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# Choosing regulatory options when environmental costs are uncertain

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# Choosing Regulatory Options when Environmental Costs are Uncertain

by

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## CONTENTS

**FIGURES**

## EXECUTIVE SUMMARY

Would it be better now to act decisively and globally to cut down greenhouse gas emissions or to wait for a reduction in scientific uncertainties?

Using a model of optimal statistical decisions it is shown when it pays to "act and learn" and when to "learn and act". The value of information in reducing uncertainty can be shown to be sensitive to accuracy and likelihood of scientific research results. The results are extended for the dynamic intertemporal decision situation when the value of new information is an outcome of an optimal stochastic dynamic programme.

# CHOOSING REGULATORY OPTIONS WHEN ENVIRONMENTAL COSTS ARE UNCERTAIN

Hans W Gottinger

**Abstract**

An optimal regulatory regime is explored in which regulating a non-degradable pollution stock, e.g., the accumulation of greenhouse gases (GHGs) in the atmosphere, would satisfy the following two outcomes:

(1) if environmental damage incurred by GHGs is unexpectedly higher in some future, the level of regulatory regret will be lower.

(2) if environmental damage is unexpectedly lower, a low pollution stock today preserves the option of increasing the stock in the future.

This policy problem can be approached as a stochastic dynamic program with learning over an infinite horizon.

Key-words. Economics of Regulation, Greenhouse Gas, Uncertainty, Stochastic Program.

# CHOOSING REGULATORY OPTIONS WHEN ENVIRONMENTAL COSTS ARE UNCERTAIN

## 1 INTRODUCTION

The concentration of greenhouse gases in the atmosphere could be perceived as a non degradable stock pollutant which causes unknown environmental costs. In view of designing commonly agreed (globally negotiated) regulatory strategies against a perceived but on its scale unknown threat the problem is one of preserving regulatory options, and placing values on the preservation of such options before irreversible but uncertain damage can occur.

We explore an optimal regulatory regime in which regulating a non-degradable pollution stock, e.g. the accumulation of greenhouse gases in the atmosphere, would serve two purposes, as found in a more general context of resource economics by Conrad (1992):

"First, if environmental damage is unexpectedly higher in the future the level of 'regret' will be lower. Second, if environmental damage is unexpectedly lower, a low pollution stock today preserves the option of increasing the stock in the future".

Such a design relates to problems of optimal stopping.

Choosing the level of GHG emission-limiting regulations that will maximize social welfare by optimally balancing the costs of emission control against the benefits of decreased environmental damage is inherently not possible, because of pervasive uncertainty about the likely size of the critical GHG budget, its relationship to the quantity of GHG emitted, the effects of GHG in the atmosphere, and the appropriate valuation of these consequences. (Lave, 1991). Moreover, we can expect to learn more about each of these areas of uncertainty through continuing scientific-technological research, and through observation of atmospheric responses to past and current GHG emissions (Flohn, 1990). Because overall we can expect these uncertainties to diminish over time, the appropriate policy is likely to be an incremental and dynamic one. The risk to delaying before further restricting GHG emissions is that, if significant emission reductions become necessary to prevent serious adverse consequences, their cost may be much larger than if emission reductions begin sooner.

On the other hand, the risk to adopting further restrictions now is that these restrictions may later prove to have been unnecessary; the costs incurred would have produced no benefits. The question is analogous to that of whether to purchase insurance; as recently formulated by Manne and Richels (1991); by imposing additional regulations now, we incur immediate costs in exchange for a potential reduction in the costs of preventing and adapting to future GHG accumulation.

This paper attempts to provide insight to this question. First, we develop a general formulation of the policy question which can be conceived as an infinite horizon stochastic dynamic program with learning. (Bertsekas, 1976, Part II). This formulation clarifies the issues, but is mathematically hard to cope with. To provide more explicit guidance, we take advantage of specific features of this problem to develop a simplified decision framework. Because of the long time delay in the relationships between GHG emissions, accumulation and effects in the atmosphere, we can structure the policy choice so that the environmental damages and benefits are approximately the same under each policy. Thus, the framework focuses attention on a comparison of the expected economic costs of alternative regulatory strategies.

The simplified framework characterizes the degree of belief about the severity of the GHG problem such that the expected economic cost of awaiting future scientific revelations before deciding at what level to regulate is greater or smaller than the expected cost of imposing interim regulations now. This required 'degree of belief' (subjective probability) defines the confidence policy makers should have in the proposition that without further emission restrictions, GHG accumulation will occur and produce substantial adverse effects.

Because alternative regulatory strategies considered in this framework are constructed to produce equivalent GHG concentration levels, it is not necessary to estimate the relationship between reduced GHG concentration and avoided damages, nor to value these damages.

This feature considerably reduces the information required to reach a decision and simplifies the analysis, since the economic costs of alternative control strategies may be compared directly. An important limitation of the analysis, however, is that it ignores the possibility that we may not learn whether GHG accumulation is likely to produce severe consequences until it is too late to prevent it.

Other formulations of uncertainty resolving regulatory strategies are possible (Welsch 1993) but they are difficult to justify in a dynamic framework as considered here.

## 2 THE VALUE OF INFORMATION IN A STOCHASTIC DYNAMIC PROGRAMME

This section formalizes the policy problem of limiting GHG emissions to prevent or limit global warming as a stochastic dynamic programme with learning. We sketch the general problem and develop a simplified decision framework, in which the value of information is derived as a solution to the stochastic dynamic programme.

The policy problem of whether and when to restrict GHG emissions can be formulated as a stochastic dynamic programme with learning over an indefinite, perhaps infinite, horizon. Define the following notation: t, discrete measure of time (for example, one unit = one year). t increases with calendar time.

$s_t$, the state variable, describes the atmospheric burden of GHGs at time t. $s_t$ is a complex function of historical emissions of GHGs from anthropogenic and other sources, past solar activity, and possibly other factors. It may be adequate to approximate it by $s_t = \Sigma_l\, a_s(l) e_{t-l}$, that is, as a weighted sum of past GHG emissions, where the weights depend on the GHGs, atmospheric lifetimes, relative depletion efficiencies, and possibly on other factors.

$\theta$ the state of nature, characterizes how damaging GHGs are. $\theta$ includes the relationships between GHGs and global warming, between global warming and increased UV radiation, and between increased UV radiation and damages in the biosphere.

$D(s_t, y_{dt}, \theta)$, current damage from global warming. D depends on the state $s_t$, certain aspects of current technology $y_{dt}$ (e.g. mitigating technologies), and the state of nature $\theta$.

$p_t$, current GHG production, assumed equal to current use.

$e_t$, current GHG emissions. $e_t = \Sigma_l\, a_e(l; y_{et}) p_{t-1}$, that is, $e_t$ is a weighted sum of past production where the weights describe the time path of emissions from each GHG application.

These weights depend on those aspects of current technology $y_{et}$ that affect the timing of emissions from specific applications and the share of GHGs produced that are eventually emitted.

$B(p_t;y_{bt})$, economic benefits from current GHG use $p_t$. The benefits may depend on certain aspects of current technology $y_{bt}$. Technological innovation may increase or decrease $B(p_t)$ by finding new uses or substitutes for GHGs.

$f_t(\theta;y_{\theta t})$, subjective probability distribution function for $\theta$. It depends on current knowledge about the relationships between GHGs, global warming, UV radiation, and effects on the biosphere $y_{\theta t}$. We assume scientists and policy makers can agree on a common probability function to characterize current understanding of these relationships. $f_t(\theta;y_{\theta t})$ is revised in each period in accordance with Bayes' rule, reflecting any knowledge gained during the period. (Gottinger, 1980) For example, if the value of some outcome variable $z_t$ is observed and the distribution for $z_t$ conditional on $\theta$ is known to be $g(z_t \mid \theta)$, then $f_{t+1}(\theta \mid z_t) = (f_t(\theta)\ g(z_t \mid \theta)/ \int f_t\ (\theta)\ g(z_t \mid \theta)\ d\theta$. In general, the rate at which knowledge about the chemical, physical, and biological relationships between GHG emissions and effects on life and important materials increases will be a stochastic function of cumulative research expenditures. It may also depend on past and current GHG emissions, since if emissions are greater, any effects on the atmosphere will be larger, detectable effects will occur sooner, and so knowledge about them will be developed more rapidly. In the opposite case, if GHG emissions are eliminated we may never learn whether significant global warming would have occurred.

$\phi_t$, current investment in technology and knowledge. $\phi_t$ is the sum of current expenditures on research addressing each area of technology or knowledge, $\phi_{bt}$, $\phi_{\theta t}$, $\phi_{et}$, and $\phi_{dt}$. Knowledge and technology in specific areas $y_{bt}$, $y_{\theta t}$, $y_{et}$, and $y_{dt}$. are all cumulative functions of past investments, for example, $y_{bt} = \Sigma_l \phi_{bt-l}$. (We assume no decay of knowledge and technology, although this could be readily incorporated.) Relationships describing the productivity of research and development expenditures $\phi$ on D, B, e and $f(\theta)$ are implicit in the functions D, B, e, and the updating rule for $f(\theta)$.

