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Private Arrangements to Cover Large-scale Liabilities Caused by Nuclear and Other Industrial Catastrophes

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Nuclear and other industrial activities create rare likelihoods for very large catastrophes. Available insurance, intra-industry pooling of risk and the net worth of those who cause the risk, provide an inadequate coverage for compensation of third-party damage. In OECD countries, the top layer of damage compensation after such catastrophes is regularly transferred, explicitly or implicitly, to governments. This constitutes a subsidy of the risk-creating industries. For a variety of reasons, traditional insurers are unwilling to assume full liability for the potentially colossal damage of industrial catastrophes. Such risks could be offloaded to the immensely larger capital market through the issue of catastrophe bonds. This would obviate the need for public subsidy, and provide a means for market pricing of the risks, but considerable needs for public intervention would nevertheless remain.

1. Introduction

Under existing arrangements, the nuclear power generators in OECD countries are unable to cover more than a fraction of the third-party damage likely to occur after a very serious nuclear accident. For while the cost of such an accident could amount to tens of billions of dollars, statutory rules limit the liability of the industry in most countries to a small fraction of such sums. Even where there is no legislated limitation on liability, the combination of insurance, risk pooling and the nuclear power companies' net worth provide a damage payment capacity far below the rare but very large needs that would arise after a serious catastrophe had occurred. Hence, the top layer of damage compensation (the "top risk") has in effect been transferred, implicitly or explicitly, to the governments of the nuclear power-producing countries. This transfer involves a subsidy to nuclear power generation.

Similar conditions apply to other industries causing small likelihoods of catastrophic accident damage, e.g. oil transportation, hydropower, airlines and chemical (the "risky industries"). Though most of these industries are subject to unlimited liability, their ability in practice to cover claims after a very serious accident, which could plausibly cost as much as a nuclear disaster, are similarly constrained. Hence, these industries, too, benefit from the transfer of the top risk to the government, an implicit subsidy.

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Public subsidies of this nature could be motivated, if the risk transfer is considered essential to make possible the operation of the industries under investigation, if their activities are deemed to yield a greater benefit to society than the cost of the transferred risk, and if no private markets exist to which such risks could be offloaded. Nevertheless, public subsidization of private activities regularly involves distortions and other problems.

The purpose of this paper, therefore, is to explore the prospects for private solutions under which the risky industries themselves assume the entire liability for catastrophe damage compensation. The purpose is also to assess the wider implications of such solutions, and to compare them with those arising from the public involvement currently in force.

Section 2 reviews the reasons for the insurance industry's limited role in covering large industrial damage liabilities. Section 3 discusses the possibilities and limitations for the nuclear and other risky industries to pool the large risks, and so to extend the coverage for accident damage above what is provided by insurance. Section 4 describes the new financial instruments needed in the private solution. Section 5 discusses the preconditions that must prevail to induce the industries to shift their risk burden to private markets, while section 6 explores the implications of such a shift. A summary of findings is presented in section 7.

2. Insurance and industrial catastrophes

Under investigation are very rare events with very costly consequences. For the nuclear industry, a catastrophic event is defined as a core meltdown followed by lethal radioactive releases, which lead to several mortalities. No such event has yet occurred in the OECD area, where about 350 reactors are operating. The statistical probability for one taking place within the group has been theoretically assessed as one in between 350 and 6000 calendar years, with potential damage costs from below \$1 billion up to tens of billions of dollars, reaching \$100 billion in very exceptional cases (one in more than a million years).[1] For some of the other industries treated in our earlier paper, there are records of catastrophes involving thousands of dead, but little analysis has been carried out to determine the statistical probability of their recurrence, and of the ensuing costs.

Insurance for the coverage of third-party liability arising from industrial catastrophes is regularly offered – and taken – but the amounts are small. They seldom exceed the \$500 million level, and where they do, the marginal insurance premium rises at an accelerating rate, to a level far above any reasonable assessment of the expected damage cost that the insurers would have to cover (Bohman, 1979). There is an obvious discrepancy between the social need for, and the availability of, insurance for industrial catastrophes.

When the insurers present the reasons for their unwillingness to provide industrial catastrophe coverage, they regularly refer to a "limited insurance capacity". We discuss below the arguments that have been put forward in support of this assertion, and scrutinize the rationale of each in the process.

The assertions of the insurance industry

Insurance presupposes an unequivocal ability of insurers to cover insurance claims. An extensive legislative regulation to secure this ability has been established in most

[1] These numbers represent a summary of the state of the art, as reflected in concurrent literature. See our companion paper Radetzki and Radetzki, 1997.

industrialized countries. It has two main concerns, namely (a) to assure that the capital reserve is adequate for covering the claims that may arise; and (b) the safety and liquidity of the investments of this capital (Försäkringsrörelse, 1995). Such regulation is frequently asserted by the insurance industry to cause a capacity constraint, on each insurer individually, and on the insurance industry as a whole (Skogh, 1995). Two arguments are said to justify this attitude: first, that large industrial catastrophes constitute non-actuarial risks, not well suited for the insurance industry; and second, that the insurance industry lacks the capital needed to cover the potentially colossal claims.

