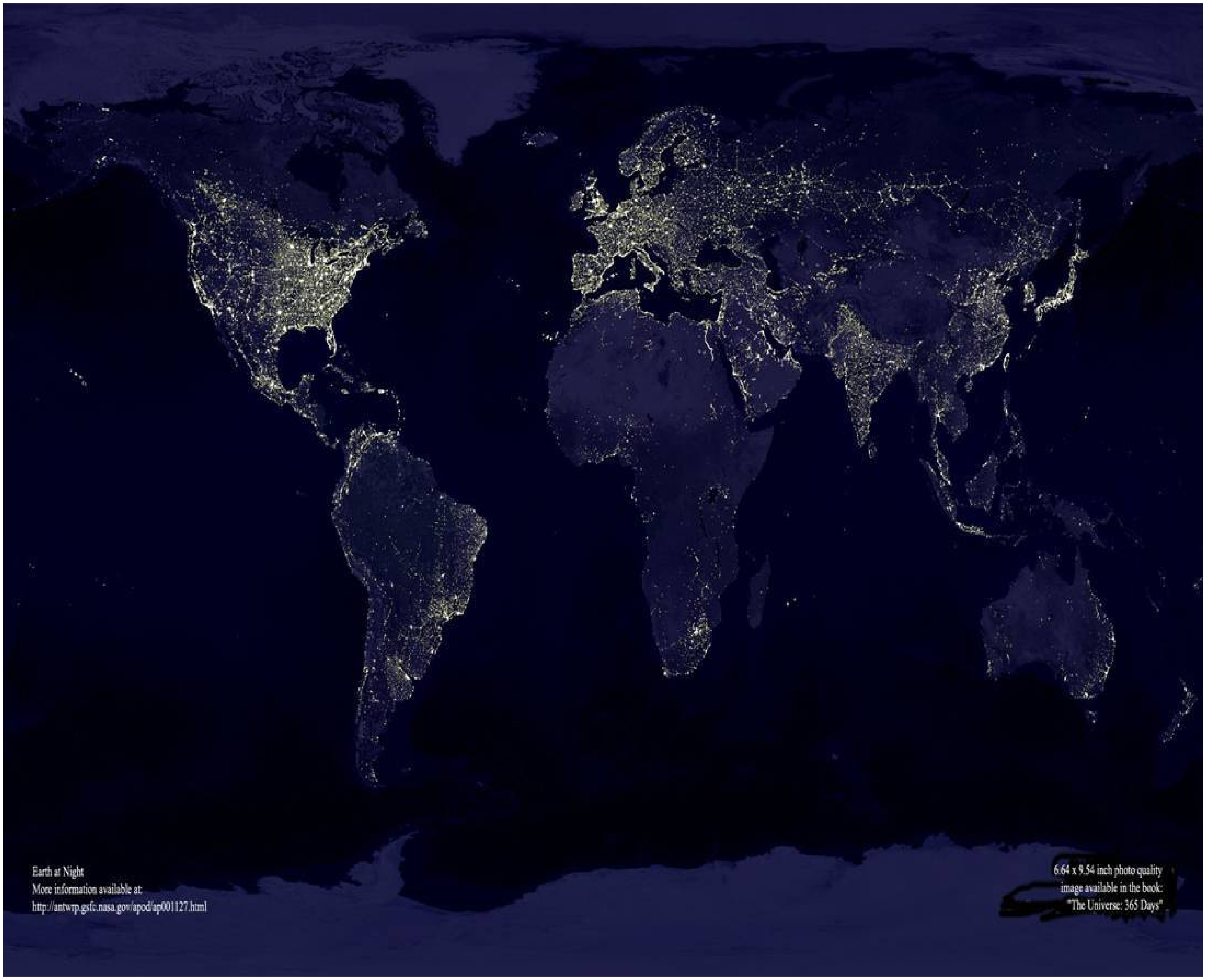
GAMBLING WITH THE FUTURE: ENERGY, ENVIRONMENT AND ECONOMICS IN THE 21ST CENTURY

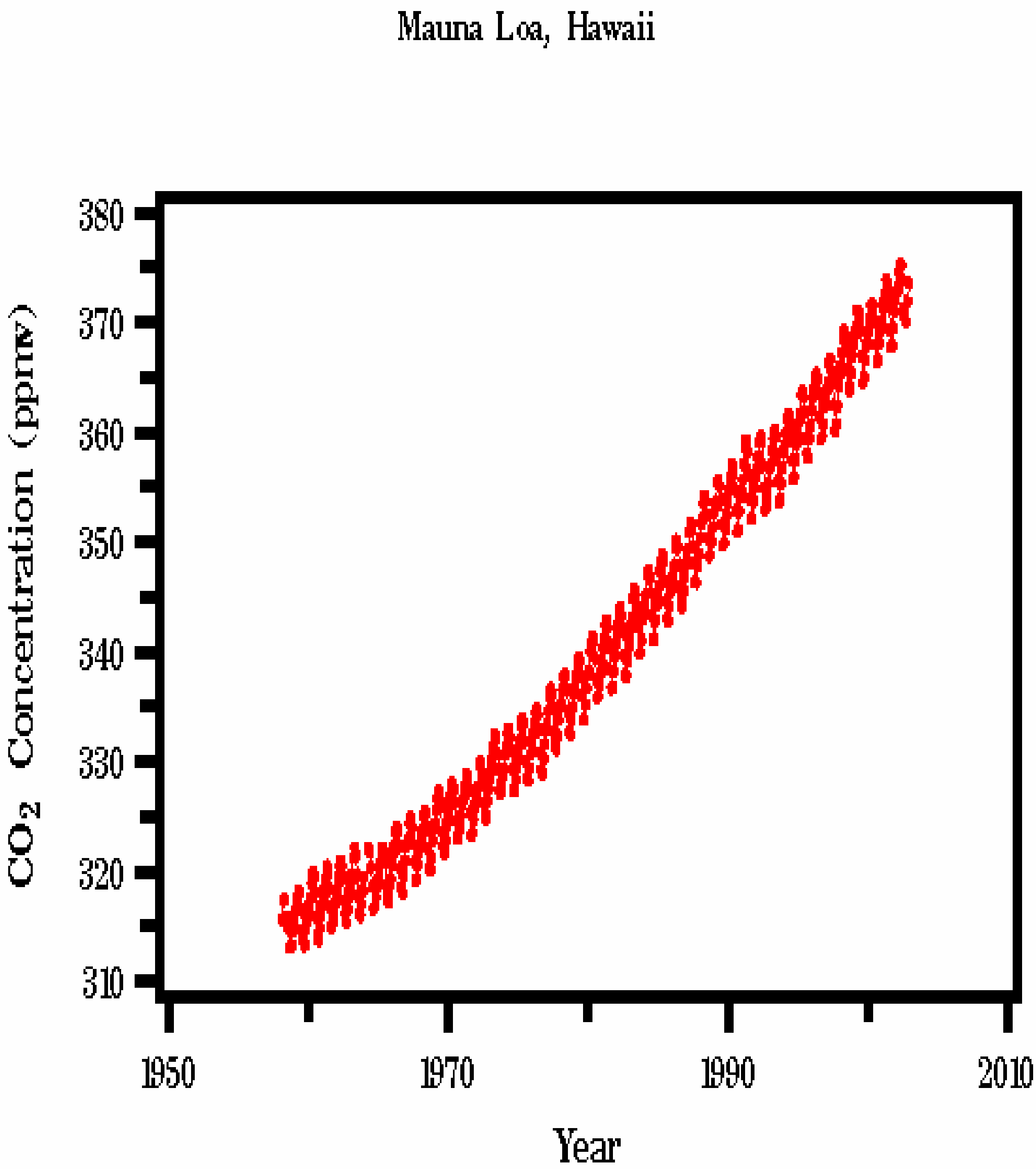
Presented to
Stanford University
Physics and Applied Physics Department
Colloquium