State transition function:

$$s_{t+1} = s_t + a_s(0)e_t - \Sigma_l \; [a_s(l) - a_s(l+1)]\, e_{t-l}$$

If $s_t$ can be represented as a weighted sum of past GHG emissions, the new state depends on decomposition of the old atmospheric burden plus current GHG emissions, as specified.

Value function:

$$V_t(s_t, y_t, p_t) = B(p_t, y_{bt}) - E|f_t \; D(s_t, y_{dt}, \theta) - \Phi_t$$
$$+ \delta \; E|f_t \; V*_{t+1}(s_{t+1}, y_{t+1})$$

where $V^*_t\,(s_t, y_t) = \text{Max}_p\,[V_t\,(s_t, y_t, p_t)]$ and $\delta$ is the one-period discount factor. (The value function is also known as the fundamental recursive relation or the Bellman equation.)

The policy problem is to maximize $V_t(s_t, y_t, p_t)$ in the current period. The decision variables are current GHG production and use ($p_t$) and current expenditures ($y_t$) on research and development ($\phi_t$), allocated among projects to refine estimates of the causes and consequences of global warming ($\phi_{\theta t}$), damage mitigation strategies ($\phi_{dt}$), GHG substitutes ($\phi_{bt}$), and emission reducing measures ($\phi_{et}$). Not all research and development expenditures will be funded out of public resources, but to account for changes in social welfare we must include the real social cost of these projects regardless of the direct funding agency.

At each state, current damage $D(s_t, y_{dt}, \theta)$ is observed. Over the near future, this observable damage is expected to be zero, or nearly zero. At present, it is not clear whether we can distinguish any greenhouse warming that may have occurred from natural fluctuations. D is defined as including only currently observable damage. The fact that future damage is expected to depend on current GHG emission is reflected in the dependence of D on $s_t$, that is, on cumulative emissions, and thereby on past GHG concentrations.

Observation of D provides information about $\theta$, thereby shifting $f_t(\theta;y_{\theta t})$, but uncertainty about $\theta$ remains.

The horizon is indefinite. It may be infinite, or effectively so, if the possibility of greenhouse warming poses a permanent constraint on human activities. In this case, in the very long run, optimal emissions may be equal to some constant, non-zero equilibrium level at which GHG concentrations remain constant. The GHG carrying capacity of the geosphere may be dependent on the chosen equilibrium GHG concentration. However, at present, it is not clear whether the stratospheric GHG concentration is dynamically stable above certain GHG emission levels. If the long-run solution is a constant non-zero GHG emission level, the question of how quickly this equilibrium is approached is a policy question that involves balancing the costs of emission reductions against those of transient and possible permanent environmental damage.

The formulation of the problem suggests that one might change the policy affecting GHG use and emissions in every period, tightening and relaxing emission controls as appropriate. A number of factors limit the desirability of this type of optimization, however, and complicate solution of the dynamic programme. For example, the benefits and damages associated with GHG use and the atmospheric response to GHG emissions may exhibit discontinuities, non-convexities, indivisibilities, and irreversibilities. If a policy to reduce GHG emissions induces an industry to close down, subsequent relaxation of the policy may not lead the industry to redevelop. It may be that the industry was profitable before it was shut down, because the non-salvageable component of investment in physical and human capital had already been sunk, but the industry is not sufficiently profitable to induce investors to re-invest in these non-salvageable components when the emissions policy is relaxed. Analogously, requiring firms to install modest emission-limiting equipment may be inefficient if there is a substantial chance that more effective equipment may be necessary later, assuming the first set of equipment cannot be salvaged or upgraded if necessary. In this case, the costs sunk in the first set of equipment would be lost when the second set is required.

The perception that regulations will be subject to frequent revision could also provide a disincentive to invest in physical or human capital that is not fully salvageable, since investors have little assurance of being able to recover their costs before new emission restrictions limit their output or increase production costs. As a result, existing industries may fail to invest in new, more efficient technologies and consequently operate above their long-run cost curves. Similarly, potentially profitable, social-welfare increasing industries may not become established.

In this most general form, the problem is mathematically intractable since it combines stochastic dynamic programming with endogenous learning. However, it is possible to take advantage of specific features of the problem to simplify it in such a way as to provide insight into the current policy question - whether to adopt additional regulations to limit GHG use and emissions now, or delay further regulation until we have a better understanding of whether the likely magnitude and consequences of global warming make it imperative.

To simplify the dynamic programme, consider the value function currently facing policy makers, where the current time is denoted 0.

$$V_0(s_0,y_0,p_0)= B(p_0,y_{b0}) - E|f_0 D(s_0,y_{d0},\theta) - \phi_0 + \delta E|f_0 V_1^*(s_1,y_1)$$

Assume that $E|f_0 D(s_0,y_0,\theta) \approx 0$, since it is not clear whether significant GHG-induced global warming has occurred and no resulting damages have been identified. Significant damages are not expected to occur for some time, since many of the potential damages from GHG accumulation are delayed.

Second, assume that the choice of $\phi_0$ can be neglected, either because the range from which it can be selected is small relative to the other terms in the value function, or because the research budget is set exogenously and is not subject to policy makers' influence or control, Typically, a large share of current research is conducted by industry; government policy makers may have little influence over the extent and direction of this work.

Using these assumptions, we can simplify the value function to:

$$V_0(s_0,p_0) = B(p_0) + \delta E|f_0 V_1^*(s_1)$$

where the notation showing the dependence on y has been suppressed because technological and scientific development is taken as exogenous. For specificity, assume that smaller values of $\theta$ correspond to states for which greenhouse warming is more likely or harmful. In what follows, we drop the time-subscript 0 to simplify notation; the optimal current action is denoted $p^*$.

This formulation captures the trade-off between current benefits from emitting GHGs, B(p), and potential future damages, incorporated in $V^*(s_1)$. Since benefits accrue in the current period but damages will not be incurred until some time in the future, the discount factor $\delta$ is a key parameter in the analysis. A higher discount factor (or lower discount rate r, where $\delta = [1 + r]^{-1}$), representing greater concern about future conditions relative to the present, will decrease optimal current production $p^*$. A lower factor (corresponding to a high discount rate) assigns relatively less weight to future benefits and damages, and so increases $p^*$.

This formulation also provides insight into the role of uncertainty and learning. If the primary source of uncertainty is whether or not GHG emissions will lead to global warming, but the consequences of such global warming, should it occur, are comparatively certain, then greater uncertainty in the sense of a smaller probability that global warming will occur increases the optimal p. In this case, the current benefits of GHG emission are relatively certain but the possible damages are contingent on global warming actually occurring. The less certain policy makers are that such warming will occur, the smaller are the expected damages, and thus the smaller the current benefits that should be foregone to prevent these damages. If, over time, scientific research increases the perceived likelihood of global warming occurring, the optimal $p_t$ will decline.

In contrast, a reduction in uncertainty about the likelihood and consequences of global warming, holding the expected damages constant, may or may not affect the desirability of adopting additional current emission restrictions. The trade-off explicit in the value function is between known current benefits and the expected value of future net benefits (benefits and damages). If the expected utility of future net benefits is held constant, the desirability of current regulations is unaffected by the degree of uncertainty. However, if the expected damages, as measured in money, are held constant and social utility is a non-linear function of the monetized damages over this range, uncertainty may affect the trade-off. In the more likely case, society may be risk averse with regard to these damages, so greater uncertainty about the net benefits will be reflected in a larger risk premium and will enhance the attractiveness of additional current emission restrictions. Decreasing uncertainty over time will reduce the risk premium and thus increase the optimal $p_t$.

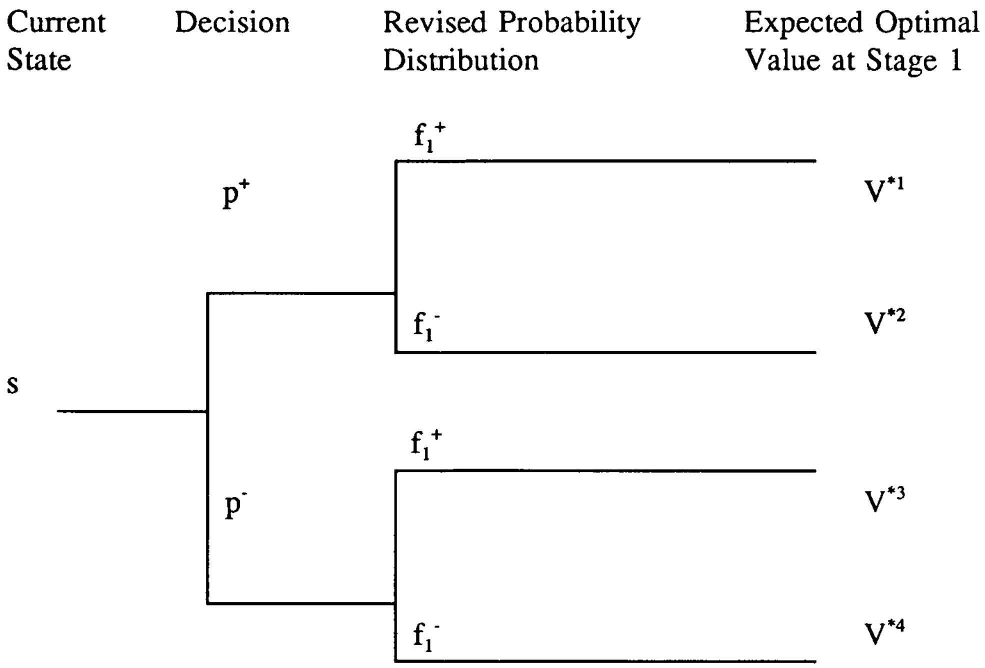
The set of possible decisions is effectively constrained, since $p \geq 0$ and the maximum feasible p is limited by demand for the products and processes to which GHGs are suited. If the density function $f(\theta)$, benefit function $B(p)$, and optimal value function $V_1^*(s_1)$ are reasonably well-behaved, the optimal $p^*$ is likely to be a monotonic function of $\theta$. That is, if $f^a(\theta)$ stochastically dominates $f^b(\theta)$ (simplistically, it assigns greater probability to larger values of $\theta$) the corresponding optimal production is $p^a > p^b$.

