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Key safety features of the VVER-1200, based on the Russian regulatory requirements

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International development of safety standards for ”Generation III” Nuclear Power Plants

International development of safety standards for Generation III Nuclear Power Plants (1)

Global co-operation to develop general design principles for new safer nuclear power plants was started after the Chernobyl accident in the INSAG group that had been established in the fall of 1985.

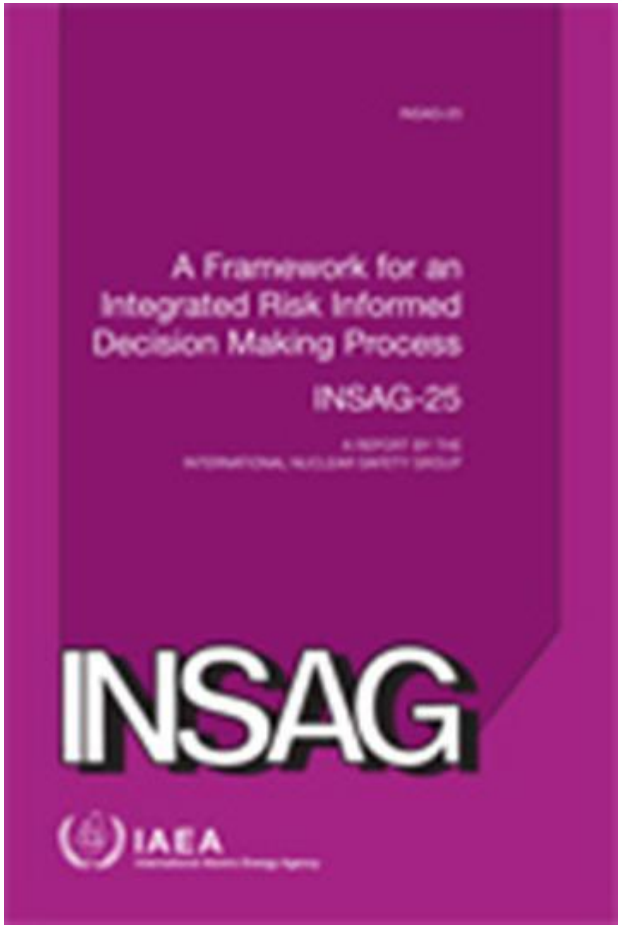
INSAG group consisted of 13 highly appreciated nuclear safety experts –appointed by the IAEA Director General.

Russian INSAG member prof. Sidorenko and his team, together with Dr. Bukrinsky who was personally invited by INSAG to support this work, made an important contribution to the new safety principles.

International development of safety standards for Generation III Nuclear Power Plants (2)

INSAG group issued several reports that showed the direction for Generation III plants:

- INSAG-3 Basic safety principles for nuclear power plants, 1988
- INSAG-5 The safety of nuclear power, 1992
- INSAG-10 Defence in depth in nuclear safety, 1996
- INSAG-12 Basic safety principles for nuclear power plants (rev of INSAG-3), 1999



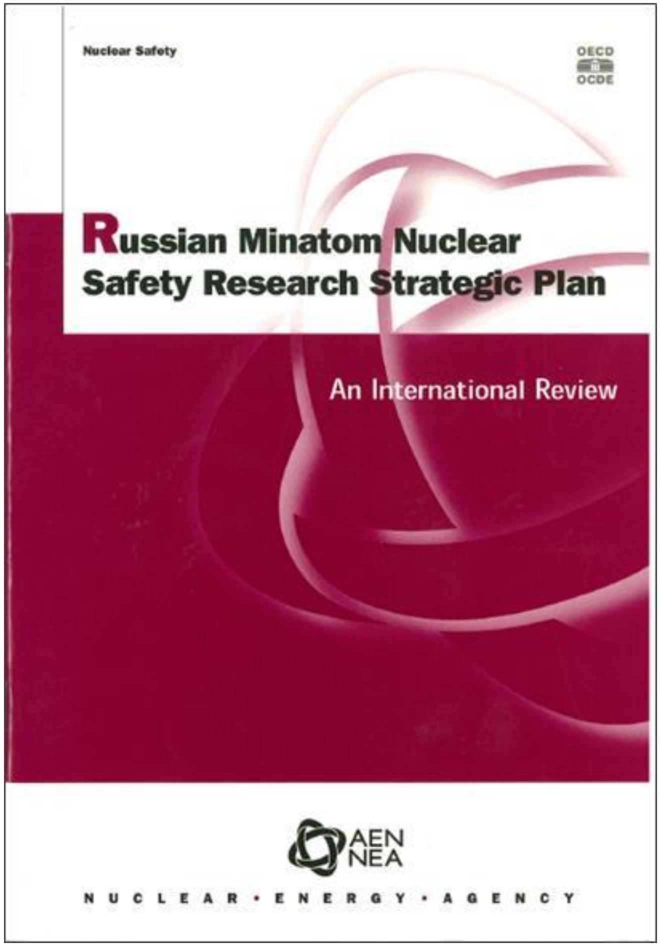
http://www-pub.iaea.org/books/IAEABooks/Series/40/INSAG-Series

International development of safety standards for Generation III Nuclear Power Plants (3)

In parallel with developing safety principles, the global coordination of nuclear safety research was arranged under the OECD/NEA.

Since the early 1990's Russia has played a leading role in the global experimental safety research and has participated actively to the OECD/NEA programs.

Many important research programs were planned and implemented under the umbrella of OECD/NEA. Large tests were conducted in Russian research laboratories and the results were assessed jointly with highest level international experts.



International development of safety standards for Generation III Nuclear Power Plants (4)

Unfortunately, the IAEA Safety Standard *“Safety of Nuclear Power Plants: Design”,* issued in 2000, did not yet take a clear step towards Generation III.

This IAEA Safety Standard was still close to the thoughts that gave basis for the Generation II plants.

