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Nuclear Power Plant Control Room Operator Control and Monitoring Tasks

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Computer Science and Mathematics Division

**NUCLEAR POWER PLANT CONTROL ROOM
OPERATOR CONTROL AND MONITORING TASKS**

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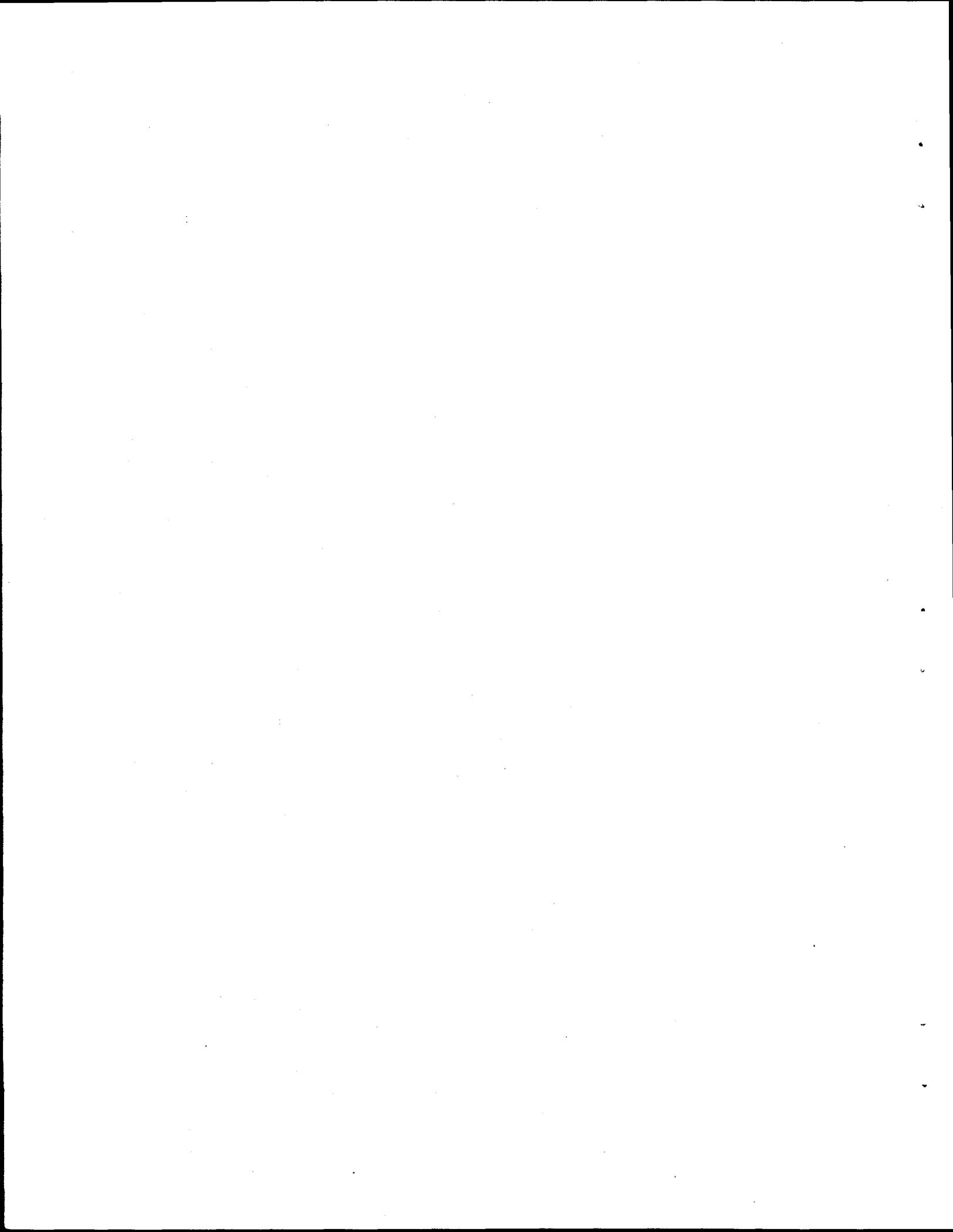
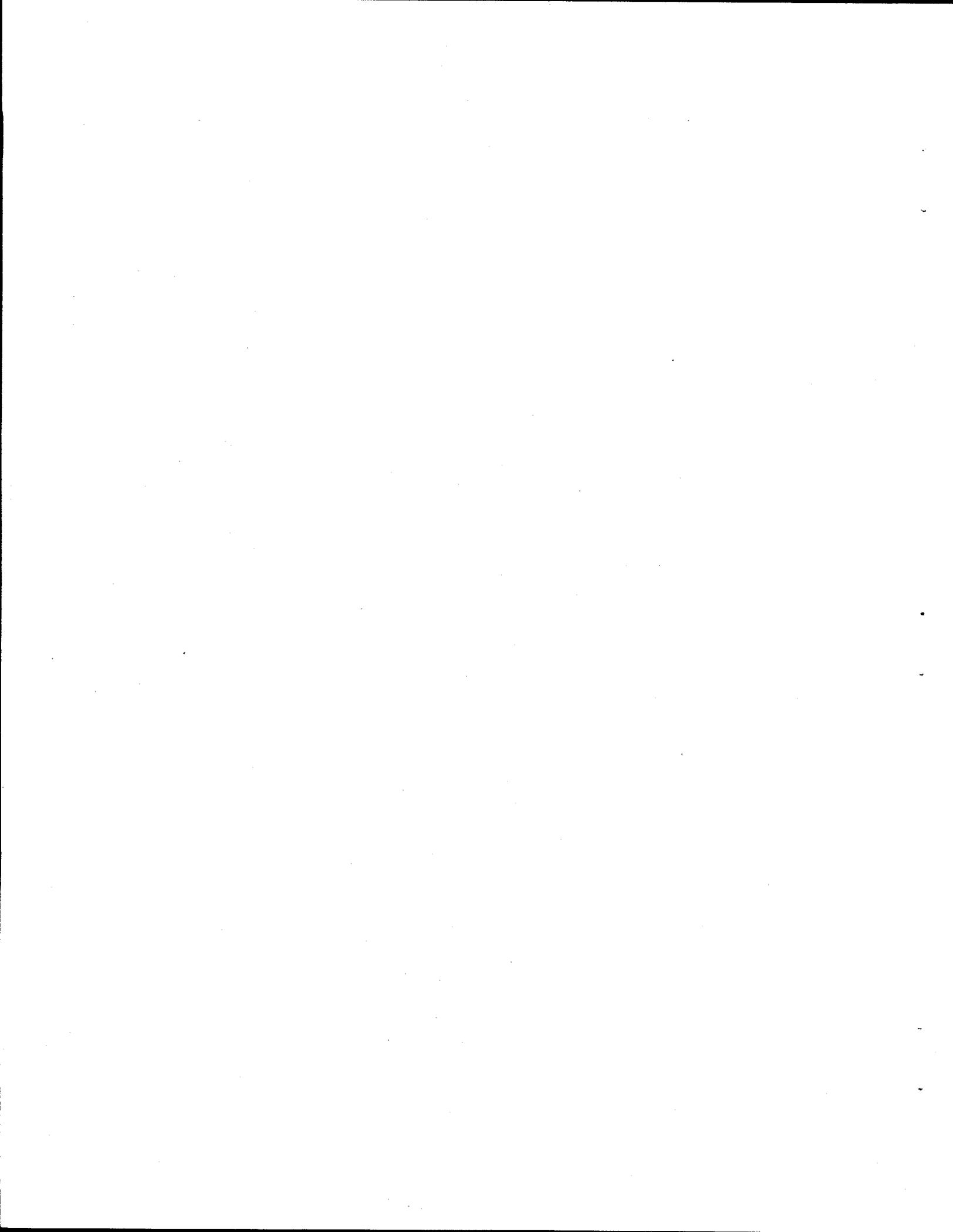