Assume that, for political or other reasons, the choice of decision is constrained so that only two policies, $p^-$ and $p^+$, can be considered. For example, $p^-$ could represent adopting a specified set of proposed emission restrictions that would become effective immediately and $p^+$ could represent maintaining the existing regulations while delaying one period to await the results of a scientific assessment study. Then, $p^-$ will be optimal for all $\theta < \theta^*$ and $p^+$ will be optimal for $\theta > \theta^*$. Similarly, if the value of $\theta$ is unknown but its distribution is $f(\theta)$, $p^-$ will be optimal for some distributions $\{f^-(\theta)\}$ and $p^+$ will be optimal for the remaining set of distributions $\{f^{+(}\theta)\}$ that assign relatively large probability to small values of $\theta$, and elements of $\{f^{+(}\theta)\}$ will assign relatively large probability to large $\theta$ values.

If the set of possible distributions $\{f(\theta)\}$ is suitably limited, it is possible to describe the boundary between the sets $\{f^-(\theta)\}$ and $\{f^+(\theta)\}$ by simple constraints on their parameter values. For example, if $\{f(\theta)\}$ includes only triangular distributions on an interval $[\theta^-,\theta^+]$, $\{f^-(\theta)\}$ will include only those distributions for which $E(\theta) \mid f(\theta) < \theta'$ for some value $\theta$, and $\{f^{+(}\theta)\}$ will include all distributions with $E(\theta) \mid f(\theta) > \theta'$. If $\{f(\theta)\}$ includes a more general set of distributions, the boundary between the sets $\{f^-(\theta)\}$ and $\{f^+(\theta)\}$ may involve higher moments of the distribution as well as the expected value.

This simplification allows us to represent the current policy problem as the simplified stage of the dynamic programme shown in Figure 5. The current state, incorporating past GHG emissions, is s. The possible decisions for the current period are $p^-$, representing new, additional GHG emission restrictions, and $p^+$, representing no additional regulations in this period. Regardless of the policy chosen, we assume that scientific research during the period will allow us to revise our current probability distribution function from $f(\theta)$ to one of two possible distributions, $f_1^+(\theta)$ or $f_1^-(\theta)$. The first corresponds to learning that potential greenhouse warming is not as serious a problem as we fear, so the expected value of future benefits and damages conditional on optimal policy thereafter, denoted $V^{*1}$ or $V^{*3}$, is relatively high. The corresponding optimal decisions in the next period, $p_1^1$ or $p_1^3$, depend on whether $p^+$ or $p^-$ was chosen in the current period. If $p^-$ was selected (additional regulations were imposed), the optimal policy $p_1^3$ might require relaxing these restrictions; if $p^+$ was selected (no additional restrictions in the current period), $p_1^1$ might correspond to continuing the policy of maintaining pre-existing regulations while monitoring scientific developments.

**Figure 1: Simplified Current Stage of the Dynamic Programme**




The second distribution, $f_1^-(\theta)$, corresponds to learning that greenhouse warming is more likely to have serious adverse consequences. The corresponding expected values, $V^{*2}$ or $V^{*4}$, are comparatively small; $V^{*2} < V^{*1}$ and $V^{*4} < V^{*3}$. The optimal policies in the subsequent period, $p_1^2$ or $p_1^4$, correspond to imposing further restrictions to limit GHG emissions. Because emissions in the current period were not limited along the path leading to $V^{*2}$, the optimal policy in the next period, $p_1^{2,}$ involves more stringent additional emission limitations than the policy $p_1^4$ that is optimal if additional emission restrictions were adopted in the current period, so $V^{*2} < V^{*4}$.

## 3 OPTIMAL POLICIES IN A STOCHASTIC DYNAMIC PROGRAMME

The optimal decision in the current period is the value of p that maximizes the value function

$$V(s,p) = B(p) + \delta\ E|fV_1^*(s_1)$$

Because we assume that the revised distribution $f_1(\theta)$ can be one of only two possible distributions, $V_1^*(s_1)$ is a Bernoulli random variable and $E \mid fV_1^*(s_1)$ depends on the subjective probability $\alpha$ that $f_1(\theta) = f_1^-(\theta)$. The expected values of the two candidate policies are:

$$\begin{aligned} V(s,p^+) &= B(p^+) + \delta\ [(1-\alpha)V^{*1} + \alpha V^{*2}] \\ &= (1-\alpha)V^1 + \alpha V^2 \\ V(s,p^-) &= B(p^-) + \delta\ [(1-\alpha)V^{*3} + \alpha V^{*4}] \\ &= (1-\alpha)V^3 + \alpha V^4 \end{aligned}$$

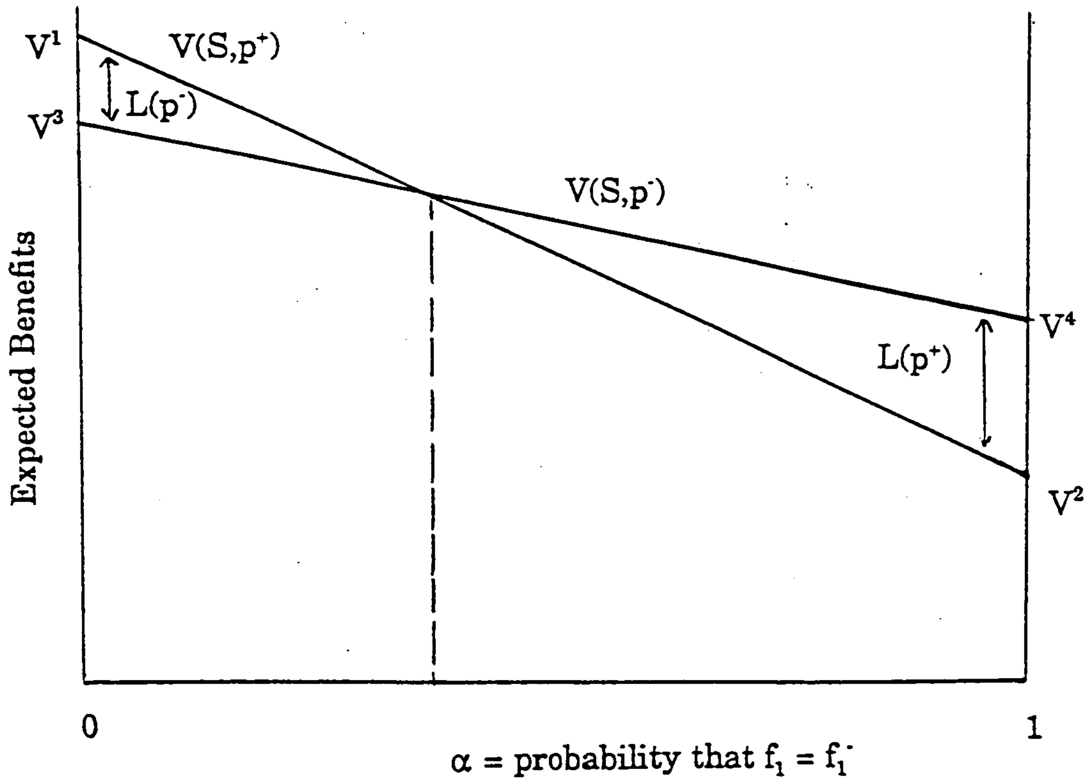
where $V^i = B(p^+) + \delta\ V^{*i}$ for $i = 1,2,3,4$. $V^1$, $V^2$, $V^3$, $V^4$ represent the value of each path at the current stage, assuming optimal decisions at all subsequent stages.

