment and containment building
- Structures are usually needed to absorb the higher level of decay heat generation immediately after shutdown and limit the initial containment pressure
- By the time structures get saturated, decay heat levels are lower and the containment cooling systems can fully cope with the decay heat removal
- Thus, capacity needed for containment cooling is reduced.

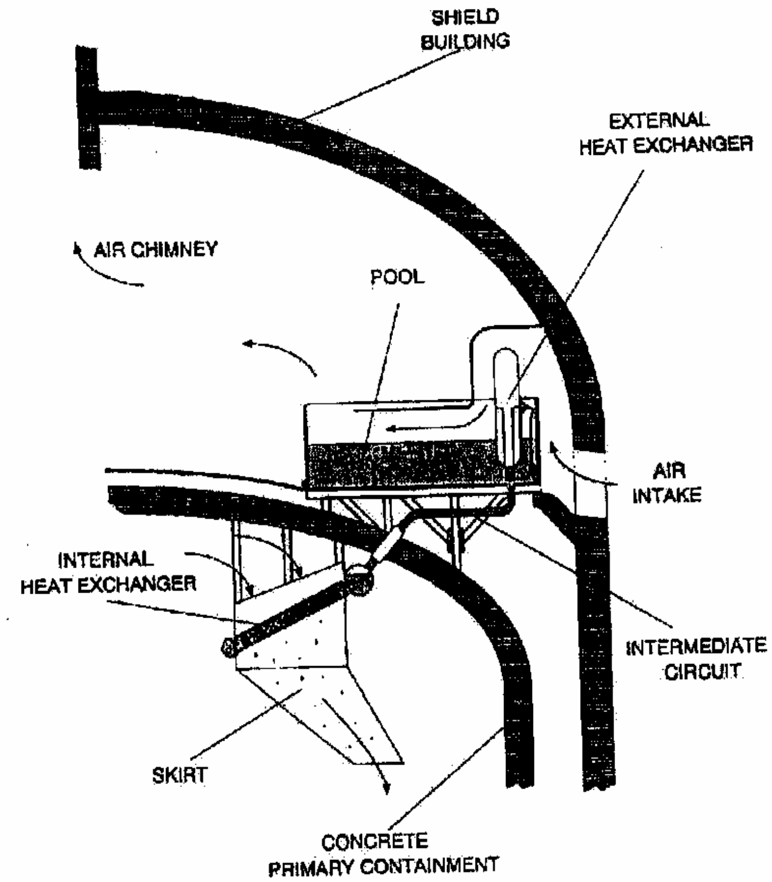
PASSIVE REMOVAL OF HEAT FROM CONTAINMENT (II)

- Other solution for decay heat removal from containment is the use of condensers
- Condensers immersed in pools can be located either inside the containment, near the roof, or outside the containment.
- In all cases the heat removal rates are enhanced by phase change, e.g., condensation, wetting of the containment walls

