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# SPLITTING NUCLEAR PARKS OR NOT? THE THIRD PARTY LIABILITY ROLE

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GÉRARD MONDELLO

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# **SPLITTING NUCLEAR PARKS OR NOT? THE THIRD PARTY LIABILITY ROLE**

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# **SPLITTING NUCLEAR PARKS OR NOT?**

## **THE THIRD PARTY LIABILITY ROLE**

**Gérard Mondello**

**February 2014**

### **Summary**

*Starting from the standard analysis of accident theory, this paper shows that determining the first-best level of care of ultra-hazardous activities also involves determining the best industrial structure. The analysis assesses the impact of the civil nuclear liability on the organization of given electro-nuclear parks. The object is to know whether these liability rules induce horizontally concentrating the management of nuclear industry or not. In a model extended from two to  $n$  plants, we show that the institutional conditions (cap on the operator's liability and the insurance compensation) play a fundamental role in the inducement to centralize or not this management. Hence, a priori, no organization framework is more efficient than the other one.*

JEL Classification : Q5, Q58, Q53, K23, L13, L52, L94

Key words: Strict liability, Electric Energy, nuclear plants, limited liability, concentration

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## **0. Introduction**

Since the major contributions of Coase (1960) and Calabresi (1961) to the revival of the "Law and Economics" stream, tort law has become a major prevention policy instrument. Indeed, beyond their original purposes of compensating and repairing harm, the liability regimes wield strong influence on wrongdoers by inducing them to take due care in managing risky activities. However, the meaning of "due care" is not that obvious. In our opinion, concerning large-scale industries, this expression jointly consists in maximizing the level of prevention and minimizing safety costs as in the usual sense but, also, determining the best organizational management structure. Hence, this paper's purpose is to enlighten this last point. Indeed, choosing the optimal care level involves defining the most suitable and efficient industrial organization. It studies how third party civil liability affects it by promoting either the concentration of the management of electronuclear plants into a single operator's hands, or, conversely, the splitting of these facilities between independent actors. Consequently, this study's main stake aims at understanding what kind of organization both optimally minimizes the accident costs and maximizes the level of prevention. The notion of accident costs comes from the theory of accidents initiated by Brown (1973) and systematized by Shavell in the eighties of past century. Both the safety level and the global cost of liability evaluate the wrongdoer's performance concerning its duty of safety.

To give an illustration of the importance of liability regimes in the designing of competition, we refer to the recent adoption of the Civil Liability for Nuclear Damage Act, 2010 or Nuclear Liability Act in India. The rapid growth of India considered as a BRICS economy involves growing needs of energy. However, its old energetic infrastructure cannot meet the new power requirement. Consequently, Indian government decided to impulse some ambitious nuclear program that should grow from 4,120 MW to 10,000 MW by 2020. Until 2010, India stood out with neither a national nuclear liability legislation nor membership in one of the international conventions. Accordingly, regarding nuclear third party liability, a national "standard strict liability" ruled the nuclear sector. This involved the full liability of the operator in case of accident. The development of the nuclear sector could not stand alone on the resources of the Indian nuclear industry. Consequently, international cooperation with nuclear countries became necessary involving the Russian Federation, France and the United States of America. However, these Countries face different civil liability regimes. While in France and Russia, the State insures foreign investments, in the USA, it is mandatory insuring nuclear plants. The Price-Anderson Nuclear Industries Indemnity Act mandates operators to

jointly fund a fund and pays up to \$10 billion. Hence, after a nuclear disaster occurrence, the plant's insurer pays the first \$375 million. Consequently, for fairly competing with Russian and French Companies, the US reactor manufacturing companies needed some adaptation of the Indian Civil Liability regime. After tumultuous debates among deputies and in the Indian press, India adopted the Nuclear Liability Act by 2010. This act provides a third party liability for nuclear damage by applying strict liability to the operator and quick reparation to the victims. This institutional change opened the competition's door to US companies.

This article's unsaid bias considers that each dangerous activity owns specific structural features that do not compare with others. For instance, petrochemical facilities, electronuclear power plants and agricultural fertilizer factories or, still, oil products transportation generate specific risks and structural pollutions that require appropriate repair measures. Consequently, all these structural factors plead for favoring per sector analysis rather than a general ill-adapted framework. That is why the present study limits itself to the sole electronuclear industry. Threefold reason explains this choice. First, this industry potentially generates large-scale and long lasting disasters (Fukushima in 2011, Chernobyl in 1986 and Three Mile Island in 1979, this, without listing the set of numerous other minor accidents). Second, standardized unit-reactors generate power and this allows comparing and combining them on a unified perspective. Third, the electro-nuclear parks management is becoming a main concern question. Indeed, in Europe (Russia and Ukraine included) this park amounts to 195 nuclear power plant units corresponding to a 170 GWe installed electric net capacity in operation. Furthermore, there, nineteen units of 16,9 GWe are under construction in six countries<sup>1</sup>. Consequently, in this area, or more very likely in the space of the European Union, choosing the optimal nuclear parks size arises as a significant question.

As the economics field of electro-nuclear is wide, we need precisely specifying our research area. Hence, we compare neither the economic efficiency of different energy sources (MIT (2003), (2009), Bickel and Rainer (2005)), nor the operating conditions of the nuclear industry under some price uncertainty (Gollier, Prout, Thais and Walgenwitz (2004), Linares and Conchado, (2009)), nor the decommissioning plants question nor the reprocessing of nuclear waste question. Our argument borrows some features from the well-known debate concerning civil liability in the electro-nuclear industry. Most of these contributions (Dubin and Rothwell (1990), Heyes and Heyes, (1998), (2000a), 2000b), Faure and Borre (2008), Faure and Fiore (2009), Rothwell (2001)) show that putting ceiling on the level of repairs

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<sup>1</sup> European Nuclear Society October 1, 2010, <http://www.euronuclear.org/info/encyclopedia/n/nuclear-power-plant-europe.htm>

implicitly comes at subsidizing this industry<sup>2</sup> by allowing the potential externality costs unpaid. The present paper does not follow this road. It aims at understanding how the civil liability regime influences the economic organization scheme for reaching the best safety level.

To show the point, the analytical framework borrows from the theory of contestable markets of William Baumol, John Panzar and Robert Willig (Baumol et. al.1988 (1982)) and extends it to the expected costs case. Taking into account uncertainty means that the regulator has to consider both the level of the expected cost of an accident and the level of care taken by the nuclear plants' operators. Consequently, this paper compares the accident cost structure (that includes the potential costs of repairs and the costs of the efforts for safety) of a centralized and a decentralized nuclear park when a regulatory agency imposes limiting or stopping the production of power of the remaining safe plants after the occurrence of a catastrophic event.

The first part of the paper describes the main feature of liability regimes in the electronuclear industry. A second part compares the costs structure of both organizations for a given level of care in a simple model with only two plants. A third part integrates both insurance premium and the care effort. A fourth part extends and generalizes the study to more than two plants ( $n$  plants), a fifth section analyzes the results and a last one concludes.

## **1. Why to cap the repairs in the nuclear industry?**

After the Tchernobyl 1986 disaster, Soviet Union escaped to the duty to compensate damages to health, crops of national and international economies. Indeed, before 1988, this country never acceded either to any nuclear conventions or to national nuclear liability law. To avoid future detrimental situations, the International Atomic Energy Agency (IAEA under UN patronage) in Vienna and the Nuclear Energy Agency (NEA under OECD in Paris) amended the existing international nuclear conventions<sup>3</sup>. The 1988 Joint Protocol linked together the IAEA's Vienna Convention on Civil Liability for Nuclear Damage of 1963 and the OECD's Paris Convention on Third Party Liability 1960. Protocols amending the Paris Convention and the Brussels Convention were signed on February 12, 2004.

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<sup>2</sup> See also the synthesis achieved by Carroll and Froggatt (2007).

<sup>3</sup> See for instance, Faure and Fiore (2009),

The joint protocol promotes a strict liability regime but maintains the liability limitation principle settled by the previous international conventions<sup>4</sup>. These last ones set on a global framework that national legislation can make more, but not less, stringent. Under the Joint Protocol, the operators of civil nuclear facilities are strictly liable for damage resulting from nuclear incidents. Furthermore, compulsorily, the operator needs contracting insurance policy or financial guarantee up to the fixed liability amounts in order to guarantee the funds availability. This disposition depends on the approval of the Members States. The accumulation of treaties and Conventions and the different rhythm of their adoption by the States induce a lack of harmonization and coordination. To put briefly, we can quote the 2005 report Eurotom on the harmonization of nuclear civil liability rules in Europe.

