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ENVIRONMENTAL BONDS AND ENVIRONMENTAL RESEARCH IN INNOVATIVE ACTIVITIES

CHARLES PERRINGS *

Department of Economics, University of Botswana, Private Bag 0022, Gaborone (Botswana)

ABSTRACT

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This paper considers the incentive to uncover potential future social costs of activities having no historical precedents. Since *ex ante* markets in the future external effects of historically unique activities are non-existent, the private incentives to uncover the possibility of "Thalidomide-type" results in such activities is weak. The paper discusses the value of sequentially determined environmental bonds as mechanisms for the generation of research funds in these cases, and derives measures for the calculation of such bonds.

1. INTRODUCTION

Decision-making under ignorance is now a well established—though not yet a core—area of microeconomic theory (see Shackle, 1955, 1969; Arrow and Hurwicz, 1972; Katzner, 1986, 1988a, b, 1989; Vickers, 1987). Little has yet been done to explore its significance for the management of environmental problems arising from economic activities. Given that many of the environmental effects of economic activities are unknown and unknowable in advance, however, it would appear to be an area in which the theory might usefully be applied. It is certainly of interest to understand how ignorance about future environmental costs might be accommodated in the decision to undertake innovative activities, and this paper addresses one aspect of such a problem. In particular, it addresses the decision-making process of environmental authorities faced with innovative private economic activities having uncertain future environmental effects.

The necessity for decisions taken in historical, irreversible time, to have unanticipated future effects is well recognized. It is also well recognized that

* Present address: Department of Economics, University of Auckland, Auckland, New Zealand.

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ignorance as to the future outcomes of present activities depends in large part on whether there exists a statistical record of the outcomes of similar activities in the past. It is quite intuitive that the difficulty of predicting the future outcomes of present activities will be greater the fewer the historical precedents for those activities. Activities for which there exist no historical precedents have been referred to by Shackle (1955, 1969) as "crucial". Because there exist no observations of the historical outcomes of such activities, there is no basis on which to identify their possible outcomes or to construct a probability distribution for those outcomes. The only source of statistical information on the future effects of such activities is the experimental (often basic) research done in advance of their introduction. This has not stopped such activities from being undertaken, of course. But it has meant that the information on which decisions have been made has most often been of a non-probabilistic kind.

The problem addressed in this paper arises from the fact that there is no reason to believe that the advance experimental research conducted by the agents proposing innovative activities will include all potential future costs conjectured to be relevant. Because the activities are historically unique there is no basis on which to establish *ex ante* markets in all potential future effects, hence there may be a range of unexpected social costs or benefits. Since the weakness of such markets opens up the possibility of "Thalidomide-type" surprises, it is worth considering whether there exists an incentive to research that will ensure that all socially relevant questions are asked about the future external effects of activities with no or few historical precedents. A passive learning process of the type discussed by Opaluch (1984) will certainly add information on the effects of innovative activities as those effects emerge, but it will not uncover in advance the probability of future social costs, unless there exist adequate incentives to research those costs.

This paper considers the use of the sequentially determined environmental bonds discussed in Perrings (1987) as incentives to research the socially interesting outcomes of innovative activities. Environmental bonds of one sort or another have long been used to encourage socially desirable methods of waste disposal in activities where the existing waste disposal technologies have a range of social effects, some more harmful than others. Environmental bonds have not previously been considered as research incentives, but it turns out that they are well suited to the purpose. The social insurance aspect of the bond is retained. This is, however, augmented by an uncertainty premium relating to the conjectured social costs of the activity. Since this leads to the sequential determination of the bond it offers both a direct incentive to undertake advance experimental research, and a means of influencing the timing of innovative activities with potentially severe social costs.

The paper approaches the analysis of the bond in stages. Section 2 considers the problem of decision making under ignorance as to the future external effects of activities with both innovative and non-innovative aspects. This covers certain issues previously addressed in the environmental economics literature by Dasgupta and Heal (1979) and Bockstael and Opaluch (1983), but focuses on work on the theory of decision-making under ignorance—particularly that of Shackle (1955, 1969) and Katzner (1986, 1988a, 1989). It suggests a measure of the value of uncertain future environmental effects which is a composite. In all cases it rests on an expected present social value of those future effects known to occur with some probability. On to this is grafted a measure of the conjectured present social value of the remaining uncertain outcomes. Section 3 introduces the environmental bond that has developed out of the materials-use fee first recommended by Mill (1972) and Solow (1971), and relates it to this measure. The intention is to fix the value to society of permitting innovative activities to proceed without research into possible future environmental costs. Section 4 considers the general incentive to undertake private research in a bond that is sensitive to the addition of new information on the effects of activities. Section 5 addresses the problem of the timing of innovative activities, and draws the analogy between the private decision to launch an innovative activity subject to a sequentially determined bond, and the more familiar search process in labour markets. A final section offers some concluding remarks.

