INHERENT SELF-PROTECTION, PASSIVE SAFETY AND COMPETITIVENESS OF SMALL POWER MODULAR FAST REACTOR SVBR-100

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1 INTRODUCTION (1)

- The current state of the nuclear power (NP) and prognoses of world NP development don't correspond its mission to realize sustainable development without releases of greenhouse gases and restriction of fuel resources. Such situation for the NP is resulting both from the certain external and internal factors.

- The major external factors are the following:

1) very high frequency of realization of the severest accidents occurred at NPPs during the life of one generation,

2) existence of developed alternative technologies for generating of electricity,

3) entering the market by renewable energy sources (RES).

- In its turn, the internal factors are measures on enhancing of reliability and safety of the NPP equipment, which are resulting to increase of specific capital costs for their construction (specific capital costs for the NPPs planned to be constructed are considerably higher as compared with the similar costs in Contracts, which were made prior to the accident at NPP Fukushima 1).

1 INTRODUCTION (2)

- At the same time, further increase of safety requirements for NPPs with traditional type reactors can result in loss of competitiveness of the NP based on water cooled reactors. For the purpose to reduce the specific capital costs and operation cost of electricity, it is required to increase a unit reactor capacity that, in its turn, is leading to growth of total costs of NPP construction and growth of construction terms.
- Thus, the financial risks are growing. An example is experience of construction of power-units EPR-1650 in Finland and France. Their terms of construction have increased almost twice, and the cost has raised two or three times more.
- The probabilistic safety analysis (PSA) methods are not convincing for the population with radiophobia. Use of PSA methods makes no sense when the initial events of severe accidents are not caused by chance, but they are the results of ill-intended people's actions.

1 INTRODUCTION (3)

- In those cases, all safety systems, which are in a standby mode, can be disabled deliberately, and the transport apertures in the protective shell are opened. Those NPPs can be used by terrorists as an instrument of political blackmail, and for that reason that problem was considered by the IAEA.
- However, the PSA methods were and are useful. Often, they are the only instruments for quantitative assessment of safety parameters. But their application in the existing types of RFs can’t deterministically eliminate the possibility of realization of the severe accident, which probability is very low. And that fact doesn’t contribute to lowering of population’s radiophobia including those countries, where electricity is in deficit, and which are the potential market for construction of NPPs.
- The Global Agreement on Climate (Paris, 2015) does not specify the concrete ways of lowering of carbon releases into the atmosphere. Moreover, the nuclear option is not provided in the Agreement, and that is conditioned mainly by radiophobia of the population, whose opinion is accounted by politicians.

1 INTRODUCTION (4)

- Along with this, in future the NP role will be very important as it makes possible generating of electricity and thermal power without limitations in fuel resources, releases of harmful substances into the environment and consumption of oxygen, which are resulting in global changes in the earth climate.

- Development of RES, which eliminate carbon releases, is possible only if the governmental support is assured.

- Those are the reasons, which provide the necessity for future changeover to the reactors with the considerably higher level of inherent self-protection. In such reactors the severe accidents requiring the population evacuation must be deterministically eliminated, i.e. the reasons to cause severe accidents will be excluded.

1 INTRODUCTION (5)

- It is much easier to convince the population in the NPP safety if it is provided by nature laws (e.g. absence of pressure in the reactor, lack of hydrogen release assure that explosions cannot occur and so on).

- It is more clearly understood for the people, who consider the events on the basis of their own experience, but not on the results of PSA.

- For the population the deterministical elimination of the severe accident requiring the population evacuation is much more important than the very low probability of its realization. That is resulting in the higher level of social acceptability of NPPs with such RFs.

- For that reason, under the equal costs, the projects of NPPs with a higher (and more “transparent”) level of inherent self-protection will stand a better chance to gain the tender on construction of NPP in the region.

2 INHERENT SELF-PROTECTION AND PASSIVE SAFETY OF SVBR-100 (1)

2.1 LOCA type accidents

- Use of the monoblock type reactor with forced LBE circulation in the primary circuit that is realized by two pumps with gas-proof electric motors.

- The reactor monoblock vessel is equipped with a protective casing. There are no pipelines and valves in the primary circuit (Fig. 1).

- Due to the monoblock design of the RF, the natural properties of LBE, which are resulting from very high LBE boiling point (1670 °C) and chemical inertness while contacting with water and air, that is possible in accidental conditions, eliminate the opportunity of LBE loss with core melting, reactor explosion and fires (no hydrogen release).

