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MARTIN MARIETTA

Assessment of the Roles of the Advanced Neutron Source Operators

March 1995

Advanced Neutron Source

MANAGED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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ACRONYMS

ANS	Advanced Neutron Source
AO	auxiliary operator
CO	cryogenics operator
DO	detritiation operator
DOE	Department of Energy
EC	experiment coordinator
HFE	human factors engineering
HFIR	High Flux Isotope Reactor
HWUDF	Heavy Water Upgrade and Detritiation Facility
MCR	main control room (of the reactor)
ORNL	Oak Ridge National Laboratory
RED	responsible engineering designer
ReO	refueling operator
RO	reactor operator
SRO	senior reactor operator
SS	shift supervisor
TRU	transuranic(s)

EXECUTIVE SUMMARY

The Advanced Neutron Source (ANS) is unique in the extent to which human factors engineering (HFE) principles are being applied at the conceptual design stage. Initial HFE accomplishments include the development of an ANS HFE program plan, operating philosophy, and functional analysis. In FY 1994, HFE activities focused on the role of the ANS control room reactor operator (RO). An operator-centered control room model was used in conjunction with information gathered from existing ANS system design descriptions and other literature to define a list of RO responsibilities. From this list, a survey instrument was developed and administered to ANS design engineers, operations management personnel at Oak Ridge National Laboratory's High Flux Isotope Reactor (HFIR), and HFIR ROs to detail the nature of the RO position. Initial results indicated that the RO will function as a high-level system supervisor with considerable monitoring, verification, and communication responsibilities. The relatively high level of control automation has resulted in a reshaping of the RO's traditional safety and investment protection roles.

1. ASSESSMENT OF THE ROLES OF THE ADVANCED NEUTRON SOURCE OPERATORS

1.1 PURPOSE OF THIS STUDY

The Advanced Neutron Source (ANS) team is committed to a design that meets the requirements of both the U.S. Department of Energy (DOE) and the Nuclear Regulatory Commission, such as Chapter 18 of NUREG-0800 (*Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants—Human Factors Engineering*) (NRC 1981). In light of the fact that the accidents at the Three-Mile Island power plant and the Chernobyl reactor involved considerable human error, and that ANS will be one of the first reactors built in the United States since the Three-Mile Island accident, an emphasis on developing a design consistent with human factors engineering (HFE) principles is highly desirable and is being pursued.

During the conceptual design phase of ANS (FY 1992), human factors efforts were initiated. These efforts included the development of a detailed Human Factors Engineering Program Plan that addressed necessary human factors activities throughout the design and construction phases (Schryver 1992). In addition, an ANS operating philosophy (Houser 1993) was developed based on 24 key operational issues identified by the ANS Project design team. In FY 1993, efforts were focused on conducting a functional analysis for ANS. To conduct ANS task analyses effectively, however, information based on the definition of the roles of reactor operators (ROs) was also necessary. This latter effort is the focus of the current study and the subject of this report. Initial efforts were focused *only* on the RO position and involved *only* activities associated with normal operation. [The roles of other types of operators associated with the reactor main control room (MCR)—the senior reactor operator (SRO), the refueling operator (ReO), the cryogenics operator (CO), the detritiation operator (DO), and the shift supervisor (SS)—or activities associated with off-normal operation will be addressed in later iterations of this report.] Special consideration was given to the RO's interaction with other operators connected with the MCR and with research support personnel [e.g., the experiment coordinator (EC)]. Appendix A describes the structured interviewing methodology used to conduct the study that led to this report. Appendix B contains a sample list of interview questions.

A working assumption of this document is that ANS will incorporate technology for a high level of automation. HFE should promote elaboration of the automation concept, ensuring equal attention and specificity to the operator role. In particular, the operator role should be fashioned to make the most of human potential in system operation. At least, the operator role should not emphasize areas where human limitations are severe.

The human operator role in advanced/intelligent systems, as well as the machine role, is often expressed through analogy to simpler systems. In fact, it is quite natural to state the human-machine relationship in terms of human-human relationships. Human-machine systems literature has introduced the intelligent machine serving in the role of (1) coach, to aid an operator with complex machine functions (e.g., procedure prompting); (2) operations officer, to carry out policies and top-level instructions of the human "chief executive officer"; and (3) tactician, offering and explaining alternative courses of action to the human decision-maker. This small list of alternative roles should demonstrate that the operator role is more than the sum of its functions, and that the human-machine relationship should be considered carefully.

The more refined an operator role description, the better. Operator roles also may be mode-specific. That is, the role of the operator in normal operation may be quite different from the role in off-normal operation. Formal methods are lacking now; however, some details are available of the Symbiosis Model, which expresses the human-machine relationship as a network of human and machine abilities (Eggleston 1987). A classification of operator roles that may be helpful in developing a vocabulary for role elaboration is also available (Kisner and Frey 1982).

2. RESULTS OF THE STUDY

The results of the study support the role of the ANS RO as a high-level system supervisor. The traditional RO role of analog system monitoring and system supervision will be considerably enhanced by the use of digital technology. Some examples of this enhancement include the use of system interactive procedures, digital measurement and data recording, and implementation of lockouts and tagouts. In general, the ANS RO's base responsibilities will remain similar to those of an RO at other DOE research reactors. This position may still require significant manual interaction with the system to facilitate testing and calibration; at this time, such activities seem to be necessary and desirable to ensure the RO's systems awareness. The ANS RO will ensure the appropriateness and thoroughness of automated safety functions. Ensuring safe and efficient operation (in terms of neutron production) and maintaining the availability of the reactor and the neutrons for research may be the primary goals of the RO. Success in these areas will comply with technical specifications and investment-protection concerns. The ANS RO will also communicate with many other personnel when coordinating special processes, such as cryogenics and detritiation.

2.1 REACTOR OPERATOR

Figure 1 shows an abstraction of the roles of the ANS RO as they fit in with RO activities and plant states. The "Tool Box" in the center of the diagram represents the human functions the RO draws upon to accomplish his/her various roles. In this systems perspective, the RO can be in any of the roles shown for any activity during any plant state. The RO may also serve multiple roles in a particular activity (e.g., while performing MCR activities, the RO could fill roles having to do with coordinating activities, solving problems, testing systems, following procedures, managing the configuration of systems, supervising control functions, maintaining trained operator status, and performing safety technician activities). This circular representation attempts to show metaphorically that the RO is at the center of the hub of the ANS facility. Most major activities at the ANS will have something to do with the RO.

The roles of the ANS RO, as defined by the responses given in the interviews, are as follows:

- supervisory controller,
- procedure follower,
- system configuration manager,
- plant activities coordinator,
- diagnostician and problem-solver,
- testing and calibration technician,
- equipment/system maintainer,
- facility decontamination technician,
- safety technician
  - — accident avoidance (RO functions as a first line of defense),
  - — reactor scram (manual response, that is, RO functions as a last line of defense),
  - — post-accident monitoring,
- trained operator (maintaining certification)

Each of these will be explained briefly.

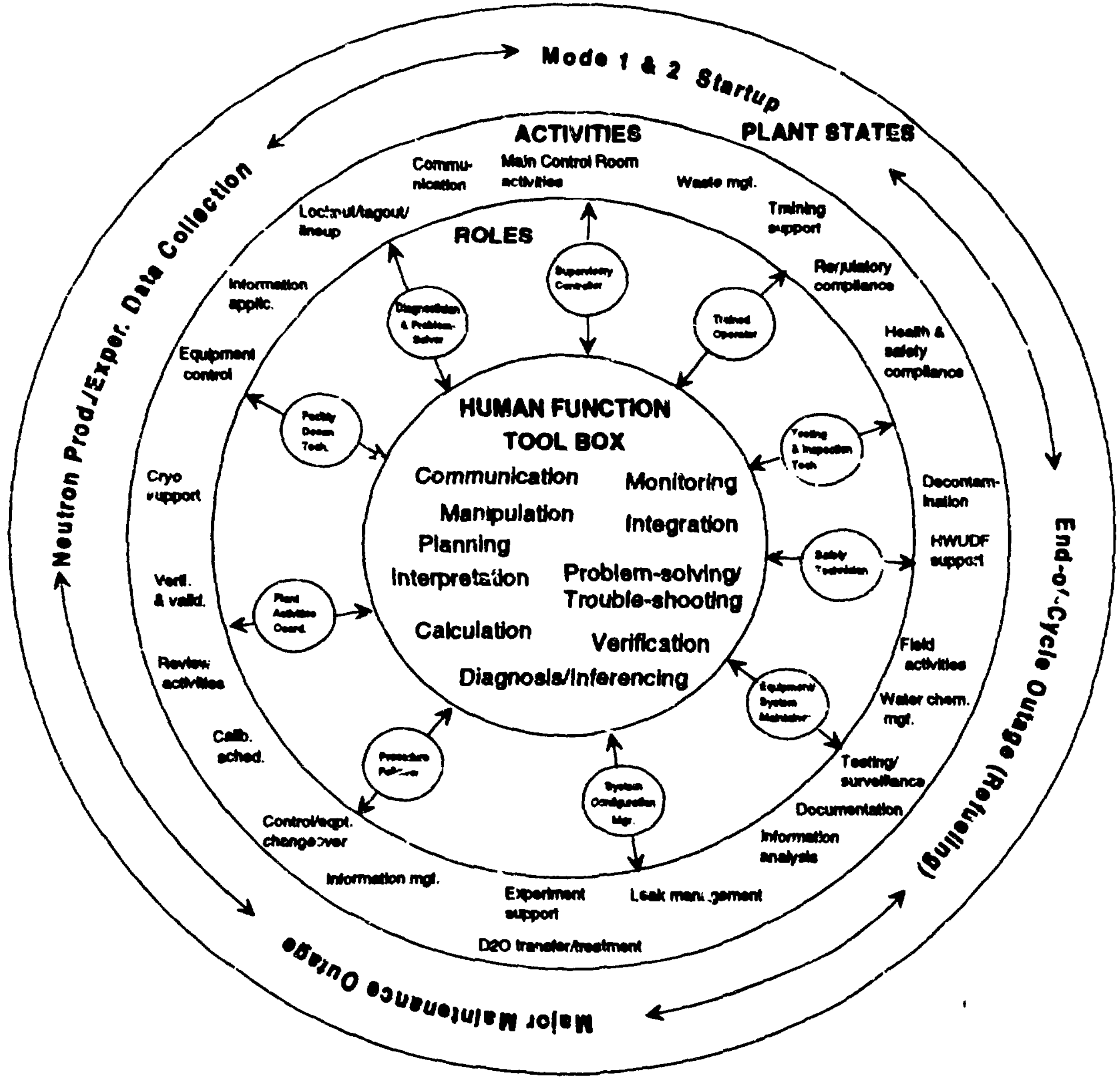

Fig. 1. The roles of the ANS reactor operator as related to reactor operator activities and plant states

2.1.1 Supervisory Controller

The role of supervisory controller is the one the RO probably will fill most often during normal reactor operation. As supervisory controller, the RO will give the okay for the automated reactor control systems to proceed with various control functions. These permissives are part of the effort to keep the RO in the loop of reactor operation, as the RO is ultimately in charge of orchestrating the ANS functions. The RO will maintain a general level of awareness of the plant state and know the status of primary equipment systems. He/she should have the ability to move to a more manual mode of control if needed and allowed. The RO is empowered to shut down the reactor whenever he/she feels circumstances do not support safe reactor operation.

