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Safety Integrity Level (SIL) Integrated with Human and Organizational Factors

Ana Paula A. V. Melo*[a], Paulo Fernando F. F. e Melo[b], Márcio Nele[c]

[a]UFRJ, School of Chemistry, Federal University of Rio de Janeiro, RJ, Brazil
[b]COPPE, Nuclear Engineering Program, Federal University of Rio de Janeiro, RJ, Brazil
[c]UFRJ, School of Chemistry, Federal University of Rio de Janeiro, RJ, Brazil
anaufrj@yahoo.com.br

From many accident/incidents analysis, human and organizational factors have been identified as root causes or contributing factors. Therefore, in order to actuate preventively, many methodologies have been proposed for the quantification of these factors in organizations.
Due to the advances of digital computing over the last decade, industries have increased the number of installed safety instrumented systems (SIS), which are instrumentation and controls installed in order to bring the process, or equipment to a safe state. However, after plant start up, these SISs may be adversely affected by human and organizational factors and may not reach, at the operation phase, the safety integrity level (SIL) calculated at the design phase.
A methodology about the control of human and organizational factors in SIS operational phase is applied in a case study in a liquefied natural gas (LNG) plant. Through the case study the human and organizational factor(s) that most impacted the SIS in the unit could be identified and thus, these problems could be preventively eliminated. It was also possible to calculate the operational SIL and compare it with the design SIL.

1. Introduction

Many studies have been proposed to quantify human and organizational factors that affect the safety of a plant in operation, in order to actuate on them preventively.
Safety instrumented systems (SIS) are basically safety systems of an industrial unit, composed by sensors, logic and final elements. With the advancement of technology, SISs are increasingly automatic and complex. Due to this increased complexity, some questions have arisen in respect to the actual level of protection provided by SIS. Given this scenario, several standards on SIS development, design and maintenance have been issued.
The standard IEC 61508 (1998) was developed to serve as a guide to help various industries to develop additional standards for specific applications (e.g. IEC 61511 (1998) for the process industry) and also to enable developing electrical / electronic / programmable electronic (E / E / PE) systems related to safety. IEC 61508 (1998) defines the risk reduction that a SIS can provide, and it is represented by the safety integrity level (SIL). Then, in the design phase of a plant, the design SIL is calculated. However, a good safety management of the plant cannot improve the safety integrity level of SIS, but a poor management or an inadequate assessment of human factors can deteriorate the system reliability (Fanelli, 2010).

2. Safety Integrity Level (SIL)

Safety integrity levels (SILs) are categories based on the probability of failure on demand (PFD) for a particular safety instrumented function (SIF). The category of failure probability is from 1 to 4, as defined in IEC 61508 (1998, 2000) and IEC 61511 (2003). According to IEC 61511 (2003), SIL 4 is the highest system integrity and SIL 1 is the lowest.

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Although IEC 61508 (2000) considers the life cycle, which also includes operation and maintenance phases, there is a small focus on how SIL is maintained, at the desired level, during the plant operation. The performance of the safety instrumented system in the operational phase is influenced by many human factors, not only design, testing and maintenance strategies, but also the system operating conditions, which include both human and organizational factors. These factors may reduce the SIL achieved during the operation phase, but usually are not taken into account (Schönbeck, 2007).

3. Impact of human and organizational factors on plant safety

Many authors have studied the connection between human and organizational factors with accidents/incidents. According to Salvi and Debray (2006), 80 % of major accidents have causes related to human and organizational factors. According to Paté-Cornell et al (1996), the most severe accidents have been shown to involve one or more human errors, usually related to management issues. Jacobsson et al (2009) examined the major industrial accidents from 1992 to 2005 and found that a large percentage (range 50-80 %) of these accidents was caused by a deficiency in the safety management system and safety culture. According to Nunes (2002), human error related to lack of training is one of the main causes of accidents in industrial activities. To prevent incidents / accidents and control risks, companies develop sophisticated systems and new technical solutions. However, in order to have a good and effective control the behaviour of workers and managers must be systematically checked.

