THE CHALLENGES OF HUMAN FACTORS ENGINEERING IN SMR LICENSING

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INTRODUCTION

Small Modular Reactors, commonly referred to by their initials, SMR, are nuclear reactors with a power output of up to 300 MW(e) each module.

In recent years many organisations and companies have been working on this type of advanced reactor designs, since they have proven to be a particularly interesting option for several applications in the near future, due to their versatility, flexibility, minimum environmental impact, limited costs and reduced construction times.

Inevitably, one of these applications is the contribution to power generation. Being, in this case, especially suitable because of their capacity for cogeneration, hydrogen production, district heating or support to remote areas with limited access to the main power grid.

In addition to the main nuclear engineering companies, start-up companies and laboratories across the world have started to propose conceptual designs going beyond the conventional pressurised water or boiling water reactors. They use different types of coolant (helium, liquid sodium, etc.) and also new and safer fuels that would allow a country to create a closed nuclear fuel cycle, reusing the waste fuel from older reactors.

Through its Department of Energy, the United States is setting aside important investments for the development of these designs, and many US companies are currently bidding to licence their models in a race to gain a leading position in what is a highly promising market.

Emerging as a part of the licensing of these new reactors is the discipline of Human Factors Engineering (HFE). This process will determine the interaction between the operating personnel and the reactor control systems. Human Factors Engineering allows the design of all operation interfaces taking into account the elements that contribute to human error, the aim being to minimise the risk of such error in any interaction between human and the plant systems.

In the case of conventional reactors, human factors engineering is based on certain initial assumptions and requirements regarding the size of the main operation staff crew of each reactor, their qualifications and duration of training programs. In the case of small modular reactors, and due mainly to their reduced dimensions, the extensive automation of processes, their passive safety systems and the modularity of their design, these assumptions will need to be reconsidered, proposing new minima that will require in-depth evaluation.

THE CHALLENGES

The US regulation 10 CFR 50.54 establishes that in an operating control room there must be at least four operators. Other countries with conventional reactors in operation have adopted identical or similar requirements, depending on design type. Referring specifically to the US regulation, a minimum number of operators is required in different combinations up to a maximum of three reactors in operation; if these reactors are operated from a minimum number of two control rooms, there should be at least eight operators. Table 1 shows the different possibilities.

Number of nuclear power units operating[2]	Position	One Unit	Two units		Three units	
		One control room	One control room	Two control rooms	Two control rooms	Three control rooms
None	Senior Operator	1	1	1	1	1
	Operator	1	2	2	3	3
One	Senior Operator	2	2	2	2	2
	Operator	2	3	3	4	4
Two	Senior Operator		2	3	[3]3	3
	Operator		3	4	[3]5	5
Three	Senior Operator				3	4
	Operator				5	6

[1] Temporary deviations from the numbers required by this table shall be in accordance with criteria established in the unit's technical specifications.

[2] For the purpose of this table, a nuclear power unit is considered to be operating when it is in a mode other than cold shutdown or refueling as defined by the unit's technical specifications.

[3] The number of required licensed personnel when the operating nuclear power units are controlled from a common control room are two senior operators and four operators.

Table 1. 10 CFR 50.54 (m)(2)(i) Minimum staff requirement.

This conventional regulation is overcome in two ways in the design of control rooms for small modular reactors:

1. More than three small modular reactors may be installed on one same site with the aim of their being operated from a single control room. Certain designs contemplate the operation of up to 12 modules from a single control room.
2. Given the high level of automation of the plant and the presence of passive safety systems, the total number of actions to be performed by the operator will be reduced, as a result of which the aim is for the team to be of the minimum size necessary to carry out these actions efficiently. Likewise, the operators will take less time to be prepared, trained and qualified, this also reducing the training programmes compared to those required for conventional reactors. Certain designs contemplate teams of 4 to 6 operators operating more than 10 modules.

These two premises are taken into account from the start in designing the control room, from the point of view of human factors engineering, in compliance with the activities and processes set out in the international licencing standards.