2.1.2 Procedure Follower

Almost every activity in which the RO will engage will involve some type of procedure. Some procedures may require sign-offs or check-offs to ensure that particular steps were completed. By the time the ANS facility is built, it is envisioned that a majority of the RO's procedures will be computerized and interactive. Such advancements will allow procedures to be kept more current, allowing greater accuracy in procedure compliance.

2.1.3 System Configuration Manager

One of the primary responsibilities of the RO is to ensure appropriate system configuration for current plant states. In a more manual mode, the RO must directly engage in activities such as valve alignments and component lockouts. For the supervisory control role, the RO must maintain an appropriate awareness of what the automated systems are doing and why. Furthermore, ROs must ensure that if a piece of equipment is down for maintenance, it is locked out/tagged out. The RO must also be aware of component and system redundancies and backups.

2.1.4 Plant Activities Coordinator

The RO is responsible for ensuring that activities involving interfaces between different systems or organizations are coordinated so that needed tasks can be accomplished. For example, the RO will probably communicate frequently with the EC to ensure that the reactor schedule and the experimenter schedule coincide. Maintenance activities, also, are a major area that will require coordination by the RO. Depending upon whether reactor maintenance activities are to be conducted under or out of the water, an RO and/or a maintenance person will be involved. The transition of responsibility from one organization to the other will require skills in coordination and teamwork.

2.1.5 Diagnostician and Problem-Solver

If an anomaly is noted in the instrumentation readings or in trends in the MCR, the RO is responsible for diagnosing the problem. If the RO deems the reactor unsafe, he/she may shut it down. The RO will determine if certain equipment items need maintenance and request that the appropriate work be done.

2.1.6 Testing and Calibration Technician

The RO will be responsible for testing certain pieces of equipment, especially those having to do with the MCR and reactor operations. The maintenance planning group will generate a calibration schedule with which the RO will comply.

2.1.7 Equipment/System Maintainer

The role of the RO in underwater maintenance was discussed and evaluated in interviews with HFIR personnel. Based on the reasoning given for the practice, it is proposed that the ROs perform underwater maintenance on the reactor components. This maintenance historically has been a part of the RO's job at Oak Ridge National Laboratory (ORNL) experimental reactors. In addition to offering job enrichment, performing maintenance on reactor components facilitates a better understanding of the facility and helps to foster a feeling of ownership.

2.1.8 Facility Decontamination Technician

The RO, in coordination with Industrial Hygiene and Health Physics, will be responsible for any necessary radiological housekeeping in the Reactor Building. This task has historically been a responsibility of the RO at ORNL experimental reactors. It was discussed and evaluated in interviews with HFIR personnel.

2.1.9 Safety Technician

The RO is responsible for complying with all Occupational Safety and Health Administration, industrial hygiene, and industrial safety regulations for industrial facilities. In addition, ANS must comply with health physics regulations related to nuclear facilities. The RO also functions as both the first and the last line of defense with regard to safety: as a first line of defense by working to avoid accidents above and beyond the capabilities of the automated control systems, and as a last line of defense by maintaining the capability to scram the reactor manually if needed. In some accident scenarios, the RO may also have duties related to post-accident monitoring.

At the HFIR facility, there are some safety-related dependencies between ROs and experimenters. In some accident scenarios at the HFIR, ROs are responsible for contacting experimenters. The nature of this relationship at the ANS needs to be explored further.

2.1.10 Trained Operator

The RO will maintain his/her certification by participating in training as part of his/her shift cycle. If needed, the RO will be responsible for doing check-outs with new operators to help them learn procedures on the job. The RO will read any required reading material disseminated by the facility management.

2.2 REFUELING OPERATOR

The ReO will be an RO who has had special refueling training. Any RO may have this special training. Figure 2 illustrates the interface between the RO and the ReO. Refueling is an automated

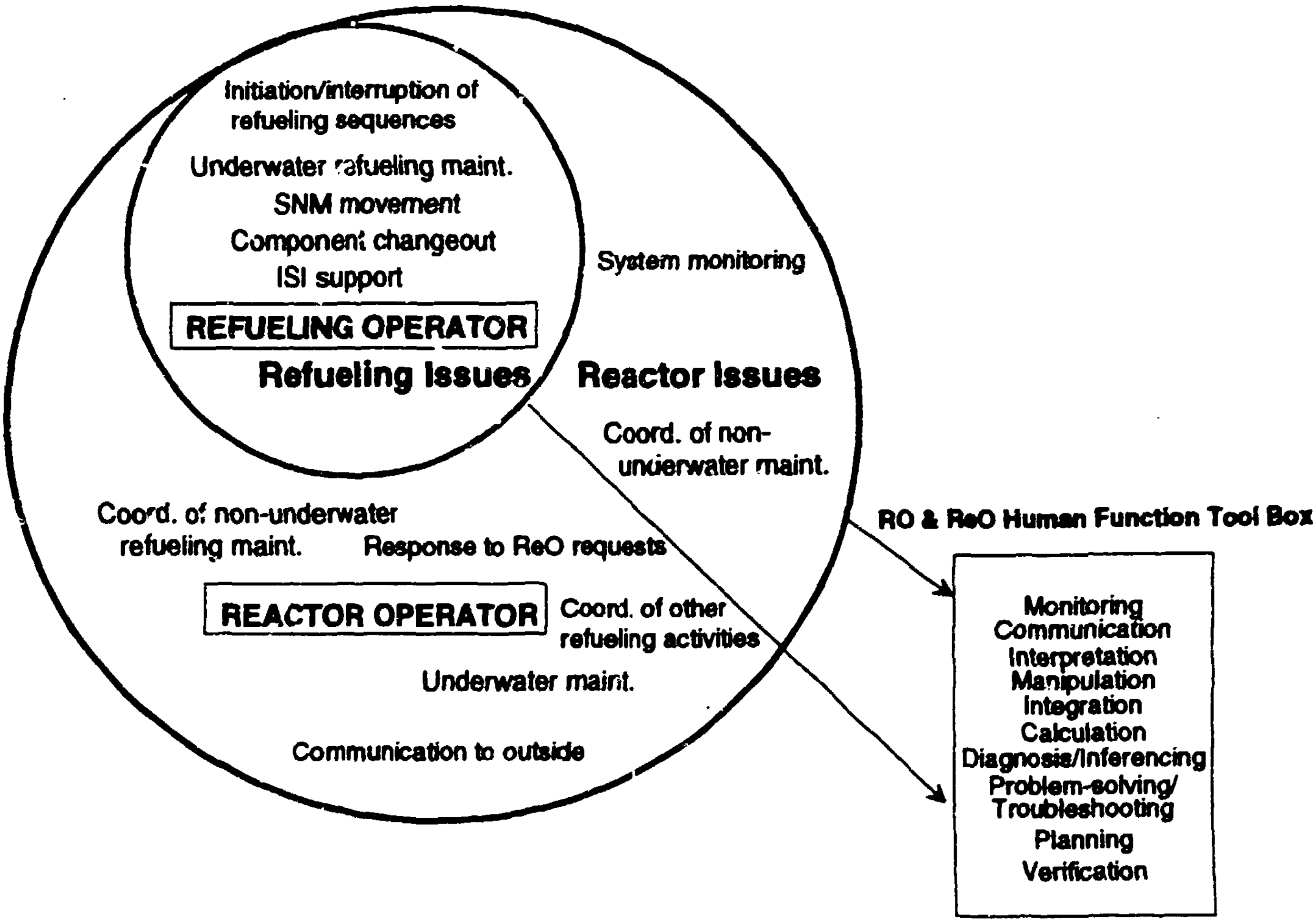

Fig. 2. Interaction between the reactor operator and the refueling operator.

two-person operation. The ReO will initiate, control, and oversee the refueling machine while it performs its programmed functions.

Both the RO and the ReO will have specific tasks during the refueling outage. While the ReO performs activities involving the new and spent fuel elements, the RO will attend to activities involving the reactor, but not refueling. In emergency situations, however, the RO becomes part of the refueling team by communicating events to people or organizations outside the facility.

Responsibilities of the RO (non-refueling operator) during refueling will include the following:

- maintenance,
- passive monitoring,
- support of non-refueling maintenance (accomplished by the Plant and Equipment Division),

- system monitoring (non-refueling monitoring),
- coordination,
- response, and
- communication (to the outside).

The maintenance responsibilities of the ReO and the RO require some explanation. The ReO will be responsible only for underwater *refueling* maintenance. The RO will perform underwater maintenance not involving refueling and will coordinate all non-underwater maintenance. In addition, the RO will coordinate all instrumentation and calibration checks. These duties are summarized in Table 1.

The responsibilities of the ReO include the following:

- Monitoring automated systems.
- Initiating/interrupting refueling sequences.
- Verification.
- Underwater refueling maintenance (same activities as the first three responsibilities).
- Communication.
- Special nuclear material movement (includes criticality safety).
- Interaction with technical support team (problem-solving).
- Component changeout:
  - Flush and purge of H_2O, D_2O interfaces
  - Air lock operations (primarily fuel movement and other activities to support refueling). Other people are also qualified.
- In-service inspection support.

During refueling operations, the ReO may assume manual control under certain circumstances (*e.g.*, if a load readout indicates an off-normal situation). The ReO is responsible for all refueling activities. In case of a problem, the ReO would be responsible for placing the fuel element in a safe configuration, bringing the refueling machine into a safe situation, and calling in a larger team to analyze and correct the problem. The operation would then proceed using contingency plans as procedures. The ReO will have no visual access unless cameras are provided for monitoring parts of the process. The operator, however, will probably have some type of simulation—graphical or otherwise—of what is happening during the refueling process. Special support may need to be provided. The refueling sequence is as follows:

1. Shut down.
2. Cool down—24 hours, full flow.
3. Activate refueling machine and select head.
4. Remove and store thermal plug.
5. Remove and store irradiation capsule.
6. Remove closure elbow—seals require refurbishment. Store after maintenance.
7. Remove and store load cylinder.
8. Place poison on upper fuel. Remove and store upper fuel.
9. Remove transuranic rack. Remove transuranics from rack. Replace transuranics and store.
10. Place poison on lower fuel. Remove and store lower fuel.

Table 1. Reactor operator/refueling operator maintenance responsibilities during refueling

Refueling operator	Reactor operator
Underwater refueling maintenance	Underwater maintenance
	Coordination of — Instrumentation and controls, calibration checks — Non-underwater refueling maintenance — Non-underwater maintenance

11. Place poison on fresh lower fuel. Transfer lower fuel to refueling machine. Place in vessel. Remove poison.
12. Replace transuranic rack.
13. Place poison on upper fuel. Transfer upper fuel to refueling machine. Place in vessel. Remove poison.
14. Replace load cylinder.
15. Replace closure elbow.
16. Replace irradiation capsule.
17. Replace thermal plug.
18. Pressurize and leak check.

The ReO will have several key monitoring activities. There is a 24-hour wait before components can be removed from the reactor, except for the thermal shield plug, which can be removed in the first 24 hours. After any component is attached to its appropriate tool, the machine will indicate "ready" after a minimum number of connections are made. The operator will then activate the next sequence. (Vibration sensors will be built into the operational sequence to facilitate tool movements). The second set of components to be removed are the irradiation capsules. Their removal requires depressurization of the primary coolant system; therefore, the reactor has to be in the natural convection mode.

