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He has presented papers at several courses in Spain and abroad, has participated in several congresses and has published articles. Mr. Vargas is a member of SCS (Simulation Computer Society), ATI (Asociación de Técnicas de Informática), SNE (Sociedad Nuclear Española) and AEIA (Asociación Española de Informática y Automática).

CURRENT TRENDS IN TRAINING SIMULATORS

R. VARGAS

INTRODUCTION

Recognition of the importance of a solid training background for nuclear power plant operators and of the influence of successful training programs as regards safe and economical plant operation, along with the use of full-scope simulators in such programs, are fundamental reasons for important technological innovation in the field of simulation.
For an engineering services company such as Tecnatom, whose aim is to be at the forefront in state-of-the art simulation technologies, the final objective of which is to prepare the operator so that he may systematically take the correct decisions for each situation, these premises have been the basis for a series of development projects. This article deals, on the one hand with the demands made on training simulators by exploitation personnel training and, on the other, with the most important characteristics to be provided by the models and the technological constraints imposed by the current status of computers. Mention is also made of a set of orientations facilitating achievement of the expected results.
Finally, taking into consideration the dynamic nature of the world of computer technology, and the fact that in this area the future becomes the present at such a rate that assimilation of technological innovations is hardly possible, due to other business constraints, the current trends of this technology and their undoubtable impact on simulation programs are described.

FULL-SCOPE SIMULATORS

BACKGROUND

Training simulators came about as a result of the need to perform a series of operations in the plants themselves, due to the requirements of the operations personnel licensing procedures established by the U.S. regulatory authorities. This process added a series of difficulties and inconveniences to those already inherent to the plant start-up phase. The first nuclear power plant operator training simulator appeared in 1968, and was based on the already relatively mature flight simulators.
Simulators were thus incorporated into the operator training and examination process.

It should be borne in mind that from the very start training simulators were subject to very wide scope criteria, as they had to faithfully reproduce the control room and incorporate models corresponding to all the myriad systems and processes that are operated from and displayed in this part of the plant.
Clearly, real time running of the models and the management of a very large number of analog and digital signals and of the instructor control and information functions, along with the technological capacity of the computers available at that time, led to development of very rigid software with extremely simple models. Table I shows a typical configuration and the devices then used.
That concept, originally a full-scope concept as regards duplication of control room hardware, suffered from restrictions with respect to the number of anomalies and operator operations that could be presented, these being limited to a previously established set.

The evolution of training simulators was valid and universally accepted until 1979. The consequences of the Three Mile Island 2 (TMI-2) accident once more constituted the driving force for a series of research and development efforts orientated towards improving the degree of realism offered by simulators, especially during severe transients.

MAIN THERMOHYDRAULIC CHARACTERISTICS REQUIRED FOR THE SIMULATION OF DIFFERENT TRANSIENTS

As will be seen below, it is important to carry out a detailed study of the phenomena ocurring during the evolution of those transients that determine the expected scope of the simulator in question, as this scope implicitly defines the requirements of the models to be used. To date there is no universal agreement with respect to these requirements, especially as regards the accuracy that training simulators should

T I
BWR simulator

Reference plant	Cofrentes NPP	
Vendor	Singer Link	
Configuration	2 GOULD 32/55 computers (1.5 mips)	
Capacity	50 KB shared memory	
	1 MB main memory	
	1 80 MB disk	
Process computer	Simulation of the plant computer (200 analog signals and 100 digital signals)	
Interface	Handswitches	985
	Lamps	4,100
	Controllers	84
	Annunciating recorders	553
Instructor's console	Malfunctions	183
	Initial conditions	60
	Controlled parameters	15
	Remote functions	80
	Fast (X10) and slow (X0.1) time	

The use of simple models, unable by themselves to reproduce the complex physical phenomena occurring during different transients, was supplemented by the use of fixed curves that literally forced the simulated instruments to respond, within the set of prescribed anomalies, in a way that had been established on the basis of complex safety and licensing codes. Logically, any deviation from the trainee actions foreseen for each of these anomalies could give rise to unforeseeable results.
All of these considerations led the instructors to pay very special attention to training sessions, within very rigid patterns, monitoring operator actions and checking for correct performance.

provide, although organizations such as EPRI have carried out different analyses of the matter.
Consequently, the scope of a simulator is defined by the following criteria:

- Absolute compatibility with the requirements established by the Regulatory Bodies.
- Experience of simulator operation accumulated by the utilities.
- Conditioning factors required in order to offer the most advanced training programs for licensed personnel.
- Current and future needs of the training plans.

