THE COST AND EFFECTIVENESS OF ENERGY AGREEMENTS TO ALTER TRAJECTORIES OF ATMOSPHERIC CARBON DIOXIDE EMISSIONS

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ABSTRACT

In this paper we examine the cost and effectiveness of various potential forms of international agreement to reduce fossil fuel carbon emissions and the associated distribution of direct costs and benefits to participation. We examine the effect of different patterns of entry into an agreement to reduce potential future emissions. Further, we examine the implication of emissions for atmospheric CO_2 concentrations. We have made no attempt to assess the indirect benefits of emissions reductions through changes in the rate and timing of climate change. We observe a significant potential for a "drop out" problem if developing nations perceive that they are economically harmed by participation. Wealth transfers associated with various allocations of emissions rights may be of significantly greater magnitude than the costs of emissions reductions themselves. Commonly suggested allocation schemes do not generally transfer wealth to developing nations in amounts which mirror their costs of participation. As a consequence of this analysis, it would be difficult to imagine any protocol which could be constructed which would not need significant renegotiation over time. On the other hand it is possible that the OECD, Eastern Europe and the former Soviet Union, and China jointly control sufficient resources and emissions that were they immediately to reach agreement on a protocol to stabilize emissions it would result in only slightly higher long-term (2095) atmospheric CO_2 concentrations than had the entire world participated. Finally, we quantify the value of accelerated technology development and technology transfer from protocol participants to non-participants.

INTRODUCTION

Ice core evidence indicates that the concentration of atmospheric CO_2 has been rising since 1750 (Boden et al., 1990; IPCC, 1990,1992). Atmospheric carbon dioxide, CO_2, has been clearly increasing since 1958 when consistent records of these concentrations began at Manua Loa, Hawaii (Boden et al., 1990; IPCC, 1990,1992). Two human activities release carbon into the atmosphere in significant quantities, land-use change, principally deforestation, and fossil fuel combustion. Emissions of fossil fuel carbon are estimated to be 6 PgC/yr in 1990 (IPCC, 1992). Land-use change is estimated to contribute direct emissions of 1.6 PgC/yr, though substantial uncertainty surrounds this estimate, ±1.3 PgC/yr (IPCC,1990).[1]

Since World War II, there has been an increasing trend toward the use of fossil fuels (Boden et al. 1990; IPCC, 1990,1992). Because fossil fuels represent carbon reservoirs that were laid down more than a million years before the present, the oxidation of fossil fuels represents an anthropogenic perturbation of the carbon cycle of potential significance. The increase in human activities has also resulted in changes to land-use over time. Replacement of forest ecosystems with other less carbon dense ecosystems has resulted in an increase in anthropogenic releases of carbon to the atmosphere. Nineteenth century rates of fossil fuel emissions were small compared to present rates, as well as estimated rates of carbon release from land-use change. Fossil fuel carbon emissions have grown from 0.1 PgC/yr in 1860 (Boden et al.,1990; Trabalka, 1985). Emissions of carbon from fossil fuel use are generally believed to be smaller than those from land-

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[1] In addition, there is evidence that terrestrial systems also provide a net annual sink for carbon (Post et al., 1990; Tans, Fung and Takahashi, 1990; Tans, 1991; Esser, 1991; Goudriaan,1987,1989,1991; Goudriaan and Ketner, 1984; and Strain and Cure, 1985).

use change before the twentieth century. Houghton and Skole (1990) estimate that nineteenth century emissions from land use change were approximately 0.5 PgC/yr.

Rapid growth in fossil fuel carbon emissions after World War II has caused concern that continued growth would drive the concentration of atmospheric CO_2 to levels approximately double the preindustrial concentration (Revelle and Suess, 1957; the Conservation Foundation, 1963; NRC, 1975,1983; Trabalka, 1985; MacCracken and Luther, 1985).[2]

A long series of studies on potential future global emissions of fossil fuel carbon exits, including: Rotty (1977,1978,1979a,b), Marland and Rotty (1979), Häfele (1981), Nordhaus (1977,1979), Nordhaus and Yohe (1983), Niehaus and Williams (1979), Edmonds and Reilly (1983,1985), Edmonds et al. (1984), Edmonds et al. (1986), Seidel and Keyes (1983), Mintzer (1987), Lashof and Tirpak (1989), WEC (1989), Rotmans, de Boois, and Swart (1989), Manne and Richels (1990,1992), IPCC (1989), Swart et al. (1992).

The Toronto Climate Conference, ***The Changing Atmosphere: Implications for Global Security***, in 1988 called on governments to "*Reduce CO_2 emissions by approximately 20 percent of 1988 levels by the year 2005 as an initial global goal.*" The conference noted that, "Stabilizing atmospheric concentrations of CO_2 is an imperative goal. It is currently estimated to require reductions of more than 50% from present emission levels." Since the Toronto Conference there has been growing interest in the feasibility and cost of reducing fossil fuel carbon emissions. Studies have focused on the cost and benefits to society of emissions reductions. Examples include: Manne and Richels (1992), Boonekamp et al. (1989), Cline (1989), Marks et al. (1989), Morris et al. (1990), Chandler (1990a,b), Makarov and Bashmakov (1990), Sitnicki et al. (1990), Haites (1990), Hourcade (1990), Skea (1990), Yamaji (1990), Chandler and Nicholls (1990), Jorgenson and Wilcoxen (1990), Messner and Strubegger (1990), Williams (1990), Walley and Wigle (1990), Edmonds and Barns (1990,1992), Barns, Edmonds and Reilly (1991), Bradley, Watts, and Williams (1991), Burniaux et al. (1991), NAS (1991), OTA (1991), OECD (1991), Peck and Teisberg (1991a), and Scheraga et al. (1991).

The problem of reducing global emissions is complicated by the fact that it requires a global effort. While the Montreal Protocol and subsequent amendments provide an example of the international community addressing a global atmospheric problem, dealing with global climate change will be considerably more difficult. Energy and the economy are far more closely coupled than are chlorofluorocarbons and the economy. The potential gains and losses to participants and non-participants are clearly greater than in the ozone issue. As a result, researchers have begun considering the terms under which nations might reduce emissions and realistic processes for implementing emissions reductions. Such studies include: Grubb (1989), Anderson (1990), Epstein and Gupta (1990), Solomon and Ahuja (1991), and Yamaji (1992). Very little work has been done to examine the interactions of alternative energy-economy evolutionary paths, and potential agreement structures on economic costs and wealth transfers.

The purpose of this paper is to explore the cost and effectiveness of various potential forms of international agreement to reduce fossil fuel carbon emissions and the distribution of costs and transfer of wealth from various forms. We examine the effect of different patterns of entry into an agreement to reduce potential future emission. Further, we explore the potential for accelerated technological change and dissemination to alter costs and effectiveness of emissions reductions agreements. It should, however, be noted that we do not predict the future. Results developed in this paper should be taken as indicative of

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[2] The preindustrial, year 1750, concentration is estimated to have been 280 parts per million volume (Boden, et al., 1990). The issue of energy and atmospheric CO_2 is not exactly new, dating to Arrhenius (1896,1908).

the type of phenomenon which may be encountered in the process of developing protocols for fossil fuel carbon emissions reductions. Results should not be taken literally.

APPROACH

Overview

Two basic tools are used to address the issue of cost and effectiveness of potential future agreements to reduce fossil fuel carbon accumulation in the atmosphere: an energy-CO_2 emissions model and a carbon cycle model. Both the processes which lead to fossil fuel carbon emissions and the processes which remove carbon from the atmosphere are surrounded by considerable uncertainty. To address that uncertainty we have developed three alternative reference cases for fossil fuel carbon emissions, and use three alternative models of the carbon removal process.

We hypothesize several alternative mechanisms through which emissions reductions might be affected. These include a uniform carbon tax adopted by participants, tradable permits, and individual national targets. We also explore the effect on atmospheric concentrations of non-uniform patterns of initial participation in the hypothetical international agreements. We also examine the potential role advanced technology can play in reducing costs both through the accelerated introduction and systems dissemination.

The Edmonds-Reilly Model

We have used the Edmonds-Reilly model (ERM), version 4.01, modified for use in this exercise, to conduct this exercise. The ERM is a well documented, frequently used, long-term model of global energy and fossil fuel greenhouse gas emissions. The model consists of four parts: supply, demand, energy balance, and greenhouse gas emissions. The first two modules determine the supply of and demand for each of six major primary energy categories in each of nine global regions:

No.	ABBREVIATION	REGION
1	USA	United States
2	WEUR&CAN	Western European OECD and Canada
3	JANZ	Japan, Australia, and New Zealand
4	EEFSU	Eastern Europe and the Former Soviet Union
5	CHINA	China and other Asian centrally planned economies
6	MIDEAST	Mideast
7	AFR	Africa (including North Africa)
8	LA	Latin America (including Mexico & Central America)
9	SEASIA	Southeast Asia

The energy balance module ensures model equilibrium in each global fuel market. (Primary electricity is assumed to be untraded; thus supply and demand balance in each region.) The greenhouse gas emissions module is a set of three post-processors which calculate the energy-related emissions of CO_2, CH_4, and N_2O. The original version of the model is documented in Edmonds and Reilly (1985), while major revisions are discussed in Edmonds et al. (1986). The model is currently configured to develop scenarios for seven benchmark years: 2005, 2020, 2035, 2050, 2065, 2080, and 2095.

Energy demand for each of the six major fuel types is developed for each of the nine regions. Five major exogenous inputs determine energy demand: population; labor productivity; exogenous energy end-use intensity; energy prices; and energy taxes, subsidies, and tariffs.

The model calculates base GNP directly as a product of labor force and labor productivity. An estimate of base GNP for each region is used both as a proxy for the overall level of economic activity and as an index of income. The base GNP is, in turn, modified within the model to be consistent with energy-economy interactions. The GNP feedback elasticity is regional, allowing the model to distinguish energy supply dominant regions, such as the Mideast, where energy prices and GNP are positively related, from the rest of the world where the relationship is inverse.

The exogenous end-use energy-intensity improvement parameter is a time-dependent index of energy productivity. It measures the annual rate of growth of energy productivity which would continue independent of such other factors as energy prices and real income changes. In the past, technological progress and other non-price factors have had an important influence on energy use in the manufacturing sector of advanced economies. By including an exogenous end-use energy-intensity improvement parameter, scenarios can be developed that incorporate either continued improvements or technological stagnation assumptions as an integral part of scenarios.

The final major energy factor influencing demand is energy prices. Each region has a unique set of energy prices derived from world prices (determined in the energy balance component of the model) and region-specific taxes and tariffs. The model can be modified to accommodate non-trading regions for any fuel or set of fuels. It is assumed that no trade is carried on between regions in solar, nuclear, or hydroelectric power, but all regions trade fossil fuels.

The energy-demand module performs two functions: it establishes the demand of energy, and its services and it maintains a set of energy flow accounts of each region. Oil and gas are transformed into secondary liquids and gases used either directly in end-use sectors or indirectly as electricity. Hydro, nuclear, and solar electric or fusion are accounted for directly as electricity. Non-electric solar energy is included with conservation technologies as a reduction in the demand for marketed fuels.

The four secondary fuels are consumed to produce energy services. In the Organization for Economic Cooperation and Development (OECD) regions, energy is consumed by three end-use sectors: residential/commercial, industrial, and transportation. In the remaining regions, final energy is consumed by a single aggregate sector.

The demand for energy services in each region's end-use sector(s) is determined by the cost of providing these services and by the levels of income and population. The mix of secondary fuels used to provide these services is determined by the relative costs of providing these services using each alternative fuel. The demand of fuels to provide electric power is then determined by the relative costs of production, as is the share of oil and gas transformed from coal and biomass.

Energy supply is disaggregated into two categories, renewable and non-renewable. Energy supply from all fossil fuels is related directly to the resource base by grade, the cost of production (both technical and environmental) and to the historical production capacity. The introduction of a graded resource base for fossil fuel (and nuclear) supply allows the model to explicitly test the importance of fossil fuel resource constraints as well as to represent fuels such as shale oil, in which only small amounts are likely available at low costs but for which large amounts are potentially available at high cost.

Note here that nuclear is treated in the same category as fossil fuels. Nuclear power is constrained by a resource base as long as light-water reactors are the dominant producers of power. Breeder reactors, by producing more fuel than they consume, are modeled as an essentially unlimited source of fuel that is available at higher cost.

A rate of technological change is also introduced on the supply side. This rate varies by fuel and is expected to be both higher and less certain for emerging technologies.

The supply and demand modules each generate energy supply and demand estimates based on exogenous input assumptions and energy prices. If energy supply and demand match when summed across all trading regions in each group for each fuel, then the global energy system balances. Such a result is unlikely at an arbitrary set of energy prices. The energy balance component of the model is a set of rules for choosing energy prices which, on successive attempts, bring supply and demand nearer a system-wide balance. Successive energy price vectors are chosen until energy markets balance within a prespecified bound.

Given the solution of the energy balance component of the model, greenhouse gas emissions for CO_2, CH_4 and N_2O are calculated by applying emissions coefficients. Emissions coefficients for CO_2 are as follows:

• liquids	19.2 TgC/EJ
• gases	13.7 TgC/EJ
• solids	23.8 TgC/EJ
• carbonate rock mining	27.9 TgC/EJ

Modern biomass is treated as if its carbon absorption occurred in the year of release. This approximation can either under- or over-estimate actual net annual fluxes depending upon whether the underlying stock of biomass is either expanding or contracting. See Edmonds and Barns (1990).

The Carbon Cycle and Atmospheric Composition

The carbon cycle describes the carbon reservoirs and exchanges between various Earth systems elements. A summary of present understanding is given in Figure 1. This figure reflects a present understanding of the system as a general ocean-atmosphere-terrestrial system with relatively strong earth-atmosphere and ocean-atmosphere linkages and relatively weak earth-ocean interchanges. Gross fluxes within the carbon cycle are dominated by natural systems, ocean-atmosphere and earth-atmosphere exchanges. (IPCC.1990: IPCC.1992; Wuebbles and Edmonds. 1991; Post et al., 1990; Bolin, 1986; Trabalka, 1985). Estimates of the gross flux between various components of the carbon cycle are subject to great uncertainty.

Over the period 1850 to 1986 approximately 195±20 PgC were introduced into the atmosphere by fossil fuel use. Over the same period approximately 117±35 PgC were introduced into the atmosphere by net deforestation. Net deforestation was the principal anthropogenic source of carbon release in the earlier part of the period, while fossil fuel use dominates releases in the latter portion. The average carbon content of the atmosphere increased by approximately 125 PgC over this same period. Thus the increase in atmospheric carbon corresponds to approximately 40% of the carbon released over the period from 1860 to 1986. This phenomenon can be observed over shorter time periods as well. Approximately 3.4 PgC/yr accumulate in the atmosphere, Table 1. The annual net injection from anthropogenic activities is thought to be range from 6 to 9 PgC/yr. Atmospheric retention is therefore approximately half of anthropogenic emissions.

Table 1: Average Global Carbon Fluxes for the 1980s

SOURCES AND SINKS	**PgC/yr**
Emissions from fossil fuels into the atmosphere	5.4±0.5
Emissions from net deforestation and land-use change	1.6±1.0
Total Net Emissions	**7.0±1.5**
Accumulation in the atmosphere	3.4±0.2
Uptake by the ocean	2.0±0.8
Total Disposition	**5.4±1.0**
Net Imbalance (the "missing carbon" sink)	***1.6±1.4***

Source: IPCC (1990). p.1.14.

The only generally agreed upon permanent sink for carbon are deep ocean and soils. The net buildup of carbon in soils is presently thought to proceed at a slower pace than the removal of carbon to oceans. At present, soils, may be a net source of carbon to the atmosphere as a result of land-use changes. Ocean models calibrated to observed removal rates, can account for only part of the 1 to 3 PgC/year removal of carbon from the atmosphere associated with human activities. The disposition of the so called "missing carbon," cannot yet be adequately explained by present research models. Nevertheless approximately 1.6 PgC/yr appear to be removed from the atmosphere in a way that cannot yet be adequately explained. This estimate is predicated on the assumption that, if it were not for human activities, that the carbon cycle would be in balance. That is, without human activities injecting carbon into the atmosphere, the total of all fluxes into and out of the atmosphere would balance. This may or may not be the case.

The terrestrial system is frequently treated as if it were in rough equilibrium with the atmosphere. CO_2 uptake by plants, 110 PgC/yr, is just balanced by releases from the biosphere to the atmosphere, 50 PgC/yr, and from soils and detritus to the atmosphere, 60 PgC/yr, Figure 1. Carbon leaving the biota to soils, 60 PgC/yr, leave both the biota and soils as neutral carbon sources (sinks). Uncertainty surrounds this conventional view of the terrestrial system. The proposition that either the carbon cycle, or terrestrial component of the carbon cycle would be in balance were it not for human activities is open to question. (Lugo and Brown, 1986; Wuebbles and Edmonds, 1991). Because CO_2 is a fertilizer for plants, the net increase in atmospheric CO_2 should in principle stimulate plant growth and add to the net carbon stock in the biota. This is referred to as the CO_2 fertilization effect. While the CO_2 fertilization effect is a well established phenomenon, the extent to which it affects the carbon cycle is a matter of heated debate. As noted earlier, estimates of up to 2.5 PgC/yr net removal have been estimated either by inference or by direct calculation, Goudriaan (1987,1989,1991), Esser (1991), Tans (1991), Tans et al. (1990). Empirical evidence provides an inconclusive basis for resolving the question at present.

The failure of researchers to adequately explain the carbon cycle leads directly to problems in the analysis of potential future concentrations of CO_2, and in the evaluation of the relative global warming potential of CO_2 as compared with other gases.

In evaluating potential future concentrations of greenhouse gases it is common practice to assume a "neutral biosphere." A neutral biosphere is one in which the emissions from land-use change are exactly balanced by uptake from the "missing sink." Of the five analyses averaged to obtain future atmospheric CO_2 concentrations in the IPCC (1990) four employed this assumption (Wigley, 1992). See also for example Trabalka and Reichle (1986).

The assumption of a "neutral biosphere" is justified on the grounds of rough parity between the present "missing sink" and estimated emissions from land-use change, Table 1. Deconvolution studies show this rough parity over approximately the period 1940 through 1980. (Post et al.,1990). Such studies infer net land-use change emissions as a residual when ocean carbon uptake models are run against fossil fuel emissions and atmospheric records from Mauna Loa and the Siple ice core[3] only. Interestingly, the biosphere appears not to have been neutral historically. The residual roughly matches reconstructed land-use change emissions over the period 1860 to 1920, but departs sharply in the following decades. Thus a net source beyond fossil fuel emissions are needed prior to 1920, and a sink in 1980, (IPCC,1990; Post et al.1990). The transition occurs about the time when the reconstructed land-use carbon emissions are of approximately equal magnitude with fossil fuel carbon emissions. (Houghton and Skole,1991; Post et al.,1990).

Ruether and Smith (1991) developed a model of carbon removal which was consistent with current understandings of historical patterns of land-use and fossil fuel carbon emissions and atmospheric accumulation. While the model does a good job of reproducing history, it is not a process model and therefore sheds no light on the mechanisms which lead to carbon removal and therefore leaves unclear the behavior of such processes under future conditions.

At present there is no clearly preferable representation of the relationship between anthropogenic carbon emissions and atmospheric CO_2 accumulation. We have therefore chosen to exercise three alternative models of carbon accumulation:

1) Constant airborne fraction model (af=0.5),
2) Ocean uptake model with "neutral biosphere," and
3) Ruether and Smith empirical carbon model (Ruether and Smith, 1991).

The ocean uptake model is that used by the IPCC (1990) to model the removal of carbon for global warming potential coefficients. The model describes the fraction of an addition of carbon to the atmosphere remaining after t years by:

$$f(t) = 0.30036\, e^{(-t/6.9993)} + 0.34278\, e^{(-t/71.109)} + 0.35686\, e^{(-t/815.727)},$$

where f(t) is the fraction of a kilogram of CO_2 remaining in the atmosphere a period of time t after release. This equation can be shown to reproduce the Mauna Loa record of carbon dioxide concentrations for the period 1959 through 1988 if the atmospheric injection is assumed to be given by the sum of the fossil fuel record as per Boden et al. (1990) and land-use change is assumed to proceed at the rate of 600 TgC/yr between 1800 and 1939 and then ceases thereafter.

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[3] See Boden et al. 1990 for these records, and primary sources.

ASSUMPTIONS

Base Line Assumptions

Three cases have been defined for use in exploring the potential effect of protocols to reduce emissions. These three cases provide alternative, internally consistent representations of energy system evolutions under the condition that no explicit measures are taken to reduce the emission of fossil fuel carbon. The point of their construction is not to argue that any is inherently likely, but rather to explore the implications for the effectiveness of protocols under different conditions. We refer to the three cases as Case A, Case B, and Case C.

The ERM employs more than a thousand parameters to generate scenarios. Some of these parameters are more important than others. We have focused on a subset of parameters to build a reference case, Case A. Key parameters include: population, labor productivity, the rate of exogenous end-use energy efficiency improvement, the fossil fuel resource base, and the non-greenhouse environmental cost of fuels. Reference case population assumptions follow IPCC (1989). These population scenarios are given in Table 2.

Table 2: Case A (Reference) Population
(x10^6 people)

Year	1990	2005	2020	2035	2050	2065	2080	2095
USA	248	272	281	287	285	284	283	284
WEUR&CAN	440	464	475	481	478	477	476	478
JANZ	149	160	163	166	165	164	164	165
EEFSU	429	463	483	508	521	530	538	543
CHINA	1,229	1,472	1,613	1,783	1,866	1,898	1,934	1,978
MIDEAST	131	192	239	310	359	383	401	409
AFR	671	997	1,272	1,709	2,026	2,212	2,356	2,416
LA	445	567	648	761	829	853	873	884
SEASIA	1,564	1,993	2,290	2,720	2,998	3,116	3,211	3,264
TOTAL	5,306	6,579	7,465	8,725	9,527	9,916	10,237	10,420

Labor productivity assumptions have been varied to create two alternative reference cases labeled: B and C, in addition to the reference Case A. These assumptions are given in Tables 3 through 5.

Table 3: Case A Labor Productivity Growth Rate Assumptions
(%/yr)

Region	2005	2020	2035	2050	2065	2080	2095
USA	1.51%	1.51%	1.37%	1.37%	1.09%	0.99%	0.99%
WEUR&CAN	1.62%	1.62%	1.36%	1.36%	1.08%	0.98%	0.98%
JANZ	1.62%	1.62%	1.36%	1.36%	1.08%	0.98%	0.98%
EEFSU	1.45%	1.45%	1.17%	1.17%	0.97%	0.93%	0.93%
CHINA	2.86%	2.86%	2.81%	2.81%	2.68%	2.85%	2.85%
MIDEAST	1.64%	1.64%	1.74%	1.74%	1.87%	2.20%	2.20%
AFR	1.64%	1.64%	1.74%	1.74%	1.87%	2.20%	2.20%
LA	1.64%	1.64%	1.74%	1.74%	1.87%	2.20%	2.20%
SEASIA	1.64%	1.64%	1.74%	1.74%	1.87%	2.20%	2.20%

Table 4: Case B Labor Productivity Growth Rate Assumptions
(%/yr)

Region	2005	2020	2035	2050	2065	2080	2095
USA	0.76%	0.76%	0.69%	0.69%	0.55%	0.50%	0.50%
WEUR&CAN	0.81%	0.81%	0.68%	0.68%	0.54%	0.49%	0.49%
JANZ	0.81%	0.81%	0.68%	0.68%	0.54%	0.49%	0.49%
EEFSU	0.73%	0.73%	0.59%	0.59%	0.49%	0.47%	0.47%
CHINA	1.43%	1.43%	1.41%	1.41%	1.43%	1.43%	1.43%
MIDEAST	0.82%	0.82%	0.87%	0.87%	0.94%	1.10%	1.10%
AFR	0.82%	0.82%	0.87%	0.87%	0.94%	1.10%	1.10%
LA	0.82%	0.82%	0.87%	0.87%	0.94%	1.10%	1.10%
SEASIA	0.82%	0.82%	0.87%	0.87%	0.94%	1.10%	1.10%

Table 5: Case C Labor Productivity Growth Rate Assumptions
(%/yr)

Region	2005	2020	2035	2050	2065	2080	2095
USA	3.02%	3.02%	2.74%	2.74%	2.18%	1.98%	1.98%
WEUR&CAN	3.24%	3.24%	2.72%	2.72%	2.16%	1.96%	1.96%
JANZ	3.24%	3.24%	2.72%	2.72%	2.16%	1.96%	1.96%
EEFSU	2.90%	2.90%	2.34%	2.34%	1.94%	1.86%	1.86%
CHINA	5.72%	5.72%	5.62%	5.62%	5.72%	5.70%	5.70%
MIDEAST	3.28%	3.28%	3.48%	3.48%	3.74%	4.40%	4.40%
AFR	3.28%	3.28%	3.48%	3.48%	3.74%	4.40%	4.40%
LA	3.28%	3.28%	3.48%	3.48%	3.74%	4.40%	4.40%
SEASIA	3.28%	3.28%	3.48%	3.48%	3.74%	4.40%	4.40%

Other assumptions held in common by all cases are given in Table 6.

Table 6: Other Parameter Assumptions, All Cases

PARAMETER	VALUE	UNITS	NOTES
Exogenous End Use Energy Intensity Improvement Rate	1.0	%/yr	Applied to all regions and all sectors
Fossil Fuel Resource Base			Total available resource from discovered and undiscovered including those producible with current techniques and those which require advanced technologies.
Oil	16,511	Ej	
Gas	17,451	Ej	
Coal	271,000	Ej	
Solar/Fusion Cost	$40.21	1990 U.S. $/Gj	Ultimate cost of delivered electricity with costs declining to this level by 2035.
Utility Response to Price Change	-3.0	none	Logit elasticity parameter; value of 0.0 indicates no response in fuel share to cost; value of minus infinity indicates least cost option captures 100% of the market.
Income Elasticity of Demand for Energy			% change in energy demand for each % change in income; values for non-OECD regions gradually reduced to those of the OECD by 2095.
OECD	1.00	none	
EEFSU	1.25		
ROW	1.40		
Price Elasticity of Demand for Energy	-0.7	none	% change in energy demand for each % change in the price of aggregate energy; this input is used to calibrate the price elasticity of demand for energy services in the model.
Non-greenhouse Environmental Cost			Increased non-greenhouse environmental cost, over and above those in existence in 1975, in constant 1990 U.S. dollars. These costs reflect both explicit and implicit costs.
Oil	$ 0.00	$/Gj	
Gas	$ 0.00	$/Gj	
Coal	$ 1.70	$/Gj	
Nuclear	$10.65	$/Gj	
Biomass Energy Resource Base	474	Ej/yr	Maximum potential supply of biomass from energy farms; minimum cost is the minimum price of solid energy needed to obtain any production, maximum price yields full utilization of the resource base.
Minimum price	$1.70	$/Gj	
Maximum price	$9.75	$/Gj	

It would have been possible to create three cases which varied multiple parameters simultaneously. We chose not to do so for two reasons. First, sufficient uncertainty exists in the variability of the labor productivity parameter alone to generate a breadth of emissions trajectories which are consistent with a significant portion of total emissions uncertainty. Second, by varying a single parameter it is possible to understand more clearly the source of variation. It is worth noting that Edmonds and Barns (1992) found that using the ERM, the costs of emission reduction are sensitive to the reference scale of emissions, independent of the source of that scale changes.

Total anthropogenic carbon emissions are the sum of emissions from three sources: fossil fuel use, land-use change, and cement manufacture. As the focus of this paper is on energy and fossil fuel use, we have chosen to use extremely simple assumptions regarding these variables. For land-use change we assume that anthropogenic emissions at 1.6 PgC/yr. Cement manufacturing grows exogenously from 0.2 PgC/yr in 1990 to 0.6 PgC/yr in the year 2095. following Swart et al. (1991).

The Role of Technology

Technology and technological change can affect the both the expected trajectory of future emissions and the cost of emissions reductions. In many ways the technological assumptions embodied in the reference case and two sensitivity cases described above are conservative. This is particularly true with regard to the technologies for energy transformation and rates of technology diffusion. We explicitly address these two concerns by exploring cases in which the potential for technological change and technology diffusion are both explicitly addressed.

Technology Potential: The two most likely areas of technological change which, in the mid term, might be expected to alter significantly the amount of energy related emissions and the cost of control are: a) electrical generating efficiency improvements. and b) non-emitting source cost reductions. The technologies already exist for substantial improvements in generating efficiencies principally through exploitation of combined cycle variants. In addition. many advocates of solar electric energy continue to be sanguine about that source becoming cost competitive with conventional sources. For this analysis. we have included one case variation with very optimistic assumptions concerning coal and gas generating efficiencies as well as solar electric operating costs.

Technology Diffusion: In addition to the financial policies that are discussed above, technologies may be transferred as a strategy for reducing emissions. During the course of this exercise we examine the consequences of different assumptions about technology transfer from nations participating in a protocol to those who are not. In participating regions aggregate energy intensity improves both to exogenous factors and endogenous factors such as the price of energy. The exogenous factors are assumed to be identical across all nations in all runs. In some cases we examine the effect of the transfer of some carbon tax induced energy intensity improvements from participating regions to non-participating regions. We do this by a sensitivity parameter which fixes the fraction of the improvement in tax induced energy intensity improvements in the participating regions which is made available to non-participating regions. This fraction ranges from 0 to 100%.

REDUCING POTENTIAL FUTURE FOSSIL FUEL CARBON EMISSIONS

Thinking About Protocols

It has long been recognized that the reduction of global greenhouse gas related emissions requires international cooperation. No single country controls a sufficient share of global fossil fuel use to control total global carbon emissions.[4] The United States is responsible for the largest share of fossil fuel carbon emissions to the atmosphere, approximately 23% (Bradley et al., 1991). Yet this share is anticipated to decline with time (Swart et al. 1991; Manne and Richels, 1990; IPCC, 1989; Lashof and Tirpak. 1989; Rotmans et al., 1989; Edmonds and Reilly, 1983; Häfele, 1981).

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[4] By any measure fossil fuel carbon emissions are the single most important contributor to potential global climate change (Reilly, 1992; Wuebbles and Edmonds, 1991; Rotmans and den Elzen, 1991; IPCC, 1990; Nordhaus, 1990a; Lashof and Ahuja, 1990).

While it is clear that some kind of protocol would be needed to establish control over anthropogenic greenhouse gas related emissions, governments have yet to agree on either the nature, timing, conditions or even the desirability of such an agreement. Consideration nevertheless is being given to principles that might guide the development of a protocol and to broad potential terms and conditions that might be included in agreements (Ghosh, 1991; Grübler and Fujii, 1991; Barrett, 1990; Morrisette and Plantinga, 1990; Morrisette et al., 1990; Sebenius, 1990; Grubb, 1989). Issues which need to be addressed in thinking about emissions protocols include: target levels, methods for achieving these levels, and the extent and timing of participation.

Targets: We have focused on fossil fuel carbon emissions rather than atmospheric concentrations. While it would be relatively simple to monitor the atmospheric concentration of CO_2, it would be extremely difficult to attribute changes in that concentration to individual counties. Furthermore, while it is possible to use carbon cycle models to infer required global emissions consistent with any desired annually and globally averaged atmospheric CO_2 concentration, the inferred emission requirement, for example to stabilize present concentrations, varies depending upon the particular carbon cycle model employed. Additional uncertainty is introduced by virtue of the fact the most desirable atmospheric concentration or rate of change of that concentration is unclear. Researchers including Nordhaus (1990b,c), Peck and Teisberg (1991b,1992), and Cline (1990,1991) have explored economically optimal strategies and have found dramatically different optimal paths under alternative assumed conditions.

Given such uncertainty, should a protocol be adopted by nations, it is likely that initial targets will be set in terms of national emissions, and that stable emissions is as likely a target as any other.[5] We therefore have selected stabilization as the target of interest for the purpose of this analysis.

Participation: We also considered in the consequences of nations adopting a stabilization target at a future date. We examine a protocol in which participants agree to hold emissions constant at rates equal to those at the time of initial participation, whether that initial participation is early or late in the analysis period. It can easily be imagined that the development process will leave emissions in developing nations significantly above 1990 levels in the decades ahead if membership in a protocol is delayed. If countries choose to join an agreement in later years, then it is unlikely that they will choose to stabilize emissions at a target year level far below then current rates. For the purposes of this study we aggregate the world community into four groups:

No.	Abbreviation	Membership
1	OECD	Organization for Economic Cooperation and Development (Regions 1,2,3)
2	EEFSU	Eastern Europe and the former states of the Soviet Union (Region 4)
3	CHINA	China, Mongolia, North Korea, Vietnam, Kampuchea, and Laos (Region 5)
4	ROW	Rest of the world (Regions 6,7,8,9)

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[5] The Toronto Climate Conference called for a 20% reduction in emissions, but there is no scientific basis for that recommendation. That is the 20% reduction level does not correspond to the achievement of any other objective, such as stabilizing the concentration of atmospheric CO_2. It is therefore at least as arbitrary a goal as stabilizing emissions.

Groups are hypothesized to begin participation in the following years in three alternative cases:

Protocol 1: **1990 Protocol.** In Protocol 1a all nations initiate participation in 1990. In Protocol 1b participation by the EEFSU is delayed until the year 2005, and participation by CHINA in the year 2020, and ROW to the year 2035.

Protocol 2: **2005 Protocol.** In Protocol 2a all nations initiate participation in 2005. In Protocol 2b participation by the EEFSU is delayed until the year 2020, and participation by CHINA in the year 2035, and ROW to the year 2050.

Protocol 3: **Late Protocol.** In Protocol 3 no protocol is signed until the year 2020 and participation by non-OECD member states lags. Last parties do not join until the year 2065.

YEAR OF FIRST PARTICIPATION

Group	Protocol 1a	Protocol 1b	Protocol 2a	Protocol 2b	Protocol 3
OECD	1990	1990	2005	2005	2020
EEFSU	1990	2005	2005	2020	2035
CHINA	1990	2020	2005	2035	2050
ROW	1990	2035	2005	2050	2065

Implementation: Three alternative mechanisms of protocol implementation will be examined. These are as follows:

1. **Uniform taxes:** Each participant in the protocol is assumed to adopt a uniform set of taxes on carbon emissions to stabilize the combined emissions of all participants:

2. **Tradable permit:** The targets of participating nations are combined. Each participant is given an emission allowance. Allowances total to the participants' combined emissions target. Each participant must cover emissions with allowances. If a participant's emissions are less than the allowance then the participant can sell excess emissions allowances. If a participant's emissions are greater than the allowance, then additional allowances must be obtained from other participants. A market is assumed to form in which allowances are traded in a manner similar to stocks, bonds, and international currencies.

3. **Individual targets:** Each participating region is assumed to be required to meet its own emission reduction target without being able to trade emissions allowances.

When tradable permits are examined, a issue arises as to the allocation of emissions allowances. As noted in the preceding discussion much work has gone into the issue of allocating these allowances. Because tradable permits create a market for emissions rights, with a single price faced by all participants, they have efficient properties similar to a common tax. They also have income redistribution properties. Because considerable income can be redistributed, the distribution of emissions rights have substantial implications for the global income distribution. A great many options have been suggested, we examine emissions allocations based on the following principles:

1. *"Grandfathered Emissions" Principle:* Emissions are allocated on the basis of rates at the time of joining the protocol;
2. *Equal Per Capita Emissions Principle:* Emissions are allocated on the basis of adult population:
3. *"No Harm to Developing Nations" Principle:* Developing nations receive sufficient emissions rights to cover own emissions and to generate sufficient revenue to cover the economic cost of participation in the protocol,
4. *"No Harm to Non-OECD Nations" Principle:* Non-OECD nations receive sufficient emissions rights to cover own emissions and to generate sufficient revenue to cover the economic cost of participation in the protocol.

The latter two propositions are not intended to be a pragmatically observable or calculatable allocation criteria. Such criteria can be examined with a model however and can be instructive with regard to potential negotiating positions that may be encountered. We calculate the implied distribution of emissions allowances which would leave developing and non-OECD nation participants no worse off in terms of GNP than had they not participated in the agreement. This calculation provides some guidance for comparison of other metrics in achieving this end. We have chosen not to examine an allocation of permits based on either GDP or per capita GDP. We consider the measurement of GDP to be too difficult at this time for such schemes to be a near term possibility.

In our analysis tradable permit rights are assumed to be usable only in the year in which they are issued. They cannot be saved and used later. Nations cannot borrow against expected future emissions. It is imaginable that an international system could accommodate saved emissions rights. During periods in which the real value of the emissions right increase faster than the real interest rate, there would a tendency for emissions rights to be saved for use in the future. This intertemporal trading would tend to limit the rate of growth of the price of carbon emissions rights to the interest rate. It is more difficult to imagine a system in which it was possible to borrow against future emissions rights. As rights are accumulated annually with no end to the process, there is a potentially infinite store of rights against which to borrow. Borrowing could be restricted, that is a nation could never be allowed to borrow more than a fixed number of years' emissions into the future. If borrowing could occur across more than a few years into the future, there would always be the danger that a participating nation might join, borrow against the future to finance current expenditures, and when the borrowing limit was reached, simply drop out of the process.

MEASURING COSTS

Confusion surrounds the concept of cost applied to carbon emissions reductions. It is not the purpose of this paper to attempt to disentangle the various threads of this issue and to provide a framework for comparison. Rather, we will attempt to define a small number of concepts and work out the implications of the application of these concepts to hypothetical fossil fuel carbon emissions protocols.

The cost concepts which are of interest are: marginal cost, total cost, average cost, GNP reduction, and terms-of-trade effects.

Marginal Cost

The marginal cost is the cost of the last unit of carbon emission reduction. In a model in which taxes are the policy instrument employed to reduce emissions, the tax rate is the cost of the last unit of emission reduction. By virtue of the fact that the model systematically reduces emissions with the least expensive actions taken first, the marginal cost is also the highest cost of a unit of emission reduction. All other tonnes of carbon were reduced at lower cost.

In the examination of protocols tax rates are raised until they are sufficiently high that the emission reduction target is achieved. When tradable permits are examined, they are modeled as if they were a tax, with income redistribution. That is, the because a market for emission allowances is assumed to form, the cost of energy is raised to the user by the purchase price of the permit. To the energy user, the disposition of the additional cost is assumed to be matter of indifference. That is the consumer is assumed to have the same reaction whether the extra costs go to the international emissions permit market or whether they go a government in the form of taxes.

This measure of marginal cost is accurate if there are no market distorting marginal subsidies in the system. That is not to say that there can be no subsidies, but rather that these subsidies cannot affect the marginal cost of energy. If there are, then the tax rate may not be the true marginal cost.

Total Cost

The total cost of emission reduction is a computed term. It is the sum of all of the marginal costs. That is, the cost of each tonne of emission reduction is added in a sum, the total of which is referred to as the total cost. The total cost and the GNP loss will be the same under appropriate circumstances (Edmonds and Barns, 1992)[6].

The total cost is calculated by introducing increasingly higher tax rates and recording the emission reduction relative to the untaxed case. This process continues until the emission reduction target is achieved. The sum of all the marginal costs is reported as the total cost. As noted above, the marginal cost and tax rate are identical as long as there are no marginal net subsidies or costs in the system. We will act as if that were the case for the purposes of this analysis, but recognize that in some of the world's nations marginal distorting subsidies and costs do exist and that we may either underestimate or overestimate costs as a result.

Average Cost

The average cost is simply the total cost of emissions reductions divided by the total emission reduction, relative to the untaxed case. As the model undertakes the least expensive emissions reductions options first, the average cost will always be lower than the marginal cost.

