COMMON MODELLING APPROACHES FOR TRAINING SIMULATORS FOR NUCLEAR POWER PLANTS

FINAL REPORT OF A CO-ORDINATED RESEARCH PROGRAMME
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Training simulators for nuclear power plant operating staff have gained increasing importance over the last twenty years. Initially they were needed to train operators for the large number of nuclear power plants being built in the late sixties and early seventies. Due to the base load operation of most nuclear power plants and their high availability factors, it was recognised that insufficient hands-on operating practice was possible to train new operators and retrain the already qualified staff, and training simulators were the preferred alternative to practising on the actual units. The need for training simulators was further recognised as a result of analysing the operator errors that lead to the accidents at Three Mile Island and Chernobyl.

One of the recommendations of the 1983 IAEA Specialists' Meeting on Nuclear Power Plant Training Simulators in Helsinki was to organize a Co-ordinated Research Programme (CRP) on some aspects of training simulators. This recommendation was approved following a thorough review of the proposed term of reference, and the programme started in 1985 under the auspices of the Nuclear Power Division of the IAEA.

There were six countries represented at the initial meeting in October 1985. The group of participants increased to eight in 1986, but returned to the original level of six for the closing session in 1988.

The main task of the initial meeting was to determine the goal and objectives of the CRP, as well as the main methods of co-ordination.

The goal statement was: "To establish and maintain a common approach to modelling for nuclear training simulators based on defined training requirements". Before adapting this goal statement, the participants considered many alternatives for defining the common aspects of training simulator models, such as the programming language used, the nature of the simulator computer system, the size of the simulation computers, the scope of simulation. The participants agreed that it was the training requirements that defined the need for a simulator, the scope of models and hence the type
of computer complex that was required, the criteria for fidelity and verification, and was therefore the most appropriate basis for the commonality of modelling approaches.

It should be noted that the Co-ordinated Research Programme was restricted, for a variety of reasons, to consider only a few aspects of training simulators. This report reflects these limitations, and covers only the topics considered within the scope of the programme.

The information in this document is intended as an aid for operating organizations to identify possible modelling approaches for training simulator for nuclear power plants.

EDITORIAL NOTE

In preparing this material for the press, staff of the International Atomic Energy Agency have mounted and paginated the original manuscripts and given some attention to presentation.

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1. INTRODUCTION

Training simulators for nuclear power plant operating staff have gained increasing importance over the last twenty years. Initially they were needed to train operators for the large number of nuclear power plants being build in the late sixties and early seventies. Due to the base load operation of most nuclear power plants and their high availability factors, it was recognised that insufficient hands-on operating practise was possible to train new operators and retrain the already qualified staff, and training simulators were THE preferred alternative to practising on the actual units. The need for training simulators was further recognised as a result of analysing the operator errors that lead to the accidents at Three Mile Island and Chernobyl.

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The goal statement was: "To establish and maintain a common approach to modelling for nuclear training simulators based on defined training requirements". Before adapting this goal statement, the participants considered many alternatives for defining the common aspects of training simulator models, such as the programming language used (ASSEMBLER, FORTRAN or higher level), the nature of the simulator computer system (analogue, digital or hybrid), the size of the simulation computers (micro, mini, mid-size or main-frame), the scope of simulation (basic principles, part task, limited scope, or full scope) or the type of reactor (PWR, BWR, CANDU, Gas Cooled). The participants agreed that it was the training requirements that
defined the need for a simulator, the scope of models and hence the type of computer complex that was required, the criteria for fidelity and verification, and was therefore the most appropriate basis for the commonality of modelling approaches.

Using the goal statement, the following six objectives were derived:

1. Establish and maintain techniques for job and task analysis.

2. Establish and maintain methods for the definition of training requirements.

3. Establish and maintain methods for relating training requirements to the appropriate modelling approaches.

4. Establish and maintain a library of modelling approaches which have been demonstrated to satisfy training requirements.

5. Establish and maintain a data base of hardware and software tools for implementing nuclear power plant models.

6. Establish and maintain criteria for simulation methods for their verification.

The following methods for co-operation were agreed on:

1. Summary of the major achievements from each national contributor to be presented at the annual meeting.

2. Report of progress and accomplishment were to be sent periodically to the IAEA Responsible Officer for distribution to all participants. These were intended to be working copies of the annual report.

3. Informal meetings between national representatives as appropriate.

4. Annual meetings (sponsored by the IAEA in 1985, 1986 and 1988, and by the representatives' own organization in 1987) to report on and discuss results achieved, and agree on future work as required.
It should be noted that the Co-ordinated Research Programme was restricted, for a variety of reasons, to consider only a few aspects of training simulators. This report reflects these limitations, and covers only the topics considered within the scope of the programme.

In the following six chapters the main results of the co-ordinated research programme are summarized.
2. JOB AND TASK ANALYSIS

2.1 INTRODUCTION

The purpose of training is to impart to the trainee(s) the knowledge and skills required to perform a job and/or task to the specified level. The method by which the knowledge and skill set is established is called job and task analysis.

Job and task analysis is usually the first step in the Systems Approach to Training Design, the other steps being:

- design
- development
- implementation
- evaluation.

In the case of nuclear generating station training simulators, the analysis phase has a major impact on the ultimate cost and usefulness of the simulator. A job and task analysis phase that identifies the correct set of training exercises to be performed on the simulator enables the appropriate complexity of models to be developed, defines the appropriate set of acceptance (commissioning) tests to be performed, allows a smooth start to the simulator training programme, and minimizes future software modifications and upgrading costs. The job and task analysis should also identify those parts of the training programme which will not be done with aid of the simulator, but will need other training approaches, including on-the-job training.

The following are the three main steps that lead to the design and development of a training programme:

a. needs analysis, to determine the likelihood that a new training programme is the appropriate way to correct an identified performance problem (instead of new equipment, changed work method, a new job aid, etc.);

b. job analysis, to determine which major components (jobs) of an enterprise or of the activities of groups of individuals, requires a new training programme;
c. task analysis, to determine which components (tasks) of the previously selected jobs require training.

Analysing the operating record of utilities operating nuclear generating stations worldwide, as well as accidents such as Three Mile Island and Chernobyl, has determined that the job of shift supervisors and control room operators requires training on a full-scope replica training simulator for the majority of control room operations. Each utility and each generating station may, however, have unique circumstances which determine which specific tasks performed in the control room should be included in the simulator training programme, and which ones can be performed most effectively in a different training environment.

In this section the key steps involved in task analysis are described, with an emphasis on training simulator applications. Although separate task analyses are needed for shift supervisors and control room operators, the process of analysis is the same, so no distinction between the two positions is made in this description.

2.2 TASK LISTING

At most utilities the tasks of shift supervisors and control room operators are documented in operating manuals, instructions, guidelines, local practices and similar documents. These reference documents should be thoroughly analysed to ensure that all tasks are listed, and that there are no incomplete or contradictory instructions amongst them. A useful guideline for defining individual tasks is to ensure that there is a specific output to each task. For example, responding to an alarm is typically the level to which a job is broken down. The collection and initial screening of this data can usually be done by individuals familiar with the jobs of shift supervisors and control room operators, but experts from the affected positions must agree that the task listing is a full description of all of their duties.