*“In sum, the protection of victims of nuclear accidents, the obligations of nuclear operators, transporters, (re-)insurers and public authorities in the EU Member States are governed by a patchwork of diverse legal regimes: (i) the liability of some operators is unlimited, whereas others have a capped liability; (ii) the operators’ insurances differ both as regards their coverage and payable fees; and (iii) the obligation to compensate victims of a nuclear accident differs both as regards the damages covered and the payable amounts.”*

Why do States choose the ceiling of redress rather than applying some “standard” strict civil liability regime? In fact, without caps, coupling tremendous nuclear hazard repairs and strict liability would constitute an insurmountable obstacle to market access Schwartz (2006, p.39): *“With no protection against a liability that was potentially unlimited both in time and amount, nuclear plant owners/operators, builders and suppliers were understandably hesitant to commit to the development of the industry.”*

Therefore, the development of nuclear industry involves relieving nuclear operators of the burden of ruinous liability claims<sup>5</sup>. The governments capped the amount of compensation payable to victims by liable operators to avoid them becoming judgment proofs. However, under the public opinion pressure against the dangers of electro-nuclear power, the level of the ceiling caps tends to increase. For instance, until 2004, under the Brussels Convention, in France, the operator’s liability was limited to €91.5 million per nuclear accident per facility and to €22.9 million per nuclear accident during transportation. The State in which the

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<sup>4</sup> Under the Joint protocol of 1988, the operator’s liability is absolute, i.e. the operator is held liable irrespective of fault, except for “acts of armed conflict, hostilities, civil war or insurrection”, terrorism acts do not enter in the exclusion category.

<sup>5</sup> More explicit still is The “*Exposé des Motifs*” for the 1960 Paris Convention that considers that “unlimited liability could easily lead to the ruin of the operator without affording any substantial contribution to compensation for the damage caused” (*Exposé des Motifs*, Motif 45).

accident occurred was liable for the compensation of victims up to a maximum of €228.6 million. Above this amount, the signatory's members of the Brussels Convention contributed collectively to compensation up to a ceiling of €381.1 million. Since the 2004 protocol, the availability of compensation amounts has increased and now it covers a greater number of victims and collateral damages. Accordingly, the operator's liability is around €700 million per nuclear accident and €80 million per nuclear accident during transportation. The responsible State of a nuclear damage will be liable for amounts above the €700 million up to a maximum amount of €1,200 million. Over this amount, the States that are a party to the Brussels Convention have to contribute to a maximum amount of €1,500 million.

In the USA, the Price-Anderson Act of 1957 rules the civil liability for damages caused by nuclear accidents. Since the 1988 amendments, nuclear power plant licensees must purchase the maximum amount of commercial liability insurance available in the private market at a reasonable price. This is currently \$200 million per plant. In addition, all nuclear power plant licensees must participate in a joint-insurance pool. In the case of a nuclear accident whose costs exceed the first layer of private insurance coverage, each nuclear plant is obligated to make payments of up to \$88 million to cover any additional costs up to about \$9.3 billion now. The compensation provision of both the first and the second layers of insurance are "no fault" and are not subject to civil liability litigation. The financial cap corresponds to \$9.5 billion. Beyond this limit, there are no further financial obligations.

## **2. A two plants model with fixed care efforts**

This section presents the feature of an over-simplified model that compares the relative performance of a centralized and a decentralized organization with only two electro-nuclear plants. Here, the probability distribution of a major accident is given and their level is independent from any care effort. This simple version helps at presenting the general framework extended to the n-plants case in section 4.

### **2.1 Notations and assumptions**

The considered economy encompasses two similar electro-nuclear plants (indexed each by  $i, j$ , and  $i, j = 1, 2$ ). Two patterns are compared. In the first one, a unique operator (or the "monopolist", indexed with M or none when ambiguity is impossible) manages both units. In the second one, two independent operators manage each only one plant (indexed with  $l, l = 1, 2$ ). Legally, each operator is liable for potential harm under a capped strict liability

regime (see assumption 3). Here, whatever the industrial structure, the operators supply the same safety effort.

**Assumption 1:** *The operators ( $M, l, l = 1,2$ .) are risk neutral.*

This assumption means that the operators look at the expected value of the accident costs and, obviously, without feeling neither aversion nor preference to risk.

**Assumption 2:** *Both plants are similar.*

Assumption 2 means that each plant belongs to the same generation and they share each other a similar engineering structure. Both have the same production capacity<sup>6</sup> and support the same operative costs. By Law, the operators' financial capacity for redress has to tally with the total available asset legally needed to repair the consequences of a major accident. Let, respectively, be  $w$  the monopolist operator's wealth and  $w_l, l = 1,2$  the one of the individual operators.  $Q$  is the amount that insurance companies cover (compensation and repairs) and  $c$  is the institutional and legal cap corresponding to the repair due to harm where  $D$  is the total damage due to a severe harm (obviously ( $D > Q$ )).

**Assumption 3:** *A capped strict liability regime rules nuclear accident where  $c$  is the amount of the legal compensation (liability cap). The value  $c$  belongs to the interval  $0 \leq c \leq D$  and  $w, w_l \geq c - Q$ .*

**Remark 0**

- i) When  $c \equiv 0$ , no-liability regime exists as in the Ex-USSR situation,
- ii) When  $c \equiv D$ , the cap is null and a "full" standard strict liability regime applies as in India until 2010 or still as in Germany.
- iii) For most nuclear countries,  $0 < c < D$ .
- iv) Assumption 3 means that insurance companies do not fully cover the cap and  $Q < c$ . The share  $Q$  is identical and fixed whatever the production structure. This involves that the operators' wealth should be such that  $w, w_l \geq c - Q, l = 1,2$ .

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<sup>6</sup> For engineers our economic assumptions could appear quite unrealistic. For instance Lochbaum (2000) notes the over-simplifications usually made to deal with this question:

- i) The plants are operating within technical specifications and other regulatory requirements,
- ii) Plant design and construction are completely adequate,
- iii) Plant aging does not occur; that is, equipment fails at a constant rate,
- iv) The reactor pressure vessels never fail,
- v) Plant workers make few serious mistakes,
- vi) Risk is limited to reactor core damage. If this set of assumptions cannot be insured for one plant, obviously it can hardly be done for a park even if plants belong to the same generation.

Then, when  $w < c - Q$  or  $w_l < c - Q$ , the operator can become judgment-proof (Shavell, 1986). However, this case is off-topic because insurance companies do not insure facilities with insufficient self-owned assets.

## 2.2 Control, time and probability distribution of major accident

Independent regulatory authorities control electro-nuclear parks. These authorities can be the government or some governmental agency<sup>7</sup>. After a catastrophic event on one plant, a control ( $S$ ) consists setting the necessary mitigation measures that the regulatory authority imposes to the operators on the remaining safe plant to avoid duplicating similar accidents. In fact, after a major nuclear hazard, generally, stations of the same vintage are put under control. This happened after the Fukushima accident. Morgan Stanley (2006, p. 46) asserts that a severe accident in one reactor can “*lead to the shutdown of the facility in question and, potentially, similar facilities that may be considered to present the same risks*”. Obviously, this aims at reducing to close zero the risk of other similar failure. The control applies to same generation plants. Hence, a lack of control from the regulatory agency or a so-called “weak control” is only a mere flight of fancy. Then, the following assumptions ensue:

**Assumption 4:** *Under a control  $S$ , after the occurrence of an ultra-hazardous accident, the regulatory agency imposes either a slowing down or a temporary brake of the activity of the remaining safe plant.*

**Assumption 5:** *After the occurrence of a major event, under assumption 4, the cost of stopping or slowing down the remaining plant is equal to  $e$ , ( $c > e > 0$ ).*

These assumptions are crucial and realistic. Assumption 4 says that the risk of similar accidents on other centrals of the same type reduces to zero. We can add that the failure of a given generation plant means that the similar stations “*do not meet the highest safety requirements and therefore pose safety risk must be identified and their safety performance must be raised to the necessary level. This task is primarily a national responsibility, but it should be facilitated through assistance measures by the international community*”, Milenin, Skokov and Supeno (1997).

## 2.3 States of nature and major accident probability distribution

The elementary states of nature correspond to the events  $A$  and  $B$  respectively A: “*a major accident occurred in a nuclear plant*” and B: “*no accident occurred*”. A is a major harm corresponding to a damage of value  $D$ . Because the electro-nuclear park is constituted of

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<sup>7</sup> For instance in France, this is insured by the “Agence de Sécurité Nucléaire” (ASN).

two stations, the set of potential events (accident  $A$ , or no-accident  $B$ ) may be described by the following sets:

- $H_1 = (A_i, A_j)$ : “Major accidents occurred on both plants  $i$  and  $j$ ”,
- $H_2 = (A_i, B_j)$ : “A major accident occurred on plant  $i$  but not on plant  $j$ ”,
- $H_3 = (B_i, A_j)$ : “No accident occurred on plant  $i$ , but a major one on plant  $j$ ”,
- $H_4 = (B_i, B_j)$ : “No accident occurred on both plants  $i$  and  $j$ ”.

$$i \neq j, i, j = \{1, 2\}.$$

Then  $\Omega^*$  is the set of sample:  $\Omega^* = \{H_1, H_2, H_3, H_4\}$ .

