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Kiel Working Paper No. 755

**Enforcement of Environmental Liability
in the Case of Uncertain Causality
and Asymmetric Information**

by Elga Bartsch



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July 1996

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Abstract: In providing precautionary incentives and allocating environmental risk, liability for environmental damages faces two difficulties: randomness of damages incurred and nonobservability of precautionary measures. Hence, a major obstacle in enforcing legal claims is the difficulty of proving causation. In order to alleviate the proof of causation, the German Umwelthaftungsgesetz introduces a refutable causality presumption. When imperfect information is taken into account, this conditional reversal of the burden of proof cannot ensure optimal precaution. Using a principal-agent model, optimality conditions for a modified strict liability rule is derived. A specific rule for the optimal allocation of environmental damages under probabilistic causation and asymmetric information is obtained using a linear model.

JEL-Classification: D80, K32, Q20.

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I. The Role of Uncertain Causality and Asymmetric Information

Although general liability law has a long historic tradition (cf. for example Landes, Posner 1987, 2ff), liability for environmental damages has become only recently an important instrument of practical environmental policy. Due to growing public concern about environmental accidents, over the past decades many industrialised countries introduced specific legal acts dealing with the liability for pollution damages¹. The Federal Republic of Germany, introduced the Environmental Liability Act in January 1991² and is currently preparing a comprehensive Environmental Code (Umweltgesetzbuch, UGB). Similarly, on the European level, various attempts to reform tend to strengthen environmental liability. The European Commission recently emphasised the role of environmental liability (cf. EU Commission 1993). Likewise, the Commission presented a draft for the Directive on Civil Liability for Damages Caused by Waste (1991, O.J. (C192) 6). Moreover, the Council of Europe agreed on a Convention on Civil Liability for Damages resulting from Activities Dangerous to the Environment (June 21, 1993, European Treaty Series 150). Other countries, notably the United States and Japan, saw major changes in their legislation with respect to liability for environmental

¹ In the context of this study, 'damages' refer to the degree of environmental degradation incurred and therefore deviates from the use of the term in the law and economics literature. There, 'damages' refer to the compensatory payments the defendant has to make to the plaintiff. These compensatory payment will be referred to as liability payments here.

² Umwelthaftungsgesetz, UmweltHG December 10, 1990, effective January 1, 1991, 1990 Bundesgesetzblatt, Teil I, BGB, p. 2634.

damages already during the 1980's. In 1980, the United States introduced the Comprehensive Environmental Response, Liability, and Compensation Act (CERCLA) already. CERCLA was followed by the Superfund Amendments (SARA) in 1986 (cf. Grigalunas, Opaluch 1988, Acton 1989) which imposes a retroactive joint and several liability on potential tortfeasors that might have contributed to the contamination of a specific site. More recently, after serious damages to coastal ecosystems have been caused by major oil spills, the Oil Pollution Liability Act (OPA) of 1990 was enacted. In Japan, the so-called four major lawsuits at the beginning of the 1970's brought a shift in environmental legislation in particular as regards victims' entitlement to compensation (cf. Zweifel, Tyran 1994, 48).

A. Civil Liability as an Instrument of Environmental Policy

The German Umwelthaftungsgesetz (UmweltHG) defines environmental liability as liability for individualised losses (health, property and, to a certain extent, ecological damages³) which are caused by an environmental impact (cf. Section 1 and 2 UmweltHG). Typically, civil liability does not provide for compensation for damages to the environment as such. Instead

³ Liability for ecological damages has been intensely debated during the legislative procedure prior to the enactment of UmweltHG. Basically, two variants of ecological damages can be distinguished. First, an ecological loss, i.e. a damage to the environment which constitutes at the same time an individual property loss (for example degradation of water quality in some privately owned fish pond). Secondly, a pure ecological damage which refers to a damage to the environment without any interference with private property rights. It is argued that the latter case only will arise in very few instances (cf. Landsberg, Lülling 1991, 36ff). Therefore, the

it aims at protecting private property rights. Therefore, all those damages that do not interfere with private property, for example that exhibit pure public goods characteristics, currently cannot be recovered under UmweltHG. However, some proposals for reform, in particular on the European level, provide for subsidiary claims to be made by government authorities or common interest groups (cf. Pappel 1995, 71ff). The enforcement problem in presence of uncertain causation and asymmetric information addressed in this study, however, will even arise a situation where only two parties are involved in the environmental problem⁴.

From an economic point of view, environmental liability law should aim at two objectives. On the one hand, environmental liability should induce the potential polluter to take an efficient level of precaution regarding the environmental risks involved in their economic activities. A Pareto-optimal level of environmental risks is achieved if the potential polluter takes into account full external costs due to expected environmental damages, when deciding upon his economic activities that relate to either the probability or the severity of environmental degradation (cf. Siebert 1991). Ideally, the anticipation of ex post liability provides ex ante incentives to take adequate precaution (see Cropper, Oates 1992, 693). On the other hand, environmental liability should bring about an optimal sharing of environmental risk between polluter and injured party (cf. Cooter 1991). Although, the implications of different liability rules for

criticism of environmental liability as a means of internalisation should not be based on the fact that it might not encompass this type of damage.

incentives have been well recognised, the risk-sharing effects have been largely neglected (exceptions being Shavell 1982, Segerson 1987, Laffont 1994)⁵.

Compared to other instruments of controlling environmental risk, liability is regarded as an attractive instrument of environmental policy, because of its efficiency in the use of decentralised information (cf. Bohm, Russell, 1985, 434). The information needed to determine the Pareto-optimal allocation of environmental risk is typically distributed among different individuals. The availability of this information constitutes the central difficulty in designing environmental policy⁶. In the institutional setting of environmental liability, (legal) action with respect to the internalisation of

⁴ Please note that although, the individual might not have a right to clean ambient atmosphere, an appropriate liability rule can enable it to recover losses it suffers from breathing polluted air.

⁵ However, the ongoing debate on insurance of environmental risks shows that the allocation of environmental risk, also constitutes highly relevant issue. In insuring environmental liability, the insurance crisis in the United States during the mid eighties indicated (cf. Winter 1991), a variety of technical problems can arise (cf. Kunreuther 1987, Breining 1990). Hence, the risk allocation implied by different liability rules is an equally important factor in the choice of a policy option as are the incentive effects. The fundamental problem in insuring environmental risk is related to the different roles of environmental media as a public consumption good (being subject to a social risk) and as a receptacle of pollutants (being subject to a private risk). Only in the case of individual risks, risk pooling is feasible (cf. Siebert 1995, pp. 265ff; Dasgupta 1982). Hence, first party insurance of the public good dimensions by private insurance companies will be impossible. Private good dimensions like individual health and private property damages can, however, be covered by first-party-insurance. As regards the public good dimension only a liability insurance is conceivable.

⁶ This information problem was first pointed out by von Hayek 1945.

third party damages is initiated by those who are directly affected. Thereby, injured parties negatively affected by environmental pollution provide information on the incidence of environmental degradation (cf. Streissler 1994, 253). Properly designed liability laws lead potentially polluting firms to anticipate not only current but also potential future environmental risks long before environmental damages manifest themselves and catch the attention of an environmental policy maker. Moreover, liability induces private individuals to acquire information on potential environmental risks generated by their economic activities without government intervention (cf. Panther 1992 for a detailed discussion). Thereby, liability constitutes an important instrument of preventive environmental policy (cf. Simonis 1984, O'Riordan, 1985, critical Kirsch 1988). Liability regimes differ in their information requirements, though. A strict liability rule does not rely on decentralised information regarding cost of precaution or the precautionary measures implemented by the individual emitter (cf. for example Feess, Hege 1994) and continuous monitoring of pollution control techniques implemented is not required. In addition, a strict liability leaves it to the polluter to choose the most efficient pollution control techniques.

In providing precautionary incentives and allocating environmental risk, environmental liability faces two problems: First, the unobservability of stochastic influence factors and second, the information asymmetry regarding the precautionary measures taken. If both incentives and risk sharing are addressed in a situation of uncertainty but complete information, both can be examined separately (as for example in Segerson 1987). It is well known from principal-agent theory, however, that, if one

allows for asymmetric information, there will be a Trade-off between incentives for precaution and optimal risk sharing (cf. Sappington 1991).

B. Uncertainty and Environmental Risk

Environmental pollution is characterised by substantial uncertainty regarding both the extent and the ultimate consequences of pollutants discharged. This complicates the implementation of optimal environmental policies⁷. Uncertainty is due to a number of reasons. The incidence of emissions and pollutants ambient in the environmental media is by far not known exactly. Neither is the exact nature of the environmental problems involved perfectly understood, nor is the interaction between different pollutants and their diffusion within and between different environmental media, nor is the accumulation of harmful substances over time exactly known. A classification of the different types of risk or uncertainty involved in environmental pollution is given by Siebert 1987, 1991, 194f.

Stochastic factors influence the incidence and the extent of environmental damages basically by two different relationships. Firstly, the diffusion process can be subject to a random variable. Then, the relationship between net emissions and the level of pollutant ambient in the environment, i.e. immissions, becomes uncertain. This can be due to uncertain meteorological and topographic conditions. A related situation

⁷ The possible consequences of uncertainty with respect to costs and benefits of pollution abatement on different policies have been analysed in the seminal works of Weitzman 1974, Adar, Griffin 1976, and Roberts and Spence 1976. More recently, Baumol, Oates 1988, p. 190ff and Siebert 1987 provide an overview of this issue.

arises when emissions of several polluters contribute jointly to ambient levels of pollutants and individual discharges cannot be observed directly. In the latter case, it is irrelevant whether the joint effect of individual discharges is deterministic or stochastic. Secondly, the relationship between the level of precaution and actual level of emissions may be subject to uncertainty. A variety of environmental accidents on different scales indicate, that polluters may only be able to control their emission of pollutants imperfectly. Then, the actual level of emissions is also a random variable⁸. In the following, it will not be distinguished whether the random influence is due to technical disturbances or stochastic diffusion processes. For the incentive scheme that will be derived, it does not matter whether there is either a single suspected polluter or whether there are several suspected polluters⁹. In both cases, it is not possible to infer from the

⁸ Please note that according to well established results in principal agent theory, ideally the polluter should be rewarded based on the variable which he controls. Therefore, if the polluter does not have complete control over the quantity of substances emitted, generally incentives should be based on the precautionary effort.

⁹ Models of multiple polluters often focus on the strategic interaction among different emission sources in the choice of their precaution levels (cf. for example Miceli, Segerson 1991, Feess and Hege 1994, Xepapadeas 1991). However, given the large number of potential contributors to pollution, in particular in non-point-source pollution, it seems rather artificial to concentrate on the strategic interdependence in precautionary levels. It seems more plausible that the substances emitted by others are regarded as fixed exogenous level plus maybe a random disturbance. Moral hazard in teams does not arise if there is no strategic interdependence. Moreover, it seems rather unlikely, that although neither the environmental authorities nor the court cannot observe the precaution level taken, that other polluter can observe this variable. For the remainder of this study it will be assumed there exists a sufficiently large number of

observed ambient pollution whether the polluter took appropriate precaution.

C. Enforcing Legal Claims under Uncertain Causation

The main problem in enforcing environmental liability is the difficulty of proving causation (Deweese, 1992, 436f). The enormous scientific uncertainty regarding exposition trails of pollutants gives rise to the problem of uncertainty over causation. In many cases, environmental damages lack verifiable, deterministic causal connection in the sense of a necessary condition of the harm incurred which is required by many legal systems, i.e. a *conditio sine qua non*¹⁰. This makes it impossible to prove causation in a deterministic sense (cf. Siebert, 1991, 188). Since the burden of proof is with the claimant, legal claims will often not be enforceable. Moreover, in the case of multiple emission sources, identification of the polluter responsible for the harm incurred may be very difficult. Uncertain causality refers to damages that have been generated by several, interacting causes whose contribution cannot easily be separated because of unobservable stochastic processes and because of asymmetric information regarding the level of precaution taken or the quantity of substances emitted¹¹.

emitters such that the individual precaution levels do not influence the precaution taken by others emission sources.

¹⁰ For overview of the legal problems involved under German law cf. Assmann 1988, Landsberg, Lülling 1991, 77ff.

¹¹ Unobservable stochastic factors both in the diffusion process and the relationship between the precaution taken and the net emissions, prevent it to infer from the observed level of concentration of ambient pollutants

D. Strategies For Solving the Problem of Proving Causation

In a situation of uncertain causation, whether a polluter can be held liable in legal disputes for any damage that is (at least partly) due to his emissions depends crucially on the procedural rules regarding the burden of proof¹². The question of who should be assigned the burden of proof is not only a normative issue, of which party should bear the consequences of unreducible ex post uncertainty, but also entails substantial incentive effects. The most obvious relieve as regards the burden of proof is to introduce a strict, i.e. non-fault based, liability. Under a strict liability, the only evidentiary requirement is that the harm suffered was caused by the operation of an environmentally risky plant. Basically, there are two different strategies under uncertain causality. One is to establish some threshold regarding causation. The other is to hold potential causes liable in proportion to the probability of causation. Both approaches will be discussed in turn below.

1. Use of a Threshold Criterion

In practise, often all-or-nothing rules with respect to causality are used. All-or-nothing rules insist on a causation in fact and deny the probabilistic linkage between precaution and damages. This might cause liability to be either excessive or non-existent. If the injured party were to establish causality with certainty, this is by the probabilistic nature of multicausal

stochastic environmental problems could be controlled optimally in a trivial way by imposing ex ante safety regulations.

¹² The German Umwelthaftungsgesetz, for example, attempts to alleviate the difficulty of proving causation by reversing the burden of proof and establishing a refutable causality presumption.

damages impossible. Therefore, the polluter never would have to face liability payments. The opposite result emerges, if the burden of proof is reversed, and the polluter were to prove that a specific damage was not caused by his emissions¹³. Assigning the burden of proof to the polluter would solve the problem of imperfect internalisation of environmental risk at the expense of an excessive liability (cf. Adams, 1986, p. 151ff, Siebert, 1987, p. 121ff).

A modified version of the all-or-nothing rule relies on a threshold level regarding causality by requiring an specific probability of causation or by imposing conditional conjectures of causality¹⁴. Following the second approach, conditional presumptions as regards causation are established. The Environmental Liability Act of 1990 provides for such a refutable conjecture of causality. It will be shown in this study that, the reversal of the burden of proof which is conditioned on compliance to legally prescribed safeguards (so-called regular operation) will lead to an inefficient level of precaution by the potential polluter.

2. Liability in Proportion to the Probability of Causation

Alternatively, proving causality might be facilitated by allowing probabilistic proof of causation and imposing strict liability proportional to the probability of causation. The idea of proportional liability was

¹³ A different situation arises; if perfect information can be obtained at some cost. In this case, as Panther 1992 shows, the burden of proof should be with the cheapest information provider.

¹⁴ For example, in Anglo-American case law the notion of an predominant probability of causation is widespread (cf. Balensiefen 1994).

developed in the United States by the California Supreme Court in context of product liability¹⁵, where potential causes were held liable according to their market shares which were used to approximate the ex post probability of causation. The analogon to market share liability in the case of multiple emission sources is liability according to the emission shares (cf. Panther 1992). This scheme is not feasible, however, if individual emission levels are not publicly observable.

The problem of uncertain causality has been first rigorously analysed by Shavell 1985, 1987, p. 123ff. Shavell considers a simple model where besides a potential injurer, an additional natural source might have caused an environmental accident. Both sources cause a loss of a exogenously fixed size with known ex ante probabilities. Whereas the background probability that the natural sources causes a damage is assumed to be fixed, the probability that the potential injurer generates a damage is inversely related to his level of care. Panther 1992, p. 181 ff, derives a similar model where, in contrast to Shavell, damages vary continuously. In determining the share in pollution discharge contributed by a given source, both, Shavell and Panther, assume that the level of precaution or likewise the emission level is publicly observable. This constitutes a strong idealisation, since in the case of many problems it is more likely that the level of precaution is, at least to some degree, private to the polluter. Precautionary pollution control measures may be unobservable either because they plainly cannot be observed at all (as in non-point source pollution) or because monitoring cost are prohibitively high. Hence, the environmental

¹⁵ Sindell vs. Abbott Laboratories, 607P. 2d 924 (Cal 1980) cert. denied,

policy maker is faced with a situation of asymmetric information. The fact that the polluter can hide his action gives rise to the problem of moral hazard.

E. Aim of This Study

Summarising the specific features of environmental damages that have been outlined above, the key difficulties in enforcing environmental liability stem from the existence of uncertainty about the ultimate impact of emissions and the importance of asymmetric information with respect to the precautionary measures taken. Past research on uncertain causality in environmental liability has largely ignored information asymmetries (cf. e.g. Shavell 1985, 1987, p. 123, Panther 1992).

The aim of this study is to extend the economic analysis of environmental liability to a situation of multicausal, stochastic damages and asymmetric information due to unobservable individual pollution control efforts. Using a principal-agent framework, an optimal liability rule will be derived. It will be argued that applying a discrete all-or-nothing decision rule regarding evidentiary requirements is not optimal. Instead uncertain causality should be taken into account in the liability rule itself. A modified strict liability rule is able to generate socially efficient precaution if the liability share of the polluter follows the ex post probability of causation given that a certain damage occurred. It will be shown that, if the polluting firm is risk neutral, the first best solution can be attained by simply holding the firm operating a environmentally risky plant liable for

all damages that might be caused by its emissions. In a more general context, however, a full strict liability may lead to inefficiencies. If polluters are risk averse, it is not optimal to hold them liable for all occurring damages, since this would cause them to carry out excessive preventive measures.

The remainder of this paper is organised as follows. The provisions of the new German Environmental Liability Act related to proving causation are analysed in the section 2. Section 3 presents a general model of optimal incentive schemes in environmental policy when pollution control by the emitting firm cannot be observed. Section 4 derives the optimal liability rule in the context of a simplified linear model which allows the derivation of results that can be interpreted in economic terms. The conclusions of the theoretical analysis and its policy implications are summarised in section 5.

