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ACCURACY, EFFICIENCY, VERSATILITY

SPANISH SIMULATORS FOR THE 90's

E. UGEDO

This new decade is known in many economic sectors as the decade of human factors. This means that strategic priorities in research and application of advanced technologies will be aimed at studying human behaviour and the different factors linking it to the machine and the productive process, always attempting to achieve better productivity and safety rates.

The electrical industry worldwide is channelling extensive resources through its companies, organizations and institutions toward the development of methods and tools that will facilitate the supervision and control of electrical power generating stations. Relevant subjects such as the degree of automation of plant control systems and the resulting distribution of duties between man and machine, early failures detection systems, optimization of alarm management in control rooms, implementation of real-time graphic terminals as operator-process interface, mechanization of operating procedures, etc., are being thoroughly debated in conferences and seminars, while methodologies are being developed and prototypes built in research firms and institutes.

When dealing with human factor-related issues, it is necessary to carefully examine the means for education and training of power generation plants operating personnel.

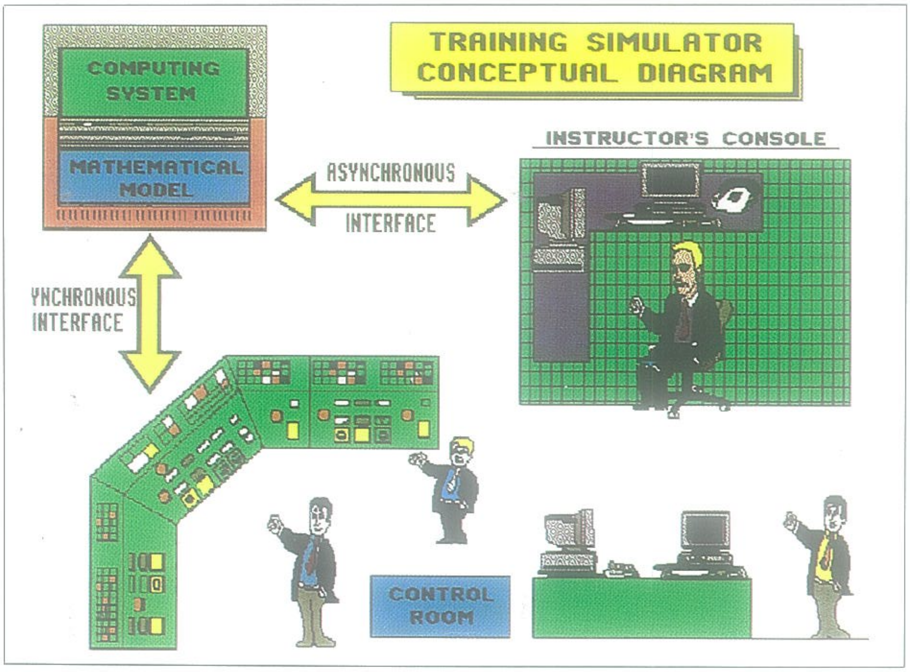
Since its implementation at the end of the decade of the 60's, the training simulator has been proving its efficiency as a vehicle for transferring knowledge and a laboratory for acquiring experience in highly qualified technological training. In the aeronautical and nuclear-electrical generation industries, where safety and availability factors require high levels of professional skill, the different kinds of training simulators are widely used. This article describes the role that the simulator plays in the professional training process of electrical power plant operators, and the evolution of the simulators to date.

Thanks to the ongoing attention paid by the Spanish electrical sector to matters of professional training, evidenced by the multiple efforts and resources devoted to training methods and means, the utility-owned Tecnatom's training centre has consolidated for the decade of the 90's an outstanding technological base at the service of personnel who watch over the operational efficiency and safety of electric power generating plants.

INTRODUCTION

In broad outline, the professional qualification of operating personnel in complex industrial facilities involves a thorough knowledge of the physical principles that form the basis of the industrial process (theoretical training), a detailed familiarization with the facility's design features and technical-administrative procedures (technological training), and the professional experience required to supervise and control the process under any possible operational scenario (professional skill). In addition to these eminently technical qualities, professional operating personnel must possess another series of attributes of a psychosomatic nature, such as emotional stability and physical fitness that maximize the safety and efficiency factors of the man-machine complex.

The technical qualification is posed in terms of knowledge and skills that any one professional should possess to efficiently perform the functions inherent in the job. By grouping together the knowledge and skills into homogeneous subject matter and rationally sequencing them, a series of quantifiable and measurable teaching objectives will be obtain-



F I *Training Simulator - Conceptual Diagram.*

ed that will help to design, develop and validate the corresponding training programs.
Part of the learning program, generally of a scientific and technological nature, is acquired in the country's official technical schools and colleges, while the more specific aspects are entrusted to specialized training centres, either forming part of the facility owner's organic structure or as independent organizations. Representative examples are the aeronautical industry, where the large airlines either individually of jointly provide training centres for crew members and other specialists, and the nuclear-electric generation industry, which promotes its own training centres.

