

Modeling and Simulation of In-vessel Core Handling in PFBR Operator Training Simulator

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Abstract—Component handling system is one of the important sub systems of Prototype Fast Breeder Reactor (PFBR) used for fuel handling. Core handling system is again a sub system of component handling system. Core handling system consists of in-vessel and ex-vessel subassembly handling. In-vessel core handling involves transfer arm, large rotatable plug and small rotatable plug operations. Modeling and simulation of in-vessel core handling is a part of development of Prototype Fast Breeder Reactor Operator Training Simulator. This paper deals with simulation and modeling of operations of transfer arm, large rotatable plug and small rotatable plug needed for in-vessel core handling. Process modeling was developed in house using platform independent C++ code with OpenGL (Open Graphics Library). The control logic models and virtual panel were modeled using simulation tool.

Keywords—Animation, Core Handling System, Prototype Fast Breeder Reactor, Simulator

I. INTRODUCTION

THE Prototype Fast Breeder Reactor (PFBR) in India is being constructed at Kalpakkam. It is a pool type, sodium cooled, plutonium-uranium oxide fuelled, reactor with a thermal power of 1250MW and an electrical power output of 500MW [4]. Nuclear Regulatory Commission (NRC) Regulatory Guide 1.149[1], has endorsed ANSI/ANS-3.5, Nuclear Power Plant Simulators for use in Operator Training [2]. According to regulations of Atomic Energy Regulatory Board (AERB), operator need to be trained in Full Scope Replica Simulator before commissioning of any nuclear reactor[3]. Keeping this in mind, Indira Gandhi Center for Atomic Research started the development of training simulator as per International Atomic Energy Agency (IAEA standards) [5] for PFBR. After completion, the training simulator will undergo verification and validation process as per AERB practice. Computer Based Operator Training Simulator for PFBR is a full scope replica type simulator purely consisting of mathematical models [6].

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They represent all the reactor processes in such a way that they derive the dynamic characteristics and behavior of the system. The training simulator of the PFBR consists of simulation and modeling of various sub systems like Neutronics System, primary and Secondary Sodium System, Steam Water System, Core Temperature Monitoring System, Instrumentation & Control System, Electrical System, Safety Grade Decay Heat Removal System and Core Handling System. Remote handling is of prime importance with respect to component handling as all the operations are carried out in such areas where it cannot be manned. Remote handling of core is carried out by specially designed equipments with increased operational reliability. There is a need in PFBR to train the operator with help of Full Scope Replica Simulator to operate the Transfer Arm(TA) and rotatable plugs using the controls provided in handling control room panel and consoles in real time. Hence the simulation and modeling of core handling system is considered challenging.

Core handling system consists of two sub systems In-vessel and Ex-vessel handling. In-vessel handling involves TA, Large Rotatable Plug (LRP) and Small Rotable Plug (SRP) operations. Ex-vessel handling involves huge equipments such as Inclined Fuel Transfer Machine (IFTM), cell transfer machine etc. This paper will address the simulation and modeling of TA, LRP and SRP operations.

External code for in-vessel core handling system has been developed inhouse in collaboration with reactor design groups. The process models are code intensive with 3D animation. 3D models were used in process models for better understanding of operators as adequate viewing is a proven pre requisite for training. Also animating the 3D models are supposed to be superior to static graphics, especially when learning concerns a chain of events in dynamic systems. Animations not only depict objects, but also provide information concerning object changes and their position over time [7]. Operator understanding gets enhanced, with the help of 3D animating models, for example, the opacity is made transparent wherever required and large scale components can be shown by zooming "in" facility [8].

II. PROTOTYPE FAST BREEDER REACTOR

The 500MW Prototype Fast Breeder Reactor (PFBR) has Primary sodium, Secondary sodium and Steam - Water system as the three main systems. The primary sodium system with two pumps and four IHX (Intermediate Heat Exchanger) is contained within the reactor assembly and the secondary sodium system consists of two identical loops each with a sodium pump and four number of Steam Generators (SG). Primary sodium in the pool absorbs heat produced by nuclear fission. Heat is transferred from primary sodium to secondary sodium in Intermediate heat exchanger (IHX). Heat gained by secondary sodium is used to convert feed water in Steam

Generators (SG) into super heated steam to drive Turbo-Generator to produce electricity.

Variable speed sodium pumps are used to circulate primary sodium in the pool and secondary sodium in the IHX & SG.