II. Effects of a Conditional Reversal of the Burden of Proof

This section will model the implications of the evidentiary requirements regarding causality, as provided for under new German Environmental Liability Act of 1991 when monitoring problems in assessing the preventive pollution control measures are taken explicitly into account. The Umwelthaftungsgesetz (UmweltHG) aims at strengthening the position of the injured party by introducing a reversal of the burden of proof (cf. Section 6 and 7 UmweltHG)¹⁶. In contrast to German tort law

¹⁶ The conditional reversal of the burden of proof takes up the idea developed by the Federal High Court in the so-called Kupolofen-ruling. In this legal dispute, the Federal High Court decided that under certain conditions, it is the duty of the plaintiff to prove that he has complied with

(cf. Section 823 et seq. of the German Civil Code), now the burden of proof is with the operator of an environmentally risky plant¹⁷. Furthermore, the legislator established a refutable causality presumption if, given the circumstances of the specific case, the operation of the facility is capable of generating the harm suffered by the plaintiff (cf. Section 6 UmweltHG). Thus, the injured party only has to prove that the defendant's facility is capable to have caused the harm, not that it actually has caused it. In order not to be held responsible, the operator of the plant would have to show that either his emissions are not capable to cause the damage incurred or that other sources (not subject to the UmweltHG) are equally capable to cause the harm (cf. 7 UmweltHG). In order to fulfil the evidential requirements of the claim for damages, injured parties have a claim on information to be provided by the polluting firm and the government authorities (cf. Section 8,9 UmweltHG).

There is, however, an important exception from the presumption of causality. If the polluter has complied to the legally prescribed standards of regular operation (besondere Betriebspflichten), the presumption does not apply (cf. section 6, para 2 UmweltHG)¹⁸. The standard of regular

the safety regulation and thereby the emissions cannot have caused serious harm (BGH Z 92/143).

¹⁷ The legal terminology of the UmweltHG assigns the legal responsibility to the operator of a plant or facility. Although, in a strict legal interpretation a plant is not the same as a firm, in this study firm or polluter will be used synonymously.

¹⁸ A second condition for an exemption from the causality presumption is that there is been no disruption in the operation of the plant. But the legal literature on the Umwelthaftungsgesetz takes the view that if all legal obligations have been met by the operator of the facility, then all cases of

operation is defined in the Federal Air Pollution Control Act (Bundesimmissionsschutz-Gesetz) In the case that regular operation has not been violated, the Environmental Liability Act requires the injured party to establish causality of the emissions of a specific plant. This corresponds to the principle of full-proof governing German tort law. The burden of proof is with the claimant. If the firm can prove compliance with the legal requirements, the general conjecture that the environmental damage was caused by the operation of the potentially harmful plant is excluded¹⁹. In this case, given the multi-causal nature of environmental pollution, it is almost impossible for injured party to fulfil the evidential requirements regarding the causal relationship between the operation of the plant and the environmental damage.

The procedural rules for the stylised decision-making under a conditional reversal of them burden of proof can be summarised in the following diagram:

disruption will also be cases of force majeure (cf. Landsberg, Lülling 1991). And since liability is excluded in cases of force majeure (see Section 4 UmweltHG), for the purpose of this study, it is sufficient to concentrate on the compliance with the legally prescribed safeguards.

¹⁹ Under certain conditions periodoc inspection will be sufficient (cf. Section 6, para 4 UmweltHG).

FIGURE 1: PROCEDURAL RULES OF THE ENVIRONMENTAL LIABILITY ACT OF 1990

time			
firm chooses level of precaution	injured party suffers a loss and sues	presumption of causality established	liability
e	$q(e;\theta)$	$s < \text{or} > n$	$l = q$

Under the assumptions made with regard to the uncertain and multicausal nature of environmental damages, the conditional reversal of the burden of proof together with the causality presumption suggests, in fact, that exclusion from the causality presumption is equivalent to the exclusion from liability. Therefore, in the following, it will be assumed that, if the polluter has taken an adequate level of pollution control, he is freed from environmental liability. If, by contrast, the firm has not taken the legally prescribed measures of environmental protection, the firm will be held liable at all for damages.

A. *The Model*

In order to focus on the analysis of the incentives of the part of the polluting firm entailed by the provisions of the UmweltHG, free-rider problems among multiple injured parties are neglected. Instead, the framework is one of a bilateral externality. Moreover, courts are assumed to enforce the liability rules perfectly and costlessly. It will also be assumed that there exists only one type of polluter with known pollution control costs who faces known a known distribution of liability payments. This assumption allows to abstract from problems that arise in the case of heterogeneous defendants.

Under a conditional reversal of the burden of proof, liability payments are awarded if the perceived care is smaller than the standard of regular operation. Thereby, a conditional reversal of the burden of proof generates similar effects as a negligence rule (cf. Schwarze 1996). Under very specific conditions, a conditional reversal of the burden of proof can induce efficient precaution. If the legal standard is defined at the socially optimal level, the polluter knows with certainty which standard will be required in litigation, and the level of precaution is perfectly observable. If the level of precaution is perfectly observable, efficient precaution will be achieved. However, these idealistic assumptions are not very likely to be given in reality. Therefore in this study, the somewhat more realistic assumption is made that there is uncertainty involved regarding the findings of compliance to the legally prescribed safety standards²⁰. In the model presented here, uncertainty is due to imperfect observability of pollution control activities. Equally, uncertainty may be due to the fact that the polluter is unable to control his level of care completely²¹. Then for a given level of precaution taken the polluter is uncertain if he is going to be responsible for proving causation in litigation. Uncertainty may be due to by an unforeseeable decision of court

²⁰ From a different perspective Jost 1993 analyses strategic behaviour in legal disputes under new German Environmental Liability Act in the presence of asymmetric information about the compliance of potential injurer with legally prescribed environmental safeguards. If information on precautionary measures is private to the polluting firm, the question is, whether the information given in court is a truthful revelation. The disclosure of information in litigation is also analysed in a related paper Jost 1995.

²¹ In this case it is necessary to distinguish between the level of care at the moment the accident happens and precaution which is only stochastically

in respect to the standard of regular of operation, when the court's interpretation of the evidence presented is not known perfectly beforehand²².

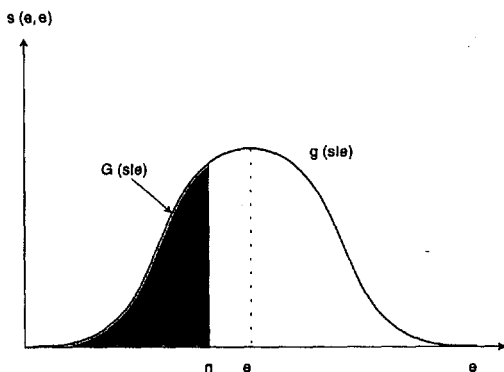
It will be assumed that only an imperfect signal s of the actual precautionary effort, denoted by e , can be observed²³.

related to care (cf. Diamond 1974, 109). In this study both expressions, care and precaution, are used synonymously.

²² Uncertainty in the court's decision on verifying causality is similar to the problem of assessing negligent behaviour. In contrast to the model presented in this study, however, in models of uncertain court decision the distribution of the signal is not parametrised by the effort level. Uncertain court decision being due to jury decisions seem to be a more severe problem in Anglo-American law than in the Continental European legal system, have been analysed by Kolstad Ulen, Johnson 1990, Cooter, Ulen 1986, Craswell, Calfee 1986, and Calfee, Craswell 1984.

²³ There is a growing literature on different aspects of errors in legal disputes: The optimal degree of accuracy and how it affects the optimal probability and magnitude of sanctions is discussed in Kaplow 1991, Kaplow, Shavell 1992, Polinsky, Shavell, 1989. The impact of the fact that not all injurers being held liable on the behaviour of injurers is analysed by Posner 1973. Png 1986, Ehrlich 1982, and Kaplow, Shavell 1994 look at the accuracy in determination of liability in models of law enforcement.

FIGURE 2: THE IMPERFECT OBSERVABILITY OF PRECAUTION



Suppose that the court can only observe $s = e + \varepsilon$, where ε is normally distributed, zero mean random variable²⁴. Let $G(s|e)$ denote the distribution function of the imperfect signal of precautionary efforts, s , for a given mean of e , with a density function, $g(s|e)$ from $g(s-e) = g(\varepsilon)$. The probability that the polluter will end up in legal dispute with a perceived level of precaution lower than the given standard of regular operation n is

²⁴ This assumption restricts the analysis to symmetric errors. Biased errors are discussed by P'ng 1986, Kolstad, Ulen, and Johnson 1990, and Craswell and Calfee 1986. Normality of the distribution is not essential. It facilitates a comparative static analysis for varying degrees of uncertainty.

$$(1) \quad p(s < n) = p(e + \varepsilon < n) = \int_{-\infty}^{n-e} g(\varepsilon) d\varepsilon = G(n-e)$$

This is the probability that the polluter will have to compensate expected environmental damage $Q(e)$. The polluting firm will be presumed to have caused the damage incurred if and only if $s < n$, where n indicates the standard of regular operation. The firm will not be liable for any damage if the observed precaution indicates that the legal obligations guiding regular operation have been met. If, however, the firm's level of precaution does not meet the legal requirements, the polluting firm will be held strictly liable for the damage incurred.

In the case of a conditional reversal of the burden of proof, the rule for assigning responsibility, $l(s)$, for a given standard of regular operation is:

$$(2) \quad l(s(e, \varepsilon)) = \begin{cases} 1 & \text{if } s(.) < n \\ 0 & \text{otherwise.} \end{cases}$$

Polluters who are found to be responsible for the damage incurred are assumed to be assessed liability payments that are equal to the observed environmental damage. Let expected environmental damages be denoted by $Q(e) = E q(e; \theta)$, with Q being a downward sloping strictly convex function (i.e. $Q_e < 0$, $Q_{ee} > 0$). $E q(.)$ denote expected environmental damages and E being the expectations operator. θ describes the stochastic diffusion process by means of a zero mean normal distribution. As in this

section decision makers are assumed to be risk neutral, the random variable θ will be suppressed for the remainder of this section.

Carrying out precaution involves some costs to the polluter which are denoted by $f(e)$, with $f_e > 0$, $f_{ee} > 0$. Hence, provided that the random variables θ and ϵ are stochastically independent, total expected costs of the polluting firm under a conditional reversal of the burden of proof are

$$(3) \quad TC = E [f(e) + l(s(e, \epsilon)) Q(e)] .$$

At the moment at which the potential polluter takes the decision about the appropriate level of precaution, he faces uncertainty because he only controls the observable signal only imperfectly. Hence, the polluter is not fully immunised against being held liable. Even if the polluter takes a sufficiently high level of precaution, there is still a positive probability that he will be held liable. The incentives to comply with legal requirements will, apart from the cost of precaution and expected liability payments, depend in particular on the degree of uncertainty with regard to the true precaution level.

Rewriting total environmental costs, TC, for a risk-neutral polluter gives

$$(3') \quad TC = f(e) + Q(e)G(n - e)$$

For analytical convenience, the assumption is made that TC is strictly convex²⁵. Let subscripts denote partial derivatives. The first-order

²⁵ That is, expected liability payments, $Q(\cdot)G(\cdot)$, have to be convex. This means that the strict convexity of the environmental damage function is preserved when it is multiplied by the distribution function $G(\cdot)$. If the

conditions for a cost-minimum under a conditional reversal of the burden of proof are then

$$(4) \quad f_e + Q_e G(n-e) - Q(e)g(n-e) = 0$$

provided that $e > 0$ ²⁶.

At the optimal level of precaution, the marginal costs of precaution have to equal the marginal expected liability payments. The change in expected damage payments can be decomposed into two separate effects which indicate the impact of a marginal increase in precautionary effort on expected liability payments:

- The "damage effect" $Q_e G(\cdot)$, describes the reduction in expected liability payments due to the marginal reduction in expected environmental damage. Due to the fact that $G(\cdot) < 1$, the incentives to take precautionary measures are weakened compared to the social optimum, because the conditional reversal of the burden of proof shelters the polluter partly from being held liable.
- The "liability effect", $-Q(\cdot)g(\cdot)$, indicates the savings in expected liability payments due to a decreased probability of being held liable

density function g is single peaked, this corresponds to the assumption that the marginal Likelihood does not decline too fast beyond the peak, that is g' must not take large negative values. For the remainder of this section this will be assumed to be the case.

²⁶ Here, it is assumed that $e > 0$ at the minimum. A corner solution, $e = 0$, can occur if the first unit of precaution does not reduce expected liability payments enough to match the cost of precaution caused by this first unit of effort. To restrict the analysis to interior solutions, it will be assumed that this case does not arise.

when precaution is increased²⁷. As the marginal probability of being held liable is $-g(n - e)$, the potential polluter can reduce the chance of being found non-compliant by increasing the level of observable precaution. The marginal change in the Likelihood of being found non-compliant is weighted by the total environmental damage for which the polluter might be held liable. This implies that incentives to take precaution measures are sharpened by the a reversal of proof.

Whether or not the cost-minimising level of precaution rises as a net result of these two offsetting effects will depend on the relative size of the damage effect versus the liability effect. Whether or not the incentives to exert precautionary effort are sharpened or weakened can be distinguished by evaluating the first-order condition at the social optimum, where $-Q_e = f_e$. Please note that the assumptions made with respect to $Q(e)$ and $f(e)$, the minimum of total environmental costs, $Q(e) + f(e)$, is characterised by the first-order condition, i.e. $f_e = -Q_e$. This gives $Q_e (G-1) - Q(\cdot)g < \text{or} > 0$. As the first term on the LHS is positive, this reflects the reduction in incentives to take precaution and vice versa for the second term. The net effect will depend on various factors, such as the cost of precaution, the liability payments the polluter has to face when being presumed to be responsible, the degree of uncertainty in assessing the level of precaution, and the risk-attitude of the polluting firm. In the following, the role of these factors will be analysed in the comparative static analysis below.

²⁷ As marginal environmental damage is negative and the probability of being held liable is positive, the first term is always negative. So is the second, as the damages and the density function are both positive.

B. Comparative Static Analysis

This section will derive the reaction of the polluting firm to changes in the cost of precaution, in the environmental damages incurred, in the standard of regular operation and in the degree of uncertainty in assessing compliance to regular operation. Some of these factors can be regarded as policy parameters of the environmental policy maker. In order to analyse the effects of such changes, parameters representing exogenous factors are introduced in the cost of precaution function $f(e)$ and the expected environmental damage function $Q(e)$. Let c denote exogenous determinants in the cost of pollution control $f(e;c)$, with $f_{ec} > 0$ and y denote exogenous factors affected expected environmental damages. There are basically two ways by which exogenous factors can affect the damage function. The first type of impact is due to an increase in the background level of pollution. This is captured by a change in the total damage. The second type of impact changes the marginal expected damage that can be prevented by an additional unit of precaution. Likewise, parameter y can be regarded as policy parameter as the environmental policy maker. So far, it was implicitly assumed that the actual harm incurred was compensated. Any change in the legal provisions that define liability payments will have similar effects on precaution as a change in environmental damages. Also, the effect of costly litigation can be represented by a shift in the expected damage functions. If, for instance, the polluter will have to bear the cost of litigation when found responsible the damage function will shift up. Parameter y can also reflect the evaluation of the physical environmental risk involved. Consequently, an increase in risk aversion leads to a clockwise rotation of the damage function (cf. Siebert 1995, pp. 266 ff). As

to the change in environmental damages, it will be assumed that the damage function will rotate clockwise, if the environmental risk potential increases, i.e. $Q_y > 0$ and $Q_{ey} < 0$ ²⁸. This is the case, for instance, if the natural assimilation capacity of the ecosystem declines and thereby the maximal damage expected at very low precaution level rises whereas the maximal precaution level where expected damages are reduced to zero or to very low levels is not changed to the same extent. The safeguards levels, n , defining regular operation are a policy parameter of the environmental legislator. The degree of uncertainty in observing compliance is exogenously given by the variance of the distribution of the observation error $\varepsilon \sim N(0, \sigma^2)$.

Implicit differentiation of the first-order condition yields

$$(5) \quad [f_{ee} + Q_{ee} G(n-e) - 2Q_e g(n-e) + Q(e) g'(n-e)] de + f_{ec} dc + [Q_{ey} G(n-e) - Q_y g(n-e)] dy + [Q_e G_n - Q(e) g_n] dn = 0$$

where G_n and g_n indicate the partial derivatives of the distribution function and the density function with respect to the regular operation standard n , with $G_n > 0$, but $g_n > 0$ if $n < e$ and $g_n < 0$ if $n > e$.

1. The Effect of Changes in Environmental Damages and Costs of Precaution

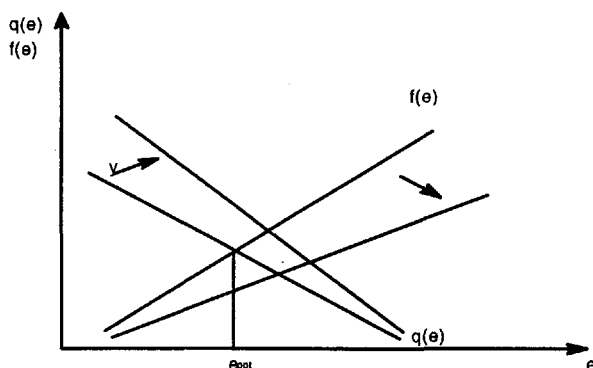
An increase in the marginal cost of precaution will lead to a decline in the level of precaution, since

²⁸ Notice that the expected damage function is negatively sloped. Hence, a steeper curve corresponds to $Q_{ey} < 0$.

$$(7) \quad \frac{de}{dc} = \frac{-f_{ec}}{f_{ee} + Q_{ee}G - 2Q_e g + Qg'} < 0 .$$

The denominator will be greater than zero, if $g'(\cdot)$ does not take large enough negative values to overcompensate the remaining three terms. It was assumed that the marginal Likelihood does not decline too rapidly for values of $n > e$.

FIGURE 3: EFFECTS OF CHANGES IN ENVIRONMENTAL DAMAGES AND COST OF PRECAUTION



The effects of changes in the extent of potential environmental pollution can be easily obtained as

$$(8) \quad \frac{de}{dy} = \frac{-Q_{ey}G + Q_y g(\cdot)}{f_{ee} + Q_{ee}G - 2Q_e g + Qg'} > 0 .$$

The optimal effort level rises as a consequence of a rise in damaging consequences of the polluters activities, for $Q_{ey} < 0$, $Q_y > 0$ ²⁹.

