BASIC SAFETY PRINCIPLES OF KLT-40C REACTOR PLANTS

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Abstract

The KLT-40 NSSS has been developed for a floating power block of a nuclear heat and power station on the basis of ice-breaker-type NSSS with application of shipbuilding technologies. Basic reactor plant components are pressured water reactor, once-through coil-type steam generator, primary coolant pump, emergency protection rod drive mechanisms of compensate group-electromechanical type. Basic RP components are incorporated in a compact steam generating block which is arranged within metal-water shielding tank's caissons. Domestic regulatory documents on safety were used for the NSSS design. IAEA recommendations were also taken into account. Implementation of basic safety principles adopted presently for nuclear power allowed application of the KLT-40C plant for a floating power unit of a nuclear co-generation station.

1. KLT-40C REACTOR PLANT FOR FLOATING POWER UNIT OF NUCLEAR HEAT AND POWER STATION

Two-circuit reactor plant (RP) with a vessel-type pressurized water reactor is used for floating power unit of nuclear head and power station. Basic RP components: reactor, steam generators and primary coolant pumps are incorporated by pressure nozzles in a compact steam-generating block. KLT-40C RP characteristics are given in Table 1.

Creation of KLT-40C RP is carried out on the basis of existing ice-breaker-type RP and established shipbuilding technologies. Technical solutions are validated by 39-five year experience of operation under navigation conditions in Arctic seas. Achieved service life of the ship reactor plant equipment and systems exceeds 130 000hrs. Basic equipment of KLT-40C RP represents industrially fabricated equipment used for serial KLT-40-type reactor plants. The reactor plant meets the quality assurance requirements according to international QA code ISO-9000. Pressurized water reactor (Fig. 1) with forced coolant circulation in primary circuit is used. The reactor is composed pressure of vessel, cover, internals removable block, core, drive mechanisms for CG and EP. The vessel is forged-welded structure. Vessel structural material is heat-resistant high-strength perlytic steel with anticorrosive overlaying.

TABLE I. KLT-40C RP NOMINAL CHARACTERISTICS

Characteristic	Value
Thermal power, MW	150
Steam output t/h	240
Pressure of steam after SG, MPa	3,8
Temperature of super heated steam, °C	290
Temperature of feed water, °C	170
Service life, years	35-40
Time between core refueling, years	2, 5-3

