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ADVANCED SAFETY FEATURES OF 3RD GENERATION VVER PLANTS

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Introduction - 1

It seems that all PWR and BWR type plants that are offered in the global markets today are called Generation III or even Generation III+ plants.

- This is quite confusing because there is no commonly agreed definition of what is meant by a Generation III nuclear power plant.

According to the new IAEA Safety Standards and a consensus report issued by WENRA, new LWRs should have more advanced safety features than currently operating plants.

- Only plants that can be proven to meet these new internationally agreed safety requirements without any uncertainties deserve the label Generation III

Introduction - 2

I start my presentation with a suggestion on what characteristics should be found in a Generation III plant.

After that I describe the respective features of the new VVER plants called AES-2006.

Features expected from 3rd generation NPPs - 1

Safety can be improved by strengthening each of the four levels of Defence-in-Depth (DiD).

Main emphasis should be at DiD level 1 – This improves also reliability and life-time profitability of the plant.

Features expected from 3rd generation 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 a crash of a large passenger airplane
- advanced **control of radiation** during normal operation: very small radioactive releases, occupational radiation doses, and radioactive waste generation

Features expected from 3rd generation 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 accidents, extended beyond the traditional design basis accidents and 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**

Safety of new VVER plants

Examples of “Generation III” characteristics

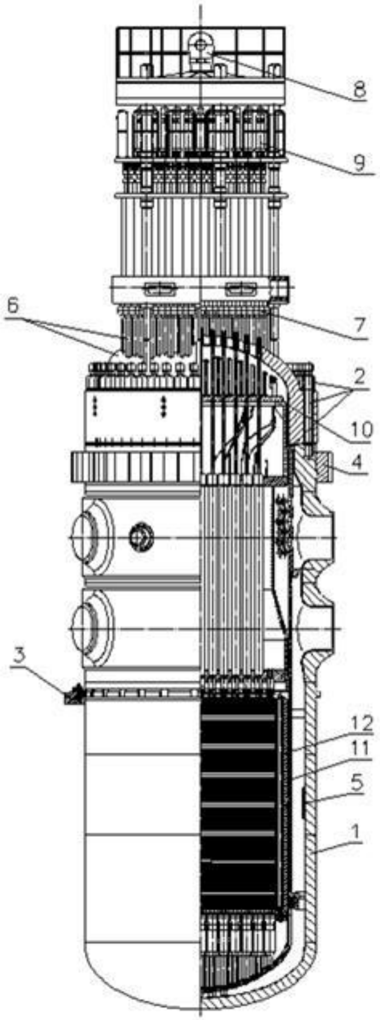
Development of Russian NPP safety

The accident at Chernobyl was a turning point in Russian involvement in international nuclear safety co-operation and in developing new safer nuclear power plants.

- Russian experts have been actively involved in the IAEA work to develop global safety principles and standards, especially in connection with pioneering INSAG work
- Since 1990’s Russia has been in lead role in NEA coordinated experimental nuclear safety research.
- International interaction has ensured that the Russian national nuclear safety requirements are consistent with the latest IAEA Safety Standards.
- AES-2006 type VVER is already designed to meet the requirements included in the 2012 version of SSR-2/1, Safety of Nuclear Power Plants: Design.