Nevertheless, new INSAG principles for enhanced safety were incorporated into the national safety requirements of some countries, for instance Russia, Finland and some other European countries.

Necessary modernization of the IAEA Safety Standard was done only in 2012, after Fukushima accident.

International development of safety standards for Generation III Nuclear Power Plants (5)

WENRA, a group established by the heads of the European nuclear regulatory bodies, initiated in 2007 development of common safety objectives for new NPPs in Europe. This work was based very much on the INSAG ideas.

The common safety objectives were agreed by WENRA in November 2010.

The WENRA safety objectives were used as reference for the new EU Nuclear Safety Directive.

The EU directive is consistent with the IAEA Safety Standard SSR-2/1 “Safety of Nuclear Power Plants: Design” of 2012 and thus gives a legal status in Europe to the key IAEA requirements.

Safety features expected from Generation III Nuclear Power Plants

Safety features expected from Gen III NPPs (1)

In the Generation III NPPs, safety must be enhanced by making each of the four levels of Defence-in-Depth (DiD) stronger than in the traditional Generation II plants.

Most important is to emphasise the DiD level 1 – This improves also reliability and life-time profitability of the plant.

Safety features expected from Gen III NPPs - 2

DiD level 1

- improved assurance of **primary circuit integrity,** also taking into account target for extended lifetime
- digital I&C systems that provide reliable and accurate **control of normal plant operations**
- advanced features to improve **fire protection**
- lay-out that provides **credible physical separation** of redundant and diverse safety systems and subsystems
- significantly strengthened **protection against natural and manmade external hazards**, such as major earthquakes and floods and crash of a large passenger airplane
- advanced **control of radiation** during normal operation: very small radioactive releases, occupational radiation doses, and radioactive waste generation

Safety features expected from Gen III NPPs - 3

DiD level 2

- **monitoring and interlocking systems** that are qualified for safety critical use and would detect deviations of main plant parameters from their normal range, providing reliable and timely return to safe operating regime

DiD level 3

- **redundant and diverse safety systems** that provide flexible management of Design Basis Accidents and Design Extension Conditions, including long-term loss of all AC power and loss of the primary heat sink
- **diverse I&C systems designed to ensure reliability of automatic protection** against complicated accidents

DiD level 4

- dedicated systems that are fully independent of other plant systems and would **eliminate significant radioactive releases** by protecting containment integrity **even after a core meltdown accident**

Development of Russian nuclear safety regulations

Development of Russian nuclear safety regulations (1)

Active contribution to the INSAG work gave since end of 1980's the emerging Russian nuclear safety community first hand information on nuclear safety principles defined in different countries.

The Russian *General Regulations on Ensuring Safety of Nuclear Power Plants (OPB 88/97)* were already in the 1990's written to be consistent with the INSAG visions on safer future plants.

The VVER-1200 plants currently being built, also called AES-2006, have been designed to meet OPB 88/97.

The VVER-1200 plants are thus designed in parallel with the global development of the nuclear safety principles and are representing state-of-the-art of the Generation III nuclear power plants.

Development of Russian nuclear safety regulations (2)

In early 2016, the revised Russian *General Regulations on Ensuring Safety of Nuclear Power Plants* were issued after a thorough discussion in the Russian nuclear community and are known as OPB 88/12.

These new safety regulations are consistent with the latest IAEA standards and EU safety objectives.

In addition, the OPB 88/12 includes new requirements that are based on the lessons learned from Fukushima, as identified

- in the “stress tests” conducted jointly by the European nuclear regulators,
- in the reports of the IAEA’s “Fukushima meetings”, and
- in the “stress tests” conducted in Russia.

The new VVER plants being offered in the market are designed to meet OPB 88/12 requirements.

Evolution towards Generation III VVERs

Generation II NPPs in operation provide smooth evolution towards new Generation

- There are 23 VVER-440 and 30 VVER-1000 plants of Generation II in operation today
- These plants have been reliable power producers
- Safety record of the VVER plants is good, notably as concerns fuel failure rate and radioactive releases to the environment.

Construction of new advanced VVER-1000 plants (1)

Two 1000 MW units (called type VVER-91) paving the way for new VVER generation were connected to power production in 2006 and 2007 in Tianwan, China.

- Tianwan is predecessor for the VVER-1200 plant now being built on Leningrad site in Russia
- Chinese customer has expressed its satisfaction with the reliability and safety of those units
- Two more similar VVER units are under construction since 2012 on the same site.

Construction of new advanced VVER-1000 plants (2)

Construction of two somewhat different new VVER units (called type VVER-92) of 1000 MW size has been completed in Kudankulam, India.

- Kudankulam is predecessor for the first VVER-1200 unit that has been connected to grid (Novovoronesh 6, grid connection in August 2016)
- Kudankulam 1 achieved full power in June 2014
- Kudankulam 2 produced first power to the grid in August 2016.

Design and construction of VVER-1200 (AES-2006) plants (1)

Design of VVER-1200 plants called also as AES-2006 was completed in 2006. Design of AES-2006 **benefitted from the experiences from the construction of plants built in China and India**.

Besides the increased size of 1200 MW power, the **AES-2006 plant has additional safety features when compared with the plants built in China and India.**

Design and construction of VVER-1200 (AES-2006) plants (2)

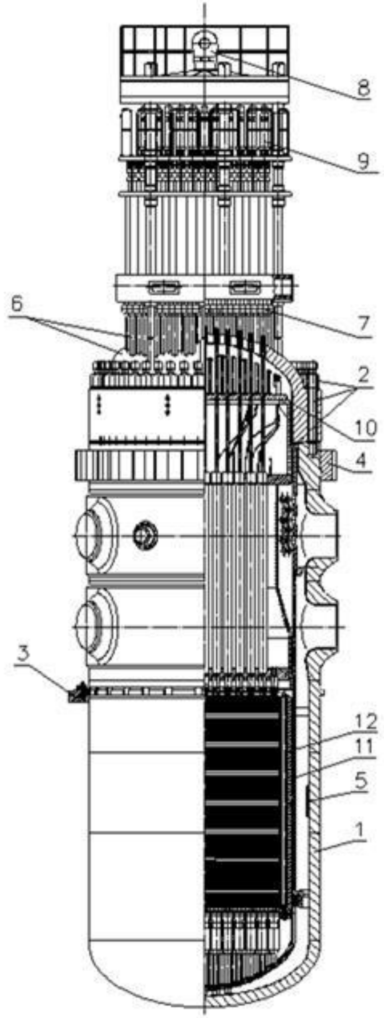
All improvements taken together make VVER-1200 a genuine Generation III NPP.

