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Human Performance Considerations for Nuclear Operations and Inspections: Cross-Cutting Issues in Nuclear Safety and International Safeguards

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ABSTRACT

For many years the relationship between human action and system safety has been discussed. In the nuclear field, this subject has received more attention in the aftermath of major events that involved human error, such as the accidents at Three Mile Island and Chernobyl and more investments in this area progressively rose throughout the decades. Several documents on good practices and recommendations on human performance were published with the aim of clarifying and helping countries to act preventively in this matter. With the literature and regulations available from nuclear safety and operations, this paper overlaps the touch points between this domain and international nuclear safeguards activities, indicating a potential new field of research: the intersection of human factors issues between nuclear safety and international nuclear safeguards. This paper also proposes, through the contextualization of its application in the industry from a temporal point of view, to raise awareness in the international community about the importance and impact of human performance in the nuclear safety and international safeguards.

Acknowledging the past events, the current conflict context between Russia and Ukraine and the prospect of new technologies and more incoming countries in the nuclear industry, it is demonstrated that the subject has current demand for its development. Between the two domains with the presentation of common aspects that affects human performance, we identify common aspects of human performance and cognition that should be taken into account in both domains, and we conclude that additional complementary research is needed. In particular, additional research is needed to understand the cognitive demands of safeguards inspection activities and how these related to the performance of these inspectors. To meet this need, we recommend research in partnership with national inspectors in order to collect relevant data, validate measures and assessments, and identify inspectors' needs. In the future, this approach could be extended to international safeguards inspections. We also conclude that among the regulatory bodies, the documents found on the subject of human performance are generally recommendations rather than regulations. There may be a need for a more assertive approach in this matter.

A cooperation between the United States and Brazil in the subject, acknowledging the experience from the first with operations and the second with inspections, being part of the Brazilian-Argentine Agency for Accounting and Control of Nuclear Materials (ABACC) is discussed to help nourish and expand the state of art in these domains. It is also suggested that the IAEA establish a multi-institution group or a permanent unit to assist the implementation of human performance programs in new countries. Finally, further research is suggested in extension of the analysis to include cross-cutting lessons of human factors related to nuclear security activities and potential impacts related to the design of emerging nuclear technologies, as the small modular reactors (SMRs).

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ACRONYMS AND TERMS

Acronym/Term	Definition
ABAAC	Associação Brasileiro-Argentina de Acontabilidade e Controle
AWE	Atomic Weapons Estabilishment
CNEN	National Nuclear Energy Commission - Brazil
DOE	Department of Energy – United States
IAEA	International Atomic Energy Agency
INPO	Institute of Nuclear Power Operations
IPEN	Nuclear and Energy Research Institute
NNWS	Non-nuclear weapon State
NNSA	National Nuclear Security Administration
NPT	Treaty on the Non-Proliferation of Nuclear Weapons
NRC	Nuclear Regulatory Commission – United States
ONR	Office for Nuclear Regulation – United Kingdom
SNL	Sandia National Laboratories
USP	University of São Paulo

CONTENTS

1. OBJECTIVES

This project aims to raise awareness in the international community about the importance and impact of human performance in the nuclear safety and international safeguards, by understanding common knowledge and challenges between both fields. With that, we also aim to help identify a new potential research field across the two domains and provide a starting point to develop training materials for initial human performance assessments.

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2. INTRODUCTION

Human performance can be defined as human activities carried out in a work setting and the results of these activities [1]. This concept is commonly used in operations within complex systems where human factors influences the overall operation in different levels. The concept begun to be applied in the nuclear field for nuclear safety, that is defined as "the achievement of proper operating conditions, prevention of accidents and mitigation of accident consequences, resulting in protection of workers, the public and the environment from undue radiation risks" [2]. Throughout the years, human performance in nuclear safety have been well discussed and developed, as will be presented in the next sections.