Both reactions deviate from the socially optimal reaction. The socially optimal reaction can be obtained by differentiation of the first-order condition for a social optimum $-Q_e = f_e$.

$$(9) \quad [f_{ee} + Q_{ee}]de + f_{ec} dc + Q_{ey}dy = 0.$$

And hence

$$(10) \quad \frac{de}{dc} = \frac{-f_{ec}}{f_{ee} + Q_{ee}} < 0$$

Likewise for a change in the environmental risk we obtain

$$(11) \quad \frac{de}{dy} = \frac{-Q_{ey}}{f_{ee} + Q_{ee}} > 0$$

Thus, whether the polluting firm will reduce (increase) precaution to a larger or a smaller extent as a consequence of an increase in the costs of precaution (potential environmental damages) under a conditional reversal of the burden of proof is not clear cut³⁰. Therefore, even if by coincidence

²⁹ Otherwise, if the partial derivatives happen to have opposite signs, the reaction of the polluter to a change in the damaging consequences of his economic activities, will be ambiguous.

³⁰ For a given change in the exogenous parameters, in both cases the denominators differ. The terms $Q_{ee}G$ and Qg' decrease the denominator and hence c.p. increase de whereas the term related to the liability effect, $2Q_e g$ reduces de compared to the social optimal reaction. In the case of a change in environmental riskiness, in addition, the numerator will differ in an ambiguous way.

in some initial equilibrium the damage effect exactly offsets the liability effect, thereby generating a social optimal level of precaution, the coincidental optimum will not be sustained.

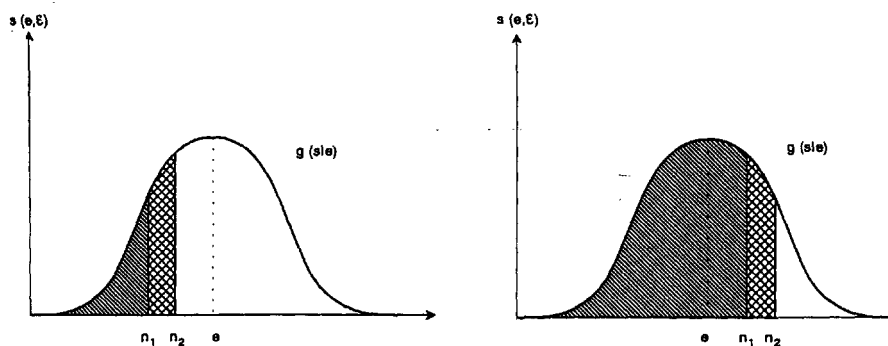
2. Effects of a Change in the Standard of Regular Operation

For a change in the definition of the standard of normal operating conditions, we find

$$(12) \quad \frac{de}{dn} = \frac{-Q_e G_n + Q g_n}{f_{ee} + Q_{ee} G - 2Q_e g + Q g'} > \text{or} < 0.$$

Thus, the reaction of the polluter to a tightening of the standard of regular operation of a plant is ambiguous. The reason for this ambiguity is the presence of two diverging effects. Whereas an increase of the standard of normal operation (for given effort level) will unambiguously increase the probability of being held liable $G(n-e)$, the impact on the marginal Likelihood $g(n-e)$ is ambiguous. Whether the marginal Likelihood of being held liable, $g(\cdot)$, will rise or fall when n rises, depends on whether initially n was smaller or greater than e (cf. Figure 4). Hence, the optimal precaution level may rise or fall if the standard is tightened.

FIGURE 4: IMPACT OF A TIGHTENING OF THE STANDARD OF REGULAR OPERATION



For $g_n > 0$ ($n < e$), the optimal precautionary effort increases when the standard of normal operation is tightened. Because the case $g_n > 0$ arises, when $n < e$, this can be interpreted as overcompliance with the safeguards of normal operation in the initial equilibrium. If however, $g_n < 0$, ($n > e$), then two different case have to be considered. The optimal effort level will increase only if $-Q_e G_n > |Q \pi'|$, otherwise the surprising result might occur that the level of precaution taken by the polluter declines when the standard is tightened. This will be the case of the polluter initially undercomplied with the standard and the change in n has a smaller marginal impact on the damage effect than on the liability effect. Hence,

insufficient precaution by the polluter cannot be corrected by tightening the standard of normal operation. The precaution level will rise unambiguously as a consequence of the stricter standard of regular operation if there is overcompliance initially or if there is undercompliance and a dominant effect of the change in n on the liability effect. This result points to the fact that when considering a divergence of the standard of normal operation from the social optimal level as a policy option, the environmental policy maker has carefully to distinguish the relative size of the different effects of a change in the standard of regular operation on the damage vis-à-vis the liability effect as well as the characteristics of the initial equilibrium.

3. The Effects of a Change in Observability of Precaution

The degree of uncertainty in observing the level of precaution constitutes an important factor in determining the optimal precaution level taken by the polluting firm. As precaution becomes less precisely observable, the density function, $g(\cdot)$, becomes flatter. When the distribution is extremely dispersed, a given change in the level of pollution control will have a relatively small impact on the Likelihood of being found non-compliant and, hence, being subject to the causality presumption. In the extreme case, where a change in precautionary effort has no effect on the probability of being held liable, the liability effect vanishes all together. In this situation only the damage effect remains and the level of precaution will decline unambiguously. On the other hand, the higher $-g(n - e)$ is in absolute terms, the more pronounced is the liability effect. In models of uncertain negligence standards, for low degrees of uncertainty a dominating liability

effect has been established (cf. for example Kolstad, Ulen, Johnson 1990, Shavell 1987, and Craswell, Calfee 1986)³¹.

To analyse the effects of different degrees of uncertainty on the precaution chosen by the polluting firm, a mean-preserving spread g_α is defined for the density function of possible signals, $g(s,e)$ (cf. Kolstad, Ulen, Johnson 1990)

$$(13) \quad g_\alpha(s, e) = \alpha g(\alpha s + (1-\alpha)e)$$

The level of precaution perceived according to this distribution differs from distribution $g(s,e)$. But it has a constant mean value of e , equal to the precaution level chosen initially. For $\alpha > 0$ the new density function is well behaved. For $\alpha = 1$, both distributions are identical, i.e. $g_\alpha = g$. If $\alpha > 1$, the probability mass becomes more concentrated around the mean. Thus, the degree of uncertainty in observing the true level of precaution diminishes. For $0 < \alpha < 1$ the distribution becomes more dispersed. Evaluating the first-order condition $TC' = 0$ at the social optimum, where $f_e = -Q_e$ yields

$$(14) \quad TC'(e^*) = f_e [1 - G_\alpha(e^*-n)] - Q(e^*) g_\alpha(e^*-n)$$

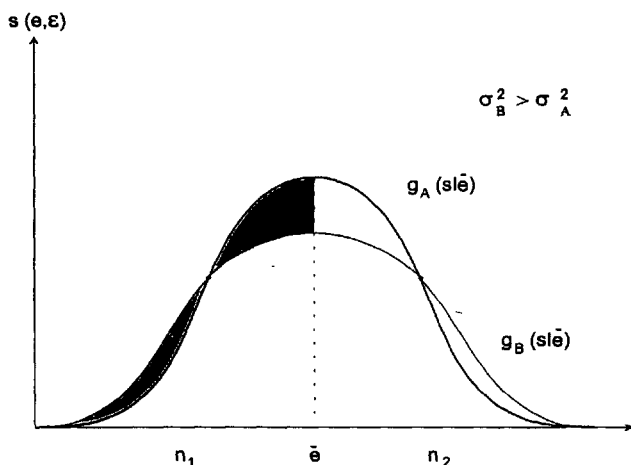
$$= f_e(e^*) [1 - G_\alpha(e^*-n)] - Q(e^*) \alpha g(e^*-n) < \text{or} > 0 .$$

where e^* denotes the socially optimal precaution level. Kolstad, Ulen and Johnson 1990, pp. 894ff, conclude that for an increase in α , (corresponding to a decrease in uncertainty), TC' will become negative and

³¹ Notice that in the case of perfect observability of e , the polluter is fully immunized against liability by choosing the legally prescribed level of regular operation.

hence the optimal precaution level will be higher than the social optimal level for some low degrees of uncertainty. The analysis, however, neglects that a mean preserving spread also affects in the cumulated distribution function $G(\cdot)$. Obviously, a mean-preserving spread will lead to a decrease in the marginal likelihood of being held liable around the mean, i.e. around the effort level that was previously optimal. This reduces the liability effect and *ceteris paribus* the effort. On the other hand, a mean-preserving spread puts more weight on the tails of the distribution (cf. Rothschild, Stiglitz 1979). This implies for the case of the symmetric distributions, that for given levels of n and e the distribution function of the more dispersed distribution has higher values of $G(\cdot)$. As G rises, however, damages are not discounted to the same extent as with a less dispersed density function. *Ceteris paribus*, this will cause the effort level to increase. Therefore, the result obtained by Kolstad, Ulen, and Johnson 1990 only holds for the region very close to the mean. Only there for a symmetric function the probability G is approximately constant, whereas marginal likelihood differ a great deal. Hence, via the liability effect an increase in uncertainty will unambiguously entail lower precaution. By contrast, at the points where both distributions intersect, the marginal probability, g , is unchanged. Then the more dispersed distribution will at the left (the right) of the two intersection points have an higher (lower) probability G , and thereby a weaker (stronger) discounting of expected damages which will increase (decrease) the precaution effort.

FIGURE 5: THE ROLE OF DIFFERING DEGREES OF UNCERTAINTY



Thus, the effect of uncertainty on optimal precaution will be ambiguous even the polluter is risk neutral. The impact will crucially depend on initial values of precautionary effort e and legally prescribed safeguards of regular operation n . For very low levels of n , ceteris paribus $g_a < g_b$ and $G_b > G_a$. Hence, precaution will rise with increased uncertainty. For values moderately lower than the mean, $g_a > g_b$ and $G_b > G_a$, if uncertainty increases. Hence the combined effect is not clear cut. For levels of n moderately higher than the mean, the precaution level will fall unambiguously as $g_b < g_a$ and $G_a > G_b$ if uncertainty increases. For very high values of n the effect is not clear as $g_b > g_a$ and $G_a > G_b$.

C. Incomplete Regular Operation Standards and Multi-dimensional Pollution Control

So far, it has been assumed that the potential polluter's precautionary activities to reduce environmental risks are adequately described by a one-dimensional variable. Although this assumption has been made to keep the analysis straightforward, it neglects a substantial problem. When the polluter faces a whole variety of possible measures to reduce the risk of emitting dangerous substances to the environment, he has not only to determine the total precaution effort but also the optimal combination of different strategies of pollution control. A standard of regular operation will typically not be in the position to cover all potential aspects of preventing current and future environmental damages. The standard of regular operation tends to be incomplete. If only a subset of risk management activities is covered by the standard, this will distort the choice among different pollution control strategies³².

For instance, it is reasonable to suppose that some pollution control activities, like the installation of equipment are easier to monitor than

³² The interpretation of the activity level as a second strategy to reduce accident risk, is a special case of the multi-dimensional model presented in Appendix A1. The allocative inefficiency has been criticized by Shavell 1980 in respect to activity level, by Polinsky 1980 in respect to the number of firms in the industry and the combined output for the case of a negligence rule. The crucial point is that the polluting firms are not assigned the full external costs and hence in a general-equilibrium, the price of the good produced will not reflect its correct scarcity. Essentially, the conditional reversal of the burden of proof contradicts the polluter-pays-principle, as the polluter when being found compliant is not assigned the external costs generated by his economic activities.

others, such as for example, management techniques, supervision and training of employees or the carefulness of the workers in charge. The main effect of an incomplete standard of regular operation is that, if effort types are observable to differing degrees, a reversal of the burden of proof sharpens the incentives to exert those effort types for which regular operation standards are defined. Then a conditional reversal of the burden of proof might have an adverse effect on the incentives to take unobservable pollution control measures, for the reason that unobservable pollution control effort does not influence the probability of being found the cause of the environmental damage incurred. Thus, a conditional reversal of the burden of proof might provide stronger incentives for observed care (depending on which effect dominates the liability or the damage effect). The incentives to take unobservable effort, however, are weakened because there only the damage effect prevails. The overall impact on unobservable precaution will depend also on whether the relationship between different types of pollution control effort is substitutive or complementary³³. Effort types are substitutes (complements) when an increase in the level of one type leads to higher (lower) marginal cost of the other type. Depending on whether the liability or the damage effect dominates in the first instance, this effect might be reinforced or offset by the interdependence. The distortionary effect will prevail to an even larger extent if there is no uncertainty involved in assessing compliance to safeguards of regular operation. With complete no

³³ The interdependencies between different pollution control strategies can relate to either the marginal cost of precaution or to the marginal impact on the expected environmental damage. Both will be influenced by the level of the other pollution control activities chosen.

error in assessing compliance to regular operation, the polluter will carry out precautionary measures which are not included in the standard. Consequently, in the case of multidimensional pollution control, an increase in uncertainty in the verification of compliance may actually improve incentives to take precaution. Thus, when effort-based rules are used in providing incentives for multi-dimensional pollution control activities, considerable distortions may arise³⁴.

D. Assessing the Impact of the Conditional Causality Presumption

The economic analysis of the provisions contained in the German Environmental Liability Act has shown that a conditional reversal of the burden of proof the UmweltHG provides for is not able to ensure the socially optimal level of precaution. Even if the standard of regular operation is set at the Pareto-optimal level of precaution, the causality presumption does not solve the problem of uncertain causation in an optimal way³⁵. If precautionary effort taken is only imperfectly observable,

³⁴ A brief description of the theoretical framework of the multidimensional pollution control model is given in Appendix A1. For a more detailed discussion of the related case of an incomplete standard of negligence see Bartsch 1995.

³⁵ Besides, the conditional reversal of proof involves additional difficulties which have not been explicitly modelled here. Some of these problems are related to criticism of negligence liability (cf. for instance Shavell 1980, 1987 Polinsky 1980 or Endres 1991). If polluting firms are heterogeneous, optimal regular operation standards have to be defined for every single polluter (see also the discussion in Shavell 1984). This would require truthful revelation of firm specific information on costs of precaution to the policy maker. The polluting firm, though, has a massive interest to

the polluter will either take insufficient or excessive precaution. It has been shown, that the induced precaution level taken by the polluting firm depends on whether the fact that the polluter will escape liability will outweigh the impact of an higher level of precaution on the probability of escaping liability.

It can easily be verified that in the framework laid out in this section, socially optimal precaution will be induced by strict liability rule with a general reversal of the burden of proof. This result, however, hinges upon two assumptions: risk neutrality on the part of the polluter and a zero mean random diffusion process³⁶. Both of them are rather restrictive. First, the polluter might be risk averse with respect to the uncertain liability payments. Secondly, in particular when there is more than one polluter the background level of environmental pollution might be strictly positive. Both facts, will be taken into account in the principal-agent model that is presented in the next section.

misrepresent this information (cf. Emons, Sobel 1991). The most substantial criticism to the use of a threshold concept, though, remains that even if under very specific conditions a conditional reversal of the burden of proof were able to ensure the efficient level of precaution in partial equilibrium setting, it will not provide the correct incentives with respect to the activity level, it will not assign the external costs caused to the polluting firm.

³⁶ Note that a fixed background level of pollution that does not affect marginal damages should in socially optimal perspective not change the precaution chosen. However, equation (8) indicates for $Q_y > 0$ and $Q_{ey} = 0$, that de/dy will be positive under the conditional reversal of the burden of proof. Equation (8) also shows that if the marginal damage level is affected by some background pollution, the reaction of the polluter will differ from the socially optimal one.

III. General Model of Environmental Policy under Asymmetric Information

This section will derive the optimal environmental policy in a situation where the pollution control effort chosen by the firm is unobservable. In the following, a general framework of a principal-agent model of environmental policy with hidden action will be outlined³⁷. Moreover, the implications of the principal-agent paradigm for optimal environmental policy will be highlighted. An optimal policy rule is obtained for a situation where due to stochastic processes the ultimate impacts of emissions on environmental quality are uncertain and where the pollution control effort chosen is not observable. The idea is to devise an institutional framework that guarantees socially optimal pollution prevention. Using a principal agent framework allows to explicitly model both aims of liability: provision of incentives to take adequate precaution and optimal allocation of environmental risks. Moreover, the principal agent approach takes into account two characteristics of environmental pollution: the role of stochastic factors and the unobservability of the precautionary measures implemented at the firm level. Moreover, it takes into account two constraints often neglected in environmental economics: incentive compatibility and voluntary participation. Given the information asymmetry regarding the precaution measures taken by the polluter, the main difficulty is that of incentive compatibility (see Siebert 1995, pp. 124ff). Therefore, the cost-minimising behaviour of the polluter is a

³⁷ The application of principal-agent models to accident liability was first pointed out by Shavell 1979.

constraint to the optimisation problem of the environmental policy maker. Taking into account incentive compatibility makes continuous monitoring the individual pollution control effort dispensable. In addition to the best response of the polluter to the incentive scheme, an second condition will constrain the design of an optimal environmental policy rule. This second constraint ensures that the polluter will not relocate or close down when the liability rule is enacted³⁸. Although, the model does not provide an explicit framework of locational competition, this second constraint allows to take into account the international dimension of environmental policy.

Now uncertain causation is considered in the liability rule itself. It will turn out, that the optimal policy rule obtained in a general principal-agent framework is crucially determined by a likelihood ratio. This likelihood ratio is similar to the ex post probability of causation in Shavell's analysis which determines the optimal proportional liability rule (cf. Shavell 1985). The ex post probability of causation is given by the probability that an accident was caused by the polluter (which can be calculated since the level of precaution is known) divided by the total probability of an accident (given by the probability that the injurer causes an accident plus the fixed probability that the accident was caused by the natural factor).

The modified strict liability rule put forward in this study takes up the general feature of optimal incentive schemes in a principal-agent model with hidden actions, that optimal outcome based remuneration are

³⁸ It will be assumed implicitly, that a benevolent environmental policy maker does not find it worthwhile to implement an environmental policy that will entail relocation or shutting down of the firm.

determined by the probability that the effort level desired by the principal was taken, given the observed outcome, relative to the probability that a less desired effort level was taken. Although, the discussion will be in terms of environmental liability, the institutional mechanism of assigning uncertain external costs to the polluter that will be derived below applies to a more general setting which attempts to provide precaution incentives and allocate risk in an optimal way. The incentive scheme can equally, for instance, represent an a system of ambient immission taxes.