Novovoronesh unit 6 that is now undergoing power ascension tests can with good grounds be called the first and only Generation III NPP in the world that is already producing power.

Examples of Generation III safety features in new VVER plants

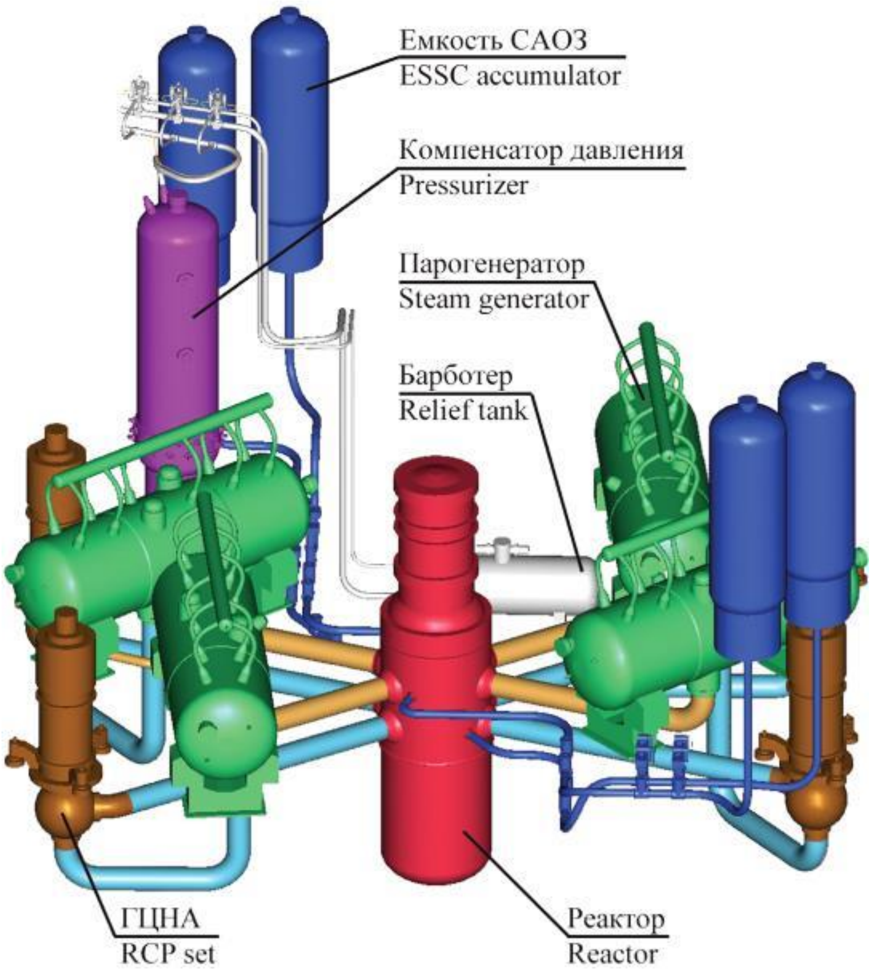
Improved assurance of VVER-1200 primary circuit integrity for 60 years operation (1)

- Reactor vessel materials and structure
  - less impurities in base metal and welds, less nickel in welds, increased vessel diameter in order to reduce neutron irradiation of the vessel;
  - according to extensive research the material maintains its ductility even in lowest possible temperatures after 60 years of operation at full power;
  - small material embrittlement by neutron irradiation can be confirmed by investigating material samples placed in optimum way on vessel wall.



Improved assurance of VVER-1200 primary circuit integrity for 60 years operation (2)

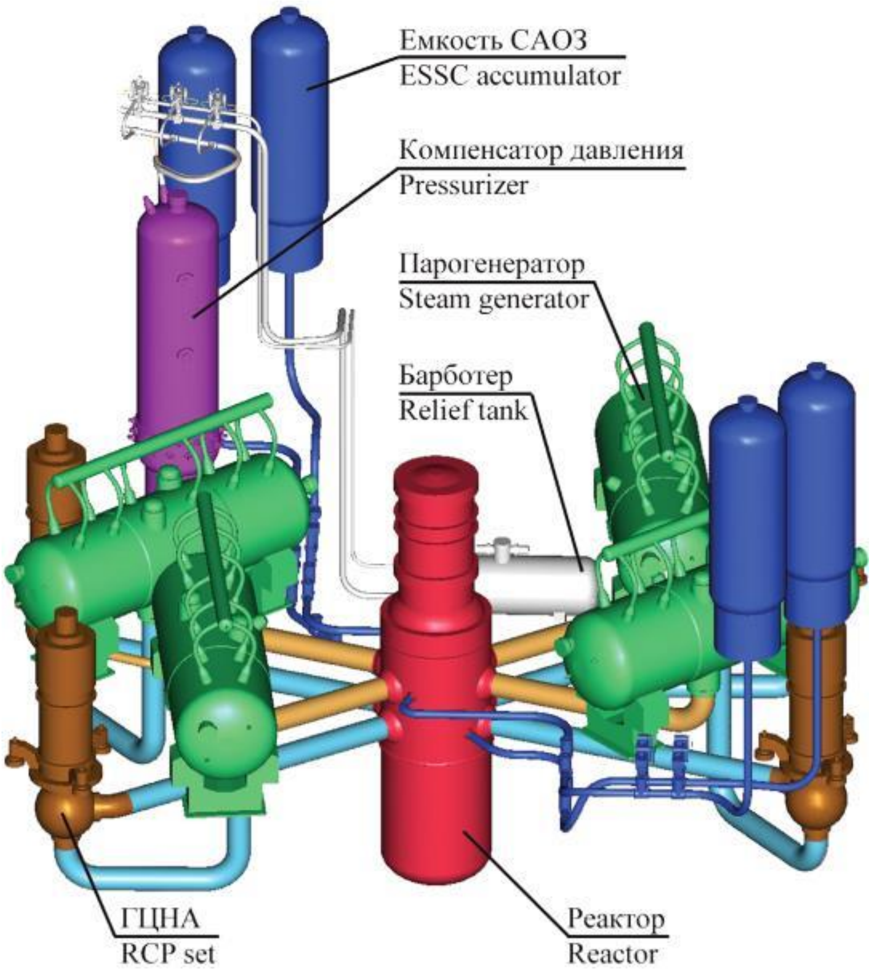
- <u>Steam generator</u> structure and operating conditions
  - improved removal of corrosive products, avoiding copper in secondary side materials, new type of water chemistry in secondary side
- <u>Reactor coolant piping</u> meets all necessary conditions of the “leak-before-break” concept
  - material properties, stress analysis, in-service inspections, leak monitoring



