THE USE OF SIMULATION IN THE TRAINING OF NUCLEAR POWER PLANT OPERATORS

DR. T. E. C. HUGHES AND MR. J. T. O'HALLORAN
The Singer Company
Simulation Products Division

Introduction

Training nuclear power plant operators has always been a problem--it absorbs the time of skilled men, requires operational equipment, and is often difficult and potentially dangerous. Because of the major expansion of nuclear generating capacity anticipated during the next ten years, there will be increased requirements for competent staff. Approximately 15,500 additional nuclear oriented plant and headquarters staff personnel will be required by utilities in the U.S. by 1982. Of the utilities expected to have nuclear power plants in operation by 1982, two-thirds of these will have had no actual operating experience with nuclear power plants (WASH-1130[1]). Utility managers must make certain that they receive full value for every dollar expended in training. They have the responsibility for the safe and efficient operation of the plant, for gaining and maintaining public trust and confidence, and for the avoidance of costly power interruptions. A cost effective training system for plant personnel will ensure efficient operation and increase return on investment.

The use of simulators for training power plant operators is becoming more widespread. Operational simulators have been used in various industries and throughout the military for a number of years in the training of operators of complex equipment, including both normal and emergency operating procedures and skills. The most widely known application of simulators has been in the training and examination of aircraft pilots. Simulators have also been used for training astronauts and for training control room operators for large power plants. These cases require trained personnel prior to the operation of actual equipment. Once a nuclear power plant is operational there is little opportunity for using it for training. Since practice of all but routine procedures will adversely affect plant reliability, plant economy, and public and personnel safety, use of the plant for training purposes is not a cost effective or safe means of solving the training problem.

Factors relating to safety, economics, and training effectiveness have influenced decisions to use nuclear power plant simulators in training and requalification programs for reactor operators and key plant personnel. In a survey of 14 operating utilities in the United States, the United Kingdom, and Canada seeking information on attitudes toward training by simulation, the utilities were asked to comment in general on their experiences with the training of nuclear power plant operators and specifically on the role of simulators for training (Bates[2], 1969). Of the 12 organizations that replied, six had had experience with simulator-trained personnel and 11 thought that training by simulation was valuable. Nine utilities expected to use simulators for training in the future. Eight utilities believed that the simulator was also good for refresher training.

Need for National Standards for Simulation

Recent studies which related the degree or scope of simulation to the training requirements for control room operators (Cox and Hughes[3], 1973) resulted in recommendations concerning the need for the development of a national standard which would accomplish the following:

a) Clearly define the training requirements to be met by the simulator.

b) State the simulation tolerances, both for system performance and system interdependency, necessary to meet the training requirements.

c) Specify the fidelity and scope of simulation of normal, emergency, and abnormal operating conditions required for training and requalification programs.

d) Provide criteria and guidelines to be followed by both the simulator manufacturer and the utility, in cooperation with the AEC, regarding the use of a simulator in training and requalification of operators in the safe operation of nuclear plants.

After further investigation it was concluded that it is necessary for the proposed standard to relate the important dependent and independent variables to the physical processes which affect the operator's tasks during startup, operation, and shutdown (Hughes, Cullingford, and Deaton[4], 1973). The standard should provide tolerance requirements for the principal simulation variables that are displayed and/or require operator response. These variables are inherent to the control, core physics, reactor coolant, steam supply, nuclear instrumentation, and all engineered safety features.

The present lack of a definitive national standard for nuclear power plant simulators for operator training is not particularly surprising. The nuclear power industry is relatively young and the advent of the full-scope, high-fidelity nuclear power plant simulator occurred just a few years ago.

Federal regulations (published August 17, 1973 in Appendix A of 10CFR55) outline requirements that each AEC licensed operator must satisfy in order to have his license renewed every two years. One such requirement is that each operator is required to execute "10 reactivity control manipulations" during the two-year period. Because of the constant level of power generation by the nuclear plant it is unlikely that each operator would be able to fulfill this requirement. Following an analysis of their requalification training program requirements, the Carolina Power and Light Company cited the nuclear power plant simulator as the "key to requalification" (Connelly and Roman[5], 1973) since the use of simulators was the best way to requalify without affecting plant operations.