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ACRONYMS AND ABBREVIATIONS

BWR - boiling-water reactor

CRT - cathode-ray tube

ECCS - emergency core cooling system

I&C - instrumentation and control

INPO - Institute of Nuclear Operations

LCOs - limiting conditions for operation

NPP - nuclear power plant

NRC - Nuclear Regulatory Commission

pH - parts hydrogen

PWR - pressurized-water reactor

RCS - reactor coolant system

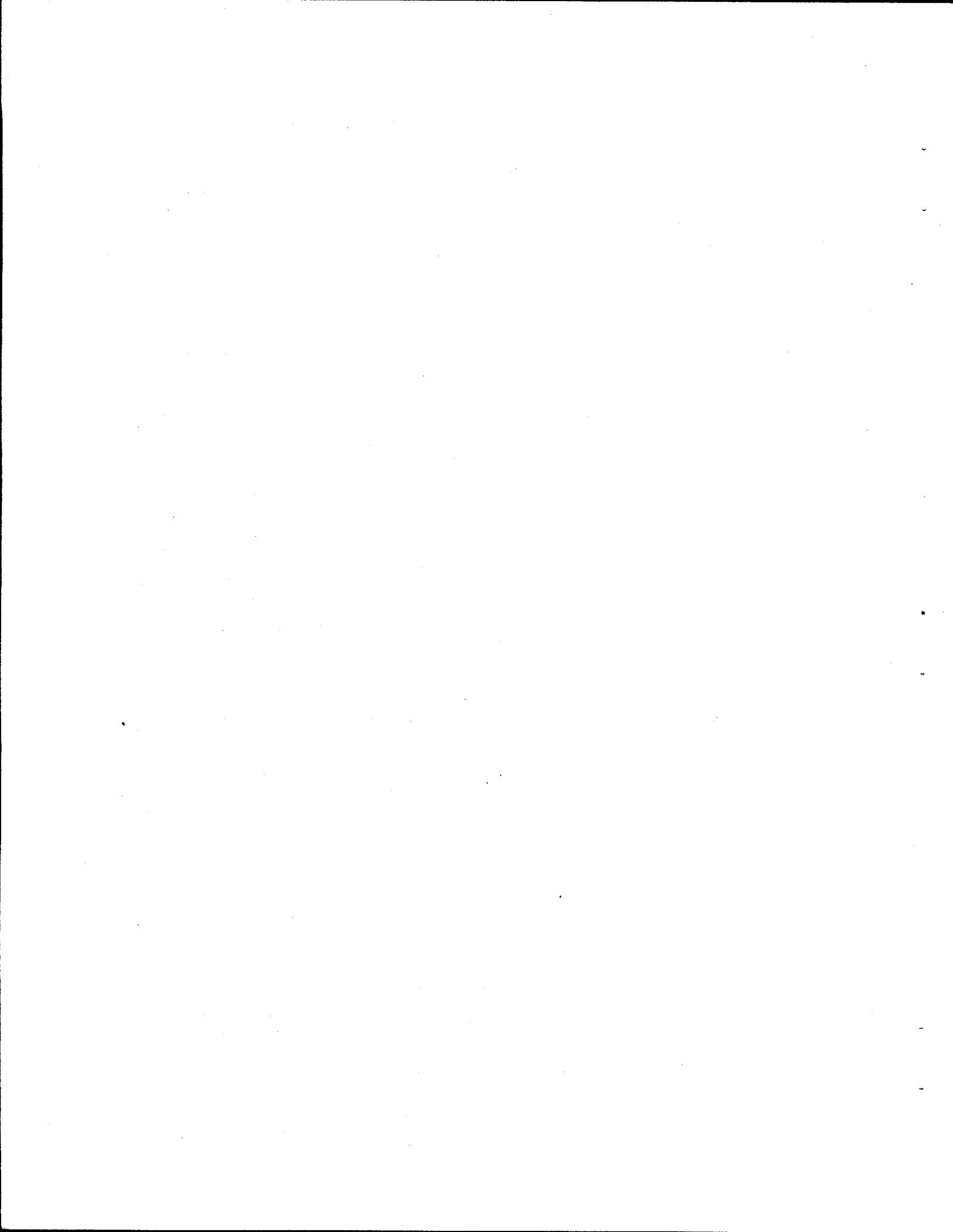
RO - reactor operator

SPDS - safety parameter display system

SRO - senior reactor operator

STA - shift technical advisor

T_{avg} - temperature average



ABSTRACT

Oak Ridge National Laboratory is conducting a research project the purpose of which is to develop the technical bases for regulatory review criteria for use in evaluating the safety implications of human factors associated with the use of artificial intelligence and expert systems, and with advanced instrumentation and control (I&C) systems in nuclear power plants (NPP). This report documents the results from Task 8 of that project. The primary objective of the task was to identify the scope and type of control and monitoring tasks now performed by control-room operators. Another purpose was to address the types of controls and safety systems needed to operate the nuclear plant. The final objective of Task 8 was to identify and categorize the type of information and displays/indicators required to monitor the performance of the control and safety systems. This report also discusses state-of-the-art controls and advanced display devices which will be available for use in control-room retrofits and in control rooms of future plants. The fundamental types of control and monitoring tasks currently conducted by operators can be divided into four classifications: function monitoring tasks, control manipulation tasks, fault diagnostic tasks, and administrative tasks. There are three general types of controls used in today's NPPs, switches, pushbuttons, and analog controllers. Plant I&C systems include components to achieve a number of safety-related functions: measuring critical plant parameters, controlling critical plant parameters within safe limits, and automatically actuating protective devices if safe limits are exceeded. The types of information monitored by the control-room operators consist of the following parameters: pressure, fluid flow and level, neutron flux, temperature, component status, water chemistry, electrical, and process and area radiation. The basic types of monitoring devices common to nearly all NPP control rooms include: analog meters, graphic recorders, digital displays and counters, light indicators, visual and audio alarms, and cathode-ray tubes.

1. INTRODUCTION

This technical report has been prepared to document the results from Task 8 ("Identify Control Room Operator Tasks") of the Nuclear Regulatory Commission (NRC) research project entitled "Review Criteria for Human Factors Aspects of Advanced Controls and Instrumentation". The results from Tasks 1-7 were described earlier by Carter and Uhrig (1990).

The purpose of the overall project is to develop the technical bases for regulatory review criteria for use in evaluating the safety implications of human factors associated with the use of artificial intelligence and expert systems, and with advanced instrumentation and control (I&C) systems in nuclear power plants (NPP). The primary objective of Task 8 was to identify the scope and type of control and monitoring tasks now performed by control-room operators in NPPs. Another purpose was to address the types of controls and safety systems needed to operate the plant. The final objective of Task 8 was to identify and categorize the type of information and displays/indicators required to monitor the performance of the control and safety systems.

2. CONTROL ROOM OPERATOR TASKS

2.1 BASELINE

Rather than generating a new task analysis from which control and monitoring tasks performed by control-room operators could be identified, a number of existing task analysis data bases, developed by the NRC and nuclear industry groups, were used instead. The baseline, from which the scope and type of tasks were identified, consisted of the following data sources:

- o the NRC task analysis of NPP control-room crews (General Physics Corporation, 1983)
- o the Institute of Nuclear Power Operations (INPO) job and task analyses for the control room and the senior control room operators (INPO, 1983)
- o boiling-water reactor (BWR) and pressurized-water reactor (PWR) task analyses conducted by the Mid-Atlantic Nuclear Training Group (Smith, 1989)

2.2 GENERIC TASKS

The fundamental types of tasks performed by the control-room operator were identified. These tasks are generic between reactor types (i.e., BWR and PWR) and include tasks performed during normal, abnormal, and emergency operations. They are also somewhat generic between job positions for control-room operators. Reactor operators (RO) are primarily responsible for control manipulations. The normal job responsibilities of the senior reactor operator (SRO) consist of supervising the activities of the RO and performing administrative tasks. However, SROs may be required to manipulate the controls during times of excessive RO overload and ROs routinely perform certain administrative tasks, such as data recording and surveillance testing.

Besides the ROs and SROs in the control room, shift technical advisors (STA) are on-site and are required to report to the control room during off-normal events. The STA is a staff engineer that

has obtained an SRO's license and specialized training on diagnosing severe accidents. The primary function of the STA is to monitor and diagnose plant conditions during transients and accidents, thereby giving the RO and SRO the opportunity to concentrate on executing procedures. Since the STA's responsibilities are primarily monitoring and diagnosis, computer-generated displays are used extensively by the STA. In most plant organizations, the STA is the primary user of the safety parameter display system (SPDS).

2.3 TASK CLASSIFICATION

The scope and type of control-room tasks identified herein consist of those that require the operator, in some capacity, to use the controls and displays in the control room. Communication tasks were not included.

Operator tasks can be divided into four classifications:

- o function monitoring tasks
- o control manipulation tasks
- o fault diagnostic tasks
- o administrative tasks

Figure 1 shows a simplified relationship between these tasks. One operator is continuously monitoring the plant. Other operators may be involved in the performance of administrative duties. Administrative directives include orders for the operators to perform planned control manipulations. If, during the monitoring activities, the operator detects a system or component fault, the cause of the fault must be analyzed and the appropriate corrective action selected. The operators are required to manipulate the controls to return the system operation to normal, although this may require them to change the operating mode. When the corrective actions have been satisfactorily completed, the operator returns to the monitoring tasks.

2.3.1 Function Monitoring Tasks

A large portion of the operator's job consists of function monitoring. When the plant is in steady-state operation, control manipulations are required infrequently. Much of the operator's time is therefore spent ensuring that all systems continue to operate normally. That is, the operator is monitoring the plant systems to detect problems. One RO is capable of monitoring the reactor during steady-state operations, while other operators on shift may be busy with administrative tasks.

Monitoring of plant functions is much more difficult during plant abnormal events. During changes in operating conditions, operators must monitor plant functions to ensure that system parameters change within expected bounds. The interrelationship of systems may require several operators to be present to monitor system performance during plant evolutions. Operational experience has demonstrated that during an abnormal event, a single operator cannot successfully perform the required control manipulations and monitoring of plant systems. This situation has necessitated increased control room staffing during reactor start ups and shutdowns.