Improved assurance of AES-2006 primary circuit integrity for 60 years operation (3)

Reactor coolant piping meets necessary conditions of the “break preclusion concept”:

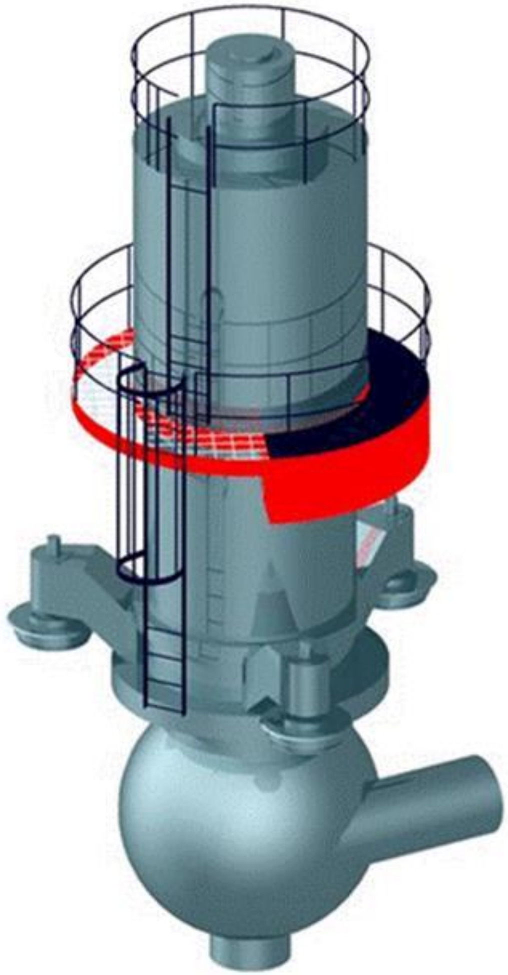
- qualified construction (materials, fabrication, QA)
- stress analysis to demonstrate adequate safety margins in all design-basis load conditions,
- qualified operation (loadings, chemistry)
- surveillance to prevent major cracking throughout plant life,
- effective in-service inspections of welds and other stressed areas,
- leak monitoring



Advanced features of AES-2006 main coolant pumps

Two special safety features of MCPs:

1. Primary circuit main circulations pumps and their motors have **water cooling and water lubricated bearings;** to eliminate risk of oil fire inside the reactor building.
2. AES-2006 pumps have **a seal structure that ensures very small leak** in all conceivable circumstances; this is important especially in connection with the complete loss of electrical power when seal injection and cooling of main circulation pump seals is lost.



Protection of VVER-1200 against manmade external hazards

Air plane crash

- **Design basis** air plane crash evaluated with conservative models and assumptions is crash of a small private air plane (**weight 5,7 tons**).
- **Design extension** air plane crash evaluated with realistic models and assumptions is a large commercial air plane (**weight 400 tons**) hitting the plant with maximum conceivable speed.
- Protection shall **provide elimination** of
  - radioactive releases as **direct consequence** of impact
  - an accident sequence due to loss of decay heat removal capability, which could be either a consequence of **direct damage to safety systems**, indirect damage due to induced **vibrations in equipment**, or indirect damage due to a kerosene (fuel) **fire**.

Protection is provided by double containment and some other buildings with thick walls and physical separation of redundant parts by distance

Diverse and redundant safety systems (1)

Provision of the three fundamental safety functions is necessary and sufficent for ensuring nuclear safety:

1. **Control of reactivity**
   - preventing uncontrolled reactor power increase
   - ensuring fast safe shutdown of the reactor when needed,

2. **Removal of decay heat to the ultimate heat sink**
   - cooling of shutdown reactor
   - cooling of used nuclear fuel

3. **Containment of radioactive materials**
   - preventing significant radioactive releases to the environment

Diverse and redundant safety systems (2)

The leading principle in the design of the AES-2006 plants is:

All fundamental safety functions shall be provided both with

- **active systems** that have very reliable AC power supply and
- **passive systems** that do not need electrical power at all.

This gives the operators a possibility to use different safety systems independently of each other and in a flexible manner, depending on the accident scenario.

Diverse and redundant safety systems (3)

All new VVER plants that are under construction have already design features that take properly into account the main ”Fukushima issues”:

- long term cooling of reactor core without electrical power,
- long term decay heat removal that is not relying on primary ultimate heat sink (sea, river, cooling tower, ...), and
- protection of reactor containment integrity with dedicated systems after a potential core meltdown accident.