Each state of nature occurs with a given probability<sup>8</sup>. Identical plants share the same probability distribution of major failure. To each elementary state of nature is associated a probability. Consequently, if  $p(A_s)$  represents the prior probability of a major accident occurrence on plant  $i$ , and  $p(B_s)$ , the probability of the event  $B_s$  (“no accident”), ( $s = i, j; i \neq j, i, j = \{1, 2\}$ ) is the probability of the no-accident case. Then,  $p(B_s) = 1 - p(A_s)$ . The model considers a single period of time (year) divided into minor intervals (days for instance). Hence, a period is made of  $T$  intervals of time (365 days for instance). Consequently, the probability of an accident occurring in the future year at a given day of this year is  $p(A_s)/T$ . This precision helps at understanding that the simultaneity of accidents on two different plants within a period is a very rare event characterized by a extreme low probability.

The Regulatory Agency’s control nature<sup>9</sup> is common knowledge and the operator knows the costs involved by the slowing down or the stopping of its activity for its security

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<sup>8</sup> It is difficult to assign a probability to rare events. As pointed by Schneider (2007) external and internal event may influence the probability distribution (external events are external flooding (Central of Blayes, France, 1999), Tsunami (Indian Ocean, 2004), external fires (Los Alamos 1996, 2000), tornado and Hurricanes (David Besse USA, 1998, Hurricane Andrex). Considering internal events, have to be understood the losses of coolant (Kozloduy, Bulgaria 2003), numerous turbine fires, and secondary cooling circuits. These events combine with human errors and violation of procedures. Hence, as such, the probability of the melting down of the core takes sense when considering the whole set of potential failure of the security system.

<sup>9</sup> We consider the question of the probability of a major accident on a larger scale than the usual question of the melting of the core of a reactor. Indeed, the accumulated fission products in a reactor form the potential radiation hazard. The melt down of the core of the reactor induces a severe accident. Safety consists in preventing the release of these radioactive products and fuel isotopes. Accidents that issue on massive rejection of such material and threat populations and natural resources are particularly rare events. Indeed, in Western plants, an airtight containment reinforced concrete building (1.2 to 2.4 meters) tends to limit the effect of a melting of the nuclear core. Probabilistic methods (Probabilistic Risk Assessment) are used since the midst seventies (Murray, 2000). The object is to determine the probability of occurrence of an undesired event such “as core damage, breach of containment, or release of radioactivity, and to determine potential causes” Murray, (2000 p.277). Considering internal relationships, a catastrophic event does not occur suddenly. It supposes a succession of failure and events trees show the probabilistic path from a current incident to the disastrous event. That justifies the use of Bayesian approaches (Chen and Chu (1995)). Studies in the midst of the nineties show that the probability of the melting of the core in Europe of the nuclear plant is quite variable and depends on the generation of the power plant.

level checking out. Obviously, this crucial information arrival reduces the probability of an accident on the remaining plant to almost zero (or zero by assumption in our model). Recall, that a period is made of T intervals of time. Once an accident occurred on a plant, the agency intervenes to avoid another one on the remaining one. Consequently, we can no longer assume the independency of an accident occurrence on the safe plant. Hence, because assumptions 4 and 5, the events associated with a major accident are dependent. We remind that, under high control, the regulatory agency prevents any other harm to happen again. We describe then the different states.

- Hence, the probability of the event  $H_1 = (A_i, A_j)$  is the probability of an accident occurrence on plant  $i$  once an accident ever happened on plant  $j$ <sup>10</sup>. The high control assumption makes impossible an accident happening on plant  $i$ , then, the corresponding probability  $p(A_i|A_j)$  is null,  $p(A_i|A_j) = 0$ .
- Considering  $H_2 = (A_i, B_j)$ ,  $H_2$  is made of two independent elements: “*an accident occurs on plant  $i$  and nothing happens on facility  $j$* ”. Indeed, the probability of an accident occurrence on plant  $i$  is independent of the well working of the other plant, and, consequently:

$$p(A_i|B_j)p(B_j) = p(A_i)p(B_j) = p(1 - p).$$

- $H_3 = (B_i, A_j)$ , corresponds to the case of an accident occurrence on plant  $j$ . Because of the regulatory agency’s intervention, the plant  $i$  keeps safe and, consequently, the probability of no-accident on  $i$  is:

$$p(B_i|A_j) = 1. \text{ Then: } p(B_i, A_j) = p(B_i|A_j)p(A_j) = 1 \cdot p(A_j) = p.$$

- Naturally, for  $H_4 = (B_i, B_j)$ , the events are independent one from the other one:

$$p(B_i|B_j)p(B_j) = p(B_i)p(B_j) = (1 - p)^2$$

Below, the table 2 gathers the events and their probability:

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The ExternE study of 1995 considered a core meltdown probability of  $10^{-5}$ . However, the probability of such an event depends on the nature of reactors that have evolved throughout time following technical progress. Lembrechts, Slaper, Pearce and. Howarth (2000) show that the range of probability of core meltdown is comprised between  $10^{-3}$  and  $10^{-6}$  according the reactor generation. For instance, they report the studies concerning a study on two French reactors, a 900 MW Pressurized Water Reactor (PWR) and a 1300 MW PWR, indicated the following risk probability of a major core meltdown (World Bank, 1991) respectively  $4.95 \cdot 10^{-5}$  and  $1,05 \cdot 10^{-5}$ .

<sup>10</sup> Or, this event will occur in a world where ever, the probability of a single accident is extremely low.

Events	Distribution of probabilities under $S$	Specified probability distribution
$H_1 = (A_i, A_j)$	$p(A_i A_j)p(A_j) = 0.p(A_j)$	0
$H_2 = (A_i, B_j)$	$p(A_i B_j)p(B_j) = p(A_i)p(B_j)$	$p(1 - p)$
$H_3 = (B_i, A_j)$	$p(B_i A_j)p(A_j) = 1.p(A_j)$	$p$
$H_4 = (B_i, B_j)$	$p(B_i B_j)p(B_j) = p(B_i)p(B_j)$	$(1 - p)^2$
		Sum =1

**Table 1:** Probability distribution under control  $S$ .

## 2.4 Comparing performance in the two plants scheme

Having defined the probability distributions on the hazardous events, we compare now the expected accident costs of each organization. This comes at assessing  $\sum_{l=1}^2 E_l(X|S)$  and  $E_M(X|S)$  (where  $E_l(X|S)$  and  $E_M(X|S)$  are the operators of expectation exerted under control  $S$ ). This comparison issues on the following proposition (where  $S$  means that the regulatory agency exerts a control):

**Proposition 1:** *Under the assumptions 1 to 3, when the regulatory agency exerts the control corresponding to the assumptions 4 and 5, if the insurance premiums are defined proportionally for each plant ( $pQ = \mu$  for each individual operator and  $\bar{\mu} = 2pQ$ , for the monopolist), then:*

- 1) *the centralized situation generates higher accident costs than the decentralized one (i.e.  $\sum_{l=1}^2 E_l(X|S) < E_M(X|S)$  when  $\frac{c-Q}{e} > 1$ ).*
- 2) *the decentralized situation generates higher accident costs than the centralized one (i.e.  $\sum_{l=1}^2 E_l(X|S) > E_M(X|S)$  when  $\frac{c-Q}{e} < 1$ ).*

**Proof:** See appendix 1.

Proposition 1 means that **a priori** no organizational scheme prevails on the other one because this depends on the institutional framework. To see the point, we study the case for which the insurance does not vanish. Hence we have either  $p^2(c - Q - e) > 2\mu - \bar{\mu}$  or  $p^2(c - Q - e) < 2\mu - \bar{\mu}$ .

Let us note that the left hand side of the above expression can be particularly weak. Indeed, we recall that in concrete world  $p$  is around  $10^{-5}$  or  $10^{-6}$ , then  $p^2$  becomes very weak ( $10^{-10}$  or  $10^{-12}$ ). Hence, when the level of insurance premium  $\mu$  does not fit with the insurance reimbursement  $pQ$ , ( $pQ \neq \mu$ ), the relevancy to compare  $p^2(c - Q - e)$  and  $2\mu - \bar{\mu}$  is raised, because  $p^2(c - Q - e)$  tends to 0. Therefore, the most probable case is the one where  $2\mu - \bar{\mu} > 0$  (the level of insurance premium of the decentralized case is higher

than under a monopolist situation) and in this case, the probability that  $p^2(c - Q - e) < 2\mu - \bar{\mu}$  is quite high. When this case arises, the centralized situation induces lesser costs than the decentralized one. However, in the theoretical framework we describe the symmetry in situations rules the game. Discussing about the effective nuclear insurance policies of the States will led us too far.