A. The Basic Framework

In setting liability rules, the environmental policy maker acts as the principal. The potential polluter, being the agent, is able to affect potential environmental degradation by taking precaution. Neither the policy maker nor the court or the injured parties can observe actions taken by the polluting firm with respect to pollution prevention. In order to focus the analysis on incentive problem on the polluter's part, free-rider problems among injured parties that would prevent them from bringing cases to trial when harm is suffered by a large number of individuals are neglected by restricting the analysis to the case of a bilateral externality. Courts are assumed to enforce the liability rules perfectly³⁹. Similarly, costs of

³⁹ In the model presented here, there is no difference between the policy maker, the court and the injured party in terms of objectives or ability to observe various variables. The environmental policy maker is not assumed to have superior information. In fact, in many cases it is more realistic that private individuals have superior information. For example, the injured party might know better than a central government authority whether the

litigation are neglected⁴⁰. Hence, legal claims will be always asserted. Out-of-court settlements which might precede the trial itself are disregarded⁴¹. Likewise, managerial incentive problems within the polluting firm are neglected (for a discussion the problems involved see Newman, Wright 1990, 1992, Gabel, Sinclair-Desgagné 1993).

For simplicity, it is assumed that potential victims of environmental pollution always take the socially optimal level of precaution. Although some authors consider explicitly the level of precaution taken by the potentially injured party (cf. for example Endres 1989, Shavell 1987), in the case of environmental problems, risk reduction by the pollutees seems to be of minor importance and is, therefore, ignored. For the sake of simplicity, information problems other than the unobservability of the precaution taken are neglected. The potential polluter is assumed to face a known distribution uncertain liability payments⁴². It will be assumed that

injurer has taken sufficient precaution. Then, the additional issue arises as to whether this superior information is verifiable in litigation.

⁴⁰ Models with costly litigation are discussed by P'ng 1987, Polinsky, Rubinfeld 1988, and Hylton 1990.

⁴¹ Note that in particular in presence of uncertain outcomes of the trial which might be due to uncertain interpretation of the evidence by the court, disputants might prefer an out of court settlement in order to avoid the costs involved of the trial. For a discussion of settlement behaviour see Landes 1971, Posner 1973, and Shavell 1982. Game-theoretic models of pretrial bargaining have been developed by P'ng 1983, Ordover, Rubinstein 1986, Bebschuk 1984. In addition to potential savings of legal cost, settlement transforms uncertain outcome of the trial into a deterministic distribution of the efficiency gain arising from internalisation of external costs.

⁴² Emons, Sobel 1991, 1990 have investigated the problem of unknown cost of precaution when agents are non-identical.

the environmental policy maker knows cost of pollution control of the polluter. Despite the fact that environmental economists have long recognised the lack of information about the cost of pollution control (Kneese 1964, Baumol, Oates 1975), models of asymmetric information are generally adopted by environmental economists only to a very limited extent. The extraction of private information from self-interested individuals is closely related to the revelation approach in mechanism design (cf. Emons 1993). The problem then is to design a scheme which induces polluting firms to reveal the true cost of pollution abatement (cf. Kwerel 1977). Dasgupta, Hammond, Maskin 1980 look at the problem of truthful revelation of private information on abatement cost in a Groves-Clarke-Vickrey setting. Conrad 1991 looks at a situation where the regulator can obtain information on abatement cost in an iterative process of setting an emission tax. Baron 1985, Spulber 1988, and Laffont 1994 derive optimal regulation for a pollution generating monopolist Ellis 1992 applies the notion of linear implementation by Laffont, Tirole, 1986 to optimal regulation of environmental pollution. The analysis also assumes that the true harm suffered by the injured party can be asserted⁴³.

The stylised timing of the interaction between the environmental policy maker, the polluter and the court can be thought of as follows. In the first step, the environmental policy maker determines the liability rule. Given the liability rule, the polluter chooses the precaution measures which are optimal from his point of view. Precautionary efforts affect both the probability of an environmental accident and the magnitude of

⁴³ Mistakes in determining the effects of damages are analysed by Kaplow,

environmental degradation. Nature moves next⁴⁴, drawing a state of the world from a known probability distribution which is unobservable for the policy maker and the court likewise⁴⁵. This random variable, $\theta \in \Theta$, describes the stochastic factors that might affect the actual level of environmental degradation for a given level of precautionary efforts, with θ being distributed according to a density function $h(\theta)$ ⁴⁶. Precautionary efforts in pollution control and the random influence determine the actual environmental damage $q(e; \theta)$. Depending on this publicly observed environmental damage level, compensatory payments are awarded according to liability rules set initially. The time structure is depicted in Figure 6.

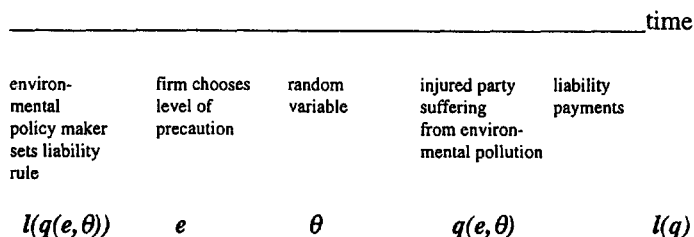
Shavell 1993, Ben-Shahar, Randow 1993, Emons 1990, Polinsky 1987.

⁴⁴ If the polluter could acquire information in the random influence before choosing a precaution level, he would be in the position to condition the precautionary effort on this observation. In this setting the policy maker has to provide appropriate incentives in order to induce truthful revelation of the private information. (for an overview see Mas-Colell, Whinston, Green 1995, 488ff).

⁴⁵ In order to have a meaningful information asymmetry in the model, it is necessary that this stochastic influence cannot be observed. For the nonobservability of the precautionary choice to have substantial consequences, it must not be possible to deduce the precaution chosen from the level of environmental damages incurred. Hence, it is assumed that the level of precaution taken affects environmental damages, but it does not fully determine them. Otherwise, the missing information on precaution could be inferred from observing the stochastic factor and the damage.

⁴⁶ As it is conventional in this type of model, it is assumed that both the environmental policy maker and the polluting firm form homogenous expectations regarding this probability distribution $h(\theta)$.

FIGURE 6: STYLISTED TIMING OF THE MODEL



In the case of multiple emission sources contributing to the same ambient concentration of pollutants, the distribution of environmental damages will also depend on preventive pollution control action taken by other emitters. The presence of other emitters would not change the results qualitatively, provided that each polluter takes the emission level of all other emitters as exogenously given. Here, it is assumed that individual polluters do not choose their precaution level strategically vis-à-vis each other. Thus, the analysis abstracts from strategic interdependence of precaution levels in the generation of environmental damages (even not in the simplest form of a Nash-conjecture). As long as one abstracts from possible strategic interaction among emission sources, the team production problem does not arise (cf. Segerson 1988).

The environmental policy maker minimises the expected net welfare loss due to uncompensated environmental damages. This net welfare loss depends on the environmental damage, q , and liability payments, l , it can extract from polluters as compensation for the harm suffered by the injured

party⁴⁷. The actual welfare loss to the environmental policy maker for a certain realisation of θ is a given by

$$(15) \quad v = v(q(e;\theta) - l(q)) = q(e;\theta) - l(q)$$

where $q(e;\theta)$ indicates the actual environmental damage and $l(\cdot)$ are liability payments the victim will be awarded by the court. If not stated otherwise, the policy maker is assumed to be risk neutral (i.e. $V' < 0$, $V'' = 0$)⁴⁸, and his expected welfare loss is

$$(16) \quad V(q,l) = E v(q,l) = Q(e) - l(Q).$$

Hence, the net welfare loss due to potential environmental pollution is the difference between environmental damages and the monetary

⁴⁷ The compensation awarded by the court can either be redistributed to them or spent according to the victim's preferences.

⁴⁸ Risk-neutrality on the part of the environmental policy maker constitutes a stronger than necessary assumption. All that is required in order to generate the same qualitative results is that the environmental authority is less risk averse than the polluting firm. This will be the case if the potential damage and hence the liability payments are relatively large compared to the net assets of the polluting firm. The victims suffering from the damage to environment may according to the Arrow-Lind-Theorem be in a better position to diversify risk (Arrow, Lind 1970, Fisher 1973). Likewise, it might be easier to obtain first party insurance in case of environmental damages, since in first party insurance typically no moral hazard problem arises. Note, however, that with a risk averse principal additional problems arise in justifying the technical framework that will be used later. In the context of the technical problems involved, the assumption of risk neutrality is not completely trivial. The role of risk aversion on the part of the policy maker is also discussed in Appendix A3.

compensation received from polluters⁴⁹. Liability payments are a function of the environmental damage incurred⁵⁰.

This objective function differs from the one that is usually assumed in a partial equilibrium analysis, where the policy maker is assumed to minimise total environmental costs which consist of the environmental damages and the cost of controlling emissions. In a principal-agent setting, by contrast, the policy maker minimises the net loss to victims which equals the part of environmental damages that is not compensated for by the polluter. This does not mean, however, that costs of precaution are neglected in the optimisation problem. The costs of pollution control are taken into account in the optimisation problem by means of the constraints. These constraints, as will be discussed in detail below, differ from those of a standard partial equilibrium problem in environmental economics. Both approaches will, in the absence of information asymmetry, lead to the same the necessary conditions for an optimal environmental policy.

Thus, the polluting firm bears total costs that are a function of the cost of preventive pollution control, $f(e)$, and the expected disutility due to uncertain liability payments for environmental damages, $u(l(q(e, \theta)))$.

⁴⁹ As it will be explained in detail below, in the framework used here the environmental policy maker will take into account the costs of pollution control because of the constraints he faces when determining the optimal environmental policy rule.

⁵⁰ There might, however, exist considerable problems in observing the damage incurred. Therefore, some authors have suggested that the incentive scheme to depend on observed pollutant concentration ambient in environmental media (see Siebert 1995, 124 or Xepapadeas 1991). This may be a practical approach for instruments such as ambient taxes.

$$(17) \quad C = E c(l(q), e) = f(e) + E u(l(q(e, \theta)))$$

with $u' > 0$ $u'' < 0$. The cost imposed on the firm by uncertain liability for environmental damages is denoted by $u(l(d))$. Since the firm is assumed to be risk averse, due to Jensen's inequality these costs will be greater than expected liability payments⁵¹. The disutility attached to liability payments is a convex function. The reason for this being that environmental damages and hence liability payments often involve figures that are significant compared to the net assets of the polluting firm. It is assumed, that there does not exist a perfect insurance market for environmental liability claims. Insuring environmental liability faces the same kind of information asymmetry as discussed here. The insurance company will also not be able to observe the precaution level. In this case the insurance premium will typically be higher than the expected loss. Carrying out pollution control activities involves some cost to the polluting firm. With respect to the disutility of effort function of the polluter, $f(e)$, it is assumed that the costs of precaution increase if effort increases. The cost function is again assumed to be strictly convex (i.e. marginal cost increase with increasing effort level), that is $f_e > 0$, $f_{ee} > 0$. Both, the environmental policy maker

⁵¹ One simple way of stating Jensen's Inequality is, that for a convex function the expectation of the function is greater than the function of expectations (cf. Varian 1992, 182). Notice that the familiar concave utility function of income for a risk averse individual for negative values of income in the third quadrant, i.e. costs, corresponds to a convex cost or disutility function in the first quadrant.

and the polluting firm, minimise their expected utility loss according to the Bernoulli-Principle⁵².

Higher precaution levels lead to a stochastically lower environmental damage. Recall that the environmental damage, $Q(\cdot)$, is a strictly convex, downward sloping function of e , so the marginal effect on environmental damage diminishes if the level of effort is increased. Hence, $Q_e < 0$ and $Q_{ee} > 0$.

B. The Optimisation Problem of the Environmental Policy Maker

Following the so-called first-order approach, it will be assumed that the set of feasible precaution and damages levels are an interval of $\mathcal{R}$, such $e \in E \subset \mathcal{R}$ and $q \in \Omega \subset \mathcal{R}$.⁵³ The damage function $q(e; \theta)$ is rather complicated to handle technically. Therefore, frequently an approach is chosen which defines where environmental damages as a random variable. Random environmental damages are described by a density function parametrised by the precaution level taken by the polluter. This parametrised

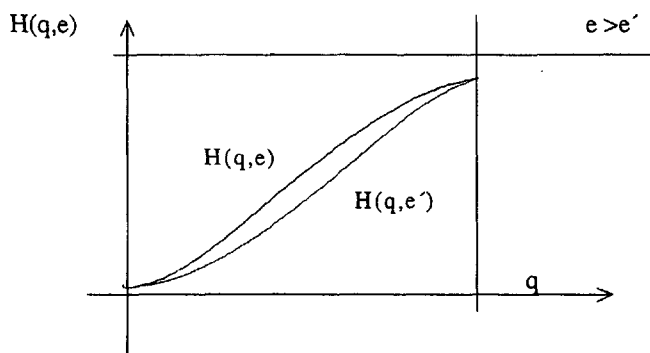
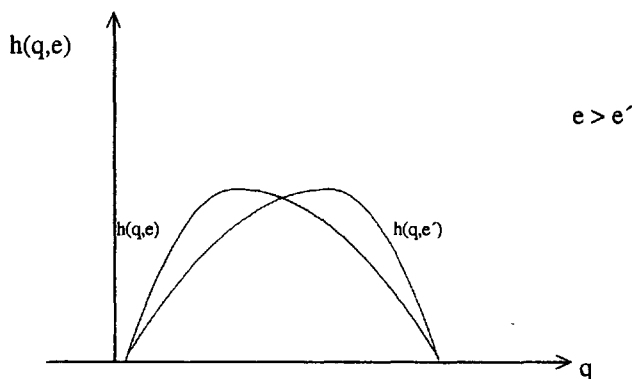
⁵² For a critique of expected utility theory cf. Machina 1987. Implications for environmental economics are discussed in the volume collected by Bromley, Segerson 1992.

⁵³ See Holmström 1979 or Shavell 1979 for the general exposition of the first-order approach in terms of employment contracts, and Grossman, Hart 1983, Rogerson 1985 and Jewitt 1988 for its limitations. The technical difficulties, first pointed out by Mirrless 1974, that arise when there are infinitely many outcomes will be disregarded here.

distribution can easily be derived, knowing the damage function $q(e;\theta)$ and density function of the random factor, $h(\theta)$. Let $H(q|e)$ denote the corresponding distribution function. As the marginal environmental damage decreases when precaution is increased ($q_e < 0$), it follows that $H_e(q|e) > 0$. A higher level of precaution will increase the probability that only damages up to a given size occur. This means, that a higher level of precautionary effort will shift the distribution function to the left in sense that the former distribution first-order stochastically dominates the new one⁵⁴. The support of the distribution function, has to remain unchanged by variations in the precaution level. Otherwise, the information asymmetry vanishes in the sense that for some damage level the precaution level the polluter has taken can be inferred. The effect of precaution on the respective functions is depicted in Figure 7.

⁵⁴ A distribution F_1 dominates a distribution F_2 iff $F_1(x) \leq F_2(x)$ for all x , with a strict inequality for some x .

FIGURE 7: IMPACT OF PRECAUTIONARY EFFORT ON THE DISTRIBUTION OF ENVIRONMENTAL DAMAGES



The environmental policy maker's optimisation problem can be stated as follows. The policy maker minimises total expected welfare loss of environmental risk by choosing a liability rule $l(q)$ and (implicitly by anticipating the polluter's best response) an effort level, e . For notional simplicity the lower and upper limits of integration are suppressed.

$$\begin{aligned}
 (18) \quad \min V = Ev &= \int_{\theta} (q(e, \theta) - l(q(e, \theta))h(\theta))d\theta \\
 &= \int_Q q - l(q)h(q|e)dq
 \end{aligned}$$

In presence of information asymmetry the subsequent cost minimising behaviour of the polluter has to be taken into account by the environmental policy maker. Consequently, the first constraint to the minimisation problem of the policy maker is the incentive compatibility of the policy rule. To put it differently, the incentive compatibility constraint, which ensures that the polluting firm finds it in his own interest to take the precaution level desired by environmental policy maker.

$$\begin{aligned}
 e \in \arg \min \{E(u(l(q))) + f(e)\} = \\
 (19) \quad (IC) \quad &\int_{\theta} u(l(q(e, \theta)))h(\theta)d\theta + f(e) = \\
 &\int_Q u(l(q))h(q|e)dq + f(e)
 \end{aligned}$$

The second crucial feature of the principal-agent framework is that participation in the incentive scheme is voluntary. In terms of environmental policy, voluntary participation reflects the fact that the government's coercive power in implementing environmental policies is limited because polluting firms can choose to relocate or to cease operation. Therefore, in addition to incentive compatibility, the environmental policy maker has to take into account that in an increasingly integrated world economy with international factor mobility, the

introduction of a liability act might cause the polluter to relocate⁵⁵. The polluting firm usually has some opportunity outside the jurisdiction where an environmental policy is introduced.

Hence, the second constraint on the set of feasible policy rules is so-called participation constraint (cf. Arrow 1986). The participation constraint stresses the fact that tightening of environmental standards can lead to relocation of environmentally dirty industries to jurisdictions with less strict environmental standards with regard to allowable emissions or safety regulations (for a more detailed discussion of international aspects of environmental policy, see Rauscher 1995, 1992, 1991, Siebert 1991, Siebert et al. 1980).

$$(20) \quad (PC) \quad \int_Q u(l(q)) h(q|e) dq + f(e) \leq m$$

The participation constraint ensures that, if the polluter chooses the optimal precaution level, expected costs including disutility from bearing uncertain liability payments, do not exceed some exogenous reservation

⁵⁵ Without loss of generality, the bargaining over the liability law can be understood as game with symmetric information where the policy maker is in the position to commit to a take-it-or-leave-it offer. In equilibrium, the polluting firm will accept the liability rule and will choose the optimal precaution level, given the rule. This, however, does not imply that the policy maker has all of the bargaining power. The relative bargaining strength can be indicated by the reservation utility level of the polluting firm.

cost level⁵⁶. This reservation cost level is determined by the best alternative opportunity⁵⁷, the polluter would have to face outside the jurisdiction currently enacting the liability rule. Obviously in a world of perfectly mobile factors of production, if the costs imposed on the polluter by environmental policy at the given location are higher than those that arise elsewhere, the polluting firm will choose to relocate. Locational choice is determined by international differences in environmental policy and the cost of relocation. The possibility to enforce the polluter-pays-principle, therefore, also depends upon the outside option of the polluting firm. Note that if the optimal incentive compatible environmental policy at the present location cannot entail lower expected disutility than m , it is optimal that the polluter relocates. The extent to which environmental policy can assign external costs to polluters in a situation of locational competition is determined by the cost of changing location and the environmental policy abroad. Changes in the relative location advantage of

⁵⁶ If instead a two country model is considered, the reservation utility level may not be an exogenous parameter, but an endogenous variable depending on the environmental policy pursued by the home country. There is a rapidly growing literature on strategic environmental policy (cf. Ulph, and Ulph 1994, Barrett 1994 and Conrad 1993 among others). In the context of principal-agent theory, so called common agency models have been developed, which look at a situation where multiple principals aim at influencing the actions taken by a single common agent (cf. Bernheim, Whinston 1986, and Stole 1991). Attraction of firms in locational competition might be such an action.