In case of having to do a task analysis prior to the station having become operational and prior to the required documentation having been prepared, the analyst would have to rely on documentation from a similar, already operating station, and update the task list as actual data became available. (Such a task list may also be helpful to ensure that all relevant station documentation was produced.)
2.3 COLLECT TASK DATA

A systematic approach is required to analyse the applicability of the (usually) very large amount of information collected during the task listing phase. The following decision points should be followed to identify those tasks which should be included in the training programme, and eliminating those items from the documentation which should not. The process of analysis should be led by a training professional experienced in the method of job and task analysis, but the evaluation of each item must be done by the best of the incumbents, and the results verified by their supervisors.

a. Many items in the operating documents do not refer to a task, but may be there as a guideline or for information purposes only. Even if the particular item is part of a procedure, it may describe a state, or describe actions in general terms. These would not normally lead to specific requirements for a simulator, and may therefore be excluded from the task list. All items remaining on the task list will be procedures to be carried out by or under the supervision of the shift supervisor or control room operator.

b. Procedures which do not directly involve the shift supervisor or control room operator should be removed from the list. From the items that remain on the list, the ones which are carried out directly by the position holder should be identified. It should also be noted whether direct action or supervision of others or both of these are involved in carrying out a procedure. All the items which have been identified to involve the position holder in one or both of these actions is a potential candidate for inclusion in the training programme in which the particular procedure should be included, and the degree of emphasis needed.

c. The typical frequency of occurrence of each identified procedure needs to be determined, and classified on the basis of HIGH frequency (at least once a month), MEDIUM (2-10 times per year) or LOW frequency (one a year or less).

d. The criticality of action is the next important parameter to be analysed. It is HIGH if improper task performance leads to severe consequences that will be time consuming and costly to correct (action on unplanned events should be initiated within a few minutes, and from
essentially memory); MEDIUM classification would be used if improper task performance leads to fairly serious consequences that may require considerable corrective action (action on unplanned events should be initiated within a few minutes); a LOW classification would be assigned to items for which improper task performance makes little difference in plant operations (action on unplanned events should be initiated in one or two hours).

e. The difficulty of learning the diagnosis and response to the situation covered by the procedure is also a significant factor in determining the type of training needed to achieve the desired performance. A HIGH degree of difficulty would be assigned to procedures which involve the diagnosis and/or response to complex events, which would be very difficult to learn to perform correctly without significant formal training and practice; MEDIUM classification should be assigned to fairly complex events which can be learnt to be performed correctly given sufficient time to train, however formal training and practice would make the learning easier and faster; events which are relatively easy to learn to diagnose and carry out without formal training and practice, would be classified as LOW.

f. Having completed the analysis of the various procedures, systematic decisions may be made as to which ones should require formal testing, and/or training and/or refresher training. Having followed the above methodology, the following decision rules are recommended:

- any item that has HIGH or MEDIUM rating in urgency, should be tested;

- any item that is rated LOW in urgency but HIGH in learning difficulty should be tested;

- of the items selected for testing, those rated HIGH or MEDIUM in learning difficulty should be trained;

- of the items selected for training, those rated LOW in frequency should be refreshed.

All control room instruments and indications involved in the above tasks would be replicated on the simulator, and all plant parameters displayed on these devices would need to be modelled.
The process by which the results of the job and task analysis lead to training requirements, and these to modelling requirements, are described in the next two chapters.
3. TRAINING REQUIREMENTS

3.1 INTRODUCTION

Based on the results of the job and task analysis, and taking into account the entrance level of education as a selection criterium, the training requirements for the different members of the shift staff can be defined.

In most countries, the training of the operators can be roughly divided in three parts:

- a fundamental training in reactor engineering, including a stage on a training reactor and a basic principles simulator at a training center.

- getting knowledge in the components and the primary and secondary system, including on-the-job training at a reference plant.

- training of plant operation on a full-scope simulator.

Besides this pre-license initial training, there is a post-license training (retraining) in which the simulators play an important role. In most countries the management of the plant is responsible for a sufficient level of training.

In the following, requirements for initial training and retraining are laid down with the emphasis on the role of simulators.

3.2 TRAINING REQUIREMENTS FOR FUNDAMENTALS AND PLANT CONCEPTS

During initial training and fundamentals refreshing, classroom lectures are complemented with demonstrations and exercises on basic principles or concept simulators. After this training phase the trainees are required to know and understand the following principles and functions (18), (31).

3.2.1 Reactor and Reactor Cooling System

- The laws of reactor kinetics, including subcritical multiplication, control rod characteristics, approach to
criticality by using control rod characteristics and 1/n plot, influence of delayed neutrons on reactivity, reactor period and the control of the chain reaction.

- The reactivity feedbacks of the fuel temperature (doppler), the reactor coolant density (temperature, pressure and void), xenon and samarium poisoning and fuel burn-up, regarding the integral and local effects in the core under different burn-up conditions.

- The reactivity budgets necessary for start-up from cold and hot shutdown or for changing power levels with regard to the desired power distribution and operational limitations. For PWR's there are limitations like DNB-ratio, constant axial offset control, shutdown margin. For BWR's there are restrictions like critical power ratio, linear planar heat generation rate.

- The principles of reactivity control by the rod control system and the boron concentration for PWR's and recirculation flow control and rod control system for BWR's.

- The consequences of using the different methods of reactivity control on the operational limits and the principles of corrective actions to maintain the operational limitations.

- The laws of heat transfer and thermohydraulics regarding the heat removal from the fuel rods, energy transport from the reactor cooling system to the turbine and the heat sink functions of safety, steam relief and turbine bypass valves, turbine condenser and suppression pool of BWR's.

PWR specific are the functions of pressurizer, steam generator and atmospheric steam dump valves. BWR specific are recirculation system, steam relief and turbine bypass valves.

3.2.2 **Principles and function of control systems**

- The principles of control systems and controllers with their characteristics and behaviours.
The fundamentally different control principles in PWR and BWR to coordinate reactor and turbine power, based on the natural load following behaviour due to positive pressure coefficient of the BWR and the negative coolant temperature coefficient of the PWR.

PWR specific are the control of coolant temperature by the control rods, the primary system pressure by pressurizer heater power and spray flow, the pressurizer level by charge and let down flow of the chemical volume control system, the steam generator level by the three element feedwater controller and the generator power by the turbine control valve.

BWR specific are the control of the power level by the recirculation flow, the steam pressure and turbine power by the turbine or bypass control valve, the reactor water level by the three element feedwater control system and the power distribution in the core by adjustment of the control rod pattern.

3.2.3 Plant systems and components

The requirements are knowing and understanding the physical phenomena in components and system and their consequences on dynamic system interaction and plant behaviour.