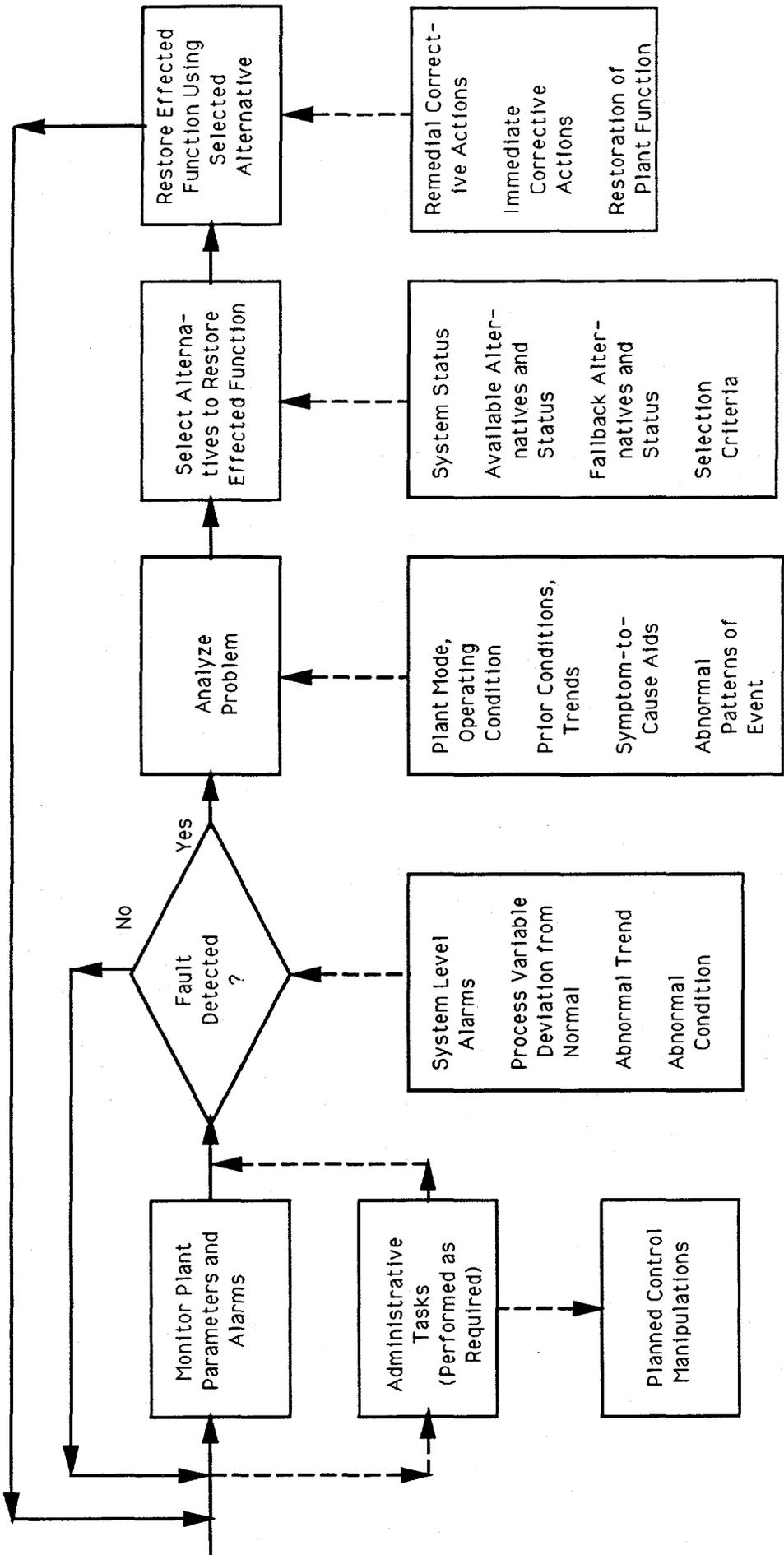


Figure 1 - Simplified Flow of Control Room Operator Actions

Monitoring during off-normal conditions is critical for determining the effectiveness of corrective actions. During rapidly changing plant conditions, the operators may need to make rapid decisions concerning the effectiveness of their most recent corrective action for achieving desired results. While rapid response may be required in some cases, a hands-off approach may be appropriate in other cases. Accurate information, accessed rapidly, is essential for decision making when safety systems are challenged.

Monitoring tasks consist of repeated observations of control-room instrumentation for the detection of component or system malfunctions, or parameter trends. Since monitoring is a function of the control-room instrumentation, it would be appropriate to describe how the operator would use the instrumentation to detect failures. Relating monitoring tasks to the instrumentation, the operator's tasks may be categorized as:

- o systems and component level alarm monitoring
- o monitoring for process variable deviation from normal
- o abnormal trend monitoring
- o abnormal condition monitoring

2.3.1.1 Systems and component level alarm monitoring

The countless control-room annunciators are the highest level of fault detection available to the operator. During routine operation, operators are alert to the activation of annunciators. Operators, however, do not seem to consciously scan the panels waiting for alarms. Other control room tasks tend to consume the operator's time. Furthermore, the continuous scanning of annunciators and meters would soon lead to operator fatigue and boredom. Rather, the operators are aware of annunciators that are active, and they are ready to detect new alarms when they are received. It is normal to have a number of annunciators active within the control room at any given time. Also, minor equipment problems may cause an annunciator to activate and clear repeatedly. A control-room operator should understand the systems well enough to know which annunciators are normal for the various plant conditions and which annunciators are of little consequence to the plant status.

Annunciators give the operators a quick means of diagnosing a problem without actually reading the annunciator tiles. Through operating experience and training, operators are able to recognize patterns of signals on the annunciator panels. Pattern recognition relieves the operator from reading every annunciator tile during normal operation, and from verifying expected automatic actions during off-normal conditions. For example, a specific set of annunciators will be active whenever the main turbine generator is tripped. Following a scram, the operators may only need to see this pattern of annunciators to know that the main turbine has tripped following the scram.

Fault monitoring with the annunciator system is made easier for the operator by use of audible alarms that accompany activation of an annunciator. The audible alarms draw the operator's attention to the panel where the annunciator is activated. While this may be distracting during off-normal conditions when a large number of alarms are received, it is necessary during steady-state operation. For example, the operator may be monitoring the reactor console and may not notice an alarm on a balance-of-plant system.

Some systems and components have, in addition to annunciators, alarm light indicators for certain vital safety equipment. These indicators may be located on the control panel alongside the controls for the monitored component. For example, indicators may be installed with pump or valve controls to indicate when a safety-related component is not in the proper lineup. To make these indicators obvious, the color cannot be red or green which have well established meanings generally related to "on" or "off". Amber is usually selected as the color for these indicators because it is easily noticeable in the rows of red and green lights on the control panel.

2.3.1.2 Monitoring for process variable deviation from normal

Monitoring of process variables requires more of a conscious effort on the part of the operator than alarm monitoring. This type of monitoring requires the operator to read a parameter value and then make some determination as to the acceptability of the parameter reading. To make this task easier, upper and lower limits of the normal operating band are often marked on the meter so that the operator can visually determine if a parameter is out of the normal range. SPDS parameter displays use color coding to indicate an out of range reading.

During normal operation, the operator will concentrate on a small set of parameters that are primary indications of plant status. As a minimum, the operator should be continuously aware of reactor power level, reactor level (BWR), steam generator and pressurizer levels (PWR), reactor and reactor coolant system pressures, hot leg and cold leg temperatures (PWR for T_{avg} calculation), and generator load. Most system problems will have some effect on one or more of these parameters. Detecting a deviation in the expected readings of one these parameters will cause the operator to begin fault diagnosis to determine the source of the problem.

2.3.1.3 Abnormal trend monitoring

While alarms and variable readings can give the operator an indication of the current plant state, trend monitoring is useful for assessing possible future plant states. Gradual changes in process variables may be an indication of system degradation that is not readily apparent simply by monitoring parameter readings. As the operator monitors process variables, a slight change of the meter reading may go unnoticed from one observation to the next. However, if the operator remembers the meter readings from the start of the shift, then at some time during the shift a gradual change in the parameter value may become noticeable. This slow change can be confirmed for those parameters that are recorded on strip chart or point recorders, or have computer logging. Reviewing these data will give the operator confirmation that indeed a latent problem may exist.

2.3.1.4 Abnormal condition monitoring

Monitoring for abnormal conditions requires detailed knowledge of plant characteristics. Knowledge of procedures and fundamentals of operation are also essential for this type of monitoring, since cues to possible problems may be subtle. Abnormal condition monitoring requires the operator to make correlations between interrelationships of plant functions. This requires knowledge of expected plant behavior for a given plant configuration and operating mode. The abnormal conditions an operator may need to detect during this type of monitoring include spurious controls operation, operator error, failure of automatic systems to respond to changes in plant state, and minor failures of support equipment. The operator would need to detect changes in plant

operating components, or system performance that may not be annunciated until some time after the malfunction actually occurs. Degraded component performance may not be manifested by great changes in parameter readings. Components operated by auxiliary operators in the plant and not placed in the correct configuration can be difficult to detect in the control room. Instruments not returned to service properly following testing can also be difficult to detect. Detecting that any of these have occurred from typical control-room instrumentation may take several hours or even days and weeks.

2.3.2 Control Manipulation Tasks

Control manipulations are the second most frequently performed operator task. While countless hours may be spent monitoring the plant, control manipulations may be required at any time. During steady-state operation, control manipulations are usually required for performing surveillance testing of safety-related equipment. Occasionally the operator may need to make minor adjustments in set points and flow rates to keep the systems balanced. To ensure that all components receive the same service time, operating components may be changed out on a regular basis. The same is true for fuel burn up. Fuel economy will require adjustments in control-rod patterns to ensure efficient fuel utilization.

Most control manipulations occur when the plant is in either start up and power ascension, normal shutdowns, or off-normal operations. These three operating states involve a large number of plant systems. Also, processes that are normally under automatic control during steady state may be controlled manually under these conditions. For example, feedwater flow is controlled manually for much of the reactor start up and heat up. Once steam flow to the main condenser (via turbine bypass valves) is established, the feedwater control may be placed in an automatic mode.

There are four main control manipulation tasks: planned control manipulations, remedial corrective actions, immediate corrective actions, and restoration of plant function.

