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KEY DEVELOPMENTS IN THE ADVANCED NPP WITH WWER-640/V-407 REACTOR PLANT DESIGN

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Abstract

The report covers the main design features of advanced NPP equipped with WWER-640 reactor, that take into account the up-to-date approaches in the process of forming safety concepts. An approach to accident management has been analysed, beyond design-basis accidents included. A description of principal safety systems has been presented as well as the interrelation of their operation. The principal features of the systems design have been shown.

1. INTRODUCTION

WWER-640 reactor (Model V-407) is a vessel-type pressurized water reactor. The majority of reactor plant components are similar to the equipment that has shown a good performance at the operating NPPs and has been adopted for commercial manufacturing for WWER-440 (model V-213) and WWER-1000 (model V-320). The NPP safety systems have been designed as passive systems that do not require any operator actions within 24 hours. Up-to-date Russian approaches have been implemented and world experience has been used in determining safety levels and their relation with the safety barriers in the process of forming safety concept.

2. LICENSING STATUS

The procedure of licensing has been envisaged in the acting regulatory documents of the Supervisory bodies, namely, of RF Gosatomnadzor.

The requirements for granting a license in Russia comprise the procedure of step-by-step project licensing, up to NPP commissioning for commercial operation. They are given in [1, 2].

Currently siting permits and NPP construction licenses have been granted for the Kola-2 site and Nuclear Research and Industrial Centre in Sosnovy Bor.

3. REGULATORY BASIS FOR ADVANCED NPP WITH WWER-640 DESIGN

The advanced NPP equipped with WWER-640 was designed in accordance with the regulatory documents and standards enacted in the Russian Federation as well as with allowance for the IAEA Safety Guides. The analysis was carried out of design compliance with a number of principal regulatory documents, applied in the USA, Germany, France. This analysis has shown that design safety can be confirmed on the basis of regulatory documents from any of these countries.

The regulatory requirements are met in the design along with an acceptable level of economic indices due to:

(1) Double containment, application of passive emergency core cooling systems and passive residual heat removal systems in the design, which have reduced the probability of severe accidents by order 2 or 3 in comparison with WWER-1000 (Model 320) [3];

(2) The fuel cost decrease through improving nuclear fuel cycle, which leads to an increase in fuel utilisation efficiency by 20-25%;

(3) Upgrading of automation and process control systems as well as furnishing them with equipment and pipelines diagnostics systems;

(4) Decrease of the amount of equipment and its total quantity of metal;

(5) Service life elongation up to 50-60 years.

4. DESIGN EVOLVING FROM THE POINT OF VIEW OF SAFETY ASSURANCE BY MEANS OF ACTIVE OR PASSIVE SAFETY SYSTEMS

The traditional demand for meeting the increasing safety needs in new NPP designs is satisfied by safety systems growth and their sophistication. This tends to result in an increase in the total cost of the Unit. Such an increase was in previous designs partly compensated for by increasing the unit power. Sophistication of the safety systems yields more complicated servicing and control, which increases the risk of human error.

For this reason, two approaches to design of new generation PWR type reactors are being simultaneously pursued at present:

- the first approach is based on the development of large power plants with the prevailing usage of active safety systems;
- the second approach is based on creating medium-size power reactors with a preferred usage of passive safety systems.

The reactor plant with WWER-640 belongs to the second approach. In the WWER-640, the significance and quantity of active systems are reduced to a minimum. In reality, there is only one safety system that is of active type, namely, the system of boron supply with high-pressure pumps in case of an ATWS-type accident. The other active systems are only required for normal operation.

The choice of systems, operating on the basis of passive principle is stipulated by several causes:

(1) A possibility to use natural phenomena forces in principle, proceeding from the correlation of the Unit scale factors and its thermal power;

(2) Engineering and economical expediency;

(3) An attempt to exclude operator's errors that can arise, for example, as a result of restoring one safety function or another.

5. PRINCIPAL GOALS AND METHODS TO IMPLEMENT SAFETY CONCEPTS

The following principal goals have been established for the safety concept of the NPP design with WWER-640:

- not less than one passive safety train shall be envisaged;
- time interval before the necessity of operator's actions to restore or maintain the principal safety functions shall be not less 24 hours;
- the content of the activities shall be aimed at safety functions restoring by simple make-up or start-up of available systems;
- an additional safety barrier shall be envisaged in case of a severe (beyond design basis) accident involving core melting.

