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Uncertainties on risk analysis: the consequence assessment in an hydrogen refuelling station

Keywords

uncertainty, risk analysis, hydrogen, consequence analysis, hydrogen refuelling station

Abstract

The paper concerns the problem of uncertainty associated to risk analysis of complex technological systems; this problem is not easy to resolve and manage. This is because such uncertainty has never been simple to quantify and, despite several innovative techniques able to properly manage uncertainties are available, none of these methodologies is integrated on the risk analysis in order to evaluate the error propagation. Also the itself risk analysis is not a precisely defined procedure but rather a complicated process of several parts and, moreover, each part is characterized by its own uncertainty. Several studies highlighted as the phases which mainly contribute to the overall uncertainty of a risk analysis are consequence and vulnerability studies.
In order to provide a signifying approach to the problem, the working team has decided to focus their attention on a very important target for population safety: the hydrogen refuelling station for automotive.

1. Introduction

Some European Benchmarking Exercises (Benchmark Exercise on Major Hazard Analysis 1992, ASSURANCE 2000) have demonstrated that different groups of analysts, facing the risk analysis of a same plant, obtain results very different from each others by orders of magnitude in the point value of risk.
Risk estimation is always affected by three beginning of uncertainty: the analyst's assumptions; the uncertainty of input data; the accuracy of simulation models. All those issues influence the final result, leading to an "uncertain" estimation of risk, here below called "Risk Uncertainty". Such uncertainty, associated to the risk analysis of complex technological systems, is not easy to be quantified since, even the evaluation of risk itself is not a precisely defined procedure but rather a complicated process of several parts, each part is characterized by its own uncertainty.
A simplified scheme of the risk analysis process consists of the following steps: 1) hazard identification for the complex system under analysis; 2) choice of the adequate models; 3) retrieval of the relevant data; 4) execution of the analysis; 5) presentation of the outcomes. All these phases are subjected to inaccuracies closely related to the complexity of the examined system.
Presently, techniques and models are available to carry out the described process, but none of them provide the degree of uncertainty/inaccuracy associated to the performed estimation, so that analyst usually limits himself to only an estimate of punctual values without information on the confidence which can be assigned to such results. In general, only basic studies are available, in which an uncertainty analysis has been applied to specific models or to complex accidental sequences in order to evaluate the error propagation. However, such an application to a complete risk analysis of a real plant, allowing to appreciate the uncertainty affecting the results achieved with the application of the classical approach, is still lacking.
Several studies highlighted as the phases which mainly contribute to the overall uncertainty of a risk analysis are the consequence assessment and the vulnerability analysis.
In order to provide a signifying approach to the problem of risk uncertainty, the working team, in collaboration with Polytechnic of Milan and the Universities of Pisa, Rome and Palermo, has focused its attention on a very current and important case for

population safety: the hydrogen refuelling station for automotive.

The problem of the uncertainty of this kind of plant is particularly important because it involves an high degree of newness, concerning a new technology in a new context. Furthermore the activity will contribute to deepen the knowledge of the safety issues related to hydrogen, making people more and more confident in its extensive use as a fuel.

The aim of the research has mainly been underlining and demonstrating that the consequence analysis is the most tricky phase of the risk analysis because the analyst can easily commit errors that are very difficult to quantify. Moreover the overall group has tried to apply new methodologies, some of these developed from the group itself, to better understand the problem of the uncertainty associated to this kind of plant. These methodologies concern studies about event and fault tree analysis, human factor, description of the same plant, finally the error propagation in the consequence analysis.

Paper describes activities performed from the working team of Turin, which mainly consists in:

- risk analysis for an hydrogen refuelling station;
- study of uncertainties that intervene in this risk analysis;
- further investigation about uncertainties that intervene in the consequence assessment;
- uncertainties evaluation in risk analysis in case of application of different simulation codes.

The activity described is founded by the Italian Ministry of Research and University (PRIN 2005) and it has been presented to the international conference on Safety and Reliability called ESREL 2007 in Stavanger, Norway.

