Development of Simulator for Materials Testing Reactors  
– Model Overview –

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ABSTRACT

The development of real-time simulators for power plants has been exceptional the last decade. With more powerful processing capacity and lower production costs of computers, mathematical models are allowed to run with shorter time step and with finer element structure. Therefore it is possible today to run engineering code in real time with non-compromising physical models.

With this advancement of technology in mind, a simulator for material testing reactors has been developed by GSE Power Systems, Itochu Techno-solutions Corporation for Japan Atomic Energy Agency, to be utilized for human resource development. The simulator is designed based on the JMTR (Japan Materials Testing Reactor); JMTR is a 50 MW thermal, light water moderated, cooled tank type testing reactor. The simulator is designed as a full scope one built on the GSE SimExec™ simulator environment.

The reactor core is modeled with REMARK™, in which a 3-dimensional, 4-energy group, time dependent, diffusion theory model is applied. Radially, the simulator has 236 assemblies with 984 nodes. 116 radial nodes simulate 24 fuel assemblies and 5 control rods with fuel follower. Axially, the REMARK™ model consists of 20 nodes. Included in the simulator is the dynamics of reactivity change due to insertion or extraction of irradiation facility.

The thermo-hydraulic properties in the reactor vessel are modeled using RELAP5-HD™, which is the real-time version of the RELAP5-3D code developed by the Idaho National Laboratory. The model consists of 43 1-dimensional nodes. The core is modeled with 5 thermo-hydraulic cooling channels (THCC) and one by-pass channel (BPC). These channels are subdivided into three axial volumes.
REMARK™ interacts with the RELAP5-HD™ thermal hydraulic model by providing power to the moderator. The RELAP5-HD™ model, in return, provides thermal hydraulic feedback to the REMARK™ model. This enables for an accurate calculation of neutron dynamics and reactivity change.

For the primary and secondary cooling loops, main heat exchangers, purification system and cooling towers, the 2-phase, 6-equation matrix solution modeling tool JTopmeret™ is used. The electric distribution is simulated using JElectric™ and allows for component wise, or total, black-out simulation. In the primary cooling loop it is also possible to initiate a LOCA scenario.

To calculate the heat generation in the 3-dimensional geometric structure of the irradiation equipment, the PDE (Partial Differential Equation) solving code TRUMP has been converted to run under SimExec™ in real-time.

All of the plant equipment is simulated individually with generic components. Each component has several generic malfunctions built-in, which permits for thousands of different malfunctions or accident set-ups.

The hardware panels are partially emulated with softpanel pictures done in JDesigner™. The JMTR’s DCS (Distributed Control System) MMI (Man-Machine Interface) pictures are fully emulated with the same tool.

All of the reactor control relays and DCS control logics are simulated in JControl™. The high fidelity level of modern simulators is not only a valuable tool for human resource training, but also an analysis tool for safety in normal/transient/accident conditions of materials testing reactors.

1. Introduction

Japan Materials Testing Reactor (JMTR) is a 50 MW thermal, light water moderated, cooled tank type test reactor owned by the Japanese Atomic Energy Agency (JAEA). The JMTR was constructed in 1968 in Oarai, Japan, and refurbished from 2007 to 2011. Reactor components were replaced, new irradiation equipment was added and a DCS was installed to control and monitor the cooling system and other systems.

The simulator for materials testing reactors based on the JMTR was commissioned in order to extend the modernization of JMTR and to improve its training possibilities.

The mathematical, real-time model of the simulator is built from several different tools depending on what physical process is to be simulated. The reactor core neutron dynamics is modeled with REMARK™. Since the thermal-hydraulics in the reactor core is of great importance for the neutron dynamics feedback loop, the RELAP5-HD™ was chosen as the in-core modeling tool. Outside the reactor, JTopmeret is used for the thermo-hydraulics in the primary and secondary cooling loops. JElectric is used to model the power supply system for all equipment and JControl is used to emulate the control and logics (C&L) of the DCS and the reactor relay C&L.

All of the simulator models are executed on the SimExec™ simulator platform. This provides powerful simulator control and gives functionalities such as: saving initial conditions (IC’s), re-initialization of simulator state, run/freeze of simulator and backtrack, among many other possibilities.