Industrial catastrophes constitute non-actuarial risks

The requirement that insurers should always maintain an unequivocal ability to cover claims, leads to a risk-averse behaviour, expressed in a reluctance to assume uncalculable risks. Traditional insurance involves a transfer of risk at a price fixed *ex ante*[2] and thus presupposes that a premium corresponding to the taken risk can be calculated. This requires that two conditions are met.

First, the insurer must be able to calculate the expected loss of the risk, i.e. the probability of insured damage multiplied by the estimated size of such damage. Knowledge of these two probabilities is ideally obtained from empirical experience. Where empirical data is unavailable, insurers sometimes rely on estimates provided by, for example, physicists and engineers. However, such estimates are deemed to be less reliable, causing a greater degree of uncertainty (Faure and Van Den Bergh, 1990; Tyran and Zweifel, 1993; and Wetterstein, 1990).

Second, the similar but uncorrelated risks insured must be numerous. The greater the number of such risks, the nearer the total damage cost will approach the underlying probability. This is *the law of large numbers*.

In the view of the insurance industry, capacity constraints often emerge because one or both of the conditions are not met. If the expected loss cannot be determined with confidence, there is a situation of uncertainty, and the risk is non-actuarial. Examples are risks related to new products or processes (Skogh, 1996). If the number of similar risks is too low, the law of large numbers is not applicable (Tyran and Zweifel, 1993). Such risks, too, are not actuarial. Examples are risks connected with heavily concentrated activity. In none of these cases is it possible to determine fully the capital that needs to be set aside for each risk. Consequently, the risks cannot be priced with confidence. It follows that insurers must speculate. The insurers normally resolve this dilemma by behaving in a risk-averse manner, venturing only a small sum of money on the uncalculable risk (Abraham, 1988; Hogarth and Kunreuther, 1992; Kunreuther, 1989; and Tyran and Zweifel, 1993).[3]

The longer the duration of an insurance contract involving a non-actuarial risk, the longer will the insurer be exposed to that risk. Unwillingness to provide insurance coverage, therefore, tends to increase with the duration of insurance. The duration of the insurers' risk exposure also depends on the type of insurance. Most property insurance covers damage that *occurs* within the duration of the insurance contract. Most liability insurances (policies

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[2] Exceptions involving *ex post* excess premiums for liabilities applicable to oil transport are discussed by Wetterstein, 1980, while Abraham, 1988, has suggested a two-step premium charge in the context of environmental liability insurance.

[3] The frequency and damage size of industrial accidents is inversely correlated. Smaller accidents occur relatively often, and their actuarial cost is consequently calculable. By offering industrial accident insurance for relatively small amounts only, the insurers restrict themselves to the actuarial domain.

providing a claims-made coverage excepted, see below) cover damage *caused* during the term of the insurance contract. Such damage may not occur until long after the expiration of the policy, but as long as it occurs within the period of statutory limitation, it is nevertheless covered under the policy. Thus, in contrast to a property insurer, a liability insurer often remains at risk long after the expiration of the policy, and the capital reserved is not liberated until the end of the period of statutory limitation (Katzman, 1988).[4] Moreover, the scope of this future liability depends on the legal situation in the field of tort law at the time of eventual claims for damage. The rules of tort law change continuously, and typically in favour of plaintiffs (Abraham, 1988). It is as if the legislator and the courts regarded the insurance firms as agencies whose purpose is to distribute social welfare, and not as commercial enterprises, disciplined by the rules of the market.

Insurers have got their fingers badly burnt by old liability insurance, especially in the environmental and health field. Extensions in the reach of tort liability for, say, asbestos, or clean-up of toxic wastes, has added greatly to the incurred and future potential losses. An alarming assessment contends that the U.S. insurance industry's outstanding environmental and asbestos liabilities amount to $272 billion, more than their total capital and surplus, and 20 times greater than the sums reserved for these claims (Carmean, 1995). A less alarming but nevertheless dramatic computation puts the U.S. insurers' potential environmental liabilities at $50 to 75 billion (*CBOT Review*, 1996, First Quarter).

One way of dealing with the uncertainties of liability insurance could be to change the coverage of liability policies. In consequence, so-called claims-made liability coverage has been created, covering claims for compensation received by the insurer during the term of the insurance contract only. While a normal liability policy implies a commitment by the insurer for the uncertain future (limited by the period of statutory limitation), a claims-made policy restricts the responsibility of the insurer to events in the past plus the period of coverage, usually one year, all provided that claims are filed during that time (Katzman, 1988; Wetterstein, 1990). With claims-made insurance, the capital reserved by the insurer is released immediately after the expiration of the term of the policy. The estimation and pricing of the risk becomes much easier in consequence (Abraham, 1986; Wetterstein, 1990). Transition to claims-made coverage therefore has a potential of reducing the resistance of insurers, and so increasing the capacity to insure, as defined by the insurance industry.

However, a transition to claims-made insurance also has the effect of restricting the scope of coverage provided, as compared with regular liability coverage (Wetterstein, 1990).[5] Since the shift as such does nothing to reduce the reluctance to provide coverage, it cannot by itself bring about an unequivocal increase of insurance capacity.

Insurers do not have the capital needed to insure industrial catastrophes

The second argument for the reluctance to assume industrial catastrophe risks is that the insurance industry lacks the capital needed to cover the very large losses that might ensue

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[4] For this reason, liability insurance is often denominated "long-tailed-business". A more comprehensive enumeration of the problems related to long-tailed insurance business is provided by Wetterstein, 1990.