To perform their job in a power plant, operators are required to learn to operate complex and costly equipment, with safety the single most important factor. Because of the constant power loading of the plant, an operator receives only a small amount of infrequent practice in starting up and shutting down his plant. In addition, the operator seldom gets practice in the maneuvering necessary to deal with failures of individual plant components such as pumps. Since routine operations of a large, new plant offers little opportunity for training in some of the most crucial, safety-related tasks, one method sometimes employed for training of power plant operators is to have the trainee practice on older and smaller plants. However, the newer plants being planned and built are not only larger, but they are also more complex, and they incorporate later designs and different operating procedures. Thus, training on older plants may not be relevent to the training requirement. Simulators can be built which duplicate the actual control room and display an accurate response to the actual procedures.

Nuclear Power Plant Staffing Projections

Figure 1, from an AEC report titled "Utility Staffing and Training for Nuclear Power, June 1973," (WASH-1130[1]) illustrates an estimate of the expected growth in the nuclear industry for the number of utilities operating commercial units through the year 1982. The total number of operational nuclear units in 1972 was 29. Through 1982, the AEC predicts that there will be 180 nuclear units in operation consisting of three 4-unit stations, eight 3-unit stations, 53 dual-unit stations, and 38 single-unit stations. In 1982 there will be 67 utility companies in the United States, of which 35 will be operating two or more units, and 19, three or more units.

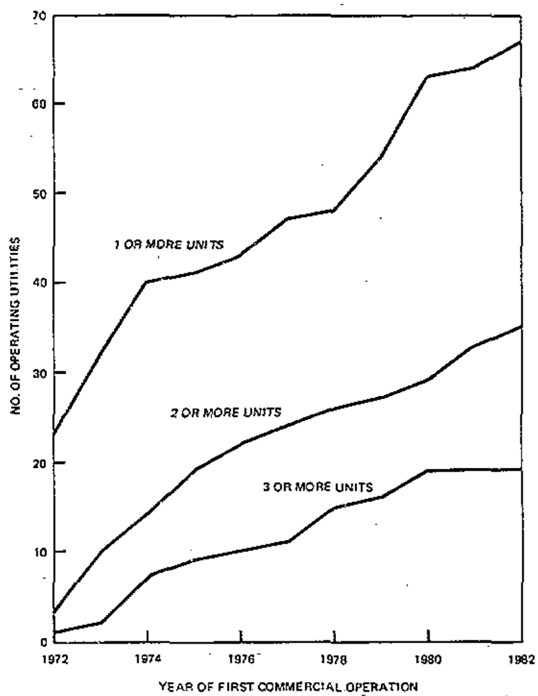

Figure 1. Utilities Operating Nuclear Power Plants

(From "Utility Staffing and Training for Nuclear Power," WASH-1130, June 1973)

The AEC has assessed the cumulative staffing impact of putting new nuclear generating units into service through the year 1982 (WASH-1130[1]). AEC estimates of the combined needs of U.S. utilities for nuclear-trained manpower are shown in Table 1 and Table 2. The total number of persons, or

TABLE 1. ESTIMATED NUCLEAR STAFFING REQUIREMENTS FOR U.S. UTILITIES BY DATE OF EMPLOYMENT (FROM WASH-1130, JUNE 1973)

Year	Headquarters	Plant Operations	Plant Technical	Technicians	Maintenance	Security
Est. Thru 1972	1758	2237	444	707	1318	457
Add. for 1973	198	180	31	90	489	167
1974	167	379	72	52	247	74
1975	196	426	73	136	152	42
1976	262	467	94	135	346	119
1977	270	661	123	162	363	111
1978	323	401	57	248	415	140
1979	419	419	65	120	728	216
1980	345	651	115	120	361	93
1981	371	761	53	216	364	93
1982	417	847	151	254	581	181
Total	4726	7429	1278	2240	5364	1693

TABLE 2. ESTIMATED STAFFING BY DATE OF EMPLOYMENT (FROM WASH-1130, JUNE 1973)

Year	*Plant Sup't. and Ass'ts.	*Operations Supervisors	* Shift Supervisors and Lead Operators	** Control Operators	Auxiliary Operators	* Lead Fuel Handlers	Fuel Handlers
Est. Thru 1972	119	82	433	698	698	69	138
Add. for 1973	15	13	32	42	42	12	24
1974	16	15	74	119	119	12	24
1975	26	16	81	111	111	27	54
1976	19	24	90	140	140	18	36
1977	6	15	136	216	216	24	48
1978	14	15	78	93	93	36	72
1979	24	23	78	93	93	36	72
1980	28	27	126	181	181	36	72
1981	31	30	148	213	213	42	84
1982	34	33	165	240	240	45	90
Total	332	293	1441	2146	2146	357	714

* Indicates licensed "Senior Reactor Operator."
** Indicates licensed "Reactor Operator."

equivalent man-years per year, are shown by job category; the dates represent the times at which the personnel should be employed in order to assure meeting all job qualification and training requirements. Table 2 represents a specific breakdown of the "Plant Operations" category shown in Table 1. Those job categories requiring personnel to qualify as licensed operators and licensed senior operators in accordance with the regulatory requirements under Federal Rules and Regulations (Title 10, Part 55) are indicated by asterisks. It is noteworthy that the licensed operators do not form a highly mobile labor pool within a utility since they are licensed for specific plants. Transfers require additional training.