2. The “classic” risk analysis

2.1 Refuelling plant description

The analyzed hydrogen refuelling plant is not still an existent plant; so system description has been based on different experiences developed in Italy in hydrogen installations (particularly the hydrogen bus project of Turin city) and on the national regulation about hydrogen refuelling station.

The hydrogen refuelling station essentially consists of the following components: water demineralization, hydrogen generation, hydrogen purification, hydrogen compression, storage of compressed hydrogen, filling system, general instrumentation. The hydrogen production by electrolyzes has been considered. The filling system has been designed to deliver hydrogen at 350 bar for refuelling vehicles powered by compressed gaseous hydrogen.

The hydrogen is generated by an electrolyser, fed by demineralised water from the demineralization unit. The hydrogen produced by the electrolyser is fed through a purifier, where impurities in hydrogen are removed by filtration, oxygen depuration and desiccation.

After purification, the hydrogen is compressed to 350 bar by a 3-stages compressor.

Afterwards compressed hydrogen is transferred to six buffer storage tanks (6 m^3 in total), which feed the filling system.

2.2 “Classic” risk analysis methodology

Before the uncertainty analysis has been begun, the “classic” risk analysis has been managed by Turin working team. Main steps are following described.

A preliminary step concerns the collection of all information, necessary to study development, mainly constituted by site characterization and system description.

The data about plant location concern anthropic and environmental factors. The first information allows to identify all possible vulnerabilities nearby the plant area, as population density, railway, motorway and other installations that can cause or be involved in domino effects. The environmental characterization is aimed to verify the area natural risks, as hydro-geological and seismic risk, and also to investigate the meteorological characteristics of the area (distribution of wind direction, wind velocity, Pasquill stability class). All these information are very important for the successive consequence analysis.

The system information is aimed to describe the plant operation, process, main components and safety systems. Present substances and their properties, quantity, storage place and condition are investigated too.

A proper quantitative risk assessment is composed by three main parts. The first one is the qualitative analysis focused on the hazard identification that is constituted by the following phases: historical analysis; functional analysis (aimed to identify all the elementary functions characterizing the plant); hazard identification analysis (criticality evaluation of the deviations from normal operation of all the identified elementary functions). When the most critical events are identified, all the possible initiating event are grouped and reference initiating event (RIE) are selected. The second part of the analysis (the quantitative evaluation) includes the event tree analysis (individuation of all the possible accidental scenarios produced by the RIE and the associated frequency) and the consequence assessment (evaluation of the damage caused by the different scenarios). The last part of the analysis consists of calculation of risk value, as a product of frequency and damage, and of discussion of risk acceptability.

2.3 Analysis aims

Analysis aims are to individuate the most critical components, to find out and study the accidental phenomena that can occur, to calculate damage to people and infrastructures and consequently to evaluate risk associated to the installation.

3. Uncertainty

3.1 Uncertainty in a generic risk analysis

Considering several studies performed by risk specialists and on the base of our studies too, the list of the possible uncertainties introduced in a classic risk analysis has been drafted. Particularly the following uncertainty sources, related to different phases of risk analysis, can be pointed out:

- System definition and description: inaccuracy and approximation due to lack of knowledge about the plant;
- Hazard identification: historical analysis managed on unreliable database or unavailability of specific information about installation similar to the examined one;
- Probabilistic Analysis (this is a very delicate issue): uncertainties due to reliability data and statistical data; inaccuracy due to lack of knowledge about operations and procedures, mission time, etc.
- Consequence analysis (this is another delicate issue): uncertainties due to phenomena modelling, input parameters of simulations, etc.
- Risk evaluation: this phase is affected by effects of all uncertainties introduced in previous steps and by uncertainty due to lack of precise and well recognized criteria for acceptability discussion of calculated risk.

3.2 Uncertainty in consequence assessment

An European Benchmarking Exercises on Major Analysis shows that the phases which mainly contribute to the overall uncertainty of a risk analysis are consequence assessment and vulnerability analysis.