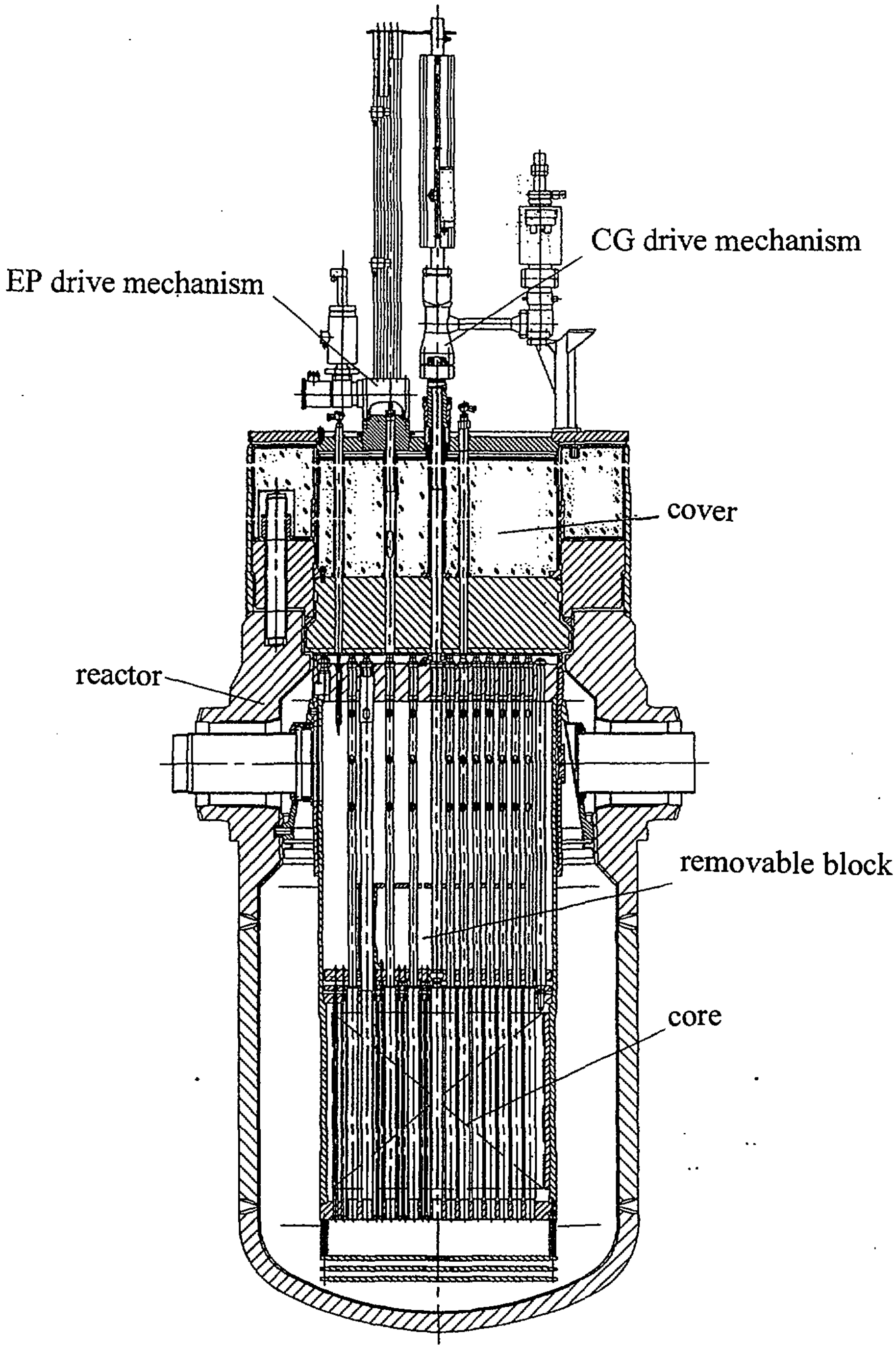

Fig.1. Reactor

The core has heterogeneous arrangement and uses dispersion-type nuclear fuel. Core consists of a set of FA and sets of reactivity control and safety rods. FAs incorporate burnable poison (gadolinium) rods to compensate the core excessive reactivity. The core uses smooth-pin type fuel element with a cladding made of zirconium alloy.

Fuel composition is selected taking into account of high compatibility with zirconium-alloy cladding, structural stability at high temperature, sufficient corrosion-erosion resistance in water environment, high heat conductivity. The core possesses negative power and temperature reactivity coefficients within the entire range of operating parameters variation during core life period.

SG is once-through coil-type heat exchanger with steam generation within tubes (Fig. 2). The SG's tube system consists of cylindrical helical coils is made of titanium alloy. The SG's shell structural material is low-alloyed steel with anticorrosive overlaying. The PCP is canned centrifugal one-stage pump with screened dual-speed (two-winding) asynchronous motor. Capacity - 870m3/h, head -0,38Mpa. The pump casing items are fabricated of austenitic stainless steel. Electric motor's rotor is fabricated of ferritic stainless steel. The pump bearings are lubricated and cooled, as well as both electric drive rotor and stator are cooled by primary coolant which circulates in an autonomous loop. Heat from the loop is removed by cooling water.