2. DECISION-MAKING UNDER IGNORANCE OF THE FUTURE ENVIRONMENTAL EFFECTS OF INNOVATIVE ACTIVITIES

No activity is wholly innovative, wholly without historical precedent. Even the most pathbreaking activities rest on, or at least include, constituent actions which have been undertaken in the past. This means that while Shackle and Katzner quite properly point to the blanks in our knowledge of the future effects of innovative activities, there remains a kernal of accumulated evidence about the effects of constituent actions conducted within well-established boundary conditions. So long as the boundary conditions are reproduced, that evidence enables a probabilistic prediction of the outcome of similar actions in the future. Moreover, the more frequently an action has been replicated in the past the more confidence we may have in the probabilities attached to its outcomes in the future.

There remain, however, those constituent actions for which there exist no historical precedents, or for which the boundary conditions change as a result of the activity. It may not be possible to predict the set of outcomes of such actions, let alone the probability of each outcome in that set. Conditions of this sort gives rise to the problem of decision-making under ignorance, since they require the decision-maker to cope with real uncertainty (in the sense of Knight, 1921) as opposed to risk. No longer is it reasonable to assume that the collection of future states of nature or the probabilities of occurrence for the future states of nature is known. Nor is it reasonable to suppose that agents make decisions 'as if' they know the collection and probability distribution of those states of nature.

Ignorance, here, is a product both of our existence in "historical" time (Katzner, 1988b), and of the irreversibility of the entropic processes at the heart of economic activity (Georgescu-Roegen, 1971; Perrings, 1986, 1987). In historical time, only the past and the present may be observed and recorded, and neither can yield more than partial knowledge about the future. In a world governed by the laws of thermodynamics, the irreversibility of entropic processes ensures that the system will necessarily evolve through a sequence of states that are not predictable from its history.

Yet economic agents do make decisions in the face of ignorance about the future states of the world that may result from those decisions. Moreover, they do seek to do this in a rational way—to make sure that their decision is the "best" of all possible decisions. Despite the fact of their ignorance about the future states of the world, despite the fact that they cannot even guess at everything that might happen, decision-makers sift through a set of options and come down in favour of one. The theory of decision-making under ignorance addresses the question of how courses of action are selected when decision-makers have insufficient information to identify the probability of occurrence of the outcomes of those courses of action.

To approach the construction of a measure of the present value of the future environmental effects of innovative economic activities, it may be useful to summarize very briefly the characteristics of the process of decision-making under ignorance (for a rigorous statement of which see Katzner, 1988a, 1989). The central assumption underpinning this approach is that that decision-makers conjecture an admittedly incomplete set of future states, and form an opinion (on non-probabilistic grounds) about the degree of disbelief they would have in the occurrence of each option. They then act on this opinion. More particularly, to each subset of the incomplete list of future states of the world associated with any one activity, the decision-maker attaches a measure of the potential surprise that they imagine they would experience if it actually occurred. As with a probability distribution, all subsets are mapped into the closed interval [0,1] by the potential surprise function. The decision-maker is faced with the problem of selecting from a collection of utility-yielding or profit-yielding choice options, subject to the potential surprise of the future states of the world associated with each choice option.

The set of choice options is ordered by what Shackle refers to as an "attractiveness function" that registers the power of the outcome of each option to command the attention of the decision-maker. An option attracting the attention of the decision-maker may generate outcomes that are more appealing (implying that they confer gains) or less appealing (implying that they impose costs). For each option the decision-maker's attention will be drawn to two values: one associated with the least potentially surprising but most *appealing* outcome; and the other with the least potentially surprising but most *unappealing* outcome. The former is sometimes referred to as the "focus gain", and the latter as the "focus loss" of a decision. These are parallel but not identical to the expected benefits and expected costs of a risky decision. The focus gain describes the least unbelievable conjectured gains of an option. The focus loss describes the least unbelievable conjectured costs.

Accordingly, the power of an outcome to fix the attention of the decision-maker depends both on the utility or profit functions of decision-makers that order those outcomes, and on their uncertainty avidity/indifference/aversion (which need bear no particular relation to their risk avidity/indifference/aversion). Outcomes will attract greater attention, the smaller the potential surprise involved if decision-makers are uncertainty averse, and the larger the potential surprise involved if decision-makers are uncertainty avid. So for example, if the outcomes associated with a decision to construct nuclear power plants include the potential losses associated with a meltdown, and if the occurrence of a meltdown causes minimal potential surprise, then for an uncertainty-averse agent that would be the focus or conjectured loss of the decision (irrespective of the supposed probability of a meltdown).

