ELSEVIER

Journal of Hazardous Materials 111 (2004) 131–138

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

First lessons of the Toulouse ammonium nitrate disaster, 21st September 2001, AZF plant, France

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Abstract

A terrible explosion of ammonium nitrate, killing 30 people, occurred on 21st September 2001, in Toulouse, in AZF plant belonging to Grande Paroisse Company, TotalFinaElf Group. The manufactured chemicals in the plant were mainly ammonium nitrate, ammonium nitrate-based fertilisers and other chemicals including chlorinated compounds. The origins of the accident haven't found yet an agreement among investigators (company, justice).

The aim of this paper is to provide abroad an overview of some lessons learnt on that accident, from many perspectives, following the national debates and parliamentary enquiry as well as the various technical accident investigations.

Keywords: Hazards; Ammonium nitrate; Disaster

1. Accident description and effects

The explosion took place in warehouse, located between process parts, storage and packaging areas for AN (ammonium nitrate). It was used as a temporary storage of 'off-specs' AN ('downgraded' AN). These materials that do not fulfil the requirements (under-sized, downgraded, start-ups and shut-downs, return from customers, production tests as new additives) from different process units of the site (fertiliser and technical grade), had badly defined properties, and were aimed to recycling in AN-based binary/ternary fertiliser process. Also, dirty products may come from the cleaning of these units.

The warehouse had no gas supply, no steam pipes and only natural light, and was supervised by dispatch department. Three different subcontracting companies worked for the handling of these downgraded AN to the storage, but no one was in the storage warehouse at the time of the explosion.

The investigations of INERIS [1] led to an estimate of about 390–450 t of 'off-spec' AN stored the day before the explosion and allowed to retrace the entries during the morning of 21 September 2001. One of the key issue is the nature of product put on top of the AN storage minutes and hours before.

The explosion produced a crater of about 65 m $\times$ 54 m in diameter and 7 m in depth. The TNT equivalent mass of the explosion was estimated by INERIS [2,3] in a range of 20–40 t of TNT. The explosion produced a seismic wave that was estimated at 3.4 on the Richter scale. The overpressure waves have broken windows within 3 km, approximately. The human effects of the explosion were 30 persons killed (22 employees and 8 in the public) and up to 2242 people injured. Also 5079 people were treated due to stress. The plant was located in the suburbs of Toulouse and the extent of damage was very large both on and off site with a cost estimated by insurers of 1500 million Euro (see Fig. 1).

2. Historical land use planning and after the accident

During, the last century, due to the multiplication by ten of the inhabitants in the urban area of Toulouse (750 000 in 2000), houses and human activities came closer and closer to the factory (see Fig. 1). After the Seveso accident, safety studies were started in 1983, LUP was approved in 1989. Inside the lethal effect zone for LUP (900 m), there were 1130 inhabitants and 16 000 inside the irreversible effect

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0304-3894/$ – see front matter
doi:10.1016/j.jhazmat.2004.02.039

Fig. 1. Effects of the explosion and nearby Toulouse city.

zone (1600 m) for LUP and emergency response. After the Seveso II Directive, the local plan finally took a clear position for long term changes [4]. These authors also stated that since that procedure was launched in 1989, the state services applied it well without authorising any new housing.

During more than 6 months, the six companies of the chemical zone were stopped (1100 employees) reviewing their safety studies in order to get another right to operate from the local administration. In April 2002, roughly 6 months later after the accident, the TotalFinaElf group decided to close the plant (450 employees plus several subcontractors and suppliers). Later on, the Prime Minister decided to close the phosgene activities of the neighbouring companies (SNPE and Tolochime).

3. Accident investigations

Five authorities carried out five separate inquiries with different perspectives:

- The Inspection Générale de l'Environnement (IGE) issued a public report (in which, some technical investigations were led by INERIS) on 24th October 2001 ordered by the French Ministry of Environment, Yves Cochet;
- The Labor Inspection (Labor Ministry) made an investigation (March 2002);
- The TotalFinaElf Group made also an investigation and reported in March 2002;
- The Police and Justice gave a preliminary press report on June 2002;
- The CHSCT (health, safety and working conditions committee) of the employees of the site subcontracted an investigation to Cidecos-conseil (June 2002).