The ReO may also support maintenance activities by examining the control rods and/or checking the seals. The operator might also pressure test the vessel with the closure elbow on.

The ReO will interact with experimenters, possibly through the EC and/or the shift supervisor (SS). The interactions with experimenters stem mainly from issues associated with the transuranic rack and isotope production capsules. There may be a need to communicate with beam room experimenters. The ReO might also need to interact with the experiment technicians/operators in the materials irradiation control room.

The ReO will interact with the SS, also. The SS coordinates all plant activities and is the central communication point for operations.

The ReO would also interact with a technical support team in case of an emergency. This team would be on call in case of an abnormal occurrence. The proposed membership of this team includes a tooling/refueling engineer, members of the reactor technology group, managers, and the plant manager/operations manager.

The ReO would also interact with underwater maintenance personnel during the refueling outage. Underwater maintenance is currently performed by ROs. Special support for this interaction may need to be provided in the facility design.

2.3 CRYOGENICS OPERATOR

The CO is responsible for the monitoring, control, and limited maintenance of the cold sources and the refrigeration units associated with them. The RO and the CO will need to maintain close communication, especially during startup and shutdown. The RO will need some basic representation of cryogenic parameters (e.g., an electronic schematic), and the CO will need more detailed representation.

The CO will be trained on the ANS cryogenics system. Training could consist of internal training as part of the usual shift, although a simulator-based cryogenics capability would be optimal. The type of training and qualifications that the CO should have has not been determined. The ANS will initially require a full shift (5 persons) of COs, but conceivably could go to a call-in system eventually.

The cold source operation is relatively independent of the reactor system operation, although both cold sources must be on-line for the reactor to be started. Coordination between the RO and the CO is not generally critical during steady state reactor operation. Significant coordination is required during reactor startup to ensure the availability of both cold sources. Also, interaction will take place during refueling and in the case of an event. In general, however, good coordination and communication between the RO and the CO primarily support efficiency in the ANS operation.

Problems could occur if the CO and RO did not coordinate startup and shutdown. For example, a malfunction could solidify the deuterium and plug a cold source. Excess heat would then cause boiling with a rapid pressure rise. The cold source must be at temperature and shielding must be in place before the RO can start the reactor. The RO can "plateau" the reactor power for a specified period of time if there is a problem with the cryogenic system.

Cryogenics control will involve a primary cold source workstation, probably in the MCR; a cold box panel located in the field near the cold sources; and compressor control panels located near the compressors. There is some concern over the potential for the CO to distract the ROs in the MCR; however, we feel that during normal operation, there will be minimal distraction, if any. In off-normal situations, control room personnel might be called upon to monitor the cryogenics workstation while the ANS reactor is operating. This could happen if the CO were working in the field or were located at the remote cryogenics control station, creating the potential for task overload for the backup monitor.

The main parameters related to the cryogenics facility will be displayed in the MCR. Full monitoring and some control capabilities will be available through a dedicated cryogenics control panel/workstation. The remote cryogenics control station will provide local monitoring and control capabilities to the COs in the field. The remote control station may not be digitally designed to the same extent as the primary cryogenics workstation in the MCR. The CO (under prescribed conditions) can give the command to transfer control from the MCR to the remote station on the second floor. During refueling, primary control of the cold sources will be in the second-floor area.

Experimenters generally will not communicate directly with a CO but will make arrangements through the EC. Cryogenic maintenance will need to be coordinated by the CO and communicated to the MCR. Maintenance planners and maintenance/operations planning sessions will ensure smooth coordination.

During normal operation, one cold source may be in a manual operating mode while the other is in the automatic mode. There is some possibility that a single CO could not handle both cold sources in manual control. Manual control can be performed through the computer safety-related 1-E system. Manual control may be in place during the first year for check-out and may happen later on when circulators are changed out.

The following preliminary responsibilities have been identified for the CO:

- monitoring of D_2, H_2, and T_2 in the control room, valves, vacuum systems;
- field work—checking valves, coordination, communication;
- leak investigation;
- leak management;
- miscellaneous servicing (gasifying liquid N_2, providing liquid He to experimenters);
- support maintenance;
- coordination control of main and local cryogenics panels (along with the RO);
- system responses—circulator changeover, startup, shutdown, transients;
- manual operation of cold source; and
- support of detritiation operations He refrigerator systems.

2.4 DETRITIATION OPERATOR

The detritiation operator (DO) is responsible for monitoring and control of all of the processes involving the Heavy Water Upgrade and Detritiation Facility (HWUDF). The HWUDF processes are controlled primarily by a supervisory control system, with support from the DOs. These operators will require special training in tritium and cryogenics technologies.

The HWUDF control room will be staffed by five DOs during the day shift. This control room will not be occupied during the off-shift. Three DOs will have detritiation control room responsibilities, and the other two will perform activities out in the plant. HWUDF control room activities will center on the following:

- receiving water from the reactor building (every 14–20 days),
- changing out resin and charcoal beds (every 10 days),
- removing tritium batches off-line and immobilizing them (every 10 days),
- managing the titanium beds in glove boxes (every 10 days), and
- regenerating the catalysts (infrequent).

Control of the HWUDF will be transferred to the MCR on the off-shift.

The HWUDF will be run in campaigns, with each campaign lasting from 14 to 20 days. Startup should take around 3 days; shutdown to a stable configuration can be done in an hour. Full shutdown requires 3 days. The RO or SRO will be capable of shutting down the HWUDF to a stable configuration if needed. Some upset scenarios may require an immediate operator response. If such an upset occurred on the off-shift, the HWUDF would have to be shut down and a DO called in. The RO or SRO will therefore need training in putting the HWUDF into a stable configuration.

During day shift, when the facility is fully staffed, the DO might have to assume manual control when changing the feeds on a combined electrolysis catalytic exchange column, when withdrawing tritium from a high-tritium column, or during tritium immobilization. Immobilization operations are 100% manual.

The following is a preliminary list of DO responsibilities:

- monitoring;
- management of system responses
  - — determining and implementing set points,
  - — verifying predetermined set points;
- field work
  - — changeout of resin and charcoal beds,
  - — checks and valve adjustments,
  - — removal of tritium batches off-line/immobilization,
  - — management of titanium beds in glove boxes,
  - — barrel management (water from experimenters),
  - — regeneration of catalysts,
  - — making up fresh electrolyte,
  - — communication;
- leak management;
- coordination control HWUDF coordination (RO → DO);
- support maintenance, in-service inspection;
- decontamination;
- special nuclear material control (assaying D_2O and tritium); and
- possibly long-term storage and management of tritium.

2.5. INTERACTIONS AMONG OPERATORS

The interactions between the RO and the ReO were described in the sections describing their jobs. This section will delineate the interactions of the other types of operators with activities associated with the MCR.

2.5.1 Interaction Among the Reactor Operator, Cryogenics Operator, and Experiment Coordinator

As shown in Fig. 3, there are areas of overlap in the activities of the RO, CO, and EC. The RO and the CO will have several coordination activities associated with the cold sources. The reactor cannot be started if the cold sources are not up and running; therefore, reactor startup and shutdown will be closely linked with the operation of the cryogenic refrigerators. Loss-of-power issues must be

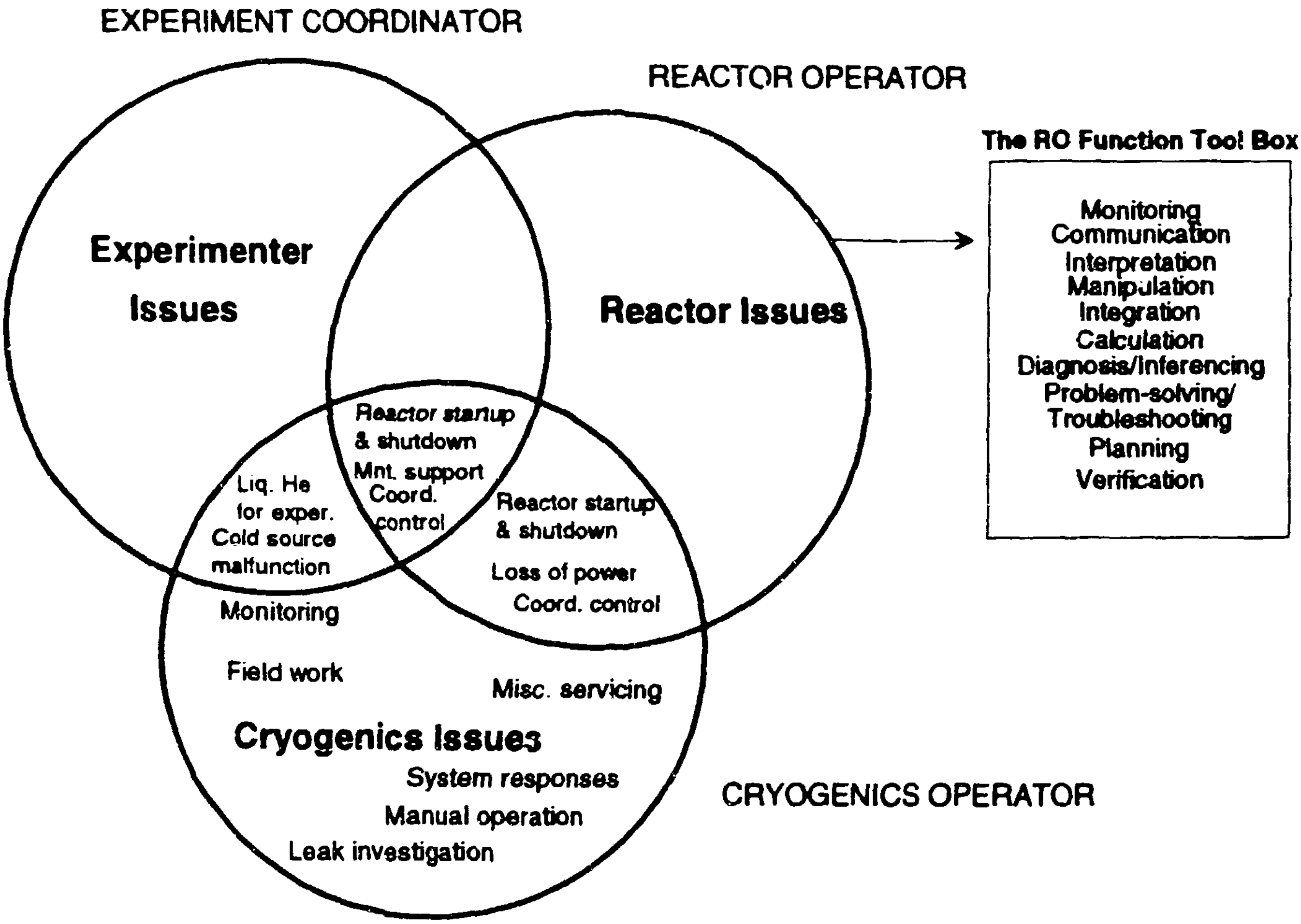

Fig. 3. Interaction among the reactor operator, the cryogenics operator, and the experiment coordinator.

managed and resolved between the RO and the CO. Depending upon the amount of time the power is lost, it may be impossible to start the refrigerators and the reactor may consequently shut down.