The important feature of this approach to decision-making is not that the decision-maker's attention is drawn most strongly towards the prospect of unlimited gains or catastrophic losses. It is that whether such prospects lead to the corresponding choice-option depends on the degree of disbelief the decision-maker has in their occurrence, noting that the degree of disbelief or the potential surprise of an outcome is not equal to one minus the probability of that outcome. To pursue the example of the last paragraph, the Chernobyl meltdown may have had no effect on the probability of similar outcomes in similar plants (supposing that data existed to calculate such a probability), but it has had a major effect on the degree of disbelief that people have in the occurrence. Indeed, it is precisely where probabilities cannot be inferred that potential surprise informs decisions.

A second feature of decision-making under ignorance is that it is of necessity subject to revision. It is a continuous process, rather than a discrete act. In terms of the concern of this paper, the undiscounted value of the future environmental costs of innovative activities used by the decision-maker will comprise two parts. The first is the expected value of the environmental costs of those constituent actions for which the data set is sufficient to estimate a probability distribution. The second is the focus or conjectured losses of those constituent actions for which the lack of historical precedent compels the decision-maker to search out the least surprising but most unappealing outcome. The present value of such costs is obtained by discounting both parts at the appropriate rate. It therefore depends on four factors: (1) the (subjective) probability of each of an exhaustive list of outcomes of choice-options with respect to those constituent actions with historical precedents; (2) the potential surprise associated with each of an incomplete list of outcomes of choice-options with respect to those constituent actions without historical precedents; (3) the utility or profit function that explains the power of each option to command the attention of the decision-maker; and (4) the rate of discount.

None of these factors is independent of time. Traditionally, we treat the preferences and discount rate of the decision-maker *as if* they were invariant over time, but it is intuitive that neither of the remaining factors can be constant over time. As the constituent actions of an economic activity are undertaken a historical record of their outcomes will be built up, so changing the boundary between the known and unknown outcomes of the activity as a whole. The development of a history for each action is the basis of the Bayesian approach to the acquisition of probabilistic "knowledge". Repeated enumeration of events makes possible the development of increasingly robust hypotheses.

More interestingly, as the limits of what is "known" in a probabilistic sense change, so too does the list of outcomes of the remaining Shackle-crucial aspects of the activity. This may affect the potential surprise associated with the outcomes that are left, although it would be wrong to suggest that the potential surprise function would be affected in any determinate way. Outcomes may be added or dropped from the list without in any way changing the potential surprise associated with what is left. In all cases, however, the decision-making process will itself evolve over time in response to the changing information available to the decision-maker, and to the decision-maker's changing perceptions of that information. It is these two characteristics of decision-making under ignorance—that it rests on conjectured gains and losses, and that it is a continuous process rather than a discrete act—which determine the properties of the bonds discussed in this paper.

3. THE GENERAL CHARACTERISTICS OF AN ENVIRONMENTAL BOND

Following the insights in the work of Boulding (1966) and Ayres and Kneese (1969) as to the significance of the law of conservation of mass for the waste disposal problem, Mill (1972) and Solow (1971) separately advanced the idea of a "materials-use fee" to be levied on specified environmental resources at a rate equal to "the social cost to the environment if the material were eventually returned to the environment in the most harmful way possible" (Solow, 1971, p. 502). The fee was initially seen to be equivalent to the refundable deposit long used to encourage the recycling of potentially environmentally harmful products. In other words, it provided an incentive for private users of environmental resources to dispose of waste products in a socially preferred way. The fee was prompted by considerations similar to those behind the use of Pigouvian taxes for pollution control including, in particular, the non-existence of an enforceable contractual obligation on the users of a resource to perform in predictable way. Where the purchaser of a resource was contractually free to dispose of it in any of a number of ways, each with different known effects, the materials-use fee provided an incentive to adopt the least socially harmful method of disposal. The fee, now commonly referred to as an environmental bond, has subsequently been recommended wherever direct observation and detection of environmental damage are impossible or extremely difficult (cf. Baumol and Oates, 1975, 1979).

To establish the basis for the particular bonds recommended here it is useful to recall that whatever the form of the levy or subsidy attached to an expected environmental external effect, it may be interpreted first of all as a premium for social insurance against losses due to acts of commission or omission. Losses due to acts of commission are the consequence of negative external effects, losses due to acts of omission are the positive external effects forgone if a programme of activity generating such effects is not undertaken. In the case of non-innovative activities the data set may be assumed to be sufficiently rich that the expected value of an external effect is known, and the premium may be accurately computed. In the case of innovative activities, however, this is not true, and the levy may be expected to perform a rather different role.