PERSONNEL TRAINING IN SPANISH NUCLEAR DEVELOPMENT

The positive results of the first generation of Spanish nuclear power plants and the power crisis in the early 70's led to a change in the structural configuration of power generation, with an increasing participation of fission-based energy sources to the detriment of oil derived fuels.
The extent of the construction program that was undertaken at that time involved the creation in some cases and the consolidation in others of the industrial infrastructure required for Spanish companies to play an increasingly important role in the different activities associated with the design, construction, erection, startup and operation of power plants.
The capacities to be developed included the integral training of operating personnel, both in disciplines of a theoretical and technological nature and in practical experimentation, i.e. training in a medium that helped the future operator acquire individual experience and the control room crew obtain the team coordination required to successfully deal with operational scenarios.
When the Spanish electrical utilities were confronted with the construction plan for second generation plants, they decided to centralize component inspection and personnel training services in Tecnatom, pursuing objectives of economy of scale, extensive availability, maximum efficiency and development of in-house technology.

THE SIMULATOR'S ROLE IN PROFESSIONAL TRAINING

Before the simulator appeared on the scene, operators were trained somewhat "in the fashion of surgeons", i.e. looking over their colleague's shoulder or manipulating the controls of low-power plants devoted to research activities. Such was the case in the Saxton plant in Pennsylvania that was equipped with a 5 MW reactor, where the first crews for the José Cabrera nuclear power plant were trained back en 1966. In no case was it possible to provide operating practice under emergency conditions.
At the end of the 60's and the early 70's, the four main North American suppliers of nuclear steam generation systems introduced training simulators in their training programs. The creation of mathematical models expressed in computer language that were capable of real-time reproduction of the dynamics of physical processes associated with electrical generation facilities, thus permitting a man-process interaction by means of an interface similar to a real life interface, helped to resolve the above indicated deficiencies. In effect, the new device provided the environmental and operational scenarios for individual and team practice in maneuvers contemplated in the real facility operating manuals, both under normal and incidental conditions and without risk to the components or affecting availability. The simulators used for training purposes consist of four basic elements, as illustrated in the diagram in Figure I:

— Mathematical models.
— Computing system.
— Operator interface.
— Instructor's console.

The *mathematical models* represent the logic and dynamic relations between the variables of the simulated physical processes. The simulation's *realism* will to a large extent depend on the precision of the models used, as well as the accuracy of the data obtained from the reference plant (geometric dimensions, materials friction and heat transmission coefficients, pumping element dynamic characteristics, etc.).
The number of modelled systems and components will determine the *scope* of the simulation. Thus, the so-called *full scope* simulator includes all the systems required to execute the reference plant's operating procedures both under normal conditions (excluding refuelling operations) and in emergencies. On the other hand, the *partial task* simulator includes one or a few systems in the mathematical model.
The *computation system* includes the computer with its memory units, auxiliary equipment, input/output units and associated base software. Its function is to execute the programmed mathematical models in real time by responding to control signals both from the operator interface and the instructor's console and generating calculated variable values that update the informative instrumentation (indicators, registers and status lights) that are accessible to the operator or instructor. It is obvious that the system's power will be determined both by the accuracy and scope of the models.
The *operator interface* is the operator's means of communication with the process control model. It allows the operator to modify the functional status of dynamic components (valves, pumps, switches) and to receive updated information on the evolution of controlled variables. In so-called *specific* simulators, the operator interface is a duplicate of the simulated facility's control room, both as regards control instrumentation and architectural aspects of the environment.

Finally, the *instructor's console*, which is the neuralgic center of the simulated installation, plays a dual role; on one hand, it allows the instructor to alter the dynamics of the current process by triggering signals that represent component abnormalities, changes in the functional state of components that cannot be controlled by the operator, and modification of variables external to the process (heat sink temperature, grid frequency or voltage, etc.); on the other hand, it enables the instructor to execute the simulator's pedagogic functions such as supervising and recording the operating crew performance.

As of 1975, the nuclear power plant operator training simulator industry began to consolidate its activities with the appearance of the first American standard, ANS-3.5, which formally defined the functional characteristics to be fulfilled by this training medium and helped user companies precisely specify the desired product.

The first orders were placed by electrical utilities, lead by Con. Edison (Indian Point), Duke Power (McGuire), Tennessee Valley Authority (Browns Ferry and Sequoyah), and VEPCO (North Anna) in the United States, and by the German consortium KWS (Biblis A and Brunsbüttel), the Swedish consortium AKU (Ringhals and Oskarshamn), Electricité de France (Bugey), VTT of Finland (Loviisa), and Tecnatom (Cofrentes and Lemóniz) in Europe. Canada and the Asian countries with nuclear power plants also included simulators in their training systems at that time. The increasing use of simulators proved their high level of efficiency both in transferring knowledge and promoting professional skill.

THE SPANISH TRAINING CENTRE'S SIMULATORS

Tecnatom's simulators fall into the *full scope and specific* category, and they typify the two concepts of light water plants that represent second power generation units. The main supplier was the North American company Singer-Link, which was awarded a turnkey contract after open bidding.

