Preliminary Insights regarding Human Reliability Analysis of New Research Reactors from the PSA Study Performed in the Framework of IAEA-led Competence Building Project

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One of the outcomes of the extra budgetary project led by the International Atomic Energy Agency (IAEA) and aimed at building competence for Probabilistic Safety Assessment (PSA) in Jordan is a detailed Human Reliability Analysis (HRA) for the Jordan Research and Training Reactor (JRTR). The competence building project named 'COMPASS-J' is a 'learning-by-doing project', which resulted not only in building advanced competence of the Jordanian team of specialists for PSA, but also in a real independent PSA study that provided interesting results and insights. This paper discusses the importance of outcomes and experience acquired on the human factor engineering from the COMPASS-J project to the Jordanian participants. The three types of human actions were considered; Types A and B in the operation mode, and concentrating on Type C human actions to study the possible human actions after the following initiating events: Loss of electrical power, Reactivity insertion accident, Loss of flow accident, Loss of coolant accident, Fuel channel blockage, and General transient.

I. INTRODUCTION

The safety of nuclear facilities does not depend only on technical matters but also on human actions. Human errors are the important factor that can either initiate an event or worsen the consequences of the event caused by non-human failures. The accumulated experience acquired with the operation of nuclear facilities in the past years shows that the operator actions factor cannot be ignored in the safety assessment of nuclear reactors.

The power of most research reactors is much smaller than that of standard nuclear power plants. Research reactors are usually designed in accordance with client specifications and have various purposes, e.g. radioisotopes production, materials analysis, education, etc. Generally, conducting a PSA study for a research reactor is easier than conducting it for a NPP because of the simplicity of the analyses for a research reactors compared to the NPPs (Ref. 1).

As mentioned in the IAEA NS-R-4 Safety Requirements (Ref. 2), a comprehensive safety assessment and an independent verification shall be carried out to confirm that the design of the installation will fulfil the safety objectives and requirements, before the operating organization completes its submission to the regulatory body. For the PSA, it is very important to analyze the human actions related with nuclear plant operation, maintenance, inspections, testing, and actions during any accident and to calculate the probability of the associated human errors. As mentioned in the IAEA TECDOC-592 (Ref. 3) based on the experience derived from PSA studies, human errors have significant contribution to the potential for severe accidents in nuclear power plants. HRA is considered as one of the most difficult tasks in PSA because it deals with a wide spectrum of human behaviours and different factors contributing to potential errors. The human actions for PSA are categorized as Type A, Type B, and Type C. Type A is the pre-initiator, Type B is the human actions that may cause an initiating event, and Type C is the post-initiator human actions. The human actions for PSA are categorized as in the IAEA safety series (Ref. 4) for three types; Type A, Type B, and Type C.

II. COMPASS-J PROJECT AND EXPERIENCE ACQUIRED ON THE HUMAN FACTOR ENGINEERING.

In May 2014, the IAEA initiated an extra budgetary competence building project COMPASS-J, which is aimed to support the development of technical capabilities in Jordan in the area of PSA needed for the future NPP projects by developing a PSA model for JRTR, which will is being commissioned currently and will reach full power operation in the near future. COMPASS-J represents a learning-by-doing activity comprising periodic meetings of the Jordanian PSA team with IAEA experts to receive feedback for the intermediate models and analyses, as well as further guidance for PSA development, and homework in between the meetings.

The IAEA Safety Guide SSG-3 (Ref. 5) on Level-1 PSA was used as the main technical guidance for performing the analysis. The PSA work during the project was divided into several tasks; i.e. initiating event analysis, accident sequence analysis, system analysis, data analysis, human reliability analysis and other tasks as shown in Figure 1. Each task was assigned to a group of participants led by a task leader who is supposed to report the work done to IAEA experts. This paper concentrates on those parts related to the human reliability study.

During the project, the participants learned about the importance of the human factor engineering in nuclear facilities by analyzing the human actions and potential errors through doing an independent HRA of JTRT under the supervision of IAEA experts in field. The COMPASS-J project has included several training courses, workshops, and review meetings. The results of the HRA study has brought the attention to some important actions that may lead to some systems unavailability or sometimes initiating event and in developing the participants' capabilities and qualifications in PSA, human factor, and reliability analysis, which can be further used for a successful nuclear power program, to support safe operation of JRTR, or in any other future nuclear projects in Jordan.