More particularly, the environmental bond recommended here would have the following overlapping functions in respect of innovative activities: (1) it would register the value placed by the environmental authority on allowing an innovative activity to proceed without further research; (2) it would provide an incentive to innovating firms to research the future effects of their own activities; (3) since the bond would yield interest income it would generate public research funds in direct proportion to the public concern about the future effects of innovative activities; (4) it would determine the timing of an innovative activity; (5) it would encourage sufficient advance experimental research to eliminate, so far as is possible in an uncertain world, catastrophic but unsurprising conjectured outcomes;

and (6) it would insure society against the irreducible residuum of conjectured but unsurprising losses.

The motivation for introducing a bond with these functions is quite simple. Where the conjectured losses caused by any activity with potential future environmental effects are substantial, care should be taken in constructing a reliable data set on which to found decisions, and the decision-maker should be confident that the resources exist to meet the worst believable case—the focus loss. Focus losses that are insignificant warrant neither extensive initial investigation, nor comprehensive insurance. Focus losses that are catastrophic demand both a major research effort, and the mobilization of resources to meet the worst case.

The incentive effects of the bond will be considered momentarily. Before doing so it is worth underscoring the fact that although there will always exist a residuum of uncertainty in innovative activities, it is possible to limit that residuum through experimental research on those constituent actions of an innovative activity for which the actual boundary conditions can be both predicted and simulated. Even in activities with a large innovative element it is possible to build up a history for each of several constituent actions through experimental research under a range of boundary conditions that approximate the real environment within which the activity is to take place —adding something to what is known, with some probability, about the future effects of the activity.

4. THE INCENTIVE TO RESEARCH IN THE ENVIRONMENTAL BOND

The environmental bond discussed here is designed to stimulate research into the future effects of innovative activities. In this respect its most important characteristic is that it would vary over time with the conjectured or focus losses associated with the innovative (or unprecedented) aspects of activities. The research incentive in the bond derives from the fact that its value would change with the state of knowledge on the future effects of the activity. Given that the cost of the bond to the innovator would be proportionate to the value of the bond, and given that the value of the bond would be a function of the information available to the environmental authority, there would be a private incentive to increase investment in the acquisition of information wherever this was be expected to reduce the value of the bond.

A construction of the measure of the undiscounted value of of the future environmental costs of innovative activities is offered in the appendix to this paper for the discrete time, fixed coefficient case. This measure, denoted $Z_i(k, t)$, defines the external costs of activity i, expected to occur in period k, as estimated or conjectured in period t. This measure would be the basis for any bond imposed by an environmental authority as security against such effects. If the activity had innovative aspects, the measure $Z_i(k, t)$ would comprise two parts: one part relating to the expected losses due to the non-innovative parts of the activity, and one part relating to the conjectured or focus losses due to the innovative parts of the activity.

The bond imposed by the environmental authority would, similarly, depend on the same two things. Let $W_i(k, t)$ denote the bond levied in period t on the ith activity, for effects expected to occur in period k. We then have:

$$W_i(k, t) = f\left[EZ_i(k, t) + CZ_i(k, t)\right], \quad f' > 0, \quad f(0) = 0 \tag{1}$$

where EZ_i denotes the expected value of the environmental costs of the non-innovative parts of activity i, and CZ_i denotes the conjectured value of the environmental costs of the innovative parts of the same activity. If the bond were imposed on an activity undertaken at time 0, this implies that it could be revised up to k times before it was surrendered or returned, i.e. $t = 0, \dots, k$.

Assuming that transactions costs were zero, the cost of the bond to the firm which is required to post it would equal the revenue to the environmental authority with which it was posted. In period t this would be $rW_i(k, t)$, r denoting the rate of interest. The bond would accordingly generate resources to research the future outcomes of present activities in two rather different ways.

First, interest income on the bond would provide a fund for public research that would vary directly with the severity of the conjectured costs of an activity. The greater the focus loss of a decision to undertake the activity, the greater the resources that would be committed to improving the quality of public information on its potential outcomes.

Second, the incentive to minimize the private cost of the bond would prompt innovators to commit resources to private research. This arises from the fact that while the bond would be set by the environmental authority (or body arbitrating between the environmental authority and the innovating firm), its value in any one period would not be independent of the research conducted by the innovating agent(s).

Consider the second incentive. The total undiscounted private cost of the bond to the agent undertaking activity i during the life of the bond would be:

$$\Sigma_t rW_i(k, t) + W_i(k, k); \quad t = 0, \dots, k$$

This is just the sum of the opportunity cost of the bond plus its value at the surrender date. Since the value of the bond in each period would be, in part, a function of private research expenditures in previous periods, a profit maximizing firm would increase its own research expenditures up to the point at which the marginal expenditure on research equalled the expected marginal reduction in the cost of the bond.