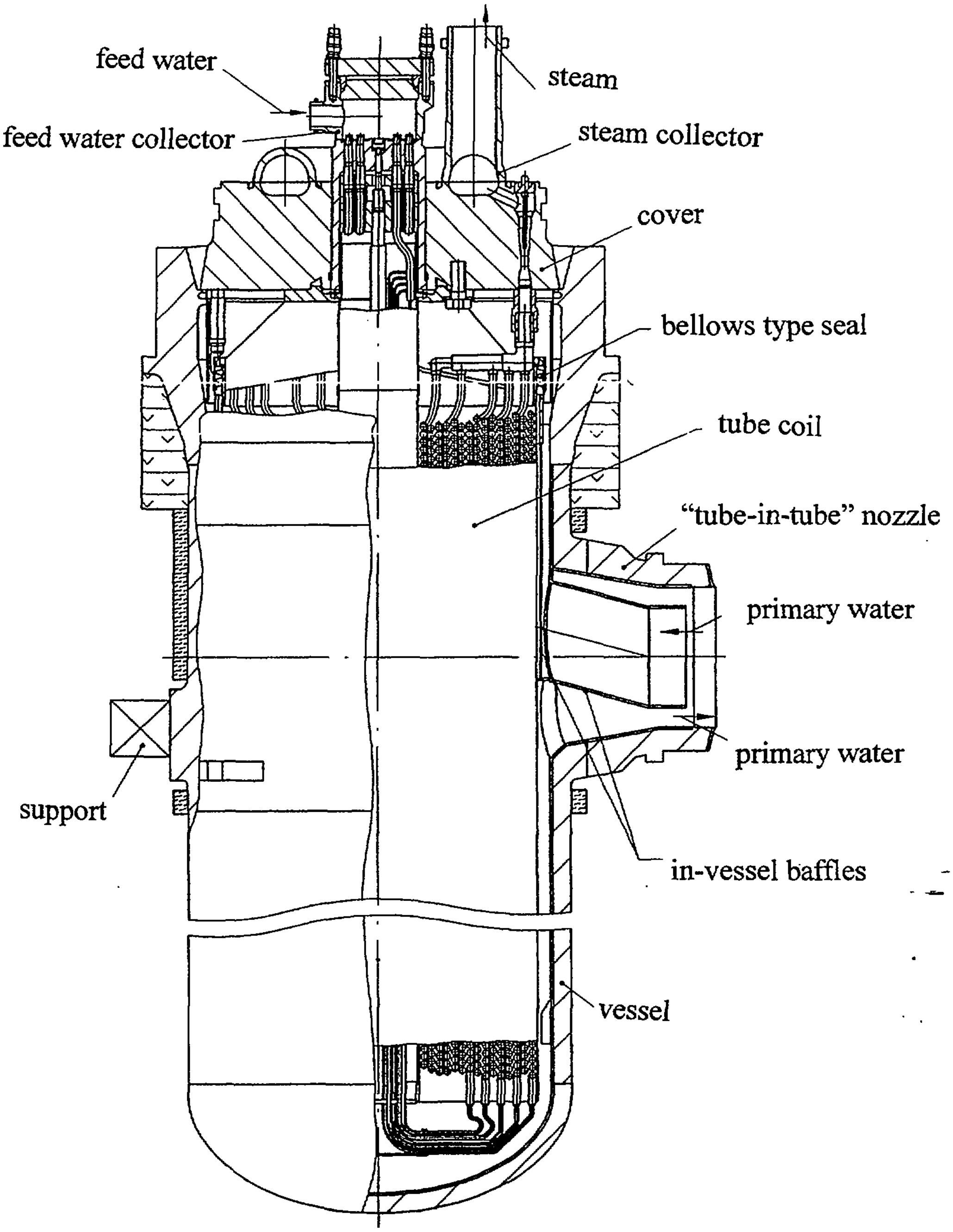

Fig.2. Steam generator

The emergency protection rod drive mechanism is an electromechanical type actuator consisting of rack mechanism with a spring, asynchronous motor and electromagnet. Scram time is not more than 0,5s. Absorber rods are inserted under spring action when holding electromagnets are de-energizated.

The drive mechanism of compensate group consists of, screwed reducer, stepped electric motor, movement sensor, reference points sensors. Working speed is 2mm/s. Emergency speed of lowering by electric motor on trip signals is 4mm/s. Average speed of lowering under gravity is 30 to 130mm/s.

The steam-generating block is arranged within metal-water shielding tank's caissons (Fig. 3). Auxiliary equipment items including pressurizes, filter, heat exchangers are also located in the tank's caissons. All radiation sources are surrounded by shielding. RP shielding consists of the tank, removable of dry shielding blocks and peripheral shielding on protective enclosure walls.