III. FULL SCOPE REPLICA SIMULATOR

PFBR Operator Training Simulator is a real time full scope, replica type simulator which provides comprehensive training to operators in the PFBR plant operations. PFBR Training Simulator can simulate the steady state and dynamic responses of the plant to operator actions in real-time [9]. The simulator is helpful in training the operators about the process dynamics, operations in normal and abnormal situations, various malfunctions & incidents, plant start-up etc. Full Scope Replica Simulator consists of Process models, Logic models and Panel models. Fig. 1 depicts the simplified block diagram of Full Scope Replica Simulator.

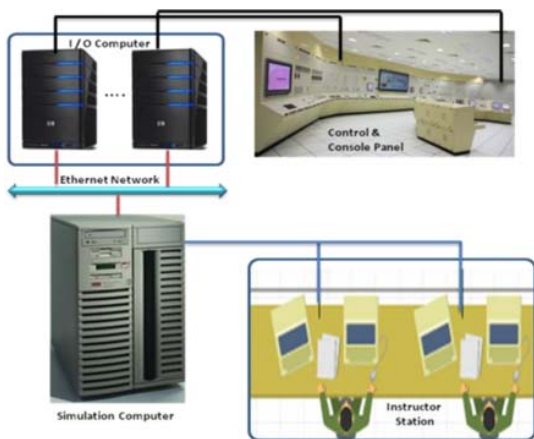


Fig. 1 Full Scope Replica Simulator

IV. METHODOLOGY ADAPTED FOR SYSTEM MODELING

First phase of core handling modeling involves collection of latest design notes, operation notes and drawings such as control panel and console drawings, bill of material (BM)/ general assembly (GA) drawings and annunciation window legend (AWL) drawings of in-vessel core handling system. After requirement gathering with the help of design experts and available documents, simulator modeling is divided up into virtual panel creation, logic modeling and process modeling as shown in Fig. 2.

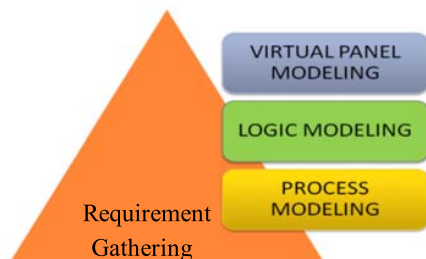


Fig. 2 In-vessel Core Handling Modeling

V. NEED FOR 3D MODELING IN INVESSEL CORE HANDLING SYSTEM

There is a constraint that the operations in in-vessel core handling have to be carried out remotely as the areas have high temperature and radiation. In a conventional system all operations will be captured by CCTV (closed circuit television) camera and fed into the control room for operator action. An extensive study has been made of the human factors in the use of camera capture as the link between an operator and a remote machine. These include the visual perception provided by various CCTV camera positions of the actual systems. But these are found inadequate because it is impossible to capture the full equipments as they are very huge. For example, some equipment is more than 23 meters in height. Also in-vessel core handling system equipments have to operate inside core filled with sodium which is opaque. Some other areas where the operators have to operate are inside fuel cells, water columns etc where there is no visibility or poor visibility. Hence the operator cannot depend on the video capture alone, and has to rely on the various outputs of position sensors, rotational sensors etc for in-vessel core handling operation. 3D animations of the actual process are additional aid for more clarity.

VI. SYSTEM DESCRIPTION

A. Core Handling System

Component handling system is divided into two categories one is core handling and the other is special handling. Core handling involves In-vessel core handling & Ex-Vessel core Handling:

- 1) In-vessel core handling includes transfer of subassemblies within the core. Access to every location over the core is provided with the help of LRP, SRP and TA.
- 2) Ex-Vessel Handling involves subassembly (SA) receipt, inspection, storage, in-vessel transfer, discharge from Main Vessel (MV), washing & storage etc.

SA handled are fuel SA, blanket SA, absorber SA and reflector SA.

Special handling involves huge equipments like IHX, primary sodium pump (PSP), absorber rod drive mechanisms (ARDM), failed fuel identification modules (FFIM), TA and decay heat removal heat exchanger (DHX)[10].

In this paper, in-vessel core handling involving TA, SRP and LRP plugs operations are dealt. TA, SRP and LRP are equipments used for in-vessel core handling. In-vessel core handling includes three types of transfer of subassemblies. Any sub assembly can be transferred into internal storage locations and from internal storage location to IVTP. Also

subassemblies can be transferred from IVTP to desired location in the core. Access to every location of the core is provided with the help of LRP, SRP and TA. LRP and SRP are placed eccentric to each other and TA. Transfer arm is offset type equipment.