These criteria impose certain requirements with respect to consistency, accuracy, operation and scope itself.

Taking into consideration only the needs of future training plans, the simulator should be capable of adequately representing the following:

- Normal operations.
- Operational transients.
- Accidents, including the corresponding mitigation and recovery actions.
- Application of new emergency response guidelines.

The above needs having been established, we could go on to define a more or less extensive set of anomalies and initial conditions that would suitably represent them; however, it would appear to be more rational to study the phenomena or states occurring and on the basis of these events define a set of selected transients triggering these physical phenomena, commonly known as dynamic modes in the specialized literature.
Table II shows a summary of the more significant phenomena occurring in PWR reactors under different operational and accident conditions.
Thus, the training plans considered herein contemplate scenarios that analyze events occurring as a result of changes, both in notation and in reactor coolant flow. Reactor trips and control rod movements belong to this category of events. This type of transient can be perfectly simulated using a singlephase model, as occurs under steady-state conditions.
For the secondary circuit, two-phase fluid modelling is required both under steady-state and transient conditions. Phenomena such as two-phase natural circulation caused by variations in void content, superheated steam due to steam generator tube uncovery, and critical leakage flows are all characteristic of two-phase flow treatment. Turbine trips, loss of feedwater, closure of the main steam valves and feedwater and steam line leaks and ruptures are typical scenarios included in training plans and incorporating the abovementioned phenomena.
The different types of loss of reactor coolant transients: leaks and medium and large size line breaks, bring two-phase flow phenomena to the reactor coolant system, where even minimum simplifications can drastically limit the scope of the model.
In studies of such phenomena relating to smaller breaks, special attention should be given to conditions such as main pump trip and start-up, which give rise to operational effects involving high steam contents, separation of phases due to the effect of gravity with the sealing of possible coolant flow paths, critical leakage flows, etc.
In the case of medium sized breaks, the phases are partially separated as a result of gravity; however, in the area immediately surrounding such breaks

high fluid velocities are reached, which make the fluid more homogeneous. In this area the respective forces of the phases are of great importance, as they determine the degree of mixing, on which will depend the medium term effects and actions during evolution of the transient. Depending on the location of the break, this phenomenon may have appreciable spatial effects; for this reason the three-dimensional characteristics of the model are applicable to this type of transient. Larger breaks involve phenomena such as core drainage and later reflooding by means of the emergency core cooling system and a series of heat transfer scenarios, which are dealt with in greater depth in the area of nuclear safety.

In those anticipated transients in which there is no reactor protection system actuation, normally known as anticipated transients without scram (ATWS), a decrease in reactor power occurs due to the high void content in the core arising as a result of high fuel temperatures and of the influence of these temperatures on total core reactivity. In such cases it is of fundamental importance that thermohydraulic considerations be duly contemplated in modelling of the core.

Regardless of purely nuclear considerations, such as rod drop accidents or the spatial-chronological evolution of fission poisons, the core model should include accurate calculations of neutron flux in response to sudden insertions of reactivity as a result of void vaporization or collapse, which are both typical thermohydraulic phenomena. This interaction is clearly seen in modelling of fuel cladding failures due to the critical heat flux being exceeded, with the corresponding release of fission products from the fuel, the oxidization of these products and the subsequent generation of hydrogen which is transported to containment.

SELECTION OF THE TERMOHYDRAULIC MODEL

Due to the phenomena briefly described above, the hydrodynamic model should deal with the phenomenon of two-phase flow in the reactor coolant system, and incorporate a non-homogeneous flow model featuring dynamic slip and thermal non-equilibrium conditions. The thermal non-equilibrium feature will initially be applicable to the pressurizer and steam generator, with the possibility existing for extension to the rest of the primary system.

The reactor coolant system is fundamentally represented by means of a network of basic elements such as the following:

- Hydrodynamic paths, volumes or cells, with solving of the coolant circulation single dimension equations.
- Nodes constituting the junctions between the above-mentioned volumes.

