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Human and Organizational Factors in Nuclear Installations:

Analysis of available models and identification of R&D issues

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EXECUTIVE SUMARY

The current socio-economical context, in which nuclear power plants operate, is characterised by fast pace of change. Market liberalisation and long-term safe operation of the plants are some of the challenges that need to be tackled by the countries with nuclear power programmes.

Human reliability aspects and organisational issues (e.g. organisational culture, organisational design, operation feedback, safety culture) are some areas where research is needed in order to further enhance the safety of the operating nuclear installations.
These research priorities are addressed, among others, by the activities carried out within the EC-JRC action "Safe Operation of Nuclear Installation" (SONIS), which replies to the need of coordinating at European level the national efforts in view of improving the safety of the European nuclear installations.

Notably, human and organisational factors have always paid a major influence on the safety of high-risk process industries. In particular, in the case of the nuclear industry, they intervene in all phases of the lifecycle.
In the last 15-20 years, the awareness that nuclear power plants are complex socio-technical systems increased, together with the recognition that safety is not only a technical matter, because it depends heavily on the behaviour of the people working in the lifecycle of nuclear installations.

Two major accidents have occurred in the history of nuclear industry: the accident of Three Miles Island (TMI), in 1979, and the Chernobyl accident, in 1986. The first event pointed out both the need to better understanding human factors and improving training and procedures; the second event highlighted the relevance of organisational issues and promoted worldwide the concept of safety culture.

Today, in spite of the huge amount of work devoted to human factors, an agreed classification of human errors is still missing, and there is the opinion that plant operational procedures should reflect more the insights gained by the study of human factors, in order to contribute to the improvement of nuclear safety. Moreover, in spite of the developments of the concept of safety and organisational culture, registered in particular in the last 10-15 years, also the concept of safety culture is not enough understood. Although several components of safety culture have been identified and there is agreement on them, a predictive system of assessment and monitoring has been not achieved yet.

These issues are the subject of the present report, which presents the results of the first year of research carried out on human and organisational issues in the framework of the SONIS action. The report refers to cases taken from the operating experience, and compares the different practices in the EU and non-EU countries running a nuclear programme.

The conclusions of the study highlight the need to improve the understanding of the influence of human and organisational factors on the safety performance of operating nuclear installations. Moreover, efforts should be devoted to developing tools and methods for monitoring the safety performances in a predictive manner.

Another interesting topic to be further explored is the valorisation within the regulatory process of the results of the research on human and organisational factors.

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1 Introduction

1.1 Background

The present EU society is characterized by a very fast pace of technological change, which is much faster than the pace of change encountered in management structures and even faster than the pace of the change in legislation and regulation. Three distinctive aspects of these changes can be identified: 1) The increased scale of industrial installations, which enhances the risks for large-scale accidents; 2) The rapid development of information and communication, which produces a high integration and coupling of the systems, with the result that an event, or decision, can rapidly propagate and widespread; 3) The aggressive and competitive environment, which may induce decision-makers to focus on short-term instead of long-term criteria, like those related to safety, welfare and environmental impact [1].

The Chernobyl accident, for instance, is a clear tragic example of the impact of a large-scale accident. Within the nuclear industry, the other landmark accident is the one that occurred at Three Mile Island, in 1979.

The conclusions of the first accident analysis report of TMI pointed out the human dimension of the accident and attributed its deep causes to the failure of the US safety organizational system [2]. In spite of these clear indications, the focus was mainly put on the concept of “human error”. As a consequence, the understanding of the causes of human errors, and controlling or reducing their occurrence and impact, became a key-priority objective of the research and industrial community.

Some years later, in 1986, the world was stroke by the Chernobyl accident, and the concept of “safety culture” was brought to the attention of the international community. The cultural perspective adopted by the technologists and criticized by the anthropologists, who lamented a depletion of the original concept of “culture”, gave relevance to the organizational facet of events, incidents and accidents. The IAEA confirmed that safety culture is both related to the individual and to the framework, which is the organization [3].

It is our opinion that there is no meaning in distinguishing between human and organizational factors, because people build up and develop organizations, and organizations influence the development of people, the way in which they act and interact. Consequently, if for practical reasons one prefers to talk of human factors, or of organizational factors, in both cases she or he should keep in mind that truth can be only achieved through an approach which is holistic.

Nuclear installation, and in particular NPPs, are complex systems, whose boundaries can be larger of what one assumes. For this reason, we prefer to reason in terms of man-technology-organization system (MTO), where the term organization not only designates the specific business (e.g. NPP), but includes also its interactions with the external world and institutions, because these interactions shape the organization and determine its existence.

1.2 The framework of the present study

Nuclear operating installations face new challenges: market liberalization, deregulation, changes in the institutional ownership, ageing of plants and workforce, increased use of external contractors. For coping with the pressures of the new socio-economical context, and to keep their safety uncompromised, nuclear installations have to optimize. Optimization is seen also in view of the long-term operation (LTO) of the facilities and it concerns several selected areas: maintenance, testing, surveillance and inspection (MS&I) programs, engineering programs supporting operation, operating procedures and human reliability aspects (including - among others - human factors, safety culture, organisational culture, organisational design, operation feedback).

The optimisation of these areas requires a large effort of development of new techniques and models, particularly in the field of component qualification, use of probabilistic assessment methods and risk-informed techniques, and improved awareness and insight of human factors, organisational design and culture.

In particular, with respect to human and organizational factors, the analysis of the operation feedback confirmed the need to improve the understanding of the role and interplay of human and organisational factors within the nuclear industry, in order to support the safety performance of nuclear installations and improve the effectiveness of regulatory practices. Consequently, it is necessary that the concerned stakeholders (e.g. operating companies and regulators) share their operating experience.

The purpose of the new project of the Joint Research Centre of the European Commission, i.e. the institutional action “Safe Operation of Nuclear Installations” (SONIS), is to facilitate the coordination of the effort among the European Countries for the sake of the improvement of the safety of European installations, developing harmonised approaches to safe plant operation. In fact, both the development and the implementation of optimised techniques require activities (e.g. for the collection of data, for the validation of modes) that cannot be managed only at the country level but need an integrated European approach.

A specific task of SONIS is dedicated to human and organizational factors in nuclear installations, with the aim of facing the related issues in an integrated research approach, providing ready-to-use, validated methods, models and recommendations for procedures.

This report covers the results of the first year of research in the framework of SONIS.

1.3 Objectives of the report

The purpose of this report is to overview selected issues, human and organisational, present in nuclear installations, in particular nuclear power plants, identifying areas where further research is needed. Due to the great deal and complexity of organisational factors affecting the safety of a nuclear installation, the issues described in the report do not constitute an exhaustive list.

The focus is on both factors intervening during the operation of a nuclear installation and factors emerging during maintenance activities.

Managers of nuclear installations, responsible of maintenance activities, and contractors represent some of the professional categories to which this report is addressed.

1.4 Structure of the report

Chapter 1 describes the socio-technical context to the outcomes of the analysis. Chapter 2 describes the intervention of human factors in safety, providing a classification of them. Chapter 3 is devoted to organisational factors and their impact on safety. Chapter 4 is focused on procedures and their implementation. Chapter 5 is devoted to human and organisational factors in maintenance. Chapter 6 is on safety culture and on the regulatory approaches for improving it. Chapter 7 presents the conclusions of the report. Chapter 8 highlights areas where future work is needed.

2 Human factors and safety

2.1 Introduction

Since the beginning of the nuclear power generation, human performance has been a very important factor in all phases of the plant lifecycle: design, commissioning, operation, maintenance, surveillance, modification, decommissioning and dismantling. This aspect has been confirmed by recent operating experience.

In fact, 48% of the events reported in the IAEA/NEA Incident Reporting System (IRS) are affected by human errors. Moreover, about 63% of the events reported in IRS and having significant human contribution, happened during operation, and 37% during shut-down [4].

In the past 15-20 years human behaviour and performance in organizations received an increasing attention.

The reason is to be found in recent events (not only in the nuclear industry), e.g. Space Shuttle Columbia Accident (2003), Davis-Besse NPP incident (2002), the collision of two trains at Paddingtion, London (1999), Chernobyl accident (1986).