Main codes are used:

- "General Principles of Safety Provision for NPPS" (OPB-88).
- "Rules of Nuclear Safety for Nuclear Reactor Plants of NPPS" (PBYA RU AS-89).
- Norms of Radiological Safety NRB-96. Hygiene's standards GN 2.6.1.054-96 Law of Russian Federation "Radiological safety of population".
- Rules of nuclear ships classification and building for Russia's sea ship navigation register.

Other effective guides and rules for nuclear stations. IAEA recommendations are taken into account at KLT-40 RP development:

- basic principles of safety referring to safety control and full-scope realization of in-depth protection strategy;
- main technical principles including the use of approved engineering-technical practice, assuring quality, account of man-factor, systemic analysis, evaluation and substantiation of safety using deterministic and probabilistic methods, analysis, account of analogues operation experience;
- execution of measures on radiation protection of personnel, population, on environment under normal operation and at emergencies including postulated severe accident with core damage;
- recommendations on specific engineering decisions referring to all-sided development of intrinsic safety, use of safe failure principle, redundancy, diversity, spatial separation of means and systems important to safety, use of passive systems and self-acting safety devices, assurance of accident control capabilities.
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2. MAIN SAFETY PRINCIPLES

Next main safety principles are taken into account at KLT-40 RP:

- use of pressurized water reactor with developed intrinsic safety provided by core feed back, reactor thermal inertia, coolant natural circulation in emergency situations, etc.