The model should also deal with forced or natural circulation, with flow reversal. Operation of the primary pumps under degraded conditions due to the production of steam is an important aspect, as is calculation of the best estimate critical leakage flow through relief valves and breaks (Fig. I shows a diagram of the complete model, with different points at which anomalies or simulatable events may arise). The steam generator model will describe the thermohydraulic behaviour of a "U"-tube steam generator, and includes the possibility of studying the phenomenon of natural convection. This model includes the heat transfer section ("U" tubes), the upper plenum and steam separation units, the downcomer, feedwater and the steam extraction system, including the different valves and the turbine bypass.

This model will be nodal and include two-phase flow with dynamic slip and heat transfer correlations for the different flow conditions (Sieder-Tate, Thom, etc.).

There is currently a wide range of thermohydraulic models from which to choose the scope requirements mentioned above.

However, regardless of the options regarding the physical basis of the model, there are other considerations intrinsic to the code that may make use of the model easier and more flexible, especially in a real time domain and an environment in which changes and modifications are frequent.

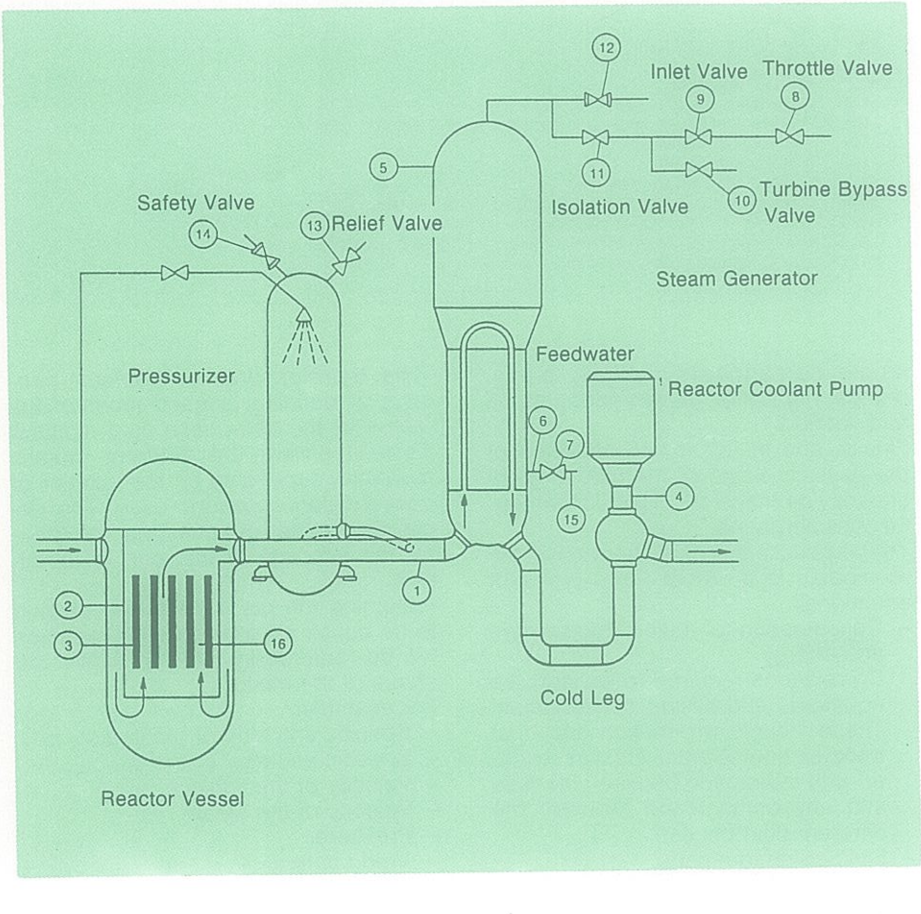
Within this set of considerations the following are worthy of special mention:

- Degree of spatial detail.
- Free, flexible and fixed topologies.
- Fixed, flexible or adaptive nodalization.
- Generalized or individual component modelling.

Degree of spatial detail

The most conservative analyses give a minimum number of 70 nodes for representation of the reactor coolant system. Besides this, advanced thermohydraulic modelling requires the solving of a large set of differential equations at each node. These two factors imply an overwhelming increase in the volume of calculation as the complexity of equation solving and the number of nodes grow. Evidently, this factor contrasts with the computational capacity of existing computers. However, this limitation does not eliminate the current need to simulate effects in two or three dimensions, as was point-

F I *Diagram of PWR model showing locations of different events*



ed out under the previous heading.
It is necessary to select a code having certain three-dimensional components, such as the reactor vessel, along with other single dimension components such as piping segments or connections between pipes.