Main uncertainty sources in the consequence analysis are related to [1], [10]:

- Hypothesis made in analysis organization: analyst has to choice which incidental phenomena intervene, to establish the incidental conditions (for example, the kind of break in a pipe, hole or guillotine fracture, etc.), to select the mathematical models, to describe the evolution of a foresight accident, etc;
- Model input data: uncertainty about input data can be caused by a large number of factors: lack of information, abundance of information (complexity), conflicting evidence, ambiguity, measurement, etc.. In this context, an important distinction has to be done between objective (or stochastic) uncertainty and subjective uncertainty: the first one comes from oscillation of some parameters around their nominal values; the other one characterizes the confidence degree which is assigned to the analyst's hypothesis and generally depends on imprecise knowledge of some parameters. For example, temperature, pressure, length, etc., are considered objective uncertain inputs; the area of outflow opening in a pipe, the leakage position, etc., are considered subjective uncertain data.
- Physical-mathematical models: the uncertainties are caused by the capability of model in describing reality and by approximations introduced in the model;
- Damage evaluation: also the uncertainty related to vulnerability criteria has to be considered together with the variability of physical quantities describing phenomenon effects (heat radiation, overpressure peak, released mass, etc.).

In order to deepen the uncertainty on consequence analysis, this work has mainly been focused on the contribution to the uncertainty due to consequence model application in order to simulate the chains of accident events.

3.3 Uncertainty in hydrogen plant analysis

In the risk analysis of the hydrogen refuelling station, it is necessary to add to uncertainties caused by methodology also uncertainties due to system newness and to the new context in which components are used.

On the base of working team considerations, uncertainties that intervene in the study of an hydrogen refuelling plant are specified in the following:

- System definition and description: because of newness of technology, there are a lot of lack of knowledge about this system. Also in layout definition, uncertainties are present and they have been partially solved only by the national regulation about hydrogen refuelling stations, that define design criteria such as technical solutions and safety distances to adopt in plant planning;
- Hazard identification: not numerous hydrogen refuelling stations exist in the world, especially realized in experimental project: so a committed accident database is not available that can be used in historical analysis for this system. Accident scenarios identification can be performed by qualitative risk assessment (by HAZID, HAZOP or FMEA), anyway the lack of experience about similar plant involves a difficult definition of qualitative frequency and damage indexes in order to identify the most critical issues.

- Probabilistic analysis: obviously, probabilistic and reliability data can not usually be applied to components of hydrogen refuelling station; in fact these elements are principally new components or existent components used in a new context. Besides, few information are available about procedures and using mode of the plant. Finally, reliability data involve an high grade of uncertainty.
- Consequence analysis: uncertainties introduce in this phase are due to different factors. In fact, in addition to uncertainties related to simulation of each phenomenon, uncertainties due to accidental scenarios that can happen have to be considered too. In case of hydrogen release, possible scenarios are not well known, particularly if an outdoor release is considered. Other uncertainties are related to model input data, because of lack of knowledge about parameters (like flame temperature) for hydrogen substance. Finally, more relevant uncertainties are due to approximation introduced by simulation codes that are usually used, that can not correctly deal with light gases like hydrogen.
- Risk evaluation: as above pointed out, the lack of criteria for risk acceptability, found in general risk analysis, also influences risk evaluation for hydrogen plant; risk evaluation has a particular importance for hydrogen plant because this new technology needs to determine a positive perception in public opinion. So, risk evaluation have to demonstrate that risk due to an hydrogen refuelling station is minor or equal to risk associated to existent fuel refuelling station (gasoline, natural gas station, etc.).

4 Activities

Referring to assertions reported above, activity done dealt mainly with the part of risk assessment concerning consequences and damages estimation. Working team reviewed the consequence analysis highlighting uncertainties associated to several evaluations, with particular attention to some accidental sequences, the most meaningful ones for frequency and magnitude.

The targets/steps of Turin working team activities have been the followings:

1. Realization of a “classic” risk analysis (without uncertainty evaluation, where actually uncertainty evaluation is substituted by expert judgement and conservative estimations) for the case-study selected, focusing the attention on the consequences analysis.