October 5, 2004

Burton Richter
Paul Pigott Professor in the Physical Sciences
Stanford University
Director Emeritus
Stanford Linear Accelerator Center

Earth from Apollo 17 (NASA)


Earth at Night
More information available at:
http://antwrp.gsfc.nasa.gov/apod/ap001127.html
6.64 x 9.54 inch photo quality
image available in the book:
"The Universe: 365 Days"

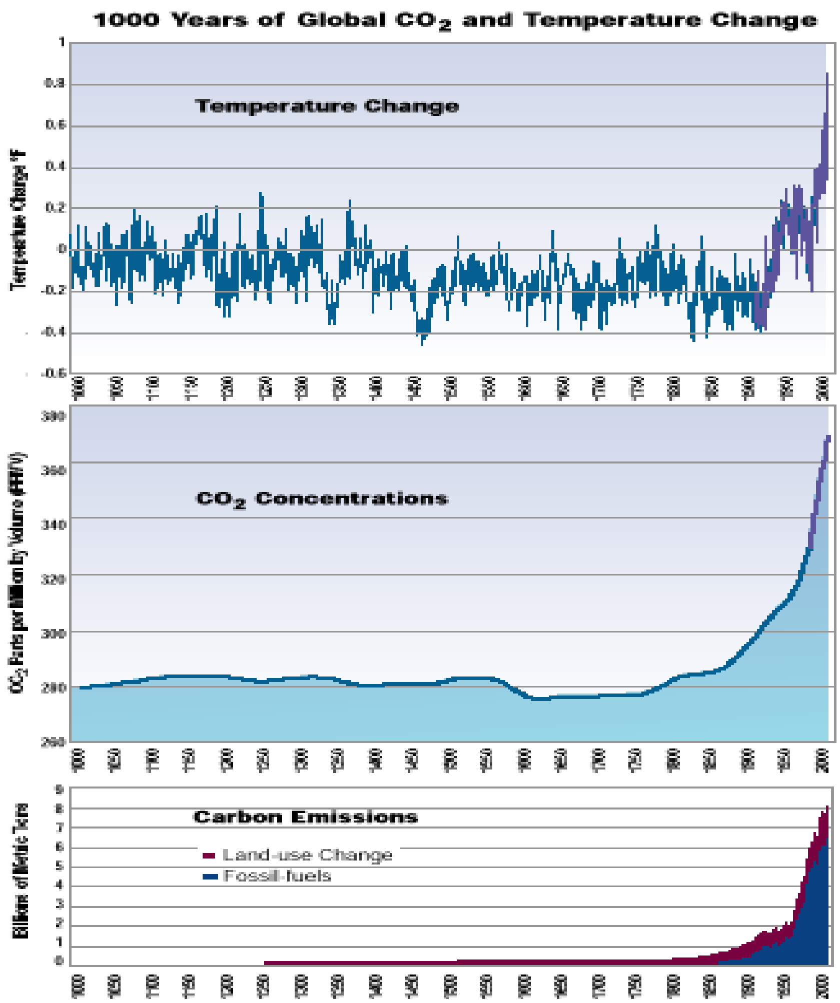


Source: Dave Keeling and Tim Whorf (Scripps Institution of Oceanography)

The Greenhouse Effect

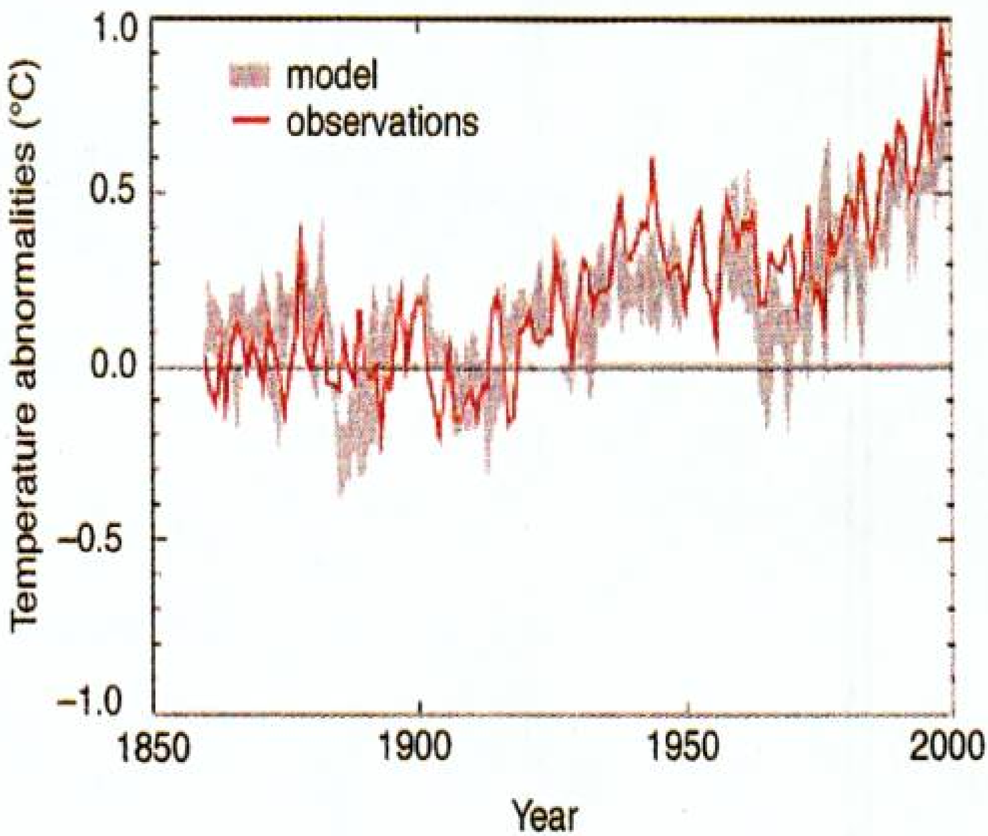
- Solar flux at earth orbit = 1.4 kW/m^2
- Average reflected = 30%
- Average over entire surface of globe = 240 W/m^2
- Average temperature of surface = 288° K
- Radiation at 288° K = 400 W/m^2
- Average temperature to radiate 240 W/m^2 = –20° C
- Water vapor is the main greenhouse gas
- Geological heat flux is about 0.1% of solar