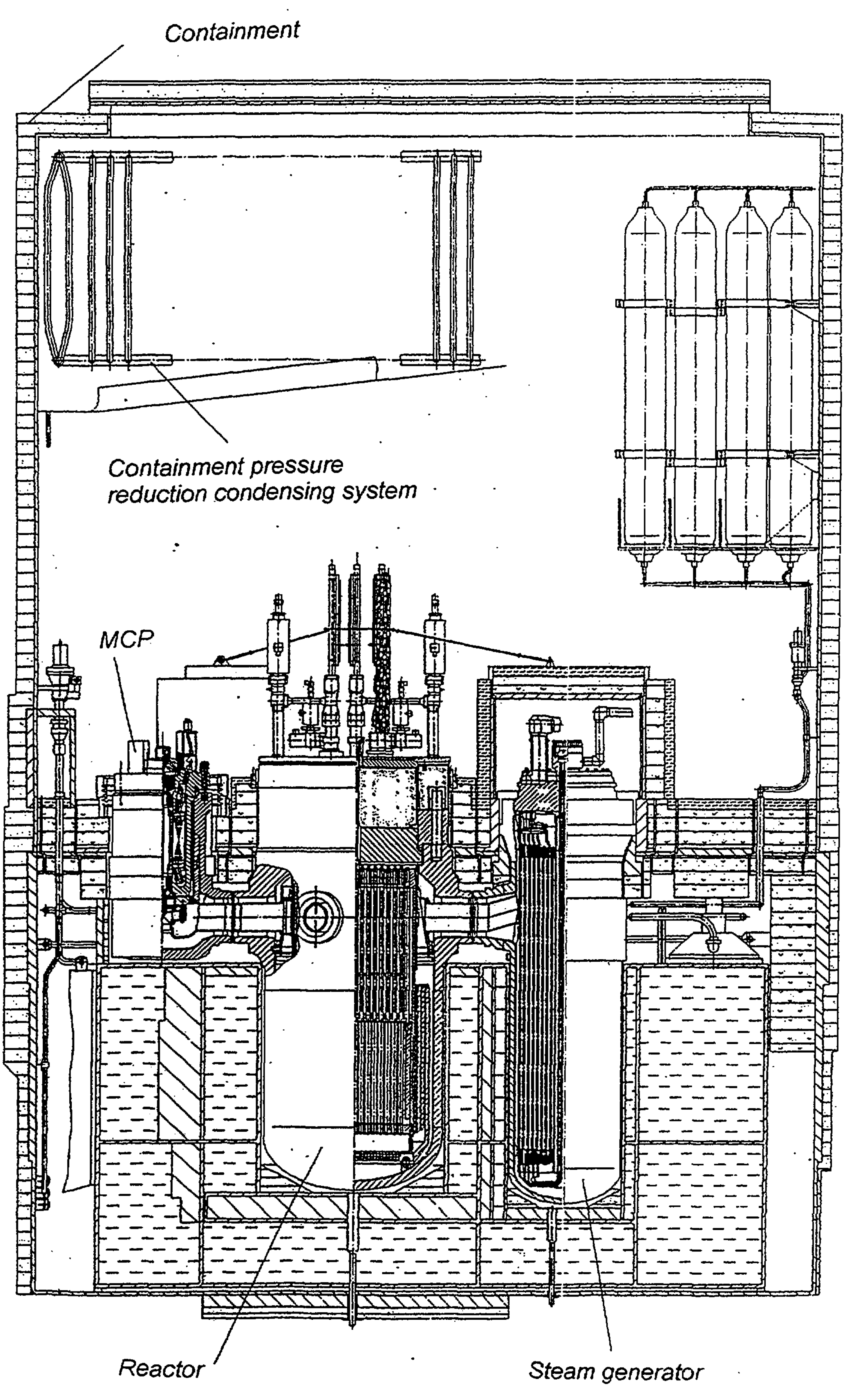


Fig.3. Reactor plant arrangement

- Provision of in-depth functional and physical protection by effective safety barriers and isolation systems eliminating the discharge of radioactive products beyond FPU boundaries at most severe accidents accompanied by additional failures (Fig. 4).
- establishment of protection against inner and outer impacts.
- Use of conservative approach when developing physical barriers, safety systems, choice and substantiation of initial events of accidents and their development scenarios.
- Use of physically separated safety systems of both active and principle of operation without use of external power sources and without personnel intervention.
- Use of highly reliable self-diagnosing automatic control systems and operator logical information support systems.
- Use of diagnostic control systems allowing to determine the actual state and remaining life of the nuclear plant most responsible equipment and pipelines.
- Realization of maximally attainable reactor plant waste-free technology limiting formation of liquid radioactive waste during the reactor plant operation.

Primary circuit system (Fig. 5) includes:

- main circulation circuit;
- pressurization system;
- purification and cooldown system,

Next safety systems are used at KLT-40 RP:

- reactor trip system;
- emergency cooldown system;
- emergency core cooling system;
- containment emergency pressure reduction system; containment system;
- reactor caisson water filling system.

Reactor trip system includes;

- four independent groups of safety rods with individual drive mechanisms actuated passively under compressed springs action;
- five independent compensating groups (CG) with individual drive mechanisms ensure reactor trip on the control system signals by:
- lowering by electric drive with emergency speed; lowering under gravity; liquid absorber injection system (back up system).

