

Resilience Engineering Strategy Applied to an Existing Process Plant

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Resilience of a system can be defined as a set of behaviours and strategies allowing the creation of a proactive defence against disturbances and interruptions that threaten the system integrity. In analogy with the widely applied methods concerning risk assessment and inherent safety, in this paper we propose a semi-quantitative resilience evaluation framework. Starting from the basic dynamic concept defining resilience as the ability of a whole process system to cope with adverse events, a set of resilience indicators is presented to determine how resilient a process is, both from the technical and the organizational viewpoints. As a case-study, the approach is applied to an existing integral process industry, in order to manage risks through prevention, reduction and mitigation by focusing on the so-called detection potential factor.

1. Introduction

The concept of resilience is gaining more and more emphasis in current safety science, technology and management. Looking at the different definition of resilience we can observe that it can be considered both reactive and proactive. In fact, as summarized by Hollnagel et al. (2006) resilience is the ability to manage great pressure, as well as conflicts between safety and production objectives. We must underline that, especially when dealing with existing plants where consolidated processes are performed, the application of inherent safety criteria is still an up-to-date research topic (e.g. Fabiano et al., 2012), while the safety standard implementation and optimal investment on prevention and mitigation measures require developing special approaches (Abrahamsen et al., 2013). The starting point for this study was the analysis of a severe incident in a coke production plant, involving fire and gas explosion scenario. As amply known, coke is a very strong macro-porous carbonaceous material produced by the carbonization at temperatures higher than 1,400 K of a single coal grade or coal blends. In the integrated steel manufacturing industry, approximately 90 % of coke produced from blends of coking coals is used to maintain the iron production process in a blast (Diez et al., 2002). Typically, 1.25–1.65 t of coal produces 1 t of coke, while generating approximately 300–360 m³ of coke oven gas (COG) (6–8 GJ/t coke). The by-product COG is a flammable and explosive gaseous mixture widely used in a large number of plant of the process and power sectors. Its inherent hazards pose a serious threat to lives and properties so that the effective control and prevention of COG releases is still an up-to-date topic. On this basis, in this paper we first performed a statistical analysis on accidents and near-misses in the considered industrial setting, so as to identify the critical plant sections, where the contributing factors of process resilience were thoroughly analyzed. Secondly, considering the case where a hazardous release from the piping system leads to possible fire/explosion scenarios, the key contributing resilience parameters (namely early detection and controllability) are identified and quantified, by applying a proper mathematical model suitable to evaluate the maximum allowed hazardous build-up under semi-confined geometry.

2. Resilience framework

Starting from the above mentioned concept of resilience, a further more technical definition can be based

on the intrinsic ability of a system to adjust its functioning prior to, or following changes and disturbances. In this way, it can sustain operations even after a major mishap, or in the presence of continuous stress. At last, resilience is the organization's ability to retain, or recover rapidly a stable condition, enabling it to pursue its activities during or after a major accident, or in the presence of great and on-going pressure (Hollnagel et al., 2006). Based on the above and taking into account a recent paper (Dinh et al., 2012), following resilience variables (RV) were hypothesized: Flexibility, Controllability, Early Detection, Vigilance, Training, Awareness e HSE management. As shown in Figure 1, the resilience recovery factors (RRF) suitable to quantify at a preliminary level the variables are as follows: Design Factor; Detection Potential Factor; Human Factor and Safety Management System. In the following, a preliminary empirical application is performed considering a peculiar scenario of gas fugitive emission in a process plant, with an inherent potential of developing into a serious accident. The applicative case-study is connected to a real incident involving COG fire and explosion within an integrated steel industry, in the coal dry distillation plant under steady-state conditions, with immediate cause connected to a release from the piping system feeding the oven batteries.

