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ANALYSIS OF THE INFLUENCE OF HUMAN FACTORS ON MAIN CHEMICAL AND NUCLEAR PLANTS ACCIDENTS OCCURRED ON LAST DECADES

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ABSTRACT

Investigation of the main chemical and nuclear plants accidents occurred on last decades point unequivocally to human error as the main cause for their occurrence. This factor is, probably, the one which has contributed more to human lives loss, human injuries, property damages and financial losses. The human error usually is associated with one or more concurrent factors to compose the main cause of these accidents. These errors are rarely deliberate actions; therefore the study of what are the main subjacent factors that influence and induce human procedure failures is an important research issue. Important researchers on Human Factors Engineering consider these Factors with increasing weight on evaluating human performance reliability. Considering this context, this work has as one of its main objectives to study human factor influence on the main nuclear and chemical accidents happened in recent decades worldwide. As initial step, a detailed analysis of accidents international database was done. The main accidents attributed to human error were selected, analyzed and structured in chronological ordination. In a following step, human factors who may have contributed to these accidents occurrence were correlated. These factors were analyzed and classified based on current literature indications. For each analyzed factor a set of deteriorating conditions which may have contributed were pointed and associated with the respective corrective actions. Initial results corroborate the actual researches view in which human error can be extended to engineers involved on equipment projects, to technicians involved on equipment construction, to personal involved on projecting operational and safety procedure guidelines, or even to the people contributing to system maintenance, and not only to the system operators.

1. INTRODUCTION

The conscience about the human factors and reliability importance has significantly been improved in the last 10 to 15 years, due mainly to the fact that a good portion of the major accidents, nuclear and non-nuclear included, had a significant human error contribution.

Human error can substantially contribute to system failures in big and complex interactive systems. For instance, in nuclear plants, human error is responsible for a considerable proportion of safety related incidents [1].

On a recent study by Subramanian [2], the proportion of Nuclear Power Plants (NPP) accidents, in world scale, identified as being caused by human error (that is, being the event main cause) is estimated in the 40-50% range. The basic indentified causes include errors due to: project, process, operator and management, work planning, inspection, tests, maintenance and training.

In chemical and petrochemical industries statistics do not differ. Almost all investigations on major accidents in the last years present human error as a direct or indirect cause as: Texas City disaster (1947), Bhopal (1984), Piper Alpha (1988) and the Texaco refinery in 1994 [3].

A synthesis presented on a publication from AIChe [3] describing the human error part on accidents, shows that 80 to 90% of all chemical processes industry were caused by human error. Over oil refineries and petrochemical industries, human error presents up to 58% participation.

Accident analysis always implies an accident model. In the last 20 years has been significant changes on these models with evolving methods and goals related to accident analysis.

The more used model has been the Epidemiologic Model proposed by Hollnagel [4]. As its name states, accident is treated as a disease caused by a combination of factors, some of which are manifested and others considered as latent, with an specific moment for combining themselves causing the accident under evaluation. This point of view sees the accident as this specific combination of “agents” and environmental factors that create an appropriate environment to its occurrence. These conditions have many origins: lack of norms, incomplete procedures, contradictory messages, production pressures, responsibility indefiniteness, inappropriate training, maintenance lack, deficient technology and so on. All of this corresponds to the notion called latent conditions [1].

Therefore, using this model, when an accident occurs which the human error is the cause, two kinds of errors can be envolved: at first, the active errors, whose effects are generally almost imediate (as an omission or a wrong procedure use) and in second place, the latent errors, whose consequences can be dormant (latent) inside the system for a long time and can only be evident when other facts combine to violate the defense systems (as project and training). Active errors are more probable to be done by the front line personnel, as for example, control room operators or production workers, though latent are done by personnel whose tasks are distant on time and space from operational activities, as for instance, project professionals and decision working teams [5].

In other work [6], the following latent errors examples are related:

- equipment and installations bad projects;
- inefficient training;
- inadequate supervision;
- inefficient communication;
- uncertainty related on high management roles and responsabilities.

In present days though, it is not appropriate to think about accidents and incidents as a human error caused by frontline personnel. Nowadays this vision is no more acceptable for the society as a whole. Organizations must recognize the need to consider human factors as an distinct element to be evaluated and managed as a effective way of controlling risks [6].