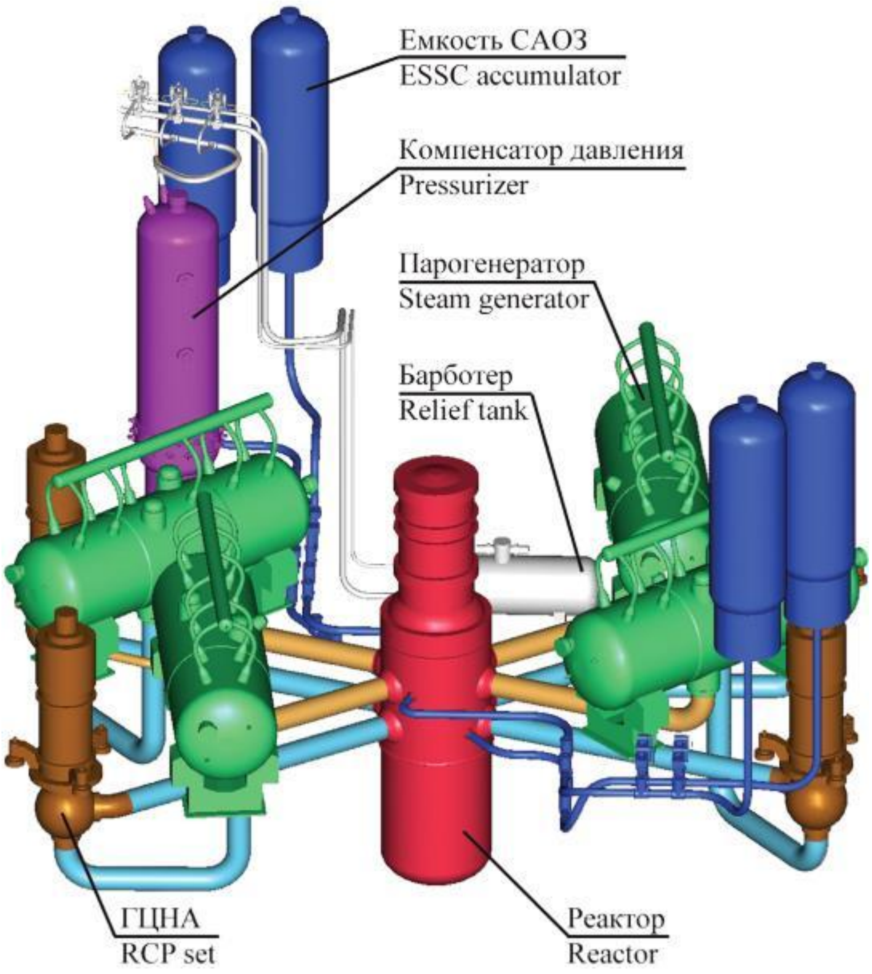
Improved assurance of AES-2006 primary circuit integrity for 60 years operation (1)

- 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.



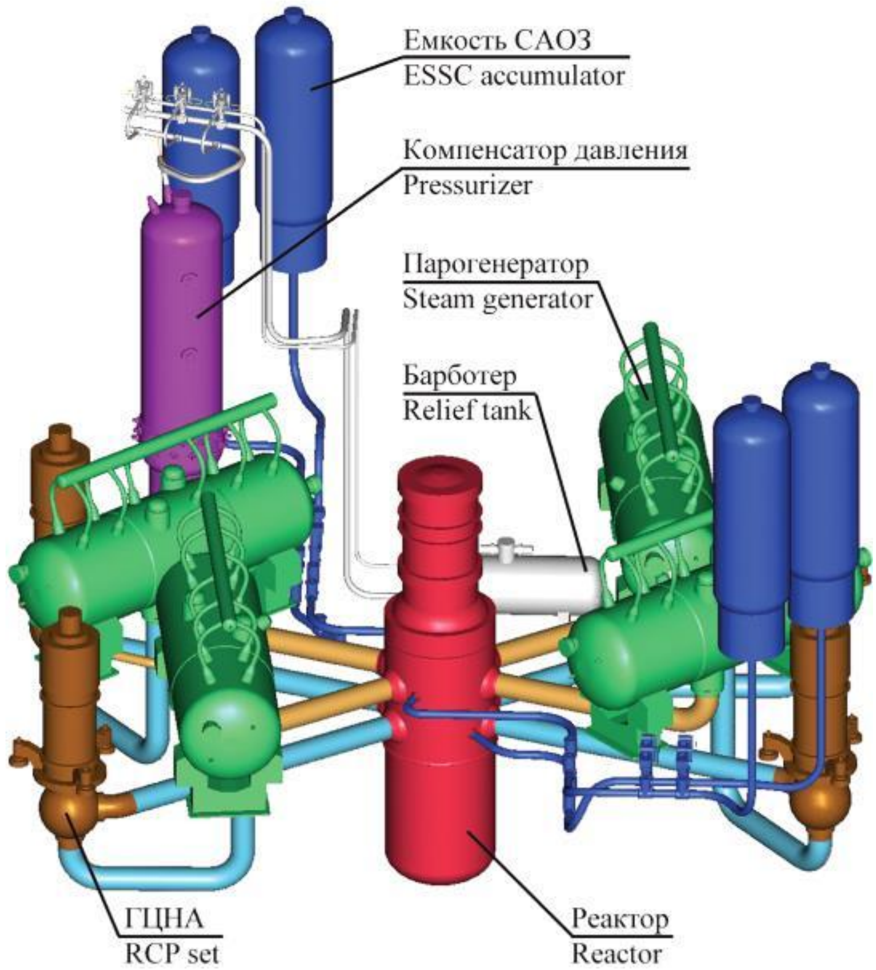
Improved assurance of AES-2006 primary circuit integrity for 60 years operation (2)

