User Requirements Specification: Basic Principles Simulator for Severe Accidents in Advanced Water Cooled Reactors

EXECUTIVE SUMMARY

The International Atomic Energy Agency (IAEA) provides comprehensive integrated education and training courses and workshops to its Member States on advanced reactor technologies with hands-on *learning by doing* using its suite of basic principles simulators. These simulators offer a comprehensive learning about the basic operational principles of nuclear power installations such as PWRs, BWRs, CANDU, HTGRs and SMRs (iPWR). They are freely available to Member States upon their requests.

There is an increasing global interest in the advancement of large water cooled reactor technologies specifically with implemented passive safety features and advanced handling of design basis accidents and severe accidents. Water cooled reactor technology, being proven and evolutionary in design, represents most of operating reactors as well as those under construction worldwide. It incorporates a series of advanced design features to meet the utility requirements and to address the latest nuclear safety requirements, including the safety issues relevant to preventing and mitigating consequences of severe accidents, such as the 2011 Fukushima accident.

In order to continue to support the interests of its Member States, the IAEA intends to add a basic principles simulator on severe accidents in water cooled reactors, to its suite of simulators and thus facilitate education and training courses that IAEA provides to its Member States on a regular basis.

This document provides the user requirements for a severe accident simulator, based on a generic water cooled reactor plant extended into phenomenology of severe accidents.

Table of Contents

1. INTRODUCTION 5
1.1. BACKGROUND 5
1.2. SCOPE 6
2. TECHNICAL AND FUNCTIONAL REQUIREMENTS OF THE RNPP SIMULATOR MODULE 7
2.1. OVERVIEW OF MAIN SYSTEMS 7
2.1.1. Reactor Core of a Reference Nuclear Power Plant 9
2.1.2. Reactor Coolant of a Reference Nuclear Power Plant 9
2.1.3. Steam and Feedwater Systems of a Reference Nuclear Power Plant 10
2.1.4. Turbine and Generator Systems of a Reference Nuclear Power Plant 10
2.1.5. Condensate Cooling System of a Reference Nuclear Power Plant 10
2.1.6. Containment of a Reference Nuclear Power Plant 11
2.1.7. Protection Systems of a Reference Nuclear Power Plant 11
2.2. OPERATIONAL EVENTS 11
2.3. MALFUNCTIONS AND DESIGN BASIS ACCIDENTS 11
2.4. SIMULATOR GUI FOR THE REFERENCE PLANT 13
3. TECHNICAL AND FUNCTIONAL REQUIREMENTS FOR THE SABP SIMULATOR MODULE 19
3.1. DESIGN ARCHITECTURE OF THE SEVERE ACCIDENT BASIC PRINCIPLE SIMULATOR 20
3.2. MAIN FEATURES OF THE SEVERE ACCIDENT BASIC PRINCIPLE SIMULATOR 25
3.2.1. Postulated Accidents Scenarios 25
3.2.2. Severe Accidents Alert Functions and Interactive Control Systems 25
3.3. SOFTWARE REQUIREMENTS FOR THE SEVERE ACCIDENT BASIC PRINCIPLE SIMULATOR 26
3.4. HARDWARE REQUIREMENTS FOR THE SEVERE ACCIDENT BASIC PRINCIPLE SIMULATOR 27
3.5. SIMULATION CONTROL 27
3.5.1. Initiation 27
3.5.2. Initial Conditions and Standard Scenarios 28
3.5.3. Simulation Time Control 28
3.5.4. Snapshots 28
3.5.5. Backtrack and Replay 29
3.5.6. Malfunctions 29
4. ADDITIONAL REQUIREMENTS 30
4.1. DOCUMENTATION 30
4.1.1. User Manual 30
4.2. SCOPE OF SUPPLY 31
4.3. TESTING, INSTALLATION AND TRAINING 31

4.4. SOFTWARE UPGRADES AND AFTER SALES SUPPORT 31

1. INTRODUCTION

1.1. BACKGROUND

The IAEA has established an integrated educational and training programme on advanced reactor technologies that includes the use of its suite of basic principles simulators in support of human resource development in the Member States. The integrated approach with these tools combines lectures on plant operational specifics and fundamentals including reactor physics, thermal hydraulics and safety aspects with hands-on "learning by doing" on the simulators.

The IAEA current definition of a basic principle simulator is based on the IAEA TECDOC on *Selection, Specification, Design and use of Various Nuclear Power Plant Training Simulators* (1993):

"*A basic principle simulator illustrates general concepts, demonstrating and displaying the fundamental physical processes of the plant. This type of simulator also serves training objectives such as providing an overview of plant behaviour or a basic understanding of the main operation modes. Such simulators may consist of complete primary and secondary circuits, sometimes with a reduced number of loops or redundancies. The scope of simulation focusses on the main systems where auxiliary or supporting systems may be neglected. The control room or panels very often have a fundamentally different design in comparison with conventional control room design. Other types of basic principle simulators may use video displays to illustrate fundamental processes such as neutron flux control or boiler level control*."

The IAEA's existing suite of basic principle simulators include:

- Pressurized Water Reactor (PWR) Simulators
  - Gen II Pressurized Water Reactor (PWR)
  - 2-Loop Large PWR (Korean-OPR 1000)
  - Russian-type PWR (WWER-1000)
  - Advanced Passive PWR (AP-600)
  - Integral Pressurized Water Reactor (SMR)
- Boiling Water Reactor (BWRs) Simulators
  - Advanced Boiling Water Reactor (BWR)
  - Advanced Passive BWR (ESBWR)
- Pressurized Heavy Water Reactor (PHWR)
  - Conventional PHWR
  - Advanced PHWR (ACR)
- Part-Task Simulator
  - Micro-Physics Simulator (Lite)

In recent years and especially after the Fukushima accident, the IAEA has seen an increasing interest among its Member States in analysis of, and safety demonstration following, severe accidents in water cooled reactors. In responding to such interests, the IAEA has supported information exchange among the Member States on the newest developments on simulation and modelling of severe accidents in water cooled reactors through recently conducted Technical Meetings on:

- *Status and Evaluation of Severe Accident Simulation Codes for Water Cooled Reactors* held in Vienna, 9 – 12 October 2017 that provided an opportunity for Member States to discuss the status of analysis codes and identify near-term needs for improvements and development;
- *Hydrogen Management in Severe Accidents* held in VIC, Vienna, 25–28 September 2018 that provided a forum for information exchange on the state-of-knowledge and the status of computer codes used to model the risks arising from hydrogen generation, distribution and combustion during a severe accident and review the current mitigation techniques.

There has also been an increased interest among Member States for education and training on severe accident progression, including physical, chemical and radiological phenomena and the associated technologies designed to cope with such events. Prediction of severe accident progression is a complex process, and the related analysis codes, management and mitigatory measures rely on a thorough and informed understanding of the fundamental underlying phenomena. Education and training on nuclear energy, nuclear reactor technologies, nuclear systems, reactor components and nuclear safety features are of great importance. To support the development of such education and training courses, the IAEA has recently developed new courses on severe accidents and training materials as a general resource for information on severe accident phenomena in water cooled reactors, also including lectures on accident progression and relevant analysis tools.