In the case of the nuclear power industry, the analysis of the events reported in IRS shows that in the last 20 years there has been a slight increase in the contribution of human errors to events, from about 45% in the 1980s to approximately 55% in recent years [4]. These data highlighted the need to improve both the management capability at nuclear installations and the efficiency of the regulatory oversight process.

The increased perception of the importance of human performance is also an effect of the significant improvement of nuclear technology across the years, which reduced the relative contribution of technical causes to safety-related events. As a consequence, more focus was devoted to human and organizational factors in the recent IRS reports.

There are also other reasons behind the high contribution of human and organisational factors to events: the new challenges that the nuclear industry is facing, the deregulation, the increased use of contractors, the ageing and turnover of the workforce, new technologies.

The current view is that not only the performance of the individual matters, but mostly the organization and the environment where the individual is operating. This perspective implies the recognition that individuals within a nuclear installation are part of a socio-technical system, and their behaviour and performance are influenced by the organization and its culture.

2.2 Concept of human error and classification of human errors

Every form of communication requires some references and agreement about some basic concepts and terms. Although it might seem scholastic, it is appropriate to start from providing the definition (one of the available ones) of *human error*.

Error means a thing done wrongly and a state of being wrong in beliefs or behaviour. James Reason suggests that the occurrence of a human error requires both the presence of a “end-state”, or objective, and of “means” to achieve it [5]. The consequence of an error is the deviation from end-states.

A second needed step is to introduce a classification of human errors, one of the many classifications available. In fact, in spite of the fast development of the discipline in the last decades, there is still no universally agreed taxonomy for human errors. Nearly every scholar who has published in the field has proposed some kind of classification.

Some literature reports that human errors are usually distinguished in “errors of omission” and “errors of commission”. Unfortunately, this simplistic presentation might be misinterpreted and one might think that this is a comprehensive classification. In reality, it is possible to divide the available classifications in three groups, corresponding to the following levels:

- Behavioural
- Contextual
- Conceptual

The *behavioural level* is that of “what appears”. It is the surface, what can be seen. At this level corresponds the distinction between “error of omission” and “of commission”.

Just below the behavioural stratum lays the *contextual level*, which considers the environment where man is acting and interacting. For instance, the air traffic controller is exposed to a stimuli-intensive environment, characterized by a relevant background noise.

The level where the underlying causes of human errors can be found is the one embracing the cognitive sphere: the *conceptual level*.

The classification of human errors that we refer to is based on Searle’s distinction between “prior intention” and “intention in action” [6]. An example will help in describing the concepts.

“I want to go to work by car” is a prior intention, which will become, when implemented, an intention in action. But, the action I want to implement is made of a great deal of separated, sequential or simultaneous actions (e.g. to insert the key in the door of the car; to open the door; to seat into the car; to close the door; etc.) each being a specific intention in action, without being anticipated by a prior intention. In fact, my prior intention is expressed by the tag “I want to go to work by car”, which is at higher level and usually combined with a mental picture. It is not my prior intention “to open the door of my car” or “to close the door”; neither “to insert the key” in the start-block.

Similar examples can be taken e.g. from the operation of a nuclear power plant, in particular from the actions that take place in a control room.

The distinction between ‘prior intentions’ and ‘intentions in action’ is synthetically expressed by Searle’s statement “All intentional actions have intentions in actions but not all intentional actions have prior intentions”.

Figure 1 [5] provides a useful algorithm for classifying human errors.

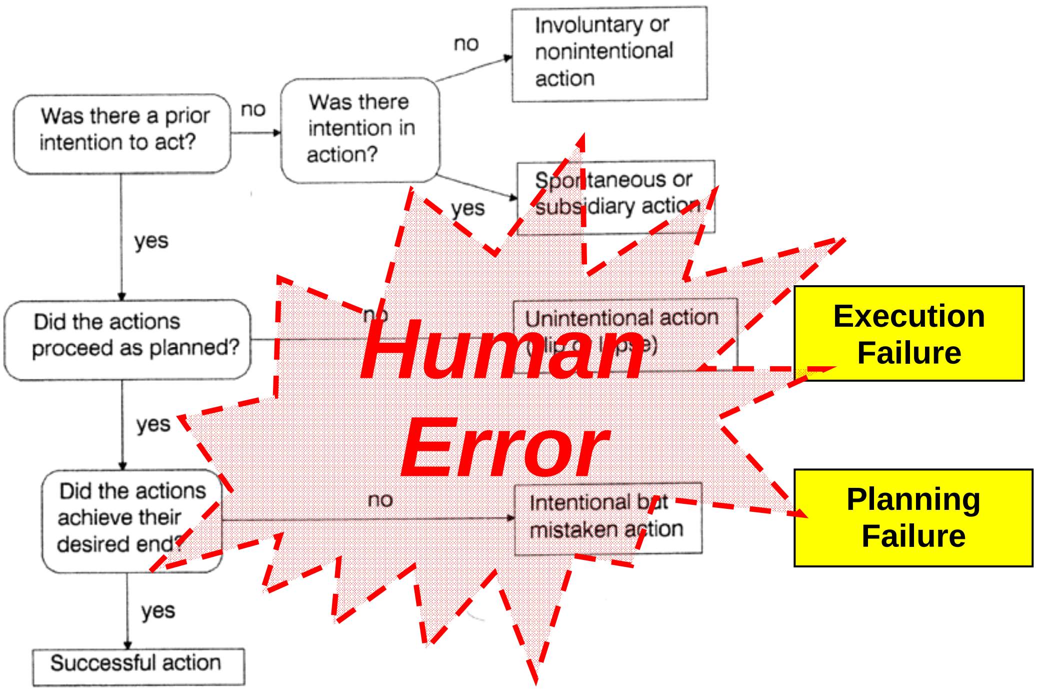


Figure 1 Classification of human errors

The action which is not supported by prior intentions and that does not correspond to any intension in actions, is an involuntary or nonintentional action. For this type of actions it is not possible to talk of “human error”, because there is no deviation from any desired objective or end-state, neither from any path of implementation of action[a].

Spontaneous or subsidiary actions are those that do not follow a prior intention, but that correspond to specific intentions in actions. This is the case, for example, of the numerous actions that I am carrying out, in a spontaneous way, when driving my car for going at work, which is the end-state I am aiming at.

Slips and lapses are unintentional actions: they represent failures in the implementation of a prior intention. The difference is that slips are observable whilst lapses happen at cognitive level (e.g. a forgotten item). For this reason, slips and lapses are failures of execution or storage.

A mistake is an error that appears when there is a prior intention and an intention in action, and the implementation of the action is correct. In spite of the correct

[a] The concepts expressed are consolidated even in law. (e.g. the distinction and different weight that nonintentional actions and intentional action have in criminal law).

implementation, the intended action does not bring to the desired end-state. This means that the cause of the failure must be searched in the planning of the action.

To the presented algorithm one could add also the “violations”, which are intended actions that one carries out being aware of the infringement of the rules in force (e.g. intended non-observance of procedures; acts of sabotage).

Figure 2 [5] gives a more detailed description of the presented taxonomy.

For the sake of completeness, it is important to recall also the distinction between ‘error of omission’ and ‘error of commission’. Briefly, the first type takes place when an item, a relevant detail, is forgotten in the implementation of an action (or procedure). The error of omission is a failure to perform an action completely. For what expressed, slips and lapses mainly lead to errors of omissions. Differently, an error of commission is an incorrect performance of an action. Human reliability analysis (HRA) studies mainly focus on errors of omission.

