TECHNICAL FEASIBILITY AND RELIABILITY OF PASSIVE SAFETY SYSTEMS OF AC600

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Abstract

The first step conceptual design of the 600 MWe advanced PWR (AC-600) has been finished by the Nuclear Power Institute of China. Experiments on the passive system of AC-600 are being carried out, and are expected to be completed next year.

The main research emphases of AC-600 conceptual design include the advanced core, the passive safety system and simplification. The design objective of AC-600 is that the safety, reliability, maintainability, operation cost and construction period are all improved upon compared to those of PWR plant. One of important means to achieve the objective is using a passive system, which has the following functions whenever its operation is required.

- providing the reactor core with enough coolant when others fail to make up the lost coolant,
- reactor residual heat removal,
- cooling and reducing pressure in the containment and preventing radioactive substances from being released into the environment after occurrence of accident (e.g LOCA).

The system should meet the single failure criterion, and keep operating when a single active component or passive component breaks down during the first 72 hour period after occurrence of accident, or in the long period following the 72 hour period.

The passive safety system of AC-600 is composed of the primary safety injection system, the secondary emergency core residual heat removal system and the containment cooling system. The design of the system follows some relevant rules and criteria used by current PWR plant. The system has the ability to bear single failure, two complete separate subsystems are considered, each designed for 100% working capacity. Normal operation is separate from safety operation and avoids cross coupling and interference between systems, improves the reliability of components, and makes it easy to maintain, inspect and test the system.

The paper discusses the technical feasibility and reliability of the passive safety system of AC-600, and some issues and test plans are also involved.

1. DESCRIPTION OF THE PASSIVE SAFETY SYSTEMS OF AC-600

The AC-600 design is based on the Qinshan phase II standard PWR nuclear power plant (2X600 MWe). Successful experience derived from QS-II is incorporated in the AC-600 design as far as possible, but the AC-600 plant will be an improvement on QS-II. AC-600 will become a major type of reactor for the next generation 600 MWe nuclear power plants in China. It has a large safety margin of operation because of the small power density of the reactor core. The high natural circulation cooling ability due to the small flow resistance of the primary system loop is very useful for reactor core decay heat removal during accidents. The major design goals of AC-600 are (1) to enhance reactor safety and reliability, (2) to improve economics, (3) to increase nuclear plant availability, and (4) to shorten the construction schedule and lengthen plant life time.

The AC-600 advanced PWR thermal power is 1930 MW with an electrical power of 600 MW. The total reactor height is 19.1 m with a maximum out side diameter of 5.04 m. The total coolant flow rate is 32100 t/ h. The reactor coolant system consists of two loops with an operation pressure of 15.6 MPa.

Three key approaches, i.e, advanced core, passive safety systems and simplified systems, have been adopted in AC-600 design. The design features are as follows:

(1) Advanced Core

- Addition of grey control rod and utilization of Gadolinium burnable poison,
- Arrangement of stainless steel reflector,
- Reduction of core power density.

(2) Passive Safety Systems

In AC-600, the safety systems, except for the low pressure safety injection pump which is active to carry on the long-term recirculation during LOCAs, are all passive safety systems, including:

- Emergency Core Residual Heat Removal System(ECRHRS)

The passive emergency core residual heat removal system on the secondary circuit side is mainly used in the event of station blackout, main steam line rupture or loss of feedwater. An independent emergency core residual heat removal train consists of one emergency feedwater tank and one emergency air cooler as well as associated piping, valves and instruments. Each reactor coolant loop has one train. Two trains constitute the AC-600 ECRHRS. When station blackout occurs, the decay heat generated in the reactor core can be removed through use of natural circulation flow in the primary coolant system, the secondary coolant and the atmosphere.

- Safety Injection System

The AC-600 safety injection system, similar to that of the existing PWR plant, is divided into a HP injection subsystem, a MP injection subsystem and a LP injection subsystem as well as the corresponding recirculation systems. The HP injection subsystem mainly consists of two core makeup tanks in which water pressure is the same as the reactor coolant pressure. The MP injection subsystem mainly consists of two accumulators with an operating pressure of 5.2 MPa. The HP and MP injection subsystems are all passive.