3. From accident statistics to resilience factors

While looking back at incidents is by no means a novelty in the safety field, a novel challenge is connected to the possibility of identifying key elements pertaining to resilience. We adopted the database FACTS managed by the Unified Industrial & Harbour Fire Dept Rotterdam-Rozenburg-NL, containing more than 24,300 records of industrial accidents with hazardous materials that caused, or could have caused serious damage and/ or that constituted a serious threat. A previous study on the whole coal sector, showed that to the highest percentages of accidents correspond to Explosion (56 %), followed by Fire (30.8%) and Release (13.2 %) (Fabiano et al., 2014). The classification of each accident involving COG in similar industrial settings, was performed in analogy with the approach outlined in a previous work (Fabiano and Currò, 2012), exploring the period from early 1930s to 2012 and considering three macro-categories respectively connected to structural cause (plant/process, code PPR), natural cause/working environment (environment, code ENV) and human factor (organization, code ORG). Under the headline Plant/process are grouped the possible causative factors directly connected to hardware and inherent characteristics of the process. The area Organization collects causative factors related to human factors at different levels and to the safety management system/safety culture. Under the headline Environment were included natural events, domino effects, items related to work place lay-out, machine safety, ergonomics and other environmental conditions. The main direct causes described in the results above are connected under the headline Plant/process and Organization, while Environment contribution is negligible. Following PPR factors were identified, in decreasing order of importance: "Component failure/malfunction"; "Failure/malfunction of equipment and control system" and "Failure/damage to reactors, vessels, equipment". Within the ORG macro-area the main direct causes are "Worker error"; "Absent/inadequate supervision"; "Maintenance"; followed by "Absent, inadequate, unclear – procedures or safety training".

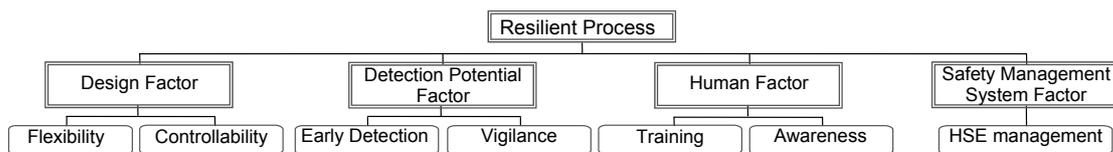


Figure 1: The basic elements of the developed resilience framework

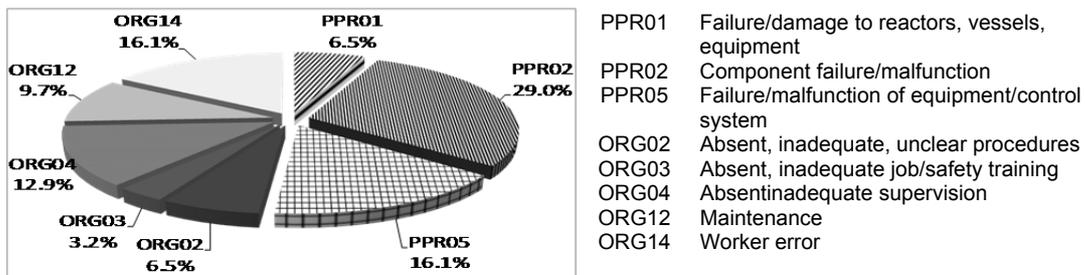


Figure 2: Main direct causes of accidents involving COG

According to a step-by step system, we try to identify how immediate causes could be linked in some kind of causal chain to underlying causes that could be connected to the resilience recovery factors previously outlined. Based on this approach, emphasis is to be placed on Detection potential factor and Human factor. The main focus of the current study was to explore the former element and the connected resilience variables (RV), namely Early Detection and Vigilance. The latter RRF is currently under investigation, by developing a case-based interview approach.