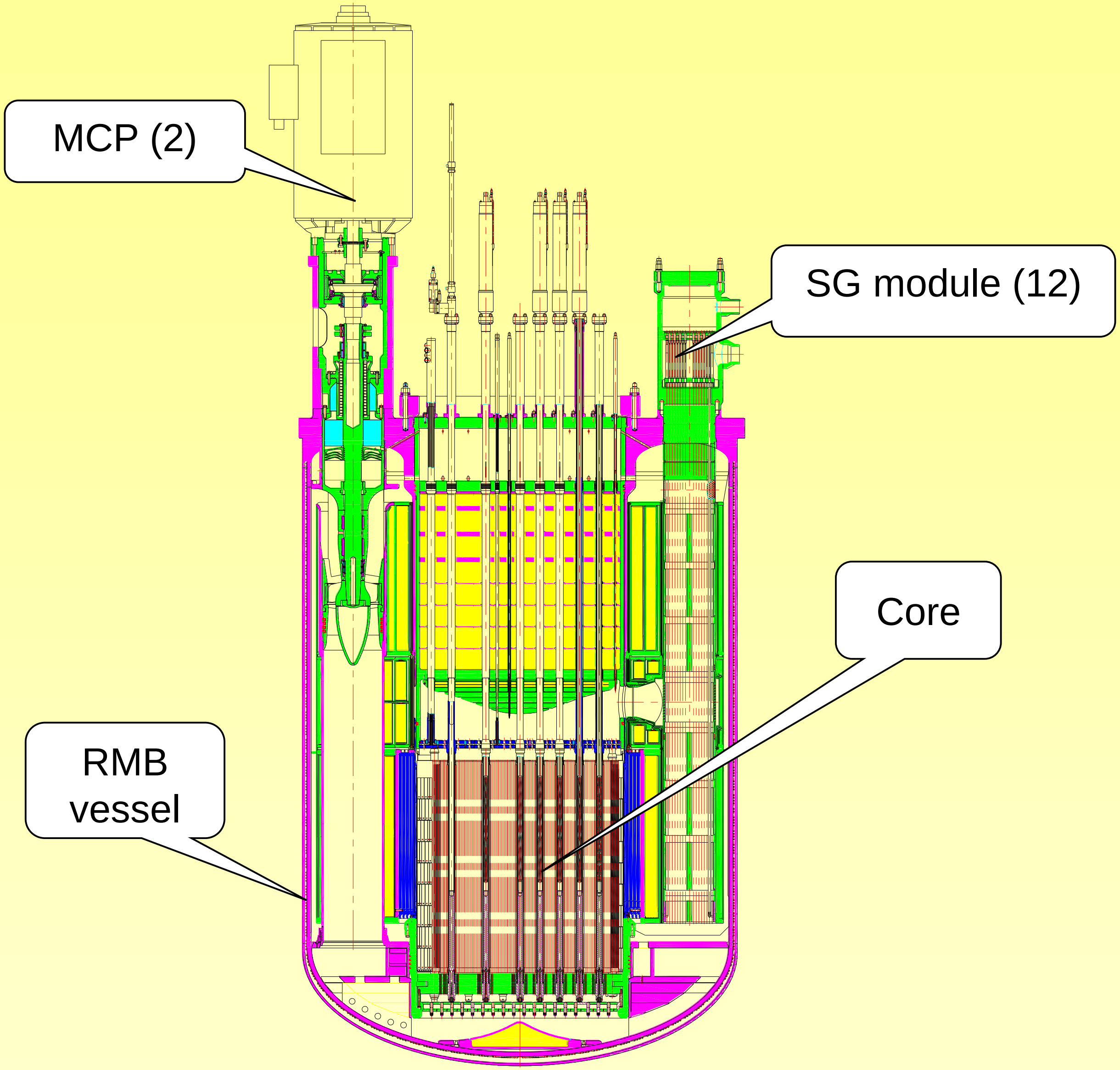


FIG.1 Reactor monoblock

2.2 Coolant compatibility with water/steam and fuel

- Realization of the RF design is based on a two-circuit scheme. The steam generator (SG) is operating with multiple forced circulation with generation of dry saturated steam. LBE chemical inertness regarding to water is eliminating the necessity in the intermediate circuit. Compatibility of oxide fuel with LBE is eliminating the event that the accidental situation with untightness in the fuel element cladding is developing in the accident with high release of radioactivity in coolant.

2.3 SG tube rapture (SGTR)

- To localize the accident with leak in SG tubes, the steam condensers are provided in the primary circuit gas system. In an event of their failure it is provided that steam-gas mixture is passively discharged to the bubbler via the rupture membranes (bursting disk). The scheme of LBE circulation in the reactor monoblock (RMB) is realizing effective gravitational separation of steam bubbles on the LBE free level under the RMB lid. Experience of operating the LBE cooled reactors at nuclear submarines (NS) has revealed, that in events of small leak in the SG (up to 10 kg/h) there is no necessity in immediate RF shutdown.