Control of reactivity – passive system

AES-2006 plant reactor has a unique safety feature when compared with other pressurized water reactors:

- When control rods have been dropped to the core the reactor will **stay in shutdown state down to temperatures below 100°C**

Control of reactivity – active system

AES-2006 plant reactors have also a 4 x 50% redundant boron injection system that can add liquid with high boron concentration to the reactor coolant.

- Even in the event that the control rods would not drop to the reactor core as would be needed as a consequence of an anticipated transient, the **boron induced shutdown is so fast that no fuel damage would occur**
- This is true protection against ATWS (Anticipated Transient Without Scram)

Removal of decay heat to the ultimate heat sink (1)

- **Active systems** can remove decay heat and bring the plant to cold shutdown stage by diverse means:
  - 4x100 % system removing heat directly from the primary circuit, as usual in PWR plants
  - via the secondary circuit (water circulation can be established in a closed loop: steam generators-steam lines-coolers-feedwater lines)

- **Passive systems** can remove the decay heat from steam generators directly to the atmosphere.

Passive system for decay heat removal at Leningrad-II plant (1)

1 – emergency heat removal tanks (EHRT) outside containment; **heat is removed by boiling of water in EHRTs in atmospheric pressure**

2 – steam lines

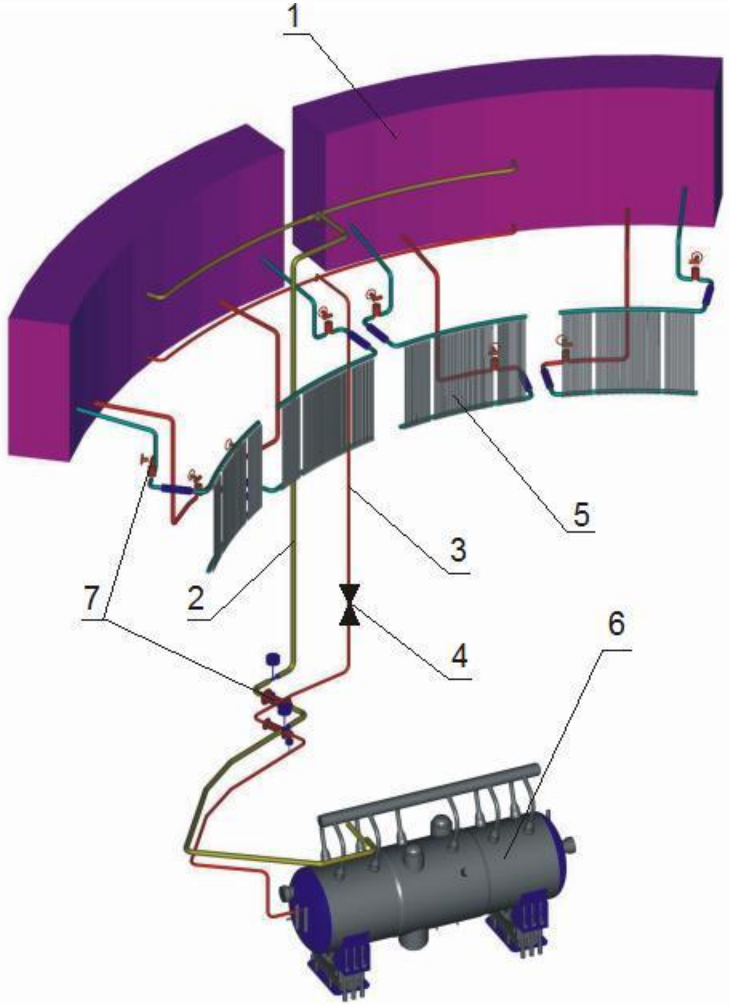
3 – condensate pipelines

4 – PSHR-SG valves

[**5** – heat exchangers of containment heat removal system PSHR-C; *it is a separate system but uses same EHRTs*]