Free, flexible or fixed topology

A fixed topology is understood as being a code designed for a specific network or mesh configuration, whilst a free topology refers to a code designed to handle any configuration. While fixed topology codes (such as those applied in some training simulators) are an acceptable solution for small networks (having few nodes), free topology codes make heavy demands as regards design effort and require a considerable computational capacity due to the extensive use of matrixes and vectors.
Flexible topologies are an intermediate approach. Essentially, the degree of freedom provided for the definition of configurations is limited to the degree required to accommodate a set of typical networks for the type of application. These flexible topologies have the advantage of being applied to a set of volumes and of relating properties common to these volumes (for example, pressure), thus defining a basic network component or block. In the real time simulation domain this alternative offers considerable advantages, especially as regards reduction of the time required for calculation.

Fixed or adaptable nodalization.

In this context, adaptation refers to the capacity of a code to dynamically change the volumes discretely representing a network. This characteristic is applied in regions of high volume density, where the state of a fluid might undergo sudden variation, in order to verify details to a given degree of accuracy.
Because of the variation in the control volumes, dynamic nodalization implies an appreciable complication of the set of conservation equations to be solved, and is typical in relation to phenomena such as core reflooding following a LOCA.

Generalized or individual component modelling.

Sets of similar components may be modelled individually or generically; a component is understood as being a part or equipment unit within the thermohydraulic network.
Obviously, the individualized modelling approach neutralizes the calculation time; on the other hand, it is less effective during the development and validation phase due to the frequent changes that the model undergoes.
Selection of a code with generic components is recommended. In this way single components (valves, pipes, pumps, etc.) must be designed, tested and verified.
Finally, and in relation to selection of the physical basis of the model, mention may be made of certain fundamental considerations.
The physical basis of all thermohydraulic models is a set of three types of equations:

- Conservation of mass, momentum and energy.
- Correlations required to support the equations expressing conservation. These include the friction and heat transfer coefficients, etc., associated with interaction between the fluid and environment and between the different fluid phases.
- Fluid state equations.

"The thermohydraulic problem" consists of defining at each moment the status of the two-phase fluid mixture. Table III shows the different models available, depending on the number of conservation equations used. The larger the number of equations, the greater the information that can be obtained.
Assuming the pressure of the phases to be equal, six independent variables will be required in order to define the status of the mixture.
For example:

- Specific enthalpy of the liquid.
- Specific enthalpy of the steam.
- Velocity of the liquid.
- Velocity of the steam.
- Pressure.
- Void content.

T II

Physical Phenomena	SS	TRIP	SLB LFW	SBLOCA	MBLOCA	ATWS
Single-phase natural circulation	--	++	++	++	--	++
Two-phase natural circulation	--	--	--	++	--	++
SG as primary heat source	--	--	--	++	++	--
SG condensation-reflux	--	--	--	++	--	--
Upper core counterflow limitation	--	--	--	+	++	--
Downcomer counterflow limitation	--	--	--	--	++	--
Local primary cooling	--	--	++	--	--	--
Condensation in pressurizer	+	+	++	--	--	--
Circulation on SG secondary side	++	+	-	-	--	--
SG tube uncovery	--	--	++	--	--	--
Gravity phase separation	--	--	--	++	--	++
Refill	--	--	--	--	++	--
Core entrainment	--	--	--	--	++	--
Forced convection two-phase flow (main reactor coolant pumps in operation)	--	--	--	++	--	++
Overheated core	--	--	--	++	++	+
Overheated steam	--	--	--	++	++	--
Sudden core cooling	--	--	--	+	++	--
Liquid density waves	--	--	--	--	++	--
Secondary side steam density waves	--	+	-	--	--	--
Condensation in accumulator	--	--	--	+	++	--
Pressurizer pressure control	++	++	++	--	--	+
Reactivity void effect	--	--	--	--	+	++
Primary loop seal effects	--	--	--	++	+	+
Oxidization of zirconium	--	--	--	+	++	--

++ = Highly significant.
\+ = Significant.
SS = Steady-state.
SLB = Steam line break.
MBLOCA = Medium break loss-of-coolant accident (7-25 %).
LFW = Loss of feedwater.
\- = Not significant.
-- = Not relevant to the event.
TRIP = Reactor trip, control rod movements, pump trip.
SBLOCA = Small break loss-of-coolant accident (0-7 %).
LBLOCA = Large break loss-of-coolant accident (25 % 2 x 100 %).
ATWS = Anticipated transient without scram.

