Answers to Questions Raised during the IAEA Passive BWR Simulator Webinar

1. **Are the mathematical models described in manuals? Thanks – IAEA Simulators.**

   For the Passive BWR Simulator, the mathematical dynamic models are described at high level – modelling structure and fundamental equations in the Simulator Manual.

   Most of the IAEA simulators are available with a well-defined theory, user and exercise manuals. The theory manual usually provided details of all the physical as well as mathematical models used to simulate a system. Control logics are also well defined to provide user a better understanding of how the system responds depending on the state of the plant.

2. **ACR-700 was scrapped more than 10 years ago, why designing simulator for the non-existing reactor?**

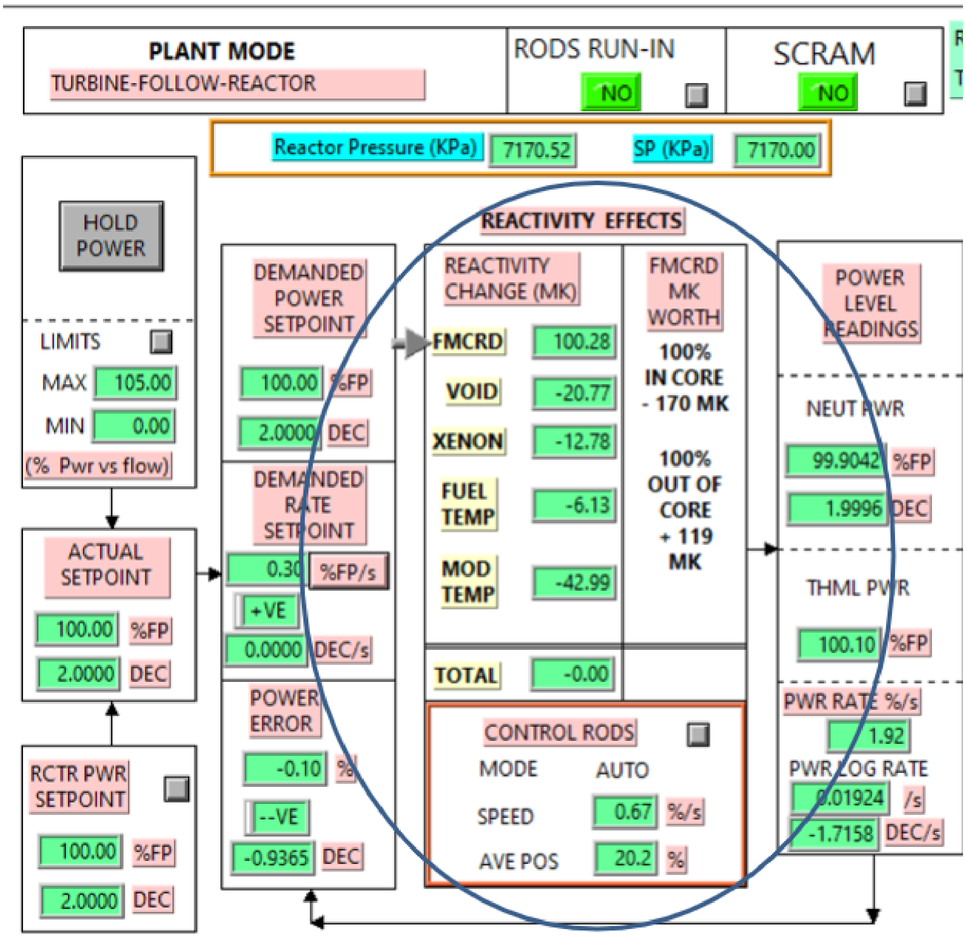
   The ACR-700 Simulator was developed for the IAEA in 2011, because at that time, Atomic Energy of Canada Limited (AECL), the CANDU technology developer, had developed the ACR-700 (Advanced CANDU Reactor-700) as the next generation CANDU with evolutionary design features of light water coolant, heavy water moderator, and the use of slightly enriched uranium fuel (2.1 % wt U-235 in 42 pins of the fuel bundle). From CANDU technology evolution perspective, ACR-700 is a new generation PHWR, although it was not deployed. Therefore, from “learning the new generation nuclear technology” perspective, the ACR-700 educational simulator provides an advanced CANDU technology learning tool for interested nuclear engineers.

3. **18% mass steam rate means over 70-80% of volume steam rate. After shutdown a positive reactivity will be inserted due to decreasing steam rate (until coolant flow rate is decreased). How long does this transient take and if recriticality is expected?**

   Subject to the presenter’s interpretation, the question is re-worded below so the audience may get a better understanding of the question:

   “Given the coolant exit quality is 18 % at 100 % full power, representing substantial negative void reactivity. After reactor scram, steam rate is decreasing, hence void density is decreased, as a result, this will result in positive reactivity change due to less void, until core flow is decreased. How long this transient will take? Is there any chance for reactor recriticality?”