Retention of knowledge is maximized if the trainees are provided with hands-on tools that ease their *learning by doing*, and thus best support the Member States in developing their understanding of severe accidents phenomena and behaviour. Therefore, the IAEA would like to offer a basic principles simulator on severe accidents in water cooled reactors, based on physical and empirical laws and adequately dynamic to allow demonstration of important severe accident phenomena and system behaviour in a water cooled nuclear power plant, including a limited number of severe accident management strategies/actions. It shall have sufficient fidelity to give realistic plant responses during severe accidents conditions. Additional required functionality of the simulator shall be the modelling of design basis accidents leading to the severe accident conditions and corresponding phenomena. It is desirable that the simulator can compare the effects of different severe accident mitigation strategies/actions, using available systems of a generic water cooled reactor nuclear power plant.

1.2. SCOPE

This document specifies the technical and functional user requirements for a basic principles simulator for severe accidents in a generic water cooled reactor (hereon referred to as “Simulator”, which consists of a reference nuclear power plant (RNPP) module and a severe accidents basic principle (SABP) module). The IAEA, as the “end user” will add this to its existing suite of basic principles simulators for educational and training purposes that are provided to its Member States upon official request and at no cost.

Chapter 2 describes the reference nuclear power plant (RNPP) simulator module technical and functional requirements. Chapter 3 details design, technical and functional requirements of the severe accidents basic principle (SABP) simulator module. Chapter 4 gives additional requirements associated with the supply of the Simulator, which are not directly related to its design or functionality.

2. TECHNICAL AND FUNCTIONAL REQUIREMENTS OF THE RNPP SIMULATOR MODULE

All display text shall be in English and use S.I. units. A reasonably detailed reference plant model is required for correct progression into the severe accident phase, which is the simulator's main focus. Therefore, core and primary side models need to be detailed, while secondary side and the turbine/generator/feedwater/condenser systems may be simplified.

2.1. OVERVIEW OF MAIN SYSTEMS

The Simulator's focus is simulating and graphically representing the initiation and propagation of severe accidents in a generic water cooled reactor nuclear power plant in addition to design basis accidents and therefore needs to include some aspects of normal operation of a reference plant. The normal operation of a reference plant shall provide important familiarization with the plant technical characteristics for users to better understand the initiation and progression of design basis and severe accidents.

The basic characteristics of the reference plant are provided in Table 2.1. The Simulator documentation shall specify all relevant information about the reference plant: tables summarizing operational conditions, flow-charts providing overall layout of the plant with details of importance and relevance to the severe accident initiation and progression and design basis accidents initiation and progression.

TABLE 2.1. Basic Characteristics of the Reference Nuclear Power Plant

Reactor type	Pressurized Water Reactor (PWR)
Coolant	Light Water
Moderator	Light Water
Secondary coolant	Light Water
Neutron spectrum	Thermal neutrons
Electrical capacity	~ 1000 MWe
Residual heat removal systems	Active and Passive
Safety injection systems	Active and Passive

Table 2.2 provides system capabilities relevant to the reference nuclear power plant that the Simulator shall include.

The following subsections present details of the parameters that, as a minimum, shall be available as transient outputs for each of the various systems within the reference plant.

TABLE 2.2. System Capabilities for the Reference Nuclear Power Plant Simulator

System	Simulation scope	Operator controls	Malfunctions
Reactor core	• Neutron flux levels over a range of 0 to multiple full power, minimum 6 delayed neutron groups • Decay heat (minimum 3 groups) • Soluble boron reactivity control. • Xenon/Iodine/Samarium changes • Tracking of fission products	• Reactor power and rate of change (input to control computer) • Manual control of reactivity devices - control rods and boron addition/removal • Reactor trip • Reactor setback • Reactor stepback	• Reactor setback and stepback fail • Control rods ejection
Reactor coolant	• Main circuit coolant loop riser, steam generator, minimum of 20 representative reactor core coolant channels • Pressure control and pressure relief	• Pressurizer pressure control: heaters; spray; pressure relief valve	• Pressurizer pressure relief valve fails open • Charging (feed) valve fails open • pressurizer heaters turned "ON” • Failure of a single and all reactor coolant pumps
Steam and feedwater	• Boiler dynamics • Boiler feedwater system • Turbine/condenser system and logic can be simplified, but shall allow imbalance with reactor power, i.e. loss of heat sink	• Feed pump on/off operation	• All feed pumps trip • All steam safety valves open • Steam header break
Overall unit	• Fully dynamic interaction between all simulated systems • Integration of the feedwater valve control and power control. • Unit annunciation & time trends	• Overall unit power control with reactor leading mode; and turbine leading mode • Computer control of all major system functions	• Spurious reactor trip • Spurious turbine trip
Safety system	• Decay heat removal system • Emergency core cooling system with automatic depressurisation system (ADS), gravity driven water injection, low pressure water injection and containment cooling sprays.	• Enable/disable any safety system	• Inadvertent initiation of ADS • Inadvertent initiation of decay heat removal system
Control Systems	• Pressuriser pressure control system • Automatic reactor power control and shutdown system		• Malfunction of pressuriser pressure control system

2.1.1. Reactor Core of a Reference Nuclear Power Plant

Table 2.3 provides the reactor core parameters of a reference nuclear power plant that shall be available in the Simulator.

TABLE 2.3. Reactor Core Parameters

Parameter	Display units	Permit user to change the parameter, Yes or No
Reactor thermal power	MW	No
Reactor thermal power	%	No
Neutron power	%	No
Control rod length in core	% total length	Yes
Control rod insertion/withdrawal rate	%/min	Yes
Control rod worth at the current position	pcm	No
Peak cladding surface temperature	ºC	No
Average cladding surface temperature	ºC	No
Average fuel temperature	ºC	No
Peak fuel (centre line) temperature	ºC	No
Reactivity: total	%dk/k	No
Reactivity: Doppler	%dk/k	No
Reactivity: moderator temperature	%dk/k	No
Reactivity: rod	%dk/k	No
Reactivity: soluble boron	%dk/k	No

2.1.2. Reactor Coolant of a Reference Nuclear Power Plant

Table 2.4 provides the reactor coolant parameters of a reference nuclear power plant that shall be available in the Simulator.

TABLE 2.4. Coolant Parameters

Parameter	Display units	Permit user to change the parameter, Yes or No
Coolant flow rate	kg/s	No
Coolant average temperature	ºC	No
Coolant temperature at core inlet	ºC	No
Coolant temperature at core exit	ºC	No
RPV (reactor pressure vessel) water level	%	No
RCS (reactor coolant system) pressure	MPa	No
Pressure setpoint	MPa	Yes
Level setpoint	%	Yes
Pressuriser heater power	kW	No
Pressuriser water level	%	No

2.1.3. Steam and Feedwater Systems of a Reference Nuclear Power Plant

Table 2.5 provides the steam and feedwater systems parameters of a reference nuclear power plant that shall be available in the Simulator. Parameters marked with † shall also be available for the steam and feedwater headers.

TABLE 2.5. Steam and Feedwater Systems Parameters

Parameter	Display units	Permit user to change the parameter, Yes or No
Steam flow rate†	kg/s	No
Feedwater flow rate†	kg/s	No
Steam pressure†	MPa	No
Steam temperature†	ºC	No
Feedwater temperature	ºC	No
Main steam control valve opening	%	Yes
Feedwater control valve opening	%	Yes
Steam bypass valve opening	%	Yes

2.1.4. Turbine and Generator Systems of a Reference Nuclear Power Plant

Table 2.6 provides turbine and generator parameters of a reference nuclear power plant that shall be available in the Simulator.