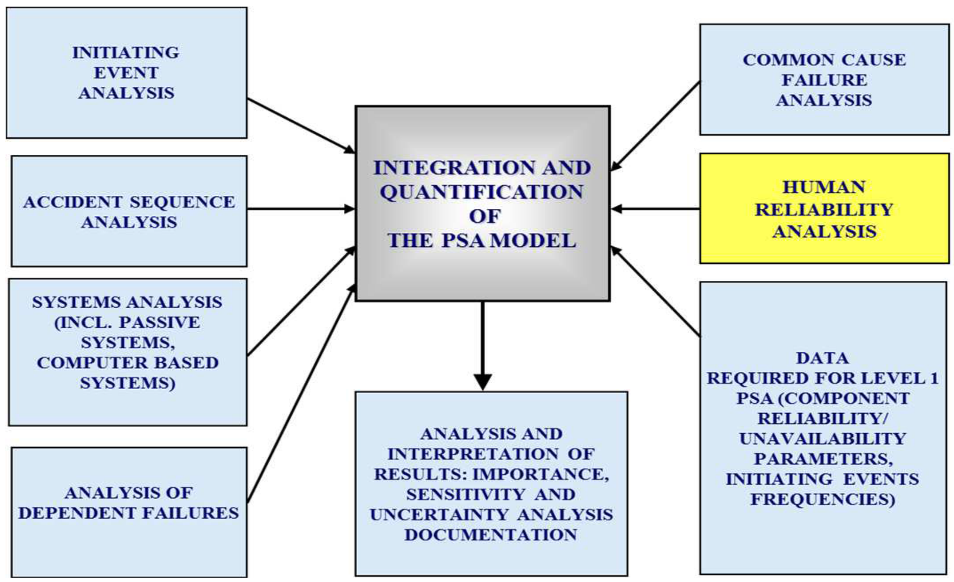

Fig. 1. Composition of PSA tasks [Ref. 6].

III.Study of the HRA of a new research reactor

III. A JRTR and Korean design Main Control Room (MCR)

The JRTR is a good example of a new Korean designed research reactors. JRTR is a 5 MWth multipurpose research reactor. It is an open pool type research reactor using low enriched uranium fuel. More information about JRTR are mentioned in Table 1.

The control room is shown in Figure 2 is composed of Reactor Protection System (RPS), Reactor Regulating System (RRS), Process I&C System (PICS), Post-Accident Monitoring System (PAMS), Information Processing System (IPS), Seismic Monitoring System (SMS), Radiation Monitoring System (RMS), and other auxiliary systems.

In addition, there is a Supplementary Control Room (SCR) used to actuate a safety action when the MCR is not available for the operator.

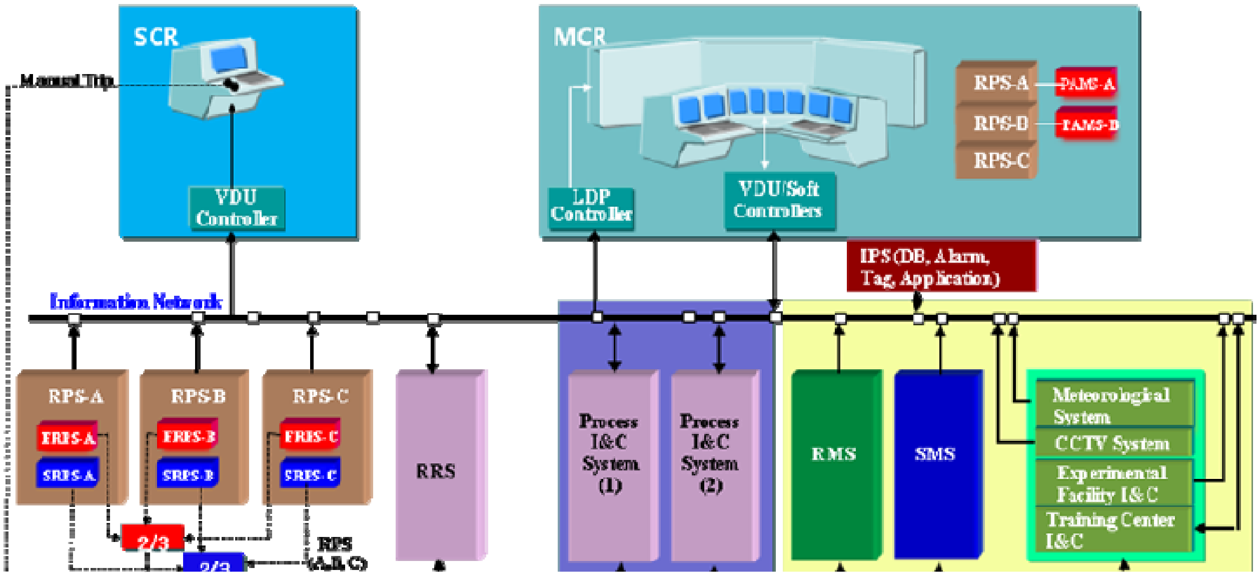

Fig. 2. Korean design research reactor MCR layout [Ref. 7].

