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PASSIVE SAFETY SYSTEMS FOR INTEGRAL REACTORS

V.S. KUUL, O.B. SAMOILOV
OKB Mechanical Engineering,
Russian Federation

Abstract

In this paper, a wide range of passive safety systems intended for use on integral reactors is considered. The operation of these systems relies on natural processes and does not require external power supplies. Using these systems, there is the possibility of preventing serious consequences for all classes of accidents including reactivity, loss-of-coolant and loss of heat sink as well as severe accidents.

Enhancement of safety system reliability has been achieved through the use of self-actuating devices, capable of providing passive initiation of protective and isolation systems, which respond immediately to variations in the physical parameters of the fluid in the reactor or in a guard vessel. For beyond design base accidents accompanied by complete loss of heat removal capability, autonomous self-actuated ERHR trains have been proposed. These trains are completely independent of the secondary loops and need no action to isolate them from the steam turbine plant.

Passive safety principles have been consistently implemented in AST-500, ATETS-200 and VPBER 600 which are new generation NPPs developed by OKBM. Their main characteristic is enhanced stability over a wide range of internal and external emergency initiators.

1. INTRODUCTION

The design of reactor plants with enhanced safety for the new generation of NPPs is one of the most important problems for the nuclear industry.

The solution of this problem is based principally on the design of reactors with inherent safety properties and deployment of passive safety systems. The basis of improved reactor plant designs developed in OKBM is the integral PWR characterized by simplicity and compactness of the primary circuit. Retaining all positive self-protection properties of PWRs, the integral reactor allows provision of further improvement in safety. This includes protection against the class of accidents most critical for PWRs, namely primary circuit loss-of-integrity. This protection has been established by exclusion of accidents with large and medium leaks. The large water inventory above the core provides a long time margin before core uncovery in accidents with primary pipeline breakage.

Decrease of the neutron fluence to the reactor vessel extends the useful life-time of the Reactor Pressure Vessel (RPV) to 60 years of operation. The integral design also eliminates the damaging influence of cold coolant on the reactor vessel during operation of powerful ECCS. Together with the inherent safety characteristics of the integral reactor, safety enhancement is achieved by passive safety systems, operating on the basis of natural processes without external power supply, and utilization of self-actuated devices to initiate them. Passive safety is applied for all kinds of accidents including accidents with positive reactivity insertion, accidents with loss of heat removal from the reactor, and accidents with primary circuit loss-of-integrity. A plant design with enhanced, perhaps maximised, safety was successfully implemented in the AST-500 nuclear district heating plant. Subsequently, the main critical design solutions for AST-500 safety, such as the integral design of the reactor and the various passive safety systems became the basis for the design of several other plants developed with natural and forced coolant circulation (e.g. ATETS-200, VPBER-600, etc.).

2. SYSTEMS FOR REACTOR EMERGENCY SHUTDOWN

2.1. A characteristic feature of the reactors developed by OBKM is the application of a highly effective mechanical system for reactivity control. This has been achieved by installation of control rod/assemblies in almost all the fuel assemblies of the core (Fig. 1). Reactor shutdown is performed by emergency protection signals leading to the dropping of control assemblies into the core following drive deenergization. In this case the reactor is transferred to a subcritical state with a reserve to allow for some control rod drive assemblies remaining stuck in a withdrawn position without the need for injection of boron solution. Residual Heat Removal Systems (RHRS) are also provided to bring the reactor system to a cold shutdown condition.