### 3. Insurance and care effort

We consider now that each operator calculates its optimal cost structure by making variable the care level,  $x, x \geq 0$  (where  $x$  is a cost). This value corresponds to the effort dedicated to safety. Obviously, this value influences the accident probability. Hence, by increasing or decreasing the care effort, the operators may influence the level of risk and the operators may lower the accident probability by taking due care. To deal with this point we adopt the Shavell (1986)'s presentation. Hence, let  $x$  be the operator's level of safety effort,  $x \geq 0$ .

**Assumption 6:** *The probability of an accident varies as  $x$  varies, with  $1 > p(x) \geq 0$ ,  $p'(x) < 0$  and  $p''(x) > 0$ .*

Assumption 6 is standard in accident theory. Before going further, recall that informational asymmetry constitutes the heart of the modern insurance theory. This factor explains both moral hazard and adverse selection phenomena in the relationships between insurance companies and their customers. Under moral hazard, the agents do not always want fulfill the implicit or explicit obligations that they contractually accepted. Under adverse selection, the agent hides his true characteristics to benefit of better insurance conditions for instance. Hence, economists have to develop incentives design to induce the agents to reveal their true features. However, economic theory develops its argument for "standard" agents: small, numerous, free to accept or resign the companies' conditions, etc. In the opposite, nuclear power plants own special characteristics that exclude the "normality" of economic relations. Indeed, first, generally, in this sector, insurance is not optional but mandatory (France, USA, UK, etc.). Second, the level of repairs after a harm occurrence is particularly high and this involves resorting to reinsurance pools companies. Consequently, the relationships between operators (or owners) and insurance companies structurally dismiss asymmetric knowledge of operating conditions, cost structures and random behavior. Furthermore, the nuclear safety authorities constantly monitor the security of facilities. Hence, this steady control cancels moral hazard. We consider these monitoring costs as constant. In

addition, unlike the standard theory, the operator is "required" to apply all safety rules and feels no interest in derogation. In fact, in many nuclear countries as for instance France, the State itself bears the burden of liability and thereby the authorities' control constitutes a guarantee for insurance companies. Concerning our model, this means that the monitoring costs by themselves are included in the safety expenses and we consider them as fixed costs. Consequently, because of the specificity of the electro-nuclear production, we assume that asymmetric information between the operator and the insurance companies is impossible. Indeed, the insurance company can every time check the effective level of safety.

Compared to the previous section, here, we consider the expected accident cost for one plant under centralized and decentralized organization taking into account the care effort. For a better and quicker understanding, we put them side by side in table 6. The main difference between the monopolist and the decentralized operators comes from  $H_2$  and  $H_3$ . Hence, when an accident occurs on one plant, the whole industry he manages is affected and he has to respond for each major accident. Consequently, in all cases, the monopolist has to integer both the cost of repairs ( $c - Q$ ) and the opportunity cost  $e$ . This is not the case for the operators of a decentralized system that respond for only one plant. Consequently, when the monopolist allocates  $x$  to the care of one plant, he has also to consider the costs induced by a potential accident on the other plant. The following table describes the situation:

Events	Probability distribution	One plant under decentralized organization	One plant under centralized organization
$H_1 = (A_i, A_j)$	0	$\mu(x) + x + (c - Q)$	$\bar{\mu}(x) + 2x + 2(c - Q)$
$H_2 = (A_i, B_j)$	$p(x)(1 - p(x))$	$\mu(x) + x + (c - Q)$	$\bar{\mu}(x) + e + 2x + (c - Q)$
$H_3 = (B_i, A_j)$	$p(x)$	$\mu(x) + x + e$	$\bar{\mu}(x) + e + 2x + (c - Q)$
$H_4 = (B_i, B_j)$	$(1 - p(x))^2$	$\mu(x) + x + \mu$	$2x + \bar{\mu}(x)$
Expected accident costs	Sum =1		

**Table 2: The distribution of accident costs**

From table 4 we can draw the expected accident costs of a plant under a decentralized organization:

$$E_l(X|S) = x + \mu(x) + cp(x) + ep(x) - Qp(x) - cp(x)^2 + Qp(x)^2 \quad (1)$$

And the accident costs of the monopolist:

$$E_M(X|S) = 2x + \bar{\mu}(x) + 2cp(x) + 2ep(x) - 2Qp(x) - cp(x)^2 - ep(x)^2 + Qp(x)^2 \quad (2)$$

Let us study the case in which the insurance policy is adapted to the care level supplied by the operators, i.e.  $\bar{\mu}(x) = p(x) Q n$ , (for  $n = 1,2$ ). Hence,  $\mu(x) = Qp(x)$  and  $\bar{\mu}(x) = 2Qp(x)$ , we apply the same argument as previously. That means that the insurance premium depends on the level of effort achieved by the operators.

Putting it otherwise, this means that the exploitation of a given plant in a centralized structure generates higher expected costs than under a decentralized system. This result summarizes under the following proposition:

**Proposition 2:** *Under the assumptions 1 to 3, when the regulatory agency exerts the control corresponding to the assumptions 4 and 5, if the insurance premiums are defined proportionally for each plant ( $pQ = \mu$  for each individual operator and  $\bar{\mu} = 2pQ$ , for the monopolist) and taking account the care effort  $x, x \in [0, \infty[$ , then:*

1) *The centralized situation generates higher accident costs than the decentralized*

$$\text{one ( i.e. } \sum_{l=1}^2 E_l(X|S) < E_M(X|S) \text{ when } \frac{c-Q}{e} > 1.$$

2) *The decentralized situation generates higher accident costs than the centralized*

$$\text{one (i.e. } \sum_{l=1}^2 E_l(X|S) > E_M(X|S) \text{ when } \frac{c-Q}{e} < 1.$$

**Proof:** See appendix 1.

These results are similar to the case with a given care level. As the care effort varies, it remains to know which organizational structure ensures the highest care level. Proposition 3 answers the point.

**Proposition 3:** *Under the assumptions 1 to 3 and 6, when the regulatory agency exerts the control corresponding to the assumptions 4 and 5, if the insurance premiums are defined proportionally for each plant ( $pQ = \mu$  and  $\bar{\mu} = 2pQ$ ), then:*

1) *The monopolistic organization insures a higher level of care than the decentralized organization when  $\frac{c-Q}{e} > 1$ ,*

2) *The decentralized organization insures a higher level of care than the monopolistic one when  $\frac{c-Q}{e} < 1$ .*

**Proof:** See appendix 1.

This result allocates a strategic status to the institutional variables: the level of the cap, the level of repairs insured  $Q$ . When the difference  $c - Q$  is low, then the chance for the opportunity cost to slow down or stopping the activity to be higher of this difference increases then a decentralized situation gives a better safety. In fact, in the two-plant case, the organization with the highest expected accident costs involves a higher effort level for safety. An economic explanation could be found in the fact that as  $c - Q$  is high compared to  $e$ , then the operator has to engage more his wealth for repairs than when the cover by insurance is better. Then, he is induced to increase the level of safety. When the insurance cover is higher

such that  $\frac{c-Q}{e} < 1$ , some outsiders can enter in the production process. However, this result is only partial and we have to verify if its robustness in extending it to more than two plants.

#### 4. Generalization: From two to n plants

We extend now the analysis to the case of n plants. This change of dimension increases the field of possible management organizations. For instance for a three plants case, the possible organizations are the following one (considering that each plant is identical to another one and to show this numeral 1 designs them). Consequently we identify three possible clusters:

$$A = \{\mathbf{a} = (\{1\}, \{1\}, \{1\}), \mathbf{b} = (\{1,1\}, \{1\}), \mathbf{c} = (\{1,1,1\})\},$$

In situation  $\mathbf{a}$ , the stations are managed on a fully decentralized scheme, while in  $\mathbf{b}$ , the management is only partially centralized while  $\mathbf{c}$  corresponds to a full centralization. Obviously, as n increases, the possible grouping also increases. This makes difficult (or impossible) to deal with the whole set of these new patterns. Indeed, in the three units' case, this would involve comparing the following cases:  $\{(\mathbf{a}, \mathbf{b}), (\mathbf{a}, \mathbf{c}), (\mathbf{c}, \mathbf{b})\}$ . Hence, as a simplification, we bind the cases under consideration to the comparing of the full centralized versus the full decentralized pattern (e.g.  $(\mathbf{a}, \mathbf{c})$ , in the three plants case).

