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Development of First Full Scope Commercial CANDU-6 Fuel Handling Simulator

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Abstract

Unique to CANDU reactors is continuous on-power refueling. In the CANDU-6 design, the fuel bundles are contained within 380 pressure tubes. Fuelling machines, one on either side of the reactor face move on a bridge and carriage system to the appointed channel and fuel under computer control. The fuelling machine is an immensely complicated mechanical device. None of the original Canadian full scope simulators incorporated the interaction of the fuel handling system. Traditionally, the final stages of Fuel Handling Operator qualification utilizes on the job training in a production environment carried out in the station main control room. For the purpose of supporting continual improvement in fuel handling training at the Third Qinshan Nuclear Plant Company (TQNPC), Atlantic Nuclear Services in a joint project with New Brunswick Power, developed the first commercial full scope CANDU-6 Fuel Handling simulator, integrated into the existing TQNPC Full Scope Simulator framework. The TQNPC Fuel Handling simulator is capable of supporting all normal on-power and off-power refuelling procedures as well as other abnormal operating conditions, which will allow training to be conducted, based on the plant specific operating procedures. This paper will discuss its development, the importance of this tool and its advantages over past training practices.

Keywords: Real Time Simulator, Modeling, Fuel Handling, Operations Support, Training

1. Introduction

Event analysis and operational experience indicate that human error is a major contributor to the occurrence of severe accidents in a nuclear power plant [1]. Following the Three Mile Island and Chernobyl disasters, the nuclear industry required plant specific full scope simulators for all nuclear power plants [2]. Control room personnel now receive comprehensive initial and continuing training on plant specific licensed control room simulators [3].

Full scope simulators have clearly demonstrated their value in the training of nuclear power plant personnel [4]. Simulators provide hands-on training that replicates the control room environment and plant response, thereby providing an arena for reinforcing expectations for following process and using event-free tools.

The original CANDU full scope simulators did not incorporate a simulation of the fuel handling system at anything but a cosmetic level. In Canada the drivers for developing CANDU fuel handling simulator were the age demographic of employees, pressures from the Canadian nuclear regulator (CNSC) to raise the bar for the level of fuel handler training, and the possibility that the fuel handling operator position might eventually become a licensed position. In the past 8 years Canadian CANDU owners have separately developed plant specific fuel handling simulators in order to address the needs of the fuel handling operations staff.

The Bruce Power, Darlington and Pickering stations have developed classroom fuel handling simulators that utilize touch screens to virtualize associated control room panels. In 2010 New Brunswick Power began in-house development of a fuel-handling simulator in response to a spent fuel in air event that occurred at their Point Lepreau Generating Station (PLGS) during plant refurbishment preparation activities. By 2013 New Brunswick Power had completed construction and validation of the first Full Scope Fuel Handling Simulator in the CANDU 6 fleet, complete with full size replica control panels.

The use of full size replica control panels in the Full Scope Fuel Handling Simulator design offers advantages as compared to touchscreen based simulators used at other Canadian nuclear plants.

2. Fuel Handling Simulator Based Training

2.1 Benefits of Fuel Handling Simulator Based Training

The Fuel Handling Simulator was based upon the philosophy of the existing station full-scope simulator. A training program designed for a specific purpose would use the simulator as a pivotal element. The simulator would be used to train operator candidates, test and verify skills, qualify the individuals for production work, verify operational and emergency procedures, develop operations documentation and handle a large number of trainees in a low risk and learner-fertile environment.

This training environment is more realistic and it has been proven that the simulators are more effective learning tool compared to regular reading, discussing, and testing techniques. The ability to repeat a scenario as many times as necessary for trainee understanding provides an accelerated training cycle, thus providing competent staff in a shorter time and so minimizing costs. In the past, portions of the Fuel Handling training were performed “on the job”. This type of training was not always consistent as it was subject to the issues that arose in the operating plant while the trainee was present. In traditional on-the-job training situations the fuel handling trainees are only exposed to limited and random occurrences of possible abnormal operations / transients. The Fuel handling simulator has the capability to train the operators on a wide variety of potential malfunctions, transients and abnormal conditions. Candidates have a better opportunity to improve diagnostic capability and procedural compliance.