   The first phase of the activity has been the application of the scheme of the classic risk analysis, as described above, applied to the studied target. The output of this phase has been a report based on a classic risk analysis for the hydrogen refuelling station, in which a quantitative evaluation of damage, frequency and risk have been produced.
2. Analysis and setting of all uncertainties that intervenes within consequence analysis. Analysis of uncertainties performed concerned uncertainty about model input data, assumptions in simulations models and analyst’s hypotheses.
3. Comparison of results obtained by application of two different parameter simulation models.

   In this third part, accidental scenarios individualized have been analyzed by two different models. So, uncertainties introduced by each model and by input parameters have been studied too. Damage values obtained in both case and also risk values associated to the scenarios have been compared and variations of risk acceptability have been considered.

Several studies have been carried out by the other working teams; particularly the following arguments have been treated (the results are not related in this paper):

4. Error propagation in the models linking for consequence analysis in order to examine how input data uncertainties spread to output data (Unit of Milan);
5. Experimental examination about confined hydrogen cloud explosion in order to examine the phenomenon and to evaluate used parameter models (Unit of Pisa);
6. Error propagation in the event tree analysis in order to examine how input data uncertainties (as failure rate) spread to output data (frequencies of scenarios); analysis about human factors (Unit of Rome);
7. Investigation about layout definition of the plant in order to highlight uncertainties introduced in this phase; error propagation in the fault tree analysis (Unit of Palermo).

5 Results

5.1 Risk analysis results

This paragraph includes the results obtained by Turin working team.

As related above, risk analysis has been organized in the following steps:

- Hazard identification (historical analysis, hazard identification analysis - HAZID);
- Event tree analysis;
- Consequence assessment.

Most important results obtained by each phase of analysis are briefly reported in the following.

Historical analysis. Because of the innovative technology, existing accidental databases report a few of specific records about accident involving hydrogen refuelling station. Therefore, the historical study has been led examining accidents that involved the general hydrogen production or storage systems and also gasoline/natural gas refuelling stations.

With reference to MHIDAS and HSELINE databases, 102 accidental events, involving hydrogen production or storage have been analyzed and catalogued depending on causes (planning mistake, human error, damage or break of components, domino effects, etc.) and consequences (flash fire, fires, BLEVE, releases, UVCE, VCE, explosions, fireballs, etc.) of the accidents. In the same databases, 99 accidents happened in refuelling stations (natural gas, gasoline) have been analyzed in consideration of accident causes and consequences.

The following results are pointed out:

- Referring to hydrogen system, the most critical components are high pressure tanks; commonly, causes of incidents are human errors and mechanical failures; incidents usually evolve in fires and explosion and only 10% of total produces an atmospheric dispersion without any consequence.
- Referring to refuelling stations, only 6 incidents happened during refuelling of vehicles but a large number occurred during fuel supplying to the station; the most important causes are collisions of vehicles with dispenser; incidents usually produced only fuel release and not other consequences.

HAZID. Hazid analysis concerned hydrogen production, storage and supplying phases. The most critical accidental event is the break of the pipes that transport hydrogen at high pressure near tanks and near dispenser. Nitrogen tank collapse has been considered too.

Event tree analysis. This probabilistic technique has been applied to two initiating event (IE): the hydrogen release from pipes near dispenser (IE A). and another near storage (IE B). It has been possible to estimate the frequency of scenarios which can happen from these two initiating events, as reported in the following table.

Table 1. Occurrence frequency for scenarios due to A and B initiating events.

Scenario	IE A (events/year)	IE B (events/year)
Jet-fire	$1.92\ 10^{-5}$	$3.65\ 10^{-7}$
UVCE/Flash fire	$8.62\ 10^{-6}$	$9.65\ 10^{-6}$
Dispersion	$1.05\ 10^{-5}$	$1.18\ 10^{-5}$

Consequence assessment. The phenomena simulation is aimed to evaluate the heat irradiation and overpressure values following a fire or an explosion; it was performed by using simplified parameter physical-mathematical models, described in the Yellow Book of TNO and implemented in Effect 4.0 software. The release flow rate has been estimated for both the hypothetical IE, described above, considering the release of hydrogen at 350 bar. The consequences of both outflows have been evaluated, considering a jet-fire (if hydrogen is ignited early) and a UVCE or a flash fire (if hydrogen is ignited later).