- Containment Cooling System

This system, utilizing completely passive equipment, consists of the containment cooling water storage tank located on the top of the containment and cooling water sprayers. It eliminates the need for the containment spray system in the current PWR plant as well as the need for an intermediate circulation cooling medium such as the component cooling water, resulting in a saving in investment and in an improvement in system operational reliability. The system is used to remove the heat from the inside to the outside of the containment during LOCA or main steam line rupture located inside the containment. First, the water in the tank on the top of the containment will be sprayed onto the surface of the steel shell of the containment by gravity, cooling the shell so as to decrease the pressure and the temperature. After emptying the tank, the natural circulation flow of air through the annulus between the steel shell and the concrete shell can remove the heat continuously. At the same time, the low head safety injection/recirculation pumps which are installed in the containment sumps can withdraw the borated water from the sumps into the reactor coolant system. The water absorbs the core decay heat and flows out through the break point (in LOCA conditions).

These passive systems guarantee the completion of the safety functions - residual heat removal, RCS inventory control, short-term LOCA safety injection, long-term LOCA recirculation, containment spraying and cooling following a transient and/or accident.

(3) Simplified System

- The SG and pumps are connected into a single structure, eliminating the U-shape cross-over leg of the coolant pipes, improving the post-LOCA safety, decreasing the resistance in the primary circuit and enhancing the natural circulation capability of the primary circuit;
- The use of the passive safety systems and the decrease of boron concentration in the RCS eliminate and/or simplify such system as the auxiliary feedwater system, and the boron recycle system as well as the HP safety injection pump.
- Most of safety grade components are arranged within the containment, resulting in the reduction in the safety graded buildings volume and capital cost.

Except the three major features mentioned above, the advanced I&C technology and modular construction approach are also employed to improve the AC-600 performance and reduce the construction schedule and cost.

The schematic diagrams and drawing of the passive system of AC-600 are shown in Fig.1, Fig.2, and Fig.3. Nomenclature, list and quantity of the main components included in the system are given in Table. 1.

2. Feasibility and reliability

The reliability of the passive safety system refers to the ability of the system to carry out function under the prevailing condition when required. The feasibility shows the reliability, maintainability, availability and the economic advantages of the system. The feasibility includes technical realization, economics, public acceptance and political support by the government, etc.

Feasibility and reliability are closely related to each other and should be considered comprehensively in the system design. The reliability is not the best as it is set the highest. In China, the development of nuclear power plant is restricted by its economies and technology level in the country. The economic estimation of the system is one important part of its feasibility research.

Based on the specialized safety systems of the standard nuclear power plant, the passive safety system design is feasible for a developing country. So this design can absorb

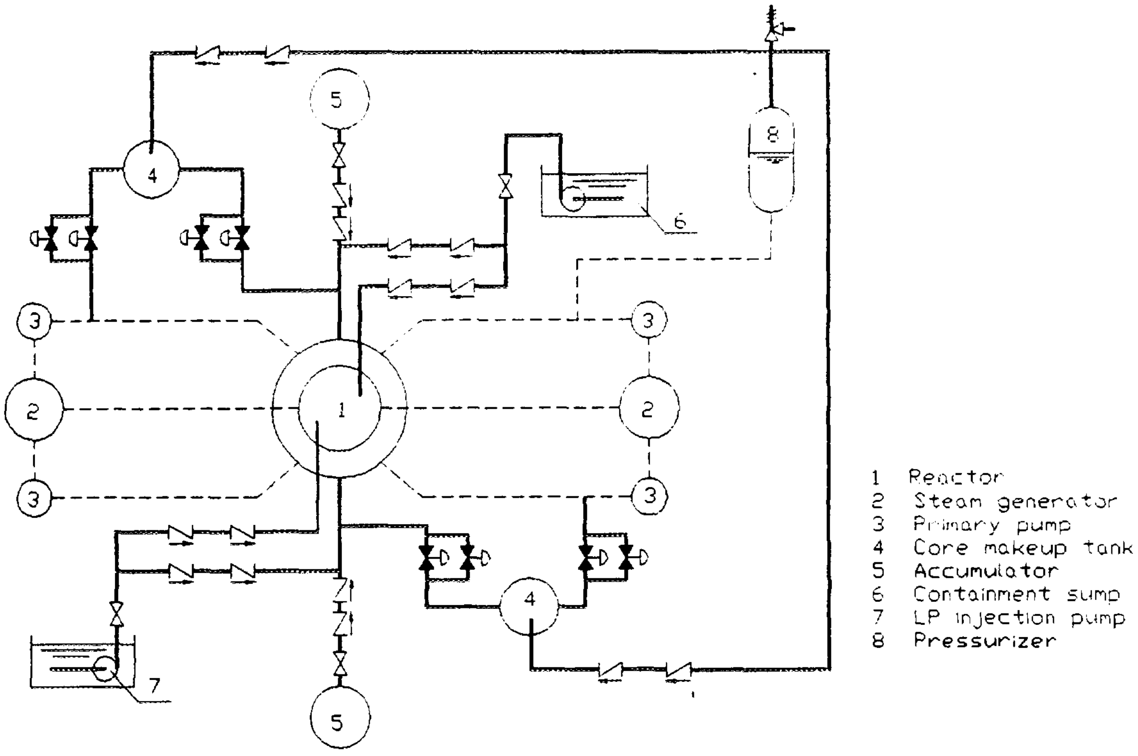

FIG. 1. Safety Injection System.

