A NUCLEAR POWER PLANT OPERATOR AID UTILIZING ON-LINE SIMULATION MODELS*

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ABSTRACT

This paper presents results on developing a nuclear power plant operator aid system that utilizes an on-line core simulator. We demonstrate that the functional pieces of the proposed operator aid system, which utilizes the on-line simulator as a source of knowledge, can be integrated. This is achieved by interfacing a 1-D (axial) core simulator with an expert system model utilizing a limited knowledge base and plant instrumentation signals obtained from another core model. This operator aid system can recognize pending or current plant Technical Specification violations, indicating the nature of the violation and the required corrective actions; maintains the on- line simulator current; and advises the operator on how to complete a power maneuver or recover from a violation (by employing the on-line simulator in a predictive mode). Based upon this successful demonstration, work has begun on demonstrating that a sufficiently high fidelity core simulator could be developed which executes in better than real-time on a modestly priced computer. Utilizing preliminary timing study results employing the ALLIANT FX/8 mini-supercomputer to solve in a vector- concurrent manner a two-group, 3-D coarse-mesh finite difference representation of the neutron diffusion equations, projections on achieving real-time capability are encouraging.

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INTRODUCTION

Within the past several years a number of projects have been initiated on utilizing expert systems in a nuclear power plant to advise the operator of abnormal conditions and the manner to respond to these conditions.[1,2] These systems, which aim to simulate the accumulated knowledge, skill and judgment of the very best human operators, contain a knowledge base which has been constructed from the knowledge extracted from experts, plant procedures, Technical Specifications, validated plant signals and pre-simulations. In our work we are incorporating one additional source of knowledge; on-line simulation of the nuclear power plant.

The utilization of an on-line simulator allows one to enhance the operator aid system in three important ways. Firstly, when validating signals, predicted responses can be included with measured responses in the validation process. Secondly, when an upset condition occurs, the on-line simulator can be used to examine alternative upset scenarios as directed by the expert system or the operator in an attempt to identify the sources of this condition. Finally, the on-line system can be used to simulate the future behavior of the plant from current conditions, either normal or abnormal, examining alternatives provided by the expert system or the operator to maneuver the plant to a new state. Clearly the fidelity of such simulator must be high and will require the employment of on-line adaptive techniques. In addition, the simulator must function in better than real-time on a modestly priced computer. We believe that these traits of the simulator are now possible due to the availability of mini-supercomputers employing parallel architectures.

This paper discusses two specific tasks of our overall effort to develop an operator aid system utilizing on-line simulation: assessing whether the various functional pieces of the system can be integrated and assessing whether a sufficiently high fidelity simulator that can run in better than real-time on a modestly priced computer can be developed. In this paper we limit our discussion to the core simulator aspect of the expert system and its applications; hence, there is an overlap with the work on power shape monitoring systems.[3-5]

FEASIBILITY OF THE OPERATOR AID SYSTEM

To demonstrate that the functional pieces of the proposed operator aid system could be integrated, we have developed a core simulator, interfaced with an expert system model, and used it as an operator aid to complete power maneuvers within Technical Specification limits of a PWR. Relevant plant instrumentation signals were not obtained from a real plant, but from another computer model of the core, referred to as the plant-core model. This model is a modified version of the NATO neutronics code.[6] NATO models the 1-D (axial) neutronics and thermal- hydraulics behavior of a typical PWR core at beginning-of-cycle (BOC) . The plant features modeled in this code are: four control banks (A-D) with a 100 step overlap; one shutdown bank; the programmed core average temperature automatic control; and the boration/dilution-feed/bleed type Chemical and Volume Control System (CVCS). The simulator-core model utilizes the DIFPAR3D code[7], a two-group, 3-D model, run as a pseudo 1-D model, *i.e.*, only one mesh is used in the X and Y directions.

The expert system is written in the OPS5 production language.[8] An OPS5 program consists of modules of productions, or rules, and an area of memory, called the working memory, which holds data. Each rule operates much like an IF...THEN programming language selection construct. Rules are executed or "fired" when the conditions defining their antecedent are satisfied. When fired, the action specified in the THEN part of the rule is initiated. Most often, the action adds, deletes, or modifies information in the working memory. The memory itself is matched against the IF part of each rule. There is no predefined sequence for executing the rules; the productions fire as sufficient information for them to do so becomes available, and new data and information are generated until a solution is achieved. In this manner, the operation of an OPS5 program is data driven, a characteristic which lends itself ideally to the monitoring of a system that is changing continuously.