TABLE 2.6. Turbine and Generator Systems Parameters

Parameter	Display units	Permit user to change the parameter, Yes or No
Turbine power demand setpoint	%	Yes
Turbine demand ramp rate	%/min	Yes
Turbine speed	RPM	No
Generator load	MW	No

2.1.5. Condensate Cooling System of a Reference Nuclear Power Plant

Table 2.7 provides condensate cooling system parameters of a reference nuclear power plant that shall be available in the Simulator.

TABLE 2.7. Condensate Cooling System Parameters

Parameter	Display units	Permit user to change the parameter, Yes or No
Temperature of heat sink	ºC	Yes
Condenser vacuum	bar	Yes

2.1.6. Containment of a Reference Nuclear Power Plant

Table 2.8 provides containment parameters of a reference nuclear power plant that shall be available in the Simulator.

TABLE 2.8. Containment Parameters

Parameter	Display units	Permit user to change the parameter, Yes or No
Containment pressure	MPa	No
Containment temperature	ºC	No
Pool level (for each pool/sump)	% of full level	No
Pool temperature (for each pool/sump)	ºC	No

2.1.7. Protection Systems of a Reference Nuclear Power Plant

The reactor protection system is designed to monitor and act on physical parameters of the plant and consists of two main systems: reactor trip system and engineered safety features actuation systems. Table 2.9 provides protection systems parameters of a reference nuclear power plant that shall be available in the Simulator. The reactor protection systems trip logic with setpoints shall be provided.

TABLE 2.9. Protection Systems Parameters

Parameter	Display units	Permit user to change the parameter, Yes or No
Safety valve flow	kg/s	No
Boron injection system flow rate	kg/s	No
Boron concentration in coolant	ppm	No
Decay heat removal system flow rate	kg/s	No
Water injection flow from high and low pressure injection systems	kg/s	No
Water injection flow rate from gravity driven injection systems	kg/s	No
Containment coolant spray flow rate	kg/s	No

2.2. OPERATIONAL EVENTS

The Simulator shall demonstrate the following standard operational events:

— Reactor power increase and decrease
— Operation in either turbine leading or reactor leading mode
— Reactor scram and restart
— Variation in speed of MCPs

2.3. MALFUNCTIONS AND DESIGN BASIS ACCIDENTS

The Simulator shall be capable of simulating malfunctions representing accidental conditions and to allow the user to understand the transient plant response in each event. The Simulator shall enable the user to be able to trigger a range of predetermined malfunctions from a predefined list. Table 2.10 presents a list of malfunctions that shall be available at a minimum within the Simulator. When selecting a malfunction, the Simulator shall enable the user to be able to specify whether it occurs immediately, or after a specified time interval, or if it is triggered by a specific event (such as a specific plant parameter reaching a specified value).

TABLE 2.10. Malfunctions of a Reference Plant

Number	Description
Anticipated Operational Occurrences	
1	Reduction in feedwater temperature (loss of feedwater heating)
2	Abnormal increase in feedwater flow
3	Inadvertent opening of a steam generator relief valve
4	Inadvertent actuation of decay heat removal system
5	Loss of containment vacuum
6	Turbine trip
7	Turbine trip with bypass valve failed closed
8	Loss of condenser vacuum
9	Closure of main steam isolation valve
10	Uncontrolled control rod assembly withdrawal at power
11	Loss of normal feedwater flow (feedwater pumps trip)
12	Failure of main coolant pumps (if applicable)
13	Inadvertent opening of a pressure relief valve
14	Steam generator tube failure
15	Inadvertent ECCS valve opening
16	Inadvertent operation of pressuriser heaters
17	Spurious turbine run-back
18	Condenser coolant pumps trip
19	Inadvertent reactor isolation – closure of all main steam isolation valves
20	Earthquake
Postulated Design Basis Accidents (DBA)	
21	DBSs relevant to the reference plant, such as but not limited to: • Reactivity initiated accidents • Loss of flow accidents • 0-100% LOCA and MSLB • SGTR • Accidents induced by equipment failures

Additionally, the Simulator shall enable the user to be able to cause individual components (e.g. valves or pumps) to fail completely or reduce their performance at any time during a simulation.

2.4. SIMULATOR GUI FOR THE REFERENCE PLANT

The Simulator GUI shall be as intuitive and user-friendly as is reasonably achievable. It shall be based around a series of display pages showing different plant views; an illustrative list of pages that could be included is presented in Table 2.11. All display text shall be in English and use S.I. units.

TABLE 2.11. **Illustrative** List of Display Pages for the Simulator Reference Plant

Display page number	**Page title**	**Page details**
1	Home page of a reference plant	List of the Simulator's display pages with hyperlinks to them. Schematic of the whole reference plant. This could be in either two or three dimensions.
2	Reference plant overview	Simplified schematic diagram of the whole reference plant showing main components and flow paths. Key plant parameters shown including: • Neutron power (% full power) • Neutron power rate (%/s) • Reactor thermal power (% full power) • Core pressure and flow • Core water level • Average coolant temperature • Average fuel temperature • Pressuriser pressure and level • Flow to/from pressuriser • SG steam flows, pressures and temperatures • Total steam flow through main steam isolation valve • Main steam isolation valve status • Main steam governor valve status • Condenser steam bypass valve status • Atmospheric steam discharge valve status • Generator output • Feedwater flow and temperature • Boiler feed pump status • Pressure relief valves status
3	Control rods and reactivity	Schematic of control rod positions and locations. Status of the control rods. Core flow vs power map. Reactivity contributions from the different types of rods, from poisons, from boron additions, and from variation in moderator and fuel temperature. Schematic showing a 'map' of core flux intensity in its different sections.

		Schematic of route that coolant takes through core.
4	Trip parameters	Displays a list of parameters which could cause the reactor or turbine to trip, step back or set back. Each parameter shall be automatically highlighted as it occurs so that the reasons for a trip can be understood.
5	Reactor coolant system	Schematics of the relevant areas of reference plant. At the relevant locations on the diagram the following parameters shall be shown: • Average fuel temperature • Average coolant temperature • Coolant temperature at base of core • Coolant temperature at top of core • ΔT (coolant temperature at top of core – coolant temperature at base of core) • Coolant flow • Coolant pressure • Feedwater flow in steam generator • Coolant flow to/from pressuriser • Steam generator pressure • Steam flow rate • Pressuriser heater status • Pressuriser vapour pressure • Pressuriser liquid level • Spray flow into pressuriser • Pressure relief flow • Coolant makeup tank level • Coolant feed/bleed flows • Valve statuses and % open values • Pressuriser level setpoint • Reactor pressure setpoint • Condenser vacuum • Status of condenser cooling pumps Relevant trend plots shown, for example: • Core coolant temperature • Pressuriser pressure; reactor core inlet pressure; reactor core outlet pressure • Reactor power • Coolant inventory
6	Turbine generator and condenser	Schematic for relevant areas of reference plant. At the relevant locations on the diagram the following parameters shall be shown: • Steam pressure • Steam flow

		• Valve statuses and % open values • Steam flow to turbine • Generator electrical output • Generator rotation speed • Power demand (%) • Power demand rate (%/min) • Turbine trip status • Manual turbine runback and trip options. Relevant trend plots shown, for example: • Reactor neutron and thermal power (%) • Generator output • Turbine speed
7	Feedwater and extraction steam	Schematic for relevant areas of reference plant. At the relevant locations on the diagram the following parameters shall be shown: • Main steam header pressure • Steam flow through governor valve • Steam flow through bypass valve • Feedwater pump statuses • Valve statuses and % open values Relevant trend plots shown, for example: • Reactor neutron and thermal power (%) • Main steam header pressure
8	Passive core cooling and containment	Schematic for relevant areas of reference plant including view of containment structure. • Availability of safety systems • Key parameters and valves statuses shown • Water levels illustrated graphically in the vessels and sumps • Temperatures illustrated using a colour scale • Containment radiation levels A link to an explanation of the passive core cooling systems would be useful.
9	Trends	An additional page which contains several plot windows that the user can use to plot trends as desired.