2.4 LOHS, ULOHS type accidents

- In all heat-removal circuits the level of coolant natural circulation (NC) is sufficient for removal of heat decay. Heat removal via the SG is provided by four independent channels of the passive heat removal system (PHRS) due to evaporation of water in the tanks. Steam is discharging in the atmosphere, grace period is 72 hours (Fig. 2). In an event of postulated failure of all four PHRS channels, the RMB pit is flooded by water. Removal of residual heat going on via the RMB vessel is facilitated by large specific surface of the RMB vessel. Management of that accident is provided by feeding of PHRS tanks or RMB pit from emergency sources of water and electricity supply (for example, fire engines and so on).

2.5 Self-protection against reactivity accidents and UTOP type accidents

- The reactor possesses a negative void reactivity effect and negative temperature reactivity coefficient due to weak neutrons moderation by collisions on nucleus lead and bismuth. In addition to emergency protection (EP) rods actuating by electric signals, the reactor is equipped with directly acting addition emergency protection (AEP) without electric drives, which rods are actuating by increase in LBE temperature (fusible locks).

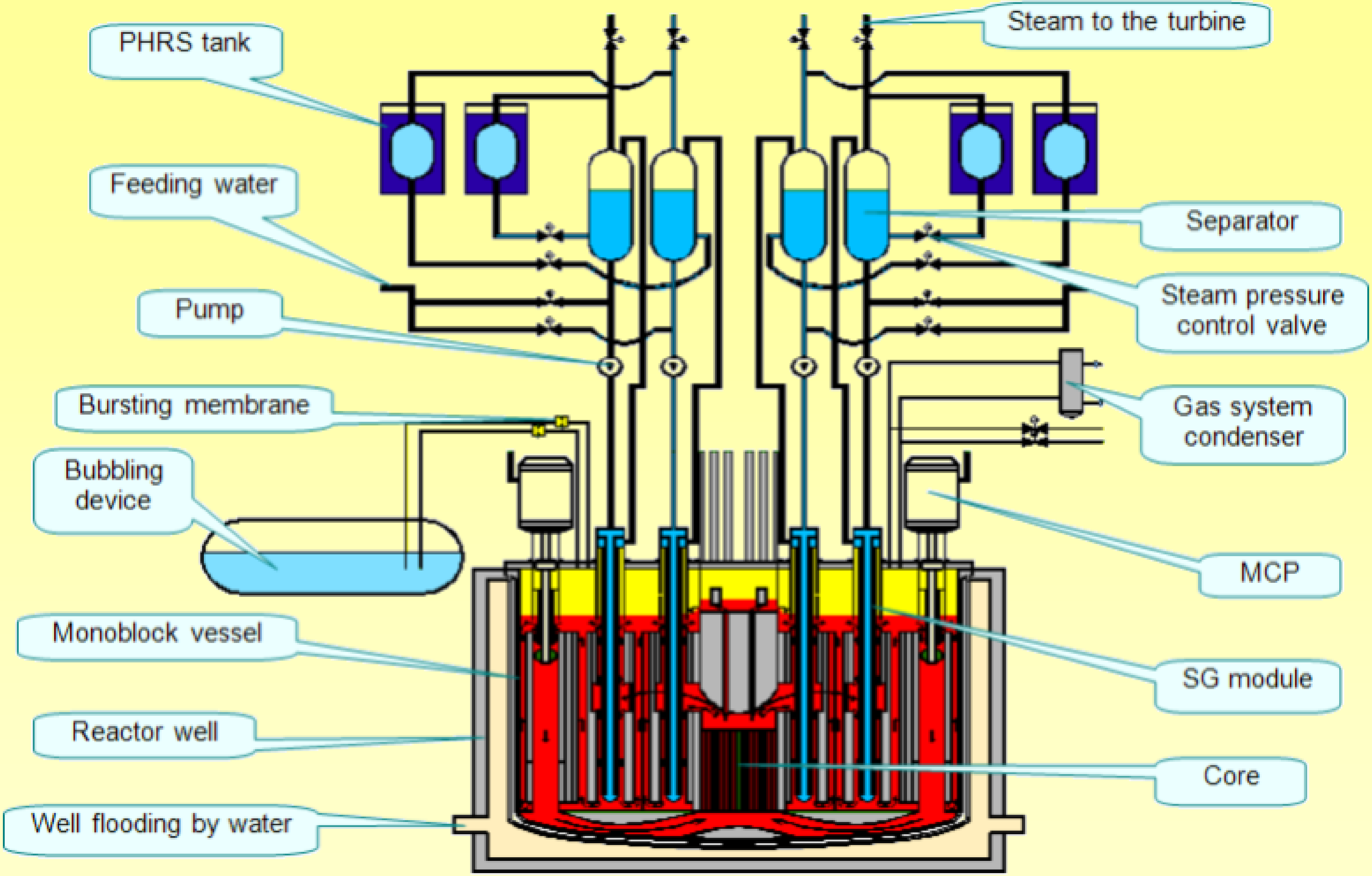


FIG. 2 Hydraulic diagram of RF SVBR-100

2.6 ULOF type accident

• In an event of simultaneous shutdown of both pumps (power supply loss) and failure of the main emergency protection system (scram), self-protection of the RF is provided passively due to actuation of AEP rods, inertial rundown of pumps and natural coolant circulation in heat-removal circuits.