Assume, without loss of generality, a single period lag between research expenditures and adjustment in the size of the bond. The value of the bond in period $t+1$, $W_i(k, t+1)$, would then vary independently with both public and private expenditures on research undertaken in period t on effects expected to occur at time k; $rW_i(k, t)$ and $R_i(k, t)$ respectively. Thus:

$$W_i(k, t+1) = g[rW_i(k, t)] + h[R_i(k, t)] \tag{2}$$

In principal the sign of both g' and h' in eq. 2 should be indeterminate, since research into the possible future effects of innovative activities should be open to all results. In practice, however, environmental research suffers acutely from the problem of moral hazard and h', in particular, would tend to be non-positive. In other words, privately funded research would tend to downplay the environmental costs of innovative activities. While there may be a problem of moral hazard on both sides, it is assumed that private agents have no insight into the effect of public research on the value of the bond. The net expected benefits to the firm of private expenditure on research in a two period problem, $E\pi_i(t+1, t)$, would then be the *reduction* in the expected cost of the bond due to private research findings, $r\{h[R_i(k, t-1)] - Eh[R_i(k, t)]\}$, less the costs of that research, $R_i(k, t)$. That is:

$$E\pi_i(t+1, t) = r\{h[R_i(k, t-1)] - Eh[R_i(k, t)]\} - R_i(k, t). \tag{3}$$

from which it is immediate that the first-order conditions for the maximization of the expected net benefits require that:

$$-r\frac{d}{dR_i(k, t)}Eh[R_i(k, t)] = 1, \tag{4}$$

or that private research expenditure in period t should increase up to the point where it is equal to the reduction in the expected cost of the bond in period $t+1$. For more complicated cases the same holds true. Profit maximization requires equality between the marginal costs and benefits of research.

5. ADVANCE RESEARCH AS A SEARCH PROCESS

A second aspect of the private research incentive in the bonds proposed in this paper concerns the role of the bond in stimulating or stopping advance research. Advance research is that research on the future effects of an innovative activity undertaken before the activity is launched. In other words it is research that may be expected to modify the value of the bond that would be levied at some future date if the activity were to take place at that date.

To take a very simple case assume that the technical coefficients of production are fixed. The expected revenue of a firm considering launching an innovative activity in period t is:

$$y_i(t)\boldsymbol{b}_i E\boldsymbol{p}(t+1),$$

where $\boldsymbol{b}_i$ denotes the vector of output coefficients in activity i, $y_i(t)$ denotes the planned level of activity, and $E\boldsymbol{p}(t+1)$ denotes the expected output price vector. Expected costs in the same period are:

$$y_i(t)\boldsymbol{a}_i E\boldsymbol{p}(t)$$

where $\boldsymbol{a}_i$ denotes the vector of input coefficients in the activity, and $E\boldsymbol{p}(t)$ denotes the expected input price vector. If the activity involves environmental costs on which a bond is payable, expected profits in period t would be:

$$E\pi_i(t) = y_i(t)\left[\boldsymbol{b}_i E\boldsymbol{p}(t+1) - \boldsymbol{a}_i E\boldsymbol{p}(t)\right] - rEW_i(k, t). \tag{5}$$

For a single period programme of production, if $E\pi_i(t) \geqslant ry_i(t)\boldsymbol{a}_i E\boldsymbol{p}(t)$ the activity is expected to be economic, and will be undertaken. If $E\pi_i(t) < ry_i(t)\boldsymbol{a}_i E\boldsymbol{p}(t)$ it is expected to be uneconomic, and will not be undertaken. For a multi-period programme of production the story is similar, with the present value of the programme required to be greater than or equal to the discounted opportunity cost of the capital invested [described in period t by $ry_i(t)\boldsymbol{a}_i\boldsymbol{p}(t)$].

The role of the bond in this case is similar to the observed wage offer in a job search process. It determines when the firm should stop its advance research into the future effects of an innovative activity and launch that activity. Staying with the single period programme of production for ease of exposition, if follows from eq. 5 that for the programme to be expected to be economic it is required that:

$$EW_i(k, t) \leqslant \frac{1}{r} y_i(t)\left[\boldsymbol{b}_i E\boldsymbol{p}(t+1) - (1+r)\boldsymbol{a}_i E\boldsymbol{p}(t)\right]. \tag{6}$$

If eq. 6 does not hold the programme will be expected to be uneconomic in period t, and the firm will not consider implementing it. The term on the right-hand side of eq. 6 accordingly represents the maximum value of the bond consistent with the expected profitability of the programme in period t. Only if the expected value of the bond is less than or equal to this maximum value will the firm consider implementing the programme. Only if the actual value of the bond levied by the environmental authority is less than or equal to the expected value of the bond will a programme under consideration actually be implemented.