There are significant advantages to a comprehensive simulator based training program, that includes “all” operations that a fuel handling operator could conceivably encounter, and that is delivered in a controlled training environment, free of distractions and time pressures to complete normal fueling operations. This approach has the additional benefit that Fuel Handling simulator based training reduces the wear and tear on the real fuel-handling machine.

During the first year of operation of the PLGS fuel handling simulator, the following benefits were realized:

- Training delivery plan development on the simulator identified numerous procedural deficiencies and led to the correction of the associated Response and Operating Manuals. The improvements made to the documentation and the training as a result of the F/H Simulator increased the reliability of the response at the panel to abnormal situations and improved the safety of all Fuelling Machine activities.

- New fuel handling operators trainees had direct access to the fueling handling panels of the simulator throughout their time in the classroom and were far better prepared before starting their on-line co-piloting.

As a result, obtaining excellence in training via fuel handling simulator-based program minimizes human errors and ensures that the conduct of operations aligns with reactor unit operating experience and expectations.

2.2 Maintenance of Fuel Handling Simulator and Training Programs:

The real plant and the simulator must replicate each other closely. If a plant modification has been implemented on the station system, required modification must also be implemented on the simulator. If it is a major modification that will affect the station expected response, the simulation response must be modified and validated by a subject matter expert (SME) accordingly. This also provides an excellent opportunity to review the operating procedures. If the change is minor and has no impact on the response observed on the simulator, then no action is required on the simulator following a plant change but this decision rationale should be documented and approved.

If time allows and the detailed design documentation is available, the simulator can be used as a verification tool before making a modification in the plant. This is particularly true if the Human Machine Interface (e.g. control panels, instrumentation, computer displays / interfaces) is affected.

Just as the simulator is maintained, so must the Simulator based Training Program. It develops the required good habits during normal operations and proper action decision mechanism during abnormal and dynamic events so as station events occur and the event analysis may change response expectations, those expectations must be integrated into the training delivered in the simulator. The training process focuses on providing the required knowledge and provides a forum to demonstrate the required abilities during simulator based events. Simulator based events are a combination of normal and abnormal operations during on-power and off-power operations. The fuel handling simulator is a flexible tool for use in training, so as the training needs change based on new operational experiences and plant specific historical data, the training objectives can and should be modified.

3. TQNPC Fuel Handling Simulator Project Scope:

The TQNPC Fuel handling simulator project had the following requirements:

- To develop a full-scope simulation of the TQNPC fuel handling panels and associated field equipment to ANSI 3.5 specification
- Panel, I/O system and modelling design to be of the same quality as the PLGS fuel handling simulator with specific improvement to enhance panel fidelity and ease of fabrication
- The simulator would incorporate digital control computer and RAMTEK display system emulations that had been previously developed for TQNPC
- The simulator should allow training on all normal fuel handling procedures and all abnormal operations as outlined in the Fuel Handling Operations manual
- The vendor would provide a complete set of training delivery plans that covered all normal and abnormal operations

The FH Simulator includes two simulation environments:

- A full scope version of the fuel-handling simulator:
  This version includes high fidelity TQNPC Main Control Room fuel-handling panels. The user (trainee or instructor) can use these replica panels to interact with the physical controls and instruments in a way that exactly mimics real-life fuel-handling activities.

- A desktop version of the fuel-handling simulator:
  This implementation can be used for training development and delivery and provides virtual representation of the panel device that allow the user to manipulate the required devices instead of through the “hard” panels. The option to project the IOS displays onto large screen monitors exist for teaching purposes.

The simulator can be used for training on normal operations, abnormal operations and/or with malfunctioning devices/controls. It is suitable to deliver training on:

- individual components, equipment, and systems;
- system logic, complete with custom Logic Block Diagrams to convey station logic/permissives;
- normal startup, operation, and shutdown;
- response to abnormal conditions
- plant and industry operating experience
- re-enforcement of theory and fundamentals;
- teamwork, communications, and diagnostics.

The simulator models all the fuelling system functionality that can be controlled and observed from the Main Control Room fuel handling panels, including the DCC graphical display system.

