Importance of Human Performance Analysis in Nuclear Safety: Toward a Brazilian Regulatory Framework

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1. Introduction

The nuclear industry has been shaped by significant events throughout the decades, many of which were caused by human error. These events have influenced the way the industry addresses human factors and human performance [1]. The motivation for developing this work originated from a previous study focused on the challenges expected in the operation of the Brazilian nuclear submarine [2]. That investigation identified the need for a more comprehensive and specific analysis for the nuclear field, one that would go beyond the context of onboard operations and encompass other relevant nuclear systems in the country, such as research reactors and activities related to the nuclear fuel cycle. It was thus recognized as important to map the available national regulatory standards concerning human performance, assessing the extent to which these standards enable, or limit, their structured implementation across the various Brazilian nuclear facilities.

Building on the existence of studies, regulations, and initiatives developed globally, which further reinforce the importance of this type of analysis, the present research proposes to justify the relevance of human performance analysis in the optimization of processes and mitigation of risks associated with human errors in Brazilian nuclear facilities. The study sought to identify fundamental elements that can support the development of national regulatory guidelines on the subject, with the aim of strengthening safety culture and contributing to the enhancement of the national regulatory framework.

2. Methodology

A qualitative, descriptive, and exploratory approach was adopted, organized in two stages: (i) an integrative literature review; and (ii) semi-structured interviews with operators of a Brazilian pool-type research reactor. The cornerstone of human performance analysis lies in understanding the human factor, that is, the lived experience of nuclear operators themselves within the context in which they work. Data collection therefore, called for a method consistent with giving voice to these operators, and was conducted through semi-structured interviews [3] honoring their subjective experience as a legitimate source of knowledge. The interview protocol was designed on the premise, well established in the human factors literature on complex sociotechnical systems [4,5], that the performance of the nuclear operator cannot be understood in isolation from the task, the physical and organizational environment, the work artifacts, and the cultural structures within which the work is embedded. Accordingly, the questions formulated were not intended to evaluate operators individually, but rather to map how the sociotechnical system shapes, and is shaped by, the everyday human activity of operation. Four thematic axes were built into the protocol, comprised in 18 questions, each addressing a specific theoretical hypothesis drawn from the literature on human performance and nuclear safety: a) work schedules, circadian rhythms, and operational fatigue [6]; b) reliance on procedures, the gap between prescribed and actual work, and complacency [7,8); c) cognitive workload, sustained vigilance, and risk and safety perception [9]; and d) human performance culture, occupational well-being, and the CNEN regulatory framework [10].

Invitations to participate were extended to three Brazilian nuclear centers, one power reactor, one research reactor, and two fuel-cycle facilities, of which only the research reactor center agreed to take part. The final sample consisted of 17 participants: 8 reactor operators, 4 operators in training, 1 radiation protection supervisor, and 4 radiation protection supervisors in training.

3. Results and Discussion

At the time of data collection, the facility operated on a flexible business-hours schedule (entry between 6:00 and 8:00; exit between 15:00 and 18:00), with no shift rotation. Longer-tenured operators reported

that, during past periods of high radioisotope demand, a rotating-shift regime was in place, with the 04:00–08:00 interval identified as the most fatiguing: “The morning was the hardest […], the body couldn't keep up with the rhythm for rest”. Recent institutional documents [11] indicate the prospect of a return to continuous shift operation to expand radioisotope production, which makes the topic newly pertinent.

Perceptions of work pace varied considerably among interviewees, described as “calm”, “tiring”, “adequate”, or “slow”, but all converged on the strongly proceduralized character of the routine. The expression “you get used to it” was recurrent. A relevant dichotomy was observed: some operators consider that proceduralization facilitates execution by reducing real-time decision load, while others assess that excessive detailing may hinder task execution. Suggestions for procedural modification do exist, but depend on centralized approval by management and quality assurance, which restricts direct participation of the operational level in everyday decisions.

All 17 interviewees considered nuclear operations to be safe, attributing this safety to strict adherence to procedures, “it is very difficult for something to go wrong”. Fear of radioactive contamination, however, was mentioned as a constant risk, mitigated through training. No serious incidents were reported; operators highlighted intrinsic safety features of the system, such as automatic shutdown in case of overheating. On a 0–10 scale for the difficulty of operation, the mean response was 7, attributed to the high responsibility involved and to the requirement of following multiple steps. An operator with more than ten years of experience explicitly raised the possibility of naturalization of safety procedures over time, a particularly significant statement, as it articulates, from within the system, the phenomenon known in the literature as complacency [12]. Only one interviewee stated that personal factors do not interfere with their performance; the others reported a perceptible decline after several hours of continuous operation, particularly when working under a shift regime. The training process was described as simultaneously the most demanding and the most motivating part of the work. Other interviewees pointed to continuous vigilance over operational parameters as the most exhausting aspect of the routine. Out of the 17 interviewees, only 1 demonstrated prior knowledge of the formal concept of human performance, acquired at international conferences. None had received specific training on human factors; institutional training focuses mainly on the execution of operational procedures. Most recognized the relevance of operator well-being in nuclear facilities, but could not indicate concrete ways to operationalize it. At the regulatory level, one interviewee suggested that the biennial psychological evaluation required could be revised to include continuous follow-up by a professional affiliated with the institution. Table 1 presents the interview results organized by their respective categories and questions.