The following technical provisions are envisaged in the reactor plant design concept with WWER-640 to implement the principal goals of the concept:

(1) Decreased power density in the core;

(2) Lower neutron flux onto reactor vessel;

(3) A higher efficiency of the system of changing reactivity due to increasing the number of CPS mechanical members;

(4) A large inventory of reactor and pressurizer coolant;

(5) Passive coping with an accident involving loss of all the sources of AC power without any operator's actions within 24 hours;

(6) Elimination of transients without any need of emergency make-up;

(7) Passive features for realisation of safety system functions; large inventories of borated cooling water inside the containment, furnished with facilities providing water flow into reactor vessel at pressure decrease inside the latter;

(8) Alternative systems of heat removal from reactor vessel and the containment ;

(9) Systems of removing hydrogen from containment;

(10) A possibility of passive external heat removal from reactor vessel;

(11) Advanced containment for elimination of core melt accidents.

6. DESIGN BASES FOR ACCIDENT MANAGEMENT CONCEPT

The principle of implementation of defence-in-depth is the basis of safety concept. The principle is realised by the usage of:

- a system of physical barriers on the way of ionising radiation propagation and radioactive substances release into the environment;
- engineering and organisational measures intended to protect the barriers and maintain their efficiency as well as direct measures to protect the population.

The system of physical barriers is traditional for NPP with WWER reactor and comprises, respectively:

- fuel matrix;
- fuel element cladding;
- primary coolant pressure boundary;
- envelope.

A system for retention and localisation of non-gaseous fission products that can be released in case of reactor vessel destruction is envisaged as an intermediate safety barrier between primary circuit boundary and the envelope. Elaboration of possible engineering solutions for this system is currently under way. Meanwhile, at least the necessary space of reactor cavity is provided. The space is intended to catch and safely confine corium. With this aim appropriate post-accident monitoring means are envisaged in the cavity space.

In accordance with [4] the system of engineering and organisational provisions is to create five levels of defence-in-depth. With this, each level of engineering and organisational provisions is assigned appropriate levels of the NPP status that characterise the conditions of power unit operation. The purpose of splitting out such horizontal links is to prevent NPP transition from a higher level to a lower one or providing purposeful and efficient reactor plant protection in case

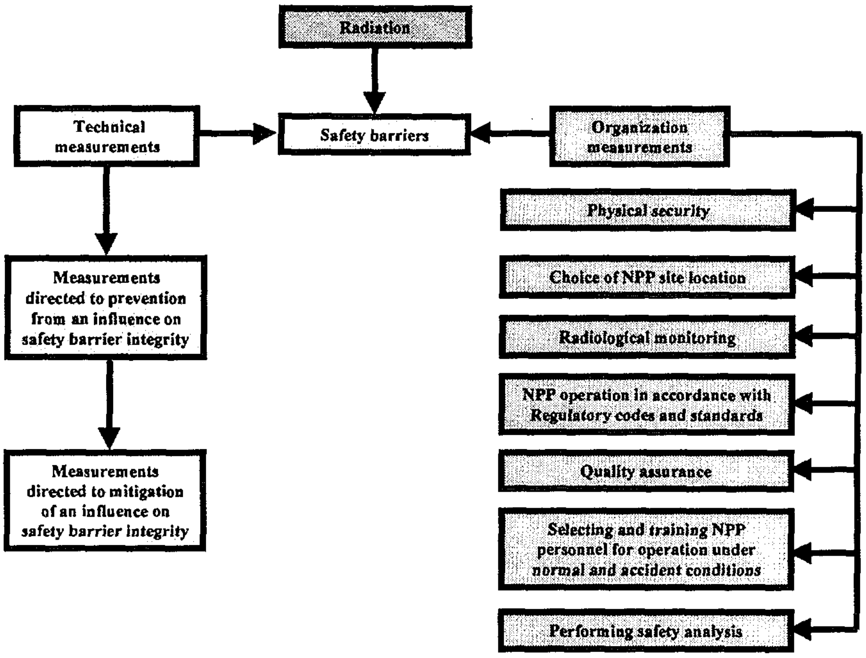

FIG. 1. The application of the defence-in-depth principle

such a transition has taken place. Figure 1 illustrates the application of the defence-in-depth principle.

Safety functions have been determined in the project in order to provide the accomplishment of the purpose of safety barriers integrity protection and its efficiency. It meets the requirements of the up-to-date regulatory documents [4, 5]. For each of the safety barriers to retain their integrity a number of conditions exists that must be permanently maintained. These conditions are ensured by means of safety functions, taken from the general list of safety functions.

7. REALIZATION OF SAFETY BARRIERS AND SAFETY FUNCTIONS IN THE DESIGN OF NPP WITH WWER-640 REACTOR

Design solutions on engineering provisions aimed at supporting the efficiency and integrity of safety barriers, enumerated in item 6, will be further analysed.

7.1 Fuel Rod Claddings and Fuel

Reactor core has been developed on the basis of the operating NPPs with WWER-1000 reactors. As a result of it a core with a lower power density was created. Safety analyses show that the fuel rod cladding temperature will not exceed 800 °C under all design basis accidents, that the fuel rods will be under these conditions for not more than 150 s, and that the local depth of oxidation does not exceed 5%.