Considering the essential role of humans in the nuclear field, the international nuclear safeguards, through its inspections, also contribute to the safe use of nuclear technology worldwide. International safeguards are a "set of technical measures applied by the IAEA to independently and objectively verify that a State's nuclear material is accounted for and not diverted to nuclear weapons or other nuclear explosive devices" [3]. The measures are executed by well-trained people, the safeguards inspectors, that just as the operators in nuclear safety, need to follow numerous procedures and execute specifics tasks on their daily jobs.

This paper will explore the intersection of both domains, nuclear safety and international nuclear safeguards, under the light of human performance measurements in order to identify common points and contribute to a better understanding of the complexity of the task of international nuclear safeguards and help identify potential improvements for their execution.

2.1. The Past: Human Caused Events in the Nuclear History and References in Human Performance

The concept of human performance has been used in the nuclear field mainly after important human error related events in the history of the industry such as the accidents of Three Mile Island (1979), Chernobyl (1986) and Fukushima (2011). Those events motivated the discussion on human factors and their influence on the overall system's safety and with that, more investment in research and initiatives from the regulatory bodies were observed. Table 1, taken from [1], shows the timing of key nuclear incidents and the subsequent publication of related human performance documents. The documents listed describe methods and best practices for the planning, implementation, and analysis of human performance programs nuclear facilities [1].

Table 1. From Pavão, S., & das Neves Conti, T. (2023), showing the temporal link between nuclear events and publications related to human performance in nuclear safety.

Year	Description
1979	Three Mile Island (EUA) accident
1979	Creation of the Institute of Nuclear Power Operations (INPO)
1986	Chernobyl (Ukraine) accident
1987	Goiania (Brazil) accident
1989	Creation of the World Association of Nuclear Operators (WANO)
1997	"Excellence in Human Performance" - INPO [4]
1997	"Organizational factors influencing human performance in nuclear power plants"- IAEA-TECDOC-943 [5]

Year	Description
2001	"A systematic approach to human performance improvement in nuclear power plants: Training solutions" - IAEA-TECDOC-1204[6]
2002	"Principles for Excellence in Human Performance" – WANO [7]
2005	"Human performance improvement in organizations: Potential application for the nuclear industry" - IAEA-TECDOC-1479[8]
2006	"Guidelines for Effective Nuclear Supervisor Performance"– WANO [9]
2006	"Human Performance Reference Manual"- INPO [10]
2009	"Human performance improvement handbook. v.1: Concepts and principles" [1] and "v.2: "Human performance tools for individuals, work teams, and management"- DOE Standards, DOE-HDBK-1028 [11]
2011	Fukushima (Japan) accident
2014	"Managing Human Performance to Improve Nuclear Facility Operation", IAEA Nuclear Energy Series NG-T-2.7[12]
2018	"Leadership, Human Performance and Internal Communication in Nuclear Emergencies", IAEA Nuclear Energy Series NG-T1.5[13]
2020	"Assessing Behavioural Competencies of Employees in Nuclear Facilities", IAEA Nuclear Energy Series NG-T1.5 [14]
2022	"Sustaining Operational Excellence at Nuclear Power Plants", IAEA Nuclear Energy Series NR-G-3.1 [15]

The International Atomic Energy Agency (IAEA) has provided many documents with recommendations on methods and tools to support the State Members to ensure their safety in nuclear operations. The Department of Energy of the United States (DOE) and the Institute for Nuclear Power Operations (INPO) played an important role on publishing guidelines that are until today references in the area. From the events happened in the past we can acknowledge that greater importance was given to the subject and more research was conducted in the field.

The operation of a nuclear facility involves a large number of procedures. With checklists and technical assessments, the operators must comply with multiple steps to ensure the safe operation of the installation. This activity requires years of training, large investments of money and time, and specific skills that are taken into account during the hiring process, such as a questioning attitude and emergency response awareness. Operations also follow IAEA Safety Standards requirements to meet the standards of the industry [2].