GNP Reduction

As noted earlier, under appropriate circumstances the total cost and GNP reduction are identical. The ERM has a GNP feedback mechanism that reduces the expected GNP as the cost of energy services rises. The response elasticity used in the ERM is based on the experience of the 1970s. During that period the increase in the cost of energy services was driven primarily by exogenous changes in the world price of oil. The corresponding change in GNP reflected both changes in relative prices and changes in the terms of

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[6] The conditions considered in Edmonds and Barns (1992) include: a single homogeneous good used for both production and final consumption; a single fossil fuel and a single non-fossil fuel; a single a closed economy, which is the case for the global economic system, but nor for individual nations; the system is in static equilibrium.

trade. The effect of a change in the price of energy services derived from a domestic tax of fuels based on their relative carbon content may or may not result in similar changes in GNP.

RESULTS

Non-Protocol Cases

The assumptions developed for the three non-protocol cases, Cases A, B, and C, were used in combination with the ERM to generate descriptions of energy use and fossil fuel carbon emissions. These scenarios span a range of energy use and emissions which allow the effects of different alternative evolutionary paths for energy systems under the condition that no measures are taken to explicitly reduce greenhouse gas emissions.

Energy Use and Fossil Fuel Carbon Emissions: Energy use and fossil fuel carbon emissions from the three non-protocol cases are compared to other reference cases found in the literature for energy (Figure 2) and fossil fuel carbon emission (Figure 3). By the year 2095 the high and low cases span a range of approximately a factor of 2.6 for energy and 2.9 for fossil fuel carbon emissions. These scenarios are within the range of reference cases found in the literature. While we take no position with regard to the likelihood of any particular scenario coming to pass, we note that all three cases fall within the range of the 25th and 75th percentile cases of the Edmonds et al. (1986) uncertainty analysis (for both energy and fossil fuel carbon emissions), and span a range that is only slightly broader than that spanned by the 25th and 75th percentile cases of the Nordhaus and Yohe (1983) uncertainty analysis (fossil fuel carbon emissions only).

Figures 4-6 show primary energy use by fuel type. All are characterized by peaking in the use of conventional oil and gas around the year 2035, and a subsequent steady increase in the importance of non-fossil fuels such as biomass, solar and nuclear and of coal. The increase in reliance on coal is the result of increased use for conversion processes, particularly electric power generation and liquefaction and gasification.

Figures 7-9 show primary energy use by region. In all three cases there is a pronounced trend for energy consumption in the developing nations to grow more rapidly than in the developed nations.

Figures 10-12 display carbon emissions by region. In Case A both OECD and EEFSU emissions actually peak early in the next century, and decline somewhat through the remainder of the period. Total emissions increase by somewhat more than a factor of two in this case by the year 2095 due to continued growth in fossil fuel use in the developing nations. In the reference and high cases total fossil fuel carbon emissions increase throughout the course of the period to 2095. As was the case with energy, developing nations increase their use more rapidly than the developed nations.

Per capita fossil fuel carbon emissions do not change much over the first 50 years of the period. This is despite the fact that United States and Chinese emissions continue to rise, Figure 13. This trend is offset primarily by the changing regional distribution of world population.

Atmospheric Carbon: Cumulative fossil fuel emissions for the three non-protocol cases beginning in the year 1990 are displayed in Figure 14.

The effects of case A emissions assumptions on the atmospheric concentration are given for three carbon cycle models, Figure 15. The airborne fraction and ocean uptake model with a neutral biosphere generate concentrations that reach 550 ppm by about 2070 to 2075. There is nothing special about the concentration which represents twice the preindustrial level. It is not a threshold for impacts. We use it only as a convenient and familiar benchmark level. The Reuther-Smith specification reaches a concentration of 540 ppm in the year 2095. This model has very different implications from either of the other two.

Case B has lower carbon emissions and consequently lower atmospheric concentrations, Figure 16. The ocean uptake model with neutral biosphere produces a concentration of 550 ppmv in the year 2095. The constant airborne fraction model produces an atmospheric concentration of approximately 600 ppmv in 2095, while the Reuther-Smith model hovers near a concentration of 450 ppmv in 2095.

Case C emissions all exceed 600 ppmv by the year 2095, Figure 17. Both the constant airborne fraction and ocean uptake models produce a concentration of 550 ppmv around the year 2060, about a decade earlier than in Case A and more than three decades earlier than in Case B.

While differences in the specification of the carbon cycle clearly imply different rates of carbon accumulation in the atmosphere, the differences introduced by alternative emissions trajectories are clearly the dominant determinant of atmospheric concentrations by the year 2095. There is no overlap in the array of concentrations associated with Cases B and C in the year 2095, and

Annual emissions rise more rapidly in the developing world than in the OECD regions. We have estimated the origins of changes in the atmospheric concentration of CO_2 due to fossil fuel releases by nations in the period following 1950 and including forecasts for the years subsequent to 1990. To do this we have tracked the date of release of fossil fuel carbon by source with the ocean uptake model. We have assumed that carbon released to the atmosphere is removed at the same rate regardless of the point or origin, though results depend explicitly on the date of origin. The ocean uptake model is asymptotically stable at 275 ppmv. The assumed 1950 atmospheric concentration of 313 ppmv becomes decreasingly important with time as carbon added prior to 1950 is slowly removed, Figure 18.

The share of the change in atmospheric CO_2 concentration attributable to the developing and developed nations changes much less than the annual emissions, Figure 18. In 1990 OECD nations account for more than 50 percent of cumulative carbon remaining in the atmosphere from releases since 1950. Developing nations account for approximately one fifth, Figure 19. Shares change over time with the developed nations share declining to 40% by the year 2050, and developing nations shares rising to more than one third, Figure 20. By 2095 developing nations finally account for more than half of the atmospheric carbon introduced to the atmosphere subsequent to 1990, though OECD nations still account for 30%, Figure 21. These shares are only slightly different when Cases B and C are analyzed. This is due to the cumulative nature of the calculation.

Protocol 1a: Immediate (1990) Participation by All Nations

One does not need a model to work out the emissions time path of an agreement to immediately stabilize the emission of fossil fuel carbon. It is the same in all cases, and is independent of the reference case trajectory. The cumulative emissions time path is a straight line as is shown in Figure 14. In addition, we have plotted cumulative fossil fuel carbon emissions for the case in which emissions are stabilized in the year 2005. There is little difference between cumulative emissions in Case B and cumulative emissions for the reference case under the assumption that they stabilize in the year 2005. There is even less difference in comparing cumulative fossil fuel carbon emissions under Case B and cumulative emissions under Case C stabilized after 2005. This result follows from the observation that the difference between the level of global emissions in the year 1990 and 2005 is only 2 PgC/yr in the reference case (2.5 under Case C, and less than 0.5 for Case B). This is due in large measure to the fact that emissions are depressed during this period by restructuring in eastern Europe and the former Soviet Union. This restructuring does two things, it temporarily lowers income levels, which lowers emissions and second, improves efficiency.

Effects on Atmospheric CO_2 Concentrations: While cumulative emissions is a considerably different concept than atmospheric concentration of CO_2, the basic results for all carbon cycle models follow the same basic trends. To simplify the presentation of results, we have adopted the ocean only model combined with the assumption of the "neutral biosphere." Under these assumptions atmospheric concentrations for Case A and 1990 stabilization are presented in Figure 22. The difference between atmospheric CO_2 concentrations under Protocol 1a and reference case emissions is greatest for Case C followed by Case A and Case B. Atmospheric CO_2 concentrations continue to rise under this regime, but the rate of increase declines and atmospheric concentrations in 2095 remain below 500 ppmv.

Uniform tax: The first tool for implementing a protocol to stabilize emissions is a voluntarily administered uniform carbon tax program. The tax rate is assumed to be the same in all nations. As all nations are assumed to participate, such a tax could be effected as either a severance or consumption tax imposed by all nations. Both taxes are energy taxes with the amount of tax proportional to the carbon content of the fuel. A severance tax is applied to the production of primary energy. A consumption tax is applied to the use of final energy. Revenues from the imposition of such taxes are assumed to be retained within countries.

From the perspective of the global economy there is little to distinguish the effect of a severance versus a consumption tax. During most of the analysis period. Only in the final two periods do the two taxes diverge, Table 7.[7] The total global costs are also virtually identical. Furthermore, there are no direct income transfers. There can be significant indirect wealth transfers.

If the tax is a severance tax, then producing nations receive not only the world price for the fuel but also collect the tax on all exported products. If the tax is a consumption tax, then consuming nations reduce demand and also their imports, reducing the value of net imports.

Results for the globally uniform energy consumption based carbon tax applied to Case A are shown below. The tax rate required to stabilize emissions increases with time.

It is also important to recall that while global emissions are stabilized, individual national emissions will in general not be stabilized. Developing nations increase fossil fuel carbon even as the world stabilizes emissions, Figure 23. The increase between 1990 and 2005 is something less than 0.5 PgC/yr, but this continues to increase such that by the year 2095 developing nations' emissions are more than 2 PgC/yr greater than in 1990. To stabilize emissions the developed world, including the former Soviet Union and eastern Europe, decrease emissions. Much of the decrease in emissions occurs in the former Soviet Union and eastern Europe, particularly in the early years of the analysis.

The cost of emissions reductions is relatively modest in the initial years, Figure 24. In 2005, total global costs of emissions reductions are only approximately 15 billion dollars with only $3 billion cost experienced in the United States. The reason costs are so low is the fact that emissions grow only about 10% between 1990 and 2005, and stabilizing global emissions with a global carbon tax requires that the United States

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[7] This divergence in the results is likely due to the treatment of synfuels in the consumption tax model. In the case of the consumption tax fossil fuel use by end-use sectors and electric utilities is taxed. Fossil fuel use by the synfuels industry is not taxed, only the outputs. Thus, only the carbon content of the final product is taxed and not the total carbon input. When the industry becomes large in the final periods, this discrepancy becomes important.

approximately stabilize its emissions during this period. As noted earlier, this relatively modest required effort is at least in part due to the assumed restructuring of economies in Eastern Europe and the former Soviet Union.

Table 7: Globally Uniform Carbon Tax Rates
Required to Stabilize Global Fossil Fuel Carbon Emissions
at 1990 Levels Indefinitely
($/mtC)

Year	Consumption Based Carbon Tax	Severance Based Carbon Tax
2005	$40	$39
2020	$99	$101
2035	$162	$171
2050	$215	$219
2065	$283	$275
2080	$401	$356
2095	$506	$398

Global average fossil fuel carbon emission per capita decline under the global emissions stabilization protocol, 1A. There are general declines in emissions per capita in all regions except China. In China the presence of large quantities of coal and accelerated economic growth combine to move average per capita fossil fuel carbon emissions steadily from 0.5 to 1.0, still below the global average for 1990, Figure 25.

Both the required tax and total cost of stabilizing global emissions grow rapidly. By the year 2020 total global costs have reached 108 billion dollars per year. In 2050 this figure is 483 billion dollars per year, and by 2095 costs are approaching two and a half trillion dollars per year. The escalation in costs is the result of a tension between a fixed emissions rate and a demand for exponentially growing economic activity. There is no "silver bullet" in this model. That is there is no technology which is a perfect substitute for other energy technologies and which will provide an essentially infinite amount of energy at a fixed cost. Liquids and gases continue to be demanded and the biomass resource which can produce them is tethered by a fixed land resource. Electricity can be produced by renewable energy resources but the alternative cost of applying these resources (relative to using conventional fossil fuels) to the entire range of electrical applications rises in the model. There is also no way in which fossil fuels can continue to be used without releasing carbon to the atmosphere.

The burden of increasing total cost with a common global carbon tax is distributed unevenly across the world. It also changes with time, Figures 26-28. Whereas it is predominantly experienced by the OECD and EEFSU regions in the early years, it is increasingly borne by China and other developing nations in later years. China bears a particularly large share of costs of stabilizing global fossil fuel carbon emissions due to its large coal resources, coal dependent infrastructure, and rapid economic growth.

The total costs of fossil fuel carbon emissions reductions are substantial and growing over time. These costs are presented relative to GDP in Figure 29. Costs rise over time as a percentage of GDP in all regions but remain below one percent of GDP throughout the analysis period in all regions except China and EEFSU. For both China and the EEFSU costs rise rapidly reaching 3% of GDP in China by 2095 and 2.25% of GDP in EEFSU.

One of the implications of the analysis of costs of emissions reductions is that the more rapid the rate of growth of emissions, and therefore the more rapid the accumulation of atmospheric CO_2, the more costly are emissions reductions to a fixed target emission rate. Conversely, the lower the rate of growth of emissions, and therefore the less rapid the accumulation of atmospheric CO_2, the less costly are emissions reductions to a fixed target emission rate. This tendency is reflected in Figures 30-32, which show the global uniform tax rate, global total cost of emissions reduction, and global total cost as a fraction of global GNP. For Cases A, B, and C costs are uniformly highest for Case C and lowest for Case B. Regardless of case costs rise with time.

Individual Targets: It would be very difficult to conceive of national governments agreeing on a common global carbon tax. A simpler mechanism for stabilizing future fossil fuel carbon emissions would be for all nations to each agree to stabilize national emissions. This scheme is not without its own problems. We have examined individual targets for Cases A, B, and C. First, individual targets shift the cost burden of emissions reductions away from developed nations and toward developing nations. By the year 2020 more than 80% of total global costs are borne by non-OECD regions.

Second, individual targets increase the total global cost of emissions reductions by more than a factor of two. Figure 33, which displays results for Case A. Ironically, costs are lower in the OECD region after the year 2005 than in the common tax case. Under such circumstances it is hard to imagine developing nations being attracted by such proposals.

Tradable permits hold promise of allowing developing nations to continue to develop and reducing costs.

Tradable Permits: Like taxes tradable permits can be shown to be economically efficient tools for reducing fossil fuel carbon emissions. That is both provide identical incentives to emitters to reduce emissions. In the case of the common tax, all emitters see a common marginal cost of emissions reductions. Since the marginal cost of emissions reductions are identical across all human activities, there is no way to change the pattern of emissions slightly and reduce total emissions costs. Tradable permits have similar properties. A market is assumed to form and permits are assumed to trade at a common market price. This price adds the same amount to the cost of using a fossil fuel as would a tax. To the user of the fossil fuel, there is no difference.

Other characteristics of the two systems are very different. In a tradable permit system, permits to release emissions into the atmosphere are owned as a property right. Ownership may be by the government or private parties. The emission right has value to an individual party. That value depends on the amount of emissions allowed to all parties and the amount allocated to the individual party.

In exploring the implication of tradable permit schemes, we examine three very different rules for allocation of permits:

1. *"Grandfathered Emissions" Principle,*
2. *Equal Per Capita Emissions Principle,*
3. *"No Harm to Developing Nations" Principle,*
4. *"No Harm to Non-OECD Nations" Principle.*

In the case in which all nations participate immediately in a protocol to stabilize emissions, emissions rights vary with time. The intertemporal paths for these four principles are shown in Figures 34-37. Figures 34 and 35 show the emissions allocations for the "Grandfathered Emissions" and "Equal Per Capita Emissions" principles. Figure 36 shows the principle applied to developing countries only, while Figure 37 shows the "no harm" principle applied to all non-OECD nations. The residual between the stabilization target emissions and the "no harm" allocation is made proportional to 1990, "grandfathered," emissions to minimize transfers among developed nations and to focus the discussion on the allocation of emissions permits between "no harm" regions and the remainder of the world.

The allocation of emissions rights using the "Grandfathered Emissions" principle and the "Equal Per Capita Emissions" principle contrast sharply with each other. Approximately half of the emissions rights are allocated to developed OECD nations under the former paradigm, while less than one fifth is allocated to these nations under the latter paradigm.

The "No Harm to Developing Nations" paradigm is an interesting contrast to either of the first two. Because costs of emissions reductions cannot be observed directly, there is no way to create a direct measure for allocating emissions trading rights. On the other hand, this paradigm does give some indication of the distribution of emissions allocations required to achieve this objective. Interestingly, in the year 2005 the allocation of resources to the "No Harm" regions is almost identical to that in the "Grandfathered Emissions" principle. This situation changes rapidly and by the middle of the next century almost all emissions rights must be allocated to the "no harm" states. At this point in time the allocation of emissions rights between developed and developing nations is similar to that of the "Equal Per Capita Adult Population" principle. The distribution of emissions rights to China is significantly higher in the "no harm" principles than in the "equal per capita adult population" principle. In the latter half of the century there are insufficient emissions rights to prevent developing nations from bearing some net costs of emissions reductions.

Financial transfers associated with the allocation of emissions rights depend critically on the allocation rule adopted. With "grandfathered" emissions rights, the developed nations (OECD and EEFSU) actually receive income transfers from the developing nations, Figure 38. The income transfer is small with the OECD and developing nations transferring resources to the EEFSU. The total transfer of wealth is small in the year 2005, but grows to more than a trillion dollars per year by the end of the analysis period.

Under the "equal per capita" emissions principle the OECD and EEFSU transfer wealth to the developing nations, Figure 39. Year 2005 transfers from the developed to the developing nations amount to $100 billion per year. By the middle of the next century growth in Chinese emissions moves China from a net supplier of emissions rights to a net buyer. Transfers from China to the other developing nations are substantial by the end of the century. Total wealth transfer amounts to about a trillion dollars per year by 2095.

Under the "no harm to developing nations" principle wealth transfers are initially modest, Figure 40. The total transfers are only approximately $15 billion per year in the year 2005. Interestingly, the "grandfathered" emissions among non-developing nations leads to revenues transferred to the EEFSU as well as to developing nations. By the middle of the century this effect ceases and the EEFSU joins the OECD nations as a net consuming nation for emissions permits. Wealth transfers escalate rapidly until more than $1.5 trillion per year is being transferred to the developing nations.

The "no harm to non-OECD nations" principle produces a pattern similar to that described above, with the curious exception that in the years 2005 and 2020 transfers from the OECD nations to the EEFSU are smaller than in the "no harm to developing nations" principle, Figure 41. This occurs because transfers are calculated to be precisely costs in the "no harm to non-OECD nations" principle. The transfers to other developing nations are, by construction, exactly as in the "no harm to developing nations" principle.

The allocation of emissions rights dramatically changes the regional distribution of net costs of participation in emissions control protocols. Net costs as a fraction of GDP are displayed in Figures 42-45. These economic burden values can be compared to those in Figure 29 above. It is important to recall that the total global cost of emissions reductions is not changed by alternative permit allocation schemes. All that is changed is the distribution of net costs among regions.

Quite clearly, the "grandfathered" emissions principle reduces the net economic burden of emissions reductions to trivial levels in OECD regions while benefitting EEFSU, Figure 42. Emissions reduction costs for China and other developing nations rise substantially. The net economic burden is quite different when the "equal per capita" principle is applied, Figure 45. China initially sells emissions rights in sufficient quantity to create a negative net cost of participation. By the year 2020 the net cost is approximately zero. It rises consistently thereafter. After the year 2035 China actually buys emissions rights from the international market. Thereafter net costs to China under an "equal per capita" emission principle actually exceed those in the common tax case. There would be substantial pressure for China to withdraw from an emissions protocol under such circumstances.

Under the "equal per capita" principle United States' costs rise in the year 2005 from trivial levels to 0.5% per year and move steadily upward from something greater than 1.0% in 2020 to more than 2.0% in 2080 and beyond. While net costs remain below 1.0% in the other OECD regions they reach 0.5% per year around 2020, and remain above that mark thereafter. Interestingly, continued rapid economic expansion of the region causes the JANZ region to acquire emissions rights under both the "grandfathered" and "per capita" allocation principles. Between 2035 and 2050 emissions are reduced sufficiently that under "grandfathered" emissions allocations the region becomes a net seller of rights. The EEFSU is the most sensitive to the allocation of emissions rights. Under "grandfathered" emissions, the region sells sufficient emissions rights that its net costs are negative. When emissions rights are allocated on a "per capita" basis the region continues to sell rights on the international market, but because the allocation is significantly diminished and continues to decline with time, net cost is reduced to approximately 0.5% per year.

If a way could be found to implement the "no-harm" principles the effect on net costs to the OECD regions would be lower than if emissions were allocated on a per capita basis but higher than if either emissions were controlled by a common tax or emissions were allocated by the "Grandfathered" principle before the year 2050. The additional burden, as a fraction of GDP, to OECD nations is modest in the year 2005, but rises swiftly thereafter. Because emissions rights in the burdened nations are assumed to be allocated in proportion to 1990 emissions, the EEFSU region is unburdened through the year 2020 in the case in the "No Harm to Developing Nations" principle.

In light of the above analysis, there are substantial problems to be overcome before a strong and effective emissions reduction protocol can be put into place. Furthermore, it is difficult to imagine the successful establishment of a protocol which would not need substantial renegotiation over time.

The Role of the Big Three

The rapid acceleration of emissions of carbon into the atmosphere in the middle and latter half of the twenty-first century is the consequence of an accelerated use of coal resulting from the combination of continued rapid economic growth, particularly in the developing nations of the world, and limits to inexpensive conventional oil and gas resources. The world distribution of coal resources (not to be confused with reserves) is not uniform. Table 8 shows the distribution of resources among world regions.

Table 8: Distribution of Global Coal Resources

Region	Resource Base (ej)	(%)
OECD	107,158	40%
EEFSU	114,328	42%
CHINA	38,742	14%
ROW	10,772	4%
TOTAL	271,000	100%

Source: Edmonds et al. (1986), Appendix A.

To explore the importance of participation by the "Big Three" regions: OECD, EEFSU, and China, we have constructed a scenario in which these regions engage in a coalition to stabilize combined emissions, but the rest of the world does not.

We have assumed that the "Big Three" institute a common two-part carbon tax with equal tax levels on production and consumption activities. In the analysis of protocol 1a, we found the issue of point of taxation (severance versus consumption tax) not to be an important issue. When some regions participate and others do not the matter become more important. If only consumption is taxed, and production goes untaxed, then a protocol participant may simultaneously reduce its own emissions while supplying fossil fuels to the rest of the world and facilitating additional emissions by the rest of the world. On the other hand, when only a subset of nations participate and a severance tax is used without a consumption tax, the opposite propensity emerges. That is, there is a tendency for fossil fuel production to be reduced, but no direct incentive for the use of fossil fuels to be diminished.

Coupling production and consumption taxes is intended to address the problem of significant non-participating regions. The consumption component of the two-part tax directly stimulates reductions in the use of fossil fuels. The production tax component not only reduces domestic production of fossil fuels, but also affects the world price of coal to the rest of the world. It is not entirely clear how to report the two-part carbon tax. We have chosen to report the carbon tax rate as the simple sum of the production and consumption components. In the case in which a region is effectively closed, carbon would in fact be taxed twice. For economies that are dominated by either production or consumption, carbon could actually be taxed only once under such a scheme. The "Big Three" scenario is developed under the hypothesis that reference, untaxed emissions are those given in Case A.

By hypothesis "Big Three" regional emissions are stabilized at 1990 levels throughout the period of analysis. Global fossil fuel carbon emissions grow through the year 2080, peaking at approximately 44% above 1990 levels. They decline sharply in 2095, Figure 46. Within the region Chinese emissions grow to more than half of the regional total, while OECD and EEFSU emissions decline.

The time profile of the common "Big Three" carbon tax varies with time, Figure 47. The tax rate rises from $25/mtC in 2005 to approximately $110/mtC in the year 2035. The tax rate declines in the year 2050, rises again in 2065 to a peak of more than $130/mtC and then declines to the point where it is not needed in the year 2095. Emissions are only 60% of 1990 levels in 1990 without any tax! This is a remarkable case exhibiting numerous interesting potential consequences of complex interregional interactions.

The decline in the tax needed in the year 2050 is the result of declining production in the conventional oil industry which peaks in 2035 at 163 Ej/yr and the consequent increase in the world oil price. The higher oil price reduces the need to tax oil to reduce consumption and associated carbon emissions. Note also that the incentive to reduce emissions is transferred to non-participants as well as participants, Figures 48-50.

Coal production in the rest of the world grows steadily through the year 2085. Coal production collapses in the year 2095 with the exhaustion of "non-Big Three" resources. Coal production in the "Big Three" declines and never recovers. It is interesting that the ERM does not allow production to increase arbitrarily from one period to the next. There is a steeply increasing supply function for sectors which grow rapidly between periods. This model feature acts to retard instant supply growth. The decline in the coal industry in OECD regions implies a reduction in expansion capability for that sector.

By the year 2095, the exhaustion of global conventional oil and gas resources, and coal resources in "non-Big Three" regions drive energy prices very high, Figure 50. The rapid increase in the price of energy causes the model's GNP feedback mechanism to reduce global GNP by approximately 5%. This reduces global energy demand to the point where carbon emissions actually decline without any tax in the final period. The magnitude of real cost associated with the unavailability of fossil fuel energy is indicated by the GNP reduction through the GNP feedback mechanism.

Stabilizing emissions in the "Big Three" alone does not stabilize global fossil fuel carbon emissions at 1990 levels until the end of the analysis. it does significantly reduce global emissions from their reference track. For example in the year 2050 emissions in Case A are 95% higher than in 1990. When the "Big Three" stabilize emissions with a production and consumption tax global emissions increase by only 31%. By the year 2080 Case A global fossil fuel carbon emissions are 186% higher than in 1990. Under "Big Three" stabilization they are only 45% higher than in 1990.

The "offshore" effect in the "Big Three" case is interesting. While this effect is generally thought to make global emission reductions relative to the reference case smaller than emissions reductions in participating regions, the "Big Three" case is more complex. In 2005, 2020, 2080, and 2095 (see Figure 51) the "offshore" effect actually leads to unintended emissions reductions by non-participants. This is affected by significant increases in energy prices. During the middle period, years 2050 and 2065, non-participants' emissions cause global emissions reductions relative to the reference case to be lower than emissions reductions by the "Big Three." The unintended emissions reductions by non-participating regions was unexpected.

The effect of "Big Three" emissions stabilization on atmospheric CO_2 concentrations, using the ocean only model and the "neutral biosphere" assumption, are shown in Figure 52. Concentration are clearly lower than in reference Case A. Furthermore, 2095 atmospheric CO_2 concentrations are as low as or lower for the Case A "Big Three" protocol than in all case A protocols analyzed except protocol 1a, in which all regions initiate immediate stabilization of emissions at 1990 levels. The effect of the "Big Three" protocol hypothesis on atmospheric concentrations is more pronounced when Case C reference emissions are considered. When Case B reference emissions are considered the effect is reduced.

It is clear from this analysis that, while accumulation of CO_2 in the atmosphere from fossil use is a global problem, that significant progress toward changing the rate of accumulation can be made even if some regions do not participate. It is important to the long term success of partial participation protocols, that fossil fuel exports by participants to non-protocol regions be limited.[8] The effectiveness of the "Big Three" in stabilizing global fossil fuel carbon emissions in the long term depends critically on the magnitude and distribution of fossil fuel resources, and particularly coal. If coal resources in the non-"Big Three" regions were found to be significantly greater than current estimates indicate, then global emissions could rise rather than decline in the latter periods.

The Consequences of Delays

To explore the consequences of delays in implementing fossil fuel carbon emissions protocols, we have constructed four other hypothetical protocol patterns: 1b, 2a, 2b, and 3, as outlined earlier. In cases in which participation is delayed, it is generally found that both those who delay and those who participate experience reduced costs. Costs are reduced to delayed participants as the tardy parties stabilize emissions at a higher level of emissions than the would have under the more stringent protocols, and because they incur no costs at all in years in which they do not participate. Interestingly, participants also experience lower emissions reduction costs. By hypothesis, it is the OECD nations which join the protocol first. They initially stabilize their own emissions, and therefore the cost of achieving that level of reduction is less than when they participate in a more broadly based coalition with a faster growing economic base. In later years, when other parties join the coalition, the level of emissions at which emissions are stabilized is larger. Cost reductions are achieved at the cost of higher concentrations of atmospheric CO_2 in all years analyzed.

Atmospheric Concentration: The effect of these protocol variants on atmospheric accumulation of carbon[9] is given in Figures 53-55 for Cases A, B, and C respectively. We begin by noting that there is little to distinguish protocols 1a, 1b, and 2a with regard to atmospheric concentrations, although immediate participation in a program to stabilize the fossil fuel carbon emissions by all nations (Protocol 1a) always leads to lowest atmospheric concentrations. Universal participation delayed to the year 2005 (Protocol 2a) yields only slightly higher atmospheric CO_2 concentrations, and immediate initiation of emissions stabilization by the OECD with delayed participation by other regions (Protocol 1a) yields slightly higher concentrations. These patterns emerge regardless of whether the reference case is A, B, or C. Greater delays in the implementation of protocols lead to more pronounced increases in atmospheric carbon, particularly when reference cases A and C are examined. Under reference Case B, the effects are less noticeable due to the fact that this case has little growth in emissions even in the absence of protocols.

Costs and Carbon: Regardless of which reference case (A, B, or C) and regardless of which protocol is examined (1a, 1b, 2a, 2b, or 3), the total cost of implementing the protocol and the atmospheric CO_2

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[8] When a "Big Three" protocol case was run in which only emissions were taxed, there was little difference in global emissions through the year 2050 when compared to the "Big Three" protocol in which half the tax was applied as a severance tax and half the tax was applied as an energy consumption tax. In the second half of the century, however, an increasingly wide gap opened between these two variants of the Case A "Big Three" protocol.

[9] Atmospheric CO_2accumulation is estimated using the ocean only model of uptake and the assumption of a "neutral" biosphere.

concentrations both rise with time, Figures 56-58. Figures 59-61 plot the same information as Figures 53-55, but focus on the relationship between cost and atmospheric CO_2 concentration between protocols. There is a clear linear trend for protocols which generate lower emissions to also be associated with higher costs. Costs of emissions reduction for each region, for each of the protocols, is plotted against time in Figures 62-67. The reduction in cost observed as atmospheric concentrations rise relative to protocol 1a, in delayed participation protocols, is shared generally.

Offshore Effects: One of the concerns associated with partial participation in protocols is that protocol participants may achieve emissions reductions goals but that non-participants may reverse these achievements by increasing their carbon emissions. The decrease in demand for carbon intensive fuels in protocol participating regions can lower the price of these fuels to non-participants and thus stimulate an increase in the quantity demanded in those regions. Alternatively, the increase in the cost of producing carbon intensive goods in protocol regions may lead to the production of these goods in other regions and their import from non-protocol regions. This effect does not appear to be important in the analysis we have conducted here. While the effect appears to be present in all of the delayed participation cases, that is Protocols 1b and 2b, the quantitative magnitude of the effect is minor, increases in non-participant emissions are denominated in tens of teragrams of carbon per year, regardless of whether the participants adopted individual regional targets or a common target for all protocol participants.

Technology and Emissions

Technology Transfer and Emissions Reduction Costs: While the offshore effect can act to reduce the effect of protocol participants on global fossil fuel carbon emission, technology transfer can operate to enhance emissions reductions by participants. We use the term "technology transfer effect" to denote the occasion when new technologies are developed by protocol participants in response to the higher cost of emissions producing activities and subsequently exported to non-participating regions.

In the ERM end-use energy using technologies change both exogenously and in response to higher prices. To explore the potential importance of the technology transfer effect we have run a series of cases in which a fraction of *endogenous* improvements in end-use energy intensity occurring in protocol participating regions as a result of higher costs of fossil fuel use are transferred to developing countries in the form of higher *exogenous* end-use energy intensity improvements. Note that this effect commences as soon as one or more regions submit to a protocol and ceases for any given non-participating region when that region joins the protocol. It is assumed that the carbon tax associated with the protocol provides an economic incentive to adopt more efficient technologies.

Specifically, we have selected the two staggered participation, uniform tax protocols from Case A (Protocols 1b and 2b). Using the same tax rates which achieve stabilization and varying the fraction of improvement transferred (alpha = 0.1, 0.25, 0.5, and 1.0), results in reductions in global emissions. In Figures 68 and 69, it is seen that, in the extreme, emissions are temporarily reduced to or below 1990 levels. Then, as non-participants subsequently join the protocols this effect dissipates. Even though temporary in nature, this transfer effect has a small but lasting effect on atmospheric carbon concentration. As seen in Figures 70 and 71, the terminal values of concentration are as much as 2% to 3% below the basic protocol cases.

In terms of total costs of emissions reduction, this effect is most pronounced in the early years when the number of non-participants is at the maximum. Figures 72 and 73 show that in the year 2020, the same total cost for emissions control can effect as much as six times the emissions reduction as the basic protocol case. However, by the year 2095, this phenomenon is barely discernable (see Figure 74).

Advanced Technology Development and Deployment: To explore the optimistic outlook for technology development, we assume that solar electric power becomes competitive ($0.05/kWh) with fossil sources shortly after the turn of the century. Moreover, coal and gas have been assigned electrical generating efficiencies of 55% by the year 2020. This scenario change results in a one-quarter reduction in emissions in the final year, brought about by a 20% reduction in primary energy demand (see Figure 75) coupled with a nearly 2-1/2 times growth in solar energy, vis-a-vis the reference case. At the same time, because of lower energy prices, secondary energy demand actually increases very slightly, accompanied by a substantial shift toward the electric mode.

Stabilization of fossil fuel carbon emissions at the 1990 level is correspondingly easier with taxes a bit over one half those from the standard scenario. In this exercise (see Figure 76), primary energy demand is reduced still further, while the use of solar electric, now even more favorably priced compared to fossil fuels, nearly doubles again. The total costs to stabilize emissions, as seen in Figure 77, are reduced substantially. Total cost reductions under Case A, Protocol 1a (globally common tax rate) range from $\$14\times10^9$/yr in 2005 to more than 1.4×10^{12}/yr in the year 2095. The implied atmospheric concentration of CO_2 is the same in this case as in all other emissions stabilization cases.

CONCLUSIONS

We have examined the cost and effectiveness of various potential forms of international agreement to reduce fossil fuel carbon emissions and the associated distribution of costs and wealth transfers. We have made no attempt to predict the future. Rather we have attempted to explore some the possible evolutionary paths that the future might take and to explore some of the potential problems and possibilities that may be encountered. We chose a set of assumptions which produces a set of three future trajectories of global energy and fossil fuel carbon emissions, labelled Cases A, B, and C, which span many of the other reference cases found in the literature. In addition, we have used the tools of economic analysis to assess the costs of stabilizing future emissions at a variety of levels ranging from those of 1990 to those of future dates. We have examined the consequences of potential protocols both in terms of the rate of emission and the concentration of atmospheric CO_2. As a consequence of this analysis several conclusions appear warranted.

Significant uncertainty surrounds the mechanism by which carbon is removed from the atmosphere. Greater uncertainty surrounds the anthropogenic injection of fossil fuel carbon.

While developing nations are expected to produce an increasing share of annual emissions over time, the cumulative change in atmospheric CO_2 from 1990 to future dates in the next century associated with the developed nations remains high. Developing nations' share exceed half of the change in atmosphere from 1990 only toward the end of the next century.

The costs of emissions are related to the method and timing of stabilization. Delays in stabilizing emissions lead to lower costs but consequently higher future concentrations of atmospheric CO_2. Stabilizing emissions at any level implies a need for continual reduction in global average per capita emissions throughout the remainder of the next century. Regardless of the cases examined, the economic costs of emissions reductions tended to fall increasingly on the presently developing nations of the world.

When individual regions acted independently to stabilize emissions economic costs were significantly greater than when they acted collectively. Furthermore, the costs of stabilizing global emissions fell more heavily on developing nations than when a common global carbon tax was assumed.

We examined several specific allocations of emissions rights, "grandfathered" emissions, where emissions rights are allocated on the basis of historical emissions, and equal per capita adult emissions, where emissions rights are allocated on the basis of either adult population or lagged population. We did not explore an allocation of emissions rights on the basis of income as we were pessimistic about present abilities to derive an agreeable metric for comparing different economies. An allocation of emissions rights on the basis of historical emissions leads to a transfer of wealth from the developing nations to the developed nations of the world and increases the cost burden to the developed world. Allocation of emissions rights on the basis of equal per capita adult population leads to transfers of wealth from the developed world to the developing regions. Wealth transfers under emissions rights allocations based on equal adult per capita emissions may greatly exceed the wealth transfer needed to leave some developing nations unharmed by participation in emissions reduction protocols.

Alternatively, wealth transfers under per capita carbon emissions rights allocations may be insufficient to leave some developing nations unharmed by participation in emissions reduction protocols. As a consequence, there is real potential for developing nations to "drop out" of protocols if they perceive that they are being harmed by participation. The "drop out" problem is driven by such pressures as accelerated economic growth and declining allowable average global per capita emissions over time. As a consequence of issues which surround the substantial wealth transfers associated with the establishment of protocols, it is difficult to envision any protocol which would not need substantial renegotiation over time.

It has long been recognized that the "Big Three," the OECD, EEFSU, and China, are critically important to any successful effort to control global fossil fuel carbon emissions. These three regions also have sufficient command over the world's fossil fuel resource base (and in particular coal resources) to cause the rest of the world to become unintended participants in the stabilization of emissions.

Short delays in reaching a meaningful agreement, or staggered participation in a protocol which begins immediately with initial OECD stabilization of current emissions levels, causes long-term (year 2095) concentrations of atmospheric CO_2 to be only slightly higher than is the case with immediate participation. Further delays in completion of an agreement exhibit increasingly higher long-term concentrations of atmospheric CO_2. These higher concentrations of atmospheric CO_2 trade against lower economic costs. The reduced economic costs appear to be generally disbursed among both immediate participants and delayed participants. We make no attempt in this paper to assess the benefits of emissions reductions and are therefore able only to describe the relationship between cost and atmospheric concentration. We are unable to provide a full economic assessment.

We observed little problem with erosion of emissions reductions by non-participants in protocols, the "off shore" effect. That is, global emissions reductions were only slightly less than emissions reductions by participants in cases in which participation was delayed (Protocols 1b and 2b). In the "Big Three" protocol we observed a reverse "off shore" effect. That is, actions by "Big Three" participants to stabilize their own emissions caused emissions by non-participants to be lower than they would otherwise have been in some years.

We have conducted experiments in which various fractions of price induced end-use energy efficiency improvements occurring as a result of carbon taxes in the OECD regions are transferred to non-participating regions. The effect of this "technology transfer" is very powerful. It can potentially leverage reductions in protocol participating regions substantially.

Finally, we examined the potential for advanced technologies to reduce the costs of stabilizing global fossil fuel carbon emissions. The value, in terms of reduced costs of emissions stabilization, of introducing advanced technologies into the energy system rise steadily with time from only a few billion dollars per year in 2005 to more than a trillion dollars per year. If these technologies were immediately available they would virtually negate the cost of emissions stabilization. In the long term they reduce costs by half.