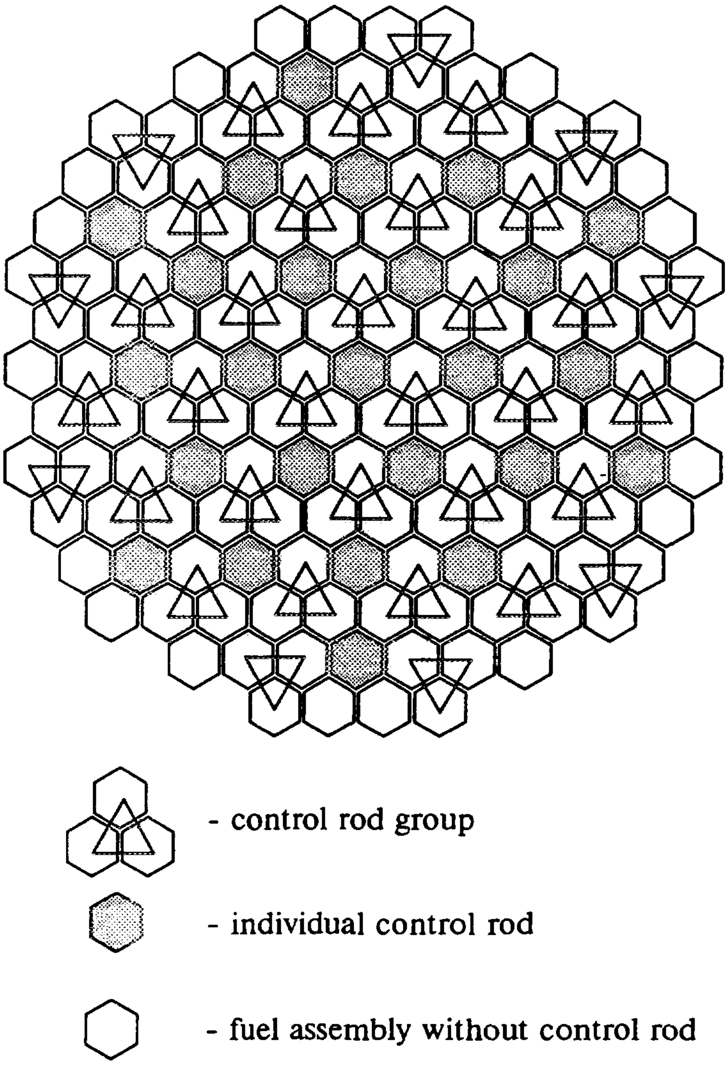


Fig. 1.
VPBER-600 Control Rods Layout

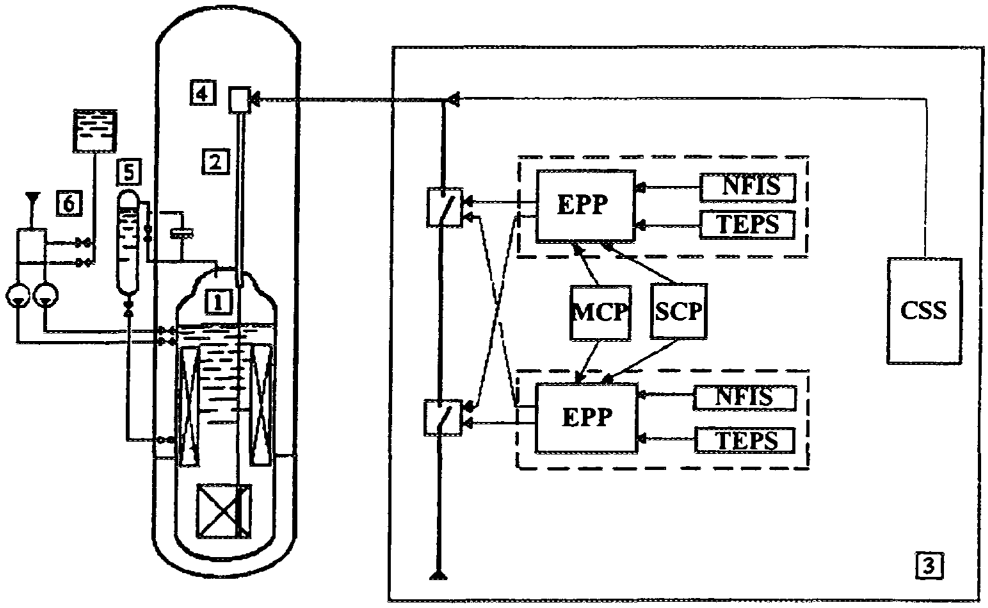
2.2. Together with automatic systems, self-actuated devices are used for deenergization of a sufficient number of Control Rod Drive Mechanisms (CRDM) to provide emergency protection. This actuation system is independent of the automatic system circuits; it responds to a pressure rise in the reactor or guard vessel (Fig.2).

