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EVALUATION OF POTENTIAL SAFETY AND ECONOMIC BENEFITS AND CHALLENGES OF MODULAR SODIUM-COOLED FAST REACTORS

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Modular SFR and its features (1)

- The modular concept of the reactor involves its serial manufacture in factory conditions, transportation in form of complete modules to NPP site and its serial construction. This approach leads to restriction of modular reactors size (first of all, diameter of main and guard reactor vessels) and, as a consequence, to power limitation.
- The limited power of modular reactor causes higher specific costs for its construction and operation per unit of electrical power compared to large sized reactor.
- Improving economy of modular SFR can be achieved by:
  - *shortening construction time;*

Modular SFR and its features (2)

- *reducing cost and improving quality of equipment manufacturing in factory conditions, in particular, due to larger seriality effect, that increases its reliability;*
- *facilitating its delivery to the site in comparison with large-dimensioned equipment for large sized SFRs;*
- *excluding long and expensive installation of this equipment in site conditions;*
- *simplification of safety systems and improving their reliability;*
- *enhancing safety against accidents, etc.*

- There are great prospects for combining modular units, for example, with placement of several modules in one reactor building, using a common refueling system, connecting them to a common turbine, etc.

Reactor core safety features (1)

- Reactor core safety characteristics are important to avoid core damage in various transient and emergency modes. And, first of all, here it is necessary to point at accidents caused by failure of reactor shutdown systems, when change of reactor power is driven by reactivity feedback only.
- Impact of core safety characteristics on economic performance of a power unit can be estimated through cost associated with elimination of consequences of severe BDBA caused by failure reactor shutdown systems. ULOF accident caused by shutdown of all primary pumps without reactor scram is the most unfavorable one.

Reactor core safety features (2)

- The analysis performed for modular sodium-cooled fast reactor PRISM demonstrates a high level of its self-protection against this accident. The reactor overcomes the ULOF accident quite smoothly without core damage and coolant boiling.
- At the same time, coolant boiling and, as a rule, reactor core damage in such an accident cannot be excluded for large sized SFR.
- It can be argued that modular SFR has higher core safety characteristics compared with large sized SFR.

Reactor shutdown system (1)

- As a rule, passive reactor shutdown systems with absorbing rods based on various physical principles to hang on them in sodium flow are planned to be used in large sized SFR:
  - *hydraulically suspended absorbing rods in sodium flow;*
  - *absorbing rods based on temperature principle of action (magnets holding absorbing rods in sodium flow up to a certain temperature level, so-called Curie point; fusible inserts that ensure retention of absorbing rods until their melting temperature is reached, etc).*

Reactor shutdown system (2)

- Regarding modular SFR, in particular, PRISM reactor design, it is proposed to use:
  - *gas expansion modules;*
  - *ultimate shutdown system (device with active principle of operation).*
- The failure probability is a defining characteristic for reactor shutdown systems. It can be reduced by replacing solid moving elements in them, which can cause device fault, for example, due to jamming solid absorbing rods because of core distortion or fuel pins swelling, etc., by devices using a liquid or gas medium as moving elements, such as in gas expansion modules.

Decay heat removal system (1)

- It is possible application of two variants of DHRS in modular SFR:
  - *the first option is conventional DHRS with heat dissipation through special heat transfer equipment (DHX, AHX). In this case, reactor power is limited only by reactor vessel size (firstly, diameter);*
  - *the second variant assumes application of passive RVACS for heat removal through reactor vessel wall. For this option, acceptable reactor power level is limited not only by reactor vessel size, but also by RVACS capacity.*
- In the first case, modular SFR is practically reduced copy of large sized SFR: a) with decreased power due to limited reactor vessel size and b) with the same expensive DHRS, which requires significant volume of reactor building and operational maintenance. This approach seems to be unpromising, as it makes difficult to achieve economic indicators corresponding to large sized SFR, basing on the following considerations:

Decay heat removal system (2)