TABLE I. JRTR specifications

Reactor type	Open tank pool
Thermal power	5 MW
Coolant and cooling method	Light water Downward forced convection flow
Moderator	Light water
Reflectors	Beryllium, heavy water
Absorber materials	Hafnium, B_4C
Shielding	Water, heavy concrete

III.B JRTR Human Reliability Analysis

An HRA was done for the JRTR that contained a detailed analysis for all probable human actions of Types A, B and C. Table II shows the specification of the human actions classifications. The scope of human actions analyzed includes the surveillance requirements, experimental facilities, startup and end of operation checklists, normal and abnormal operation procedure, and emergency operating procedures. A quantification process was used to calculate the Types A and B human errors probabilities based on the Technique for Human Error-Rate Prediction (THERP) based on the reference of NUREG/CR-1278 (Ref. 8).

TABLE II. Human actions classification

Type A	Actions associated with testing, maintenance, repair and calibration that, if not carried out correctly, could lead to equipment unavailability
Type B	Actions that either by themselves or in combination with equipment failures lead directly to initiating events/faults
Type C	Actions occurring post-fault these can either occur in the performance of safety actions or can be actions that aggravate the fault sequence

III.B.1. Type A human errors

For Type A human errors, the probabilities of the associated errors to lead to the unavailability of any system or component during operation were calculated. Screening criteria were used for Type A actions; they were not quantified if a at least one of the following three point is valid:

- By design automatic re-alignment of equipment occurs on demand,
- Full functional test is performed after maintenance/assembly, and
- Equipment status is indicated in the control room.

Many Type A human errors were found and their probabilities were screened out or quantified. Four examples are shown in Table III. The first two may cause an unavailability of the RPS so their probabilities were calculated. The other two may cause unavailability of the SSR position indication and late detection of loss of coolant accident (LOCA), but these failures will have an indication in the control room, so they were screened out.

TABLE III. Type A failures examples

Tasks	Condition	Surveillance	Human failure event	Consequence/possible IE	Probability
Instrumentation and control systems	Reactor protection system	Reactor protection system function and response time	Fail to detect a delay in the response time test ot the completion time is more than the required	RPS could be not capable to shut down the reactor within the required time	1.6e-1
Instrumentation and control systems	Reactor protection system	Reactor protection system field instruments calibration	Wrong calibration	RPS could be not capable to shut down the reactor at the set point parameter value but the Alternate Protection System (APS) will do the function of trip	5.2e-3
Reactivity control mechanism	Position indications: secondary shutdown rods (SSR) position during operation	Check the status of position indication for the down switches of SSR	Fail to detect the status of down switch in the operation work station (OWS)	Wrong position indication of the SSRs in OWS	Screened out because this failure has an indication in the control room
Reactor cooling and connected systems	Reactor pool water Level	Check the reactor pool water level	Fail to find that the pool level is lower than determined level	Late detection of LOCA accidents	Screened out because this failure has an indication in the control room

III.B.2. Type B human errors

For Type B human errors that could lead to an initiating event, the probabilities were calculated for all of the identified errors. For some of the Type B human errors, the recovery mechanism was assumed, because there is a possibility of recovery, for example, by performing double checks by a second person, receipt of new indications, post-maintenance tests, and arrival of new personnel. Some examples of the Type B errors which may cause the events of excess reactivity insertion, loss of secondary cooling, and loss of flow are shown in Table IV.

TABLE IV. Type B failures examples

Tasks	Condition	Surveillance	Human failure event	Consequence/possible IE	Probability

Reactivity limit	Reactivity of irradiation rig	Evaluate the reactivity of a fixed irradiation rig within the limit in planning the irradiation of the rig	Wrong evaluation of the reactivity	Insertion of excess reactivity	1.7e-4
Instrumentation and control systems	Reactor regulating system	Perform RRS software and hardware test	Fail to find inoperability of the RRS system	Insertion of excess reactivity	2.6e-4
Startup procedure	Secondary cooling system (SCS) operation	operate the pump for cooling tower spray	Fail to operate the pump for cooling tower spray	Loss of secondary cooling	4.3e-5
Startup procedure	Primary cooling system (PCS) operation	Operate PCS pumps	Fail to operate PCS pumps	Loss of flow	4.3e-5