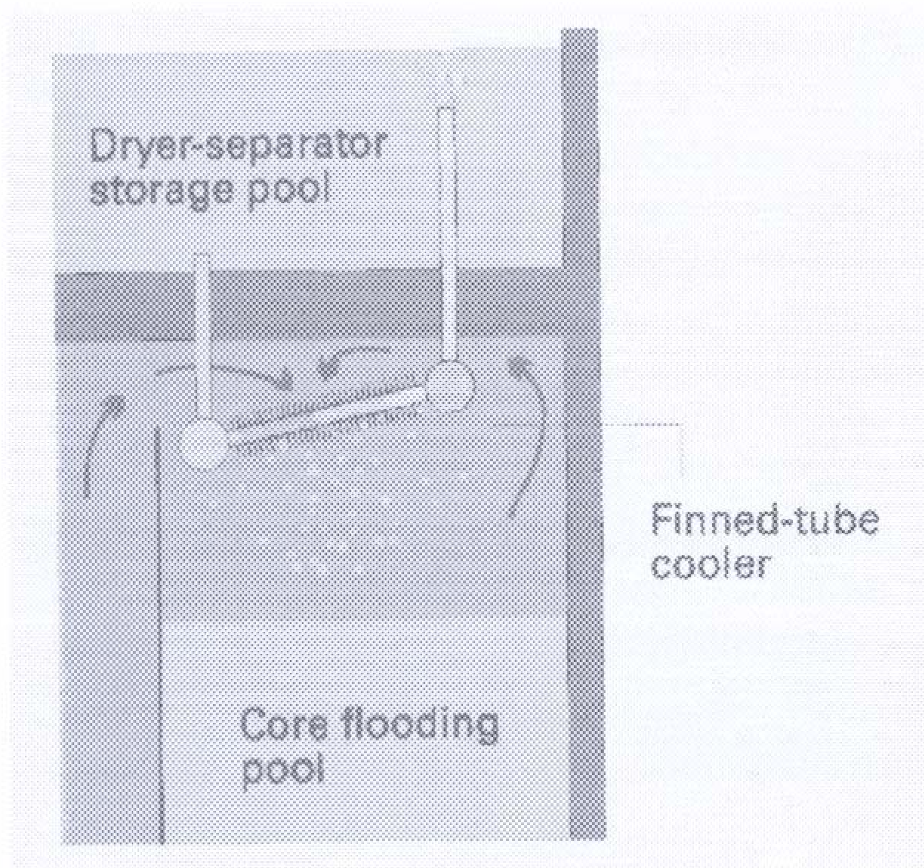
AP600 Passive Containment Cooling



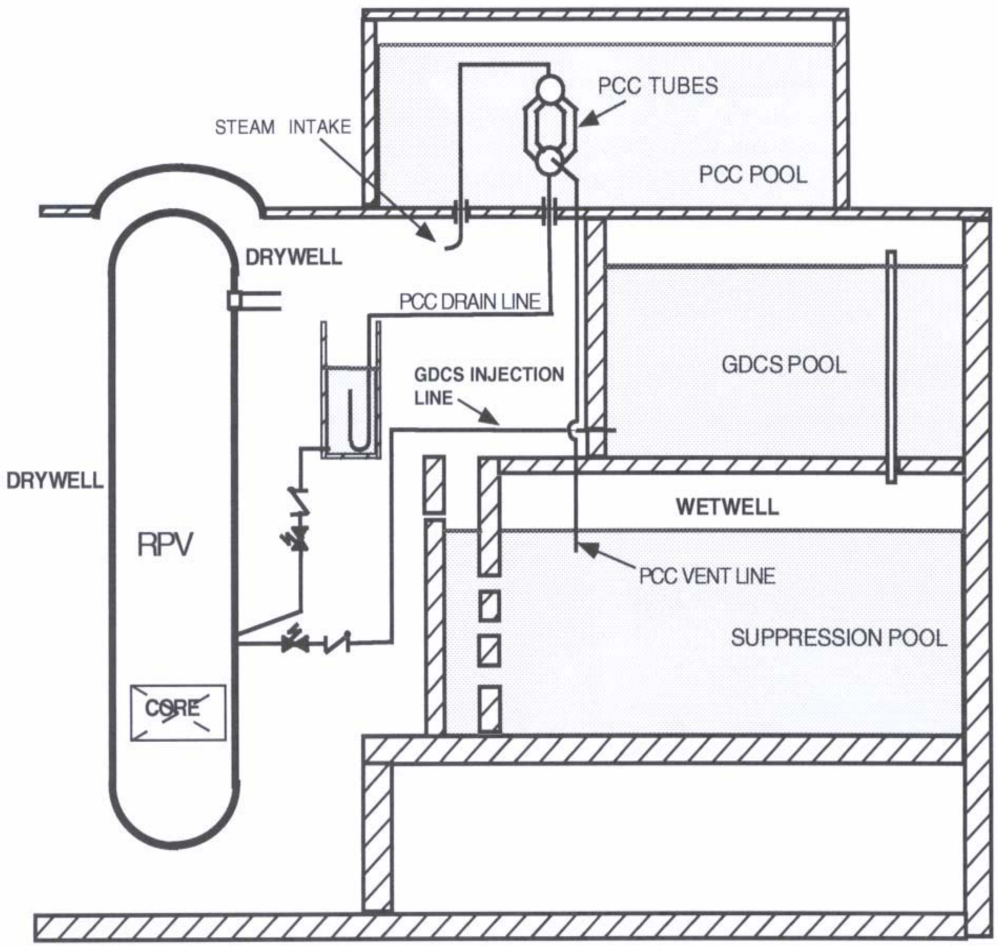
AP 600 alternate passive containment solution