A Tecnatom team (operational specialists, modelling engineers and hardware technicians) was assigned to the manufacturer's installations throughout the entire construction period of the simulators, not only to thoroughly control product quality, but also to acquire experience for subsequent application to the maintenance and upgrading of the trainers during the in-service period.

Technological self-sufficiency in this field of activity is of utmost importance if the complexity of the models and the need for modifications and improvements on an almost daily basis are taken into account. This is due to the following reasons:

— The specific nature of the simulator, which makes it necessary to incorporate all modifications made in the reference plant and affecting the simulator's performance. As is well known, design changes in nuclear facilities are frequently made, especially after the TMI incident in March of 1979.

— Operating experience provided by plants with a similar design, which reveals new incident scenarios and requires precise modelling of the associate phenomenology.

— Functional discrepancies that are detected in the simulator as its performance is compared to operational data produced by the reference plant.

All this requires a very qualified structural support that appreciably affects operating costs but which serves to maintain high levels of quality in tune with the importance of the services rendered by the simulators.

Throughout the 12 years since they were introduced, simulators have been used at an average rate of 2,650 hours/year for the PWR and 1,324 hours/year for the BWR. The most common applications have been practical courses for obtaining operator and supervisor licenses, seminars for preparing for the license examination, and periodic requalification courses for license holders. In addition, more than twenty applications have been developed, not only of an educational nature, but also analytical applications aimed at qualitatively evaluating possible system design modifications in reference plants.

Table I shows the number of trainees that have attended the Tecnatom training courses at least once during the period 1979-1990.

T I

Candidates to Operating License	
Foreign plants	123
Angra I (Brazil)	
Caorso (Italy)	
Döel (Belgium)	
Laguna Verde (Mexico)	
Leibstadt (Switzerland)	
Qinshan (China People's Republic)	
Trino (Italy)	
Spanish plants	245
Total	368
(This collective does systematically requalify itself on an annual basis)	
Technical Personnel with different appointments from electrical utilities, engineering companies, regulatory agencies and others	
Foreigners	667
Spaniards	2,662
Total	3,329

ENGINEERING CODES FOR THE FULL SCOPE TRAINING SIMULATOR

Training simulator technology has been under continuous development to try to extend the valid range of models used, and thus increase the number and complexity of accident scenarios posed to operators. Two essential factors have made this possible:

— Availability of thermohydraulic and neutron codes from which sufficiently validated models are derived that faithfully reproduce very complex phenomenological scenarios.

— Availability of a computing configuration that provides the technical and economic calculation capacity required to execute the above models.

Both circumstances prevailed in the second half of the preceding decade, and thus Tecnatom decided, as did most simulation centers, to thoroughly modernize its simulation models and, as a result, the computing support platform.

The simulation centers considered three possible strategies for the modernization process, which are discussed below in order of less to more complexity and cost:

Updating

This consists of a timely and continuous upgrading of already existing models to achieve more realistic behavior in response to certain phenomena; eventually, it could include the addition of more computing power in the event that existing equipment is saturated. In fact, from the time they start training activities, all simulation centers perform corrective maintenance to resolve functional model discrepancies, until technological advances in the field of codes and computer equipment advise an in-depth revision such as the one considered in the two following alternatives.

Reconstruction

This consists in keeping the current operator interface (control room), and producing much more accurate models both thermal-hydraulic and neutronics for nuclear steam supply systems. The associated increase in computing power involves a change in the computing platform to more powerful configurations. During development of new models, the old configuration is maintained to continue rendering training services until it can be replaced, after a brief interruption in services. This alternative poses logistic problems, as two configurations must coexist and vie for the sole operator interface. It is viable only when the training load is light and the old and new configurations can share the operator interface. The economic advantages of this solution are appreciable only when the simulator owner organization can manage training and remodelling activities with its own assets.

Replacement

This consists in the construction of a whole new simulator and keeping the old configuration for training purposes. As there are no shared elements, reciprocal interferences between construction (new simul ɔr) and training (old simulator) activities are avoided. The construction period is shorter than in alternative b), but the costs are higher.
By weighing the cost and availability factors, each training center has adopted its own strategy. The *replacement* strategy has been adopted by several centers in the United States, while in Europe there is a tendency to opt for construction and updating.