2.7Unauthorized “freezing” of LBE in the RF

• In an event of the shutdown reactor and low level of residual heat, the self-protection against unauthorized LBE “freezing” in the RF is provided by zero change of the LBC volume upon transition from a liquid state into solid one and high plasticity of solid LBE. The operability of the equipment in events of LBE “freezing-unfreezing” is verified not only experimentally at large-scale prototypes but in conditions of RF operation at the NSs.

3 DEFENSE-IN-DEPTH BARRIERS (1)

Elimination of radioactivity release into the environment is provided by the system of disposed defense-in-depth barriers, which includes:

- Fuel pellet UO_2 that is chemically compatible with LBE, which are retaining the main part of accumulated fission products.

- Fuel element cladding made of ferrite-martensitic type steel that is corrosion-resistant in LBE, and is withstanding emergency overheating up to 900 °C without damage during 5 minutes and is eliminating formation of hydrogen in the accidental conditions.

- LBE is retaining iodine, caesium and some other fission products (with an exception of gaseous ones), which can ingress in it in an event of tightness failure in the fuel element cladding. The concentration of ^{210}Po formed in LBE under irradiation by bismuth neutrons is very low (10^{-6} %) and it forms thermodynamically resistant intermetallic compound with lead. Those factors reduce evaporation of polonium from LBE by a factor of 10^9 and that provides a comparatively favorable radiation situation in an event of postulated tightness failure in the primary circuit or gas system pipelines operating without excess pressure.

3 DEFENSE-IN-DEPTH BARRIERS (2)

- Polonium is defining the radiation situation in an event of tightness failure in the RF gas system and requires providing of corresponding radiation safety measures. Those measures were developed and realized in the process of operating the LBE cooled RFs at the NSs. They were very effective as **none of the personnel (both military and civilian ones), who took part in elimination of accident consequences, got the polonium in-take dose that exceeded the permitted one** (about 20 t of radioactive LBE leaked in the reactor compartment of the 27/VT facility).

- The tight vessel of the RMB equipped with a protective casing and gas system pipelines eliminating release of radioactivity into the RF box.

- The tight RF box protected against external impacts by reinforced concrete overlap of 1.5 m in thickness, which air is slightly rarefied relatively to that in the central hall (CH), rarefication is produced with the help of a ventilation system discharging the air into the atmosphere via the ventilation tube through the system of filters.

- The protective reinforced concrete shell of the reactor building, which thickness is 1.5 m, and which is purposed for additional protection against external impacts (such as aircraft fall).

4 RADIO-ECOLOGICAL SAFETY

- At the stage of storage of spent nuclear fuel (SNF) the elimination of radioactivity release is provided as follows: after removal from the reactor the fuel sub-assembly (FSA) is imbedded in a steel case filled with liquid lead, which then is put into the storage cell where removal of residual heat is realized passively due to natural circulation of atmospheric air.

- At this point, there are four safety barriers on the way of radioactivity release into the environment, namely: fuel pellet, fuel element cladding, solidified lead and leakproof steel case.

- In accordance to experience of NS's RFs, no liquid radioactive wastes (LRW) are produced as refueling is performed without removal of coolant from the primary circuit and its further decontamination, which is a cause of formation of LRW in large quantities.

5 TOLERANCE TO EXTREME INITIAL EVENTS (1)

To assess the safety potential of reactor SVBR-100, the preliminary calculation analysis of the consequences caused by the postulated severe accident was performed under combination of such events as:

- Destruction of the protective shell of the reactor building.
- Damage of the reinforced concrete overlap of the reactor box.
- Rupture of gas system pipelines of the RMB, located in the concrete pit below the ground level, with direct contact of the free surface of LBE under the RMB lid and atmospheric air.
- Total blackout of the NPP.

That combination of initial events is only possible in extreme occasions, such as military actions, terroristic attacks, nature disasters, which occur very rarely, and so on. The results of the performed calculation analysis have revealed that even in an event of extremely unfavourable atmospheric conditions, no population evacuation beyond a three-kilometre zone is required.

For reactors with water or sodium coolants such combination of initial events can result in catastrophic consequences.

5 TOLERANCE TO EXTREME INITIAL EVENTS (2)

- The performed analysis has revealed that RF SVBR-100 isn't an amplifier of external impacts and, therefore, the scale of damages will be only determined by the energy of external impacts.