Another simplification induced by the control S leads to consider two situations for the whole park: the no-accident case when for the considered period no-accident occurs and the accident situation that can happen on one plant only without other possibility of another major harm. Indeed, once an accident occurred on a given plant, all the remaining safe  $n - 1$  plants will slow down or stop their activities.

The question to know is whether this extension maintains the two-plants results or whether these one come from particular conditions. To see the point, we go on comparing the conditions for having the expected accident costs of the centralized organization higher or lesser than the decentralized one. We issue on the following propositions:

**Proposition 4:** *Considering n plants, the assumptions 1 to 3 and 6, when the regulatory agency exerts the control corresponding to the assumptions 4 and 5, if the insurance premiums are defined proportionally for each plant ( $pQ = \mu$  and  $\bar{\mu} = npQ$ ), and taking account the care effort  $x, x \in [0, \infty[$ , then:*

1) *the centralized situation generates higher accident costs than the decentralized one*

$$(i.e. \sum_{l=1}^n E_l(X|S) < E_M(X|S) \text{ when } \frac{c-Q}{e} > 1.$$

2) *the decentralized situation generates higher accident costs than the centralized one*

$$(i.e. \sum_{l=1}^n E_l(X|S) > E_M(X|S) \text{ when } \frac{c-Q}{e} < 1.$$

3) *These results are true for low values of the probability of a major accident  $p(x)$ .*

**Proof:** See Appendix 2

The difference with the two-plant case comes from the major accident probability that should be sufficiently low to induce the result. This condition also verifies when we study which kind of organization provides the highest level of care. This issue on the following proposition:

**Proposition 5:** *Considering  $n$  plants, the assumptions 1 to 3 and 6, when the regulatory agency exerts the control corresponding to the assumptions 4 and 5, if the insurance premiums are defined proportionally for each plant ( $pQ = \mu$  and  $\bar{\mu} = npQ$ ), then:*

- 1) *The monopolistic organization insures a higher level of care than the decentralized organization when  $\frac{c-Q}{e} > 1$ ,*
- 2) *The decentralized organization insures a higher level of care than the monopolistic one when  $\frac{c-Q}{e} < 1$ .*
- 3) *These results are true for low values of the probability of a major accident  $p(x)$ .*

**Proof:** See Appendix 2.

Juxtaposing propositions four and five leads to consider that the higher expected costs of accident involve the highest level of care independently of the organizational structure. This is summarized in this last proposition:

**Proposition 6:** *From proposition 4 and 5 we draw the following result:*

- *When  $\frac{c-Q}{e} > 1$ , the monopolistic organization insures both the highest accident costs and the highest level of care compared to the decentralized organization,*
- *When  $\frac{c-Q}{e} < 1$  it is the decentralized organization provides the exact reverse.*

**Proof:** Obvious from propositions 4 and 5.

Proposition 6 asserts that a priori no given industrial organization may be considered as prevalent. The institutional factors induced by the legal level of repairs, the insurance policy and the costs associated to the checking of the safe stations are determinant factors that favor either an horizontal concentration or not. Putting it otherwise, propositions 4 and 5 show that the extension to  $n$  nuclear facilities reinforces the results of the two-plants case. Particularly, the institutional framework is a leading factor in determining the expected accident costs and the most suitable level of care. The institutional variables appear here as the level of the cap and the level of insurance compensation. As in sections 2 and 3, the above results depend crucially on the ratio between the share of the operator's wealth dedicated to repairs after the compensation made by the insurance companies  $c - Q$  and the opportunity cost of slowing down the safe plant activity  $e$ .

## 5. Discussing the results

The different points are studied as the following remarks.

**Remark 1:** When the insurance premium does not vanish, i.e. when  $pQ \neq \mu$  and  $\bar{\mu} \neq 2pQ$  in such a way that  $2\mu \neq \bar{\mu}$ , then the above results are put into question. It seems difficult them to draw definitive conclusions in this case. However, considering concrete practices, this situation is far from being anecdotic (see for instance, Faure and Borre (2008), Faure and Fiore (2009)).

**Remark 2:** In the case of no insurance, that is to say  $Q = 0$ , then  $c > e$ , (we cannot imagine that the cost of stopping or slowing down a plant can cost more than a major accident). This involves that a centralized management insures systematically a higher safety level.

**Remark 3:** Clearly, proposition 6 calls for defining a decision rule for helping the regulator's choice. Indeed, it establishes that the more costly structure insures the highest level of care and the lesser costly one a lesser safety level. Then, how can the regulator choose between both situations? However, the paper does not supply the decision rule because this goes beyond its scope. Indeed, no assumption is made about the regulator's preference and the space lacks to make complete considerations. Indeed, does the above argument show that the regulator's attitude towards risk influences the choice of the organizational structure? This point is an important matter because his attitude reflects the society's preferences about nuclear concerns. Hence, a risk-averse regulator means that society is reluctant to accept the nuclear risk and is ready to pay more for more safety. This point deserves attention and thus we will be further developing it in remark 4.

**Remark 4:** Let us consider a decentralized organization. Propositions 2 and 5 show that the regulator expects an effort level equal to  $x_0$  ( $x_0 > x^*$ ). But, this is only true when  $c - Q < e$ . Then, when  $c - Q > e$ , the centralized organization offers a better risk coverage. Consequently, when the difference between the cap and the insurance compensation is higher than the opportunity cost ( $c - Q > e$ ), the society's interest consists in centralizing the electro-nuclear park and exploiting it monopolistically. Let us go further and extend remark 2 of the last section. Hence, let us assume that under this decentralized organization, when  $c - Q < e$ , the legal rules change and significantly increase the level of the cap to  $\bar{c}$  (where  $c < \bar{c}$  and  $\bar{c} - Q > e$ ). This situation means that the centralized

organization offers a better care level. Indeed, the new equilibrium values are  $x_0' < x^{*}$  (proposition 5).

**Remark 5:** However, the above situation (Remark 4) does not involve automatically the choice for a monopolistic organization. Indeed, the policy choices at the regulator's disposal are twofold. First, the regulator can induce the operators to merge for accessing to a centralized management. This complies with the above argument. However, second, he can also induce the insurance companies to increase the level of compensation from  $Q$  to  $\bar{Q}$  with now  $\bar{c} - \bar{Q} < e$ . This relationship ensures that the new first-best levels of care  $x_0''$  and  $x^{*''}$  will be such that  $x_0'' > x^{*''}$ . This is a solution when the regulator cannot merge the decentralized plants. Hence, the structure will keep decentralized with the highest level of care. The same kind of argument applies, for instance, if the regulator seeks to minimize the level of the accident costs assuming that the level of security of the less costly structure is sufficient. The argument is the exactly opposite.

## 6. Conclusion

Third party liability is an important factor in the process that determines the accident costs of ultra-hazardous activities. The authorities can make liability so heavy that they can induce the reorganization of this industry as one possible answer to lessen the global accident costs of major hazard. Hence, looking for the best management of disseminated nuclear plants, the regulator can push the nuclear operators to change their management structure by grouping the stations under a unique management or, the reverse. Obviously, the regulatory agency's level of control is a determinant factor. The succession of major and minor accidents since almost fifty years involves an accrued monitoring and stricter controls from these agencies' side. This involves also the increase of the opportunity costs of slowing down or stopping the activity of plants after a major accident on one of them. Consequently, the variations in the ceiling caps, the level of insurance compensation and the opportunity cost induce corresponding changes in the ratio ((Cap – insurance compensation)/opportunity costs). Propositions 1 to 5 underline the importance of this ratio in determining the relative accident costs and the level of safety of a given type of management.

This result confirms our prior intuition that, concerning complex industrial organizations, determining the first-best level of care and minimizing the accident cost involves the necessity to design the best management organization structure. Hence, once the regulator has chosen the nature of the liability regime he wants to enforce, he has to define the

best industrial structure that consists in our simple model choosing the nature of the horizontal concentration. However, even if necessary, changing the industrial structure is not always possible. Consequently, the regulator can induce the insurance (and reinsurance) companies to change the compensation level  $Q$  to maintain (or increase) the desired industrial structure and the required level of safety or costs. These last considerations lead to involve the regulator's responsibility in the electronuclear protection process. Indeed, this last one is not only in charge of defining the safety level standards but he also becomes an active actor by his influence on the formation of the accident cost structure of the considered industry. Nevertheless, as shows it proposition 6 and remark 3, the regulator has also to choose between lesser expected accident costs associated to a lower level of safety compared to a high cost and high level of care. The future researches have to focus on this fundamental point.