6 – steam generators

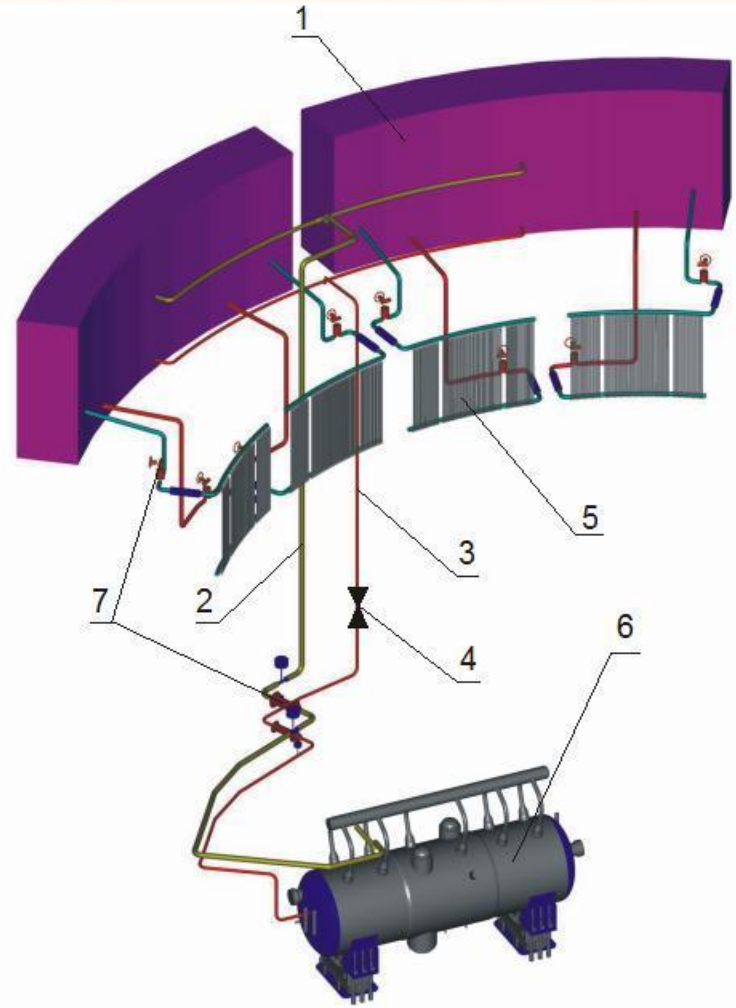
7 – cutoff valves



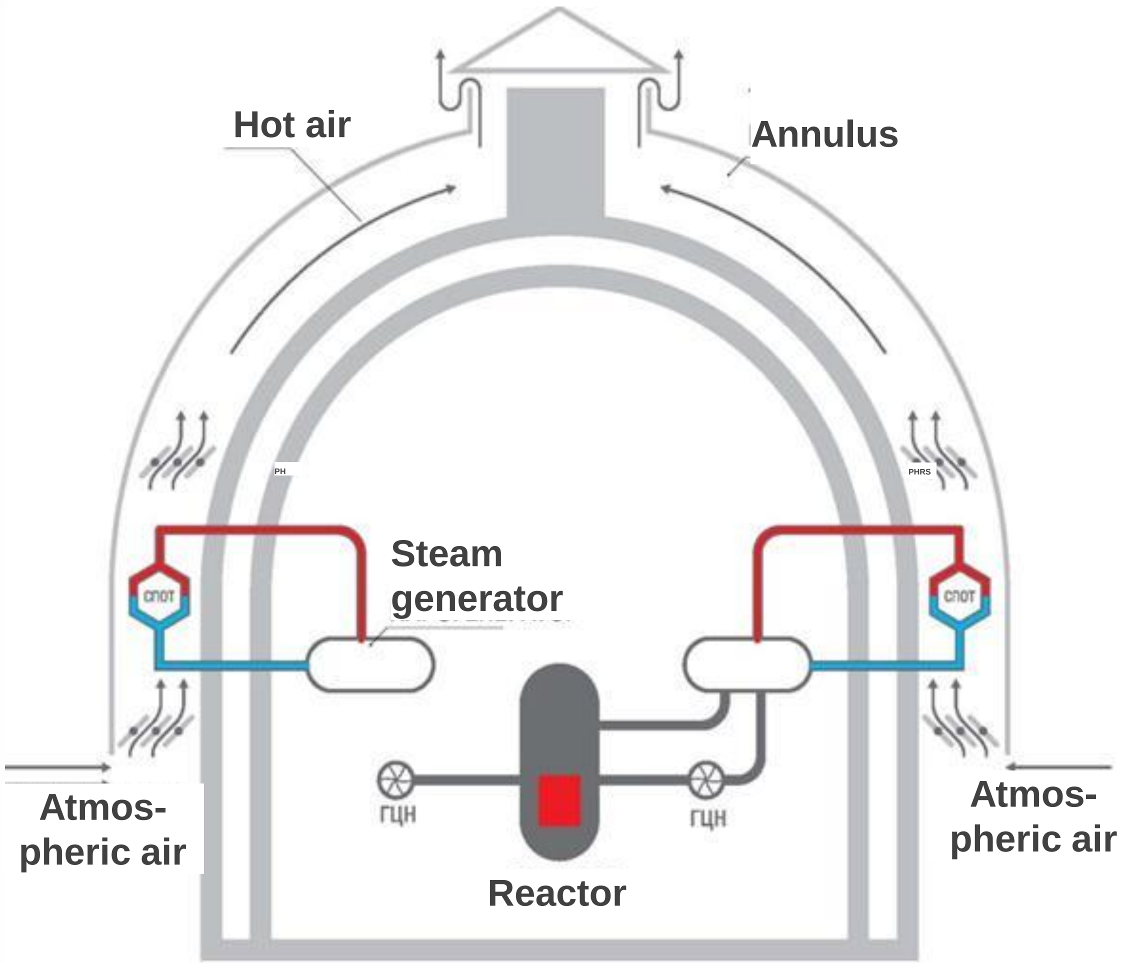
Passive system for decay heat removal at Leningrad-II plant (2)

Operation of 3 out of 4 EHRT tanks provides **cooling** for 24 hours, all 4 tanks **for 72 hours**. All tanks can be connected as communicating vessels and then all water is available.

After Fukushima accident, a permanently installed independent system and a diverse system using mobile pumps, for refilling the emergency heat removal tanks, were added to the design.



Passive system for decay heat removal at Novovoronesh-II plant



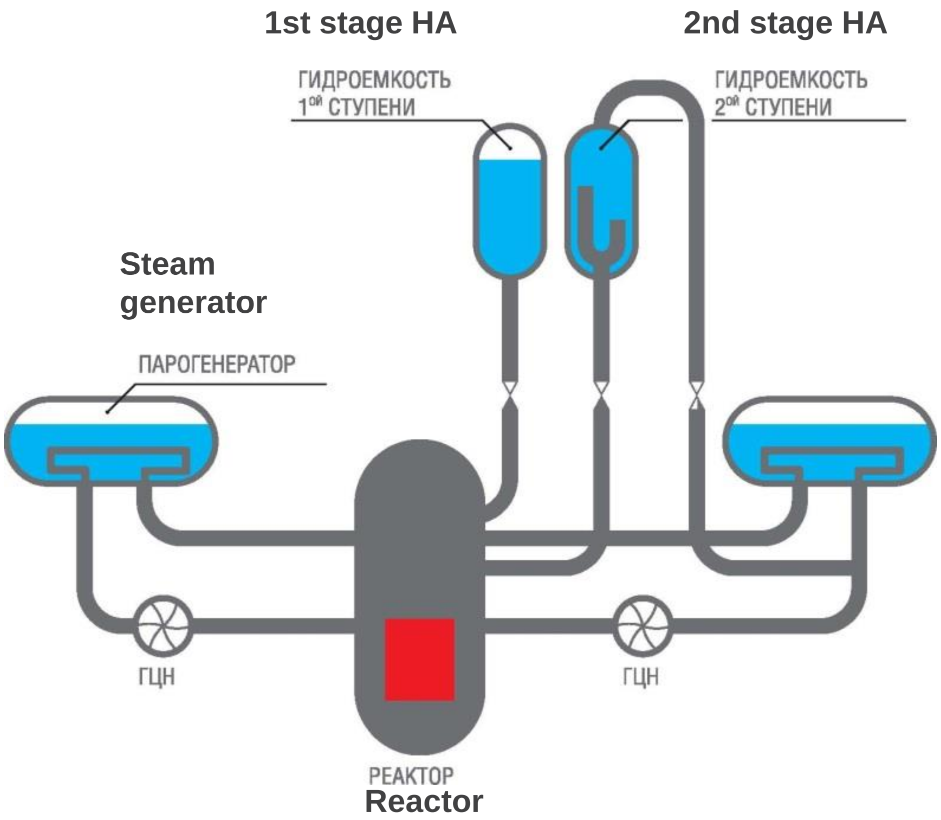
- The passive heat removal system operates with natural circulation in closed loops, by condensing steam in coolers
- No need to add any water and thus no time limit for operability
- Passive devices control the air flow rate to provide cooling of primary circuit at proper rate

