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Considerations of Human Factors in the Design and Operation of Research Reactors

A.M. Shokr

Reactors Department, Nuclear Research Center, Atomic Energy Authority, Cairo, Egypt.

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ABSTRACT

The feedback from the severe accidents occurred at nuclear power plants showed that safety of nuclear installations does not depend only on technical matters but also on human performance. Human errors can initiate an event or can make, by intervention, the event consequences worse. Human factors are of a particular importance for research reactors since the status of these facilities change frequently and the operators have an easy access to the reactor core and to the associated experimental facilities. This paper discusses the experience with human factors and their impact on the safety of research reactors and application of technical and administrative provisions to address these factors in the design and operation phases of research reactors for continuous improvements in safety and performance of these facilities.

Key words: Research Reactors/ Human Factors/Nuclear Safety

INTRODUCTION

Consideration of human factors in all stages of research reactors lifetime are of a special importance as the status of the reactors change frequently and the operators have an easy access to the reactor core and to the experiments and experimental devices associated with the reactor. The Code of Conduct on the Safety of Research Reactors (1) recommends that the regulatory body should require the operating organization to take human factors into account throughout the lifetime of research reactors. The Code also recommends that the operating organizations should take into account the capabilities and limitations of human performance throughout the lifetime of the research reactor for all operational states and under accident conditions, also taking into account human factors relating to experiments.

Additionally, the IAEA safety standards for research reactors (2) require that:

- Human factors and human-machine interfaces shall be given systematic consideration at an early stage of the design and throughout the entire design process;
- Special consideration shall be given to human factors and the application of ergonomic principles in the design of the control room and reactor systems as appropriate;
- The design should be such as to minimize the demands on the operators so as to reduce the burden on the operators and reduce the scope for human errors.

The following sections discuss the experience with human factors and their impact on the safety of research reactors and application of technical and administrative measures to address these factors

Corresponding author E-mail: e-mail: amashokr@gmail.com

in the design and operation of research reactors for continuous improvements in safety and performance of these facilities.

HUMAN FACTORS AND SAFETY OF RESEARCH REACTORS

The operation of a research reactor is characterized by human actions and interventions on a daily basis, whether the reactor is at power operations or in shutdown conditions. In comparison with nuclear power plants, the operators of research reactors have direct interaction with the reactor core, and have more frequent core management and fuel handling activities as well as access to experiments and experimental devices. Therefore, it is essential to systematically consider human factors when analysing the safety of research reactors, along with:

- Fulfilment of the overall safety objectives and the reactor safety functions (reactivity control, removal of decay heat, and confinement of radioactive material);
- Application of the defence-in-depth concept and the fundamental safety principle of prevention of accidents**;**
- Adoption of design basis and application of design principles and criteria for protection against common cause failure, and ergonomics including human-machine interface;
- Performance of safety analysis;
- Establishment of organizational structure and consideration of other organizational factors, including management system, communication, and training programmes of operating personnel (i.e. supervisors, operators, maintenance, radiation protection, and technical support staff);
- Establishment and implementation of maintenance programmes, operating and emergency response procedures.

The feedback from the self-assessments, made by thirty-eight countries, of research reactor safety showed that consideration of human factors is one of the issues of a common concern and it is an area that needing improvements (3)**.** The awareness that safety of nuclear installations, including research reactors, does not depend only on technical matters but also on human performance and organizational factors have been increased during the past twenty years, in particular following the severe accidents occurred at the three-miles island (1997), Chernobyl (1986), and Fukushima-Daiichi (2011) nuclear power plants in which human and organizational factors had a significant contribution to the initiation and progression of the accidents (4, 5)**.**

In addition to inadequate consideration of the capabilities and limitation of human performance throughout different stages of the lifetime of nuclear reactors, the other reasons of the high contribution to human and organizational factors to incidents are inadequate relevant regulations, the need to improve safety culture, increased use of contractors, ageing and turnover of reactor personnel and rapid changes in technology (5)**.**

Additionally, human errors have been one of the important root causes of events reported to the Incident Reporting System for Research Reactors (IRSRR), representing about 40% of the total number of events (6)**.** Additional analysis has been performed to identify actions that need to be taken to prevent reoccurrence of these events, as provided in Table 1.

As shown in Table 1, the actions need to be taken cover different stages and activities of a research reactor lifetime. Adequate consideration of these factors results in a significant safety enhancement in operation and utilization of the reactor.