4. Theoretical

In view of improving the score of the Detection potential factor, the theoretical focus is the calculation of the allowed build-up of COG gas, here defined as the maximum amount of the flammable compound in the environment following the continuous release, evaluated on the basis of tolerable effects on human vulnerable structures in case of ignition. The allowed build-up can be identified making reference to the corresponding hazards for man inside the building, namely radiating heat exposure (rad) and overpressure (expl) according to the condition (Palazzi et al., 2011):

$$n_r^* = \min\{n_{r(rad)}^*, n_{r(expl)}^*\} \quad (1)$$

4.1 Thermal radiation scenario

In order to quantify the maximum allowed accumulation within in a semi-confined volume, in presence of ignition and combustion of the gas mixture, the following hypotheses are adopted: instantaneous mixture combustion and adiabatic combustion temperature of the smokes; thermal exchanges occurred only by radiation and conduction through the ceiling. Stefan–Boltzmann law yields the total radiant energy:

$$\dot{Q}_{rad}'' = \varepsilon \sigma T_{ad}^4 \quad (2)$$

The maximum allowed duration of exposure to thermal radiation corresponding to the threshold values of damage to humans (Mudan, 1984) is:

$$t^* = 631 \cdot (Q_{rad}'')^{-4/3} \quad (3)$$

By assuming smoke temperature constant during thermal exchanges, the heat conduction flux decreases as times goes on:

$$\dot{Q}_{cond}'' = \frac{k \cdot (T_{ad} - T_c)}{(\pi \cdot \alpha \cdot t)^{0.5}} \quad (4)$$

By integrating over time Eq(2) and Eq(4), we obtain

$$Q'' = Q_{rad}'' + Q_{cond}'' = \varepsilon \sigma T_{ad}^4 t + \frac{2k \cdot (T_{ad} - T_c)}{(\pi \cdot \alpha)^{0.5}} t^{*0.5} \quad (5)$$

finally, the global heat exchanged, can be expressed by:

$$Q = Q'' A_c \quad (6)$$

The allowed build-up, in terms of moles of released gas can be obtained as

$$n_{r(rad)}^* = \frac{Q}{-\Delta \tilde{H}_C} \quad (7)$$

4.2 Explosion scenario

In order to quantify the maximum allowed accumulation to prevent explosion in a confined volume, a conservative approach involves that thermal energy is instantaneously and equally spread out all over the volume, with a nearly instantaneous pressure increase. We assume that the maximum admissible overpressure corresponds to the threshold value quoted by different sources (e.g. Palazzi et al., 2013). The threshold approach is also envisaged by legislation (e.g. D.M. 151/2001) and by technical standards (TNO, 1992). A threshold value of 0.07 bar represents a consistent assumption also for possible failure of connection in small equipment, caused by static overpressure (Henrych, 1979). The safety criterion can easily be expressed as $p_f - p_0 = \Delta p \leq \Delta p^*$. With the approach in Palazzi et al. (2013), under the assumption $n \approx n_0$ (i.e. the moles before and after the ignition are about the same), one can write:

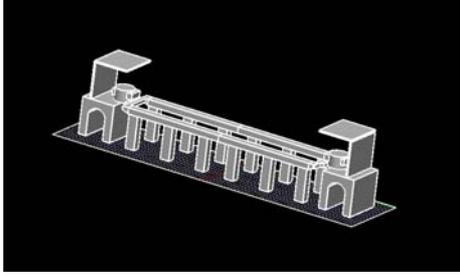


Figure 3: Schematization of the local beneath each coke oven battery with coffered ceiling

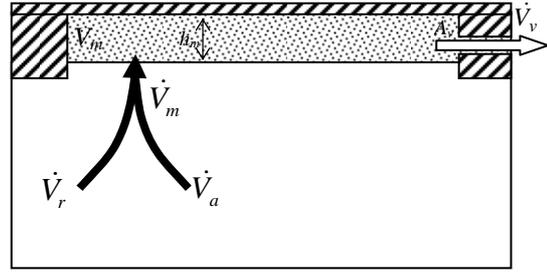


Figure 4: COG fugitive emission and buoyancy driven stratification in a single ceiling panel

$$\Delta p = \frac{n_0}{V} R \Delta T; \quad \Delta T = \frac{n_r}{n_0} \cdot \frac{-\Delta \tilde{H}}{\tilde{c}_p} \quad (8); (9)$$

Hence the safety condition can be expressed as

$$n_r^* \leq \frac{\tilde{c}_p}{-\Delta \tilde{H}_c} \frac{V \Delta p^*}{R} = n_{r(\text{expl})}^* \quad (10)$$

5. Results and discussion

The application of the methodology to an existing process plant is presented in the following.