1000 Years of Global CO_2 and Temperature Change



Records of northern hemisphere surface temperatures, CO_2 concentrations, and carbon emissions show a close correlation. Temperature Change: reconstruction of annual-average northern hemisphere surface air temperatures derived from historical records, tree rings, and corals (blue), and air temperatures directly measured (purple). CO_2 Concentrations: record of global CO_2 concentration for the last 1000 years, derived from measurements of CO_2 concentration in air bubbles in the layered ice cores drilled in Antarctica (blue line) and from atmospheric measurements since 1957. Carbon Emissions: reconstruction of past emissions of CO_2 as a result of land clearing and fossil fuel combustion since about 1750 (in billions of metric tons of carbon per year).

IPCC – Third Assessment Report



Climate Change 2001: Synthesis Report

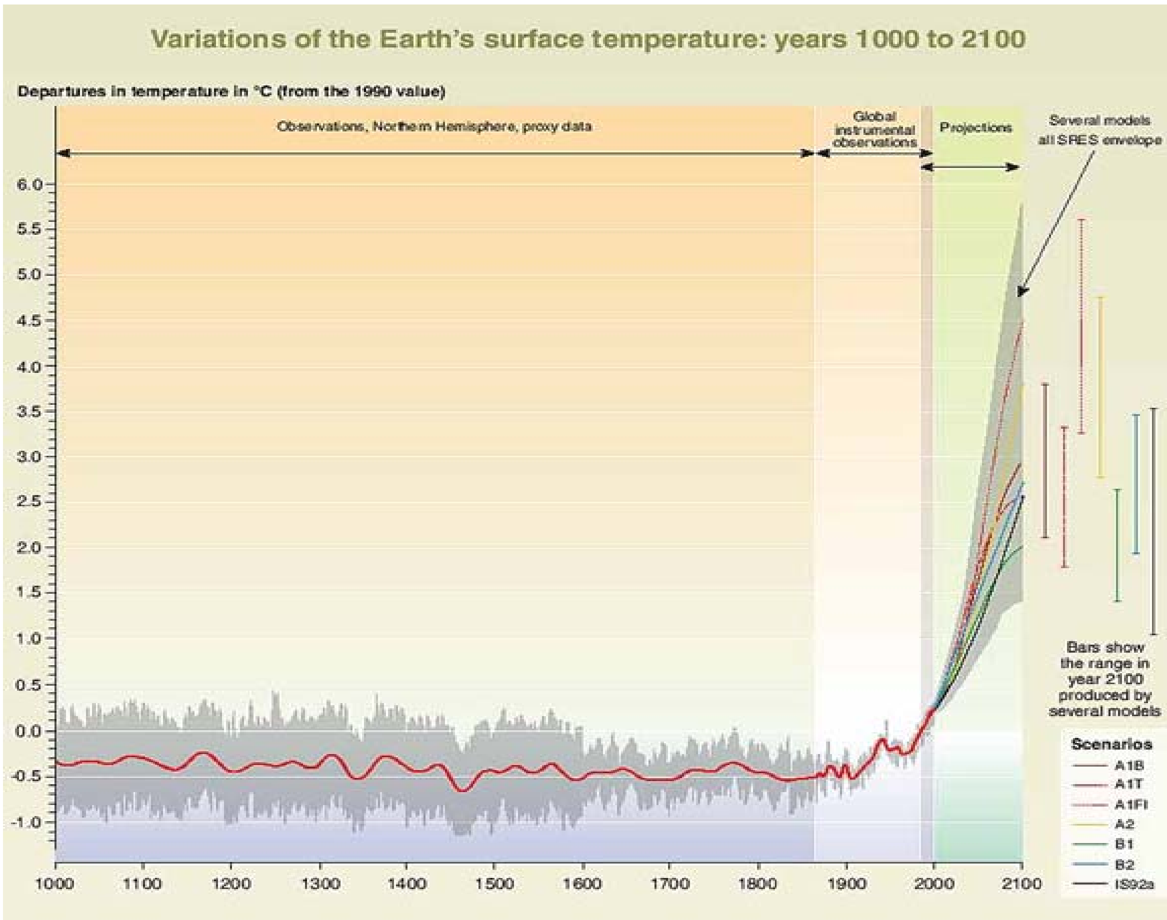
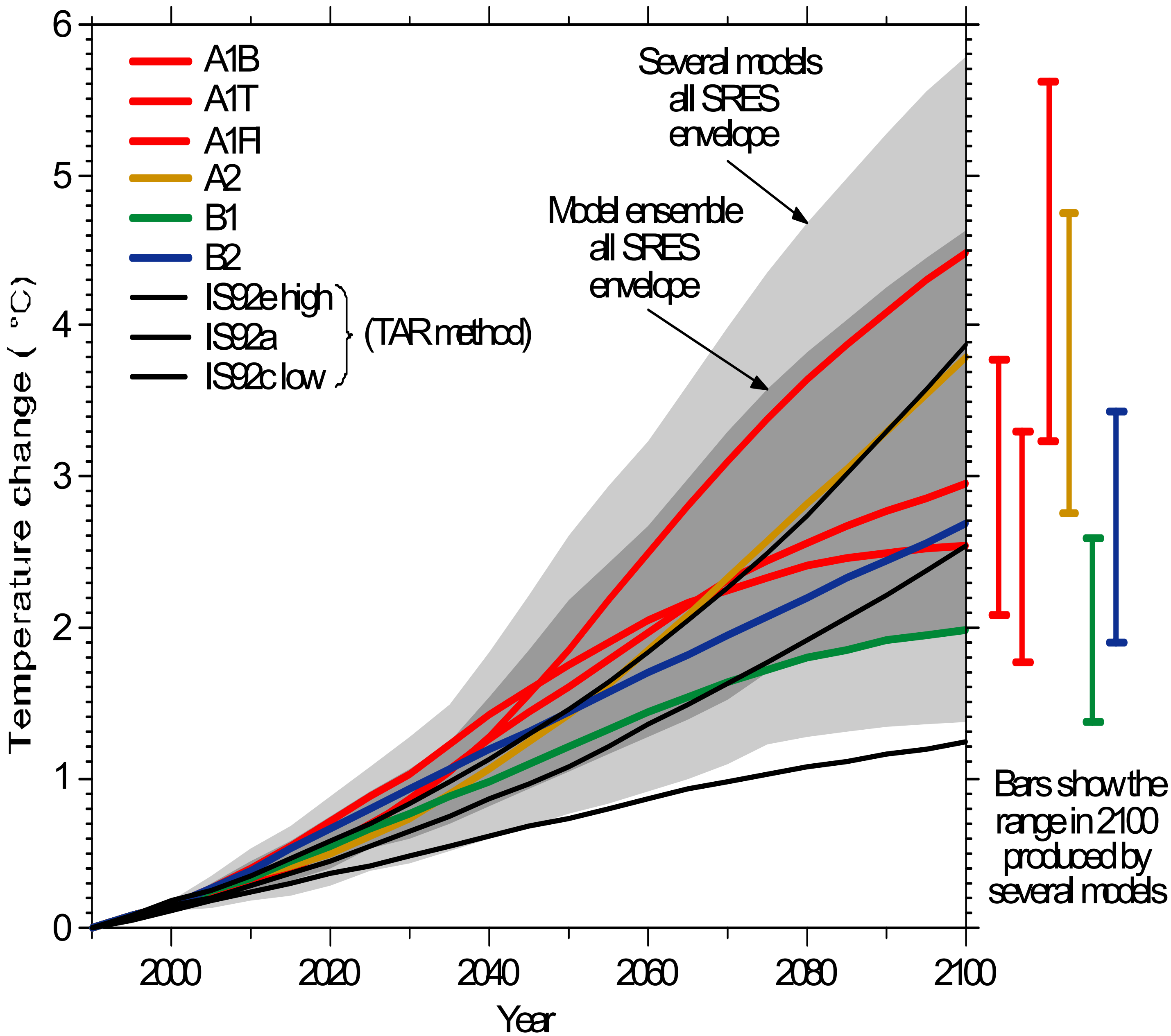
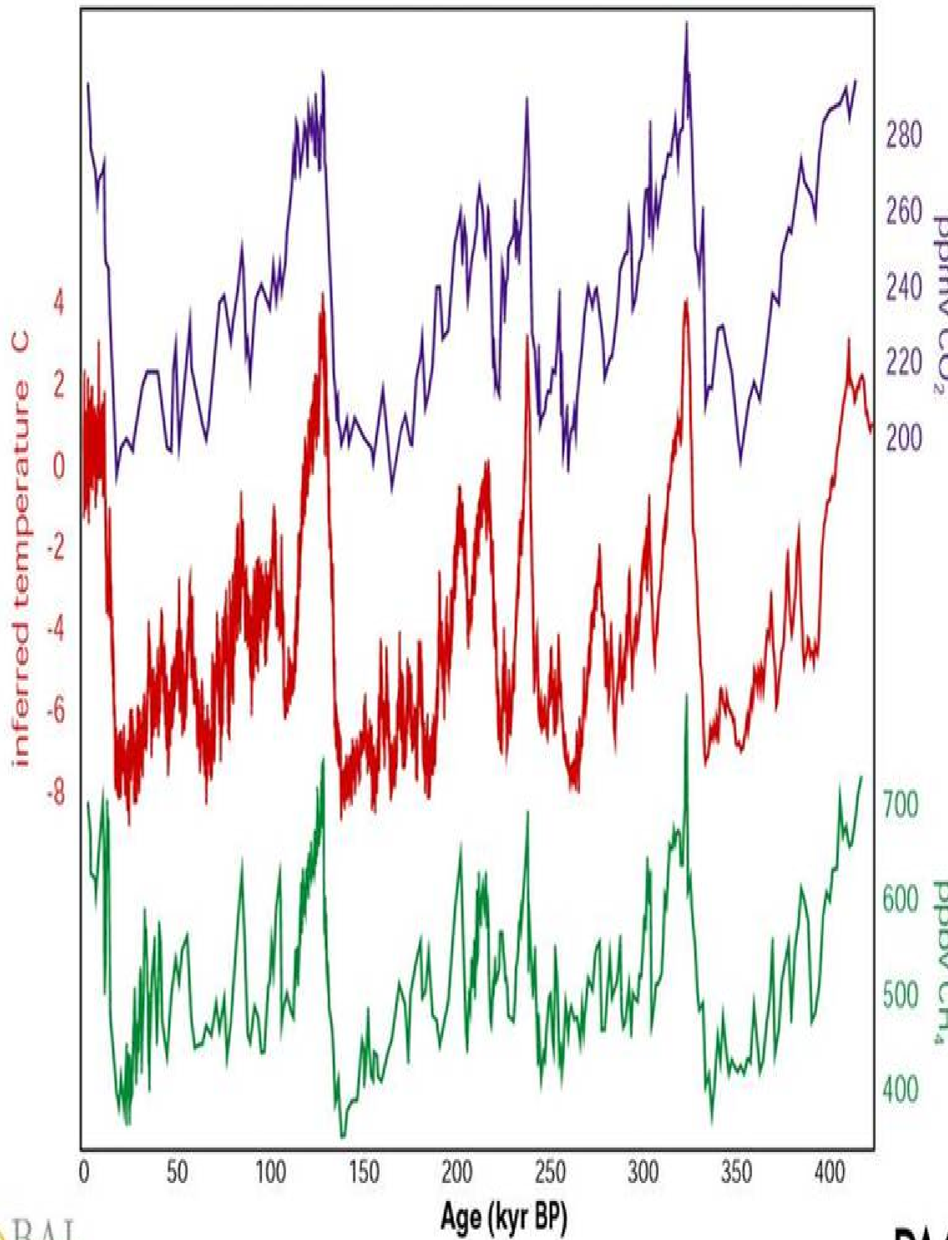