As illustrated in Figure 2, the optimal choice between the policies depends critically on $\alpha$. The figure shows the expected benefits $V(s,p) = B((p) + \delta\ E \mid f\ V_1{}^*\ (s_1)$ for each policy as a function of $\alpha$. For small $\alpha$, $V(s,p^+) > V(s,p^-)$, since small $\alpha$ indicates that greenhouse warming is not likely to be a serious problem, so significant emission restrictions are not likely to be required in future periods. For large $\alpha$, $V(s,p^+) < V(s,p^-)$ since further restrictions are likely in future periods. The value of $\alpha$ for which the expected values conditional on each policy are equal is called the "critical probability" q.

Figure 2 also illustrates the expected cost of choosing the wrong policy. The expected cost is a linear function of the difference between the subjective probability that emission-limiting regulations will be necessary and the critical probability. When $\alpha = q$ the expected cost is zero; for other values of $\alpha$ it can be calculated as:

$$E(L) = |B(p^{+}) - B(p^{-}) + \delta\ [(1 - \alpha)(V^{*1} - V^{*3}) + \alpha(V^{*2} - V^{*4})]|$$

**Figure 2:** **Expected Benefits of Alternative Current Policies. The lines labelled $V(s,p^+)$ and $V(s,p^-)$ show the expected benefits of policies $p^-$ (impose additional restrictions on GHG emissions) and $p^+$ (do not impose additional restrictions at present) as a function of the probability $\alpha$ that additional emission restrictions will be required in the near future.**




The costs of choosing the policy that is revealed with hindsight to have been incorrect, $L(p^+)$ or $L(p^-)$, are:

$$L(p^+) = -\,[B(p^+) - B(p^-) + \delta\,(V^{*2} - V^{*4})]$$
$$= V^4 - V^2$$

$$L(p^-) = -\,[B(p^-) - B(p^+) + \delta\,(V^{*3} - V^{*1})]$$
$$= V^1 - V^3$$

$L(p^+)$ measures the loss if $p^+$ (no new regulations) is chosen in the current period but we learn that substantial emission reductions are necessary ($f_1(\theta) = f_1^-(\theta)$). Since $B(p^+) > B(p^-)$, the higher benefits from choosing $p^+$ in the current period partially offset the higher future damages and control costs incorporated in ($V^{*2}$ - $V^{*4}$). Analogously, if $p^-$ (additional emission restrictions) is chosen but we learn these restrictions are not necessary ($f_1(\theta) = f_1^+(\theta)$) the cost is $L(p^-)$. The foregone benefits in the current period, $B(p^-)$ - $B(p^+)$, may be partially offset by possible increases in future production and emissions reflected in ($V^{*3}$ - $V^{*1}$). $L(p^+)$ largely reflects the long-term control-cost savings possible if emission restrictions begin earlier; $L(p^-)$ primarily reflects foregone benefits in the current period due to unnecessary restrictions.

The critical probability solves the formula:

$$\left.\begin{array}{ll} q = \dfrac{1}{1+\dfrac{L(p^+)}{L(p^-)}} & L(p^-)>0, L(p^+)>0 \\ q = 0 & L(p^-) \leq 0 < L(p^+) \\ q = 1 & L(p^+) \leq 0 < L(p^-) \end{array}\right\}$$

It depends on the relative costs of the two possible errors. If either possible cost is not positive the critical probability degenerates to zero or one, and one of the decisions is always better. In the usual case, however, both losses will be positive and q is a function of their ratio. If the ratio $L(p^+)/L(p^-)$ is large, the cost of delaying additional emission restrictions when such restrictions will be necessary in later periods overwhelms the cost of imposing additional restrictions that later prove unnecessary. Thus, q is small, and $p^+$ is preferred only if policy makers are very sure that subsequent emission restrictions will not be needed. Alternatively, if $L(p^+)/L(p^-)$ is small, the costs of stringently restricting emissions in the future are small relative to the foregone benefits of limiting emissions in the current period, q is large, and additional regulations should not be imposed in the current period ($p^-$) unless policy makers are reasonably certain that emission reductions will be necessary in the future.

Evaluating the critical probability requires estimating the values of the losses from choosing each policy when, after the fact, the other policy turns out to have been preferred, $L(p^+)$ and $L(p^-)$. These losses in turn depend on the expected values assuming optimal regulations thereafter, $V^{*1}$, $V^{*2}$, $V^{*3}$, and $V^{*4}$, Thus, the solution to the current policy question depends on the expected welfare conditional on optimal regulations in each of the following periods.

Since stochastic dynamic programmes require knowing the expected value of future stages to determine optimal decisions, there are two solution methods. (Ross, 1983, Chapters 1,2) If the problem has a finite horizon, one can begin with the final period. The expected values corresponding to each possible terminal state are calculated. From these, one can find the optimal expected values and policies corresponding to each possible state at the penultimate stage. Using the optimal values for each penultimate state, one can solve for the optimal expected values in the proceeding stage, and continue back to the current stage.

If the dynamic programme does not have a finite horizon, as in this case, solution is not straightforward. Often, such problems can be solved only if the optimal values and policies are constant or geometrically declining over time. Solution may depend on being able to write the value function and state transition function in simple analytic form.

In order to describe the solution to the current stage of the policy problem illustrated in Figure 1, we make a series of assumptions that enable us to approximate the optimal values $V^{*1}$, $V^{*2}$, $V^{*3}$, and $V^{*4}$ in the next period. Specifically, we assume that the state s can be adequately represented by cumulative weighted GHG emissions, where the weights correspond to the estimated relative global warming efficiencies of each compound.

Second, we assume that optimal policies beginning in the next period will produce equal cumulative weighted emissions as of a fixed future date, denoted the planning horizon.

Regardless of which policy is chosen for the current period, no significant global warming is likely to occur before the horizon so the damages associated with warming are negligible and do not depend on the current policy choice. Thus, the only difference between the expected optimal values in the next stage depend on the costs of reducing future GHG emissions: If emissions are not restricted in the current period, achieving the same cumulative emissions through the horizon will require more stringent restrictions in future periods. Since the marginal cost of reductions is presumably increasing and convex, the present value of the cost of achieving a fixed cumulative decrease in emissions through the horizon may increase if the restrictions are constrained to a shorter time period.

A more precise solution would recognize that the optimal level of damages to accept might be greater if GHG emissions are not restricted in the current period. Since the cost of achieving a fixed reduction in cumulative emissions through the horizon may increase if current emissions are not restricted, it might be optimal to accept slightly more warming-induced damage, and incur slightly smaller control costs in this case. However, the error introduced through this assumption should not be large.

Third, to calculate the optimal expected values corresponding to each of the four possible states $s_1$, we assume the expected value is the same as the value if the optimal cumulative weighted GHG emissions through the horizon became known at that time. Thus, $f_1^-$ and $f_1^+$ might each concentrate their mass at a single point, so that at the next stage we know that cumulative emissions should be limited to $\psi^-$ (if the new distribution is $f_1^-$) or $\psi^+$ (if it is $f_1^+$). One way to understand this assumption is to assume that, at the end of the current period, scientific research will yield sufficient understanding of the causes and consequences of warming that we can then select an optimal level of GHG emissions, balancing the costs of warming against those of emission control. The optimal cumulative emission level will be either $\psi^-$ or $\psi^+$. A more general interpretation would be that uncertainty about the appropriate level of cumulative emissions through the horizon will be substantially reduced, and that $\psi^-$ or $\psi^+$ reasonably characterize the possible cumulative emission limits that will appear to be appropriate at that time.

This simplified analysis abstracts from several important features of the problem in order to make it possible to calculate a numerical solution and provide quantitative guidance to policy makers. First, it assumes that information will arrive early enough that significant adverse effects can be prevented by imposing sufficiently stringent regulations at that time. The only penalty for not imposing additional emission restrictions in the current period is the lost opportunity to distribute any required emission reduction over a longer period, and thereby potentially reduce their cost. Since the environmental consequences do not depend on whether regulations are adopted immediately or not, the analysis reduces to a comparison of the expected economic costs of the alternatives.

Second, many aspects of the simplified problem are discrete, not continuous as in the real problem. For example, in the simplified problem only two information outcomes are possible: a more realistic subjective distribution for the appropriate level of emission limits would assign positive probability to a continuous range of emission limits. To offset this limitation, the critical probability can be calculated for the entire range of possible cumulative-emission limits, to assess its sensitivity to these choices. Similarly, new information that substantially reduces uncertainty about the ultimate consequences of emissions arrives in a discrete package at a predetermined date. This simplification should bias the results in favour of delayed contingent regulations, because in the real problem information will arrive in smaller bits at irregular, somewhat unpredictable intervals and the uncertainty will never be completely resolved, so we can never avoid the risk of regulating more stringently than necessary.

Third, in the simplified problem the date and type of new information are independent of the chosen regulatory strategy (learning is passive). In fact, the rate of scientific progress may depend on the regulations chosen: in the extreme case, if emissions are severely limited we might never learn whether significant global warming would have occurred.

Finally, the simplified problem abstracts from the issue of choosing the appropriate level of emissions and corresponding environmental and welfare consequences. In principle, this issue can be solved by comparing the costs of environmental modification with those of emission control, although the consequences and costs of environmental change cannot credibly be measured at present. Despite these simplifications, this simplified problem elucidates many of the issues pertinent to the decision.