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## Appendix 1

### Proofs of the propositions for the two plants case

**Proposition 1:** Under the assumptions 1 to 3, when the regulatory agency exerts the control corresponding to the assumptions 4 and 5, if the insurance premiums are defined proportionally for each plant ( $pQ = \mu$  for each individual operator and  $\bar{\mu} = 2pQ$ , for the monopolist), then:

1) the centralized situation generates higher accident costs than the decentralized

$$\text{one ( i.e. } \sum_{l=1}^2 E_l(X|S) < E_M(X|S) \text{ when } \frac{c-Q}{e} > 1.$$

2) the decentralized situation generates higher accident costs than the centralized

$$\text{one (i.e. } \sum_{l=1}^2 E_l(X|S) > E_M(X|S) \text{ when } \frac{c-Q}{e} < 1.$$

#### Proof:

To prove the proposition 1 we compare the expected accident costs of the decentralized and the centralized structure. This needs two steps.

**Step1:** In order to make the comparison simpler we computerize the different costs in the following table:

Events Under high control		One plant (decentralized)	Two plants (monopolistic)
$H_1 = (A_i, A_j)$	0	$\mu + (c - Q)$	$\bar{\mu} + 2(c - Q)$
$H_2 = (A_i, B_j)$	$p(1 - p)$	$\mu + (c - Q)$	$\bar{\mu} + e + (c - Q)$
$H_3 = (B_i, A_j)$	$p$	$\mu + e$	$\bar{\mu} + e + (c - Q)$
$H_4 = (B_i, B_j)$	$(1 - p)^2$	$\mu$	$\bar{\mu}$
	Sum =1		

**Table 6:** Expected costs under high control

We get respectively the expected costs of a decentralized plant:

$$E_l(X|S) = cp + ep - cp^2 - pQ + p^2Q + \mu \quad (1a)$$

and the costs of the monopolist:

$$E_M(X|S) = 2cp + 2ep - cp^2 - ep^2 - 2pQ + p^2Q + \bar{\mu} \quad (2a)$$

for the centralized situation.

Considering the monopolist case, we now that once an accident occurred on one plant, ( $H_2 = (A_i, B_j)$ ), the operator has to stop or slow down immediately the activity of the other facility. Hence, the payoff is  $c + e + \bar{\mu} - Q$ , which occurs with a probability  $p$ . However, considering that a specific plant  $j, j = 1,2$  works “well” with a probability  $(1 - p)$  does not prevent, that the other one could fail with a probability  $p$ . A priori, he does not know which plant (either 1 or 2) could fail. Hence, because they are similar, one may consider that Nature (N in the decision tree) chooses among them with an equal probability ( $\pi = \frac{1}{2}$ ) the failing plant. Consequently, the formula should write as:

$$\begin{aligned}
E_M(X|S) &= \frac{1}{2} (p(1-p)(\bar{\mu} + e + (c-Q)) + (\bar{\mu} + e + (c-Q))p + (1-p)^2\bar{\mu}) \\
&+ \frac{1}{2} (p(1-p)(\bar{\mu} + e + (c-Q)) + (\bar{\mu} + e + (c-Q))p + \bar{\mu}(1-p)^2) \\
&+ (1-p)^2\bar{\mu}
\end{aligned}$$

This writing can become interesting when some plant is frailer than the other one.

**Step 2:**

We compare the costs of  $\sum_{l=1}^2 E_l(X|S)$  and  $E_M(X|S)$  and for

1)  $\sum_{l=1}^2 E_l(X|S) < E_M(X|S)$  we get:

$$p^2(c-Q-e) < 2\mu - \bar{\mu} \text{ or } p^2(c-Q-e) > 2\mu - \bar{\mu} \quad (3a)$$

And for:

2)  $\sum_{l=1}^2 E_l(X|S) > E_M(X|S)$  we get

$$p^2(c-Q-e) > 2\mu - \bar{\mu} \text{ or } p^2(c-Q-e) < 2\mu - \bar{\mu} \quad (4a)$$

Then, after comparing,  $\sum_{l=1}^2 E_l(X|S)$  and  $E_M(X|S)$ , when  $\bar{\mu} = 2\mu = 2pQ$  which complies with the assumption of proposition 2, then:

-  $p^2(c-Q-e) > 0$  when  $\sum_{l=1}^2 E_l(X|S) < E_M(X|S)$   
Or, equivalently, this is true for

$$\frac{c-Q}{e} > 1$$

-  $p^2(c-Q-e) > 0$ , when  $\sum_{l=1}^2 E_l(X|S) > E_M(X|S)$ .  
Or, equivalently, this is true for

$$\frac{c-Q}{e} < 1$$

Q.E.D.

**Proposition 2:** Under the assumptions 1 to 3, when the regulatory agency exerts the control corresponding to the assumptions 4 and 5, if the insurance premiums are defined proportionally for each plant ( $pQ = \mu$  for each individual operator and  $\bar{\mu} = 2pQ$ , for the monopolist) and taking account the care effort  $x, x \in [0, \infty[$ , then:

1) the centralized situation generates higher accident costs than the decentralized

one (i.e.  $\sum_{l=1}^2 E_l(X|S) < E_M(X|S)$  when  $\frac{c-Q}{e} > 1$ .

2) the decentralized situation generates higher accident costs than the centralized

one (i.e.  $\sum_{l=1}^2 E_l(X|S) > E_M(X|S)$  when  $\frac{c-Q}{e} < 1$ .

**Proof:**

To establish the proof we rewrite the expected accident costs functions as the following. Let  $\varphi(x)$  be the expected cost function of the centralized organization, such that:

$$\varphi(x) = E_M(X|S) = 2x + \bar{\mu}(x) + 2cp(x) + 2ep(x) - 2Qp(x) - cp(x)^2 - ep(x)^2 + Qp(x)^2 \quad (5a)$$

And,  $f(x)$  the expected accident cost of the operator  $l, l = 1,2$ .

$$f(x) = E_l(X|S) = x + \mu(x) + cp(x) + ep(x) - Qp(x) - cp(x)^2 + Qp(x)^2 \quad (6a)$$

Consequently, we can see that defining the relationship between insurance premium and insurance repairs as:

$$\mu(x) = Qp(x) \text{ and } \bar{\mu}(x) = 2Qp(x)$$

The system rewrites as:

$$\varphi(x) = 2x + 2cp(x) + 2ep(x) - cp(x)^2 - ep(x)^2 + Qp(x)^2 \quad (7a)$$

With:

$$f(x) = x + cp(x) + ep(x) - cp(x)^2 + Qp(x)^2 \quad (8a)$$

We can establish a relationship between  $\varphi(x)$  and  $f(x)$ :

$$\begin{aligned} \varphi(x) - 2f(x) &= 2x + 2cp(x) + 2ep(x) - cp(x)^2 - ep(x)^2 + Qp(x)^2 - \\ &2(x + cp(x) + ep(x) - cp(x)^2 + Qp(x)^2) = p(x)^2(c - e - Q) \end{aligned} \quad (9a)$$

From  $1 \geq p(x) \geq p(x)^2 \geq 0$ , it results that  $p(x)^2(c - e - Q) > 0$  for  $(c - e - Q) > 0$ , then  $\varphi(x) > 2f(x)$  and the reverse for  $(c - e - Q) < 0$ . We can summarize the results in the following table 5.

$(c, Q, e)$	$\frac{c - Q}{e} > 1$	$\frac{c - Q}{e} < 1$
Expected costs	$\varphi(x) > 2f(x)$	$\varphi(x) < 2f(x)$
<b>Results</b>	The centralized situation involves higher costs than the decentralized one.	The decentralized situation involves higher costs than the centralized one.

**Table 5**

$\varphi(x)$  and  $f(x)$  are convex, they decrease for low values of  $x$  and increase as  $x$  grows because of high values of  $x$ ,  $p(x)$  and  $p(x)^2$  tend to 0 ( $1 \geq p(x) \geq p(x)^2 \geq 0$ ). This element is important to determine what structure will give the highest safety level.

**Proposition 3:** *Under the assumptions 1 to 3 and 6, when the regulatory agency exerts the control corresponding to the assumptions 4 and 5, if the insurance premiums are defined proportionally for each plant ( $pQ = \mu$  and  $\bar{\mu} = 2pQ$ ), then:*

- 1) *The monopolistic organization insures a higher level of care than the decentralized organization when  $\frac{c-Q}{e} > 1$ ,*
- 2) *The decentralized organization insures a higher level of care than the monopolistic one when  $\frac{c-Q}{e} < 1$ .*

**Proof:**

Let be  $x_0 > 0$  this value such that  $f'(x_0) = 0$ , hence  $x_0$  is the first best level of care of the decentralized structure. If  $x^* > 0$ , is the one of the centralized organization the question is to know if  $x^* \lesseqgtr x_0$ . To study this, let us consider the derivative of  $\varphi(x)$  in  $x_0$ :

$$\varphi'(x_0) - 2f'(x_0) = [p(x)^2(c - e - Q)]' \quad (10a)$$

As,  $f'(x_0) = 0$ , this is equivalent to:

$$\varphi'(x_0) - 0 = 2p(x_0)p'(x_0)(c - e - Q) \quad (11a)$$

$\varphi(x)$  is a convex function that decreases for low values of  $x$  and is increasing as  $x$  is rising.