Figure SPM-10b: *From year 1000 to year 1860 variations in average surface temperature of the Northern Hemisphere are shown (corresponding data from the Southern Hemisphere not available) reconstructed from proxy data (tree rings, corals, ice cores, and historical records). The line shows the 50-year average, the grey region the 95% confidence limit in the annual data. From years 1860 to 2000 are shown variations in observations of globally and annually averaged surface temperature from the instrumental record; the line shows the decadal average. From years 2000 to 2100 projections of globally averaged surface temperature are shown for the six illustrative SRES scenarios and IS92a using a model with average climate sensitivity. The grey region marked "several models all SRES envelope" shows the range of results from the full range of 35 SRES scenarios in addition to those from a range of models with different climate sensitivities. The temperature scale is departure from the 1990 value; the scale is different from that used in Figure SPM-2. Q9 Figure 9-1b*



A1B
A1T
A1FI
A2
B1
B2
IS92e high
IS92a
IS92c low
(TAR method)
Several models all SRES envelope
Model ensemble all SRES envelope
Bars show the range in 2100 produced by several models
Temperature change (°C)
Year
0
1
2
3
4
5
6
2000
2020
2040
2060
2080
2100

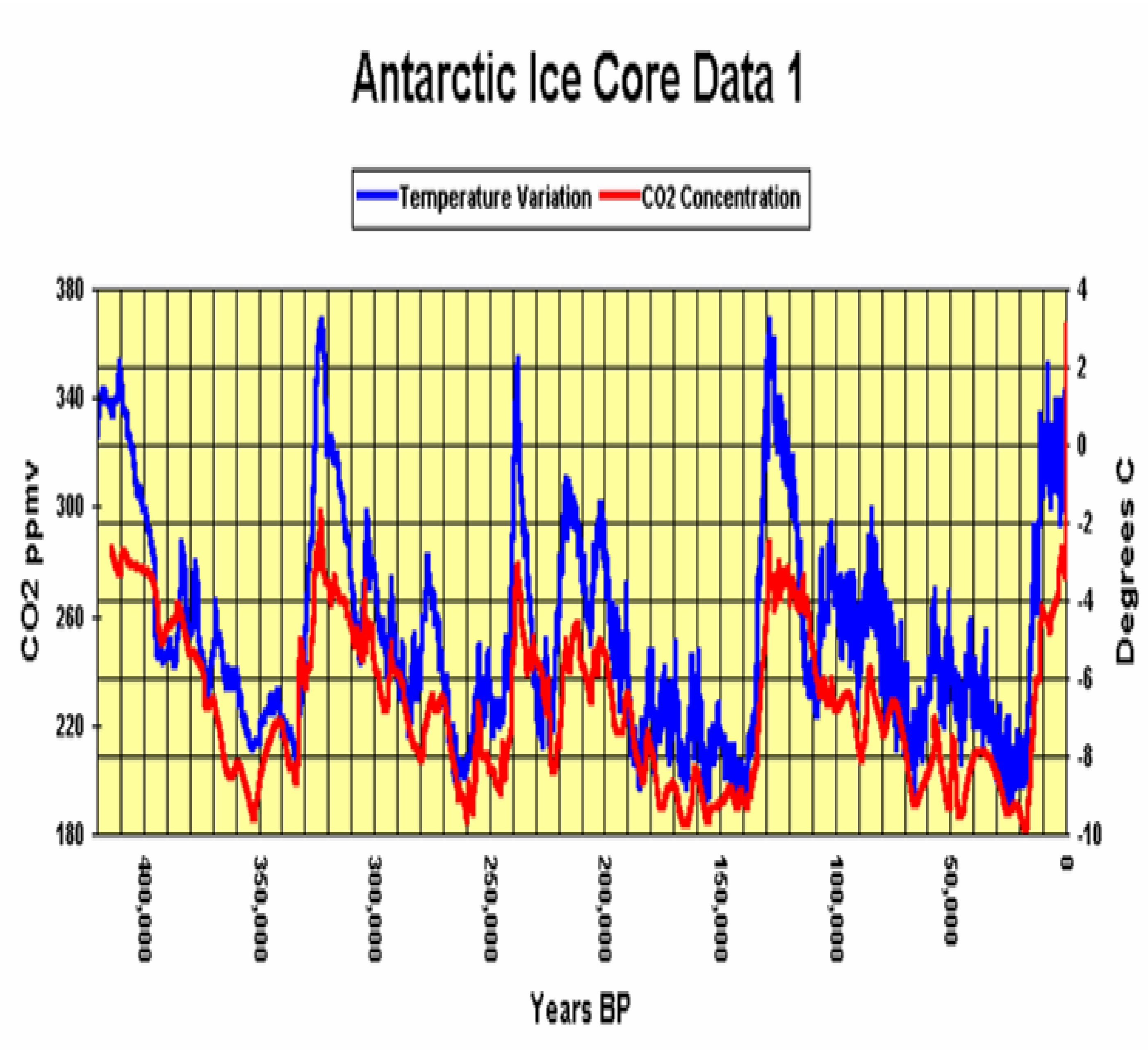
4 glacial cycles recorded in the Vostok ice core