[5] For this reason, claims-made liability coverage is not practicable when liability insurance of a certain scope is mandatory, as for nuclear operators. According to the 1960 Paris Convention, the operator of a nuclear plant has a strict liability for damage caused by the nuclear activity during ten years from the day of the event causing the damage. The liability is to be covered by insurance or other financial guarantee. It is obvious that a claims-made liability insurance coverage is not sufficient to meet the requirement of the Convention.

from such an event. In 1995, the market value of capital and surplus held by the insurers and reinsurers of property and casualty in the U.S. was assessed at some $230 billion (Lewis, 1996). The numbers could be twice as large for the OECD area as a whole. This capital supports all property–casualty lines, of which only a fraction relates to losses from catastrophe-related claims. Assessments for the U.S. suggest that an event leading to insured losses of $5 billion or more (termed a cataclysm) would lead to several insolvencies in the insurance industry (Cutler and Zeckhauser, 1996), while a disaster costing $20 billion and above would risk impairing the entire insurance system (Lewis, 1996). This may be an exaggeration. Hurricane Andrew in 1992 carried an insurance loss of $18 billion, but did not impair the functioning of the insurance system as a whole. One may surmise that similar consequences would apply at the OECD level.

The limited capital base of the industry does not constitute a capacity constraint in an absolute sense. As already noted, legislative regulation of the insurance industry has been structured to assure the ability of the insurers to pay the claims that may arise. In contrast, regulation does not impose any absolute bar to particular kinds of risk, nor against venturing of large sums on a particular risk. So long as the payment of claims is assured by a sufficient capital base, and so long as the insurance company follows the regulatory provisions regarding investments of this capital, it is ordinarily free to insure in whatever way it likes. Hence, the insurance industry is at liberty to venture into more sizable risks, for which there is an insurance demand, provided that additional capital is procured. The equity capital and reserves of insurers and reinsurers constitute the ultimate buffer for excessive unanticipated losses.

However, a guiding principle in the insurance industry is that the premium income from each insurance class should suffice for the coverage of claims in all normal circumstances. Serious problems emerge when this principle is juxtaposed against the theoretical insurance needs of, for example, the nuclear industry. Assume, hypothetically, that there is an established actuarial likelihood of 0.3 per cent per year of a catastrophe occurring in one of the 350 reactors in the OECD area, with damage costs of $20 billion that the nuclear industry would like to cover by insurance. The annual net actuarial premium works out at $60 million, i.e. 0.3 per cent of $20 billion. But since the catastrophe could occur next year, the insurers will immediately need a $20 billion reserve on standby in order to meet the legislative requirements for solvency. Adherence to the standard principle that the premium from each insurance class provide the necessary reserves, would imply raising the initial annual insurance premium 300-fold, which is not practicable.[6] In these circumstances, the reluctance of the insurers to assume the responsibility for third-party liability related to industrial accidents in excess of a few hundred million dollars, is understandable, though unsatisfactory.

The distinction between catastrophes caused by industry and by nature

The extreme caution exercised by insurers *vis-à-vis* industrial catastrophes contrasts starkly with their large-scale engagements in natural disasters, like hurricanes and earth-

[6] Some difficulty in establishing an adequate capital buffer exclusively from premium income will always be there. In our example, this difficulty is exacerbated by the extremely low likelihood of catastrophe, and by the huge potential damage size. With potential damage of moderate size, it would be more practicable to shift resources from other insurance classes to cover claims, without seriously impairing the capital structure of the insurance firm as a whole.

quakes. Insured losses for major natural disasters in the 1990s have been assessed at the following sums (*The Economist*, 19 April 1997):[7]

Hurricane Andrew (U.S., Florida, 1992)	$18 billion
Northridge earthquake (U.S., California, 1994)	$13 billion
Mireille tornado (Japan, 1991)	$6 billion
Daria storm (Europe, 1990)	$5 billion
Vivian storm (Europe, 1990)	$4 billion
Kobe earthquake (Japan, 1995)	$3 billion

It should be added (Kunreuther, 1996), that the insured losses of Hurricane Andrew could have approached $50 billion, if it had taken a more northerly path, hitting Miami. Similarly, the insured bill for an earthquake of the Northridge intensity with its epicentre in Los Angeles would have ended in excess of $50 billion. The *total damage* of the Kobe earthquake has been assessed at $100 billion, but the insured losses were limited. With a propensity to insure as high as in the U.S., the insured losses in Kobe could well have exceeded even the $50 billion just quoted.

Potential damage payments of such magnitude, and the fact that the much smaller actual payments for Hurricane Andrew and the Northridge earthquake did indeed create serious problems to the U.S. insurance industry, and caused the failure of at least ten insurance companies (*Wall Street Journal*, 12 July 1996), calls for an explanation of different insurer behaviour *vis-à-vis* industrial and natural disasters.

A first answer is that natural disasters are preferred by the insurance industry, because they mainly involve neat property and life risks, with little of the drawn-out and unclear liability risk characteristic of industrial catastrophes.