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June 19, 1992

Figure 1

THE CARBON CYCLE

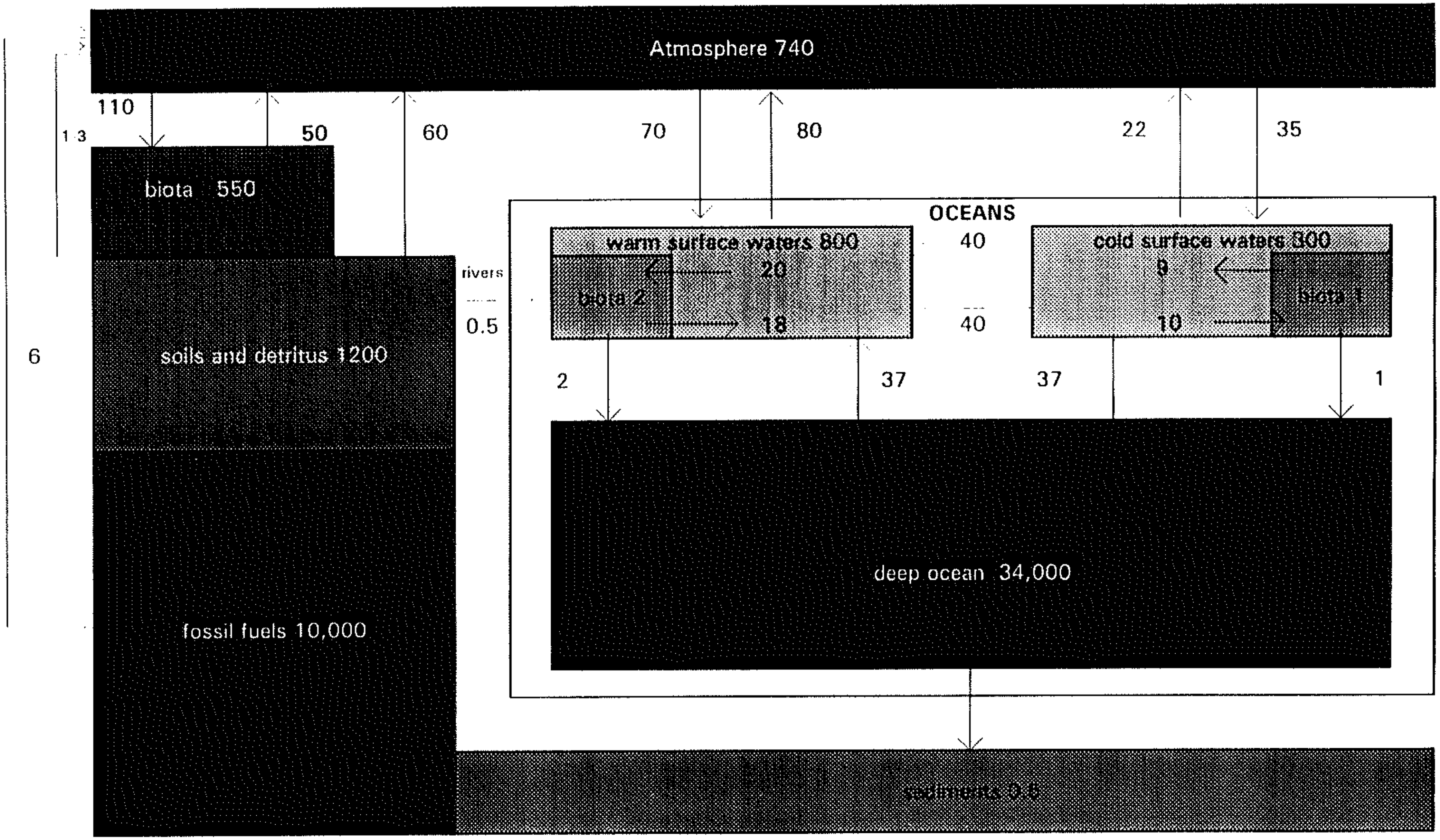
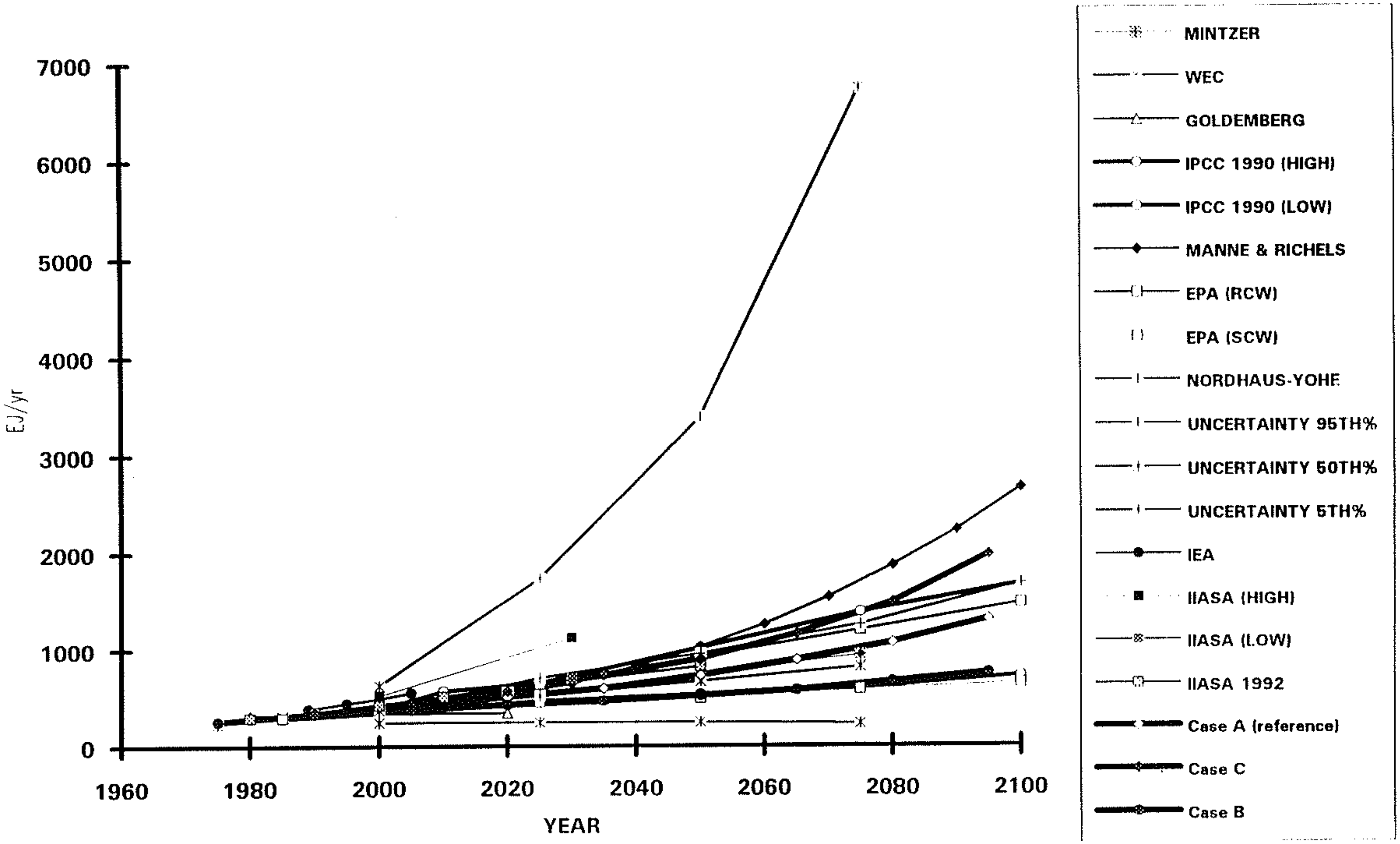


Figure 2



Global Primary Energy Consumption
Reference Cases for Various Studies

Figure 3

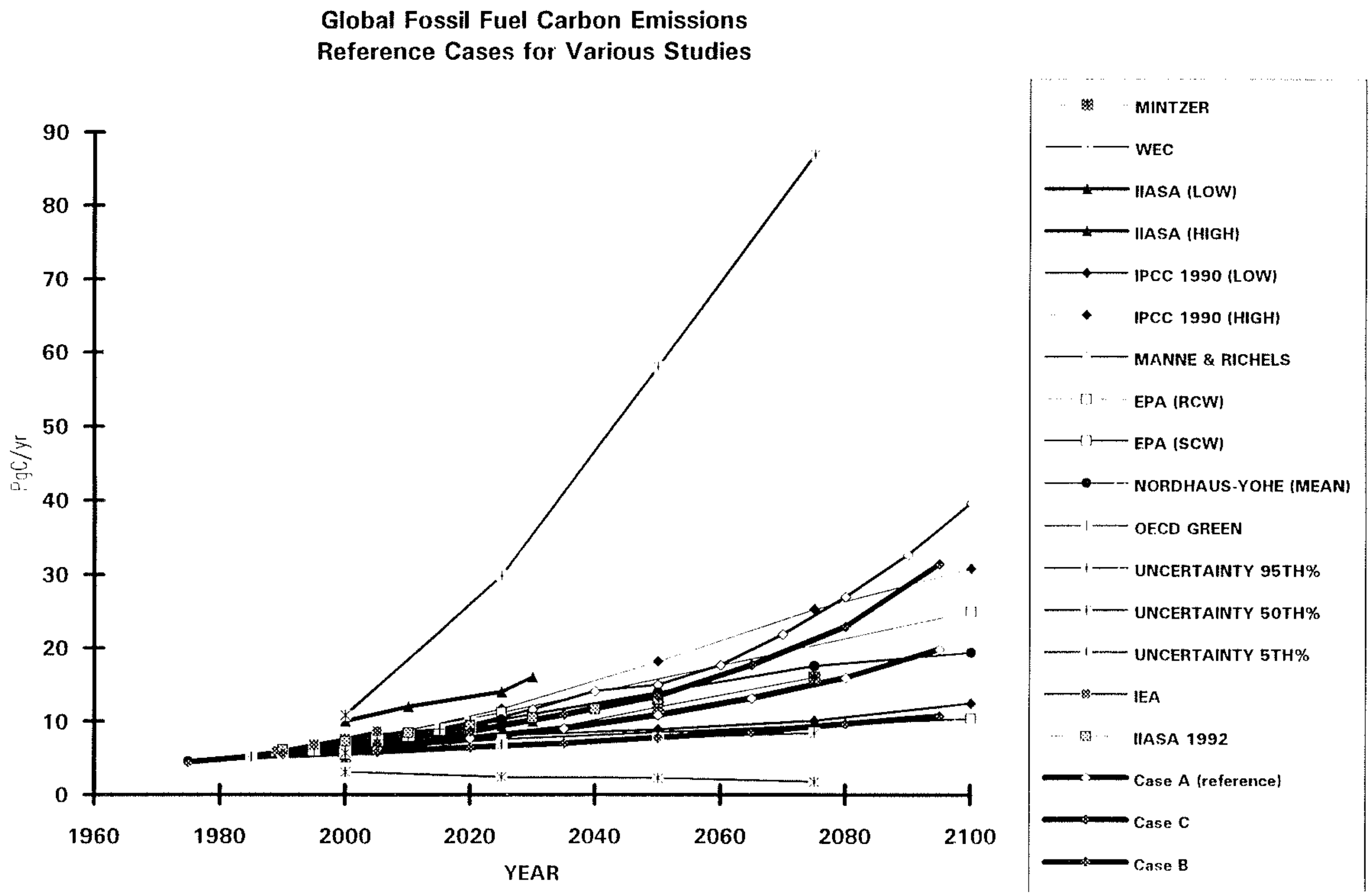
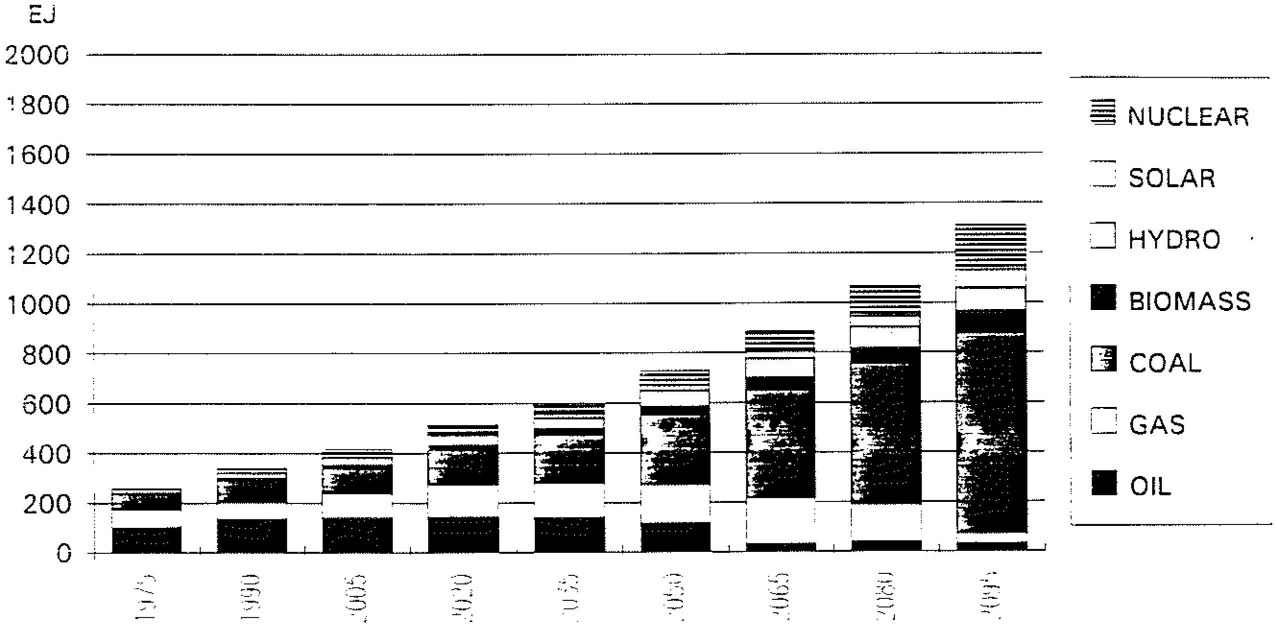
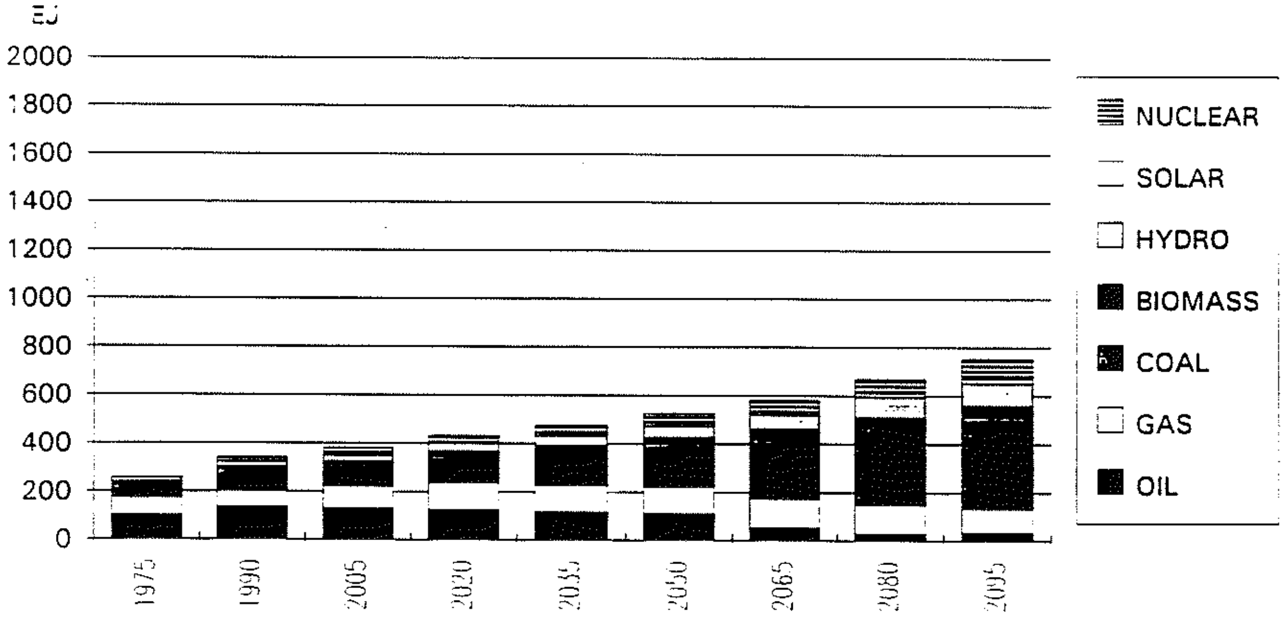

Global Fossil Fuel Carbon Emissions
Reference Cases for Various Studies
PgC/yr
90
80
70
60
50
40
30
20
10
0
1960
1980
2000
2020
2040
2060
2080
2100
YEAR
MINTZER
WEC
IIASA (LOW)
IIASA (HIGH)
IPCC 1990 (LOW)
IPCC 1990 (HIGH)
MANNE & RICHELS
EPA (RCW)
EPA (SCW)
NORDHAUS-YOHE (MEAN)
OECD GREEN
UNCERTAINTY 95TH%
UNCERTAINTY 50TH%
UNCERTAINTY 5TH%
IEA
IIASA 1992
Case A (reference)
Case C
Case B

Figure 4



NON-PROTOCOL CASE A PRIMARY ENERGY CONSUMPTION BY TYPE: 1975-2095

Figure 5



NON-PROTOCOL CASE B PRIMARY ENERGY CONSUMPTION BY TYPE: 1975-2095

Figure 6

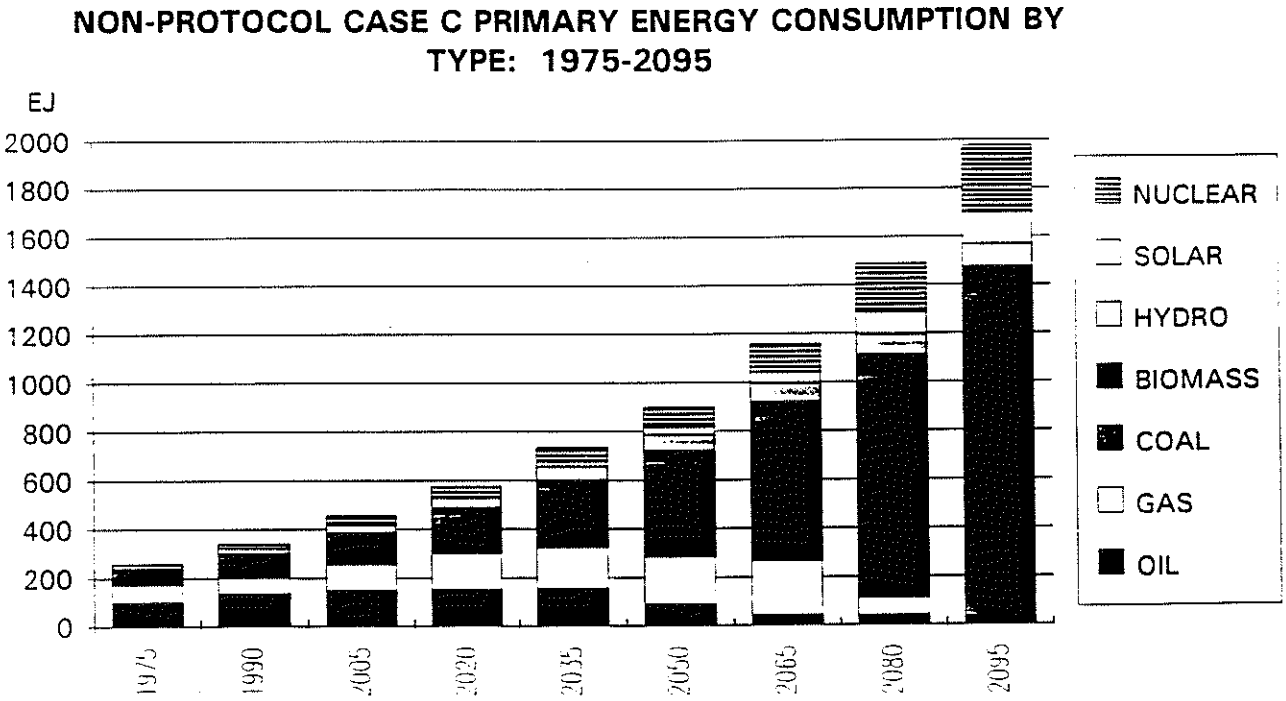

NON-PROTOCOL CASE C PRIMARY ENERGY CONSUMPTION BY TYPE: 1975-2095
EJ
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1975
1990
2005
2020
2035
2050
2065
2080
2095
NUCLEAR
SOLAR
HYDRO
BIOMASS
COAL
GAS
OIL

Figure 7

NON-PROTOCOL CASE A PRIMARY ENERGY CONSUMPTION BY REGION: 1975-2095

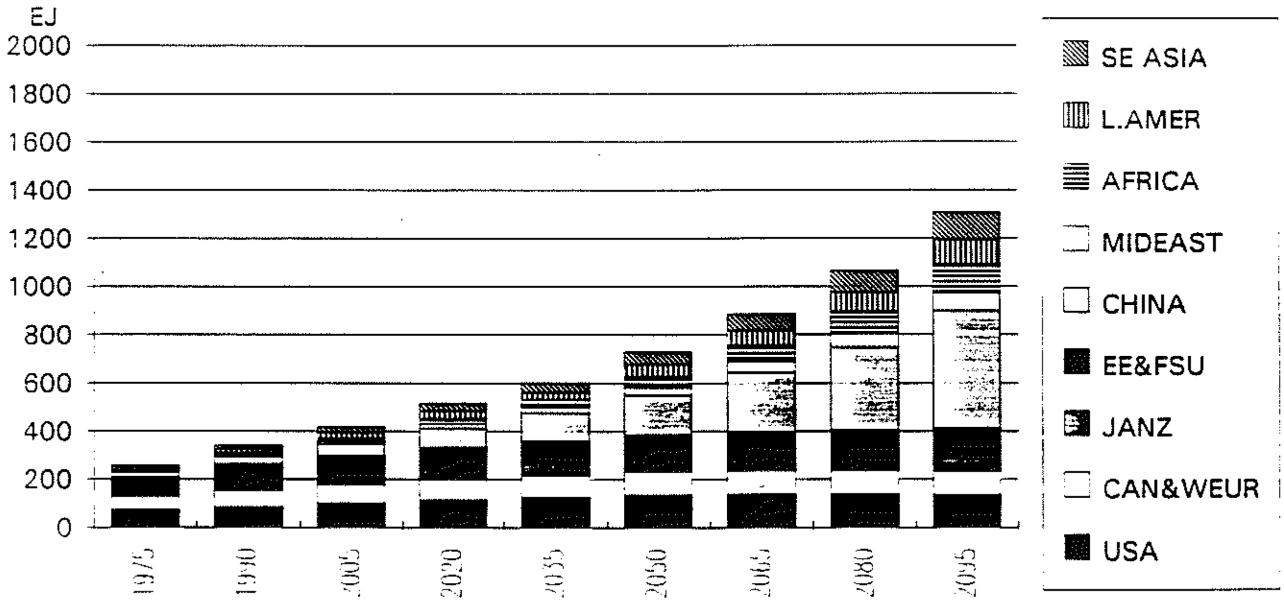


Figure 8

NON-PROTOCOL CASE BPRIMARY ENERGY CONSUMPTION BY REGION: 1975-2095

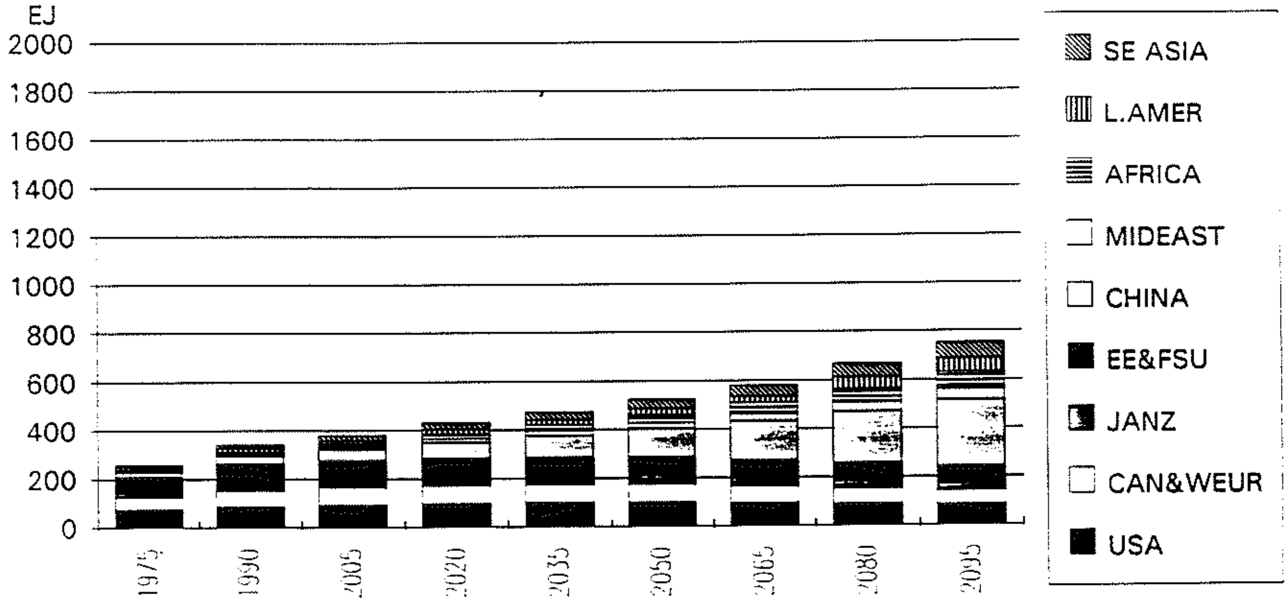
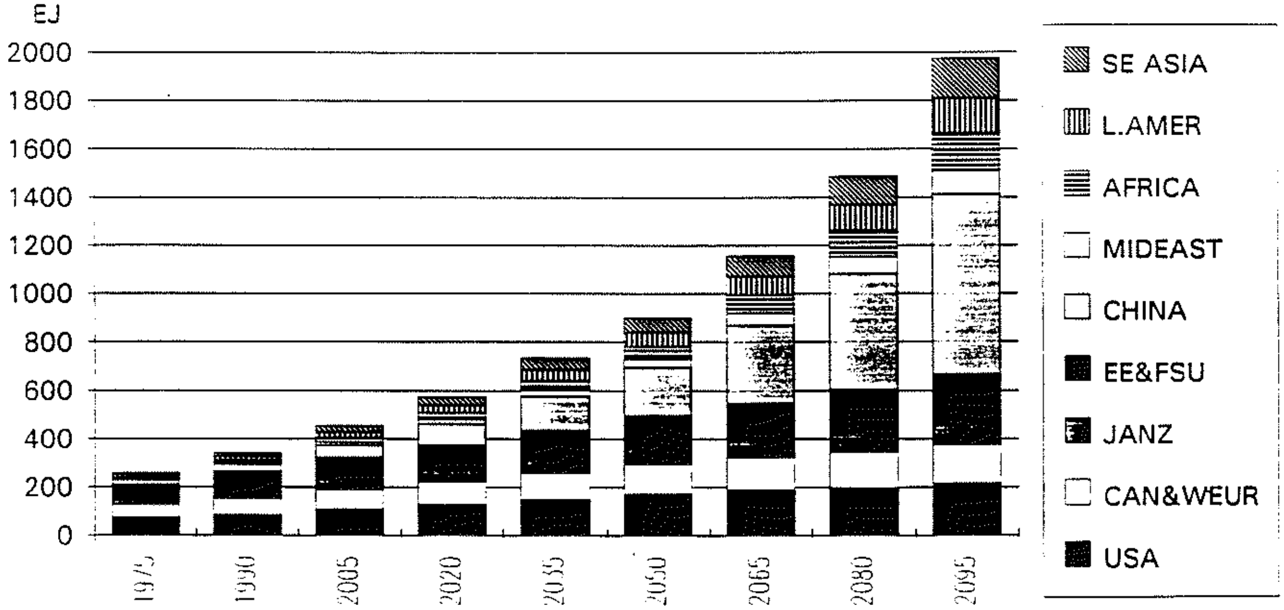
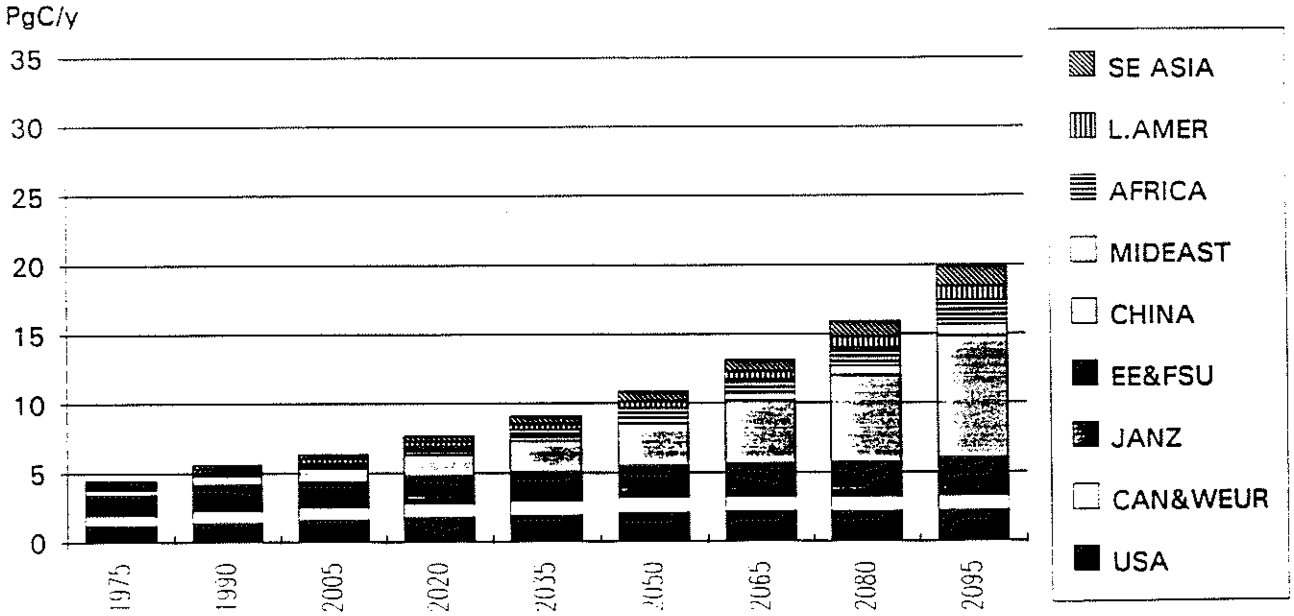


Figure 9



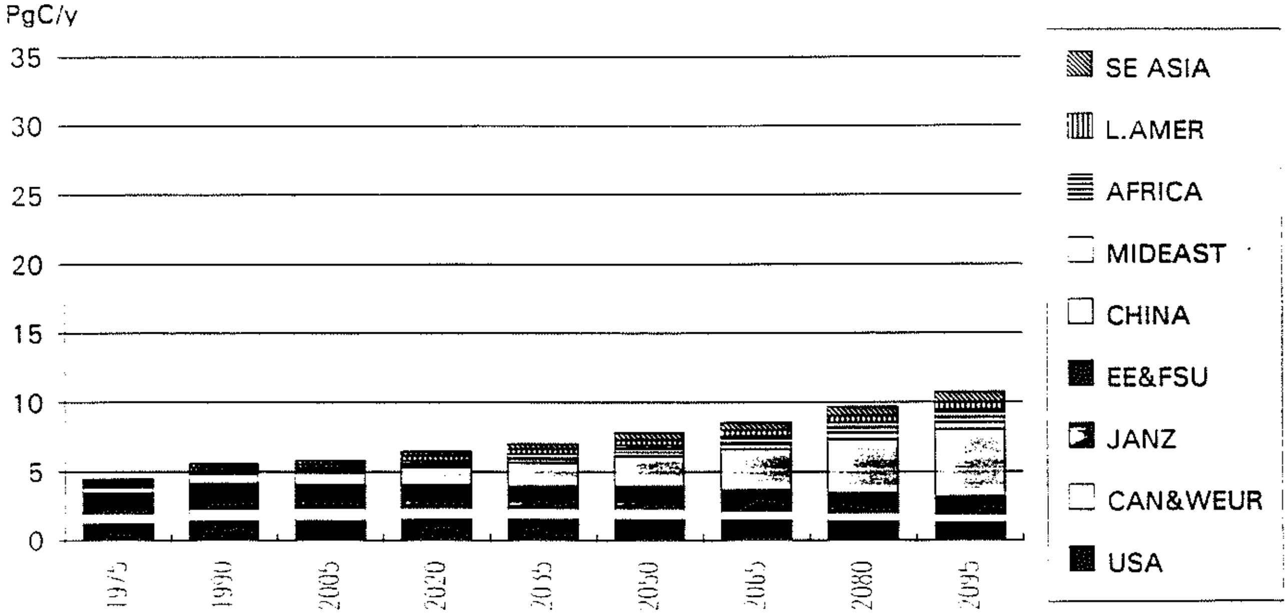
NON-PROTOCOL CASE C PRIMARY ENERGY CONSUMPTION BY REGION: 1975-2095

Figure 10



NON-PROTOCOL CASE A (REFERENCE) FOSSIL FUEL CARBON EMISSIONS BY REGION: 1975-2095

Figure 11



NON-PROTOCOL CASE B FOSSIL FUEL CARBON EMISSIONS BY REGION: 1975-2095

Figure 12

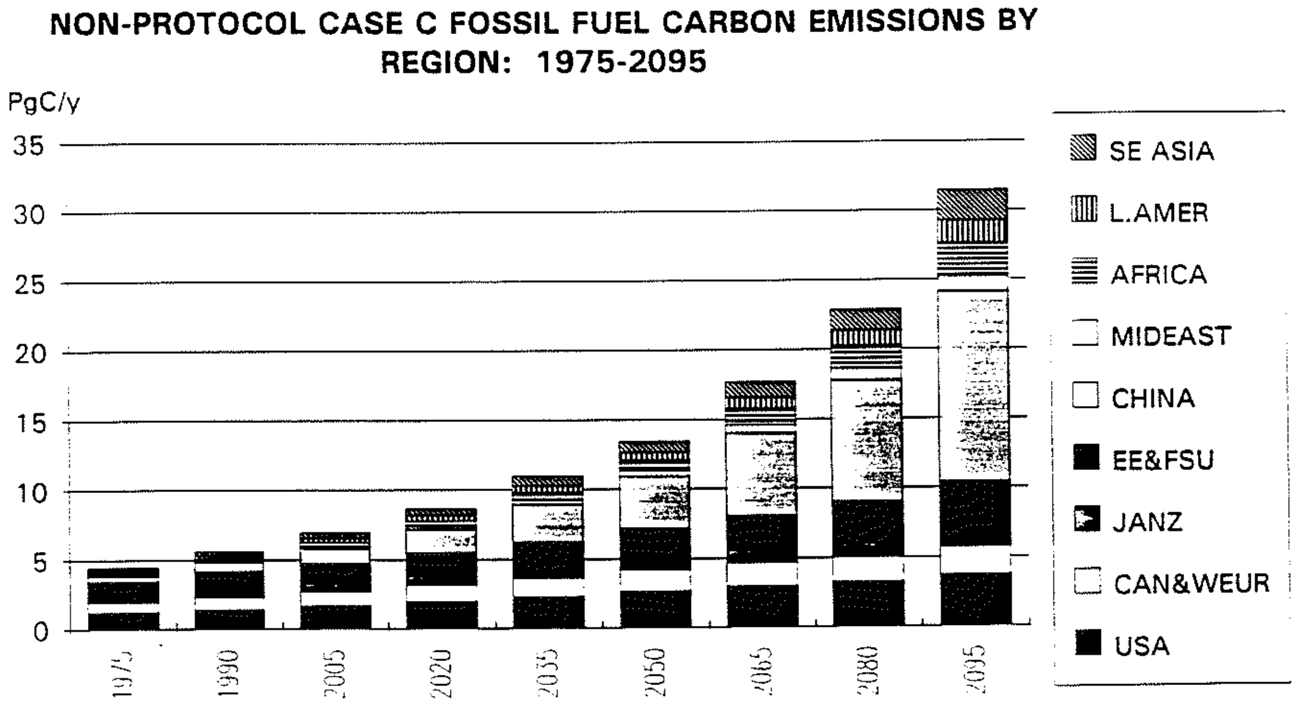

NON-PROTOCOL CASE C FOSSIL FUEL CARBON EMISSIONS BY REGION: 1975-2095
PgC/y
35
30
25
20
15
10
5
0
1975
1990
2005
2020
2035
2050
2065
2080
2095
SE ASIA
L.AMER
AFRICA
MIDEAST
CHINA
EE&FSU
JANZ
CAN&WEUR
USA

Figure 13

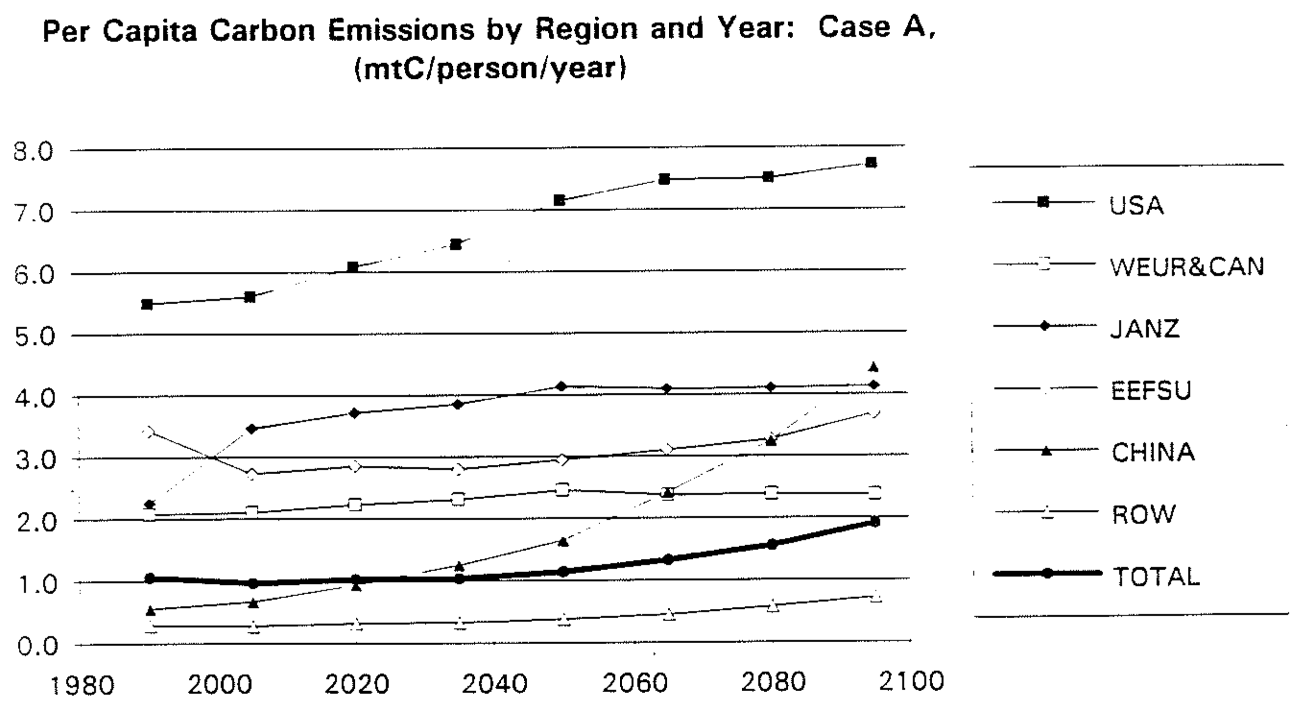
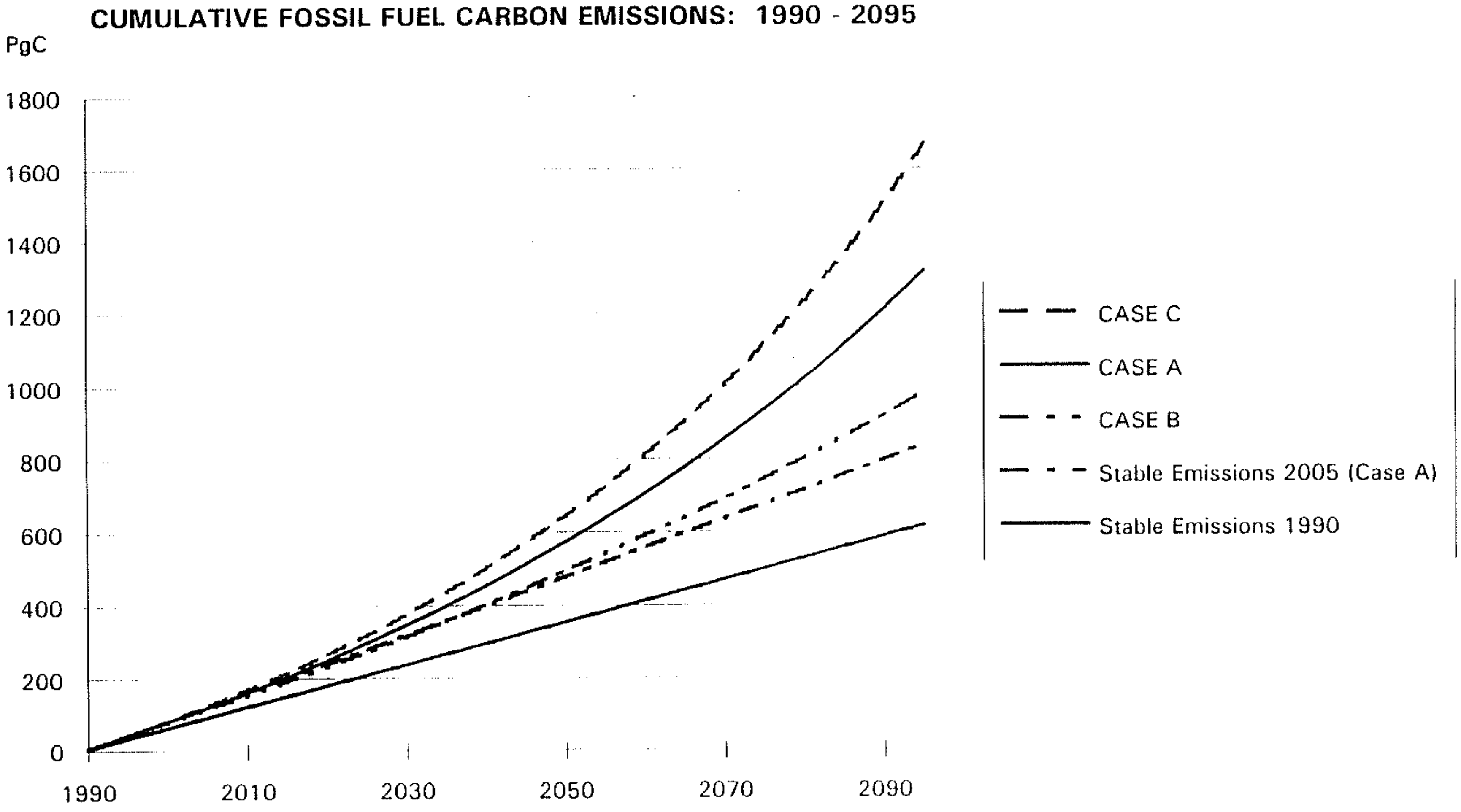

