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Information Asymmetries, Uncertainties, and Cleanup Delays at
Superfund Sites

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Proposed Running Head: Information Asymmetries and Delay

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ABSTRACT:

Superfund cleanup has been extremely slow. Traditional analysis has centered around reducing negotiation and litigation to expedite the cleanup process. We investigate other factors which provide possible incentives for delay, namely discounting, risk aversion, and compensation for off-site damage. We find that liability share plays an essential role in PRPs' incentives to delay. Commonly adopted EPA strategies, such as negotiating with PRP steering committees and buying out *de minimis* PRPs, may also lead to delay. The paper also designs a Bayesian mechanism for information extraction, and finds that the lump sum transfer mechanism is not always efficient. (JEL D82, Q28)

1 Introduction

A major obstacle in the implementation of the Superfund program is the information asymmetry between the EPA and the Potential Responsible Parties (PRPs). For a particular polluted site, each PRP will have private information about its own contribution to the site, including the nature and geographic distribution of the substances contributed. Typically, this private information will be imperfect, due to gaps in PRPs' records of the magnitude, transportation and diffusion of their contributions. However, PRPs' private information is typically more precise than the information that is directly available to the EPA. Because of this informational asymmetry, as well as the huge cost of cleanups and the strict, joint and several liability rule, the process of apportioning the liability shares among PRPs has been characterized by prolonged negotiation and extensive litigation. As a result, the cleanup of Superfund sites has proceeded at an unexpectedly slow pace. Dower (1990) estimated that on average it takes 12 years or more for a site to be completely cleaned up from the date of EPA awareness. Numerous experts on Superfund implementation have identified the litigation and negotiation process as the main reason for the slow cleanup, and call for ways of reducing the incentives for excessive litigation and negotiation.¹

However, as Dixon (1994) observed, the PRPs actually benefit from the delay because it reduces their *discounted* cleanup costs. Cost saving due to discounting may be significant; as reported by Birdsall and Salah (1993), prejudgment interest is the single largest cost item at a site and accounts for nearly one-third of the total costs involved.² Thus, discounting provides an incentive—in addition to disagreement about liability shares—for PRPs to litigate and negotiate, as legally acceptable ways to delay the cleanup process.

At most Superfund sites, the extent of contamination, and hence aggregate liability, is highly uncertain. It is, therefore, suboptimal for both the PRPs and the EPA to proceed very rapidly to

the cleanup phase of the remediation process; rather, time is needed to conduct field investigations that will reduce uncertainty about the nature of the pollution problem. If the investigation period is too short, inappropriate remediation strategies may be adopted: if the extent of contamination is overestimated, then excessive resources may be allocated to remediation; if it is underestimated, then the remediation plan may be inadequate, resulting in exacerbated health risks and costly revisions to the original cleanup schedule. The greater the uncertainty, therefore, the longer is the optimal investigation period, and hence the longer is the optimal delay in cleanup. When the EPA estimates the initial level of uncertainty, it must rely on the PRPs' documents and reports. By strategically misreporting their private information, PRPs can manipulate the EPA's decision and either hasten or delay proceedings.

This paper investigates the effects of the inherent information asymmetry, and its implications for government policy. To sharpen the analysis, we assume away the issue of apportioning liability shares among the PRPs. This serves to single out the other factors which contribute to the PRPs incentives to delay and the strategies the PRPs can pursue, and to identify which government policies will be appropriate.

Apart from differences between their respective rates of discount, there are other differences between the PRPs' and the EPA's objective functions that lead to divergences in their preferred cleanup schedules. In particular, they have different degrees of risk aversion and face liabilities that differ in both their nature and their extent. The EPA is less risk averse than the PRPs, due to risk pooling among the many sites an EPA office is overseeing. The PRPs only pay part of the off-site costs and the residual costs of a site. We will analyze the impacts of these differences on the speed of cleanup.

Current debates on Superfund implementation have not adequately addressed the role of uncertainty about the nature and extent of contamination. Zimmerman (1988) pointed out that the

uncertainty is extremely important in shaping the outcomes of the cleanup efforts and affecting the expected costs of the cleanup. Moreover, the role of uncertainty has been systematically downplayed by the parties involved. In contrast to Zimmerman (1988), our analysis recognizes that uncertainty is crucial not only because of the risk aversion of the parties involved, but more importantly because of an inherent information asymmetry about its nature. This asymmetry leads to inefficient decisions, and in many cases, to a delayed cleanup schedule.

To address the information asymmetry, we propose a mechanism for the EPA to extract accurate information from the PRPs. The EPA is concerned with both minimizing total expected cleanup costs and minimizing transfers to PRP's. These two concerns are shown to be in direct conflict, and their relative importance affects the efficiency of the final cleanup schedule. In addition, a lump-sum transfer scheme is not necessarily the optimal mechanism for inducing truth-reporting.

In Section 2, we formulate the problem of choosing the optimal cleanup schedule under uncertainty and investigate the factors affecting the PRPs' incentive to delay. Section 3 designs a Bayesian mechanism for the EPA to extract information from the PRPs. Section 4 examines different transfer mechanisms and their implications. Finally, Section 5 concludes the paper.

2 A model of Superfund cleanup

In general, contaminated sites are characterized by a multiplicity of attributes, including concentration, toxicity, dispersion, etc. In this paper, we will abstract from these complexities and assume that sites are fully characterized by the *volume* of total contamination. Let I denote the number of PRPs, indexed by $i = 1, \dots, I$. Prior to any investigation of the site, each PRP has private information about its contribution level. This information is assumed to be imperfect, however, due perhaps to the incompleteness of PRP records or to movement of the contaminant. Accord-

ingly, assume that i 's contribution m_i is a random variable with mean \bar{m}_i and variance σ_i^2 . Assume further that \bar{m}_i is common knowledge, while σ_i^2 is known only by agent i . We assume that the σ_i 's are independent of each other, so that no PRP can infer from its own information the extent to which other PRP's contributions are uncertain. The total volume of contamination at the site is denoted by m , where $m = \sum_i m_i$. Clearly, m is a random variable with commonly known mean $\bar{m} = \sum_i \bar{m}_i$. The variance of m , $\sigma^2 = \sum_i \sigma_i^2$, is not commonly known: each PRP has partial information about σ^2 (i.e., information about the variance of its own contribution), while the EPA has no independent information at all about the variance.

We assume that each PRP is uncertain about the level of its contribution to the site, but has private information about the *variance* of this level. We interpret this variable as the *degree* of the PRP's uncertainty about its contribution level. One natural specification is that PRP i 's contribution is uniformly distributed on an interval $[\bar{m}_i - \gamma_i, \bar{m}_i + \gamma_i]$, and that i alone knows γ_i . Clearly, this is equivalent to private information about the variance of i 's contribution. Given that the focus of this paper² is on the length of the investigation period and the timing of the cleanup, it is natural to emphasize information asymmetries relating to the variance of contributions, because the length of investigation is a function of the *quality* rather than the *content* of currently available information.

At the beginning of the planning stage, the EPA requests each PRP i to report σ_i , the variance of its own contribution. Based on the reports, the EPA determines a schedule of field investigation to generate further information (i.e. to reduce the variance). We assume that investigation of length t reduces the variance from σ^2 to $\frac{\sigma^2}{t\alpha}$, where α represents the effectiveness of the investigation.³ Since it is common knowledge that the EPA will choose an investigation length based on reported σ_i 's, each PRP can strategically misreport its uncertainty to manipulate the EPA's decision. Intuitively, if PRP i prefers to delay the cleanup beyond the socially optimal investigation period, it will report

a value for σ_i that exceeds the truth.

Since PRPs will typically mis-report their private information, our assumption that the EPA treats PRP reports as accurate is open to question. Our justification for proceeding in this way is that it enables us to focus attention on PRPs' incentives to manipulate information. This in turn will facilitate the construction of policies designed to offset or mitigate these incentives. Indeed, in Section 3 we show that the EPA can construct mechanisms that will elicit truthful reporting from the PRPs.