A second plausible answer is that there is better actuarial experience of natural disasters, because such events occur more frequently. For the U.S., for instance, the probability of a $20 billion natural catastrophe has been assessed at 2 to 3 per cent per year (Cutler and Zeckhauser, 1996; Lewis, 1996), while our assessment of a nuclear catastrophe of this magnitude in the OECD as a whole suggests an annual probability of 0.3 per cent or less (Radetzki and Radetzki, 1997). Furthermore, the greater likelihood of natural catastrophes reduces somewhat the problem of slow reserve build-up when very rare events are insured.

A third explanation for the widespread insurance of natural catastrophes which clearly endanger the viability of the entire insurance sector, is a consequence of the inability of each insurance company to perceive the aggregate dangers of small and seemingly harmless individual decisions to insure. The insurer easily perceives the realms of overall plausible accident damage, when an industrial plant is insured. But he does not ordinarily take the overall insured hurricane damage into account when he signs a policy for an individual home in a hurricane-prone area, where, furthermore, the protection against hurricane damage is only a supplement to protection against fire, burglary, etc. Following traditional insurance principles, the insurer is eager to insure more homes, in order to spread his risks, but in this case the effect is opposite, a concentration of risk. The application of *the law of large numbers* helps to spread the risks only if these risks are uncorrelated. However, it fails the insurance

[7] The largest insured loss for an industrial accident contained in the compilation published by *The Economist* is the Piper Alpha oil platform explosion in the North Sea in 1988, involving total payments by many insurers, of $2.7 billion.

industry when the insured objects are subjected to the risk of one single event, but where this is not fully apparent to the individual insurer. While the small decisions appear to be inconspicuous, the aggregate total may prove quite dangerous to the industry, as was the case following the Hurricane Andrew and the Northridge earthquake in the U.S.

How valid are the reasons of the insurers for their inhibitions vis-à-vis *industrial catastrophes?*

In principle, the statement that insurance capacity is limited is incorrect. The requirement that insurers maintain an unequivocal ability to cover claims does not imply an absolute limit to insurance capacity. The *economic* constraint on insurance capacity is directly related to the size of capital that needs to be reserved for claims payments. It is true that the cost of raising the capital needed by the insurer, whether in the form of equity or accumulated premium income, is bound to rise, as the total is increased. The cost of capital will also depend on the prudence of the insurer. It could be that traditional insurers, assuming only calculable risks, will be able to obtain the capital needed for their operations at a lower cost than insurers who venture large amounts on non-actuarial risks. But so long as the insurer is not constrained by *regulation of prices*, he can always compensate his rising capital costs by charging more for the coverage he offers. At a sufficiently high price, any risk should appear to be attractive to the insurer, wiping out, in practice, the dividing line between insurance and gambling (Pfenningstorf, 1988; Wetterstein, 1980 and 1990). Hence, in the absence of price regulation, there is no absolute *economic* constraint on the capacity to insure. Therefore, in a strict sense, the term “limited insurance capacity” is a misnomer.

There is no doubt, however, that *traditional insurance* is not well suited to take up the full risks of nuclear and other industrial catastrophes. Insurers are specialists in spreading actuarial risks, whose outcomes can be predicted with reasonable certainty. In addition, the potential damage costs of industrial catastrophes are truly enormous, both in absolute amounts, and in relation to the insurance industry’s overall capital base. The insurers’ standard procedure, to build up adequate reserves from current premium income for calamitous outcomes in each insurance class, is not practicable for large industrial catastrophe risks because the probability of such events is extremely low. Given this, the insurance industry may find it hard to raise the capital needed to provide coverage for the top risk, even if it were interested in doing so.

In these circumstances, insurers either heavily overprice the insurance for non-actuarial risk, i.e. the upper layers of industrial catastrophes,[8] or shy away from it altogether (Pfenningstorf, 1990). Such unwillingness to undertake certain risks seems to be especially common in insurance markets with imperfect competition, where satisfactory profits are easy to attain, and comfort replaces profit maximization as a corporate objective. For example, unwillingness to insure has been asserted particularly often and with particular emphasis in the insurance market for nuclear risks, where a pool co-operation among insurers has restrained competition (Faure and Van Den Bergh, 1990).

In conclusion, for insurance capacity to be increased, the traditional principles and attitudes characterizing the insurance business must change. The business can no longer be

[8] An example is the insurance of the first jetliners. Because of uncertainty about the accidents to which these vehicles might be exposed, insurers initially charged a premium eight times higher than that which with hindsight proved sufficient (Skogh, 1996).

limited to actuarial risks, and alternative methods of obtaining risk capital must be considered. Such changes are unlikely in the near future. Hence, the risky industries have to look elsewhere for coverage of industrial catastrophe liabilities over and above a few hundred million dollars.

Other approaches for assuming such risks, e.g. ones that do not presuppose the pricing of risk *ex ante*, and thus do not require the risk to be actuarial, ought to be tried instead (Faure and Skogh, 1992; Skogh, 1995, 1996). Search for alternative means is also prompted by the unwillingness of the insured parties to pay excessive insurance premiums for risks that are highly uncertain, and that in any case may be covered by the government. Empirical evidence reveals that where insurance is not mandatory, there is a clear negative relationship between the extent of uncertainty and the demand for insurance (Hogarth and Kunreuther, 1985).