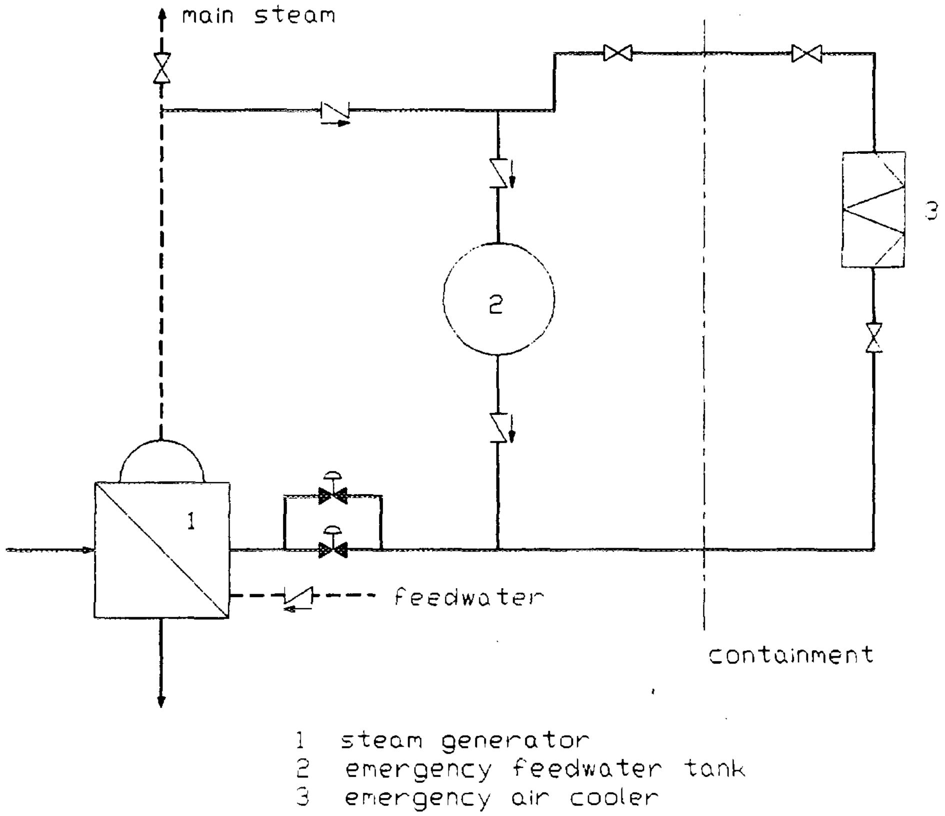

FIG. 2. Emergency Core Residual Heat Removal System.