The analogy of this to a search problem is obvious. Denoting $F[\pi_i(t)]$ to be the maximum return attainable on a programme under consideration for implementation in period t, and $\overline{W}_i(k, t)$ to be the maximum acceptable value of the bond equal to the RHS of eq. 6, we have:

$$F[\pi_i(t)] = y_i(t)[b_i Ep(t+1) - a_i Ep(t)] - r\min[W_i(k, t); EW_i(k, t)]. \tag{7}$$

The maximum attainable return is the expected profits from production less the minimum of the actual or expected cost of the bond. The decision rule is quite simple. If $W_i(k, t) > \overline{W}_i(k, t) \geqslant EW_i(k, t)$, the actual value of the bond is greater than its maximum acceptable value, the firm will not implement the programme and will continue to research its future costs (or will consider abandoning it altogether). If $W_i(k, t) \leqslant EW_i(k, t) \leqslant \overline{W}_i(k, t)$ the firm will implement the programme. The environmental authority would thus have an instrument for delaying an innovative activity conjectured to have negative future social costs where it was thought that further research was desirable.

6. CONCLUDING REMARKS

It is widely held that the external effects of information, together with problems of appropriability and moral hazard, ensure that competitive markets will lead private agents to avoid investment in basic research, and to overspecialize in applied research (cf. Dasgupta and Heal, 1979). This creates particular problems in innovative activities with environmental effects that are conjectured to occur with some delay. Such delays are significant for a number of reasons. The most important of these is that they heighten uncertainty and so encourage a myopic vision of the future. The more myopic the vision of competitive agents, the less the incentive to undertake basic experimental research. Moreover, the more that private rates of time preference are driven above the social rate of time preference, the lower the probability that internalization of external effects by the assignment of private property rights will be socially optimal (Fisher, 1981; Seneca and Taussig, 1984; Perrings, 1987).

Since there is no reason to believe that private agents will invest in experimental research at socially optimal levels in cases where the external effects of current activities may be significantly delayed, it is worth considering whether there exist incentives to ensure that due weight is given to the social importance of research in innovative activities. This paper constructs a measure of the present social value of the future expected and potential external effects of non-innovative and innovative activities, respectively, and treats this as a proxy for the social value of research. It is suggested that this measure forms the basis for the sequential calculation of environmental bonds.

Given the motivation of the paper, two properties of such environmental bonds turn out to be of particular interest. First, by implicitly weighting the "worst case" or the maximum conjectured loss associated with any activity at unity, the bonds enable a risk averse society to signal to private agents the social value placed on advance experimental research in cases where the outcome is uncertain. Second, given that the expected value of the future external effects of activities is contingent on the set of current relative prices facing the agents undertaking those activities, the bonds enable the environmental authority to change the distribution of outcomes by changing current relative prices. These properties would seem to make the bonds useful both in preventing innovators from evading the potential costs of activities undertaken in ignorance, and of avoiding the worst of those potential costs.

Finally, it is worth noting that the irreducible uncertainty of innovative activities in an evolutionary system means that there will always exist the possibility of surprise. The environmental bonds recommended in this paper would not eliminate this possibility, but they would provide the incentive to firms to anticipate so far as possible the future outcomes of present activities, regardless of the time-horizon employed in their own planning process.

APPENDIX

Let the technology of the ith economic activity in period t be described by the n-dimensional time-indexed row vectors of input and output coefficients, $\boldsymbol{a}_i(t)$ and $\boldsymbol{b}_i(t)$. The level of activity in period t is denoted $y_i(t)$. Assume that m components of these vectors, $m \leqslant n$, refer to economic (positively valued) inputs and outputs, and that the remaining $n-m$ components refer to non-economic (zero-valued) inputs and outputs. The latter describe inputs and outputs for which there exist no well-defined private property rights—for whatever reason. We can thus identify a corresponding time-indexed vector of prices, $\boldsymbol{p}(t)$, m components of which are positive, all others being equal to zero. Since the list of economic inputs and outputs is incomplete for $m < n$, there are up to $n-m$ inputs and outputs which are unobserved through the price system. If these non-economic inputs or outputs are linked backwards or forwards to other economic activities we have the familiar problem of external effects.