- The principal properties of water and steam and their relevance to the behaviour of systems and the balance of plant during start-up, shutdown and power operation under normal and abnormal conditions.

- The principles of mass and energy balance related to components like steam generators, pipes, turbines, pumps, condensers and heat exchangers, as well as for the balance of whole plant under steady state and transient conditions.

- The function of energy conversion in pumps and turbines and their relevant characteristics of static and dynamic behaviour.

- The principal operational limitations of important components due to mechanical, thermal or radiation conditions.

- The potential reactivity feedbacks and influence on heat removal from the core due to events in plant systems and components.
3.3 SIMULATORS FOR FUNDAMENTALS TRAINING

Basic Principles Simulators are used to develop a deep understanding of the principal functions and physical phenomena governing the behaviours of the reactor and the most important plant systems. To achieve this, special man-machine interface techniques are used to visualize and demonstrate physical effects which are not so obvious on the instruments of real plants and full-scope replica simulators.

Because of the limited scope of the simulated systems, the input-output signals and simulation models of Basic Principles or Concept Simulators are cost effective training tools for initial training and refresher training in fundamentals and plant concepts. They are used for vendor independent, generic training simulators (1)* or as plant simulators (2 - 10), depending on the national training situation.

3.3.1 Procedural training requirements

The additional requirements for operating a plant are:

- To reinforce the theoretical knowledge and understanding of fundamental principles and concepts.

- To recognize instrumentation failures and follow the relevant procedures.

- To know, understand and use the various controls, instruments and alarms of the simulated systems.

- To understand and perform the typical procedures, to know the events that can occur in the systems and to develop the skills necessary for corrective actions.

- To develop the skills required to control the actual plant systems with regard to the operating and administrative operating procedures.

* For references in round brackets, see Appendix 1.
- To develop a correct mental model of the dynamic system interaction based on observation of the control room instrumentation and the detailed system and component knowledge acquired during the preliminary training.

- To recognize and diagnose abnormal behaviour and problems early, by analysing the available information, symptoms and trends of indicated signals.

- To know and understand the strategies of plant procedures and corrective actions to mitigate and to control malfunctions and abnormal events according to the relevant and operating procedures and technical specifications.

- To develop the ability to anticipate plant responses to operator actions, equipment failures and accidents.

3.3.2 Simulators for procedural training

Part task and microsimulators provide a limited scope of the reference plant and a selective simulation of the relevant systems and components. The simulation models of the simulated systems are very detailed, providing all necessary input-output signals for the main operating procedures to train individual operators in a time and cost effective way before full-scope simulator training.

Full-scope replica simulators simulate all plant systems, they are plant specific and can be used for training of all operating procedures covering start-up, shutdown and power operation under normal, abnormal and accident conditions [1].

3.3.3 Team work training requirements

- To function as a member of the control room team by applying teamwork, communicating effectively within the team and understanding the different roles of the other team members.

- To work cohesively in diagnosing and correcting problems and initiating appropriate and co-ordinated recovery actions.
- To develop awareness and experience of changes in team behaviour and communication under accident conditions.

Full-scope simulators are the only training tools to develop proficiency in use of operating procedures, integrated system operating skills and team work as a member of the operating team under all operating conditions.
4. MODELLING REQUIREMENTS

The modelling requirements should be defined based on the training requirements. This means that the plant to be simulated should be considered with respect to:

- systems, subsystems and components to be included
- operational regimes of the systems included
- physical phenomena to be seen in simulator responses.

4.1 SYSTEMS TO BE SIMULATED

The scope of the simulation should be defined depending on the required use of the simulator. Different systems, subsystems and components of the plant can either be included or left out from the simulation. In a full-scope simulator it is important that all the systems the operator is using for taking the plant through the required exercises are included for the simulation. In a part task simulator only those systems directly involved in the defined task need to be included. Some of the included systems may also be simplified to account only for their functional characteristics.

For part task simulators there are different simplifications possible e.g. lumping parallel lines together to form a single line with the same capacity. Auxiliary systems such as component cooling, lubrication, etc. can be left out to some extent also in full-scope simulators. A part task simulator can be concentrated only on one specific subsystem e.g. the reactor in the case the simulator is intended to be used for illustrating the main dynamics of reactivity, neutron inventory, xenon poisoning, etc.

When the systems to be included have been defined, then the main variables to be simulated can be specified. This means that temperatures, pressures, flows, water levels etc. are listed for each of the systems.

4.2 THE OPERATIONAL REGIME

The operational regime of each of the simulated systems, subsystems and components should be defined. On a general level this means that one should consider
- normal operation
- start up and shutdown operation
- disturbances and accident conditions

For a full-scope simulator it is necessary to have the whole range of operation starting from a cold shutdown condition of the plant and including also emergencies caused by severe malfunctions of different components. In part task simulators a more limited range of abnormal conditions are included based on the training requirements specified.

For part task simulators the range of operation could be restricted e.g. to power operation or specific system manoeuvres.

On the component level different simplifications can always be made with regard to operational regime e.g. a tank is considered to contain water all the time, which means that the pipes, pumps and valves used to fill the tank could be left out.

4.3 PHYSICAL PHENOMENA TO BE SEEN IN THE SIMULATION

An important part in the definition of the modelling requirement consists of the specification of different physical effects to be seen in the simulation. This means that the systems and transients to be simulated should be described with respect to the phenomena, which should be possible to observe.

The specification of the malfunctions should be carried out in the same way by stating the different effects, which should be seen when the malfunctions are activated.

Examples of the specifications of this kind are:

- the core should be simulated in such a way that the effects of a new core versus an old core could be seen.

- the shrink and swell of the primary coolant as the effect of changes in the coolant temperature should be seen.

- the effects of local boiling in the primary circuit should be seen during the loss of coolant accidents.
4.4 MODELLING ACCURACY

The modelling accuracy should be defined for the different systems and transients to be simulated. The modelling accuracy can be defined both in a quantitative and a qualitative way. The quantitative requirements should be subdivided into requirements in a steady state and requirements during transients of the simulator. The accuracy requirements during the transients are generally lower than during steady state conditions.

The accuracy is not necessarily the same for all the variables simulated. Special care should be taken to ensure a sufficient accuracy of the simulation of the main variables of the plant.

The accuracy requirements for transients could be subdivided into requirements for the values and requirements for the time-constants. The value requirement means that an excursion observed in one of the simulated variables should be of the correct magnitude. The time accuracy means that the excursion should have the correct duration.

A typical qualitative requirement for full-scope simulators is that the operator should not be able to observe any difference between the response of the simulator and the reference plant. Another essential requirement is that the ordering of events signalled, e.g. by the alarm log, should be correct.

In addition to the requirements for real time simulation there are cases, where either a slower or a faster than real time simulation is needed. A slower than real time simulation is usually easy to achieve, but a faster than real time simulation can usually be obtained only for processes evolving very slowly in time.