- Those type RFs assure their high resistance not only in events of single failures of the equipment and personnel errors, but in events of deliberate ill-intentioned actions when all special safety systems operating in a standby mode can be intentionally disabled. Such catastrophic accidents as Chernobyl or Fukushima disasters as well as fires similar to that occurred at reactor "Monju" are in principle impossible at those reactors.

- This is extremely viable for realization of NPPs construction, especially in some countries where the level of terroristic threat is high. The obtained results are conditioned mainly by a low value of potential energy accumulated in the LBE. For water, sodium and heavy liquid-metal coolants this energy is 20, 10 and 1 GJ/m^3 respectively.

6 COMPETITIVENESS OF NPPS BASED ON RF SVBR-100 (1)

- It is very important to support and enhance the economic competitiveness of the NP in conditions of growing safety requirements and alternative competitive power technologies available at the markets. It is impossible o assure large-scale NP development without finding the solution to this issue.

- For that purpose, it is necessary to provide economic competitiveness of some NPPs with FPP on natural gas and also provide the conditions for attraction of investments for development of the NPP fleet.

- With regards to that, the small and medium power reactors (SMR), which share in the future NP is expected to be at the level of not less than 30 %, must meet the highlighted requirements of competitiveness and investment attractiveness.

- It is evident that for the SMRs it is difficult to meet those requirements as there is a tendency to increase the specific capital costs (concerning the large power NPPs) at lowering of reactor module's power.

6 COMPETITIVENESS OF NPPS BASED ON RF SVBR-100 (2)

- It can be expected that those negative tendencies will be overcome by the principle of modular construction of SMR based NPPs and effect of cost decreasing due to production scales and learning curve in the process of equipment manufacturing and SMR construction.
- The additional barrier to provide the investment attractiveness of the innovative SMR projects is the initial expenditures for development and demonstration of reference solutions at first such NPPs (FOAK). In its turn, it is resulting in postponement of the phase of commercialization of those SMRs.
- Overcoming of those barriers by economical (market) methods can be only realized by technologies, which provide high profitability of the single NPP.

6 COMPETITIVENESS OF NPPS BASED ON RF SVBR-100 (3)

Along with highlighted factors of enhancing the competitiveness and investment attractiveness, the serial NPPs with RF SVBR-100 use the additional opportunities based on application of the following:

- The compact equipment, the labor expenditures in its manufacturing can be compared with that for large power NPPs.
- Sizeable lowering of the number of safety systems due to the high level of inherent self-protection.
- Entire factory manufacturing of reactor modules and their transportation to the NPP site in readiness by different kinds of transport including railway. The small power and dimensions of those reactors make possible organization of their conveyer production that improves the quality of works and lessens the costs. On the basis of the same tested module, it is possible to construct the modular nuclear steam supplied systems (NSSS) of different power capacities of 100 MWe-fold for different purpose NPPs without performance of additional R&D. The effect of serial production is shown by Japanize organizations CRIEPI and TOSHIBA concerning to modular sodium fast reactor 4S of 80 MWe.

6 COMPETITIVENESS OF NPPs BASED ON RF SVBR-100 (4)

Those researchers have revealed that the cost of a single module is reduced three times for their conveyer production in the specialized factory shop in the quantity of twelve modules per year (Fig. 3).