International safeguards inspections involve a set of technical measures applied by inspectors from the International Atomic Energy Agency (IAEA) to assure that the State Members are using the nuclear technology for only peaceful purposes. It relies upon the Article III of the Treaty on the Non-Proliferation of Nuclear Weapons (NPT), where each non-nuclear weapon State (NNWS) is required to conclude a safeguards agreement with the IAEA. [3] By supporting the IAEA with those assessments, the international safeguards inspectors play an essential part in the ongoing development of nuclear technology worldwide. Among their responsibilities, the inspectors are required to measure nuclear materials, examine seals, review surveillance data, verify design information, take environmental samples, and more. They must use checklists to verify that the declared material matches the infield verification and elaborate detailed reports to document their inspections.

Just like the operators, the inspectors receive extensive training before working on-site. They are trained for six months and are supervised by more experienced inspectors typically for one year before working on their own in the field. The IAEA employs around 385 inspectors from around 80 countries [4].

In the case of international safeguards inspections, there is no open-source documentation of instances where human errors have had a negative impact on inspection results. In the absence of historical examples or exemplars similar to the analyses of human error that have been conducted in the nuclear safety domain, we hypothesized and treated theoretically the challenges for accurate human performance and possible consequences of human errors in the international safeguards domain.

2.2. The Present: The Russia-Ukraine Conflict

The current conflict between Russia and Ukraine brought back the importance of the discussion of human performance in safety operations and also to safeguards inspections. With the Russian forces taking control of the nuclear facilities in Ukraine, and military activities in close vicinity of the plant, there are fears of a potential nuclear safety incident. The workers in Ukraine's nuclear facilities have faced extreme challenges that are known to impact human performance for a long time. This unprecedented situation mobilized the whole industry and the AIEA Director General has given statements in this regard since its beginning, in 2022 February 24th. The highlighted related human performance issues for both operation safety and safeguards inspections are presented in the text box below.

Update 8 – 03MAR2022:

> "Ukraine has informed the International Atomic Energy Agency (IAEA) that staff who have been kept at the Chornobyl Nuclear Power Plant (NPP) since Russian military forces took control of the site a week ago were **facing "psychological pressure and moral exhaustion",** Director General Rafael Mariano Grossi said, stressing that they must be **allowed to rest and rotate so that their crucial work can be carried out safely and Securely**". [5]

Oral Report to the Board of Governors 09JUN2022:

> "Every day it continues; every day that vital maintenance work is delayed; every day that supply chain interruptions cause a break in the delivery of vital equipment; **every day the decision-making ability of Ukrainian staff is compromised**; <u>every day the independent work and assessments of Ukraine's regulator are undermined</u>; the risk of an accident or a security breach increases".
>
> "The teams of **inspectors** of the IAEA also **had to stay longer at the NPP**. Separately, staff members of the IAEA Department of Safeguards:
> - Verified declared nuclear material and activities at facilities selected by the IAEA, and
> - Checked the functioning of the remote safeguards data transmission from the Chornobyl NPP to IAEA headquarters which was re-established at the end of April after two months of interruption.
> […] As I said in my opening statement to the Board, one clear line of Ukrainian operational control and responsibility is vital, not only for the safety and security of Zaporizhzhya NPP, but **also so that IAEA inspectors are able to continue to fulfil**

their regular, indispensable verification activities. There can be no delay in this. The transmission of safeguards information between Zaporizhzhya NPP and the IAEA has now been interrupted for more than a week."

"At Zaporizhzhya NPP we have reached the point where **the presence of inspectors is essential**. Though our safeguards systems are designed for data to be stored locally even when they are not being transmitted, the ongoing break in data reaching the IAEA is insupportable. Without the data, and without the in-person inspections that must occur in regular intervals, **the IAEA cannot assure the nuclear material at Zaporizhzhya NPP is safeguarded**" [6].

Update 153 – 13APR2023:

"The staffing situation at ZNPP remains complex and challenging. Over one-third of the original **staff have left the area**, some of those remaining have signed work contracts under a newly formed Russian operating organization and some remain employed by Energoatom. A significant number of the latter are now on-call, with the rest - mainly key operating staff - still working at the ZNPP, under the direction of Russian appointed management. In recognition of the staff shortages, **operators from Russian NPPs have been receiving simulator and on the job training at the ZNPP**. Once trained, they may be asked to come to work at ZNPP in case of staff shortages".