It is taken care that at a time only one subassembly is handled in the core. Continuous Neutron monitoring is done during in-vessel core handling operation for safety.

B. Core Structure

The reactor core is made up of subassemblies, arranged in a hexagonal lattice as shown in Fig. 3. Of these, the active core is made up of 181 fuel subassemblies (FSA). There are two enrichment regions in the active core for power flattening. There are 2 rows of radial blanket subassemblies and 12 absorber rods, comprising 9 Control and Safety rods (CSR) and 3 Diverse Safety Rods (DSR) arranged in two rings. Enriched boron carbide is used as the absorber material. The radial core shielding is provided by stainless steel and B4C. B4C is the absorber material inside the absorber rod.



Fig. 3 2D Core Model

C. Operation Mechanism of TA, LRP and SRP

In-Vessel core handling basically means remote handling of all subassemblies available in the PFBR core. They can be accessed with the help of LRP, SRP and TA. Transfer arm consists of guide tube (GT) and Gripper Hoist (GH). The GT encloses the GH. Gripper hoist assembly at the lower end consists of three gripper fingers which enable the TA to hold the SA. The gripper fingers are kept at 120 degree apart to GH main cylinder and will rotate with its centre along the main cylinder axis at 15 degrees. The gripper fingers open to hold the SA and close to release the SA. All subassemblies have unique location identities. Fuel movement chart consists of SA numbers and rotational angles to reach them. Depending on the fuel movement chart the LRP, SRP and TA rotate to position the TA to the desired location for either picking up or releasing the SA. In other words, Positioning of TA to the required core location is by the combined rotation of LRP, SRP and TA. SRP, LRP and TA rotation was modeled with the accuracy as per the design requirements. SRP was enabled to rotate from 0 to 180 degree.

LRP was enabled to rotate from 0 to 360 degree. TA rotation was enabled from 0 to -90 degree and 0 to + 90 degree. Translation of GT and GH was kept 1mm/sec. The 3D Graphical User Interface (GUI) developed is shown in

Fig. 4. The display of remote equipments in operation, their speed of rotation and the time taken for rotation and their angle will be displayed in real time in the GUI. The status of operation also will be changing online depending on the operation.

The completed 3D GUI in-vessel core handling system model includes dialog box modeling. This model mimics the hardware panel and can be considered as soft panel for control.

It contains automatic selection and manual selection features. During automatic sequence selection, the operator has to acknowledge at each step. Clockwise rotation and anticlockwise rotation for SRP, LRP and TA rotation can be selected. Upward and Downward movement selection is also possible for GT translation and GH translation, outward and inward movement is possible for gripper fingers. Apart from soft panel selection the operator can execute the individual steps through physical buttons in hardware panel. For each manual selection, jog and microjog options are provided. Rotation and translation modeling for SRP, LRP, TA was done for manual mode too.

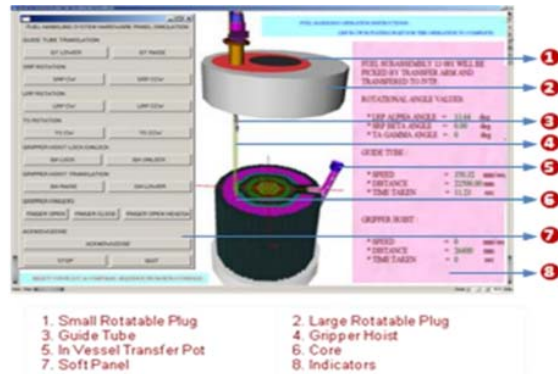


Fig. 4 3D GUI Model

The operator can operate either from panel or console. During commissioning and maintenance the operators can operate from local control centers (LCCs). The operator has two choices computer guided sequence or manual sequence as shown in Fig 5.