⁵⁷ The parameter m can also be interpreted as the primary distribution of property rights. The victims-pays-principle would correspond to $m=0$, whereas the polluter-pays-principle corresponds to the full external costs including abatement in another industry of the economy or in the same industry in another country.

a country under mobility of firms across national boundaries correspond to changes in comparative advantage of internationally immobile firms, which are mobile between different sectors of the economy. Therefore, the reservation cost level, m , can also be interpreted as the environmental protection costs the firm would have to face in another sector of the same economy. In evaluating different locations, many factors play a role. Moreover, locational decisions are heavily driven by expectations of future developments of environmental policy at home and abroad, and potential technical progress in pollution control technologies. In accordance with the empirical evidence, it is assumed here that costs induced by environmental regulation are of minor importance compared to other location factors (cf. e.g. Tobey 1990, Hettige, Lucas, Wheeler, 1992, Klepper 1994). Equally, one could suppose that the cost of industrial delocation are substantial such that the polluter-pays-principle can be enforced. It will be assumed that the special case, where the policy maker actually finds it advantageous that the polluter relocates productive activities abroad does not arise⁵⁸.

⁵⁸ A participation constraint on the part of the environmental policy maker would capture a similar overall optimality constraint of the policy maker according to which the net welfare loss due to uncompensated harm from pollution should exceed the net benefit of consumption of the good generating emissions in its production. The reservation utility of the principal is usually disregarded as he offers the incentive scheme which he will only do to his own advantage.

C. Optimal Allocation of Environmental Risk in Absence of Incentive Problems

By assuming for a moment that the precautionary effort by the polluter does not influence the distribution of uncertain environmental damages, the following analysis allows to focus on optimal sharing of environmental risk between the polluter and the victim. If only the operation of the environmentally risky plant but not precaution taken affects the distribution of uncertain environmental damages, the polluter should not take precaution. Therefore the costs of precaution, $f(e)$, can be neglected in the following discussion of optimal risk-sharing.

The liability rule is assumed to consist of two branches: $l(q, k) = l(q) + k$. The fixed amount, k , can be thought of as an ex ante compensation for increased risk exposure. The fixed payment can be used to finance a fund which is responsible for compensation of victims which were not able to be compensated by liability payments. Only the variable amount $l(q)$ depends on the actual environmental damage incurred. This variable part represents ex post liability for environmental damages. Conditions for optimal risk sharing can be derived by minimising the net welfare loss due to uncompensated environmental damages $Ev(q - l(q))$ subject to the participation constraint $Eu(l(q)) \leq m$ ⁵⁹. This yields the following first-order condition for the optimal liability rule,

⁵⁹ As $l(q)$ is contingent on the realisation of the random variable θ , the first-order condition depends on actual rather than expected marginal utilities. See Raiffa 1968 for a more detailed discussion.

$$(21) \quad v'(q-l(q)) = \mu u'(l(q))$$

where μ is the Lagrangian-multiplier on the participation constraint, with $\mu \geq 0$. The sign of the Lagrangian multiplier follows from the second-order condition for a minimum $v''(q-l(q)) + \mu u''(l(q)) > 0$ and the signs of the second derivatives of the utility functions $v'', u'' \geq 0$. Differentiating the first-order condition for the optimal ex post liability rule with respect to the damage incurred gives

$$(22) \quad l_q = \frac{v''}{v'' + \mu u''}$$

with l_q denoting the partial derivative of the optimal liability rule with respect to q . Equation (22) highlights the importance of the curvature of the respective disutility functions for the optimal allocation of risks. As regards the second derivatives of the disutility functions, there are four different cases to be distinguished. These are summarised in the following Table.

TABLE 1: PARETO-OPTIMAL ALLOCATION OF ENVIRONMENTAL RISKS

Polluter		
Policy maker	risk neutral ($u''=0$)	risk averse ($u'' > 0$)
risk neutral ($v''=0$)	indeterminate	$l_q = 0, l(\cdot) = k$
risk averse ($v'' > 0$)	$l_q = 1, l(\cdot) = q + k$	$0 < l_q < 1,$ $l(\cdot) \neq q + k, l(q) \neq k$

If $l_q = 0$, the polluter will not be held liable at all for the damages incurred. He will only have to pay a fixed amount ex ante. If $l_q = 1$, by contrast, the polluter is strictly held liable of the full damage actually incurred. When both, polluter and policy maker are risk averse, the environmental risk will be truly shared between them. The optimal allocation of environmental risk depends on the relative magnitudes of the second derivatives v'' and u'' . Consequently, the polluter will only be held liable for some portion of realised damages. If the policy maker is risk neutral, a risk averse polluter will be fully insured against the risk of environmental degradation. Thus, the polluter is fully insured against all stochastic influence that might affect the extent of environmental degradation. In this case the polluter will only have to pay a fixed amount k . On the other hand, if the polluter is risk neutral, he will be fully liable ex post of any occurring damage, and the optimal liability rule will be $l(q,k)=q+k$. The fixed amount k which the

polluter has to pay is determined by the participation constraint⁶⁰. In the case where both are risk neutral, the optimal apportioning of risk is not uniquely determined. Thus for the case presented in the previous section, that is a risk neutral environmental policy maker and a risk averse polluter, the polluter should not be held liable at all ex post. This, however, does not imply that the polluter can use the environment as a receptacle of wastes free of charge.

D. Optimal Environmental Policy when Precaution is Observable

Before deriving the characteristics of the optimal environmental policy under asymmetric information in the next section, this section will establish the optimal policy in absence of informational constraints as a reference situation. If the precautionary effort chosen by the polluter is perfectly and costlessly observable, the environmental policy maker can enforce the Pareto-optimal level of precaution by imposing a sufficiently heavy severe sanctions in the case that the polluter does not comply with the legal standard. Basing the incentive scheme on the effort level allows to obtain optimal risk sharing.

When the precaution level is observable the optimal policy is determined by minimising the expected net welfare loss due to pollution subject to the participation constraint of the polluter, i.e.

$$(23) \quad \min \quad \text{Ev}[q(e) - l(q(e), \theta)]$$

⁶⁰ Note that the fixed amount will vary with the ex post liability.

$$\text{s.t. } Eu[l(q(.))] + f(e) \leq m$$

Since precaution can be observed, incentive compatibility is not a constraint on optimisation problem of the environmental policy maker. Again, the first-order condition for the optimal liability rule can be obtained by differentiating the Lagrangian with respect to liability payments, l ,

$$(24) \quad -v'(q-l(q)) + \mu u'(l(q)) = 0.$$

with $u'' > 0$, $\mu \geq 0$ denoting again the Lagrangian-multiplier on the participation constraint. Since the policy maker is assumed to be risk neutral ($v' = \text{constant}$), liability payments do not vary with realised damages ($l_q = 0$). Thus, if precautionary efforts are observable is is optimal not to impose any ex post liability for occurring damages. However, this does not imply that the polluter can use the environment as a receptacle of waste free of charge. The result just established only states that if precaution is observable, there should not be any ex post liability for occurring damages if the polluter is risk averse. This result corresponds to the full insurance of a risk averse polluter by a risk neutral policy maker derived in the previous section: If the environmental policy dictates the polluter's choice of precautionary effort and there no problem as to providing incentives, the risk neutral policy maker should bear the environmental risk. It is optimal to levy a fixed ex ante payment on the polluter. The optimal ex ante compensation for environmental risk is determined by the fact that, if the polluter chooses the level of precaution that the policy maker wants him to choose, the participation constraint has to be satisfied with equality i.e. $k = m - f(e)$. Hence, given that the

environmental policy can be specified in terms of the precaution level, e , the polluter will be required to pay a fixed amount k , such that he will have to carry exactly his reservation cost level.

Considering the level of precautionary effort the policy maker wants the polluting firm to take, under optimal risk-sharing, the effort level can be obtained by substituting the constant liability payment, k , into the Lagrangian and differentiating with respect to effort level, e . This yields the following first-order condition for the optimal precaution level

$$(25) \quad Q_e + \mu f_e = 0 \quad .$$

Hence, the policy maker will set the legal standard such that the marginal expected damage prevented equals the marginal cost of precaution (weighted by the shadow cost of inducing the polluter to participate). This precaution level is the unconstrained Pareto-optimal (or first-best) effort level e^* which can be implemented with perfect information regarding the precaution level. The first-best level of precaution is determined by the equality of marginal expected environmental damage prevented and the marginal cost of precaution.

Due to risk aversion of the polluter, an effort based scheme is preferable to an outcome based incentive scheme being subject to random influences. In terms of environmental liability, one effort-based incentive scheme is a negligence rule⁶¹. The traditional analysis of environmental liability shows

⁶¹With the difference that here, however the polluter has to pay a fixed amount, whereas under a negligence rule he only has to cover his costs of precaution.

(cf. Endres 1991), that it is usually sufficient to impose the full damage costs in the case where the polluter has not taken due care e^* ⁶². Under a negligence rule the polluter bears the cost of precaution and is fully insured against environmental risk, provided that he has taken due care. The risk of random environmental damages is borne by the risk neutral policy maker (victims). If it turns out that the polluting firm has not chosen appropriate precaution, it will be sanctioned sufficiently to ensure compliance.

$$k \text{ if } e=e^*$$

$$(26) \quad l(e) =$$

$$l(q, k) = q + k \text{ if } e < e^*$$

Achieving a first best solution, however, will not be possible, since typically the precautionary measures taken are at least to some degree private information to the polluter.

E. The Optimal Policy Rule with Unobservable Precaution

The first-best environmental policy described in the previous section accomplishes two objectives. It specifies optimal precaution to be taken by the polluting firm, and it provides full insurance against random environmental degradation. When the precautionary choice it not

⁶² This result is highly sensitive towards the fact that very deviation from due care will be detected. If this is not the case the sanctions imposed when found negligent have to be adjusted upwards (see Polinsky, Shavell 1979, Cohen 1987).

observable, though, these two objectives will often be in conflict. The reason for this trade-off between risk sharing and providing precautionary incentives is that the only way to induce the polluter to take precaution is to hold him liable for the environmental damages incurred. These environmental damages, however, are random.

The first-order approach replaces incentive compatibility constraint (IC) by the first-order condition that the polluter's total expected cost function is stationary with respect to e ⁶³. Under the assumption that we can differentiate through the integral, the first-order condition for a cost-minimum of the polluting firm can be written as

$$(27) \quad (FC) \quad \int_Q u(l(q)) h_e(q|e) dq + f_e = 0$$

where h_e denotes the partial derivative of the density function with respect to e .

Pointwise minimisation of the welfare loss to the policy maker (i.e. minimisation for every q) with respect to the optimal liability payments subject to constraints (FC) and (PC), gives the following necessary conditions for every $q \in Q$,

$$(28) \quad -h(q|e) + \mu u'(l(q))h(q|e) + \lambda u'(l(q))h_e(q|e) = 0$$

Derivation of the Lagrangian with respect to the effort level yields

⁶³ The conditions under which this procedure is legitimate are discussed in the Appendix.

$$(29) \quad \int_0 (q - l(q))h_e(q|e)dq + \lambda \left(\int_0 u(l(q))h_{ee}(q|e)dq + f_{ee}(e) \right) = 0$$

Again μ is the Lagrangian-multiplier on the participation constraint and the λ the multiplier on the first-order constraint (FC).

These two conditions together with the first-order condition (FC) and the binding participation constraint (PC')

$$(20') \quad (PC') \quad \int_0 u(l(q))h(q|e)dq + f(e) - m = 0$$

determine the solution to the optimisation problem of the environmental policy maker. As to the binding participation constraint (PC'), it is well known from principal-agent theory that under the optimal contract the expected utility of the agent has to equal the reservation utility (cf. Hermalin 1993). If a given effort level is implementable⁶⁴, the optimal incentive contract will just satisfy the participation constraint. If the incentive scheme does not satisfies the participation constraint, another

⁶⁴Note that, it is assumed that all precaution levels are implementable, which is not necessarily the case. A level of precaution is only implementable, if there exists no pollution control strategy for the polluter that induces the same density over observable damages and which is less costly in terms of cost of pollution control. The intuition of this is the following: If there were such a strategy - one that produced the same expected liability payments as the one the environmental policy maker wants to implement, but which cost the polluter less than the one the environmental policy maker wants to implement, then it is clearly impossible to implement that strategy. Therefore, the density over outcome induced by different effort levels in pollution control have to be distinct from each other (see Grossman, Hart 1983 for a discussion of the existence of an solution).

incentive scheme would exist that ensures incentive compatibility, but involves higher liability payments for every observed level of damage that occurs. This implies a lower uncompensated damage and hence a higher level utility for the environmental policy maker. Therefore, the original liability rule has not been optimal. This implies that the cost assigned to the polluting firm, are equal to those the firm would have to face on other countries. Thus, the binding participation constraint corresponds loosely speaking to an equilibrium condition in locational arbitrage.

Thus, we have a system of four equations (28),(29), (FC) and (PC') and four unknowns: l, e, λ , and μ . The optimal liability rule is determined by (28), the corresponding precaution level by (FC). The Lagrangian multipliers are given by the adjoint equation (29) and (PC'), respectively.

Notice that, the solution specifies the optimal liability rule as a function solely of the damage incurred. Thus, the type of liability rule considered here is a strict, i.e. non-fault based, liability. Although, in general, the specific form of this rule will depend on many factors, some conclusions can be drawn. In general, the results obtained in hidden action models of worker compensation are confirmed for this reformulated model of environmental policy. Rearranging terms in the equation determining the optimal liability rule yields the following condition for the optimal liability rule

$$(28') \quad \frac{v'(q - l(q))}{u'(l(q))} = \frac{1}{u'(l(q))} = \mu + \lambda \frac{h_e(q|e)}{h(q|e)}$$

In order to draw some conclusions of how the LHS of equation (1') and therefore liability payments, $l(q)$, will vary with the RHS (and in particular

with the likelihood ratio), the signs of the Lagrangian-multipliers have to be determined. From the optimal risk sharing result, it is clear that μ , the policy maker's shadow price on the participation constraint, which indicates the increase in the policy maker's welfare loss from a marginal decrease in the reservation cost level, is positive.

Holmström 1979, p. 90, shows for the problem managerial compensation that $\lambda > 0$. This, however, does not follow immediately, for the case environmental policy discussed here. In contrast, it can be shown that under certain conditions λ will be negative⁶⁵. The signs of the Lagrangian multipliers can be used to derive some insight into the optimal environmental policy rule. A binding incentive compatibility constraint implies that liability payments cannot be fixed. Hence, a binding incentive compatibility constraint requires a deviation from optimal risk-sharing.

For $\lambda < 0$, equation (1') indicates that, the LHS of equation (1') has to increase above μ when $h_e < 0$ and vice versa. The LHS increases in turn, if u' decreases, which it does if liability payments decrease. The precise way

⁶⁵ Applying Lemma 1 of Jewitt 1988 shows that, if u is an increasing convex function and $f_e > 0$, then any λ satisfying (FC) and (1) is negative. The reason for this is, that substituting (1) into (FC) gives

$$\int (u(l(q))(\frac{1}{u'(l(q))} - \mu)h(q|e)dq = \lambda f_e$$

Using the fact that the expectation of $h_e(q|e)/h(q|e) = 0$ gives

$$\int \frac{1}{u'(l(q))} h(q|e)dq = \lambda$$

The LHS of the first equation is simply the covariance of u and $1/u'$ which is equal to λf_e . Since u and u' are monotone in opposite directions, they have a non-positive covariance, and since f_e is positive by assumption, it follows that $\lambda \leq 0$.

in which optimal liability payments will relate to the realised damage level, crucially depends on the likelihood ratio. It will depend on whether, given the distribution function, if a certain damage level is observed it is relatively more likely that the polluter has taken appropriate precaution than that he has not taken appropriate precaution. Thus, liability payments decrease in states where the damage level incurred whose probability is decreased if precaution is increased ($h_c < 0$). On the other hand, when a decrease in precaution raises the probability of a damage level to occur, liability payments have to increase. The environmental policy rule will require the polluter to cover less environmental damages for levels of damages incurred that are statistically more likely to occur when a sufficient level of precaution was chosen. Similarly, liability payments will be higher for damage levels that are relatively more likely to occur when insufficient precaution was taken. Although, an intuitive interpretation of the results derived involves statistical inference, the policy maker (and the court), knows exactly which precaution level was chosen given the liability rule from (FC). The peculiar form of the environmental policy rules is due to incentive compatibility. By structuring liability payments in this way, the environmental policy maker ensures that the polluter will take an appropriate level of precaution. Moreover, the relationship depends on the nature of the utility function. For simplicity, it has been assumed that $v' = 1$. If this assumption is relaxed, the results become even more blurred.

In general, there is a deviation of the liability payments from Pareto-optimal risk sharing which would imply a constant liability payment. This deviation is due to the trade-off between providing incentives to take precaution and sharing the risk involved optimally. In general, it will be

optimal to hold the polluter strictly liable for part of the occurring damages. A partial strict liability rule trades-off optimal risk allocation and incentives to take precaution. The optimal structure of liability payments will depend on the relative probabilities that, given the observation of a damage level, the desired precaution level has been taken.

The very general form of the liability rule derived above, leads to a somewhat surprising implication, that the optimal liability payments will not necessarily increase monotonically with the level of environmental damages incurred. Hence, it can not be taken as certain that higher levels of environmental degradation will entail higher liability payments (cf. Grossman, Hart 1983). For the optimal liability payments to increase with the level of observed damages, the likelihood ratio has to be decreasing in q . This means that it is relatively more likely for a higher (lower) environmental damage level to occur when a low (higher) level of precaution was taken. This property is known as the Monotone Likelihood Ratio Property (cf. Milgrom 1981), and it is not implied by first-order stochastic dominance. Fortunately, the conditions under which the first-order approach used in this section is legitimate imply that liability payments rise with observed damages (cf. Appendix).