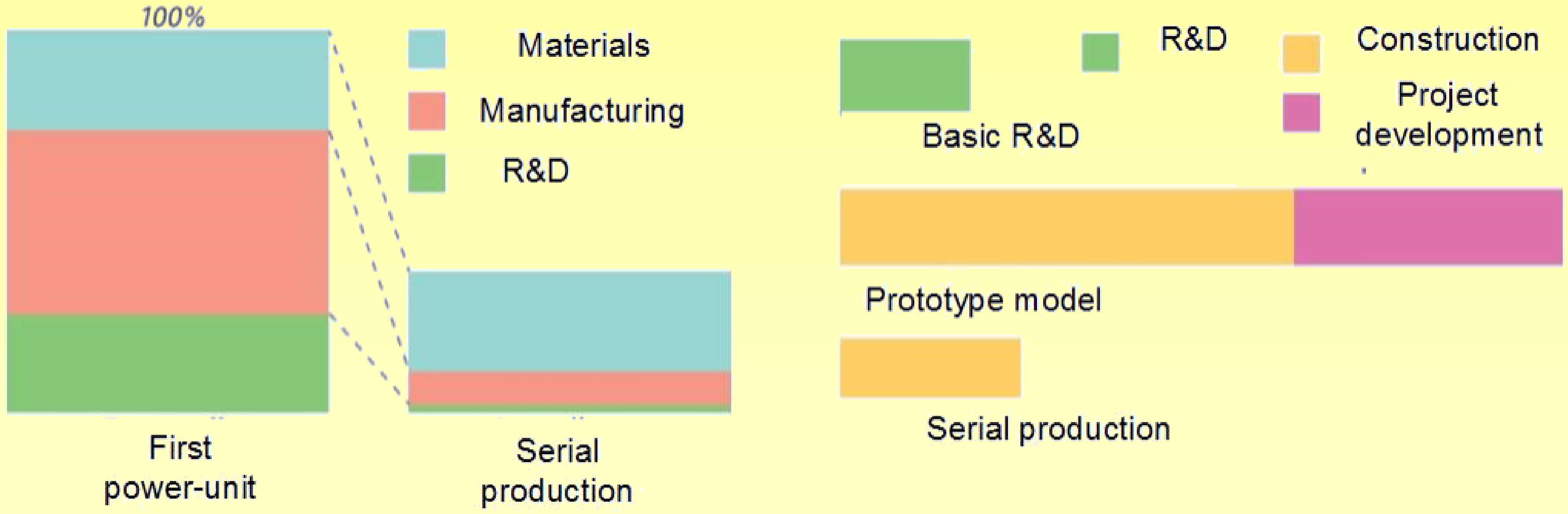


FIG.3 Effect of serial production

6 COMPETITIVENESS OF NPPs BASED ON RF SVBR-100 (5)

Modular structure of the NSSS power-unit is providing the following:

- The higher level of reliability (failure-resistance of the power-unit as a system of separate RFs) and safety (lessening of the potential radiation risk) as compared with a power-unit based on a single large capacity reactor;
- The opportunity not to provide the standby power-unit of large capacity in the areas of decentralized power supply;
- Under long operation of the reactor without refueling (7-10 years), the loading factor (LF) is not less than 90 %. The LF will be determined by reliability indices of the turbine installation. When the RF is shutdown in turn for refueling or technical maintenance, the power-unit's capacity is reduced noticeably less as compared with that of the power-unit based on a single reactor of large unit capacity;

6 COMPETITIVENESS OF NPPs BASED ON RF SVBR-100 (6)

- Continuous loading of machine-building plants, that considerably reduces the expenditures for manufacturing. Due to the fact that the unique engineering equipment is not required for manufacturing of the RMB, as it is required for the high-pressure vessels of thermal reactors, the opportunity to form the competitive market of manufacturers is arising;
- Use of the methods of standardized designing of different capacity power-units and production line methods of organization of constructing and mounting works. Thus, together with a high level of serial production of RFs, reduction in terms and costs of power-units construction is provided;
- Location of small and medium capacity modular NPPs in the energy consumption centers, that eliminates the expenditures for construction of powerful electric transmission lines;

6 COMPETITIVENESS OF NPPs BASED ON RF SVBR-100 (7)

- Power-unit's implementation in operation (commissioning) in turns with stepped raising of capacities as assembly and precommissioning works have been completed for the group of modules. This is lowering the term for pay-back of capital investments due to the earlier output of products and starting to pay off a credit as compared with that of the power-unit based on the reactor of large unit capacity.
- Due to all listed points the competitiveness of RF SVBR-100 is considerably increasing.
- The expected reduction of the investment cycle of NPP construction that is provided by modular structure of the NSSS and factory supply of ready modules is very important for nearing the technical and economical parameters of the NPP to corresponding parameters of modern steam-gas power plants with short investment cycles and, thus, allowing considerable reduction of the financial risks.

6 COMPETITIVENESS OF NPPs BASED ON RF SVBR-100 (8)

- As there are only two states of RF functioning, namely, operating and shutdown, control of the modular NSSS is carried out by one operator using the common power master unit. If there is any fault in a single RF, it is automatically shutdown and is cooled down autonomously, away from the turbine installation systems.
- On expiring of the RF lifetime (50…60 years) and unloading of the spent nuclear fuel and LBE, the basic RF element – RMB – will be dismantled and placed in a storage of solid radioactive wastes. A new RMB will be installed instead. The other elements of the RF and power-unit can be dismantled and replaced as well, i.e. the renovation can be performed.
- At this point, the lifetime of the modular NPP will be only limited by that of reinforced-concrete construction structures and can be expanded up to 100…120 years and more at lower costs as compared with those required for construction of the new power-unit.

6 COMPETITIVENESS OF NPPs BASED ON RF SVBR-100 (9)

- When the power-unit has been completely decommissioned, practically no radioactive materials are remaining in the NSSS building after the RMBs have been dismantled. Thus, the cost of decommissioning is considerably reduced.

- The innovative Project of the NPP with reactor facilities SVBR-100 is in fact the First Generation design based on a conservative approach. It has predetermined a high potential for further improvement of the Project, which will be realized as the corresponding R&D have been accomplished and operating experience has been gained.

In particular:

- Increasing of LBE temperature at the reactor outlet, while the maximal temperature of the fuel element's cladding is increased from 620 to 650 °C (there are all the necessary backgrounds) will provide (as the computations have revealed) the growth of the reactor thermal power by ~10 % without change of the reactor design and cost.