Also parallel actions were launched by the authorities:

- A Parliament Commission (Loos et al. [5]) that led a large number of visits and interviews at a national level issued a public report in February 2002;
- The Environment Ministry organised also a national debate on industrial safety after Toulouse, led by Philippe Essig that issued a public report (February 2002).

Notice that INERIS was mandated within IGE to investigate on products, effects, direct causes of the explosion but had to finish its mission with IGE the 24th October 2001. Further interviews, tests on products were planned to identify direct causes but were not conducted to avoid interference with Justice. After that mission, INERIS mainly worked with the Environment Ministry for the “after-Toulouse” and the new law for industrial safety. This aspect will be discussed later on.

Before discussing several lessons, a few comments on investigations process may be addressed. The co-operation between the different investigations and in particular between the Justice and the IGE was not officially settled. In the transportation field in France, since a recent law in January 2002, exchange of critical information is allowed between the Justice and safety investigation of independent boards (air, marine and in rail, road and tunnels). Another problem is that operators and managers were then interviewed by five different investigations. In the same idea, the Parliamentary Commission [5] recommended a controlled access for different investigators to the key technical elements that are collected by the Justice. Last comment, all investigations were ad hoc commission. As an example here, the IGE and INERIS started with the help of the local control administration (DRIRE) to interview operators 1 week after the explosion and to investigate damages 10 days after it.

4. Direct causes

At the present time, there is still a controversy on the direct causes of the explosion between the Justice, the company and the media. The key element is to find the ignition source of the AN stored. The Justice's main assumption is discussed later (see Section 5.1.1). The TotalFinaElf company is focusing mostly on a huge underground electric arc between a transformer on SNPE's site (owned by the French State) and EDF's electric line. Other assumptions as terrorism act or malicious intent have been investigated as well, but has not appeared relevant so far.

5. Lessons learnt

In this part, dealing with the lessons learnt, it appeared relevant to locate the various findings and conclusions from the investigations and parliamentary enquiry within the socio-technical system as shown on Fig. 2 [6]. This representation shows various levels (hazardous process, operators, staff, management of company, control authority, government, associations, public pressure, market, etc), that are part of the functioning of the system as a dynamic whole. Major accidents always question the global system dynamic. The following lessons learnt have turned into recommendations to the stakeholders and into regulations. The principle of this paper is to show where these lessons have an impact. They will be presented according to a bottom approach from the hazardous substances and process involved to the higher levels of the system (process, company's management, regulation . . .).

5.1. Hazardous process/installation

5.1.1. Hazards of AN

The synthesis of ammonium nitrate (NH_4NO_3) needs to be performed from two raw materials—ammonia (NH_3) and nitric acid (HNO_3)—through an exothermic reaction. Sev-

