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A Pooled Knowledge Basis on Pressure Equipment Failures to Improve Risk Management in Italy

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In process industries common practice, failure rates (FRs) have an essential role for evaluating accident likelihood, which, in turn, drives most decisions of Competent Authorities, including installation licensing and land use planning (LUP). FRs currently in use for process equipment derive basically a few from major systematic studies conducted in the sixties and seventies. Many new materials, new production and management method have been introduced and their effects on aging mechanisms on a large scale are still unknown. Authorities could make questionable decisions, trusting in poor or generic FRs. A few European Competent Authorities are trying to face the problem, by stating a set of trusted FRs, suitable just for LUP. INAIL, as in charge for pressure equipment control throughout Italy, is gathering data for updating generic failure frequencies. The proposed solution is aiming to provide "numbers", on which Authorities and enterprises can count, but above all to pool the knowledge about failure modes, in order to better address the management of equipment throughout the process industry. A hard work of knowledge organization is necessary but it may dramatically improve probabilistic risk assessment, LUP decisions, as well as risk based maintenance and inspection planning.

1. Introduction

Operators of major accident hazard establishments, according to the Seveso Directives, must submit to the competent authorities a “safety report”. It must provide a quantitative risk analysis, which includes, according to the common practice, the top-events identification by the HAZOP method and the accident likelihood calculation by the Fault Tree (FT) and Event Tree (ET) Analysis. These analyses are basically driven by the general failure rates (FRs), as derived from scientific literature, public domain databases and, eventually, proprietary databases. These probabilistic evaluations, supplemented by consequence modeling and potential impact area computation, are essential for Authorities to make vital decisions about new plants approval, emergency planning (including resource allocation) and land use planning LUP. Even the identification of critical system with hazardous plants is driven by the FRs, which, in such a way, affect also the safety management procedures.
In a few countries, like France and Italy, the compatibility criteria rely more on the severity of the possible "consequences". The probability enters as a filter for scenarios and related damage areas to be included (typically > 10^{-6}). In other countries, such as Netherlands or UK, are used the decisions driven by probabilistic methods, such as the F – N curves which combine in a chart accident frequencies and consequences, represented as number of victims, in order to represent societal risk (Uijt de Haag and Ale 1997). The accident event frequencies depend, in turn, on the combined frequencies of failure of any single items. In both cases general failure frequencies drive shared decisions. The scientific weakness of the generic failure frequencies have been discussed by a historical review of Fragola (1996). Authorities must anyway accept a trade-off to make standardized and uniform decisions. An inadequate value of a single FR value in the FT is able to affect vital decisions. Recent innovations are increasing component reliability; but if the authorities accept any arbitrary extrapolations of FRs, could make imprudent decisions, excluding possible catastrophic events. A conservative approach is highly preferable for the Authorities' decisions. Major accidents continue to happen, even in regulated industries and involving companies or facilities that were considered to be high performers. In 2005 an explosion, considered unbelievable in the

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safety report, destroyed a tank farm with severe consequences for a large built area in Buncefield (UK). The final report on the "lessons learned" complains a level of trust too low for the risk assessment and highlights, inter alia, the need of improved FRs to support LUP decisions (HSE 2007). Following this report, an initial feasibility study on upgrading fault frequencies according to the decision-making process was promoted by the British authorities (Manuel et al. 2012). It has to be stressed than in consequence based method, as likelihood acts as absolute filter, the error propagation could be even higher than in F-N curves, where the propagation is buffered.
The present paper focuses just mechanical failures on pressure equipment. For pressure equipment it is less difficult to gather data, because INAIL follows all pressure life-cycle, certification, installation, periodical verification and disposal, according to the national regulations. Instrument failures and human errors are equally important; but are not included in the paper, as INAIL is not in charge of the matter.
Since the early 70s a huge effort was made to provide the nuclear and chemical engineers with a credible set of reliability data of pressure vessels. In an article by Bush (1988), the historical studies, conducted over 60-70 years in three major industrial countries, USA, UK and Germany, are reviewed and compared in a critical way. In the review eight national studies on pressure vessels are reported in detail. In each study, 10.000 to 100.000 pieces of equipment were observed for ten years and more. Those studies consider as a whole 3 My-pressure vessels (both fired and unfired) with some thousand faults.
In the early 80's, the first scientific LUP studies were presented for the areas of Canvey Island in UK (Canvey 1981) and Rijmond in NL (COVO 1981). The two studies proposed two sets of failure frequencies, which have been widely used for area risk studies. Both FRs sets have been derived from larger historical datasets, handled by a number of experts, which customized them for process industries. This values are still trusted, due to the lack of alternatives. Since the 90s, two things occurred that completely changed the industry: quality management, which was completely revolutionized by ISO 9000, and the management of the certification that was revolutionized by the EU Directives, including Pressure Equipment Directive (97/23/EC - PED). Furthermore, plants are aging more and more, due to the poor investments; the "new" materials, introduced in the 70s and 80s are not well known on a large scale. Also acceptance criteria for in-service inspections are critical for ageing equipment. For all these reason, it's essential to update the recognized national and international information sources for the FRs, in particular for the pressure equipment.