Maintenance problems with cryogenic systems also may cause the reactor to shut down. As one of the responsible engineering designers (REDs) mentioned in an interview, "The reactor can't run with a bad vacuum, but it can run with a partially bad vacuum" (i.e., the vacuum pumps can accommodate leaks up to a point, after which the vacuum acts as an insulator in the vacuum vessel and cryogenic temperatures cannot be produced). The CO might have to make subjective judgments about the level of leak that is occurring. A loss of vacuum could lead to freezing of the cooling water and a flashing of the deuterium in the cold sources. The use of multiple-walled vessels and backup vacuum systems protects against this serious accident. However, the CO may need special help from design features to make good decisions about the extent of a leak that is encountered. Another problem that might arise is a circulator deviating from the usual operation. The CO would have to decide (based on experience, equipment manuals, and operator guidelines) how much deviation is allowed before the circulator would have to be changed out.

The RO may be required to monitor the state of cryogenic operations generally. Since the RO and the CO are in close proximity in the MCR, the RO may be called upon to aid in the transfer of control from the MCR to the remote panels as needed. The RO will also offer support in diagnosing and identifying maintenance problems with the cryogenics systems.

The EC and the RO will interact on problems that experimenters have with reactor operation. The operation of the beam shutters will be in the domain of research operations, whereas the RO will have responsibility for the beam tubes themselves. The method of handling this division of responsibility administratively has not yet been studied. The EC should notify the RO of the status of major experiments, important configurations to consider, and the readiness of the experimenters for startup. This holds true for both in-core and beam experiments. Issues concerning in-core experiments will also need to be coordinated with the materials irradiation control room, which is in the same building as the MCR.

The EC will be a knowledgeable person who is on site to work with the experimenters. At the HFIR, there sometimes are communication problems between the experimenters and the ROs. The EC should help avoid such problems at the ANS facility. There should also be an informed person in the research operations organization with skills and training in operating and controlling beams. Such a person may or may not be in addition to the EC. This person could also deal with the experimenter control rooms and exercise some work control over support personnel for the experimenters. More study is needed of the organizational structure of the research operations group.

Table 2 provides a preliminary list of parameters involving the experimenters on which the RO will need information in the MCR. This list will be expanded and more details provided as design data become available. In the future, plant systems that are involved in particular activities, and the interactions between the plant systems, will be shown in detail. More input is needed on this subject from the design team.

2.5.2 Interaction Between the Reactor Operator and the Detritiation Operator

The activities of the RO and the DO are relatively independent except in the transfer of tritiated water from the reactor building to the HWUDF. Figure 4 depicts the relationship that is envisioned between these two types of operators. The RO ensures that the water is pretreated before it is sent to the HWUDF. This is to ensure that beta and gamma contamination are confined to the reactor building. This treatment is carried out using evaporators that are the responsibility of the RO. The RO will also coordinate the water transfer to and from the HWUDF. This batch transfer will take place every 14–20 days, depending, to some extent, on the availability of both the reactor and the HWUDF. The transfer of the heavy water is the only part of the HWUDF process that is a batch process—the detritiation and upgrade process is continuous. The transfer back to the reactor building puts the heavy water in one of the four interconnected reactor grade storage tanks.

Table 2. Potential monitoring/control activities in Main Control Room related to experiment systems

Parameter	Essential	Good to have	Reason for displaying in normal plant state: Reactor safety	ALARA	Personnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage)	Security	Reason for displaying in off-normal plant state: Reactor safety	ALARA	Personnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage	Security	System interfaces To be determined (TBD)
Neutron beam transport															
Horizontal beam (HB) 1,2,3,6,7,8 & 9															
Vacuum	✓		✓			✓	✓		✓				✓		
Beam monitor		✓				✓									
Leak detection		✓					✓					✓	✓		
Coolant flow (plug, thimble)		✓				✓	✓					✓	✓		
Main shutter (open or closed)		✓		✓	✓					✓	✓				
Radiation monitor in experiment area	✓			✓	✓					✓	✓				
Video of experiment station(s)		✓				✓		✓		✓	✓			✓	
HB 4a, b															
Hot source cooling, status	✓		✓				✓		✓				✓		

Table 2. (continued)

Parameter	Essential	Good to have	Reason for displaying in normal plant state: Reactor safety	ALARA	Personnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage)	Security	Reason for displaying in off-normal plant state: Reactor safety	ALARA	Personnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage	Security	System interfaces To be determined (TBD)
HB-4a, b (cont.)															
Beam monitor		✓				✓						✓			
Leak detection		✓					✓						✓		
Coolant flow (plug, thimble)		✓					✓						✓		
Main shutter (open or closed)				✓	✓					✓	✓				
Radiation monitor in experiment area	✓			✓	✓					✓	✓				
Video of experiment station(s)		✓				✓		✓			✓			✓	
HB 5-10 (through tube)															
Loading station status															
Valving and transport system status	✓		✓				✓		✓		✓		✓		

Table 2. (continued)

Parameter	Essential	Good to have	Reason for displaying in normal plant state: Reactor safety	ALARA	Personnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage)	Security	Reason for displaying in off-normal plant state: Reactor safety	ALARA	Personnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage	Security	System interfaces To be determined (TBD)
HB 5-10 (cont.)															
Sample location - in reflector vessel (RV) or being loaded	✓					✓	✓				✓		✓		
Vacuum	✓		✓				✓		✓				✓		
Leak detection		✓					✓					✓	✓		
Coolant flow (plug, thimble)		✓				✓	✓					✓	✓		
Main shutter (open or closed)				✓	✓					✓	✓				
Radiation monitor in experiment area				✓	✓					✓	✓				
Video of experiment station(s)				✓	✓	✓		✓		✓	✓	✓		✓	
Large Slant Beam Tube (LSBT)															
Isotope Separation On-Line (ISOL) facility status		✓			✓	✓	✓			✓	✓		✓		
Fire detection and safety systems status			✓	✓	✓		✓		✓	✓	✓		✓		

Table 2. (continued)

Parameter	Essential	Good to have	Reason for displaying in normal plant state: Reactor safety	ALARA	Personnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage)	Security	Reason for displaying in off-normal plant state: Reactor safety	ALARA	Personnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage)	Security	System interfaces To be determined (TBD)
LSBT (cont.)															
Vacuum	✓		✓						✓						
Beam monitor		✓				✓						✓			
Leak detection		✓					✓						✓		
Main shutter (open or closed)				✓	✓					✓	✓				
Radiation monitor in experiment area				✓	✓					✓	✓				
Video of experiment station(s)					✓	✓					✓	✓			
Cold Guide Systems															
Vacuum		✓					✓						✓		
Leak detection		✓					✓						✓		
Coolant flow (plugs)		✓					✓						✓		
Main shutter (open or closed)		✓			✓		✓				✓		✓		
Beam monitors		✓				✓						✓			

Table 2. (continued)

Parameter	Essential	Good to have	Reason for displaying in normal plant state: Reactor safety	ALARA	Personnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage)	Security	Reason for displaying in off-normal plant state: Reactor safety	ALARA	Personnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage	Security	System interfaces To be determined (TBD)
Cold Guide Systems (cont.)															
Radiation monitor in experiment area				✓	✓					✓	✓				
Interlock system status				✓	✓					✓	✓				
Status of all containment penetration valves	✓		✓		✓			✓	✓		✓			✓	
Scattering instruments (42 and 43)															
Personnel within containment		✓			✓						✓				
Video of stations		✓				✓					✓				
Safety interlock system status	✓				✓			✓			✓			✓	
Message traffic from researchers		✓				✓					✓	✓		✓	
Transuranic production															
Horizontal tube (HT) -2 cooling status	✓						✓						✓		

Table 2. (continued)

			Reason for displaying in normal plant state						Reason for displaying in off-normal plant state						
Parameter	Essential	Good to have	Reactor safety	ALARA	Per-sonnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage)	Security	Reactor safety	ALARA	Per-sonnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage	Security	System interfaces To be determined (TBD)
Transuranic production (cont.)															
HT-2 leak detection status		✓				✓	✓					✓	✓		
HT-2 rabbit status (in, out, in tra[illegible])		✓				✓						✓			
Data base on targets within RV (mat'l, react., etc.)		✓				✓						✓	✓		
HOT CELL status		✓			✓		✓					✓	✓		
Video of transuranic (TRU) handling station		✓			✓			✓			✓			✓	
Personnel in containment		✓		✓	✓					✓	✓				
Status of target transport within and out of containment		✓			✓	✓					✓	✓			
Status of stored targets		✓		✓			✓			✓			✓		
Material irradiation															
Status of in-core experiments	✓		✓				✓		✓				✓		

Table 2. (continued)

Parameter	Essential	Good to have	Reason for displaying in normal plant state: Reactor safety	ALARA	Personnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage)	Security	Reason for displaying in off-normal plant state: Reactor safety	ALARA	Personnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage	Security	System interfaces To be determined (TBD)
Material irradiation (cont.)															
Data base on in-core experiments		✓				✓						✓			
Cooling of slant hole (SH) -1, SH-2	✓		✓				✓		✓				✓		
SH-1, 2 leak detection		✓					✓						✓		
Personnel within containment		✓		✓	✓					✓	✓				
Analytical chemistry															
Cooling for pneumatic tube (PT) 1, 2, 3, 4, & 5 and pneumatic facility (PF) 1, 2		✓				✓	✓					✓	✓		
Leak detection for PT 1, 2, 3, 4, & 5		✓				✓	✓					✓	✓		
Valving, systems, and target status for PT 1, 2, 3, 4, & 5 and PF 1, 2		✓				✓	✓					✓	✓		

Table 2. (continued)

Parameter	Essential	Good to have	Reason for displaying in normal plant state: Reactor safety	ALARA	Personnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage)	Security	Reason for displaying in off-normal plant state: Reactor safety	ALARA	Personnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage	Security	System interfaces To be determined (TBD)
Analytical chemistry (cont.)															
Status for containment penetration for 40 & 120 cc pneumatic systems	✓		✓						✓	✓	✓			✓	
Sample location for transport from National Activation and Analysis Facility (NAAF) -1 to NAAF-2		✓			✓	✓					✓	✓			
Personnel within containment		✓		✓	✓					✓	✓				
Radiation monitors for handling areas	✓			✓	✓					✓	✓				
Data base for targets		✓				✓						✓			
Status of g irradiation facility and video		✓		✓	✓					✓	✓				
Prompt g system		✓			✓					✓	✓				
Radiation monitors		✓		✓						✓	✓				
Shutter position		✓			✓	✓					✓	✓			

Table 2. (continued)

Parameter	Essential	Good to have	Reason for displaying in normal plant state: Reactor safety	ALARA	Personnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage)	Security	Reason for displaying in off-normal plant state: Reactor safety	ALARA	Personnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage	Security	System interfaces To be determined (TBD)
Neutron depth profiling															
Radiation monitors		✓		✓	✓					✓	✓				
Shutter position		✓				✓						✓			
Personnel within containment		✓		✓						✓	✓				
Experiment computer and data system															
Link available for all data		✓				✓						✓			
Cold source															
Overall system status	✓					✓	✓					✓	✓		
Deuterium	✓		✓		✓		✓		✓		✓		✓		
Vacuum	✓		✓				✓		✓		✓		✓		
Helium (cryogenic)	✓						✓						✓		
Helium (blanket)	✓		✓		✓		✓				✓		✓		
Leak detection		✓					✓						✓		
Vent	✓														

Table 2. (continued)