The expert system knowledge base, very limited to narrowly focus on the indicated demonstration, consisted of the relevant plant instrumentation signals, the Technical Specifications of a modern Westinghouse PWR core, operating procedures, and the on-line simulator. The Technical Specifications concerning the axial flux difference (AFD) and the control rod insertion limits were the only ones included in this knowledge base, since the 1-D core models used provide information pertinent to these specifications.

The expert system controls the on-line simulator in two modes: the tracking mode and the predictive mode. In the tracking mode the simulator is driven by plant signals that are passed from the plant-core model through the expert system. These plant signals include the operating power level, control rod positions, the core inlet temperature, and time. Criticality of the simulator in this mode is maintained by adjusting the soluble boron concentration. If the axial offset (AO) of the simulator deviates by more than 3% in AO units from plant signal, the simulator's lead control bank position is changed to adjust the AO deviation, provided that the rod position change is within 12 steps of the plant signal. The intervals of 3% (AO) and 12 steps (lead bank position) were chosen to be consistent with measurement uncertainties typical of nuclear power plants. In this early work when adjusting the rod position to adjust the simulator AO fails, linear interpolation of the AO deviation was used to correct the simulator predicted AO. Currently, on-line adaptive techniques are being developed for adjusting deviations between the plant signals and the on-line simulator.

In addition to keeping the simulator current and adjusting it to agree with the plant signals in the tracking mode, the expert system also determines, using these signals, if the reactor AFD and control rod positions are within the Technical Specification limits at the current operating power level. If a violation of these limits is detected, the expert system alerts the operator to the violation indicating its nature, the required actions, and the time allowed by the Technical Specification for the violation to exist. The system, also, identifies conditions that might lead to future violations of the limits, *e.g.* a control bank is at the insertion limits or the lead control bank is inserted 5 or fewer steps. Since these conditions are not violations, the expert system displays them to the operator as warnings.

Figure 1 displays the operator interfaces to the system. The top half of Figure 1 appears on one CRT and is based upon the plant signals, with the exception of the xenon axial offset (XAO). The lower half of Figure 1 appears on another CRT and is the interface to the operator

aid system. A violation of the axial flux difference (AFD) is being noted. Other examples of the system's monitoring capabilities can be found in reference 9.

In the predictive mode, the expert system employs the on-line simulator, upon operator request, to advise on how to complete a power maneuver or recover from a Technical Specification violation. In this case the on-line simulator is driven by both operator input, *i.e.* desired core power level versus time, and the expert system rules. The expert system, running the simulator in time steps, first attempts to reach the desired power level at the end of the step using an "idle" operation. By idle operation we imply no change in soluble boron concentration and adjustment of the lead control bank are made such that criticality is maintained at the programmed core average temperature, *i.e.*, automatic control. If successful, it proceeds to the next step; otherwise, a search for the boron concentration required to avoid Technical Specification violations is performed. In the event that this action results in boration or dilution rates beyond the plant capability, the maximum rate is used in the current step and an attempt is made to recover from the violation within the time allowed by the Technical Specifications. If none of these actions is successful, the system advises the operator that the specified maneuver cannot be executed under the current plant conditions. Figure 2 displays the differences in key core parameters between the plant signals and simulator if the advice of the operator aid system, on how to complete the power maneuver displayed in the bottom figure, is followed. Notice that in this study the boron search, when required, was not optimized; a brute-force search was used until the parameter in violation is restored within its target band. This resulted in excessive movements of the lead control bank, especially toward the end of the maneuver, as shown in Figure 2. In future work, the boron search could be optimized so as to minimize the waste water, maximize the spinning reserve capacity (SRC), or minimize the rod movements.