There shall be common parameters displayed on each of the pages (views) from Table 2.11 (illustrated group of pages and views) within the GUI in a consistent screen (page) location:

1) Simulation status – running, frozen, not initiated, replay;
2) Simulation time;
3) Simulation run speed;
4) Simulator control buttons which are common to all pages, for example – run, freeze, stop, save, manual trip for reactor, manual trip for turbine, help, plot;
5) Key plant parameters – Reactor neutron and thermal power, generator output, main steam header pressure, pressure vessel water level;
6) Malfunction selection controls – this will allow a malfunction to be initiated from any display page;
7) Indicators for turbine or reactor trips and what has caused it – this could be achieved by the inclusion of alarm indicators for key alarms (e.g. reactor scram, turbine trip, malfunction active);
8) Indicators for if passive safety systems are available/poised, have been actuated and are active or depleted (e.g. green/yellow/red flashing light) – for decay heat removal system, automatic depressurization system, water injection system, containment cooling sprays.

Other common features of the GUI shall include the following:

1) Components shall have name labels next to them to identify them to the user;
2) The status of all components (on/off, open/closed, malfunction) shall be clearly represented, for example using colour coding;
3) The display of each component shall indicate whether it is under automatic or manual control;
4) Key parameters shall be shown, such as those listed in Table 3.1; units shall be given for all parameters;
5) The display shall indicate whether a parameter or component can be controlled manually;
6) Certain reference nuclear power plant features or malfunctions will not always be present, such as sprays or leaks; when these occur, these shall be shown on the schematic diagrams in the relevant locations;
7) Arrows shall be used to indicate flow directions on schematic diagrams;
8) Parameters shall be identified by name where possible, not by code/acronym, to assure correct understanding by the users;
9) Plots shown within a display page, shall allow the user to manually change their scales and ranges;
10) In any display page, it shall be possible to create a plot in a new window displaying any single, or combination of, user defined parameter(s) as a function of time.
11) To assure its educational purpose, the Simulator shall provide basic information about each plant system and each component's purpose and operation, along with the basic equations and theory for the physics model of that system or component. This will assist in the understanding

of the basic principles associated with the reference nuclear power plant. It is suggested that this information is displayed by clicking on an '**INFORMATION**' button next to each component (optional requirement).

12) It is desirable that the Simulator include a '**HELP**' button located within the tool bar that shall provide a basic overview of the controls of the Simulator reference plant and how to operate it and include a search function so that the user can look for help by inserting key words; it is suggested to include an electronic version of the user manual.

13) On schematic diagrams, the containment position shall be clearly identified; for example, on a diagram which does not show the structure of the containment but does show flow paths in/out of the containment, a line shall be included to represent the containment boundary.

14) The units associated with each parameter shall be included in every occurrence of that parameter.

Some examples of the GUI from the IAEA's existing suite of simulators are presented for illustration purposes in Figures 2.3. to 2.5.