4.5 COMPUTATIONAL REQUIREMENTS

Training simulators are usually intended to be operated in real time. This sets very strict requirements both on the models and on the computer to be used for the simulation. Advancing the simulator a small time step requires the calculation of all the model equations, which then should be possible to do in a shorter time than the time step in consideration. The computational load will depend very heavily on the type of transients exercised. It is therefore advantageous to specify the computational requirements on a worst case timing consideration.
One way to ensure the real time requirement in all transients is to build in a catch up facility, which will detect a momentary overload of the computer. In the case an overload is occurring, then the time step is momentarily increased to allow the computer to catch up the real time of the simulation.

Numerical stability of the solution is very important to ensure during all types of simulated transients. The numerical stability depend on the method used for integrating the differential equations and on the size of the time step used. Explicit integration methods always place a danger of numerical instability for large time steps. Implicit methods have the advantage of being numerically stable for large time steps and they also ensure that the solution will converge towards the correct steady state.

Special care should be used in handling the water and steam properties, because they will exercise a considerable computing load. In (11) a method for a fast calculation of the material properties has been suggested.

The solution of the thermohydraulic load flow (simulation of the piping network) can be handled using a matrix formalism. Accounting for the sparsity of the matrices, makes it possible to get very rapid calculations (12).

The feature of the models to indicate that their range of validity has been exceeded would be very valuable from a training point of view. With such a feature it is possible to signal a warning to the instructor that the responses of the simulator may not be valid any more. One such signal could be connected to the real time requirement to indicate that the capacity of the computer has been exceeded. Other signals could be connected to the indication of certain model assumptions, which are not valid anymore e.g. the emptying of a tank supposed to contain water.

4.6 OTHER REQUIREMENTS

The modelling requirements will also be influenced by the operational requirements of the simulator. One of the operational requirements is connected to maintaining and changing the models. A simulator will always grow in complexity with time and therefore it is important to be able to include new models, to make the modelling more refined and to change the parameters of the models included. The simulated plant will also undergo yearly revisions, which might be necessary to reflect in the simulator.
To ensure enough flexibility in maintaining and changing the simulator the modelling approach should be modular. The parameters of the models should be collected to well defined parameter areas and should not be written into the main body of the program modules.

There should also be enough flexibility for additional computers to be included to account for expansions in modelling scope and accuracy.
5. MODELLING APPROACHES

5.1 INTRODUCTION

Real-time modelling of the complex processes of nuclear power plants needs
- deep understanding of the physical phenomena to be modelled,
- modelling experience to formulate the problem properly,
- mathematical skills to solve effectively the formulated problems,
- great amount of experiments to determine the permitted
  simplifications and their effects on accuracy, transient behaviour,
  etc.

- accurate transient measurements for fitting the tunable parameters of
  the models.

For the above reasons one well-tested and verified model is a very
valuable product. The modelling requirements defined in Chapter 4 determine
basically the modelling approaches to be used during the construction of the
simulator.

In the last 20 years very extensive development has been done in this
field and now some basic methods can be formulated. The most important basic
rules can be summarized as follows:

- a model should be clear, structured, self documented and well
  commented,

- those parameters which form connections to other models should be
  listed at the beginning of the module,

- data structures should be defined only once and all models include
  this definition,

- the use of transfer functions and algebraic expressions must be used
  with care, usually differential equations are recommended.
5.2 MODEL CONSTRUCTION METHODS

Three different kinds of modelling approaches can be distinguished as

- special purpose models,
- general solutions,
- best estimated codes.

Special purpose models divide the simulated process according to technological units and every aspect of the given unit is described in the same module. The advantage of this approach is that the model is compact, well documented and easy to replace by a new one. However, this method is not effective when large networks (hydraulic, electrical) are involved, because the same element types (e.g. valves) are described in different models many times (and sometimes many ways).

General purpose models describe physical phenomena instead of technological units. Typical application areas:

- hydraulic networks (pressure, flow, concentration, etc.),
- electrical networks (current, voltage),
- automatics (plant logics, safety logics, etc.).

The advantage of this approach is that it provides a unified solution for every component of the same type and the description of the actual plant topology is easy.

Best estimated codes can be used only on super computers (above 30 Mips, and the capability to vectorize processing). In these codes the simulated process is described as in safety analysis codes. This approach provides very accurate results but it requires extreme computing power.

5.3 CORE MODELLING

Practically two different kinds of core modelling approaches are used in full-scope simulators: coupled point kinetics method and expansion based method. In general for cores with large physical dimensions (e.g. CANDU cores), the coupled kinetics method can be better if the nodal structure is fine enough [2, 3]. The major advantage of the expansion-based method in the
case of PWR cores is that it provides a fine and realistic flux distribution with less CPU load than the coupled kinetics method [4]. Since the arrangement of a fuel assembly, the control rod movement and the coolant flow in a PWR core are all in the axial direction, the expansion based method emphasizes the solution in the axial direction and the neutron flux distribution, with different computation rates [5]. However, coupled kinetics method are widely used with very good results [6, 7].

For basic principles simulators one dimensional core models are also used with good results [8, 9]. Point models with six delayed neutron groups will usually suffice.

5.4 THERMODYNAMICS MODELS

The thermohydraulic modelling for a PWR is simpler than for a BWR, because (except for abnormal cases), single-phase flow can be assumed in PWRs. In general, one-dimensional analysis of the network is adequate to calculate the pressure and flow. The basic equations can be derived from three conservation laws:

- conservation of mass,
- conservation of momentum,
- conservation of energy.

Fortunately, the temperature change is very slow in most cases, therefore the third equation can be solved independently from the first two.

The flow in a closed network is either laminar or turbulent. If the Reynold's number is small enough (less than about 2000), the flow can be regarded as laminar and the flow rate is proportional to the pressure drop of the given component. This assumptions can be used for valves, seals, and filters. However, more often the flow is turbulent, in this case the flow rate is proportional to the square root of the pressure drop. This nonlinear relationships has to be linearized and the general method for the solution of the system equations is to use matrix representation. Because the thermohydraulic pipe networks are usually sparse, sparse matrix techniques can be applied [10].
In BWR simulators, and during loss of coolant accidents in PWR simulators, two-phase thermohydraulic models have to be used. In these models separated field equations for the mass of both fluid components (vapour and mixture of liquid and vapour), separated liquid and vapour energy equations, and integrated field equation for mixture momentum are solved [11, 12]. A great amount of different thermohydraulics models exist, so here we can only refer to the literature [13].

5.5 PRESSURIZER MODELS

In general point models with lumped parameters are used [14, 15, 16, 17] for modelling the physical behaviour of a pressurizer. Most often three volumes are used: two for liquid and one for vapour phases. Energy balance and volume balance equations for the liquid and vapour phases are formulated. The following assumptions can be used:

- spray water droplets reach the water surface at saturation temperature,
- the specific volume of the water phase is equal to that in the saturated state,
- the energy change caused by the alterations of the water specific volume is neglected.