With this, fuel assembly design has been improved due to:

(1) Application of progressive structural materials;

(2) Providing fuel assemblies repairability;

(3) Usage of gadolinium as burnable poison;

(4) Fuel enrichment radial profile shaping within the fuel assembly

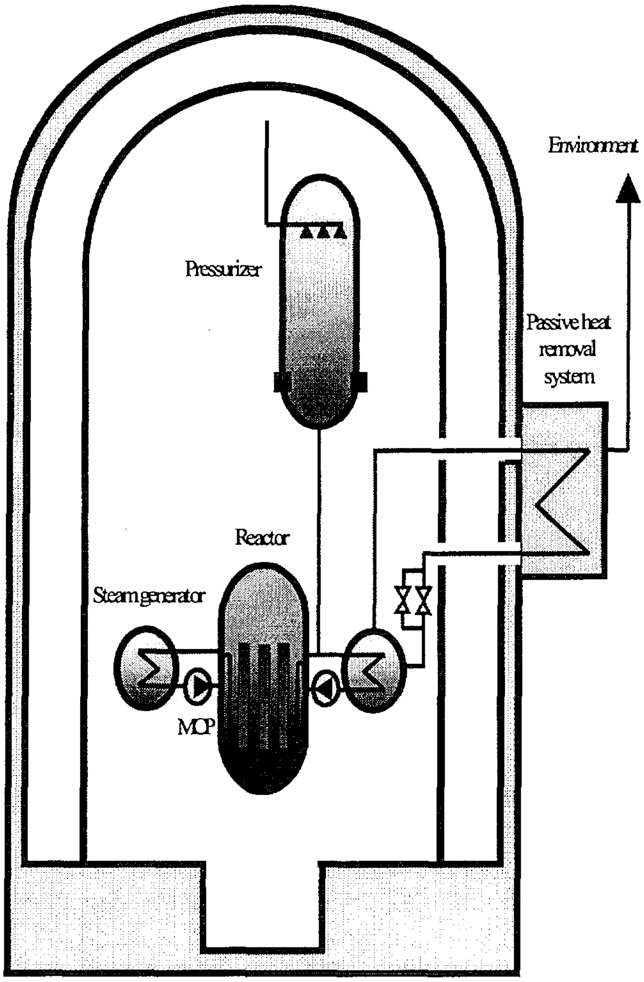

FIG. 2. The operation of passive heat removal systems under non-LOCA conditions

7.2 Primary Pressure Boundaries

Circulation loops are not equipped with loop seals and consist of straight tubes and bends in the places of connection to steam generators and pumps.

Main circulation circuit equipment layout as well as passive heat removal equipment layout provides residual heat removal from the core into the tanks of chemically demineralized water and further to the atmosphere following reactor shutdown by natural circulation. Reactor power that can be removed from the core by coolant natural circulation on the basis of the calculated data is 10% of the nominal value, which guarantees a reliable residual heat removal.

Thus, in case of accidents not involving primary coolant loss following reactor shutdown by appropriate signals of emergency protection system, heat is removed from the core, as shown in Figure 2, due to primary coolant natural circulation to steam generator boiler water. The steam generated comes into the steam generator passive heat removal system (PHRS). In the SG PHRS steam is condensed on the internal surface of the tubes that are cooled on the outside with water stored in the demineralized water tanks. The condensate then flows back into the steam generators by gravity.

7.3 Containment

A double protective and confining containment arrangement is provided in the design of NPP equipped with WWER-640 reactor.

The primary hermetic envelope is made of steel.

The secondary envelope, the containment proper, is made of concrete. This containment is designed to protect reactor from external impacts, namely:

- aircrash,
- shock wave.

Small under-pressure is maintained inside the gap between the envelopes and exhaust air passes through filters into the ventilation tube.

The outer containment is separated from the steel envelope and it does not transfer the loads produced by any external impacts to the steel envelope. Both envelopes are supported by the reactor building bedplate and fixed to it.

All the primary equipment and pipelines are housed inside the reactor hall hermetic envelope, and all the connections pass through hermetic penetrations, that prevent pressurized coolant release from the envelope under any accident situations. The system of passive ECCS is also housed inside the envelope.

The reactor plant is so located that in case of an accident involving considerable primary coolant loss, and actuation of the ECCS, the reactor plant is flooded together with the fuel pond, which provides reliable cooling of all the fuel inside the envelope. Thus, the concrete pit where the reactor is located, the floor of the steam generators' compartment and the compartment walls form an emergency heat removal pond.