The following sections present two arrangements that might cater for the unattended needs for the transfer of the top layer of damage liability, with fewer reservations, and at lower cost, than traditional insurance.

3. Mutual risk sharing[9]

Non-actuarial risks could be shared by those exposed to such risks, without the need of *ex ante* pricing. Two or more parties can simply agree about an *ex post* sharing of the cost of accidents caused by their activities. The parties to the agreement will have to pay the actual cost of losses only, with no fear of being overcharged, as is the case with insurance.

However, for a pool of mutual risk sharing to be possible, each party to the agreement must consider the risks of the others as similar to the risk he is facing himself.[10] When uncertainty prevails, the extent of risks cannot be estimated with confidence. However, as long as there is no evidence that one party's risk is greater than another's, the diversification of risks created by the risk-sharing pool has a potential to attract every risk averse risk bearer (Skogh, 1995). With time, the difference in the risks created by each pool member might become clear. This does not imply the end of the pool, but merely that the terms of the risk-sharing agreement should be renegotiated.[11]

Against this background it is not surprising that mutual risk-sharing has a long parentage, and that it is applied as a method for increasing the potential compensation provided in case of nuclear accidents. In the U.S., the Price–Anderson Act requires the licensees of each of the 115 operating nuclear reactors to participate in a mutual risk-sharing agreement. In case the damage from a nuclear accident exceeds \$200 million, which is covered by regular mandatory insurance, each participant to the agreement is obliged to provide a pro rata share of indemnity up to \$67 million per reactor. Thus, by way of mutual risk sharing, the financial compensation of third-party damage in case of a nuclear accident is

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[9] The content of this section has been greatly inspired by the fundamental contributions of Göran Skogh.

[10] For mutual risk-sharing to be successful, several other conditions must be met as well. These are not dealt with here, but see, for example, Skogh, 1996.

[11] See Skogh, 1999. All this indicates that risk-sharing, just as insurance, presupposes that risks are estimated *ex ante*. Risk-sharing is based on an agreement to share risks that are considered similar. The issue whether or not to accept risk-sharing, and if so, on what conditions, thus presupposes that the risks are compared *ex ante*. Note, however, that as distinct from an insurance contract, a risk-sharing agreement does not presuppose that each risk is determined and priced exactly. What is required is only that the relative size of each risk, compared to the other risks in the pool, can be estimated.

increased from \$200 million to \$7.6 billion (Marrone, 1993). The amounts have since been raised to provide for a total closer to \$9 billion.

Inspired by the U.S. arrangements, Faure and Skogh (1992) discuss the possibility for establishing a European convention that stipulates a strict liability for nuclear plant owners far above the existing arrangements for guaranteed compensation (up to \$435 million according to the Brussels Convention). The scheme would limit liability to \$100 billion, an amount large enough to cover the full cost of any likely nuclear catastrophe. Each of the approximately 100 nuclear plants in OECD Europe would be obliged to join a mutual risk-sharing agreement with a maximum liability of \$1 billion per plant, to be paid in the event of accident damage claims. A critical issue is how the nuclear power operators could assure the high levels of liability obligations. Some firms in the industry could not by themselves guarantee such sums without risking bankruptcies in case of a serious catastrophe. The authors suggest that a fraction of the liability might be obtained by pushing the insurance industry to make more intensive use of international reinsurance, to provide policies for higher amounts. Insurers could also be prodded to make damage payments possible as part of the pooling scheme. However, the major part of the liability envisaged in the example sketched by Faure and Skogh would have to be reinsured by the national government of each plant-owner.

The suggested European order could indeed enlarge the amounts of compensation available in case of a nuclear accident. However, since a large part of the compensation would be guaranteed by states, presumably without charge, it implies that nuclear activity will continue to be favoured by a state subsidy, much as is currently the case.

We conclude our discussion on insurance and risk-pooling by noting that the solution of the uncertain risk problem at our hand requires the commitment of very large sums of money. Coverage of the non-actuarial risks posed by industrial catastrophes is a highly speculative business. This is why the insurance industry can resolve our problem only a small part of the way. Risk-pooling by the risky industries themselves provides a further step. Given the limited capital resources held by these industries, risk-pooling too, is inadequate. The nuclear liability arrangements in the U.S. give a realistic picture of what insurance and risk-pooling in combination can reasonably accomplish. The two together assure about \$9 billion for covering the third-party costs of nuclear disasters, but the cost of such disasters could plausibly amount to tens of billions of dollars, so a large part of the problem has been thrown into the government's lap. Hence, it is necessary to search further private means for risk transfer, to relax the dependence on government.

4. Can financial markets manage the uncovered liabilities of industrial catastrophes?

In this section we consider the possibility of setting aside and/or assuring sufficient resources for coverage of industrial catastrophe damage by reliance on new financial instruments, to be placed in the huge international financial markets. Though the focus is on industrial catastrophes, we coincidentally discuss natural catastrophes in some measure, for though the two are different in many respects, they have the enormous potential cost of damage in common.

We have two related approaches in mind, but believe that only the first one, where capital assets are actually set aside, is fully practicable insofar as industrial catastrophes are concerned.

The first approach involves a transfer of the top risks to hedge funds, pension funds, and other institutions which manage diversified capital portfolios on a large scale. We believe that these institutions would be more willing and better able than insurers to handle the very large size of potential damage liabilities represented by industrial and natural catastrophes.