Condition (1') also implies that the optimal liability rule is not likely to have a simple form. The particular form of the liability rule is driven by the informational content of various damage levels incurred. The likelihood ratio will often not vary in a simple manner with observed damages. Only in some special cases, more intuitive solutions can be obtained:

- When the incentive compatibility constraint does not bind (i.e. $\lambda = 0$), and there are no conflicting interests between the policy maker and the polluting firm, the polluter has to pay a fixed fee depending the multiplier on the participation constraint⁶⁶. This case can arise if the precaution level the policy maker wants to implement is also the least costly one from the point of view of the polluting firm. This can occur, if production costs can be reduced by adopting environmentally friendly technologies. Even if carrying out some environmental protection may be cost reducing at the firm level, the precaution level minimising private costs will in general not be the same as the one minimising social costs.

- The case where the precautionary effort taken has no effect on expected environmental damage ($h_e(q|e) = 0$) has already been discussed in the previous section in the context of optimal risk-sharing for the absence of incentive problems.

- If the polluting firm is risk neutral ($u'' = 0$) and has sufficient assets to cover damages, a full strict liability with a complete coverage of all occurring damages by the polluter is optimal. According to optimal risk-sharing a risk neutral polluter can be assigned full strict liability for all occurring damages. The polluter is simply held liable for all occurring damages, although they may not to the full extent be caused by his

⁶⁶ Note that, if the polluter is risk averse, in order to achieve Pareto-optimal risk sharing the RHS of (1') has to be constant ($u''=0$). This would imply that h_e/h is constant, implying that $\int h_e = \int h = \text{const.}$. Since $\int h = 1$ per definition, it would follow that $h_e = 0$. This contradicts the assumption $H_e > 0$ for some q . Thus, optimal risk sharing, is only feasible if $\lambda=0$ (cf. Borch 1962, Holmström 1979).

emissions⁶⁷. The reason is that when the polluter is risk neutral, there is no conflict between risk allocation and setting incentives for precaution. A risk averse polluter, by contrast, when held fully liable for uncertain environmental damages, would respond by carrying out excessive precaution. In the case of the polluter being risk averse, optimal risk sharing would imply full insurance of polluters against the risk of being held liable for randomly caused damages. Then, however, the incentive to take precaution disappear. This, is the well known phenomenon of moral hazard.

The preceding analysis only enables to derive very general results as to the optimal liability rule. Although, conditions were established under which liability payments will vary with observed damages, the exact specification of liability payment depending on observed damages is heavily driven the underlying distribution function. Therefore, it is not possible (without knowing the specific characteristics of the likelihood ratios) to derive regularities for optimal liability rules. Even when the monotonicity result can be established, we still do not have an explicit rule for apportioning

⁶⁷ In section 3.3, it has been shown that $l(q) = q+k$ is an optimal risk allocation. Since the participation constraint binds at the optimal liability rule and for a risk neutral polluter $Eu(l(q)) = El(q)$ the expected disutility attached to uncertain liability payments equal the expected liability payments. Hence, expected liability payments have to equal the cost level attached to the outside option, m , minus the cost of precaution, i.e. $El(q, \theta) + f(e) = m$ or $El(q) = m - f(e)$. Then, if the liability rule is $l(q) = q + k$, the polluter will minimise $E(q+k) + f(e) = Eq + f(e) + k$. This does not differ from the optimisation problem the policy maker of minimising $Ev = Eq - El(q) = Eq - m + f(e)$. If $k = -Eq(e^{FB}) - f(e^{FB}) + m$ first-best solution can be attained. This is due to $\min E(q+k) + f(e) = Eq + f(e) + k + m - m = Eq - El(q) + k - m$.

realised environmental damages between the polluter and the injured party. Such an explicit relation between the actual level of damages and the liability payments will be derived in a simplified version of the hidden action model of environmental policy that is presented in the next section.

IV. A Simplified Model of Environmental Liability under Asymmetric Information

The previous analysis has shown that, the general principal-agent model with unobservable precaution of the polluting firm does not allow to derive explicit conclusions about the specific form the optimal incentive scheme. The structure of the optimal incentive scheme was highly sensitive concerning any change in the underlying probability distribution. However, results which have a more intuitive economic interpretation can be obtained by using a linear model (cf. Varian 1992, pp 453ff). Linear incentive schemes exhibit some very convenient properties. Firstly, linear schemes are fairly robust. If, for example, the underlying distribution function is not exactly known, the incentive mechanism should still be optimal. The same is true if the agent has a somewhat richer set of possible actions at his disposal than the model takes into consideration (as for example in the case of multidimensional pollution control which is discussed in section II.3). Furthermore, linear incentive schemes are easily specified and understood even if individuals only have bounded information processing capacities. Hence, transaction costs involved in designing such schemes are limited. For these reasons, in reality linear compensation schemes are frequently used (cf. Schmutzler 1996, 253, footnote 8).

Starting out from the empirical observation that compensation scheme actually observed in reality are often relatively simple compared to the optimal incentive scheme that are obtained in a principal-agent model like the one studied in the previous section, Holmström and Milgrom 1987 have shown in a dynamic principal-agent model that under certain conditions, the optimal contract will be linear in time aggregate performance measures. Holmström and Milgrom derive for an intertemporal incentive problem, that at any point in time, the agent should choose the effort level which affects a drift vector of a Brownian motion to be constant over time regardless of the output path. In this setting, compensatory payments will be a linear function of the final outcome alone. Although intermediate outcomes can be observed, observed outcomes will be taken into account in the incentive scheme. Thus, in a stationary environment in which the agent repeatedly chooses levels of effort and only imperfect signals of efforts can be observed, the optimal incentive scheme will in the limit have a linear form. In the continuous version of the model, the agent is assumed to control the instantaneous drift rate of a multi-dimensional Brownian motion. It is shown that the optimal incentive scheme for the multi-dimensional Brownian model is a function of the end-of-period outcome levels of the different dimensions of the of the process. Even if intermediate outcome were observable, the scheme would not be based on intermediate outcomes, but only on aggregate information⁶⁸.

⁶⁸ This result can only be established in general Only for the case where the agent's action set is one-dimensional for the multi-dimensional case, the

The intuition of the Holmström, Milgrom model can be sketched as follows: if outcome were a linear function of the effort level and a normally distributed random variable, and the agent chooses effort over time and observes intermediate outcomes, the agent is in the position to condition to effort on this intermediate outcome. For a one-period contract, Mirrless 1974 has shown that by a stepwise incentive scheme that punishes the agent severely in the case of very bad outcomes and offers a fixed payment otherwise, first-best efficiency can be approximated. In a repeated setting, however, at the end of the time path the agent will only exert some effort if there is a danger that the final outcome will be sufficiently low to trigger punishment. If a linear scheme is chosen instead, the agent can be induced to exert effort steadily over time. Linear incentive schemes have the property of providing incentives independent of the preceding efforts of the agent. Thus, the optimality of linear compensation schemes arises because linear incentive schemes provide incentives regardless of the timing of outcome realisations. Such an intertemporal incentive problem can for instance be due to accumulation of pollutants over time.

The results derived by Holmström, Milgrom 1987, imply that the optimal liability rule should be computed as "if the agent were choosing the mean of a normal distribution ... and the principal were restricted a priori to using a linear rule" (cf. Holmström, Milgrom 1987, p. 305). Therefore, let feasible liability rules be restricted to linear functions of observed damages,

$$(30) \quad l(q, k) = k + a q ,$$

optimal scheme will also be linear in aggregate outcome, but will also require more information.

where the parameters of liability rule are denoted by a and k . The parameters will be discussed in more detail in section 4.1.

Environmental damages are preceived to be a linear function of precautionary efforts by the potential polluter, e , and a normally distributed random variable, θ , representing the stochastic factors influencing the degree of environmental degradation

$$(31) \quad q(e, \theta) = -e + \theta.$$

Thus, environmental risk is modelled at being normally distributed⁶⁹. The results derived by Holmström, Milgrom 1987, though, imply that the underlying view of the stochastic process generating environmental damages, has not to be as simple. Nor has the representation of the stochastic components of the diffusion process in fact to be normally distributed.

The cost to the polluting firm for a given state of the world, θ , is denoted by

⁶⁹ Some authors have claimed that it is reasonable to suppose that in the case of environmental risks the conditions of the central limit theorem are given (see for instance Holzheu 1994). Moreover, for simplicity, it will be assumed that the random diffusion process θ has a zero mean. Allowing a strictly positive, exogenous background level of environmental pollution will not change the result that will be derived below substantially. A fixed background pollution will not alter the incentive compatibility condition which describes the cost-minimising behaviour of the polluter under the liability rule (see equation (IC)). A constant background level of pollution will only enter the participation constraint and might affect the location decision by the polluter.

$$(32) \quad c' = l[q(.)] + f(e)$$

Again, total costs depend on uncertain liability payments, $l(.)$, and the cost of pollution control effort, $f(e)$ with increasing marginal costs of preventive measures⁷⁰. Let the precautionary activities of the polluting firm be described by a one-dimensional variable⁷¹. As an illustration, the costs of prevention will be chosen to have a simple quadratic form.

$$(33) \quad f(e) = e^2$$

Hence, the total costs to the polluter for a given realisation of the random variable θ are

$$(32') \quad c'(e, k, a, \theta) = k + (-e + \theta)a + f(e).$$

The expected "disutility" of the polluter associated with these costs is assumed to have the following exponential form

$$(34) \quad U = E u(q, e) = E[\exp(r c')] = E \{ \exp [r(l(k, e, a, \theta) + f(e))] \}$$

Hence, the disutility function of the polluter exhibits constant absolute risk aversion that is indicated by parameter $r = u''/u' > 0$. This parameter indicates the curvature of the disutility function and is an analogue to the Arrow-Pratt measure of absolute risk aversion. Notice, that the familiar exponential utility function, $u = -\exp(-rw)$, where w is the wage income

⁷⁰ While more general results can be obtained by considering general forms of the cost of precaution function, a specific functional form is chosen to simplify the analysis without loss of insight.

⁷¹ Alternatively, it can be assumed that different activities are always combined in an efficient manner. A model of multi-dimensional efforts in pollution control is outlined in Appendix A1.

of the agent, corresponds to a disutility function where both minus signs disappear and the function is convex in the cost level.

The expected net welfare loss is again given by

$$(35) \quad V(q,l) = E [q(e,\theta) - l(k, q)]$$

where $E q(.) = -e$ indicates the expected damage and $l(.)$ are the liability payments. Note, that one could distinguish between ambient level of pollution or the physical environmental damage, which is a linear function of pollution control effort and hence, is also a normally distributed random variable, and the environmental damage in terms of disutility. For simplicity, it is assumed that $v(q) = q$. The benefits of reduced pollution taking into account preferences of injured party may equally be a concave function of efforts $v(q(.)) - l(.)$ or $v(q(.)) - l(.)$ (cf. Holmström, Milgrom 1991).

A. Parameters of the Optimal Strict Liability Rule

Given the framework presented in the previous section, the parameters of the optimal linear liability rule, k and a , and the level of pollution prevention induced, e , depend on three exogenous parameters: the polluter's risk aversion indicated by parameter r , the reservation cost level of the firm, and the variance of stochastic influence σ^2 . Any linear liability rule, $l(.) = k + aq$, consists of a fixed payment, k , and the liability share, a , of the polluting firm in environmental degradation. Under German legislation damage dependent liability payments that exceed the harm incurred, i.e. punitive damages, are excluded. Therefore, the variable part of liability payments may be regarded to be constraint as follows: $0 \leq a \leq$

1. It should be clear that this, although, it might be sensible given the objectives of civil law, it is not necessarily optimal in terms of incentives. Therefore, in the following we will carefully have to scrutinise under which conditions (i.e. parameter values), limiting liability payments to the actual harm incurred is also optimal.

In the benchmark case of $a = 0$, the polluter has not to cover any environmental damage that is caused (at least partly) by his emissions. This corresponds to the case of no ex post liability where injured party bears the risk of a stochastic deterioration of environmental quality. Whether the injured party will also have to bear some of the costs of environmental degradation will depend on the size of the fixed ex ante payment k . In the second boundary case, $a = 1$, the polluter has to cover all damages irrespective of the level of care taken. This is the case of a strict liability rule with complete coverage of all damages (full strict liability). The polluting firm bears all the risk of a random deterioration of environmental quality, and pollutees do not bear any risk in this respect. For values of $a < 1$, damages are compensated only incompletely. Here the polluter will only be liable for some portion of realised damages (modified strict liability). Neither the polluting firm nor the injured party will bear the full risk of a random deterioration of environmental quality.

The fixed amount, k , which is independent of the actual damage deserves some more detailed explanation. It will be shown that this fixed amount has no allocative implications with respect to precaution. The fixed payment can be interpreted as a distribution parameter, which serves to divide the efficiency gain obtained by the internalisation of the uncertain external effects between the polluter and the injured party being represented in this

model by the environmental policy maker. It constitutes an ex ante compensation for imposing environmental risks on society. These payments could be used to finance an collective compensation fund that can either be used to clean-up existing damages (like the Superfund) or to compensate victims of pollution which for some reason where no able to enforce their claim (because e.g. the injurer cannot be identified).

B. Determination of the Optimal Liability Rule

For a liability rule to be efficient, its parameters have to be chosen such that they minimise net welfare loss among all incentive compatible liability rules which are also individually rational from the point of view of the polluting firm⁷². Therefore, the optimisation problem of the environmental policy maker can be stated as follows. The policy maker minimises the difference of expected environmental damages and expected liability payments

$$(36) \quad \min V(.) = E[q(e, \theta) - l(q(e, \theta))] = -e - k + ae$$

with respect the liability share, a ,

the fixed ex ante payment, k ,

and the induced precaution level e .

⁷² The somewhat confusing terminology used in principal agent theory, implies that individual rationality refers to voluntary participation and not to incentive compatibility as the every day meaning of individual rationality might suggest.

subject to the incentive compatibility constraint

$$(IC) \quad e^* \in \arg \min U = E u(c'(l, e)) = \exp (rc')$$

and the participation constraint

$$(PC) \quad U = E u(c'(l, e^*)) \leq m ,$$

where m denotes the cost level attached to the outside option of the polluter.

1. Incentive Compatible Liability Rules

The optimisation problem can conveniently be solved in two steps. In the first step the best response of the polluting firm to a linear liability rule with parameters (k, a) is determined. The polluter will choose the level of precaution that minimises his expected disutility given the liability rule. Since risk follows a normal distribution and equally environmental quality and liability payments are linear functions of this risk, expected disutility to the polluter and the expected net welfare loss are also distributed normally. Accordingly, expected disutility depends on the summary statistics of the distribution, i.e. variance and mean. Together with the specific form of the expected disutility function, the normality of the distribution implies that the certainty equivalent cost of the polluting firm can be computed as the expected costs plus a risk premium. The risk premium equals half the variance times the risk aversion parameter. The expected disutility of the polluter for a given linear liability rule corresponds to a certainty equivalent cost CEC of

$$(37) \quad CEC = E u(c') = k - ae + f(e) + \frac{1}{2} ra^2\sigma^2$$

The costs to the polluter consist of expected liability payments, $k - ae$, and the cost of precautionary measures, $f(e) = e^2$. The certainty equivalent costs are greater than expected costs by an amount $\frac{1}{2} ra^2\sigma^2$ related to the degree of risk aversion and the variance of uncertain liability payments, i.e. the costs of risk bearing. Risk arises from the fact that environmental damages and thereby liability payments is only imperfectly correlated with precautionary efforts⁷³. The imperfect correlation gives rise to the possibility that the polluter is held liable although the damage was at least partly caused by a stochastic event. Although under a zero mean normal distribution on average the probability of being held liable for higher damages due to adverse stochastic effects and the probability of lower damages due to favorable stochastic effects on the assimilation capacity just offset each other, the possibility of being held liable excessively is valued more by the polluter than is the possibility of escaping part of the external cost.

Minimising the certainty equivalent, CEC, with respect to the effort level e yields the polluter's best response, described by the first-order condition

$$(FC) \quad a = f_e = 2e.$$

⁷³ Although being stated in term of costs, the certainty equivalent resembles the so-called μ - σ approach in decision making under uncertainty (see Holzheu 1994 for an application to environmental liability).

Hence, the individually optimal pollution control effort, e^* , depends only on the liability share a and is given by

$$(38) \quad e^*(a) = a / 2$$

This implies that neither the fixed amount, k , nor the reservation utility level, m , nor any fixed background level of pollution have any impact on the polluter's effort in preventing environmental accidents. The reaction of the polluter to a change in the liability rule can also be derived by differentiating the first-order condition totally

$$(39) \quad de/da = 1/f_{ee} = 1/2.$$

Thus, the change in precautionary effort induced by a rise in the ex post liability share of the polluter is inversely related to the increase in marginal cost of pollution control measures. The faster the rate at which marginal cost rises, the less the reaction of the polluter in terms of carrying out additional precaution to a sharpening in incentives.

2. Individually Rational Environmental Policy

Substituting the first-order condition of the polluting firm (FC) into the certainty equivalent CEC yields the certainty equivalent cost at the optimal level of precaution given the liability rule $l(k,a)$

$$\begin{aligned} (PC) \quad CEC(e^*) &= k - a [e^*(a)] + f(e^*) + \frac{1}{2} r a^2 \sigma^2 \\ &= k - a^2/4 + \frac{1}{2} r a^2 \sigma^2 \leq m \end{aligned}$$

Taking into consideration that the polluter might relocate in response to a tightening of environmental liability, the certainty equivalent costs exceed the costs attached to the outside option of the polluter. Moreover it had been argued previously that under the optimal liability rule, the participation constraint has to bind. The equality of condition (PC) is ensured by parameter k . As k does not affect the level of precaution the policy maker wants the polluting firm to take, this reflects the idea that in tort law compensatory payments serve to redistribute damages⁷⁴. Hence, the efficiency of the liability rule does not depend on k . The participation constraint only limits possible values of k to

$$(40) \quad k = m + a^2/4 - \frac{1}{2} r a^2 \sigma^2 .$$

The intercept term, k , can be raised if the cost level attached to the outside option of the firm, m , rises due to a stricter environmental policy abroad. The fixed amount will also be higher for lower degrees of risk aversion and lower degrees of uncertainty⁷⁵.