T III

Model	Equations (Correlations)					Restrictions		
	Fw	Fi	Qw	Qi	Total	Tk	vr	Total
3C:1M.1K.1E	1	0	1	0	2	2	1	3
4C:2M.1K.1E	1	0	1	1	3	1	1	2
4C:1M.2K.1E	2	1	1	1	5	2	0	2
4C:1M.1K.2E	1	0	2	2	5	1	1	2
5C:1M.2K.2E	2	1	2	2	7	1	0	1
5C:2M.1K.2E	1	0	2	2	5	0	1	1
5C:2M.2K.1E	2	1	1	1	5	1	0	1
6C:2M.2K.2E	2	1	2	2	7	0	0	0

Nomenclature:
cC:mM.kK.eE: c = total number of conservation equations.
m = number of mass conservation equations.
k = number of momentum conservation equations.
e = number of energy conservation equations.
Fw = Friction with walls.
Fi = Friction between phases.
Qw = Heat flux across walls.
Qi = Heat flux between phases.
Tk = Fluid temperature/specific enthalpy.
vr = Relative velocity between fluids.

T IV

SCOPE: Analysis of operational transients and severe transients such as LOCA's or ATWS's, with and without depressurization.

MODELS:

- Neutron model: 3-D with spatial feedback.
- Heat transfer model: 1-D heat transfer in cladding and structures along the entire transfer condition curve, including radiated heat.
- Hydraulic model:
  - Two-phase model with 7 equations (mass and energy for steam and liquid and mass for air).
  - Constituent correlations for friction and heat transfer between phases, depending or flow conditions.
  - 3-D model for reactor vessel.
- Numerical methods: Implicit, two-step method making it possible to violate the Courant limit.

COMPONENTS:

Vessel: 3-D (cylindrical coordinates) with steam separators and jet pump.
Characteristics of the simulator code.

- Pipe: 1-D with arbitrary number of cells.
- Tee: 1-D with arbitrary number of cells in each leg.
- Valve: Modified "pipe" component.
- Channel: Modified "tee" component for modelling of flow leakage to the bypass.
- Fill: Environmental condition (Velocity).
- Break: Environmental condition (Pressure).
- Control: Capacity to model adding elements, integrators, leads, lags, etc.

The main disadvantage of the six equation model is the high number of correlations required to provide a definition and the nature of these correlations. This disadvantage arises as a result of the uncertainty involved in obtaining and experimentally measuring the model. In concluding this study of the different options, a code was selected; its characteristics are shown in Table III.

IMPLEMENTATION OF A WIDE SCOPE CODE IN A REAL TIME ENVIRONMENT

Codes similar to those indicated in Table IV have traditionally been used in analysis of design basis accidents (DBA). More recently, as a consequence of the TMI-2 accident and others (Ginna, St. Lucie, etc.), these codes have become vitally important, not only as regards those aspects that impact on the reactor coolant circuit but also in relation to core kinetics, the secondary system (BOP) and associated controls. The analytical functions were extended to include prediction, design and the verification of procedures.

These codes, for example TRAC-PF1, TRAC-BD1, RELAP-5/MOD2 and RETRAN-02, require the use of large scientific computers, and even so are still unable to provide responses in anything near real time, at least as regards certain scenarios of interest.

In the light of this situation, a group of institutions and companies have initiated research and development orientated towards adapting existing design codes to a real time simulation environment. In this way, the high degree of accuracy and validation and the wide scope of these codes might provide an incalculable benefit for training simulators. In this context mention should be made of the efforts of institutions such as the National Laboratories of the United States (LANL, INEL and BNL), the French Commissariat for Atomic Energy (CEA) in collaboration with EdF and Thomson, KWU with GRS in Germany and Tecnatom with General Electric in Spain.

In summary it may be stated that the research and development programs being carried out have three basic objectives: a drastic reduction of runtime, the establishment of an agile interactive man-code interfaces and a reduction of the costs associated with the computational systems that have been necessary to date.