Two types of pressure actuated power breakers (PAPB) are being developed: a PAPB built in as an integral part of the CRDM or a remote PAPB built into the reactor cover. The latter may deenergize a single CRDM or a group of CRDMs.

2.3. A passive system of boron emergency injection is intended for complete scram of the reactor core and maintaining it in a subcritical state in the case of the mechanical system malfunctioning (Fig.2). System actuation is performed by opening pneumatically operated valves on the pipelines connecting the boron solution tank and the reactor pressure vessel, or by a rupture disk actuated directly by a rise in the primary circuit pressure. Boron solution is supplied to the reactor by gravity due to the elevation of the boron solution tank above the reactor, once the pressures in the reactor and in the tank have been equalised.(Fig.2).

3. EMERGENCY HEAT REMOVAL SYSTEM

3.1. The AST-500 (AST-500M) emergency heat removal system will use the main heat exchanger loops for heat removal. Heat is removed in a three circuit scheme by natural coolant circulation and evaporation of water from designated tanks (Fig.3).



1 - Reactor
2 - CSS CRDM
3 - Control and safety system (CSS)
4 - Direct-acting device
5 - Passive channel for liquid boron injection
6 - Active channel for liquid boron injection

CSS - control rod controling system
NFIS - neutron flux instrumentation set
TEPS - technological equipment protection set
EPP - emergency protection panel
MCP - main control panel
SCP - standby control panel

Fig. 2.
Reactivity Control Means

An air heat exchanger is provided on one of the channels side by side with the water tanks. This ensures an unlimited period for residual heat removal without the need for power supply or water make-up (Fig.4).

When an accident occurs, the system is initiated by valves actuated by signals from the automatic control system or by direct reactor parameter effects (pressure, level).