Per Capita Carbon Emissions by Region and Year: Case A,
(mtC/person/year)
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
1980
2000
2020
2040
2060
2080
2100
USA
WEUR&CAN
JANZ
EEFSU
CHINA
ROW
TOTAL

Figure 14



CUMULATIVE FOSSIL FUEL CARBON EMISSIONS: 1990 - 2095

Figure 15

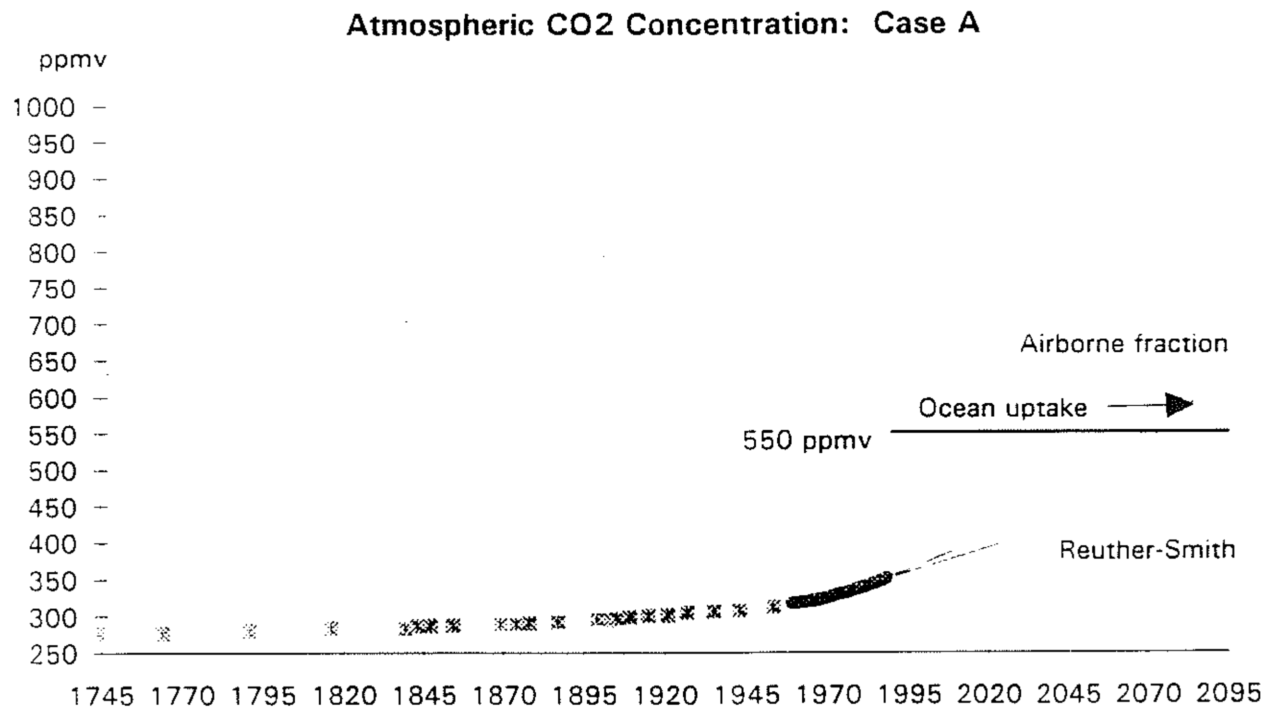

Atmospheric CO2 Concentration: Case A
ppmv
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
250
Airborne fraction
Ocean uptake
550 ppmv
Reuther-Smith
1745
1770
1795
1820
1845
1870
1895
1920
1945
1970
1995
2020
2045
2070
2095

Figure 16

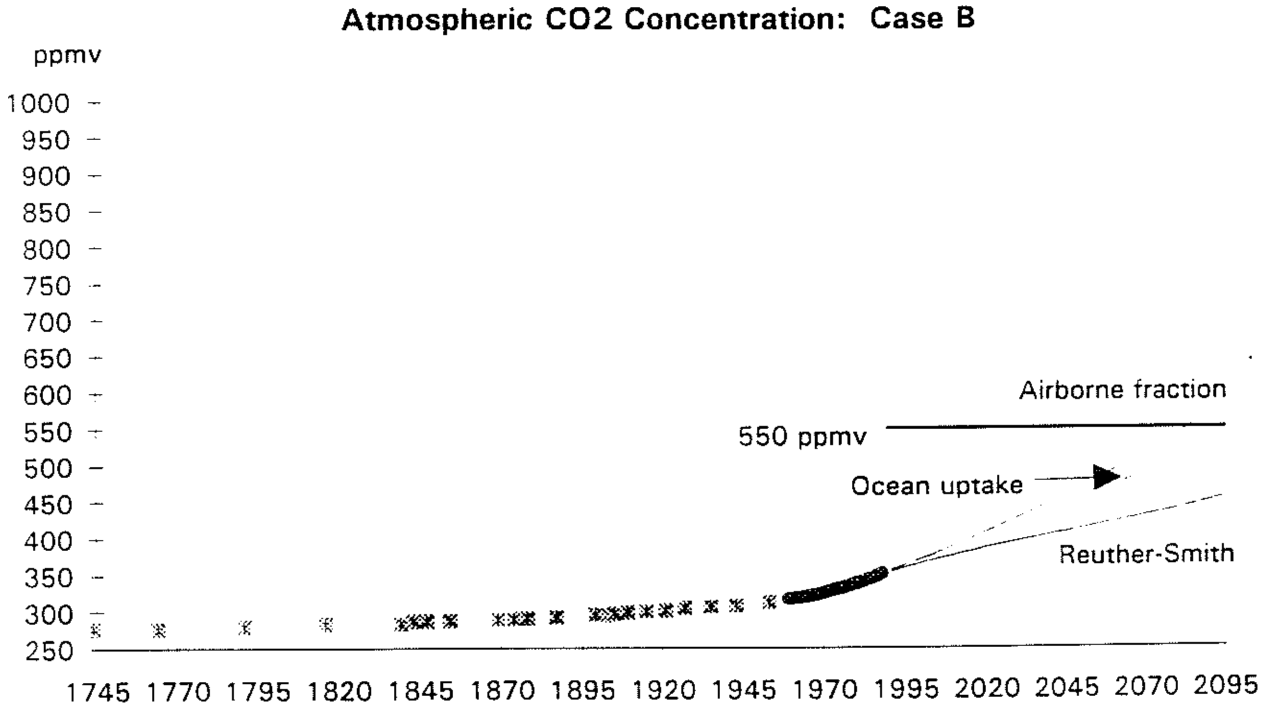

Atmospheric CO2 Concentration: Case B
ppmv
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
250
1745
1770
1795
1820
1845
1870
1895
1920
1945
1970
1995
2020
2045
2070
2095
Airborne fraction
550 ppmv
Ocean uptake
Reuther-Smith

Figure 17

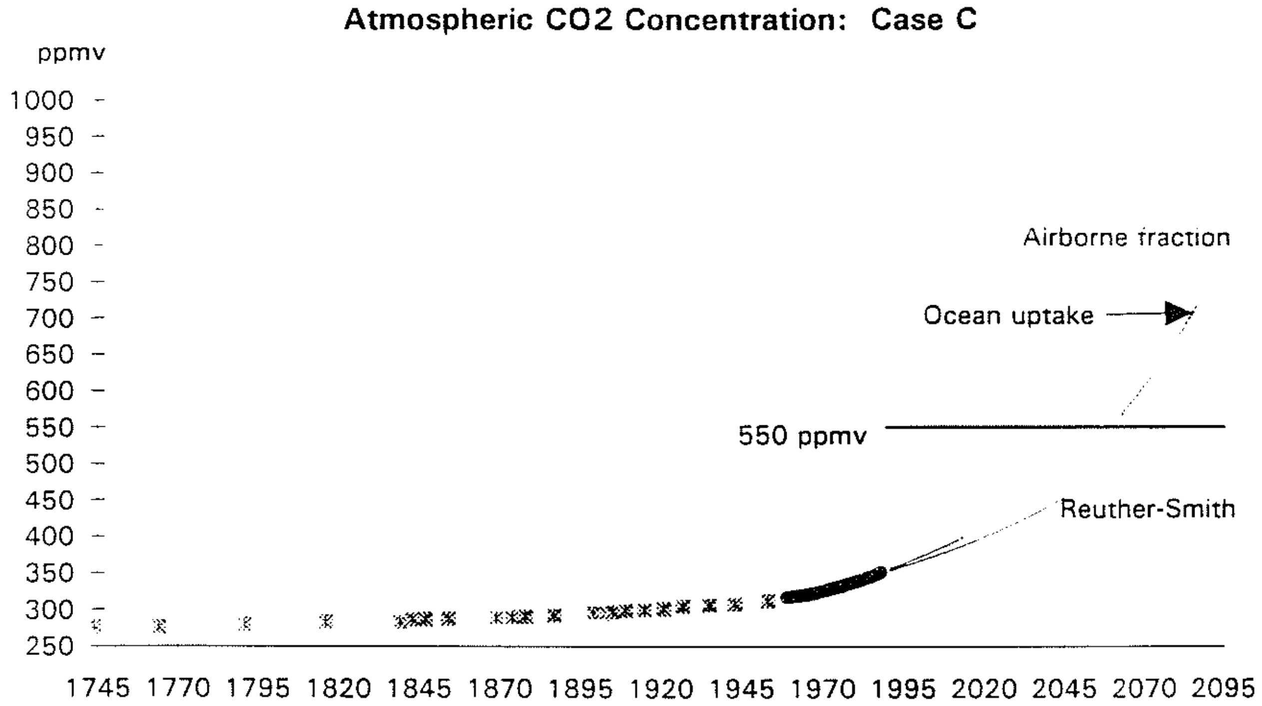

Atmospheric CO2 Concentration: Case C
ppmv
1000
950
900
850
800
750
700
650
600
550
500
450
400
350
300
250
Airborne fraction
Ocean uptake
550 ppmv
Reuther-Smith
1745
1770
1795
1820
1845
1870
1895
1920
1945
1970
1995
2020
2045
2070
2095

Figure 18

Atmospheric CO2 with Post-1950 Emissions Removed at Globally Averaged Rate Using the Ocean Uptake Model

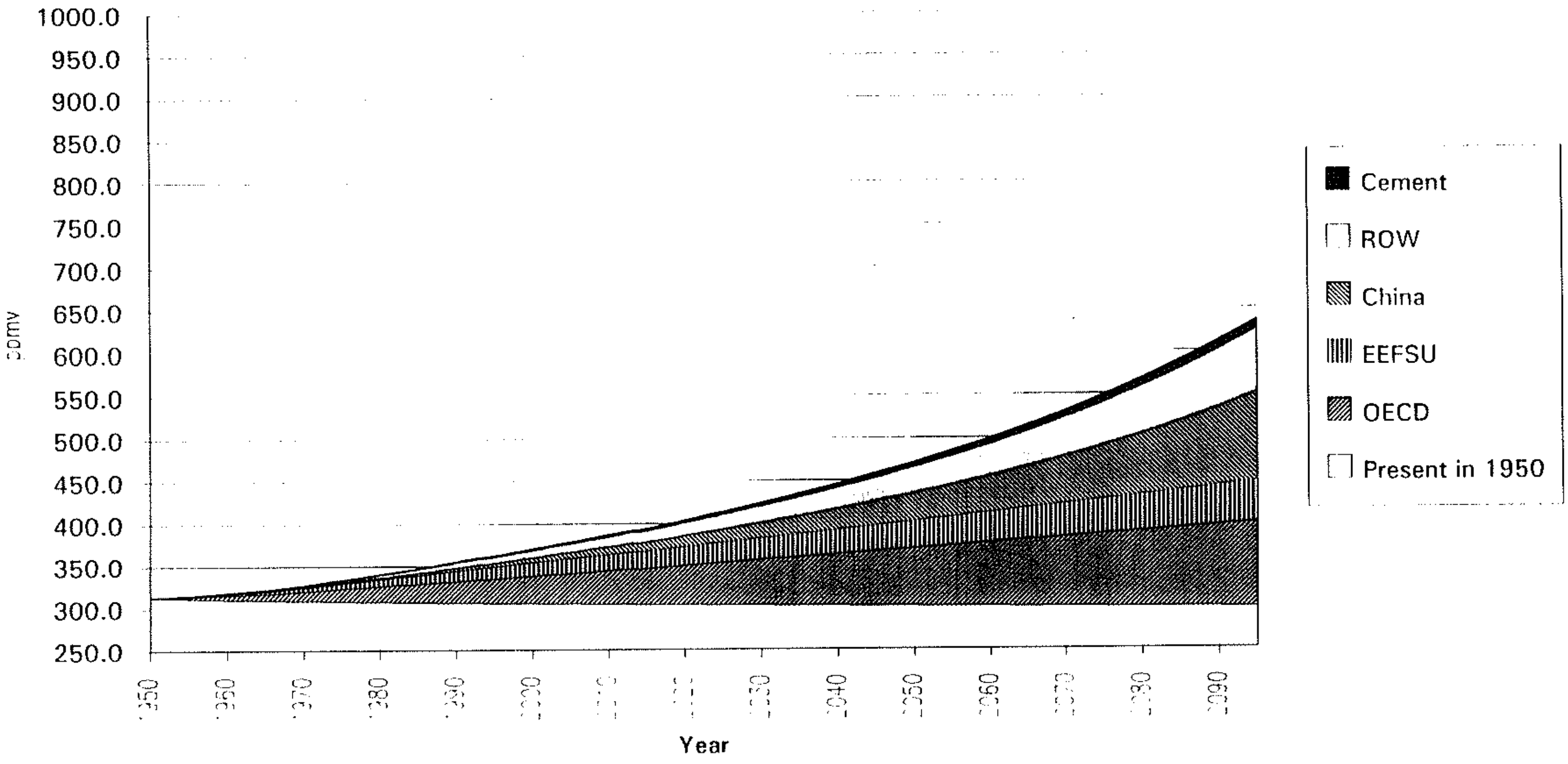


Figure 19

Atmospheric CO2 with Post-1950 Emissions Removed at Globally Averaged Rate Using the Ocean Uptake Model: 1990

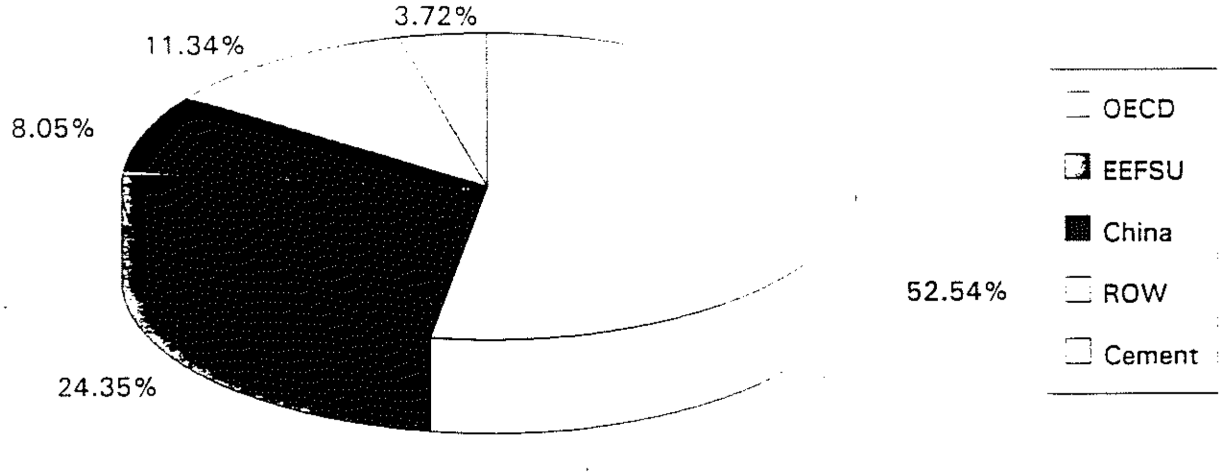


Figure 20

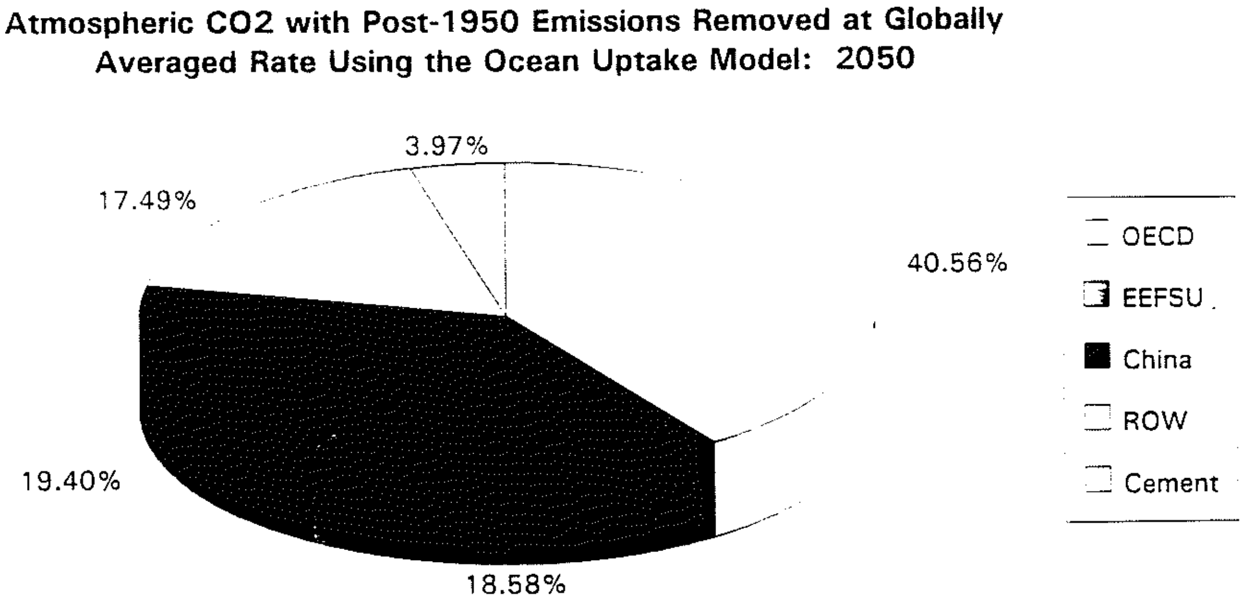
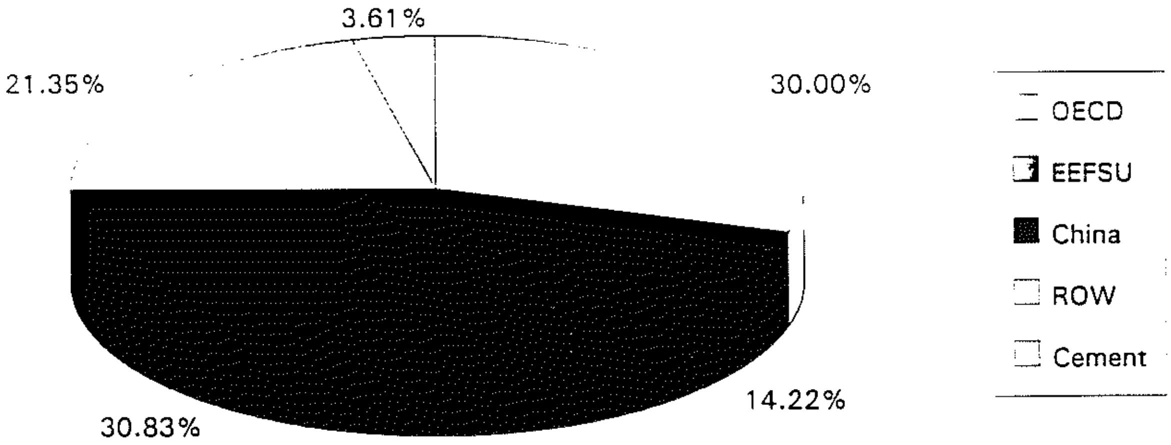
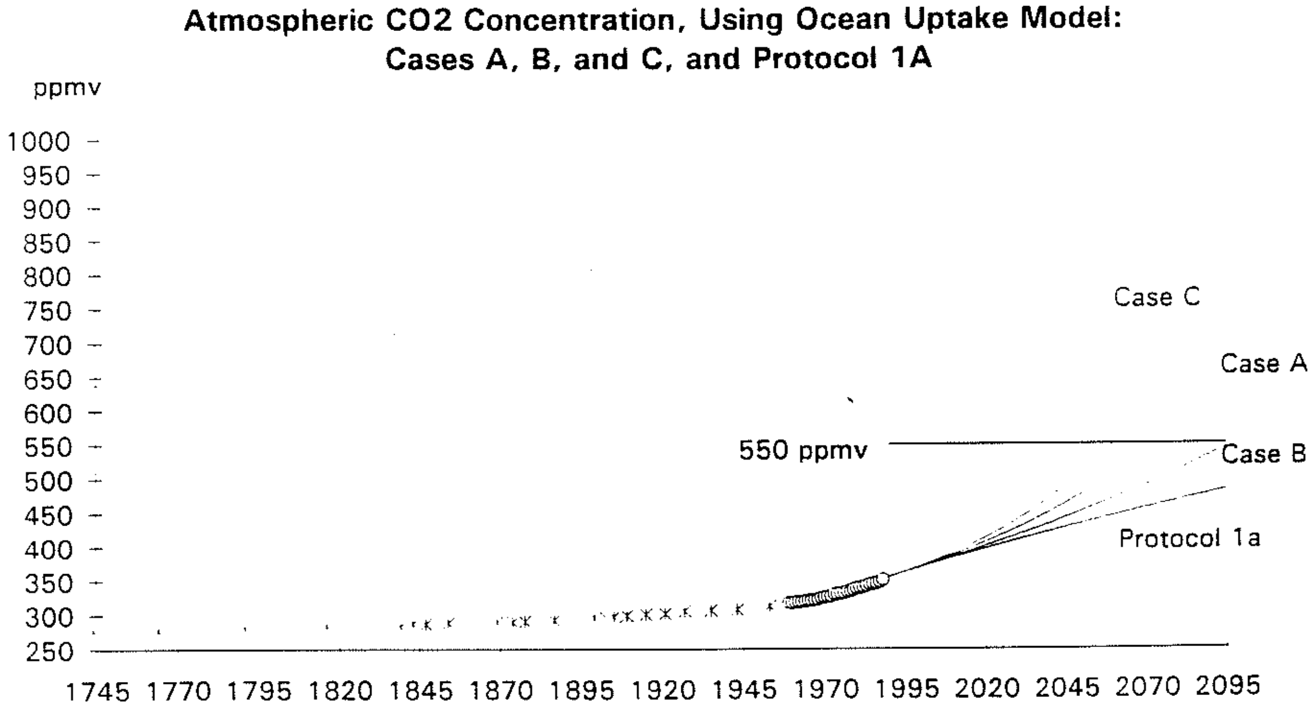

Atmospheric CO2 with Post-1950 Emissions Removed at Globally Averaged Rate Using the Ocean Uptake Model: 2050
3.97%
17.49%
40.56%
19.40%
18.58%
OECD
EEFSU
China
ROW
Cement

Figure 21



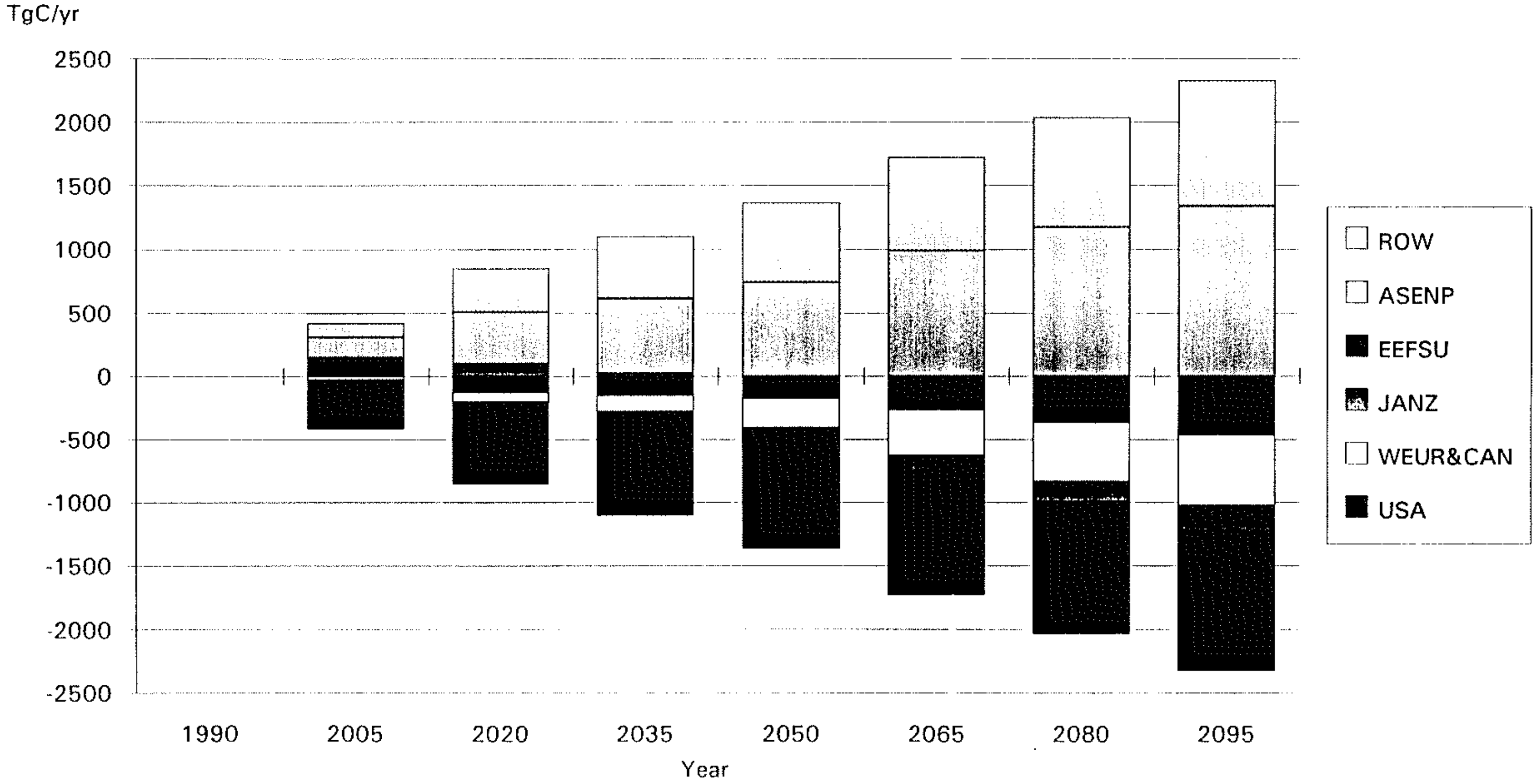
Atmospheric CO2 with Post-1950 Emissions Removed at Globally Averaged Rate Using the Ocean Uptake Model: 2095

Figure 22



Atmospheric CO2 Concentration, Using Ocean Uptake Model: Cases A, B, and C, and Protocol 1A

Figure 23



Common Global Carbon Tax to Stabilize Emissions Beginning in 1990: Change in Emissions Relative to 1990 (TgC/yr)

Figure 24

Common Global Carbon Tax to Stabilize Emissions Beginning in 1990: Total Cost of Emissions Reductions by Region and by Year (1990 US $x10^9)

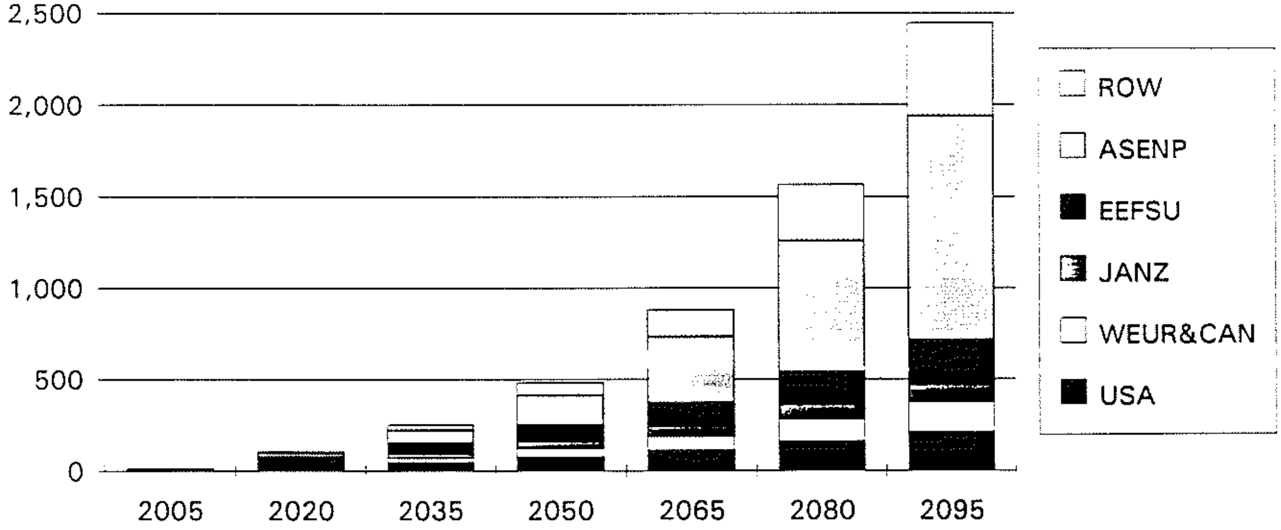


Figure 25

Per Capita Carbon Emissions by Region and Year: Case A, Common Global Carbon Tax (mtC/person/year)

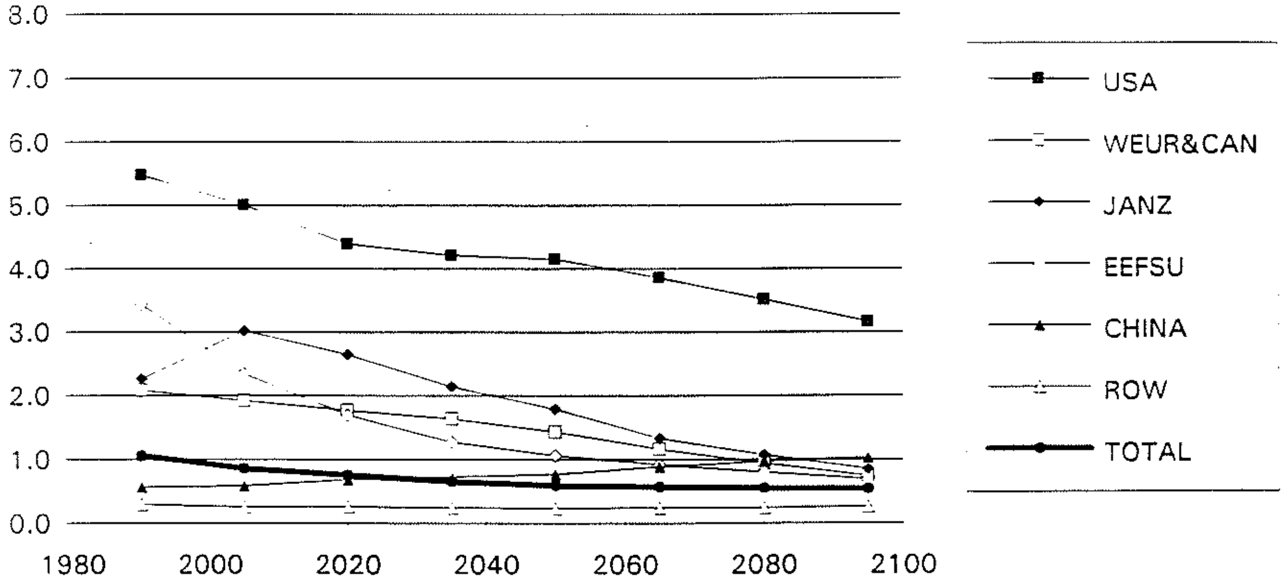


Figure 26

Common Global Carbon Tax to Stabilize Emissions Beginning in 1990: Distribution by Region, 2005

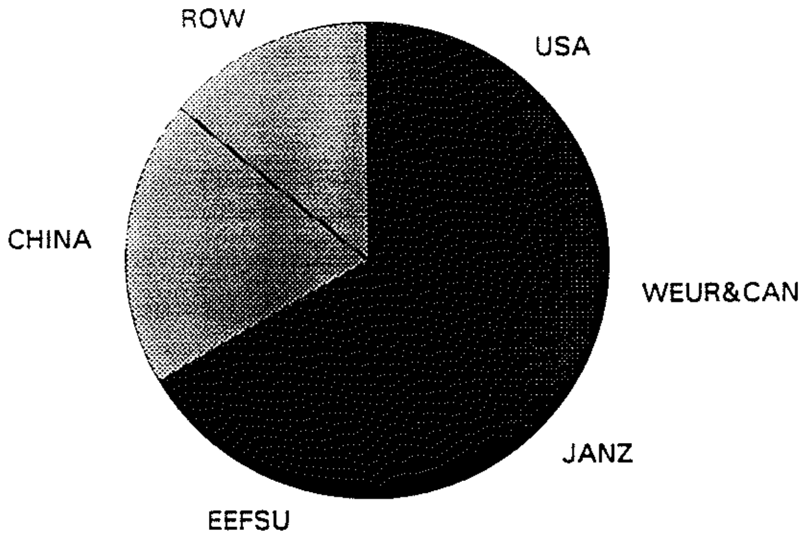


Figure 27

Common Global Carbon Tax to Stabilize Emissions Beginning in 1990: Distribution by Region, 2050

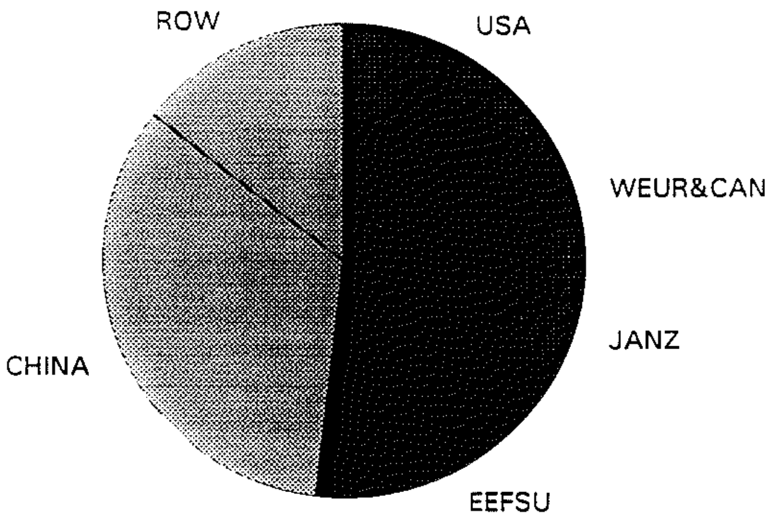


Figure 28

Common Global Carbon Tax to Stabilize Emissions Beginning in 1990: Distribution by Region, 2095

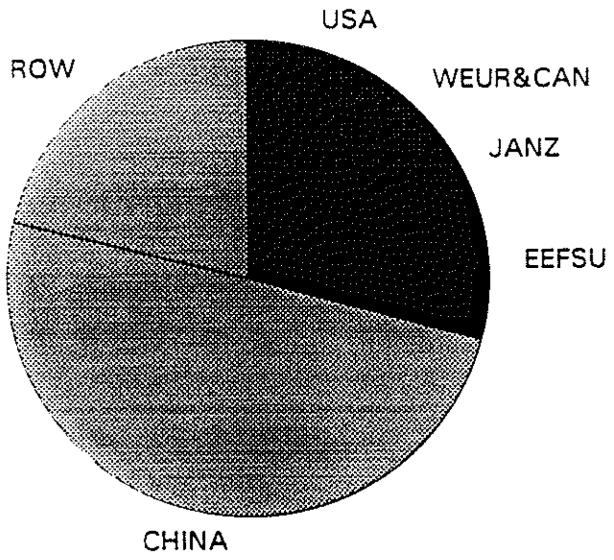


Figure 29

Common Global Carbon Tax to Stabilize Emissions Beginning in 1990: Total Cost of Emissions Reductions Relative to GDP by Region and by Year (%)