Among the research efforts aimed at reducing runtime, the following may be mentioned:

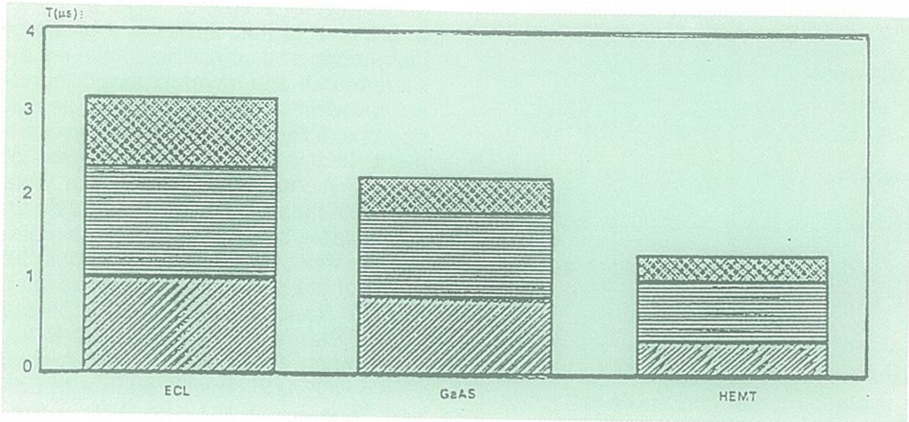
- Minimization of data processing requirements: the codes, originally developed for CDC computers with very reduced resident memory capacities, have data processing requirements that might well be minimized using current computers (with large main memory capacities).
- Replacement of correlations with tables: the correlations used require the calculation of complex algebraic functions implying a large amount of computation time.
- Replacement of these functions with optimized searches through tables

TABLE V

Computer	OS/Compiler	Ratio	MFLOPS
CRAY X-MP-4 (1 proc.8.5 ns)	CFT 77 1.2 (Rolled Blas)	0.18	66
ETA 10-E	ETA V/FTN200 (Coded Blas)	0.20	61
NEC SX-2	FORTRAN 77/SX (Rolled Blas)	0.28	43
ETA 10P (1 proc. 24 ns)	ETA V/FTN200 (Rolled Blas)	0.45	27
CRAY.IS	CTF 77 2.1 (Rolled Blas)	0.46	27
NAS AS/XL V60	VAST/VS 1.4.1 opt = 3	0.58	21
Amdahl 1200	77/VP V10L20 (Rolled Blas)	0.65	19
CDC Cyber 205 (2 pipe)	FTN (Rolled Blas)	0.70	17
Fujitsu VP 200	Fortran 77 (Rolled Blas)	0.70	18
Siemens H120F	Fortran 77 (Rolled Blas)	0.83	15
DEC VAX 8550/8700/8800	VMS V4.5	13	0.97
Gould 32/9705 mult. acc.	Fort77 + 4.3	31	0.39
VAX 11 780 FPA	VMS V 4.5	88	0.14
Micro VAX 11	VMS V 4.5	94	0.13

(Source: Jack J. Dongarra "Performance of Various Computer Using Standar Linear Equations Software in a Fortran Environment", 30-IX-88.

F II



allows a substantial reduction in computation time to be achieved.

- Selective iterations: there are certain calculations that can be extracted from the process of iterative solution, this implying and advantage as regards runtime.
- Code division: this task consists of splitting the code into two or more independent programs which can be run as multiprocesses.
- Vectorization of the calculation process: this makes it possible to efficiently use all the vectorial calculation capabilities foreseen for future computers.
- Possibility for execution in relatively large time steps (0.25 seconds), depending on the ease with which the numerical methods used can be modified.

This type of advanced simulators should incorporate graphics workstations making it possible to work directly on the models in question, independently from the rest of the classic structure of simulators. Consequently, these workstations, which may be either totally autonomous or embedded in the main computer depending on the architecture and graphics system selected, should carry out a reduced set of simulator functions (start-up, shutdown, initiation of anomalies, detention, etc.), allow insertion of operator actions, incorporation of data or parameters into the models and generate complete and agile graphics information outputs. This would facilitate the task of updating the system (verification, validation and correction of anomalies).

Finally, and in reference to configuration analysis, it is quite obvious that the computer required will depend directly on the minimum code runtime achieved using the above-mentioned reduction techniques.