Table (1): Causes of events reported to the IRSRR and recommended actions to prevent their reoccurrence

Event cause	Recommended prevention actions
Inadequate design of systems and components	Adequate implementation of ergonomic principles and consideration of layout, ease of handling, and workspace in the design basis of systems and components; and enhancing the process of identification of latent design errors, including those in experimental devices
Unclear roles and responsibilities	Improvement of communication of expectations as to roles and responsibilities
Inadequate communication, including inadequate transfer of information during shift turnover	Enhance the management system and establishment of formal procedures for transfer of information during shift turnover
Bad housekeeping – inadequate labelling of equipment	Conduct of periodic walkthrough the facility and continuous improvements to housekeeping
Deficiencies in work scheduling	Improve management of human resources to minimize high workloads, and improve work schedule to avoid the implementation of operations with safety significance at end of operation shifts and operation schedule (e.g. during the afternoon of the last working day within the week)
Improper planning or preparation of work	Enhance questioning attitude and establishment of procedures for pre-job briefing and post job assessment
Deficiencies in procedures and their effective use	Periodical review of operating procedures and enhancing training programmes, including training on operations that are not frequently performed
Complacency and over-confidence in the verification process	Enhance safety culture
Inadequate supervision of operations with safety significance	Improve training of managers in provision of direction, monitoring, and assessment, and enhance quality checks in the verification process of completion of operations with safety significance

CONSIDERATIONS IN THE DESIGN

Human factors should be considered as early as possible in the design of the reactor and the associated experimental facilities. Research reactor designers reported methods for human factors analysis that provide feedback on whether a system can be operated safely as designed or it needs modifications in order to minimize the likelihood of operator-caused incidents [7]. At the design stage, the operating procedures are also designed, and proposals for operation actions and procedures can be analyzed to identify error precursors likely initiating an event.

The following practices have been identified effective for consideration of human factors in the design of the research reactor systems and components, including experimental facilities:

- Identification of latent design errors: Human reliability analysis, and use of fault trees in frame of the probabilistic safety assessment and databases for human reliability;

- Establishment of human factors' design basis: Systems and components' design basis should include ergonomics, simplicity, ease of operation, maintenance and handling, automation, and tolerance to operator's error;
- Use of advanced computational tools (three-dimensions modelling, simulation and visualization);
- Use of prototypes to evaluate the system operability and required operator's actions;
- Use of passive safety systems and components (e.g. use of flapper valves for coolant natural circulation, use of fail-safe design criteria, control rods drop by gravity, etc.);
- Reduction of systems and processes complexity through the use of design provisions to minimize operational constraints;
- Adoption of design provisions for proper work environment: Adequate work space for maintenance, and comfortable environmental conditions (radiation fields, temperature, humidity, light, etc.);
- Adoption of design provisions for comprehensive and easily manageable information that is compatible with the decision to be taken by the operators and time; and provisions for verification and validation of results;
- Verification of systems operability and adjustment of operating procedures and testing manuals during the commissioning.

It is also important to mention that application of the practices mentioned above will also make the research reactor operation more efficient.

Design of Instrumentation and Control System

The design of the Instrumentation and Control (I&C) system is of a particular importance with respect to the application of human factor engineering and human-machine interface (2). The system architecture should guarantee the provision of all necessary information and operator's control in the main control and emergency control rooms, and should take account for assignments of manual and automatic actions and priority of these actions. The system should provide for manual actions to shut down the reactor for safety concerns.

The design criteria of the reactor protection system should include automation, fail-safe, and protection against common cause failure, and if a manual action needs to be taken, all information supporting the operator to make a valid judgment should be displayed at the control room. In addition to that, adequate time needs to be provided by the system to allow the operator to take the necessary safety actions. The design of the I&C system should also consider the protection against operator's error by implementing range limits, interlocks and trips. The human-machine interface should be designed based on the ergonomic principles and should provide the operator with suitable warnings and alarms when the reactor facility is approaching a state of interlock or disabling of operator's actions. Audible and visual alarms should also be timely provided. These alarms should also alert the operator in case of failure or malfunctioning of the reactor control system.

The design of the control room should take into account the human factors engineering such as minimization of physical and mental efforts of the operator, adequate working environment conditions in terms of radiation fields, lighting, noise, temperature, humidity and vibration. This also includes conditions resulting from accident conditions such as fire, smoke, toxic material, earthquakes, and flooding. The layout of the information to be presented in the control room should also be considered to not overwhelm the operator. It is also a good practice to dedicate a control panel to the operation of the experimental facilities. In case that the control panels of the experimental facilities is not integrated with the reactor control room, adequate communication tools should be provided between the control rooms.