The cost of remediating a contaminated site can be represented by four categories: the on-site cost, the off-site cost, the investigation cost, and the residual cost. The *on-site cost* is defined as the cost of cleaning up the site, including both containment and removal/processing costs. It is increasing in total volume m . The *off-site cost* includes all costs incurred off the Superfund site, including in particular those resulting from health and environmental hazards. Off-site cost is increasing in *exposure* time, denoted by t , i.e., the time between the incidence of contamination and the completion of remediation. For simplicity, we identify exposure time with the length of the investigation period and denote both by t . That is, we assume that the EPA begins investigation immediately after the contamination occurs, and that remediation is accomplished instantaneously. (While neither assumption is plausible, they are imposed without loss of generality.) The *investigation cost* is the cost of field investigation, and increases in t . The *residual cost* is the cost that occurs due to the incompleteness of the remediation program. It is increasing in m . Therefore, the total remediation cost is increasing in both m and t . For simplicity, we assume that the cost function is affine in m , $C(m, t) = bm + c(t)$, with $b > 0$ and $c'(t) > 0$.

The present discounted cost with discount rate r has mean $e^{-rt}C(\bar{m}, t)$, and variance $b^2e^{-2rt}\sigma^2$. Assuming a negative exponential utility function and normal distribution of m , it is straightforward to show that a decision maker with subjective estimate, ν^2 , of the variance of volume m minimizes

w.r.t. t the expected utility loss, $V(t, \nu^2 | \bar{m}, r)$, defined as follows:

$$V(t, \nu^2 | r, \bar{m}) = e^{-rt} C(\bar{m}, t) + ae^{-2rt} \frac{\nu^2}{\alpha t} \quad (1)$$

where a is proportional to the decision maker's Arrow-Pratt risk aversion coefficient. We shall refer to a as the uncertainty cost coefficient. The first term is the discounted total cost of volume \bar{m} , and the second is the added cost of uncertainty in m due to risk aversion. We assume that the PRPs have the same degree of risk aversion, which may be different from that of the EPA.

We will assume throughout the paper that PRP's have previously agreed to bear liability in proportion to their commonly known *expected* contributions. That is, agent i agrees to bear the share k_i of total liability, where $k_i = \frac{\bar{m}_i}{\bar{m}}$. This assumption dramatically simplifies the analysis that follows. To see its implication, suppose that i 's liability share k_i were to depend on *realized* rather than expected contributions, i.e., suppose that $k_i = \frac{m_i}{m}$. Under this specification, k_i would be a random variable, positively correlated with total remediation cost, and the uncertainty facing PRP's would be higher than if the k_i 's were fixed in advance. The marginal benefit to PRP's from investigation would therefore be increased, and PRPs would have even greater incentives to induce the EPA to delay cleanup.

2.1 The EPA's choice based on reported information

At the beginning of the planning process, the i 'th PRP submits s_i to the EPA, representing the variance of its contribution. The EPA's initial information about the variance of the aggregate contamination level at the site is represented by $s^2 = \sum_i s_i^2$. The EPA then chooses the cleanup schedule to minimize its expected utility loss. Let $V_0(t, s^2)$ denote the EPA's expected utility loss

function, i.e.,

$$V_0(t, s^2) = V(t, s^2 | r_0, \bar{m}) = e^{-r_0 t} C(\bar{m}, t) + a_0 e^{-2r_0 t} \frac{s^2}{\alpha t} \quad (2)$$

Clearly, expression (2) is identical to (1) except that the generic variables ν and r are replaced by the EPA-specific parameters s and r_0 . The first order condition for a minimum of (2) can be written as:

$$C_t(\bar{m}, t) = r_0 C(\bar{m}, t) + a e^{-r_0 t} \frac{s^2}{\alpha t^2} + 2a r_0 e^{-r_0 t} \frac{s^2}{\alpha t} \quad (3)$$

where $C_t(\bar{m}, t) = \frac{\partial C(\bar{m}, t)}{\partial t}$ measures the marginal cost of investigation. The RHS measures the marginal benefits of investigation. An increase in the investigation period delays the time at which remediation costs are incurred, lowering the net present value of the total cost. This relationship is reflected in the first term on the RHS of (3). Moreover, a longer investigation period reduces uncertainty, reducing the expected utility loss. This relationship is reflected in the second term. A longer investigation period also delays the time at which the cost of uncertainty is incurred. This fact is reflected in the third term.

In the analysis that follows, we shall rewrite equation (3) as

$$C_t(\bar{m}, t) = r_0 C(\bar{m}, t) + B_0 s^2 \quad (4)$$

where

$$B_0 = \frac{a e^{-r_0 t}}{\alpha t^2} (1 + 2r_0 t) \quad (5)$$

2.2 The impacts of discount rate and liability share

In this section, we assume that the PRPs pay the true total cost of cleanup, and they have the same degree of risk aversion as the EPA. That is, the PRPs and the EPA have the same uncertainty cost coefficient a . This assumption will isolate the effect of the discount rate on the incentive to delay, by removing all other incentives to do so. As noted above, we assume that for each $i = 1, \dots, I$, PRP i has already agreed to bear the share k_i (defined on page 8) of the total liability. We also assume that the PRPs have the same discount rate, denoted by r_1 , which is presumed to exceed the EPA's discount rate, denoted by r_0 . Let $t(s^2)$ denote the investigation length that solves the first order condition (4). It represents the EPA's response to the reported information from the PRPs. Knowing the function $t(\cdot)$, and given $s_j^2, \forall j \neq i$, each PRP reports the value of s_i that will minimize the present discounted value of its own expected cost, V_i , where

$$V_i(t(s^2), \sum_{j \neq i} s_j^2 + \sigma_i^2) = k_i e^{-r_1 t(s^2)} C(\bar{m}, t(s^2)) + a k_i^2 e^{-2r_1 t(s^2)} \frac{\sum_{j \neq i} s_j^2 + \sigma_i^2}{\alpha t(s^2)} \quad (6)$$

Since a PRP's report is naturally bounded below by zero, PRP i obtains either an interior solution or a corner solution (i.e. $s_i^2 = 0$) in minimizing the expected cost (6). So that we can manipulate the first order conditions, we will focus on interior solutions of the PRP's problem. For s_i to be an interior minimum of expression (6), it must satisfy the first order condition:

$$C_t(\bar{m}, t) = r_1 C(\bar{m}, t) + B_i \left(\sum_{j \neq i} s_j^2 + \sigma_i^2 \right) \quad (7)$$

where

$$B_i = \frac{a k_i e^{-r_1 t}}{\alpha t^2} (1 + 2r_1 t) \quad (8)$$

A solution to the model exists if and only if there exists a vector $\{t, s_1, s_2, \dots, s_I\}$ that satisfies satisfy (4) and (7) for $i = 1, \dots, I$. Since for each PRP i , t has to satisfy both (4) and (7), a comparison of these two equations implies a relationship between σ_i and s_i . Any discrepancy represents misreporting by the PRP, and if $s_i > \sigma_i$, over-reporting occurs. Subtracting (4) from (7) and adjusting, we obtain the following expression for the solution to the PRP's problem:

$$s_i^2 = \frac{B_i}{B_0} \sigma_i^2 + \left(\frac{B_i}{B_0} - 1\right) \sum_{j \neq i} s_j^2 + \frac{(r_1 - r_0)C(\bar{m}, t)}{B_0} \quad (9)$$

where

$$\frac{B_i}{B_0} = k_i \frac{e^{-r_1 t}(1 + 2r_1 t)}{e^{-r_0 t}(1 + 2r_0 t)} \quad (10)$$

A sufficient condition for over reporting is $B_i \geq B_0$. If k_i , and hence $\frac{B_i}{B_0}$, is sufficiently small, it is possible that s_i will be less than σ_i , that is, PRP i will under-report his true variance. From equations (9) and (10), we see that there are two forces that affect a PRP's reporting incentives. Because its discount rate is higher than the EPA's, it has an incentive to over-report; because its individual liability share is less than unity, it has an incentive to underreport. Indeed, a PRP with a sufficiently small liability shares may in fact prefer to clean up more rapidly than the EPA, and will thus have an incentive to underreport its level of uncertainty.