CORE-SIMULATOR DEVELOPMENT

Based upon the successful demonstration on integrating the functional pieces of the operator aid system, work began on demonstrating that a sufficiently high fidelity core simulator could be developed which executes in better that real-time. The demonstration noted above employed a VAX 11/750 minicomputer and did not address real-time capabilities. The computer selected to assess real-time capability is an ALLIANT FX mini-supercomputer. This computer employs a 64 bit word length architecture and introduces parallelism in several manners. Up to eight Computational Elements (CEs) can be configured, each computational element having a CPU with a vector unit with a practical rating of a few MFLOPS. In addition, up to twelve Interactive Processors (IPs) can be configured, which can handle scalar code, I/O, and operating system needs. Machine resource allocation can be controlled either by the operating system or user. A hierarchical memory organization is employed. A compiler option in conjunction with compiler directives within the source code allows scalar, vector, concurrent, and vector-concurrent operations to be initiated.

We have been converting and tuning the DIFPAR3D code[7], developed for the CRAY X/MP, for efficient execution on the ALLIANT. The major focus has been on taking advantage of concurrent operation, which has a low overhead on the ALLIANT, since the CRAY work

previously identified vectorization potential. Further details on this effort can be found in an accompanying paper.[10] Table 1 presents some preliminary timing study results employing the ALLIANT FX/8 computer. The sample problem is a modern Westinghouse PWR core at the beginning of Cycle 1 with thermal- hydraulics feedback treated. An 18x18x30 (XxYxZ) coarse mesh discretization is employed. This corresponds to a (2x2) mesh per fuel bundle and quarter core symmetry. Since the DIFPAR3D code currently solves the static versus kinetic few-group neutron diffusion equations, the reported timings were obtained by adjusting the measured timings to account for the differences in the number of times subroutines would be called in the static versus kinetic code versions. Using a single computational element, a vector speedup of about 2.1 is obtained, which is about half the value obtained from ideal vectorized test loops. This is believed to occur because reduction operations, *e.g.* inner products, and function calls, *e.g.* SQRT, are completed utilizing firmware and potentially because of cache hit problems. The concurrent efficiencies are consistent with about 90% of all operations being done concurrent. Further gains in this area are presently being pursued. In particular, there are several subroutines which are each executed 100% concurrent, yet measured concurrent efficiencies are about 50% on eight CEs. In regard to better than real-time capability, it is likely that this can be achieved utilizing the current simulation model. With further reduction in run-times by further code tuning, using eight CEs, the ALLIANT run-time should be about one second per time step. This implies that time step sizes must be larger than this value if the ALLIANT FX/8 is to be employed for real-time simulation. This time step size is judged to be acceptable for the operator aid system application. However, the current coarse-mesh finite difference based code is poor and the fidelity of modeling the full versus quarter core will increase run-times. For these reasons we believe that it will be necessary to employ a nodal model with one mesh per assembly, reflector albedo boundary conditions, and a one and a half energy group treatment. Collectively these changes should reduce run-time by about a factor of thirty over the current DIFPAR3D simulation model.

CONCLUSIONS

Progress on the development of an operator aid system that utilizes an on-line simulator as part of its knowledge base is presented. This paper reports on two specific areas where progress has been made: demonstrating that integration of the functional pieces of this system is possible, and demonstrating that a high fidelity core simulator could be developed to execute in better than real-time on a relatively inexpensive computer of the mini-super class. An accompanying paper[11] reports upon development of a real-time system thermal-hydraulics code. Demonstrating the integration of the functional pieces was successfully completed by developing and utilizing a simple operator aid system that uses a 1-D (axial) on-line simulator. This operator aid system can recognize Technical Specification violations, keep the simulator current with the plant instrumentation signals, and advise the operator on how to recover from Technical Specification violations and how to complete planned power maneuvers.

To demonstrate that a better than real-time core simulator operating on a modestly priced computer could be developed, the two-group, three-dimensional, coarse-mesh finite difference code DIFPAR3D has been converted to take advantage of vector- concurrent operations on the ALLIANT FX/8 mini-supercomputer. Timing study results to date indicate that

better than real-time execution is possible for the current core simulator using about one second time steps. However, to simulate in real-time full core effects with good fidelity, it will be necessary to employ a nodal simulator.