5.1.1 Vulnerability analysis and risk evaluation

Damage values due to the different scenarios have evaluated considering the following criteria: in the event of an explosion, it was supposed that the 5% of people, which is hit by an overpressure wave higher than 0.3 bar, dies. This hypothesis is conservative: in fact Lees [4] suggests a death probability minor than 1% about overpressure inferior to 1-2 bar. In the event of a jet-fire, vulnerability has been considered equal to 100% for people directly reached by the flame, while it has been supposed to be 5% for the people interested by a heat irradiation higher than 12.5 kW/m^2 (also this hypothesis is conservative, if it is considered that Lees proposes a lethality equal to 1% for a 10.2 kW/m^2 continuous for 45.2 s or more). In the event of a flash fire, vulnerability has been considered equal to 100% for people present in the area with a LFL concentration or higher.

Considering a density of people, both in the plant area and near the installation, of about $5 \cdot 10^{-3}$ un/m^2, scenarios study produced the following evaluation of damage and risk values.

Table 2. Damage and risk calculated for scenarios due to A and B initiating events.

IE	End of sequence	Damage value (dead/event)	Risk value (dead/year)
A	Jet-fire	5.30E-02	1.21E-06
	Flash fire	1.35	1.39E-05
	UVCE	2.14E-01	2.20E-06
B	Jet-fire	9.50E-02	2.03E-06
	UVCE	2.14 E-01	2.07E-06

5.2 Uncertainty in consequence analysis

Scenarios simulation has been performed by parametric models described in the TNO Yellow Book, by using Effects 4.0 software, as reported above.

In particular, simulations required to link several models, so the uncertainty propagation from a model to the sequent one is a severe problem.

With reference to each model, uncertainties associated to analyst's hypothesis, to input data and to simulation code approximations are synthetically pointed out in the following.

5.2.1 Release

In a hydrogen release simulation, uncertainties introduced by analyst's hypothesis or choice concern release location and release modes (particularly about intervention or not of shut-down systems); choice of simulation model; choice of some input data, like pipe length, breakage type and diameter.

Applying a semi-continuous release model of gas from pipe connected to vessel available in Effects, the most important uncertainties introduced by model input data are reported in the following:

- Pipe length, initial pressure and temperature, hole diameter that, as reported, depends on analyst's hypotheses;
- Pipe roughness, that depends on tube material;
- Discharge coefficient, this parameter involves an intrinsic uncertainty due to grade of knowledge of its value and an uncertainty due to the hole diameter chosen by the analyst.

About modelling, the most important uncertainties and approximations introduced are: process is considered adiabatic and gas behaviour is considered ideal; shut-down systems can not be considered by this model.

5.2.2 Jet-fire

In a hydrogen jet fire simulation, uncertainties introduced by analyst's hypothesis or choice concern simulation model and, about model input data, jet orientation.

With reference to the Chamberlain model available in Effects, the most important uncertainties introduced by input data of the model are:

- Gas flow rate: this input data is mainly affected by release model uncertainty;
- Release height, gas initial pressure, gas initial temperature, ambient temperature and relative humidity, fraction of CO_2 in atmosphere: uncertain data that depend on analyst's hypothesis;
- Wind velocity: input value is uncertain because of lack of knowledge about meteorological conditions and so it has been chosen by analyst;
- Outflow angle: this data is affected by uncertainty due to analyst's choice, considering system geometric conditions.

The most important uncertainties introduced by this model are related to idealising the flare flame shape as a frustum of a cone which emits radiation with uniform surface emissive power; total irradiative flux is described by a set of semi-empirical correlations, which have been developed and validated against a wide range of laboratory wind tunnel tests; finally, obstacles can not be considered by this model.

5.2.3 Dispersion

In a hydrogen dispersion simulation, uncertainties introduced by analyst's hypotheses or choice concern particularly the choice of simulation model, because available models are very limited in describing the real phenomenon.