While it is theoretically possible that PRP's may have exactly the right incentives to report truthfully, the following Proposition establishes that this is in fact highly unlikely. In fact, a necessary condition for truth-telling is that all PRPs have equal liability shares, i.e., that $k_i = k_j$, $\forall i, j$.

Proposition 1 *A necessary condition for a solution to exist is that*

$$k_i \left(\sum_{n \neq i} s_n^2 + \sigma_i^2 \right) = k_j \left(\sum_{q \neq j} s_q^2 + \sigma_j^2 \right) \quad i, j = 1, \dots, I \quad (11)$$

Proof: Equating the first order conditions for i and j in (9), we get $s_i^2 - \frac{B_i}{B_0} \sigma_i^2 - (\frac{B_i}{B_0} - 1) \sum_{n \neq i} s_n^2 = s_j^2 - \frac{B_j}{B_0} \sigma_j^2 - (\frac{B_j}{B_0} - 1) \sum_{q \neq j} s_q^2$. Cancelling out the terms without the coefficients $\frac{B_i}{B_0}$ and $\frac{B_j}{B_0}$, we get (11).
QED

An immediate implication of equation (11) is that as long as there are PRPs with unequal liability shares, some PRPs will misreport their private information. Since it is typically the case at Superfund sites that PRPs have diverse characteristics, Proposition 1 implies that truthful reporting will rarely occur. This result is intuitive. Except for their levels of uncertainty, σ_i^2 , the PRPs are differentiated only by their respective liability shares. PRPs with different liability shares will have different objective functions, different preferred investigation times and hence different incentives for reporting their private information to the EPA.

From (11), if $k_i \geq k_j$, then $\sum_{n \neq i, j} s_n^2 + s_j^2 + \sigma_i^2 \leq \sum_{q \neq i, j} s_q^2 + s_i^2 + \sigma_j^2$ or $s_i^2 - \sigma_i^2 \geq s_j^2 - \sigma_j^2$. That is, a PRP with higher share of liability is more likely to over-report its uncertainty than one with lower share of liability. If both PRPs over-report, the former will over-report more than the latter. This result further illustrates the role the liability share plays in affecting the PRP's reporting behavior. Moreover, we can identify a critical level of liability share, above which over-reporting occurs and below which under-reporting occurs.

Theorem 1 *Define the critical level of liability share k^c as*

$$k^c = A_0 - A_1 \frac{(r_1 - r_0)C(\bar{m}, t)}{s^2} \quad (12)$$

where

$$A_0 = \frac{e^{-r_0 t}(1 + 2r_0 t)}{e^{-r_1 t}(1 + 2r_1 t)}$$

$$A_1 = \frac{\alpha t^2}{ae^{-r_1 t}(1 + 2r_1 t)}$$

Then for PRP i , given s_j^2 , $j \neq i$,

$$s_i^2 = \frac{k_i}{k^c} \sigma_i^2 + \left(\frac{k_i}{k^c} - 1\right) \sum_{j \neq i} s_j^2 \quad \forall i = 1, \dots, I \quad (13)$$

Thus PRP i will over-report its uncertainty if $k_i > k^c$; under-report its uncertainty if $k_i < k^c$; and report the truth if $k_i = k^c$.

Proof: From (12), we get $(r_1 - r_0)C(\bar{m}, t) = \frac{(A_0 - k^c)s^2}{A_1}$. By substituting this equation into (9) and using $B_i/B_0 = k_i/A_0$ and $B_0 = A_0/A_1$, we obtain (13). The rest of the theorem is obvious from (13). QED

In (12), the critical share level, k^c , is decreasing in the total cost $C(\bar{m}, t)$ and the investigation effectiveness coefficient α , and increasing in the uncertainty cost coefficient a . More PRPs over report as k^c falls. Therefore, over-reporting is more likely when remediation is costly, when field investigation is productive and when the EPA and PRPs are less risk averse. As the cleanup cost rises, delaying saves more discounted cost for the PRPs (more than what is saved for the EPA). When field investigation is more productive, the PRPs have to over report more to achieve the desired delayed schedule. As a becomes lower, the cost due to uncertainty decreases for both EPA and the PRPs. But a comparison of (2) and (6) reveals that the cost decreases more rapidly with a for the EPA than for a PRP. Thus, the EPA will prefer a faster schedule than the PRPs, and the PRPs will have to over-report more to counterbalance this. Summarizing, the less risk-averse are

the PRP's and the EPA, the greater will be the incentives for PRPs to over-report.

Note that the EPA can compute k^c from information that is publicly available. Knowledge of this critical level would be useful, as it would allow the EPA to target those PRPs that are more likely to mis-report their uncertainty, and to scrutinize their reports more carefully. An implication of this paper is that the EPA should in particular target the PRPs with high liability shares, since these are the participants who are most likely to cause delays in the remediation process.

From (13), we can identify conditions under which PRP i obtains an interior solution (i.e. $s_i^2 > 0$):

Theorem 2 *If $k_i \geq k^c$ (so that PRP i over-reports or reports the truth), this PRP always obtains an interior solution (i.e. $s_i^2 > 0$) in its minimization of (6). If $k_i < k^c$ (so that the PRP under-reports), a necessary and sufficient condition for an interior solution (i.e. $s_i^2 > 0$) is*

$$k^c < k_i \left(1 + \frac{\sigma_i^2}{s^2 - s_i^2} \right) \tag{14}$$

That is, for an under-reporting PRP to obtain an interior solution, the PRP's liability share or its true variance should not be too low.

Theorem 1 focused on the incentives to delay facing an individual PRP. Whether or not the EPA's chosen investigation schedule will be more rapid or slower than its full-information schedule is determined by the *total* reported uncertainty s^2 . Remediation will be too slow if and only if $s^2 > \sigma^2$. Proposition 1 established the necessary conditions for the NE, but does not guarantee the existence of such an equilibrium.

Lemma 1 *In the solution to our model, the following is true:*

$$s^2 - \sigma^2 = [I - (\sum_i \frac{1}{k_i})k^c]s^2 \quad (15)$$

Proof: Substituting $\sum_{j \neq i} s_j^2 = s^2 - s_i^2$ into (13) and adjusting, we know $s_i^2 - \sigma_i^2 = (1 - \frac{k^c}{k_i})s^2$. Summing this up for all PRPs, we get (15). QED

Theorem 3 *If $k^c \leq \frac{I-1}{\sum_i 1/k_i}$, our model does not have a solution. Otherwise, $s^2 > \sigma^2$ if $k^c < \frac{I}{\sum_i 1/k_i}$, $s^2 < \sigma^2$ if $k^c > \frac{I}{\sum_i 1/k_i}$, and $s^2 = \sigma^2$ if $k^c = \frac{I}{\sum_i 1/k_i}$.*

Proof: Similar to the case of individual PRPs, we restrict the solution s^2 to be positive. For a positive solution to exist in (15), it must be that $I - (\sum_i \frac{1}{k_i})k^c < 1$. The relationship between s^2 and σ^2 is obvious from (15). QED

The nonexistence of a solution corresponds to the case where PRPs mutually reinforce their over-reporting incentives. From (13), we find that for lower k^c , a PRP is more responsive to other PRPs' reported uncertainty. If k^c is too low, a PRP responds to other PRPs' over-reporting by over-reporting much more. This PRP's over-reporting in turn reinforces other PRPs' over-reporting, causing nonexistence of a solution.