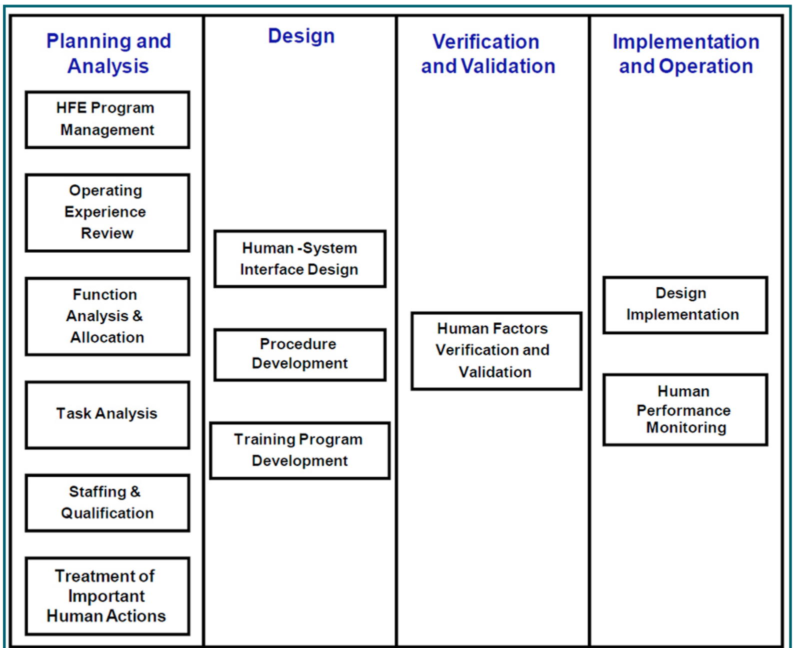

Figure 1. Elements of the HFE program's review model from NUREG-0711.

INTERNATIONAL STANDARDS AND THE PROCESS

Most modular reactors are in an early stage of design, the aim being to obtain a licence in the country in which their construction is most favourable. HFE must be carried out during the design of the systems and their control stations. This is generally accomplished based on processes established by human factors engineering standards, mainly NUREG-0711 (Figure 1) and IEC 60964 and IEC 61839.

However, as a result of the two challenges described in the previous section, these processes are addressed in a way that differs from the habitual approach, focusing on the objective of demonstrating that the reactors can be operated safely by a small number of operators from a single control room.

ANALYSIS
Operating experience as a starting point

As is the case for most activities in the nuclear sector, the first tasks consist of reviewing and analysing all the relevant operating experience available. In this respect, as the technology is new, the analysis might be thought to be limited. However, information on operating experiences with reactors of a similar power level or higher power level but with similar technology may be found in international databases.

The conclusions drawn from the analysis of operating experience will serve as input information for the rest of the processes, with specific actions taken where necessary. Furthermore, such analysis serves as a starting point for the permanent monitoring of new operating experience.

From plant goals to each system functions and the automation degree

The first question we ask ourselves is what the fundamental objectives of our plant are. The answer to this question is generally divided into two parts:

- To generate power efficiently and to transfer it to the grid, and
- To protect the public and the environment against potential radioactive emissions.

The different applications of modular reactors may add new functions, such as hydrogen production or district heating.

The next step consists of breaking the plant goals down into more specific elements, the main functions of the plant, which in turn will be broken down into the functions of each of the plant systems. We will determine what requirements need to be controlled or displayed in the operation interface in order to fulfil these functions. Furthermore, at this point the alignments adopted by each system to fulfil this function, known as "operating modes", are detailed. A comparison of these operating modes serves to describe changes to the equipment, for example a valve switching from open to closed or a pump switching from off to on.

In view of the extensive automation of most SMR designs, many of these changes are expected to occur automatically or passively, without human intervention. However, the suitability of each of these automatic changes will need to be assessed, taking into consideration the capabilities and limitations of current automatic systems. As a result of this assessment, an automatic change may be accepted or an alternative proposed, for example incorporating an operator action.