2. Objectives

The scope is to improve the quality of the data on equipment failures used in Italy and to promote a more effective use in risk management, both for companies and authorities. Since 2012, INAIL is in charge to organize a data base of the verification activities for working equipment, including fired and unfired pressure vessels and pressure piping (Bragatto et al. 2012). In Italy there are some 100,000 pressure equipment in service. Every year some 5,000 new certified pressure equipment are installed. Almost 60% are certified as pressure assembly and 40% as individual pressure equipment. The equipment discarded for irreparable failure or natural end of lifecycle, are communicated. A periodical inspection is mandatory and period (2 to 10 years) depend on the equipment classification, according to the PED Directive. Inspections are mandatory also for equipment installation, as well as for modification or repair. Thus a huge mass of data is going to be collected in the next years, never available before. This is a good chance indeed to organize the knowledge about pressure equipment life cycles, defects, anomalies and failures.
The goal of the present research is to support this effort and namely the objectives are 1) compare the present sources of FRs for pressure equipment; 2) propose a policy for general failure frequencies in shared decisions making; 3) define a model to organize the knowledge about pressure equipment failures, suitable for an improved risk management.
In order to make shared decisions, stakeholders need precautionary failure rates. To achieve this goal, larger and better data must be gathered and well known statistical methods have to be applied. Knowledge hidden in the collected data is, instead, much more important for the management of risk, where you do not need to know when it will happen the fault, but how it will happen, how can be predicted in advance and avoided. The potential of RBI for optimizing plants in chemical industry has been widely discussed in a recent paper by Medina et al. (2011). This knowledge resource for risk management are not available to small and medium-sized enterprises, which have difficulty in applying advanced policies, as discussed by Bragatto et al. (2009). Thus to achieve the third objective more sophisticated methods must be investigated, as described in detail in the next chapter.

3. Methods

The first step to achieve the objectives has been a critical review comparison of data currently used in Europe, in order to identify strengths and weaknesses of the different approaches. The second step has been the analysis of the knowledge potential of data gathered in the verification activities throughout Italy, which are in charge of INAIL. Starting from this analysis, the strategy to extract knowledge from the expected mass of data, must be defined. For this purpose the potential of ontology for knowledge management is briefly discussed.

3.1 European Experiences

As a first step has been considered the recognized sources of the European countries adopting probabilistic methods for LUP decisions, as they are much more committed to maintain shared FRs the other ones. The main sources are the following:

a) The “PURPLE BOOK” is a study ordered by the Dutch Competent Authority to the TNO (Uijt de Haag & Ale 1997). The values of frequencies are the result of discussions between representatives of the competent authorities and the government. The frequencies are often based on old data available at that time, in combination with expert judgment (Pasman 2011).

b) FRED (UK) is managed by HSE, the British Competent Authority (HSE 2012). The method is similar to that of the Purple Book, i.e. processing of consolidated data and expert judgment. The study, however, is more recent and the approach is much more conservative, thus the FRs are systematically higher.

c) AMINAL (BE), the study AMINAL from Belgium is recent (Aminal 2009). Data are presented in a quite different format, the content is content is similar to the above mentioned “Purple Book”.

d) American Petroleum Institute (API) It is highly influencing the Oil & Gas industry not only in USA but worlwide. The general FRs are provided for many types of equipment, in the frame work of the resources to be used to implement a Risk Based Inspection (RBI) program (API 2008).