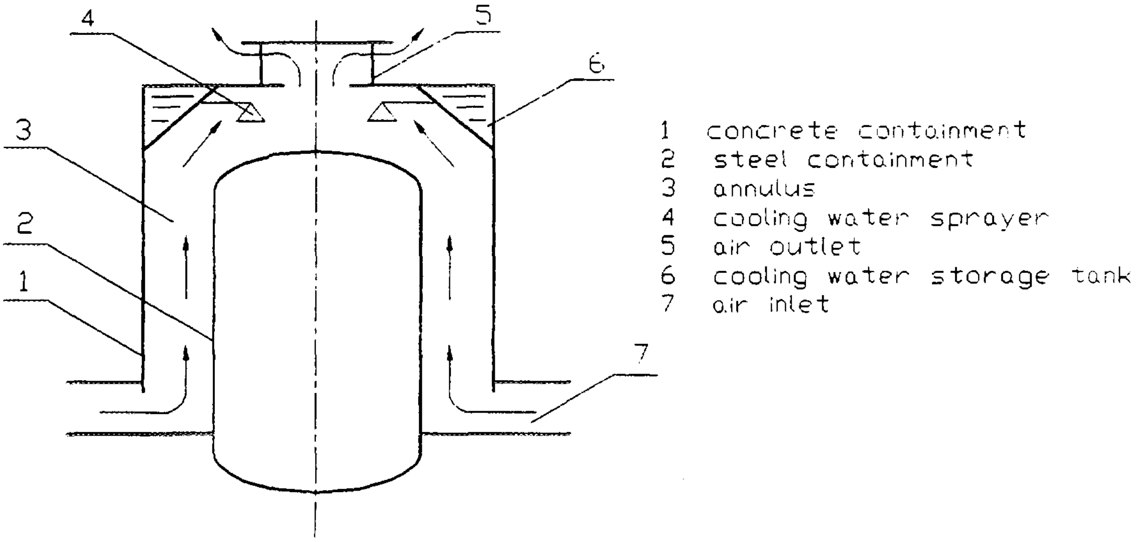

FIG. 3. Containment Cooling System.

Table 1

No:	Name	Quantity
1	core makeup tank	2
2	accumulator	2
3	emergency water tank	2
4	special sump	2
5	low pressure safety injection pump	4
6	emergency air cooler	2
7	water storage tank	1

successful experiences derived from the standard NPP and lessens the large research investment. In the system design, in order to improve the reliability of the system, the following subjects must be considered:

(1) Under the precondition of ensuring the function, the system should be designed simplified and standardized as much as possible. The simplification of the system is involved not only in its components but also in its operation.

(2) To meet the single failure criterion, it is necessary to avoid the cross and intersection between systems and to make the systems independent.

(3) The system is designed to a high level of safety which is obtained by an adequate level of redundancy in key components. All of these improve the reliability of the key components as well as the system. The key components include:

- The active components in the passive safety systems, such as the LP injection pump;
- The equipment with mechanical action when it is operating, such as the fail open valves of the ECRHRS;
- Instruments for inspecting and monitoring.

(4) The monitoring and control system provides an automated diagnosis of the state and operating conditions of the NPP. Monitoring and presentation of the information on the reactor coolant system, on all the safety-related systems, on the containment, on all operating conditions of the NPP and remote control of these systems are carried out. A post-accident monitoring system is provided to estimate the state of the NPP facilities and to present information important to safety.

(5) Integrity of the passive safety systems is provided by appropriate design and provisions, such as in-service inspection, monitoring, test and quality control. All components of the passive safety systems are subject to strength calculation under design conditions, and to stress, strain and seismic analyses under design basis accidents. The detection of leak before break is also used in the operation of system.

All the above mentioned are not the only subject for improving the system reliability, there are still other items such as power source, inspecting signal, etc. whose failure may lead to decreasing the system reliability. To improve the reliability of individual components within a system is to improve the system reliability as a whole.

3. FEASIBILITY AND RELIABILITY OF AC-600

3.1. Features of the system design of AC-600

(1) The design of the system follows some relevant rules and criteria used by current PWR plants. The system has the ability to withstand single failures. Two complete subsystems have been designed, each designed for 100% working capacity.

(2) The separation between normal and safety operation makes the systems dedicated to their function and avoids the use of common components in different systems, improves the reliability of components and makes it easy to maintain, inspect and test the system.

(3) The passive core makeup tank (CMT) takes the place of the HP injection system used in current standard PWR nuclear plants, so the HP injection pump and its mechanical/electric system are all eliminated. The CMT can operate at full pressure of the reactor core coolant, injecting rapidly and efficiently plenty of cold water into the core by gravity, avoiding the failure caused by electric power or other active component failure and the difficulty of water injection into the core due to the high coolant system pressure.

(4) The passive emergency core residual heat removal system replaces the secondary side residual heat removal system which consists of an emergency feedwater system and emergency steam release system. This replacement avoids failure due to a secondary system accident. Because the system is designed to operate with closed natural circulation by natural laws, such as evaporating, convection and gravity, its reliability is improved and its operation is not restricted by volume of a water source or by time.

(5) The passive containment cooling system replaces the containment spray system, and eliminates the boron injection subsystem used in standard NPP. The containment sump takes the place of the refueling water tank and the recirculation sump which serve both as the water sources of LP injection and recirculation, and this replacement

eliminates the exchange between two operation models mentioned above, simplifies the specialized safety facilities, makes the operation convenient and reliable and improves the inherent safety of the system.

(6) The components of the passive safety system, located on the primary coolant system side, are arranged in the steel shell of the containment; such a measure reduces the possibility of radioactive medium leakage from the system and/or component, and improves the inherent safety of the NPP.