Parameter	Essential	Good to have	Reason for displaying in normal plant state						Reason for displaying in off-normal plant state						System interfaces To be determined (TBD)
			Reactor safety	ALARA	Per-sonnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage)	Security	Reactor safety	ALARA	Per-sonnel safety	Good practice (ease of operation)	Cost avoidance (eqpt. damage	Security	
Cold source (cont.)															
Personnel within containment		✓		✓	✓					✓	✓				
Video of safe room and control arec	✓	✓		✓	✓					✓	✓				
Heavy water cooling	✓		✓				✓		✓				✓		
Hot source															
Overall system status	✓														
Vacuum	✓		✓		✓	✓			✓		✓				
Helium (pressure)			✓				✓		✓				✓		
Heavy water cooling	✓		✓				✓		✓				✓		
Leak detection		✓					✓					✓			
Personnel within containment		✓		✓						✓	✓				
Radiation monitors		✓		✓	✓					✓	✓				

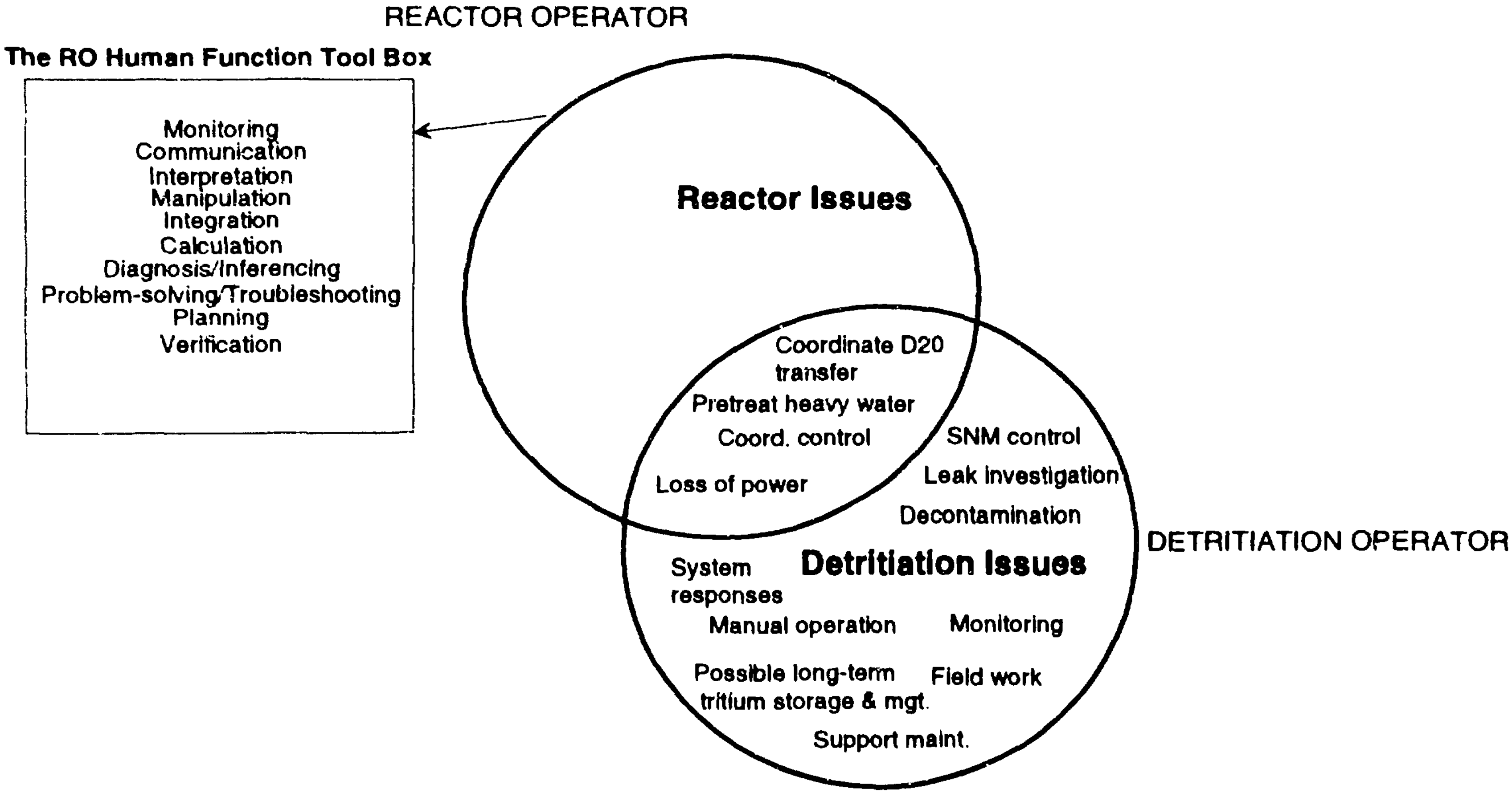

Fig. 4. Interaction between the reactor operator and the detritiation operator.

As the process currently is envisioned, the RO will perform the monitoring activities associated with the HWUDF in the off-shift. The RO will be capable of shutting down the HWUDF if necessary. Some upset scenarios will require immediate operator response. If such an occurrence were experienced after hours, the RO would have to shut down the HWUDF and call in a DO. An RED suggested that such a scenario could be better mitigated by training a senior reactor operator (SRO) in the areas of cryogenics and detritiation. With such training, the SRO could provide necessary expertise during non-day-shift periods.

2.5.3 Interaction Between the Reactor Operator and the Senior Reactor Operator

The SRO is a supervisory reactor operator with higher-level responsibilities than the RO. Figure 5 illustrates the relationship between the RO and the SRO. The role of the SRO is expected to involve dealing with off-normal responses in cryogenics, detritiation, and experiments in the off-shift. Since control for some ancillary ANS processes will be transferred to the MCR during the off-shift, the SRO will fill a need for an operator with specialized knowledge about certain abnormal occurrences. The special training required for this position would be in addition to the regular RO training. More study of this issue is needed.

The SRO will also have some supervisory duties during startup and shutdown, loss of power, and monitoring. If an RO should have to leave the MCR to attend to field activities, the SRO might be called upon to perform monitoring and control functions in his/her absence.

2.5.4 Interaction Between the Senior Reactor Operator and the Refueling Operator

Figure 6 shows the suggested relationship between the SRO and the ReO. The ANS operations representative has proposed that one of the two people on the refueling team be an SRO. This was suggested because the refueling team is responsible for moving special nuclear material (i.e., fuel elements), which introduces accountability concerns and fuel handling concerns (i.e., tipping over and overheating of a fuel element). Although overturning a fuel element probably would not cause a re-criticality, major cleanup activities and increased radiation exposure would be associated with this problem. It also has the potential to shut down the facility. This off-normal situation will be studied further in the future.

2.5.5 Interaction Between the Cryogenics Operator and the Detritiation Operator

The CO and the DO probably will not interact as much as the original concept of cross-training may have suggested. After the interviews, it appears that cryogenic and detritiation operations are separate and distinct, having few points of interdependence. However, one point of overlap was proposed. The COs will have special training in refrigerators; therefore, they should have skills that would prove useful in attending to the helium refrigerators associated with the HWUDF. Figure 7 depicts the relationship between the two types of operators. More study needs to be done of interaction between the CO and the DO.

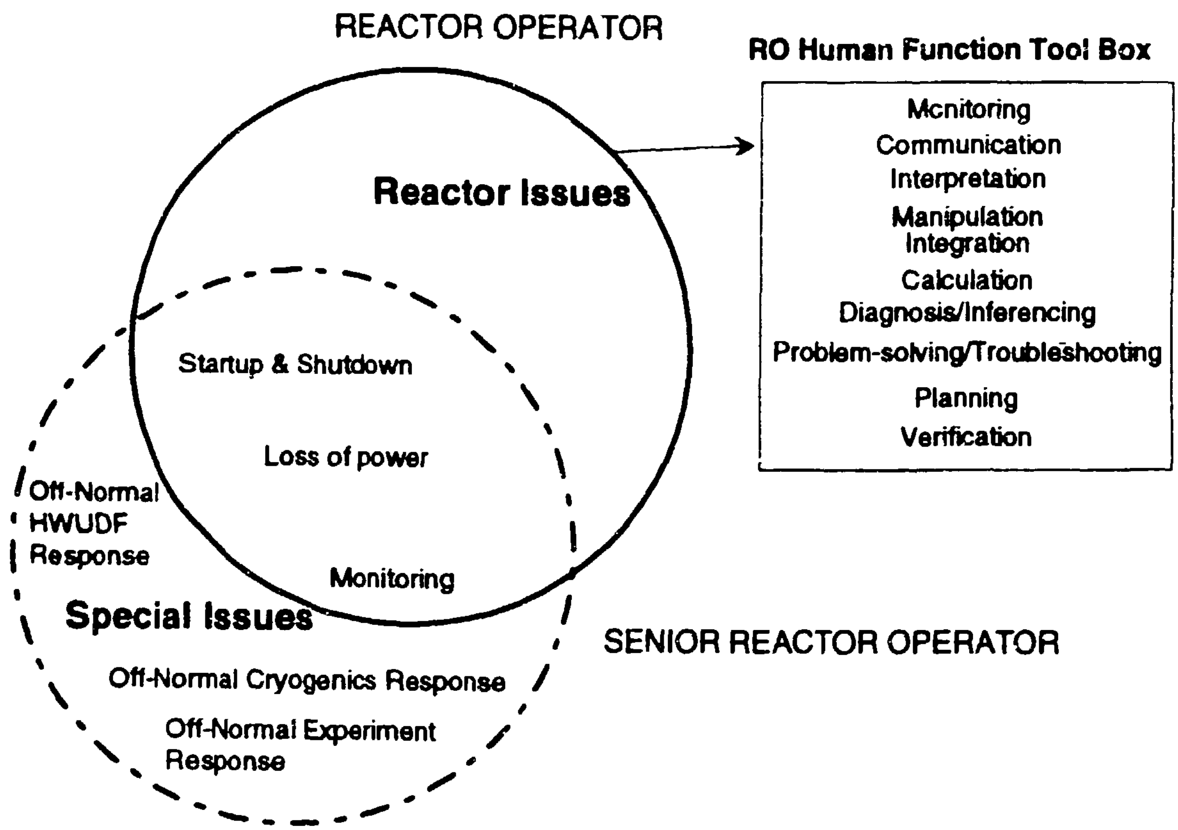

Fig. 5. Interaction between the reactor operator and the senior reactor operator (preliminary).