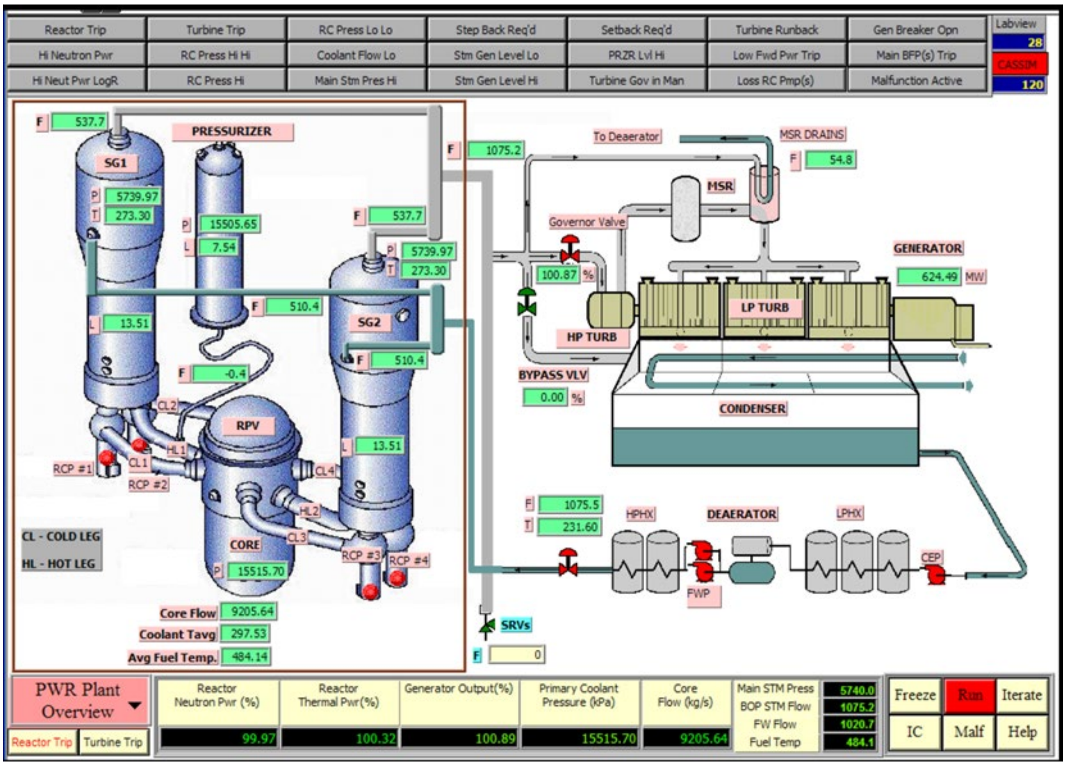

Figure 2.3. Simulator GUI Example: Cassiopeia Technologies Inc. 2007

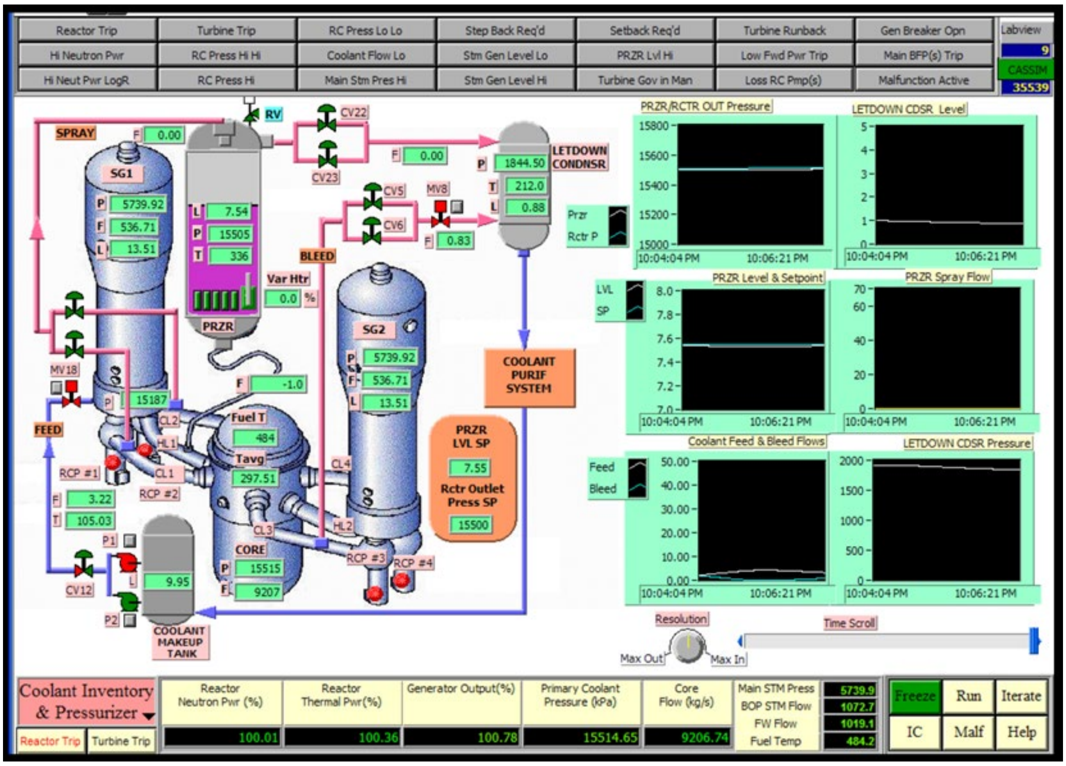

Figure 2.4. Simulator GUI Example: Cassiopeia Technologies Inc. 2007

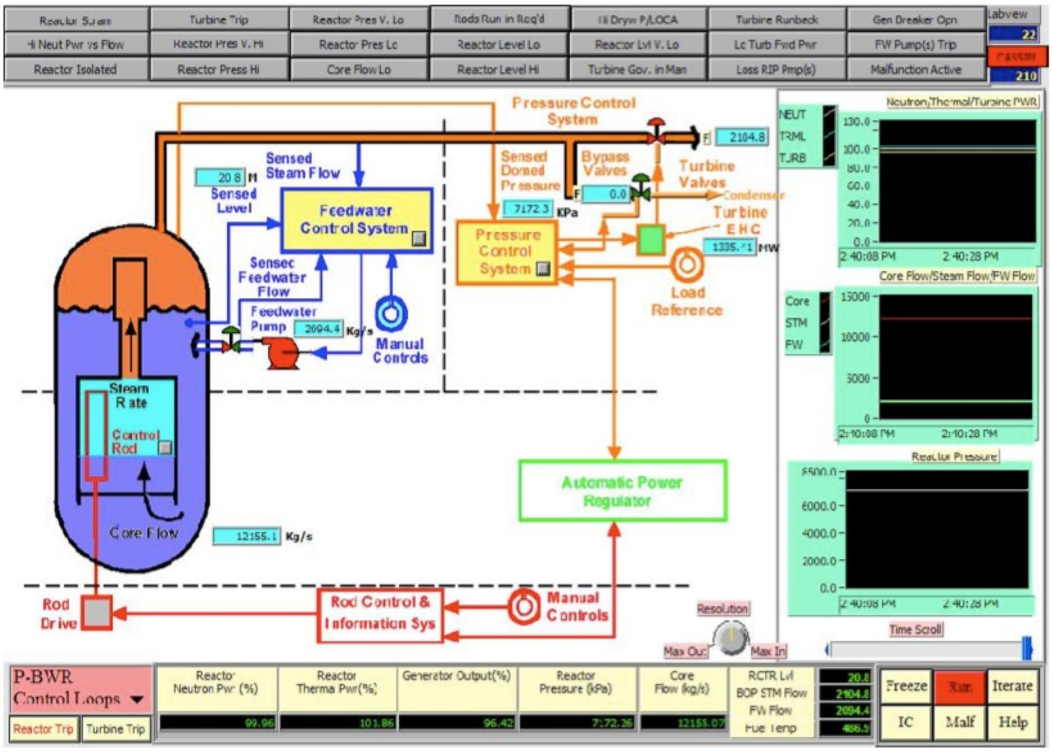

Figure 2.5. Simulator GUI Example: Cassiopeia Technologies Inc. 2009

3. TECHNICAL AND FUNCTIONAL REQUIREMENTS FOR THE SABP SIMULATOR MODULE

The severe accident Simulator shall be a desktop software system to provide input/output (I/O) interface to an established and validated severe accident code (such as but not limited to MELCOR, MAAP, ASTEC, SOCRAT, SCDAP/RELAP) by using graphic user interface (GUI) technologies. The intended use of the Simulator is shown in Figure 3.1. All display text shall be in English and use S.I. units.

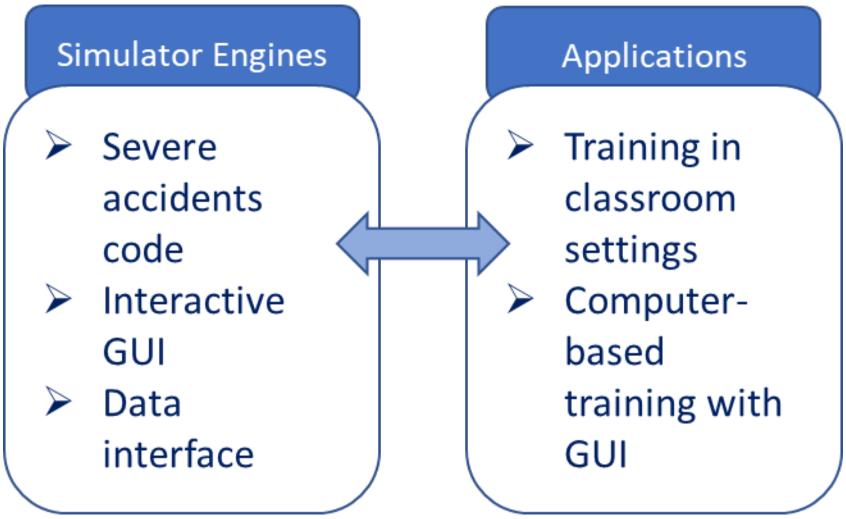

FIGURE 3.1. Intended Use of Severe Accident Basic Principle Simulator

The Simulator GUI shall be as intuitive and user-friendly as is reasonably achievable in thus allowing the user to focus on understanding the principles represented by the Simulator, not on its operation. The GUI shall be based around a series of display pages showing different plant views, as outlined in Section 3.2.

The Simulator shall be optimized for training and education on the fundamental principles of severe accident phenomena, their interactions, and reference nuclear plant behaviour showing the accident progression through images and data displays.

The Simulator shall represent a reference plant, mirroring the behaviour of the plant including control and safety systems, and response to user's actions. The Simulator GUI shall display a coloured layout and main parameters of the primary system, containment and the secondary system. The status of important parameters and colour-coded values shall be displayed on the screen.

The severe accidents Simulator shall have, therefore, the following overall features (applicable to the initiation and progression of design basis and severe accident scenarios):

- *Simulator engine* (i.e. severe accident simulation code): description of the code and how it is used in the simulator;
- *Accident event displays*: simulation code to display changes in plant state during the accident progression;
- *GUI*: graphical representation of the changes in plant state during the accident progression;
- *User interactive actions*: during the simulation the users shall be able to manipulate

valves/pumps interactively to simulate various accident progressions without modifying the input file; a variety of accident conditions shall be available in auto and/or interactive mode allowing the user to interfere with the transient, change conditions and analyze the response of a reference plant.