Since the primary cooling circuit is a closed system and the liquids are practically incompressible, if a given quantity of water is injected through the spray water system into the pressurizer, the same mass of water will flow through the surge line into the reactor vessel. This is an immediate effect. However, when subcooled water is injected through the surge line into the pressurizer, first the incoming water acts as a piston and the pressure will be increased. A heat equalization will take place between the subcooled and saturated water volumes with finite mixing time. This can be modelled as a heat transport through a surface separating the saturated and subcooled volumes. The heat transfer coefficient depends on the number of operating electric heaters because the circulation caused by the heaters affects the heat transfer. If the incoming water enthalpy is higher than the saturation enthalpy, the equalization process terminates promptly, because the boiling takes place in the whole water volume immediately.
Steam generators are specific to PWRs and CANDUs, and very different models are used for the different plant types.

All of these models calculate the heat transfer from the primary coolant in the same way. Only the nodalization of the primary side is different, it changes from three to fifteen nodes.

The heat transfer calculation in the secondary side is more diverse. There are two main methods to solve this problem: the direct method and the simplified one.

In the direct method the downcomming and raising paths of the natural circulation are nodalized and the nodes are calculated separately. This method can be very accurate but time-consuming.

In the simplified method the effects of the various velocities of the natural circulation are either neglected or calculated from experimental curves. This method is based on the direct dependence of the heat transfer from the heat flux itself.

Having the heat transfer determined, the state of the secondary side is usually calculated from a point model with lumped parameters from the following equations:

- conservation of mass,
- conservation of energy,
- the sum of the volumes of different phases, gives the known volume of the SG.

In some cases, however, the correct description of the behaviour needs more than one node in the secondary side (steam header rupture, shutoff of the fast isolation steam gate valve, etc.).

There is another, but important parameter to be calculated: the water level swelling up. This phenomenon is essential in modelling of the water level controlling automatics. The direct method describes this effect correctly; for the simplified method some further assumptions are needed to calculate the steam volume below the water surface.
5.7 TURBINE MODELLING

The secondary circuit of a nuclear power plant differs considerably from the conventional ones because the turbine operates at a much lower temperature and greater water content. Extensive research has been carried out in this field [1, 19 – 23] to develop accurate models with small CPU load. The usual approaches are based on point models with lumped parameters in which several stages of the turbine are concentrated into one model. However, the HP and LP turbines need different descriptions.

Most of the HP turbine models contain two parts: one is a chamber distributing the inlet steam and the other is an energy converter. In the chamber the inlet, outlet and extraction flows and pressures determine the state properties of the steam. Taking into account the mass balance equation and the heat transfer between the chamber and its wall, this problem can be solved. It can be assumed that flows as a function of pressures follow the Stodola's law [24]. In the energy converter adiabatic expansion is assumed. The thermodynamic efficiency can be calculated from the exhaust steam flow using a second order polynomial.

The structure of the LP turbine models is similar to that of HP turbines, but here the expansion crosses the saturation line and at the end of the expansion two phase flow has to be calculated. However, experiments have shown [18, 19] that there exists a metastable expansion at the great distance below the saturation line, where only steam is present. In other words, the spontaneous condensation can be neglected and this expansion can be described by the Wilson theory [18].

5.8 WATER/STEAM PROPERTY CALCULATION

The calculation of water/steam properties (specific density, specific enthalpy, etc.) is essential for modelling the turbine. Basically two methods can be used:

- different approximation functions,
- lookup tables.

For approximation methods polynomial approach [25] and spline technique [26] can be used. These two methods were compared [9] and the spline
technique provides faster solution. The benefit of the approximation functions is the small memory demand and their continuity, however, these methods are time consuming.

The use of lookup tables is very fast but it needs large memory space. However, property calculations can be done in reasonable memory size if variable step length is used with pointer tables describing the step changes in the whole argument region [27].

5.9 **REGENERATIVE HEATER AND CONDENSER MODELLING**

For the regenerative heaters point models can be used [23] containing three parts:

- a mixer,
- a coller, and
- a concenser

of the bleed steam. Mixing is defined by mass and heat balance equations. In the cooler the overheated heating steam is cooled until its saturation, while in the condenser this saturated steam is condensed. In the condenser the steam content is defined by its property parameters and separate saturated steam and saturated water flows can be calculated.

Both the bleed cooler and bleed condenser are calculated as heat exchangers.

5.10 **POWER GENERATOR MODELLING**

Real-time simulation of electrical power generation requires the modelling of the main generator with is excitation system and the representation of the power grid. In general the turbine model provides the net mechanical power for the main generator, while the later computes shaft acceleration of the turbogenerator complex. The main generator model is basically an energy balance equation of a rotating body, where the grid is represented by a load and an inertia [28]. Since electric power networks can be described by network equations similar to pipe calculation equations [29], the same sparse matrix solution method can be used for solving the electric network equations as for pipe networks [10].
5.11 **CONTAINMENT MODELLING**

The function of a containment is to retain the radioactive products in case of failure of the pressure system boundaries, by preventing their release to the environment. The containment can be separated into the following main parts as:

- drywell, which contains the pressure vessel,
- hotwell, which contains the suppression pool, where the steam coming from the drywell is to be condensed,
- a pressure-relief separator device connecting the hotwell and the drywell.

The containment model has to take into account the temperature, pressure, humidity, water level, etc., in case of emergency situation [30].
The earlier chapters have described many of the essential training and technical considerations that lead up to determining the need for a training simulator, and choosing the scope and complexity of the models. In order to realize a working training tool from these concepts, they must be translated into hardware and software. This chapter describes the essential hardware and software tools that are required to develop and execute the simulation modules so that a working simulator that meets the Training Requirements is realized.

The choice of hardware for a simulator is derived from the Training and Modelling Requirements. The Training Requirements would have determined the extent of replication of the main control panel and its instrumentation, and in combination with the Modelling Requirements the type and capacity of the simulation computer, as well as the nature of the panel to computer interface, are essentially determined. It has to be noted that a full scale simulator is a very large installation needing different support systems, such as

- Main Power Control Centre, which filters, controls, protects and distributes the incoming power,
- Fire Protection System,
- Panel Check-out System, which permits the checking of all devices in the Control Room,
- Suitable building with air conditioning.

The limited scope simulators are much smaller configurations which can be installed in a normal classroom.

Similarly, the type of software environment needed, the extent of a real time executive and supporting utilities, are essentially determined by the scope of the proposed simulator.

Because the nature of the equipment is significantly different between a full-scale and a limited-scope simulator, they are described under separate headings.
6.1 FULL-SCOPE SIMULATOR HARDWARE

6.1.1 Main control panels

The Main Control Panels provided with a full-scope simulator are usually replicas of the reference plant's control room panels. The front-of-panel appearance, feel, operation and dynamic response should be completely realistic, by using the same models and types of indicators, handswitches, pushbuttons and annunciators, whenever possible. Exceptions from full replication should be identified in the Training Requirements.

Process controllers need to be stripped-down versions, having only the front-of-panel controls available to the trainee, the control algorithms being contained in the simulation software.