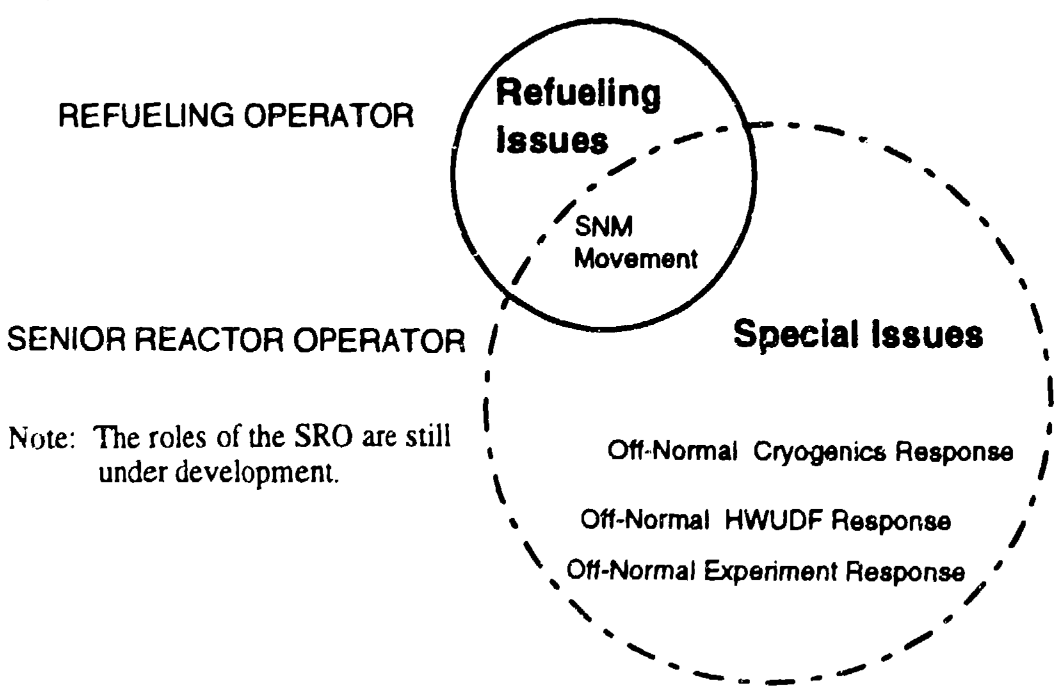

Fig. 6. Interaction between the senior reactor operator and the refueling operator (preliminary).

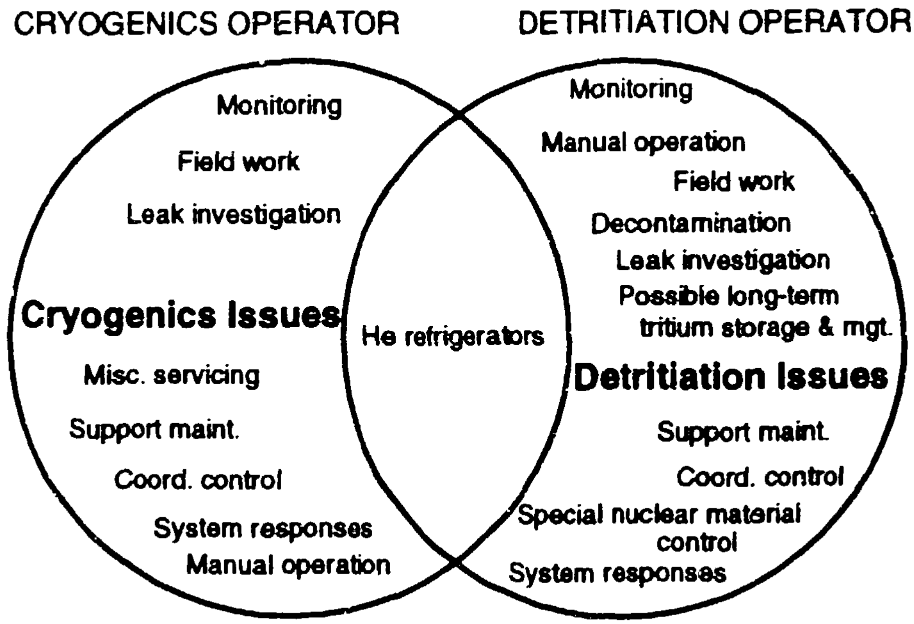

Fig. 7. Interaction between the cryogenics operator and the detritiation operator.

2.5.6 Interaction Among the Senior Reactor Operator, Detritiation Operator, and Cryogenics Operator

The SRO will interact with the DO and the CO in off-normal situations, especially during the off-shift. Figure 8 shows the preliminary interaction of the SRO with the CO and the DO. As the assessment of the operators' roles continues, the role of the SRO, especially, will be targeted for further analysis.

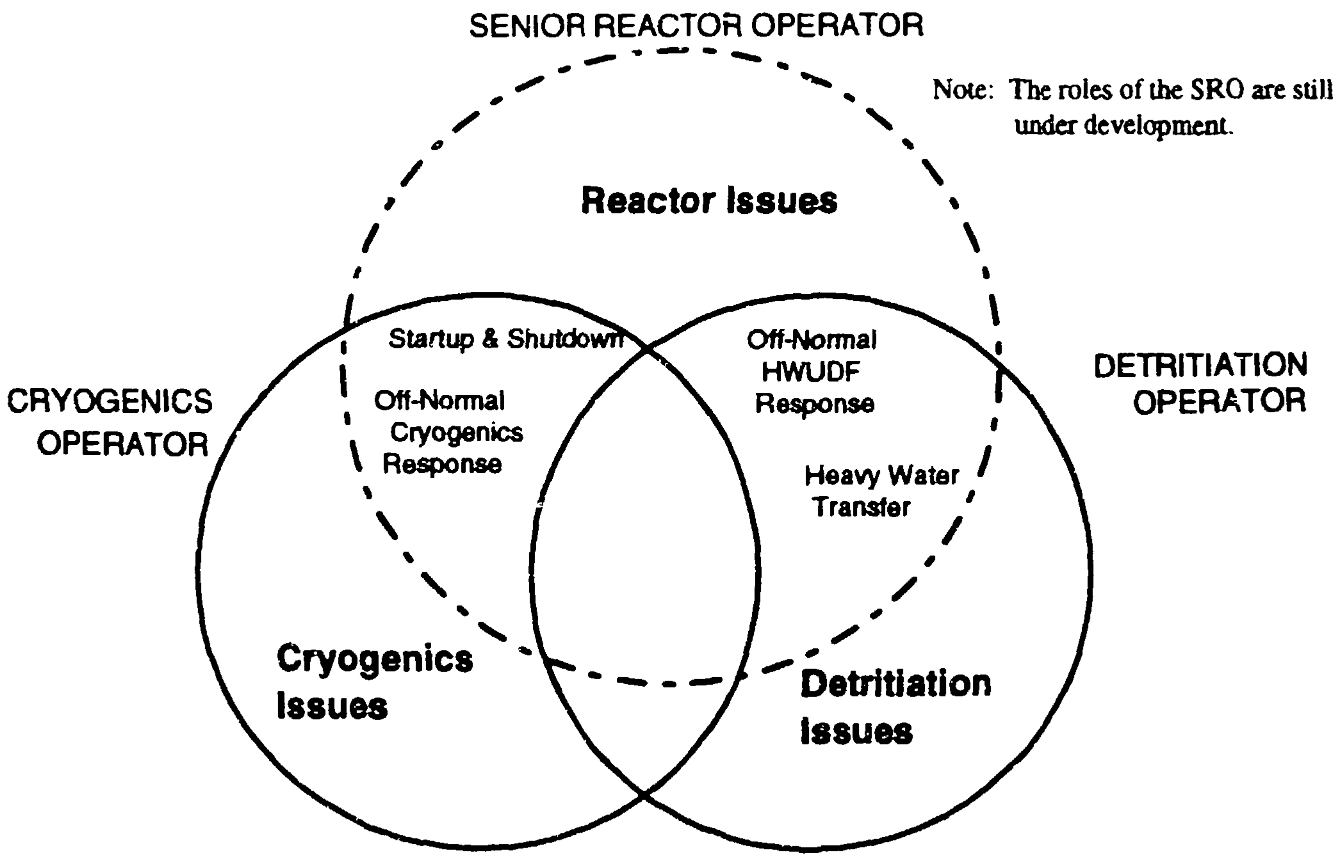

Fig. 8. Interaction among the senior reactor operator, the detritiation operator, and the cryogenics operator (preliminary).

3. ITEMS FOR MORE STUDY

The following are questions that arose during the study of the roles of the RO during normal operation. These questions could not be addressed extensively because of resource and time constraints. However, they will be tagged for consideration during the next iteration of this study.

1. Who will do the power monitoring?

2. What is the philosophy behind the SRO position? Will this operator do "busy" activities or be just a passive manager of activities? What types of activities will be the special domain of this operator?

3. Is convection cooling still an issue after 42 days?

4. Will the SRO do the flush-purge operation?

5. Is there a need for the DO to check the pretreatment of the heavy water for beta and gamma contamination? Will the assay include this type of check?

6. What is the process for recovering from a failed fuel element (leaker)? Which project document will this process be recorded in?

7. What will be the interaction between the RO and experimenters in accident scenarios?

8. Are there other safety-related dependencies between ROs and experimenters?

9. Will the ReO need to interact with personnel in the materials irradiation control room? If so, in what ways?

10. What kind of facility design support is needed for interaction between the ReO and underwater maintenance personnel?

11. What type of training and qualifications will the various types of operators need?

12. How will the operation of the beam tubes vs the operation of the beam shutters be handled administratively?

13. In detail, what types of interactions will the CO and the DO have?

14. What would be the best titles for the operator roles involved?

15. How does the special process operator concept (i.e., the CO and DO) measure up against the auxiliary operator concept (i.e., cross-trained ancillary operators)?

16. What is the best organizational structure for research operations?

17. How should the ANS maintenance organization be structured? Should maintenance staff be dedicated to the ANS facility? Should there be maintenance staff dedicated to supporting experimenters?

18. What has been the historical performance of refueling tools such as those proposed for the ANS? What are potential problems related to this equipment?

4. CONCLUSIONS

The concepts behind the definitions of the roles of the DO and the CO suggest that the original ANS view of the auxiliary operator (AO) position should be rethought. The AO was envisioned in the *Basis for Operations* document as being a different kind of operator from the RO. In the original ANS conceptual design report, the AO was defined as the operator who would deal with cryogenics, detritiation, power monitoring, and other ancillary processes. It was suggested that cross-training from one ancillary process to another would be appropriate. In contrast, an AO in the nuclear power world is a kind of "junior reactor operator"; a person can "work his/her way up" from AO to RO. Obviously, this AO role is different from the one originally envisioned for ANS. After the interviews, cryogenics and detritiation were deemed to be separate and distinct processes that would require distinct training/skills. The names of the various roles also may need to be evaluated to avoid confusion due to semantics.

This AO concept will be evaluated against the concept of a special process operator. Two subsets of special process operators—a CO and a CO—are proposed. Each of these types of operators would receive specialized training for the particular system to be controlled/maintained. There is one possible area of overlap for these operators: The refrigeration expertise of the COs could perhaps be used to help the DOs in maintaining the helium refrigerator associated with the detritiation process.

During the analysis of the refueling sequences, it was determined that the process of dealing with a failed fuel element (a leaker) needs to be explored further. The RO likely will have some role in mitigating the effects of a substandard core. It was suggested in one of the interviews that perhaps one of the redundant transfer locks could be used temporarily to store the leaker for 2 years.

Information from the interviews strongly suggested the need for an EC to function as a liaison between the experimenters and other ANS site functions, including reactor operations. Those interviewed expressed the view that the ANS, as a user facility, should have a dedicated individual responsible for representing the needs of the experimenters in areas such as scheduling, the configuration of shutters, and beam tube vacuums. They feared that communication between experimenters and ROs might be a problem. The experience at the HFIR was that some ROs had been called directly by individual experimenters. Such a situation has a tendency to detract from the RO's duties and may be a source of friction between the ANS facility (i.e., the ROs) and its customers (i.e., the experimenters). Establishing an ANS EC provides a positive image of the ANS as being sensitive to its customers' needs. The experimenter community has expressed a desire to have an EC at the facility at all times. This around-the-clock coverage would ensure that service could be provided for the experimenter community in the variable hours necessitated by research requirements. There also might be safety-related problems that would require that ROs contact experimenters. This issue needs to be explored further.