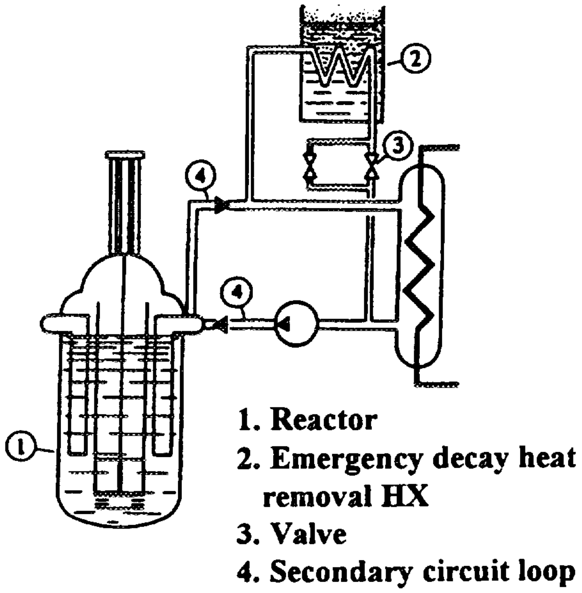


Fig.3

Emergency decay heat removal channel switched to the secondary circuit valves

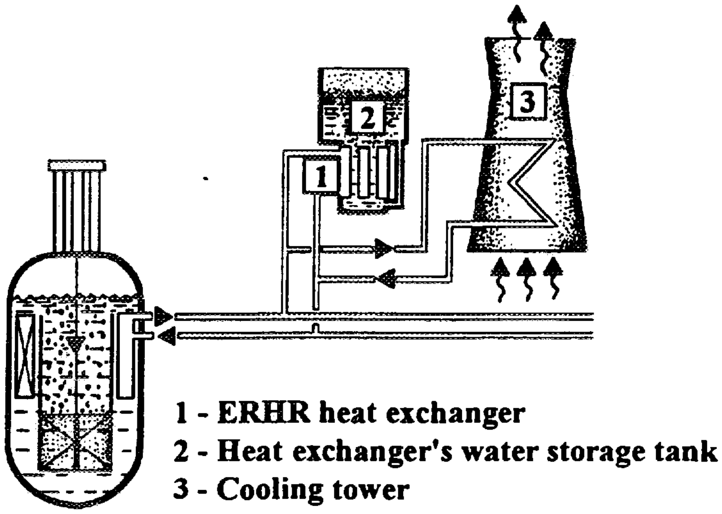


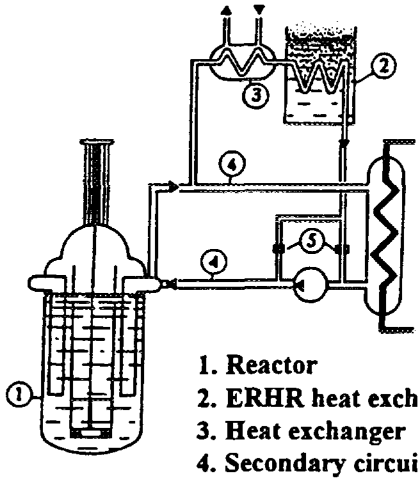
Fig.4

Emergency decay heat removal channel connected to the secondary circuit

3.2. In the ATETS-200 power reactor, heat is removed through the steam generator by natural circulation of coolant following secondary loop isolation from the steam-turbine plant. Secondary water circulates through the SGs and the RHR heat exchanger located in a water storage tank.

3.3. To exclude failure of heat removal capability in AST-500, a continuously operating heat removal system with an auxiliary heat exchanger situated in parallel with the main cooling heat exchanger is proposed. In this case the heat drawn by the auxiliary heat exchanger is used for the district heating network (Fig. 5).

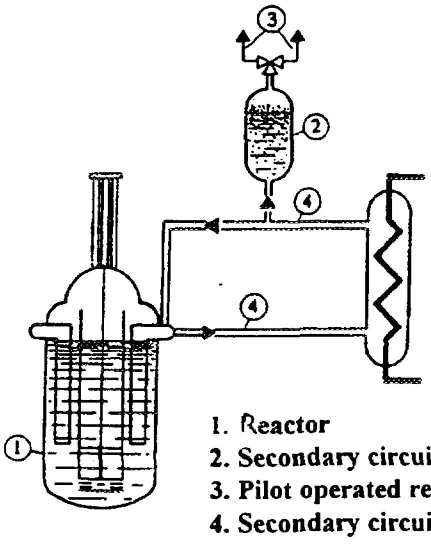
3.4. Owing to the considerable water inventory in the AST-500 plant intermediate circuit, evaporation of intermediate circuit water through a relief valve (Fig.6) can be considered as an auxiliary system of emergency heat removal during beyond design base accidents.



1. **Reactor**
2. **ERHR heat exchanger**
3. **Heat exchanger**
4. **Secondary circuit loop**
5. **Orificing devices**

Fig.5

Emergency decay heat removal channel permanently connected to the secondary circuit