— Graphic animation of plant behavior during accident progression.

3.1. DESIGN ARCHITECTURE OF THE SEVERE ACCIDENT BASIC PRINCIPLE SIMULATOR

The severe accident Simulator shall mimic the reference plant behavior under postulated design basis and severe accident conditions, initiated from operating conditions and shutdown conditions, and provide the following displays:

— Display of the safety relevant plant parameters, operational plant parameters, and initiating events for various postulated design basis and severe accident scenarios;

— Display windows showing thermal-hydraulics phenomena, chemical/mechanical behavior of the containment systems, including sublevel information on the water levels of the reactor coolant system, the reactor core temperature distribution, core melting and relocation sequence, release and transportation of fission products, core concrete interactions, engineering safety system status, and other parameters of relevance to the simulated accident scenario;

— Display windows showing the alerts, historical trend graphs, status of the reactor building, and the equipment;

— Display of 3D plant generic components, subsystems and systems.

The Simulator shall consist of the following sub-modules (windows):

— System menu and tool bar;

— Reference plant view;

— Postulated accident scenario summary;

— Interactive control;

— Parameter help view;

— Input editor;

— Reactor vessel view;

— Reactor coolant system view;

— Containment building view;

— Accident progression view;

— On-line switch between real time, slow time, and faster than real time execution.

The main screen of the Simulator shall display parameters, flow charts and plant system overviews, and shall include all necessary information for the user to follow the initiation and progression of the postulated accident scenarios.

Figure 3.2 shows a generic architecture layout of a simulator page regarding the severe accidents scenario selection and monitoring of its progression. Any acronyms or codes that are used shall be clearly explained in a glossary within the user manual.

Table 3.1 provides a list of pages (views) that shall be included in the GUI Simulator in an organized way.

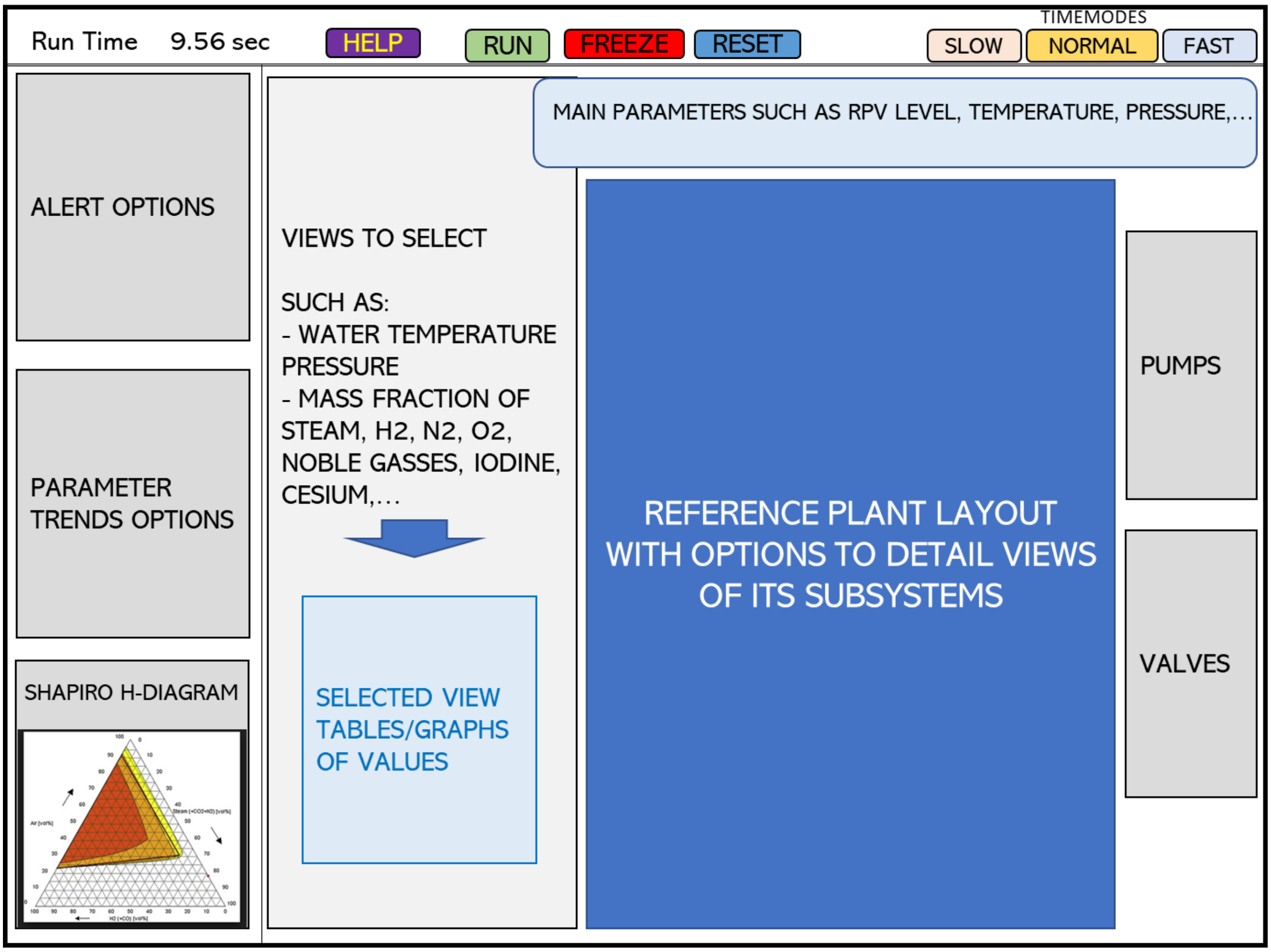

FIGURE 3.2. Generic Architecture Layout of a Severe Accidents Simulator

TABLE 3.1. **Illustrative** List of Display Pages for the Severe Accidents Simulator

Display page number	Page title	Page details
1.	Home page of a reference plant to initiate a severe accident	List of the Simulator's display pages with hyperlinks to them. Schematic of the whole reference plant. This could be in either two or three dimensions. List of initiating events of severe accidents scenarios
2.	Reference plant overview per severe accident scenario	Simplified schematic diagram of the whole reference plant showing main components and flow paths. Key plant parameters shown including: • Neutron power (% full power) • Neutron power rate (%/s) • Reactor thermal power (% full power) • Core pressure and flow • Core water level • Average coolant temperature • Average fuel temperature • Pressuriser pressure and level • Flow to/from pressuriser • SG steam flows, pressures and temperatures • Total steam flow through main steam isolation valve • Main steam isolation valve status • Main steam governor valve status • Feedwater flow and temperature • Boiler feed pump status • Pressure relief valves status
3.	Control rods and reactivity	Schematic of control rod positions and locations. Status of the control rods. Schematic showing a 'map' of core flux intensity in its different sections
4.	Reactor coolant system	Schematics of the relevant areas of reference plant. At the relevant locations on the diagram the following parameters shall be shown: • Fuel temperatures • Coolant temperatures and void • Coolant flow rate and flow regime • Coolant pressure • Feedwater flow in steam generator • Coolant flow to/from pressuriser • Steam generator pressure • Steam flow rate

		• Pressuriser level • Coolant makeup tank level • Coolant feed/bleed flows • Valve statuses and % open values Relevant trend plots shown, for example: • Core coolant inventory, pressure and temperature • Void distribution • H2 concentration
5.	Turbine generator and condenser	Schematic for relevant areas of reference plant. At the relevant locations on the diagram the following parameters shall be shown: • Steam pressure • Steam flow • Valve statuses and % open values Relevant trend plots shown, for example: • Steam flow • Valve statuses and % open values
6.	Feedwater	At the relevant locations on the diagram the following parameters shall be shown: • Feedwater flow rate and temperature • Valve statuses and % open values
7.	Passive core cooling and containment	Schematic for relevant areas of reference plant including view of containment structure. • Availability of safety systems • Key parameters and valves statuses shown • Water levels illustrated graphically in the vessels and sumps • Temperatures illustrated using a colour scale • Containment radiation levels (atmosphere and sump) • Containment steam, air, and H2 concentration(s) • H2 combustion regime (e.g. Shapiro diagram) and combustion events • PAR operation, temperatures and flowrates • Tracking of fission products A link to an explanation of the passive core cooling systems would be useful.
8.	Trends	An additional page which contains several plot windows that the user can use to plot trends as desired.