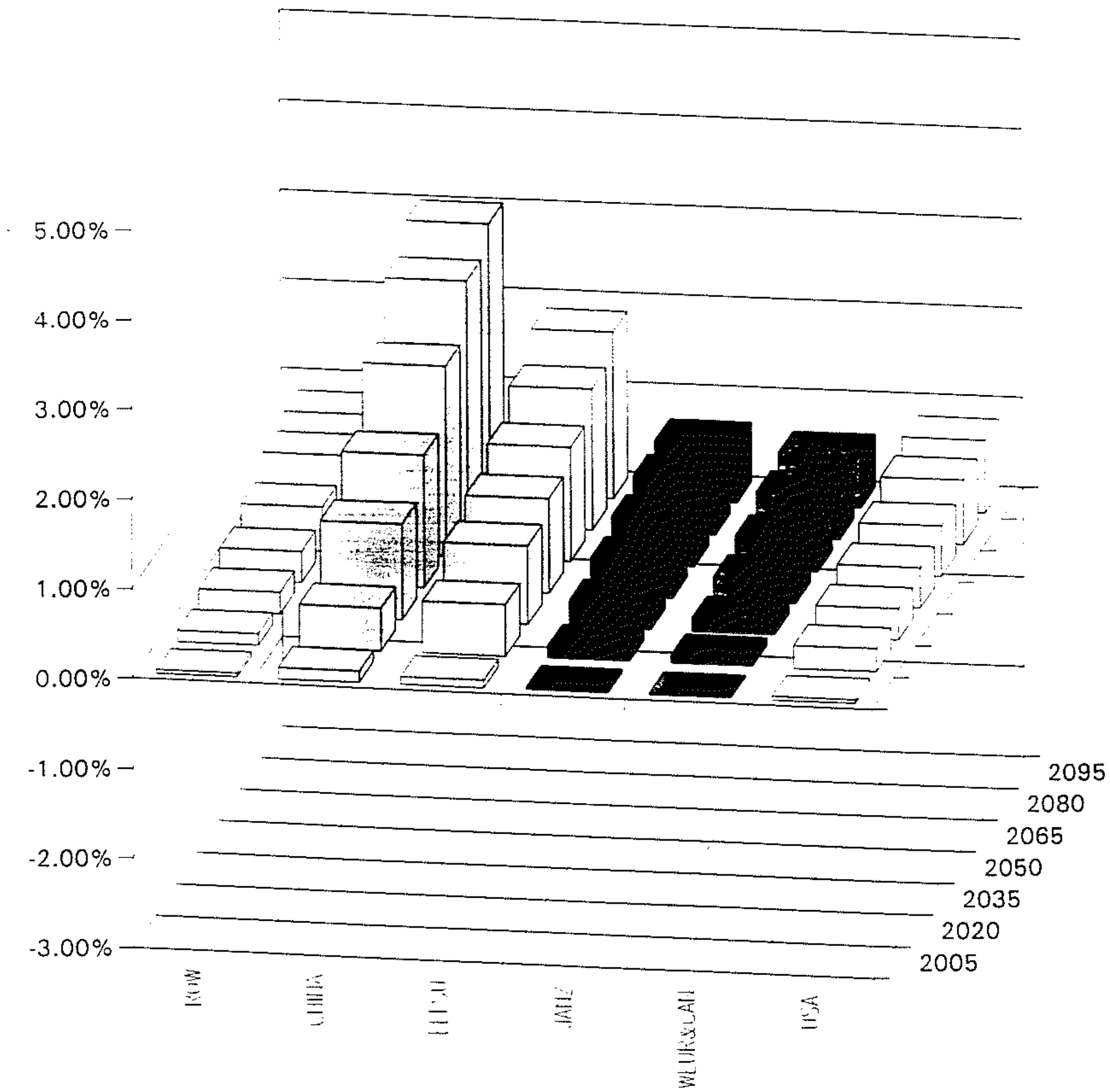
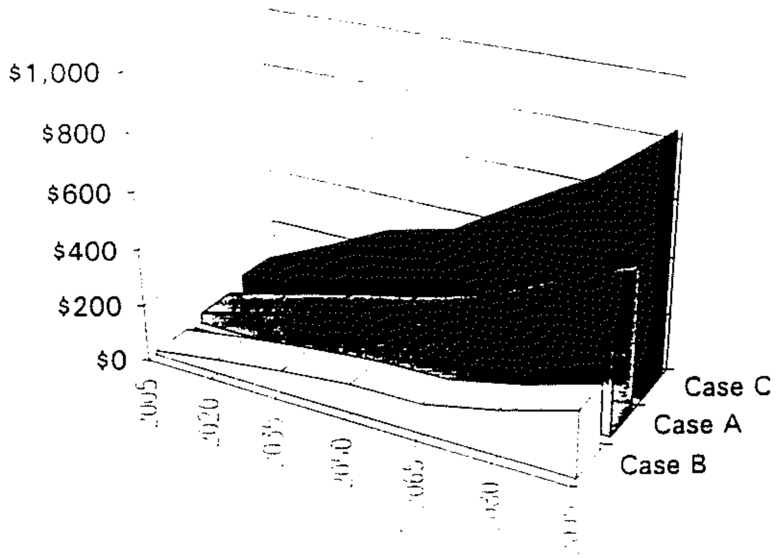


Figure 30



Uniform Global Tax Rate Comparison of Cases A, B, and C
($/mtC)

Figure 31

Comparison of Total Cost for a Uniform Global Tax Rate: Cases A, B, and C ($x10^9/yr)

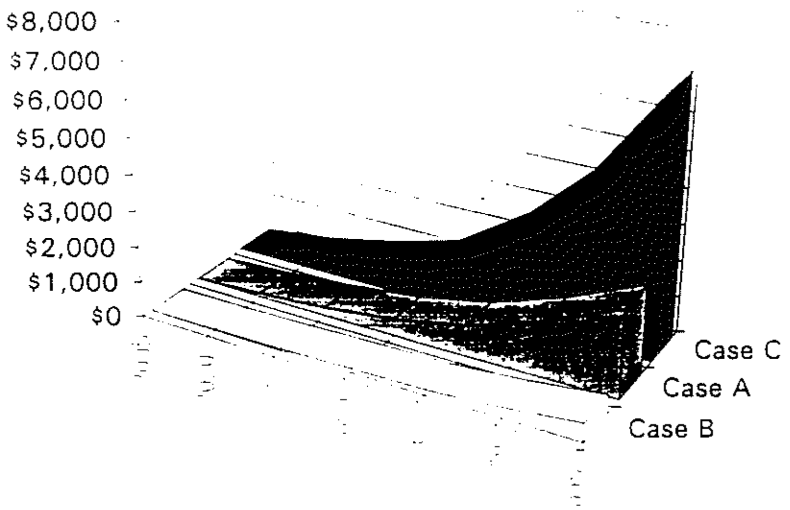


Figure 32

Comparison of Total Cost Relative to GNP for a Uniform Global Tax Rate: Cases A, B, and C (%/yr)

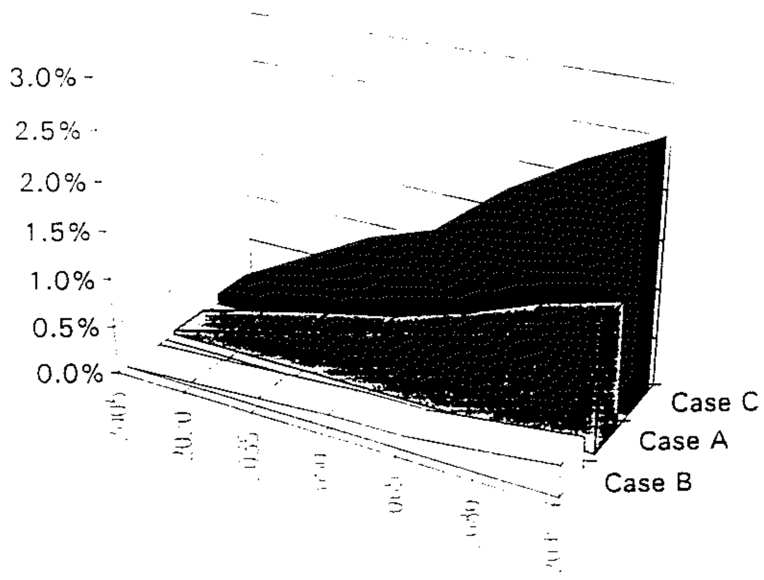


Figure 33

Percentage Change in Total Cost of Fossil Fuel Carbon Emissions Stabilization by Individual Region Relative to a the Total Cost of Global Fossil Fuel Carbon Emissions with a Common Global Tax, by Region and by Year: Case A (%)

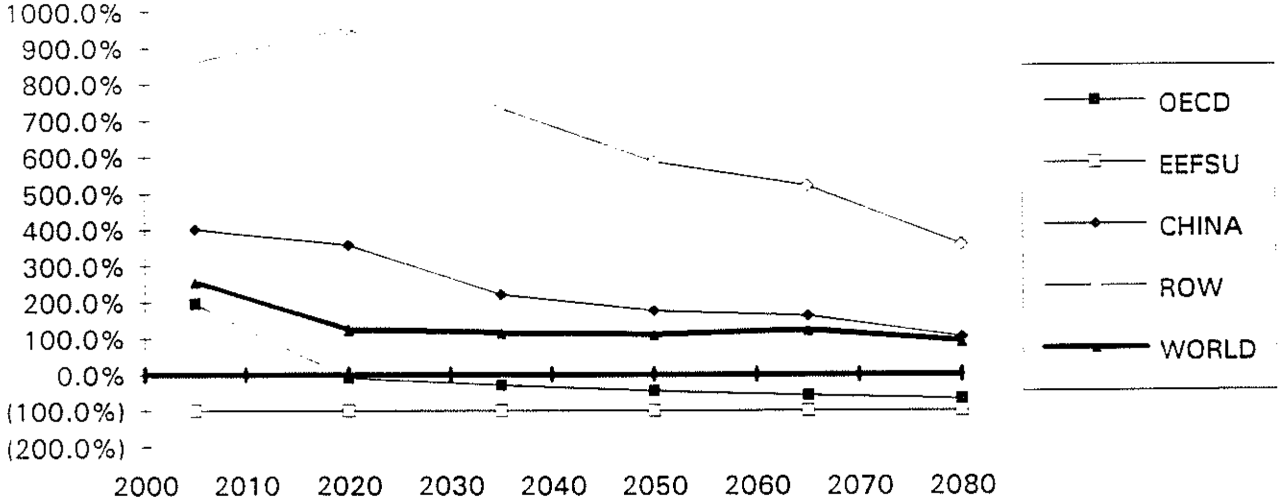


Figure 34

Tradable Permit Allocation with "Grandfathered Emissions Rights" Case A, Protocol 1a, Immediate Universal Pariticipation to Stabilize Emissions at 1990 Levels (%)

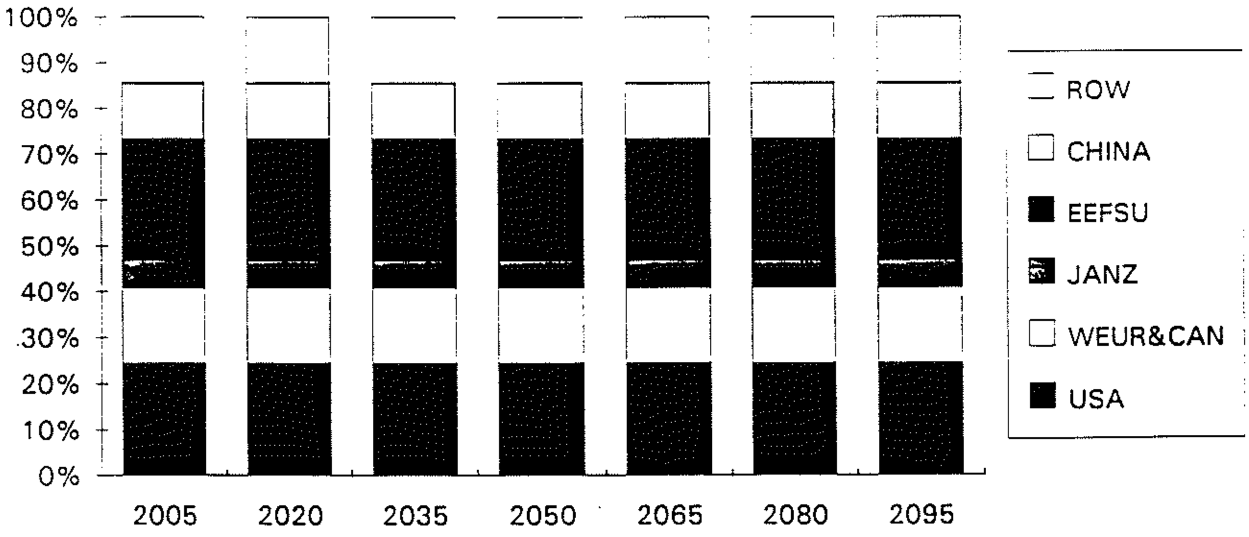


Figure 35

Tradable Permit Allocation with Emissions Rights Based on Adult Population, Case A, Protocol 1a Immediate Universal Pariticipation to Stabilize Emissions at 1990 Levels (%)

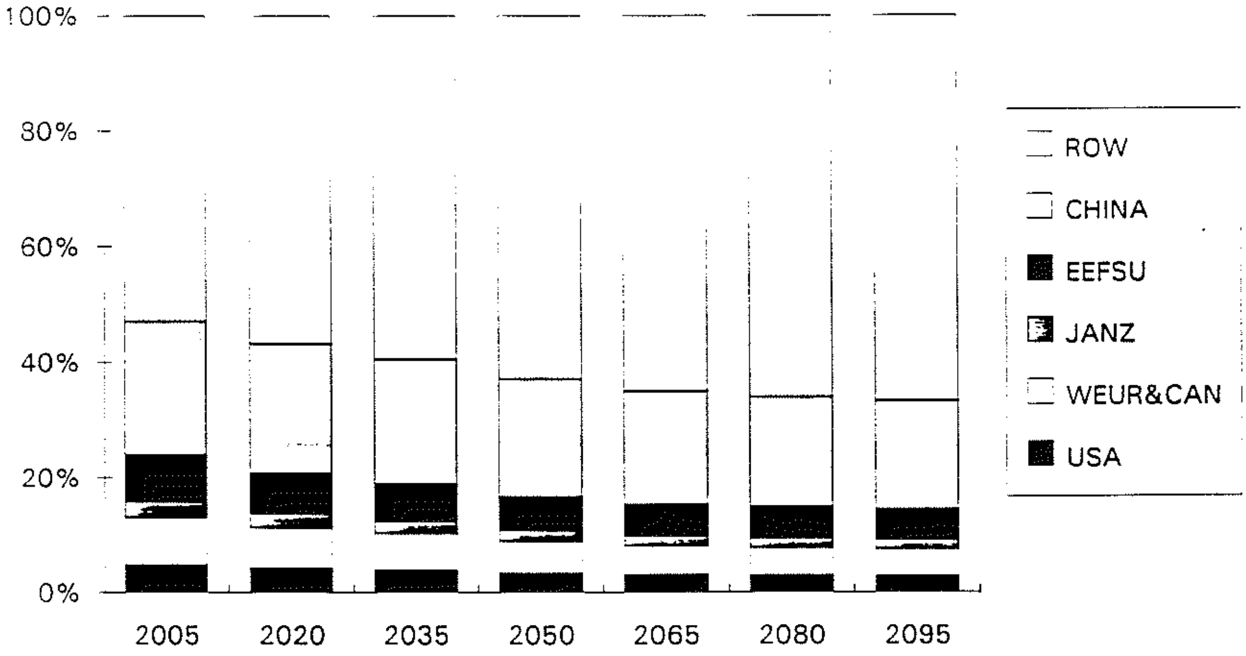


Figure 36

Tradable Permit Allocation with Emissions Rights Based on "No Cost to Developing Nations" Principle, Case A, Protocol 1a Immediate Universal Pariticipation to Stabilize Emissions at 1990 Levels (%)

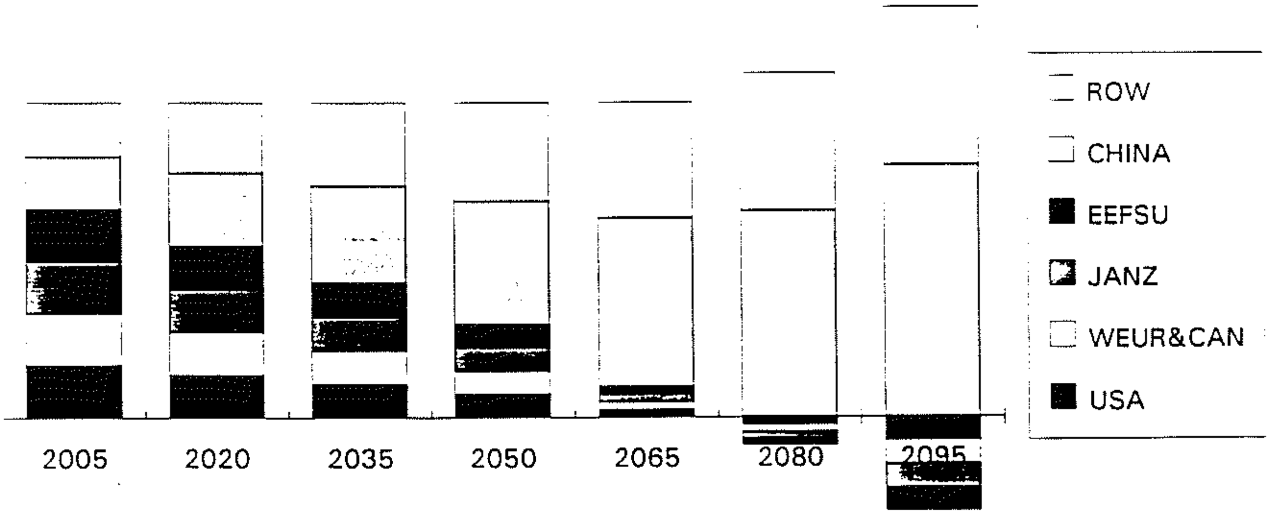


Figure 37

Tradable Permit Allocation with Emissions Rights Based on "No Cost to Developing and EEFSU Nations" Principle, Case A, Protocol 1a Immediate Universal Pariticipation to Stabilize Emissions at 1990 Levels (%)

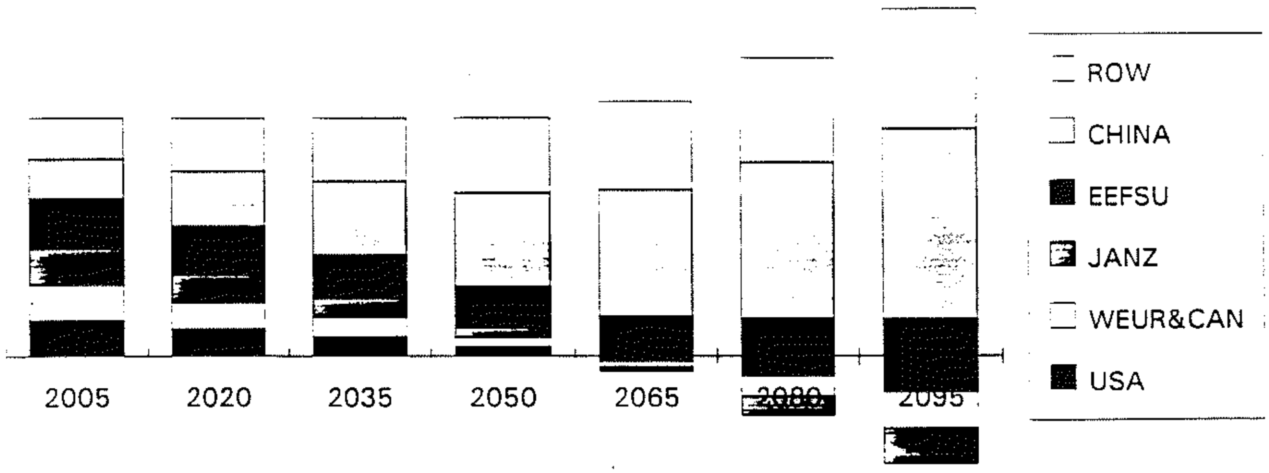


Figure 38

Income Received from Sale of "Excess" Emissions Rights Derived Under the "Grandfathered Emissions" Principle, Case A, Protocol 1a Immediate Universal Pariticipation to Stabilize Emissions at 1990 Levels ($x10^9)

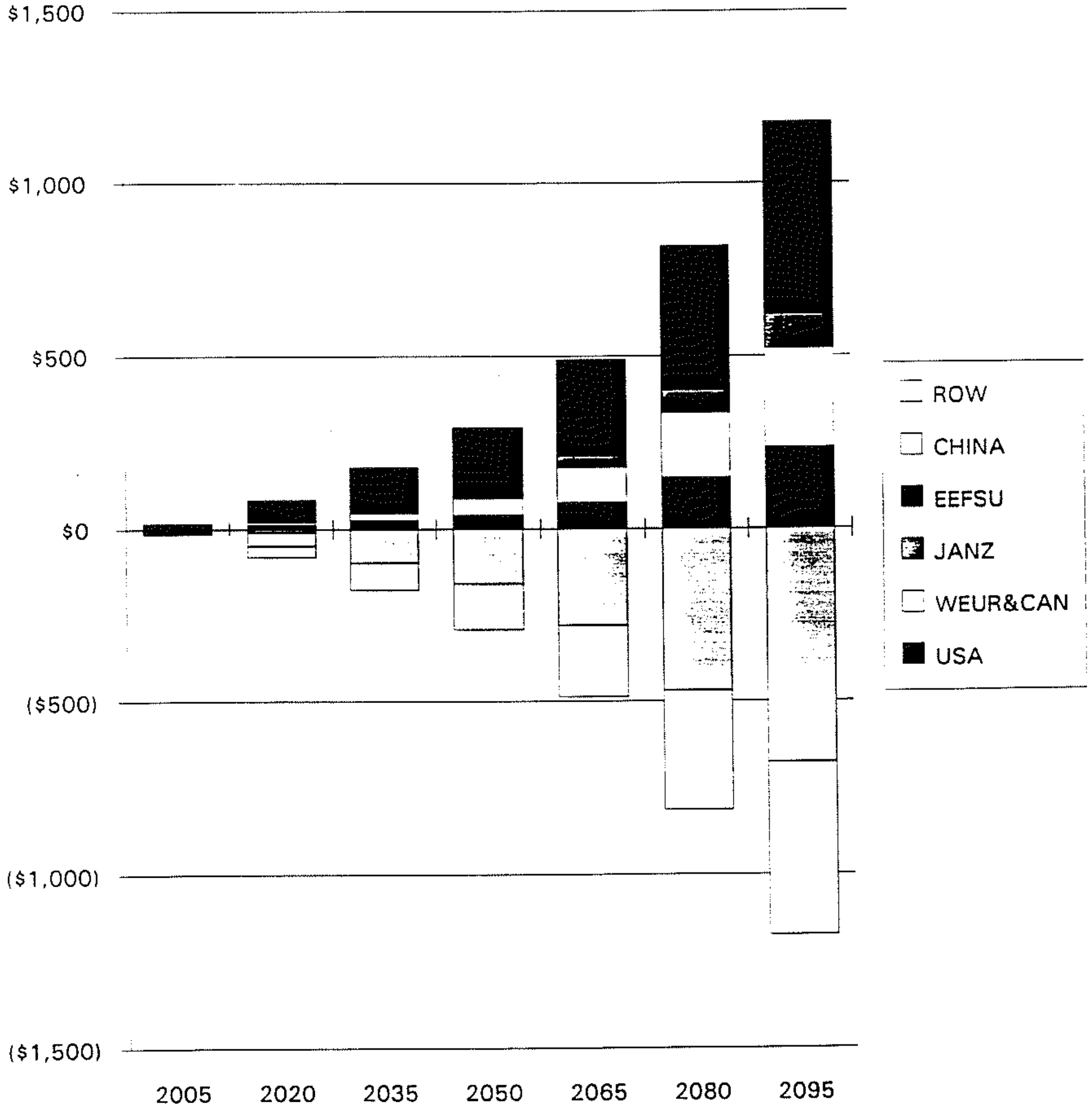


Figure 39

Income Received from Sale of "Excess" Emissions Rights Derived Under the "Equal Per Capita" Principle, Case A, Protocol 1a Immediate Universal Pariticipation to Stabilize Emissions at 1990 Levels ($x10^9)

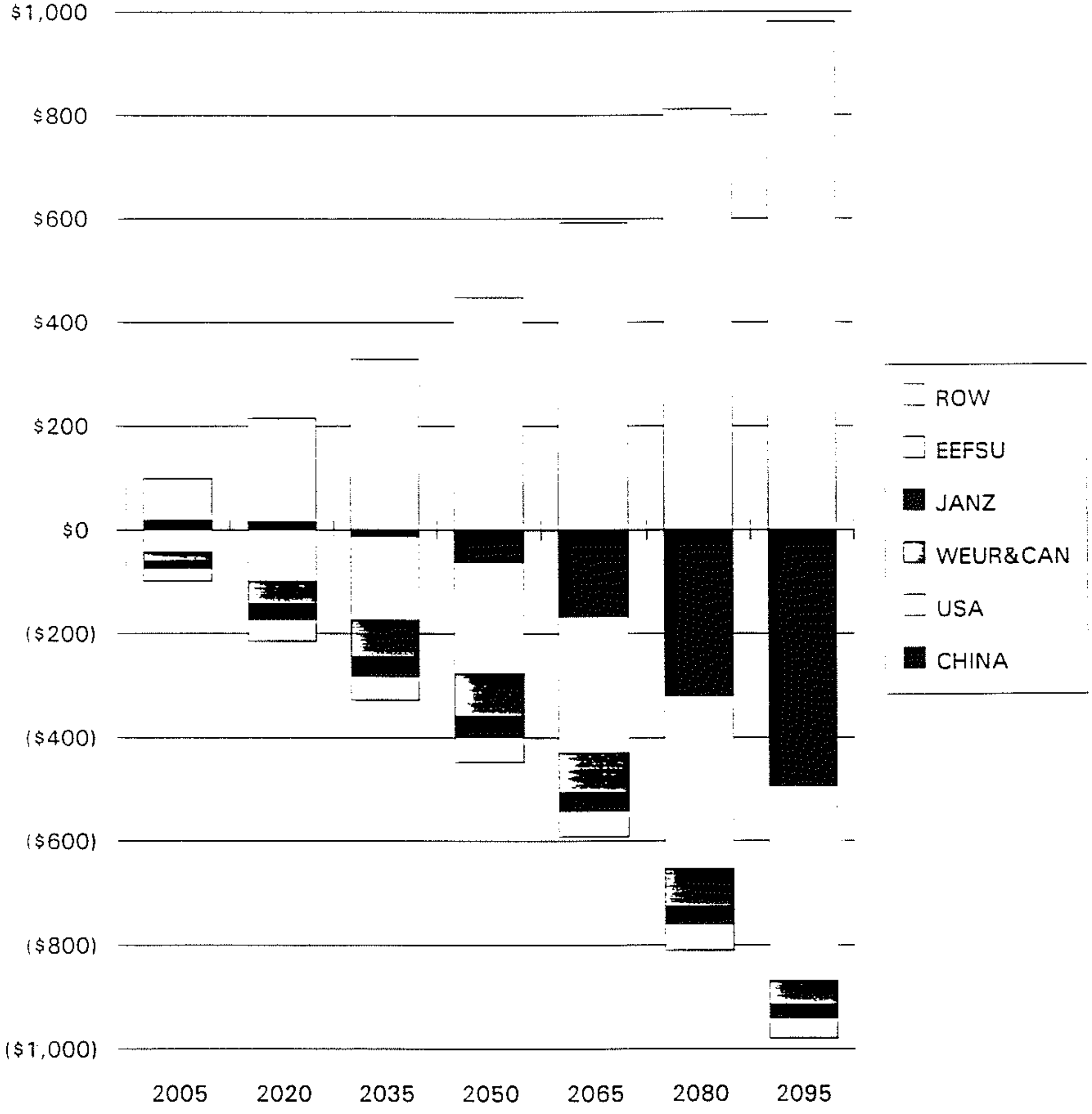


Figure 40

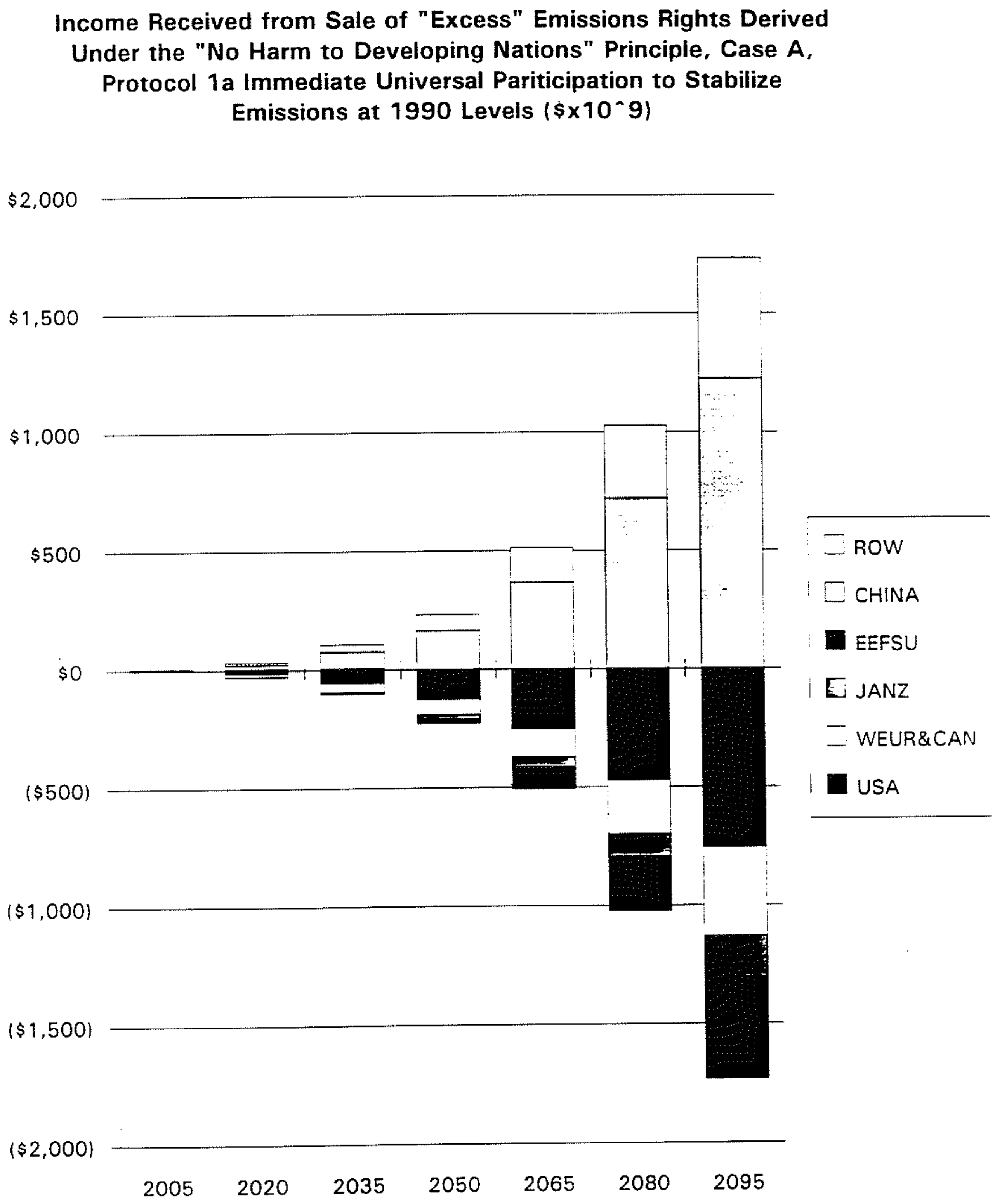
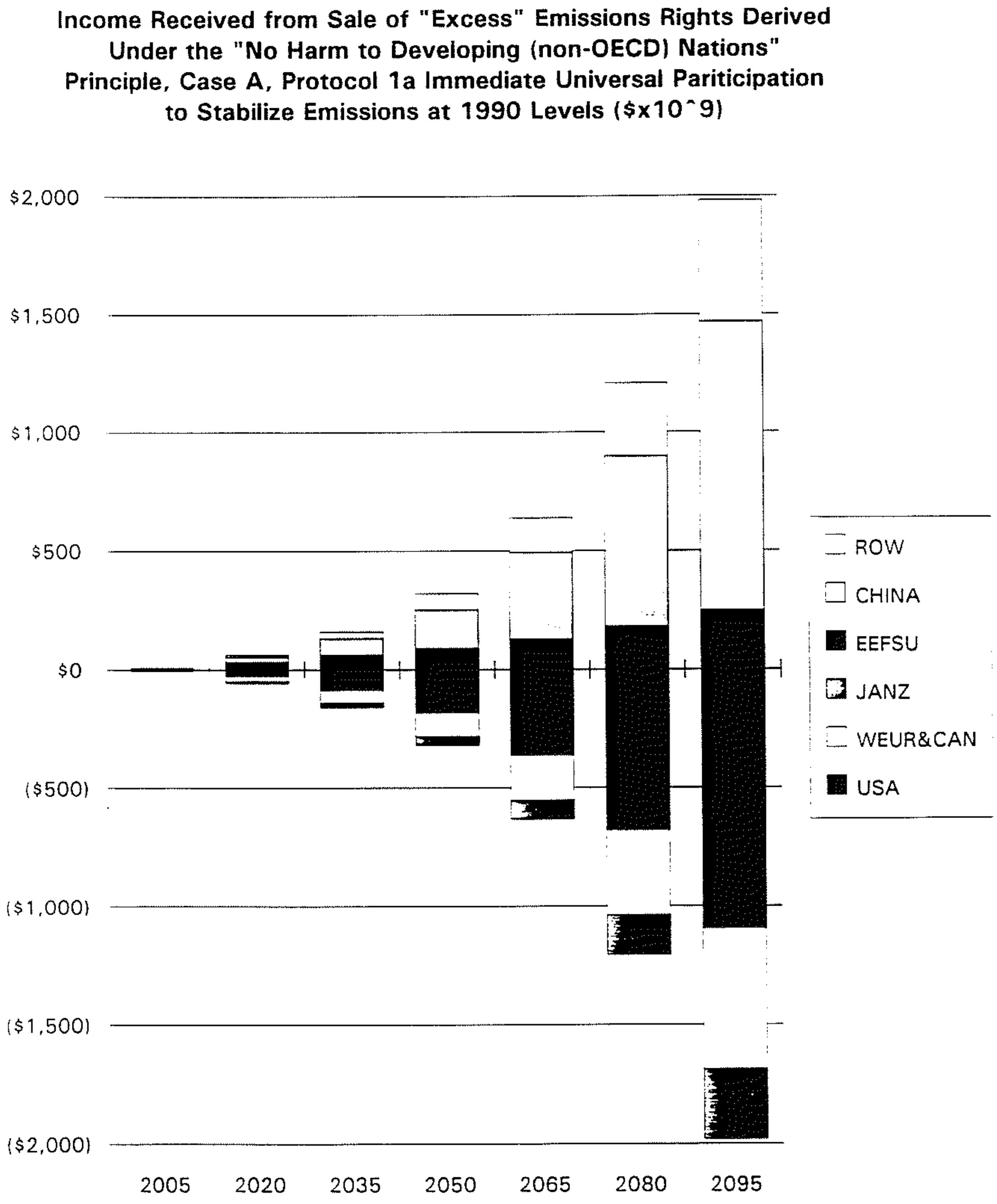

Income Received from Sale of "Excess" Emissions Rights Derived Under the "No Harm to Developing Nations" Principle, Case A, Protocol 1a Immediate Universal Pariticipation to Stabilize Emissions at 1990 Levels ($x10^9)
$2,000
$1,500
$1,000
$500
$0
($500)
($1,000)
($1,500)
($2,000)
2005
2020
2035
2050
2065
2080
2095
ROW
CHINA
EEFSU
JANZ
WEUR&CAN
USA

Figure 41



Income Received from Sale of "Excess" Emissions Rights Derived Under the "No Harm to Developing (non-OECD) Nations" Principle, Case A, Protocol 1a Immediate Universal Pariticipation to Stabilize Emissions at 1990 Levels ($x10^9)
$2,000
$1,500
$1,000
$500
$0
($500)
($1,000)
($1,500)
($2,000)
2005
2020
2035
2050
2065
2080
2095
ROW
CHINA
EEFSU
JANZ
WEUR&CAN
USA

Figure 42

Total Cost of Emissions Reductions Relative to GDP plus Net Transfers of Wealth from Sale of Excess Emissions Rights by Region and by Year: Case A, Tradable Permits, "Grandfathered Emissions" Principle (%)

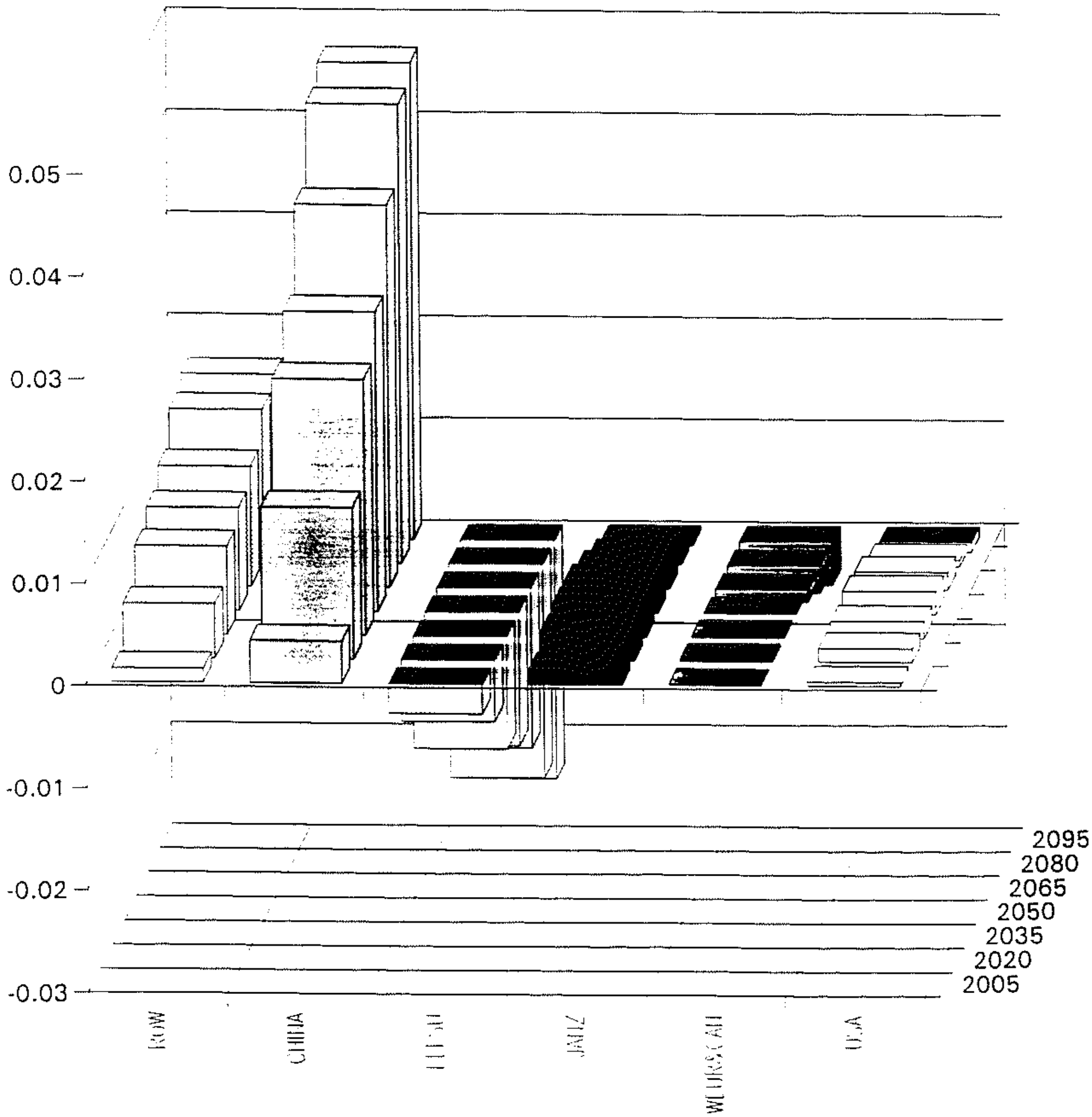


Figure 43

Total Cost of Emissions Reductions Relative to GDP plus Net Transfers of Wealth from Sale of Excess Emissions Rights by Region and by Year: Case A, Tradable Permits, "Equal per Capita Emissions" Principle (%)