The reactivity effects at 100 % full power are shown below (simulator assumptions)



Note at 100 % full power, the void reactivity with 18 % quality at core exit is –20.77 mk as noted above.

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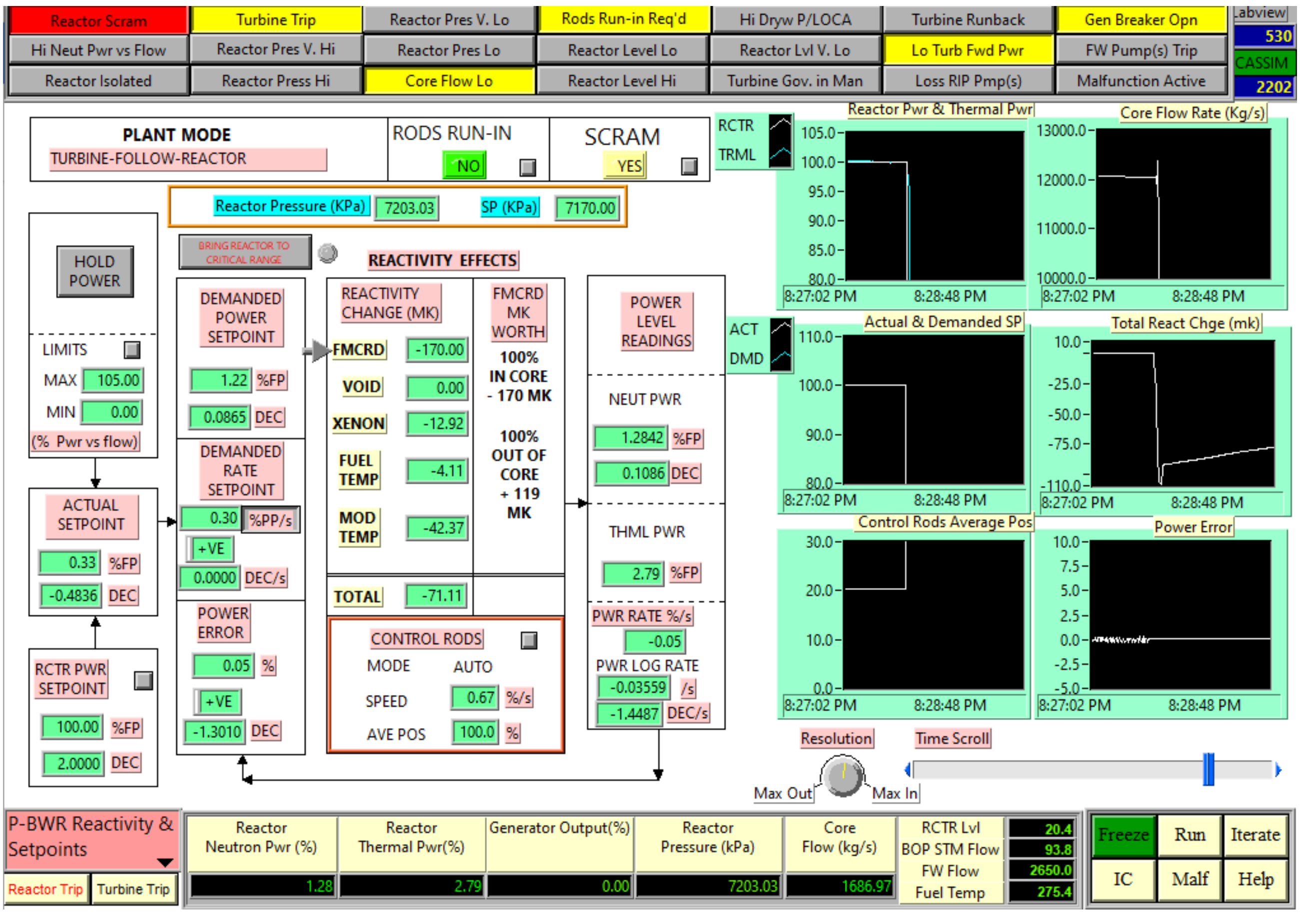
After reactor scram for 2.5 minutes, see the snapshot below regarding the change of reactivity effects. Notably the void reactivity is changed from –20 mk to 0 mk,