2. Reactor Core Neutron Dynamics Model

To calculate and model the core dynamics, control rods and nuclear instrumentation, we have used the REMARK model tool. REMARK is a 3-dimensional, time dependent, diffusion theory
model. For this project the REMARK model was modified to use a 4-energy group model. The core model nodalization consists of 236 assemblies with 984 nodes. 116 radial nodes simulate 24 fuel assemblies and 5 control rods (Figure 1). Axially, the model consists of 20 nodes (Figure 2). The REMARK model is executed with a rate of 4 Hertz.

The REMARK model is interfacing with four other systems as listed below:
1. RELAP5 HD thermal hydraulic model
2. Control Rod Drive Mechanism
3. Nuclear Instrumentation
4. Irradiation facilities

One of the most crucial features of a nuclear core model is the thermal-hydraulic feedback loop. In this case the feedback loop is driven by the boundaries between the REMARK and the RELAP models. The parameters exchanged the models are listed below (Table 1).
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>From Process Model</th>
<th>To Process Model</th>
</tr>
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<tbody>
<tr>
<td>Power</td>
<td>Watts</td>
<td>REMARK</td>
<td>RELAP5 HD</td>
</tr>
<tr>
<td>Liquid Density</td>
<td>g/cm³</td>
<td>RELAP5 HD</td>
<td>REMARK</td>
</tr>
<tr>
<td>Vapor Density</td>
<td>g/cm³</td>
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<td>Liquid Temperature</td>
<td>K</td>
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<td>Vapor Temperature</td>
<td>K</td>
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<tr>
<td>Fuel Temperature</td>
<td>K</td>
<td>RELAP5 HD</td>
<td>REMARK</td>
</tr>
</tbody>
</table>

Table 1. RELAP – REMARK parameter exchange.

The RELAP5-HD is modeling the reactor core as 6 radial channels and 3 axial nodes. RELAP is sending the thermal-hydraulics to the respective axial and radial nodes of the REMARK model. Since there are more REMARK nodes than RELAP nodes in the core, all REMARK nodes that fall under a specific RELAP5 HD core channel have their generated power summed up and sent to the RELAP heat structure nodes (Figure 2).

![RELAP and REMARK axial mapping](image)

Figure 2. Axial mapping of RELAP and REMARK. The arrows indicate the direction of REMARK generated heat.

For the control rods REMARK interacts with the control rod drive mechanism (CRDM). The CRDM specifies the control rod position depending on demand signal, and/or CRDM power...
supply, malfunctions and so on. REMARK then uses the control rod position of a given control rod and determines the new neutronic parameters based upon rod position. Radial rod locations are shown in Figure 1 above. The nodalization of a moving control rod and fuel follower can be found in Figure 2. During the movement of a control rod, the material composition in a computational cell (node) changes dynamically, which requires a dynamic change of the cross sections based on the axial fractions of all material in and out of the node.

The core model calculates flux readings and sends it to the Nuclear Instrumentation models (NI). The measurements are used in the control logics to regulate the CRDM to keep desired power output.

In the core model, 6 Irradiation Facilities (IF) are included:

1. Capsule irradiation facility with temperature control by heater and pressure
2. Capsule irradiation facility with neutron fluence control
3. Capsule irradiation facility (advanced water-chemistry controlled irradiation facility)
4. Power ramp test facility (BOCA/OSF-1 irradiation facility)
5. Hydraulic rabbit irradiation facility
6. OWL-2 irradiation facility

The preconditions for interaction between core and IF’s in the simulator are that nuclear heating, flux and fluence in facilities are given by the core. Then the reactivity to the core is given by fluctuation of materials in the IF’s. Core coolant does not change due to heating in facilities as it is deemed negligible. The radial locations of the IFs in the core are illustrated in Figure 1. When a material specimen is moving axially, the material composition in the node will change dynamically and the cross-sections, based on the axial fractions of all material in and out of the node, changes dynamically.

2. Core Thermo-Hydraulic Model.

One of the key features in a nuclear simulator is the ability to accurately model the void coefficient feedback loop in the core. This is crucial for the core transients that will occur when changing power levels, but also for the unexpected transients for different accident scenarios. For this reason the simulator is using the RELAP5-HD to model the in-core thermal-hydraulics. This is the real-time version of the well proven “best-estimate” code RELAP5-3D. The simulation model is designed by employing a non-equilibrium, non-homogeneous, two-phase flow option. The semi-implicit solution scheme is used to solve the set of equations. Because of the choice of the semi-implicit solution scheme the execution frequency of the RELAP5-HD model has to be at least 40 Hz in order to fulfill the Courant Limit acceptance criteria. In the reactor model an 80Hz calculation frequency is used.