A full scope simulator is comprised of three systems:

- The plant, which is a simulation that includes the logic, instrumentation, control wiring/relays and process systems, running on the Simulator Computer System.
- The Digital control computer (in this case a software emulation of the hardware computer system) running the station FH control application and display/alarm messaging software, interfaced to the replica DCC HMI (Keyboards and monitors). The DCC is connected to a simulator "virtual" hardware I/O system to receive its required inputs from the simulation software [i.e. plant processes] and provide the desired control response through the normal Fuel Handling outputs which is then fed back into the simulation software to reflect the expected plant / equipment response.
- The Control Room panels allow the end user to interact with all control panel devices (hand switches, digital controllers) and observe the response on the appropriate device (lights, meters, encoders, etc.), as would occur in the real plant.

The simulation of the Instrumentation and Control has three major components: field, local controls and control room. Field components and field response are simulated by the simulation software down to the individual Electrical Drawing (ED). The simulation of these devices / logic will correctly respond to power supply and common services (e.g. instrument air) failures.

The primary control function that drive the field devices (Ram, motors, valves, etc.) and also provides alarms and signals are simulated via an emulation of the Digital Control Computer (DCC) which is executing the same Fuel Handling application and display software as at the plant.

Control room components are comprised of the 9 fuel handling panels and the FH Printer computer and the control room furniture / work stations. A custom I/O system connects the Control Panels to the simulation computer system. An I/O hardware interface provides communication between the full-scope FH Simulator's hardware panels and the computer hosting the simulation software.

In addition to the simulation of the real plant systems, the simulator also includes an instructor operating station (IOS) which allows the simulator instructor to monitor and control the FH Simulator / Simulation. Since TQNPC Fuel handling simulator is integrated into the existing unit side simulation, it allows the FH Simulator to take advantage of existing software developed for control computer emulation. A simplified version of TQNPC Fuel Handling System can be seen in Figure 1.

The scope of the simulation covers on-power operations for a high flow or a low flow channel and off-power conditions (defuelling, refuelling, grappling) for all normal and abnormal conditions, including maintenance procedures which involve field personnel interaction (via instructor controls).

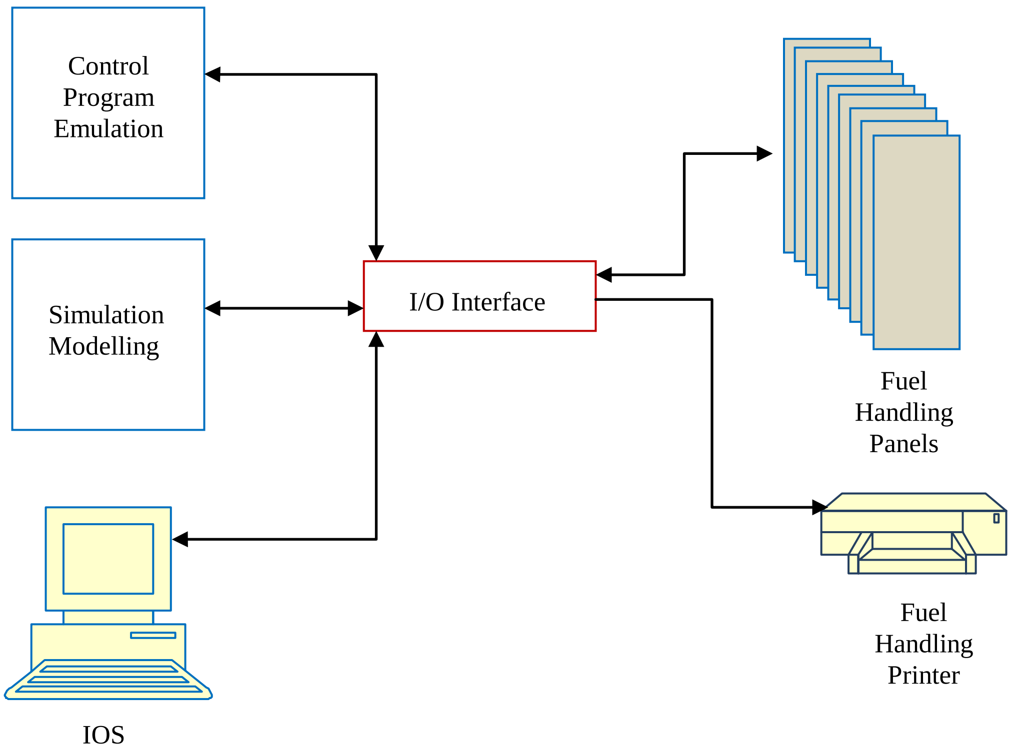

Figure 1 Simplified TQNPC Fuel Handling Simulator Architecture

3.1 Panels

The full-scope FH Simulator consists of nine hardware panels which exactly replicate the layout and dimensions, including the look and feel of all panel devices, for the fuel handling control panels located in the TQNPC main control room (Figure 2). Integrated into these panels are two keyboards (alphanumeric and function keyboards) per system which were custom built to replicate station design.