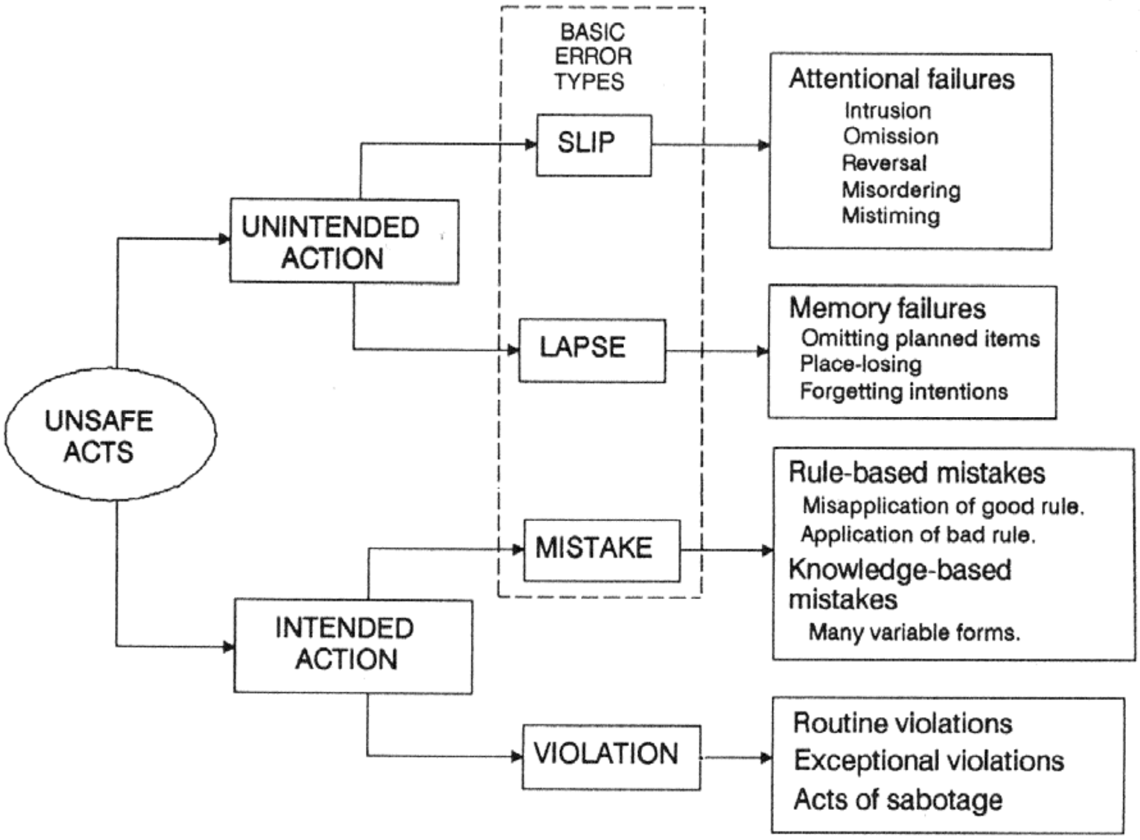


Figure 2 Classification of human errors including violations

2.3 Intervention of human factors in other industries: the experience of air traffic controllers

As showed by Figure 3, the contribution of human factors on failures is perceived also in other industries. In particular, it is remarkably relevant in the Air Traffic Control (ATC).

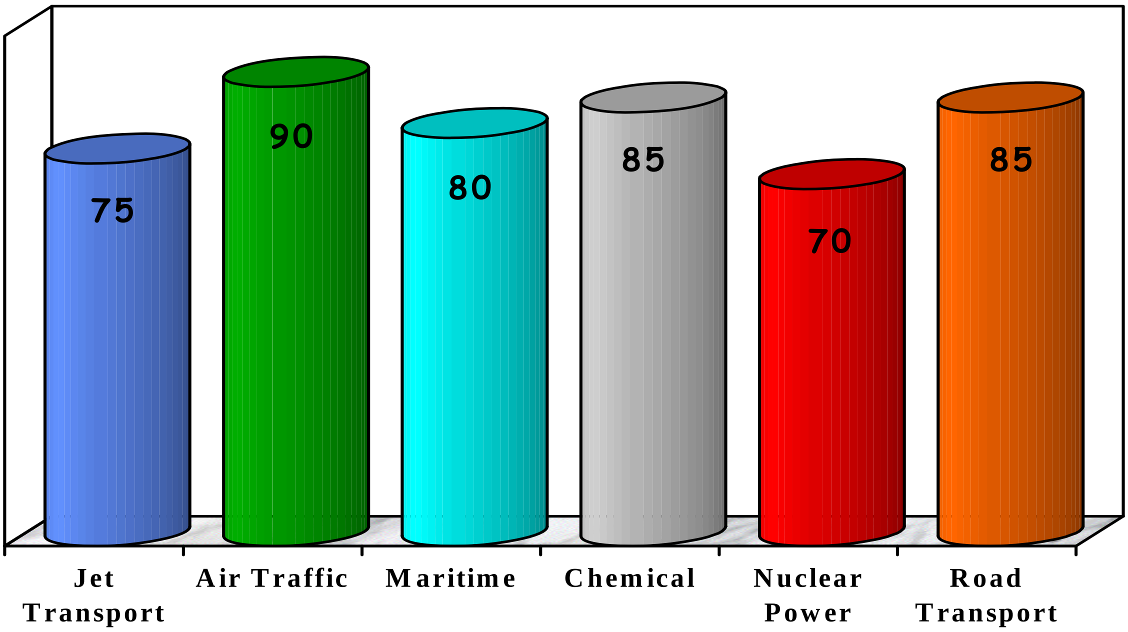


Figure 3 Contribution of human factors to events registered in high-risk industries. The values are in % (Courtesy of Paul Richardson and Luci Staples (AMEC NNC)).

The task of the controllers is characterized by high intensity of the demands on both visual and auditory perceptions. Air Traffic Controllers (ATCs) have to process a major amount of information in a limited time-window, and have to maintain their performance for periods of up to 2h at a time over a shift. Several types of attention may be involved: focused attention (e.g. monitoring of a specific emergency situation); selective attention (i.e. carry our related tasks simultaneously; e.g. listening to a pilot report and checking the data track block); divided attention (i.e. to carry out different tasks simultaneously; e.g. listening to the radio-telephone and writing on the strips); sustained attention (e.g. radar monitoring during night shifts). And the controllers have to shift their attention from one source of data to another.

In a review of ATC incidents and accidents occurred between 1985 and 1997 it was found that attentions and memory failures were the most common types of errors by ATC personnel [7]. A study carried out in 1996 was focused on 143 aviation incidents involving flight crew and air traffic controller errors related to situation awareness. Of the 262 errors identified, 72% of the ATCs errors and 77% of the flight crew errors were errors of perception [8].

Following these findings, a study was carried out on the errors of perception [9]. The study recalls the two main theoretical views of perception: 1) the *indirect* or *constructivist* theories, which consider perception as an active process that is dependent on internal processes as expectations, hypotheses, long-term memory, motivation and emotion; 2) the *direct* or *ecological* theories, which consider that the visual stimuli are sufficient to the interaction of people with the environment, without the involvement of internal processes.

The two approaches imply that perception is the outcome of processes of different nature: top-down processes, in the case of indirect theories; bottom-up processes in the case of direct theories. The study provides insight into the types of perceptual errors that occur in ATC.

The errors identified have been distributed in two categories: a) Errors of detection (mainly errors of visual detection); b) Errors of identification and comparison (mainly hear-back errors).

Associated error mechanisms have been also identified: expectations bias; distraction and preoccupation; spatial and perceptual confusion, perceptual tunneling (that happens when the controller becomes too focused, and looses visual information on other sides of the display); stimulus overload and vigilance failure.

This taxonomy is at a different level from that between errors of omission and errors of commission (see §2.2): as said, the latter concerns the behavioural level, whilst the former, mentioned in the present section, concerns the conceptual level.

As mentioned earlier in this report, we agree with the approach of considering human factors within the organisational framework and in relation with the other organisational elements. Next chapter is dedicated to the organisational issues relevant for nuclear safety.

3 Organisational factors and safety

3.1 Introduction

It has been said that immediately after the TMI accident the focus of the industrial and scientific community has been put on “human error”. Research programmes have been run worldwide which have improved the structure and content of training, as well as the man-machine interface and procedures. It has been also said that after the Chernobyl accident a new perspective was gradually adopted, which changed the way we perceive events.

The view developed by the scientific community since the mid 1980s is that events, accidents, incidents and crisis, are not just the consequence of technical failures and human errors, but they are delivered in a favourable organizational[b] context as a result of historical evolution.

In this perspective, human errors are some of the direct and immediate causes which generate an event, which is favoured by local causes (e.g. technical and ergonomic conditions, environmental characteristics) and by global organizational conditions (e.g. production pressures, lack of communication among stakeholders, weak safety culture) [2].