2.3.2.1 Planned control manipulations

Changes in plant state are planned to meet both long-term and short-term needs. Long-term needs include shutdown for refueling outage, shutdown or load reduction for preventative maintenance and surveillance testing, and adjustments for seasonal load projections. Short-term needs include changes in operating conditions for fuel economy, corrective maintenance, compensation for variations in seasonal demands, and compensation for utility-wide capacity factors (availability of other plants on the grid).

The operator in the control room receives directions from the shift supervisor, who is working from a plan of the day, or from some other directive given by management or engineering. All planned control manipulations are performed by written procedure. To ensure that the procedural steps are performed, and that they are performed in sequence, sign-off is required for each step.

Performing control manipulations as part of normal planned activities is somewhat different than those actions performed in response to off-normal conditions. The operator does not experience the same sense of urgency under these conditions. The operator will operate a control in response to a directive in the procedure, then wait for the feedback from the instrumentation to indicate that

the change in system state has been effected. This deliberate action-and-feedback control manipulation allows the operator to ensure that systems respond as expected.

2.3.2.2 Remedial corrective actions

Plants are designed such that minor equipment or instrument failures do not have a significant impact on overall operation. Such minor failures are expected to occur during normal operations. However, the operators must diagnose and correct such failures to maintain system availability and to ensure safe operation of the plant. On safety-related systems, redundant instrumentation or components are normally available. Redundant components may start automatically. However, on balance-of-plant systems (e.g., main steam, condensate, feedwater, etc.), the operator may need to take quick action to prevent a plant shutdown since redundant components may not be available. For example, a controller operating in automatic to maintain a set flow rate or level may fail either closed or open. The operator may need to take the remedial action to place the controller in the manual mode to prevent the process variable controlled by the device from reaching a trip limit. Operators are trained to quickly recognize the most common failures of this type and to take quick corrective action to maintain plant availability.

Remedial actions, in cases where safety-related equipment is involved, are required to meet technical specifications. Degraded safety systems may require plant operation at reduced power levels, or commencement of an orderly shutdown. While the plant is capable of operating under degraded conditions, safety is compromised in that limits on fuel, reactor vessel, and containment may not be met in the event of a design basis accident. The remedial actions required by technical specifications ensure that the plant can withstand the design basis accidents.

2.3.2.3 Immediate corrective actions

Immediate corrective actions are those actions performed immediately following a transient or accident. Operators are required to have immediate actions memorized so that they may be performed without benefit of procedures. Procedures are referenced as soon as possible to ensure that all of the immediate actions have been completed. These corrective actions are not intended to correct the root cause of the problem. Rather, they are intended to remove equipment from service that should not be in operation for the plant state while placing other equipment in service that is required. The most obvious case to illustrate this type of action is the reactor scram. Operators are trained repeatedly on events that have a reactor scram as a common occurrence. Regardless of the cause of the scram, the operators perform the same set of actions to place the systems in the correct operating state for shutdown.

Additional corrective actions are taken to restore plant functions that invariably deviate from normal following a reactor scram. For example, the rapid decrease in heat generation will cause a level transient in the steam generator (PWR) or the reactor vessel (BWR) due to "shrink" (collapse of steam bubbles). Corrective action is required to return the water level to normal without overfeeding the boiler.

2.3.2.4 Restoration of plant function

Severe accidents require a response from operators that is significantly different than would be

expected in transients that occur with high frequency. By definition, an accident is an event that involves multiple equipment failures and/or operator errors. With NPP systems, there could be an endless variety of accidents that an operator may need to respond to quickly and correctly. Symptom-based emergency procedures provide the operator with direction for handling any accidents by directing him to maintain vital safety function. Safety functions include reactivity control, heat transport (primary and secondary), containment control, and heat sink.

Each plant function may be maintained and controlled by more than one mechanism. Naturally, the normal means of controlling plant functions is the most desirable, but when the normal control is not available the operator must use alternate control paths. How the operator selects the alternative success path for controlling any given plant function will be discussed later. Although the alternate control paths may be less efficient or effective, the operator can at least restore partial control over the affected plant functions until the normal conditions can be fully restored.

Control manipulations during severe accidents will, as with any other operation, be performed via the procedures. Since the control manipulations are taken during off-normal conditions, the operators are performing tasks that they may have only performed during simulator training. Therefore, the unfamiliar, and possibly unknown, system response requires the operators to exercise extreme caution. As with most other types of operation, the operator will activate a control and then will wait for the appropriate feedback from the instrumentation. The expected feedback should indicate that the action had the desired effect. Although the actions in such cases need to be performed quickly, operators need to verify that their actions achieve the desired results. Typically they may only wait to observe the change in trend of a parameter before moving on to another action. This is in contrast to normal operations where the operator may wait for the parameter to reach a steady state. If an action does not restore the plant function, an alternate action needs to be selected and initiated. This process is repeated for each plant safety-related function until the plant is in a safe, stable condition.

2.3.3 Fault Diagnostic Tasks

When a change in plant status is identified by the operator monitoring the plant, it must be correctly diagnosed and the appropriate corrective action taken. This process involves comparison of plant-parameter information obtained during the monitoring tasks to the expected condition, limits, and set points described in the procedures. This is a two-part process consisting of analyzing the problem and selecting the best alternatives for corrective action. The process may be a procedure driven trial-and-error process until the cause of the condition and the corrective action can be determined. Usually this process is limited by time constraints. The operator has added stress imposed during emergency conditions due to the urgency of the situation. This problem must be considered when evaluating safety-related controls and displays used for fault diagnosis.

A number of human models have been developed for the decision making-process. These human models consider the decision-making process as being made up of several steps. For simplicity, however, these steps are generalized for this discussion. The first major step in the human-decision making model, problem recognition, has already been discussed under function monitoring (i.e., problem detection) tasks. Subsequent steps in the process involve information gathering and making a determination of the best course of action for the situation. Condensing the human

models for describing the tasks performed by an operator, one may say that there are two components to fault diagnosis, problem analysis and selection of alternatives.

2.3.3.1 Problem analysis

Problem analysis, as part of the decision-making process, requires the operator to gather and filter information from a multitude of alarms and indications. Once the operator has determined what information is relevant to the situation, then he makes a determination of actual systems status. The operator uses plant conditions determined in the function monitoring task, predetermined rules (procedures), and previous experience (training and on-the-job) as inputs to problem analysis. There are five inputs into the problem analysis. One or more of these inputs will be needed to successfully diagnose an off-normal event. However, with symptom-based emergency procedures, the operator may not fully diagnose the problem since much of the diagnosis is embedded in the procedures.

Plant mode operating condition. The plant conditions at the start of an event are an important input into the analysis since certain initiators can immediately be eliminated as possible causes. The operators can focus their analysis for credible events for the operating conditions that existed at the beginning of the event. For example, scrams initiated by the intermediate range neutron monitors are bypassed when the reactor is in power operations. Therefore, the operators would not consider the possibility of neutron monitoring system trip originating in this system. This would lead them to analysis of the power range neutron monitoring system and malfunctions that could lead to a trip on high power range monitor readings (control rod problems, instrument failures, uncontrolled reactivity addition, etc.).

Prior conditions, trends. The operator must be cognizant of the state of the plant including any on-going events, maintenance activities, and system or plant function problems. All members of the shift receive at turnover a report on plant status. This reporting process includes a review of the control-board indications and parameter status as well as work in progress outside the control room. The operators need to be aware of any condition or trend which may threaten the performance of systems or plant safety. Knowledge of problem conditions and trends prior to a malfunction will lead the operators' investigation toward the problem area. The operator also uses the trend and other plant conditions to determine the urgency of the problem and/or cause of the condition. An example is reactor building sump pump operation which may indicate a leak from a nearby process system. An increasing frequency of sump pump starts would indicate that the leak rate is increasing toward a limit. Should the reactor suddenly trip because of high containment pressure, the operator should focus the problem analysis toward a possible pipe break inside containment. The location of the sump drain area provides further analysis by indicating suspect systems or components. Therefore operators' analysis is aided by knowing the frequency of sump pump operation prior to the event.

Symptom-to-cause aids. During normal operating conditions, the annunciator response procedures are used to evaluate and respond to single alarm conditions. Annunciator response procedures provide the operator with information on the cause of the alarm, remedial corrective actions, and additional corrective actions for a particular alarm condition. This provides the operator with a "pre-identified" analysis of the event and the appropriate corrective actions. The operator must verify the cause of the event and evaluate the appropriateness of the annunciator procedure

corrective actions. However, the use of annunciator response procedure guidance may be of little or no use when multiple alarms are received and the event is beyond the scope of the annunciator response procedure. Event-based abnormal response procedures are provided for guidance in these situations.

Event-based procedures provide "symptoms" of the event for which the procedures were written and provide immediate operator actions and follow up operator actions. One drawback to this type of procedure is that it requires the operator to identify what failure caused the condition, and to then select the appropriate procedure. The operator must evaluate the plant inputs against the "symptoms" of the abnormal procedures to verify that the appropriate procedure and response has been selected.

The SPDS is provided to aid the control-room crew in diagnosing problems by processing plant inputs and presenting information in a format which provides a concise status of plant parameters and systems. The SPDS's main use is to support the execution of symptom-based emergency procedures, but it is also useful as a tool for other applications as well. The SPDS monitors the critical safety function parameters defined by the symptom-based emergency procedures and displays this information in a single location for operators to use during diagnosis. The inputs are filtered for bad inputs prior to processing. By concentrating the information in one location, diagnosis time is reduced since there is no need to reference meter and recorder spread throughout the control room.