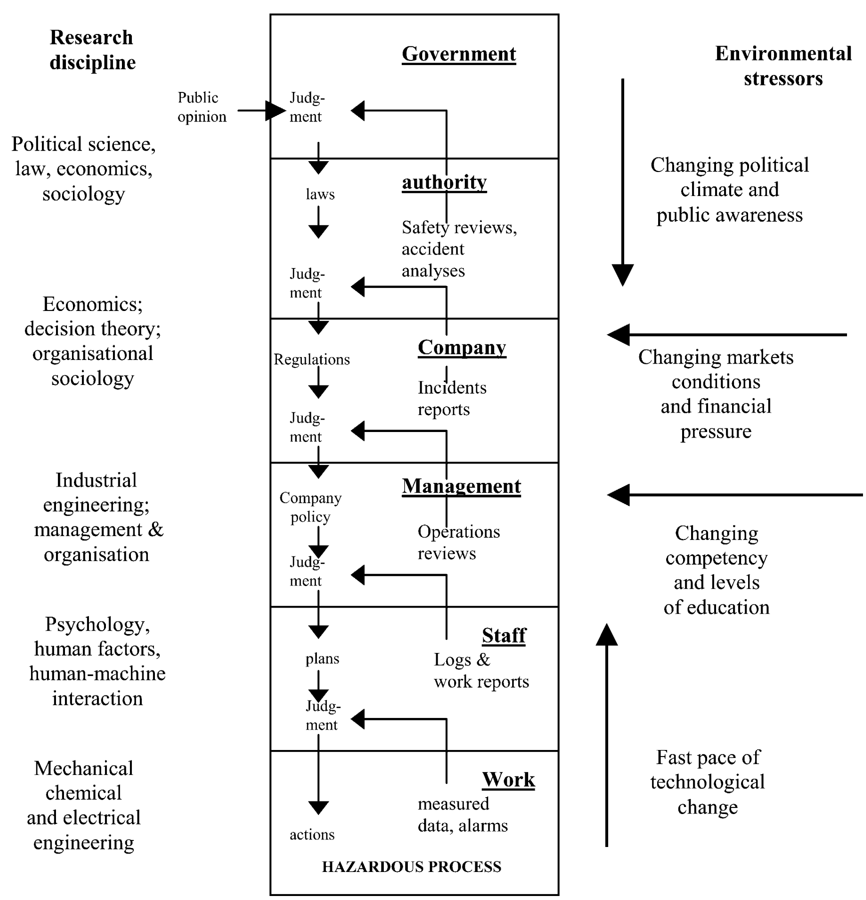

Fig. 2. Representation of the socio-technical system (2000) [6].

eral kinds of AN-based products can be obtained for different use: the "fertiliser grade" and the "technical grade" as a component in explosive preparations. The major explosion which occurred in Toulouse, was a severe reminder of the inherent hazards associated with the handling and storage of AN:

- Thermal decomposition of AN-based products;
- Detonation of AN-based products, that may happen when worsening conditions are gathered: confinement or self-confinement (when stored in relatively large quantities), contamination (presence of impurities) and thermal source (fire or explosion for example). It's important to distinguish as well neat AN and impure AN because their explosive properties may be very different, even for very poor impurity content.

Investigations on Toulouse's explosion showed its origin was neither a fire nor a first explosion followed by the mass explosion. Studies have therefore focused on reviewing the role of contamination in AN decomposition, and in particular the chemical incompatibility. Dangerous reactions may occur between AN and products such: halogenated (specially chlorinated) compounds; combustible/organic materials; divided metals, specially in contact with molten AN.

Some calorimetric (DSC) experiments have been conducted at INERIS with some products present on Toulouse's site before the explosion. These tests have shown that a mixture between AN and DCCNa (SDIC, sodium dichloroisocyanurate) or AN and ATCC (trichloroisocyanurate acid) is strongly incompatible. In presence of small moisture content, the reaction is violent and starts as soon as the products come into contact, even at temperature close to ambient temperature. These reactions, in addition of the decomposition catalysis from chlorine ion, involve the production of a very unstable substance, trichloramine NCl_3, which is very sensitive and is able to explode. This scenario is suspected to be, according to the preliminary results of the Justice's investigations, the most probable origin of Toulouse's accident.

Investigations of INERIS showed that between 5 and 31% of the total AN mass stored have detonated. Also in Oppau, in Germany in 1921, 10% of the stored AN has effectively exploded. With regard to INERIS's recommendation, the Environment Ministry issued a new regulation, on 21st January 2002, that made compulsory to take the value of 10% of the AN mass stored into the detonation scenario calculation for safety studies and land-use planning (LUP).

5.1.2. Domino effects

On this aspect, no major domino effect has been observed. However, one of the conclusion of Barthelemy et al. [7] is to review all the safety studies with AN (storage and production) and consider the domino effect risk between AN storage and ammonia storage. Indeed, the disaster could have been worsened if toxic gases (chlorine or ammonia) wagons or tanks nearby had been damaged or if it occurred at a busy hour with the motorway nearby (where some people have been injured). On the SNPE neighbouring site, "if there was no domino effects, it's not by chance, but because of the know-how of the pyro-technicians, which the three principles are: (quantities) division, separation, and many safety barriers".