## 4 RESOURCE COSTS AND CRITICAL PROBABILITIES: AN ILLUSTRATIVE EXAMPLE

Calculation of the critical probability for any proposed immediate regulation and cumulative-emission limit requires calculation of the present value of the resource costs of alternative regulatory trajectories (the values $V^1$, $V^2$, $V^3$, and $V^4$ in Figure 2). These resource costs are measured as areas under derived demand curves for GHGs.

The calculations assume that the regulations will consist of taxes imposed on GHGs. Using a tax, the effective price of GHG-related products can be increased so that consumers will switch to alternate products and manufacturers will substitute other more conservative processes, or other technological options that become cost effective. The size of the tax can be varied to induce the desired amount of emission reductions. The use of such a tax induces manufacturers and consumers to adopt the economically efficient set of emission-reducing measures, thereby minimizing the annual resource costs of emission reductions. To minimize the present value of the cost of limiting cumulative weighted emissions, the taxes should be proportional to the relative GHG - contributing share of each product or process and rise over time at the discount rate that firms and consumers use in making investment and consumption decisions.

If a tax is applied, the resources costs of the regulation can be measured by the area under the derived demand curve for each GHG between the unregulated price and the price including tax.

The level to which cumulative weighted emissions can be constrained depends on the date at which emission regulations are imposed and the stringency of the regulations. Figure 3 illustrates the effect of these factors. The abscissa indicates the initial base tax, ranging between zero and five monetary units (MUs). In the standard case, GHG demand is assumed to grow and the tax increases 3 percent per year. The three lines in the figure correspond to regulations beginning in 1995, 2010, and 2030. Suppose, in the absence of regulations (that is, with a tax equal to zero), global cumulative weighted emissions from 1995 through 2030 total about 63.5 billion metric tons (bMt). If regulations were to begin in 1995, limiting emissions to 50 bMt would require an initial world-wide tax of about MU 0.90/lb, limiting emissions to 40 Mt would require an initial tax of about MU 1.90/lb, and the minimum attainable level of cumulative emissions, if the initial tax were MU5/Mt would be about 32.5bMt. If regulations were not initiated until 2010 larger taxes would be necessary to limit emissions to the same levels: A 50 bMt limit would require a tax beginning at MU 1.20/Mt; a 40b Mt limit would require a tax beginning at MU 2.83/Mt. The smallest attainable cumulative emissions, if regulations did not begin until 2010, would be about 37.2 bMt. If regulations were not imposed until 2030, the range of attainable cumulative emissions is further reduced, and even higher surcharges would be required to hold emissions to any attainable level.

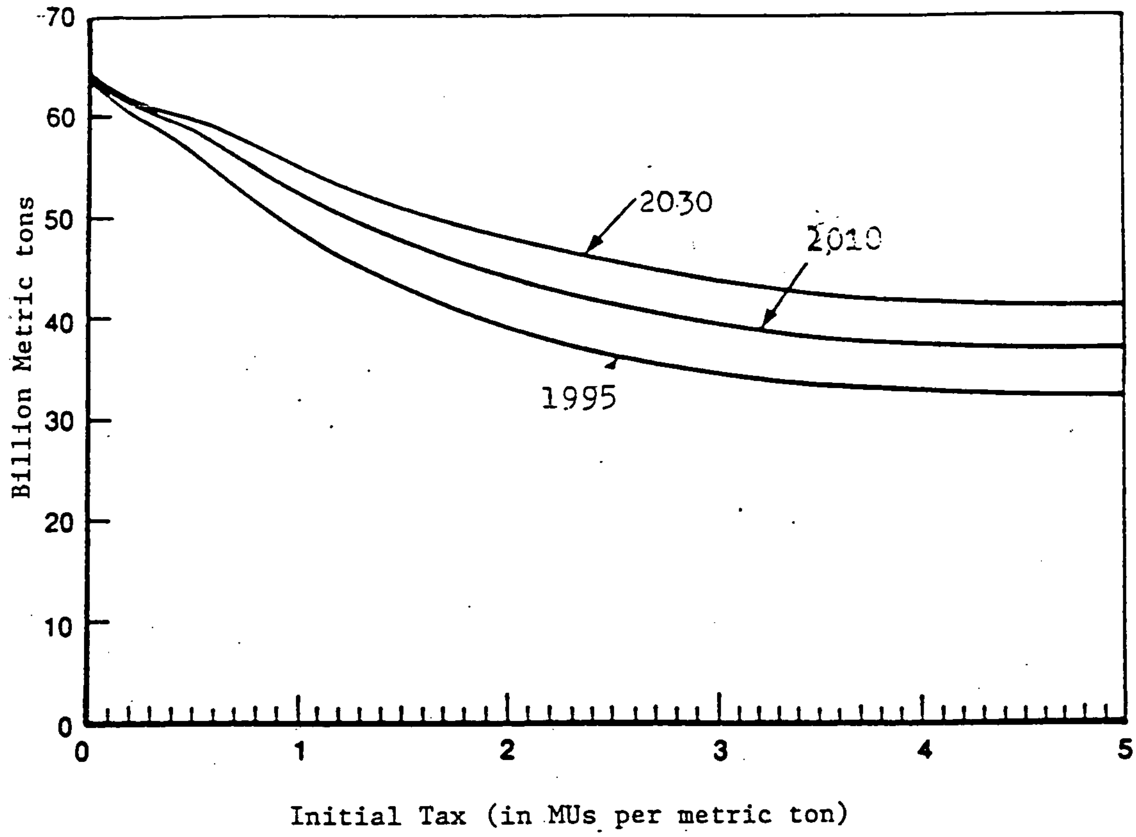



Figure 3: Cumulative weighted emissions through 2030 as a function of the initial data and tax.

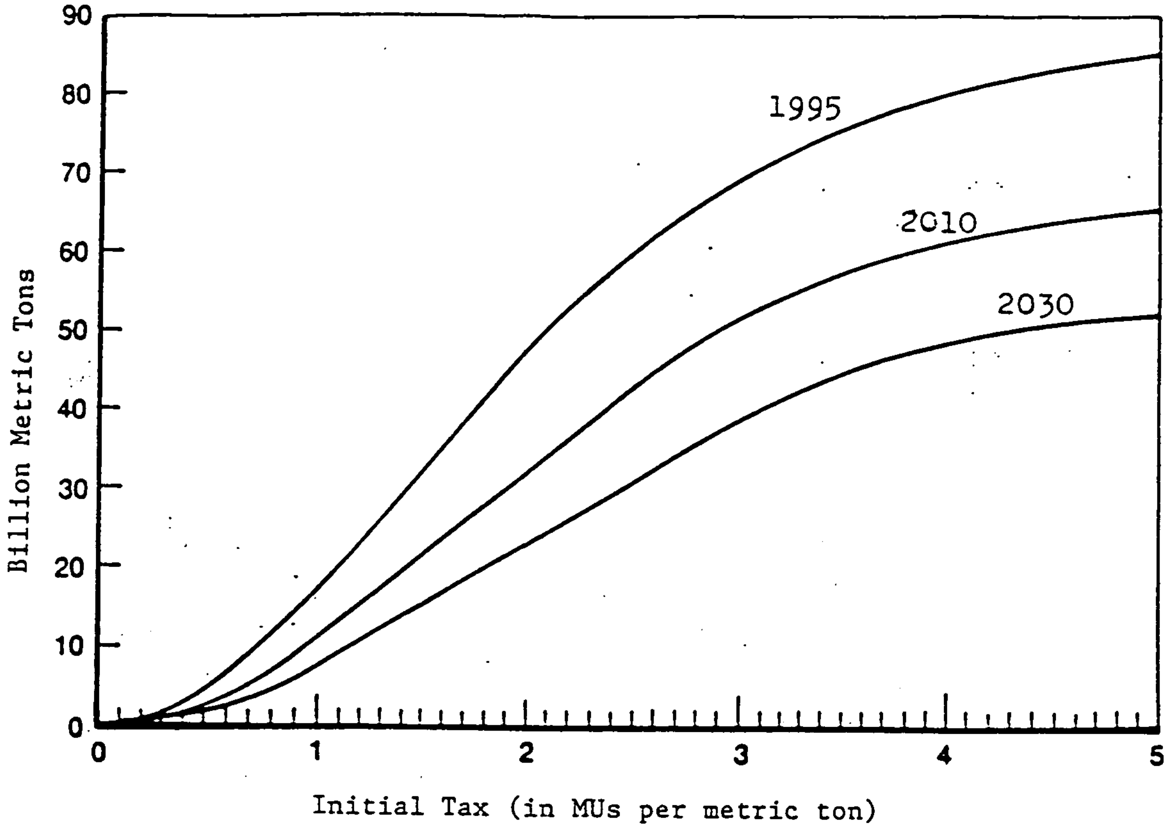



Figure 4: Present value of resource cost as a function of the initial data and tax, using a 3% discount rate.