The nodalization of RELAP is divided into two parts, the thermo-hydraulic nodes and the heat structures within RELAP. The thermo-hydraulic model consists of 43 1-dimensional nodes. A schematic picture of the nodalization can be found below (Figure 3).
To more accurately calculate the void coefficient, the nodalization of the thermo-hydraulic cooling channels (THCC) is more refined. We have used five THCC’s and one by-pass channel (BPC). These channels are all subdivided into three axial volumes.

Heat structures are used to represent solid structures such as fuel plates, vessel walls and reflectors, in order to calculate the heat transferred across solid boundary of hydrodynamic volumes. The heat structures, used in the JMTR’s model, are illustrated in Figure 4.

As it is described above, the core consists of five thermal-hydraulic channels (THCC) and one bypass channel (BPC). To these channels a number of heat structures with different functions are attached.
The most important heat structures are the ones representing the heat generation inside the fuel plates and conducting heat from the centers of the fuel plates to the coolant between the plates. The central part of the fuel plate has a symmetry condition while on the surface of the plate you find a hydraulic boundary connected to the THCC volumes. There are 30 elements of heat structures (six per one thermal-hydraulic channel) and in these the heat generated by the neutronics is added (Figure 5).
Moreover, there are heat structures for simulation of heat generation inside the reflectors’ material and heat transfer to the bypass channel (HSBP-02).

The reactor vessel is submerged in a reactor pool. In order to simulate a heat exchange between the coolant inside the reactor vessel and the water in the reactor pool, we have introduced heat structures for the heat flow through the wall of the reactor vessel. The reactor pool is simulated in JTopmeret.

3. Other Simulator Models.
For the coolant loops, purification system and cooling towers, JTopmeret™ was used, a 6-equation, 2-phase thermo-hydraulic modeling tool. JTopmeret has been used in a large number of real-time simulator projects and is a well-proven, robust tool for thermo-hydraulic real-time simulation. This tool relies more on empirical data for modeling but still provides accurate transitions for different events. The coolant loop model calculates the flow, pressure, temperature and so on, of the system depending on the state of plant equipment (pumps, valves, external parameters and so on). It sends this information to the RELAP model via an inlet pressure boundary and receives the reactor outlet flow via a flow boundary. In the primary coolant loop
model a Loss-of-Coolant-Accident (LOCA) is added using a mass flow boundary to drain the primary loop, simulating a leakage.

The secondary coolant loop is transporting the heat to force draft cooling towers which fully simulates the cooling capacity depending on air temperature and air humidity, among other dependencies. This allows for example, changing the outside air properties to change the cooling capacity of the cooling towers for different weather conditions. Moreover, the emergency cooling loop and purification system are fully modeled in JTopmeret.

In the JTopmeret systems, standard equipment (components) such as pumps, valves, check valves, transmitters and so on, are modeled. The components electro-mechanical properties are simulated individually and are generated automatically from a database. Each type of component has a number of default malfunctions built in, so that an instructor can initiate an arbitrary equipment malfunction. This means that a very big number of different accident scenarios can be realized and analyzed with the full scope simulator.

All the reactor control relays and DCS control logics (C&L) are simulated in JControl™ and provide the same regulation and safety logics to the simulator as it does to the real reactor plant.

The electrical system is simulated in JElectric™ and includes the two back-up diesel generators. This enables the user to arbitrarily shut down grid, diesel generators or busses, to simulate local or complete black-outs.

The hardware panels are partially emulated with softpanel pictures done in JDesigner™. The DCS MMI pictures are fully emulated with the same tool.

All of the above mentioned systems run at an execution rate of 40 Hz.

To calculate the heat generation in the 3-dimensional geometric structure of the irradiation equipment, the PDE (Partial Differential Equation) solving code TRUMP has been converted to run under SimExec™ in real-time.


Owing to the recent developments in simulator technology, not only are more refined mathematical models available to more precisely calculate physical phenomena, but also shorter time steps and finer element resolution are further increasing the accuracy of the model. On top of that, better production methods, such as auto generated models from databases, allows for more detailed simulators where no part of the plant has been oversimplified or neglected in the simulator. These improvements give a full scope simulator, which goes beyond being just a training tool for operators. A simulator user can now implement most of the conceivable equipment malfunctions or accidents tests which gives the possibility to analyze the combined process and control logics behavior.