5.2. Work and staff

The various enquiries dealt on the relationship between subcontractors and employees but no in-depth human factor analysis was performed on the company real operating work context (at the exception of the report from Cidecos-conseil), namely the storage and the conditions in which storage was operated.

However, as recommended by several investigations [8], the Environment Ministry made compulsory in its new law of 30 July 2003 [9], to involve more widely the employees and also to integrate the subcontractors in the risk management process. Notice that employees are the main victims (almost 80%, other are firemen and public) of the accidents involving hazardous materials (not working accidents, 1992–2001 in France, ARIA database, BARPI). The scope of the internal health, safety and working committee (CHSCT), will include therefore also the risk of major accidents. It will have the possibility to request technical assistance from an expert. It could alert the local administration. It will be involved in the safety studies review process for licensing a facility and give its opinion on the emergency means.

5.3. Management

On the AZF industrial site, 25 subcontracting companies worked continuously (100 subcontractors every day versus 250 employees for a total of 469 employees). Three different subcontracting companies worked in the warehouse (the downgraded AN was picked up, unloaded and removed by them) and the maintenance of this warehouse was carried out by another subcontractor.

Cidecos-conseil, a consulting company, hired by AZF's, carried out an organisational investigation. They consider that the subcontracting was a "determining factor" of the accident. One consequence of the operational subcontracting of the warehouse is a disengagement of AZF employees for its operational management; AZF has lost the control (in INERIS interviews, inadequate communication has been identified) of some activities carried out by the subcontractors. Essig [8] insists on the need of a control of the subcontractors through labelling as performed in the petroleum industry. He stated that the need for high qualification is not compatible with the interim work. In its report of January 2002, the French Parliament Commission made various proposal concerning subcontracting.

The new law aims at monitoring the use of subcontracting on Seveso sites. A list of the job that can not be managed by interim workers or by subcontractors will be discussed with the CHSCT. The CHSCT will be divided in two commissions, one with the employees of the company and one for a site with other companies and main subcontractors.

One can state, however, that no specific analysis of the safety management system of the company and the way it worked was performed by the various investigations, which would have been useful to identify the specific root causes of the accident.

5.4. Company

Nothing has been issued at the level of the company, no specific organisational enquiry has been performed. This is closely linked with the previous remark and has constituted, we believe, a weak point of the investigations so far.

5.5. Regulators (DRIRE), third experts

5.5.1. More control: new means for the administration

A few days after the Toulouse disaster, the European Parliament (EP) issued a paper [10]. The EP "regrets that the Member States, despite repeated warnings, do not provide themselves with sufficient numbers of competent and specialised inspectors and calls, consequently, for such staff to be recruited and suitably trained, and for minimum qualification criteria for inspectors to be updated in order to guarantee the same level of safety on classified sites in the EU". This was also underlined by Barthelemy et al. [7] that proposed to the French Administration to multiply by two the number of Inspectors in the next 5 or 6 years (800 before and 1400 inspectors are now planned by 2007).

They stressed on the fact the local control authority was compelled to make priority choices even in the Seveso sites. The local administration carried out seven inspections in 3 years (1998–2001) mainly on Seveso activities (and environmental pollution control): chlorine and ammonia storage, safety studies and Safety Management System. As a reminder, the AN off-spec storage was not covered by the legislation.

5.5.2. Emergency response and planning

In the following days of 21st September, 1570 firemen and militaries, 950 policemen were involved in the emergency response and housing monitoring. The problem was that they arrived themselves without any plan and any discussion by phone as the classical phone lines were partly destroyed and the mobile phone network was saturated. In those kind of situations, the experience of forest fires should help to organise the arrival of little groups of vehicles [11].