Primary pressure is decreased in case of loss-of coolant accidents by means of the passive heat removal system and by mass and power release into the envelope. Following primary pressure decrease to 4-6 MPa, check valves open at the ECCS tanks and boric solution begins flowing into the reactor vessel. The further cooldown and pressure decrease in case of small-break and medium-break LOCAs are realised via steam generator PHRS and hermetic envelope PHRS.

When the primary circuit and hermetic envelope pressure differential has decreased to 0,6 MPa, the passive valves of the emergency depressurization system, which connect the loops hot and cold legs with the fuel ponds space, open.

The opening of the depressurizing valve will yield further pressure decrease. When the primary circuit and ECCS tanks pressure differential has decreased below 0,3 MPa, the tanks begin reactor flooding.

This results in establishing a natural circulation along the following flow path, as shown in Figure 3: reactor lower plenum - core - reactor upper plenum - "hot" leg - pipeline with valve system for depressurization - fuel pond - pipeline with valve system for depressurization - "cold" leg - reactor lower plenum. The given flow path provides long-time heat removal from the core in case of LOCAs combined with loss of all electric power.

As the level in the emergency pond increases (approximately up to the level of the "hot leg" nozzles on the reactor vessel), the valves of connecting line between the emergency pond and the fuel pond open. As a result, the entire inventory of water stored inside the steel envelope will become involved in the process of cooling the core and the spent fuel.

The integration of the ponds leads to water mixing with a mean temperature below the saturation temperature. The water of both ponds continues getting heated, and in about 10 hours the water reaches boiling temperature. The generated steam condenses on the internal surface of the hermetic envelope, and the condensate flows back into the pond. This steam condensing is

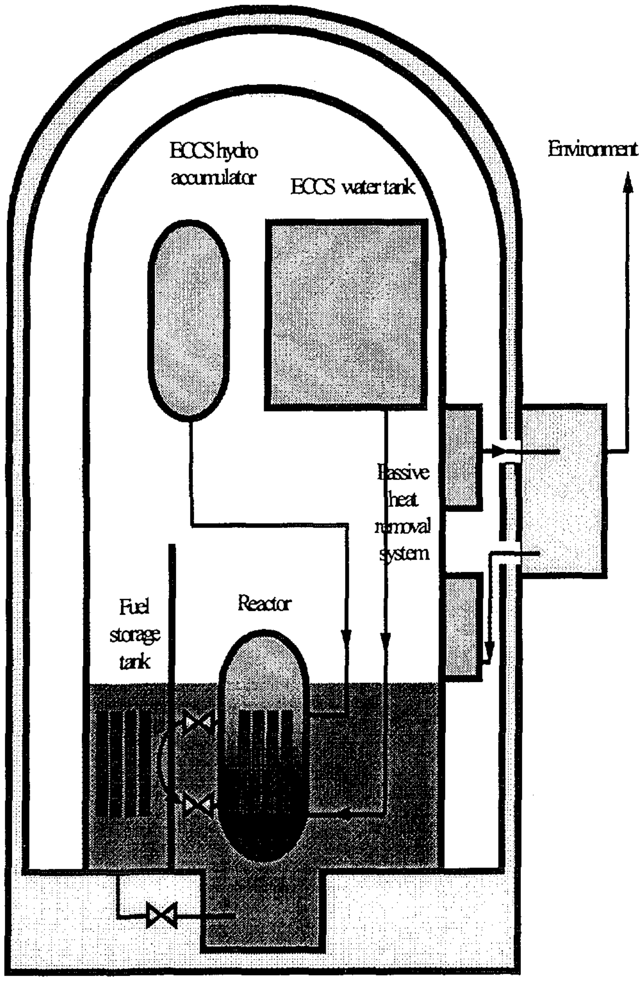

FIG. 3. The operation of passive heat removal systems under LOCA conditions

provided by the system of hermetic steel envelope cooling (HE HRS), which is designed for 24 hours operation without any operator actions.

Long-time heat removal from the core is thus provided in case of loss-of coolant accident and loss of all power.

8. CONCLUSION

As a result of assuming the decisions, solving the following safety-related problems is provided in the design:

(a) Reliable cooldown and long-time core heat removal (for 24 hours) without any operator actions is provided;

(b) Control and protection system keeps the core sub-critical at any moment of the fuel cycle under any loss-of-coolant accident even in case of clean condensate supply;

(c) Passive reactor core flooding on the outside under any loss-of-coolant accident to remove heat from reactor vessel bottom by natural convection in case of postulated core destruction and corium agglomeration on the vessel bottom.

List of Adopted Abbreviations

VSP	- valve system for depressurization
WWER	- water-cooled and water moderated power reactor
SG	- steam generator
ECCS	- emergency core cooling system
HE HRS	- hermetic envelope heat removal system
PHRS	- passive heat removal system
CPS	- control and protection system
SF	- safety function

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