A significant portion of the interviews involved discussions about the relationships between ROs and maintenance staff. At the HFIR, many maintenance activities are the responsibility of the ROs. This structure is a result of tradition and reflects a high feeling of organizational ownership. Maintenance staff assigned to work at HFIR can be rotated to other work assignments not connected with HFIR; they are not accountable to the Reactor Research Division, which is responsible for running the HFIR. Interviewees thought that retaining a maintenance role for the ANS ROs would be quite valuable. The primary motivation seemed to be opportunities for job enrichment for ROs and encouragement of a strong feeling of organizational ownership.

In addition, it was suggested that a maintenance team be established that would be dedicated solely to ANS. Such a team would not rotate to other assignments around ORNL but would work closely with reactor operations and other ANS staff. A dedicated staff would build a deeper knowledge and experience base about the ANS and would foster increased accountability and organizational ownership. Furthermore, the existence of such a team would encourage intergroup camaraderie rather than rivalry. The dedication of maintenance staff to support experimenters should also be explored. Experimenter needs are different from, but also important to, the reactor operation portion of the facility.

5. IMPLICATIONS FOR DESIGN

5.1 GENERAL

HFE is a critical element of systems engineering. It facilitates the consideration of human skills, abilities, and special job knowledge in the design of systems in which people are required to function. Without such considerations, the appropriateness of the design with respect to overall system objectives and functions is relatively likely to be poor.

As part of the system engineering team for the ANS advanced conceptual design, the HFE analysts engage in many different types of data collection. These include examining selected existing complementary reactor systems (e.g., HFIR and CANDU reactors); studying previous operating experiences (e.g., run reports, operating logs, maintenance histories); reviewing preliminary conceptual design documents; interviewing operations, maintenance, and engineering staff with experience in complementary reactor systems; and interviewing design engineers. The result of these efforts is a strong information base that can be used to make and justify recommendations for human-centered design. In particular, the HFE analysts will use this information base to support a number of HFE activities, including allocation of function decisions (between team members and between humans and automation); staffing decisions; job descriptions; the design of communication, monitoring and control interfaces; and the design of procedures, operator aids, and training. It should be emphasized that after the initial information base is formed, the HFE analyst will engage in a number of iterations with the sources of the information base while working on the HFE activities. Such iteration is necessary to ensure that design recommendations from the HFE analysts do not unduly compromise the design recommendations from other members of the design team.

One of the primary objectives of HFE is to resist premature implementation of system requirements that lock the design into a particular automation concept or operator role definition that is either antiquated (i.e., lags state-of-the-art technology) or incompatible with existing HFE guidelines and principles. One method of ensuring such resistance is to incorporate HFE expertise as early as possible into the design effort. In particular, such experts will ensure that system objectives and functions are stated in such a way that appropriate function allocation and role definitions are reflected implicitly. To the greatest extent possible, the HFE analyst will employ formal analysis methods to define appropriate objectives and functions. Furthermore, the HFE analyst will make the assumptions behind such system objectives explicit so that they can be examined objectively in light of the HFE knowledge base.

As the design matures through conceptual design to Title I and Title II, the HFE analyst will continue to revisit system objectives and functions in an iterative way with other members of the design team. This is necessary to ensure the evolution of a design that reflects the needs of the hardware, software, systems, and persons who will operate and use the facility.

5.2 SPECIFIC

- A simulator-based cryogenics training capability would be helpful. This is particularly true given the transfers of control possible (1) from the field to the MCR and (2) from the CO to other MCR personnel.

- There may be a need for in-depth on-the-job training for DOs. More thought needs to be given to this issue in the task analysis phase of human factors study and in the design of the HWUDF.

- More thermal hydraulics work needs to be done to define what the operator needs to do in the case of an overturned fuel element. Interaction between the various MCR personnel needs to be defined for this event.

- It might be difficult to accomplish the current refueling process in 3 days. Attention will be given to potential issues such as task overloading, team structuring, procedures, training, and operational aids.

- The interviewers indicated that information about the performance of refueling tools, especially in comparison with their historic performance, would be valuable information for refueling operators. The availability of trends related to refueling tool performance could provide an early indication of potential problems in the refueling process.

6. SUMMARY AND FUTURE DIRECTIONS

The role of the RO is being studied in support of the HFE activities that are integral to the design of ANS. A structured, open-ended questionnaire was developed and administered to personnel with significant reactor experience at HFIR and engineers involved with ANS systems design.

Preliminary results indicate that the ANS RO will be a high-level system manager with considerable monitoring, verification, and communication responsibilities. The relatively high level of control automation in the ANS design has resulted in a reshaping of the RO's traditional safety and investment-protection roles. In addition, the need for one or more complementary personnel seems to have been substantiated.

Near-term human factors efforts beyond this fiscal year will focus on automation concerns, the completion of task analysis activities, development of suggestion/justifications for levels of automation selection, and contribution to the ANS site staffing study. In the longer term, efforts described in the Human Factors Engineering Program Plan will be implemented.

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Appendix A

DESCRIPTION OF METHODOLOGY

BACKGROUND

A.1 NEED FOR DETERMINING REACTOR OPERATOR CONCEPT

The Advanced Neutron Source (ANS) is one of the first reactors to be fully designed and built since the accident at the Three Mile Island nuclear power plant. The ANS is unique in the extent to which human factors engineering (HFE) principles are being considered at the conceptual design phase. Furthermore, the ANS has as part of its design goals the increased use of automation in reactor start-up, normal operation, refueling, maintenance, etc. Because of a strong desire to reflect appropriate human factors principles in the design of the ANS and because of the increased emphasis on automation, it is imperative that the ANS design appropriately reflect the roles of humans and automation in order to facilitate high levels of operability, predictability, reliability and safety.

No commercial reactor in operation in the United States has been built using HFE principles. Many of the various types of designers who contributed to these designs had little training for formally considering the human element within their designs. As a result, their designs reflected oftentimes erroneous and even possibly dangerous assumptions about human performance, capabilities, and skills. Procedures and training were generally relied upon to "make up for" the inadequacies in the design. Poorly-designed procedures and ineffective training have often made the work of operations and maintenance personnel more difficult. This consequently has ensured a relatively high probability of human error when levels of workload, stress, and fatigue are simultaneously high. Given this information, however, one may ask why there have not been more serious accidents within the nuclear community. A suggested answer is that the human element in system operation is creative and adaptive and functions well in high-uncertainty situations. As a result, there likely are numerous instances where operations and maintenance personnel have "pulled the situation out of the fire."

In recent years, automation has provided support to operators in a number of areas including alarm filtering, alarm diagnosis, and recording process variables. In general, a movement away from analog-based systems to digitally-based systems has allowed for an increase in the amount of data and information available to reactor operators. Such an increase, if addressed appropriately, has the potential for enhancement of the overall safety associated with reactor operations. Herein is where the challenge of automation lies. That is, how can a balance best be reached between automating functions that are technically feasible to automate and retaining the human in the loop at a level that does not degrade human performance? Because humans bring capabilities and skills that are difficult or impossible to emulate (e.g., decision making in high-uncertainty situations, the ability to make inferences, attention allocation to important facts in high-noise environments), it is not always prudent to merely "automate the human out of the system."

If one were to choose the philosophy of automating all that it is possible to automate (within some resource constraint such as funding) without regard to the impact on the resulting control environment, a very unrewarding and highly error-prone situation would result. For these situations, humans would likely function as a back-up to automated systems in the event that the automated systems malfunctioned. They would be tasked with monitoring the automated systems, which rarely fail, and taking over if necessary. Such a scenario sets the stage for human failure. Potential difficulties that need to be addressed in design are as follows:

1. Humans are poor long-term passive monitors; early detection of an upcoming event is therefore not likely,
2. In a situation when a rare event does occur, operators tend to be skeptical about its existence and typically considerable time passes before their disbelief is dispelled.

3. The lack of "hands-on" operation minimizes opportunities for feedback, and operators generally require a certain amount of time to become "situationally aware,"

4. The "keyhole effect" (i.e., the ability to display only a small portion of data and information at any one time on a small number of workstations) and poor display navigation (i.e., strategies for getting to needed data and information) inhibit appropriate communication between the automated system and the human operator.

5. Team/crew performance is inhibited because of the tendency for operators to become totally immersed in their workstation displays during times of high stress (such immersion typically blocks out many extrinsic factors, including attempts by teammates to include the immersed operator in problem-solving activities).

What is needed is a "human-centered" automation perspective. Such a perspective is based on understanding the respective capabilities of humans and automation and achieving an appropriate balance between the two. Within the design process, it requires that the roles of humans in operations, maintenance, etc., be designed along with the hardware and software of the system. Such simultaneous consideration minimizes the potential for "default" roles (i.e., roles that are a result of the poor engineering of systems) and can lead to designs that demonstrate reduced human error and, in effect, enhanced safety margins in systems operation. This report is focused on the definition of the role of the ANS reactor operator (RO) and is an initial effort in the execution of the human HFE program plan (Schryver 1992).

A.2 BASIS FOR THE APPROACH TAKEN IN THIS STUDY

Studies of the roles of nuclear operators are not new. A number of them emerged shortly after Three-Mile Island (Kisner and Flanagan 1981; Corcoran et al. 1980), and others (Knee and Schryver 1989; Spelt 1993) emerged as studies associated with, or stimulated by, the advanced reactor concepts such as the Advanced Liquid Metal Reactor and the Modular High Temperature Gas-Cooled Reactor. These studies helped to put into perspective the need to pay attention to the role of humans as part of the overall design process, and they emphasized the need for a good match between the responsibilities of a job position and its associated control capabilities. Some studies (Cororan et al. 1980) provided succinct statements of an operator's role in, for example, nuclear plant safety. They indicated that there were three operator roles: (1) set up the plant to respond properly to adverse events, (2) operate the plant so as to minimize the frequency and severity of adverse events, and (3) assist in mitigating the consequences of adverse events. Others (Knee and Schryver 1989) examined permutations of different levels of responsibilities and control to provide a matrix of roie types. With respect to the design of the ANS, these studies emphasized that study of the role of the ANS operator was necessary and provided guidance with respect to the approach used in the current study.

Previous research related to the role of the RO (Spelt 1993) was used as a basis for conducting ANS-related research on the role of the RO. This 1993 study focused on determining the degree to which a consensus exists with respect to the role of the RO in various types of nuclear power generating stations in North America. The results of this determination provide a framework for ascertaining the similarities and differences among the RO definitions for the various existing and planned reactors.

The approach for the current study of the RO's role involved three primary elements. The first built on the previous research to develop a classification system for describing the role of the RO. Defining the classification system involved passive monitoring, cognition, physical manipulation/control, training requirements, and communication. The second element involved identifying specific job characteristics that define the RO's position. These characteristics included allocation of responsibility and control, determination of communication patterns and anticipated content, and coordination and interdependencies within operations teams. The third element involved an operator-centered control room model (see Fig. A-1) that accounted for all of the influences experienced by an RO in a control room environment. Taken in concert, these three elements provided a framework fo. he development of a structured interview.