CONSIDEARTIONS IN THE SAFETY ANALYSIS

Even with all preventive measures in place, human actions or errors can still cause an initiating event. Human errors are identified as one of the categories of postulated initiating events (PIEs) that should be considered in the safety analysis of research reactors [(2)]. Human reliability analysis can be considered as a part of probabilistic safety assessment and the analysis of the potential for and consequences of PIEs caused by human are performed in parallel with the identification of PIEs and the description of the accident sequence. Special attention needs to be paid to human factors in facilities in which core configuration changes are regularly made (e.g. critical assemblies). Examples of PIEs in which human errors need to be considered in the safety analysis (either because human error can initiate the event or human intervention can make the event worse) are provided in Table 2.

Table (2): Examples of PIEs that are initiated or made worse by human errors.

PIEs	Remarks/Comments
Loss of electrical power supply	Operator intervention can make the event sequence or consequences worse
Criticality during fuel handling	Human error can initiate the event – error in fuel insertion or mishandling of reactivity controlling elements (e.g. reflectors)
Insertion of cold water in the core	Human error can initiate the event
Influence by experiments and experimental device	Human error can initiate the event by insertion of fissile materials or removal of absorbing material
Maintenance errors with reactivity control devices	Human error can initiate the event
Reduction in coolant flow due to bypassing of the core	Human error can initiate the event – unplugging a core position, maintenance error in natural circulation valves, etc.
Mishandling of an experimental device resulting in core bypassing	Human error can initiate the event – misplacement of an experimental device
Loss of coolant (LOCA)	Human intervention can make the event sequence and consequences worse – erroneous in primary pump operation or in isolation of broken cooling pipe
Damage of a beam tube resulting in LOCA	Human error can initiate the event – erroneous in handling heavy loads resulting in mechanical damage to the beam tube
Mechanical damage to core components or fuel	Human error can initiate the event – mishandling of fuel, dropping or a heavy load onto core or fuel
Loss or reduction of radiation shielding	Human error can initiate the event – mishandling of shielding, erroneous opening of doors used as barriers for radiation protection (e.g. primary pump room doors)
Internal fire or explosion	Human error can initiate the event or intervention makes it worse

Table 2 shows that management and handling of irradiation facilities and experimental devices should be evaluated for potential causes of PIEs, taking into account the design of operation tools, ergonomics, use of an overhead crane or other lifting equipment, size and mass of objects being moved or handled over the reactor pool.

In performing analysis of the event sequence and consequences, the analysis related to human errors should include identification of the specific causes of human errors, and evaluation of the effect of human error either in initiating an accident or worsening the development of accident sequences. In addition, operators' action, including manual shutdown of the reactor, should not be credited in the safety analysis for specified period of time following a PIE.

The design is an iterative process with the safety analysis. Table 2 also implies that the assessment of human factors may lead to design modifications. For example, the pool-top operations in a research reactor may result in an impact on important structures inside the pool (e.g. neutron beam tubes), which may lead to a significant PIE if damaged (e.g. LOCA), and may need a protective structure to be included in the design. The results of the analysis may also lead to imposing of operational limits and conditions (OLCs), such as mandatory levels of supervision for specified tasks, restrictions on the general use of the overhead crane, restriction on the maneuvering path of heavy objects hoisted over the reactor pools.

CONSIDERATIONS IN THE OPERATION PHASE

Integrated Management System

Implementation of an effective integrated management system will result in an enhanced safety by ensuring that health, environment, safety, security, quality and economic requirements of a research reactor organization are applied in an integrated manner. Safety is a paramount within the management system, overriding all other demands. Implementation of an integrated management system will promote and support development of a strong safety culture by ensuring common understanding of the safety, supporting individuals to carry out their tasks safely and successfully, and reinforcing learning and questioning attitude at all levels of the organization.

Although establishment and maintaining a strong safety culture, including analysis of human behavior, is an area that needs further research, demonstration, by the management of a research reactor, of commitment to safety is essential for addressing organizational and human factors. These include development of institutional values and individual behavior expectations, empowering individuals and managers to feel responsible of the work they are performing or supervising, and communication of organization policy, behavior expectation, and commitment to safety within the reactor organization [(8)].