⁷⁴ Note that k appears two times, each time with a different sign. This implies that money can be transferred from one party to the other one-by-one in utility terms. This is due to the fact that the payment k is certain.

⁷⁵ It can be shown by using the quadratic cost function that the relationship between the parameters of the incentive scheme, a and k , though, is ambiguous $dk/da = 2a/4 - \frac{1}{2} 2 a r \sigma^2 = \frac{1}{2} a - a r \sigma^2 = a (-r\sigma^2 + \frac{1}{2})$, $dk/da > 0 (<0)$ if $r\sigma^2 < \frac{1}{2}$ ($r\sigma^2 > \frac{1}{2}$). Hence, the more risk averse the polluter or the higher the variability of the random shock, the less likely it is, that k rises with a .

This allows to simplify the incentive problem by disregarding for the moment the requirement that both parties are willing to participate in the mechanism by assuming that the polluter does not relocate as a consequence of the the liability rule. This means that the analysis focuses on the short run with a given location of economic activities. Whereas a long run analysis has to take into account that plants can relocate. Now any linear incentive scheme that minimises the net welfare loss subject to the incentive compatibility constraint is efficient.

3. Derivation of the Optimal Linear Liability Rule

Having characterised all incentive compatible (and individual rational) liability rules, in the second step the environmental policy maker chooses the optimal liability rule. The net welfare loss is given by the environmental damage minus the liability payments received from the polluter, for a given state of the world θ ⁷⁶

$$(42) \quad V(.) = E v(.) = q(e, \theta) - l(q(.)) = q(e) - (k + aq) = (1 - a)(-e + \theta) - k$$

which due to risk neutrality is equal to a certainty equivalent loss of

⁷⁶ It can also be shown, that minimising the objective function of the environmental policy maker is equivalent to minimising total environmental cost. If the participation constraint of the polluting firm is disregarded and for convenience set equal to zero, $CEC^* = 0$, this implies, that $L(.) = e^2 + \frac{1}{2} r a^2 \sigma^2$. This can then be substituted into the objective function of the environmental policy maker yielding total expected environmental costs $TCE = -e + e^2 + \frac{1}{2} r a^2 \sigma^2$. Total costs are then minimised with respect to a subject of the incentive compatibility constraint.

$$(43) \quad CEP = (1 - a)(-e) - k$$

The environmental policy maker minimises this certainty equivalent with respect to the liability share of the agent, a , subject to the incentive compatibility constraint (FC). The share in environmental damage that minimises certainty equivalent CEP is⁷⁷

$$(44) \quad a = \frac{-Q_e}{1 + r\sigma^2 f_{ee}(e)}$$

For $E_q = -e$ and $f(e) = e^2$, the optimal liability share becomes

$$(44') \quad a = \frac{1}{1 + 2r\sigma^2}$$

It can be seen that typically the marginal liability payments a will deviate from marginal expected environmental damages. The optimal liability share of the polluter will decline as either risk aversion or the variance of exogenous stochastic variables increase. In this case the polluter faces higher costs of risk bearing (inducing him to take excessive precaution). On the other hand, it can never be optimal to free the agent from all liability, as in this case he would not exert any pollution control efforts at all. Equally, in the presence of risk aversion of the polluter it is never optimal to hold him liable for all damages. Holding the polluter liable for all occurring damages can only be optimal if the agent is risk

⁷⁷ As $TCE'' > 0$, the first-order condition is sufficient for a cost minimum.

neutral ($r=0$). If σ^2 is greater than zero, i.e if there is uncertainty involved, the liability share of the polluter, a , will become smaller. The risk of a random deterioration of environmental quality is shared between the polluter and the victims.⁷⁸

Substituting the optimal share, a , for the case of a quadratic cost function into the first-order condition of the polluter yields

$$(45) \quad e^* = \frac{a}{2} = \frac{1}{2+4r\sigma} \leq \frac{1}{2}$$

It can also be seen from the above equation that first-best effort in prevention of environmental pollution, which is $\frac{1}{2}$, only can be implemented if the agent is risk neutral ($r=0$) or if there is no uncertainty (σ^2). In general, however, the effort of the polluting firm to reduce stochastic negative side effects of production will be lower than the first-best effort level.

Under certain conditions an (informationally) unconstrained Pareto-optimal allocation is obtained. The first-best optimum is characterised by marginal compensatory payments that are equal to the marginal damage prevented, $a = -Q_e = 1$. Special cases where the first-best solution can be attained include the case of risk neutrality of the polluter ($r = 0$) and complete certainty in respect to causes of environmental degradation ($\sigma^2 =$

⁷⁸ An upper limit of the liability share of one will only be optimal if marginal environmental damage prevented by an extra unit of precaution equals one.

0)⁷⁹. In both cases, no allocative inefficiency arises. One way of interpreting this result is that, under these specific assumptions, a liability rule can be designed to internalise the stochastic externality perfectly and share environmental risk optimally between parties. This is ensured by a strict liability rule with complete compensation of all occurring environmental damages (full strict liability).

Apart from the special cases discussed above, first-best efficiency cannot be achieved because of imperfect information and risk aversion of polluter. In the general case where the liability share, α , lies strictly between zero and one, marginal liability payments are proportional to marginal damage prevented⁸⁰. But expected liability payments are smaller than marginal damage. Thus, incomplete compensation of damages is second-best Pareto optimal. By setting liability payments equal to the share in observed damages as defined in equation (44), the environmental policy maker can achieve an optimal second-best outcome, i.e. the efficient use of the environment subject to the informational constraints. It is the absence of perfect information, that causes a deviation from first-best efficiency.

⁷⁹ From discussion in section III.D it is known that with complete certainty, the full information solution would enable the environmental policy maker to link the liability payments directly to the pollution control efforts. The external effect is internalized completely and the risk averse polluter does not bear any risk in respect to the stochastic influence factors.

⁸⁰ This share is necessarily smaller than one, as $-Q'(e) = 1$. The liability share is greater than zero if, $0 \leq 1 + 2r\sigma^2 \leq 1$. $1 + 2r\sigma^2 = 0$ iff $\sigma^2 > -\frac{1}{2}r$.

4. Conclusions From the Linear Model

The previous analysis has shown that the optimal value of liability parameter, a , depends on the precision of measuring precautionary efforts by observed damages. When precaution is observed more exactly, i.e. σ^2 converges to 0, the liability share, a , converges to the marginal benefit of additional precaution Q_e . Furthermore, the optimal value of the liability share is influenced by the polluter's risk tolerance. The higher the absolute risk aversion of the polluting firm denoted by parameter r , the more the share of liability payments in actual damages deviates from marginal damage prevented. Finally, the optimal liability rule depends also on the reaction of the polluting firm to a change in incentives ($de/da = 1/f_{ee} = 1/2$). The more responsive the agent is to sharpened incentives, i.e. the lower f_{ee} , the closer the cost share is to marginal damages.

The results obtained for the optimal liability share in environmental damages of the polluter under a non-fault liability rule, indicate that the extent to which the allocation will deviate from first-best efficiency depends on the following factors: First, the information quality, i.e. the ability to infer insufficient precaution from the observed environmental degradation. Secondly, the welfare loss increases with the degree of risk aversion of the polluting firm. Thirdly, the response of the polluting firm to a sharpening of incentives is an important determinant of the welfare loss. The more costly it is for the polluter to react to changes in incentives, the smaller is the effect of a rise in the liability share on the precaution undertaken by the polluter. Fourthly, the benefit of precautionary measures, i.e. the size of the expected environmental damage prevented, will determine the willingness of the environmental policy maker to

provide incentives. If the marginal benefit of providing incentives increases, while the cost of risk bearing remain unchanged, the environmental policy maker optimally will increase damage related liability payment.

The environmental allocation under the modified strict liability rule will deviate from full information allocation because of the difference between marginal damages and marginal liability payments. This difference will raise total environmental costs. It has been shown that the size of this welfare loss depends on a number of factors, some of them outside the control of the environmental policy maker. In an principal-agent setting, it is the principal who suffers the welfare loss due to asymmetric information and uncertainty, which prevents a first-best solution to the externality problem. The agent's welfare level equals always his reservation utility under the optimal environmental policy. The additional costs will cause the optimal precautionary effort the environmental policy maker wants to implement to be lower than the first-best effort level. The difference between the total environmental costs in the first-best scenario, and the costs that arise in second-best setting is given by the costs of risk bearing. The costs of risk bearing indicate the cost of providing incentives⁸¹. The welfare loss increases with a deterioration of the possibilities to diversify risk (captured by increased risk aversion parameter r), with increasing variance of stochastic factors influencing environmental damages, and

⁸¹ In the context of the theory of the firm it has been called agency costs (cf. Jensen, Meckling 1976). Agency costs are the difference between the first-best welfare level and the one that can be attained under the optimal second-best liability rule.

with decreasing costs attached to the outside option (i.e. with relaxing environmental liability laws abroad). If the costs of providing incentives, and therefore agency costs, become very high, the net welfare loss of the policy maker (the injured party) due to pollution may outweigh the net benefits derived from the economic activity generating the emissions. This global optimality requirement is captured by the participation constraint of the environmental policy maker.

Assuming that the reservation cost level of the polluting firm and the costs of precaution are exogenously given, the environmental policy maker has the following policy options to improve the efficiency of environmental liability. First, as the agency costs vary inversely with the degree of risk aversion of the polluter, any policy strategy that opens up to the polluter better opportunities to diversify the risk of uncertain liability payments will entail a more efficient use of the environment. Apparently, if there were a perfectly functioning market for liability insurance, a risk averse polluter would act as being risk neutral⁸². The insurability of environmental damage are, however, subject of a substantial debate (see e.g. the volume edited by Kleindorfer, Kunreuther 1987, or the discussion in Eisen 1992, and Wolters 1995). Apart, from technical problems involved in many details of such an insurance (such as insuring creeping damages, "Allmählichkeitsschäden", or damages arising from regular operation), the fundamental problem of unobservable precaution remains. The insurance company will face the same information asymmetry as the one discussed

⁸² The German Environmental Liability Law provides for a compulsory coverage, with liability insurance as one possible option, in sections 19 and 20 of the UmweltHG.

here (cf. Shavell 1982 Stiglitz 1983)⁸³. Due to the moral hazard phenomenon the precautionary effort will decline if the polluter is fully insured against liability for environmental damages (cf. Pauly 1974). Thus, it will be optimal for any insurance company to offer less than full insurance (cf. Shavell 1979a, 555). Although, one might expect a competitive insurance market to generate more imaginative solutions to the moral hazard problem than government authorities (cf. Siebert 1991). But not only the efficiency but also the existence of a market equilibrium⁸⁴ may be substantially endangered, if polluters possess private information regarding some characteristics of their risk potential (cf. the seminal paper by Akerlof 1970, more recently Hellwig 1987). Then the insurance companies will face the additional problem of adverse selection (see Rothschild, Stiglitz 1976, Wilson 1977). Furthermore, if the objectives of the insurance company and the environmental policy maker do not

⁸³ The analytical framework of principal agent theory can also be applied to the optimisation problem of an insurance company facing moral hazard. In a competitive insurance market, the participation constraint has to be replaced by a non-profit condition which ensures that premiums are actuarial fair. The insurance company will then maximise profit subject to an incentive compatibility constraint and the non-profit condition. Apparently, full insurance cannot be optimal when precautionary actions by the polluter cannot be observed. The polluter will have to face part of the liability. This result corresponds to the analysis presented in this paper.

⁸⁴ Whereas a so-called (separating) Rothschild-Stiglitz equilibrium (cf. Rothschild-Stiglitz 1976), based on a Cournot-Nash-conjecture regarding the contracts offered by competitors, might not exist at all, if insurance companies anticipate the reaction of their competitors regarding the contracts offered, there will always exist a stable pooling equilibrium (so-called Wilson Equilibrium, cf. Wilson 1977). The Wilson equilibrium result, however, does not hold for a continuum of different risk types (cf.

coincide and, hence, more than one principal aims at influencing the decisions taken by a common agent, a so-called common agency problem will arise (cf. Bernheim Whinston 1986, Stole 1991). A second strategy to improve efficiency of the optimal modified strict liability rule, is to increase to precision of observing precautionary effort (i.e. to reduce σ^2). So far, the analysis ignored the fact that the efficiency of the liability rule can be improved the incorporating additional information on the behaviour of the polluting firm⁸⁵.

V. Policy Implications

The previous discussion of the linear model has shown, that only under certain conditions, a full strict liability rule under which the compensation equals on the level of environmental damages incurred, can achieve first-best efficiency. A modified strict liability might, however, achieve a second-best efficient outcome by forcing the polluter to compensate victims for part of the occurring damages. This result is in sharp contrast to traditional models of environmental liability. There any deviation of liability payments from damage incurred will lead to sub-optimal results (see Schwarz 1993, Endres 1991, 1989, Heyn 1993). Once information asymmetries are taken into account, however, the optimal liability rule will

Riley 1979). If markets are imperfectly transparent, Zink 1989 shows that a Cournot-Nash market equilibrium will exist.

⁸⁵ It has been shown that an incentive mechanism as function solely of outcome is able to achieve a first-best solution if the agent is risk neutral. In this case a full strict liability rule will be Pareto-optimal in this case. If the polluter is risk averse including an additional variable might improve efficiency.

involve liability payments that are lower than damages. The reason for this is that a modified strict liability insures the polluter partially against the risk of a random deterioration of environmental quality. The principal agent models presented here implies a modified strict liability rule that does not hold the polluter liable for the full environmental damage. This modified strict liability rule can be regarded as an optimal institutional mechanism for sharing environmental damages between the polluter and the environmental policy maker respectively.

Given the variability of the liability payments, the expected total costs imposed on the polluter must be strictly lower than the fixed ex ante payment in the case where the precautionary choice can be observed. Since the polluter cannot be assigned expected costs that exceed his reservation cost level m , he has to be compensated for the environmental risk he has to bear by means of lower liability payments. Therefore, as a result nonobservability of the precautionary choice leads to a higher welfare loss of the environmental policy maker when implementing a certain precaution level. Note, however, that although non-observability leads to a welfare loss, the liability rule derived here is a constrained (or second-best) Pareto-optimum. This can easily be seen, because the environmental policy maker minimises the uncompensated environmental damage to be borne by the injured party subject to not burdening the polluter with higher environmental costs than he would have to face in the absence of environmental liability and subject to an incentive compatibility constraint.

The discussion has already pointed to potential efficiency gains that could be realised if the precaution taken by the polluter were observable.

Therefore, by improving the precision of the measurement of pollution control efforts including additional information may increase the allocative efficiency. The policy maker's optimisation problem with monitoring is very similar to the one presented earlier, with the only difference that now expectations are taken with respect to the joint distribution of outcome and the additional signal (for an exposition see Appendix). Although a general principal-agent model does not allow to derive specific regularities regarding the incentive scheme, it allows quiet strong propositions as to the variables on which the incentive mechanism should be based⁸⁶. The monitoring literature has shown that, if the agent is risk averse, it is optimal to incorporate additional information in the incentive scheme (cf. Holmström 1979, 1982) provided that the outcome is not a sufficient statistic for the effort. The basic idea of incorporating an additional signal in the incentive scheme is, that it is less likely that consideration of the signal, s , in the liability rule reduces the chance that when high level of damages is observed it is incorrectly inferred that low precaution was taken. It is less likely that both variables observed, q and s , indicate at the same time a low effort was taken although the polluter has taken a high level of preventive pollution control. Essentially, the reason for incorporating signal in the liability rule, is not that it provides additional information on effort. After all, the effort taken by the polluting firm can

⁸⁶ There is a large literature on the optimal use of additional information. Besides the seminal paper of Holmström 1979, lateron extended in Holmström 1982, Harris, Raviv 1979, Shavell 1979, Gjesdal 1982 and Singh 1985 have discussed the value of additional signals for the case of costless monitoring. Other papers which look at the similar questions are Lazear, Rosen 1981 and Nalebuff, Stiglitz 1983.

be computed given the liability rule. Consideration of the signal allows to discriminate the liability payments more according to the observations, as the chance of a misassessment is reduced (see Rees, 1987, pp. 65ff) thereby providing more pronounced incentive effects.

In terms of environmental liability, this implies that a liability rule that includes additional information on effort would induce potential Pareto-improvements as long as the polluter is risk averse (cf. Shavell 1979). The fundamental decision between non-fault liability and an effort-based liability however has to be based on a comparison of the informativeness of the respective signals. Here the issue is not to incorporate additional information. From principal-agent theory, it is known that the incentive scheme should be based on the variable which is a more precise signal of the precautionary effort taken (see Grossman, Hart 1983). The main problem would be to establish which of the two types of liability rules is based on the more precise monitor of pollution control efforts. But a negligence rule constitutes a institutional mechanism that tries to take into account information on actions taken by the agent in a very specific way. A negligence rule focuses on the information on the effort in a dichotomous way. If it turns out that the standard of due care has not been taken, the polluter will have to cover all environmental damages incurred. Otherwise, the polluter will only have to bear the costs of precaution and some fixed ex ante fee. Defining a standard of due care can only induce the optimal level of precaution if actions can be observed perfectly by the environmental authority. If precautionary effort, however, is not perfectly observable, similar problems as those discussed in the context of the conditional reversal of the burden of proof arise. The effects of a conditional reversal of the burden of proof have shown that, when only an imperfect signal of

the true effort is observed, depending on the precise parameters of the model the polluter will either overcomply or undercomply with the standard of due care. A dichotomous incentive scheme is not necessarily the optimal way to incorporate additional information⁸⁷.

⁸⁷⁸⁸ Usually in worker-compensation problems, it is required that the distribution function is convex in effort in order to ensure the overall concavity of the agents utility maximising problem (cf. Rogerson 1985).