Our assertion is based on the observation that these institutions handle capital on an incomparably greater scale than insurers, and so are better able to absorb the risks. We noted above that the capital and surplus of insurers and reinsurers of property and casualty in the U.S. had recently been assessed at some $230 billion. Similar assessments suggest that the U.S. capital market is 60 to 80 times larger, representing a total value in a range of $15,000 to 20,000 billion (Lewis, 1996; *CBOT Review*, 1996, First Quarter). Corresponding numbers are not available for the OECD area as a whole, but one may surmise that they are about twice as large, and that their relative sizes are not very different from those in the U.S.

Assume that there is a permanent need to keep $100 billion on standby in the OECD area for the compensation of damage from nuclear disasters. Setting aside such a sum would involve a substantial strain on the insurance industry, for the amount corresponds to more than 20 per cent of the industry's current total capital. Not so for the capital markets, where this reserve would absorb only about 0.3 per cent of total assets.

The capital set aside by the portfolio managers could have a variety of forms. One of many possibilities would be a catastrophe bond, whose principal would be forfeited to the extent needed for damage compensation, in the event of a nuclear catastrophe with costs in excess of $9 billion, i.e. above the level that insurance and pooling arrangements could reasonably provide for. The bond-holders' risk of capital loss would need to be compensated through a coupon above the rates on risk-free bonds issued by the treasuries of major countries.

The features of the catastrophe bonds that we have in mind would be quite akin to that of junk bonds issued by commercial enterprises with weak credit standing. Junk bonds suffer from the risk that part of the principal will be lost in the event that the issuing firm goes bankrupt. Junk bonds, therefore, compensate the holders for the risk by offering higher interest.

The interest mark-up on the nuclear catastrophe bonds, above that carried by risk-free long-term paper issued by treasuries, would have to be determined by a market assessment of the risk. For junk bonds, the differential regularly amounts to several percentage points, reflecting the significant probabilities of commercial failure of the issuing enterprises. For nuclear catastrophe bonds, the mark-up would amount to a small fraction of 1 per cent, if the extremely low probabilities of a large catastrophe derived from theoretical analyses, are to be believed.[12] In the end, of course, the market would set the rate differential, and the need to do that would stimulate further efforts to determine the underlying risk.[13]

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[12] Our companion paper (Radetzki and Radetzki, 1997) has assessed the third party cost of *all* nuclear accidents in a range between a "realistic" level of U.S. cents 0.01 per KWh, and a very cautious upper bound of U.S. cents 0.1 per KWh. The average annual total for all OECD nuclear reactors works out at between $170 million and $1700 million. Only a small fraction of this total pertains to the very rare accidents with costs above $9 billion. If this fraction is one-tenth (our guess), then the cost of the risk carried by the bond-holders would amount to $17–170 million ($0.05–0.5 million per reactor), equal to a 0.017–0.17 per cent mark-up on the envisaged $100 billion bond issue.

[13] In a private communication, Tomas Kåberger has suggested that the bond issue could be divided into tranches, with the first $10 billion tranche employed to cover damage costs in the range of $9–19 billion, the second in the $19–29 billion, and so on. The interest mark-up above risk-free bonds would decline for the consecutive tranches, given that the need to use them for damage compensation would become increasingly rare.

The nuclear catastrophe bonds would offer the holders an additional attraction over e.g. junk bonds. Capital portfolio managers seek attractive returns, but also diversification, to assure stability. The value of most of their assets, including shares, prime and junk bonds, and real estate, tends to fluctuate in a co-ordinated manner over the business cycle. The risk element of nuclear catastrophe bonds would not. Hence, a marginal addition of catastrophe bonds to the assets of a portfolio would enhance diversification and reduce value fluctuations over the business cycle, a clearly desirable feature.

$100 billion of catastrophe bonds would have to be issued in the first place. The issuer could be a group of insurers of nuclear operations, desirous to expand their business into an unexploited but potentially remunerative area. The bonds could alternatively be launched by a pool of nuclear operators, or by an intergovernmental institution set up for the purpose.[14] The money received for the catastrophe bond issue could be placed in government bonds, with the annual difference between interest paid and received charged to the nuclear industry. With the capital safely invested in risk-free assets, the only risk carried by the catastrophe bond-holder would be the damage claims after a sizable nuclear disaster.

Similar arrangements could be established to cover the potential liabilities of other industries whose activities create rare risks of very costly catastrophes, and also to cover the costs of natural disasters. Detailed proposals for how a natural catastrophe bond scheme could operate in the U.S. have been made by Litzenberg, Beaglehole and Reynolds (1996). Given the far greater frequency of natural catastrophes, the interest differential between these bonds and risk free government bonds works out at several percentage points, and yet the authors assert that the offload of risk would carry a cost far below that offered by e.g. reinsurance.

The second approach takes its starting point in the fact that industrial catastrophe risks are non-actuarial and that their coverage is a highly speculative exercise. Natural catastrophes share the non-actuarial feature, though their longer track history and more frequent occurrence makes assessments of likelihood and determination of cost ranges somewhat easier. At the same time, it is a fact that modern capitalist societies have established important institutions for the offload of risk from hedgers, e.g. commodity producers or currency users, to speculators. Commodity and currency exchanges, amongst others, have developed a plethora of instruments like options and futures, in which speculators take colossal aggregate positions.

