Innovations and Safety Ensuring in WWERs on the Base of Collaboration on the National and International Levels

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Contents

1. Examples of enhanced innovative analyses of safety parameters in **calculations** and **measurements**
   1.1 DECs modeling by up-to-date BE-codes developed in collaboration in Russia and abroad
   1.2 Innovative measurement of coolant mixing in **collaboration** with “Bushehr” NPP

2. Achievement of reasonable **balance** between **efficiency** and **safety**, generally at WWER’s nuclear fuel’s innovations
The innovations are motivated by an increase in competitiveness but create challenges for the safety. Retention and even increase in safety level when power uprating and other innovations is a complex problem. It may be resolved on the basis of collaboration.

Here are presented some examples - enhanced innovative safety analyses for the DECs modeling by up-to-date BE-codes (SAPFIR, KORSAR/GP, MCU, MCNP), developed by the different organizations (Kurchatov institute, NITI (Sosnovy Bor, Russia), Los Alamos National Lab.).

These are also example of the innovation measurements of coolant mixing in the collaboration with “Bushehr” NPP – (patent of RF №2503070 received by OKB GP in December 2013 y.)
As a result collaborations on international level (IAEA, EUR and others) the innovations are also implemented into the ideology of safety substantiation. This relates to the amendment of knowledge and the removal of excessive conservatism. It concerns to the statistical approaches (BEPU) and also to the deterministic conservative approach which is a first-priority till nowadays.

The presence of the reasonable balance between the effectiveness, reliability and safety in the innovations of nuclear fuel of WWERs and PWRs is intensified also by the processes of competition and inter-penetration of the producers of fuel for the opposite market (Westinghouse FAs for the WWERs and Russian producer of FAs for PWRs).
OKB GIDROPRESS is the General Designer of WWER type of Reactor installations.

OKB GIDROPRESS intensively collaborates on innovations with many organizations: NRC Kurchatov Institute, TVEL, Rosenergoatom, VNIINM, NITI, MSZ, NZHK, Rostechnadzor, OKBM, MEPhI, NPPs, IAEA, NEA, AER and other organizations in Russia and abroad.
So it relates to Topic 1: **Driving forces of collaboration on innovations**, namely (from TOR for this DF9):

- Examples of successful nuclear technology development when the required levels of effort and knowledge were available **only through the collaboration** of different specialized parties;

- Motivation for collaboration: cost savings, enhanced assurance for regulators, beneficial outcomes for all parties);

- Examples of the actual impact of the collaboration on the safety and economic of NES.
Precision $K_{\text{eff}}$ calculations by Monte-Carlo (MCU, MCNP)
Emergency Water inside

Steel

FA

FA

Wood

Air outside

Concrete floor

Multideck arrangement of transport containers for two fresh FAs

Precision $K_{eff}$ calculations by Monte-Carlo (MCU, MCNP)
Deborated slug (i.e. some volume of water without absorber CB=0) may be formed in of circulation loops. **First RCP start-up** is the most dangerous situation. Accelerated slug enters into the core and may bring it into the **above-criticality with dangerous neutron splash**. Discharged energy may disrupt the fuel rods.

However the **reality is better** due to the coolant **mixing**. At the core enter there is a coolant with CB **more than zero**.
Russian NPPs WWER-1000 were modernized recently with increasing: campaign (till 18 month), power (till 104%), fuel length (by 5+10=15cm) and Non-Overlapping (NoCR) of CRs and fuel. All these aspects worsen the accident with Heterogeneous Dilution (deborated SLUG).
Sharp decrease but $CB_{\text{min}}$ in Slug is not Zero!!

Deborated slug

Δt~3 s

Boron Concentration, g/kg
Local Power-Linear Heat Rate, W/cm
100-200 Nominals

Deborated slug

half-width $\Delta t \sim 20-30$ ms

Total Power, %Nnom 2-5 Nominals
Reactivity DECs with Cooling (BEPU)

Core Power (Nt) and Power by 4 core quadrants (Pow_sect_i, i=1,…,4) for 3 Phases of MSLB
Reactivity DECs with Cooling (BEPU)

- **Integral power, %**
  - Up to 40%Nom

- **Local power W/cm**
  - Up to Nominal

- **Non-positive reactivity**

- **Reactivity, $\beta_{eff}$**

- **DNBR, rel.un.**
  - No Crisis

5 Nominals
Coolant Mixing

Use of Emergency Boron System (TW) for Coolant Mixing Studies at the Bushehr NPP

By effect of TW system on Power Distribution it was obtained good information about Coolant Mixing. Besides it was revealed the good sensitivity of systems of neutron and thermal monitoring.

This method is extremely cheap – in fact Cost=Zero. But measurements on the working Units gives a very useful and proper knowledge.
54 NTMC (SPND+TC) in FAs of the “Bushehr” core.

SPND – 54 x 7 pcs. (by height).
Four Circulation Loops and six IKs around the WWER-1000 core
On the base of neutron signals **SPND (KV)**

Coolant Mixing

Local mixing coefficients when **TW1** works

Loop1
On the base of TC signals (DT)

Coolant Mixing

Local mixing coefficients when TW1 works
Tests by old and new methods have been performed on the “Bushehr” NPP. **New method** gives **larger** parameters than **Old** one:

- about $25-30^\circ$ **larger** swirls;
- **1.5** times **larger** shares of flow rate coming from each loop into the adjacent (CCW) loop.
Fuel efficiency in WWERs has been increased during last 20 years particularly due to:

- replacement of steel elements in active part of FAs by Zr elements;

- transition from two-years fuel cycle to three, and then four-year cycle, and

- reduction of lateral neutron leakage (L3P). It promoted also the collateral increase the RPV life time and increase of EP effectiveness.
However there is a competition in safety and economical parameters between different variants. Any implemented improvement has not only the positive influence but also the negative one.

For example the very favorable implementation of L3P loading scheme leads also to some disadvantages in safety – worsening of Power Peaking Factor (Kq) and Temperature Coefficient of Reactivity (TCR).

Another example is a competition between strategies of frequent refueling (reactor campaign 6-12 months with maximal Burn-up) and seldom ones (reactor campaign 18-24 months with maximal Load Factor).
Burnup vs Cycle Length for different enrichments and quantities of fresh FAs for WWER-1200
Modern fuel cycles are able to satisfy the main requirements of Russian and foreign customers.

In the short term characteristics of fuel cycles can be improved by use of new uranium high-capacity FA of the fourth generation.

In the long run the high enriched fuel with the erbium oxide integrated in each fuel rod of FA is reasonable to use. It will further improve the fuel usage efficiency of an 18-24month fuel cycle.
The following innovative measures implemented on the basis of collaboration will help to improve economy and to maintain the necessary level of safety:

- Evolution of safety methodology to BE-approach and BE-codes,
- The coupled simulation of 3D effects in the link NF/TG/HD,
- Harmonization of DSA and PSA,
- Risk-Informed Approach to decision making by the optimum balance of safety and efficiency and
- Optimization of NTD.
Thanks for your attention