- *it does not allow to simplify safety systems and reduce the list of expensive equipment manufactured;*
- *it requires additional volumes of the reactor building for DHRS placement, its special installation on site and maintenance during power unit operation.*

- It is more preferable and promising to refuse from expensive DHRS by means of application of simple and reliable decay heat removal systems through walls of reactor vessel, pipelines and equipment of the secondary circuit. It can significantly reduce the amount of capital costs for construction of DHRS, operational cost for its maintenance, reduce volume of the reactor building, as well as decrease probability of severe BDBAs caused by DHRS failure, which may require significant costs for elimination of their consequences.

Localizing safety system (1)

- In SFR, localization functions are performed by sodium systems and equipment, including reactor vessel, guard vessel, as well as gas communications of the primary circuit, containment, sodium fire extinguishing systems, including passive fire extinguishing ones, emergency ventilation systems. The performance of localizing functions in modular SFR is provided in the same way as in large sized SFR and does not have any specific features. Failure to perform localizing functions leads either to power unit outage or to occurrence of beyond-design basis accidents. And consequences for modular SFR and large sized one are approximately the same.
- Failure to perform localizing functions is mainly caused by breakdown of integrity of localizing systems, in particular, sodium systems. In this respect, probability of such events in modular SFR is lower than in large sized SFR. This is due to the following circumstances:

Localizing safety system (2)

- *probability of breakdown of integrity of sodium and gas communications, guard vessel, containment elements is directly proportional to their surface, which is less in modular SFR than in large sized one;*
- *quality of manufacturing and control of modular SFR equipment in factory conditions is higher than that of large sized SFR equipment in site conditions, therefore, probability of its failure in modular SFR is lower than in large sized one.*

- Impact of failures in localizing systems on economic performance of power unit is realized through costs associated with elimination of consequences of accidents resulting from these failures.

Severe beyond-design basis accidents (1)

- Until now, consequences of such beyond-design basis accidents, as a rule, were not taken into account when evaluating economic performance of power units due to low probability of their implementation. However, experience of already occurred severe accidents shows that probability of practical occurrence of such accidents increases in conditions of a large-scale nuclear power development accompanied with a significant growth of power units number, requiring large financial costs to eliminate accident consequences even in case of occurring single accident. Accordingly, this can lead to a noticeable increase in cost of operation of each power unit on average.

Severe beyond-design basis accidents (2)

- In this regard, it is advisable to carry out economic assessments for nuclear power facilities, taking into account risk-informed factors associated with elimination of consequences of possible severe beyond-design basis accidents. Namely, it is proposed to include in the methodology for calculating specific cost of electricity of power unit a component of anticipated cost for eliminating consequences of severe beyond-design basis accidents, taking into account possible probability of their occurrence. This component can be included in cost of electricity as insurance premiums.

Method for accounting of possible BDBA consequences in cost of electricity

Specific cost of electricity under normal operation conditions of the power unit is calculated according to formula:

$$LUEC_0 = \frac{S_\Sigma + S_D}{Q_\Sigma} = \frac{(S_0 + D_0)\cdot N}{W_0 \cdot DLT \cdot LF \cdot 8760 \cdot N} = \frac{S_0 + D_0}{W_0 \cdot DLT \cdot LF \cdot 8760}$$

It is assumed that BDBA occurs in the middle of the design lifetime of emergency power unit. Taking into account cost of eliminating possible consequences of severe BDBA and losses due to reduced electricity production caused by premature decommissioning of emergency power unit, the expression for specific cost of electricity is written in the following form:

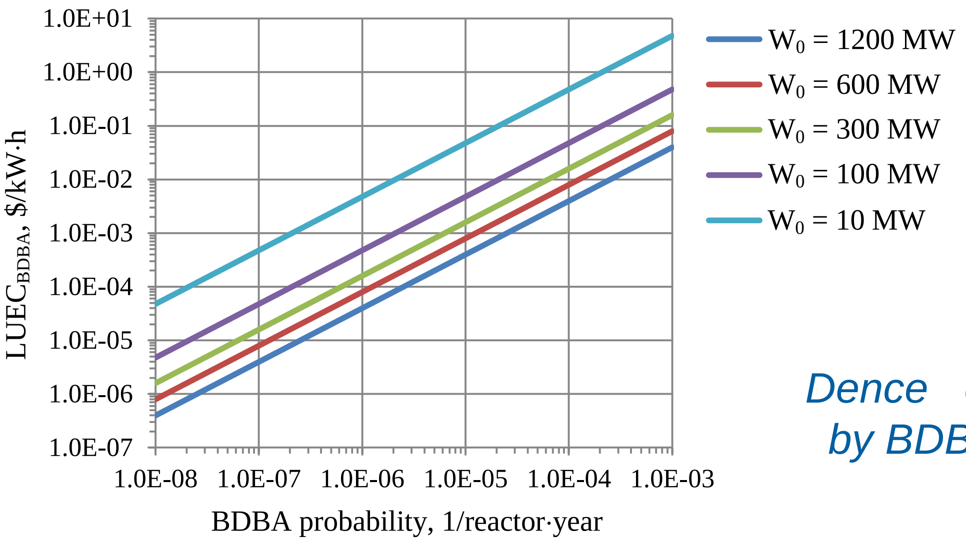
$$LUEC_{\text{mod}} = \frac{LUEC_0}{\left(1 - \frac{DLT}{2}\cdot\sum_i P_{BDBAi}\right)} - \frac{D_0 \cdot DLT \cdot \sum_{i=1}^{M} P_{BDBAi}}{Q_0 \cdot \left(1 - \frac{DLT}{2}\cdot\sum_{i=1}^{M} P_{BDBAi}\right)} + \frac{DLT \cdot \sum_{i=1}^{M} P_{BDBAi}\cdot C_{BDBAi}}{Q_0 \cdot \left(1 - \frac{DLT}{2}\cdot\sum_{i=1}^{M} P_{BDBAi}\right)}$$

Since $\sum_{i=1}^{M} P_{BDBAi}$ <<1

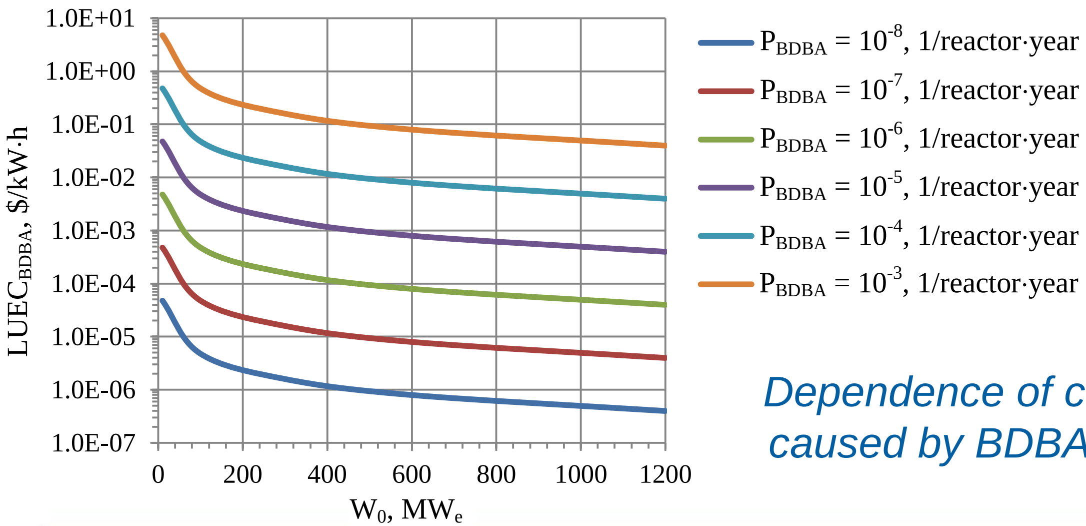
$$LUEC_{\text{mod}} \approx LUEC_0 + \frac{DLT \cdot \sum_{i=1}^{M} P_{BDBAi}\cdot C_{BDBAi}}{Q_0} = LUEC_0 + LUEC_{BDBA}$$

where $$LUEC_{BDBA} = \frac{\sum_{i=1}^{M} P_{BDBAi}\cdot C_{BDBAi}}{W_0 \cdot LF \cdot 8760}$$