Plant staff and the management system represent an important line of defence in nuclear installations. Although management and organizational factors have a major impact on safety, it is only recently that they received the attention that deserve.

When analyzing an event from the organizational point of view, it is important to define the organization and its boundaries. In the case of high-risk industries,

[b] Context favourable to the development of an accident.

considering the strong link between all the involved actors (e.g. plant, safety control organization, sub-contractors) the term organization is often used to encompass, together with the in-house business, directly affected by the event, also other related businesses or institutions, and even the entire industrial sector concerned.

An organization is shaped by its interactions with the external world. In particular, the organizational approach applied to nuclear power plants should take into consideration the system NPP-Regulator, because the relationship between the NPP and the regulatory authority is the most important for the excellent performance of the NPP.

3.2 Organisational factors common to high-risk industries

The difficulty of analyzing and interpreting organizational factors is due to the fact that such factors are not in a chronological order, which means that they are not related in a linear cause-effect way. For this reason, the latest decision and human error directly involved in an accident should be considered in relation to the critical decisions made before the accident, and even the decisions which took place during the design phase of the technical installation or establishment of the organization. In this way, it is possible to outline what is called the "*organizational network*" of the accident, which developed as a function of space and time beyond the boundaries of the organisation.

Organisational accidents have a "*incubation time*" which is the time during which the organizational context becomes favourable to the release of the accident, and the available barriers degrade. During this time there are warning signals. The *weak signals* are symptoms which already give indication of the forthcoming catastrophic event; unfortunately, weak signals are difficult to be detected, interpreted and acted upon. In most of the cases, weak signals are recognized too late: when the accident is already happened.

The strongest warning signals are the *precursor events*, which are incidents or accidents without catastrophic consequences, because controlled in time, or because of the presence of barriers that did not allow the event to develop further.

The analysis, under organizational perspective, of incidents and accidents which occurred in several process industries, and in transportation, revealed the recurrent presence of a certain number of factors which plaid a decisive role in the delivery of the incident or accident. The major recurrent factors are [2]:

- Weakness of the organizational safety culture;
- Complexity and inappropriateness of the organization
- Limits of operational feedback
- Production pressures
- Failure of the control mechanisms.

It has been said that the relationship NPP-Regulator plays a major role in the achievement of excellent performances by a NPP. There is general agreement that excellent performers are those NPPs which had been able to combine operation performances and safety at the highest level.

There are several examples worldwide showing that if this balance is not maintained, then the suitability of the utility in managing high-risk technology will be challenged by the public and by the regulator. Safety is a condition that, if not fulfilled, will jeopardize the existence of a business and – even – of an entire industry.

In the following section we are going to quote some examples [10] which are indicative both of the relevance of the good functioning of the system NPP-Regulator, and of the strong need of good Leadership for guaranteeing safety.

3.3 Examples of organisational factors consequences on the NPP-Regulator system

Ontario Hydro

In Canada, Ontario Hydro (OH) shut down seven of their nineteen units in 1997 because of long standing problems inherent to management, process and equipment. An assessment initiated by new senior nuclear management found areas for performance improvement in all operating stations. It was concluded that urgent actions were needed for changing the culture, structure and management of Ontario Hydro Nuclear (OHN).

Some of the OH safety management shortcomings resulted in the non-observance of the procedures and in the tendency to put production ahead of safety, which clearly indicated degradation in safety culture. This situation created problems as the plants got older and as the original experienced staff were replaced.

Corporate management and the regulator were also part of the cultural context, because they tolerated the situation. Although internal and external reports and peer reviews, including corporate evaluations, had revealed significant operational problems for many years, the senior management answer was ineffective.

Various programmes were implemented, without success, with the purpose of improving the situation. Furthermore, no analysis of the reasons of these failures has been carried out before of starting new programmes.

The lack of effective corporate oversight of the management aspects of the nuclear programme, an insular and complacent attitude, the failure to maintain a constant long-term vision, as well as the failure to establish critical oversight and self-assessment with a questioning attitude at all levels of the organization, were regarded as primary causes of the consequent decline in performance.

For many years the regulator, the Atomic Energy Control Board (AECB), had expressed its criticism towards the utility's performance, and had required improvements in a number of areas, as condition for the utility to maintain the license of the stations. They had addressed several observations to the President and Board of Directors of Ontario Hydro, with little effect.

Millstone

Another case in US is represented by the Millstone plant, whose units were in 1996 all shut down by the utility holding the license, the Northeast Nuclear Energy Company. The USNRC ordered the implementation of independent third-party oversight to verify the adequacy of the licensee efforts to establish adequate design bases and design controls, in such a way to have additional assurance that the licensee had identified and corrected existing problems in the design and configuration control processes.

NRC was also concerned about the ineffective way the licensee management handled safety issues raised by its employees. For this reasons, NRC emitted in 1996 a second order to the licensee to develop a comprehensive plan for handling safety-related issues raised by the employees, and to have an independent third-party overseeing the implementation of the plan.

Millstone problems included ineffective leadership, lack of good safety culture, and inadequate resources provided by the corporate management.

The primary cause of problems at Millstone appeared to be a breakdown and failure of management leadership from the CEO to senior site executives, who were not aware of the serious state of key performance issues.

An effective corrective action programme and crucial self-evaluation processes were not fully appreciated by senior management even after they were identified by outside and regulatory agencies. In top of all this was the very poor management communication from the top to the bottom of the organization and a consequent lack of trust between management, employees and the regulator.

Other US cases

There had been in US also other cases of shut-down due to safety management problems. In 1987 the NRC ordered the shut-down of the Peach Bottom Atomic Power Station operated by Philadelphia Electric Company. The reasons were: case of operator sleeping, inattention to duties, failure to adhere to procedures, and management inaction or inadequate action.

European cases: Sweden

During the period 1990-93, SKI noted the recurrence of MTO-related events at Barsebäck Kraft AB. The plant was undergoing a review of management and organization, and a reorganization was envisaged, which was expected to tackle the problems.

In reality, a major reorganization was implemented, without previously assessing its impact on human performance. Consequently, the reorganization instead of solving the matters increased the MTO-related events.

The regulator, aware of the situation, put the plant under special supervision, which implied the introduction of a major improvement effort carefully monitored by the regulator. The plant was considered suitable for ‘normal supervision’ in 1997.

The reported examples, taken from different national and cultural context, are indicative of some major organisational (and human) issues that can affect the safety of a NPP. They represent cases of plants that had been upon a time good performers.

For instance, OH showed excellent performance during the construction and commissioning of the units. Most of the staff went through the commissioning period and was very experienced: they were very familiar with the plant.

The good performance and awareness of expertise level, and some of the cultural characteristics which produced operational excellence in the early years became factors contributing to the primary causes resulting in the shutdown.

These factors contributed to the development of a unhealthy cultural context in which not only the plant management, but also the corporate management and the regulator ended up to be trapped.

Lessons learnt

A lesson to be learned is that often problems, even though proved by objective evidence, are not taken seriously enough or early enough to impede their further growth; until the point where significant regulator actions become necessary. In particular, there is a common scenario that is typical of plants that “had very good initial performance that started to slip”.

This scenario involves three distinct phases, namely: a period of denial, or even arrogance in which the utility believes there is no problem, and the regulator has it wrong; then comes the recognition that there is a problem and the conclusion that the problem has to be dealt with seriously and urgently; finally, the difficult recovery process from a too degraded situation [10].

The denial may take many different forms. In the OHN case, it appears to reflect a lack of acumen on a senior corporate management level (e.g. inappropriate follow-up of two independent corporate peer reviews conducted in the early 90s). In the case of Millstone, the regulator had identified in a report that an unhealthy work environment existed, which did not tolerate dissenting views and did not welcome or promote a questioning attitude.

The reported cases show that although regulatory strategies may vary between countries they face some common issues. A major one is to identify criteria for when regulatory action should be initiated against the progressive degradation in the performance of safety management. Moreover, both regulators and utilities initially had a strong focus on technical issues and have been handling safety issues related to management and human performance in a reactive way, i .e. in response to failures identified through various types of events.

In the Canadian and US experiences it appeared that the regulator during the initial phases of identification of weaknesses in safety management processes has been not able to effectively influence top management to make necessary improvements. Repeated changes in management approach and introduction of new, often unsuccessful programmes, without due analysis, was accepted by the regulator rather than treated as a major indicator of problems with the safety management processes.