Figure 3 illustrates the case of relatively high inelasticity of demand for GHG-related products: Even with taxes of several MUs per Mt, compared with unregulated prices on the order of 0.50 MUs/Mt simulated cumulative emissions over the next 35 years fall by no more than half. Limiting cumulative emissions to 35.2 bMt, the level corresponding to continued emissions at 1992 rates would require an initial tax of MU 2.80/Mt, if regulations begin in 1995 and would not be possible (under these assumptions) if regulations were delayed until 2010.

The resource costs (lost economic surplus) associated with restrictions that reduce GHG emissions are substantial. Figure 4 illustrates the present value (in 1992 using a three-percent discount rate) of the resource costs associated with a tax beginning at the level indicated on the abscissa and increasing at three percent per year. Using Figs. 3 and 4, one can estimate the resource cost associated with various cumulative-weighted-emission levels. For example, to limit cumulative emissions through 2030 to 50 bMt requires a tax beginning at MU 0.90/Mt if regulations begin in 1995. As shown by Figure 4, the present value of the associated resource cost is MU 14.4 billion. If the regulations are not implemented until 2010 the required initial tax is MU 1.22/Mt, which is associated with a resource cost of MU 15.8 billion in present value.

Figure 5 illustrates the critical probability that determines whether the expected cost of regulating immediately is greater or smaller than the expected cost of waiting for new information before regulating. The critical probability varies with the cumulative emissions that can be tolerated and with the proposed level of immediate regulations. For example, assume that if research during the current period produces $f_1^-$ as the distribution of effects, optimal regulations will limit cumulative emissions through 2030 to 55bMt. If the distribution is $f_1^+$, the 63.5 bMt of emissions that would occur without regulations will be acceptable. The proposed immediate regulations consist of a base tax of MU 0.30/Mt., increasing 3 percent per year. If the new information indicates that cumulative emissions must be limited to 55bMt, the tax will be doubled in 2010 (the path leading to $V^4$ in Figure 1). If the new information indicates that no regulations are required, the tax will be dropped (path 3), and no further costs will be incurred. Alternatively, if the proposed interim regulations are not adopted and the new information indicates that cumulative emissions must be limited to 55bMt, it would be necessary to impose a tax of MU 0.79/Mt in 2010 that would increase 3 percent annually (path 2). If the new information indicates cumulative emissions of 63.5bMt can be tolerated, no regulations would ever be imposed (path 1).

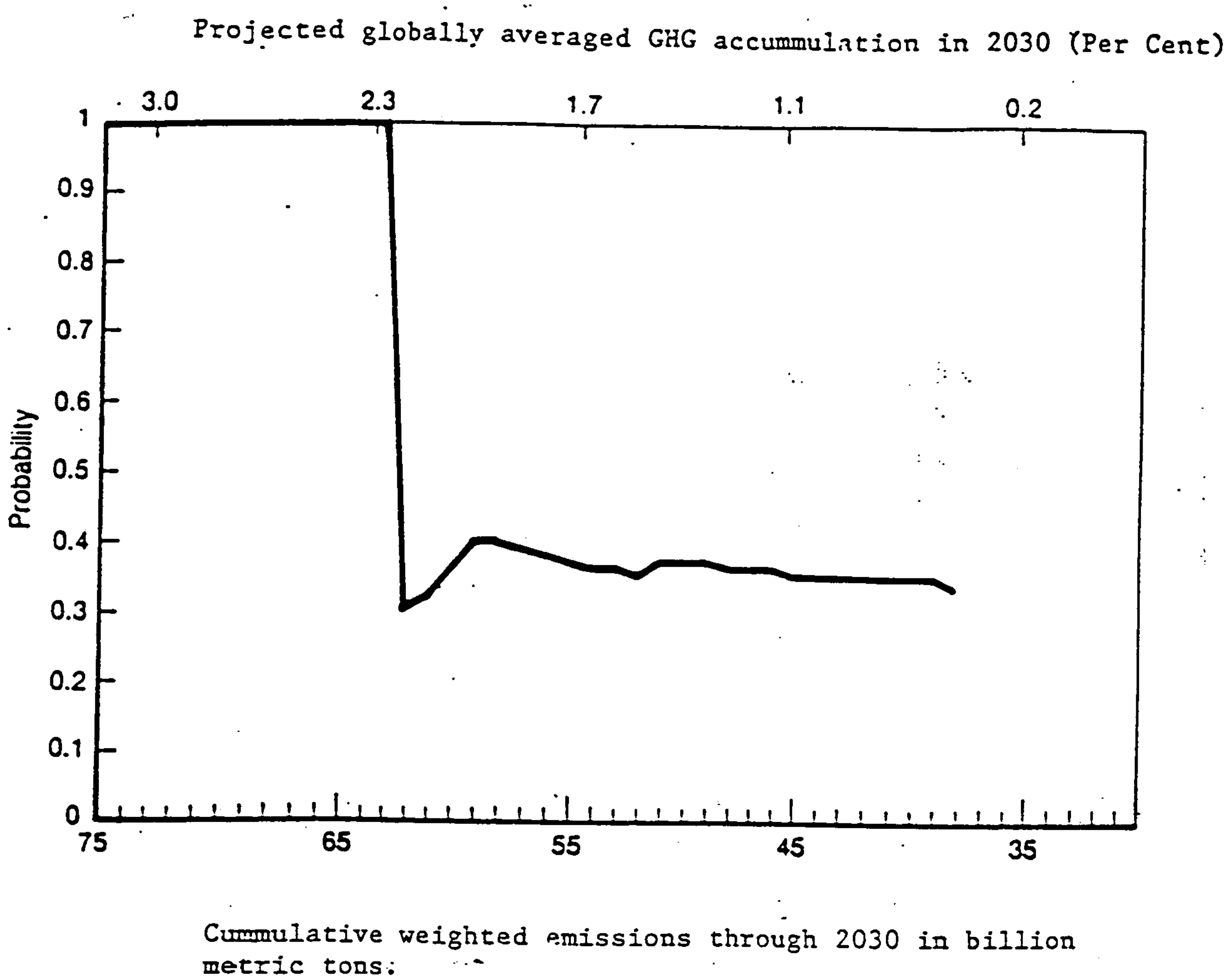



Figure 5: Critical probability as a function of acceptable cumulative weighted emissions through 2030: standard case.

The critical probability can be calculated from the present values of the resource costs associated with each of these four possibilities. Since we do not explicitly evaluate the benefits of GHGs we express these as deviations from the value of the path with no emission restrictions, $V^1 = B(p^+) + V^{*1}$. The values $V^1$, $V^2$, $V^3$, and $V^4$ are $V^1$ - 0, $V^1$ - MU 6,785 million, $V^1$ - MU 295 million, and $V^1$ - MU 6,286 million. From these, $L(p^+)$ = MU 6,785 million - MU 6,268 million and $L(p^-)$ = MU295 million - MU0. Using the formulae for the critical probability in Section 2.

$$q = \frac{1}{1 + \dfrac{6785 - 6268}{295 - 0}}$$
$$= 0.36.$$

Thus, if the probability that regulations limiting cumulative emissions to 55bMt will be required is greater that 0.36, the expected cost of adopting regulations now will be less than the expected cost of awaiting new information and regulating in 2010 only if necessary. If the probability that such regulations will be required is less than 0.36, the expected costs of waiting will be lower than the expected costs of regulating now.

The critical probability varies with the level of cumulative emissions that can be tolerated, but is essentially dichotomous. As shown in Figure 5, if the level of cumulative emissions that can be tolerated is approximately equal to the unregulated level (63.5bMt) or higher, immediate regulations cannot be cost-justified. However, if emission reductions may be necessary (to lower cumulative emissions to 62bMt or less), the critical probability drops to about 0.35. Over the cumulative-emission range from about 62 to 38bMt the critical probability is nearly constant. Finally, if the new information might indicate that emissions must be limited to 37bMt or less, the critical probability cannot be calculated since it is not possible to limit emissions to this level using the assumed demand curves if regulations are delayed to 2010 (Figure 3). Thus, Figure 5 indicates that, if the level of acceptable cumulative emissions equals or exceeds the unregulated level, immediate regulations are not appropriate. If some emission reductions may be required (about 25bMt or less), it is cost-effective to wait for better information only if the probability that such reductions will be necessary is less than about 0.35. If larger reductions may be necessary, the critical probability cannot be calculated using the simulated demand curves.

For reference, the abscissa of Figure 5 also indicates the projected decrease in globally averaged GHG accumulation in 2030 corresponding to various levels of cumulative emissions (indicated along the top of the figure).

Although one might expect the critical probability to decline with the stringency of the proposed immediate regulations, this is not necessarily the case. Recall from the definition of the critical probability that it depends on the ratio of the costs of choosing each policy if it proves wrong ex-post, $L(p^+)/L(p^-)$. $L(p^+)$ largely reflects long-term cost savings from beginning emission restrictions earlier; $L(p^-)$ primarily reflects foregone near-term benefits because of unnecessary restrictions.