- (1) It is easy to see that at  $x_0$ ,  $\varphi'(x_0)$  is negative when  $(c - e - Q) > 0$ . Indeed,  $p'(x_0)$  negative in  $x_0$  while  $f'(x_0) = 0$ , consequently,  $\varphi(x)$  in  $x_0$  has not yet reached its minimum value. Then  $x_0 < x^*$ .
- (2) By a symmetric argument, when  $(c - e - Q) < 0$ ,  $\varphi'(x_0) > 0$ , and  $x_0 > x^*$ .

We summarize these results in the following table:

$(c, Q, e)$	$\frac{c - Q}{e} > 1$	$\frac{c - Q}{e} < 1e$
$\varphi'(x_0) =$	$p(x_0)p'(x_0)(c - e - Q) < 0$	$p(x_0)p'(x_0)(c - e - Q) > 0$
<b>Results</b>	$x_0 < x^*$ .	$x_0 > x^*$

**Table 6 Comparing the care levels**

QED.

## Appendix 2

### Proofs of the propositions for the n-plants case

**Proposition 4:** *Considering  $n$  plants, the assumptions 1 to 3 and 6, when the regulatory agency exerts the control corresponding to the assumptions 4 and 5, if the insurance premiums are defined proportionally for each plant ( $pQ = \mu$  and  $\bar{\mu} = npQ$ ), and taking account the care effort  $x, x \in [0, \infty[$ , then:*

4) *the centralized situation generates higher accident costs than the decentralized one*

$$(i.e. \sum_{i=1}^2 E_i(X|S) < E_M(X|S) \text{ when } \frac{c-Q}{e} > 1.$$

5) *the decentralized situation generates higher accident costs than the centralized one*

$$(i.e. \sum_{i=1}^2 E_i(X|S) > E_M(X|S) \text{ when } \frac{c-Q}{e} < 1.$$

6) *These results are true for low values of the probability of a major accident  $p(x)$ .*

#### Proof:

In spite of the increase of the number of plants, we can proceed to an integrated analysis of the situation.

a) In this aim, first, we deal with the monopolized case. Hence, under strong control, the centralized situation involves two random levels of costs. Either,  $\bar{\mu}(x) + nx$  when no accident occurs or  $(\bar{\mu}(x) + (n-1)e + nx + (c-Q))$ , when, on the contrary a catastrophic event happens. Indeed, as ever mentioned above, the level of costs will always be the same for the monopolist. Hence, beyond the insurance and safety costs ( $\bar{\mu}(x) + nx$ ) we add the cost of the repairs ( $c-Q$ ) and the costs of the breaking down or the slowing down of the  $(n-1)$  remaining safe plants  $(n-1)e$ . Consequently, we can consider that the “no-accident situation” happens with a probability of  $(1-p(x))^n$ . Consequently, the other costs take place with the probability  $1 - (1-p(x))^n$ .

Hence, if  $\Phi(x)$  expresses the expected accident costs of the centralized organization, and considering that the premium accident is calculated as the following  $\bar{\mu}(x) = np(x)Q$ , then we express  $\Phi(x)$  as :

$$\Phi(x) = (1 - (1 - p(x))^n)((x + np(x)Q + (n-1)e + c - Q)) + (1 - p(x))^n(nx + np(x)Q) \quad (12a)$$

(where  $\Phi(x) = E_M(X|S)$ ).

b) Considering the decentralized organization, the accident expected costs consists in three random values. Hence, we present the following table that gathers the probability distribution, the expression of the probabilities and the associated accident costs:

$p(A_i B_j)p(B_j) = p(A_i)p(B_j)$	$p(x)(1-p(x))^{n-1}$	$x + u + c - Q$
$p(B_i A_j)p(A_j) = 1.p(A_j)$	$(1 - (1 - p(x))^{n-1})$	$x + u + e$
$p(B_i B_j)p(B_j) = p(B_i)p(B_j)$	$(1 - p(x))^n$	$x + u$

Then, as previously we define the expected cost function of the decentralized organization:

$$F(x) = p(x)(1 - p(x))^{n-1}(x + p(x)Q + c - Q) + (1 - (1 - p(x))^{n-1})(x + p(x)Q + e) + (1 - p(x))^n(x + p(x)Q) \quad (13a)$$

(with  $u = p(x)Q$  and  $F(x) = E_l(X|S)$ ).

Similarly to the two plants case, we compare both situations, that is to say, we try to understand whether it is more costly to favor either a decentralized or a centralized organization by putting side by side their accident expected costs. This means studying the conditions for having :

$$n F(x) \geq \Phi(x) \text{ or } n F(x) < \Phi(x).$$

$$p(x)(1 - p(x))^{n-1}(x + p(x)Q + c - Q) + (1 - (1 - p(x))^{n-1})(x + p(x)Q + e) + (1 - p(x))^n(x + p(x)Q) - ((1 - (1 - p(x))^n)(nx + np(x)Q + (n - 1)e + c - Q)) + (1 - p(x))^n(nx + np(x)Q) \geq 0, \text{ or after simplifying:}$$

$$(c - e - Q)(-1 + (1 - p(x))^{-1+n}(1 + (-1 + n)p(x))) \geq 0 \quad (14a)$$

Verifying the conditions involves that  $(c - e - Q) > 0$ , and

$$(1 - p(x))^{-1+n}(1 + (n - 1)p(x)) - 1 \geq 0 \quad (15a)$$

This is true if

$$(1 - p(x))^{n-1}(1 + (n - 1)p(x)) \geq 1$$

As,  $(1 - p(x))^{n-1} < 1$ , and  $\lim_{x \rightarrow A} (1 + (n - 1)p(x)) \rightarrow 1$ , A this value of  $x$  for which  $(n - 1)p(x) \rightarrow 0$ , then  $(1 - p(x))^{n-1}(1 + (n - 1)p(x)) < 1$  and

$$(1 - p(x))^{n-1}(1 + (n - 1)p(x)) - 1 < 0 \quad (16a)$$

Hence, when  $(c - e - Q) > 0$ , as  $(1 - p(x))^{n-1}(1 + (n - 1)p(x)) - 1 < 0$  (for sufficient low values of  $x$  then:

$$n F(x) < \Phi(x) \quad (17a)$$

Consequently, for  $(c - e - Q) < 0$ , we get the reverse:  $n F(x) > \Phi(x)$ . QED.

**Proposition 5:** *Considering  $n$  plants, the assumptions 1 to 3 and 6, when the regulatory agency exerts the control corresponding to the assumptions 4 and 5, if the insurance premiums are defined proportionally for each plant ( $pQ = \mu$  and  $\bar{\mu} = npQ$ ), then:*

- 1) *The monopolistic organization insures a higher level of care than the decentralized organization when:  $\frac{c-Q}{e} > 1$ ,*
- 2) *The decentralized organization insures a higher level of care than the monopolistic one when  $\frac{c-Q}{e} < 1$ .*
- 3) *These results are true for low values of the probability of a major accident  $p(x)$ .*

**Proof:**

- 1) We consider  $\Phi(x)$  and  $F(x)$  such that:

$$\Phi(x) = en + nx + nQp(x) - en(1 - p(x))^n + c - e - Q - c(1 - p(x))^n + e(1 - p(x))^n + Q(1 - p(x))^n \quad (18a)$$

$$F(x) = p(x)(1 - p(x))^{n-1}(x + p(x)Q + c - Q) + (1 - (1 - p(x))^{n-1})(x + p(x)Q + e) + (1 - p(x))^n(x + p(x)Q) \quad (19a)$$

We study first the behavior of these function on the interval  $[0, \infty]$ .

As these functions are similar, we limit the study to  $F(x)$ .