In general, and with the exception of cases like Sweden, regulator did not put much effort on management and organizational capability to handle the interaction between technology, economics, human factors and safety in a changing environment.

Furthermore, regulators in general have not paid in the past as much attention to the impact of organizational changes on safety as they have on technical plant modifications. More strict regulatory requirements on potential safety consequences of organizational changes as well as careful regulatory review of these changes may have prevented some of the problems experienced by the utilities.

It has been said before that the violation of procedures was one of the most worrying symptoms of safety degradation registered, for example, at Ontario Hydro. Unfortunately, records of events indicate that the non-observance of procedures is a recurring failure.

4 Operating Procedures and human and organisational factors

4.1 Introduction

After the TMI accident the focus of the human reliability research has been put on human performance and, consequently on man-machine interface issues, training and improvement of procedures. Procedures are a form of aid that guides operators in performing tasks. They can be considered an important part of the human-machine interaction system, and they greatly influence the operator performance and reliability.

Moreover, they are part of the management system and aim at supporting human performance. For what said, procedures have both human and organizational facets.

Consequently, the objective of the procedures design is to achieve procedures which are:

a) Technically correct,

b) Clearly understandable (without introducing task overload),

c) Easily executable in a correct way.

Although well-trained and expert operators can deal with normal tasks without the help of manuals, in situations as normal plant start-up and shut-down most operators reported physic and cognitive overload.

4.2 The application of procedures and nuclear safety

The existence and implementation of operating procedures in hazardous industries, as the nuclear power industry, should support a high level of safety for the plants. But, the existence of procedures itself is not a guarantee of safety, as showed by e.g. the accident of Three Miles Island. A major point of discussion is how procedures should be used by operators.

From the point of view of the procedure's designer and of the executive manager and training supervisor, the operator must apply to the letter and step-by-step the instructions written in the procedures. This viewpoint assumes that all the relevant equipment is available; that the passage from a process state to another is achieved via a chronological sequence of operator's actions; that the operator that will use the procedure be an "average" operator with a given competence. What is missing, in general, are competence requirements for the operators that will use the procedure, because the underlying assumption is that everything that must be done is written in the procedure.

This view contains a first big limitation, which is the fact that a procedure is the mirror of the theoretical and practical knowledge of the operation of a process, valid in a certain moment. There is, usually, a gap between the procedure and the reality, which will be showed by the future operational experience and future research. As a consequence of it, procedures are often updated or substantially changed.

But how the operators use procedures?

This has been showed by a study, carried out by EDF on more than 100 realistic tests on full-scale simulators, during which the operators had to cope with accident scenarios [11]. The study revealed that:

a) Divergences from the strict observance of procedures are rare in accident situations, but, due to their frequency, they cannot be ignored;

b) These deviations are the result of a gap between the procedure and reality, because not all events that operators face are foreseen by procedures.

This latter aspect is due to the fact that, whilst operation is dynamic, procedures have a static nature, which do not consider factors as e.g. the interactions between the process parameters and between the members of the operation team.

The major conclusion of the study is that the most appropriate application of procedures is to have strict observance of them, when they adhere to the real situation, and to rely on the operator's expert judgment when procedures divert from reality. For this purpose, and for supporting a more pro-active role of the operator, the operator's training must allow the operator to understand the phenomena occurring under emergency operating conditions [11].

In recent times the use of computerised procedures has become more and more widespread.

The next paragraph deals with this type of procedures.

4.3 Computerised procedures

It has been said that procedures are aids for operators, in particular in circumstances characterized by unexpected behaviour of the system. In particular, the support of aids is necessary in emergency situations. In these circumstances, the operators refer to paper-based or computer-based emergency operating procedures (EOPs). The former type is the traditional one; the latter was introduced with the development of information technology. For this reasons, computerized procedure systems (CPSs) have been introduced in new NPPs or modified NPPs since the 1980s.

An important aspect is that the content of procedures has been continuously changed and adapted to the development of control technology and automation in NPP control rooms; differently, the structure of the procedures remained substantially the same [12].

Computerized EOPs provide enhanced support to operators, in particular due to the advantage of the interactive features. However, the difference between hard-copy and computerized EOPs is not only in the medium, but also in the presentation style of the information. Little research has been carried out on the comparison of the graphical computerized procedures mainly used (i.e. flowchart procedures, success trees and their combination).

The study carried out by Xu et al [13] suggests that the presentation style can influence significantly the error rate when operators – even well-trained ones - are carrying out EOPs; this aspect is often ignored and should be taken into consideration by designers. They also confirmed that task complexity significantly influences the operation time and the error rate in EOPs operation. Their study also confuted the opinion that the execution of computerized EOPs is simpler and easier than of paper-based ones; furthermore, it showed the need of adequate training for performing computerized EOPs. The main limitations of their study was that the emergency operation system was neither a NPP control room nor a simulator, but a simulated computer software system in a laboratory; moreover, the subjects of the study were university undergraduate students (with background in engineering) and not operators.

4.4 Evaluation of the complexity of emergency operating procedures

It has been reported that symptom-based EOPs have been widely used to enhance the safety of NPPs by means of a reduction of the operators' workload in the relevant conditions.

The drawback of the symptom-based EOPs is that the operators are obliged to perform required tasks (made of several steps) for restoring process disturbances and, meanwhile, carry out other tasks for maintaining plant safety functions. As a consequence, these procedures may add additional burden on operators who have both to monitor symptoms and oversight the whole process in which EOP steps have to be carried out.

To tackle the problems, specific requirements for developing EOPs have been prepared, and their aim is to have EOPs that allow operators to easily understand the context of the emergency intervention, and implying tasks that can be carried out within an "acceptable" workload and "task performance time", the latest being the time elapsed between a task entry and exit.

Whilst time requirements for the performance of the procedural steps can be extracted from several plant design and maintenance documents, it is difficult to define the acceptable workload or acceptable workload range, because it is affected by several organizational factors difficult to be quantified, because they are plant specific. Anyway, as reported by Park et al [14] some researchers suggest that the acceptable workload would range from 50% to 75%.

To ensure that the EOPs satisfy the mentioned requirements, checklists are used. The advantage of checklists is the easiness of the use; they also present disadvantages. For example, the results of the use of checklists are subjective, because they are dependent on the experience and on the knowledge level of the inspection personnel. Moreover, the fact that the EOPs satisfy the items of checklists does not guarantee that the EOPs fulfil the mentioned requirements.

For example, in the case of steam generator tube rupture (SGTR) event, the operators should carry out the relevant EOP, fulfilling all the steps of the required tasks within a certain time [14]. Even the case that the EOPs satisfy all items of the checklist does not guarantee that operators can finish the steps within the required performance time, or that the workload of the operators is acceptable. This is due to the fact that the checklists approach is suitable for a qualitative and not for a quantitative estimation. As a consequence of this qualitative aspect, the development of EOPs implies that their validity be certified through a mock-up test or a walk-through.

Because the evaluation based on mock-up tests and walk-through is difficult to be carried out, because it implies demanding and time-consuming activities, Park et al [14] have developed a method for quantifying the degree of step complexity (SC), which is a measure of the complexity of the step of a EOP; this measurement is based on entropy measures which have been used to evaluate the degree of complexity of software in software engineering.

The measure of SC is based on the sub-measures of the major factors that complicate the performance of EOP steps. In particular, on the basis of research results and of the operating experience of different industries, as nuclear power production, chemical plants and aviation industries, the following major factors have been identified:

1. The amount of information of each EOP step;
2. The logic structure of each EOP step;
3. The number of actions included in each EOP step.

For measuring the SC, the entropy measure has been used. This concept has been adopted in several research areas because it is able to provide a degree of complexity. On the basis of the concept and considering the three identified major complexity factors, the following respective complexity sub-measures have been carried out:

1. Step Information Complexity (SIC);
2. Step Logic Complexity (SLC);
3. Step Size Complexity (SSC).

And the SC of an EOP step has been calculated as function of them.

The appropriateness of the SC measures, as defined, has been validated versus subjective and objective assessment techniques, respectively the NASA Task Load Index (NASA-TLX) [15] and step performance time data.