## 5 CONCLUSIONS

Formulation of sensible policies for dealing with global warming is greatly complicated by some fundamental scientific uncertainties that are unlikely to be fully resolved in the near future. This poses an awkward policy dilemma: by the time reliable answers are forthcoming, the damage inflicted on us will have increased greatly, if the pessimists turn out to have been right and we do not follow their prescriptions for drastic changes now. On the other hand, enacting a drastic programme may impose economic costs and social disruptions, especially on poorer regions, that would be clearly excessive if the problem turns out to be less severe than many currently anticipate.

Over the past ten years, with increasing intensity and persistence, there have been a number of major reduction plans of GHG emissions or its components. Proponents of such plans have been arguing that significant reductions are justified as some kind of insurance policy against long-term climatic change and disruption. Others suggest that before embarking on costly programmes we should first remove scientific uncertainties associated with the physical mechanisms likely to induce global warming. Moreover, if such mechanisms were shown only to cause moderate warming one may rely more on adaptive, market-driven strategies than on complex, costly regulatory schemes. (Gottinger and Barnes, 1993, Schelling, 1988)

Our model allows calculation of a "critical probability" that characterizes the conditions under which the insurance benefits of immediate regulations exceed their cost. This critical probability can function like the standard of proof required in judicial settings. Like the standard of proof, it specifies the degree of confidence policy makers must have that GHG emissions will need to be restricted to avoid significant adverse ecological effects in order for them to judge that additional emission restrictions should be adopted at present. If policy makers' perceived probability that emission reductions will be required is greater than the critical probability, the strategy of adopting regulations immediately will impose lower expected resource costs; if the probability is lower, waiting for improved understanding of the likelihood and consequences of GHG accumulation before acting will be cost-effective.

The conventional decision-analysis approach would require policy makers to assess their complete subjective probability distributions for the extent and consequences of future. This distribution would be used to integrate the value of alternative outcomes across branches of a decision tree, and the output would consist of expected values corresponding to alternative policies. With this approach, the role of the subjective probability judgments and the sensitivity of the policy choice to variations in these judgments would be concealed through the integration. Sensitivity analysis would require recalculating the expected values for each probability distribution.

In contrast, the critical-probability approach focuses attention on the subjective probability judgement and makes its role in the conclusions transparent. This approach does not require scientists and policy makers to develop a complete distribution, but only to assess whether the bulk of the distribution lies to one side or the other of a specified cut off. It reduces the level of agreement needed to obtain a consensus for policy and clarifies the beliefs that require agreement. Policy makers may be reluctant to be publicly identified with a precise distribution but much more willing to state whether they believe the evidence is sufficiently convincing or not. Because assessing a complete subjective probability distribution is time consuming, unfamiliar, and not well done by many policy makers (Kahneman et al., 1982), this alternative to the conventional approach may be of value.

The application presented here is particularly simple, because we have considered only Bernoulli probability distributions, for which a single probability characterizes the entire distribution. But the approach could be extended to more general distributions. If it were, policy makers might have to make a more difficult judgement than one about the level of a single probability, but they would only have to determine whether their own distributions correspond to one or another subset of the admissible distributions. In many cases, this should be an easier task than specifying the shape of the entire distribution.

Sensitivity analysis for this problem shows that, over a wide range of assumptions, the critical probability is a nearly dichotomous function of the extent of emission reductions that may be necessary. If the cumulative emissions that will occur in the absence of additional regulations will not produce significant adverse environmental changes, immediate regulations cannot be cost-effective. If emission reductions may be necessary, the critical probability falls between about 0.3 and 0.5 over the domain of cumulative-emission limits for which it can be calculated.

GHG emission and climatic change are global issues: Their effects, if realized, will be felt world-wide. This paper explicitly avoids the important issues associated with the coordination of action among nations. It focuses instead on the logically prior question of whether, form a global perspective, immediate regulations may be appropriate. The results suggest that whether immediate regulations are cost-justified depends primarily on the quantity of future emissions that is acceptable and the likelihood that regulations to limit emissions to that level will be necessary.

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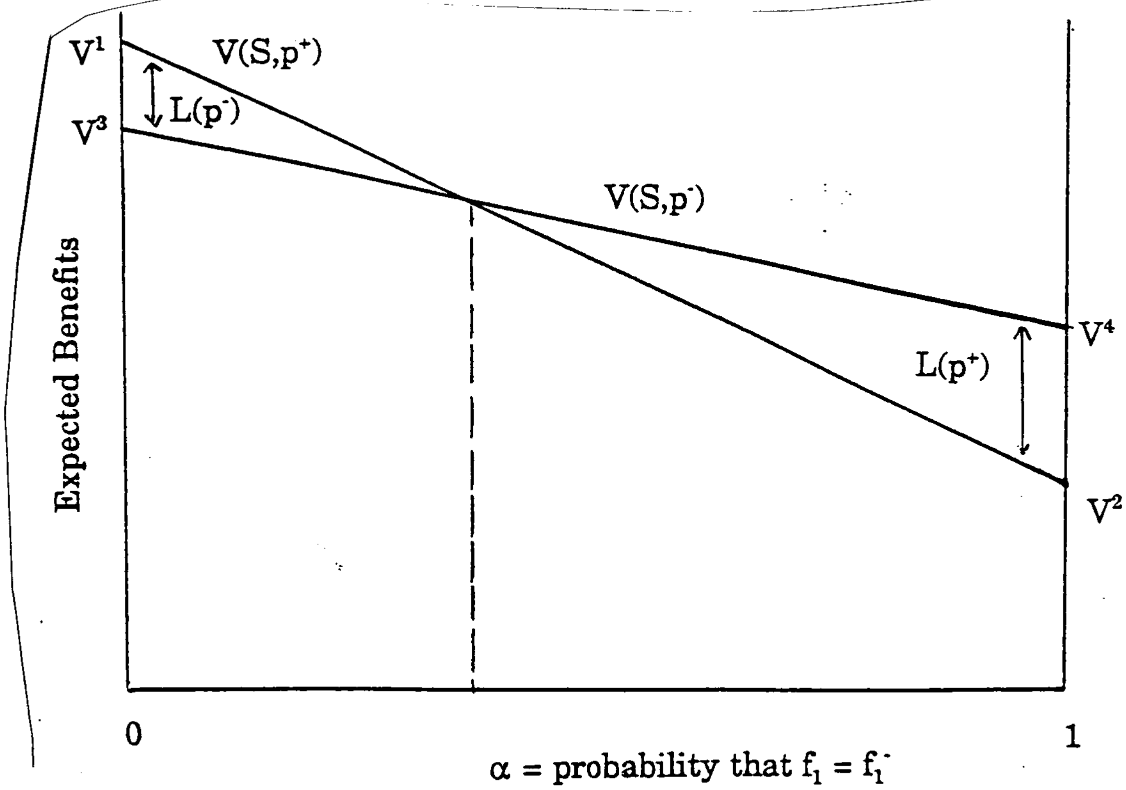
limiting regulations will be necessary and the critical probability. When $\alpha = q$ the expected cost is zero; for other values of $\alpha$ it can be calculated as:

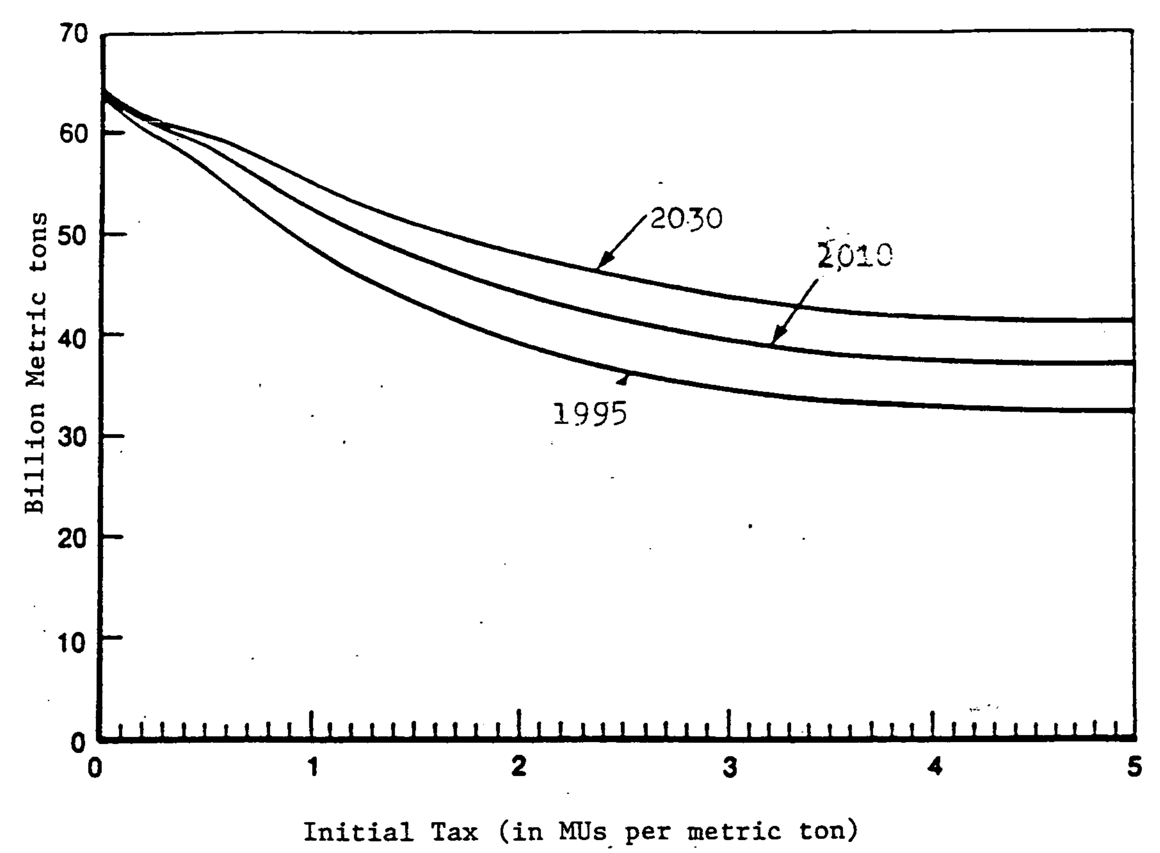
$$E(L) = |B(p^+) - B(p^-) + \delta\ [(1 - \alpha)(V^{*1} - V^{*3}) + \alpha(V^{*2} - V^{*4})]|$$