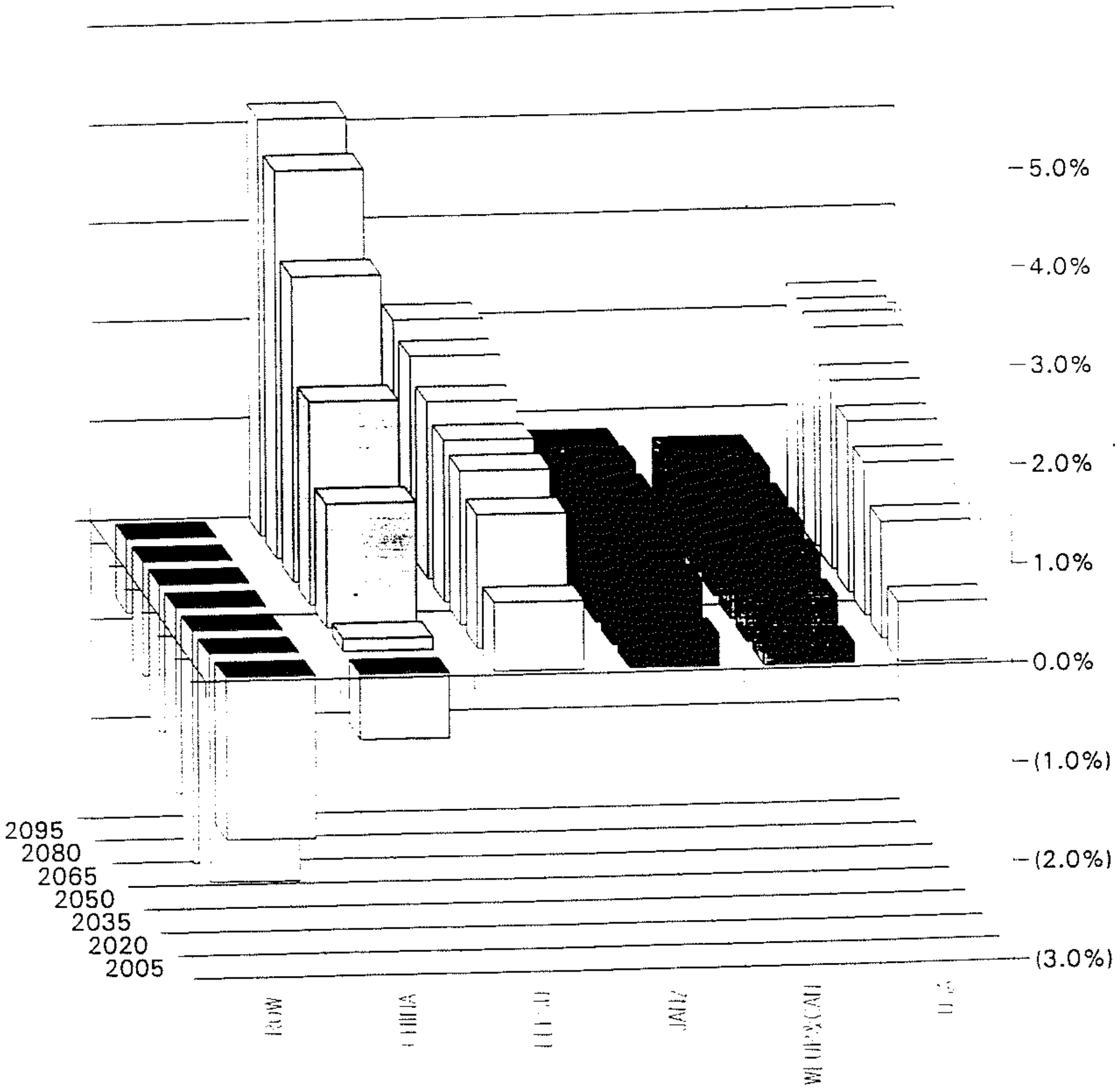


Figure 44

Total Cost of Emissions Reductions Relative to GDP plus Net Transfers of Wealth from Sale of Excess Emissions Rights by Region and by Year: Case A, Tradable Permits, "No Harm to Developing Nations" Principle (%)

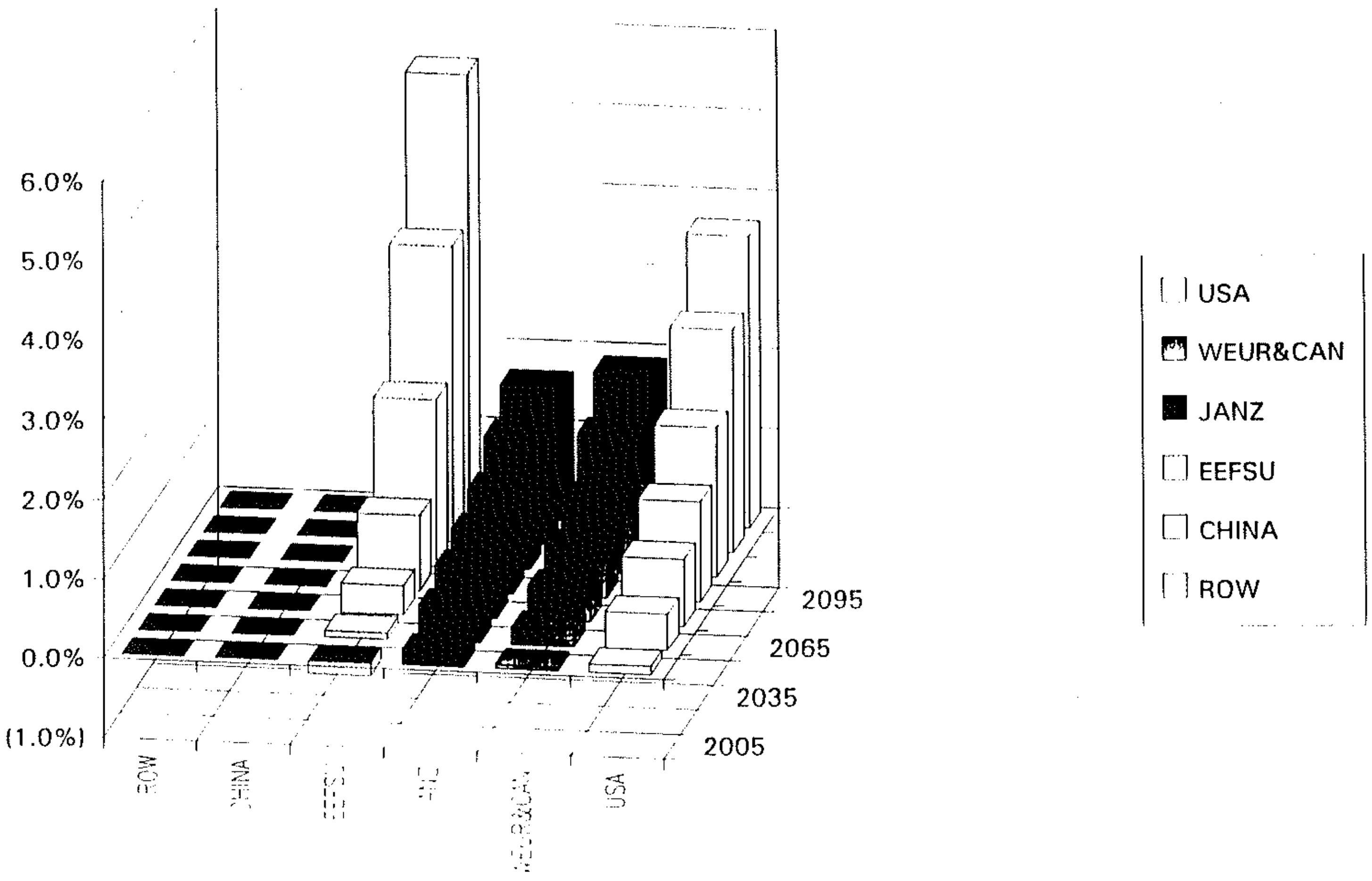


Figure 45

Total Cost of Emissions Reductions Relative to GDP plus Net Transfers of Wealth from Sale of Excess Emissions Rights by Region and by Year: Case A, Tradable Permits, "No Harm to Non-OECD Nations" Principle (%)

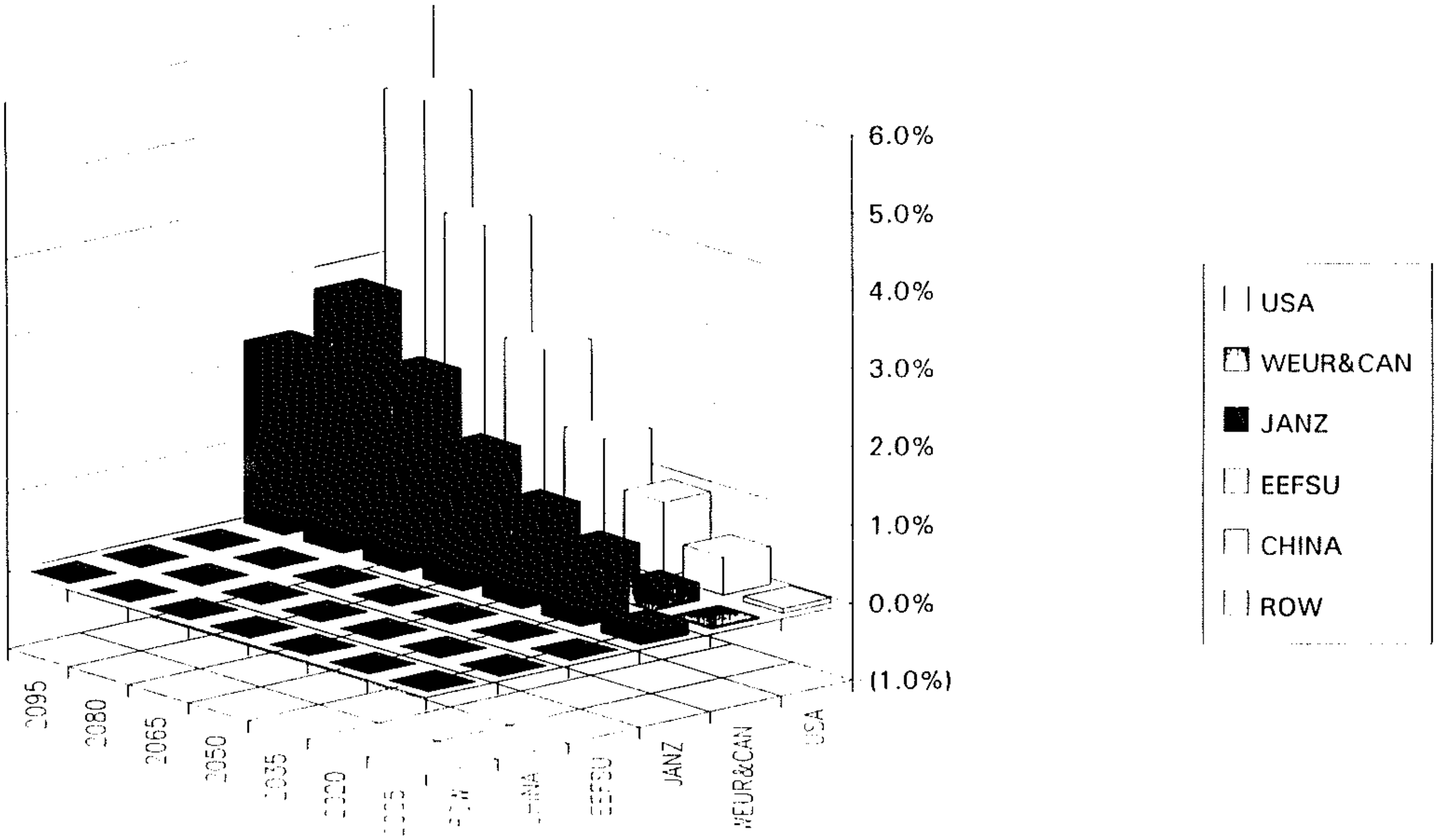
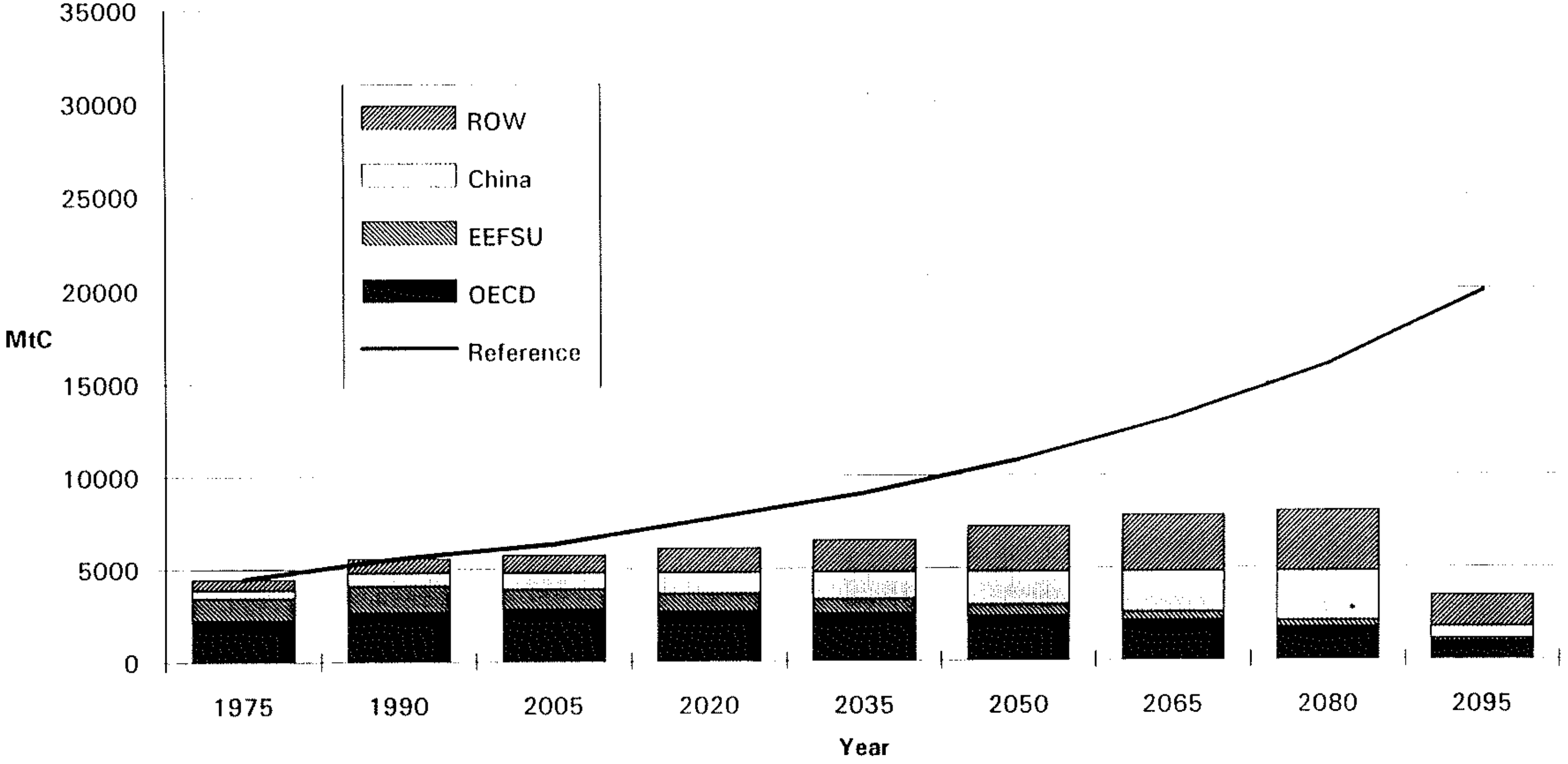


Figure 46

"Big 3" Protocol: Global Fossil Fuel CO2 Emissions by Region and Year, Reference Case
A



6/1/92

Figure 47

Carbon Taxs: Case A, "Big Three" Only

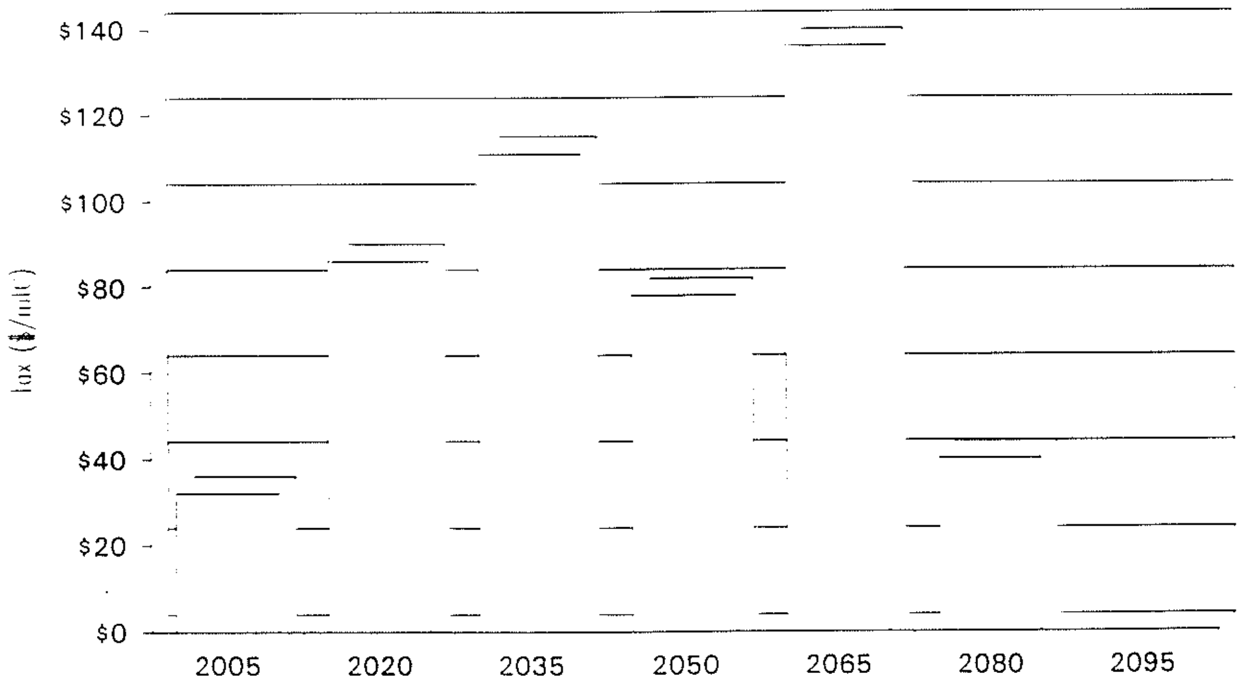


Figure 48

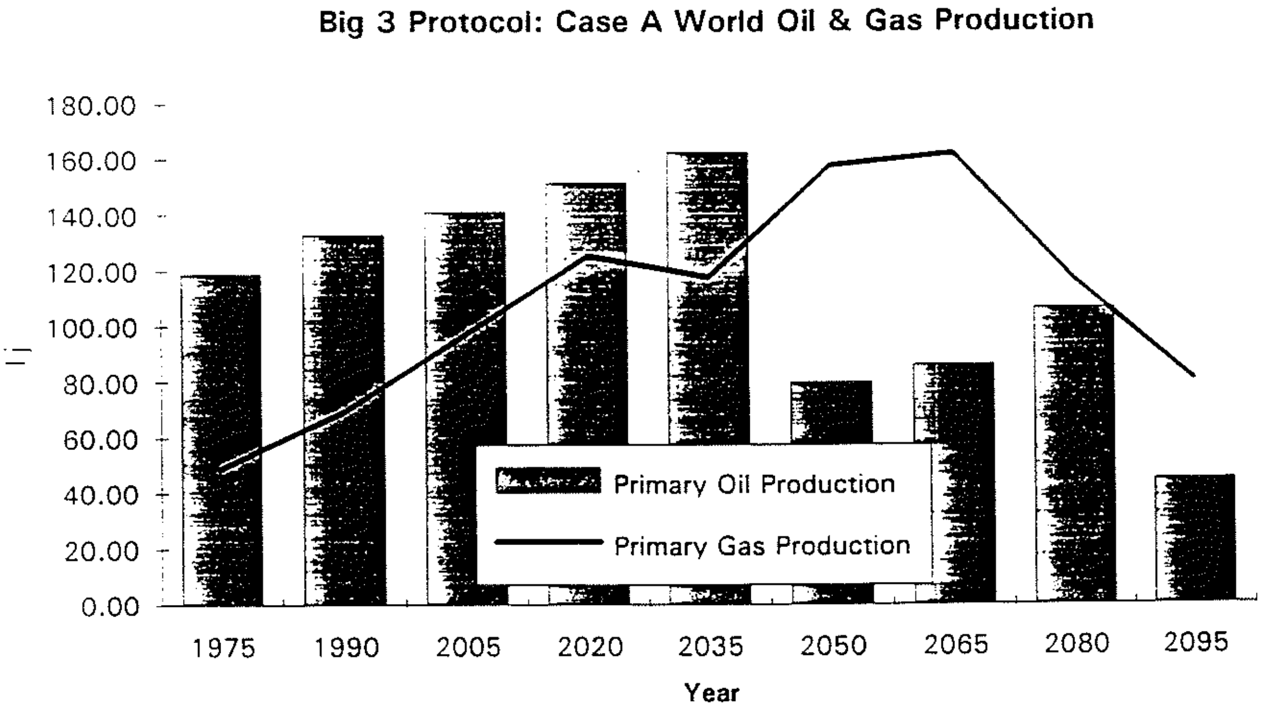

Big 3 Protocol: Case A World Oil & Gas Production
180.00
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
Ej
1975
1990
2005
2020
2035
2050
2065
2080
2095
Year
Primary Oil Production
Primary Gas Production

Figure 49

World Coal Production: Big 3 Protocol, Reference Case A

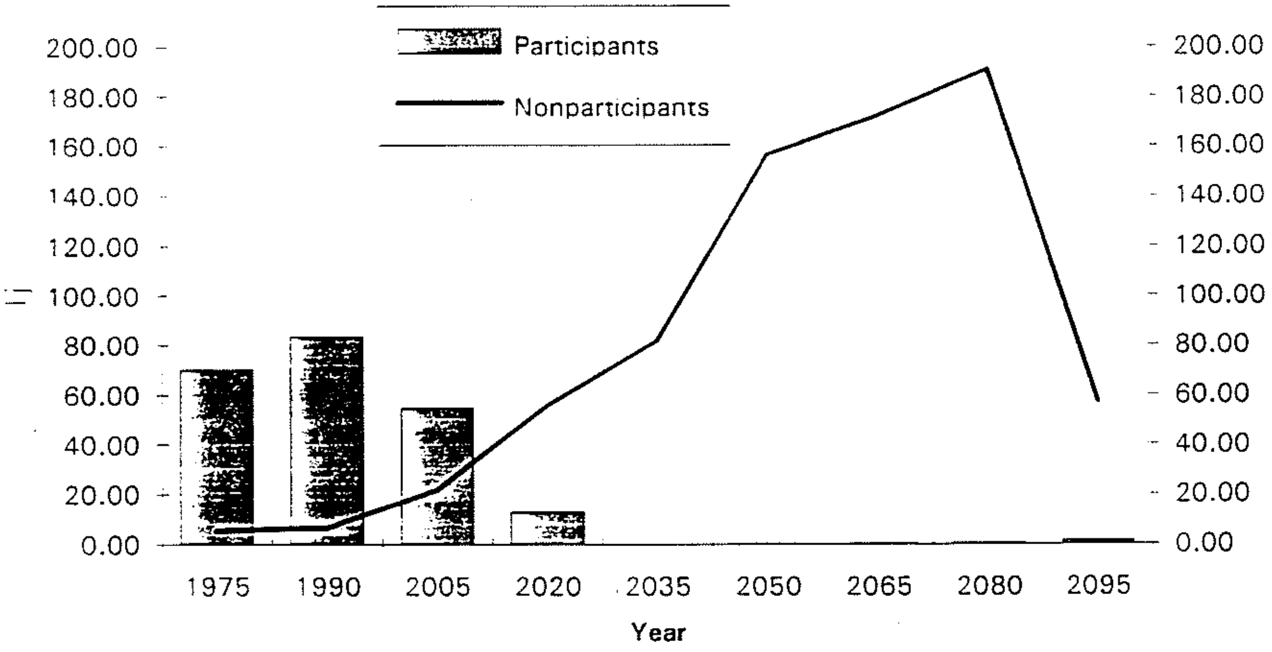


Figure 50

Percentage Difference Between World Energy Prices in the "Big Three" and Reference Case A

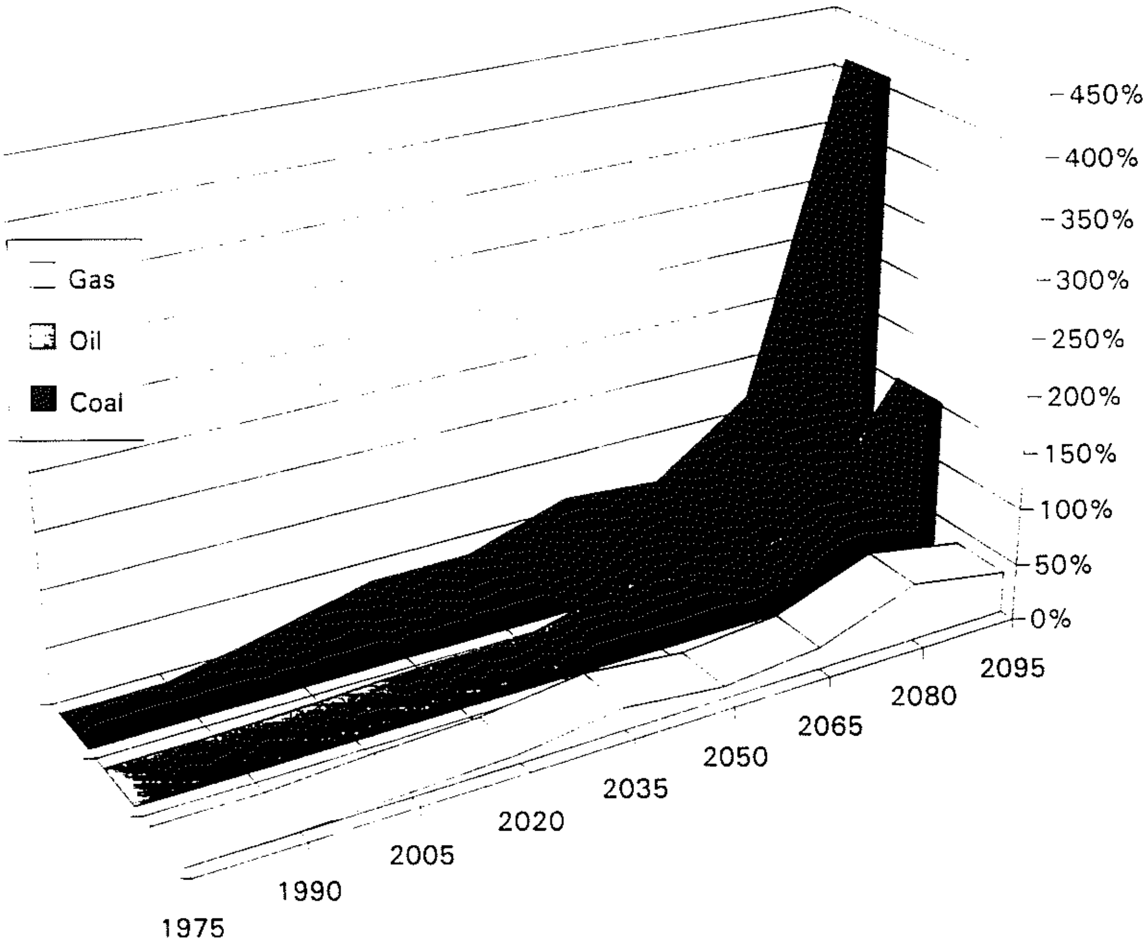
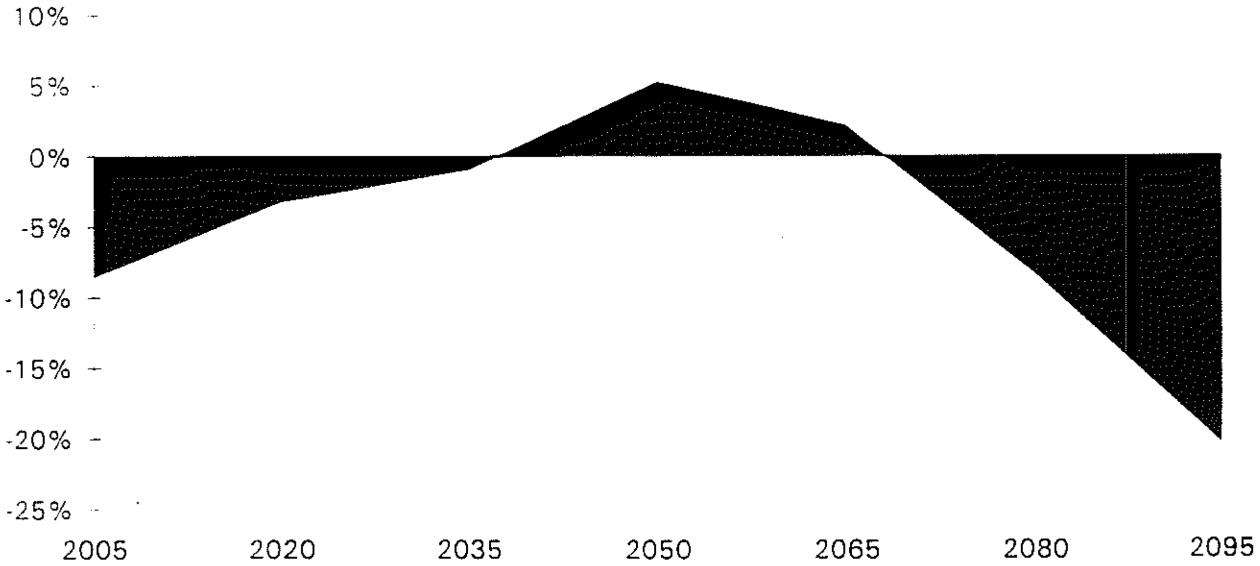


Figure 51

The Offshore Effect: Percentage Difference Between Global and Big 3 Emissions Reductions, Case A



]

Figure 52

"Big 3" Protocol: Atmospheric CO2 Concentrations, Reference Case A

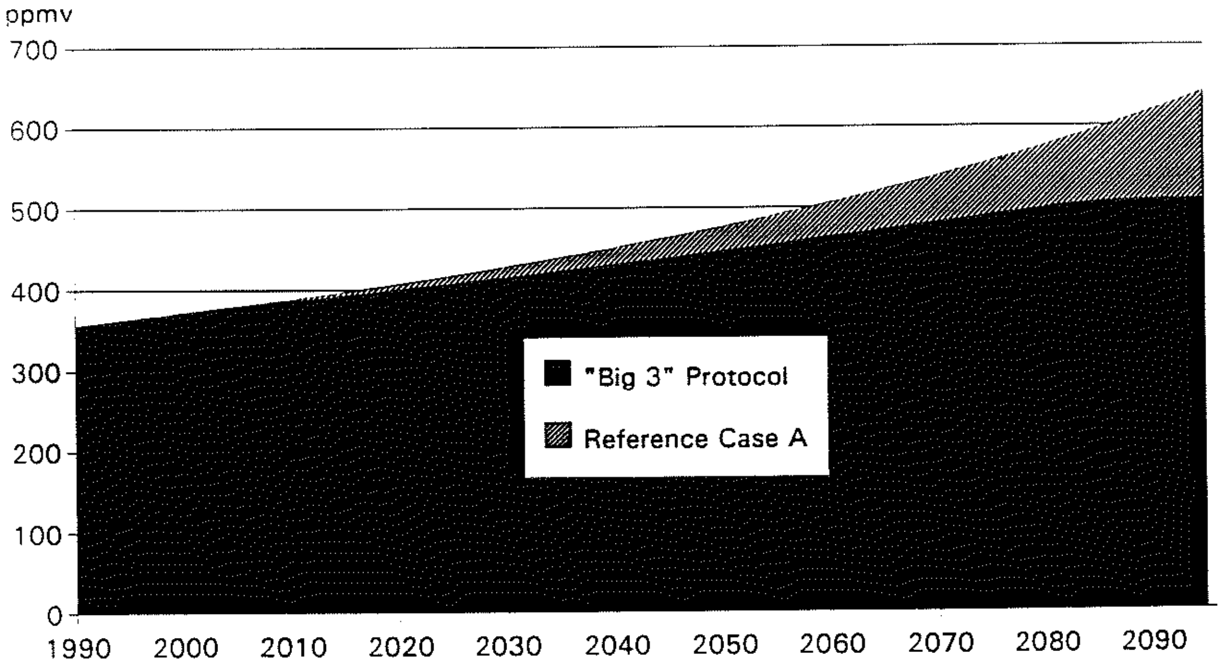
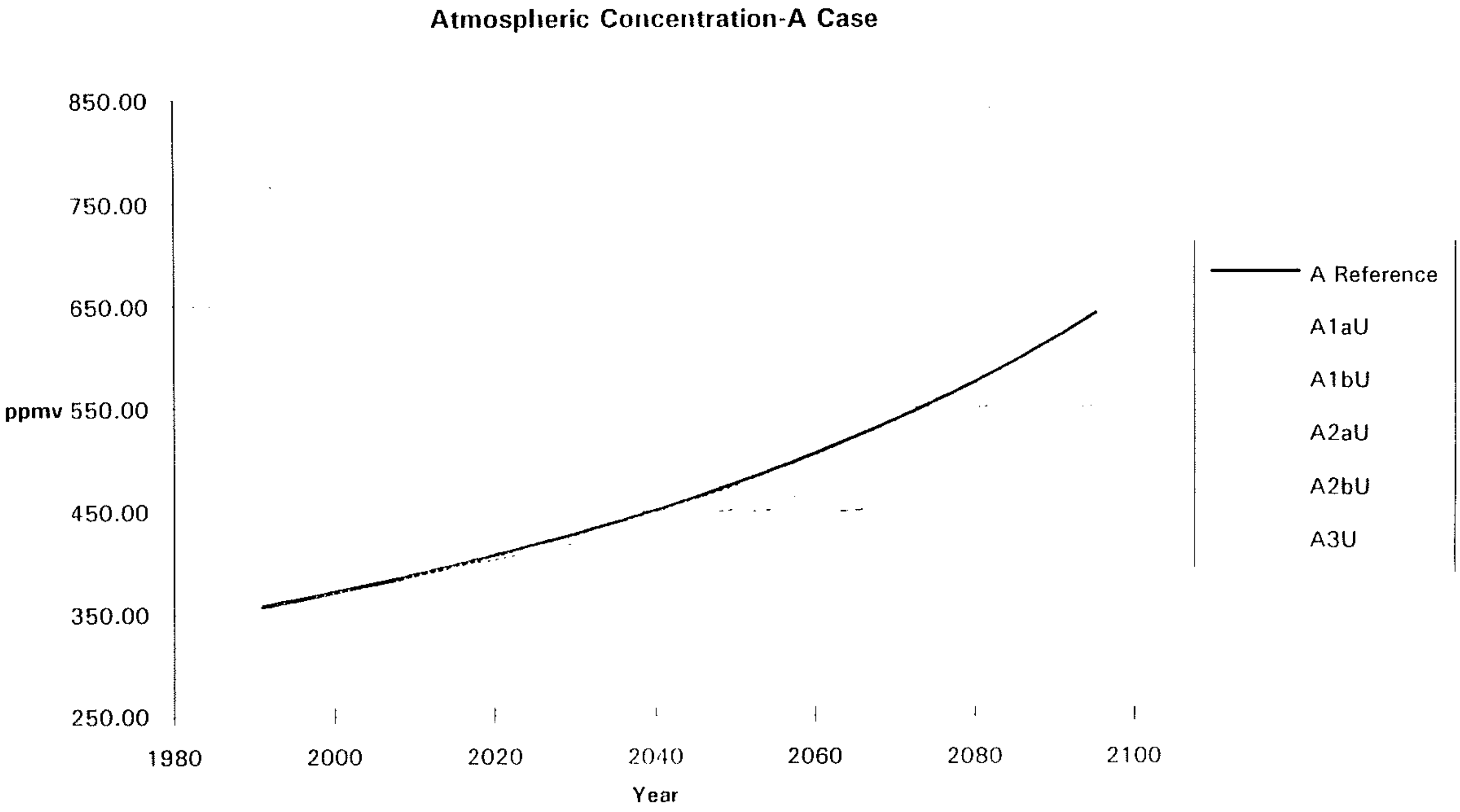


Figure 53



6/16/92

Figure 54

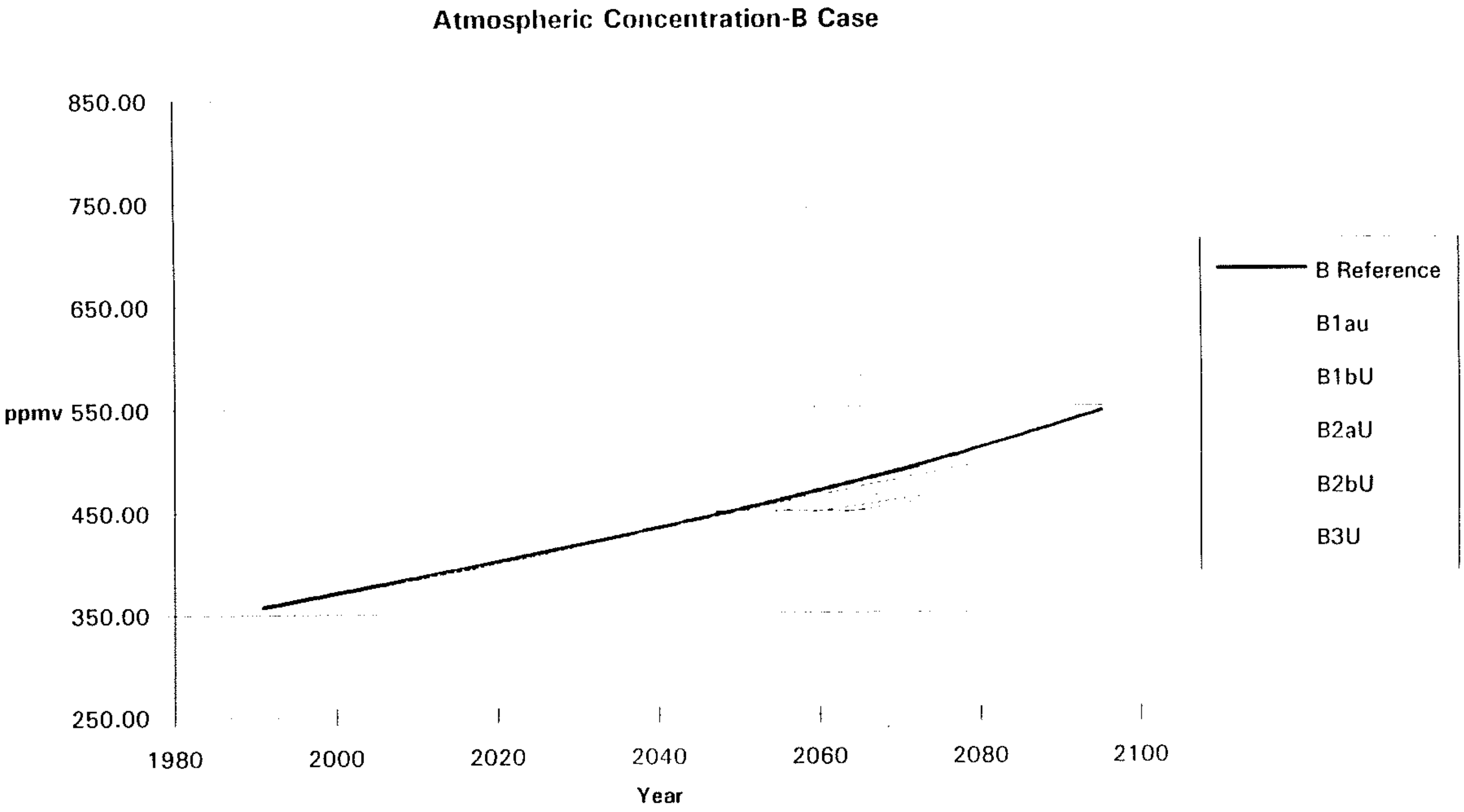
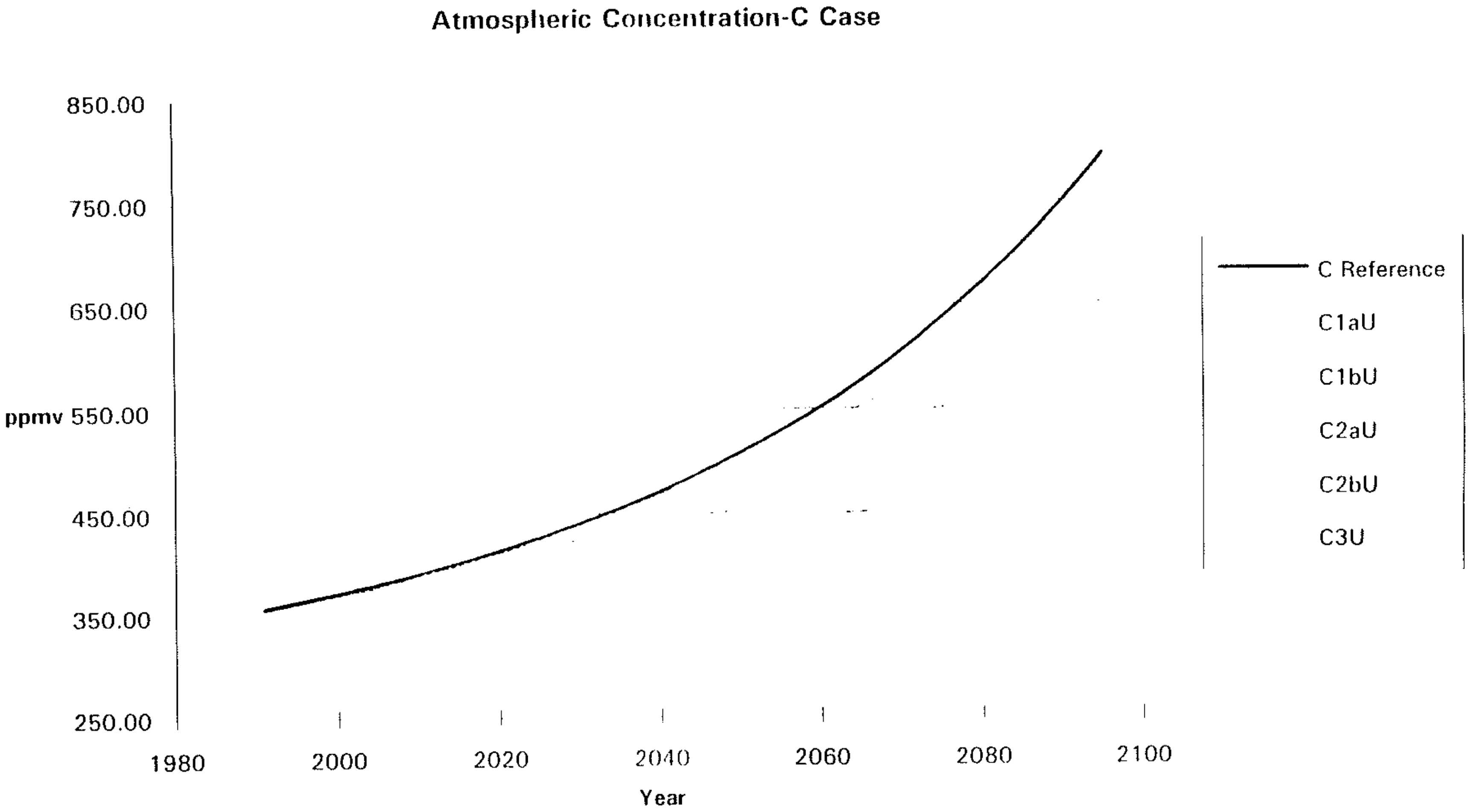