Appropriate prevention and control measures addressed to the detection potential RF must consider both massive release from the main COG collector and low rate continuous releases from the feeding pipes. The former immediately detectable leaks are faced by an automatic shut-down and interception system based on operative parameter detection, ensuring the respect of the limiting gas volume. In this respect, specific sensors and actuators are required and if data are indirectly obtained by parameter estimation, ad-hoc procedures are recommended (e.g., Reverberi et al., 2013). Dealing with latter aspect, considering the COG buoyancy and the complex geometry, preventive measures are as follows:

- Natural and/or forced ventilation, in order to provide an effective dilution of the release below the lower flammability limit (LFL) or the critical build-up;
- Design of gas sensor network and enforcement of reliable periodic inspection program, according to a frequency preventing the attainment of critical build-up.

The gas feeding section of the oven is localized in separated local beneath each battery (Figure 3) which is characterized by a complex geometry consisting of coffered ceiling, each one volume being limited by the supporting beams in reinforced concrete: the accident scenario may be schematized as a gas release in a semi-confined region, with a venting area A_v . As depicted in Figure 4, the volumetric flow rate $\dot{V}_m = \dot{V}_r + \dot{V}_a = \dot{V}_r / x_r$ and \dot{V}_v impact on the accumulation of a gas volume $V_m(t)$ according to the volumetric balance $\frac{dV_m}{dt} = (\dot{V}_m - \dot{V}_c)$. By defining::

$$V_m^* = \min\{V(n_r^*), V_c\} \quad (11)$$

where the first term in brackets is the critical build-up volume according to eq. (1) and the second term is the volume of the ceiling, which cannot be exceeded, so as to avoid the spreading of COG into the adjacent ceiling volumes. The “safety criterion” is expressed by the condition $V_m \leq V_m^*$, which, as demonstrated in the following can be explicated in terms of natural or forced ventilation design parameters since the venting flow rate may be expressed by:

$$\dot{V}_v = \text{constant} \quad \text{in case of forced ventilation} \quad (12)$$

$$\dot{V}_v = f A_v v_v = f A_v \mu (g h_m)^{1/2} \quad \text{in case of natural ventilation} \quad (13)$$

5.1 Natural ventilation

Taking into account the volumetric balance and Eq(13), one can write, being

$$\mu = \left(\frac{\rho_a}{\rho_m} - 1 \right)^{1/2} = \left(\frac{M_a}{M_m} - 1 \right)^{1/2} \quad (14)$$

$$\frac{dV_m}{dt} = A_c \frac{dh_m}{dt} = \dot{V}_m - fA_v \mu g^{1/2} h_m^{1/2} \quad (15)$$

Integrating Eq(15) one can write

$$\int_0^{h_m} \frac{dh_m}{\dot{V}_m - fA_v \mu g^{1/2} h_m^{1/2}} = \int_0^t A_c dt \quad (16)$$

and following expression is obtained:

$$t = \frac{1}{A_c} \left(\frac{\dot{V}_m}{fA_v \mu g^{1/2}} \ln \frac{\dot{V}_m}{\dot{V}_m - fA_v \mu g^{1/2} h_m^{1/2}} - h_m^{1/2} \right) \quad (17)$$

The maximum height of build-up approaches the limiting value:

$$\lim_{t \rightarrow \infty} h_m = \frac{\dot{V}_m^2}{f^2 A_v^2 \mu^2 g} \quad (18)$$

It must be noticed that in any case the height of the gas build-up must be lower than the height of a single ceiling panel, so as to avoid the spreading of COG into the adjacent ceiling volumes. The safety criterion, in terms of allowed volume of gas V_m^* , considering the mass balance and Eq(18), can be written as

$$\frac{\dot{V}_m^2}{f^2 A_v^2 \mu^2 g} \leq \frac{V_m^*}{A_c} \quad (19)$$

and at last:

$$A_v \geq \frac{\dot{V}_m}{f\mu} \sqrt{\frac{A_c}{gV_m^*}} \quad (20)$$

The limiting value corresponding to $A_v \rightarrow 0$ yields the correct analytical solution $t^* \rightarrow V_m^* / \dot{V}_m$.