3.1 Verification of human and organizational factors of safety instrumented systems

Schönbeck (2007) reviewed models and theories related to human and organizational factors and adapted them to create a new approach. He also proposed to consider the impact of human and organizational factors in safety instrumented systems.

Using the relationships between basic life cycle processes and the eleven general failure types (Reason, 1990), he reduced the general failure types to eight and slightly reformulated them, in order to reflect human and organisational factors in the operational phase of safety instrumented systems. They are: Maintenance management, procedures, error enforcing-conditions, housekeeping, goal compatibility, communication, organization and training. They were called safety influencing factors. Some of these factors were also identified by other authors as relevant points that need to be checked, such as: communication, considered by Gordon (1998), training, communication, considered by Paté-Cornell et al (1996); maintenance, considered by Hurst et al (1996) in the PRIMA project; procedures, housekeeping, training, communication, considered by Hale et al (2010).

The author proposes the calculation of SIL during the operational phase of a plant, called operational SIL, which may be lower than the design SIL, obtained in project development, due to human and organizational factors in SIS operation phase. His methodology starts with the design SIL. The first step is to estimate the proportion of the SIL design, which can be explained by human and organizational factors. Some SISs are more sensitive to human and organizational factors than others. This ratio is denoted by θ, which may be estimated using expert judgment or may be based on experience with similar systems.

In the second step, a relative weight ($\tilde{\omega}_i$), (($\tilde{\omega}_i$) ≥ 0 for all i = 1,..., 8) is assigned for each safety influencing factor i. This relative weight can be established as part of a safety audit, or can be assigned to the application domain (e.g.: offshore) using expert judgment (Schönbeck, 2007).

After establishing the relative influence of each factor, these weights are normalized by Equation (1) (Schönbeck, 2007):

$$Wi = \frac{\widetilde{W}i}{\sum_{i=1}^{8} \widetilde{W}i} \tag{1}$$

The third step is to rate the safety influencing factors using checklists and questionnaires through an audit, preferably questions with answers "yes" or "no". Each safety influence factor is rated on a scale from 0 to 1, where zero indicates that improvements are unnecessary and the opposite, further improvements are required. Then the number of questions answered that do not cause concern are divided by the total number of questions, and this fraction is subtracted from 1, obtaining (*Ri*).

The fourth step is the calculation of operational SIL using Equation (2) (Schönbeck, 2007).

$$operational\ SIL = (1 - \theta \sum_{i=1}^{8} WiRi)\ design\ SIL \tag{2}$$

Step five provides a guide for corrective and preventive actions. The safety influencing factor with the highest rate (R_iW_i) contributes more to the difference between the design SIL and the operational SIL, so it requires more attention.

4. Objective

The safety integrity level, calculated during the design phase of an LNG plant, is related to human and organizational factors in the operation phase of this plant, and a new operational SIL is calculated. The goal is to understand how or if these factors can affect the design SIL.
The study was conducted in the liquefaction unit of natural gas that is installed and has been operating in Paulinia (São Paulo, Brazil) for five years. This unit has a liquefaction plant, LNG storage tanks and pumps for truck filling. For confidentiality reasons, the plant name will not be revealed.

5. Methodology – Case Study

This section describes the methodology for calculating the operational SIL to an LNG plant. The five steps previously discussed are described in detail.

5.1 Step 1: Estimate θ

The first step of the methodology is to estimate the portion of the design SIL that can be explained by human and organizational factors, denoted by θ. Depending on the system design and operating conditions, some safety instrumented systems are more sensitive to human and organizational factors than others.
The design SIL of one of the safety instrumented function of the LNG plant is SIL 2, and it contains the following safety instrumented systems: a pressure gauge, temperature indicators, a high temperature alarm, a high temperature switch, a controller, a low flow switch and an automatic valve with position indicator. It was decided to adopt the same assumption as the author, who in his illustrative case considered $\theta = 0.5$, derived from the incident investigation process industry (Hurst el al, 1996; Papazoglou et al, 1999).