Corollary 1 *A mean-preserving spread of PRP's liability shares reduces the tendency toward over-reporting and the likelihood of nonexistence of a solution.*

Proof: Assume that $k_1 < k_I$. Let $\bar{k} = \frac{\sum_i k_i}{I}$ and consider the parameterized family of liability allocations $(h_1(\epsilon), \dots, h_I(\epsilon))$, where $h_i(\epsilon) = k_i + \epsilon(k_i - \bar{k})$. Note that $\sum_i h_i(\epsilon) = \sum_i k_i$, that for ϵ sufficiently small, the $h_i(\epsilon)$'s all lie between zero and one, and are strictly more dispersed than the k_i 's. Hence for positive but sufficiently small ϵ , $(h_1(\epsilon), \dots, h_I(\epsilon))$ is indeed a mean-preserving spread of the original liability allocation. To proof the corollary, it is sufficient to show that $\left. \frac{d \sum_i (h_i(\epsilon))^{-1}}{d\epsilon} \right|_{\epsilon=0}$ is positive and apply Theorem 3. Accordingly, we have

$$\begin{aligned} \left. \frac{d \sum_i (h_i(\epsilon))^{-1}}{d\epsilon} \right|_{\epsilon=0} &> - \sum_i \frac{(k_i - \bar{k})}{[k_i + \epsilon(k_i - \bar{k})]^2} \\ &= - \sum_i \frac{(k_i - \bar{k})}{\bar{k}^2} \\ &= 0. \end{aligned} \quad (16)$$

The strict inequality holds because $\bar{k} > [k_i + \epsilon(k_i - \bar{k})]$ if and only if $-(k_i - \bar{k}) > 0$ and $\bar{k} < [k_i + \epsilon(k_i - \bar{k})]$ if and only if $-(k_i - \bar{k}) < 0$. QED

Theorem 3 and its corollary establish that whether or not the investigation period exceeds the EPA's optimal length depends on the value of k^c and the magnitude and dispersion of the liability shares of individual PRPs. Delay is less likely to occur when k^c is high, when the k_i 's are each individually low, or when the allocation of liability across PRPs is relatively heterogeneous.

Theorem 3 implies that the existence of many *de minimis* PRPs actually helps expedite the cleanup process. Consequently, *de minimus* buyouts will increase delay unless the *de minimis* PRPs are required to pay a premium above their expected costs. To see this, suppose that the *de minimis* PRPs are bought out with a zero premium. In this case, the shares of the PRPs that remain will increase but the total expected cleanup cost will decrease by the same proportion. Thus, the first term in equation (6) will remain constant. However, the second term will increase, since the level of total uncertainty remains constant but each of the remaining PRPs is now held responsible for a large share of it. This prediction has important policy implications: *de minimis* buy-outs, currently employed by the EPA to reduce transaction costs,⁴ may have the side-effect of aggravating the cleanup delay, unless they occur at a sufficiently high premium. This effect has been systematically neglected in Superfund debates and policy formulation, and our results highlight its importance.

As the number of PRPs involved at a given site increases, each individual PRP's liability share will on average decline. Our model predicts that in this case, the likelihood of delay will decline. On the other hand, empirical evidence suggests that delay is *more* likely to occur at sites involving large numbers of PRPs. There are several possible reasons for this disparity. First, the transactions cost of remediation may be an increasing function of the number of PRPs involved. Second, sites involving more PRPs tend to be more expensive to clean up, so that the cost factor,

which increases delay, may dominate the effect of decreasing individual liability shares. Third, at any large site involving multiple parties, the PRPs are likely to form a steering committee to represent the collective interests of the group in negotiations. That is, in the context of the present model, the steering committee will act as a single decision maker, responsible for a very large share of the total liability. Hence it will have a much higher incentive to over-report than the individual PRPs that make up the committee.

2.3 Impacts of risk aversion and costs

In addition to the informational and discount rate differences discussed above, further incentives for misreporting arise from differences between the EPA's and the PRPs' degrees of risk aversion and their cost functions. Since the basic structure of our problem is unaffected by introducing these differences, we will merely discuss their implications rather than incorporate them into our formal model.

The theory of portfolio diversification implies that the PRP's are at least as risk averse as the government agency (the EPA) that regulates them. Each PRP is involved with only one Superfund site, while the regulating agency has jurisdiction over many. For the EPA, worse than expected outcomes at some sites will, on average, be offset by better than expected outcomes at others. Hence the EPA will be less concerned about outcome variability *at any given site* than a PRP whose only source of liability exposure is this particular site.⁵ This observation implies that PRP's will, other things being equal, prefer investigation periods that are at least as long as the EPA's optimal length. That is, risk aversion differences leads to more over-reporting.

The EPA, representing society, and the PRPs also bear different costs in the cleanup process. Even if the EPA can successfully force the PRPs to undertake the cleanup, very often the PRPs will not pay the total cost associated with a Superfund site. Typically, PRPs do not pay the total

cost associated with a Superfund site. First, there is usually an orphan share, for which they may or may not be held responsible. In addition, they are not typically held fully responsible for off-site and the residual costs. For example, CERCLA does not specify the rules for compensating for health hazards and property losses. Harmed parties must resort to private litigation to recover any damages they might have suffered. Since the plaintiff bears the burden of proof and the causal link between the PRPs' contributions and the damage is often difficult to establish, citizens are frequently deterred from litigating against PRPs by significant legal fees and a low probability of prevailing. Therefore, PRPs are held responsible for only a portion of the full off-site cost. Similarly, since the state government, together with the PRPs, are jointly responsible for monitoring and maintaining CERCLA site after the cleanup had been completed, PRPs' expected share of the residual cost is less than unity. The fact that the PRPs face a lower total cost than the EPA *reduces* their tendency to over-report: specifically, this fact will lower the value of s_i^2 in (9) and increase the value of k^c in (12).

The effect of investigation time on the off-site cost also differs for the PRPs and the EPA. When citizens sue for compensation for health damage, it is generally impossible to establish accurately the relationship between exposure time and damages incurred, and so, generally, the courts do not take into account exposure time in determining compensation packages. As a result, the cost function increases with time at a lower rate for the PRPs than for the EPA. This factor, together with the fact that the PRPs are more risk averse than the EPA, implies that other things being equal, the PRPs will prefer a longer investigation time than the EPA. Thus, the divergence between the EPA's and PRP's cost functions *increases* PRPs' incentives to over-report. It follows that effect of the divergence between the cost functions facing the PRPs and EPA is ambiguous.

Given (9) and Theorems 1 and 3, one might observe that the EPA could deduce each PRP's true level of uncertainty based on its reported uncertainty. However, if the PRPs knew that the

EPA were attempting to extract truthful information by following this formula, they would modify their reporting schedules accordingly. That is, they would no longer take (4) as given when they reported their uncertainties. This would lead to a new set of reporting incentives, and the EPA's information extraction problem would simply be transformed. In short, the EPA's information asymmetry problem cannot be solved simply by a more sophisticated inference procedure. How to extract the truthful information from the PRPs is the subject of the next section.

3 A Mechanism for Inducing Truthful Revelation

In this section, we construct a mechanism which will induce truthful reporting by PRPs. We follow the last section and assume that the PRPs do not pay the full cleanup cost, are more risk averse than the EPA, and have common discount rate $r_1 > r_0$. By the Revelation Principle, we can restrict our attention to direct mechanisms. We denote by θ_i the *type* of player i and set θ_i equal to the variance of i 's contribution, σ_i^2 . We assume that θ_i is distributed on $[\theta_i^l, \theta_i^u]$ with cumulative distribution function $F_i(\cdot)$, and that the distributions of the θ_i 's are independent of each other. For the usual technical reasons, we impose the so-called *monotone hazard-rate assumption*,⁶

$$(A3) \quad \frac{d}{d\theta_i} \left(\frac{f_i(\theta_i)}{1-F_i(\theta_i)} \right) \geq 0, \quad \forall i = 1, \dots, I.$$

The distribution of each θ_i is common knowledge. Denote the vector of types by $\theta = (\theta_1, \theta_2, \dots, \theta_I)$. In a direct revelation mechanism, each PRP reports to the EPA an admissible type (i.e., a value drawn from $[\theta_i^l, \theta_i^u]$), the EPA chooses a cleanup schedule $t(\theta)$, and makes a vector of transfers to the PRPs $w(\theta) = (w_1(\theta), w_2(\theta), \dots, w_I(\theta))$. The transfer may take the form of subsidized field investigation, full release from future liability, or direct monetary reimbursements for costs.

The mechanism may be formulated as an EPA-sponsored cleanup program to which PRPs contribute by following certain procedures. Since PRPs cannot be forced to participate in the

program, the government must still regulate the behavior of PRPs who choose not to participate. In fact, these regulations will affect the expected costs of non-participating PRPs. The government may coordinate the design of both the program and the regulations to provide appropriate incentives for PRP participation and to reduce the cost of inducing participation. This is a topic for future research.