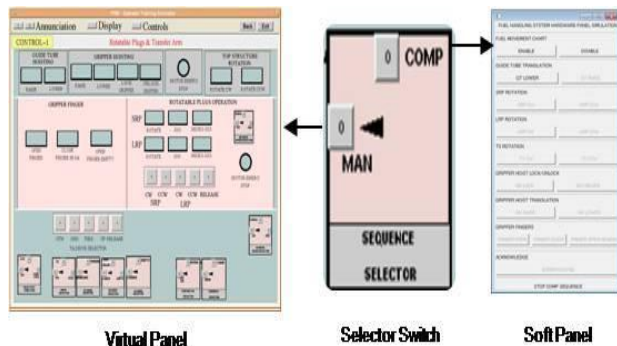


Fig. 5 Operator Choices

Each step will be acknowledged by the operator. The computer guided sequence has a soft panel designed using dialog buttons. The various buttons available are like GT lower / raise, GH lower / raise, SRP rotation clockwise (CW) /counter clockwise (CCW), gripper finger open/close etc. The dialog buttons also have acknowledge and stop buttons. On clicking the fuel movement chart, it will display the subassembly name, their position and also it will indicate which subassembly to be picked or deposited first.

An operator cannot bypass any sequence in computer guided sequence. However, in manual mode the operator can bypass sequence provided the logics are satisfied. For example, in manual mode the operator cannot lower the gripper hoist at any position. The lowering will take place only for pre determined set of three LRP, SRP and TA angles. On manual selection, the operator can execute the individual steps by clicking the control panel/console buttons. For each manual selection, jog and microjog options are provided. Jog accuracy is kept around 1 degree and microjog around 0.5 degrees. If the operator selection is through computer guided sequence, the operation can be stopped any time by clicking the stop button. This button and fuel movement chart display buttons will be enabled throughout the computer guided sequence. The other buttons will be enabled depending on the relevance. For example after clicking the GT button the next button that will be enabled is acknowledge button, following that SRP rotation button etc. This was one of the design requirements to avoid operator action errors. As the process models will be executed in real time, the actions were tested thoroughly. For example, the guide tube will be lowered on clicking either the soft GUI button or hard button in handling control room console/panel. Guide tube will be lowered at the rate specified in the design note. The total time taken for GT to get lowered is 20 minutes. At the end of the guide tube lowering action, speech program are enabled so that it will prompt the operator to acknowledge the action and perform the next operation. The process models contain both the steady state and transient behavior of the TA, SRP and LRP operations. Steady state is the normal operation of the system. Transients such as Guide tube stuck at the reference position, Gripper hoist stuck at the reference position, gripper finger failed to open etc were also modeled. Due to transients, the relevant alarms were enabled and operator was prompted to take the necessary corrective measures. Fuel movement chart is presently designed using text file for ease of use. But as next version platform independent MySQL is planned to be used for storing the data. MySQL is a relational database management system (RDBMS) based on Structured Query Language (SQL).

VII. CODING

The process model of the in-vessel core handling system is as shown in Fig. 5. The code was written using C++ with open GL libraries. The application outline includes C++ headers

and CATIA (Computer Aided Three-Dimensional Interactive Application) models.

The 3D models inside the code were actual models of the equipments developed using CATIA. Some of the models were however also modeled using GUI libraries using triangle strip set and meshes. A simple triangle strip set is illustrated in Fig 6. For modeling any physical geometry the object has to be split into triangles. A triangle 2D mesh will have number of triangles as 3 and number of nodes as 5. Then the triangle index will be a set with $\{2,1,3,0,1,2,2,3,4\}$.

Using this, geometry of the 2D mesh can be defined. Similarly 3D meshes are used for solid modeling and the models can be extruded, beveled for the shapes required using C++ and OpenGL.

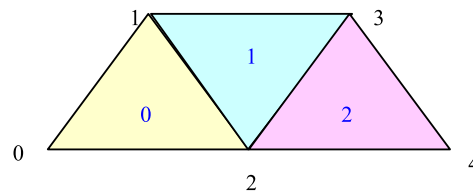


Fig. 6 Triangle strip set -2D Mesh

After including and designing the necessary 3D models, a top level window was created. A user interface for interacting with GUI was also designed. This acted as soft inputs to the system. After initialization of all variables used, OpenGL drawing area and render area were designed so as to create a scene graph. A viewer was also created which contains lights, cameras and interactivity to the scene graph. This viewer is then configured and made visible and event loop is triggered. A module is also written to handle events, engines, multithreading etc. There are five main methods that the rest of the application is built around, they are

```
int initialize();
int GuideTube ();
int GripperHoist();
int GripperFinger ();
int TopStructure ();
```

Based on these methods the rotational sensors and translation sensors were modeled using the inputs as the data received and the sensor type. They were designed using engines such that on soft button click the action takes place by scheduling or unscheduling the event based on demand. For example, GuideTube method will contain three types of engines. Translation mathematical engine will lower the guide tube or raise the guide tube satisfying the logics. Rotational engine models rotational sensors, such that guide will rotate clockwise or anticlockwise based on demand. The generalized flow chart for guide tube is as shown in Fig. 7. The initialize method will initialize all the variables at the start of the program.