The internal and external emergency plan were not prepared to this scenario and its gravity. The previous training help the firemen and others to have adequate behaviour. However, the first firemen were not protected with adequate equipment for any toxic cloud and with devices to detect those toxic gases.

The information of the population was not possible without the buzzer (did not work) or the radio. In case of a domino effect on a toxic gas storage, the confinement emergency action with broken windows was not ensured. The communication network should be designed to have a separate network for crisis management [11].

5.5.3. New means for third experts

First of all, it was stated [7] that the Environment Ministry and the local administration needs to have a strong technical support as in the nuclear field with the IRSN for French Nuclear Safety Authority. "The means of INERIS and IRSN should be strengthened and their exchanges developed. They should also receive funds from taxes to set on the hazardous sites (taxes that would be very low compared to the Nuclear sector)". One of their major role is to criticise safety studies. In that sense, the French Environment Ministry gave additional funds to INERIS to increase the research on chemicals properties, on learning from experience, on safety studies and on emergency response.

5.6. Government, French National Parliament

5.6.1. Risk assessment

The experience of Toulouse's disaster, was seized by Barthelemy et al. [7], Essig [8] and Loos et al. [5], to ask for a methodology review of the safety studies in France. First of all, Barthelemy et al. [7] stated for a need of better quality and harmonisation or safety studies of any site. Indeed, on different AN manufacturing sites, there have been ranges of distances for lethal or for irreversible effects that are with one order of magnitude. Barthelemy et al. [7] recommended to the Environment Ministry, to define the rules on the scenarios to assess (storage, wagon, trucks and piping system), the external interference (natural hazard as earthquake, centennial flooding, domino effects, dam rupture, plane fall and also malicious intent . . .) and to define criteria's for effects on people. INERIS is working on a research project for the French Environment Ministry in order to review the content of safety studies in that sense. Also Barthelemy et al. [7] called for an harmonisation of the safety studies between industrial and pyrotechnics sites and also through EU. Essig [8] also reminds us "we cannot limit the industrial risk only on the Seveso sites, this aspect is much wider".

Notice that malicious intent should now be part of what can be foreseen with the 11th and the 21st of September. One could mention that on the 10th of last years (1992–2001), 6.7% of the accidents notified to the database ARIA of BARPI (French Environment Ministry) are/or are suspected to be malicious intent.

5.6.2. Introducing uncertainty (probabilities) regarding the French deterministic approach

Essig, [8] Loos et al. [5], pointed out the need for introducing uncertainties of the accidental scenarios as probabilities in the risk assessment like in the UK and in the Netherlands. Indeed, the deterministic approach does not really integrate the industrial risk management improvements in LUP, by the administration. The new law asks, therefore, to take into account the probability and the kinetic of scenarios in the new safety studies. However, they pointed the need to keep on assessing scenarios with a consideration of a possible failure of the safety barriers designed and implemented (deterministic approach).

5.6.3. Risk assessment and transportation

Essig [8] underlines that one should consider the instantaneous rupture of a wagon even if no accidents were yet observed. Essig [8], with his experience as a former President of French national railway company (SNCF), underlines that we are facing a major problem because of a weak perception of the risk implied by hazardous goods transport. In additions, he proposes also to set up an Intelligent Transport System like in Frankfurt in order to monitor with mobile communication systems the flux of the rail transportation goods which would help for emergency response.

5.6.4. Vulnerability and risk acceptance

Barthelemy et al. [7] considered that if the societal risk is too high and that LUP and emergency response have to be ensured without any possibility of reducing risk at its source, then sites should be closed. They proposed a threshold of unacceptable societal risk (lethal concentration 1% and 10 000 people in the perimeter). No national risk acceptance threshold has been defined in France until now. This could be a long debate, but some disagrees as Essig [8] that writes “Risk acceptance can not be written in a decree”. The new law aims to improve local discussions and decisions in order to negotiate local risk acceptance.