**Figure 2:** **Expected Benefits of Alternative Current Policies. The lines labelled V(s,p⁺) and V(s,p⁻) show the expected benefits of policies p⁻ (impose additional restrictions on GHG emissions) and p⁺ (do not impose additional restrictions at present) as a function of the probability $\alpha$ that additional emission restrictions will be required in the near future.**




The costs of choosing the policy that is revealed with hindsight to have been incorrect, $L(p^+)$ or $L(p^-)$, are:

emissions to the same levels: A 50 bMt limit would require a tax beginning at MU 1.20/Mt; a 40b Mt limit would require a tax beginning at MU 2.83/Mt. The smallest attainable cumulative emissions, if regulations did not begin until 2010, would be about 37.2 bMt. If regulations were not imposed until 2030, the range of attainable cumulative emissions is further reduced, and even higher surcharges would be required to hold emissions to any attainable level.

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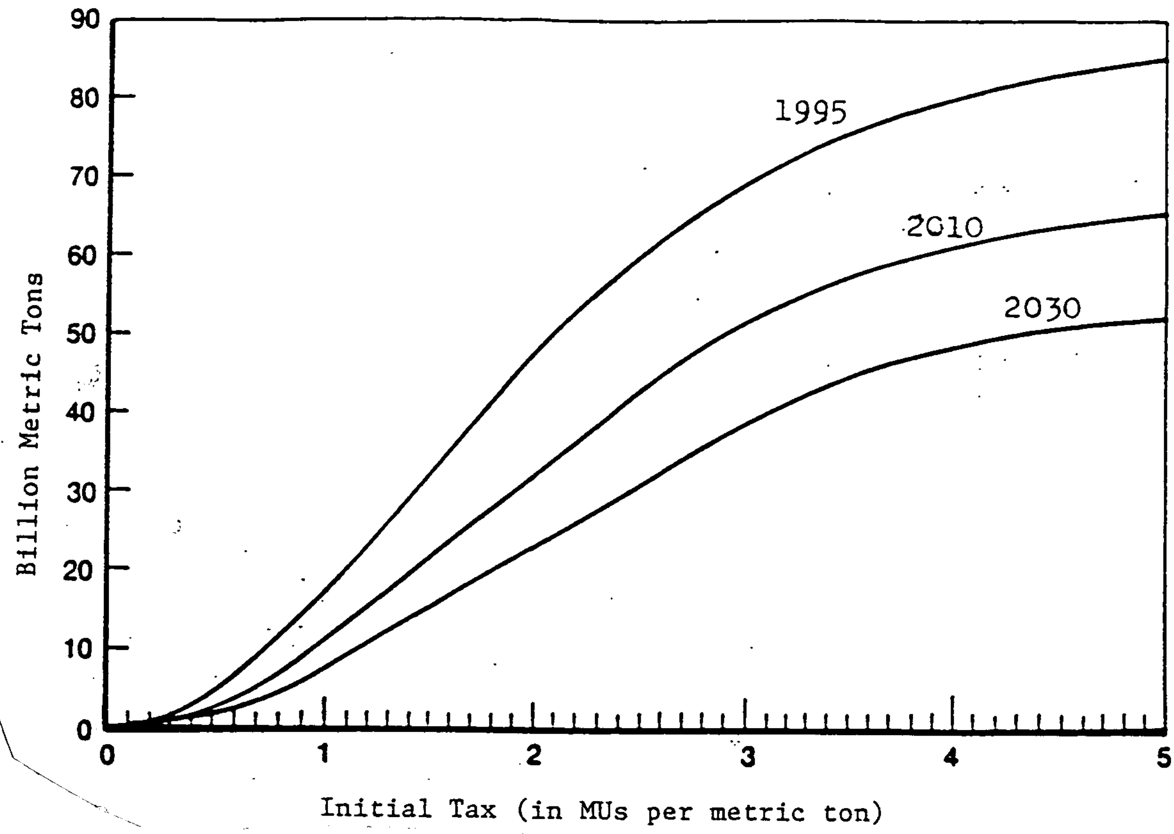


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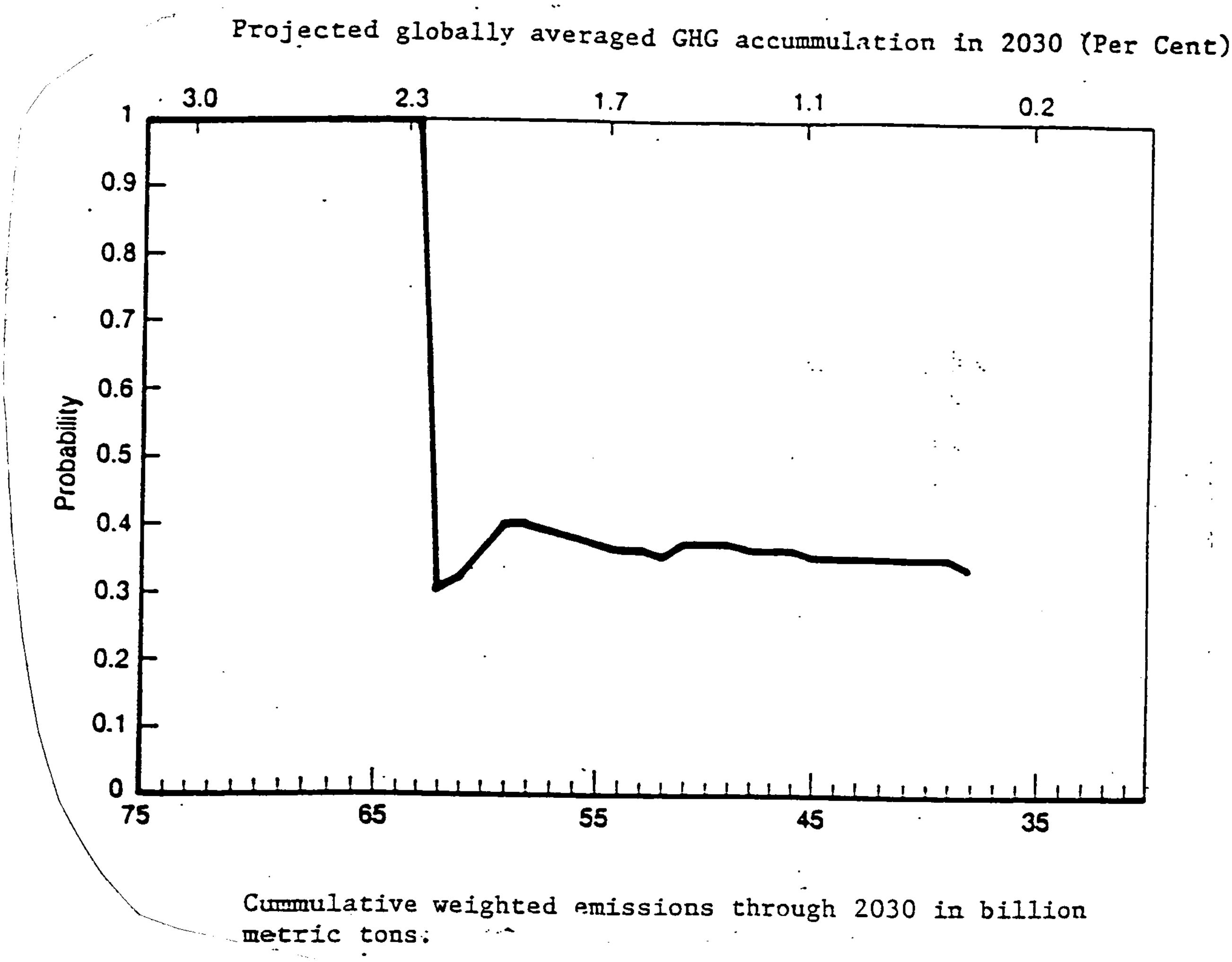


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