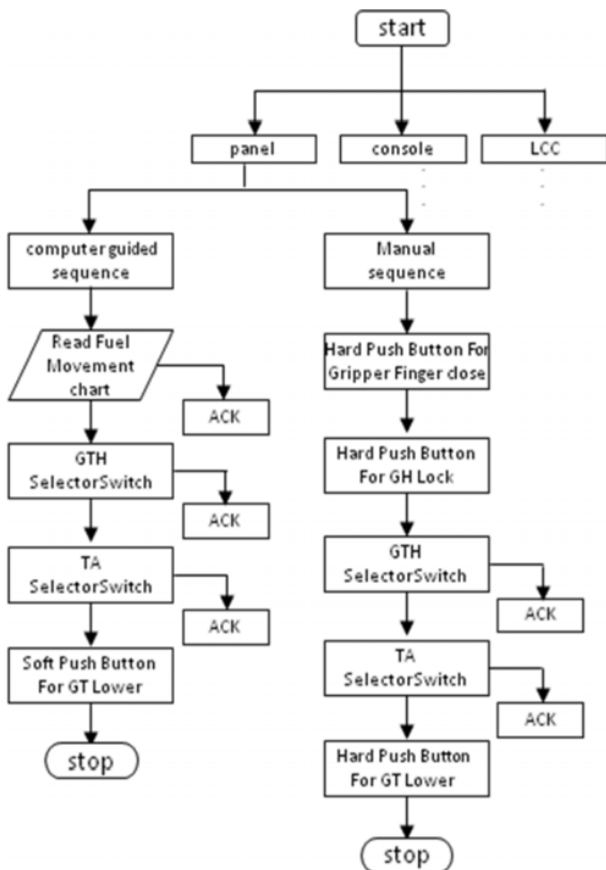


Fig. 7 Flow chart

VIII. ANIMATION CAPABILITIES

A set of specialized C++ classes was used for real time rendering of 3D models. Moreover the program was multithreaded to increase the overall performance. Examiner viewer was used while modeling as this has the ability to spin around the scene. The virtual camera used in the examiner viewer was able to focus the operation at closer angles. The cameras have position and orientation as their inputs to be programmed. Most of the scene graph requires lights to be added, the lights can be configured as directional light which can shine in one direction, spot light which is a cone of light or point light which can shine in all directions. In the render area an event callback is registered so that they can handle events. This callback can then redirect the events to specific routines that the application is based upon. Then event gets processed. For the ease of convenience of the operators the frame rates per second are made to perceive easily for eyes. The models were made animating in real time according to the operator choices, manual mode or computer guided sequence. When the gripper fingers open inside the subassembly to be held, the virtual camera programmed using specialized C++ classes is focused inside the subassembly to see the three gripper finger locked Fig. 8.

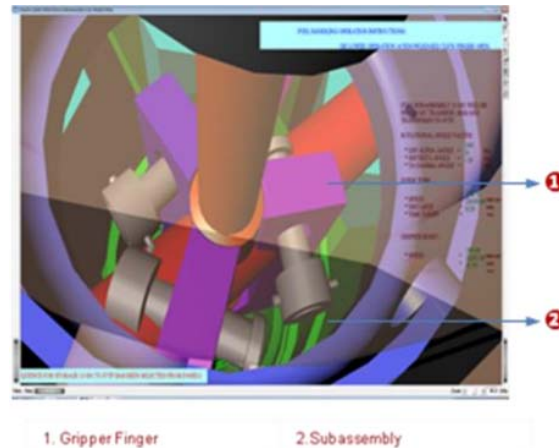


Fig. 8 Gripper finger opening to pick subassembly

Camera zooming and rotation was also done for better viewing and understanding. Camera position will be captured through a field sensor and rotated such that the animating materials are zoomed nearer for better visualization. A scrollbar for message display depending on action, depicting the action being done is developed such that it will educate the operator, what to do and what is being done currently. The Speech Application Programming Interface (SAPI) Software Development Kit (SDK) was installed and voices were setup which will prompt the operator after completion of each steps.