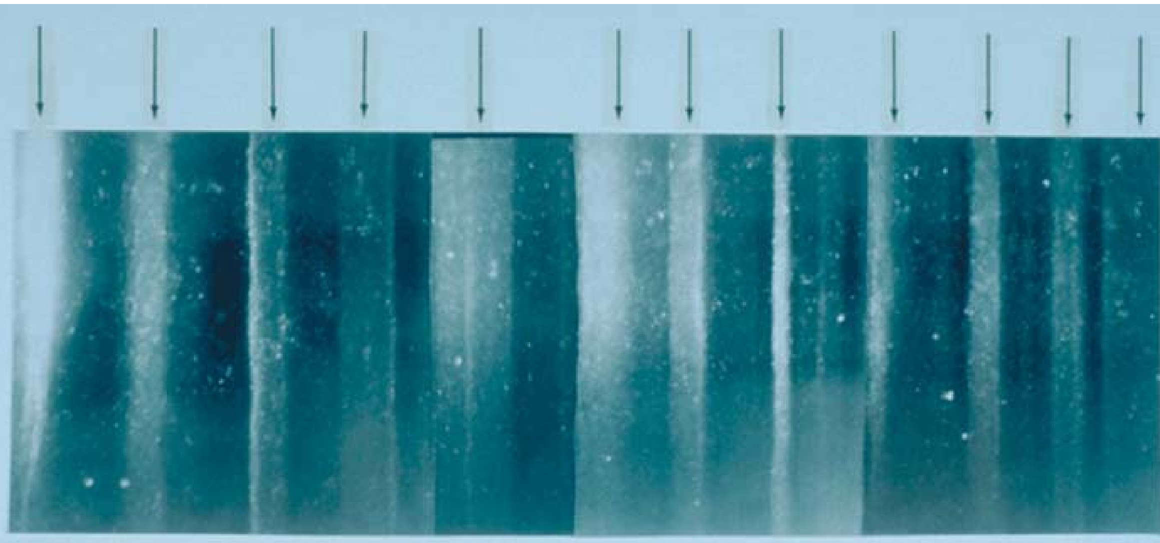


GLOBAL IGBP CHANGE

J.R. Petit et al., *Nature*, **399**, 429–36, 1999.

PAGES PAST GLOBAL CHANGES


Antarctic Ice Core Data 1
Temperature Variation
CO2 Concentration
380
340
300
260
220
180
CO2 ppmv
4
2
0
-2
-4
-6
-8
-10
Degrees C
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
Years BP



19 cm long section of GISP 2 ice core from 1855 m showing annual layer structure illuminated from below by a fiber optic source. Section contains 11 annual layers with summer layers (arrowed) sandwiched between darker winter layers.

Removal Time and Percent Contribution to Climate Forcing

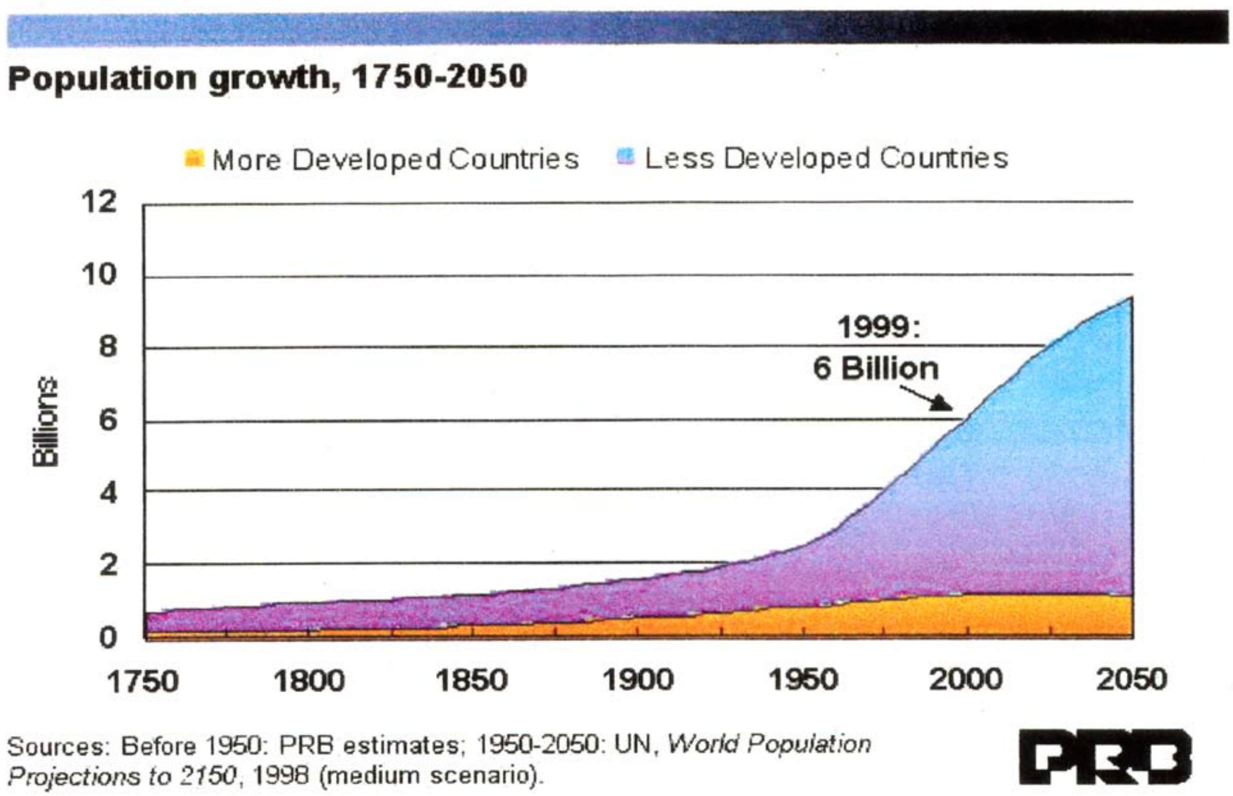
Agent	Rough Removal Time	Approximate Contribution in 2006
Carbon Dioxide	>100 years	60%
Methane	10 years	25%
Tropospheric Ozone	50 days	20%
Nitrous Oxide	100 years	5%
Fluorocarbons	>1000 years	<1%
Sulfate Aerosols	10 days	-25%
Black Carbon	10 days	+15%

Projecting Energy Requirements

$$E = P \times \left(\frac{I}{P} \right) \times \left(\frac{E}{I} \right)$$

E	=	Energy
P	=	Population
I	=	Income
I/P	=	Per Capita Income
E/I	=	Energy Intensity