- Steam generator structure and operating conditions
  - The original SGs that have been properly operated have good operating experience – no replacements have been needed and are not expected during 60 years lifetime
  - New plants have improved removal of corrosive products from SGs, copper is avoided in secondary side materials, and secondary side has new type of water chemistry



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

- Reactor coolant piping meets all necessary conditions of the "leak-before-break" concept
  - material properties,
  - stress analysis,
  - in-service inspections,
  - leak monitoring

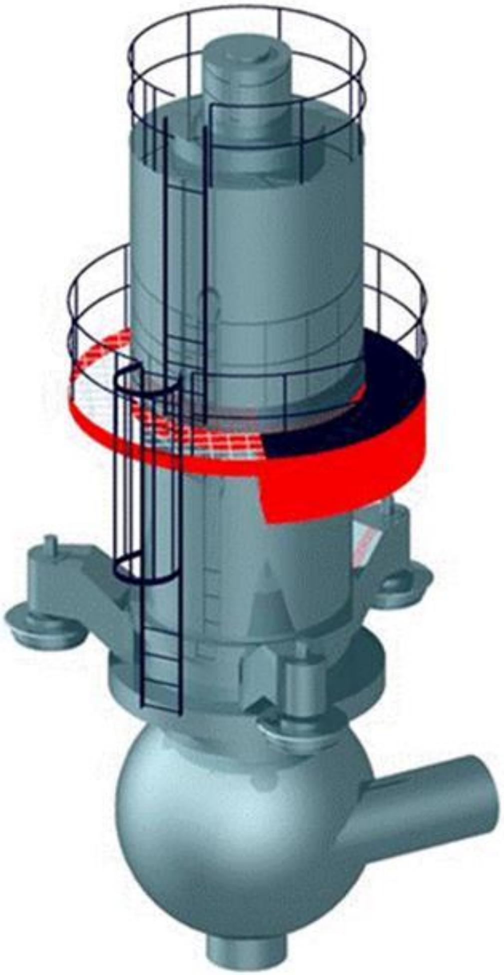


Advanced features of AES-2006 main coolant pumps

Two special safety features of MCPs:

1. Primary circuit main circulations pumps and their motors have **water cooling and water lubricated bearings**, while most PWR plants have oil cooling and lubrication that entails elevated risk of large fire inside the reactor building.

2. An issue that is important in connection with the complete loss of electrical power is the potential leak from the primary circuit main circulation pump seals. AES-2006 pumps have **a seal structure that ensures very small leak** in all conceivable circumstances.



Advanced approaches to fire protection at AES-2006 plants

Reduction of fire hazards

- Water cooling and water lubricated bearings of primary circuit main circulations pumps and their motors eliminate the risk of large fire inside the reactor building

Reliable and safe fire suppression

- Water based ”high fog” systems that have been effective in suppressing fires in many real fire accidents at different facilities are used for suppressing oil and electrical fires; these systems do not spread poisonous or suffocating materials and thus their use is not hazardous to operating staff or environment.

Lay-out of AES-2006 plants

Lay-out provides systematic separation of diverse safety systems and of redundant subsystems of safety systems

- Separation is based on placing diverse systems and redundant subsystems to **different buildings or different building compartments** so that a fire, flood or any other internal or external threat cannot cause loss of an entire safety function.

Protection of AES-2006 against natural hazards

Seismic design against Safe Shutdown Earthquake (SSE)

- Russian sites are chosen so that an earthquake causing horizontal peak ground acceleration (pga) 0,125g (specified intensity of SSE) is not estimated to occur more often than once in 10 000 years.
- Nevertheless, **vital systems and components are designed to withstand an earthquake intensity of 0,25g**. This gives **an opportunity** to offer foreign sites an optional SSE **up to 0,41g** without changes in plant spaces or lay-out.
- Strength of **buildings and concrete structures** of exported plants can be designed for site specific conditions **as requested by customer**.
- Seismic analysis is done with conservative models, as defined in international standards; in addition a verification analysis is made with realistic models and 40 % higher intensity to demonstrate adequate margin of design.
- Response of structures is studied for several different frequency spectra.