RECONSTRUCTION OF TECNATOM'S SIMULATORS: THE SAM PROJECT

On the basis of experience accumulated throughout seven years of simulator operation and updating, Tecnatom decided on the *reconstruction* solution.
The first step was to define the concrete dynamic behavior required of the new models, in order to resolve the intrinsic limitations of the old model. Table II

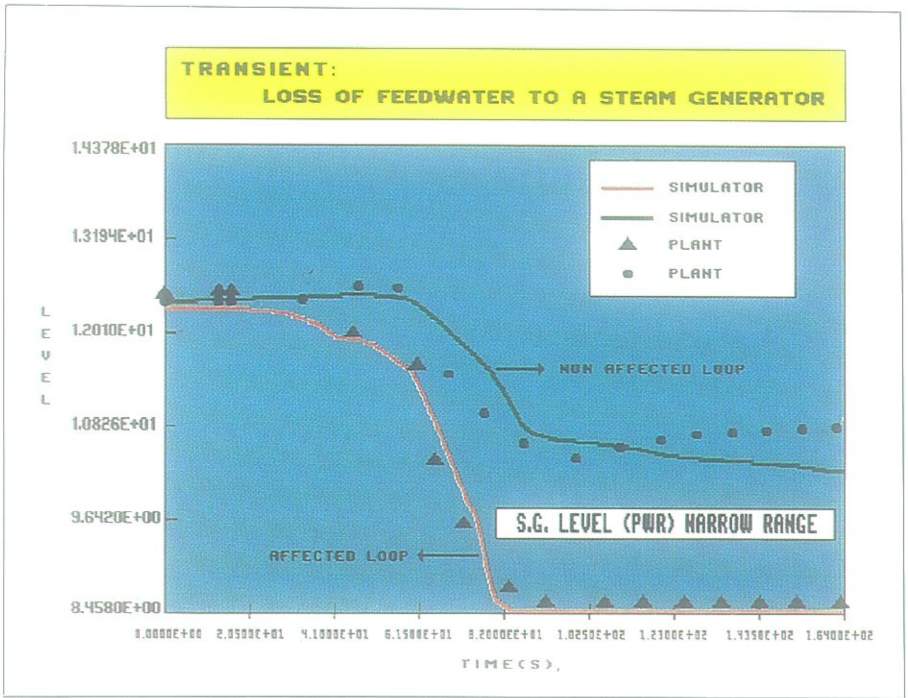
T II

COMPARATIVE TABLE OF FUNCTIONAL CHARACTERISTICS TECNATOM SIMULATORS

	Initial Configuration 1978/1979	Present Configuration 1991
Model	One point kinetics. Residual heat: 2 delayed neutron groups. No void feedback (PWR).	Tridimensional kinetics: 1.450 nodes (BWR), 628 nodes (PWR). Residual heat: 6 delayed neutron groups.
	Single phase flow/water steam thermodynamic equilibrium.	Two-phase flow (not homogeneous/thermodynamic imbalance).
	Sonic flows not considered.	Sonic flow in breaks and relief valves: subcooled liquid, two-phase, steam.
	Natural circulation set at a constant value (only when there is no forced flow).	Natural circulation. Countercurrent flows.
	—	Metal/water reaction. Generation and transport of H_2 to containment.
	—	Fuel cladding failure. Fission product release.
	1-phase level model.	2-phase level tracking.
	—	Presence of incondensables in startups/accidents.
	—	Effects on level of sudden vessel/generator pressure variations: swelling and shrinking.
	Calculation of heat transfer by conduction.	Heat transfer by conduction/convection/radiation.
	Constant heat transfer coefficients.	Various heat transfer regimes: boiling, subcooled, boiling in film, etc.
	—	Liquid and steam carry under/carry over in steam separators.
	Vessel model w/5 control volumes in which mass balance equations for liquid and steam & the total energy equation are resolved.	7-equation model (conservation of mass, energy and moment for liquid and steam, and conservation of mass for air) resolved in 79/126 (BWR/PWR) nodes or control volumes.
	Containment: simplified model for a MARK III.	Containment: saturated model that satisfactorily predicts the behaviour of a MARK III.
	Homogeneous boron concentration.	Boron transport model.
	—	Neutron flow instability under conditions of high power and low core flow.
	—	Core uncovery: critical orifice flow (CHF/DNB). Limitation by countercurrent flow/"breakdown" (CCFL). Reflooding.
	—	Reverse flow in jet pumps.

Computing System:

	Initial Configuration 1978/1979	Present Configuration 1991	
Computer	2 SEL 32/55	CRAY X-MP/14SE +	ENCORE 32/67
Computing power	1,5 MIPS	200 MIPS	5 MIPS
Word length	32 bits	64 bits	32 bits
Central memory	1 MB	32 MB	8 MB
Operating system	RTM	UNICOS	MPX



F II *Loss of Feedwater to a Steam Generator.*

indicates the most characteristic phenomena included in the new model specification, and how it resolves the limitations inherent in the original model. The overall objective pursued on including these phenomena was to equip the simulators with the capacity to reproduce any incidental scenario, thus providing the operator with the use of all symptom-oriented emergency operation procedures to return the plant to a stable and safe condition. The only postulated environmental limitation is maintenance of reactor core integrity.

To achieve these objectives, a predictive type engineering code must be selected that is sufficiently validated by comparison with experimental data either from plants or test facilities (for example, LOFT). This is the philosophy that guides the R&D project launched by Tecnatom in 1986, called *Simulator Advanced Models (SAM)*, being the following the most representative activities:

- Surveying and selecting the engineering code.
- Obtaining and validating the reference model (benchmark).
- Optimizing the validated reference model to produce the simulation model.
- Generating additional models to simulate phenomena associated with incidental scenarios (fuel cladding failures, accumulation and transport of H_2 and noncondensables, etc.).
- Integrating the advanced models that affect nuclear steam supply systems into the balance of plant systems of the previous simulator.
- Determining the required computing power. Selecting and acquiring the computing platform.
- Performing functional and acceptance tests on the simulator.