SWR 1000 Containment Cooling Condenser



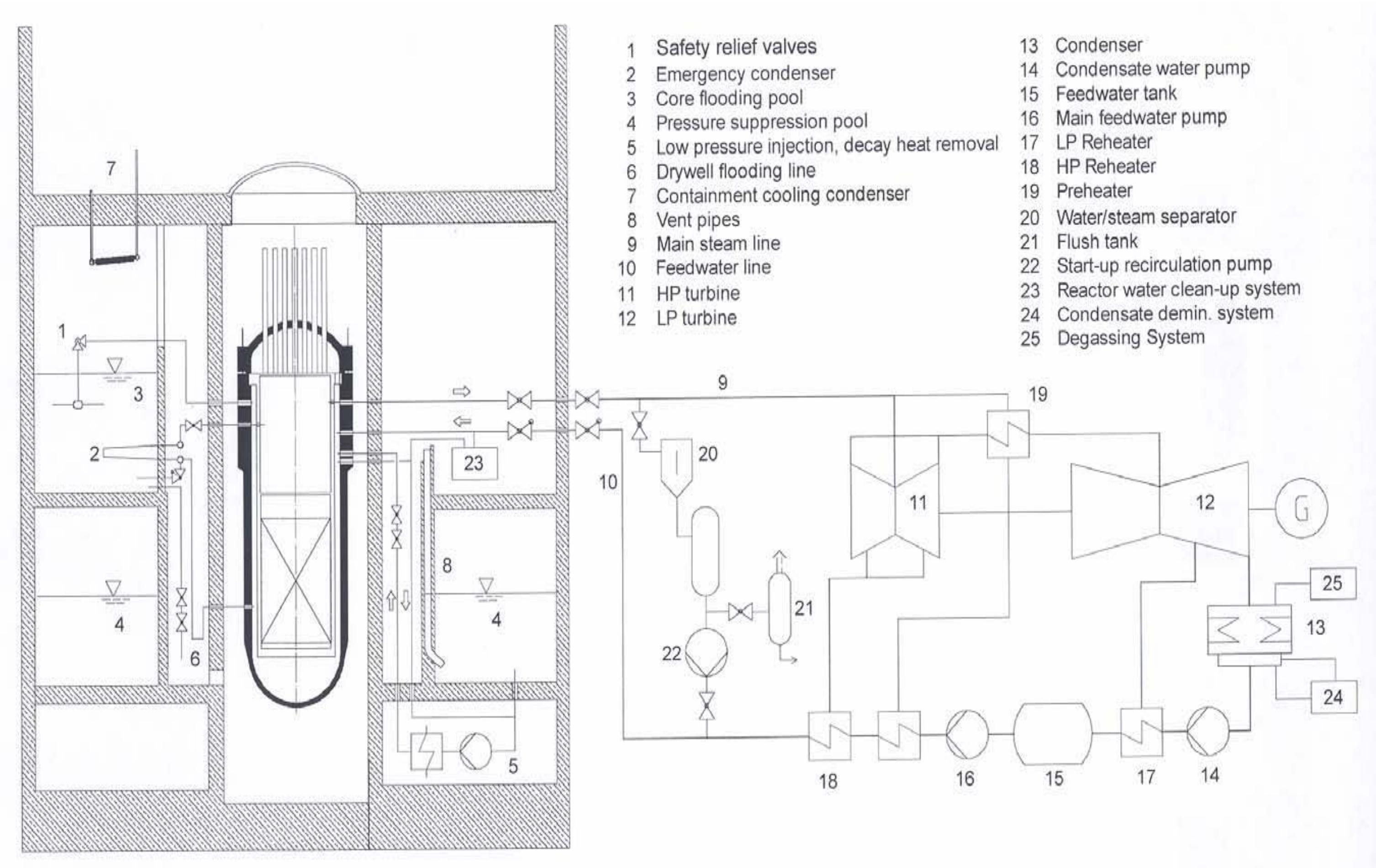
ESBWR Passive Containment Cooling System



EXAMPLE: SAFETY FUNCTIONS, IN CASE OF TRANSIENTS AND IN THE EVENT OF ACCIDENTS FOR HPLWR DESIGN

- Use of both passive and active safety systems for performing safety-related functions
- Consider heat storage capacity is low in the primary circuit
- As fast as possible, cooling flow has to be maintained
- Later on, the core has to be flooded with water from all available sources
- In some incidents ,apply the principle of Automatic Depressurization System (ADS) following by low-pressure injection, as in design of ALWRs
- Use of accumulators in addition or instead of pumps need to be investigated in detail

Schematics of the HPLWR Primary Circuit, Safety Systems and Containment Concept



HPLWR SAFETY SYSTEM

- Rely on passive safety features to flood the core when necessary and to cool the containment
- As the HPLWR design matures, need of new passive systems will be assessed and integrated into the design

CONCLUDING REMARKS (I)

- Passive ALWR designs emphasize enhanced safety by means of improved safety system reliability and performance.
- These objectives are achieved by means of improved safety system simplification and reliance on immutable natural forces for system operation.
- Most systems rely on boiling or condensation to obtain sufficiently high heat transfer rates under natural circulation conditions
- Simulating the performance of these safety systems is central to analytical safety evaluation of advanced passive reactor designs.

CONCLUDING REMARKS (II)

- Since the new passive ALWR designs incorporate significant changes from the familiar current LWR designs and place higher reliance on individual systems, a thorough understanding of these designs is needed with respect to system interactions.
- In addition, there is a close coupling in both plant designs between the reactor coolant system and the containment during an accident.