It is easy to see that:

$$\lim_{x \rightarrow 0} F(x) = (Q + e) \quad (20a)$$

$$\lim_{x \rightarrow \infty} F(x) = x \quad (21a)$$

However, these functions have a decreasing section as  $p(x) \in [0,1]$

To define a decreasing part of  $F(x)$  we have to see if it exists an interval  $[0, x_0]$  such that  $F'(x) \leq 0$ :

$$F'(x) = 1 + \left( Q - (1 - p(x))^{-2+n} (-c + e - en + Q + n(c - Q)p(x)) \right) p'(x) \leq 0 \quad (22a)$$

This means that

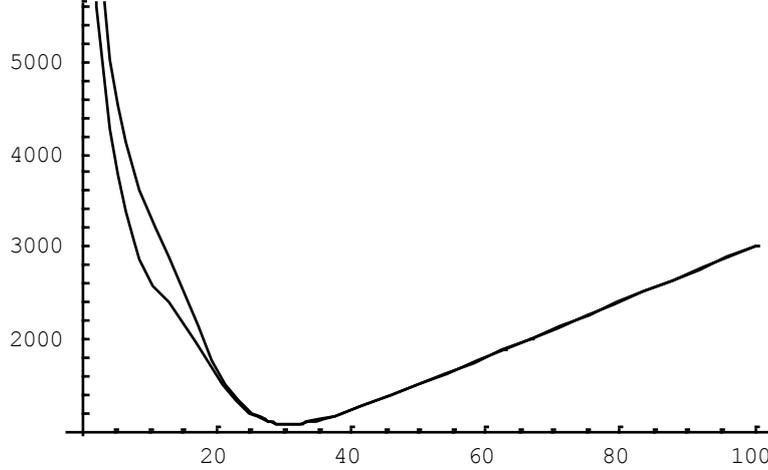
$$1 + \left( Q - (1 - p(x))^{-2+n} (-c + e - en + Q + n(c - Q)p(x)) \right) p'(x) \leq 0, \text{ then} \\ (Q - (1 - p(x))^{-2+n} (-c + e - en + Q + n(c - Q)p(x))) p'(x) \leq -1 \quad (23a)$$

Or, equivalently :

$$Q > (1 - p(x))^{n-2} (-c + e - en + Q)$$

Then, for low values of  $x$  (which means that  $(1 - p[x])^{n-2}$  tends to 0) the relationship is verified. Hence, on the interval  $[0, x_0]$  the function is decreasing and beyond  $x_0$  this function increases as  $x$  increases.

A numerical example that is not developed gives the pattern of both functions.



2) Comparing  $x^0$  and  $x^*$  (the first best of the decentralized and centralized structures)

We notice that:

$$nF(x) - (-en(1 - p(x))^{-1+n} - nx(1 - p(x))^{-1+n} + nx(1 - p(x))^n \\ + cn(1 - p(x))^{-1+n}p(x) - 2nQ(1 - p(x))^{-1+n}p(x) \\ + nx(1 - p(x))^{-1+n}p(x) + nQ(1 - p(x))^np(x) \\ + nQ(1 - p(x))^{-1+n}p(x)^2) = en + nx + nQp(x)$$

Then, replacing  $en + nx + nQp(x)$  in  $\Phi(x)$  :

$$\begin{aligned}
\Phi(x) - nF(x) &= -(-en(1-p(x))^{-1+n} - nx(1-p(x))^{-1+n} + nx(1-p(x))^n \\
&\quad + cn(1-p(x))^{-1+n}p(x) - 2nQ(1-p(x))^{-1+n}p(x) \\
&\quad + nx(1-p(x))^{-1+n}p(x) + nQ(1-p(x))^np(x) \\
&\quad + nQ(1-p(x))^{-1+n}p(x)^2)en(1-p(x))^n + c - e + -Q - c(1-p(x))^n \\
&\quad + e(1-p(x))^n + Q(1-p(x))^n
\end{aligned} \tag{24a}$$

We differentiate this difference under the assumption that  $x_0 > 0$  is this value where

$$F'(x_0) = 0$$

$$\begin{aligned}
&\Phi'(x_0) - nF'(x_0) = \\
&= cn(1-p(x_0))^{-1+n}p(x_0) - en(1-p(x_0))^{-1+n}p'(x_0) - nQ(1-p(x_0))^{-1+n}p'[x] \\
&\quad - en^2(1-p(x_0))^{-1+n}(en(1-p(x_0))^{-1+n} + nx(1-p(x_0))^{-1+n} \\
&\quad - nx(1-p(x_0))^n - cn(1-p(x_0))^{-1+n}p(x_0) + 2nQ(1-p(x_0))^{-1+n}p(x_0) \\
&\quad - nx(1-p(x_0))^{-1+n}p(x_0) - nQ(1-p(x_0))^np(x_0) \\
&\quad - nQ(1-p(x_0))^{-1+n}p(x_0)^2)p'[x] + en(1-p(x_0))^n(n(1-p(x_0))^{-1+n} \\
&\quad - n(1-p(x_0))^n - n(1-p(x_0))^{-1+n}p(x_0) - e(-1 \\
&\quad + n)n(1-p(x_0))^{-2+n}p'(x_0) - (-1+n)nx(1-p(x_0))^{-2+n}p'(x_0) \\
&\quad - cn(1-p(x_0))^{-1+n}p'(x_0) + 2nQ(1-p(x_0))^{-1+n}p'(x_0) \\
&\quad - nx(1-p(x_0))^{-1+n}p'(x_0) + n^2x(1-p(x_0))^{-1+n}p'(x_0) \\
&\quad - nQ(1-p(x_0))^np'(x_0) + c(-1+n)n(1-p(x_0))^{-2+n}p(x_0)p'(x_0) \\
&\quad - 2(-1+n)nQ(1-p(x_0))^{-2+n}p(x_0)p'(x_0) + (-1 \\
&\quad + n)nx(1-p(x_0))^{-2+n}p(x_0)p'(x_0) - 2nQ(1-p(x_0))^{-1+n}p(x_0)p'(x_0) \\
&\quad + n^2Q(1-p(x_0))^{-1+n}p(x_0)p'(x_0) + (-1 \\
&\quad + n)nQ(1-p(x_0))^{-2+n}p(x_0)^2p'(x_0)
\end{aligned} \tag{25a}$$

Dividing the whole expression by  $p'(x_0)$ , the condition to be negative is that:

$$\begin{aligned}
n(1-p(x_0))^{-2+n} \left( -(c-e-Q)(-1+p(x_0)) + en(1-p(x_0))^n(-c+e-2en+Q+ \right. \\
\left. 2n(c-Q)p(x_0)) \right) < 0
\end{aligned} \tag{26a}$$

As

$$\begin{aligned}
n(1-p(x_0))^{-2+n} > 0, \text{ it result that we have to show that} \\
\left( -(c-e-Q)(-1+p(x_0)) + en(1-p(x_0))^n(-c+e-2en+Q+2n(c- \right. \\
\left. Q)p(x_0)) \right) < 0
\end{aligned} \tag{27a}$$

$$en(1-p(x_0))^{n-1}(-c+e-2en+Q+2n(c-Q)p(x_0)) < -(c-e-Q)$$

As  $en(1-p(x_0))^{n-1} > 0$ , we have to show that

$$-c+e-2en+Q+2n(c-Q)p(x_0) < 0 \tag{28a}$$

Or,

$$\begin{aligned}
2n(c - Q)p(x_0) &< c - e - Q + 2 e n \\
e \frac{(1-2n)}{1-2np(x_0)} &< (c - Q)
\end{aligned} \tag{29a}$$

As by definition  $1/2 < n$ , for low values of  $p(x_0)$ , the result is true  $\left(\frac{(1-2n)}{1-2np(x_0)} < 0\right)$ .

It remains to verify that the absolute values of the inequality are such that :

$$|en(1 - p(x_0))^{n-1}(-c + e - 2en + Q + 2n(c - Q)p(x_0))| > |(c - e - Q)|$$

That involves that:

$$en(1 - p(x_0))^{n-1}(-c + e - 2en + Q + 2n(c - Q)p(x_0)) < -(c - e - Q),$$

Developing it, we get:

$$\begin{aligned}
-en(1 - p(x_0))^{n-1}(c - e - Q) + en(1 - p(x_0))^{n-1}(-2en + 2n(c - Q)p(x_0)) \\
< -(c - e - Q)
\end{aligned} \tag{30a}$$

We set X, as:

$$\begin{aligned}
en(1 - p(x_0))^{n-1} &= X \\
-X(c - e - Q) + X(-2en + 2n(c - Q)p(x_0)) &< -(c - e - Q) \\
X(-2en + 2n(c - Q)p(x_0)) &< (X - 1)(c - e - Q) \\
\frac{X}{(X - 1)}(-2en + 2n(c - Q)p(x_0)) &< (c - e - Q)
\end{aligned}$$

As  $p(x)$  tends to 0 and  $\frac{X}{(X-1)}$  is positive, the relationships becomes

$$-2 \frac{X}{(X-1)} e n < c - e - Q \tag{31a}$$

Which is true for low values of  $p[x]$ . Consequently:

$$\Phi'(x^0) < 0 \tag{32a}$$

As both functions are convex, increasing in  $x$ , but with an inflexion point which corresponds to their minimum, in  $x^0$  and  $x^*$ , when  $\Phi'(x^0) < 0$  (with  $F'(x^0) < 0$ ) then the minimum of  $\Phi$  is still not reached and  $x^0 < x^*$ . QED

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