Considering the kinetic energy of the release jet that prevails on atmospheric turbulence, and the low density of hydrogen that causes a fast rise of the gas when the kinetic energy has been lost, a turbulent free jet model, available in Effects, has been chosen to simulate the gas dispersion.

Applying turbulent free jet model, the most important uncertainties introduced by input data are:

- Initial pressure and temperature, hole diameter that depends on analyst's hypothesis;
- Discharge coefficient, as reported in release model.

About turbulent free jet model, the most important uncertainties and approximations introduced are due to flow rate calculating, that depends only on initial pressure and hole diameter, to the time of interest that is only the first instants of phenomenon; besides, model can not evaluate cloud evolution and its movement and obstacles can not be considered in modelling. Finally, this model overestimates the maximum distance reached by LFL concentration and it does not return area corresponding to LFL concentration.

It is important to point out that this model does not need other model results as input data and so it is not affected by uncertainties previously introduced, differently to other dispersion models available in Effects like Gaussian ones.

5.2.4 Flash fire

In a hydrogen flash fire simulation, the most important uncertainties introduced concern the evaluation of area interested by LFL concentration; this parameter is calculated in consideration of dispersion model results and in consideration of analyst's hypothesis about area definition.

5.2.5 Explosion

About a hydrogen cloud explosion simulation, main uncertainties due to hypotheses and choice of analyst concern definition of model to study the explosion and of some input data like the confined cloud fraction and the explosion curve number.

Applying the Multienergy explosion model available in Effects, uncertainties introduced by input parameters are reported in the following:

- Ambient temperature, that depends on analyst's hypothesis;
- Exploding mass, that is affected by uncertainties of

dispersion model;

- Confined fraction of inflammable cloud: this parameter depends on system geometry and on analyst's hypothesis;
- Curve number, that depends on analyst's hypothesis; it allows to define explosion curve and so it has a great influence on final results.

The most important uncertainties due to explosion modelling concern the definition of curve number, for which specific criteria are not available: this parameter is the main uncertainty source of the model; besides, steady flame speed is approximate to be constant and cloud is considered hemispheric, homogeneous, at stoichiometric concentration and ignited in the centre of cloud; finally, geometric characteristics of system are only partially taken in account (confinement grade of system).

5.3 Comparison of parametric models results

After uncertainty analysis, the study of EI A sequence has been manage by the working team with another software, called Phast (DVN), that implements other parameter models. In this way the team has showed how the analyst's choice about the software is very important and discriminating.

Simulations performed by Phast software assumed the same accidental conditions previously defined for the Effects simulations. In consideration of this, in the following table damage values for all scenarios considered have been reported; Effects and Phast results are compared too.

Table 3. Comparison of damage values calculated by Effects and Phast codes.

IE	End of sequence	Damage value (dead/event) EFFECTS	Damage value (dead/event) PHAST
A	Jet-fire	5.30E-02	4.60E-02
	Flash fire	1.35	5.3E-01
	UVCE	2.14E-01	0

Risk values due to damage values in *Table 3* are reported in *Table 4*.

Table 4. Comparison of risk values calculated by Effects and Phast codes and acceptability evaluation.

End of sequence	Risk value (dead/year) EFFECTS	Risk value (dead/year) PHAST	EIHP criteria
Jet-fire	1.21E-06	1.05E-06	Effects: A Phast: A
Flash fire	1.39E-05	5.46E-06	Effects: L Phast: A
UVCE	2.20E-06	0	Effects: A Phast: A

Risk acceptability has been discussed with reference to criteria proposed in the EIHP - European Integrated Hydrogen Project (*Figure 1*).

As it is pointed out by values in *Table 4*, main differences between the evaluations performed concern flash fire and UVCE modelling. Referring to flash fire, differences between damage evaluation performed by Effects and the one performed by Phast are due to the calculation of the area with a concentration equal or higher than LFL concentration. In particular, area calculated by Effects is about three times the one calculated by Phast software. About the UVCE, Phast codes denies that an outdoor explosion can occur, taking in account release conditions and hydrogen quantities. So differences between the two software are more relevant.