The EPA's objective is to minimize both the utility loss of the cleanup and the total transfers to the PRPs. Let q be the weight the EPA puts on the utility loss, and $(1 - q)$ on the transfers, with $0 \leq q \leq 1$. Then, the optimal Bayesian mechanism for the EPA can be found by solving:

$$\min_{t(\cdot), w(\cdot)} R = E_{\theta} [qV_0(t(\theta), \sum_i \theta_i) + (1 - q) \sum_i w_i(\theta)] \quad (17)$$

s. t.

$$\theta_i = \arg \min_{\hat{\theta}_i} E_{\theta_{-i}} [V_i(t(\hat{\theta}_i, \theta_{-i}), \sum_j \theta_j) - w_i(\hat{\theta}_i, \theta_{-i})] \quad \forall i = 1, \dots, I \quad (18)$$

$$E_{\theta_{-i}} [V_i(t(\theta), \sum_j \theta_j) - w_i(\theta)] \leq \bar{V}_i \quad \forall i = 1, \dots, I \quad (19)$$

where $\theta_{-i} = (\theta_1, \dots, \theta_{i-1}, \theta_{i+1}, \dots, \theta_I)$, and \bar{V}_i is the expected utility loss PRP i suffers if it does not participate in the mechanism (as affected by the government regulation). Equation (18) is the Incentive Compatibility (IC) constraint, which specifies that PRP i has no incentive to mis-report given that all other PRPs are truthfully reporting. Equation (19) is the Interim Individual Rationality (IIR) constraint, which ensures that PRP i cannot do better by opting out of the mechanism.

Using standard arguments as in Fudenberg and Tirole (1991) and Laffont and Tirole (1993), we establish in Appendix A that the problem in (17)-(19) is equivalent to the following problem:

$$\min_{t(\cdot)} E_{\theta} \left\{ qV_0(t(\theta), \sum_i \theta_i) + (1-q) \sum_i [V_i(t(\theta), \sum_j \theta_j) + \frac{F_i(\theta_i)}{f_i(\theta_i)} \frac{\partial V_i(t(\theta), \sum_j \theta_j)}{\partial \theta_i} - \bar{V}_i] \right\} \quad (20)$$

where $E_{\theta} \frac{F_i(\theta_i)}{f_i(\theta_i)} \frac{\partial V_i}{\partial \theta_i}$ is the expected information rent that PRP i receives. Thus, equation (20) identifies the EPA's task as being to minimize the weighted sum of the EPA's expected cost, the PRPs' expected costs, and total expected information rents.

The first order condition for a solution to (20) is:

$$qE_{\theta} \frac{\partial V_0}{\partial t} + (1-q)E_{\theta} \sum_i \frac{\partial V_i}{\partial t} = -(1-q)E_{\theta} \sum_i \frac{F_i}{f_i} \frac{\partial^2 V_i}{\partial \theta_i \partial t} \quad (21)$$

Letting $\bar{\theta}_i$ denote the expected value of θ_i and integrating by parts, (21) can be rewritten as:

$$qE_{\theta} \frac{\partial V_0}{\partial t} + (1-q)E_{\theta} \sum_i \frac{\partial V_i}{\partial t} = (1-q)\text{MIR} \quad (22)$$

where MIR is the marginal information rent, defined by:

$$\text{MIR} = \frac{a_1(1+2r_1t)e^{-2r_1t}}{t^2} \sum_i k_i^2 (\theta_i^u - \bar{\theta}_i) \quad (23)$$

Figure 1 illustrates how optimal cleanup schedule is determined. The first best solution, given by $E_{\theta} \frac{\partial V_0}{\partial t} = 0$, is at t_0 , and the solution without any mechanism for extracting information is at t_1 . The solution under the optimal mechanism is at t^* which lies between t_0 and t_1 . If the EPA did not have to pay information rents to the PRP's, the optimal solution would be at \hat{t} . The effect of information rents is to increase the length of the investigation period still further beyond the

first-best level.

If the EPA is concerned only with preserving its financial resources (i.e., with minimizing Fund expenditures), and not with the cleanup schedule, then q would be set to zero and the solution to the optimal mechanism would be at \tilde{t} . This would be highly inefficient, because \tilde{t} is far to the right of t_0 but it would minimize the expected transfer to PRPs, thus best preserving the Fund. If the EPA is concerned only with the cleanup schedule, and not with preserving the Fund, then q would be set to unity, and the solution to the optimal mechanism would coincide with the first-best solution, i.e., t_0 . In this case, there would be no efficiency loss but, since t_0 is furthest from \tilde{t} , the expected transfer to PRPs would be very high. More generally, it can be seen from equation (22) that as q rises, the optimal cleanup schedule t^* moves closer to t_0 , and the expected transfer becomes higher. The weight q therefore represents a fundamental tradeoff between the objective of minimizing the total cleanup costs and the requirement of preserving the Fund.⁷

Figure 1 also illustrates how the tradeoff between cleanup efficiency and the magnitude of transfers depends on the degree of information asymmetry. A measure of this asymmetry is the width of the supports of the θ_i 's, i.e., the intervals $[\theta_i^l, \theta_i^u]$. If these intervals were very small, the EPA would have near perfect information about θ . In this case, θ_i^u would be close to $\bar{\theta}_i$, for each i , and the term MIR (see equation 23) would be close to zero. In Figure 1, the downward sloping curve would be very close to the horizontal axis, and the solution for the optimal mechanism would be very close to \hat{t} . Thus, not surprisingly, shrinking the supports of the θ_i 's increases efficiency while at the same time reducing the amount of information rents that have to be transferred to PRP's.

The nature of the tradeoff between efficiency and transfer size depends also on the structure of individual PRPs' liability shares (i.e., the k_i 's). This is evident from equation (23). A mean-preserving spread of the (k_i) 's will increase $\sum_i k_i^2$ and hence MIR. Similarly, if a number of small