5.6.5. Land use planning recommendations

The trend of major accidents recorded in the MARS (Major Accident Reporting System) database of the EC [12], is approximately 30–40 major accidents per year throughout the EU. So, one of the conclusion is that controlling major accident hazards by reducing the risk on-site is not sufficient to promote a sustainable development for both industry and urban areas without LUP in the next decades [13]. Another conclusion is that the Seveso I and II Directives have their limits which was a shocking surprise for part of the public opinion that lived in the “zero risk” belief.

Several statements were made by the European Parliament (EP) 2 weeks after the Toulouse disaster. They asked, in a context of sustainable development (safety, employment and environment), for a new risk management based on the logic of “risk removal”. The EP also “called on the Member States to initiate urgently an in-depth review of policies on regional and urban planning in the vicinity of risk sites, including as regards the fiscal aspects”. The EP “considers that, in the case of high-risk industrial sites, consultation procedures between public authorities and elected representatives, local residents, industry and staff representatives should make it possible to restructure these sites”. Finally, the EP “strongly opposes to any attempt to relocate dangerous sites to countries where environmental and social standards are lower than those in force in EU territory”.

After investigating the historical LUP, Mathieu et al. [4] mentioned that the final lessons are that it is possible to act inside the LUP zone, which appears today being too small and that it is not possible to interfere on a housing built before the LUP creation.

In the new law, LUP will be managed through technological risk prevention plan (PPRT). In particular, local stakeholders as the public will be involved in decision-making process to restructure LUP through PPRT (see Section 5.9.3).

5.6.6. Learning from experience

Considering this experience on AN, Barthelemy et al. [7] claimed for further development of learning from experience on accident and near-misses with the ARIA database operated by the BARPI (Environment Ministry). The Parliamentary Commission led by Loos et al. [5] asked for several measures in order to improve the learning from experience tool: increasing fines for the lack of incident notification, increasing the degree of penalty by the Justice, develop European incident/accident database network, help to set up databases on efficiency of equipment in the industry, create exchange group in different technical field at a European level . . . .

5.7. EC, European Union Directives

5.7.1. New regulation for AN-based product in the European Union

AN-based products were classified in Europe, according to the Seveso II Directive (96/82/EC) in two different categories depending on the explosion hazards it presents (fertiliser and technical grades). The updating of the Seveso II Directive was adopted in view of classifying two new categories: “off-spec” materials (unclassified AN), taking into account one of the lesson of Toulouse’s explosion and AN-based composite fertiliser because of other accidents in EU with self-sustaining decomposition.

5.7.2. White book of the EC

About the materials knowledge and in a broader point of view than the AN, the Parliamentary Commission (Loos et al. [5]) recommended France to push for the White book presented the 27th February 2001 by the EC for the future policy on chemicals materials. At the present time, 99% of the materials (marketed before September 1981) are not tested. The purpose is that all the chemicals materials should be tested and should require a risk assessment: end of 2005 for existing chemicals that are manufactured for more than 1000 t, end of 2008 for manufacturing more than 100 t, and end of 2012 for more than 1 t manufactured. This proposition receive support from trade-unions and environmental associations but not from industrials [5].

5.8. Justice

The Parliamentary Commission led by [5], made also some proposals upon the role of the Justice. Some proposals states the need for strengthening the penalties of law's non-fulfilment. A harmonisation is asked to the local environmental authority (DRIRE) for its notification role to the Justice. Also, the teaching of environmental law should be strengthened for the Judges.

5.9. Environmental stressors

5.9.1. Changing political climate and public awareness

5.9.1.1. The public in the decision-making process. The accident showed that public was not efficiently informed (were surprised) and the public opinion in Toulouse surveys confirm this lack of transparency on the accident. The new law insists on that point with three measures. The first one will be to create for each hazardous site a local information and consulting committee involving all stakeholders as for the nuclear and the waste treatment sites. It will be granted by the Government. The local committees will discuss the means to better inform the public of the different risks and the way to reduce them. Secondly, in order to report to the public, public meetings will have to be organised when safety studies are submitted to authorities. Finally, the law makes compulsory to inform when selling or renting any housing in the vicinity of effects perimeters.