Protection of AES-2006 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

Modern digital protection systems of AES-2006 plants

- VVER plants **can be offered** with
  - digital protection systems that are designed and qualified initially for nuclear applications and **proven with extensive experience** at the 24 French plants (1300 MW series) since 1983 – at equipment level the technology is modernized in line with todays' state-of-the-art
  - digital systems for controlling **normal operation and limitation functions**, purchased **from a different contractor** to ensure diversity and independence
  - **hardwired** analog I&C systems as **back-up** for main parts of the digital protection systems

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

All VVER and PWR reactors can be shutdown by cutting power of the electromagnets that hold them above the reactor core

- Gravity force causes the rods to drop into the core.

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

- When control rods are in 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
- **<u>This is more efficient protection against ATWS (Anticipated Transient Without Scram) than found in most other reactors</u>**

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

- **Active systems** can remove decay heat
  - to the heat sink used by the condenser coolant system (e.g. sea, river, cooling tower)
  - to a separate “spray pond” used by the safety systems as an alternative heat sink
  - to the atmosphere – feed and bleed from steam generators.

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

Passive system for decay heat removal at Leningrad-2 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

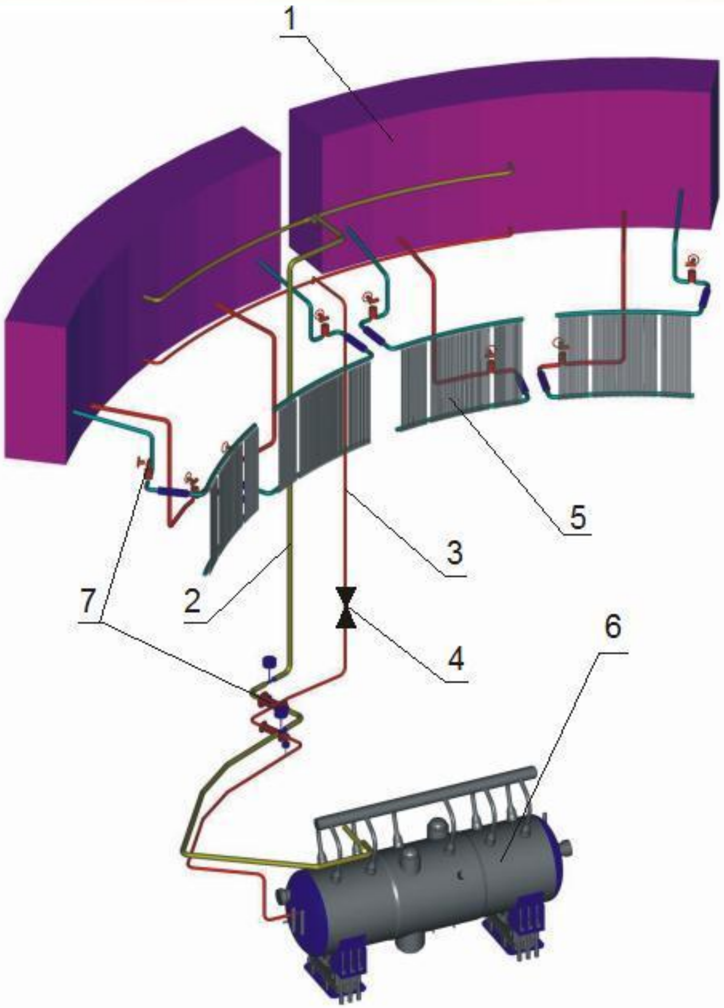
3 – condensate pipelines

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



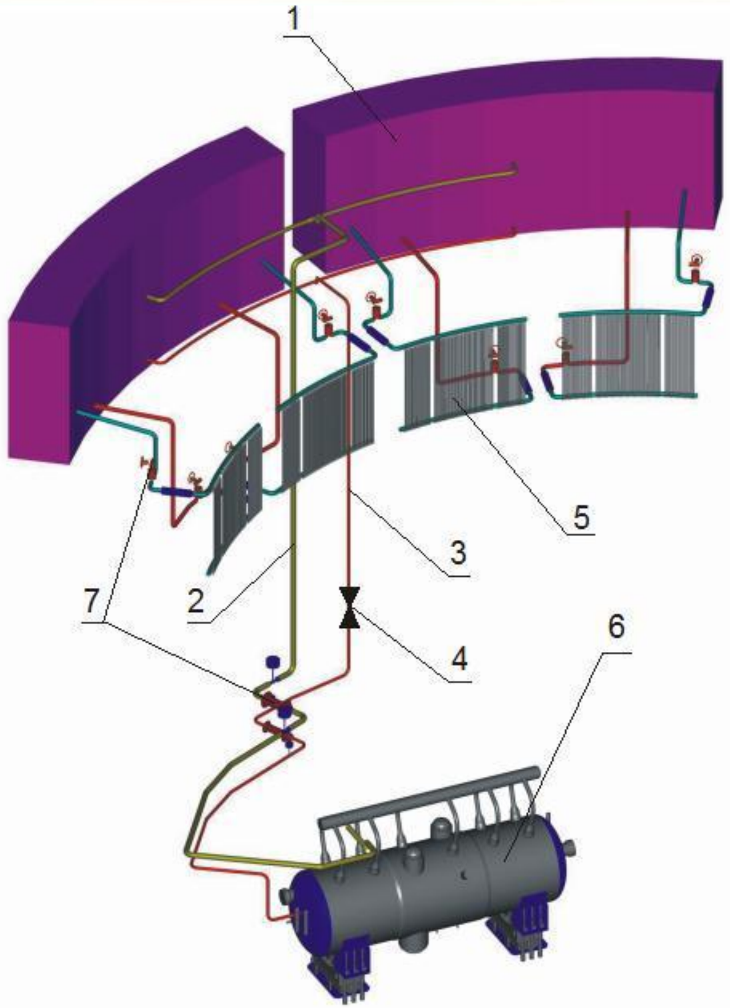
Passive system for decay heat removal at Leningrad-2 plant (2)