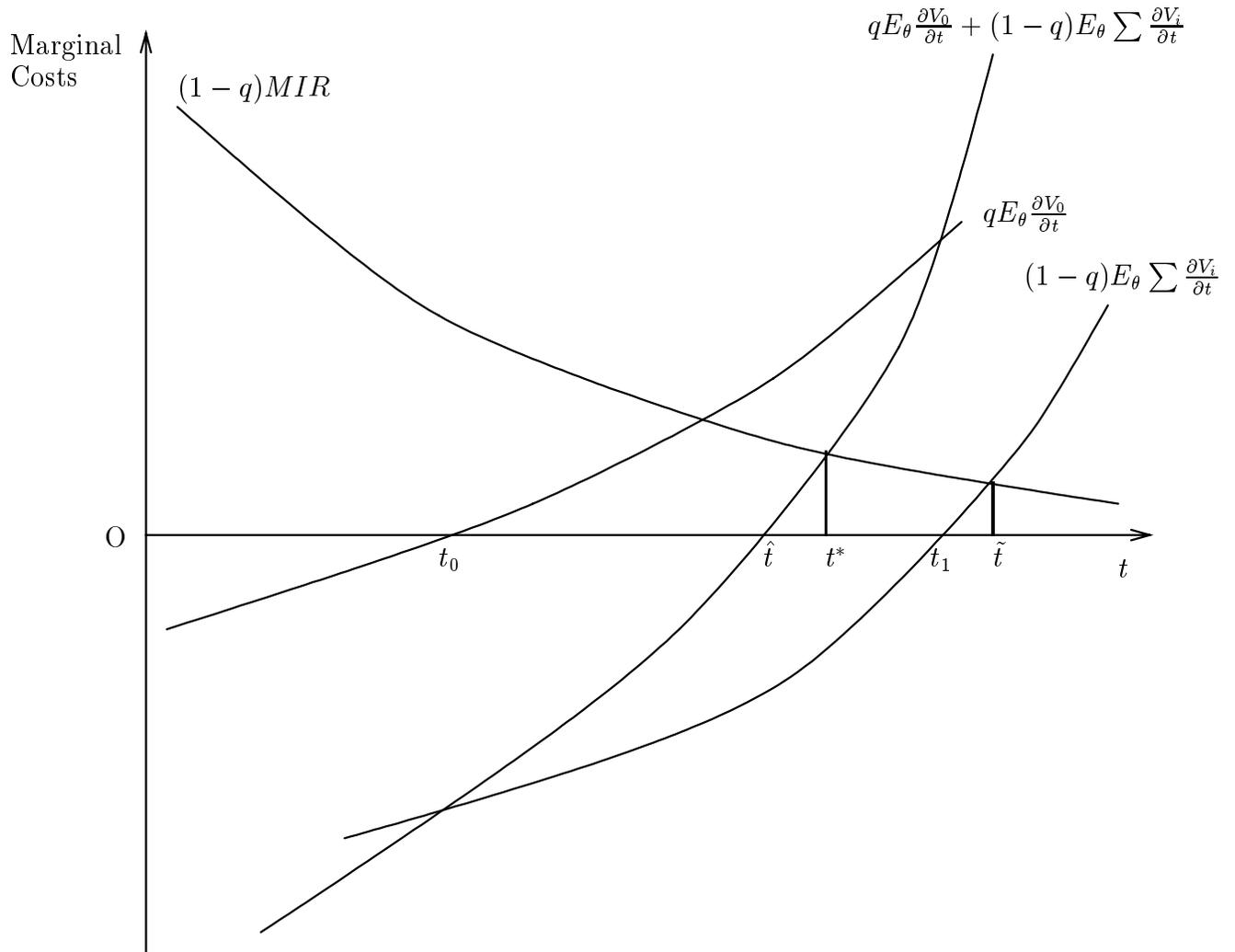


Figure 1: Optimal decision when PRPs have incentive to delay

PRPs are consolidated into a single PRP with a larger liability share, then MIR will also increase. Finally, MIR is also increasing in the uncertainty cost coefficient a_1 .

Note that we have not imposed a budget balancing constraint in the mechanism design problem. However, the EPA can affect the cost to PRPs of not participating in the mechanism (i.e., the \bar{V}_i 's), and in this way reduce the cost of cleanup sufficiently to achieve a balanced budget, if necessary. For example, the EPA can and does impose additional penalties on PRPs who do not settle with the EPA, including forcing them to bear partial responsibility for the orphan share.

4 Relative Efficiency of Different Transfers

In the mechanism described above, transfers to the PRPs took the form of lump-sum payments. However, this form of transfer may not be optimal, depending on the parameters of the problem. In this section, we consider alternative forms that the transfers might take, and compare them to the baseline developed in the preceding section. Specifically, we will consider transfers based on the orphan share and variable adjusted liability shares. The EPA has used orphan share to expedite the cleanup process. A variable adjusted liability share is a variant of the orphan share approach, in that each PRP faces different orphan shares.

A transfer scheme is more efficient if it can extract true information from the PRPs at a smaller cost to the EPA. Equations (36) and (37) in Appendix A indicate that truth-reporting and participation (and the fact that the EPA prefers less transfer) require the expected transfer of each PRP i to be

$$E_{\theta_{-i}} w_i(\theta) = E_{\theta_{-i}} V_i(t(\theta), \sum_j \theta_j) - \bar{V}_i + \int_{\theta_i}^{\theta_i^u} E_{\theta_{-i}} \frac{\partial V_i}{\partial \tilde{\theta}_i} d\tilde{\theta}_i \quad (24)$$

Thus to induce truthful reporting, any transfer scheme has to guarantee that the expected com-

pensation received by each PRP satisfies (24). Because PRPs' cost functions differ from the EPA's, the cost to the EPA of delivering a vector of transfers need not necessarily be equal the expected value of these transfers to the PRPs. Thus, to evaluate the relative efficiencies of different transfer schemes we must compare the expected cost to the EPA of delivering a given vector of transfers to the PRPs.

4.1 Orphan share

It is typically the case that PRP's are held responsible for the so-called *orphan share* of total contamination, i.e., the share which is contributed by parties that are now insolvent, or which cannot be attributed to any known PRP, and which then becomes the responsibility of the solvent PRPs. In practice, however, the EPA has frequently taken over responsibility for some fraction of the orphan share, as a way of inducing PRPs to cooperate. In this subsection we consider whether this kind of policy would be an effective way to induce truth-telling by PRPs. Specifically, suppose that the total orphan share is $\bar{p} = 1 - \frac{\sum_j \bar{m}_j}{\bar{m}}$ and that the EPA specifies a schedule of shares, $p(\cdot) < \bar{p}$, with the following interpretation: if the PRPs announced vector of types is θ , then the EPA will take responsibility for the fraction, $p(\theta)$, of total costs (or, equivalently, the fraction $p(\theta)/\bar{p}$ of the total orphan share). Note that from the perspective of the i 'th PRP, the part of the orphan share that remains i 's responsibility will be a random variable, because it depends on the other PRPs' announced types.

Suppose the other PRPs' announced types are $\bar{\theta}_{-i}$ and let $\tilde{p} = p(\theta_i, \bar{\theta}_{-i}) < \bar{p}$. Consider the effect on the i 'th PRP of an offer by the EPA to accept responsibility for \tilde{p} of total costs. This share corresponds to a contribution of expected volume, \tilde{m}_p , such that $\tilde{p} = \frac{\tilde{m}_p}{\bar{m}}$. Before this offer, PRP i 's share of the total cost, k_i , is equal to $\frac{\bar{m}_i}{\sum_j \bar{m}_j}$. After the offer, PRP i 's share of the total cost is reduced to $k'_i = (1 - \tilde{p}) \frac{\bar{m}_i}{\sum_j \bar{m}_j} = (1 - \tilde{p})k_i$. Thus, the EPA's action has reduced PRP i 's cleanup

liability from $k_i \tilde{C}(m, t)$ to $k'_i \tilde{C}(m, t) = (1 - \tilde{p})k_i \tilde{C}(m, t)$, and its new utility loss is

$$(1 - \tilde{p})k_i e^{-r_1 t} \tilde{C} + (1 - \tilde{p})^2 a_1 k_i^2 e^{-2r_1 t} \frac{\sum \theta_j}{\alpha t} \quad (25)$$

Expanding (25), and subtracting from it PRP i 's utility loss in the absence of the EPA's offer, i.e. (6), we see that for PRP i , a share schedule of $p(\theta)$ is equivalent to the following net transfer schedule $w_i(\theta)$:

$$w_i(\hat{\theta}_i, \theta_{-i}) = p(\hat{\theta}_i, \theta_{-i}) k_i e^{-r_1 t(\hat{\theta}_i, \theta_{-i})} \tilde{C}(\bar{m}, t(\hat{\theta}_i, \theta_{-i})) \\ + (2p(\hat{\theta}_i, \theta_{-i}) - p(\hat{\theta}_i, \theta_{-i})^2) a_1 k_i^2 e^{-2r_1 t(\hat{\theta}_i, \theta_{-i})} \frac{\hat{\theta}_i + \sum_{j \neq i} \theta_j}{\alpha t(\hat{\theta}_i, \theta_{-i})}. \quad (26)$$

Equation (26), together with (24), determines the share schedule, $p(\theta)$, that would induce the i 's PRP to report truthfully. Since different PRPs have different k_i 's and \bar{V}_i 's, the required schedule of p will not be the same for all PRPs. Thus a single schedule cannot induce truth-reporting. This is of course not very surprising: a single instrument ($p(\cdot)$) cannot achieve the multiple goals of inducing truth-telling by multiple distinct individuals. While this instrument is widely used, it is ineffective as a vehicle for extracting truthful information revelation from every PRP.

4.2 Variable adjusted liability share

An alternative means of implementing transfers to multiple PRPs is to adjust their liability shares individually. Suppose that PRP i 's liability share is adjusted by a schedule $p_i(\theta)$. That is, given a realization of $\bar{\theta}_{-i}$, a PRP of type i now bears only the fraction $k_i(1 - p_i(\theta_i, \bar{\theta}_{-i}))$ of the total cost. A policy of adjusting each PRP's share separately can be represented by a vector $P(\theta) =$

$\{p_1(\theta), \dots, p_I(\theta)\}$. Reasoning as in the preceding subsection, the adjustment schedule for PRP i is equivalent to a lump-sum transfer schedule given by equation (26), with p replaced by p_i . We will refer to w_i as the “adjustment benefit” received by PRP i due to the adjustment schedule $P(\theta)$.