The human factors classical definition is the scientific study of interaction between human and machine. According to Health and Safety Executive [6], human factors can be defined as environmental, organizational and working factors, and also as the human and individual characteristics which have influence over work behavior in a way that may cause health and safety prejudices. This definition includes the human characteristics, taking into account biomedical, psychological and psychosocial reasons.

The main objective of this work is to demonstrate how human factors contribute for nuclear and chemical plants accidents. In order to attain this goal, research on reports and other related documents relative to TMI, Tokaimura, Piper Alpha and Bhopal accidents was done. Human errors were identified and their human factors contributions were analyzed. Concluding remarks are done suggesting measures that should have been taken in time and that could possibly avoided accident occurrence.

Research was done based on reports and documents published by regulatory and directive international institutions of both nuclear and chemical sectors, as the International Atomic Energy Agency (IAEA), the U.S. Nuclear Regulatory Comission (NRC), the Health and Safety Executive (HSE), the American Institute of Chemical Engineers (AIChE) and other related ones.

2. HUMAN FACTORS ANALYSIS ON ACCIDENTAL SCENARIOS

In this section, accidental scenarios with great human error participation, both active as latent, will be analysed. TMI, Tokaimura, Piper Alpha and Bhopal accidents were analyzed and presented important human factors that contributed for their occurrence. An event summary and related human factors identification and analysis will be presented for each accidental scenario.

A complementary reading, with a complete description of each accident is possible to be found on referenced cited reports.

2.1 Three Mile Island Unit 2 (TMI-2)

The accident occurred in Three Mile Island Unit (TMI-2) near Middletown, Pa., on March 28, 1979. Despite it has been the most severe accident in the history of U.S. nuclear Power plants, there were no deaths or injuries to the plant workers or nearby community members. Events such as malfunctioning equipment, problems related to design and human error led to a partial core meltdown of the TMI-2 reactor, but there was very little release of radioactivity from the site.

2.1.1 Events summary

As reported in [7] and [8], the accident began about 4:00 a.m. on March 28, 1979, when the plant suffered a failure in the secondary system, on the non-nuclear section of the plant. The main feed water pumps stopped working, caused by both mechanical and electrical failure, which prevented the steam generators from removing heat. First the turbine, then the reactor automatically shut down. Immediately, the pressure in the primary system (the nuclear portion of the plant) began to increase. In order to prevent the excessive pressure, the pilot-operated relief valve (PORV), located at the top of the pressurizer, opened. The valve should have closed when the pressure decreased by a certain amount, but it did not. Signals available to the operator failed to show that the valve was still open. As a result, cooling water leaked through the valve stuck in the open position causing a overheating in the reactor core.

As coolant flowed from the core through the pressurizer, the instruments available to reactor operators provided confusing information. There was no instrument that showed the level of coolant in the core. Instead, the operators judged the level of water in the core by the level in the pressurizer, and since it was high, they assumed that the core was properly covered with coolant. In addition, there was no clear signal that the pilot-operated relief valve was open. As a result, as alarms rang and warning lights flashed, the operators did not realize that the plant was experiencing a loss-of-coolant accident. They took a series of actions that made conditions worse by simply reducing the flow of coolant through the core.

Because adequate cooling was not available, the nuclear fuel overheated until the point to rupture the zirconium cladding (the long metal tubes which hold the nuclear fuel pellets) and the fuel pellets began to melt. Later, it was found that about one-half of the core melted during the early stages of the accident.

Although the TMI-2 plant suffered a severe core meltdown, the most dangerous kind of nuclear power accident, it did not produce the worst-case consequences that reactor experts had long feared. In a worst-case accident, the melting of nuclear fuel would lead to a breach of the containment building walls and release massive quantities of radiation to the environment, but this did not occur.

2.1.2 Human factors related

This analysis was based on reports [7] and [9], which deal with the Accident Investigation. To complement this analysis, another report [10], which also makes important observations about the accident, was also examined.

After analysis of human factors associated to the events, the following weaknesses were observed:

Inadequate responses to previous incidents / ineffective communications
A near miss at another unit was not communicated to this unit.

Inadequate supervision and Maintenance / administrative lack of supervision

- Maintenance failures had occurred 2 days before. Two block valves were left in the closed position after maintenance. No steps had been taken to prevent them recurring;
- The warning light showing valves closed was covered by maintenance tag.

Poor design of plant and equipment
Turbine trips. Subsequently, PORV sticks open.