The BWR reference code was selected on the basis of *TRACG*, which was developed by General Electric for transient analyses in a wide range of transients from pump trips to severe incidents such as LOCA and events with reactor trip inhibition (ATWS). A collaboration agreement between General Electric and Tecnatom proposed a program of improvements and additions to the reference code in order to improve its efficiency and reduce computing times without diminishing its accuracy. The improvements include the following:

- Implicit formulation for numeric resolution of mass and energy equations, which provided for more accurate energy balances and more exact solutions for relatively long periods of time (250 milliseconds).
- Replacement of existing correlations in TRACG (which, as they are complex algebraic expressions, consume large amounts of computer time) by interpolation tables of thermodynamic and materials properties.
- Various modifications aimed at reducing the number of nodes, such as elimination of cells for T joints.
- Modifications in the iteration scheme to prevent repetition of the iterative process in those calculations that have already satisfied the convergence criteria.
- Optimization of routines that perform massive data processing in memory.

The additions to the original code include the following:

- Hydrogen generation and fission product leak models that take metal-water reactions and fuel cladding failures into account.
- Neutron flow instability model at high power levels and low level of flow through the core.
- Representative model of induction motors.

Both the TRACG engineering code and the model derived therefrom with the pertinent modifications and additions, which is called *TRACS*, have been extensively qualified, the first by a 3-stage sequenced process in which the code's response to individualized phenomena, the performance of dynamic components, and the interaction of different models in integrated effect tests are successively verified. The second, TRACS, is qualified by comparing the results obtained from executing operational scenarios that generate a set of the most complex phenomena with data provided by plants in operation or by a benchmark. Figures II, III and IV show superimposed evolutions of the simulator and of the reference plants in operational transients.

In parallel with development of TRACS for the BWR simulator, Tecnatom undertook on its own the reconstruction project of the pressurized water simulator on the basis of the TRAC code, which was subjected to a process similar to the one described above. The result was the simulation model baptized as *TRAC-PWR*.

Once both models were obtained, the computing power required for execution was estimated. A systematic evaluation was made of the computer market —five machines were preselected— throughout an entire year, to come up with the computing platform shown in figure IV, that was defined in 1988.

The vectorial computer *CRAY X-MP/14SE* can simultaneously execute the recently developed advanced thermohydraulic and neutron models, while the *ENCORE 32-67* computers can separately process the models left over from the previous system, which include the secondary and auxiliary plant systems. The characteristics of the main supercomputer provide for automatic code vectorization, which results in substantial savings in computing time. Table II indicates the significant increase in computing power with regard to the initial platform composed of two SEL 32/55 computers.

Once the computing platform was provided and the steam generation system models were ready, the latter were integrated into the auxiliary sytem models, and then the connection to the operator

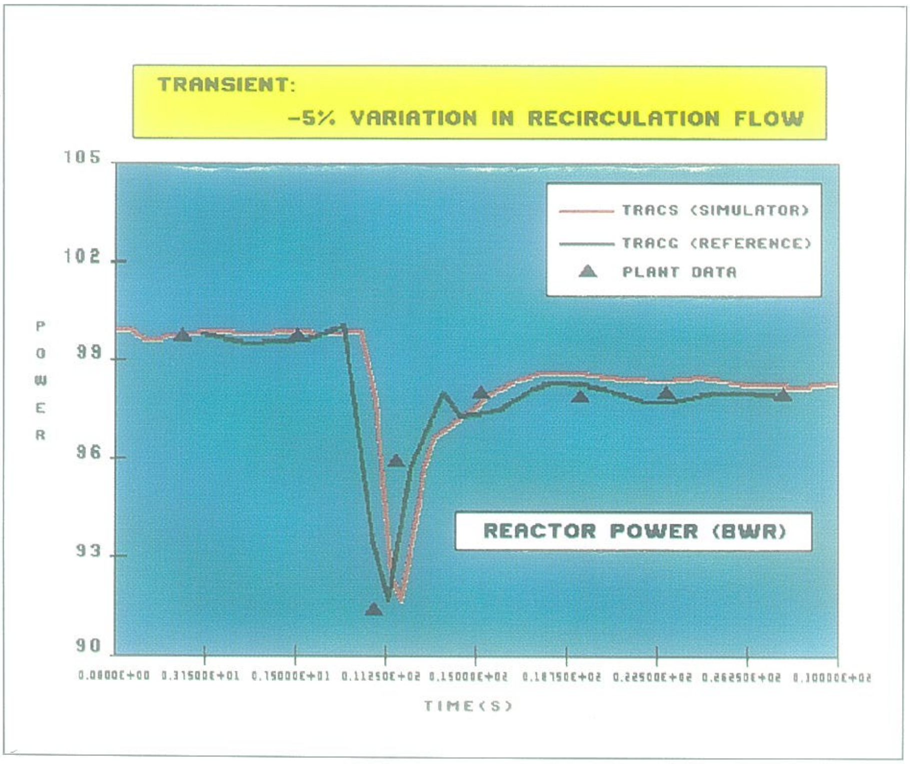
interface (control room) and instructor's console was made. When the configurations of both simulators were completed, the project team transferred them to the respective test team —Tecnatom instructors with operating expertise— to execute the acceptance protocols. The operating procedures of the simulated plant along the entire operating spectrum —normal conditions, transients and accidents— forms the protocol base, and the functional data compiled during the lifetime of light water plants form the reference framework for determining simulator suitability.
The process took longer than expected, throughout all of 1990, due in part to the low availability of the simulators for testing purposes, since there was an unusually high demand for the simulators for teaching purposes. The advanced PWR simulator was put into service in December of last year, and that same month it was used in a requalification course for experienced operators, who are the most qualified judges of product excellence. Having received favorable appreciation from this first Spanish team, it has been routinely used for courses given since then. "The operators have confidence in the simulator", as one Spanish plant coordinator said after witnessing the simulator's performance during several weeks. Along that period the simulator was driven through the tortuous operational scenarios postulated in the requalification courses, which put the operating team's skill to the test in the accurate diagnosis of problem causes and the timely application of the countermeasures considered in the operating procedures.
On the other hand, the test protocols for the BWR simulator have been completed, and in the middle of March 1991, at the very time of this article, the last model adjustments were being made. It will not be put into routine service until further tuning and reception of user feedback.