(7) In order to improve the feasibility of the safety injection systems, AC-600 design is based on the principle of a combination of passive and active features. There are two full pressure CMTs, two accumulators and four low head safety injection /recirculation pumps which are installed in the containment sumps. In a large LOCA, the flow rate into the RCS from a CMT is larger than that from a high head safety injection pump in the conventional design. It is necessary for AC-600 to use an active pump which can perform the functions of the low head safety injection/recirculation system.

(8) The measures of increasing the vertical distance between the steam generators and the reactor core and reducing the primary flow resistance are used in the AC-600 design to increase the natural circulation cooling flow rate of the primary coolant system. If the reactor operates at 25% of the rated power, the natural circulation flow rate is about 4852 t/h (15.12% of the rated flow rate) after the reactor coolant pumps shut down. The natural circulation flow rate increase is a very important part of AC-600 passive safety.

(9) For operation of the safety injection system, except the subsystems of low pressure active safety injection and recirculation, sources of alternating current are not required. The air-operated valves needed for the function of emergency heat removal are air driven by compressed air from compressed air storage tanks. The power supply of the subsystems for low pressure active safety injection and recirculation are provided by diesel-generators or by offsite power source (during the recirculation stage after LOCA). In the passive emergency core residual heat removal system, the fail open valves on the piping are driven also by compressed air.

(10) The passive safety systems of the AC-600 design are based on the specialized safety systems of current NPP. The design and manufacture of the components of the passive safety systems such as tanks, valves, are all mature. The operating conditions of the components are good and based on previous experience and the economy is also good due to reduced need for research and development investment. All the above mentioned prove that the feasibility of the system is improved as measured by its reliability.

3.2. Failures of AC-600

The following accidents will be analyzed for the AC-600 design in order to provide some important parameters for AC-600 engineered safety system design and safety assessment.

- Increase of heat removal by the secondary system;
- Decrease of heat removal by the secondary system;

- Decrease of reactor coolant system flowrate;
- Reactivity and power distribution anomalies;
- Increase in reactor coolant inventory;
- Decrease in reactor coolant inventory;
- Radioactive release from a system or component;
- Anticipated transients without scram.

List of beyond design basis accidents (severe accidents):

- Total loss of ultimate heat sink;
- Loss of main and auxiliary feedwater;
- Station blackout;
- Loss of safety injection pumps.

4. MAJOR RESEARCH SUBJECTS OF AC-600

As it is a new concept and replaces the specialized safety systems used by the standard NPP by passive safety systems, there are still many problems about the feasibility and reliability of the systems to be researched.

During the 8th five-year plan (1991-1996), NPIC undertook the AC-600 overall design and research and AC-600 key technology test and research development subjects assigned by the State Scientific and Technological Commission and CNNC. Some of these subjects relating to the passive safety systems are as follows:

1) Integrated design and research on AC-600 main equipment, passive safety systems and simplified systems;
2) Full-pressure core makeup tank test and research;
3) Passive containment cooling system wind tunnel test and research;
4) Secondary side passive emergency core residual heat removal system test and research;
5) Passive LP safety injection/recirculation system test and research;
6) Research on the system redundant principle;
7) Test and research on instruments for inspection and control;
8) The system failure model and reliability research.

During the 9th five-year plan (1996-2000), NPIC will place the emphasis on the key technology peculiar to AC-600 and engage in design and test on the design technology, advanced nuclear power techniques and key equipment encompassing 33 subjects. By the year 2000, NPIC will have completed the AC-600 nuclear plant preliminary design, key technology research and key tests with a good knowledge of the complete design technology to the extent that a utility order for an AC-600 plant can be accepted and AC-600 engineering conditions will be essentially prepared. The major design and test subjects on the passive safety systems are as follows:

(1) Tests and research on the passive containment cooling system entirely;
(2) Mock-up test and research on the passive safety systems;
(3) Typical nuclear grade valve development;
(4) Tests and research on pumps immersed in water.

The research on the above subject is proceeding well. By the end of the 8th five-year plan, NPIC will have completed not only the research on some subjects but also the AC-600 PWR plant overall design.

In the design and research subjects, many up-to-date techniques are used for core design optimization, the passive safety system design and the simplified system design. The computer codes and data base will start to be established for AC-600 accidents analysis.

In the test subjects, emphasis is placed on the emergency core residual heat removal system, passive containment cooling system, etc, together with corresponding tests, and research reports to provide a test data base for use in the safety review.