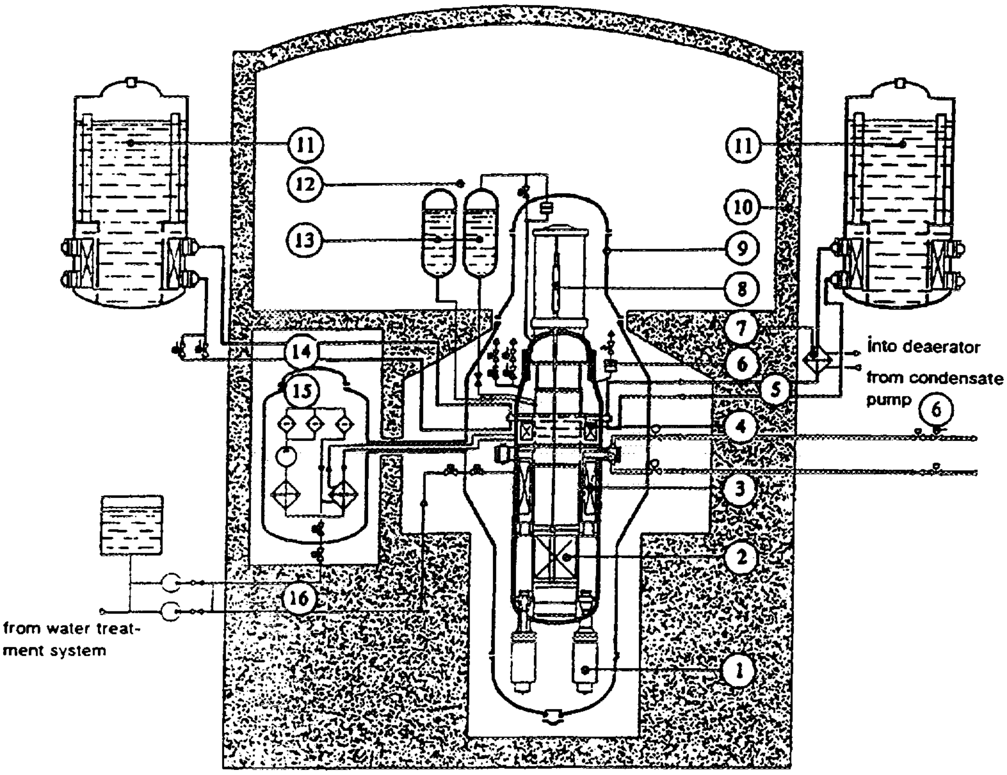
1. **Reactor**
2. **Secondary circuit pressurizer**
3. **Pilot operated relief valve**
4. **Secondary circuit loop**

Fig.6

Emergency decay heat removal channel via the pilot operated relief valve in the secondary circuit

3.5. A passive emergency heat removal system considered for installation in VPBER-600, is independence of the secondary circuit and requires no isolation from the steam turbine plant. For this purpose, special emergency cooling heat exchangers are arranged above the SG level but below the primary water level (Fig.7). Heat is removed through an intermediate circuit by natural coolant circulation (Fig.8). Another continuous passive heat removal system is also being considered. In this case the heat drawn from the primary circuit by the emergency heat removal channel is used for heating the secondary circuit feed water (Fig.8).

3.6. An independent passive cooling system intended for beyond design accidents with complete loss of normal reactor heat removal capability is being considered for some integral reactors designs. A condenser-heat exchanger is arranged above the RPV head. Primary circuit heat is transferred through a double wall condenser-heat exchanger by natural circulation to a water inventory tank and removed to the atmosphere (Fig.9). The channel is self-actuated in response to primary pressure increase via a rupture disk.



1. Main circulating pump
2. Reactor
3. Steam generator
4. Heat exchanger - condenser
5. Continuous heat removal system
6. Self-actuating devices (direct action)
7. Intermediate heat exchanger
8. CRDM
9. Guard vessel
10. Containment
11. Heat exchangers unit
12. Emergency boron injection system
13. Tank with boron solution
14. Passive heat removal system
15. Coolant clean-up and boron reactivity control system
16. Primary circuit makeup system