Figure 2 TQNPC Fuel Handling Simulator Panels

3.2 I/O Interface (Panels)

The input/output (I/O) interface provides communication between the full-scope FH Simulator's hardware panels and the computer hosting the simulation software. Each of the 9 fuel handling panels contains a Wago automation PLC and the IO modules necessary to operate the panel devices. Each panel can be independently tested during and after construction. The PLC in each panel is linked to I/O server via Ethernet. I/O server manages the data interchange between the panels and modeling computer custom drivers and it was designed to commnicate between the modelling computer (LINUX) and the Wago hardware via a Windows-based I/O server custom driver.

3.3 Instructor Operating Station

The instructor operating station allows the simulator operator to monitor and control the FH Simulator. It has following properties:

- fuel handling related process dynamic flowsheets that one can observe the system parameters from,
- freeze/unfreeze functionality for the modelling software
- store restore functionality that captures or recaptures the simulation conditions
- insert/delete malfunctions that can occur in power plant for the use of operators for training
- logic block diagrams that give the allowable operations depending on other parameters in the system
- create and execute a lesson plan

3.4 Modelling Software

The modelling sofware mimics the system response as observed from the user / trainee perspective. It responds to the inputs received from the control computer program (i.e. automatic action initiated from the DCC control system) and the panel hardware (i.e. operator actions). The modeling software sections can be seen in Figure 3

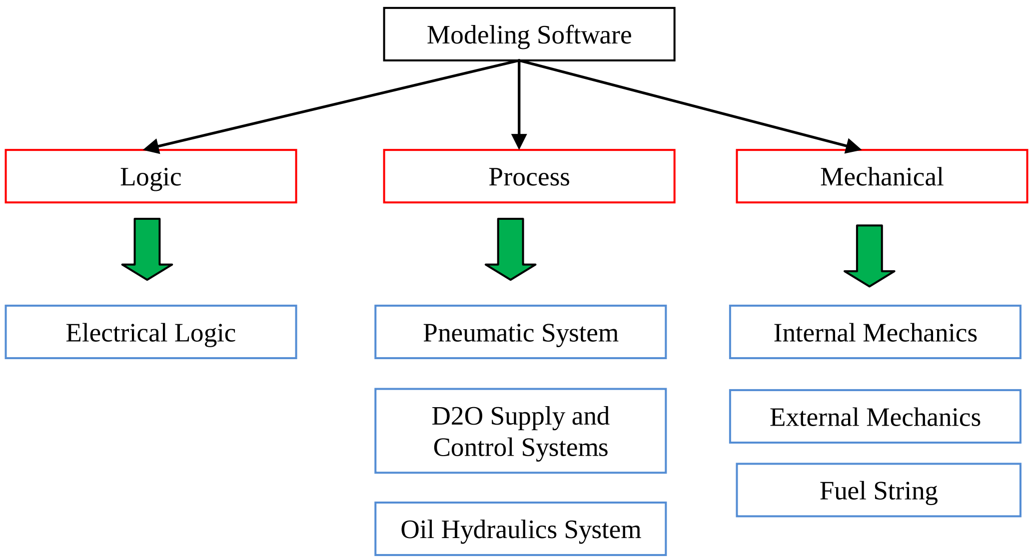

Figure 3 TQNPC Simulator Modelling Software

Control logic modelling provides the control and interconnecting functions as depicted in the station elementary drawings. The control logic forms a central role within the Fuel handling System by connecting all major components together, providing the interconnections between control computer, panel hardware, and field devices. Because the fuel handling system includes no large loads current and voltage are modelled based on logic alone.

