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COMMIX Analysis of AP-600 Passive Containment Cooling System*

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Abstract

COMMIX modeling and basic concepts that relate components, i.e., containment, water film cooling, and natural draft air flow systems, of the AP-600 Passive Containment Cooling System are discussed. The critical safety issues during a postulated accident have been identified as (1) maintaining the liquid film outside the steel containment vessel, (2) ensuring the natural convection in the air annulus, and (3) quantifying both heat and mass transfer accurately for the system. The lack of appropriate heat and mass transfer models in the present analysis is addressed, and additional assessment and validation of the proposed models is proposed.

Introduction

The Westinghouse AP-600, an Advanced Pressurized Water Reactor (APWR), utilizes a passive containment cooling system (PCCS) to remove heat released inside the containment vessel following postulated design-base accidents (DBA) such as a main steamline break (MSLB) or loss-of-coolant accident (LOCA). During a DBA, steam is released and thus pressure inside the containment vessel increases. The major purpose of the AP-600 PCCS is to control the internal pressure of the containment vessel to below design value.

A schematic sketch of AP-600 PCCS is shown in Fig. 1. The vessel consists of a vertical cylindrical shell of large length-to-diameter ratio and is capped at both top and bottom by a dome that is also a body of revolution with a meridian cross section in the shape of a semiellipse with a horizontal major axis. During a DBA, heat released to the interior of the steel containment vessel is removed by the evaporation of a continuously flowing thin liquid film on the outside surface of the vessel, thus lowering the temperature of the steel vessel wall so that steam condenses on its inside surface. The external liquid film is formed by flooding water at the top of the ellipsoidal dome. Evaporation of the falling liquid film is enhanced by buoyancy-driven flows (natural draft) of moist air in an annular space between the outside of the steel containment vessel and the concrete-shield building wall. Air enters the annular space through inlets in the building wall, rises in the annulus as the air is heated by the steel vessel wall, and exits the shield building through outlets above the containment vessel.

Computer Modeling

For design optimization and for simulation to determine operating requirements, use of a computer model is a natural and economical approach for such a large system.

The COMMIX[1–4] code solves a system of time-dependent and multidimensional conservation of mass, momentum, and energy, and k–ε turbulent transport equations in which k is the turbulent kinetic energy and ε is the dissipation of k. To ensure PCCS performance, it is necessary to predict the (1) air flow produced by the natural draft due to heat removal, (2) evaporation rate at the outside surface of the vessel, and (3) condensation rate on the inside surface of the vessel. To this end, a transient liquid–film tracking model has been developed and implemented in the COMMIX code. This model computes liquid-film thickness, velocity, and temperature on both sides of the vessel wall.[5] The inside liquid film is formed by filmwise condensation, which is assumed in the model and appears to agree with Westinghouse experimental observation. The effect of the wavy liquid film on heat and mass transfer is explicitly accounted for. Determination of operating stability and basic criteria are specifically in the realm of mathematical analysis and computer modeling.

The critical safety issues for the AP–600 PCCS have been identified and are discussed below.

1. Maintaining the liquid film outside the steel containment vessel during a postulated accident for a period of time as designed.

   It is desirable to maintain complete coverage of the outside of the steel containment vessel during a postulated accident. Effective wetting of the vessel is assisted by the use of a coating on the vessel surface. From consideration of interactions of surface tension, viscosity, and gravity, it was shown that at a contact angle of 20°, a stable film is attainable at a minimum flow of 4×10^{-5} $m^3/m \cdot s$ based on a force criterion and a minimum flow of 10^{-4} $m^3/m \cdot s$ according to an energy criterion.[6] The current design of the AP–600 exceeds these minimum flows. Ideally, a circumferential uniform film with fine wave crests is expected to flow down the wall of the vessel, but its uniformity might be affected adversely by the counterflow of the air in the natural draft and nonuniformity of its circumferential distribution. Imperfection of manufacture and coating process also may lead to hydrodynamic instability due to the slower flow of the thin film than of a thick film, which may lead to flowing in streaks over a given height. This condition can be improved by introducing a tangential component of water flow in the design of its distributor. Because this tangential component tends to be dissipated by wall friction over a relatively short height, it helps to even out the initial distribution of water in the film, but will not ensure a uniform film.

   Thermal instability[7] of the liquid film may arise due to nonuniform internal heating in the vessel or to nonuniform water film thickness due to tolerance in the manufacture of the vessel and its surface finish; instability may also be caused by the asymmetry of the natural draft air flow over the liquid film. Based on the limited experimental data available to us, no thermal instability has been observed.

2. Ensuring natural convection in the air annulus during the entire course of a postulated accident.

   A stable natural draft of air in the annulus between the containment vessel and the baffle can be maintained as long as the air is not cooled by evaporation of the liquid film to below the inlet air temperature. Such cooling is not expected in the usual course of a postulated accident. One possible contingency is the heating of inlet air by condensation of moisture in the air in upward flow at the top of the baffle, thus reducing the natural draft. Such a situation is believed to be preventable with spray-on insulation on the outside of the metal baffle. The specific design can be determined by computation for the highest humidity to be encountered in the ambient air and for the evaporation rate of the liquid film.

3. Quantifying both heat and mass transfer accurately throughout the postulated accident.

   Coupled with the liquid-film tracking model, pertinent heat and mass transfer models are needed to predict the performance of the AP-600 PCCS system. An assessment of the relevant heat and mass transfer models used in the COMMIX code is made by comparison of the COMMIX results and the Westinghouse experimental data. As a first attempt, the heat and mass transfer models used in the CONTAIN[8] code were implemented in the COMMIX code. The heat transfer models consist of the correlations for natural convection, turbulent natural convection, and forced convection. The mass transfer model is developed based on the basis of the heat and mass analogy.