There shall be parameters displayed on each of the pages (views) from Table 3.1 (illustrated group of pages and views) within the GUI in a consistent screen (page) location:

1) Simulation status – running, frozen, not initiated, replay;
2) Simulation time;
3) Simulation run speed;
4) Simulator control buttons which are common to all pages, such as: run, freeze, stop, save, manual trip for reactor, manual trip for turbine, help, plot;
5) Key plant parameters: reactor neutron and thermal power, generator output, main steam header pressure, pressure vessel water level;
6) Severe accident scenario selection and controls; this will allow a scenario to be initiated from any display page;
7) Indicators of severe accidents progression; this shall be achieved by the inclusion of alarm indicators for key alarms (Section 3.3);
8) Indicators for if passive safety systems have been actuated (e.g. yellow flashing light): for decay heat removal system, automatic depressurisation system, water injection system, containment cooling sprays.

Other common features of the GUI shall include the following:

9) Components shall have name labels next to them to identify them to the user;
10) The status of all components (on/off, open/closed, malfunction) shall be clearly represented, for example using colour coding;
11) The display of each component shall clearly indicate whether it is under automatic or manual control;
12) Key parameters shall be shown, such as those listed in Table 3.1; units shall be given for all parameters;
13) The display shall clearly indicate whether a parameter or component is able to be controlled manually or not; all operations listed in Table 2.2 shall be available;
14) Certain reference nuclear power plant features or malfunctions will not always be present, such as sprays or leaks; when these occur, these shall be shown on the schematic diagrams in the relevant locations;
15) Arrows shall be used to indicate flow directions on schematic diagrams;
16) Parameters shall be identified by name where possible, not by code/acronym, to assure correct understanding by the users;
17) Plots shown within a display page, shall allow the user to manually change their scales and ranges;
18) In any display page, it shall be possible to create a plot in a new window displaying any single, or combination of, user defined parameter(s) as a function of time;
19) To assure its educational purpose, the Simulator shall provide basic information about relevant

plant systems and each component's behavior during the severe accident propagation and progression, along with the basic equations and theory for the physics model of that system or component. This will assist in the understanding of the basic principles associated with the reference nuclear power plant. It is suggested that this information is displayed by clicking on an '**INFORMATION**' button on severe accident scenario;

20) It is desirable that the Simulator include a '**HELP**' button located within the tool bar, as illustrated in Figure 3.2 that shall provide a basic overview of the controls of the Simulator reference plant behavior during severe accident propagation and progression, and include a search function so that the user can look for help by inserting key words;

21) On schematic diagrams, the containment position shall be clearly identified; for example, on a diagram which does not show the structure of the containment but does show flow paths in/out of the containment, a line shall be included to represent the containment boundary;

22) The units associated with each parameter shall be included in every of its occurrence.

3.2. MAIN FEATURES OF THE SEVERE ACCIDENT BASIC PRINCIPLE SIMULATOR

3.2.1. Postulated Accidents Scenarios

The Simulator shall enable design basis accidents scenarios and severe accidents scenarios initiating from full-power, part-power operating condition and from reactor shutdown condition. The design basis accidents shall be defined based on the reference plant specifics to include as a minimum small, medium and large LOCA, loss of flow, and loss of Class IV power scenarios.

The severe accidents scenarios shall as a minimum include the following:

- Station black out (SBO) scenario leading to severe core damage;
- Complete loss of feedwater flow (LOFW) scenario;
- Steam generator tube rupture (SGTR) scenario.
- LOCA leading to severe core damage and H_2 release to containment
- Scenario leading to RPV failure and MCCI (e.g. failure of ex-vessel flooding)

3.2.2. Severe Accidents Alert Functions and Interactive Control Systems

Table 3.2 provides a list of the alarm parameters, instruments, monitoring objectives, and related strategies as an example that the Simulator shall include with the purpose of helping the trainees understand the accident scenario, plant behaviour and measures to be taken. The Table shall be fully completed for the proposed severe accident Simulator.

The Simulator Manual shall provide detailed descriptions of the models applied, assumptions included, and level of details provided within the simulation model of the postulated accidents' scenarios.

TABLE 3.2 List of Severe Accidents Alert Functions

Parameter	Content provided in Simulator	Monitoring objective	Related instrumentation	SAM Measures
Secondary Side	• Pressure • Radiation	• Tube rupture	• Radiation level	MSIV
Reactor cooling system	• Pressure • Temperature • Void	• Integrity • Coolability	• Primary coolant system pressure and temperature	Depressurize
Reactor core degradation	• Reactor core exit temp. • Fuel temp. and cladding oxidation • H_2 production	• Core damage	• Core water level	Core flooding
Reactor core melting	• Fuel melting • Cladding melting • Control rods melting	• Core damage • Fuel relocation • Eutectic formation • Fission product release	• Core outlet temperature	Core flooding
Relocation	• Porosity • Tracking of materials • Tracking of H2 • Tracking of fission products	• RPV Integrity • Fission product release	• Core outlet temperature • Core bottom temperature	Core flooding
Containment	• Pressure • Melt coolability and concrete interaction (MCCI) • H2 mixing • H2 combustion • Fission products release	• Integrity/ failure • Control H2 concentration and combustion • Control fission products release	• H2 detectors • Radiation detectors • PARs	Venting Manual spray activation Fan activation

3.3. SOFTWARE REQUIREMENTS FOR THE SEVERE ACCIDENT BASIC PRINCIPLE SIMULATOR

The Simulator will be used by many individuals in many IAEA Member States, running on computers of various specifications. As a minimum, the Simulator shall be capable of running in the Windows 7, 8 and 10 operating systems. The Simulator shall be flexible to accommodate future changes in operating systems.

The Simulator shall be capable of plotting parameters in real time. It shall be possible to plot more than one user defined simulation parameter on a single chart. Plots shall be able to be exported into Microsoft

Office programs or exported as image (.png, .jpg) files. The user shall be able to manually change the scales and ranges on plots in addition to there being an automatic scaling feature (to give optimum display). The Simulator shall be capable of generating a full transient report (e.g. events table) along with any associated plots that the user may require. These reports shall show the details and time of occurrence of any user or Simulator initiated plant status change. The Simulator shall be capable of using the computer's printer drivers to print charts or reports directly from the Simulator software. It shall also be capable of saving these to .pdf format.