Decisions-making / low skill and competence levels of operators.
The operator reduced a throttling (curtailment) of the high-pressure injection (HPI) of water into the reactor coolant system. If they had left as before, the HPI would be allowed to operate automatically as planned and the reactor core would have remained covered.

Training for operators not adequate

- At TMI only two hours per year were dedicated to training the operators on operational problems and from experiences at other reactor plants (lessons learned from other accidents);
- They were not able to recognize the relationship between the temperature and pressure of the water in the primary circuit, and to understand it was boiling.

Human-machine interface poor design

- Operators deceived by control panel. During the first minutes of the accident, more than 100 alarms were sounding, and it was not possible to suppress the less important ones in order to let the operators focus on the main issues;
- The light indicators of the PORV valve were not connected to the actual position of the valve, and this provided false information to the operators, leading them to think that the valve was closed while it was stuck open;
- Some key indicators were placed in inappropriate places. In normal conditions the operator could not even see them;
- The information was not presented in a clear and simple way. For example, even if the pressure and temperature of the coolant of the reactor were shown, there was no indication that the combination of the two meant that the water was turning into steam.

Another factor that also contributed to the accident in a general way was the way the shifts in which the operators were organized. It was inappropriate because long-duty periods or sleep loss reduce the physical and mental capacity of even the best-trained operator.

2.2 Bhopal Accident

On December 3 of 1984 more than 40 tons of the methyl isocyanate (MIC) gas leaked from a pesticide plant in Bhopal, India, immediately, it killed at least 3,800 people and caused significant morbidity and premature death of thousands more. This accident was the worst in the history of chemical industry.

2.2.1 Events summary

According to the report [11], on December 2 of 1984 at 11:00 p.m., while most of the one million residents of Bhopal slept, an operator at the plant noticed a small leak of the methyl isocyanate (MIC) gas and an increasing pressure inside the storage tank. Apparently, a faulty valve allowed a ton of the water used to clean internal pipes to mix with forty tons of MIC.

The depurator system used in the vent-gas scrubber, which is a safety device responsible for neutralize toxic discharge from the MIC system, had been turned off three weeks before. A refrigeration unit of 30 tons that normally served as a safety component to cool the MIC storage tank had been drained from its coolant for use in another part of the plant.

Pressure and heat from the vigorous exothermic reaction in the tank continued to build. The flare gas safety system was out of action and had been for three months. Around 1:00 a.m., on December 3rd, a loud noise echoed through the plant when a safety valve released a plume of MIC gas into the early morning air. Within hours, the streets of Bhopal were littered with human corpses and the carcasses of buffaloes, cows, dogs and birds. An estimated 3,800 people died immediately, mostly in the poor slum colony adjacent to the plant. Local hospitals were soon overwhelmed with the injured, a crisis further compounded by a lack of knowledge of exactly what gas was involved and what its effects were. It became one of the worst chemical disasters in history and the name Bhopal became synonymous with industrial catastrophe.

2.2.2 Human factors related

This analysis was based on an AIChE report [12] that deals with accident investigation.

Do not need a deeper analysis to observe that the main causes of the accident focused on *management decisions*:

- a decision to store 10 times more methyl isocyanate than required on site;
- a decision to deep cuts in manning levels;
- a decision to neglect a flare system in need of repair;
- a decision to place a scrubber system on stand-by to save on operating expenses;
- a decision to remove coolant from the refrigeration system used to cool the MIC storage tank to reduce costs.

Facts that made the accident even more severe were due to *planning*:

- inadequate emergency planning and community awareness;
- lack of conscience awareness of the potential impact of MIC on the community by the people operating the plant;
- lack of communication with community officials before and during the incident;
- inadequate community planning, allowing a large population to live near a hazardous manufacturing plant;
- insufficient attention to safety in the process design.

According to other report [13], in other human factors involved in the events, the following weaknesses were observed:

Maintenance

- Inadequate maintenance was a longstanding complaint at the Bhopal plant. The poor maintenance of the major safety systems has already been described;
- No regular cleaning of pipes and valves;
- According to the workers, leaking valves and malfunctioning gauges were common throughout the facility [13];
- A likely source of the water was a faulty maintenance.

Training

Training was a major problem at the Bhopal plant. The worker said that they had been given little or no training about the safety and health hazards of MIC or other toxic substances in the plant; they thought the worst effect of MIC was irritation of the eyes [13].