These instruments could, in principle, be used to assure against the risk of industrial catastrophes. For instance, the nuclear industry could buy an option, issued by speculators and guaranteed by the options exchange, permitting the industry to collect from the issuers a predetermined sum of money, after a catastrophe with a total cost in excess of, say, $9 billion. Options for a sufficient amount, held by the nuclear industry, or by its insurers, could, conceivably, finance the cost of even a serious catastrophe.

However, several problems cast doubt on an arrangement of this kind. First, no capital is set aside in the proposed arrangement. Although the right to exercise the option is guaranteed in principle by the exchange, the suddenness with which the need to do that arises after a catastrophe, and the huge amounts potentially involved, could catch the exchange unaware, with the speculators reneging or going bankrupt while belatedly trying to satisfy margin calls. Second, the need to assure the risky industries' ability to compensate for accident damage is of a very long-term character, while the options typically have short duration, certainly much

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[14] Tyran and Zweifel, 1993, have formulated a complex proposal for the institutional arrangements of such a scheme.

shorter than bonds. The need for frequent renewal could well create complications, destabilizing the arrangement.

Financial markets do provide a potentially very large-scale supplement to insurance and risk-sharing arrangements for covering industrial catastrophe risks. In theory, it is therefore possible to envisage arrangements in which the risky industries are adequately assured of the funds needed for even colossal catastrophe damage compensation up to a level of, say, $100 billion (i.e. more than ten times the amount currently guaranteed by the U.S. nuclear power industry), through a combination of (a) insurance, covering the damage costs of smaller, actuarially calculable accidents; (b) sharing of risks for medium-sized catastrophes through industrial operator pools; and (c) the assurance of damage payments for the very large catastrophes, currently the implicit or explicit responsibility of governments, through the issue of catastrophe bonds or catastrophe options.

5. Legal preconditions for the transfer of the top risk to private markets

With the legal provisions currently in force, there is little incentive for the risky industries to act in favour of privatization. This is particularly true of those risky industries (nuclear power generation, oil transport) whose liability is limited in most OECD countries. A transfer of the top risk to private markets presupposes that such limitations in liability are eliminated. However, most risky industries are already subject to unlimited liability. In these industries, liability claims in excess of what is covered by insurance have to be paid by the firms themselves, with an ensuing possibility of bankruptcy. This clearly provides an incentive for the shareholders to acquire guarantees, e.g. through the issue of catastrophe bonds, against which such claims could be settled. It is not clear that this incentive is enough, given the very large amounts that have to be secured, and the rare nature of the events that would trigger compensation payments. Legal obligations to provide financial guarantees for such payments appear to be necessary.[15] To avoid wrecking the risky industries on which the obligation is imposed, such obligations would have to be introduced in a gradual manner, in tandem with the launch of catastrophe bonds or options.

Efforts are also needed to develop markets in which the new instruments can be traded. Attempts have been made, mainly in the U.S., to launch catastrophe bonds as well as catastrophe options, to provide security against natural disasters. So far, the success in marketing these instruments has been mixed, and illiquidity prevails in the markets where they are traded (Cutler and Zeckhauser, 1996). This may be a natural state of things at the present stage. Markets usually take time to develop (*CBOT Review*, 1996, First Quarter; Radetzki, 1980). Junk bonds, a major instrument in contemporary finance, did not exist prior to the 1970s, and it took a number of years and serious marketing efforts before they took off in earnest. An important measure to speed up the creation of a market for the new instruments would be to clarify in no uncertain terms the liability that the holders of the catastrophe bonds would have to cover. The latter is an important and tricky issue, since third-party compensation claims after industrial catastrophes are likely to be drawn-out and ambiguous.

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[15] Some of the problems related to such legislation are discussed in the following section.

6. Implications of shifting the risk burden to the risky industries

The requirement that the risky industries themselves provide guarantees for compensation payments up to, say, $100 billion, and the simultaneous development of liquid catastrophe bond markets would help setting an objective price for the top risks, and so settle a contentious debate concerning nuclear power generation, that has been raging for decades, on what these costs are (Tyran and Zweifel, 1993). Transfer of the top risk to the industries themselves would involve an internalization of a cost that has hitherto been external. Those who object to the political decision that handling of top industrial risks should be in the public domain, would no longer be forced to share the responsibility. The cost of the top risk (i.e. the spread between the risk-free interest rate and the interest rate paid to the catastrophe bond-holders) would differ between the risky industries, in accordance with the market perception of the extent of risk caused by each. Incentives to undertake precautionary measures to reduce the cost, would be strengthened. If the transfer of the top risk to a particular risky industry through the suggested arrangements were to involve costs making the industry non-viable, then that would be an important signal that the markets do not find the activity worthwhile. These are important advantages of the outlined scheme.

It must be underlined, however, that the private market solution is far from complete. In two respects, at least, market forces would have to yield to political considerations.