III.B.3. Type C human errors

The human actions Type C following the accidents were analyzed to estimate the probabilities of the human failures. The analysis process was done based on one of the newest HRA techniques; the Standardized Plant Analysis Risk (SPAR) HRA (SPAR-H) method based on the reference of NUREG/CR-6883 (Ref. 9) and its framework for Performance Shaping Factor (PSF) was used. After that, the probabilities of Type C human actions were calculated for the postulated control room scenario (operator actions) after the events of Loss of Electric Power (LOEP), Reactivity Inserted Accident (RIA), Partial loss of Flow Accident (P-LOFA), loss of Flow Accident (P-LOFA), Loss of Secondary Cooling flow (LOSC), Loss of Coolant Accident (Small LOCA), Core Bypass Accident (Core Bypass), Large Loss of Coolant Accident (Large LOCA), General Transient (GTRN).

For all events, all human failures were analysed including the failure of diagnosis and action, and the dependencies were also considered in the quantification of probabilities. One example of Type C human failure after the GTRN is when the automatic trip function of RPS is failed and the operator fails to manually actuate the RPS trip signal (control rods insertion). The other needed human action is after GTRN when the automatic trip of RPS and APS are failed and also the operator failed to actuate manually the RPS and APS trip signal. The analyses for the diagnosis and the action parts are shown in Table V and VI respectively. Figure 3 shows the dependency of the manual APS trip action which has a dependency on the manual RPS trip action (it is needed if the RPS manual trip fails). The dependency of APS and RPS manual trip actions is moderate (same crew, time is not close, different location, and with no additional cues).

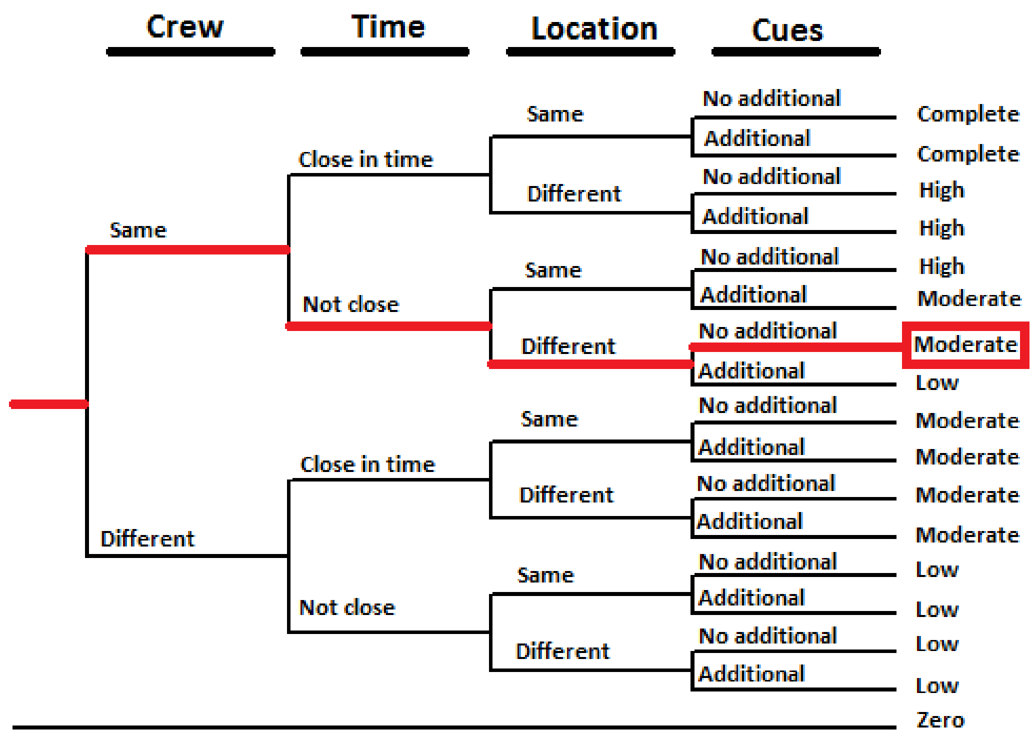

Fig. 3. Dependency analysis of the APS manual trip actuation.