A.3 DESCRIPTION OF THE APPROACH

Initial efforts were focused *only* on the RO position and involved *only* activities associated with normal operation. (Off-normal operation will be addressed in later studies.) Special consideration was also given to the RO's interactions with research support personnel. However, some information was gathered about the activities of other main control room operators, and data also emerged about what might happen in specific off-normal situations. In addition, the study addressed only five technical areas: (1) reactor operations, (2) refueling operations, (3) maintenance, (4) cryogenic operations, and (5) detritiation operations.

In preparation for developing the questionnaires for the interviews, the ANS human factors team reviewed existing ANS system design descriptions and other literature and met with selected ANS subject matter experts. The team engaged in several internal iterations that involved the development of preliminary lists of responsibilities, communication interfaces, and task activities. This information was subsequently distilled into the final questionnaires.

A.4 TOPICS COVERED IN THE INTERVIEWS

A questionnaire was developed for each of the five technical areas. Although the content and focus of the questionnaires were different, the emphasis of this study on the RO position allowed use of a similar format and structure. The questionnaire for neutron production consisted of 33 open-ended questions in the following areas: (1) general (e.g., responsibilities and automation issues), (2) safe and reliable operation (technical specification compliance), (3) communication (intershift and intrashift), (4) maintenance and miscellaneous support, (5) hazard control (e.g., Occupational Safety and Health Administration and contamination control), (6) special resource monitoring, and (7) certification requirements (training).

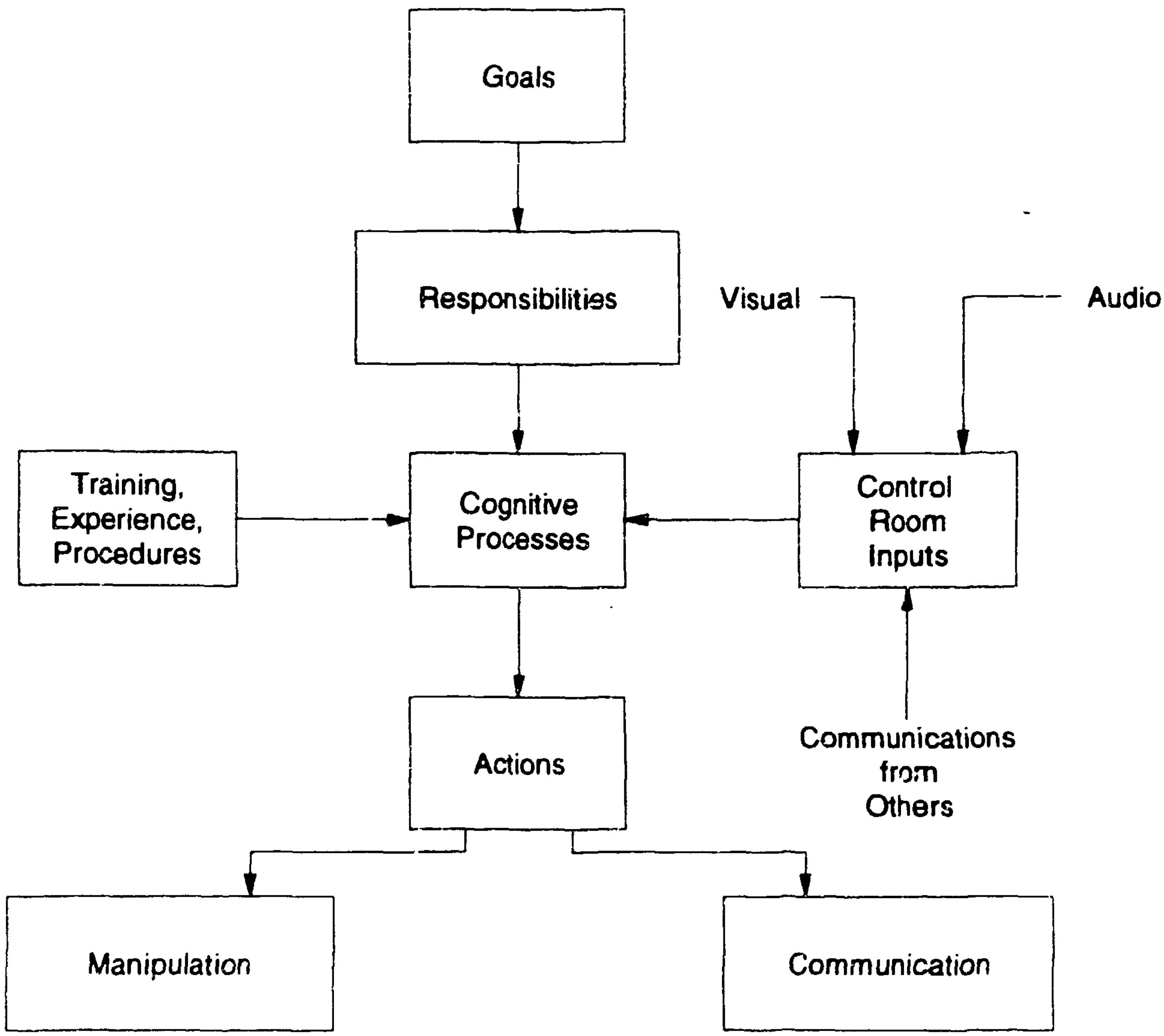

Fig. A-1. Operator-centered control room model.

A.5 THE INTERVIEWS AND SUBSEQUENT ANALYSES

Each of the interviews was conducted over a 2-hour time period, and the open-ended questions encouraged discussion. Responses and comments were recorded manually.

Following the interviews, the ANS human factors team compiled their notes and integrated them into a single document. The team then reviewed the integrated documents for accuracy, resolved inconsistencies, and formulated a consensus on the role of the RO for each of the technical areas.

A.6 DESCRIPTION OF THE GROUPS INTERVIEWED

The groups interviewed included representatives from the ANS design team, High Flux Isotope Reactor (HFIR) operations management, HFIR operations, and industrial and other government facilities. The interviewees from the ANS design team were engineers involved in the design of specific reactor systems. In particular, design engineers in the following areas were contacted: instrumentation and controls, detritiation, cryogenics, cooling systems, core components, refueling, irradiation facilities, and beam facilities.

Those interviewed from HFIR operations management were personnel with engineering, operations, and training backgrounds. Some had operations experience at other reactors. The interviewees primarily had experience with control room technologies from the 1960s and 1970s. Their recent experiences with the modernization efforts at HFIR provide insight regarding the advantages and disadvantages associated with newer instrumentation, control and interface technologies, and strategies.

The HFIR operators interviewed were a shift crew of HFIR's certified operations staff. Many had nuclear military backgrounds but gained their primary RO experience at HFIR.

One representative from industry, a plant concentrating in nuclear power and detritiation, was contacted. This facility was especially targeted for contact because it had dealt with advanced controls.

A.7 HUMAN FACTORS ISSUES IN AUTOMATION

Imperfection in the design of nuclear power plants, and limitations in the extent to which plant and human behavior can be analyzed effectively, ensure that there is a continuing role for the RO for the foreseeable future. As automation takes over the more prescriptive tasks, the role of the operator becomes that of a situation manager—an innovator to manage the unexpected (IAEA-TECDOC-668 1992). Automation of nuclear power plants will move human operators to a higher level of supervisory control. Prior research (Spelt 1993) shows that nuclear power plant control room design, especially those aspects associated with advanced reactor concepts, is exhibiting a clear trend away from the traditional hands-on operator to one whose role is to passively monitor automated and inherently safe processes and occasionally issue permissives at preestablished hold points. The introduction of computers into the control room radically alters the work environment and the cognitive demands placed on the operator. While these changes tend to reduce physical workload, especially in terms of continuous manual control, mental loading may increase as new emphasis is placed on monitoring process variables and automated functions and compensating for system failures.

It is well known that humans are poor monitors for low-frequency events. Long periods of boredom, with the associated decrease in vigilance and the lack of interaction with the control system, may slowly remove the operator as an active element of the system. Such a decrease in familiarity with the state of the system has been called "out-of-the-loop" familiarity. Human factors experts believe that operators may be slower to detect abnormal disturbances and may require a longer response time if they are not an integral part of the control loop. Poor out-of-the-loop familiarity generally results from attempting to automate everything technically and economically feasible, thus minimizing the RO's role. The problem with this approach is that it does not consider the viability of the operator's job description in light of human performance research. A human-centered (i.e., RO-centered) approach would be more appropriate so that the automation is an extension of the operator rather than a replacement for human activity.

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APPENDIX B

SAMPLE INTERVIEW QUESTIONS

INTERVIEW QUESTIONS

Attached are the interview questions that were used to gather information about the role of the reactor operator for neutron production during normal operation. The other interview questions substituted the different top-level operations functions for "neutron production" (i.e., maintenance, detritiation, cryogenics, and refueling), and the questions were amended accordingly. In the process, information was gathered concerning the other types of operators associated with MCR operations.

Role of the Reactor Operator for Neutron Production during Normal Operation

General

1. What do you see as the responsibilities of the Advanced Neutron Source (ANS)/High Flux Isotope Reactor (HFIR) reactor operator (RO) for neutron production during normal operation? Why? (Should lead to "responsibilities" list)

   A. How is automation likely to impact the role of the ANS RO?

   B. Elaborate on the human/system relationship (i.e., how much (and what type of) control should be allocated to automation and how much (and what type of) control should be allocated to the human operator).

   C. In what situations may an operator assume manual control?

Safe/Reliable Operation

2. How do you perceive the ANS/HFIR RO supporting safe and reliable neutron production?

   A. **Technical Specification Compliance**

      I. How do you perceive Technical Specification compliance being conducted/achieved in the ANS?

      II. From your knowledge of Technical Specification compliance, what can you suggest that might improve the efficiency of Technical Specification compliance/minimize error in compliance?

      III. How is Technical Specification compliance currently achieved? What problems do you perceive with the current Technical Specification compliance system? What suggestions do you have for improvement?

      IV. What is the impact of automation likely to be on the Technical Specification compliance process?

B. Monitoring

What are the key monitoring activities that the RO is likely to engage in to support safe and reliable neutron production? Why?

I. Functionality limits

II. Awareness of reactor system states

III. Schedule adherence

IV. Verification of control functions (automatic or manual)

V. Field monitoring

C. Procedures/Directions

Discuss how you see the RO achieving procedure compliance. Can procedures be more helpful?

Communication

3. What are the communication requirements of the RO?

A. Synchronous versus asynchronous

B. Discuss the types of information communication. To whom? How is this currently done/should this be done?

I. Within shift

II. Between shifts

C. Frequency of communication

Maintenance/Miscellaneous Support

4. What maintenance activities should be the responsibility of the RO? Why?

A. Briefly describe the RO's role in in-service inspection/testing?

B. How should the ROs support non-RO maintenance activities?

C. How should ROs support experimenter activities?

Hazard Control

5. What ANS-specific industrial hygiene/industrial safety/radiation protection activities do you envision that the RO must support?

Special Resource Monitoring

6. Are there any special resources (e.g., D_2O, tritium, fuel) that the RO must monitor? What are they? How are they monitored? How often are they monitored?

Achieving/Maintaining RO Certification

7. What is the RO expected to do to achieve and maintain certification?

Final Questions

ANS

8. How will the ANS be more advanced than any previous design (state-of-the art, leading technology)?

HFIR

9. From your RO experience, what suggestions do you have that might improve the RO's job?

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