World Population Growth



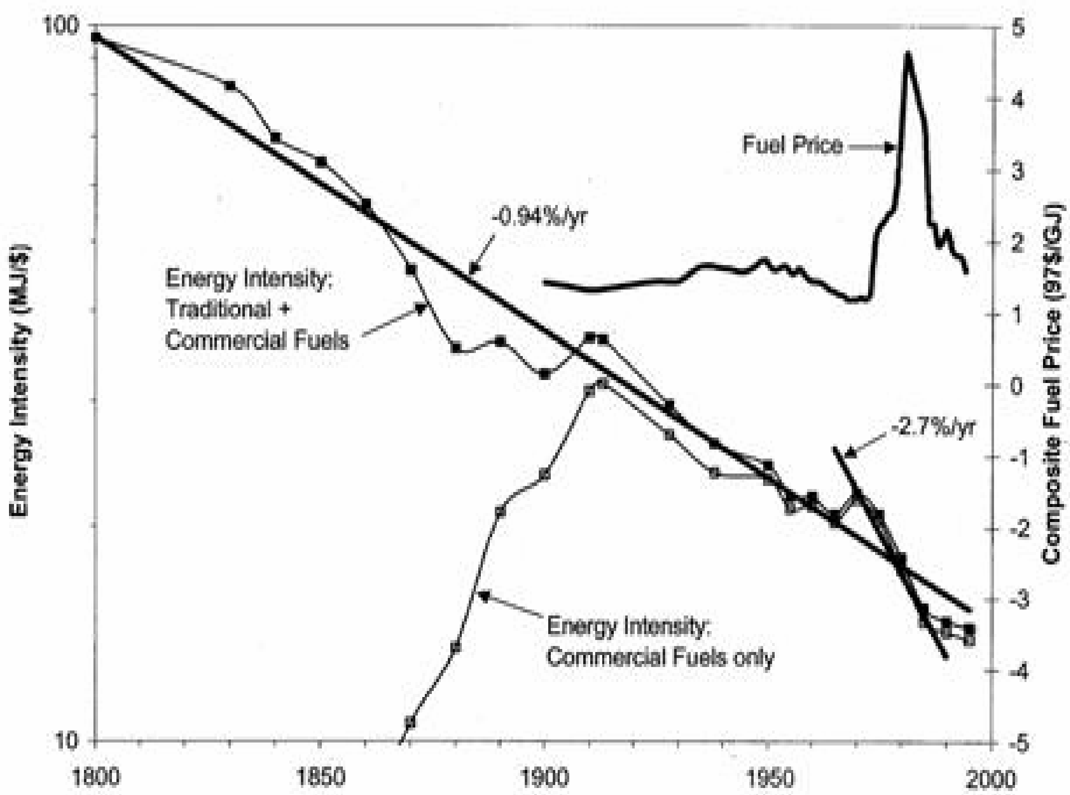
Comparison of GDP
(trillions of constant U.S. dollars)
and
Per Capita in Years 2000 and 2100
(thousands of constant U.S. dollars per person)
(IIASA Scenario B) (2002 exchange rates)

	2000		2100	
	GDP	GDP per Person	GDP	GDP per Person
Industrialized	20.3	22.2	71	70.5
Reforming	0.8	1.8	16	27.4
Developing	5.1	1.1	116	11.5
World	26.2	4.2	202	17.3

Energy Intensity
(Watt-year per dollar)
(IIASA Scenario B)

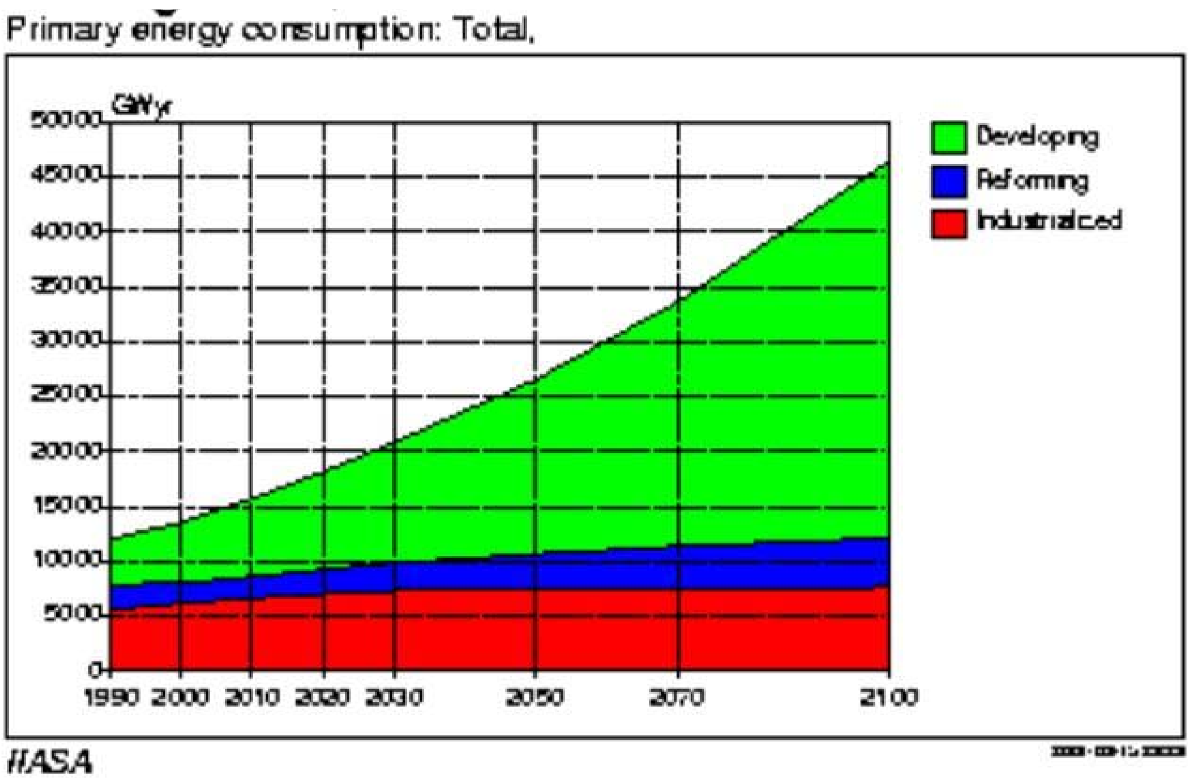
Watt-year per dollar	2000	2050	2100
Industrialized	0.30	0.18	0.11
Reforming	2.26	0.78	0.29
Developing	1.08	0.59	0.30
World	0.52	0.36	0.23