Fig.7

VPBER-600 reactor plant flow diagram

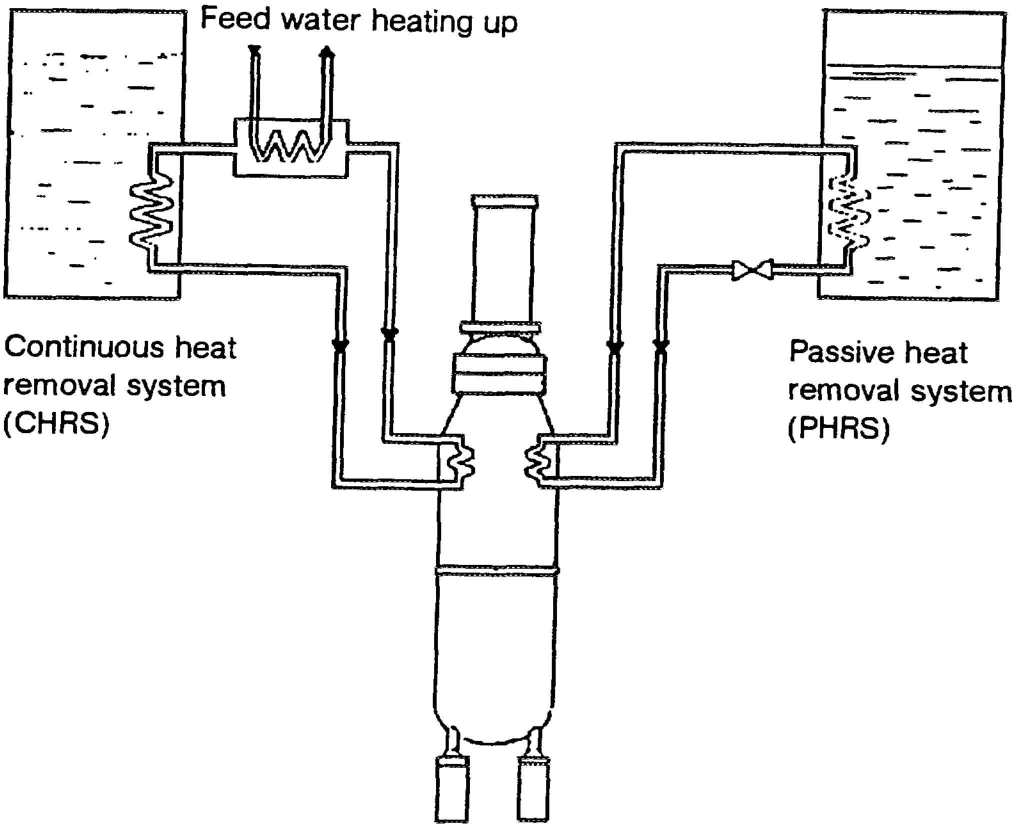
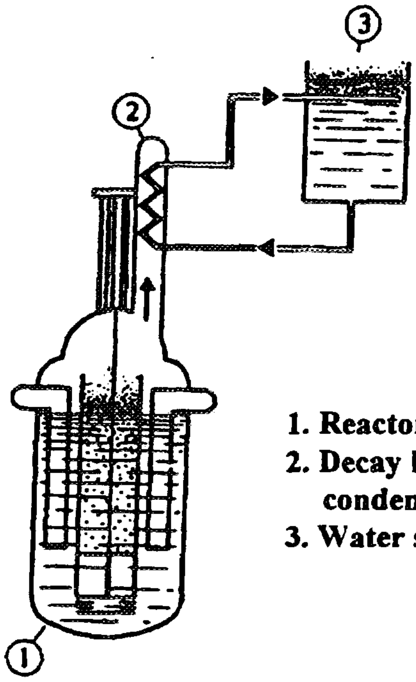


Fig. 8

Emergency residual heat removal system



1. Reactor
2. Decay heat removal condenser
3. Water storage tank

Fig. 9

Self-actuated ERHR channel on the reactor

4. ISOLATION SYSTEMS

4.1. Integral reactor compactness allows to locate the reactor in a strong-leaktight guard vessel (GV). The guard vessel is a passive protective and isolating device, ensuring safety in the case of primary pipeline rupture or reactor vessel loss-of-integrity (fig.10). Its design pressure is that expected to occur following a primary circuit loss-of-integrity. The GV prevents core uncovery and provides core cooling. It also provides for confinement of radioactive products. There is no need for active water injection systems for core cooling in emergency situations when a guard vessel is used, because the reactor core is kept covered by water.

The guard vessel performs an important function during severe accidents. When postulating complete core melting, corium confinement in the reactor vessel is provided by the guard vessel. Along with the integral reactor feature of decreased thermal load on the vessel, the presence of water in the guard vessel during primary circuit loss-of-integrity accidents ensures, from the very outset of the accident, external cooling of the reactor vessel. High efficiency of heat removal due to the relatively high pressure in a guard vessel is an important factor in mitigating the consequences of the accident.