3.2 Other potential source of data

The HSE study is trying an innovative path, to consider as a valuable information source the major accident records, which, by the Seveso Directive, must be reported to the Competent Authorities. The difficulty is figuring out which is the reference population, because there are no data on the total number of pipes and pressure vessels at the Seveso establishments (Manuel et al. 2012). The proposal to exploit Google Earth is applicable just for external pipelines, not for establishments. Furthermore, only the catastrophic failures can be considered. The National Archives of fatalities managed by INAIL could be interesting as the reference “equipment population” is wider, but just faults with fatal consequences may be studied. That is misleading, as there are many major failures without injuries.

3.3 Control Bodies

The mandatory periodical inspections of pressure equipment, which is present in many European Countries, including Italy, could provide a valuable source of information. The first verification before installation, the periodic controls, the tests after repairs and modifications, the accident evidences and the decommissioning notice could provide essential information. Unfortunately most information is scattered throughout the local agencies and the regional authorities. A few years ago, in Emilia-Romagna, an Italian region, the competent authority presented a valuable report, which analyzed in detail the anomalies recorded in mandatory pressure equipment verifications (Frabetti et al. 2002). Some 46,000 items were under observation for five years, thus the study is significant indeed. Furthermore for each failure there is a free text description useful for further deepening. This is an interesting experience, which should be continued and extended to the national level.

3.4 The National pressure equipment Database

In Italy there is a national pressure equipment database; but, until now, it has been aiming at organization and supervising purpose. There is a more technical database just for equipment working under pressure at high temperature (up to 700/800 °C). This type of equipment includes large steam generators, large heat-exchangers (up to 700/800 °C) and refineries processing furnaces. For them there is a special regulation aimed to control the hazards coming from creep conditions. The creep database contain information about: a) plant type, b) construction year, c) design temperature and pressure, d) operating history (number of failures, repairs and modifications during the service life), e) theoretical residual life (via numeric evaluation), f) damaged components, g) materials, h) metallographic results, i) classified creep damages and micro-damages. The creep database is a valuable example, but its structure is suitable just for creep hazard, which has been studied worldwide for decades. The duties of the new regulation are much more complex, as all types of pressure equipment are included with a much greater diversity of damage mechanisms, materials, service conditions, mechanical features. For that reason the grid for data gathering cannot be a rigid structure, which could become a cage for such a wide matter. A smart web-based interface has been developed, in order to have a quick and effective input even from inspectors on the field. The accidents recorded in the past by local agencies are a further valuable information source, even though a harmonization effort is required.

3.5 Knowledge management: the proposed approach.

A better management of the knowledge could be useful to promote the use of failure information in risk management. The use of a free text is misleading, as you must trust in the individual goodwill. Much better to have a model, to be used as a tool both to enter and to extract information and practical knowledge. For this purpose the potential of "ontology", a new approach in knowledge management, has been investigated. "Ontology" is suitable to capture and structure knowledge about some domain of interest. An ontology is a formal description of a set of concepts referred to a specific domain. It is often equated with taxonomies, which are commonly used as starting point in ontology design. Ontology has the effective capabilities of analysis and deductive reasoning, and, working with a knowledge-base, they are able to infer relations not explicitly represented. This logical model allows the use of a "reasoner", a tool that checks whether all definitions in the ontology are mutually consistent. A critical component of the ontology management system is the inference engine, which provides mechanisms for defining relations and rules and for interpreting the semantics of an ontology. This potential may be exploited for the definition of new empirical rules, to be applied in the risk management. To support these activities, "ontology editors" are used. One of the most popular is Protégé, by the Stanford University (Protégé 2000). It supports developers in ontology design through a user-friendly interface, automatically generates code, and provides tools for validating, enquiring and checking the ontology developed. Camossi et al. (2008) proposed an ontology-based method for addressing Certification of Pressure equipment. In that paper, the "ontology" includes the "taxonomy" of pressure vessels, the rules for the safe design, construction and operation, the inference rules and the logical axioms; it has been exploited to relate safety with geometrical and physical data. The present application is not so far, even though further taxonomies have to be added to complete the picture. In § 4.3 the new developed taxonomies and ontology are discussed in detail.