As mentioned elsewhere in the text, human and organisational factors play a major role in every phase of the entire plant lifecycle. The following chapter reports the results of a research carried out on HOF in maintenance of NPPs.

5 Human and organisational factors in maintenance of NPPs

5.1 Introduction

The FP7[c] EC-JRC action Safe Operation of Nuclear Installations (SONIS) encompasses, as task, the project Safety of Eastern Nuclear Facilities (SENUF), which was launched in FP6[d]. This project is mainly focused on maintenance and maintenance optimization, replying to the need of the Industry to guarantee the safety of the nuclear power plants whilst achieving the optimization of costs, which is compulsory due to the competitive pressures of the open electricity market.

[c] FP7 is the 7th Euratom Framework Programme for Research, Development and Demonstration. It covers the period 2007-2011.
[d] FP6 is the 6th Euratom Framework Programme for Research, Development and Demonstration, which ended in 2006.

Although the focus of human reliability research has been given to the performance of control room crew in post-initiating event conditions, it has been recognized that also maintenance has a significant impact on the severity of an incident (e.g. by erroneously disabling safety-related equipment). In particular, common cause and other dependent human failures of safety systems may relevantly contribute to the reactor core damage risks.

5.2 Analysis of human originated common cause failures in maintenance activities

The role of human failures in maintenance activities has been the subject of a research carried out at the nuclear power plants of Olkiluoto (Units 1 & 2) and Loviisa (Units 1 & 2). In the former NPP, 4400 fault repair work orders have been considered along a period of three years (from 1992 to 1994); among them, 334 human error cases have been identified: 206 single errors and 14 common cause failure events; in the latter, the three-year maintenance history, form 1995 to 1997, has been considered.

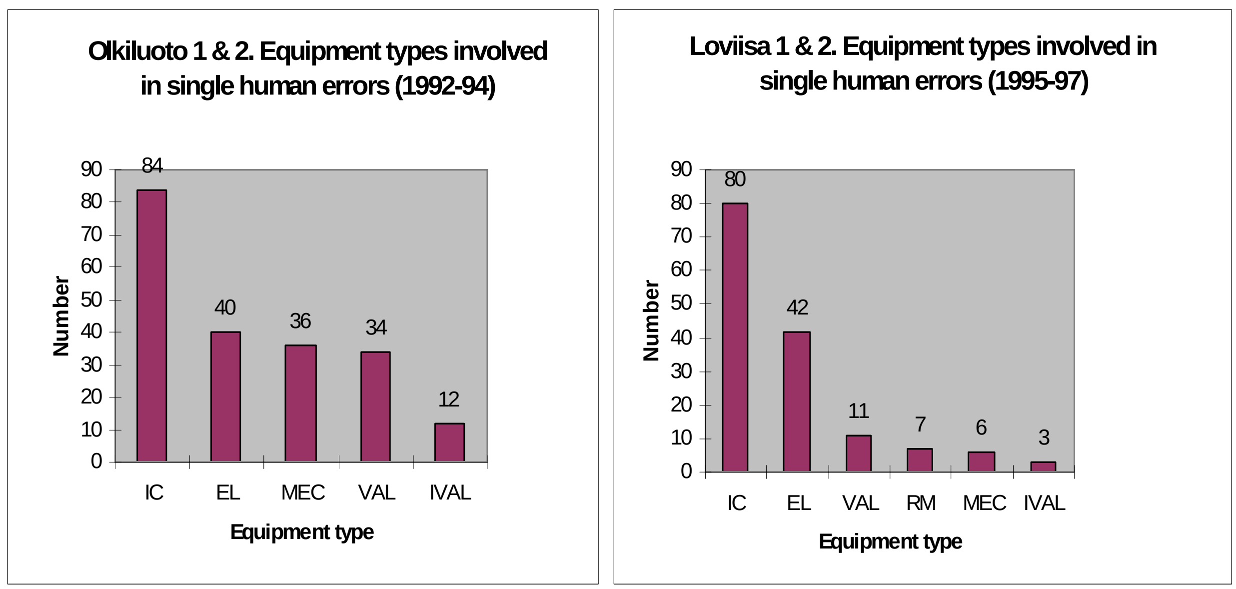
The 14091 fault repair work orders concerning this period have been analysed and 183 human error cases have been identified: 149 single errors and 34 common cause failures [16,17]. In the following paragraph, the definition of common cause failure and common cause non-critical failure are reported.

Definition of common cause failure (CCF) and common cause non-critical failure (CCNF)

Common cause failures are similar failure cause or mechanism that may result or have resulted in multiple functionally critical failures in redundant subsystems. Common cause non-critical failures are similar failure mechanisms, which produce the deviation of the performance of redundant or parallel equipment from standards. CCNFs can be considered as early warning of causes that can develop into CCFs.

Main Results of the Finnish study

The analysis of the selected human error cases occurred at Olkiluoto and Loviisa showed that in both cases the higher number of single human errors concerned the instrumentation and control, and the electrical equipment (see Figure 4). The errors were mainly errors of commission, due to lack of attention.



IC = Instrumentation & control equipment or software, **EL** = Electrical equipment, **MEC** = Mechanical equipment, **VAL** = Process valves, ventilation dampers or channel hatches, **IVAL** = Block or primary valves in instrument lines, **RM** = Radiation monitoring equipment.

Figure 4: Type of equipment affected by single human failures registered at Olkiluoto and Loviisa

Analogously (see Figure 5), also the common cause failures and non-critical failures interested mainly the I&C and electrical equipment. Modifications and preventive maintenance were the tasks that mainly brought to HCCFs and HCCNFs. It has been found that the human common failures and non-critical failures have been mainly caused by planning deficiencies and insufficient knowledge (see Figure 6). Moreover, a distinctive aspect was that only a minor percentage of the human multiple errors were detected during the outage and operability verification phase (installation checks, functional testing, start-up testing), whilst more than half of them became evident during the start-up and power states. This shortcoming emphasized the presence of weaknesses in the operative and organizational barriers.

The research pointed out the need of improving the operability verification after maintenance, both in terms of planning and of testing programme. In particular, it was suggested to have the planning of the operability verification better integrated into the maintenance process and to have the operability verification tailored on the type and extent of interventions carried out, and not as a standard procedure.

The need of establishing, maintaining and improving organizational barriers (e.g. review of the start-up testing, of the appropriate review of the work and test planning of the work-orders) was also pointed out.

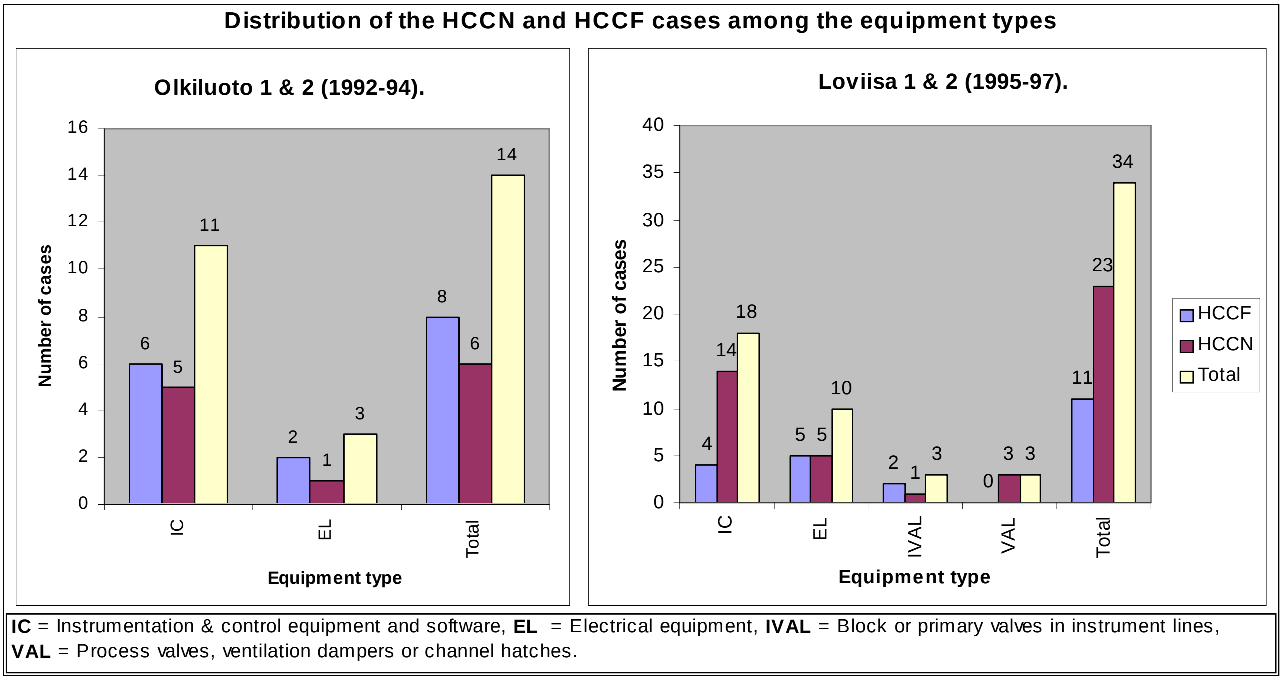


Figure 5: Type of equipment affected by multiple common cause human failures registered at Olkiluoto and Loviisa