   Based on the limited COMMIX calculational results, several observations have tentatively been reached. (1) The air-side flow is forced convection in the Westinghouse integral tests; the heat and mass transfer analogy is applicable. This is in contrast to the actual AP-600 where air flow is driven by natural convection. Validation of heat and mass transfer models employed in the COMMIX code with natural convection experimental data is needed. (2) The flow of the air/steam mixture inside the steel shell is mixed convection. Therefore, none of the heat transfer models is appropriate for this flow. Applicability of the heat and mass analogy is also not certain. The situation is further complicated because flow stratification was predicted by the calculations (more steam at top of the steel shell and more air at its bottom) in agreement with direct experimental observations. One notes that determination of condensation rate under mixed convection and in the case of domed geometry such as that in the containment is in need of basic data and correlations. It is therefore recommended that additional assessment and validation of mixed convection heat and mass transfer models used in the COMMIX code with the AP-600 PCCS experimental data be conducted.

The first two safety issues are necessary to make the PCCS work as expected; the third is essential to prediction of PCCS performance. The current NRC plan is to validate the COMMIX code with the pertinent PCCS experimental data.

Conclusions

Based on limited analyses of Westinghouse AP-600 PCCS experimental data, reasonable agreement between the COMMIX calculated results and the integral measurements of the total condensation and evaporation rates and overall averaged heat flux was obtained. The agreement needs to be improved for the temperature distribution in the containment vessel wall. This is presumably due to the inappropriate heat and mass transfer models used in the present analyses. Additional assessment and validation of the COMMIX code with experimental data are needed.

It has been demonstrated that with a thorough understanding of fundamentals, the COMMIX code is a powerful means of analyzing and modeling the AP-600 PCCS system in order to optimize design and operation. The time-dependent nature of COMMIX makes it possible to follow through and model a complete scenario of a postulated accident and make design provisions for possible contingencies.

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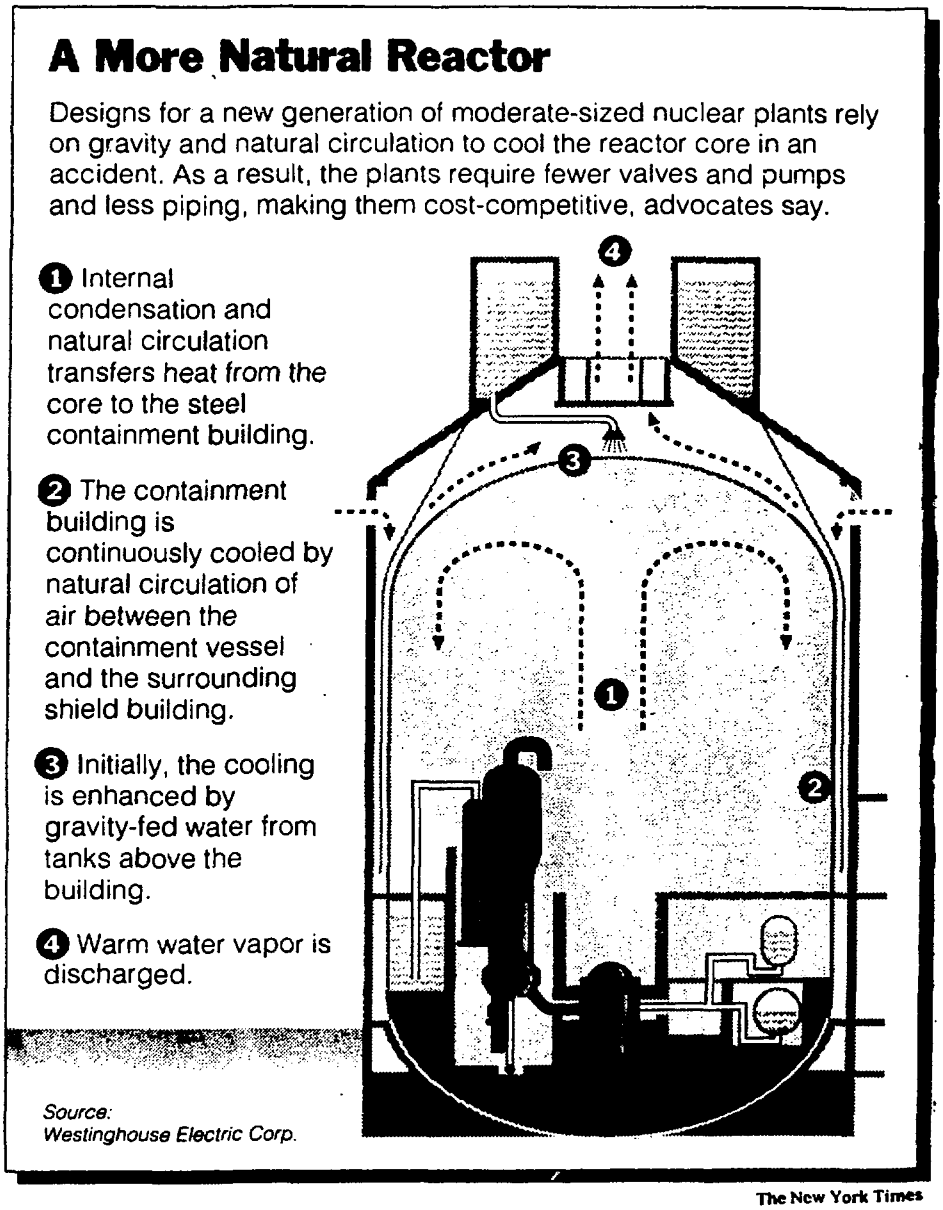

Fig. 1. Schematic Sketch of AP-600 Passive Containment Cooling System