Atmospheric Concentration-B Case
ppmv
850.00
750.00
650.00
550.00
450.00
350.00
250.00
1980
2000
2020
2040
2060
2080
2100
Year
B Reference
B1au
B1bU
B2aU
B2bU
B3U

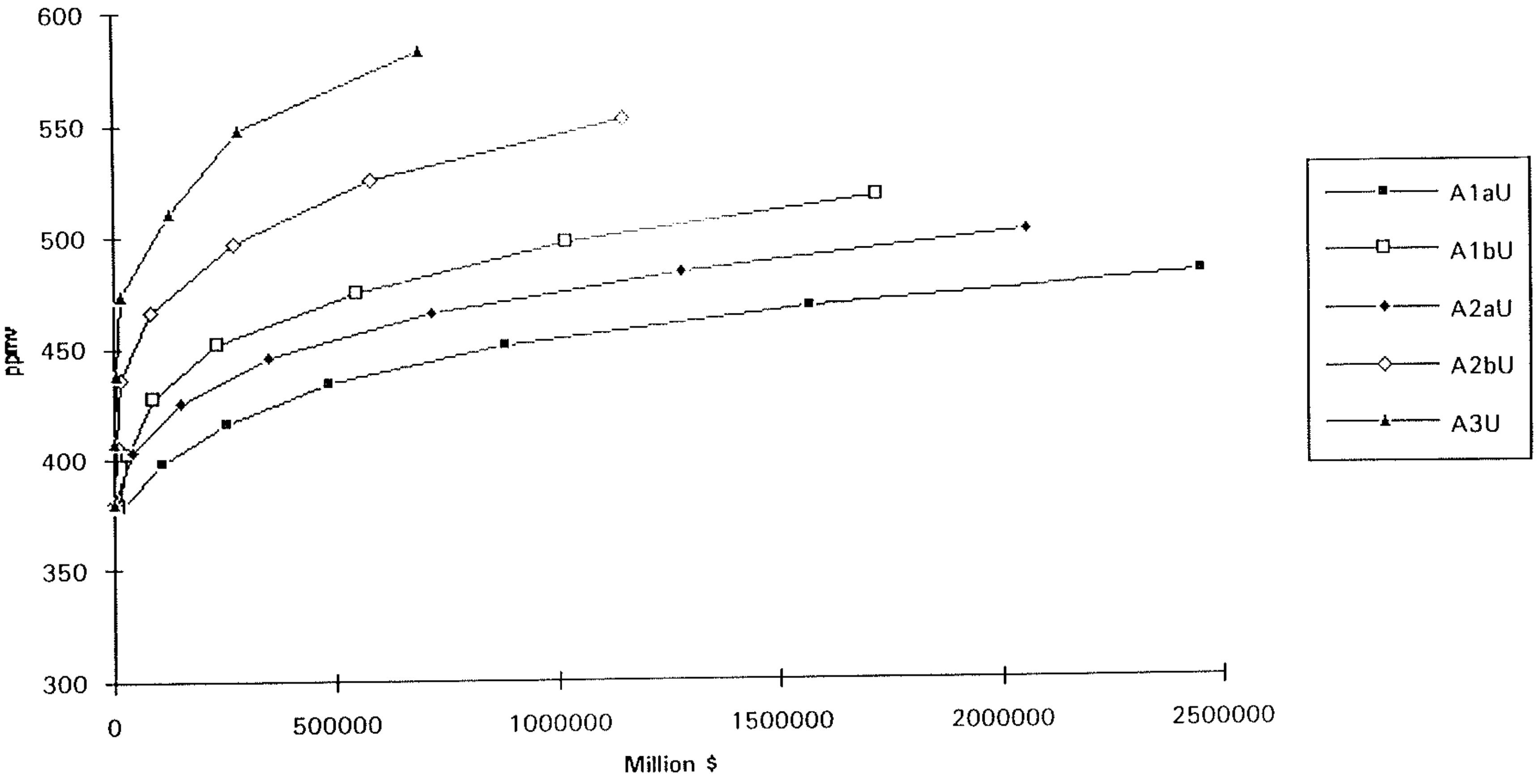
Figure 55



6/16/92

Figure 56

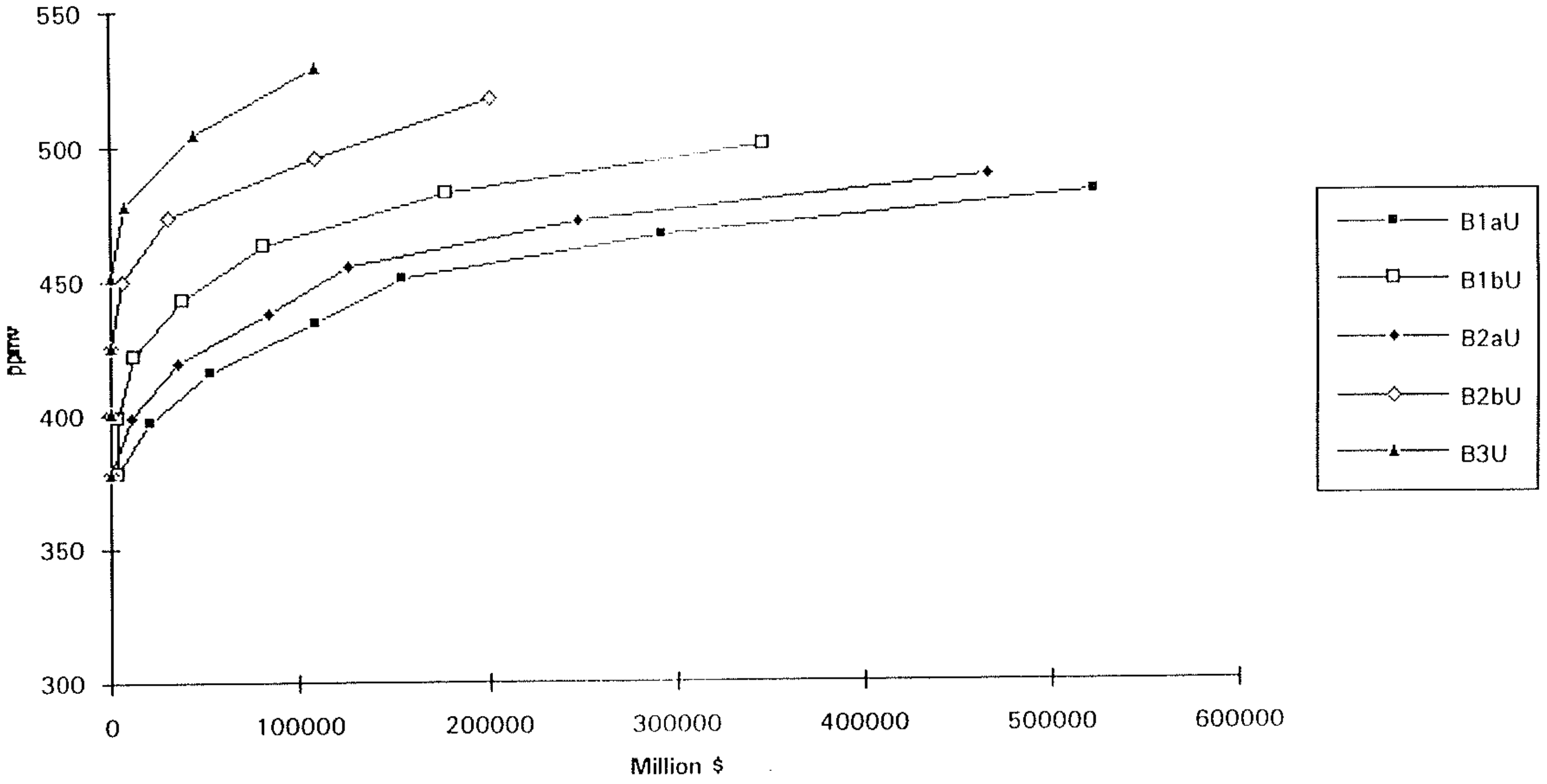
Atmospheric Concentration vs. Total Cost-Case A



5/19/92

Figure 57

Atmospheric Concentration vs. Total Cost-Case B



5/19/92

Figure 58

Atmospheric Concentration vs. Total Cost-Case C

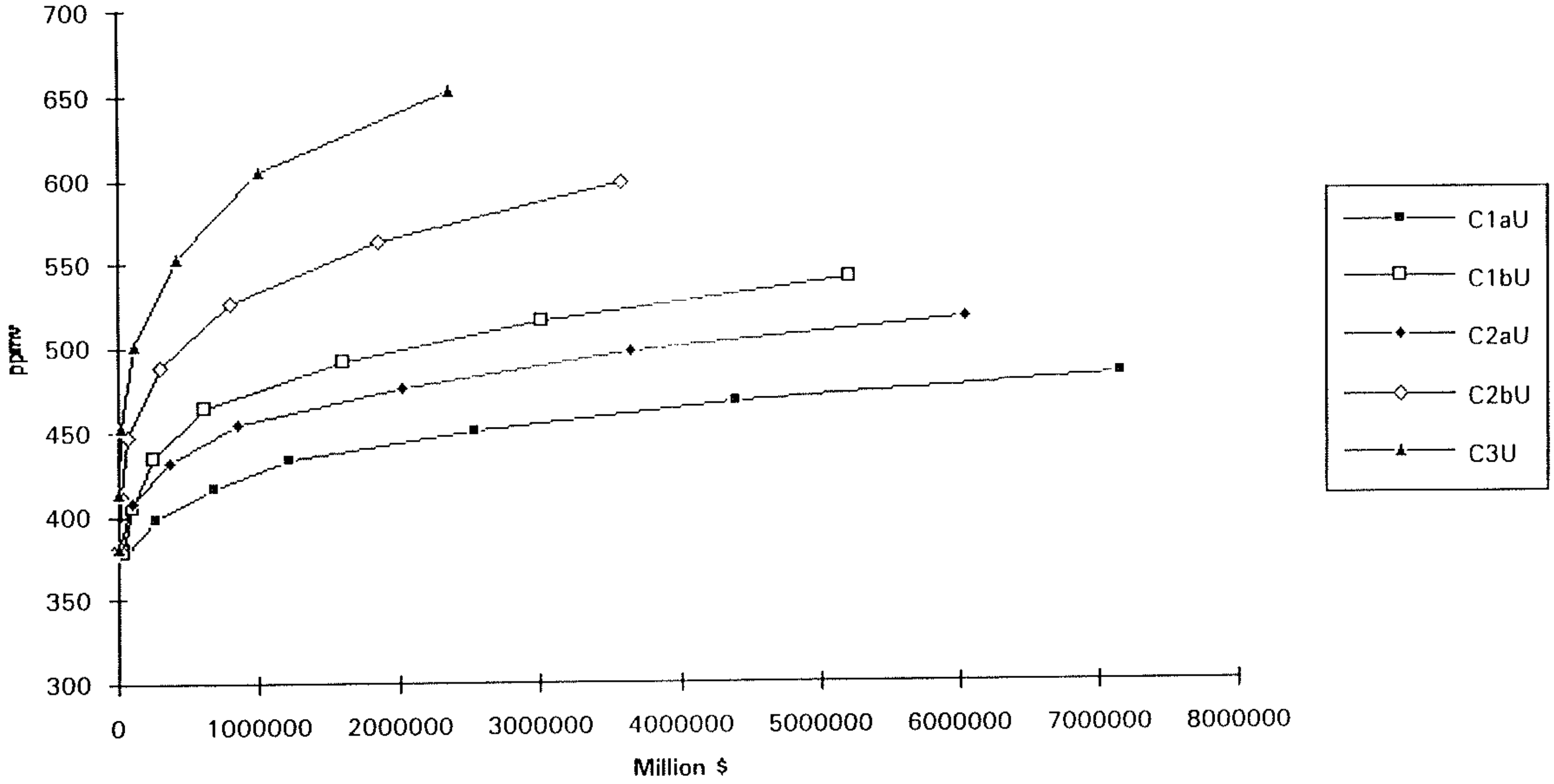
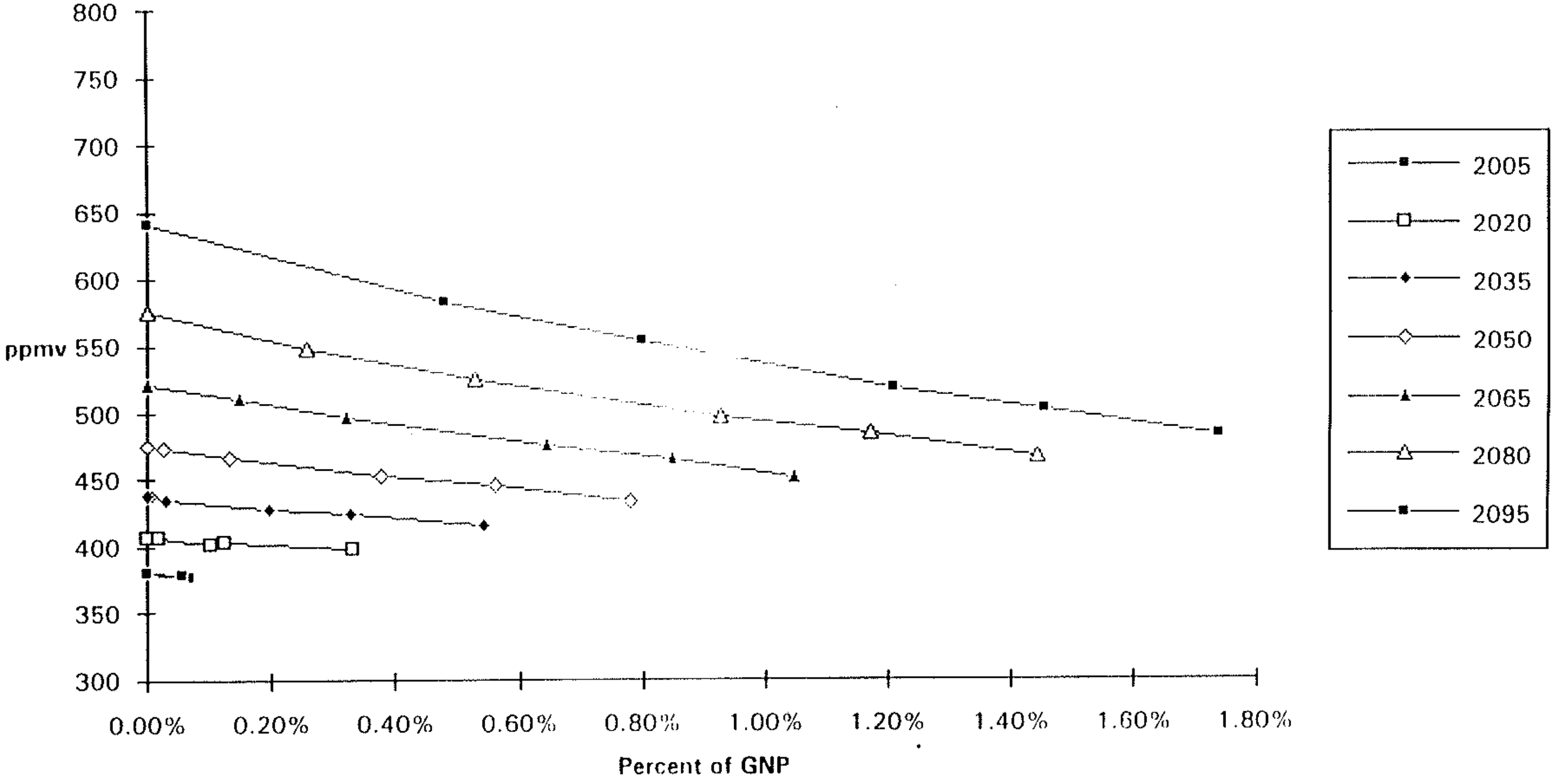


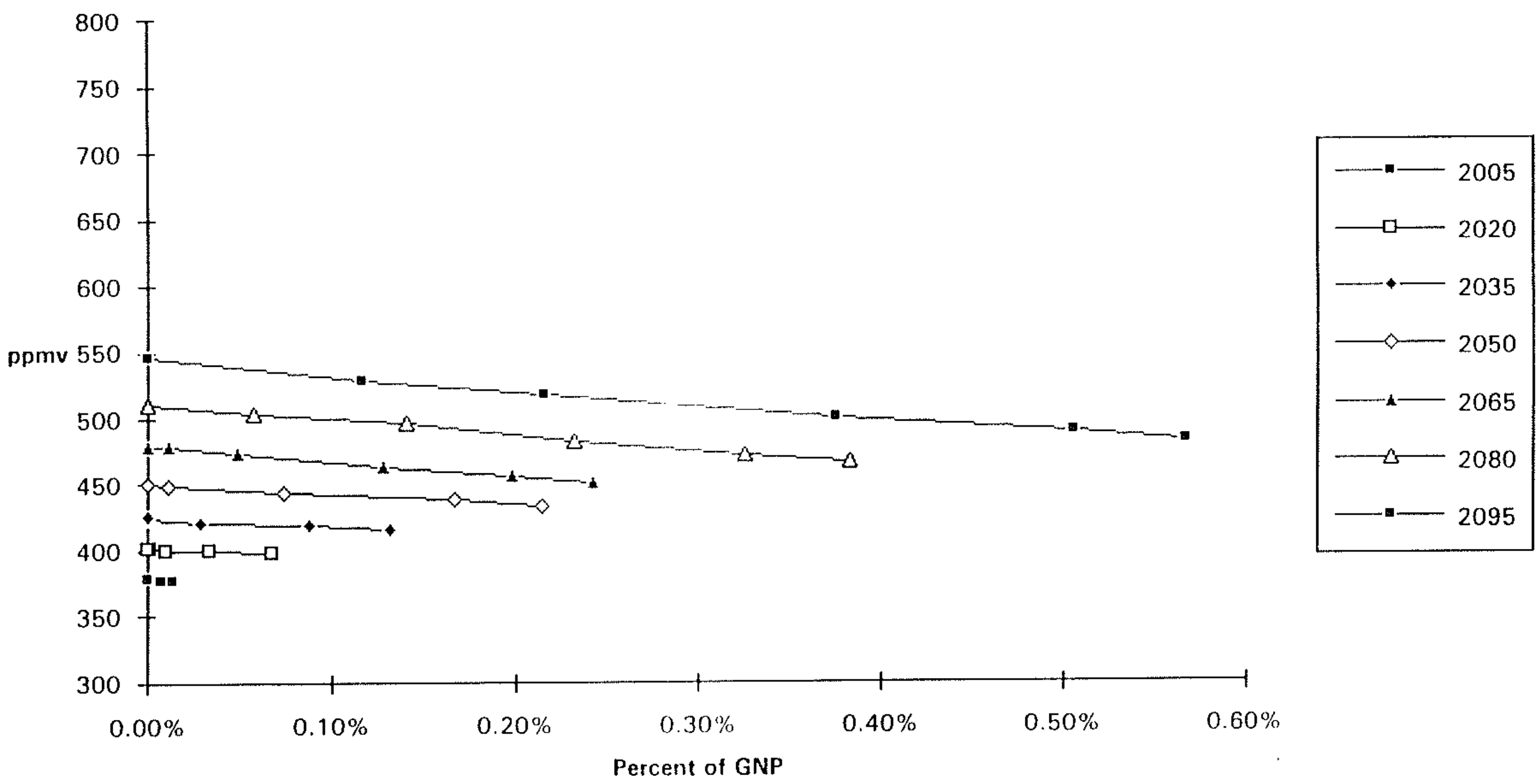
Figure 59

Atmospheric Concentration vs. Total Cost-Case A



6/17/92

Figure 60

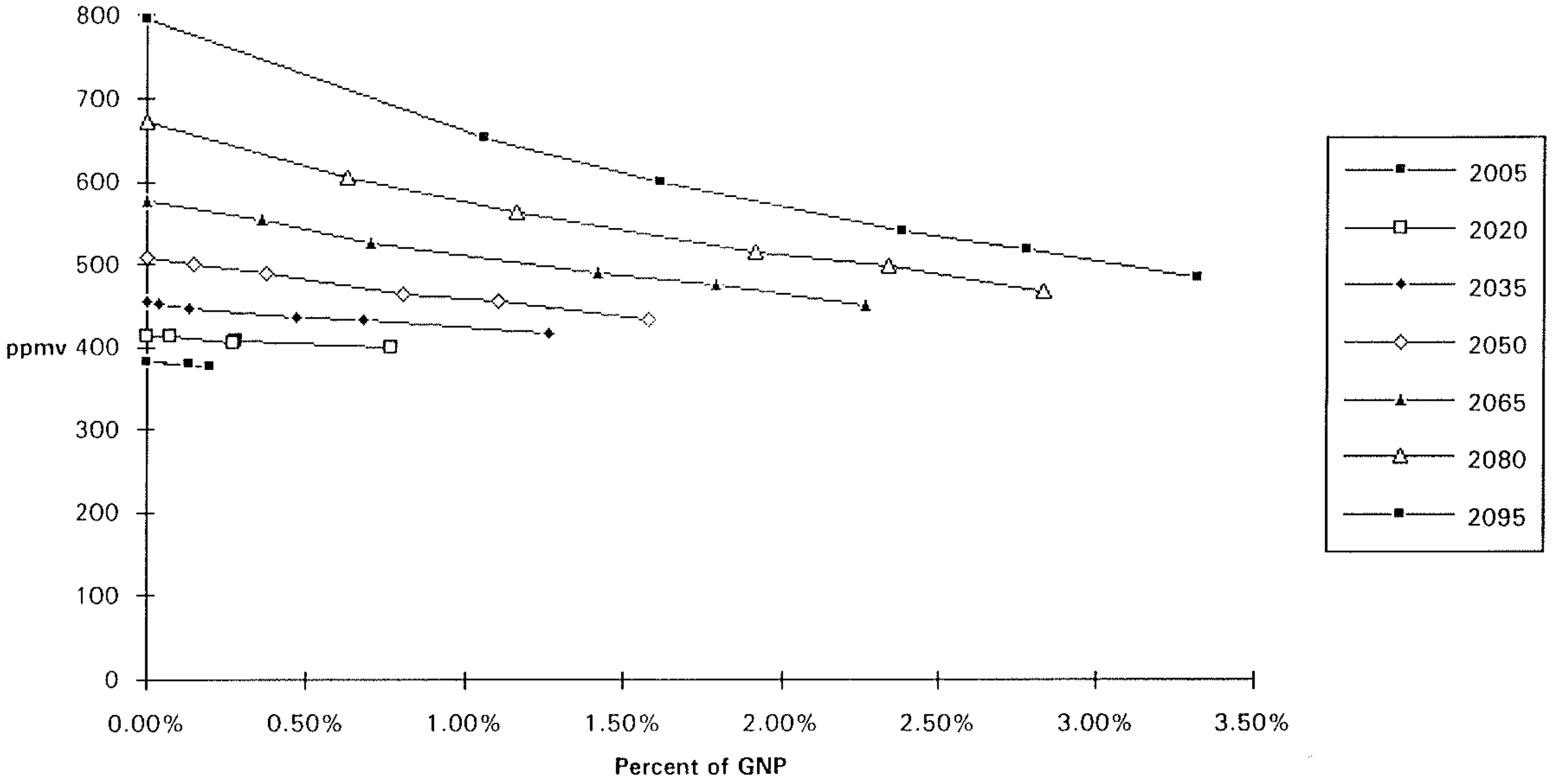


Atmospheric Concentration vs. Total Cost-Case B

6/17/92

Figure 61

Atmospheric Concentration vs. Total Cost-Case C



6/17/92

Figure 62

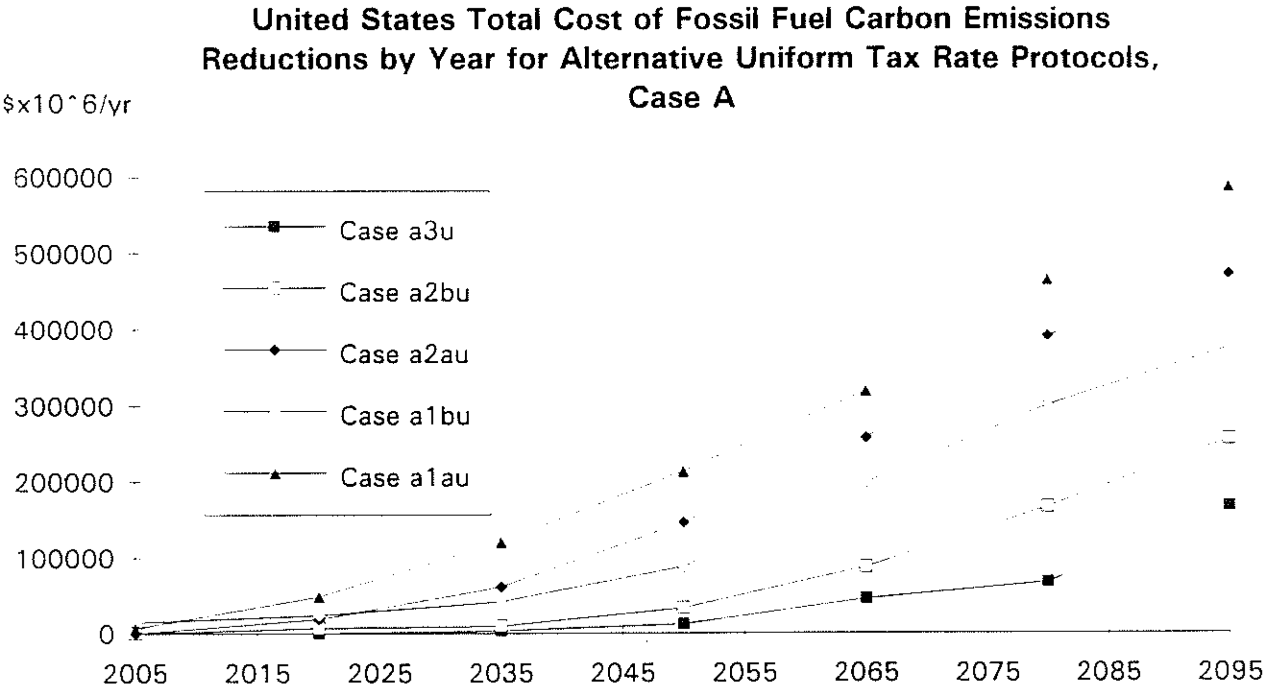
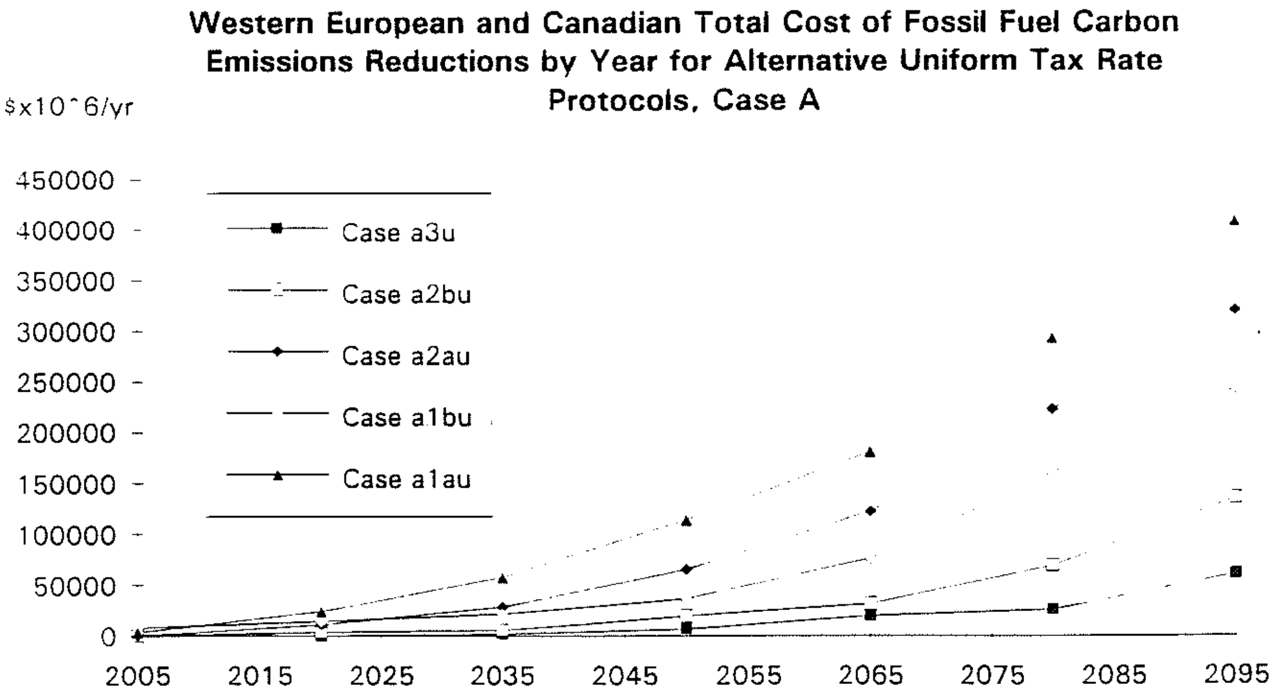

United States Total Cost of Fossil Fuel Carbon Emissions Reductions by Year for Alternative Uniform Tax Rate Protocols, Case A
$x10^6/yr
600000
500000
400000
300000
200000
100000
0
2005
2015
2025
2035
2045
2055
2065
2075
2085
2095
Case a3u
Case a2bu
Case a2au
Case a1bu
Case a1au

Figure 63



Western European and Canadian Total Cost of Fossil Fuel Carbon Emissions Reductions by Year for Alternative Uniform Tax Rate Protocols, Case A

Figure 64

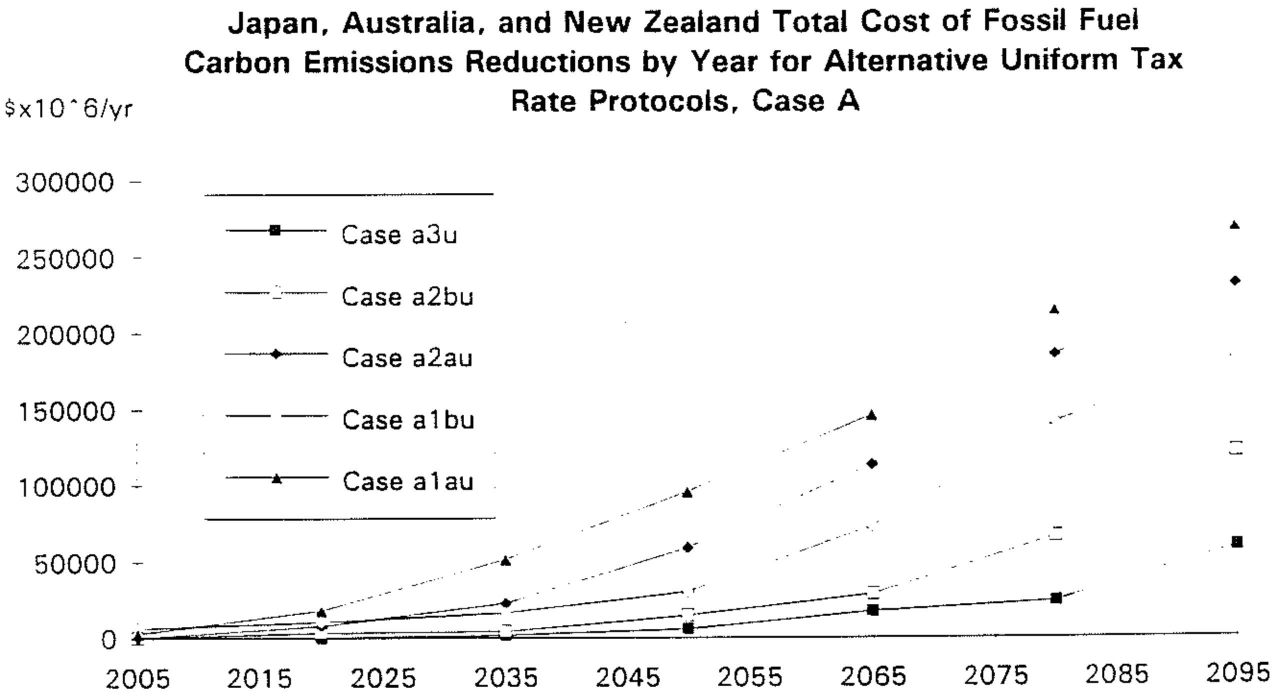

Japan, Australia, and New Zealand Total Cost of Fossil Fuel Carbon Emissions Reductions by Year for Alternative Uniform Tax Rate Protocols, Case A
$x10^6/yr
300000
250000
200000
150000
100000
50000
0
2005
2015
2025
2035
2045
2055
2065
2075
2085
2095
Case a3u
Case a2bu
Case a2au
Case a1bu
Case a1au

Figure 65

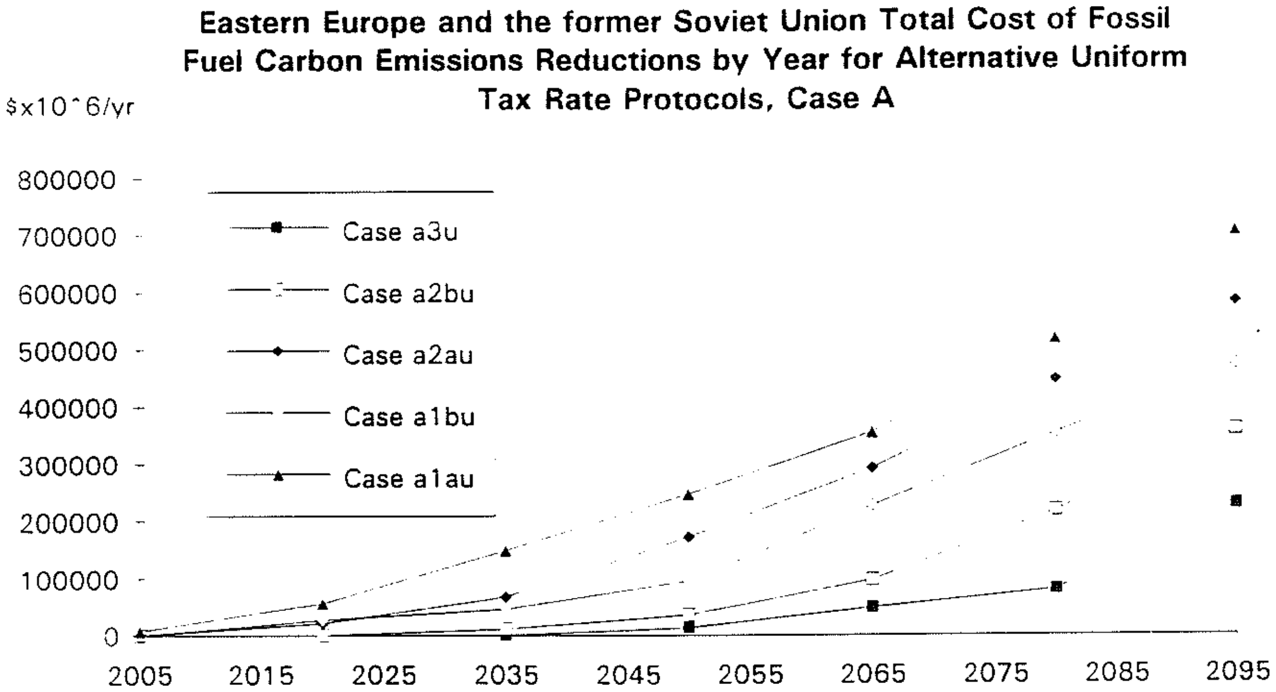

Eastern Europe and the former Soviet Union Total Cost of Fossil Fuel Carbon Emissions Reductions by Year for Alternative Uniform Tax Rate Protocols, Case A