4. Results

4.1 Synopsis of "official" data and early results.

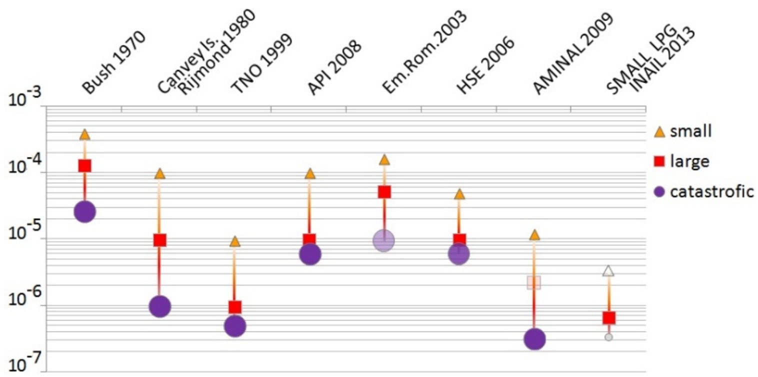

Figure 1: Comparing pressure equipment failure frequencies since 1970 to now.

The FRs for pressure equipment reported in the four sources cited in § 3.1 Aminal, Fred, TNO and API have been compared with the values of Emilia-Romagna study and the values used in the Canvey and Rijmond studies. The values derived from Bush's historical studies have been added to have a reference point. The national database is at an early phase and just provisional data on small LPG pressure tanks (up to 13 m^3) are available at now; 10 major failures have been reported in the last decade, for a population 1.6 10^6 parts. The resulting FR (6,2 10^{-7}) has been included in the comparison, as shown in fig.1. The synopsis has been quite difficult because each data set adopts different criteria. For uniformity were considered only failures with loss of containment. The small and large classification depends only on the diameter of the loss, greater and less than 10 mm. The full aperture of the bottom or shell is considered catastrophic. In the Emilia-Romagna data set, the "small failures" include also the major defects detected during the routine controls and the number of catastrophic events is too low to be significant. A general improvement of pressure equipment from the Sixties (Bush) to now (Aminal, HSE) is clear, but the recent datasets seem affected by different national approaches. More precautionary in UK (HSE) and less in Flanders and NL (Aminal, TNO). Whilst the Emilia-Romagna campaign seems support the HSE frequencies, LPG early results could support a less conservative approach, but it has to be stressed that small LPG tanks are very simple, highly standardized and mostly used for domestic or similar purpose, thus they may be supposed much more reliable than other equipment.