The overall data regarding resources used in both projects are 76 man-years of in-house labor and outside expenses of 300 million pesetas, basically devoted to the computing complex and auxiliary installations. This large investment is justified by the high level of training demanded by Spanish plants, which are aware that the improvements contributed by the SAM project will motivate the operating crews and develop their positive attitudes toward training.

To conclude this paragraph with a reference to the pioneering countries in simulation technology, we should mention the Electricité de France's SIPA project with the CATHARE-SIMU model, which was derived from the CATHARE advanced engineering code and is supported by a CRAY X-MP/28. The simulator is similar in many ways to the Tecnatom PWR as regards functional characteristics and is intended for training and design analysis.

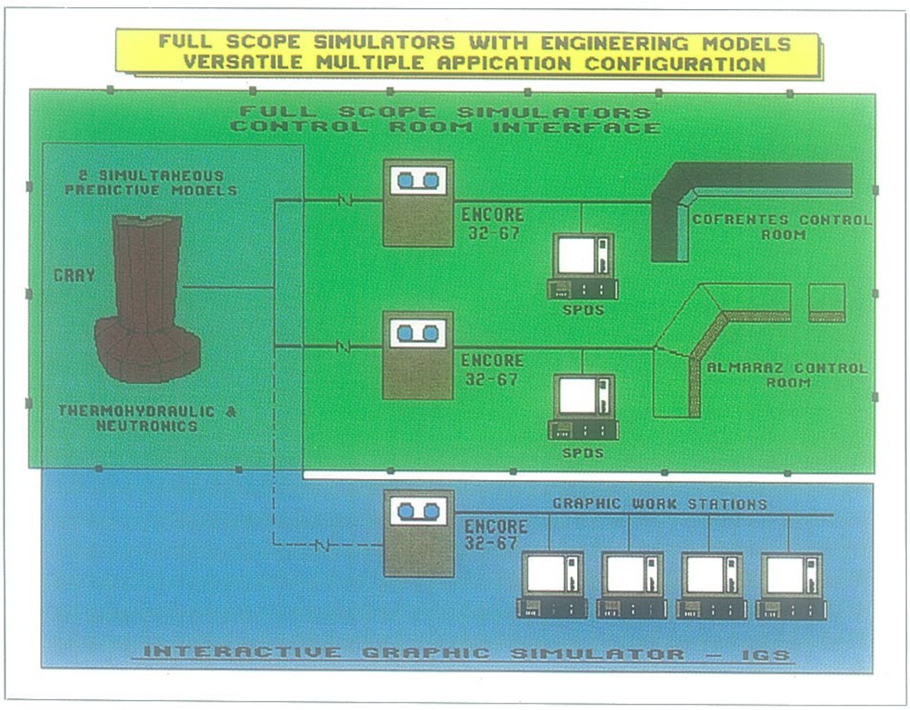
THE INTERACTIVE GRAPHIC SIMULATOR: POWER + FLEXIBILITY + VERSATILY

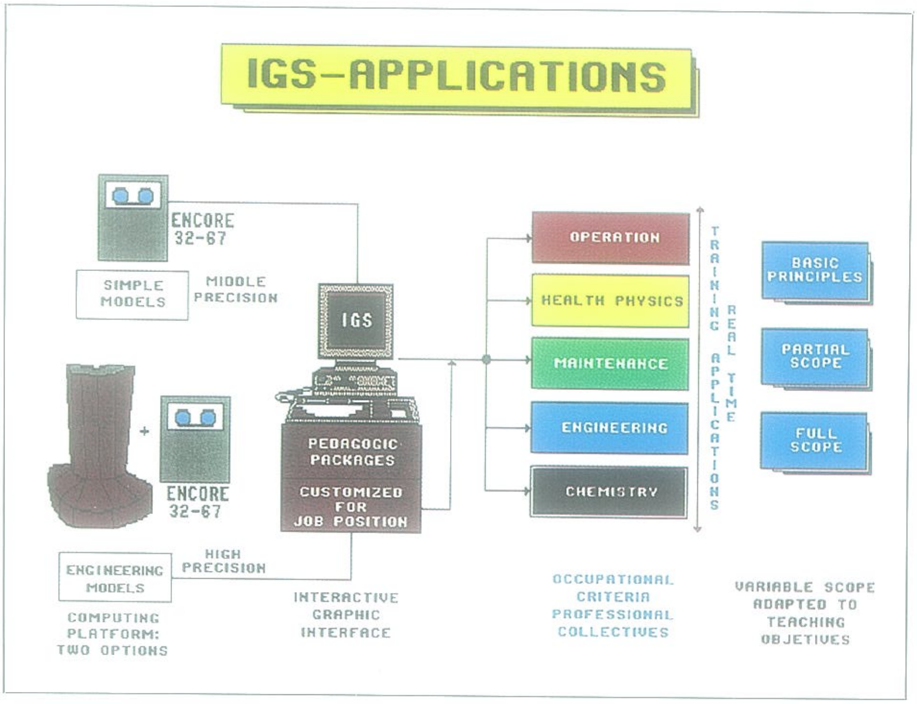
In addition to the considerable effort devoted to developing advanced simulation models during the 80's, Tecnatom has actively participated in a large number of activities aimed at optimizing the man-machine interface in the control room environment. Some representative examples of these activities are ergonomic revision of panel and instrument lay-out, adaptation and validation of emergency operation procedures, and implementation



F III *5% Variation in Recirculation Flow.*

F IV *Full Scope Simulators with Engineering Models, Versatile Multiple Application Configuration.*





F V *IGS Applications.*

of safety parameters display systems (SPDS).

Since all modifications made in reference plants that affect the operator performance must be transferred to the corresponding simulators to preserve trainer fidelity, Tecnatom's specialists have had to develop several communication protocols between the computing complex that supports the simulation and the graphic stations that have been installed in the simulator control rooms to provide the operator with SPDS functions.