Procedures

- Language also may have contributed to the misunderstanding about MIC and other hazards. All signs and operating procedures were written in English, even though many of the workers have spoken only Hindi;
- Poor evacuation measures;
- Dangerous and irresponsible operating procedures.

Communications

No alarm sounded properly to warn of gas cloud.

Equipment

- Flare tower disconnected;
- Vent gas scrubber in inactive mode;
- No gas masks available.

Human Machine Interface

- No online monitor for MIC tasks;
- No automatic sensors to warn the temperature increase.

As can be seen, the circumstances in which the accident occurred in Bhopal, regarding to human errors, are different from those of the TMI accident. At TMI was observed a predominance of active errors, while in this, were predominant latent errors.

2.3 Accident in Piper Alpha

2.3.1 Events summary

On July 6 of 1988, the Piper Alpha oil platform has suffered a series of catastrophic fires and explosions. This platform, located in the North Sea, about 110 miles from Aberdeen, Scotland, had 226 people on board at the moment of the event, which 165 died and furthermore, two employees from emergency response died during efforts to rescue. The platform was completely destroyed.

Subsequent investigation was hindered by a lack of physical evidence; however, based upon eyewitness accounts it was concluded that, most likely, a release of light hydrocarbon (condensate; i.e., propane, butane, and pentane) occurred when a pump was restarted after maintenance [14].

Without the knowledge of staff who installed the pump, a relief valve in the output of the pump had been removed for maintenance and instead had been installed on a superficial way a pipe of blind flange (a flat metal disk), which was not clearly visible at the pump. The night shift engineer found the “permit-to-work system” for the routine maintenance but not that of the pressure valve. After the pump has been turned on, there was a leakage from the flange, producing a cloud of flammable hydrocarbons, which found an ignition source.

The Piper Alpha platform was at the hub of a network of platforms interconnected by oil and gas pipelines. The initial explosion ruptured oil lines on Piper Alpha and the leaks were fed by the still-pressurized inter-platform pipelines. Managers on other platforms who were aware of a problem on Piper Alpha (but not its severity) assumed that they would be instructed to shut down their operations, if needed. However, the explosion had interrupted communications from Piper Alpha and considerable intervals (from 30 to 60 minutes) passed before these other platforms were shut in.

A series of follow-on explosions occurred as the fires on the platform weakened natural gas riser pipelines on Piper Alpha. The intensity of the fires prevented rescue efforts, either by helicopter or by ship. At the height of the event, natural gas was being burned on Piper Alpha at a rate equivalent to the entire United Kingdom natural gas consumption rate.

Many of the platform crew retreated to the crew accommodation module, as they had been trained, to await evacuation. No organized attempt was made to retreat from the accommodation module, even though it became increasingly apparent that the conditions in the module were becoming untenable. 81 persons died from smoke inhalation in the crew quarters, awaiting further instructions that never came. The survivors found ways, on their own initiative, to get to the water (some jumping to the sea from considerable heights on the platform).

2.3.2 Human factors related

A superficial analysis of the events that followed, it is found that the accident was caused by an accumulation of errors and questionable decisions. Most of them were rooted in the organization, its structure, procedures, and culture. The failure resulted essentially from an accumulation of management errors. One of the conclusions Pate-Cornell [15] has arrived at was that human errors, questionable decisions, and bad judgments that have been identified above and contributed to the accident can therefore be divided into the following categories:

- questionable judgment in the management of productivity vs. safety;
- flaws in the design philosophy and the design guidelines;
- production and expansion decisions;
- personnel management;
- insufficient attention to maintenance and inspection.

After a detailed review of the facts which led to the accident, and based on the reports [14] and [15] and as a subsidy the work [16], the following human factors can be pointed out as deficient:

Communication

The change of shift was not systematically done. There was failure of communication when writing “permit-to-work system” (two were produced for the same pump). A piece of equipment (a critical pump with one redundancy) had been turned off for repair and the night crew that operated the platform had not been informed of it. This problem, in turn, was mostly a failure of the “permit-to-work system” that did not ensure proper communications.

Supervision / Inspection

- The blind flange that was installed in the place of the pressure valve was not leak tight. Therefore it could not stand the high pressures. There was no inspection after fitting and this could have led to early leaks;
- Inspection on Piper Alpha appears after the fact to have been lacking in many areas, particularly in safety equipment, life rafts, fire pumps, or emergency lighting do not seem to have received proper attention.