"…**the site staff** who are required **to live on site in two-week shifts** as a result of the conflict, are facing difficulties travelling to and from the nearby city of Slavutych, where most of them live. One bridge across the River Uzh has been damaged and a temporary bridge has been submerged due to spring flooding. Despite these difficulties, a planned 8 April rotation of work shifts was carried out successfully" [7].

It is evident the concern with the operation and its workers, and the appeal of the IAEA's Director General recalls the influence of certain factors on safety and related risks. The work of nuclear safeguards inspectors was also impacted, as indicated above. Data transmission was interrupted for more than two weeks in June 2022, which makes it more difficult to assert that the materials were not being diverted. As this report is being written in summer 2023, inspectors have been able to access the facilities and have periodically carried out on-site inspections and no diverted material was found [8].

The example of the current conflict highlights the close relationship between nuclear safety and safeguards, especially in wartime, and the importance of understanding the factors that impact human performance for both safe nuclear facility operations and international safeguards inspections. Further than that, the situation evokes the past and lessons learned with the accidents caused by human error and can provide new insights for the subject.

2.3. Future: New Technologies and Incoming Nuclear Programs

Nuclear energy plays a fundamental role in the global response to climate change. The goal of reaching net zero global CO_2 emissions by 2050 has led to a renewed momentum for nuclear power. The use of nuclear power has eliminated about 70 gigatonnes of CO_2 emissions over the past 50 years [10]. According to the World Nuclear Association [9], about 30 countries are considering, planning,

or starting nuclear power programs. These range from sophisticated economies to developing nations such as Bangladesh, Egypt, and Turkey. Beyond new NPPs of traditional design, new nuclear power technologies such as small modular reactors (SMRs) will support the expansion of the nuclear industry, raising new challenges for human performance and human-machine integration systems. With the prospected expansion, existing regulations will have to be reviewed, strengthened and modified for both operations and inspections activities.

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3. HUMAN FACTORS ISSUES IN NUCLEAR SAFETY AND SAFEGUARDS

As outlined above, human performance is a crucial component of safe operations in nuclear facilities and accurate reporting in nuclear safeguards inspections. Both domains share similar pressures and constraints on human performance, yet there has been little research on the links between the two. Given their similarities, it is highly likely that research on human performance in nuclear safety can be translated into recommendations for safeguards inspectors.

To explore this possibility, we conducted a review of the existent literature on human performance for nuclear safety, e.g., operations, and examined its possible application to international safeguards. In addition to scientific research on human factors in nuclear safety, we reviewed regulation policies to better understand how this subject has been approached by nuclear regulatory bodies in different countries. Finally, we reviewed the existing literature on human performance in the safeguards domain. Based on these reviews, we conducted a comparative analysis across the activities executed in nuclear operations and international safeguards inspections.

In addition to the literature review, interviews and meetings were conducted with experts from Sandia National Laboratories and other institutions, from fields including human factors engineering, risk management, systems engineering, cognitive science, psychology, and a number of international safeguards specialties such as containment and surveillance, nuclear material accounting, and safeguards policies. These rich discussions complemented the investigation, enabling the identification of applications to other contexts. Our findings from these comparisons and discussions are presented in the following sections.

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4. RESULTS AND DISCUSSION

4.1. Cross-cutting issues and human performance aspects

From the nuclear safety side, operators are exhaustively trained and credentialed to work in the field. Even with the amount of training and preparation, operators in the field face challenges through their activities and those may influence their performance, allowing mistakes to happen.

There are some points that must be addressed in this type of operation. Nuclear facilities are considered high risk facilities because of the nature of their activities. The operators are responsible for the safety of the overall system and related subsystems. This can cause high stress, which in turn can influence their attention and decision making. When it comes to commercial facilities, there is also the necessity of making sure the production reaches its profit goals, what can introduce additional sources of stress, such as time pressure. Due to the nature of operations in nuclear facilities, shift rotation and appropriate shift handoffs are essential for adequate cognitive function and again, decision making in case of any emergency. Humans are a huge part of the system and therefore, their actions can result in excellent, good, and bad outcomes. Mistakes can happen, but also, good performance can lead to great prevention of accidents. Treating the humans as if they are outside of the system weakens the strength and safety of it, making it more vulnerable, extending the challenges of their integration. So, the humans are not always a source of problem, in many cases they contribute to the solution of it.