It is usually preferred to have the Main Control Panels, with all the instrumentation, as well as all other control room equipment and other objects to be replicated in the simulator control room, to be supplied by the original control panel instrument vendors. In cases where the simulator is being acquired several years after the reference plant was built, considerable difficulties may be experienced in obtaining the desired instruments.

6.1.2 Main control panel interface

The Main Control Panel Interface processes the necessary inputs and outputs between the Main Control Panel and the Simulator Computer System. It consists of an intelligent controller or a special computer, I/O buffers, and a number of chassies containing the fuctional elements for digital inputs and outputs, and analogue inputs and outputs. All I/O should be performed at least at 10 Hz (20 Hz preferred) in order to give the appearance of continuous motion.

The interface system should have its own power supply, and extensive self diagnostic features.
6.1.3 **Simulator computer system**

The capacity of computers required to meet the typical Training Requirements of full-scope replica simulators has increased significantly over the years, both in terms of memory and execution speed. A typical configuration can be considered to consist of a quad VAX-11/780 system, that includes a shared memory that provides for efficient communication between the various modules of the simulation program. Any other computer system that meets or exceeds the memory, computational and I/O capabilities of the VAX 11/780 could also be used as a simulation computer, for example a dual GOULD 6780.

Typically each of the four computers would have at least 5 Mbytes of main (private) memory, a large moving head disk and a control console/floppy disk subsystem. Shared memory capacity should be at least 512 Kbyte.

The moving head disks and magnetic tape units used in the system would be connected to their processors via Massbus adapters (or equivalent), which should provide a throughput of at least 2 Mbytes/second. All other peripherals may be connected to their processors via Unibus adapters (or equivalent), having a throughput of at least 1.5 Mbytes/second.

Computers that can execute best estimate code require at least 30 MIPs of execution speed, such as Cray XMP 14, or an Alliant FX40.

6.1.4 **Plant process monitoring computers**

Most nuclear power plants constructed in the last ten years utilize computers to monitor and/or control (and in a few recent plants also to protect) key station parameters and systems. There are three basic approaches for realizing the functions of such plant control or monitoring computers:

(a) The plant computers may be replicated in hardware, and their original software modified to allow for such simulator specific functions as freeze, initialize and malfunction insertion. Particular care has to be taken to supply information from the simulation computer in a form suitable for the plant monitoring computer.
(b) If the type of computer used in the reference plant is no longer available, or not suitable for simulator operation, another computer, with a sufficient degree of software compatibility to the plant computer, can be used.

(c) In certain cases it is more advantageous to regard the plant computer as one of the process systems, and simulate its functions via the simulation computer.

In each of the above cases, the peripheral equipment essential to control room operations (such as keyboards, printers and display units) should be replicated to the extent possible with equipment available at the time of simulator manufacture.

The choice of method depends on the availability of identical or similar hardware, the compatibility of the plant and simulation computers, and the complexity of the functions performed by the plant computer.

6.1.5 Instructor console

The instructor's facility allows for the monitoring and control of the training session. From the hardware point of view two basic types may be distinguished: those which are in the form of a permanent installation, with several CRTs, usually separated from the simulated control room, and the transportable systems, consisting of typically one CRT and keyboard (or even simpler input/output devices), located within the simulated control room.

The CRTs should present to the instructor a comprehensive set of parameters which monitor the state of the simulated plant, allow for the introduction of malfunctions and the modification of preselected parameters, as well as such simulator specific functions as freeze, initialize, etc. These functions can usually be realized by alpha-numeric CRTs, although as the amount of information to be handled by the instructor increases, it has been found that his task is made more effective by using graphics monitors with colour capability. The input device may be the regular keyboard, or one that is specifically designed for the task, or direct input via the CRT, such as mouse, force stick or touch sensitive screen.
Limited scope simulators can be either compact simulators or basic principles simulators. In compact simulators the modelling complexity of the plant is similar to that of full-scope ones, but the similar appearance to the real control room is omitted. For this reason this device is considerably less expensive than a replica simulator and its hardware is much smaller. In basic principles simulators most of the plant specific features are also omitted and only basic physical relationships are modelled. For this reason its hardware is even simpler.

6.2.1 Man/machine interface

The man/machine interface of limited scope simulators consists of control panels with hardwired instruments and CRT display units. The instruments may be a subset of the ones actually used at the reference plant, particularly for compact simulators designed for a specific generating unit, or they may be chosen on purpose to be different, to avoid the danger of confusion between the limited scope simulator and the real plant.

The CRT display units may be used to supplement the information presented on the instruments, such as graphical trends of parameters not normally measured, or the CRT may be the man/machine interface itself, displaying images of the instruments as well as parameter trends, and providing input to the model via a touch screen or other cursor control devices.

These different type of man/machine interfaces, their impact on hardware and software requirements, as well as their advantages and disadvantages are covered in considerable detail by the annual reports of the participants in the co-ordinated research programme.

6.2.2 Simulation computer system

Since limited scope simulators can be constructed with quite different machines, this section can provide only examples and any computer having similar computing capacity can be used.
A compact simulator can be composed from two micro-VAX computers because relatively high computing capacity and at the same time very limited I/O capacity are needed. In general there are not so many variables that common multiport memory would be needed. The two computers can be connected to each other via some kind of data network (e.g.: Ethernet). Both computers need at least 4-Mbyte operating memories and large capacity disc units. The Control Desk and the display terminals are connected to one of the two computers through an asynchronous multiplexor unit. All of the I/O transfer are organized with one computer and in this way the whole computing power of the other CPU can be used for number-crunching.

A basic principles simulator needs the computing capacity of at least a PDP-11/44. Here again some Mbyte operating memory is needed and a large capacity disc support is essential. Floating point arithmetic unit is highly recommended. The control desk and the terminals are connected to the computer in the same way as in compact simulators.

The computer required for a micro-simulator is typically a good quality personal computer, such as an IBM-PC/AT with a mathematical coprocessor. The graphics capability of such machines needs to be improved, the resolution provided by the Enhanced Graphics Adapter (EGA) is usually acceptable. The use of a touch-sensitive screen is the preferred input device.

Often the choice of computer will depend on local preferences, including servicing and previous experience of the training centre with a particular machine.

6.3 SOFTWARE

The simulator software consists of the following major elements:

(a) A real-time simulator executive, which controls, schedules and manages the operation of the simulator. This executive is specifically developed for the needs of a training simulator environment, over and above the standard operating system of the selected simulator computers.
(b) Simulation software, which solves the mathematical models of the generating station systems within the constraints of the real time environment.

(c) Communication software, which transfers the information between the data base and Man/Machine interface system (Control Room or Control Desk).

(d) Development and maintenance tools, which perform program compilation, linking, updating, testing, debugging and file creation and maintenance.

6.3.1 Executive software

The operating system of the simulation computers will be able to direct the operation of the entire simulator. It will be able to ensure that efficient use is made of all system resources, support both on-line and off-line software development, perform all supervisory functions, error handling, processing, and interfaces to all system components. In particular, it will include the following features:

- task management
- interrupt handling
- task scheduling
- memory management
- file management
- device handlers/drivers
- error and diagnostic routines
- operator commands
- batch processing

6.3.2 Simulation software

The simulation software can be divided into three main parts as follows:

- model programs,
- equation solution system,
- common subroutine library.