Having provided access to the simulated process variables through the SPDS graphic terminals, it was decided to further equip the terminals with interactivity, i.e. the capacity to modify the operating state of the simulated dynamic components. In this way, the configuration called *Interactive Graphic Simulator, IGS,* materialized. This configuration is illustrated in Figure IV, where it can be seen that the only difference with regard to the so-called "full scope simulators" is the operator interface. The computing platform supporting the simulation complex permits simultaneous service for any two of three combinations.

In order to comparatively analyze the features of the total scope simulator and the IGS, we must necessarily refer to the differentiating component - the operator interface. The existence of a control room in the former allows the operator to familiarize himself with the habitat and exercise psychomotive abilities, as well as practise team work. The freedom obtained with the IGS graphic interface in presenting customized teaching packages to the student based on occupational criteria and specific training objectives results in greater versatility and a wider field of application. Figure V shows the graphic operator interface with the available options, which give it a practically unlimited flexibility. Apart from being able to select the pedagogic package design to teach a certain discipline, it is possible to choose between different computing platforms sized in terms of the scope and precision requirements associated with the predefined teaching objective.

The reader is referred to Figures VI and VII for examples of the graphic interface's capabilities.

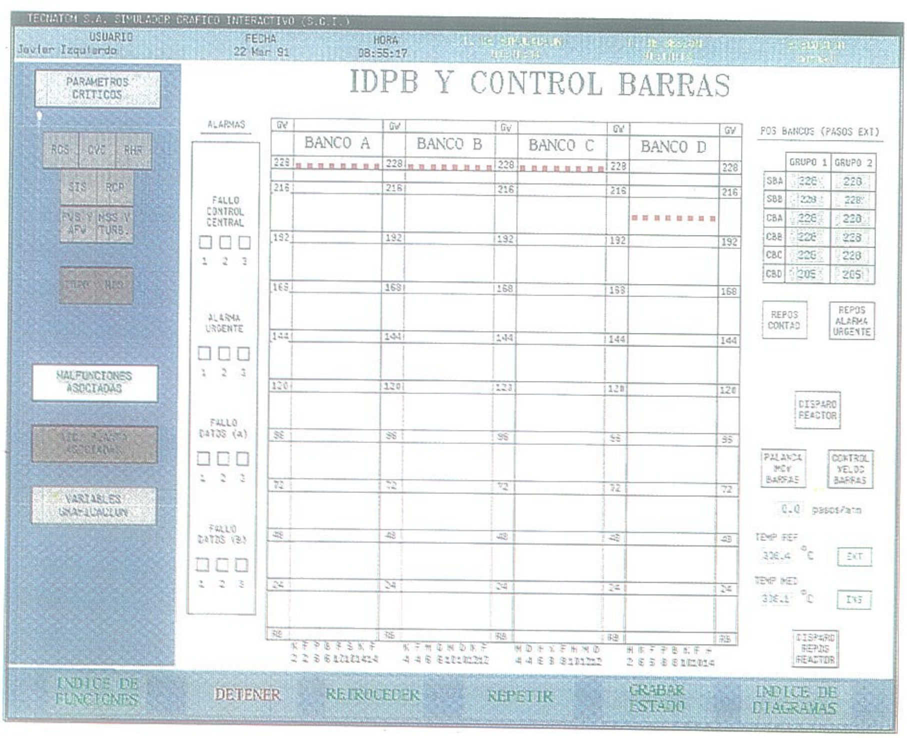
Figure VI shows the PWR panel section that houses the control rod indicators and controls (control banks). Figure VII is the flow diagram (partial) of the chemical and volumetric control system, which shows the control station screen for an automatic valve called up by the operator to modify its position.