IX. VIRTUAL PANEL

Virtual panels are excellent replacements of hardware panels during initial stage of process model development. The process models are developed and tested extensively using virtual panels. A virtual control panel is just a collection of controls which are graphically represented in 2D screen. They can be operated by button clicks using mouse. Virtual Panel models mimic both plant control and console panels [11]. Virtual panels consist of same layout as that of actual plant. Indicators, Digital recorders, Lamps, Control switches, Annunciation windows etc are represented in virtual panels. The dynamic models drawn in virtual panel changes real time. The virtual panels response with application data. Handling control hardware panels where drawn using simulator software tool. The virtual panel replicating the hardware panel had four control panels and four consoles. Each control and console panel had two display stations each, apart from indicators, selector switches, keys, push buttons etc. One display station was for showing animated 3D GUI and the other was for CCTV display. The first control panel and console was dedicated for the operations of TA, LRP and SRP. The panel also had alarm windows for indicating the critical parameters. If neutronic count went high crossing the threshold, it was indicated by the alarm window turning red

in color. The second control panel /console was for IFTM, third control panel / console was for fresh sub assembly and fourth control panel / console was for spent subassembly respectively.

X. LOGIC MODEL

The control logic schematic of the in-vessel core handling network was modeled using logic model tool available within the simulator environment. The controls and interlocks were modeled using standard libraries like AND gate, OR gate, NOT gate etc. Application specific functional blocks were also created. The logic models were processed as per the set points and thresholds available in the requirement document. The output signals derived using logic models were used for controlling and providing interlocks. Sample logic is shown in Fig. 9.

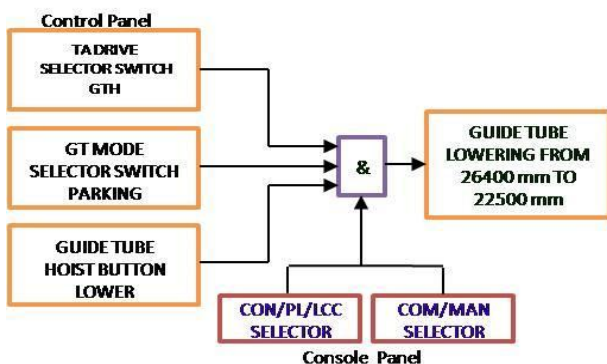


Fig. 9 Logic indicating Guide tube lowering

XI. INTEGRATION AND TESTING

The Process Models are tested independently and then integrated with the simulator and tested thoroughly. The integration with simulator tool is as shown in Fig. 10.

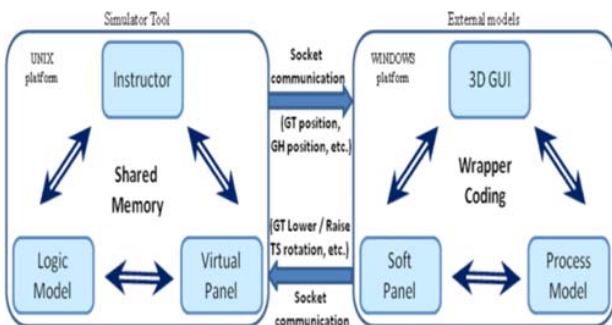


Fig. 10 Integration of Simulator tool with External Models

Here the process networks are linked using socket connection which allows the input / output / feedback signal to flow between the networks [12]. The input and output process parameters are then checked and compared with the actual process parameters. The deviation in simulator output parameters from the actual process parameter are narrowed

down by tuning the network components. After process models are successfully integrated, normal operation or transient loading or malfunction initiation from instructor station is carried out and it is tested for the reflection in the animated GUI with their corresponding behavior verification.

XII. CONCLUSION

Modeling of remote handling system like in-vessel core handling has been introduced in the nuclear simulator so that the operator can be well trained without committing errors. Training simulator is generally aimed at training the operators in main system and their associated plant dynamics. Failure of fuel subassembly due to mal operation of core handling system which could be due to possible human error and has caused major plant shutdown in nuclear industries. There are many other incidents related to core handling system which poses challenges to reduce the operator error. Modeling and simulation of in-vessel core handling system helps in training the operator to encounter such malfunctions, possible errors in handling the system, logic related errors and system related errors etc. The operator are made to get acquainted in handling the system in a smarter way and increase the level of confidence in handling the system especially for handling the in-vessel subassemblies. The operator can be well trained on fuel handling procedures, like adequacy of torque applied while lifting the subassembly, ascertaining the appropriate seating of fuel subassembly, observations and checks like when to start and where to stop etc. The operator reflexes are also tuned so that failure in in-vessel core handling system can be reduced to a larger extent.

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