Several regulations and recommendations on operational safety (following procedures and training related to the system's operation) have been published, but there's a gap on how to adequately measure performance and how to use the data to support the operators on improving their own performance rather than using it as an evaluation to "finding someone to blame." Some of the aspects that influence human performance in nuclear operations safety, according to the literature are:

- Workload (fatigue)
- Stress
- Time pressure
- Following many procedures
- Selective attention
- Sleep deprivation
- Multitasking

In international nuclear safeguards, IAEA inspectors are trained, evaluated, and go through an apprenticeship-like period in which they work with more senior inspectors while they become comfortable completing field assignments. They have to fill out different documents with many details in a short amount of time, which requires great attention to detail. That aspect also applies to surveillance inspections, when scrolling through large numbers of images can be time-consuming and tedious, making it possible the inspector to become fatigued and miss important information in the images. Inspectors must be aware of subtle details and many times go further in the analytical investigation to make sure the facility is complying with the agreements in force. Differences in culture and language can also create obstacles for international safeguards inspectors in the field. Communication skills are key and it is suggested to address those aspects during the process of admission as well.

Prior work at Sandia on cognition-informed safeguards [11] identified factors that may affect the safeguards inspectors' cognitive performance and identified strategies to help the inspectors to mitigate challenges that they may face in the field. The key factors identified in this research are as follows:

- Attention and inattention
- Cognitive biases
- Cognitive off-loading (taking notes to reduce mental processing)
- Prevalence effects (search for rare events of objects)
- Sleep deprivation (Jet lag)
- Stress
- Task switching and multi-tasking
- Wayfinding (sense of direction in the plant)
- Communication (working in a multilingual environment)

Between safety and safeguards, there are similar aspects related to human performance. Workloads, stress, sleep deprivation, attention to detail and fatigue are shared in common. We can conclude that the literature and scientific research available for human performance with respect to nuclear safety can be applied to international safeguards inspections. The differences appear based on the type of activity and the associated risks, but many factors that impact human performance and strategies for mitigating those factors are applicable to both domains.

4.2. A suggested prior national inspection level approach

As additional research is indicated, in order to better address the international safeguards inspectors' challenges, it is suggested to start with an analogous investigation on a national inspector level, from their current regulatory bodies to help map the main aspects related to the task of inspection that can influence the overall performance. That also could consequently help improve the work of the national inspectors, enabling the identification of further needs. One of the recurring performance issues that make it more difficult for the IAEA to fulfill its safeguards mission and draw sound conclusions it's the late or imprecise reports from the States. This kind of application can also contribute to pinpoint relevant aspects to contribute to IAEA trainings in this regard. Developing adequate and valid assessments and methods can provide the IAEA identify more ways to support international safeguards inspectors and help them in their activities.

4.3. The example of the Brazilian-Argentine Agency for Accounting and Control of Nuclear Material (ABACC)

The Brazilian-Argentine Agency for Accounting and Control of Nuclear Material (ABACC) is a bilateral organization created in 1991 by Argentina and Brazil to verify the peaceful use of nuclear materials and installations in both countries. In order to fulfill its mission, ABACC operates with the support of approximately 45 inspectors from each country. In 2022, the institution celebrated 30 years of existence and has carried out more than 3200 inspections verifying nuclear material inventories and activities declared by Argentina and Brazil [12].

The safeguards inspections executed by the institution are a way to support the IAEA with the international safeguards and are constituted of similar measurements. The inspectors are expected to write reports with their comments and conclusions about the verification activities including judgments about the appropriateness of these activities and the safeguards approach, as well as recommendations about resolved or unresolved discrepancies [13]. Also, help avoid unnecessary duplication of efforts between ABACC and the IAEA. ABACC is a good example of cooperation regarding inspections safeguards and contain an expressive experience in the regard, providing multiple training to safeguards inspectors.