Training

There were not enough qualified and trained personnel on board at the time of the accident. Operators were not trained on upset conditions.

Human Machine Interface

- In the control room the monitoring panels were not clearly visible and one could not easily warn where the alarms originated from;
- There were very non-critical alarms that lead the control operators to ignore the series of alarms after the first explosion. There are guidelines for designing alarms.

Maintenance

Maintenance error that eventually led to the leak was the result of inexperience, poor maintenance procedures and poor learning by the organization. The most critical maintenance problem was the failure of the permit-to-work system and the carelessness with which the valve was removed and replaced by a blind flange assembly without proper tagging, thereby putting pump out of service. The night shift was not informed of this situation and tried to restart this pump in which the initial leak seems to have started.

2.4 Accident in Tokaimura

2.4.1 Events summary

As reported by IAEA [17], on 30 September, 1999 at 10:30 a.m. a criticality accident occurred in the conversion building (auxiliary plant) at the uranium conversion facility of JCO Company Limited in Tokaimura, Japan. The main function of the plant is to convert isotopically enriched Uranium hexafluoride into uranium dioxide fuel. This is one step in the process of making reactor fuel rods.

A solution of enriched uranium (18.8% ^{235}U by mass) in an amount reportedly several times more than the specified mass limit had been poured directly into a precipitation tank, bypassing a dissolution tank and buffer column intended to avoid criticality. In order to speed up the process, they mixed the oxide and nitric acid in stainless steel bucket rather than in the dissolving tank. This new way of operating followed instructions in the JCO operating manual which had not received Japan’s Science and Technology Agency (STA) approval. After the Licensing process in fact, no inspection or periodical audit was performed by the competent authority. The total amount of enriched Uranium poured from the bucket directly into the precipitation tank was about 16.6 kg (the precipitation tank was designed for 2.4 kg of uranium per batch).

This action was reported to have been in contravention of the legally approved criticality control measures. The sequence was a flash of blue light inside the plant as the result of what has been called a nuclear fission chain reaction. The Tokyo Electric Power Company rushed 880 pounds of sodium borate to the plant to absorb the radiation emitted, but the workers had difficulty getting close to the processing tank. The two technicians near the vessel began to experience pain, waves of nausea, difficulty in breathing, and problems with mobility and coherence. The gamma radiation alarms activated immediately. The blue flash was a result of the Cherenkov radiation that is emitted when nuclear fission ionizes air.

This has resulted in the overexposure of several workers, two of whom had as a consequence reportedly suffered very severe acute radiation syndrome, and one other to a moderate degree. Members of the public had received radiation doses too.

2.4.2 Human factors related

In a preliminary evaluation, it is observed that the accident at the JCO nuclear fuel processing facility in Tokaimura seems to have resulted primarily from human error and serious breaches of safety principles, which together led to a criticality event.

Based on the cited reports [10, 17] one can conclude that the following human error related problems have occurred:

- The JCO had modified the procedure approved by the Japan’s Science and Technology Agency (STA) for processing highly enriched Uranium, in order to speed up the production and the workers were following this “unlicensed procedure”;
- In Japan, periodic inspection during operation seems not to be a legal requirement for facilities of this type. The competent authority never performed any periodic inspection on the facility;
- The procedures used were completely different from the one specified for the equipment and methods used, and were not approved by the regulatory authorities;
- Shortcuts in the procedure recommended the use of stainless steel buckets to move the uranium and mix manually instead of using the means that were specifically designed for such task;
- The company trained new employees on safety for one week but taught nothing about the dangers of a self-sustaining nuclear reaction;
- Before the accident, supervisor(s) and, possibly, manager(s) directed personnel to accelerate processing further. Apparently, workers were directed to use the buckets, over batch (processing two “orders” for nuclear fuel into one process in order to save time and increase profits), and possibly, skip other steps. Being under time pressure is one of the environmental conditions that raises error probability;
- The company also failed to install basic defensive measures, such as alarms or high walls, to alert and protect the neighboring residential area. These cost-cutting measures undertaken by the company clearly undermined the safety of its employees and the populace of Tokaimura.

3. MEASURES THAT COULD HAVE AVOIDED THE ACCIDENTS

In this section, human factors related measures that could have been taken to avoid the accidents or to minimize their consequences are presented.