Modelling approaches are described in Chapter 5 thus they are not treated here.
Since most of the models are described in the form of differential equations some kind of common equation solution system should be used. Because different kind of integrating methods are needed for the different models depending on their mathematical character, thus different solution algorithms have to be incorporated in the equation solution system.

A common subroutine library is usually written to contain those functions which are needed in different models, such as water/steam properties.

6.3.3 Communication software

Communication is a very great task in full-scope simulators; it is much smaller in limited scope ones. In full-scope simulators it is divided into two main parts as:

- control room communication, and
- plant computer communication.

In the area of Control Room Communication it is essential that the output variables could be overwritten or drifted if the instructor wants to do that. For the simulation of malfunctions in the instrumentation these features are needed. The data-transfer to and from the control room should be organized in such a way that the feeling of continuous operation is provided.

The Plant Computer Communication should transfer data to and from the plant computer with the same rate as in the real plant. Here the collection of the events from the different models is crucial, because the correct order of events is essential for the event logging function of the Plant Computer.

6.3.4 Development and maintenance tools

The various software tools available for the manufacture and maintenance of a simulator greatly contribute to the efficiency of the software development and modification process. The following is a sample of the important software tools that are currently available, and their main features:
(a) Precompilers, which resolve the symbolic references to the data base.

(b) Macro Assembler that has the following capabilities:

- all assembler passes to be stored on disk
- symbolic addressing
- mnemonic representation of instructions
- absolute and relocatable object code
- complete error diagnostics
- free format source statement input
- ability to define macros within the user program
- conditional assembly directives
- cross reference table symbol listing.

(c) FORTRAN compiler of the optimizing type, with extensions that improve programming efficiency for real time applications and reduce development costs. The compiler, FORTRAN 77 or equivalent, should have the following features:

- comprehensive diagnostic capability
- the object code generated by the compiler should be position independent
- support external functions and procedures written in assembly language
- able to create shareable code
- able to generate a symbolic listing from any compiled program
- the libraries used by the High Level Language should be re-entrant and compatible with the Assembler coded programs
- the compiler should provide for the conditional compilation of statements.

(d) Text Editor to create, modify and maintain source program files. The editing capabilities should include the following:

- upper and lower case characters
- single and multiple line additions, insertions, replacements and deletions
- identification of field sequence checking and labelling
- random or sequential updating capabilities.
(e) Library Update and Cataloging utility to maintain object program libraries on disk. It should be capable of:

- object program addition and deletion
- renaming and duplication of object programs
- library listing, copying and resorting
- cataloging of load modules
- capability of creating and initializing directories.

(f) Link Editor and Loader to link and combine an assembled main program with object programs of all relevant subprograms into a single executable program which has no unresolved references. Such self-contained modules are ready for execution, or for storing in the object library. The Link Editor and Loader should also be able to generate a comprehensive symbol table map.

(g) Data File Creation and Maintenance utility to access, create and modify catalogued data files. This processor should have the following features:

- creation and maintenance of a random access directory
- creation and maintenance of data sets within a directory
- file compare function
- file dump function.

(h) Debug processor to find programming errors interactively. Using this processor, execution of a program can be traced, selective dumps of memory and register contents can be specified, and modifications made to the program. The Debug processor should have the following capabilities:

- activate and abort the program to be debugged
- display and modify selected memory locations and general purpose registers
- set multiple breakpoints or stop under specified conditions.
7. FIDELITY AND VERIFICATION

7.1 INTRODUCTION

It has been recognized along this Co-ordinated Research Programme that one of the main difficulties was to establish accuracy requirements and the definitions of the basis for comparisons. In the past, reference data could be either obtained from the Final Safety Analysis Reports (FSAR) or simply by the good engineering practice of the instructors. The need to increase the realism of nuclear power plant simulators has led that those transient responses are not adequate for simulator comparisons. The objective of this chapter is to analyse the actual sources of information available and to define an approach to evaluate the fidelity of the models to be developed.

7.2 SCOPE OF THE SIMULATOR

The first step is to define the cases that the simulator should cover, depending on the type of plant, number of systems and components to be included and detailed phenomena to be observed by the simulator users in close relation with the range of operation and the transients to be performed (13).

The methodology suggested by EPRI [31] was used to define the dynamic modes to be covered for each one of the main equipments and then identify the minimum set of transients that will exercise all the dynamic modes.

7.3 CURRENT CRITERIA

In spite of the simulators have to generate a realistic picture of the real process with the result that an experienced operator cannot notice any essential difference in comparison with the real reference plant [32].

This general statement has been followed by some specific quantitative criterions. As no European standard exist, most of the countries use the American National Standard ANSI/ANS 3.5 [33] as the basis of comparison and it has been used by some simulator manufacturers as a guide for their modelling requirements.

The ANS standard sets numerical criteria for accuracy in terms of the allowable error. In the standard there is a definition of what are the
critical variables. However there is no specification of what should be the basis for comparison, implicitly assuming that there will be a data base with the "true" answers.

In the Electric Power Research Institute (EPRI) work [31], published in 1985, the main criterium is that the comparisons between the simulator and benchmark codes or data, have to go through the "control room filter".

Having a control room filter means that the only variables that are of interest for validation purposes are the variables that the operator can see. It also means that the accuracy expected does not have to be greater than the instrument accuracy and that the transient response will be subjected to the filtering of instrument inertia.

The EPRI work also offers several definitions of error to be used in comparisons.

The work done by EPRI was carried out considering that the benchmark code should be used to compare the simulator results would be RETRAN, even though the methods recommended could be applied with any other code.

There is a steering committee at the Nuclear Regulatory Commission (NRC) of the United States discussing what the requirements for the nuclear simulators should be.

The information from the NCR committee has not been analyzed and it is unknown whether it is available to the public at this date or not.

7.4 DISCUSSION

The difficulty to define the basis for comparisons increases when it is realized that usually the scope desired for the simulators goes well beyond the range currently covered by plant data, and also, to the limit of reliable applicability of the codes commonly used, and the experiemental data available to support them.

Regarding the ANS criteria, it is commonly accepted that FSAR transient responses are not adequate for simulator comparisons, since generally they represent limiting responses rather than "best estimates". The other
limitation is the lack of specification of the cases that should be run to consider that a simulator has been validated.

In the EPRI methodology the first limitation is the assumption that all the comparisons are going to be done against a given code. There is no guidance on what to do in the cases where it is desired to use the simulator and the base code is not applicable.

The suggested definitions for the errors become difficult to apply without further considerations when one is looking at long transients (thousands of seconds) where there might be a time shift between the responses being compared, that would result in seemingly large differences at a given time, event though on an overall analysis both responses may be in acceptable agreement.