Pneumatic system simulates the process for the instrument air distribution system important to Fuel Handling equipment. The air supply system in the Fuel Handling system is strictly a distribution network and relies on obtaining the health of the supply from the unit based on its supply pressure. Three levels of modeling are used for pneumatic system. The top level is the instrument air tanks. Since air system is a part of unit side simulation, the pressure availability information of the tanks is taken from the instrument air system. The mid-level is the air stations which provide air to multiple fuel handling equipment. The emergency nitrogen connections are also modeled at this level. The last level is the target fuel handling equipment. Due to the simplicity of the system, the air flow rate and control devices on the air paths are not modeled; instead, pressure available to the fuel handling equipment is modeled based on the air availability.

The D_2O Supply and Control model is an admittance matrix solution to the D_2O flow network which provides the required flows and pressure through the flow network. Specifically, the flow paths supplying D_2O to the fuelling machine head and fuelling machine rams and the return flowpaths are modeled. The major devices on these flow paths performing any control function are also modeled. To support various training scenarios, a small number of manually operating valves are also considered in this network.

The Spent fuel transfer auxiliaries and New fuel transfer auxiliaries are simplistically modeled in sufficient detail to provide the panel indications and the effect of these auxiliaries on F/M magazine and snout flow.

The D_2O supply and D_2O control system are modeled by first denoting the entire system with pressure nodes. The nodalization of the network has been determined largely based on the instrumentation (e.g. flow transmitters, pressure transmitters, temperature transmitter) and the location of the control valves present in the D_2O Supply and Control Systems. The mass conservation equation is applied to each pressure node. Between the pressure nodes are the links in which the fluid flows. The momentum equation is applied to each link. The mass conservation equations in pressure nodes and the momentum equations in links are combined to give a set of closed equations from which the pressure at each node can be obtained simultaneously. The process of the D_2O supply and D_2O control systems is modeled by first solving the pressure distribution in the system, then obtaining the flow distribution in the system and finally determining the temperature distribution in the system. The thermodynamic parameters (pressure, temperature, and enthalpy) are calculated in pressure nodes, and the hydraulic parameters (flow) are calculated for each path between two pressure nodes.

The oil hydraulic process is modeled very simply with oil suply pumps being on or off. The system pressure distribution is determined based on the status of the pumps. The pressures at various points in the system are controlled by the pressure regulating valves to their setpoints, otherwise, the pressures at these points decay to atmospheric pressure. The oil pressures at different locations in the oil hydraulic system are simulated for the mechanical models and D_2O supply and control systems. The simulation is a static model for oil hydraulics, the steady state conditions are based on nominal operating pressures at certain points in the system as given in design manulas and various flowsheets. The temperature of the system is modelled by considering the thermal heat loads and heat removals.

The Internal Mechanics model simulates the mechanical devices internal to the fuelling machine head and their interactions for the fuel handling system. Each device is modelled separately. However, the interdependecny of the tool movement on the other internal mechanical devices or string limitations are also considered. The External Mechanics model simulates devices for the fuel handling system; those that do not have a direct impact on the positions of fuel bundles and fuelling tools with respect to their frames of reference. The limitations due to the movement of the other devices (external and internal) and hydraulic/pneumatic state of the driving working fluid are also taken into account while modelling the external mechanical devices.

The Fuel string model simulates all of the tools and their interaction between each other that go into the channel such as fuel, ram adapter, grapple adapter, guide sleeve, guide sleeve insertion tool, FARE tool, shield plug, closure plug, snout plug, grapple, grapple extension, flow adapter extension and also keeps track of number of fuel bundles in the channel. The on power calculations use upstream and downsteram concept, the off power calculations use pushing and receiving machine concept. Depending on the status of the tool (in the magazine, in the channel, or latched to a ram) the calculation logic differs. Since the configuartion of the ports and the possible operations that can take place at the ports are not exactly the same, also a port specific calculation is perfomed. This module provides limitations for the internal and some of external mechanical devices and other tools in the string depending on the the overall position of the string.

4. TQNPC Fuel Handling Simulator Test Plan

The overall test plan was comprised of:

- Detailed system level logic tests
  These tests included very detailed tests to ensure all system logic responded as per the station 200 plus Electrical Drawings (ED). This included the verification of the response to:
  - manual (i.e. panel interaction) and auto (ie. DCC control) operations,
  - the required permissives being met / not met (e.g. limit switches based on ram and bridge positions, system pressures / temperature / tank levels)
  - failure of various power supplies throughout the instrumentation and control circuits.
- Integrated operations test
  Once system level logic was thoroughly checked, the integrate system response was verified as detailed below.