Abnormal patterns of events. From training and past experience, the operators expect a certain dynamic response for a given plant event. This includes automatic actions from normal operating systems and safety systems, changes in parameter readings, patterns of alarms, and even certain sights and sounds. When a plant response which is outside the norm is detected, the operator will direct problem analysis toward determining the cause of the unusual system response. This abnormal pattern of events, combined with the operator's knowledge of plant systems and controls, provides clues to the root cause of the malfunction.

A good example is the behavior of the plant following a scram at power caused by a relatively minor malfunction or operator error. This is a familiar event to most experienced operators. If the operator notices any parameters, such as primary or secondary pressure, level, and neutron flux, that do not respond as expected in the first thirty minutes, then he will begin investigating the cause of the problem. For less familiar events, the operators rely on their knowledge from simulator response, procedures, transient and safety analyses, and experience from similar events.

Plant function characteristics. The critical plant safety functions have been analyzed extensively by architect-engineers, the NRC, owner groups, and even the utilities. The critical plant safety functions for any NPP can be monitored by certain critical parameters defined by the plant symptom-based emergency procedures. The critical parameters and limits provided by the emergency procedures provide the operator with bench marks for comparison with plant conditions to analyze the threat to critical plant safety functions. Relationships between critical safety parameters may be included in the symptom-based emergency procedures or on the SPDS as graphs or graphic displays. When the relationship between two critical parameters approaches a forbidden region of operation, the operators must take action to maintain the plant safety function.

2.3.3.2 Selection of alternatives

Once the operator has recognized and analyzed the plant condition, the task of determining the appropriate corrective actions must be initiated. With the redundant and interconnected systems in a typical plant, there is usually more than one "success path" for restoring or maintaining any single plant function. Much of the work in selecting the appropriate course of action is accomplished via the procedures. If the operator's analysis of the event is correct, the appropriate procedure should be selected and followed precisely. However, if the operators encounter situations where more than one procedure applies, or the procedures are deficient, knowledge and skill must be used to augment the procedures. Even when executing appropriate procedures, the operators are required to make an evaluation of the validity of the action for the plant conditions. Selection of the appropriate alternative requires the operator to first identify possible corrective actions and to then make some judgement as to the possible outcome of each action. The operators should then compare the possible outcomes for the risk and benefit (i.e., which possible alternative can place the plant in a safe and stable condition with minimum risk). This will lead the operator to select the best course of action.

In selecting the best course of action from the available alternatives, the operator must consider the following three factors.

System status. The status of normal operating and safety systems determines what components are available for use in the corrective actions. Systems that are out of service are indicated in operating logs and are discussed during shift turnover. Systems that are affected by the initiating event must be evaluated by the operators as part of the fault diagnosis. Component failures can, obviously, render a system inoperable. However, most minor failures leave a system at least partially functional, if only as a flow path. Degraded systems may serve some useful function when used in conjunction with other systems. The operator determines system status from indications on the control board, such as valve lineup, pump running or available, alarms, and parameter readings. With the system status information, the operator can adapt procedural steps to accomplish the desired goals with the systems and components available. When selecting alternatives between systems, operators should first attempt to use the normal operating systems to the greatest extent possible. The standby and emergency core cooling systems (ECCS) should be a second choice when the normal systems fail to meet the desired goals. Auxiliary systems (service water, condensate transfer, fire protection, etc.) should be used only as a last resort since extraordinary actions may be required to inject coolant into the reactor or reactor coolant system with these alternate systems.

Guidance for selection. Procedures provide the operator with predetermined, optimum actions which can be used to correct plant problems. The operator may rely on normal operating procedures, annunciator response procedures, abnormal operating procedures (incorporated as a separate section in normal system operating procedures), and symptom-based emergency procedures. Operator training stresses the use of procedures so that errors in judgement and execution are minimized during stressful situations. This ensures that plant operations adhere to "rule-based" rather than "knowledge-based" or "skill-based" behavior as much as possible.

Normal operating procedures may, in some cases, give the operators more than one acceptable means of operating a system. The possibilities for successful operation with inoperable components may be discussed with a series of "if" statements. During off-normal conditions, the operators

should follow the normal system operating procedures as much as possible. Therefore, some of the task of selecting the appropriate components and flow paths will be accomplished by the procedure.

Annunciator response procedures provide the operator with the initiating signal(s) for alarms, the immediate corrective actions, and additional corrective actions for a particular alarm condition. This provides the operator with a "pre-identified" analysis of the event and corrective actions for events that involve minor malfunctions. However, responding to individual alarms during complex events may be ineffective. In these cases, abnormal and emergency procedures should be referenced.

When "event indications" are matched with symptoms of abnormal event-based procedures, the operators are provided adequate guidance for corrective actions. The guidance provided in the event-based procedures is the optimum solution for the diagnosed condition. For some plant conditions more than one procedure may be required. In this case, the operator must prioritize the actions of the multiple procedures. Since event-based procedures rely on the operator to make a correct diagnosis of the root cause of the event, this type of procedure is no longer used for events where there is an immediate or potential threat to vital safety functions. Symptom-based procedures are used in cases where reactor scram, or a threat to any of the radiation release barriers (fuel, reactor vessel, and containment), is involved.

The procedure hierarchy mandated by the NRC requires operators to enter the symptom-based emergency procedures when any of the critical parameter limits is exceeded. The concept of the symptom-based procedure is that the operator is directed to identify plant conditions, branch in the procedure as appropriate for the conditions, and then take the appropriate control and/or monitoring actions. All of this is to be accomplished without benefit of actually diagnosing the root cause of the event. The emergency procedures include contingencies for maintaining vital safety functions for almost any credible accident. The guidance of the procedures can be used to assure that the critical plant safety functions are being maintained. Symptom-based emergency procedures will direct the operators to select and use systems on a priority basis, similar to that discussed earlier, normal systems first, then ECCS, followed by auxiliary systems.

When a plant condition does not fit any of the procedure guidance described above, or the systems and component availability is below that assumed by the procedure, the operator must depend on previous experience and training for selection of alternatives; that is, skill and knowledge must compensate for the lack of clearly defined rules.

Selection criteria. The operator has selection criteria which are contained in procedures, as described in the preceding discussion. This guidance is used if at all possible. If this is not possible, then the training and experience of the operators should guide the selection of alternatives (i.e., skill- and knowledge-based behavior). Both the ROs and SROs would be a part of the decision-making process. This decision-making process will include, as discussed earlier, identifying the alternatives, predicting the outcome of each, and then comparing risks and benefits of each course of action. The decision making process will focus on determining the course of action that will place the plant in a safe, stable condition the quickest, while maintaining critical safety functions within acceptable bounds.

2.3.4 Administrative Tasks

Administrative tasks are performed daily by all control-room operators. These tasks consume a significant portion of the operators' time. They include those tasks that are performed to ensure plant safety in the event of an accident. Routine log-keeping and reporting of off-normal events are also considered administrative tasks.

2.3.4.1 Surveillance testing

The control-room operator is involved in surveillance testing of safety related equipment to ensure its availability in the event of an accident. A major task at all plants is to operate systems for operability testing. Systems and components, such as instrumentation, pumps, and valves, are operated periodically to determine if they are fully operational. Surveillance test procedures provide space for recording parameter readings. Test data are reviewed by operations supervision, quality assurance, and engineering. Two factors must be considered with surveillance testing: the test must be performed within the required frequency and the test results must be acceptable. Failure to comply with either of these requirements could result in a violation of technical specifications.

Surveillance testing often places plant systems in a configuration different from the normal system lineup. The RO performing the tests must be aware of this in the event that the system is needed for its safety function during testing. Also, the RO must ensure that the system is returned to the normal standby line-up following the surveillance test.

The control-room operators also support other groups in performance of their surveillance tests. When the I&C group is performing instrument calibration or testing safety related circuits, the ROs and SROs must be aware of the potential for reactor trip, or undesirable automatic initiation of safety equipment. Part of the support task is to acknowledge expected alarms, bypass instrument channels during testing, and be aware of potential problems that may arise from the testing. Also, the operators must ensure that different work groups do not concurrently perform tests that could lead to a scram or technical specification violation. For this reason, the control room serves as a communication center and administrative control point for all plant maintenance and testing. Work control practices ensure that all work on plant equipment has no effect on the operation or safety of the plant.

2.3.4.2 Technical specification verification

The RO on shift has the task of logging and verifying that process parameter limits are within the acceptable bounds of the technical specification. This task ensures that the operator is performing the required monitoring of safety-related parameters. The control board is also reviewed regularly by the RO for unusual conditions, such as mispositioned valves or some other process parameter, which could make a system required by technical specifications inoperable. Any out of normal condition found by the RO is logged and brought to the attention of the SRO for further action. Prior to changing modes, the operability of technical-specification required systems must be verified. This process is normally controlled by an administrative procedure and is verified by the SRO in charge of the unit.

2.3.4.3 Log-keeping

A number of operating logs are maintained by the control-room staff. Readings of plant parameters are recorded with some prescribed frequency (hourly, twice per shift, once per shift, etc.). Recording this information ensures that the operators are monitoring the plant, that undesirable trends are detected, and that system performance may be evaluated. The RO on the control board maintains a written log of system/component starts and stops, procedure and test runs, system problems, events, and the limiting conditions for operation (LCOs) that are entered. The SRO's log would contain similar activities, such as major system problems, LCOs entered, any problems brought to his attention by the RO, events with potential for escalation, and events which require emergency classification.