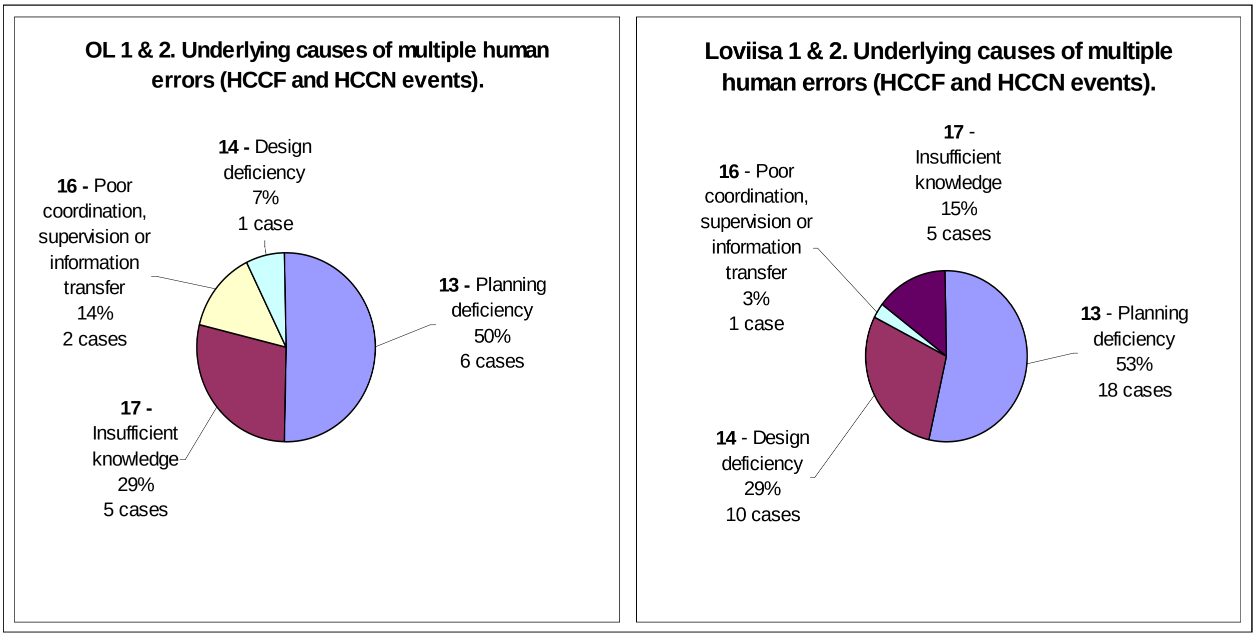


Figure 6: Underlying causes of multiple human failures at Olkiluoto and Loviisa

6 Safety Culture

6.1 Introduction

Safety culture is one of the factors that affect the degree of safety and consequently the performance and existence of an organization. The idea of safety culture existed already in 1980, but it was widely spread after the International Nuclear Safety Advisory Group (INSAG) Summary Report on the Post-Accident Meeting on the Chernobyl Accident in 1986. In spite of the diffusion and widespread use of the term - not only in publications about hazardous technologies - safety culture is not fully understood and no agreement on its definition has been reached. As a consequence, there is no agreed and validated method for measuring safety culture.

6.2 Culture, organizational culture and safety culture

The culture concept has been traditionally used by anthropologists. As reported by Choudhry *et al* [18], a reference definition of culture is given by The American Heritage Dictionary, which defines culture as “the totality of socially transmitted behaviour patterns, arts, beliefs, institutions, and all other products of human work and thought considered as the expression of a particular period, class, community, or population”.

As suggested by Sorensen [19], “INSAG has borrowed the term ‘culture’ from either anthropologists or the organizational development community (who in turn borrowed it from anthropologists)”; anyway, “INSAG publications make no reference to the bodies of literature in those fields”. The same Chroudhry et al [18] agree with Brigges on the fact that ‘culture’ as used by anthropologists is different from ‘culture’ used by the organizational development scholars.

According to Reason [20], the definition that best captures most of the essentials of organizational culture is the one given by Uttal in 1983: “Shared values (what is important) and beliefs (how things work) that interact with an organization’s structures and control systems to produce behavioural norms (the way we do things around here).”

Another reference definition of organizational culture is given by Schein [21]: “A pattern of basic assumptions – invented, discovered, or developed by a given group as it learns to cope with its problems of external adaptation and internal integration; that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those problems”.
Schein proposed also a three-level model of culture, widely adopted, which considers culture made of:

1. Artifacts
2. Values en Beliefs
3. Basic Assumptions.

The term ‘artifacts’ denotes the observable daily features of the organization: e.g. office layouts, jargon, activities, rituals.

‘Values and Beliefs’ include the espoused values of an organization, e.g. the judgments about what is good and what is bad, and statements as “safety is our top priority”.

‘Basic assumptions’ represent the model of reality that the organization has and transmit to its members. This includes, e.g., how the organization regards people, how the organization sees the external world. It is a tacit dimension, which actually drives the organizational behaviour.

It is important to note that artifacts are, as said, easy to be seen, but difficult to be interpreted. It is possible to understand them only if we have some insights on the basic assumptions of the organization.

The Schein’s model has been applied to safety cultural [22,23]. As mentioned before, the concept of safety culture has been introduced by the International Nuclear Safety Advisory Group (INSAG) in the Summary Report on the Post-Accident Meeting on the Chernobyl Accident in 1986 [24]. The concept was further developed [25], and defined later as follows [3]:

“Safety culture is that assembly of characteristics and attitudes in organizations and individuals which establishes that, as an overriding priority, nuclear plant safety issues receive the attention warranted by their significance”.

As pointed our by Reason, the INSAG definition is more a statement which specifies “an ideal but not the means to achieve it”, and he considers more useful the definition given by the UK’s Health and Safety Commission in 1993 [27]:

“The safety culture of an organization is the product of individual and group values, attitudes, competencies, and patterns of behaviour that determine the commitment to, and the style and proficiency of, an organization’s health and safety programmes. Organizations with a positive safety culture are characterized by communications founded on mutual trust, by shared perceptions of the importance of safety, and by confidence in the efficacy of preventive measure”.

6.3 Components of safety culture

INSAG-4 [26] reports about “*universal features of safety culture*” and distinguishes between two general components of safety culture: the first being “*the necessary framework within an organization*”; the second being “*the attitude of staff at all levels in responding to and benefiting from the framework*”.

Reason identifies four main components of safety culture [28]:

1. Reporting culture, i.e. an organizational climate in which people are willing to report about their errors and near-misses;

2. Just culture, i.e. an atmosphere of trust which encourages people in providing essential information and which clarifies the boundary between acceptable and unacceptable behaviour;

3. Flexible culture, i.e. the essential feature which allows an organization to adapt and reconfigure;

4. Learning culture.

These four subcomponents interact to create an informed culture, i.e. an environment in which “those who manage and operate the system have current knowledge about the human, technical, organizational and environmental factors that determine the safety of the system as a whole”.