- Use of nitride fuel can provide twice increase of the reactor lifetime (the operability of fuel elements should be verified) and correspondingly reduce the operation costs.

7 R&D KEY RESULTS TO SUBSTANTIATE THE RF SVBR-100 PROJECT (1)

At present the following results can be related to the key results of R&D on the RF SVBR-100 project:

- The RF design has been developed in a scope required for launching of production of the equipment with a long manufacturing cycle.
- The commercial production of all basic components and semi-finished products required for manufacturing of the basic equipment including experimental melting and fabrication of large capacity blanks for vessel structures has been renewed.
- The corrosion resistance of fuel elements cladding has been justified for the full lifetime, i.e. for 50 000 of hours.
- The tests of short fuel elements prototypes in research reactor BOR-60 has been performed.
- For conduction of tests in reactor BN-600 in radiation conditions, which are maximal close to those of SVBR-100, the experimental prototypes of fuel elements with standard dimensions have been manufactured.

7 R&D KEY RESULTS TO SUBSTANTIATE THE RF SVBR-100 PROJECT (2)

- The physical model of the SVBR-100 core has been constructed, and its neutron-physical characteristics have been investigated at the BFS critical facility (IPPE).
- The mechanical tests of the separate units and devices of the refueling system, flange connector, and unit of sealing of the reactor cover, CPS element drives has been performed.

The final part of the R&D program is oriented to such long works as:

- Reactor tests of pilot batch of factory supplied fuel elements.
- Construction of the facility and tests of the prototype models of MCP.
- Construction of the facility and tests of full-scale (one channel) passive heat removal system, delivery tests of flow regulator of the PHRS with passive feedback.
- The tests of the steam generator scale model.
- The complex of works on creation and implementation of the normative base of reactor facilities with HLMC including certification of materials.

8 CONCLUSION (1)

Due to the highlighted above, the following findings can be made:

a) Reactors SVBR-100, in which there is no accumulated in the RF coolant potential energy that is capable to cause damage of the protection barriers under the certain initial events, make possible deterministical elimination of severe accidents with catastrophic release of radioactivity requiring the population evacuation.

b) Those RFs are not amplifiers of external effects and, therefore, the scale of damages will be only defined by energy of the external impact. Such type RFs possess the robustness properties, which assure their high resistance not only in events of single failures of the equipment and personnel's errors (human factor effect), but in events of deliberate ill-intended actions.

c) Those properties of RF SVBR-100 must make possible overcoming of the population's radiophobia that has increased again after the accident happened at NPP Fukushima 1. And that is very important for development of the large-scale NP and sustainable development.

8 CONCLUSION (2)

d) Implementation of reactors SVBR-100 in the NP makes possible elimination of the progressing conflict between safety requirements and economics requirements that is typical for traditional type reactors because enhancement of safety isn't reached due to the increase of the number of safety systems and protection barriers, but it can be reached due to the higher level of inherent self-protection, i.e. without detriment to economical parameters.

e) The high level of inherent self-protection and passive safety, competitiveness and satisfaction of nonproliferation requirements (uranium enrichment less than 20 %) assure high export potential of these reactors.

f) It is possible to construct not only safer NPPs based on reactors SVBR-100, but more competitive ones, as compared with NPPs based on traditional type reactors. In the closed nuclear fuel cycle those reactors will operate in a mode of fuel self-providing without consumption of natural uranium.

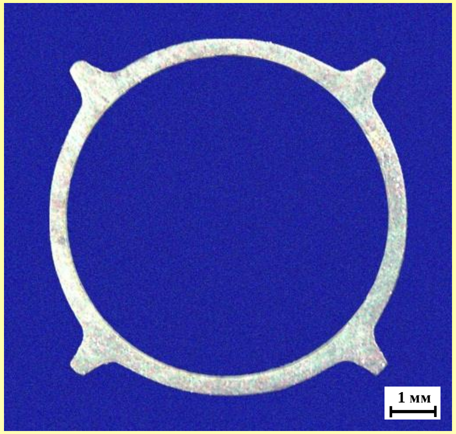
8 CONCLUSION (3)