4.2. For the three-circuit heat transfer scheme in AST-500, the intermediate circuit functions as a passive protection and isolation system ensuring retention of primary circuit radioactive product.

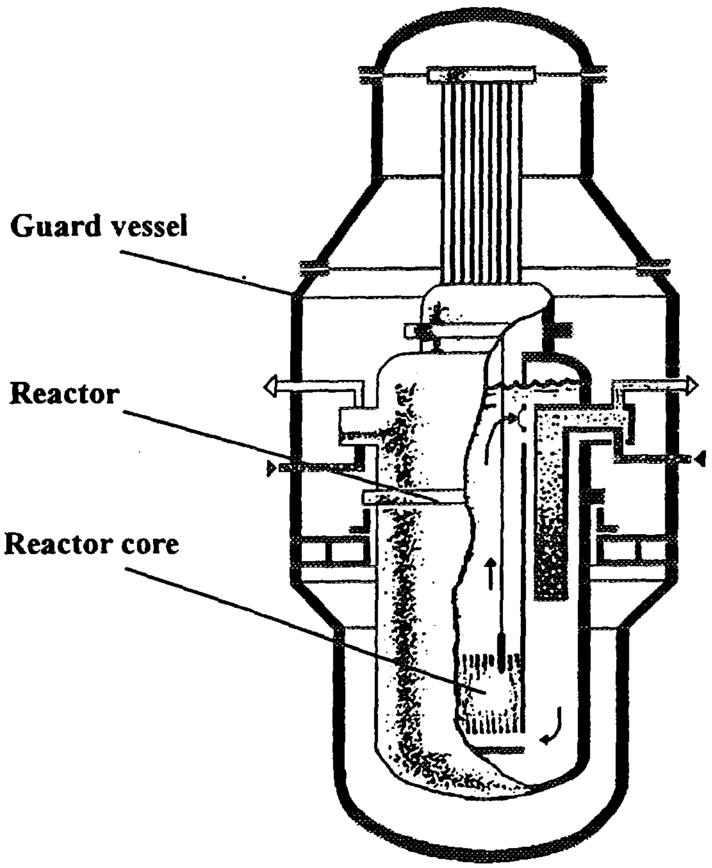


Fig.10

AST-500 Reactor

4.3. In the VPBER-600 reactor plant double isolation valves designed for primary circuit pressure are built in to each loop. One group of valves is activated by a signal from the automatic control system, the other one is actuated either by a signal from the automatic control system or passively as a result of low coolant level in the RPV.

5. MAIN FEATURES OF PASSIVE SAFETY SYSTEMS

The wide spectrum of passive safety systems presented in this paper allows their common main features and advantages to be identified.

- The operation of passive safety systems relays on natural processes and does not require supply of external energy. This ensures the reliability of the safety system in the condition of a station blackout for a long or unlimited time;
- Failure-free operation of passive systems relaxes the need for system redundancy, provides for simplification, and enhances the economics;
- An important benefit in the use of some passive systems is the possibility of checking during operation their efficiency and conformity to design performance requirements;
- Enhancement of system reliability is achieved by use of self-actuating devices leading to reliable operation of protective and isolation safety systems following any change in the reactor physical parameters;
- Use of passive safety systems gives effective protection against erroneous actions or personnel non-action and creates an additional protective barrier against sabotage;
- Specially designed passive systems or devices for prevention of failure of emergency reactor shutdown, prevention of over-pressurization of the reactor in the event of loss of all means for heat removal, and the ensured cooling of the reactor vessel from the outside practically excludes damaging severe accidents.

6. CONCLUSION

The safety concept of integral PWRs using natural or forced circulation of coolant (e.g. AST-500, ATETS-200 and VPBER-600 type) developed by OKBM for power plants of the new generation is based on the wide use of multi-purpose passive safety systems. This concept ensures, in principle, a higher level of safety, enhanced techno-economic indices and stability of nuclear power units in the case of severe accidents.