However, in this area advances in the science of computation are producing a shift of the center of gravity among manufacturers of high-performance computers, a shift that is leading to a point that is still to be clearly defined. This segment of the market, along with other similar segments such as structural analysis, aerodynamic, hydrodynamic, geological, meteorological and molecular simulation and image processing, among others, point to a scientific computer model running in a departmental environment, offering easy connection to other conventional and processing environments and providing a robust set of graphics libraries. We are currently witnessing a race against the clock between the constructors of superminicomputers, high performance parallel processors and scientific supercomputers, a race that they hope will allow them to enter or dominate these important segments of the market.

Table IV summarizes the performance of certain single processor systems with respect to resolution of a system of differential equations of the order 100, with complete accuracy (64 bits) and programmed in FORTRAN. Reference (1) contains a detailed study of the results of this test program, which was carried out in October, 1987. It should not be overlooked that the spectacular nature of these data might undergo considerable variation, depending on the nature of the program or problem to be tested. Thus, factors such as the possibility of running a fractionable code in a multiprocessor environment, the possibility for the operating system to optimize parallel instruction execution of the existence of a metalanguage for the optimized recognition of vectorizable structures might divide runtimes by a factor of 10 in the case of two computers having a similar timescale cycle.

Evidently, there is the technological limit of the computer timescale, currently oscillating between 8.5 ns, in the case of liquid nitrogen-cooled systems, and 19 ns, in the case of air-cooled systems. In this respect, however, a substantial reduction might be expected given the important progress being made in the field of semiconductor physics. In this respect, Fig. 2 shows the cycles to be expected using different technologies, based on the work of Tushar R. Gheewala mentioned in reference (2). Consequently, we find ourselves on the threshold, to be reached during the decade of the 1990's, of 2,000 scalar MFLOPS, extendable to a range of between 2,000 and 4,000 vectorial MFLOPS, i.e., power levels some 10 times greater than those existing at present.

CONCLUSIONS

Following analysis of the characteristics of scope and accuracy which training simulators will contribute to current research and development projects, we can state that it will be possible to use such simulators as instruments for the following:

Basic training

- Normal operations.
- Normal operational events (trips, etc.).
- Accidents, including organization of human resources and use of the emergency operating procedures (EOP's).

Advanced training

- Understanding and application of EOP's.
- Understanding and analysis of real operational events (GINNA, TMI, etc.).

Requalification

- Training of the overall human team in highly complicated scenarios or under degraded conditions.

Training of crisis response teams.

- Exercise and check crisis response teams under real operational conditions.
  These exercises include simulation of the most severe scenarios, with the widest time scope and the least available information.
- Content and format of surveillance procedures.

Validation and improvement of:

- Content and format of EOP's and normal operation procedures.
- Content and format of the remote shutdown panel.
- Development of new diagnostic methods for postulated accidents and events.
- New operational strategies.
- Testing of modifications.

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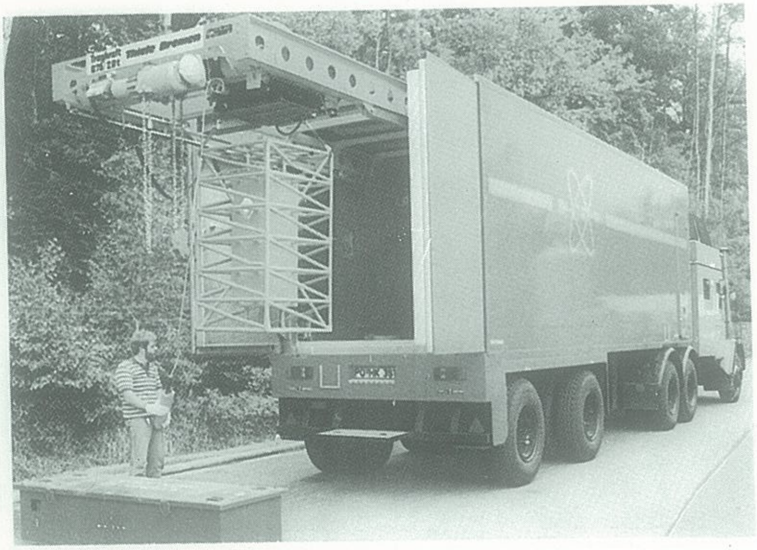

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