Consider, the construction of measures for these effects. Let us first take only those activities or aspects of activities for which there exist some historical precedents. Assume that the delay between the external effect of activity i on activity h is k periods. This defines the "time-distance" between the activities. A unit increase in the current level of activity in i may be assumed (on the basis of historical experience) to generate a set of s possible outcomes in activity h in period k. That is, we can identify a set of S values for the output vector $\boldsymbol{b}_h(k)$ dependent on the level of activity $y_i(0)$. We may denote this set of values $\boldsymbol{b}_{h,i}^s(k, 0)$, $s = 1, \ldots, S$. It is subject to the probability distribution $\pi_{h,i}^s = \pi[\boldsymbol{b}_{h,i}^s(k, 0)]$, with $\pi_{h,i}^s > 0$, and $\Sigma_s \pi_{h,i}^s = 1$. We thus have complete (historically acquired) knowledge of the set of outcomes possible for activity h in period k as a result of the level of activity in i in period 0. From this it is possible to define the output losses or gains associated with that level of activity. We denote these output losses or gains

$$E\Delta \boldsymbol{b}_{h,i}^s(k, 0) = E\boldsymbol{b}_h^s(k, 0) - E\boldsymbol{b}_{h,i}^s(k, 0) \tag{A1}$$

where $E\boldsymbol{b}_h^s(k, 0)$ is expected output in activity h if the level of activity in i were currently zero, and $E\boldsymbol{b}_{h,i}^s(k, 0)$ is expected output in activity h when the activity in i is at its actual level.

We may now use this measure to establish the value to society of the general environmental external effects of activity i in period k. Let $x_{h,i}(k, 0)$ denote the welfare cost of the risk of loss of output in activity h in period k as a result of the current level of activity i. Further, let the weighting factor for the risk attached to expected future environmental external effects be a function, ϕ, of this welfare cost. The (undiscounted) expected social value of the external effect of the current level of activity in i on h at time k, denoted by $EZ_{h,i}(k, 0)$, may accordingly be defined as follows:

$$EZ_{h,i}(0) = y_h(k)\{E\Delta \boldsymbol{b}_{h,i}^s(k, 0)\phi[x_{h,i}(k\ 0)]\}E\boldsymbol{p}(k+1) \tag{A2}$$

where $y_h(k)$ is the planned level of activity in h at time k, and $E\boldsymbol{p}(k+t)$ is the expected output price vector at time k.

To obtain a present social value for the general future external effects of the activity i at time k, we need only to discount this and to sum over all affected downstream activities. That is:

$$\begin{aligned} EZ_i(k, 0) &= \Sigma_h EZ_{h,i}(k, 0) \\ &= (\Sigma_h y_h(k)\{E\Delta \boldsymbol{b}_{h,i}^s(k, 0)\phi[x_{h,i}(k, 0)]\}E\boldsymbol{p}(k+1))(1+r)^{-k} \end{aligned} \tag{A3}$$

Now consider the corresponding measure for the external effects of innovative activities, in which decision-makers are in ignorance about the outcomes of those activities. There is no basis on which to construct a probability distribution for the effects of current activity in i on any other activity since there are no historical precedents. We have seen that in such cases decision-makers will have their attention drawn to the focus-loss or focus-gain of the activity—to the least unbelievable conjectured losses or gains from the activity. So for the effects of current innovative activity in i on activity h at time k we may identify two additional physical measures: $C_L \Delta \boldsymbol{b}_{h,i}(k, 0)$, which describes the focus-loss, and $C_G \Delta \boldsymbol{b}_{h,i}(k, 0)$, which describes the focus gain.

We have already assumed that there exists an expected output potential for the activity h in period k when $y_j(0) = 0$, and have denoted this $E\boldsymbol{b}_h^s(k, 0)$. There are thus four cases of interest:
(i) if $C_G \Delta \boldsymbol{b}_{h,i}(k, 0) = C_L \Delta \boldsymbol{b}_{h,i}(k, 0) = E\boldsymbol{b}_h^s(k, 0)$, current activity in i will be conjectured to have no effect on activity h in period k;
(ii) if $E\boldsymbol{b}_h^s(k, 0) > C_G \Delta \boldsymbol{b}_{h,i}(k, 0) \geqslant C_L \Delta \boldsymbol{b}_{h,i}(k, 0)$ current activity in i will be conjectured to have negative effects on activity h in period k;
(iii) If $C_G \Delta \boldsymbol{b}_{h,i}(k, 0) \geqslant C_L \Delta \boldsymbol{b}_{h,i}(k, 0) > E\boldsymbol{b}_h^s(k, 0)$ current activity in i will be conjectured to have positive effects on activity h in period k; and
(iv) If $C_G \Delta \boldsymbol{b}_{h,i}(k, 0) > E\boldsymbol{b}_h^s(k, 0) > C_L \Delta \boldsymbol{b}_{h,i}(k, 0)$ current activity in i will be conjectured to have effects that may be either positive or negative.

In each of the last three cases there will be potential gain in improving the quality of the information required to make a decision.