2.3.4.4 Event reporting

The SRO is normally responsible for the task of determining reportability of events. Technical specifications and the emergency plan provide criteria on reportability. The SRO must compare any off-normal event to the criteria and make a determination of the appropriate notifications. The emergency plan has certain emergency-action levels which require actions and notifications as conditions warrant. The SRO in charge of the shift normally assumes these duties. Accurate reporting of an off-normal event is required so that weaknesses in plant design, operating procedures, instrumentation, and emergency planning can be identified. To adequately reconstruct the event for reporting, the SRO will need accurate log-book entries from the operator, complete and accurate computer-logging data, and any strip charts that are available for parameters affected by the event.

3. TYPES OF CONTROLS

There are three general types of controls that are currently used in NPP control rooms. They include switches, pushbuttons, and analog controllers. Each is briefly described below, along with their general functions.

3.1 SWITCHES

For most NPP applications, switches are the "dead-man" or spring return type. As the name implies, this kind of control returns to a neutral position when released. The primary types of controls include toggle and rocker switches. In light-water reactor applications, there are two kinds of spring return switches in common use. One version of the spring return switch has three positions. The center position is the neutral position, in which no control signal is transmitted. The other two positions of the switch are closed/stop and open/start depending on whether the switch controls a valve or pump respectively. This type of switch is usually utilized for controlling valves. The convention on the arrangement of the switch is that it is rotated counterclockwise for the closed or stop position and clockwise for the open or start position. This eliminates the need for the operator to read the label on the switch each time it is operated. When this type of switch is used for controlling a valve, there are two possible conditions for change of state of the component. If it is desired to have the valve either fully open or fully closed, when the switch is

manipulated, the valve will experience a full travel. Turning the switch in the opposite direction has no effect until the valve has reached the end of travel. If it is desired to permit positioning of the valve at some intermediate position, the control circuit will only activate the valve operator as long as the switch is held. If the switch is released prior to full travel of the valve, valve motion will stop at the intermediate position. This allows the control-room operator to throttle the valve to control either system flow or pressure. A variation of this is in use by some of the newer NPPs. When the operator turns the switch and releases, valve travel begins in the direction requested. If the operator desires partial opening of the valve, he may lift the control handle of the switch to stop valve travel. This eliminates the need to hold the switch until the desired degree of opening is reached.

Another type of spring return switch, more commonly used for pumps, is one that has a red and green "flag" to indicate the last command issued by the switch. The reason for using this type of switch is that the operator can determine if the status of the component agrees with the switch. For example, if a pump has experienced an inadvertent trip, the flag on the switch will indicate that the pump should be running.

In addition to the three normal positions for the switch (stop, neutral, and start) switches used for pumps and some valves have a fourth switch position called "pull to lock". This feature allows the operator to lock the switch in the stop position during maintenance on the component. This ensures that an operator will not inadvertently operate the switch without first determining the reason for the switch being placed in that position. To operate a switch from this position, the operator must push down on the control handle to release the switch to the normal after stop position.

Multi-position switches are used primarily for selecting control channels, switching instrument function, or selecting monitoring channels. The number of possible positions on this type of switch depends on the function of the switch and the circuit. There are a variety of multi-position switches in use, each with special labeling to indicate the function of each switch position. The types of multi-position switches include J-handles, continuous adjustment rotary controls, rotary selector controls, and thumbwheels.

3.2 PUSHBUTTONS

There are two kinds of pushbuttons used in NPPs today. They include round and legend-type pushbuttons. Legend pushbuttons are rectangular self-illuminated controls which display a written legend, usually as one or more small illuminated tiles. They serve as both a control and a display (i.e., legend light). Depending on system design, a legend may be lighted either when the operator activates the pushbutton or when a change occurs in system condition. Legend pushbuttons may have more than one display area.

Pushbuttons are used for a variety of purposes. Although not used as extensively as switches, pushbuttons are useful for inserting a signal into a control circuit when only a momentary signal is needed to initiate a system response. One of the more common uses of pushbuttons is for resetting a sealed-in automatic function. A sealed-in function is one that initiates automatically when a monitored parameter exceeds a set point, but will not automatically reset when the

parameter falls below the set point. To reset a sealed-in function takes a positive operator action, e.g., depressing a pushbutton.

3.3 ANALOG CONTROLLERS

Perhaps the most specialized type of control is the analog controller. This type of device is used in control circuits where automatic system response is desired, but where manual operation may be necessary during system start up or shutdown. Analog controllers are normally used to control system flow either through valve opening or pump speed. There are a number of different analog controllers in use, but all designs have a few basic features in common. Each controller has a manual mode and an automatic mode of operation. In addition, if several parallel components (e.g., feedwater pumps) are operated simultaneously, the individual components will have a controller which may be operated by a master controller. If a master controller is used, its output signal only affects the output of the individual controller that is in automatic. For example, if three feedwater pumps are in service, each of the individual controllers is placed in "automatic" when the individual flow rates are balanced. The master controller, if it is also in automatic, will change the speed of all three pumps in response to a change in feedwater demand. If all three individual controllers are placed in automatic and the master controller is placed in "manual", the operator may manually control the speed of all three pumps from the master controller.

3.4 STATE-OF-THE-ART CONTROLS

There are a number of state-of-the-art controls that have not as yet been implemented to any great degree within the current NPP control rooms. These controls will, however, most probably be used in the next generation of NPPs and in control-room retrofits. These state-of-the-art controls include computer keyboards, four arrow key controls, joysticks, light pens, mice, track (roller) balls, stylus and grid, touch-sensitive devices, and voice activation.

Computer keyboards are simple adaptations of the basic typewriter. There are, however, two major differences. The first difference is the absence of type bars that print on paper the keys that the typist depressed; computer keyboards send signals to display the pressed keys on the visual display screen. The second major difference is the presence of a number of special function keys, interfaced to software programs, that enable the user to manipulate what is displayed. Two main types of computer keyboards are available, alphabetic and numeric. The characters on the alphabetic keyboard are arranged using the "QWERTY" format. The numeric keyboard is arranged in a 3x3+1 matrix and exists in two formats, "telephone" or "calculator" style.

The four arrow key control consists of four keys (i.e., left, right, up, and down) and is used to control computer screen cursor position. The keys are arranged in a two-dimensional layout which can take the shape of either a box, cross, or inverted-T. Advantages of this type of control are that it allows for non-destructive movement and accurate positioning of the cursor.

Joysticks consist of two potentiometers mounted at right angles and perpendicular to a vertical stick. These devices are also used to control cursor position on the display screen. There are two kinds of joysticks, isotonic and isometric. Isotonic means that cursor movement depends on the direction

and displacement, but not the speed or force, with which the joystick is moved. Isotonic joysticks are well suited for tasks in which positioning accuracy is more critical than positioning speed. The isometric joystick lever deflects only minimally in response to applied force, but may deflect perceptibly against a stop at full applied force. Cursor movement is controlled by the direction and force applied to the lever. Isometric joysticks are particularly appropriate for applications that: (a) require the cursor to return to center after each entry or readout, (b) involve feedback to the operator that is primarily visual rather than kinesthetic from the joystick itself, and (c) involve minimal delay and tight coupling between control input and system reaction.

The light pen is a light-sensing device used primarily to indicate position on a display screen. It is the preferred cursor control for: rapid input functions not demanding preciseness, tracking moving objects, gross drawing, multiple selection, detecting the presence of a computer-generated track, and serving as a two-axis controller.

The mouse is a small handheld device that can be moved across any flat surface to control the position of a follower on an associated display. It can contain a small number of function keys. The mouse is used for data selection or to coordinate values.

A track ball device consists of a sphere suspended on low-friction bearings. It is turned in place (usually by the hand) to control the position of a follower on an associated display. The ball does not return automatically to the point of origin; interfacing systems must provide this. Because the track ball can be continuously rotated in any direction, it is well suited for applications where there may be cumulative travel in a given direction.

The stylus and grid device consists of a grid with a spatial layout that corresponds to that of the display. The grid senses the position of the stylus to control the position of a follower on the display. This control is excellent for graphic entry and provides spatial correspondence between displays and control movement.

The touch-screen device is a control with a spatial layout that corresponds to that of the screen. It is activated by being touched and records the location of the touch. This control generally consists of a transparent surface attached directly to the face of a display screen and can be used for cursor control or to activate menu items.

A voice-activated system recognizes words or sequences of words spoken by an operator and responds as if a function key was activated. The words or word sequences must however be specified in advance. The advantages of this control are that it does not require the use of hands or the user to shift gaze. The technology for this control is undergoing rapid changes.

4. TYPES OF SAFETY SYSTEMS

Remote operation of NPP equipment requires a sophisticated system of I&C for both operator information systems and input signals to automated control systems. In turn, the control systems utilize a relatively sophisticated scheme for balancing the dynamics of a complex set of fluid systems. Plant I&C systems include components to achieve the following functions:

- o measure critical plant parameters (nuclear instrumentation systems, non-nuclear instrumentation systems, and in-core monitoring systems).
- o control critical plant parameters within safe limits (control rod drive system and integrated plant control system for turbine, generator, and steam cycle).
- o automatically actuate protective devices if safe limits are exceeded (reactor protection system and engineered safety features actuation system).