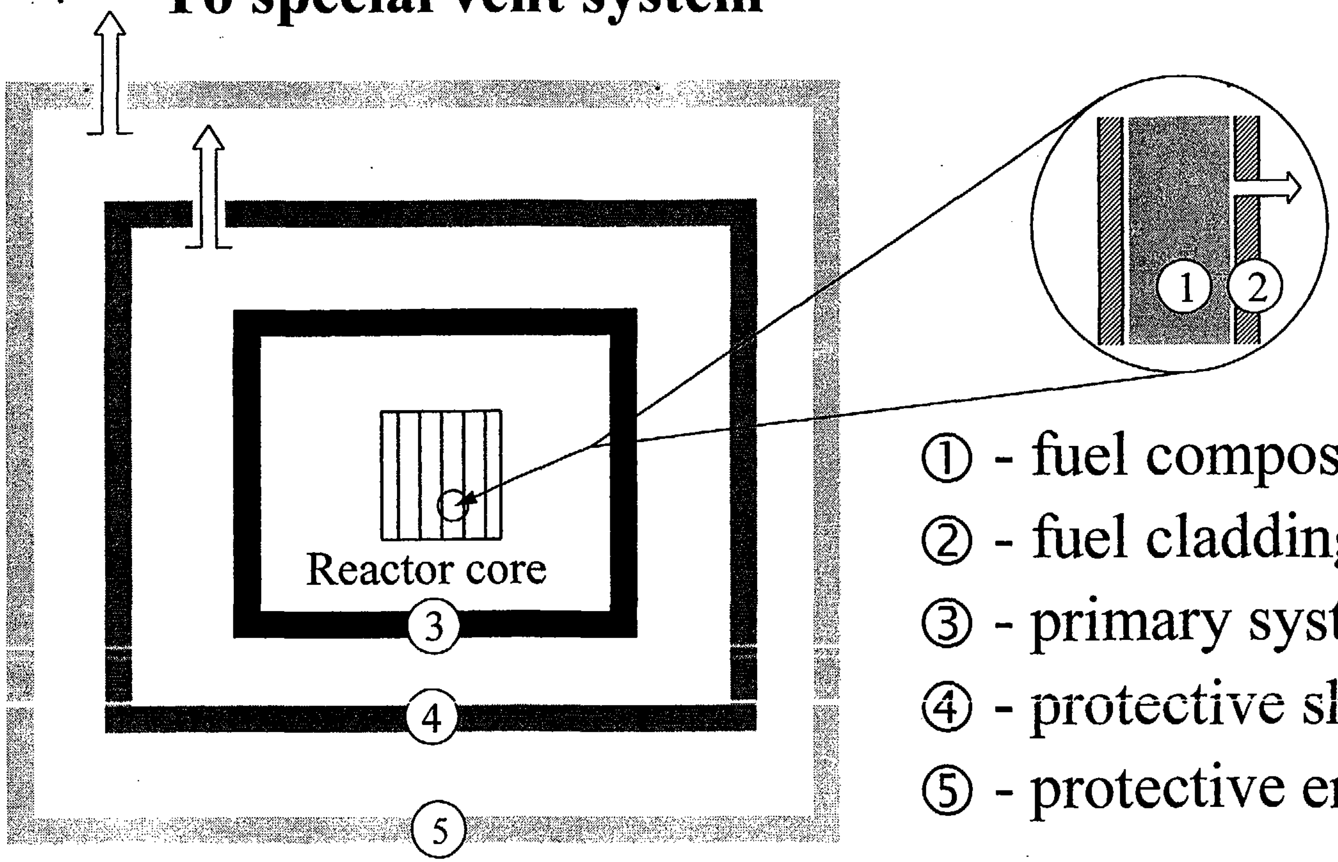
It is provided for lowering under gravity using safety devices for CG-drives de-energization executing by increase of primary circuit pressure.

Emergency cooldown system consists of':

- active cooldown train through primary circuit purification system's heat exchanger with heat transfer via third circuit to ambient sea water;
- active cooldown train through steam generators with heat removal to process condenser and then to sea water;
- two passive cooldown trains through steam generators with heat removal to emergency cooldown water tank heat exchanger and then to the atmosphere by means of water evaporation in tank.

The system is actuated both control system and direct action of process parameter, i.e. by increased primary pressure using hydraulically- controlled air distributors.

To special vent system



① - fuel composition
② - fuel cladding
③ - primary system boundary
④ - protective shell
⑤ - protective enclosure

⇧ **Permissible spreading of radioactivity limited by allowable value of protection barrier non-leaktightness**