The other problem is the excessive emphasis on the variables that the operator is able to see, that in some cases are only indirect indications of the plant status. Even though it is true that a simulator is for operator training and that if for all cases it correctly displays the variables observed by the operator it is doing its job, it seems that there are other variable selections that could make the comparison procedure simpler and more reliable.

7.5 PROPOSED CRITERIA

Based on the discussion stated above some considerations should be considered before establishing reasonable accuracy requirements for nuclear plant simulators. (14)

The desired scope, current data available, accuracy of the best estimated codes and instruments of the plant, events perceived by operators such as time and sequences are important considerations to be taken into account to define the criteria.

7.5.1 Accuracy requirements

These accuracy requirements provide some guidelines for defining simulation fidelity experienced by some of the participants to perform the prescribed operating events with the level of realism required to satisfy
the criteria of the job and task analysis. We consider that there are five aspects that have to be satisfied but that have different nature in themselves.

1. Time of the events.
2. Sequence of the events.
3. Magnitude of the variables observed.
4. Trends
5. Final state.

TIME OF THE EVENTS. The accuracy in timing of the event should be defined in terms of what a person can perceive. Some figures are included in reference (15). The relationship between the happening of an event and the values of the relevant state variables should be maintained. This means that the occurrence of an event is related to time, but also, and some times more strongly, is related to the behaviour of other variables.

SEQUENCE OF EVENTS. This is closely observed by the operators and should be watched exactly in the transients.

MAGNITUDE OF THE VARIABLES OBSERVED. An overall criteria could be 5%, provided that the other criteria are also satisfied and with the restrictions somewhat relaxed (15).

TRENDS. Overall trends should be matched, emphasizing direction more than precise rate of change.

FINAL STATE. This criteria is essential and it must be insured that after a given set of actions the simulator goes to the appropriate final state, even if there are some deviations in some parts of the evolution. The deviation of the magnitude of the critical variables observed have to be less than ± 1% if the instrument accuracy of the readings or the "best estimate" predicted value allow this accuracy.

7.5.2 Variables that should be compared

It is suggested that the variables that should be used as primary basis for comparisons are not necessarily the ones observed in the control room.
The variables to analyze are the "state variables":

1. Pressure.
2. Liquid temperature.
3. Gas temperature.
4. Liquid mass.
5. Vapour mass.

These variables are a smaller set than the control room variables and also they are a direct representation of the true state of the system. If the state variables are correctly predicted there is assurance that the future evolution of the system will be adequately predicted and that the control room signals can be correctly calculated.

7.5.3 Basis for comparisons

The simulator should be compared against the benchmark data base, that will necessarily be integrated by:

1. PLANT DATA. This represents a small fraction of the overall scope of the simulator but its importance is evident.
   - Steady state reference plant data.
   - Operational transient data for the reference plant.
   - Data collected during commissioning test.

2. BENCHMARK CODES. Supported by experimental evidence obtained from separate effects tests and full scale and reduced scale systems tests.

3. OTHER. "Educated guesses" on the expected plant behaviour for those situations outside the proven range of the codes.

Example of validation methodology

This methodology was applied by one of the participants in order to validate a full-scope Boiling Water Reactor type simulator upgraded with new models corresponding to the Nuclear Steam Supply and Containment Systems. The new simulator scope had to achieve the training requirements.
imposed by use of the symptom based emergency procedures, developed since TMI accident, in order to evaluate the transient and initiate appropriate operator actions. Since the performance of these procedures drives the plant to situations far beyond the capabilities of the actual simulator, new advanced models were developed.

In reference (16) is shown how the dynamic modes were defined, the transient selection, the matrix decision between dynamic modes and transients, the critical variable definition and the validation transients execution with some results included.
8. CONCLUSIONS

The participants of the Co-ordinated Research Programme (CRP) had experiences in and were actively working on a wide range of training simulators, from advanced full-scope to basic principles and micro-simulators. This wide range of expertise was particularly remarkable considering that only eight countries participated in the programme.

The main accomplishment of the Co-ordinated Research Programme for the Development of Common Modelling Approaches for Training Simulators for Nuclear Power Plants was that the participants were able to combine their wide range of experiences and interests to establish a common approach to modelling for all these cases.

The participants concluded that a process which is based on the ultimate training goal of the simulator should be the basis for defining the modelling approach. A detailed analysis of the training needs ensures that the model developed to meet these needs will neither be too simple, nor excessively complex, resulting in more efficient software development, simplifying future software modifications, as well as minimizing the complexity, cost and maintenance needs of the hardware.

However, because of the wide breadth of the subject matter, the relatively few participants in the programme and the commercial nature of many technical details, only selected aspects of the chosen common modelling approach could be investigated, and no claim is made that all aspects of training simulator modelling were covered in-depth. Similarly, the maintenance aspect of the common approaches, i.e. the documentation of new techniques, will be the task of a future group.

The participants found that while there were significant interactions and exchange of ideas, these were more at the conceptual than the detailed technical level, because of the limited extent of overlap in the fields of interest of the participants. Prior to the start of the CRP, the original scope was narrowed significantly, but it was found to be still too ambitious for the small group to cover in greater depth.

The annual meetings were an excellent forum for interaction, and the technical discussions were aided significantly by the distribution of many of
the country reports prior to each meeting. It was also very fortunate that a specialists' meeting was held during the course of the CRP, at which the participants were able to meet in addition to the Agency sponsored meetings. The specialists' meeting also helped to obtain additional material and to learn about each other's programmes in greater depth.

In order to obtain greater in-depth results, either the scope of the work would need to be restricted to people who work in closely related aspects of the chosen topic, or one or more participants should devote a significant portion of their time (possibly with specific Agency funding) to the compilation of the data. Although a wealth of information exists on various aspects of training simulators, much of this is still proprietary to the simulator manufacturer, or has not been organized into a readily usable form. Since the interests of manufacturers will always be to keep much of their capability in-house, owners of simulators and future users should exchange information amongst themselves in order to keep abreast of developments. The Agency could be instrumental in this process.

The report's main topic was modelling approaches, but the software aspects could not be considered independently from the hardware. However, only the main features of the hardware were covered, the reader must turn to other documents for an in-depth treatment. Similarly, although training requirements were an important part of this CRP, the use of simulators in training could not be considered. Both of these important topics could be the subject of future Agency sponsored programmes.

It is hoped that the results accomplished during this CRP will be of use to others in the nuclear power plant training simulator field.
REFERENCES


[31] EPRI REPORT NP-4243: "Analytic Simulator Qualification Methodology"


Appendix 1

REPORTS SUBMITTED TO THE IAEA BY THE CRP PARTICIPANTS


(13) BWR Simulator Training Requirements, Tecnatom, S.A. Spain.


(15) Accuracy Requirements for Nuclear Simulators, Tecnatom, S.A., Spain.


(18) Darlington Negative Pressure Containment System, Ontario Hydro, Canada (1985).


(22) Fast Solution Methods for Real Time Simulation, Technical Research Centre of Finland, Finland (1986).


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