5.2 Step 2: Weight the safety influencing factors $\tilde{\omega}_i$ and calculate normalised weight factors $\tilde{\omega}_i$

The second step is to assign a relative weight ($\tilde{\omega}_i$) (($\tilde{\omega}_i$) ≥ 0 for all i = 1, ..., 8) for each safety influencing factor i. The same influencing factors considered by Schönbeck (2007) were used, but it was decided to group the factors “housekeeping” and “organization”. The term organization often has been used as a synonym for housekeeping (Siqueira, 2011). There were obtained then, seven safety influencing factors, which are presented in Table 1.

Table 1: Safety influencing factors in the operational phase of safety instrumented systems.

Safety influencing factor	Description
1 – Maintenance Management	Management, rather than execution, of maintenance activities
2 – Procedures	Quality, accuracy, relevance, availability and workability of operating, and maintenance procedures
3 - Error-enforcing Conditions	Conditions that force people to operate in a manner not foreseen during system design
4 –Housekeeping/Organization	Orderliness in the workplace
5 – Goal compatibility	Compatibility of goals at and between individual, group, and organizational level
6 - Communication	Possible lack of communication due to system failures, message failures, and misinterpretation
7 - Training	Specific expertise relevant to operators’ jobs

Once there was no evidence that points to the opposite, as suggested by Schönbeck (2007), it was established that all influencing factors have the same importance. Therefore, the relative weights of each factor i, ($\tilde{\omega}_i$)) = 1.

Using Equation (3), these weights are normalized.

$$Wi = \frac{\widetilde{Wi}}{\sum_{i=1}^{7} \widetilde{Wi}} \tag{3}$$

Replacing the values Equation (3), *Wi*=0,143.

5.3 Step 3: Rate the safety influencing factors (*Ri*)
In order to calculate the *Ri* rate, checklists were developed for each safety influencing factor i.

5.3.1 Checklists Development
Checklists containing ten to fifteen questions were developed for each safety influencing factor listed in Table 1. For the checklists development, questions were based on the concepts of each safety influencing factor as well as on some references, such as: Gruhn and Cheddie (2006); datasheet from FM Global, a insurance company that partners with companies to support the objectives of risk management (FM-Global, 2011); the site of risk and safety management (AcuSafe, 2011); Mann- Hummel website (Mann-Hummel, 2011), which develops, manufactures and markets complex automotive components for enhancing the importance of safety, cleanliness and organization of the company, Salas et al (2006), which contains a checklist on management resources and organizational factors; Souza (2011), which presents some checklists as a means of identifying hazards and the Instructions of safety, environment and health for Petrobras contractors (Petrobras, 2011).
On the checklists heading there is a field to indicate how long the interview was and another one to indicate the work area of worker. There is no field to identify worker's name.
The questionnaires contained only objective responses (positive, negative or not applicable) to facilitate subsequent verification of responses and accelerate the audit process.

5.3.2 Safety influencing factor (Ri) measurement
On 11/30/2011 workers from the LNG plant were interviewed, using the checklists developed to measure the rate of the safety influencing factors *Ri*. Seven workers from operation, four workers from maintenance and one operation supervisor were interviewed. The average time spent per interview was 20 minutes. At the beginning of the day, before the interviews, it was explained to them that the goal of the interviews was to identify if any improvement was needed in the plant. It was informed to them that the interview would not last so long, because there were only affirmative or negative answers. The total number of plant workers was four maintenance workers, one operation supervisor and thirteen operators. On 11/30/2011 all available employees were interviewed.
The only influencing factor not applicable to all workers was "Maintenance Management". It was applied only to maintenance workers and to operation supervisor. All other factors were applicable to all workers.
The rate of each influencing factor from Table 1 was measured during an audit using the checklists. The number of indicators that did not need improvement was divided by the total number of applicable questions used for this safety influencing factor and then this fraction was subtracted from 1, providing the rate Ri for safety influencing factor i. It was subtracted from 1 because 0 means the best and 1 the worst rate.
For example, for the safety influencing factor "Maintenance Management", applicable to the four maintenance workers and the operation supervisor: a worker answered that three questions (of twelve) were not part of his routine and he answered positively to the other nine questions, two other workers answered one question negatively and the other eleven questions positively and the other two workers answered positively to the twelve questions, so Ri= 0,035.
A similar calculation procedure was executed for all the other six factors analyzed. The obtained values are shown in Table 2 (second column).