The integrated operations test plan for the TQNPC simulator included the following:

- On Power Sequences (59 sequences arrange into 15 Jobs)

These simulator tests comprised all the normal fueling operations that would be carried out during On Power refuelling. These tests include operations such as:

- Loading new fuel into the upstream fuelling machine
- Performing fueling on Flow assisted Fueling (FAF) channels (i.e. high flow channels)

- Performing fueling on Flow assisted ram extension (FARE) channels (i.e. low flow channels)
- Discharging spent fuel from the downstream fueling machine
- Miscellaneous "maintenance" operations such as
  - Deposit or retrieve FARE tool in Spent Fuel Port
  - Replace defective closure plug at ancillary port

- Off Power Sequences (51 sequences arranged into 15 Jobs)

These simulator tests comprised all "special" fueling operations which would be performed Off Power. These include operations such as:

- Defueling (and subsequent refuelling) a channel in preparation for channel inspections during a unit outage. [Note: only the defueling and then refueling of the channel using the specialized Off Power jobs would be performed on the training simulator]
- Grappling all fuel bundles in a channel using only one fueling machine to defuel a channel [Note: these operation would only be performed at the station to defuel a channel should one fueling machine breakdown and thus only one fueling machine would be available. Special tooling / devices are required.]

- Abnormal Operations (53)

These simulator tests were used to validate specially designed Training Scenarios that will be used to train fuel handling operators to diagnose and respond (as per approved operating procedures) to equipment malfunctions during fueling operations.
For example (but not limited to):

- 10 spent fuel in air training scenarios were developed to cover equipment failures at critical steps in the fueling process
- 4 instrument air failure scenarios were developed
- Numerous D2O system failures (including pump and hose failures)
- DCC Y failure (with and without restart)

Experienced fuel handling operators (SME) from both PLGS and TQNPC performed these tests and assessed the simulator performance against approved operating manuals and available station data (e.g. FH alarm summary logs, station electronic data acquired through station data loggers).

All issues identified were recorded and dispositioned following the approved "issues acceptance" process.

5. Challenges of Fuel Handling Simulator

The biggest challenge associated with this project was to interface the simulation software with the emulation of the DCC. This must be done correctly as the control and HMI function (ie. displays, alarms, keyboard input) are critical to replicating the operating environment in a simulator environment.

Although a DCC X and Y emulation existed for the Unit simulator, this software application had to be extensivley modified to integrate the Fuel Handling Inputs / Outputs into the existing infrastructure for DCC Y. In the plant configuration the display and control software is only run in DCC Y making it’s I/O system different from DCC X.

Also unique to the FH software application and resulting in additional challenges not present on a “unit” simulator, is the fact that the station FH control application is executed much faster (ie. every 100 ms) than any unit control program (e.g. RRS is the fastest control program which typically runs at 500 ms with all others at slower frequencies). This required extreme care when interfacing the simulation to the DCC to ensure that the I/O is updated in a timely fashion and that “order of execution” issues are optimized so that this communcation will elimnate any delays and prevent DCC Y and the FH control application from failing during it’s “error detection” rountines.

6. Conclusion

The use of a full scope Fuel Handling replica simulator in the training of nuclear power plant staff is essential to improving training and maximizing staff understanding of system operation and thus help to reduce human errors during plant operation. Regulatory bodies already require plant specific full scope simulators for all new nuclear power plants as a part of the authorization of “unit” certified staff. Currently the fuel handling operator is not one of these certified positions. However, a fuel handling specific simulator greatly enhances the training and provides the most realistic hands-on tool for the fuel-handling operator training. Full scope simulators have clearly demonstrated their value in the training of other nuclear power plant personnel. In this regard, the CANDU industry has begun to recognize the need for enhanced training to support fuel handling.

Atlantic Nuclear Services, in a joint project with New Brunswick Power, developed the first commercial full scope CANDU-6 Fuel Handling simulator and integrated this capability into the existing TQNPC Full Scope Simulator. The TQNPC Fuel Handling simulator is capable of supporting all normal on-power and off-power refuelling procedures as well as other abnormal operating conditions to allow training to be conducted based on the plant specific operating procedures.

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