5.2 Forced ventilation

The volumetric balance can be written as :

$$\frac{d}{dt}(V_m x_r) = \dot{V}_r - \dot{V}_v x_r \quad (21)$$

Integrating Eq(21) under the condition $V_m(0)=0$, following design parameters are obtained:

$$V_m = \begin{cases} 0 & \text{if } \dot{V}_v \geq \dot{V}_r / x_r \\ (\dot{V}_m / x_r - \dot{V}_v) t & \text{if } \dot{V}_v < \dot{V}_r / x_r \end{cases} \quad (22)$$

The safety criterion $V_m \leq V_m^*$ is respected when the maximum allowed duration of the gas build-up is:

$$t \leq t^* = \frac{V_m^*}{\dot{V}_m - \dot{V}_v x_r} \quad (23)$$

6. Conclusions

The industrial plant was provided with natural ventilation openings, sized according to the maximum allowed gas build-up under the hypothesis of fugitive emissions. In addition, (early detection RV) a gas sensor network (CO/H₂) was designed and an emergency ventilation system was added preventing the

attainment of critical build-up and designed according to the mathematical model previously outlined. A reliable periodic inspection program, based on the calculated frequency preventing a hazardous accumulation was developed as well, impacting positively the resilience variable “vigilance”. A further improvement of the resilience DPF can be based on the definition of the links between the causes of failure and the measures adopted by the company to prevent them, entering in detail into the effects of management and organizational variables (Milazzo et al., 2010).

Nomenclature

A_c	ceiling surface, m^2	p_f	final pressure, bar	V_c	ceiling volume, m^3
A_v	venting area, m^2	Q	total heat transfer, kJ	V_m	maximum build-up volume, m^3
\tilde{c}_p	heat capacity, $kJ\ mol^{-1}\ K^{-1}$	Q''	heat transfer rate, kW	\dot{V}_m	total flow rate of COG, $m^3\ s^{-1}$
f	effective venting area, m^2	Q''_{cond}	conductive heat rate, kW	\dot{V}_r	release flow rate, $m^3\ s^{-1}$
$\Delta\tilde{H}_c$	combustion enthalpy, $kJ\ mol^{-1}$	\dot{Q}''_{cond}	conductive heat flux, $kW\ m^{-2}$	\dot{V}_v	venting flow rate, $m^3\ s^{-1}$
h_m	build-up height, m	Q''_{rad}	radiant heat rate, kW	x_r	molar fraction of COG, -
k	ceiling thermal conductivity, $9.2 \cdot 10^{-4}\ kW\ m^{-1}\ K^{-1}$	\dot{Q}''_{rad}	radiant heat flux, $kW\ m^{-2}$	α	ceiling thermal diffusivity, $m^2\ s^{-1}$
M_a	molecular mass of air, $kg \cdot mol^{-1}$	t	duration of exposure, s	ε	flame emissivity, 0.2
M_m	molecular mass, $kg \cdot mol^{-1}$	T_{ad}	adiabatic temp. of comb., K	ρ_a	air density, $kg \cdot m^{-3}$
n_r	moles of COG, -	T_c	ceiling surface temp., K	ρ_m	mixture density, $kg \cdot m^{-3}$
n_0	initial number of moles, -	T_f	explosion temperature, K	σ	Stefann-Boltzmann constant, $5.67 \cdot 10^{-11}\ kW\ m^{-2}\ K^{-4}$

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