Figure 66

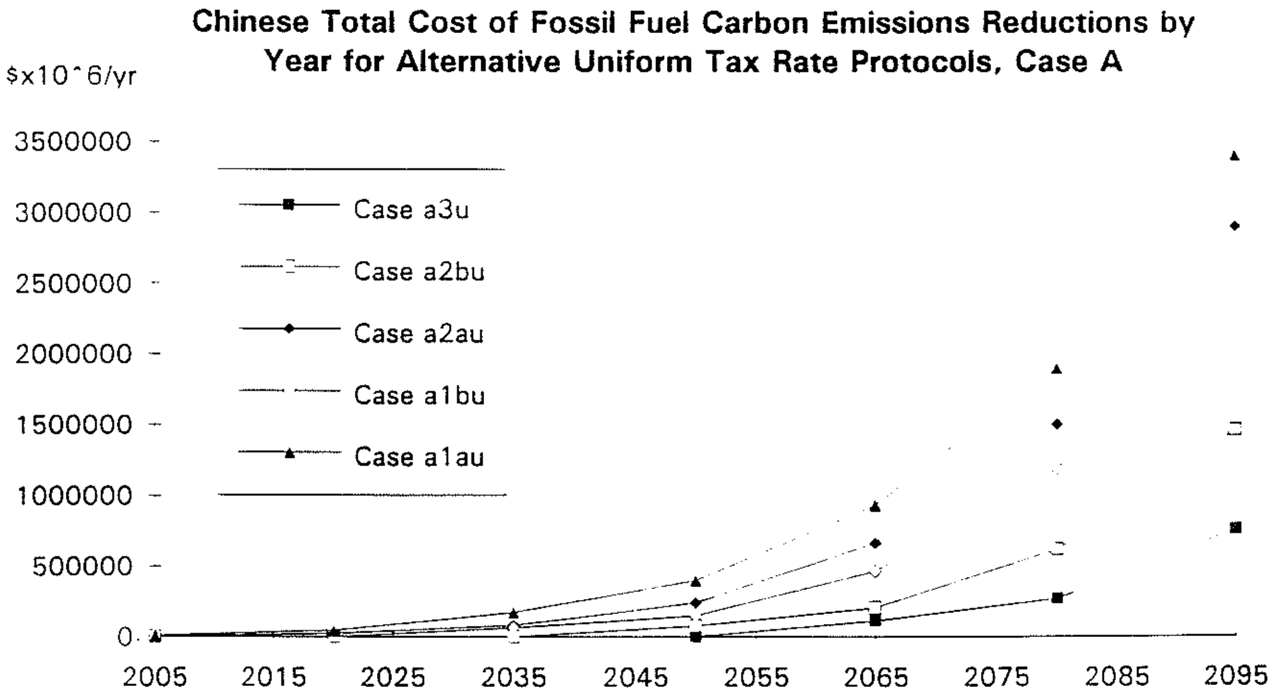

Chinese Total Cost of Fossil Fuel Carbon Emissions Reductions by Year for Alternative Uniform Tax Rate Protocols, Case A
$x10^6/yr
3500000
3000000
2500000
2000000
1500000
1000000
500000
0
2005
2015
2025
2035
2045
2055
2065
2075
2085
2095
Case a3u
Case a2bu
Case a2au
Case a1bu
Case a1au

Figure 67

Rest of World Total Cost of Fossil Fuel Carbon Emissions Reductions by Year for Alternative Uniform Tax Rate Protocols, Case A

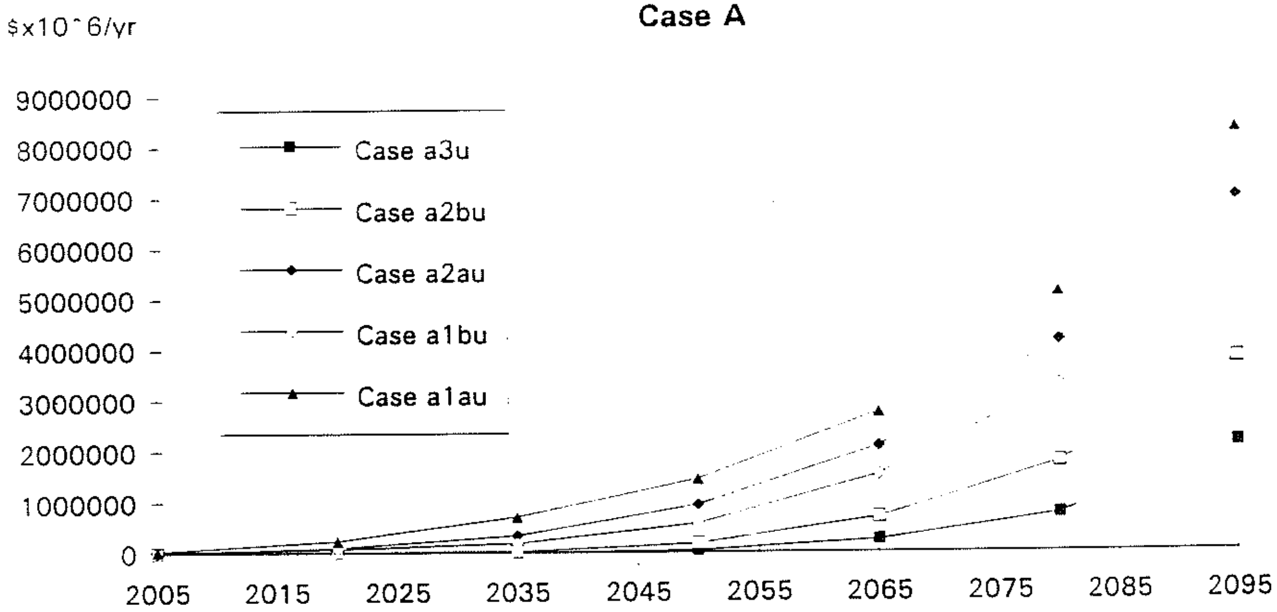


Figure 68

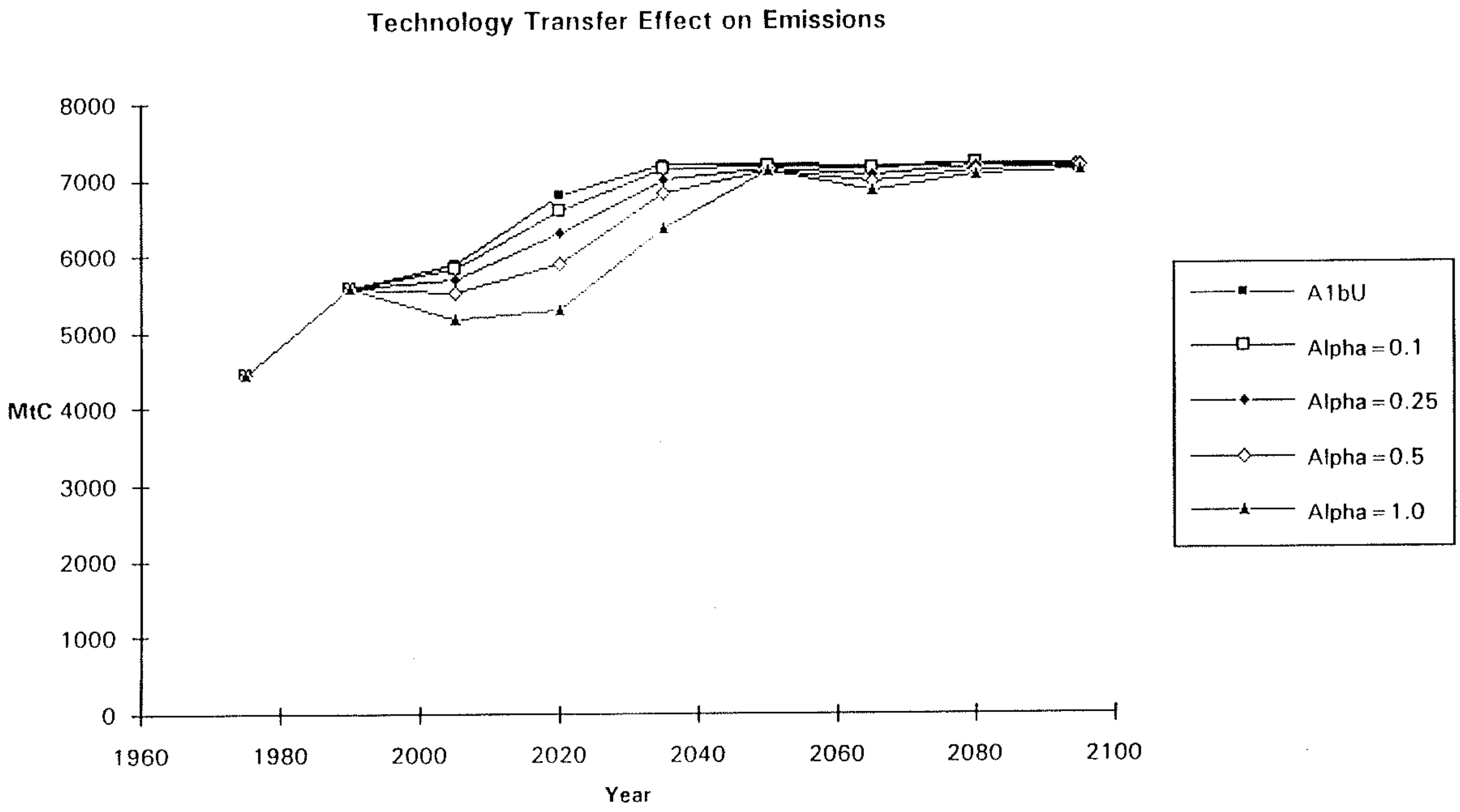


Figure T1

Figure 69

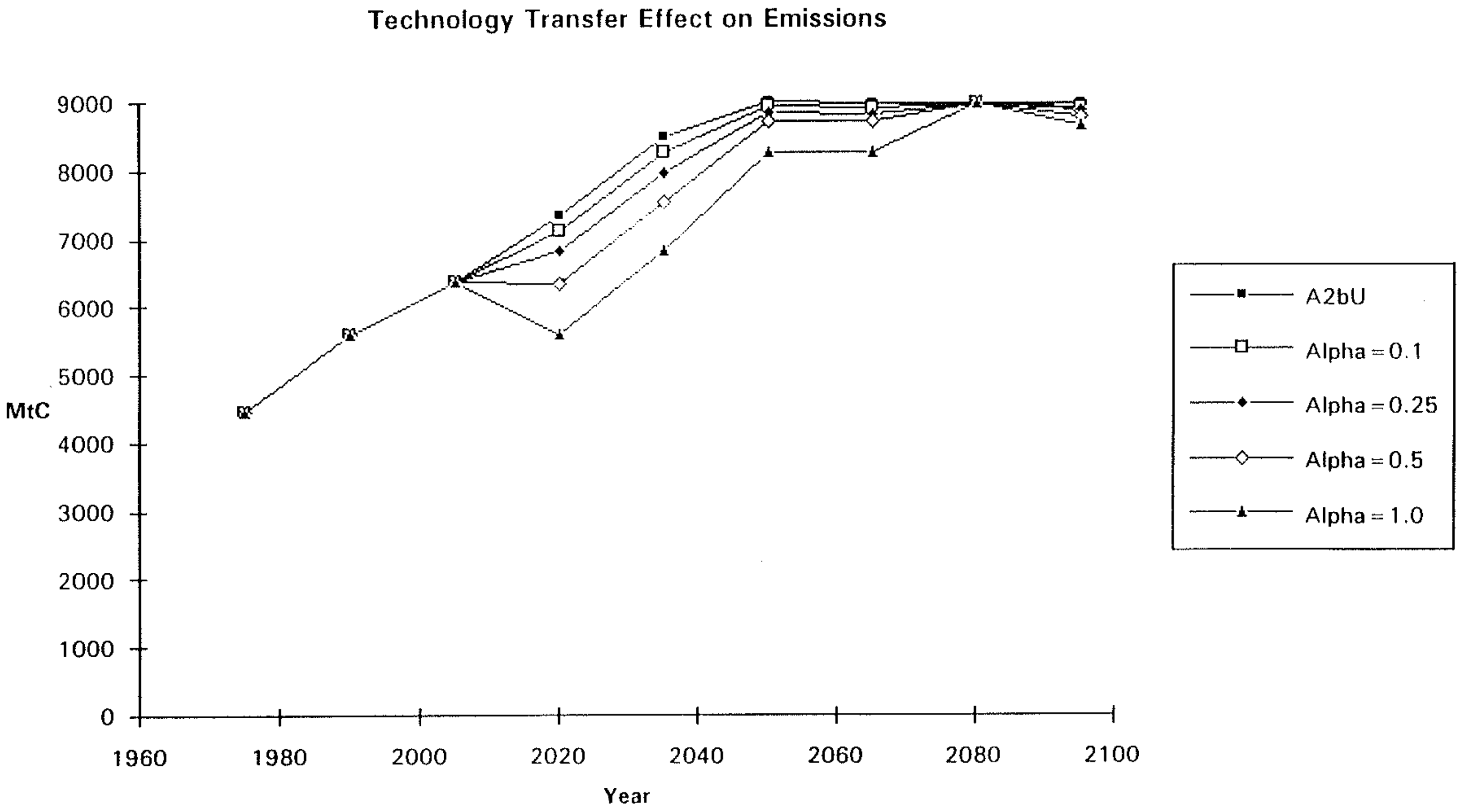


Figure T2

Figure 70

Technology Transfer Effect on Atmospheric Concentration

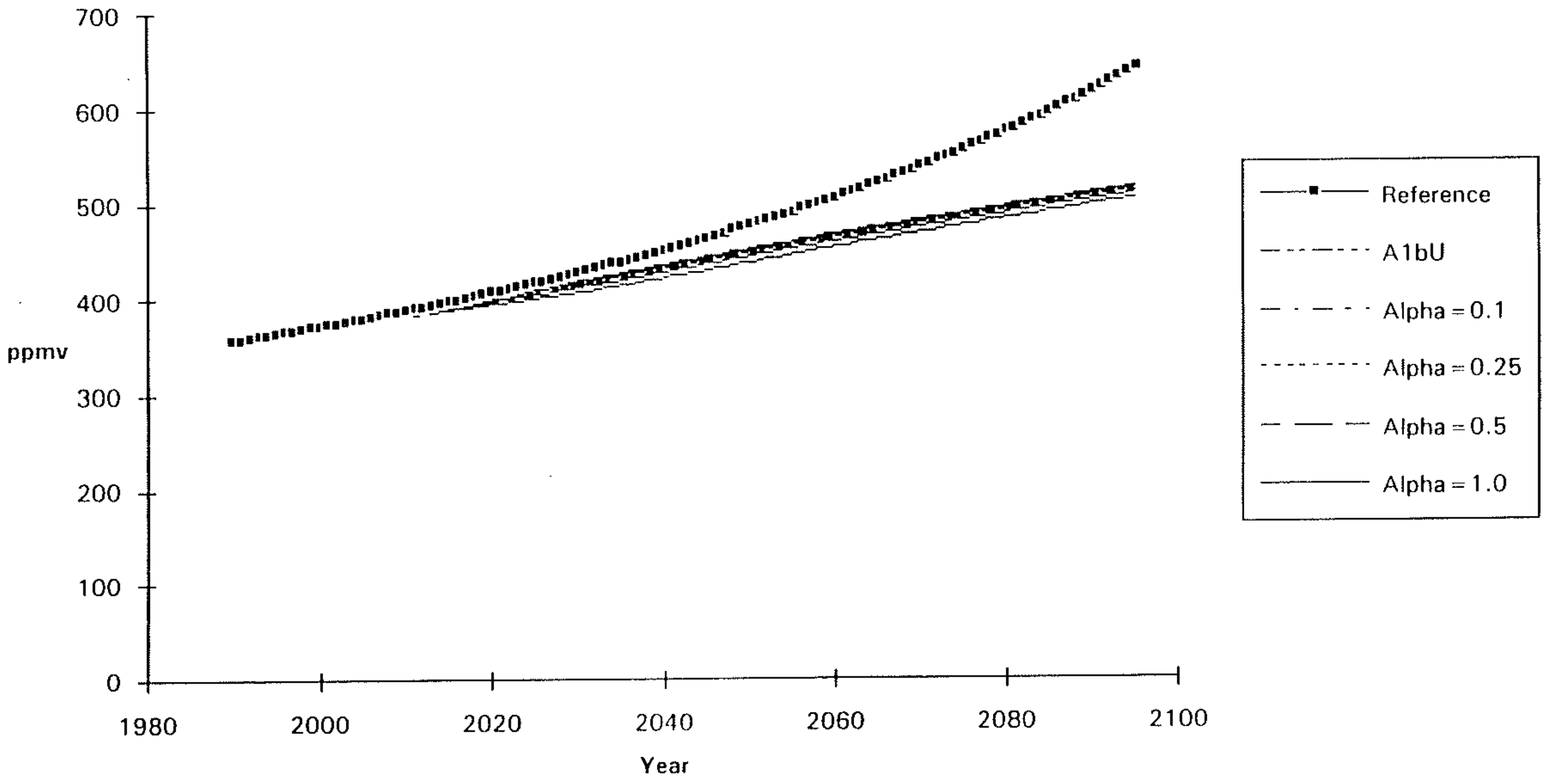


Figure T3

Figure 71

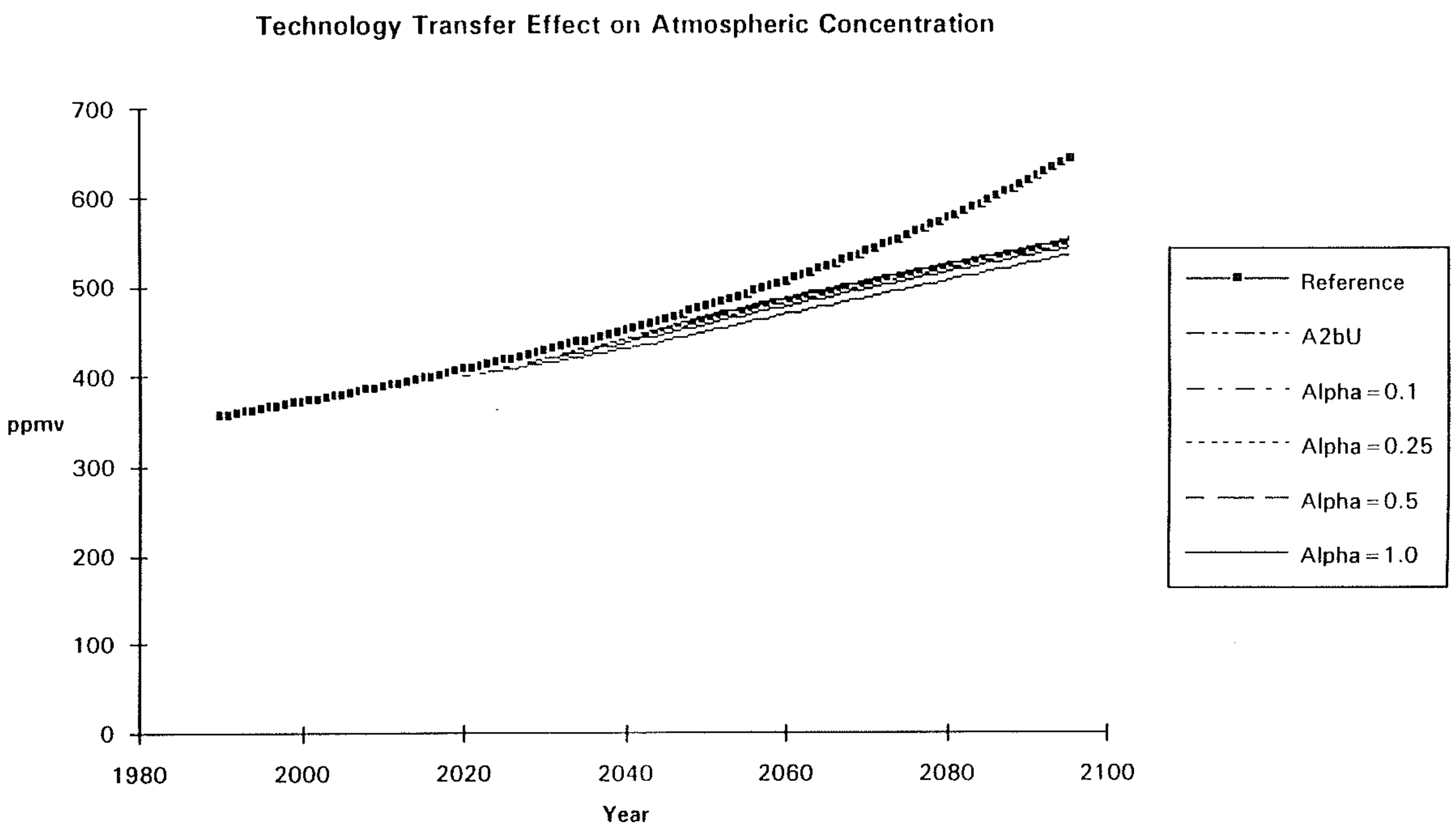


Figure T4

Figure 72

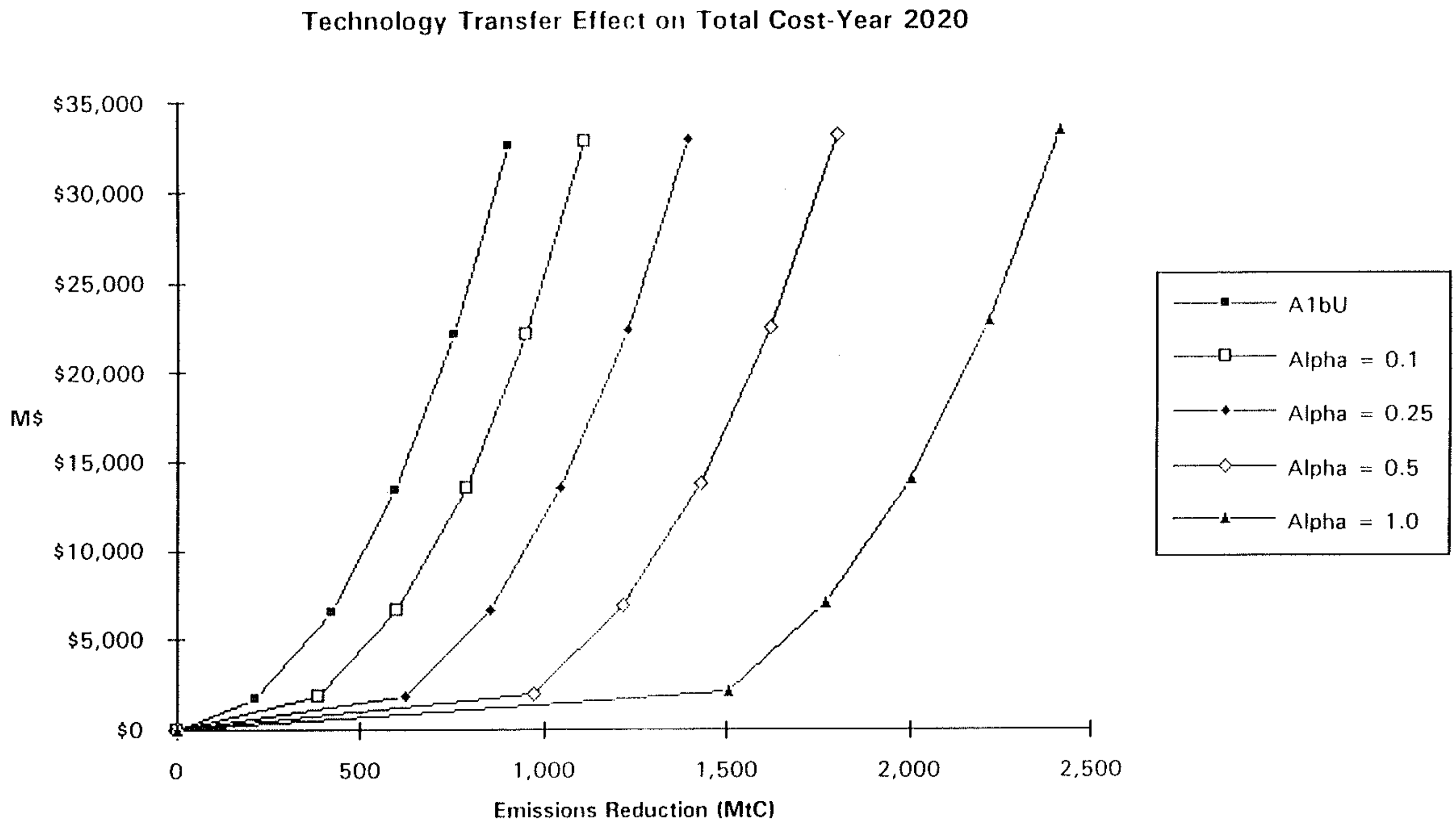


Figure T5

Figure 73

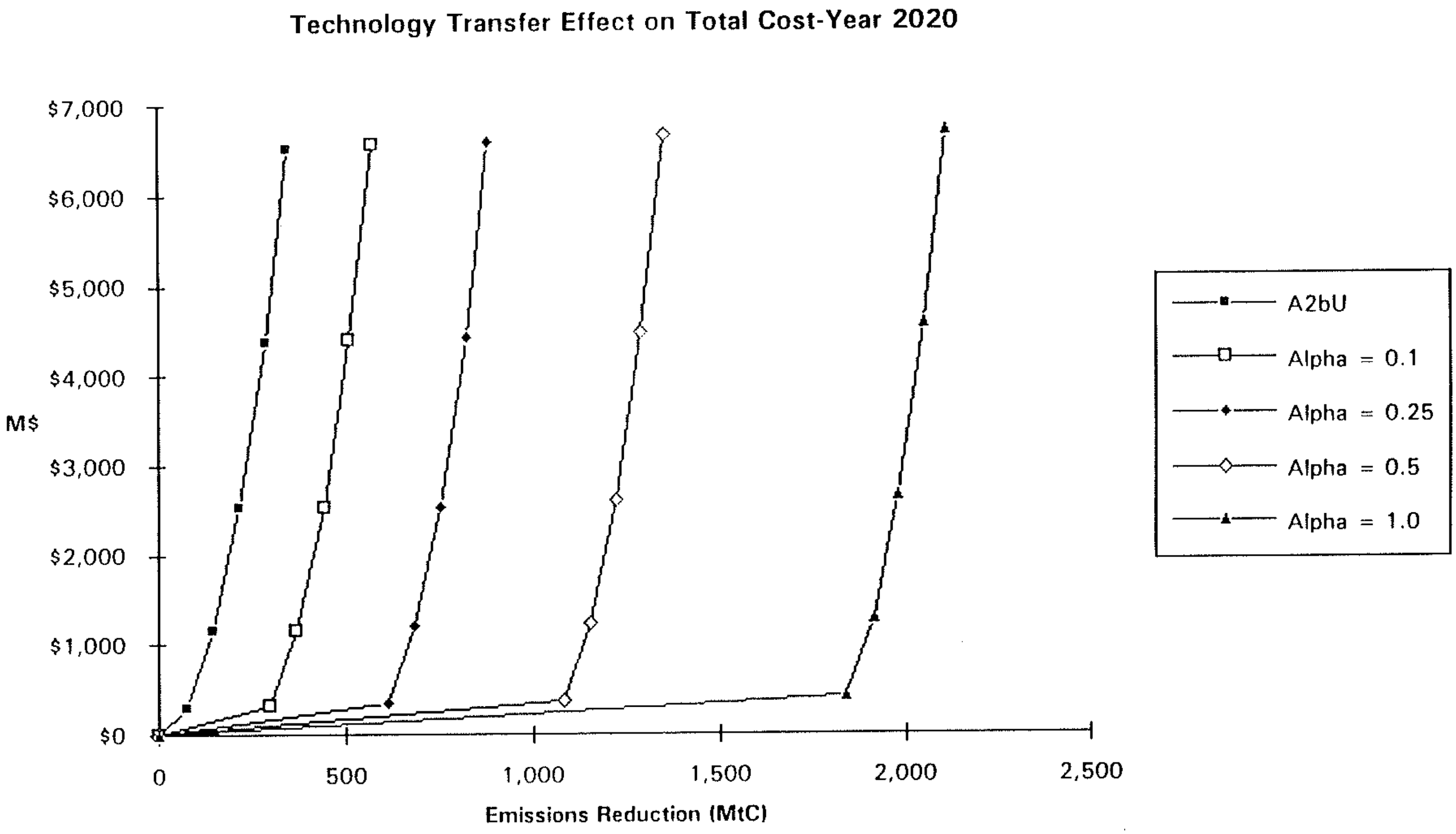
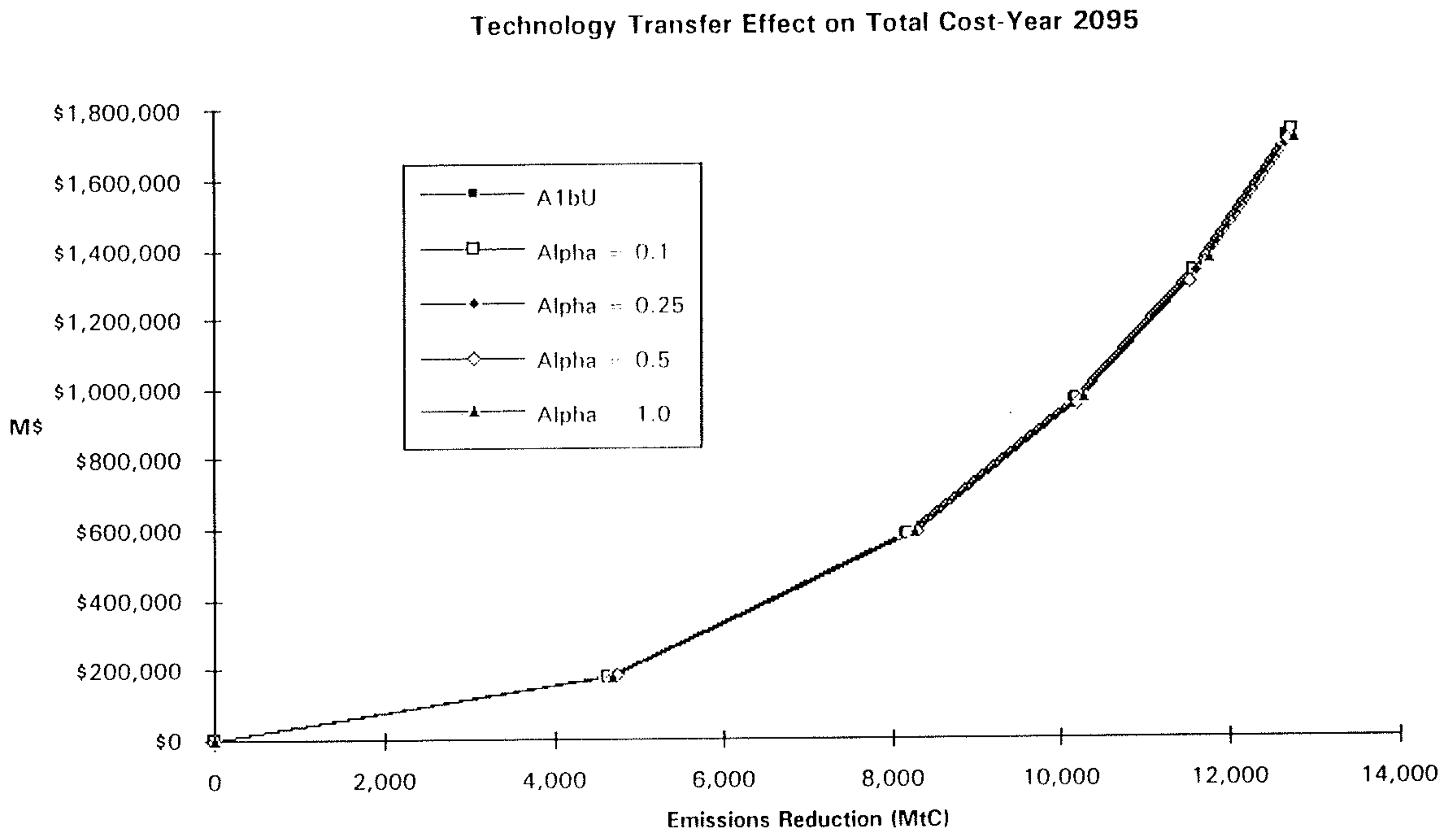


Figure T6

Figure 74



Technology Transfer Effect on Total Cost-Year 2095

Figure T7

Figure 75

Primary Energy by Fuel: Case A with Advanced Energy Technologies (Ej)

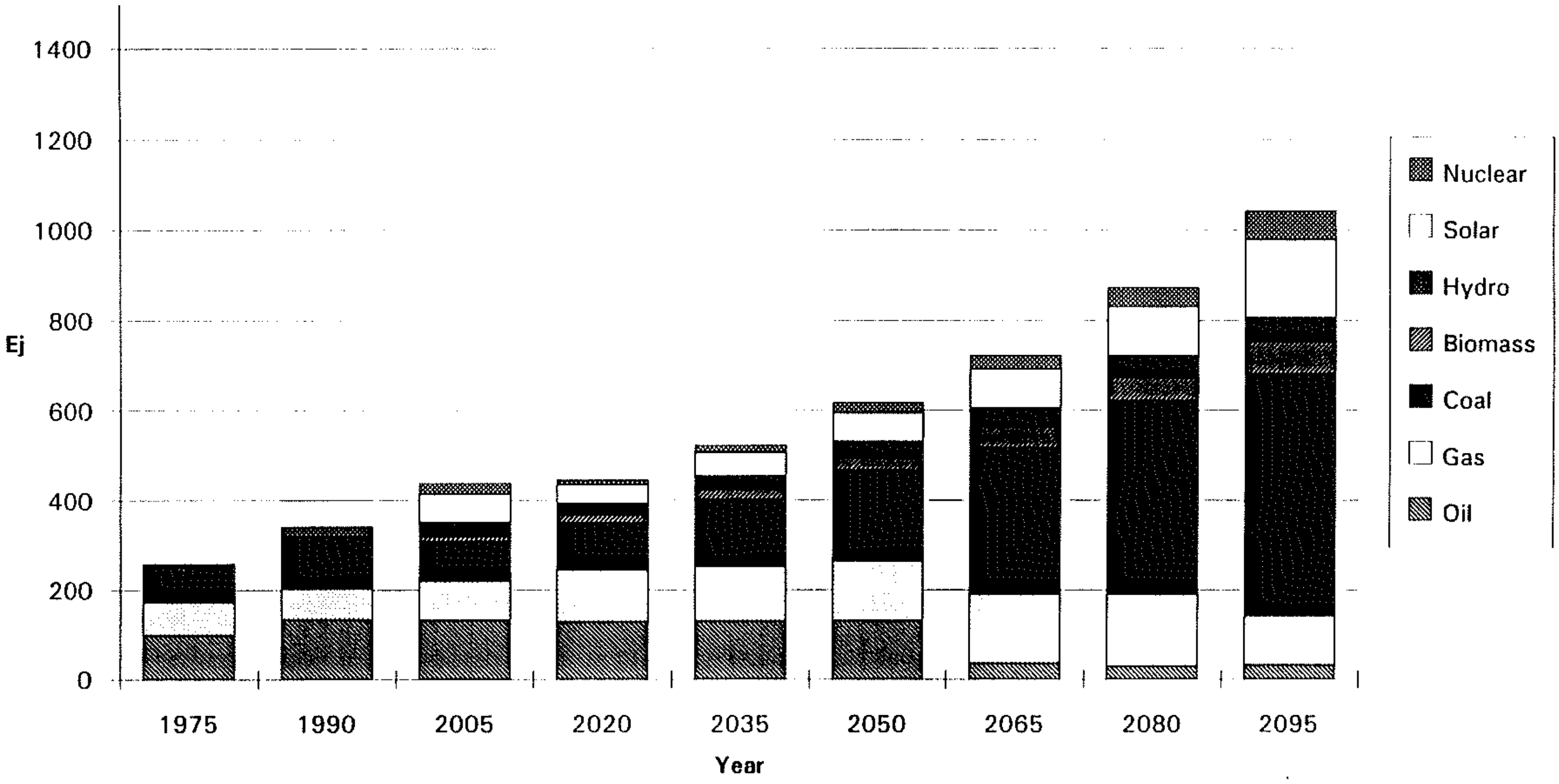


Figure T8

Figure 76

Primary Energy by Fuel: Protocol 1a, Case A with Advanced Energy Technologies (Ej)

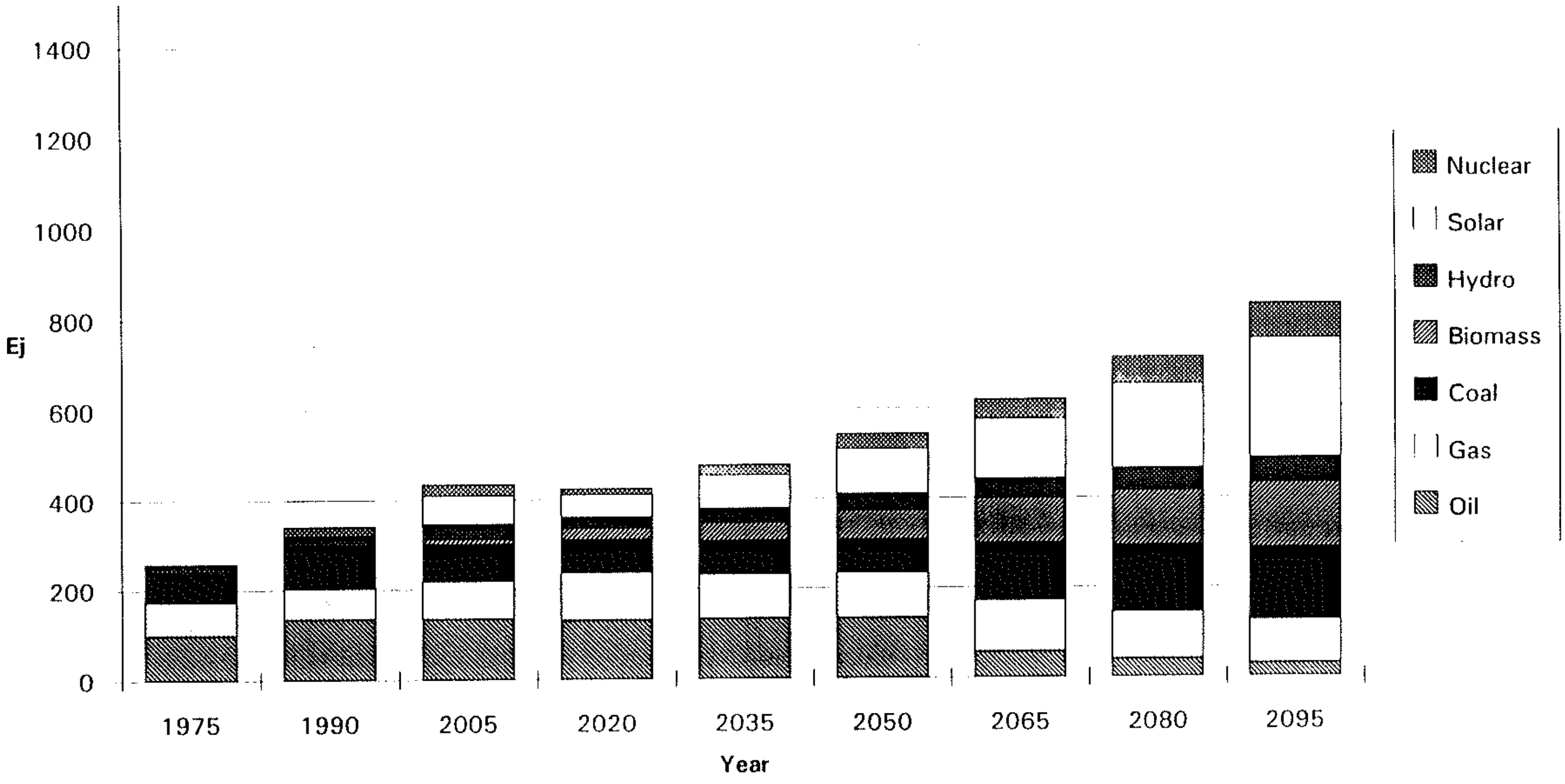


Figure T9

Figure 77

Total Cost of Stabilizing Fossil Fuel CO2 Emissions at 1990 Levels Under Protocol 1a for Reference and Advanced Technologies Case A ($x10^9/yr)