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, a fixed battery driven pump was added to design that **can refill the EHRT tanks and spent fuel pools from a separate storage tank, batteries have a capacity for 72 hours.**

Also, connections were made for transportable small diesel generator for dedicated **recharging of batteries** and thus for providing water without time limit.

Furthermore, connections were made for two transportable **diesel driven pump** units that can also refill EHRT tanks and spent fuel pools.



Containment of radioactive materials (1)

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 materials (2)

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 material (3)

- The strategy for protection of the AES-2006 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 AES-2006 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)

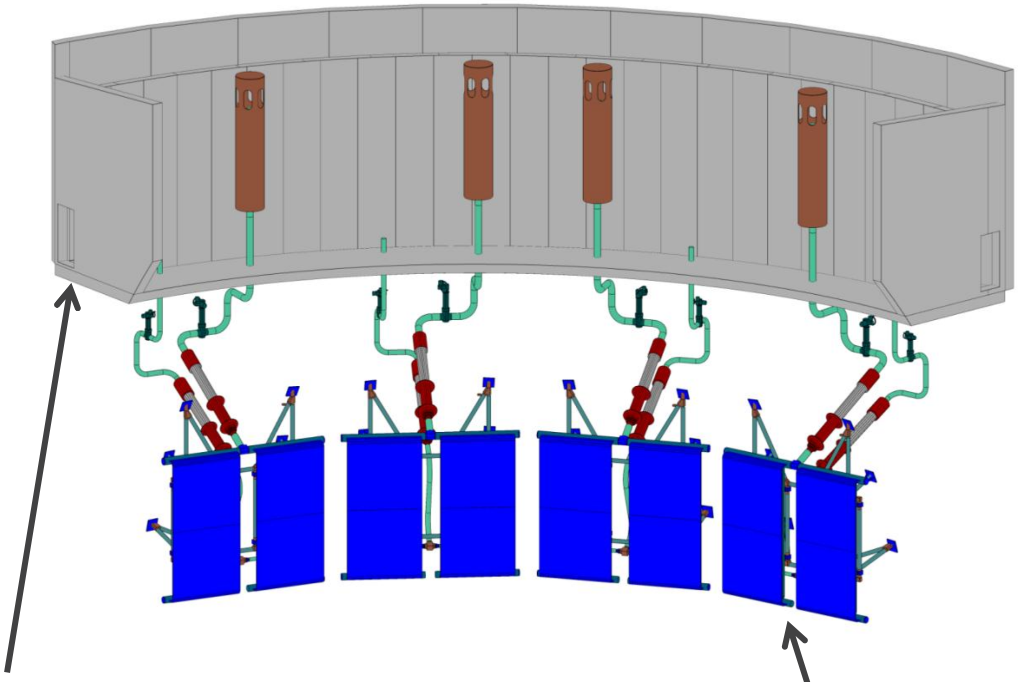
The physical phenomena addressed in the AES-2006 design include:

- reactor core meltdown in high primary circuit pressure,
- containment overpressure due to the steam generated inside the containment,
- 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,

Passive catalytic hydrogen recombiners at operating VVER

Containment of radioactive material (5)