By similar construction to eq. A3, and assuming uncertainty aversion, the conjectured present social value of the environmental costs of the current level of the ith activity occurring at time k is:

$$
\begin{aligned}
C_L Z_i(k, 0) &= \Sigma_h C_L Z_{h,i}(k, 0) \\
&= \{\Sigma_h y_h(k)[C_L \Delta \boldsymbol{b}_{h,i}(k, 0)]\, Ep(k+1)\}(1+r)^{-k} \qquad \text{(A4)}
\end{aligned}
$$

$i = 1, \dots, m.$

This may be interpreted as the focus or conjectured loss associated with the unresearched implementation of the ith activity in the present period. Accordingly, for activities with both innovative and non-innovative aspects the appropriate measure is ungainly but straightforward

$$
\begin{aligned}
& EZ_i(k, 0) + C_L Z_i(k, 0) \\
&= (\Sigma_h y_h(k)\{E\Delta \boldsymbol{b}_{h,i}^s(k, 0)\phi[x_{h,i}(k, 0)] \\
&\qquad + [C_L \Delta \boldsymbol{b}_{h,i}(k, 0)]\}\, Ep(k+1))(1+r)^{-k} \qquad \text{(A5)}
\end{aligned}
$$

This last measure will be the relevant one wherever there do not exist sufficient observations to estimate an expected value for the future costs of present activities within acceptable limits of confidence. In all such cases the expected present social value of the future effects of current activities should be augmented by the conjectured losses associated with the Shackle-crucial or innovative aspects of those activities.

REFERENCES

Arrow, K.J. and Hurwicz, L., 1972. An optimality criterion for decision-making under ignorance. In: C.F. Carter and J.L. Ford (Editors), Uncertainty and Expectations in Economics. Kelly, Clifton, N.J., pp. 1–11.

Ayres, R.U. and Kneese, A.V., 1969. Production, consumption and externalities. Am. Econ. Rev., *59*: 282–297.

Baumol, W.J. and Oates, W.E., 1975. The Theory of Environmental Policy. Prentice Hall, Englewood-Cliffs, N.J.

Baumol, W.J. and Oates, W.E., 1979. Economics, Environmental Policy, and the Quality of Life. Prentice Hall, Englewood-Cliffs, N.J.

Bockstael, N.E. and Opaluch, J.J., 1983. Discrete modelling of supply response under uncertainty: The case of fishery. J. Environ. Econ. Manage., *10*: 125–137.

Boulding, K.E., 1966. The economics of the coming spaceship earth. In: H. Jarrett (Editor), Environmental Quality in a Growing Economy. Johns Hopkins Univ. Press, Baltimore, Md., pp. 3–14.

Dasgupta, P.S. and Heal G.M., 1979. Economic Theory and Exhaustible Resources. Cambridge Univ. Press, Cambridge.

Fisher, A.C., 1981. Resource and Environmental Economics, Cambridge Univ. Press, Cambridge.

Georgescu-Roegen, N., 1971. The Entropy Law and the Economic Process. Harvard Univ. Press, Cambridge, Mass.

Katzner, D.W., 1986. Potential surprise, potential confirmation and probability. J. Post-Keynesian Econ., *9*: 58–78.

Katzner, D.W., 1988a. The Shackle-Vickers Approach to Decision-Making in Ignorance. Univ. of Massachusetts, Amherst, Mass. (mimeograph).

Katzner, D.W., 1988b. The Role of Empirical Analysis in the Investigation of Situations Involving Ignorance and Historical Time. Univ. of Massachusetts, Amherst, Mass. (mimeograph).

Katzner, D.W., 1989. The comparative statics of the Shackle-Vickers approach to decision-making in ignorance. In: T.B. Fomby and T.K. Seo (Editors), Studies in the Economics of Uncertainty: in Honour of Joseph Hadar. Springer, Berlin (in press).

Knight, F.H., 1921. Risk, Uncertainty and Profit. Houghton-Mifflin, Boston, Mass.

Mill, E.S., 1972. Urban Economics. Scott Forseman, Glenview, Ill.

Opaluch, J.J., 1984. Dynamic aspects of effluent taxation under uncertainty. J. Environ. Econ. Manage., *11*: 1–13.

Perrings, C., 1986. Conservation of mass and instability in a dynamic economy–environment system. J. Environ. Econ. Manage., *13*: 199–211.

Perrings, C., 1987. Economy and Environment: A Theoretical Essay on the Interdependence of Economic and Environmental Systems. Cambridge Univ. Press, Cambridge.

Seneca, J.J. and Taussig, M.K., 1984. Environmental Economics. Prentice Hall, Englewood-Cliffs, N.J.

Shackle, G.L.S., 1955. Uncertainty in Economics. Cambridge Univ. Press, Cambridge.

Shackle, G.L.S., 1969. Decision, Order and Time in Human Affairs. Cambridge Univ. Press, Cambridge.

Solow, R.M., 1971. The Economist's Approach to Pollution Control. *Science, 173*: 498–503.

Vickers, D., 1987. Money Capital in the Theory of the Firm. Cambridge Univ. Press. Cambridge.