After deciding whether the actions will be automatic or performed by humans, we will be left with a group for further analysis – actions to be performed by a human – which will be few compared to conventional reactors of higher power levels.

Treatment of important human actions

The aim now is to identify and focus on those actions or groups of actions to be performed by humans that are most important. Mainly because any error might have a more significant impact on plant safety. At this juncture it will be necessary to consider situations not taken into account when analysing conventional high-power reactors, for example:

- Emergency scenarios beyond safety limits occurring simultaneously in several reactors.
- Online refuelling.
- New actions or types of accidents deriving from the choice of technology: coolant, moderator, shielding, type of fuel.
- Once these have been identified, the analysis will propose a special treatment for each.

Operation tasks

With all the tasks set down on paper, and knowing which are most important, it is now time to analyse what will be required from each and how the operator is going to carry them out. This is accomplished through task analysis.

For example, let us imagine that an operator must start up a centrifugal pump. Our analysis will tell us that we need the operation interface to provide a control to let the operator to perform the action on that equipment. Furthermore, we need some way of checking that the pump has in fact started, so we will need indication showing the status in the operation interface. Finally, we need an alarm to warn us of any risk of cavitation. Consequently, for this task we need a control, an indication and an alarm. Additional operational needs are also identified at this point, such as communication with the plant or consulting data tables and graphs.

This process is adhered to for all tasks in all systems, until a complete list of the requirements to be met by our operation interface is achieved.

Taking the most important tasks, we will now perform an analysis at greater depth, identifying them within an operating scenario and assigning a responsible person in the operation staff: the shift supervisor, the reactor operator, electrical operator or local operators, depending on the type of task.

In the case of modular reactors, one same operator may be responsible for several reactors. These scenarios will take into account simultaneous actions in several reactors, this implying a higher workload for the operators, who would be required, in the most critical case, to address several emergency procedures at the same time.

Task analysis will also provide input information for the development of operating procedures and training programmes. As the number of actions performed by humans is smaller, as has been pointed out above, the training programmes will be briefer. Furthermore, these programmes should be oriented towards the simultaneous operation of several reactors.

An initial approach to the main control room staffing

Subsequently, the assignment of operators in task analysis is evaluated, mainly in order to determine whether the task performance time is below the minimum required.

Once all the tasks have been evaluated and accepted in this way, it will be possible to determine the number of control room operators required to carry them out safely, as well as to establish the knowledge and skills they will need to perform them.

DESIGN

The conclusions of the task analysis and the list of requirements will be used to define the control room interfaces. The degree of digitalisation of the control room will be high and there will be only a few small hardware panels set aside for tasks that - given their critical nature and direct safety significance - need additional hardwired back-up to the software.

As regards design, guidelines NUREG-0700, IEEE 1023 and ISO 11064 will also serve as a basis for the drawing up of a style guide applicable to all the operating panels and screens of the plant, thereby providing the necessary consistency and uniformity. This is a key aspect in any design that aims to minimise human error.

Given the nature of the most critical scenarios, which will simultaneously compromise the safety of several reactors, there is a certain type of screens that becomes particularly important in control room design, the so-called high level or high-performance screens (Figure 2).

These displays will, a priori, govern the control room and allow the operators to monitor one or several reactors in a short space of time. For this purpose, it will be necessary to define new ways of parameter grouping, in accordance with the style guide, for example by means of parametric polygons or bar diagrams.

The high-level screens will summarize the status of each reactor, including the values of those indicators that are most important for the safety and efficiency of the modules in each operating mode.

VERIFICATION

Verification consists of checking that the design meets the requirements imposed by the guidelines referred to in the previous section. For this purpose and depending on the number of interfaces to be verified, a sampling strategy shall be established, based on both safety criteria or interfaces on which important actions are performed and on the characteristics of the latter.

For example, the verification of a group of operation screens with similar static and dynamic components may be accomplished by selecting a sample and applying the changes and comments of the verification to all of them.