Simulators for Requalification Training

Recently the AEC issued a rule change which requires that licensed operators participate in requalification programs to demonstrate continued competence for license renewal. While requalification program requirements involving manipulation of reactor controls for reactivity changes may be met using the nuclear power plant controls, the AEC regulation both permits and encourages the use of simulators. This regulation (Appendix A to 10CFR55) permits the use of a simulator as a means for reactor operators to demonstrate skill and/or familiarity with reactivity control systems. These manipulations shall consist of a minimum of 10 reactivity control manipulations in any combination of reactor startups, shutdowns, or control manipulations to demonstrate operator competency. A simulator may be used for practice if it "reproduces the general operating characteristics of the facility involved, and the *arrangement* of the instrumentation and controls of the simulator is similar to that of the facility involved."

Another provision of 10CFR55, Appendix A, requires the evaluation of operator actions during actual or simulated abnormal and emergency conditions. While this requirement may be met using the controls of the actual plant, here again the AEC permits and encourages the use of a simulator which "*shall accurately reproduce* the operating characteristics of the facility involved, and the arrangements of the instrumentation and controls of the simulator shall closely parallel that of the facility involved." If the control panel of the actual facility is used for evaluation, actions that the operator would take to handle the emergency or abnormal condition are only discussed; control manipulation is not required. Table 3 summarizes how AEC requirements for a simulator vary with the intended application. Note that requirements are more stringent for evaluation than for practice purposes.

According to a recent interpretation of Appendix A to 10CFR55 (Holman, J. J. and Collins, P. F.[6]), the use of a simulator may be acceptable in meeting the requirements for reactivity control manipulations and demonstrations of understanding of apparatus and mechanisms if the simulator design is based on a nuclear steam supply vendor's product line. However, for the purpose of evaluation of operator response to abnormal and emergency conditions, a simulator may be used only if it possesses sufficient scope and fidelity of simulation in approximating the dynamics of transient operation of the particular plant on which the operator is licensed.

The training value of simulators is recognized by the AEC and their use is encouraged in Appendix A to 10CFR55. AEC acceptance of simulators which provide a full scope, high fidelity duplication of the

TABLE 3. 10CFR55 APPENDIX A SIMULATOR REQUIREMENTS

		TRAINING REQUIREMENTS	
		Practice of at Least 10 Reactivity Control Manipulations	Evaluation of Operator Response to Abnormal and Emergency Conditions
SIMULATION EQUIPMENT	Reproduction of Operating Characteristics (Performance)	"General"	"Accurately"
SIMULATION EQUIPMENT	Arrangement of Controls and Instruments (Configuration)	"Similar"	"Closely Parallel"

NOTE: Words in quotation marks indicate the level of simulation equipment requirements (*performance* and *configuration*) needed to satisfy the training requirements.

controls and transient responses of nuclear power plants attests to their training value. The fact that simulators are now being built with sufficient fidelity of simulation to provide complete, continuous, real time representations of dynamic responses of nuclear power plants is particularly significant; this capability permits their use in a full range of training experiences including training in all normal and abnormal operating procedures. The trainee can perform in a variety of training exercises on a simulator, whereas practice on a real reactor in coping with problems encountered in abnormal and emergency operation is severely limited.

Since power outages, for whatever reason including training, can result in losses of about $100,000 per day, it is understandable that utilities recognize that the use of the simulator presents a cost effective "key to requalification" (Connelly and Roman[5], 1973).

Simulator Use in Initial Training

A practical distinction between the use of the actual plant controls in training and the use of the simulator is reflected by the AEC policy in accreditation for time spent on a simulator in operator training programs. The AEC has recognized the training effectiveness of nuclear power plant simulators and awards credit on a three-for-one time basis for such use. Up to one year of such training (four months on a simulator) is accepted in lieu of plant experience in qualifying for initial licensing.