I&C systems must meet strict regulations and requirements on capability, functionality, and redundancy. Capabilities of the systems are based on the plant functions that must be remotely monitored and controlled. Because large areas of a NPP cannot be entered during operation, more systems need to be automated and remotely controlled than in fossil fueled plants. The I&C system, therefore, must be capable of monitoring and controlling vital safety functions with minimal assistance from auxiliary operators outside the control room. For a typical PWR, the following functions must be maintained for safe operation of the plant:

- o reactivity control
- o reactor coolant system (RCS) inventory control
- o RCS pressure control
- o RCS heat transport
- o secondary system heat transport
- o containment integrity
- o electrical distribution
- o control air supply
- o auxiliary thermal transport
- o indirect radioactivity release control

A similar set of safety functions could be specified for a BWR. The differences would be that with the BWR there is a feedwater system and a reactor recirculation system instead of a RCS, and there is no secondary system heat transport.

Capabilities of the I&C systems are dictated by the components that must be monitored and controlled during operation and during shutdown. Controlling nuclear fission in the reactor is drastically different from controlling mechanical devices. Any changes the operator may effect on the fission rate are indirectly through manipulation of mechanical controls. Sensors, detectors, and controllers/positioners are required for operating such fundamental components as pumps and valves which may be found in nearly every NPP system. Other common plant components are electric motors, diesel engines, heat exchangers, condensers, demineralizers, and ion exchangers. Electrical systems may require remote operation of breakers, relays, and disconnects.

Redundancy in I&C systems is necessary to ensure that system malfunctions do not inhibit safe operation. All protective systems must meet the single failure criteria. This means a single component failure or operator error will neither prevent a protective action from occurring when needed nor initiate the protective action when it is not needed. Two approaches for accomplishing this are the "two-out-of-three" and the "one-out-of-two twice" logic schemes. Both approaches use redundant instruments to monitor each parameter and only initiate the protective action when detected on more than one instrument.

5. MONITORED PARAMETERS

Parameters for monitoring the plant are selected for a number of different reasons. Obviously, safety is the primary reason for monitoring many plant parameters. Investment protection is also a concern where large machinery, such as the main turbine, is involved. Such costly machinery is usually heavily instrumented. Operators also need information on system performance to achieve and maintain optimum operating conditions. Some parameters are monitored, over the long term, as an indication of a slowly developing problem. For example, leakage inside primary containment has a very low limit. Detection of this leakage must be observed over several days to note any increasing trend.

In general, instrumentation is connected to components and systems to measure the following types of parameters.

- o Pressure - Fluid and gas (e.g., steam) pressures in NPP systems are monitored for both system performance and safety purposes. Steam pressure usually is a more accurate indication of steam temperature than direct temperature measurement. Strict pressure safety limits are placed on any vessel (reactors and heat exchangers) to ensure the physical integrity of the vessels. Pressure sensors are also used to measure fluid flow and vessel levels.
- o Fluid flow - Every system in the basic heat transfer cycle accommodates fluid flow, as do nearly all auxiliary systems. Maintaining a balance and compensating for changes in demand on the systems require extensive information on fluid flow. Flow is most commonly measured by differential pressure across a venturi or across an elbow in the piping. Flow rate is directly proportional to the square root of the differential pressure.
- o Fluid level - Water level in reactors, steam generators, storage tanks, condensers, feedwater heaters, and waste sumps are all monitored routinely during all modes of operation. Level is usually measured indirectly by using the difference in pressure between a reference (constant) column of fluid and a variable column of fluid. A large number of automatic protective actions are initiated from water level measurement, since this is a good indication of possible under-cooling, or a possible break in the system.
- o Neutron flux - Power level in a reactor is determined by measuring neutron flux, since fission produces free neutrons in proportion to the fission rate. Because very low to very high levels of neutron flux must be measured, several different instrument ranges are used. Depending on the reactor type and the instrument range, detectors are mounted inside

and outside the reactor vessel. Safety systems (reactor scram or prevention of control rod withdrawal) may be initiated for two reasons: reactor power level or rate of increase threatens the integrity of the fuel, or the power level cannot be supported by coolant systems.

- o Temperature - High temperature is most accurately measured by thermocouples. Reactor vessel and coolant systems are heavily instrumented for temperature measurement for both safety and investment protection. PWRs have thermocouples installed at the core exit to measure fuel and coolant temperature.

- o Component status - Literally hundreds of valves, pumps, and breakers are monitored for status indication in the control room. Component status indication usually consists of open, closed, and percent open for valves, on and off for electric motors (pumps and fans), and revolutions per minute for some pumps.

- o Water chemistry - Water chemistry is strictly controlled to limit corrosion of critical components and as a factor in overall plant efficiency. Two control-room indications of water chemistry that are available to the operator are pH (parts hydrogen) and conductivity (a measure of dissolved ions in the water).

- o Electrical - Electrical systems, because of their importance to safety, are usually well instrumented for voltage and current. The main generator and the off-site electrical distribution system are also instrumented for reactive load. Phase differential is also monitored to allow the operators to ensure that the generator is in phase with the distribution grid prior to closing the generator output breakers.

- o Process and area radiation - The transport of radioactive contaminants to the environment is monitored to ensure that no danger is posed to the general public by operation of the plant. Process systems that transport radioactive materials or have the potential for contamination are monitored continuously. Area radiation monitors are located throughout the plant and off-site to detect and signal alarm in the event of airborne contamination.

6. TYPES OF CONTROL ROOM INFORMATION

For reliability purposes, control-room information systems consist of hundreds of hard-wired meters and recorders to display NPP information. The operator must scan large areas of vertical panels to obtain a complete and accurate plant status. One objective of the extensive human-factors research in the nuclear industry has been an attempt to improve the efficiency of the operator for monitoring plant status. Groupings of controls and meters, as well as the increased use of computer displays, have made the operators more efficient in their monitoring tasks.

The most common information display is one that provides the operator with the value of a parameter, that is the "meter reading." This type of information is used by the operator routinely to ensure that all conditions are within the expected norm. Operators are constantly monitoring a small set of important plant parameters to ensure that there are no problems with the NPP

systems. Should the operator detect a parameter reading that deviates from the expected range, information from additional sources is needed to help diagnose the problem.

Trend is a useful diagnostic tool in that it provides the operator with a history of parameter values and an indication of whether a parameter is approaching a limit. Operators understand the cause-and-effect of equipment malfunctions and failures, and how key parameters will trend following such malfunctions. Trend will also aid the operator in planning his response to a malfunction. Operators are usually aware of the time available before a limit on key parameters is exceeded. If a fast trend is observed, prompt corrective actions can be initiated. If a limit is approached slowly, the operator will try to avoid quick changes in the systems.

A typical control panel has several rows of control switches, each switch with a set of light indicators. These indicators not only provide the operator with information on the status of the individual components, but they also collectively give the operator the lineup of all plant systems. Computer displays have been used to depict system lineup, since it is very difficult to determine the status of all systems quickly simply by scanning the control panels. Small changes in system lineup with no associated alarm can go undetected by the operator without some type of aid.

Annunciators are another useful source of information for the operator. The hundreds of alarms installed in the control room are also factored into the operator's mental model of the plant. Annunciator systems have evolved beyond the simple binary systems of the past. Alarm systems can alert the operator when an alarm condition is received and when it is cleared. Alarms on computer-generated displays can indicate different alarm levels. For example, an alarm may indicate a trip level is being approached, followed by an alarm that the trip level has been exceeded.

Some other less common types of information displayed in the control room include trip margins and rate of change. A trip margin indicator is incorporated into the chart recorders for the power range neutron monitors for BWRs. Trip set points are adjusted for coolant flow on these instruments, so the operator needs an indication of where the trip point is for a given core flow. Both PWRs and BWRs use period meters for indicating the rate of change of the neutron flux during reactor start up. A high rate of change on the period meters will automatically inhibit control rod withdrawal or even initiate a reactor scram in PWRs.

7. CONTROL ROOM INDICATORS AND DISPLAYS

The basic types of monitoring devices common to nearly all NPP control rooms include:

- o analog meters
- o graphic recorders
- o digital displays and counters
- o light indicators
- o visual alarms (annunciators)
- o audio alarms
- o cathode-ray tubes (CRT)

7.1 ANALOG METERS

The most useful type of device for routine monitoring of NPP systems is the analog meter. The preferred type of analog meter is the vertical bar type. Basically this is a meter with a scale from bottom to top and a pointer that moves vertically along the scale. The reason for this preference is that this type of meter may be read from different locations with a minimum of perspective error. The operator does not need to stand directly in front of the meter to accurately read the parameter value. There will, however, be some slight differences in parameter values read by operators of differing heights. Most process systems use the vertical bar type meter to display system flow, pressures, temperature, neutron count rate, pump or turbine speed, water level, or valve position. The control-room meters are driven by locally installed transmitters that send a signal to the control room. The signal is converted to electrical potential to provide the needle deflection on the meter.

Another type of analog meter that is used less frequently than the vertical is the dial type which has a circular scale and resembles a clock face. Dial-type meters are used mainly on electrical distribution systems to display voltage and amps. Also, dial-type meters are used on other systems on a somewhat limited basis. The dial-type analog meters are used in applications where the operator will most likely be standing directly in front of the meter. When an operator attempts to read a dial meter from the side, there can be a large error due to their visual perspective.

7.2 GRAPHIC RECORDERS

Graphic recorders are often used in place of, or in addition to meters. For important plant parameters both display types may be used. Recorders are used where a permanent record of a parameter is required. There are two types of recorders used in NPP applications, continuous (strip chart) and discrete (point) recorders.