Containment overpressure protection system at Leningrad-2

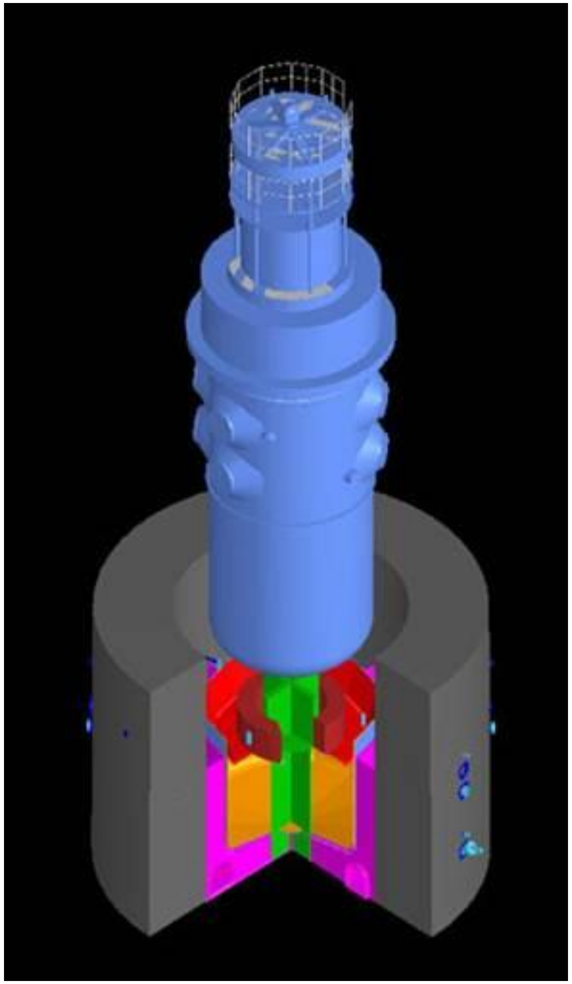


Cooling tank outside
the containent

Condensing plates inside
the containment

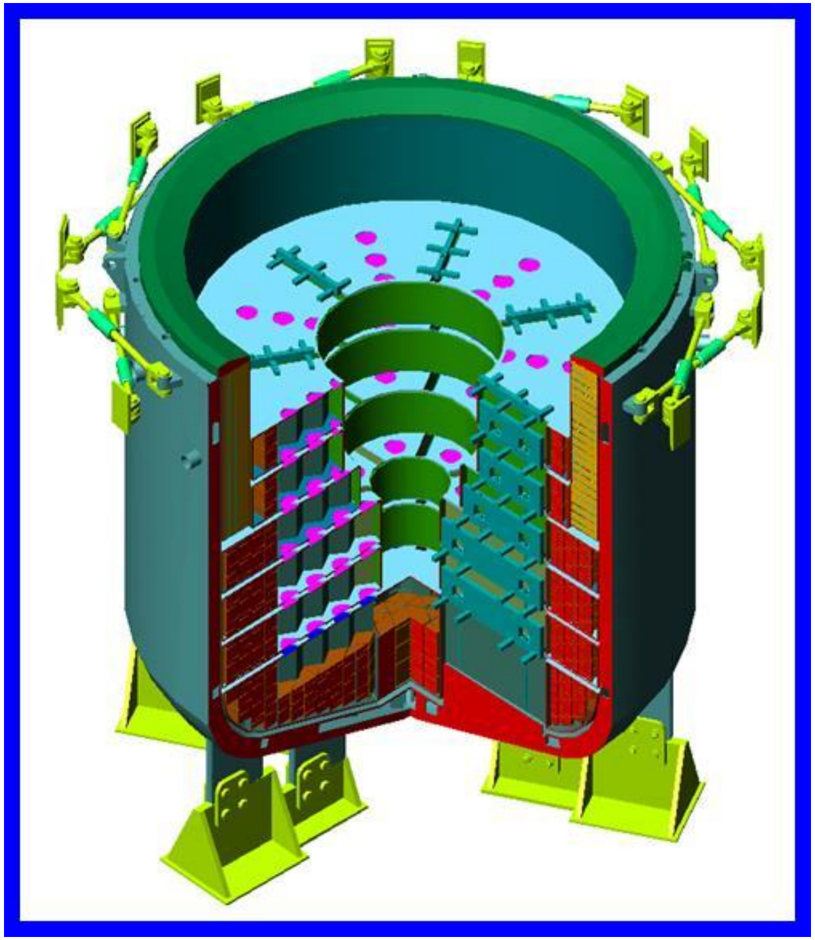
Containment of radioactive material (6)

- 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.