4.2 Knowledge organization

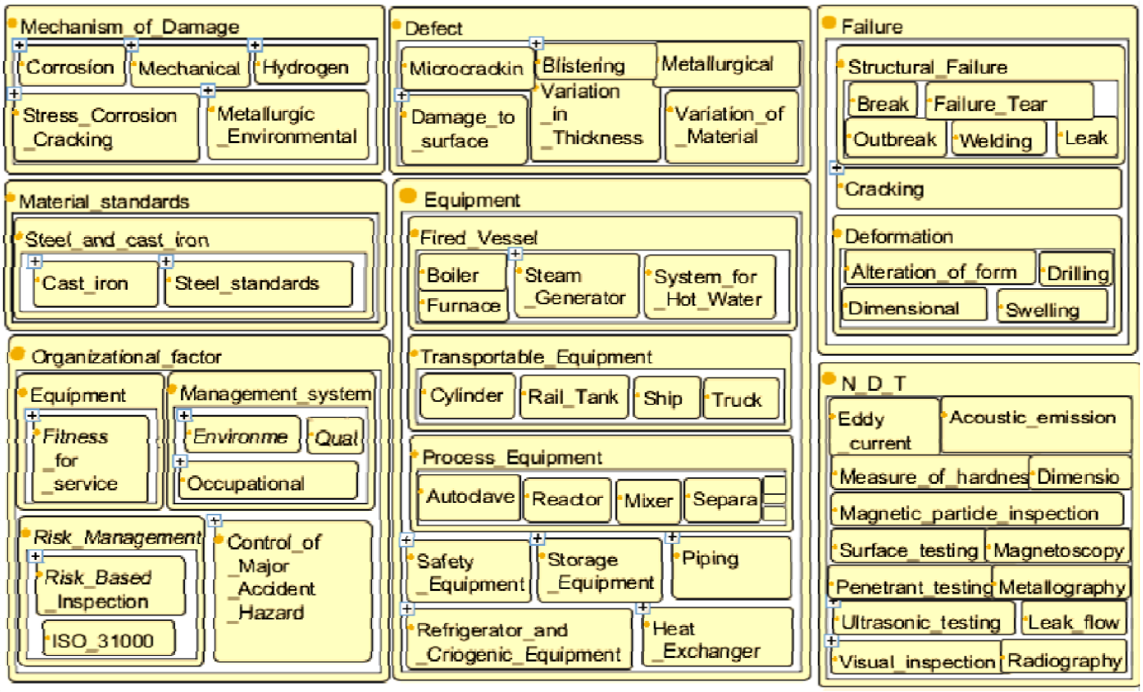

Figure 2: The picture of Pressure Equipment Failure Ontology

The method of ontology, as described in § 3.4, allows to organize a sort of grid to gather the data from the field. The ontology of pressure equipment failures has been built from the taxonomies of the topics that they are interested. The taxonomy can be seen as two-dimensional projections of the ontology, which is then constructed by combining, through relationships, classes defined by taxonomies. In Figure 2 the a few taxonomies that have been inserted in the ontology are represented in a form extremely compact. The model is stressed to support the study of the effects on failure of the organizational models and “new” management system. A further focus is on “new” materials, and of the accepted defects in inspections, discussed in the introduction. As essential for the model, the Failures and Defects taxonomies are shown at higher detail in figure 3. The ontology is made available via web (ISPESL 2012) to the inspectors working in the field, so that the data is collected in a smart way. At this stage new rules may be implemented, while data begins to flow from the inspectors to the central database.

5. Conclusions

The systematic collection of data on pressure vessels subject to mandatory verification, and their failures, is a great opportunity to increase knowledge on the matter. An updated set of general failure frequencies for risk assessment and decision making, is urgent, even though the updated values by HSE are, at now, suitable for a conservative approach, as demonstrated by the resulting comparison. The structured grids to collect information from the field is the main result of the present research. The developed ontology is suitable to organize the inspector practical experience, which, otherwise, would be isolated and useless. The structured data that will be collected throughout Italy, using the ontology developed here. The failure rules, extracted by means of the ontology, will be exploited to promote sound risk management procedures throughout the Italian Process Industries, including SMEs, which could overcome the present delay in implementing risk based inspections and maintenance programs.

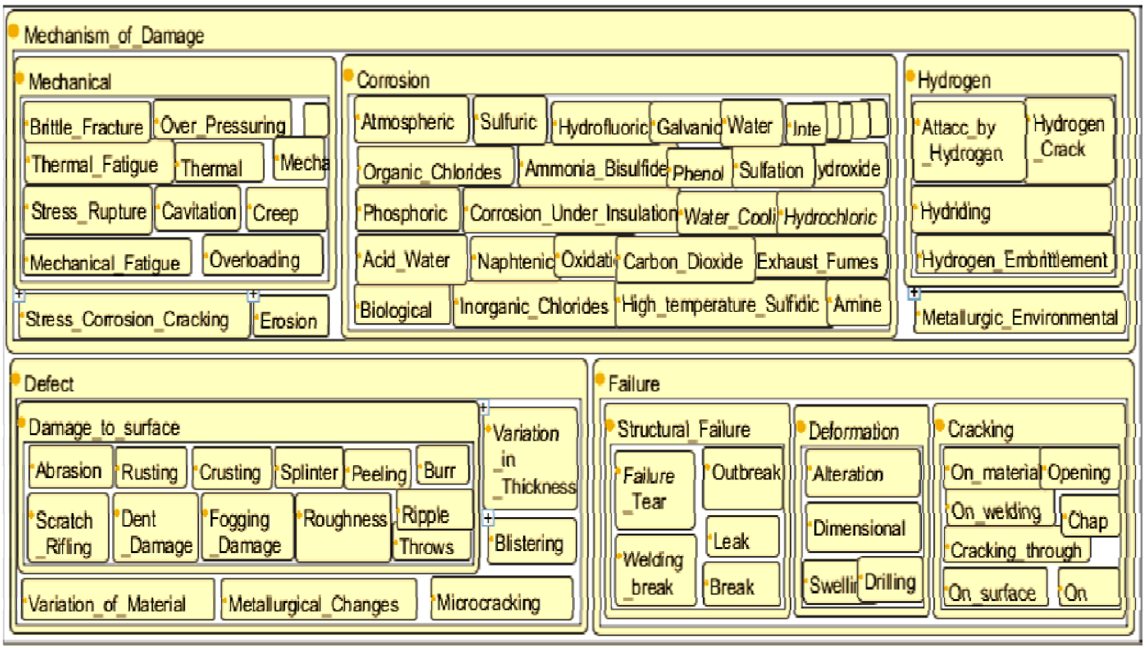

Figure 3: A detail of the Pressure Equipment Failure Ontology

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