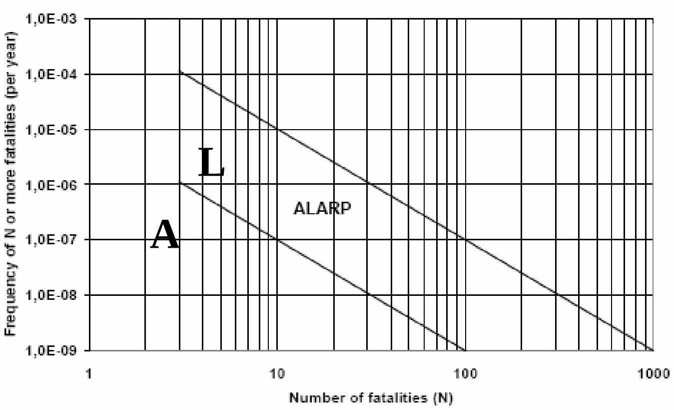

Figure 1. Societal risk curve, FN curve with ALARP region as proposed in EIHP Project

6 Conclusion

Activity performed has been aimed to highlight uncertainties that intervene in a classic risk analysis, with reference to a case study of particular interest: the hydrogen refuelling station for automotive. The problem of the uncertainty of this kind of plant is important because it involves an high degree of newness, concerning a new technology in a new context.

At present, uncertainties individualized are evaluating: in particular, studies have been focused in the consequence assessment that contributes significantly to the overall uncertainty of the analysis.

So, the first step has been a comparison between the application of two different parametric codes, that allowed to point out the most important uncertainties due to analyst's hypotheses, input data and modelling approximations.

To perform the next studies, apart from the comparison among models of different accuracy for the evaluation of consequences and the application of CFD codes, it will be of fundamental importance to have access to experimental data of the simulated phenomena. That will be possible thanks to the collaboration with the other project partners and in particular with the working group of Pisa University which activities concern the experimental simulation of hydrogen ignition phenomena. In the future release and dispersion experiments will foresee. In this way comparison between experimental tests and computer simulations will allow to complete the evaluation of uncertainties introduced by the models. Instead the Turin working team, in collaboration with CNR-ISAC of Turin, is working to develop a Lagrangian particle dispersion model for hydrogen to better study the phenomenon.

The expected output will be the assessment of models uncertainties coming from the comparison between the experimental tests and the results of the parametric and fluid dynamic models, up to highlight their effective impact on the uncertainty in risk estimation.

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References

[1] Armacost, R. & Pet-Edwards, J. (1999). Integrative risk and uncertainty analysis for complex public sector operational systems. *Socio-Economic Planning Sciences*, 33, 105-130.

[2] Cadwallader, L. C. et al. (1999). *Safety Issues with Hydrogen as a Vehicle Fuel*. INEEL/EXT-99-00522, Lockheed Martin, Odaho.

[3] Carpignano, A. & Ponte, E. (2002). The Uncertainty propagation in the simulation of industrial accidents. *Proc. European Safety and Reliability Conference ESREL 2002*. Lyon, France.

[4] Lees, F. P. (1996). *Loss Prevention in the Process Industries*. Butterworths, London.

[5] Norsk Hydro ASA and DNV. (2003). *Risk acceptance criteria for Hydrogen Refuelling Stations*. European Integrated Hydrogen Project [EIHP2], Contract: ENK6-CT2000-00442.

[6] Ogden, J. M. (1999). Developing an Infrastructure for Hydrogen Vehicles: a Southern California Case Study. *International Journal of Hydrogen Energy* 24.

[7] DNV, *PHAST Professional*, handbook to use the software.

[8] Ponte, E. & Gerboni, R. (2003). Hydrogen fuel cell bus: operating experience in Italy. *Proc. European Safety and Reliability Conference ESREL 2003*, Maastricht, Netherlands.

[9] TNO, (1997). *Methods for the evaluation of physical effects. "Yellow Book"*. Report CPR 14E (III ed.), NL.

[10] Zimmermann, H. J. (2000). An application-oriented view of modeling uncertainty. *European Journal of operational research*, 122, 190-198.