4.4. Regulations and Recommendations

It was conducted a literature review through regulations from different nuclear regulatory bodies to compare how human performance is perceived in different countries. For both operation safety and inspections safety (at a national level) the regulatory bodies suggest human factors/human performance approaches to ensure secure activities. Among the chosen range of literature that included the Comissão Nacional de Energia Nuclear in Brazil, (CNEN) the Nuclear Regulatory Commission in the United States (NRC) and the Office for Nuclear Regulation in the United Kingdom (ONR), it was not found specific regulations on how to assess human performance from a cognitive perspective. The information was also confirmed with representants of those institutions in scheduled meetings.

The approaches on human factors analysis differ from country to country, but are mostly focused on human reliability analysis, also known as HRAs. The HRAs are a way to quantify the likelihood for human error in each facility using different possible methods. The HRA considers the system for its analysis and that data is sent from the licensees to the regulator commission for control. The identification of the aspects that most likely influence the human performance can be a significant tool to contribute and aggregate to those evaluations.

From the perspective of IAEA documents, they also are observed as recommendations on having human performance programs and its assessments in the nuclear facilities.

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5. CONCLUSIONS

This project provided cross-cutting aspects between nuclear operation safety and international safeguards inspections, indicating a potential new area for research with current demand. Between the two activities, was concluded that many aspects are similar regarding their influence on human performance and the differences appear based on the type of activity and the associated risks.

The continued research and development of this subject can help improve the existing human performance programs and assist the incoming States to nuclear technology to implement robust measures and ensure operation safety in this matter. This type of investigation, if conducted in a national level with national inspectors as suggested, can also help provide valuable data to the IAEA for international safeguards inspections application, in order to improve training and optimize those activities.

It was also shown that the available publications of regulatory bodies are recommendations on having this type of analysis in the nuclear field, but as a recommendation, this subject can be taken for granted many times, as it has been done in the past. So, the discussion and further research development may lead to a more assertive approach to the creation of regulations in this domain.

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6. POTENTIAL FURTHER RESEARCH, APPLICATIONS, AND FUTURE COOPERATION

Further than safety and safeguards, this investigation can be extended for the application on nuclear security improvement, helping identifying threats, prevent errors in nuclear material accounting and control activities and also enhance training aspects in the field. Additional research and data collection focusing human performance and human-machine interface design can also help provide guidelines for the new incoming technologies operation and inspections, as the SMRs.

It is important to understand and better define the specific skills, based on the aspects showed in this research for example, for the selection of inspectors in international safeguards and improve those for nuclear facility operators. An admission model based on scientific performance valid data can help ensure the right people for the right activities, and consequently help mitigate the probability of human error in inspections.

A cooperative work between research institutes and the national regulatory bodies can help identify the needs from the operators and inspectors and build together methods and measurements to enhance their performance, taking into account their daily basis challenges and having a more direct and real approach, surpassing and validating hypothesis in order to better address the problems.

A potential cooperation between the United States and Brazil, acknowledging the experience and expertise with operations from the first and with inspections from the second being part of ABACC, can help nourish the state of art on this matter in these domains and foster collaborations with other Member States as identified the importance of the subject. Thus, as a follow up, the suggestion is to prepare a workshop in Brazil on "*Human Performance – operations and inspections"*, having among the presenters experts from different areas related to human performance such as human factors, safeguards, cognitive science, systems engineering, and others. The presenters from NNSA/DOE, IPEN, ABAAC, IAEA and possible other institutions, will be able to exchange experience and raise the discussion on the importance of the field to the industry.

Lastly, should be considered the establishment of a permanent multi-institutional group or a permanent unit, as a suggestion to the IAEA in order to provide training/guidance in specific human performance matters to new incoming States in the nuclear field, for the continued improvement of the existing State Members human performance programs and as a developing interface to the application for international safeguards inspections.

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