5.9.1.2. The public opinion pressure. In the days following the accident, there were public demonstrations calling for "Never this again, neither here nor elsewhere". Also on other similar and Seveso sites, high public pressures were observed on the local authorities (political, administrations) and on the industrials. A kind of climate against chemical plants spread and tried to push for radical decisions. Indeed, it was easy to identify scapegoats as many sites in France, would have the same feature. Also the media reported in those troubled days claims for putting those site away from France. The green political forces claimed also that the agriculture could avoid using those fertilisers and so the country would not need anymore those plants.

5.9.2. Changing competency and levels of education: developing a risk culture

The Parliamentary Commission led by Loos et al. [5] considers that the human factor is at the head of the struggle versus major accident hazard. There is a need to eradicate the culture of secret with the employees, the external population. Also regarding other risks as transportation, food, home, medical and sports, Essig [8] writes "It seems to me that our society should have a minimum of coherence in the understandings of the risk and their consequences" with the distinction of risks that are chosen and those which are not. This understanding of the risk is a problem of culture. In the past, people accepted the risk and accidents as a fatality. Then a culture of indifference and use has developed with the technological progress and led to the myth of the zero risk in the nineties. Essig [8] declares "There is a lack of a true safety culture in France". France is late regarding some countries in Europe and this is due to the incompatibility between safety rules or procedures and some French people behaviours that wants sometimes to turn around the rules, according to Essig [8].

Essig [8] identifies factors for developing a risk culture: safety teaching at universities, school; safety management as a criterion for others (financial, social); the involvement of trade-unions and safety norms.

5.9.3. Changing market condition and financial pressure

In the new law, the French Environment Ministry identified two main questions: How to deal with the existing situation without increasing hazard? How to treat present very hazardous cases? The first principle is that each increase of a LUP perimeter from industrials will lead to compensation from them. In the vicinity of Seveso sites, PPRT will define no (or reduced) man's land and those that need housing protections (windows, . . .). This plan could use financial incentive tools in order to let the people leave their house or in order to exclude them. The cost will be shared by companies, local authorities and the State. The government considers this proposal as new in Europe, planning of which will take years.

Also the role of insurer's was pointed, as they could be more incentive to promote risk management and risk reduction. The new safety studies will have to estimate probabilities of occurrences of major accidents scenarios but also the cost of the potential economical damages to the goods (as a reminder, the new law focuses only on 670 Seveso site high threshold versus a total of 1250 Seveso sites in 2001).

In parallel, in the new law, in case of major accident, the victims will be compensated faster by making compulsory for the victim's insurer to pay for its damages. Then the victim's insurers will deal for compensation with the Industrial insurer's.

5.9.4. Fast pace of technological change

As mentioned before (Section 5.9.1.2), the concept of reducing risk (or hazard) at its origin and the necessary doubtful attitude, upon the real need of the existing products, storage's sizes and processes, gained power mainly in the mind of the authorities (French, European), the public and the industrials. The need for inherent safe design is reminded and further developments in the direction of process intensification research should be again promoted in those types of industries.

6. Conclusions

The objective of this paper was to provide abroad an overview of the first numerous lessons of the biggest industrial disaster in France ever happened, on 21st September 2001, in Toulouse. The lessons identified by different authors have been presented in this paper according to the overall risk management process involving different actors at different levels of the socio-technical system.

Several investigations gave lots of analysis and propositions that help the French Environment Ministry to implement a new law. The new law focuses on several points (public information; public, employees and subcontractors involvement in the decision-making process; new land use planning, improving financial compensation for victims; . . .) that complete the Seveso II Directive. The aim was therefore not to change Seveso II Directive in France, but rather to strengthen it. Some lessons have also been implemented at a EU level (White book, AN changes in Seveso II Directive).

Acknowledgements

Advice was received from Sandrine Descourriere, Yvon Mouilleau, Olivier Salvi, Christian Michot and Didier Gaston. This paper presents only some views of the authors and also other views, opinions, propositions of several authors in the literature that have been kept.

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