Passive system for core cooling after loss of coolant accident at Novovoronesh-II plant

The **1st stage Hydro Accumulators** are as those normally used in Gen II plants: intended for fast flooding of the reactor core during large-break leaks of the reactor coolant circuit.

The **2nd stage Hydro Accumulators** are intended for passively flooding the reactor core after the 1st stage has run out of water. They can keep the water level in the reactor vessel above the reactor upper end for at least 24 hours, even after largest possible pipe break.

(new VVER-TOI design has **3rd stage Hydro Accumulators** that provide passive core flooding for 72 hours)



Containment of radioactive materials (1)

The target for protecting the reactor containment after a possible core meltdown accident was set in the USSR soon after the Chernobyl accident.

All European nuclear regulators agreed in 2010 that this target has to be met by all new NPPs in Europe.

After Fukushima Daiichi accident, this target has received worldwide support.

Installation of the shell of the core catcher

Containment of radioactive materials (2)

Protection of the reactor containment even in connection with a core meltdown accident has been one of the original design principles used for AES-2006 plants.

Experimental research for proving the respective design features has been done for more than 20 years, including Russian led OECD/NEA program.

Containment of radioactive material (3)

- The strategy for protection of the VVER-1200 containment after possible reactor core meltdown is that
  - **all physical phenomena that could occur in connection with core meltdown** and endanger the containment integrity **are taken into account** and
  - **dedicated means and systems** are provided to ensure containment integrity.
- Protection of the VVER-1200 containment integrity is based on
  - **systems that are completely independent and separated from the systems that are intended to prevent a severe reactor core damage.**

Containment of radioactive material (4)

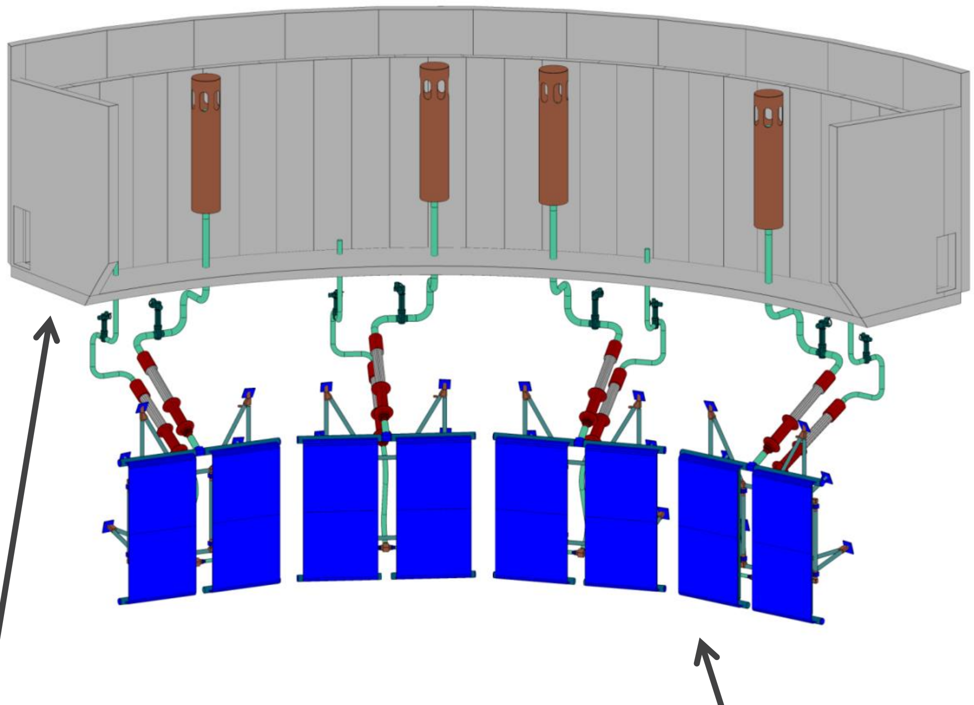
The physical phenomena addressed in the AES-2006 design include:

- reactor core meltdown in high primary circuit pressure,
- accumulation of hydrogen inside the containment and consequent hydrogen explosion,
- penetration of the molten reactor core through the containment bottom, and
- recriticality of the molten reactor core
- steam explosion,
- containment overpressure due to the steam generated inside the containment,

Passive catalytic hydrogen recombiners at operating VVER

Containment of radioactive material (5)