Fig.4. Schematic diagram of protective phisical barriers

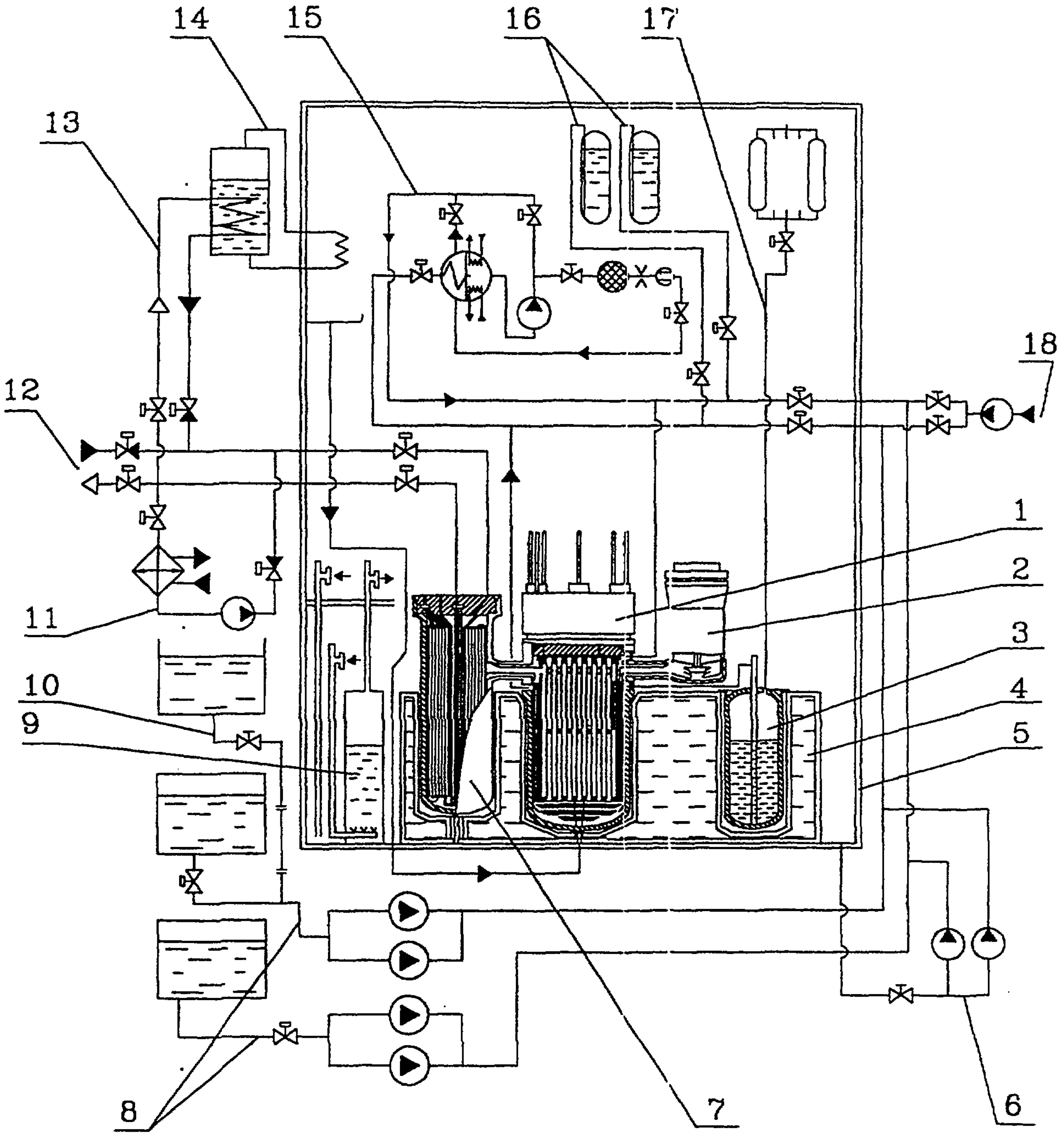


Fig.5. Reactor plant principal flow diagram

1 - reactor; 2 - reactor coolant electric pump; 3 - pressurizer; 4 - metal-water shielding tank; 5 - protective shell; 6 - recirculation system; 7 - steam generator: 8 - engineered emergency core cooling system; 9 - bubbler system for pressure supressure in protective shell; 10 - liguid absorber removal system; 11 - engineered emergency shutdoun cooling system; 12-to steam turbine plant; 13 - passive emergency shutdoun cooling system; 14 - protective shell pressure supressure emergency condensation system; 15 - primary circuit purification and cooldown system; 16 - passive emergency core cooling system; 17 - pressurization system; 18 - from STP

Water inventory in the tank ensures the RP maintaining in safe state for not less than one day without personnel intervention.

Emergency core cooling system consists of two trains. Each train meets the single failure principle. System includes high and low pressure sub-system. High-pressure sub-system includes passive (hydro-accumulators) and active pumps and water storage tanks) features for water injection in reactor. Low-pressure sub-system ensures returning a condense accumulated in containment, into the reactor by recirculation pumps.

Containment emergency pressure reduction system uses passive principle of operation. Suppression of emergency pressure is provided by steam condensation in bubbling tank, on heat exchange's surfaces and on containment walls. Reactor caisson water filling system is intended to protect reactor vessel against melting through during severe beyond design-basis accident involving loss-of-coolant and core and melt. Water and condensate are supplied to the reactor caisson from bubbling tank, condensate collector and shielding tank's plating (elevation head). System works passively by steam condensation in pressure reduction system's heat exchangers and by condensate supply into reactor caisson under gravity. Containment a robust leak-tight compartment designed for internal pressure of 0,5MPa (abs.). There no are systems and equipment within the containment containing sea water. A partial vacuum of 300 Pa is maintained in the containment during the RP power operation.