Table 2: Results of safety audit using the checklists and weight rate of safety influencing factor (WiRi)

Safety influencing factor	*Ri*	*WiRi*
1 – Maintenance Management	0.035	0.005
2 – Procedures	0.035	0.005
3 - Error-enforcing Conditions	0.02	0.003
4 –Housekeeping/Organization	0.00	0.000
5 – Goal compatibility	0.031	0.004
6 – Communication	0.007	0.001
7 - Training	0.016	0.002

5.4 Step 4: Operational SIL Calculation
The fourth step is to calculate the operational SIL, which was obtained by using Equation (4):

$$operational\ SIL = (1 - \theta \sum_{i=1}^{7} WiRi)\ design\ SIL \quad (4)$$

An operational SIL= 1.98 was obtained. The result of Equation (4) is approximated to the nearest integer value, so it was set equal to 2.

5.5 Step 5: Preventive and Corrective Actions
Step five provides a guide for corrective and preventive actions. The influencing factor with the highest weight (*WiRi*) contributes more to the difference between the design SIL and the operational SIL, so more attention is needed (Schönbeck, 2007). Table 2 (third column) shows that the safety influencing factors that had the highest weight rate (*WiRi*) were "Maintenance Management" and "Procedures", followed by "Goal Compatibility", "Error-enforcing Conditions", "Training" and "Communication". Housekeeping/Organization got weight rate equal to zero.

6. Conclusions

Using the checklists, through the interviews, it was possible to achieve the goal and calculate the operational SIL of a SIS in a LNG plant in operational phase. At the beginning of interviews, workers were a little nervous, however, once they began to answer the questions of the questionnaires, they realized that there was no identification and that the goal of the questions was to help them. So, they felt more comfortable.

Interviews were made quickly, 20 minutes for each worker, since the workers had to meet their daily activities. As the answers were objective, it helped speeding up the interviewing process.

Although the approach to an integer value, the results of interviews indicate that the LNG plant keeps the same value of design SIL in the operation phase, demonstrating that there is no reason to question the correct administration of human and organizational factors. No factor that presented an imminent danger was identified. For the visit and interviews performed, it was noted that the work area was well organized, clean and tidy. It was also realized an enormous commitment of workers to safety, a fact that was corroborated by the interviewing results.

It was observed that the methodology of Schönbeck (2007) is useful to check whether human and organizational factors are negatively impacting the safety instrumented systems and to indicate which safety influencing factor needs more attention, working as a guide to corrective or preventive actions.

Regarding safety influencing factors, "Housekeeping/Organization" had a very good result, since all questions were positively answered by all workers. The safety influencing factor that showed the worst results were "Procedures" and "Maintenance Management". About the factor "Procedures", the question that had two negative responses was "Maintenance procedures are detailed enough and they are easy to understand, in order to avoid any bad-interpretation or important decision for maintenance workers?" The other influencing factor, "Maintenance Management", obtained two negative answers for the question "Management invests in preventive maintenance of equipment?" In third place was "Goal Compatibility" which had two negative responses to the question "Is there management support with respect to incentive training of workers?" This information should be used as a starting point for a deeper analysis of these safety influencing factors.

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