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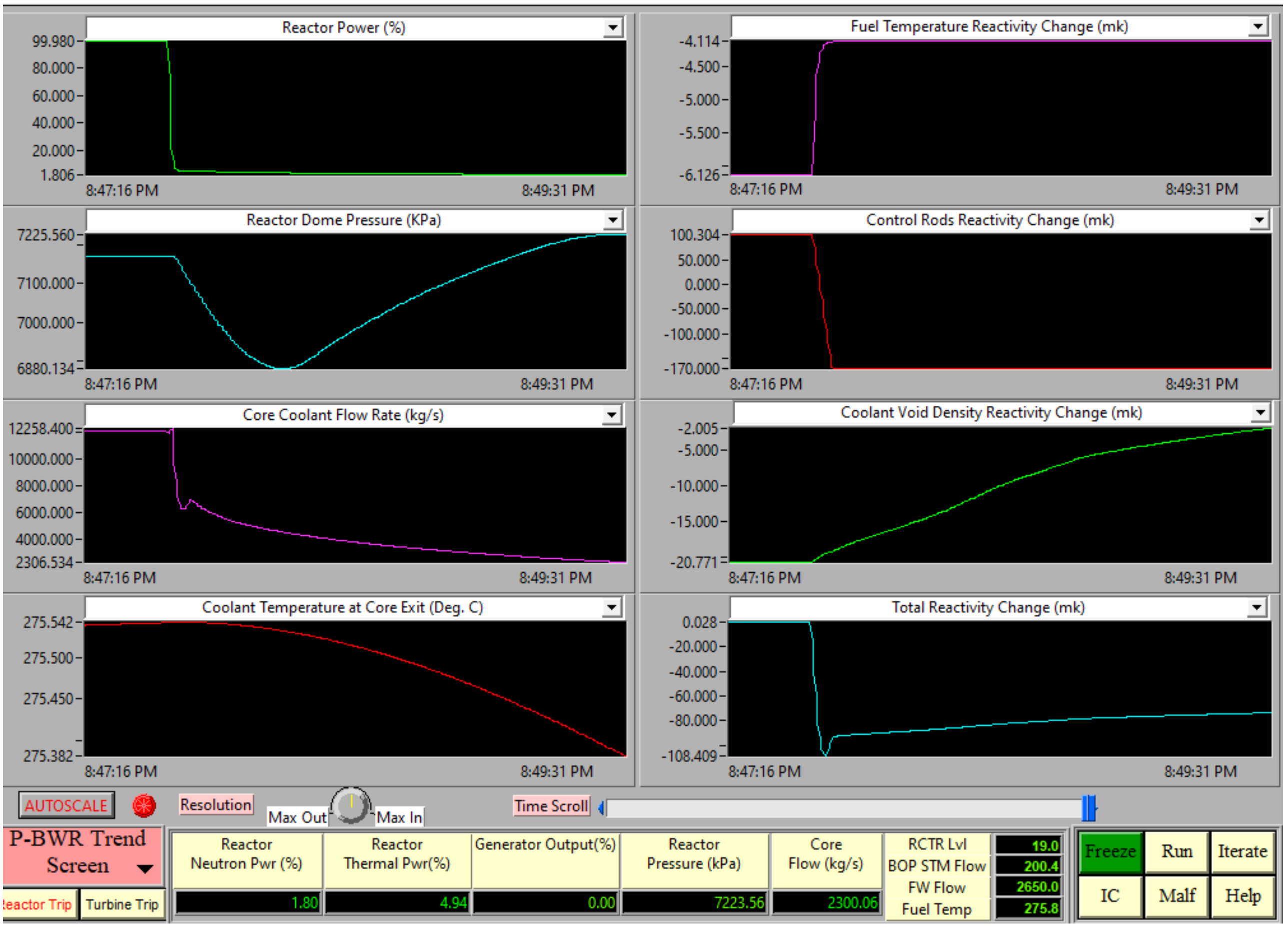
Below are the detailed time trends for the various parameters after reactor scram for 2.5 minutes.



- Control rods are fully inserted, providing –170mk of negative reactivity;
- Core coolant flow drops from 12258 kg/s to 6000 kg/s rapidly and then gradually decreasing to 2306 kg/s;
- Void reactivity has ramped up from –20 mk to -2 mk and keeps decreasing to 0 mk;
- On the bottom right, the trend for total reactivity change delta K (mk) drops from 0 mk to –108 mk at scram, and then after that, the delta K is gradually increasing to steady level of –71 mk on account of void volume decreasing due to decreasing steam rate, until void reactivity becomes 0 mk.

In answering the questions:

- It takes about 2.4 minutes for core flow to get to the lowest flow value ;
- 2.5 minutes after reactor scram, delta K is at – 71 mk. There is sufficient negative reactivity in the core to guarantee reactor shutdown state. Hence there is no chance for reactor re-criticality.
- In addition, there is a Standby Liquid Control System (SLCS) which can inject boron to the core to ensure long term guarantee shutdown, if required.
- One cautionary note: all the mk values and transients discussed above are strictly Passive NWR Simulator's assumptions. The simulator developer does not have public domain information on ESBWR design data for reactivity effects and for this transient.