Let $\tilde{P} = \{\tilde{p}_1, \dots, \tilde{p}_I\}$ be the realized vector of adjustments given a certain realization of PRP types, θ . The EPA’s expected utility cost becomes

$$(1 + \sum_i \tilde{p}_i k_i) \tilde{C}(t) e^{-r_0 t} + (1 + \sum_i \tilde{p}_i k_i)^2 a_0 \frac{\sum_i \theta_i}{\alpha t} e^{-2r_0 t} \quad (27)$$

Subtracting (2) from (27), we see that the adjustment vector \tilde{P} costs the EPA the following amount:

$$(\sum_i \tilde{p}_i k_i) \tilde{C}(t) e^{-r_0 t} + ((1 + \sum_i \tilde{p}_i k_i)^2 - 1) a_0 \frac{\sum_i \theta_i}{\alpha t} e^{-2r_0 t} \quad (28)$$

We define $w_0(\theta)$ as the “adjustment cost” to the EPA due to the adjustment schedule $P(\theta)$:

$$E_\theta w_0(\theta) = E_\theta [(\sum_i p_i k_i) \tilde{C}(t) e^{-r_0 t} + ((1 + \sum_i p_i k_i)^2 - 1) a_0 \frac{\sum_i \theta_i}{\alpha t} e^{-2r_0 t}] \quad (29)$$

Appendix B shows that a transfer scheme based on variable adjustments will be strongly more efficient (i.e. for any realization of θ) than a lump sum transfer scheme if for any level of t , the adjustment cost to the EPA is lower than the sum of the adjustment benefits to the PRPs, i.e. if $w_0 - \sum_i w_i < 0$ with probability one.⁸ Comparing the adjustment cost to the EPA (29) with the adjustment benefit received by the PRPs (26), we see three sources of difference between w_0 and $\sum_i w_i$. The EPA has a lower discount rate, which causes the EPA’s cost w_0 to be higher. The EPA faces a higher degree of uncertainty due to the transfer than the uncertainty that is reduced for the PRPs. In particular, we can show that $(1 + \sum_i p_i k_i)^2 - 1 > \sum_i (2p_i k_i^2 p_i^2 k_i^2)$. This factor also causes the EPA’s cost w_0 to be higher than the benefits the PRP received ($\sum_i w_i$). The third difference

relates to the uncertainty cost coefficient. The EPA is less risk averse so that $a_0 < a_1$. This factor causes the EPA's cost to be lower than the benefits received the PRPs. The net effect depends on the relative magnitude of the three factors. The lump-sum transfer tends to dominate the variable liability share mechanism when the required adjustment p_i 's are high, when the discount rates of the EPA and PRPs are very different, and when their degree of risk aversion is not very different. Otherwise, the variable liability share mechanism dominates the lump-sum transfer mechanism.

The optimal cleanup schedule under a variable adjustment mechanism will differ from the optimal schedule with lump-sum transfers. Appendix B gives a sufficient condition for the variable liability share mechanism enabling a faster cleanup schedule than the lump-sum transfer mechanism. In our current context, that condition requires $k_i \tilde{C} e^{-r_0 t} + 2(1 + \sum_j p_j k_j) k_i a_0 \frac{\sum_j \theta_j}{\alpha t} e^{-2r_0 t} < k_i \tilde{C} e^{-r_1 t} + (2 - 2p_i) k_i^2 a_1 \frac{\sum_j \theta_j}{\alpha t} e^{-2r_1 t}$, $\forall i$. We see that variable liability share mechanism leads to faster cleanup than lump-sum transfers when the adjustments are low, the discount rates r_0 and r_1 are not too different, and uncertainty cost a_0 and a_1 are much different.

The required transfer p_i is determined endogenously in the mechanism, depending on the cleanup cost and other cost parameters. It is therefore difficult to analytically classify the relative advantage of variable liability share versus lump-sum transfers based on the cost structure of the site. A numerical solution is needed for that purpose. Despite this difficulty, we have seen that in some situations, the variable adjusted liability share mechanism does dominate the lump sum transfer mechanism. The policy maker should thus be flexible when selecting a transfer mechanism to extract information from the PRPs.

5 Conclusion

The extreme delays in Superfund implementation have been blamed upon the excessive litigation and prolonged negotiations. This paper shows that the PRPs may have other incentives to delay, even if liability allocation and the choice of cleanup method are not an issue. These incentives arise because of differences among the parameters of the EPA's and the PRPs' objective functions. For example, the PRPs are expected to have higher discount rates than the EPA's and to be more risk averse than the EPA. Moreover, the EPA's costs increase with time at a faster rate than do the costs that the PRPs must bear. Taking into account all these differences, delay is more likely if the total cost associated with a Superfund site is high and if field investigation is an effective means of reducing uncertainties about the extent of contamination.

PRPs' incentives to delay are closely related to the magnitude of their liability shares. For an individual PRP, the higher the liability share, the greater is the incentive to delay. The paper identifies a critical level of liability share with the property that if a PRP's liability share exceeds this level, it will have an incentive to delay. Delay is also more likely if the PRPs' expected shares are more homogeneous.

Our findings have several policy implications. First, the EPA should exert more effort to prevent delay at large and expensive Superfund sites. In particular, the EPA should pay special attention to the quality of the reporting by PRPs with high liability shares. Second, the EPA should be clear that the liability shares that PRPs *expect* to bear not be significantly higher than the shares they actually bear. The third implication follows from the two preceding ones. The EPA has been encouraging PRPs to form steering committees and has been encouraging *de-minimis* parties to buy out their liability. While these practices reduce transaction costs, they also increase the likelihood of delay, and this side-effect should be taken into account by the EPA.

We also construct an optimal Bayesian mechanism that allows the EPA to induce truthful revelation by the PRPs. The properties of this mechanism depends on the EPA's preference for economic efficiency versus preservation of Fund resources, and there is a fundamental tradeoff between these two goals. We also demonstrate the importance of appropriately selecting the instrument through which PRPs are compensated. In particular, we show that a mechanism that involves lump sum transfers may in some cases be less efficient than one which relies on adjusting PRPs' liability shares.

APPENDIX

A Transforming the original mechanism design problem

We first simplify the (IR) constraint (19). Let

$$u_i(t(\theta), w_i(\theta), \sum_j \theta_j) = V_i(t(\theta), \sum_j \theta_j) - w_i(\theta) \quad (30)$$

and

$$U_i(\theta_i) = E_{\theta_{-i}} u_i(t(\theta), w_i(\theta), \sum_j \theta_j) \quad (31)$$

then, from the Envelope theorem,

$$\frac{\partial U_i(\theta_i)}{\partial \theta_i} = E_{\theta_{-i}} \frac{\partial u_i(t(\theta), w_i(\theta), \sum_j \theta_j)}{\partial \theta_i} = E_{\theta_{-i}} \frac{\partial V_i(t(\theta), \sum_j \theta_j)}{\partial \theta_i} = \frac{ak_i^2 e^{-2r_1 t}}{\alpha t} > 0$$

Therefore, given the allocation (the cleanup schedule and the transfer), the PRP i with higher uncertainty level will expect to incur higher cost, thus (19) is equivalent to $U_i(\theta_i^u) \leq \bar{V}_i \quad \forall i = 1, \dots, I$. Since the EPA wants to minimize its transfer to the PRPs, the (IR) constraint is equivalent to

$$U_i(\theta_i^u) = \bar{V}_i \quad \forall i = 1, \dots, I \quad (32)$$

We then transform the (IC) constraint (18). We first show that $u_i(t(\theta), w_i(\theta), \sum_j \theta_j)$ satisfies

the sorting condition, in particular,

$$\frac{\partial}{\partial \theta_i} \left(\frac{\partial u_i / \partial t}{\partial u_i / \partial w_i} \right) > 0 \quad (33)$$

Noting that $\frac{\partial u_i}{\partial w_i} = -1$, and $\frac{\partial u_i}{\partial \theta_i} = \frac{\partial V_i}{\partial \theta_i} = \frac{ak_i^2 e^{-2r_1 t}}{\alpha t}$, it is easy to verify that (33) is true. Theorems 7.2 and 7.3 in Fudenberg and Tirole (1991) then show that the (IC) constraint (18) is equivalent to:

$$\frac{dU_i(\theta_i)}{d\theta_i} = E_{\theta_{-i}} \left[\frac{\partial V_i}{\partial \theta_i}(t(\theta), \sum_{j \neq i} \theta_j + \theta_i) \right] \quad (34)$$

and

$$E_{\theta_{-i}} \frac{\partial t(\theta)}{\partial \theta_i} \geq 0 \quad (35)$$

where (34) is the result of a direct application of the envelope theorem.