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Appendix

VII. Appendix A1: The Multidimensional Pollution Control Model

Two types of precautionary pollution control

observable precaution e_1

unobservable precaution e_2

Expected environmental damage $Q(e_1, e_2) = E q(e_1, e_2; \theta)$

$\theta \sim N(0, \sigma^2_\theta)$ stochastic diffusion process

marginal expected environmental damage $Q_1, Q_2 < 0$

with subscripts 1,2 denoting the partial derivatives with respect to e_1 and e_2 .

strictly convex $d^2Q > 0$:

$Q_{11} > 0, Q_{22} > 0, Q_{12} = Q_{21}, Q_{11} Q_{22} - Q_{12}^2 > 0, Q_{12} < 0$;

Cost of precaution $f(e_1, e_2)$

marginal costs of precaution $f_1, f_2 > 0$

strictly convex $d^2 f > 0$:

$f_{11} > 0, f_{22} > 0, f_{12} = f_{21}, f_{11} f_{22} - f_{12}^2 > 0, f_{12} < 0$;

A. *Socially Optimal Precaution*

$$\text{Min SC}(e_1, e_2) = Q(e_1, e_2) + f(e_1, e_2)$$

First-order conditions are given by

$$Q_1 + f_1 = 0$$

$$Q_2 + f_2 = 0$$

B. *Conditional Reversal of the Burden of Proof*

The polluting firm will be presumed to have caused the damage incurred if and only if $s_1 < n$ with s_1 being an imperfect signal of the actual effort e_1 , $s_1 = e_1 + \varepsilon_1$ with $\varepsilon_1 \sim N(0, \sigma_\varepsilon^2)$ denoting observation error, described by a density function $g(\varepsilon_1) = g(s_1 - e_1)$.

Causality will be presumed for a given standard of regular operation

$$I(s_1(e_1, \varepsilon_1)) = \begin{cases} 1 & \text{if } s_1(e_1) < n \\ 0 & \text{otherwise} \end{cases}$$

The probability that the polluter will be subject to the causality presumption

$$p(s_1 < n) = p(e_1 + \varepsilon_1 < n) = \int_{-\infty}^{n-e_1} g(\varepsilon_1) d\varepsilon_1 = G(n - e_1)$$

where $G(\cdot)$ denotes the cumulative probability distribution.

Total expected cost of the polluting firm

$$TC = f(e_1, e_2) + Q(e_1, e_2)G(n - e_1)$$

Assuming strict convexity of TC, the following first-order condition guarantee a minimum of total costs under a conditional causality presumption for the polluting firm

$$f_1(e_1, e_2) + Q_1 G(n - e_1) - Q(\cdot)g(\cdot) = 0$$

$$f_2(e_1, e_2) + Q_2 G(n - e_1) = 0$$

provided that $e_1, e_2 > 0$ at the optimum.

Under the conditional presumption of causality a change in precaution entails two effects on marginal expected liability payments

$$(1) \quad \text{damage effect} \quad Q_i G(\cdot), \quad G(\cdot) < 1,$$

lowers c.p. the level of both precaution types

$$(2) \quad \text{liability effect} \quad -Q(\cdot)g(\cdot),$$

increases c.p. the level of (observable) precaution

Evaluating the first order conditions at the social optimum (i.e. - $Q_i = f_i$) shows that $D_2 (G-1) > 0$, i.e. that e_2 unambiguously declines, whereas $Q_1 (G-1) - Q(\cdot)g < \text{or} > 0$ implying that the net effect on e_1 is ambiguous.

However, as both first-order conditions have to be satisfied simultaneously, changes in the optimal level of one effort type will lead to a change in the optimal level of the other effort type. Depending in whether different pollution control strategies are substitutes or

complements, the effects derived above may be reinforced or partly offset by the interdependences among optimal precaution levels.

1. Optimal Interdependent Choice of Pollution Control Measures

The total precautionary impact of a conditional causality presumption depends on both the direct impact and the indirect impact caused by the interdependencies of different pollution control strategies. Neither the direct impact nor the indirect impact is clear cut. Two cases have to be distinguished

SUBSTITUTES $f_{12} > 0$ $Q_{12} > 0$

COMPLEMENTS $f_{12} < 0$ $Q_{12} < 0$

If efforts are substitutes, the marginal cost of (marginal damage prevented by) carrying out one type of precaution rises (decreases in absolute terms) with an increasing level of the other effort type. If, on the other hand, efforts are complements, marginal cost (marginal effectiveness) of one effort type declines (rises) as the level of other type increases. Therefore one would expect, the optimal choice function describing the cost-minimising level of one effort type for alternative levels of the other effort type, to be positively sloped in case of complements and to be negatively sloped in the case of substitutes.

Differentiating the first-order condition under a conditional reversal of the burden of proof and rearranging terms yields,

(1) observable precaution

$$\frac{de_1}{de_2} = \frac{Q_2 g(\cdot) - f_{12} - Q_{12} G}{Q_{11} G(\cdot) - 2Q_1 g(\cdot) + Q g'(\cdot) + f_{11}}$$

(2) unobservable care

$$\frac{de_2}{de_1} = \frac{Q_2 g(\cdot) - f_{12} - Q_{12} G}{Q_{22}(G(\cdot)) + f_{22}}$$

SUBSTITUTES

$$de_1/de_2 < 0 ; \quad de_2/de_1 < 0 \quad \text{unambiguously}$$

COMPLEMENTS

$$de_1/de_2 < \text{or} > 0 ; \quad de_2/de_1 < \text{or} > 0 \quad \text{ambiguous}$$

$$|Q_2 g(\cdot)| < |f_{12}| \quad |Q_2 g(\cdot)| < |G(\cdot)Q_{12}|$$

$$\Rightarrow \quad de_1/de_2 > 0$$

$$\text{otherwise} \Rightarrow \quad de_1/de_2 < 0 \quad \text{counter-intuitive !}$$

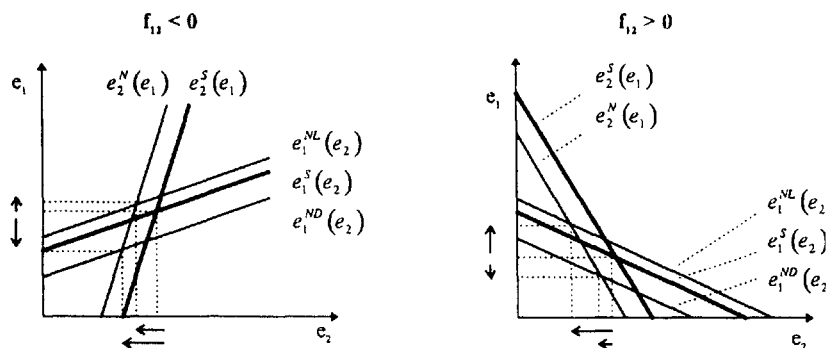
Hence, for the case of substitutes the interdependence is unambiguous. For complements, however, the counter-intuitive case might arise that the observable (unobservable) effort decreases when the unobservable (observable) effort is raised, although efforts are complements. The following table summarises the different inbdirect effects one can observe depending on whether efforts are substitutes or complements.

TABLE A1: OPTIMAL INTERDEPENDENT CHOICE OF POLLUTION CONTROL STRATEGIES

	Full information	Conditional Presumption of Causality
$f_{12} > 0$	$de_1/de_2 < 0$ $de_2/de_1 < 0$	$de_1/de_2 < 0$ $de_2/de_1 < 0$
$f_{12} < 0$	$de_1/de_2 > 0$ $de_2/de_1 > 0$	$ Q_2g(\cdot) > f_{12} $ (reg.) $de_1/de_2 > 0$ $de_2/de_1 > 0$ $ Q_2g(\cdot) < f_{12} $ (irreg.) $de_1/de_2 < 0$ $de_2/de_1 < 0$

The total impact of the provisions under UmweltHG on precaution depend on both, whether or not the liability or the damage effect dominates and on whether different strategies in pollution control are substitutes or complements. Assuming for simplicity that optimal choice function can be represented by straight lines, the different cases are illustrated in Figure A1.

FIGURE A1 : ILLUSTRATION OF THE OVERALL IMPACTS OF CONDITIONAL CAUSALITY PRESUMPTION



As it has been derived above, in the case of substitutes, the optimal choice functions will be negatively sloped, whereas in the case of complements, they will have a positive slope. Superscript S denotes the first-order condition for a social optimum. The optimality condition under the conditional causality presumption are indicated by superscript N. The damage effect will c.p. lead to an inward shift of the optimal choice function. By contrast, the liability effect will c.p. lead to an outward shift of the optimal choice function for the observable effort type. Therefore, in the case of a dominant damage (liability) effect, this curve will shift to the left (right).

Thus, a dominant damage effect will in the case of substitutes lead to moderate reductions of both effort types. In the case of complements, by contrast, the cost-minimising levels of both effort types will decrease more for a given shift of the optimal choice functions. In this case, the damage effect will be reinforced by the interdependence between different pollution control strategies. By the same reasoning, a dominant liability effect, raising e_1 , will be reinforced when different strategies are substitutive. Table 2 summarises the different precaution levels that will be induced.

Table 2: Precautionary Effects under a Conditional Presumption of Causality

	dominant damage effect	dominant liability effect
observable effort	$e_1^N < e_1^S$	$e_1^N > e_1^S$
unobservable effort	Substitutes $f_{12} > 0$ $e_2^{NL} < e_2^{ND} < e_2^S$	$f_{12} > 0$ $e_2^{NL} < e_2^{ND} < e_2^S$
	Complements $f_{12} < 0$ $e_2^{ND} < e_2^{NL} < e_2^S$	$f_{12} < 0$ $e_2^{ND} < e_2^{NL} < e_2^S$

Note that in the case of perfect observability of e , the polluter will exert no unobservable effort in pollution control at all when effort are substitutes.

VIII. Appendix A2: Limitations of the First-Order Approach

There are some technical problems involved in using the first-order approach (cf. Grossman, Hart 1983). The objections raised by Grossman, Hart 1983 have lead to the by now standard procedure of stating the principal agent model with hidden action with a finite number of possible actions and a finite number of possible outcomes (cf. e.g Kreps 1990, pp. 529ff). The results derived for the optimal incentive scheme are, however, very similar. As the focus of this paper is not on the technical details of solving principal-agent models, it will be assumed that the conditions hold under which the first-order approach being more convenient in applied work is valid. Moreover, the Grossman, Hart approach only produces interpretable results under fairly strong conditions (which in turn are sufficient for the first-order approach to be valid in the first place, cf. Jewitt 1988).

The crucial point is that it not generally legitimate to substitute the incentive constraint (IC)

$$(IC) \quad e \in \arg \min_q \int u(l(q))h(q|e)dq \quad f(e)$$

by the first-order condition (FC)

$$(FC) \quad \int_Q u(l(q))h_e(q|e)dq + f_e = 0.$$

The first-order condition is only sufficient for a global cost minimum for the polluting firm, if the total cost function of the polluting firm is convex in precautionary effort e . The total costs will be convex, if its components are convex functions of precautionary effort. As the costs of precaution, $f(e)$, are convex by assumption, the crucial part of the total costs function to look at is the disutility attached to uncertain liability payments. Whether the disutility attached to liability payments is convex will in turn depend on the liability rule itself. And the liability rule itself is endogenously determined. For the case of sharing output between the manager and the owner of a firm, conditions have been derived under which the first-order approach is valid (cf. Mirrlees 1975, Rogerson 1985). Applying those conditions to the internalisation of uncertain environmental damages discussed here, the conditions which ensure convexity are the Concavity of the Distribution Function Condition (CDFC) and the Monotone Likelihood Ratio Property (MLRP)⁸⁸.

The CDFC simply states that the distribution of damages $H(d,e)$ is concave in precaution at all levels of damage, i.e. $H_e > 0$, $H_{ee} < 0$. Intuitively, this means that an increase in precautionary effort has a decreasing marginal impact on the probability of an improvement in environmental quality. In addition, the density function of damages $h(q|e)$ being parametrised by the precaution taken has to have a monotone likelihood ratio. More precisely, the MLRP in the internalisation problem presented here requires that

$$\frac{\partial}{\partial q} \left[\frac{h_e(q|e)}{h(q|e)} \right] < 0$$

The MLRP states that the observation of a higher level of damage is more relatively likely, if a lower level of precaution has been taken, i.e. the likelihood ratio is monotone decreasing in q . Thus, if a higher damage is observed, one can infer statistically that the polluter has taken lower precaution. The MLRP also implies that (if the first-order approach is valid) that liability payments increase with observed damage q , i.e. $l'(q) \geq 0$. Many distributions, as for example the normal distribution, satisfy the MLRP.

To prove formally that the total cost function of the polluter will be convex for every optimal incentive scheme integrate the overall cost

$$C(e) = \int_Q u(l(q))h(q|e)dq + f(e)$$

by parts, which gives

$$C(e) = [u(l(q))H(q|e)]_q^{\bar{q}} - \int_q^{\bar{q}} u'(l(q))l'(q) H(q|e)dq + f(e)$$

$$C(e) = u(l(\bar{q})) - \int_q^{\bar{q}} u'(l(q))l'(q) H(q|e) dq + f(e)$$

The first term is constant, and the integral will be a convex function if the distribution function $H(q|e)$ is concave in e . Since all weights are positive ($u' > 0$ and $l'(q) \geq 0$), the weighted sum of $H(\cdot)$ will as well be convex. Thus, $C(e)$ is a convex function of e . Q.e.d

IX. Appendix A3: The Role of Risk-Aversion on the Part of the Policy Maker

Throughout most of the analysis the environmental policy maker has been assumed to be risk neutral. This section addresses the question of the implications of risk aversion on the part of the environmental policy maker in the linear framework presented in section 4. Due to potential irreversibilities of a certain use of the environment or unknown threshold levels in the assimilative capacity of ecosystems, the environmental policy maker might very well be risk averse (cf. Siebert 1995, 265ff). Moreover, for public good dimensions of the environment, risk pooling is not possible. A risk averse policy maker will implement a tighter environmental policy than a risk neutral decision maker. This is the well known principle of preventive environmental policy (cf. Simonis 1984).

Let the environmental policy maker have same type of exponential net welfare loss function, as the polluting firm, i.e.

$$V = E \{ \exp[r_p(q(e, \theta) - l(q(.)))] \}$$

where r_p is the degree of risk aversion of the policy maker. Accordingly, the certainty equivalent of the net welfare loss of the policy maker will be

$$\begin{aligned} \text{CEP} &= q(e, \theta) - l(q(.)) + \frac{1}{2} r_p a^2 \sigma^2 \\ &= -e - (-ae + k) + \frac{1}{2} r_p a^2 \sigma^2. \end{aligned}$$

Minimising this certainty equivalent with respect to the liability share, a , subject to first-order necessary condition for a cost minimum of the polluter, yields

$$a = \frac{-Q'(e) - f_{ee} r_p \sigma^2}{1 + f_{ee}(r_p + r_a)\sigma^2} = -Q'(e) + \frac{f_{ee} r_a \sigma^2}{1 + f_{ee}(r_p + r_a)\sigma^2}$$

The parameter r_a denotes the risk-attitude of the polluter. If the environmental policy maker is assumed to be risk averse, the liability share will be the higher (the lower), the higher the degree of risk aversion of the policy maker (the polluter). For very high levels of risk aversion of the polluter, the liability share converges to the marginal environmental damage prevented and the induced precautionary effort towards $\frac{1}{2}$ (cf. Ströbele 1992 for a similar discussion).

X. Appendix A4: Efficiency Gains from Monitoring Pollution Control Activities

The model is now extended to allow for monitoring of the polluter. It is assumed that even with monitoring the polluter there remains some information asymmetry such that courts, when enforcing the optimal liability rule, cannot observe the level of precaution taken exactly. Instead they only observe an imperfect signal, s , of the true effort taken.

$$s = g(e, \theta) .$$

To keep the analysis straightforward, it will be assumed that the observation function $g(e)$ are known beforehand⁸⁹. The only decision the

⁸⁹ In particular, at this stage it is excluded that the principal by devoting more resources to monitoring can reduce the variance of the error term's distribution. In this case, there is no marginal calculus as to whether more monitoring should be carried out. Therefore, monitoring costs are neglected altogether. Obviously, monitoring that they can not exceed the

environmental policy maker has to take then is as to whether this additional information should be included in the liability rule. And if so in which way should the observation enter the optimal liability rule. Monitoring may reduce the information asymmetry but including an additional uncertain variable in the incentive scheme will give rise to additional costs because the polluter is assumed to be risk averse. Therefore, even if the signal could be observed costlessly, there will in general be a trade-off. The environmental policy maker may, however, still find it advantageous to base liability not only on the damage observed but also on the additional signal of the level of precaution taken. So now, when designing a liability rule, the policy maker will choose a rule $l(q,s)$ that depends on both the damage $q(e,\theta)$ and the signal $s(e;\theta)$.

Let the joint density distribution function of the signal, $s \in S \subset \mathcal{R}$, and the environmental damage q be $h(q,s|e)$. The joint distribution function is understood as being parametrised by the precaution effort. The environmental policy maker faces the following minimisation problem

$$\min_v = \int \int_Q q(e,\theta) - l(q,s)h(q,s|e) dq ds$$

subject to

welfare gain achieved by improvements in the incentive mechanism caused by including additional information. It should also be noted, that even, if monitoring would be costless, it is not necessarily improving the situation if the signal is included, since due to imperfect observability, there also risk involved.

$$(PC') \int_s \int_Q u(l(q(e, \theta))) h(q, s|e) dq ds + f(e) \leq m$$

$$(FC') \int_s \int_Q u(l(q(e, \theta))) h_e(q, s|e) dq ds + f_e = 0$$

This problem is identical with the one presented earlier, with the only difference that now expectations are taken with respect to the joint distribution $h(q, s, e)$. Accordingly, pointwise minimisation gives the counterpart to equation (28').

$$(28') \frac{1}{u'(l(q))} = \mu + \lambda \frac{h_e(q, s|e)}{h(q, s|e)}$$

Thus, if the likelihood ratio varies with the observed signal s , the liability rule will be modified according to the signal. If s is thought to represent, for example, the safeguards installed ($h_e(s) > 0$), the liability payments for a given level of q will be lower when s is incorporated in the liability rule. Consideration of the signal, s , in the liability rule assigning compensatory payments reduces the chance that when high level of damages is observed it is incorrectly inferred that low precaution was taken. It is less likely that both variables, q and s , indicate at the same time a low effort was taken although the polluter has taken a high level of preventive pollution control⁹⁰. Obviously, it is only useful to incorporate the signal if liability

⁹⁰ Essentially, the reason for incorporating signal in the liability rule, is not that it provides additional information on effort. After all, the effort taken by the polluting firm can be computed given the liability rule. Consideration of the signal allows to discriminate the liability payments

varies with the signal. This will be the case if q is not a sufficient statistic for e .

more according to the observations, as the chance of a misassessment is reduced (see Rees, 1987, pp.65ff).