Special system is provided for filling the containment with water and its subsequent sealing to exclude destruction of containment at FPU sink. Main trends of severe accident control strategy limitation of core damage size:

- prevention of core melting;
- preservation of core vessel integrity with confinement of core materials inside the vessel; preservation of protection envelope integrity with account of a severe accident consequences; limitation of escape of radioactive products into the environment.
- Reactor intrinsic safety is due to:
- negative coefficients of core reactivity providing for self-termination of chain reaction in the core at unauthorized rise of reactor power and temperature;
- passive principle of reactor shutdown by working members;
- high accumulating capability;
- elimination of large diameter pipelines in the primary circuit-limiting outflow of coolant at the circuit depressurization.

TABLE II. KLT-40C RP DOSES LIMITS AND CRITERIA

Effective irradiation dose	Dose limits for personnel	Dose limits for population
At normal operation	2 rem/year	0,1 rem/year
At design basis accidents	10 rem	0,5 rem (on SPZ boundary)
At beyond design basis accidents	20 rem	0,5 rem (on SPZ boundary)
Limits of damageability expressed through primary circuit fragmentary activity	Operation limit Safe operation limit	$10^{-3} Ci/kg$ $10^{-3} Ci/kg$

3 ENVIRONMENTAL SAFETY OF ATETS WITH KLT-40C RP

Based on operation experience of nuclear ice-breaker fleet (more than 150 reactor-years nether):

☑ no single event personnel overexposure was registered;

☑ average close is in 10 times lower than allowable limit.

Environmental safety of atest with KLT-40C RP is shown in table III.

TABLE III. ENVIRONMENTAL SAFETY OF ATETS WITH KLT-40C RP

Mode	Name	Value
Normal Operation	Radioactivity discharge	
	Σ IRG	10 Ci
	Σ I and Cs isotopes	<0, 01 Ci
	Irradiation dose for population	~0, 01 mrem
	Heat discharge	
	To atmosphere	270 кW
	To outboard water	1650 кW
Maximum design basis accident	Radioactivity discharge	
	Σ IRG	11 Ci
	Σ I isotopes	0,01 Ci
	Σ Cs isotopes	~10^{-6} Ci
	Irradiation dose for population	~0, 02 mrem

4. RADIOACTIVE WASTES (RAW) MANAGEMENT PRINCIPLES

All radioactive wastes are stored on FPU board during operation.

Wastes are not neither stored, processed nor disposed FPU sitting water area.

Tanks and casks arranged in shielded compartments are used to collect RAW and store them at FPU.

Gaseous RAW are practically absent during operation including refueling operations.

Amount of RAW is mainly determined by refueling operations and amounts to (for one reactor plant annually):

☑ liquid RAW is 8 m^3;

☑ solid RAW is 2.5 m^3.

Liquid RAW are as a rule low active with average activity of 10^{-6} Ci/kg. More than 70% solid RAW are low active as well.

5. ENVIRONMENTAL AND ECONOMIC INDEXES OF NPPS WITH KLT-40 RP

NPP with KLT-40C RP

☑ Saves 300000t of equivalent fuel per year.

☑ Saves 400 mln m^3 of air oxygen per year.

☑ Does not charge the atmosphere with tons per year of:

	compared to coal-fired plant	compared to oil-fired plant *
solid particles (dust, ashes)	730	130
sulphuric acid	12000	8400
nitrogen oxides	3400	2200
vanadium pentoxide	4	56

*) The data are given for a 300 MW(th) thermal stations sulphur content in coal and mazut is 2% efficiency of solid particles separation is 99%.

The KLT-40C NSSS created with reliance upon the proven technology of nuclear propulsion plants of icebreaker type, involving also utilization of ship-building technologies, is a reliable and safe plant capable of minimizing environmental impacts compared to alternative fossil-fired power plants. NPP with such NSSS can be situated in close vicinity of settlements.