We now transform the objective function (17) by considering the transformed (IC) and (IR) constraints. From (34) and (32),

$$\begin{aligned} U_i(\theta_i) &= U_i(\theta_i^u) - \int_{\theta_i}^{\theta_i^u} E_{\theta_{-i}} \frac{\partial V_i}{\partial \tilde{\theta}_i}(t(\tilde{\theta}_i, \theta_{-i}), \sum_{j \neq i} \theta_j + \tilde{\theta}_i) d\tilde{\theta}_i \\ &= \bar{V}_i - \int_{\theta_i}^{\theta_i^u} E_{\theta_{-i}} \frac{\partial V_i}{\partial \tilde{\theta}_i} d\tilde{\theta}_i \end{aligned} \quad (36)$$

The integration part on the RHS of (36) is the information rent of PRP i if its uncertainty is less than θ_i^u . Noting that

$$E_{\theta_{-i}} w_i(\theta) = E_{\theta_{-i}} V_i(t(\theta), \sum_j \theta_j) - U_i(\theta_i) \quad (37)$$

from (30) and (31), the objective function (17) can be rewritten as:

$$\begin{aligned}
R &= E_\theta q V_0 + (1 - q) \sum_i E_{\theta_i} (E_{\theta_{-i}} V_i - U_i) \\
&= E_\theta (q V_0 + (1 - q) \sum_i V_i) - (1 - q) \sum_i E_{\theta_i} U_i(\theta_i)
\end{aligned} \tag{38}$$

However, from (36) and applying integration by parts,

$$\begin{aligned}
E_{\theta_i} U_i(\theta_i) &= \bar{V}_i - \int_{\theta_i^l}^{\theta_i^u} \int_{\theta_i}^{\theta_i^u} E_{\theta_{-i}} \frac{\partial V_i}{\partial \theta_i} d\tilde{\theta}_i dF_i(\theta_i) \\
&= \bar{V}_i - F_i(\theta_i) \int_{\theta_i}^{\theta_i^u} E_{\theta_{-i}} \frac{\partial V_i}{\partial \theta_i} d\tilde{\theta}_i \Big|_{\theta_i^l}^{\theta_i^u} - \int_{\theta_i^l}^{\theta_i^u} F_i(\theta_i) E_{\theta_{-i}} \frac{\partial V_i}{\partial \theta_i} d\theta_i \\
&= \bar{V}_i - E_\theta \left(\frac{F_i(\theta_i)}{f_i(\theta_i)} \frac{\partial V_i}{\partial \theta_i} \right)
\end{aligned} \tag{39}$$

Substituting (39) into (38), we get (20), and under assumption (A3), (35) is not binding.

B Mechanism with variable adjusted liability share

Let $p = (p_1, \dots, p_I)'$ be the vector of variable adjustments. Now the mechanism design problem of (17)-(19) becomes

$$\min_{t(\cdot), p(\cdot)} R = E_\theta [q V_0(t(\theta), \sum_i \theta_i) + (1 - q) h(p(\theta))] \tag{40}$$

s. t.

$$\theta_i = \arg \min_{\hat{\theta}_i} E_{\theta_{-i}} [V_i(t(\hat{\theta}_i, \theta_{-i}), \sum_j \theta_j) - g_i(p_i(\hat{\theta}_i, \theta_{-i}))] \quad \forall i = 1, \dots, I \tag{41}$$

$$E_{\theta_{-i}}[V_i(t(\theta), \sum_j \theta_j) - g_i(p_i(\theta))] \leq \bar{V}_i \quad \forall i = 1, \dots, I \quad (42)$$

where $E_{\theta}h(p)$ is given by the right hand side (RHS) of (29), and $E_{\theta_{-i}}g_i(p_i)$ is given by the RHS of (26) with p replaced by p_i . $h(p)$ measures the equivalent net transfer from the EPA for variable adjustments p . $g_i(p_i)$ measures the equivalent transfer received from the EPA for PRP i when its adjustment is p_i .

We can transform the (IIR) and (IC) constraints in a way similar to that specified in Appendix A. In particular, (30)-(37) remain exactly the same with $w_i(\theta)$ replaced by $g_i(p_i(\theta))$. The only difference is that to achieve the required transfer, the expected cost to the EPA is different. In particular, (37) implicitly defines p_i as:

$$E_{\theta_{-i}}g_i(p_i(\theta)) = E_{\theta_{-i}}V_i(t(\theta), \sum_j \theta_j) - U_i(\theta_i) \quad (43)$$

A much stronger condition for (43) is to let it be satisfied for every possible θ_{-i} , in addition to in expectation. This would implicitly define p_i as:

$$p_i(\theta) = g_i^{-1}(w_i(\theta)) \quad (44)$$

where

$$w_i(\theta) = V_i(t(\theta), \sum_j \theta_j) + \int_{\theta_i}^{\theta_i^u} \frac{\partial V_i}{\partial \theta_i} d\tilde{\theta}_i - \bar{V}_i \quad (45)$$

Substituting p into $h(p)$ gives the cost to the EPA, and EPA's decision problem becomes

$$\min_{t(\cdot)} R = E_{\theta}[qV_0(t(\theta), \sum_i \theta_i) + (1 - q)h(\{g_i^{-1}(w_i(\theta))\}_{i=1}^I)] \quad (46)$$

Since with lump sum transfer, the EPA's cost of transferring w_i is simply $\sum_i w_i$, variable adjustment strictly dominates lump sum transfer if $h(g^{-1}(w)) < \sum_i w_i$, or $w_0 - \sum_i w_i < 0$.

In (46), the first order condition involves differentiating the expected transfer with respect to time t . In the case of lump sum transfers, the derivative is $E_{\theta} \sum_i \frac{\partial w_i}{\partial t}$. In (46), it becomes $E_{\theta} \sum_i \frac{h_i(p)}{g'_i(p_i)} \frac{\partial w_i}{\partial t}$, where $h_i(p) = \partial f(p) / \partial p_i$. A sufficient condition for variable adjustments to cause a sooner cleanup schedule in the optimal mechanism is $\frac{h_i(p)}{g'_i(p_i)} < 1, \forall i = 1, 2, \dots, I$.

Notes

¹See, for example, Dixon (1994) and Church and Nakamura (1993).

²Prejudgment interest is accumulated when the government or a PRP sues other PRPs for past cleanup costs.

³So long as investigation *does* reduce uncertainty in some way, our results are not sensitive to the precise specification of the investigation technology.

⁴See Dixon (1994).

⁵While this justification seems perfectly reasonable provided that the regulatory agency is has wide jurisdiction, it would be much less so if the agency's jurisdiction was very localized. In this case, if the agency's preferences truly reflected those of the local community it represented, it might well be considerably more risk averse than the PRP's. For example, local communities are likely to be much more risk averse about health hazards resulting from contamination than the corporations that caused these hazards, if only because of the possibility of bankruptcy.

⁶The condition is satisfied by most usual distributions, such as normal, uniform, logistic, exponential, etc.

⁷Evidence of this tradeoff can be observed by comparing the ways in which different regional EPA offices deal with PRPs. Some adopt a "public works approach," which focuses mainly on getting the cleanup done. The EPA conducts its own investigation and cleanup, and then pursues the PRPs for contributions. The cleanup is usually quick, but Fund resources tend to be exhausted very quickly. Other offices adopt a "litigation" approach, which is mainly concerned with Fund preservation. Under this approach, cleanup usually occurs more slowly (Church and Nakamura

(1993)).

⁸A less restrictive requirement for efficiency is to require that this inequality holds only in expectation.

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