Effective communication among all levels within the facility needs to be in place to assist in understanding safety, and to reinforce team work. This includes establishment of formal and informal communications including between shifts in normal operating conditions and in emergencies.

Organizational Structure and Training Programs:

Factors that should be considered in determining the organizational structure and staffing of a research reactor include organizational factors that could affect human performance, so that work can be carried out safely and satisfactorily without imposing unnecessary physical and psychological stress on operating personnel. Human factors are the basis for specifying the minimum staffing requirements for various disciplines required for safe operation in all operational states of the reactor, including during operation shift, refueling operations, and shutdown conditions.

Physical and mental health of the reactor operators should ensure their capability to operate the reactor in normal conditions and during an accident. Psychometric and psychological tests may be used in the selection of the operating personnel. The need to ensure positive attitude towards safety should be one of the criteria for recruiting personnel, appraising performance and promoting personnel [(9)].

Safe operation of a research reactor requires an operating organization with a structure that is clearly specified, and staffed with qualified operating personnel who have a deep knowledge of the technical and administrative requirements for safety. The training program should include topics on duties and responsibilities of the operating personnel and their lines of communications, topics on safety culture and implication of human errors on the reactor safety. The program should also include the importance of operating within OLCs and following approved written procedures. Retraining is essential to ensuring that the knowledge, skills, and attitude of operating personnel are maintained. The retraining program should include selected topics from the initial training, modifications into recued to facility and procedures, and operations that are infrequently, or difficult to be, performed(10).

Maintenance

The feedback from the analysis of operating experience pointed out the need of improving the operability verification after maintenance (11). In particular, the analysis showed the need to have the planning of the operability verification better integrated in the maintenance programme and to have the operability verification tailored to the type and extent of interventions carried out.

Operating and Emergency Response Procedures

Operating procedures are considered an important part of the human-machine interaction system, and they greatly influence the operator performance and reliability. Moreover, operating procedures are an essential part of the management system, and therefore they have both human and organizational facets. Consequently, the procedures should be technically correct, clearly understandable without additional guidance, and easily executable without introducing an additional workload. In addition, the OLCs are implemented through operating procedures.

In relation to consideration of human factors, the following practices have been identified for improvements of establishment and effective implementation of operating procedures:

- Involvement of operating personnel in the development process;
- Clarity of procedures to avoid any confusion and ambiguities;
- Use of checklists with clear acceptance criteria (specifically for maintenance, periodic testing and inspection procedures);
- Compatibility of the procedures with the environment in which they will be used;
- Consideration to the layout and design of the facility and staffing requirements;
- Adaption of a trial period of use before formal approval (in some cases use of prototypes to evaluate operability and to define operation actions);
- Training on the use of procedures (new ones or procedures that used infrequently);
- Adequate review and approval process;
- Periodic review and updating to incorporate the experience acquired in-house or from other facilities.

The above mentioned practices also apply to the emergency response procedures. However, consideration of human factors in development of emergency response procedures is a difficult task and an area needing further research and development. The evaluation of the stress factors is not a simple task, and although the timeframe for actions during an emergency is mostly facility-specific, it is also specific to the accident scenario, which cannot be always expected in particular for the case of extreme external events such as the case of the Fukushima-Daiichi accident. Emergency drills and exercises are therefore essential as well as training of the reactor operators to deal with unexpected situations.

CONCLUSIONS

Due to the nature and purpose of research reactors, operators have a direct access to reactor core and associated experimental facilities, and handling of these items is frequent. The feedback from the accidents at nuclear installations showed that safety of these facilities does not depend only on technical matters but also on human and organizational performance. For these reasons and for recognizing the limitation for human performance, human factors should be considered in a proactive manner in all the stages of a research reactor lifetime.

The paper identified and presented along with discussions, the practices recommended for application in the research reactor design and operation phases to take into account the capabilities and limitations of human performance for continued improvements in the safety and utilization of these facilities. These cover the design of the reactor systems' and associated experimental facilities, safety analysis, integrated management system, organizational structure, training programs, maintenance, and operating and emergency response procedures. Areas that need further research and development were also identified. These include analysis of human reliability for the use in the safety assessment; organizational factors such as effective implementation of integrated management system. They also include establishment of a strong safety culture, and individual and organizational behavior; development of emergency response procedures; and training or reactor operating personnel on unexpected emergency situations.

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