The first concerns the maximum financial guarantee to be assured by the risky industries. Unlimited guarantees are not practicable. Government involvement is necessary to determine the maximum amount to be guaranteed, and to differentiate it across the risky industries. We see no way in which these issues could be handled by markets on their own. The $100 billion total chosen in our example, should be adequate for covering virtually all industrial catastrophe costs. Nevertheless, catastrophe damage above that level cannot be entirely precluded. The cost of such damage would continue to rest with the government and constitute a subsidy, albeit a far smaller one than under existing arrangements for the nuclear power industry.

The second issue concerns the identification of the risky industries which would be required to provide far-reaching financial guarantees for damage coverage. Basically, all human activities carry a potential risk of causing damage of catastrophical proportions. All should therefore, in principle, be required to assure large financial means for damage compensation. In practice, such impositions on all activities are not feasible. Inclusion in the risky group would constitute a substantial disadvantage to an industry, given that no corresponding financial guarantee requirements are imposed on other industries. Classification of industries in this way again presupposes political decision-making, and involves a further deviation from a pure market solution.

We conclude that it is possible to implement a large-scale transfer of the responsibility for industrial catastrophe damage compensation from governments to private financial markets. We note that such a transfer promotes the establishment of impartial catastrophe risk-pricing, and removes a variety of political distortions that afflict existing arrangements. These are the clear advantages of the suggested change.

At the same time it needs emphasizing that important political elements will remain even after the transfer has been implemented. Government decisions will continue to be made in singling out the risky industries, and in determining the size of the financial guarantees for each. In order to limit the remaining political distortions, it is essential to design objective rules for these decisions, based on scientific analyses of risk, and not on political whim.

The privatization of the top risk management that we have outlined has much in common with a system where the government remains responsible, but imposes a fee on those who cause the risk. The main advantages of the private solution have been spelled out above. But the privatization will be far from complete. At the same time, it will involve considerable effort in establishing new institutions, and trial and error in their operation. The private solution designed above would have to be empirically tested before one could make an unambiguous claim that it is superior to an arrangement where the government continues to assume the top risk and compensates itself by imposing a tax on the risky industries.

7. A summary of findings

Nuclear and several other industrial activities create rare probabilities for very large catastrophes. Costly third-party damage will arise when catastrophes occur. Insurance to cover the liability for such damage is regularly not available for more than a small fraction of the total catastrophe cost. A second layer of third-party compensation can be provided by intra-industry risk pooling arrangements. Unlimited liability of the agent who caused the catastrophe assures a third layer, but this cannot exceed the agent's net worth. The three layers together provide for a very inadequate coverage of third-party liability in the event of very costly catastrophes, and the responsibility for the top layer of damage compensation is regularly transferred to governments, implicitly or explicitly.

Public assumption of the responsibility of the top risk involves a subsidy to the industries that cause the risks. Given the well-known distortions and inefficiencies that typically follow from subsidization, it is appropriate to explore whether private markets, existing or potential, could take over the top risk for industrial catastrophes.

Our search for private solutions which could assure even very large damage compensation has involved a detailed analysis of the reasons for the extremely cautious behaviour of the insurance industry in this area. We found the reluctance of insurers to be due to (a) the non-actuarial nature of the industrial catastrophe risks, combined with the long-lasting liability that they often involve, and (b) the very large scale of potential claims.

Risk-sharing, based on the U.S. nuclear power industry model, provides a substantial additional layer of resources for catastrophe damage compensation, but it is nevertheless inadequate, on account of the limited net worth of individual risky industries.

We explored the possibilities for a transfer of industrial catastrophe risks to financial markets, and found that catastrophe bonds could provide opportunities for a cost-effective transfer of these risks above that which can reasonably be covered by the combination of insurance, intra-industry risk pooling and the net worth of firms in the risky industries. Such bonds could be issued by the insurers, or the risky industries themselves, or an international institution established for the purpose. Hedge funds, pension funds, and other portfolio managers, the potential holders of the proposed instrument, would obtain an attractive risk diversification. These agents handle capital resources large enough to be able to absorb almost any conceivable industrial risk transfer needs.

Catastrophe bonds could make it possible to transfer the responsibility for the top risk from governments to the risky industries. However, the creation of a market for such bonds presupposes legislation which makes it mandatory for the firms to provide financial guarantees for catastrophe compensation claims. The development of this market also requires clear rules identifying the extent of liability borne by the industrial firm causing a catastrophe, and, by implication, by the catastrophe bond-holders.

The industrial catastrophe bond market provides a prospect for relieving the governments of a large part of the risk that they currently carry. It offers a means for objectively revealing the cost to society of catastrophe risk. Imposing that cost on the industries that cause the risk, should reduce the distortions in the structure of industry caused by the subsidization of risk by governments.

At the same time, it is evident that privatization of industrial catastrophe risk-handling will never be complete. Since financial guarantees provided by the risky industries cannot be unlimited, it follows that some of the risk will always remain with governments. Public authorities will have to single out the risky industries which will be obliged to provide financial guarantees, and decide the amounts required from each. Political distortions might impact on these decision processes. Thus, the main detriment of the public solution which prompted us to seek alternatives, will remain in some measure.

Clearly, therefore, the suggested privatization is not without problems. Until it has been tested in practice, it is hard to claim that the private solution outlined above is unambiguously superior to an arrangement where the government continues to assume the top risk and compensates itself by imposing special taxes or fees on the risky industries.

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