Table I: Synthesis of thematic categories emerging from the analysis of the semi-structured interviews.

Questions	**Category**	**Subcategory**	**Representative verbalization**
Q1	Work regime and circadian cycle	Fatigue on the early-morning shift (04:00–08:00)	*“The morning was the hardest… the body couldn't keep up with the rhythm for rest.”*
Q2, Q8	Proceduralization	Acceptance of procedural rigidity	*“You get used to it.”*
Q8	Proceduralization	Tension between prescription and excessive detail	*“Some steps may seem excessive at first glance…”*
Q4	Safety perception	Confidence in procedural adherence	*“It is very difficult for something wrong to happen.”*
Q5	Risk perception	Fear of radioactive contamination	*“There are risks of contamination.”*
Q5, Q8	Complacency	Naturalization and reduced rigor over time	Report from operator with more than 10 years of experience
Q6, Q7	Cognitive load	Self-perceived operational difficulty	0–10 scale: mean 7 (high responsibility)

Q9	Personal factors	Performance decline after continuous hours	*"Performance tends to decrease after a few hours…"*
Q10	Vigilance	Continuous monitoring as demanding aspect	Constant vigilance over operational parameters
Q11–Q13	Human performance	Lack of formal knowledge of the concept	Only 1 of 17 interviewees knew the concept
Q14	Occupational well-being	Recognition without operationalization	Could not suggest concrete forms of implementation
Q15, Q16	CNEN regulation	Demand for continuous psychological follow-up	Suggestion to revise the biennial evaluation

Source: prepared by the author from the 17 semi-structured interviews.

The international regulatory landscape for human performance in nuclear operations converges on a set of principles, operator qualification, error prevention, workload management, and continuous improvement. For Brazil, the authors argue that a national standard cannot be built by simply importing these frameworks: operations differ substantially between facilities. A power plant, such as Angra, and a research reactor, such as the Argonauta, share the same underlying technology but very different sociotechnical configurations. The proposal, therefore, adopts a systems-theoretic perspective [13], in which safety is treated as a property of the whole system rather than of isolated components, and recommends a prior comparative study across Brazilian installations to identify what generalizes and what does not.

On this basis, six methodological stages are proposed: (a) characterize the sociotechnical system using systems theory and mapping operational differences between facilities such as nuclear power plants versus research reactors; (b) define the study sample and group by identifying personnel profiles (operators, maintenance, inspection); (c) apply assessments through validated metrics; (d) develop an integrated analysis of results focused on optimizing human factors, human-machine interfaces, work organization, procedures, and safety culture. The process culminates in (e) producing a final report that diagnoses improvements and (f) structure a dedicated team of ergonomists, human factors engineers, work psychologists, and HRA specialists, supported by qualification and retention mechanisms capable of sustaining the program over time.

4. Conclusions

The combined evidence from the integrative literature review and the semi-structured interviews confirms both the global maturity of the discussion and the persistence of significant gaps at the national level [14]. The interviews revealed that, although operators unanimously recognize the safety of nuclear operations and attribute it to strict procedural adherence, only one of the seventeen participants was familiar with the formal concept of human performance, and none had received specific training in human factors. Operators acknowledged the relevance of occupational well-being and reported perceptible performance decline after prolonged operation, yet could not articulate concrete mechanisms for operationalizing these concerns within their routine. Particularly significant was a statement by a more experienced operator, regarding the naturalization of safety procedures over time, an emic articulation of the phenomenon described in the literature as complacency, and a clear indication that procedural rigor alone is insufficient to sustain safety over the long term. The dichotomy observed between operators who perceive proceduralization as a cognitive aid and those who view it as an obstacle to execution further reinforces the need for analyses grounded in the actual sociotechnical configuration of each facility, rather than in generic assumptions about operator behavior.

Among the limitations of this study, the restriction of the sample to a single facility, resulting from institutional access barriers tied to operational confidentiality, must be acknowledged, as it precluded the originally intended comparative analysis across different types of nuclear installations. A further obstacle identified was the terminological ambiguity surrounding the Portuguese term "*desempenho humano*,"

which simultaneously denotes "human performance" in its technical-operational sense, and evokes "*avaliação de desempenho*" as employed in organizational psychology and human resources practice. This semantic overlap proved to be a concrete barrier both to operator acceptance of the topic and within the available Portuguese-language literature, given the fear that error-capture tools might be converted into instruments of individual evaluation. Any institutional initiative aimed at implementing a human performance program should therefore be explicitly dissociated from individual appraisal processes, with clear communication of its systemic nature and its commitment to operational safety.

Future work should extend this analysis to small modular reactors (SMRs), to the Brazilian Multipurpose Reactor, and to nuclear inspection activities conducted by CNEN, ABACC, and the IAEA. Equally important is the constitution of a dedicated research group capable of producing the knowledge base required to inform the future guidelines of the National Nuclear Safety Authority (ANSN), and the modernization of Brazilian normative instruments, as to reflect the current state of the art in human factors, ergonomics, and nuclear safety.

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