An independent team will carry out a design verification contemplating the minimum number of persons in the control room established previously and aimed at confirming that the tasks to be performed using the screens designed may be carried out correctly. This will be accomplished by selecting those screens that will be used in the most critical situations, those that are most widely used, those that display important actions or those in which a human error might have relevant consequences.

VALIDATION

Validation is the process by which the design is demonstrated to fulfil its objective. Consequently, it is the process that gives meaning to all previous processes and is used to determine the acceptance or rejection of the following based on certain validation criteria:

The size of the operating crew and their level of knowledge and qualifications are enough for the performance of the tasks in the time required (this being the most important challenge in the process due to its diverting from the standards).

- The design of the interfaces contains all the elements required for the safe operation of the reactors.
- The conclusions of previous analyses are correct.
- The operating procedures and the training programmes of the operators have adhered to the same human factors conventions and are consistent with the design.

If the conclusion is negative, it will be necessary to go back to the previous processes affected and modify them until the

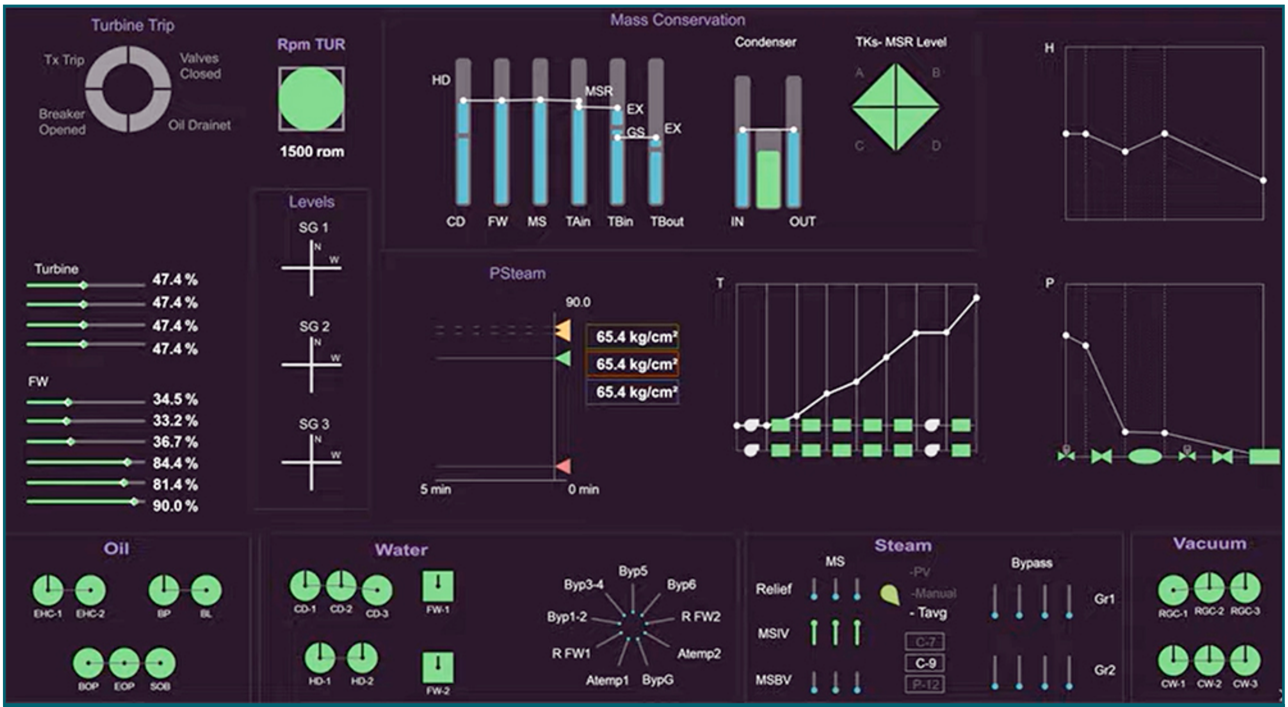

Figure 2. High performance display developed by Tecnatom S.A. (TecOS Supervise).