Strip chart recorders are used when the operator may be concerned with a parameter trend (e.g., water level, pressure, or neutron flux). A typical strip chart recorder will have two ink pens to record the parameters on moving paper, one pen being dedicated full-time to each channel which inputs to the recorder. Most two-pen recorders use red and black pens to distinguish between the recorded channels. The scale on a strip chart recorder may either be linear-linear or linear-logarithmic, depending on the monitored parameter. Log scales are used for neutron count rate or period display. Some chart recorders are equipped with two-speed chart motors to allow chart recording at a faster speed. The fast speed is used when the operator wants to monitor small changes in the parameter value over a short period of time. Small changes are difficult to distinguish on the chart paper when slow speed is used.

Point recorders are used to record a large number of similar parameters, but continuous display of the individual parameters is not necessary. Point recorders provide time-phase recording of the input channels, plotting them in sequence. A point recorder uses a wheel with inked number stamps to mark the chart. A legend on the face of the recorder is provided to inform the operator of the parameter associated with each numbered point. Inside the recorder is a digital counter that the operator can reference to determine which number the recorder is stamping at a given time. In some cases, the operator may switch the recorder to monitor a single parameter that is of

interest for a particular situation, e.g., vibration on a particular turbine bearing that has caused an alarm.

7.3 DIGITAL DISPLAYS AND COUNTERS

Digital displays (e.g., light emitting diode and liquid crystal displays) are beginning to be used more extensively in the control room. They are useful for displaying parameters in a format that can easily be read from a distance. Also, digital displays may be used to display parameters that can assume only integer values. The attraction for digital displays is that the operator can read the parameter without the error that occurs with meters and recorders when read from an angle. Digital counters are used for integer display, but cannot be read from a distance. A common application of digital displays and counters is for control rod position indication. A control rod may occupy only a limited number of positions, so the digital display or counter is a perfect choice. In BWRs a back lit digital display is used for control rod position indication, while PWRs use digital counters.

7.4 LIGHT INDICATORS

Light indicators are perhaps the most widely used form of display in the control room. Light indicators are used extensively because of their simplicity, economy, and ease of understanding. By definition, light indicators show the existence of some state by the glowing of a light. There are two types of light indicators, non-legend and illuminated-legend indicators. Non-legend light indicators are represented by conventional pilot lights, bulls-eyes, and jewel lights. A legend-light indicator is a transilluminated display containing an inscription which is highlighted when the light comes on. In the control room, legend-light indicators are normally used to show status, the legend being worded to tell the status in effect when the light is glowing. Legend-light indicators may be individually placed or grouped together in status-indicating matrices.

Each control on the control-room panel has a set of light indicators to indicate the status of the component associated with the control. Also, locally operated valves may have a set of light indicators in the control room so that the operator may monitor the status of the valves. In general, the light indicators are color coded red or green by the following conventions.

- o Valves - Light indicators for valves are red for open and green for closed. If both red and green light indicators are on, the valve is at some intermediate position.
- o Pumps and other motor driven components - Red indicates the component is energized, green for not energized.
- o Electrical breakers - Green indicates the breaker is open; red indicates the breaker is closed.

A variety of other light indicators are installed to indicate the status of control circuits, isolation circuits, and system alarms (discussed below). Generally, whenever a status light is installed on the control panel that is not associated with a valve, motor, or breaker, some color other than red or

green is used to distinguish the special light indicator. White, yellow, amber, and blue lights are often used for this purpose.

7.5 VISUAL ALARMS (ANNUNCIATORS)

Control-room operators obtain a significant portion of their information from annunciators. A large number of annunciators are installed in a typical control room to inform the operators of off-normal situations that affect personnel safety and/or equipment integrity. Annunciators are grouped in panels. Ideally, an annunciator panel will only contain alarms associated with a particular system. However, due to space limitations, this ideal grouping of annunciators is rarely achieved. An annunciator panel containing alarms for a particular system will be located directly above its associated system. The individual alarms consist of a translucent plastic lens engraved with the alarm message and a set of back lights. There are different alarm schemes used to indicate the status of the alarm. Some NPPs simply flash the annunciator when the alarm signal is received. The alarm will flash until the operator acknowledges the alarm, at which time the alarm will be back lit without flashing. Another scheme that is used by some plants is color coding of the alarm. When the alarm signal is received, the alarm will flash in red until the operator acknowledges the alarm. After the alarm is acknowledged, the annunciator will remain red without flashing. When the alarm condition clears, the annunciator will change to green until the operator acknowledges the cleared signal, at which time the back light will go out.

7.6 AUDIO ALARMS

Audio alarms are part of the annunciator system. Whenever an alarm condition occurs, the alarm system will activate an audio alarm to alert the operator. The horn for the annunciators is located inside the control panels. Each control panel will have one horn. When any annunciator on a given panel is activated, the horn will sound to inform the operator of the location of the alarm.

One problem that has been encountered with audio alarms is the ambient noise levels in the control room. During many emergency situations there are a large number of alarms received and cleared every minute. When annunciators are being activated on every panel in the control room simultaneously, it is difficult for the operators to communicate over the noise. Therefore, the audio alarms must be loud enough to alert the operator, but not so loud as to make communications difficult.

7.7 CRTs

The use of computer displays is increasing, due to the large quantity of information that can be processed and displayed by the computer. In the past, computer displays consisted of little more than digital display windows that could provide the operator with the value of a single parameter. Following the Three Mile Island, Unit 2 accident, the NRC required NPPs to install a SPDS to increase the monitoring capabilities for key plant functions. A typical SPDS will display information in both text and graphics. Information in either form may be color coded on the CRT display to give a visual indication of whether the displayed parameter is within specified limits. System-

pipng diagrams are used in SPDSs to allow the operators to monitor and diagnose critical safety functions of the systems. These system diagrams include such information as the status of pumps and valves, flow rates, levels, rod positions, etc.

Process computers are increasingly using CRTs for monitoring normal operation of the plant. Advanced control-room designs will rely more on the CRT than on the analog meter for providing the operator with system and parameter information. Because of the quantity of information available on the process computer, the possibilities for computer-generated displays are virtually unlimited. Control-rod pattern information and neutron flux distribution in the core are readily available on CRTs in some of the newer control rooms. Piping and instrumentation drawings can be displayed for most NPP systems, along with the important parameters associated with each system. CRTs are also capable of displaying alarms in a number of different formats. Parameter trend displays can also be called-up for most key parameters.

7.8 ADVANCED TECHNOLOGIES

There are a number of display devices that will be available for use within the NPP control room in the near future. They include: flat-screen technologies, such as vacuum fluorescent displays, electroluminescent displays, and plasma displays, and large screen optical projection systems.

Vacuum fluorescent displays typically emit a bright, bluish light that can be read over a wide viewing angle. The use of proper filtering and/or phosphors can however provide multiple colors in the same display and enhance contrast. Both alphanumeric and graphic vacuum fluorescent displays are available. Electroluminescent displays provide excellent contrast ratios and have above average readability, even in very bright environments. Work is being done to develop a full color capability with this technology. Plasma devices offer a bright display through the use of ionized neon gas. They can be used for graphic applications.

There are two types of large screen optical projection systems. They are front and rear projection devices. The use of front projection displays is the preferred medium. Rear projection displays are to be used only where physical obstructions to front projection result in poor visibility or where work areas require high ambient illumination for other activities.

8. CONCLUSIONS

The fundamental types of control and monitoring tasks currently performed by reactor operators can be divided into four classifications: function monitoring tasks, control manipulation tasks, fault diagnostic tasks, and administrative tasks. Function monitoring can be further subdivided into: systems and component level alarm monitoring, monitoring for process variable deviation from normal, abnormal trend monitoring, and abnormal condition monitoring. There are four main control manipulation tasks, planned control manipulations, remedial corrective actions, immediate corrective actions, and restoration of plant function. Fault diagnosis has two components, problem analysis and selection of alternatives. The administrative tasks consist of: surveillance testing, technical specification verification, log-keeping, and event reporting.

Three general types of controls are used to operate today's NPPs, switches (spring return), pushbuttons (round and legend), and analog controllers. There are a number of state-of-the-art controls that have not as yet been implemented to any great degree within the current generation of NPP control rooms. They include: computer keyboards, four arrow key controls, joysticks, light pens, mice, track balls, stylus and grid, touch-sensitive devices, and voice activation. Plant I&C systems include components to achieve a number of safety-related functions: measuring critical plant parameters, controlling critical plant parameters within safe limits, and automatically actuating protective devices if safe limits are exceeded.

The types of information utilized by the control-room operators to monitor the performance of the control and safety systems consist of the following parameters: pressure, fluid flow and level, neutron flux, temperature, component status, water chemistry, electrical, and process and area radiation. The basic types of monitoring devices common to nearly all NPP control rooms include: analog meters (vertical bar and dial), graphic recorders (continuous and discrete), digital displays and counters (e.g., light emitting diode and liquid crystal displays), light indicators (non-legend and illuminated legend), visual and audio alarms, and CRTs. There are a number of display devices that will be available for use within the NPP control room in the near future. They include: flat-screen technologies (e.g., vacuum fluorescent, electroluminescent, and plasma displays) and large screen optical (front and rear) projection devices.

The results from this phase of the research project will be used in the next set of tasks. Task 9 through 13 will be oriented towards the development of a set of guidelines, based upon human factors engineering principles and criteria, to conduct human factors engineering reviews of advanced control-room designs and advanced technology human-system interfaces in NPP control rooms.

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