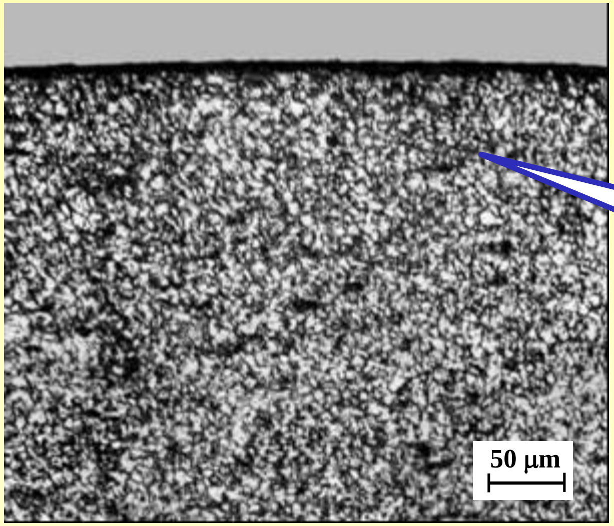
g) RFs SVBR-100, which require a stage for their mastering including ~~of~~ real operating experience in the NPP conditions, can be used first for construction of SMRs operating in the local or regional power-systems and generating the heat together with electricity. Such NPPs will make possible replacement of the coal FPP, which are the main pollutants of the environment.

h) It is planned that the technology of reactors SVBR will be realized at the experimental-industrial power-unit (EIPU). The project is realized by JSC “AKME-engineering” established by State Corporation “Rosatom” and JSC “Irkutskenergo” in the form of state-private partnership. At present JSC “AKME-engineering” has obtained the “Rostehnadzor” license for location of the EIPU in city Dimitrovgrad (Ulianovskaya region).

9 ANNEX (1)

Corrosion resistance of fuel elements claddings in LBE





Verified:

by tests at non-isothermal circulation facilities;

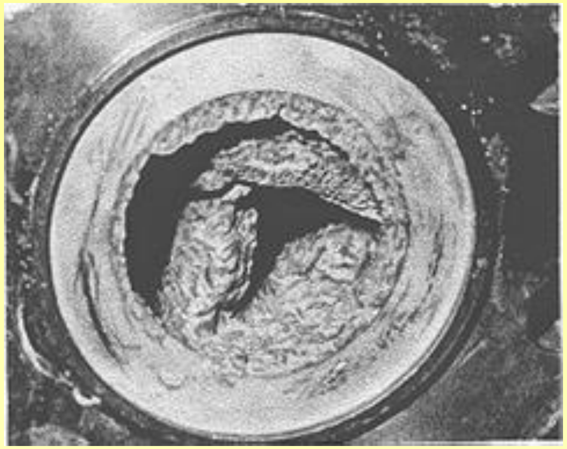
by testing in loops of reactors MR and MIR;

by the results of operating the fuel elements in the cores of LBC cooled RFs at NSs.

50000 hours of testing in LBE.
Steel EP-823 under 600 – 620 °C

9 ANNEX (2)

Hydrogen treatment of pipelines after testing the circulation pump in 1970 - 1980 years



Before hydrogen treatment

After hydrogen treatment

9 ANNEX (3)

Table 2.4.1: Relative change of volume (%) of technically pure lead, bismuth and LBE at melting (p ~ 0.1 MPa)

Lead	Bismuth	LBE
+ 3.7	- 3.7	~ 0

Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies 2015 Edition (OECD – NEA)

9 ANNEX (4)

Table of basic parameters

Parameter	Value
RF thermal capacity, MW	280
RF electric capacity (gross), MWe	101.5
Steam flow rate, t/h	580
Steam pressure/ temperature, MPa/°C	6.7 /283
LBC temperature, input / output, °C	340 / 490
Average power density of the core, kW/dm^3	160
Average linear load on the fuel element, kW/m	26
Fuel: type, $UO_{2,}$ U loading, 9016 kg, U-235 average enrichment, %	
Core lifetime, thousand full power hours	50
Interval between refueling, years	~ 8
RMB dimensions: D×H (diameter × height), m	4.53 / 7.55
RMB weight without core and coolant, t	270

9 ANNEX (5)

More on lead-bismuth cooled reactors see in the book:

The presented Collection includes articles and reports dealt with SVBR-100 – a modular fast reactor with heavy liquid-metal coolant (HLMC) lead-bismuth alloy. The papers were published in different journals and Proceedings of Conference Reports and could be interesting to many readers. Now the R&D on application of HLMCs in nuclear technologies are launched in many countries. Such activities are conditioned by natural properties of HLMC, namely: very high boiling point and chemical inertness to water and air. Therefore, significant enhancement of safety can be achieved due to deterministical elimination of such accidents as Three Mile Island accident (the USA), Chernobyl disaster (the former USSR) and Fukushima accident (Japan). Current works on HLMC reactors are in the most advanced state in Russian Federation because Russian reactors with lead-bismuth HLMC were mastered in conditions of operating nuclear submarines.

Lead-Bismuth Cooled Fast Reactors

Georgii Toshinskii

Lead-Bismuth Cooled Fast Reactors

Collection of Selected Articles and Papers

Professor Georgii Toshinskii works on development of lead-bismuth cooled reactors for nuclear submarines. He received four Government Awards and his articles are published in different Journals. Now he is a Scientific Supervisor of works on development of reactor SVBR-100 – a modular fast reactor with lead-bismuth coolant for civilian nuclear power

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