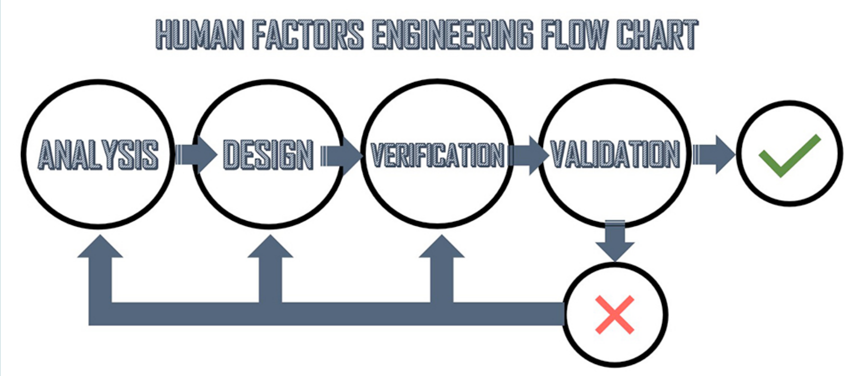

Figure 3. Simplified HFE Program Flow chart.

definitive design is achieved. For example, if during a validation it is detected that a given action should be changed to automatic, since this would reduce the risk of human error, then it will be necessary to go back to the analysis of functions and their degree of automation, as explained above. This will subsequently modify other analyses such as task analysis (Figure 3).

Validation is a simulated representation of the most challenging scenarios for the operators. These scenarios are selected either because of their high workload, their difficulty or because they contain important tasks and actions that might impact plant safety.

As has been commented on above, in the case of SMR's these scenarios will cover situations simultaneously affecting several reactors, or all of them, the objective being to demonstrate their safety and see how the operator performs with the means available to him.

In order to carry out the validation, each of the companies or organisations involved in a licensing process must have a partial or full-scope simulator, or a digital twin of the control room of the future SMR. They should also have preliminary plant procedures and training programmes to be used by the operators performing the scenario.

In addition, the human factors engineering team shall observe and monitor the actions of the operators in order to detect any operator action that might lead to an error, to correct this behaviour.

A validation program that reflects the reality of the project in each stage shall be set. In other words, different validations should be performed throughout the lifetime of the design and manufacturing project, so the operating team becomes familiar with it and for the modular manufacturing of the interfaces. Early validations may be performed on mock-ups or in virtual environments, as a preparatory step for final validation on the full-scope simulator.

CONCLUSIONS

If the result of the validation or validations is positive, the final main control room staffing may be established based on it. This provides a justification based on the entire orderly human factors engineering process performed.

In this way, HFE provides support in relation to the two challenges posed by the new modular reactors: the operation of several reactor modules from a single control room by a reduced operation staff trained in a short space of time, compared to conventional high power plants. This covers the initial part of the licensing of a generic SMR design, the design certification.

Apart from this complete HFE analysis, there remains another path to be trodden in the next phase of reactor licensing: design implementation and human performance at a specific site. This implies iteration of the review of the bases established by HFE in the generic design, dealing with any deviation with respect to the specific design, with a view to ensure the same staffing and qualifications and interfaces design set out in the previous phase.

BIBLIOGRAPHY

– NRC NUREG-0800, Chapter 18 "Human Factors Engineering", revision 3.
– NRC NUREG-0711, Human Factors Engineering Program Review Model, revision 3.
– NRC NUREG-0700, Human-System Interface Design Review Guidelines, revision 2.
– IEC 60964, Nuclear power plants - Control Rooms- Design, 2019
– IEC 61839, Nuclear power plants - Design of control rooms - Functional analysis and assignment, 2000
– IEEE 1023, IEEE Guide for the Application of Human Factors Engineering to Systems, Equipment and Facilities of Nuclear Power Generating Stations, 2004
– ISO 11064, Ergonomic design of control centers, 2013.■