6.4 Approaches for improving safety culture

Although there is no prescriptive formula for improving safety culture, some common characteristics have been identified, and approaches that has been successful in a number of countries. In the recent years there has been increased focus on the improvement of safety culture via a systematic approach which is based on the establishment of a management system. In fact, general consensus exists on the fact that safety “has to be achieved and maintained by means of an effective management system” and that the management system “has to ensure the promotion of a safety culture” [29].

Moreover, there has been increased attention to the contribution of human behavioural sciences to the development of safety good practices. With the purpose of improving safety culture, some countries have chosen for an approach emphasizing the use of behavioural sciences, whilst others have preferred to enhance safety performance via the management system approach. There is consensus that a good approach should consider both behavioural science and management system approaches, and take into account also the national and organizational cultures [22]. The development and maintenance of safety culture needs both a top-down and bottom-up approach. In this respect, the role of leadership is paramount.

Organisations with a mature safety culture focus more on the overall goals than on compliance with procedures. Three stages of development of the safety culture of an organization have been identified, and can be used as a basis for the assessment of the maturity of the safety culture of an organisation:

1. Stage I – Safety based only on rules and regulations;
2. Stage II – Good safety performance becomes an organizational goal;
3. Stage III – Safety Performance can always be improved.

The typical features showed by an organization in each of the three stages are given in the quoted reference. The main points are summarized hereafter.

An organization positioned at Stage-I perceives safety as an external requirement imposed by national government, regional authorities and regulatory body. The organization is not aware of and not interested in the influence on safety of behavioural and attitudinal aspects; mainly it is focused on procedural compliance. A Stage-I organization usually shows a blame-culture, which blames people who failed to comply with the rules. Communication is also very poor, and departments and functions are isolated or in conflict. As a consequence, a Stage-I organization is usually not able to anticipate problems.

In Stage-II, the organization is aware of the importance of safety, and sets objectives and targets for safety performance, as for other aspects of the business. Still, the organization shows lack of awareness of the behavioural issues. A Stage-II organization usually encourages cross-departmental and functional communication and co-operation. Mistakes are occasion for developing the control in place and retraining the staff. A blame-culture, although less marked, is still present. The organization still regards safety as separated from – and competing with – production.

In Stage-III the organization is focused on safety performance and is aware of the impact of behaviour and attitudes on safety. A stage-III organization pays major attention to: management style, communication, people development, and is committed to continuously improve. Mistakes are regarded as learning opportunities, and require a clear understanding of what has happened. Safety and production performances are seen interrelated and not conflicting. The organization has usually a collaborative relationship with the regulator, suppliers, customers and contractors.

The time-schedule needed to an organization to evolve through the mentioned stages depends on the initial state of the organization and on its commitment to change and on its resources devoted to the process of change. In general, the enhancement of safety culture is a lengthy process.

6.5 Influence of the regulatory body on the safety culture of the licensee

The operating organization, i.e. the company or utility authorized by the regulatory body to operate one or more nuclear power plants, "is completely in charge of the plant, with full responsibility and commensurate authority for approved activities in the safe production of electric power" [30]. Other organizations, such as designers, manufacturers and constructors, employers, contractors, consignors and carriers also have legal, professional or functional responsibilities with regard to safety [31].

The regulatory body too, by fulfilling its statutory obligations, plays a fundamental role with respect to safety. There are remarkable differences in the regulatory approach to safety.
From a practical point of view, three main types of approaches may be identified [32]:

1. Compliance-based;
2. Outcomes-oriented;
3. Process-based

In the first approach, the focus is on the application of standards and requirements. With the second approach, the regulatory body focus is on establishing indicators and monitoring them, investigating cases of negative trends.
The latter approach is focused on the organizational systems that ensure continuous safe operation. The operating organization has to demonstrate to the regulatory body that a continuous assessment of the key processes is in place, and that areas for improvement are identified and receive appropriate follow-up.

The compliance-based approach seems to be the less effective for improving the safety culture of the organization, because it is founded on the assumption that safety relies in particular on the compliance with rules. The risk of this approach is to regard safety under a technical perspective, disregarding the complexity of safety culture.

The second approach presents the difficulty of identifying suitable indicators, in particular leading indicators that have a predictive function. The process-based regulation may offer the advantage of flexibility, if the operating organization implements a flexible process-design which allows it to adapt to the changing environment. More that the second approach, and even more than the first one, the process-based regulation underpins the establishment of a learning culture within the licensee, because it spreads more within the organization the feelings of responsibility and ownership of safety.

In the reality, the generic regulatory approaches present a combination of the main features of the described approaches.

The regulatory framework establishes a relationship between two (or more) organizations, one being the regulatory body, and another being the operating organization. One of the tasks of the regulatory body is to promote safety culture in the organizations under its jurisdiction. For this purpose it is important that regulatory personnel are trained on safety management, safety culture and on how to intervene on organizations for achieving the desired changes. Vice-versa, the risk is that the regulatory action will not favour, or even impede, the development of an effective safety culture within the licensee. Another fundamental factor is the existence of a positive, open dialogue between regulator and licensee.

7 Conclusions

The research carried out during the first year of SONIS activity confirmed that human and organizational factors are very important contributors to events occurring in the nuclear industry. Their impact on the safety of nuclear installations is even enhanced in the changing socio-technical context which characterizes the energy market, because the ongoing liberalization, deregulation, changes in the institutional ownership and outsourcing impose new organisational challenges on the nuclear industry.

Human factors have been an area of research and development since the accident of Three-Miles Island (1979). In spite of the efforts devoted to the topic, the need to achieve a unified approach is felt.

It is confirmed that factors as weakness of safety culture, inappropriateness and complexity of the organisation, limits of operational feedback, production pressures, failure of control mechanisms are major contributors to events occurred in several process industries.

The study shows that special attention has been devoted to procedures, notoriously a form of aid which guides operators in performing tasks; they are very useful especially in cases (e.g. emergency operation) where the absence of procedures would imply a consequent physical and cognitive overload on the operator.

The operation experience shows that the use of procedures can also have drawbacks, in particular if procedures are too complex and/or unclear. For this reason, it is recommended that human factors specialists are brought into the process of designing procedures.

The responsibilities and limitations of the regulatory framework is another area of concern, and the need to exploit the results of the research on human and organisational factors, to enhancing the effectiveness of the regulatory oversight, is pointed out.

Among others, the role of the regulator should be to help the licensee in the enhancement of its safety culture. In this view, it seems that process-based regulation is the most suitable for allowing the licensee to develop own solutions for self-regulation and safety culture awareness.

Finally, it is stressed that managerial tools as management systems have a key role in enhancing the safety of operating nuclear installations, and that the current trends aim at integrating the management systems. This process implies that safety, environment, human resources and economical aspects, are not treated separately but receive a comprehensive, holistic approach.

8 Suggestions for future work

From a theoretical point of view, additional efforts are needed to improve the understanding of the influence of human and organisational factors on the safety performance of nuclear installations.

From a practical point of view, efforts should be devoted to conceive a method or tool for monitoring the safety performances in a predictive manner.
As a first step, it would be interesting, and strongly recommended, to review the available deterministic and probabilistic methods and tools for assessing and monitoring the effects of human and organisational factors, as well as the available operational experience.

Because of the global trend, in the nuclear industry, towards the integration of management systems, and considering that licensee organisations and regulators have limited experience of the impact of the integration of safety management in management systems as a whole, the topic should be further investigated and the relevant experience collected and compared.

Efforts should also be devoted to use the outcomes of the research on human and organisational factors in the regulatory process, for improving the regulatory efficacy.

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Abstract
The nuclear industry faces new challenges: market liberalisation, deregulation, changes in institutional ownership, ageing of plants and workforce. In the current competitive context the nuclear utilities aim at the long-term operation (LTO) of their plants.
In this perspective, to guarantee safety is paramount.
Human and organizational factors (HOF) have plaid a major role since the beginning of the nuclear power industry, because they concern every phase of the plant lifecycle. In the last 15-20 years their contribution to events has received increasing attention from operators, regulators, and from the scientific community. The progress achieved in the area has shifted the focus from the individual operator performance towards the performance of the organizational system which is the context to the individuals' actions.
This study provides an overview of the HOF challenges in the Nuclear Industry. Some cases from operating and regulatory experience are reported and suggestions for future work are given.

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