Written procedures

Many human errors can be prevented by ensuring clear, accurate procedures exist and by management reinforcing that the procedures must be used and followed. This will help reduce worker's reliance on skill and memory to perform a task, assist workers in decision making and to help ensure a given task is performed consistently. These procedures should be reviewed and approved by the competent authority. Procedures not approved or unauthorized must not be used, as was the case of Tokaimura. This could have been prevented if regular inspections in the facility by the authority that had licensed the plant were foreseen [19].

Emergency operating procedures

The use of properly prepared procedures in plant operations is another important ingredient in the matrix of operational safety. Emergency operating procedures should consider system interactions and be written in such a manner that they are unambiguous and useful in crisis control.

Maintenance errors

As was mentioned by Health and Safety Executive [6], the factors that can lead to human error in maintenance are basically the same as for other types of job. To avoid such errors and encourage good performance in maintenance work, it is important to have at least the following:

- Enough competent people to carry out maintenance work and to check work done;
- Adequate supplies of spares and consumables;
- Good communications between the group and the management specially a good "permit-to-work system";
- Systems for investigating problems that occur and for making improvements;
- Structured processes to identify and assess human error potential in safety critical maintenance tasks (and to reduce this potential).

Inappropriate training on the emergency response

It was a common problem in all accidents. The training also should prepare operators of hazardous activities as problem solvers, since it is not possible to "foresee everything that will go wrong and write instructions accordingly" [18]. Everyone connected with nuclear power technology or chemical process must accept as a fact that unusual situations can occur and accidents can happen. Operations personnel in particular must not have a mindset that future accidents are impossible [10].

Control room

In the particular case of the TMI accident, few and relatively inexpensive improvements in the control room could have significantly facilitated the management of the accident. Human factors design is a vital aspect of safety operation of a Nuclear Power Plant [10]. It is always recommend the implementation of Human Factors principles, primarily the ergonomic aspects. Projects should consider the safety and human limitations.

Human-machine interface

Human-machine interface design take into account human capabilities and limitations regarding the design of jobs, machines, operations and work environments. The control systems and related displays should also be integrated and easily identified for the operators. In short, the operators must be provided with the knowledge and information necessary to fulfill their responsibilities. Similarly, the project must consider the safety and human limitations.

Work shifts

Chiara [10] mentions that to avoid the effect of fatigue the shifts and the turns should be carefully planned. Furthermore there are strategies, or ergonomic devices, that can be used for incrementing operator alertness. These include physical activity, light therapy with a high-intensity light box, planned naps etc.

Management commitment

For the goal of significant improvement in operational safety to be achieved, management must show a commitment to the goal through positive action. This requires, among other things, involvement of top managers in operational safety matters and a commitment to upgrade the knowledge of the fundamental technology and the hazards of the activity at all levels of their organization. It’s possible to improve processes and equipment if the relationship of the management with the front line is not the one-way communication type.

Personnel training and qualification

A requirement to improved operational safety is an improvement in the qualifications of personnel. In the case of nuclear facilities is a complex technology that demands highly competent personnel at all levels. A principal element in achieving the desired level of competence is training. Once a level of competence is achieved, it must be continually reinforced. Thus, training should be an ongoing process. Utility management must assure itself that personnel occupying all positions are able to perform the tasks required of them in normal and accident situations.

Time pressure to accomplish the task

This problem was observed in Tokaimura and also in some situations in Bhopal. Being under time pressure is one of the environmental conditions that raise error probability

4. CONCLUSIONS

The obtained results with the carried out accident reports analyses confirm that introductory theory of this work. The present human error concept do not support human error attribution to frontline personnel, as process operators or maintenance technicians. The present way to prevent these accidents is based on anticipated identification of organization and system latent errors. The analyzed accidents demonstrate that human error is not only present on operator interventional actions, but on a series of failures which remain latent until the moment when they are activated by a local problem, as for instance, a pressure or temperature raising.

An interesting fact was observed during this research, is that the common conclusion of all these reports is related to human factors, operational personnel qualification and training, human element integration in the project, regulatory and operation of safety systems in the installation.

Finally it can be concluded that human factors principles integration though all the project, including construction, operation, maintenance and tests aspects, will improve in a significant way the installation safety management.

Suggestions for future work

A more complex analysis involving accidents in which human error has an important role in other areas such as aviation, medicine and flow of vehicles is to be published elsewhere.

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