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Table 1. Performance of the core simulator utilizing an ALLIANT FX/8 in the vector-concurrent mode.

Measure	Number of CEs							
	1	2	3	4	5	6	7	8
CPU Time (Sec)	6.45	3.41	2.73	2.16	1.95	1.67	1.51	1.33
Concurrent Efficiency (%)	-	94.6	78.7	74.6	66.2	64.4	61.0	60.6

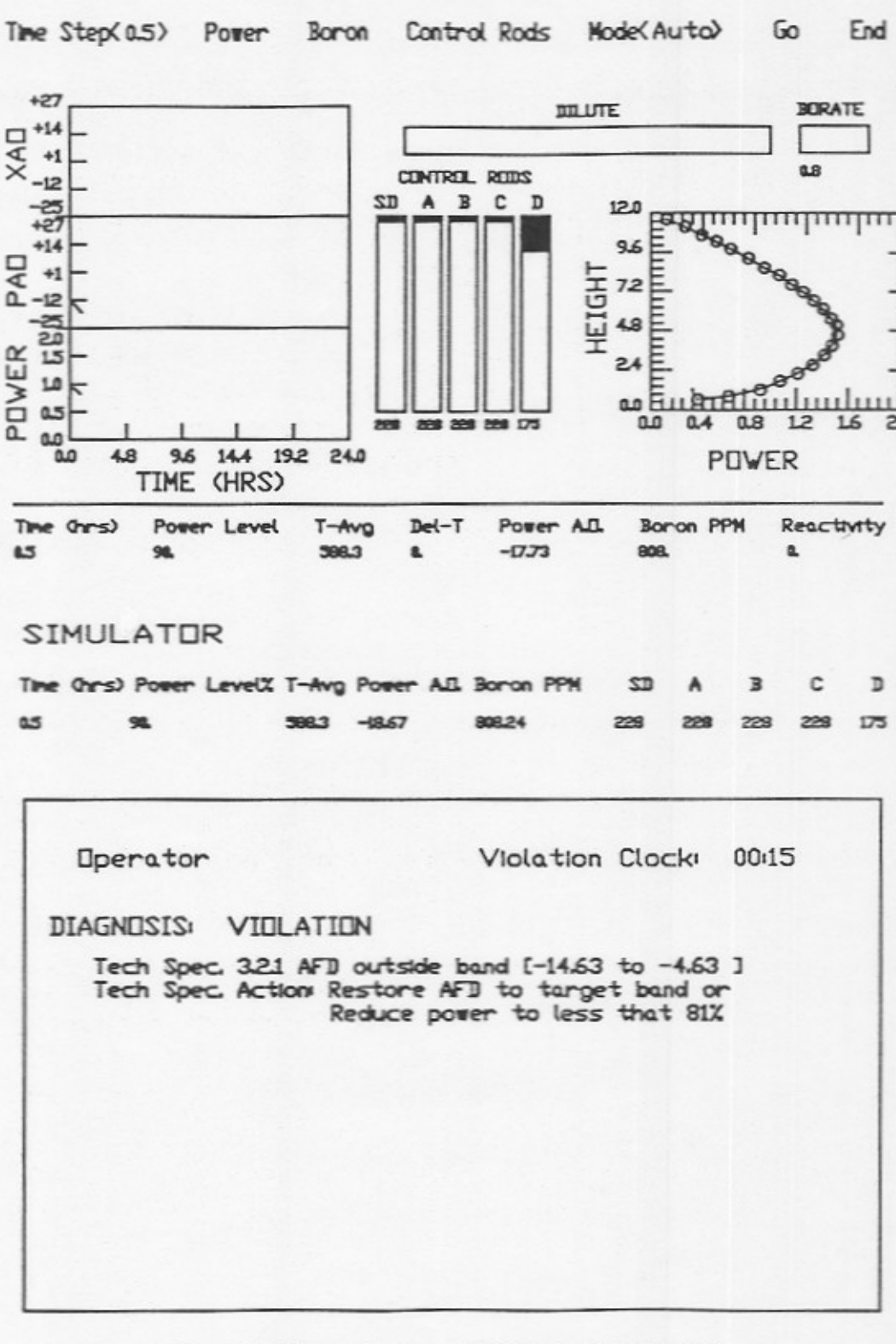

Figure 1. Expert System AFD Violation Detection

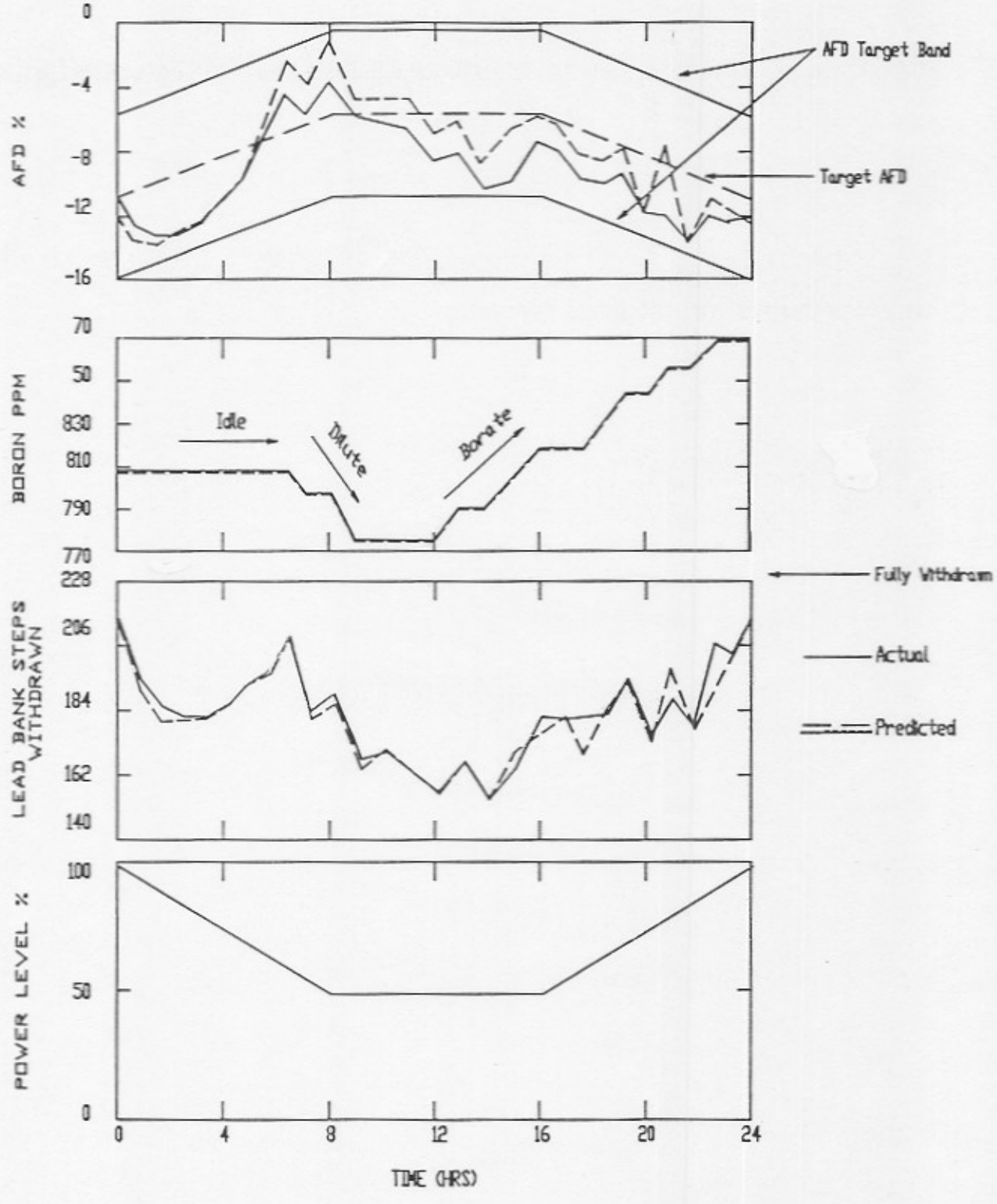

Figure 2. Load-Follow Maneuver Predicted
(dashed line) and Actual (solid line) Reactor Parameters