The IGS is being favorably received by the different professional collectives that have had the occasion to use it in training sessions. In some ways, this tool's capabilities provide training opportunities that are not found in the full scope simulator. To be able to access and observe the evolution of internal process variables (modelled) that are not indicated on the control room instrumentation considerably reinforces the cognitive training aspects.

FINAL CONSIDERATIONS

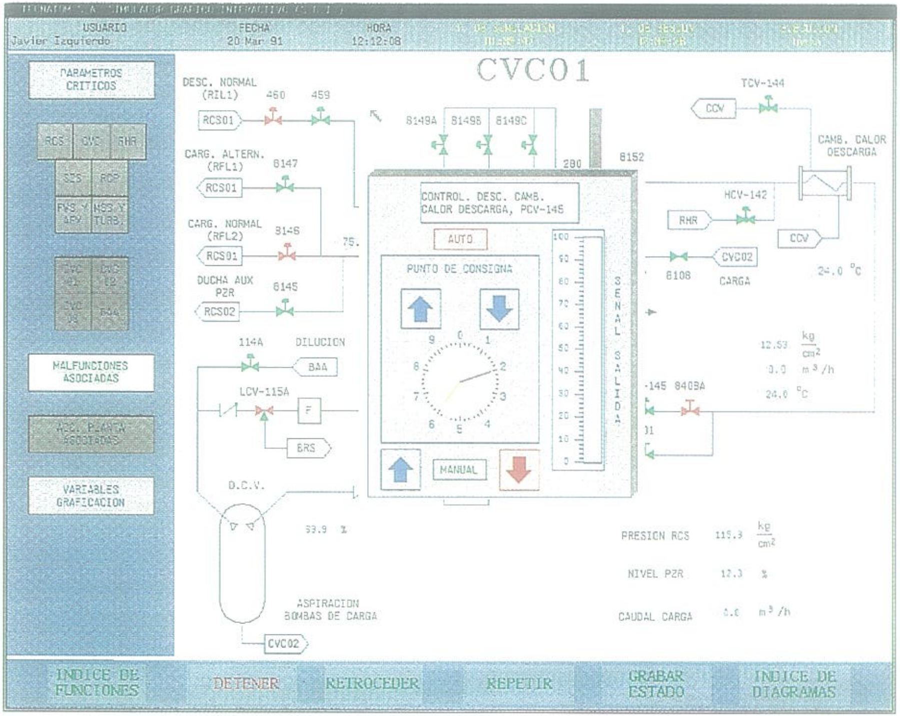
As explained above, a training simulator's effectiveness in transferring knowledge and professional skills depends on the accuracy with which the model reproduces the real facility's dynamic performance. Therefore, a prior requirement for the intended modelling is access to actual design data that provide a precise, complete and detailed definition of the

F VI *IDPB and Control Rods.*



simulated facility. A further requirement is access to performance data of the simulated station (or similar plant) that are used to check the model through a validation process. Both the design and performance data have been diligently provided by the nine Spanish light water units, thus making it possible to repeatedly verify the simulator models within a wide range of operational transients obtained from historic operating files. Furthermore, the plant operation specialists contributed their invaluable critical analysis and judgment when recorded data were lacking, and Tecnatom's modelling specialists were permitted free access to the stations at all times to observe specific operational developments "in situ". Team work has been the key in achieving the designated objectives.

In the coming years, Tecnatom will continue to develop simulation models as operating experience provides new performance references. The aim is to broaden current simulation limits so as to enter the dynamics of the so-called *severe accidents* once the applicable codes have been sufficiently validated in experimental facilities. The current computing platform will evolve toward low-cost, easily portable open operating systems. Pedagogic packages will continue to be developed in the IGS to satisfy specific training needs of new collectives, and finally an attempt wil be made to maintain the organizational and technological structure needed to address training needs associated with the next generation of power stations.



F VII *CVCO1.*