Training may qualify as experience if acquired in appropriate nuclear power plant simulator training programs on the basis of one month's training being equivalent to three months working experience in plant operation. At the time of appointment to the active position, reactor operators to be licensed by the AEC must have two years of power plant experience of which a minimum of one year must be nuclear power plant experience or equivalent training on a nuclear plant simulator. If not already eligible by experience and previous training, a candidate may become eligible to take the examination by a combination of participatory assignments at operating reactors or suitable reactor simulators, participation in construction or startup activities at the nuclear plant involved, and related technical training.

According to the provisions of the National Standard ANSI N 18.1-1971 titled "Selection and Training of Nuclear Power Plant Personnel," it is possible that the two year experience criterion for the licensing of a reactor operator may be shortened by as much as eight months if a simulator is used (one year equivalent experience for four months simulator training). Individuals who successfully complete a training program using a simulator will be considered eligible for licensing by the AEC before startup of a new unit provided that:

1. They have completed an acceptable course in nuclear technology fundamentals.

2. They have manipulated the controls of any real nuclear reactor throughout ten complete startups (research or test reactors such as the General Electric NTR Critical Facility have been used for this purpose).

3. They have experienced several months of daily observation of an operating power reactor. (This experience is observation only and does not require manipulation of controls.)

Power Plant and Flight Simulators

The use of simulators in aircraft pilot training is well known. There is a common factor in relating programs for pilot training to those of power plant operator training. Both airplanes and nuclear power plants are, to the trainees, challenging devices which are increasingly expensive and complex; and in their operation, safety is a major factor. Both pilots and nuclear power plant operators can now train for their complicated responsibilities using simulators designed to emphasize sensory perception of events by the trainee. Both the modern flight training simulator and the modern power plant operator training simulator are controlled by a digital computer specifically designed for real time simulation.

In the 1950's the problems of simulating the high speed, low altitude environment of attack aircraft offered special challenges to the Navy. The need existed to apply advanced simulation techniques to represent the Navy's new high performance aircraft through a broader range in terms of values and rate of change (Kelly[7], 1971). There was experimentation in computational systems that would provide more rigorous solutions of equations, and thus be more suitable (than the analog computers of that period) for simulating the wider range, higher rate performance of jet attack aircraft. In 1950, the Naval Training Device Center awarded a contract to the University of Pennsylvania for a study of the practicability and feasibility of using digital computation in simulation. As a result of that study, the Universal Digital Operational Flight Trainer Tool (UDOFTT) was constructed in 1960. This constituted the first practical step in the application of digital technology to flight training simulation. Subsequent Navy flight trainers have demonstrated the great flexibility and capability inherent in simulation based on digital computation with advantages in rapid and accurate calculations, greater reliability, lower power requirements and improved maintainability.

The modern nuclear power plant simulator presents to the operator trainee a training device with many of the same training advantages and capabilities that are available to the pilot trainee in a modern flight simulator. Both of these men are trained (to handle complicated responsibilities)with digital simulators designed to emphasize sensory perception of events by the trainee. Both trainers are controlled by a digital computer specifically selected for its real-time simulation capability.

Nuclear Propulsion Operator Training with a Simulator

Another example of the effectiveness of training simulation related to nuclear reactors has been reported (Gross[8], 1973). In his paper concerning training for the N.S. SAVANNAH'S crew, Gross stated the following advantages:

- Eliminated need for an expensive shore based prototype reactor
- Provided training prior to availability of the ship
- Used to train replacement personnel
- Reduced need to divert operational equipment to training.

Gross then cited the Maritime Administration and the Maritime Reactor Branch of the AEC's Division of Reactor Development in recognizing the value of the simulator in operator licensing qualification training.

Like the commercial nuclear generating station, the vessel had a reactor as the basic energy source. Unlike the commercial station, the principal energy conversion process in the ship resulted in mechanical energy whereas the conversion in the nuclear generating station results in electrical power. The ship had a geared turbine with a single screw. The demands on fast ship maneuverability involving rapid power transients imposed stringent training requirements for safe and efficient operation which were met on the simulator.

Training Mission of the Simulator

For a real time simulator to be comprehensive, and yet economically feasible, care must be taken in selecting and developing systems and effects to be simulated. The approach taken in developing system models typically has been to construct the models on a modular basis with each model corresponding to a plant system. One of the primary justifications of a nuclear power plant simulator is the ability to subject the operator to various types of emergency situations (McNally and Chen[9], 1972). The adequacy of a particular system model depends on its ability to simulate both normal operations and malfunctions.