Containment overpressure protection system at Leningrad-II



Cooling tank outside the containent

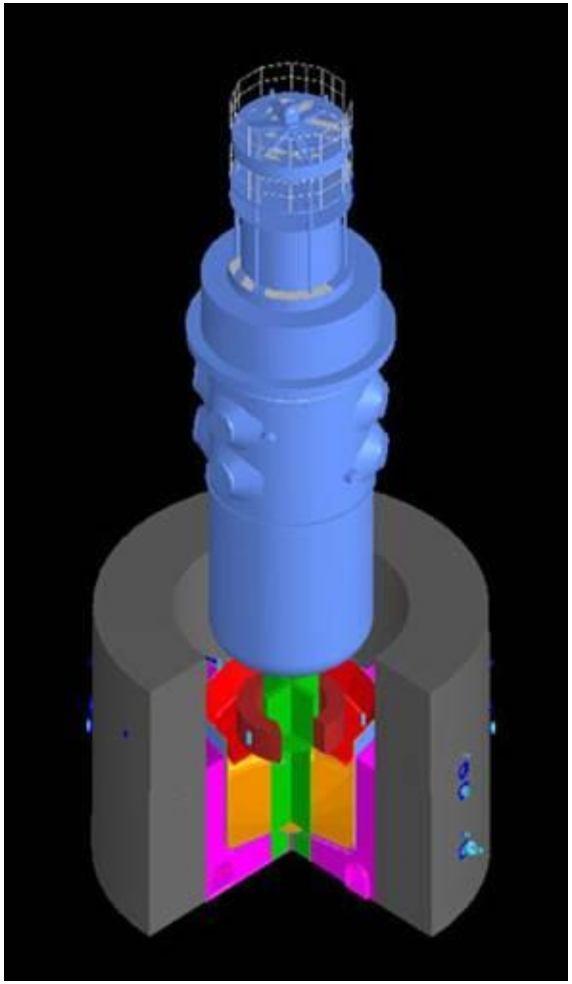
Condensing plates inside the containment

- No closed valves in cooling loops (however, each pipeline penetrating containment has a motor operated isolation valve); circulation starts by gravitation if containment temperature increases.
- Cooling tanks are adequate for 72 h of operation. They can be refilled with dedicated self-standing system from large condensate tanks located inside well protected buildings.

Containment of radioactive material (6)

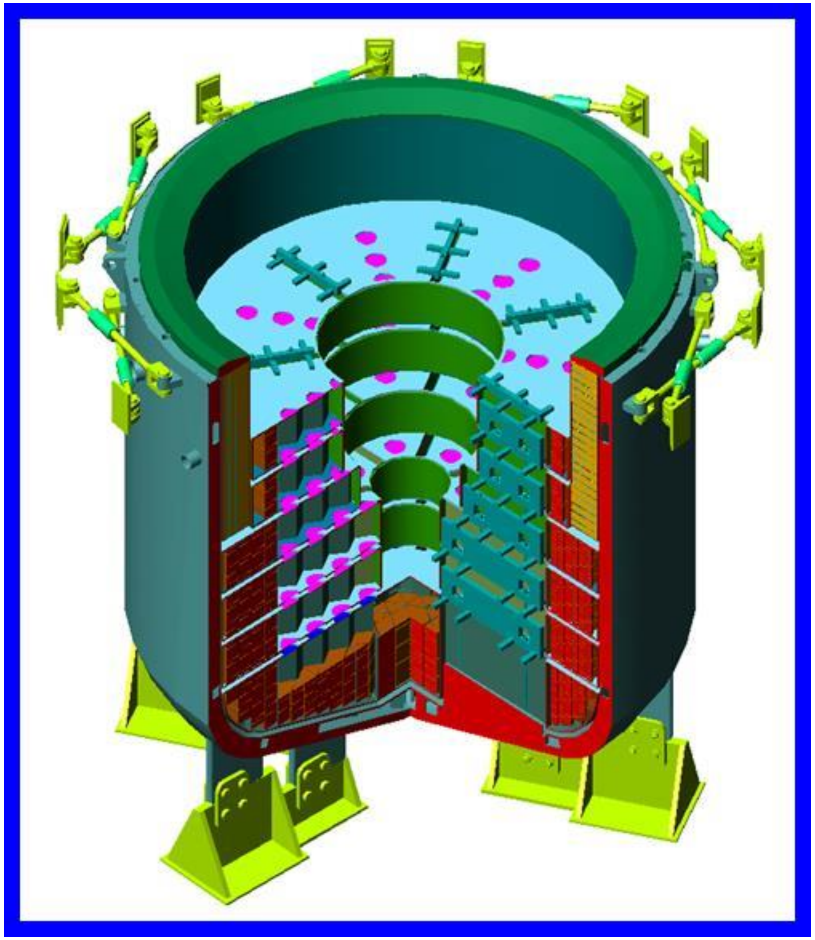
”Core catcher”

- Placed below the reactor vessel to **protect the containment structures** against impact of molten core (very high temperature of more than 2000°C).
- Retains and cools core melt and solid fragments of the core, parts of the vessel and reactor internals resulting from core damage.
- Transfers passively the heat to cooling water surrounding the “core melt pot” and thus **ensures long term cooling** and solidification of the molten core.



Containment of radioactive materials (7)

- Molten core is mixed with neutron absorbing material placed inside the “core melt pot” to ensure that no chain reaction can start in the mixed materials inside the core catcher.
- In no accident scenario there is water inside the “core melt pot”. This eliminates the risk of steam explosion.
- Core catcher decreases significantly the hydrogen generation (typically by factor 4) because the hot metal captures oxygen from the aluminum oxide in the pot and not from water.
- Crust formed on the top stops transfer of radionuclides into the containment.



Conclusions

- The VVER type nuclear power plants have gone through a continuous evolution during 50 years and have demonstrated their safety and reliability in power generation.
- The AES-2006 plants have safety design features that take into account the latest development of safety requirements and safety technology.
- All fundamental safety functions are ensured by multiple different safety systems, both active and passive.
- The VVER designers have developed already before the Fukushima Daiichi accident the NPP safety features that have been commonly suggested to new nuclear power plants after the accident.