TABLE V. Manual actuation failure after GTRN analysis (diagnosis)

PSFs	Diagnosis PSF levels and selected diagnosis multiplier	Diagnosis evaluation notes
Time available	Insufficient information; Multiplier =1	The time available is assumed to be nominal.
Stress	Nominal; Multiplier =1	Not extreme because we also have APS manual actuation, and not nominal because it's not normal to lose the function of automatic trip.
Complexity	Obvious diagnosis; Multiplier = 0.1	This case complexity is obvious surely because in the case of the RIA and automatic trip failure, the expected solution is to manually trip the reactor.
Experience / Training	Nominal; Multiplier = 1	The operators training is available, and the operator will normally try to shut down the reactor if he notices abnormal situation.
Procedures	Nominal; Multiplier =1	The manual trip procedure is available in the abnormal operating procedure.
Ergonomics / HMI	Good; Multiplier = 0.5	Everything is monitored in the MCR by the large display panel (LDP) and OWS. The safety system PAMS is a safety classified monitoring system additional to the non-safety classified systems which they all are supplied by uninterruptable power supply electricity.
Fitness for duty	Nominal; Multiplier = 1	The Operator is fit to do the RPS trip manual actuation action.
Work processes	Good; Multiplier = 0.8	This action is not significantly affected by work processes.

TABLE VI. Manual actuation failure after GTRN analysis (Action)

PSFs	Action PSF Levels and selected action Multiplier	Action Evaluation Notes
Time available	Nominal time; Multiplier =1	The time available is assumed to be nominal.
Stress	Nominal; Multiplier =1	Not extreme because we also have APS manual actuation, and not nominal because it's not normal to lose the function of safety class system.
Complexity	Nominal; Multiplier =1	The RPS trip manual actuation action is nominal.
Experience / Training	Nominal; Multiplier = 1	The RPS trip manual actuation action is nominal.
Procedures	Nominal; Multiplier =1	The RPS trip manual actuation action is nominal.
Ergonomics / HMI	Good; Multiplier = 0.5	The operator must push two out of three buttons at the RPS cabinets. Not good and not poor because it is a simple action.
Fitness for Duty	Nominal; Multiplier = 1	The operator is fit to do the RPS trip manual actuation action.
Work Processes	Nominal; Multiplier = 1	This action is affected by work processes. There must be a report to the regulatory body in the case of any trip occurred.

III.B.4. Results analysis and discussion

There are many interlocks in the design of the JRTR helping to reduce the severity of human failure actions, some of them are enough to reduce the consequences of the human error from Type B to Type A. Even though Type A human errors do not cause an initiating event, it is important to study them because some errors could lead to unavailability of some important systems during the accident and could escalate the accident to a more severe one.

The resulted Type B human failures from the JRTR human actions analysis are few and the main sequence is the insertion of excess reactivity accident, some human failures may cause loss of secondary coolant accident, loss of flow accident, or a general transient accident. These are few as the design considers the experience learned in the accidents that occurred in reactors around the world due to human failures, and the human factor has been considered in the JRTR design.

Type C human failures probabilities were analyzed, including human diagnoses and actions. In the JRTR, the diagnoses part was the dominant in the final probability because the human actions are simple and the operator is familiar how to manually perform these actions, but he needs more time and work on diagnosing after the accidents.

The human actions following the initiating events include the recovery action of the operator to trip the reactor by RPS or APS push buttons, the recovery action of the operator to manually open siphon break valves using the RPS, and the manual actuation of the EWSS injection valves. It was found that failure to satisfy these recovery actions are an important contributors to core damage frequency so the factors affecting this human actions such as stress,…etc should be paid some higher attention.

IV. CONCLUSIONS

The PSA study for JRTR is the first domestic PSA study for a nuclear facility in Jordan. An extensive human reliability analysis was performed as part of it. The study was completed in the framework of an IAEA-led competence building project to train the Jordanian specialists for advanced safety assessment in the view of the preparation for a nuclear power plant project.

The human actions failures study is very important for the nuclear facilities, including three types of errors; Type A, Type B, and Type C. Type A is important because some failures may cause unavailability of some important systems that should be available during some accidents, Type B human actions are important because they may lead to initiating events which will lead to trip the reactor and the Type C which is the post-accident actions, their failures may lead to core damage, or the accidents consequence become worse. In JRTR, most of systems unavailabilities are indicated in the control room, so most of Type A human errors were screened out from the quantification process. It is obvious that the human failures have larger failure probabilities when they have dependency with any other human failure.

In new research reactors' designs automation of human actions is becoming more evident so the dependency on the human is being reduced.

The potential human error to cause RIA (Type B) deserves further analysis. More studies and investigations could be beneficial for the human factor in the fuel blockage accident. Some modifications could be applied into the available procedures in order to enhance human actions success probabilities.

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