Simulators help in improving decision-making by developing judgement. Perhaps the greatest benefit derived by pilot and air crew training simulators lies in the systematic presentation of repetitive experience (Wheatcroft[10], 1973), and simulators have a definite advantage in this area since recovery and reset of the training situation can be accomplished rapidly through the computer. In view of the similar requirements for training in the operation of complex operations of nuclear power plants and aircraft, the value of the systematic presentation of repetitive experience in nuclear power plant simulators can be appreciated. Improvements in decision-making come from repetition, as in any other skill. In most cases of training in decision-making on a simulator, realism is important. Such is the case for training to handle emergency and abnormal events in the nuclear power plant. The information provided to the trainee must be realistic and the acceptable decisions must be the same ones which must be made on the job. A good nuclear power plant simulator must provide feedback of information to the trainee to tell him whether or not he has been successful.

It is apparent that since the role of nuclear power plant simulators is to provide training under all normal and emergency conditions, the development of such a simulator must include details which will provide a complete, continuous, real time representation of the physical characteristics of the power plant to be simulated. To accurately represent the physical and functional characteristics of the plant, it is necessary that complete and detailed information relative to the plant design be available to the simulator designer. The design data takes on several forms (Abbey[11], 1973). First, the physical characteristics of the plant(including component performance and the layout and instrumentation of the control room) must be described. The second general category of data relates to the physics of the plant systems. A third category of data includes such information as the turbine thermal characteristics, reactor physics, heat transfer characteristics and heat balance data. These three categories of data constitute several hundred individual items which are necessary to assure simulation accurate enough for training purposes. Data reduction involves tasks such as (1) establishing steam table functions, (2) developing

Boolean equations from logic diagrams, (3) developing mathematical expressions to represent the plant systems, and (4) the use of off-line computer time to reduce the reactor physics data to a form suitable for real time simulation, all while maintaining a level of fidelity commensurate with the training requirements of the nuclear power plant simulator.

Reports of recorded abnormal occurrences at nuclear power plants provide data that may be used for qualitative assessment of the nature and extent of these events in the nuclear industry (OOE-OS-001[12], 10 May 1974). Table 4, taken from the reference, provides a summary of the proximate cause category versus number of events for abnormal occurrences in U. S. commercial power plants in 1973. Component failure was the proximate cause of well over half of the events. Personnel error was the second most frequent cause of the abnormal occurrences, accounting for about 15 percent of the total. Clearly, training of power plant personnel can have a significant impact on plant reliability.

TABLE 4. PROXIMATE CAUSE CATEGORY VERSUS NUMBER OF EVENTS

Proximate Cause Category	Number of Events
Personnel Error	132
Design Error	51
External Cause	14
Procedures Defective	71
Component Failure	442
Other	78
Unspecified	73
TOTAL	861

Summary and Conclusions

Training in normal operating procedures and in procedures to cope with emergencies is required for nuclear power plant operators. To meet this training requirement, simulators have been designed and built so that the operator actions possible in a real control room are also possible in the simulated control room. Nuclear power plant simulator development has occurred because of increased power plant sophistication and the recognition of the value of training using simulators. As nuclear power plants grow more complex, as operations become more demanding, as operating costs grow and as demand for available trained manpower increases, utilities will require more simulators to provide operator training for large-scale, modern plants and for plants of advanced conceptual design.

Current and planned nuclear power plants generate on the order of 1000 Mwe. These plants can cost approximately $600 M, and power outages can result in losses of $100,000 per day due to the reduction of electrical generation. This large financial investment is the responsibility of three to five operators with support personnel who must weigh their decisions against administrative and regulatory standards to assure a safe and efficient operation of the plant.

In view of the potential hazards to the public welfare and in consideration of the costs associated with plant down time, management in the nuclear power industry must: (1) eliminate those factors which jeopardize safety of operations and (2) enhance those factors which affect the efficiency of operation and increase the return on investment.

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ABOUT THE AUTHORS

DR. THOMAS E. C. HUGHES received his B.S. degree in Physics from the Virginia Military Institute and his M.S. and Ph.D. degrees in Nuclear Physics from the Virginia Polytechnic Institute and State University. Prior to joining The Singer Company, Simulation Products Division, he was a research physicist and a member of the academic profession. At The Singer Company, he has been involved in nuclear power plant training programs development, and he has conducted research in fidelity of simulation and in nuclear reactor core physics simulation modeling. Dr. Hughes is professionally affiliated with the American Nuclear Society.

MR. J. T. O'HALLORAN received his B.A. degree in General Education in 1963 from the University of Nebraska and his M.S. degree in Business Administration in 1968 from The George Washington University. Mr. O'Halloran is the Manager of the Training and Educational Processes Department of The Singer Company and is involved in a wide variety of technical training programs for government and industry.