Analysis of impact of BDBA conditions on specific cost of electricity



Dependence of
Dence component of specific cost of electricity caused by BDBDBA influence on probability of its occurrence



Dependence of component of specific cost of electricity caused by BDBA influence on nominal electrical power of the power unit

Recommendations on ways of improvement of modular SFR (1)

- One of the most effective measures to improve economic performance of modular SFR is to increase as much as possible its rated thermal and electrical power, while remaining within framework of the modular concept, based on factory manufacture of reactor equipment. The increase of power of modular reactor helps to reduce specific capital cost per unit of installed power of the facility, as well as reduce specific cost of electricity.

- A more preferable and promising option is the system of decay heat removal through the wall of reactor vessel RVACS, considerations in favor of which are expressed in section devoted to description of DHRS for modular SFR. The conducted researches testify to significant potential of this system, the capacity of which due to optimization of width of the gap between guard vessel and reactor silo, increase of heat transfer surface to air and height of exhaust chimneys can provide a safe heat sink for modular reactors with a rated thermal capacity of up to 1000 MW.

Recommendations on ways of improvement of modular SFR (2)

- The influence of severe BDBAs on value of specific cost of electricity becomes insignificant with probability of BDBA occurrence in modular SFR lying in range of $4 \cdot 10^{-8} – 1 \cdot 10^{-6}$ 1/reactor·year depending on rated power of the reactor unit. Further reduction of probability of BDBA occurrence does not lead to any significant reduction in specific cost of electricity. At the same time, it is important that simplification and reduction of safety systems do not lead to an increase in probability of BDBA occurrence. For a more accurate calculation of specific cost of electricity, special attention should be paid to ensuring correct data on probability of occurrence of possible BDBAs and on cost of eliminating their consequences.

CONCLUSION (1/2)

- The report analyzes how enhancement of safety systems and characteristics of modular SFR can improve its economic performance in relation to large sized SFR. Specific cost of electricity, which takes into account all other economic characteristics, such as metal consumption, capital cost, fuel cost and personnel cost, construction time, etc., is chosen as universal indicator for comparison of economic indicators of modular and large sized SFR.

- The method is developed to take into account risk-informed factors associated with elimination of possible severe BDBA consequences in specific cost of electricity. Calculations done by this method show that contribution to specific cost of electricity of component caused by possible expenses for eliminating BDBA consequences is negligible at the range of probability of BDBA occurrence in modular SFR equal to $4 \cdot 10^{-8} – 1 \cdot 10^{-6}$ 1/reactor·year depending on rated power of the reactor unit.

CONCLUSION (2/2)

- It is shown that one of the most promising measures to improve economic performance of modular SFR is transition from an expensive and complex decay heat removal system, which is used in large sized SFR, to a simple system of passive decay heat removal through the reactor vessel wall, as well as to raising nominal reactor power by increasing capacity of this DHRS.

- The analysis shows impossibility of reaching the same economic indicators for modular SFR as for large SFR only by implementing safety measures, in particular by simplifying and improving safety systems and characteristics of modular SFR.

- However, improving safety characteristics of modular SFR in combination with measures that take its advantage due to factory manufacturing principle can create good conditions for closing the gap in economic performance between modular and large sized SFR. In this regard, it is necessary to compare economic indicators for specific SFR designs, taking into account the whole complex of their characteristics.

Thank you
for your attention !