4. **What is the long-term reactivity management mechanism for the design? by poison concentration or control rod withdrawal over time?**

   The ESBWR reactivity control is mainly from the movement of fine motion control rods (FMCRD). As mentioned in the presentation, variable feedwater temperature control has been added to provide a second means of reactivity control in addition to the fine motion control rod drives. But this was not implemented for the Passive BWR simulator. Instead, flow control in accordance with the power –flow map is used in the Passive BWR Simulator to provide secondary reactivity control by varying feedwater flow to change the void density, in accordance with the power-flow map requirement.

5. **Do you use separate Doppler and fuel temperature coefficient of reactivity or they are combined?**

   It is the same. The Doppler reactivity coefficient is the change in reactivity due to a change in the temperature of the fuel. As it is well known, this change results from the broadening of the resonance absorption cross sections as the temperature increases. At beginning of life, the Doppler contribution is primarily due to U-238; as the exposure increases the Pu-240 build-up contributes to the Doppler coefficient. The Doppler reactivity coefficient provides instantaneous reactivity feedback to any rise in fuel temperature, on either a local or gross basis.

6. **Is this ESBWR using a flux mapping neutron detector system?**

   Yes it uses sophisticated neutron monitoring system, see ESBWR Plant General Description on Neutron Monitoring System on page 6-10:

   ESBWR_General Description Book.pdf (gepower.com)

7. **FMCRDs why the term "Fine Motion" is added with control rods?**

   The term fine motion for the FMCRD means that, during normal reactor power regulation, the control rods are controlled by an electric step motor which can provide fine motion of the control rods in small millimeters step.

8. **Overall, does the design of the ESBWR/BWRX300 have a positive void coefficient or a negative void coefficient as it relates to the coolant temperature and pressure?**

   As presented in the Webinar:

   The Passive BWR Reactor Neutronic data used for the Simulator

Passive BWR Reactor Neutronics Data – Only used for Simulator	
Reactivity Coefficients (nominal values; actual value vary with temperature). Note: Core fuel burnup reactivity change is not simulated.	Source: US NRC BWR Training Manual (public domain)
Moderator Void Coefficient (dK/K/% voids)	- 1 x 10-3; ~ - 1 mk/% voids or –100 PCM/% voids
Moderator Temperature Coefficient (dK/K/deg C)	- 1.8 x 10-4; ~ - 0.18 mk/deg C or – 18 PCM/deg C
Fuel Temperature Coefficient (dK/K/deg C)	- 1.8 x 10-5 ~ - 0.018 mk/deg C or – 1.8 PCM/deg C

   All reactivity coefficients: void, coolant temperature, fuel temperature for BWR are **strongly negative** as shown above.

9. **Can you please explain a little bit more about the negative reactivity associated with the Gadolinium (Gd) in the fuel? Yes, some isotopes of Gd do have a high cross-section and they do burn-up rapidly as the neutron power increases.**

   Burnable absorber, in the form of gadolinia, is distributed in selected rods of the fuel assemblies. It is used for reactivity control during the early portion of each cycle. The Gd2O2, is distributed axially in the bundle to improve the axial power distribution. One of the main characteristics of operating with a highly self-shielded burnable absorber is the little need to move control rods as the cycle progresses since the reactivity effect of conversion of the gadolinium isotopes can be made to very nearly match the depletion effect of the fissile isotopes.

For details, see page 6-10 of ESBWR_General Description Book.pdf (gepower.com)

Below is the excerpt:

Reactivity Control

Reactor shutdown control in BWRs is assured through the combined use of the control rods and burnable poison in the fuel. Only a few materials have nuclear cross sections that are suitable for burnable poisons. An ideal burnable poison must be essentially depleted in one operating cycle so that no residual poison exists to penalize the cycle length. It is also desirable that the positive reactivity from poison burnup match the almost linear decrease in fuel reactivity from fission-product buildup and U-235 depletion. A self-shielded burnable poison consisting of gadolinium(III) oxide (Gd2O3), called gadolinia, dispersed in selected fuel rods in each fuel assembly provides the desired characteristics. The gadolinia concentration is selected such that the poison is essentially depleted during the operating cycle. Gadolinia has been used in BWRs since the early 1970's, and has proven to be an effective and efficient burnable poison. In addition to its use for reactivity control, gadolinia is also used to improve axial power distributions by axial zoning of the burnable poison concentration.

The core is designed so that adequate shutdown capability is available at all times. To permit margin for credible reactivity changes, the combination of control rods and burnable poison has the capability to shut down the core with the maximum worth control rod pair fully withdrawn at any time during the fuel cycle. This capacity is experimentally demonstrated when reactivity alternations are made to the reactor core, such as during the initial core startup, and during each startup after a refueling outage.