To ensure that the Simulator is of value to as broad a range of users as possible, it would be highly desirable for the Simulator to be programmed such that it is platform independent and able to run on a wide range of operating systems. For example, this could be achieved through a web browser interface that is common to various operating systems. Where possible, standard programming languages, communications protocols, subroutines, macros, software parts and software development tools shall be used. Exceptions shall be clearly stated in the tender submission. Any parts of the code that are hardware or operating system dependent shall also be identified explicitly.

The Simulator shall include facilities to allow the user to record the scenarios' data from any selected simulation. The Simulator shall be capable of saving simulation data to standard file formats (e.g. comma separated variable, Microsoft Office Excel) so that it may be analysed by users later.

All software written by the Contractor shall use standard coding practices. Comments shall be used extensively to explain the operation of the program. The following items shall be considered when developing the code:

- Variables and constants must follow the naming convention as defined in the user manual's glossary;
- Variables and constants within the code shall be appropriately defined with correct units;
- Derived or empirical values generated during development must be identified as such.

The Contractor shall provide to the IAEA the underlying Simulator code and data, for maintenance, development and use in other simulators (***optional requirement***).

3.4. HARDWARE REQUIREMENTS FOR THE SEVERE ACCIDENT BASIC PRINCIPLE SIMULATOR

The Simulator shall be capable of running on general purpose desktop and laptop personal computers with a minimum CPU speed of 1.5GHz, requiring at most 4GB of runtime memory and 50GB of data storage.

3.5. SIMULATION CONTROL

3.5.1. Initiation

The Simulator shall enable the user to be able to initiate a simulation by selecting a set of initial conditions (ICs) and pressing a 'run' button.

3.5.2. Initial Conditions and Standard Scenarios

The Simulator environment shall enable the user to start a Simulator from various plant conditions by choosing from the list of predefined ICs, and execute a standard severe accident scenario, as illustrated in Table 3.4.

The Simulator shall enable the user to generate a customized set of initial conditions for operational conditions of a reference plant; the severe accident scenarios shall be well defined and conditions for initiating such scenarios well explained.

TABLE 3.4. Simulator Initial Conditions and standard Scenarios

Initial condition reference number	**Plant initial state**
1.	100% power, end of core life.
2.	100% power, middle of core life.
3.	100% power beginning of core life.
4.	Hot zero power
5.	Hot reactor critical condition
6.	Cold shutdown condition
7.	Refueling shutdown conditions
Standard scenario reference number	**Severe accident scenario**
8.	SBO
9.	LOFW
10.	SGTR
11.	LOCA leading to severe core damage and H2 release to containment
12.	Scenario leading to RPV failure and MCCI (e.g. failure of ex-vessel flooding)

3.5.3. Simulation Time Control

A Simulator shall run in real time, except for very fast phenomena, such as hydrogen combustion, where a less-than real time condition shall be clearly indicated. In addition, it shall be possible for the user to manually slow or speed up the run time during the simulation.

The Simulation shall be able to be frozen and restarted at any time. For this, the Simulator shall include a ‘freeze’ button that allows the user to pause the simulation at any point, which shall also pause associated data recorders and plots. The Simulator shall include a ‘run’ button that shall restart the simulation from the point at which it was paused and a ‘stop’ button shall ask the user to save the Simulator’s data records and plots before exiting the simulation environment. These Simulator functions are illustrated in Figure 3.2. It shall also be possible for the user to step through a simulation; at the end of each time step the simulation shall freeze until the user initiates the next time step manually. This shall be useful for tutorial purposes or for debugging behaviour during scenarios.

3.5.4. Snapshots

At any point during simulation, the Simulator shall enable the user to freeze the simulation and copy the plant conditions to a new custom set of ICs in a ‘snapshot’, or “restart file”. This will allow new simulations to be started from that state in the future.

3.5.5. Backtrack and Replay

During the simulation, the Simulator shall automatically record plant conditions at a limited set of user defined transient times. The user will then be able to 'backtrack' the simulation to one of these stored sets of plant conditions.

3.5.6. Malfunctions

The Simulator shall enable the user to initiate one or more malfunctions either from a predefined list of generic malfunctions or by manually overriding the performance of one or more specific components. This will allow the user to see how the simulator responds and to learn how best to operate the plant in this faulty condition.

4. ADDITIONAL REQUIREMENTS

4.1. DOCUMENTATION

As a minimum, the Contractor shall provide the IAEA with the following documentation:

— Design specification: detailed design specification shall be provided to the IAEA;
— Complete Simulator User Manual, to be distributed by IAEA to its Member States upon request.

4.1.1. User Manual

The User Manual shall include as a minimum, the following sections (Microsoft Word or pdf):

1. Introduction
2. Purpose
3. Historical background
4. Simulation principles
5. Description of the reference plant design and its various systems and clearly state any parts of the plant which have not been simulated; inclusion of diagrams is desirable
6. Simulator installation, start-up and initialisation instructions
7. Discussion of the main features of the Simulator and its operation
8. List of Simulator display screens and description of their main features
9. Simulator exercises for standard operations – steps taken and expected results
    a) Introductory exercises
    b) Reactor Start-up and Heat up
    c) Power manoeuvre: 10% power reduction and return to full power (for both turbine lead and reactor lead)
    d) Reduction to 0% full power and back to 100% full power
    e) Turbine trip and recovery
    f) Reactor trip and recovery
10. Simulator exercises for "standard" severe accidents scenarios, with clearly described changes in plant state and expected results
    a) SBO leading to severe core damage
    b) LOCA leading to severe core damage and H_2 release to containment
    c) Scenario leading to RPV failure and MCCI (e.g. failure of ex-vessel flooding)
11. Detailed description of mathematical models
12. Description of control logic used in the Simulator
13. Glossary explaining any acronyms used
14. References
15. Appendix I: software description
16. Appendix II: hardware requirements for Simulator

4.2. SCOPE OF SUPPLY

In addition to the provisions of Article 11 of the IAEA General Conditions of Contract, IAEA shall acquire all exclusive rights, including all transferable intellectual property rights (IPR) and use rights, in the Simulator, including its specification, algorithms, architectural approach and technical solution and specifically all rights in software, sources and comments as contained therein. Such rights shall include the absolute right to develop, modify or have modified such software.

There shall be no licence fees, once the Simulator is handed over to the IAEA.

There shall be no limits on the number of users that can use the Simulator.

4.3. TESTING, ACCEPTANCE AND TRAINING

The following process will be followed for initial verification and validation of the Simulator:

- *Verification* conducted by IAEA to confirm that the program code is a correct implementation of the functional requirements, including the physical models and control logic.
- *Acceptance testing* by IAEA staff and subject matter experts through an IAEA consultation meeting. This will involve extensive trials of the Simulator. The focus for this testing will be ease of use of the Simulator (e.g. GUI) and realism of the plant behaviours, specifically during the postulated severe accidents. Following this, changes may be requested that the Contractor shall implement prior to acceptance of the Simulator by the IAEA.
- *Acceptance Test Procedures* shall be provided to IAEA by the Contractor prior to delivery of Simulator.

During verification and acceptance testing, all discrepancies shall be recorded and tracked by both the Contractor and the IAEA.

The contractor shall provide software revisions and bug fixes to resolve issues identified during verification and acceptance testing.

After acceptance by the IAEA, training (3 days minimum) shall be provided by the Contractor to three IAEA staff on the use and administration of the Simulator.

4.4. SOFTWARE UPGRADES AND AFTER SALES SUPPORT

The contractor shall provide any software upgrades to the Simulator made for any reason for a one-year period, starting on the day of acceptance, as well as 3 days training related to the upgrades of the Simulator for three IAEA Staff.