Energy Intensity and Composite Fuel Price in North America



Sources:

Three Regions, Scenario B

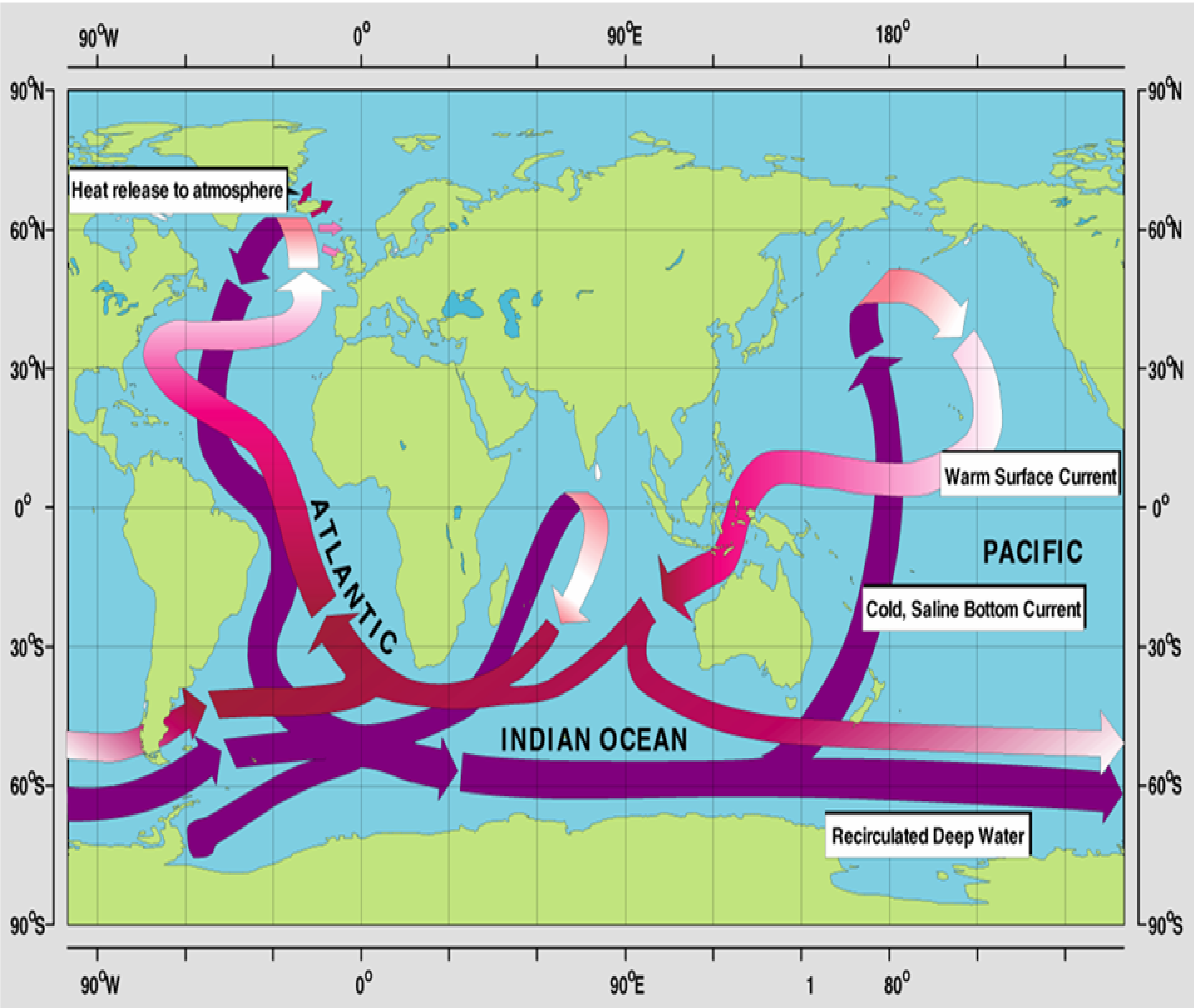


Summary

Item	2000	2050	2100
Primary Power (Terawatts)	14	27	40
Population (Billions)	6.2	8.9	9.0
Energy Intensity (Watt-years/$)	0.52	0.36	0.23

Assumptions:

1. IIASA "Scenario B" (middle growth).
2. United Nations' Population Projection (middle scenario).
3. A 1% per year decline in energy intensity is assumed (historic trend).



90°W
0°
90°E
180°
90°N
60°N
30°N
0°
30°S
60°S
90°S
Heat release to atmosphere
ATLANTIC
INDIAN OCEAN
PACIFIC
Warm Surface Current
Cold, Saline Bottom Current
Recirculated Deep Water
1
80°

Primary Power Requirements for 2050 for Scenarios Stabilizing CO_2 at 450 ppm and 550 ppm

	2000	2050	
Source		450 ppm	550 ppm
Carbon Based	11 TW	7 TW	12 TW
Carbon Free	3 TW	20 TW	15 TW

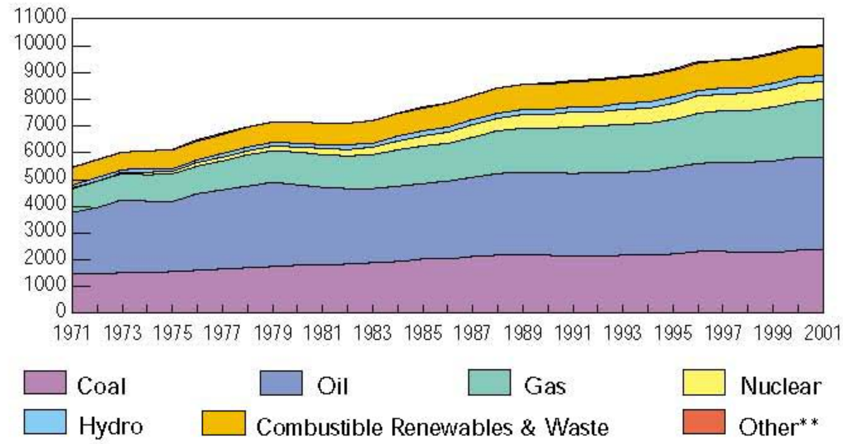
M. Hoffert, et al., Nature, 395, p881, (Oct 20, 1998)

SUPPLY

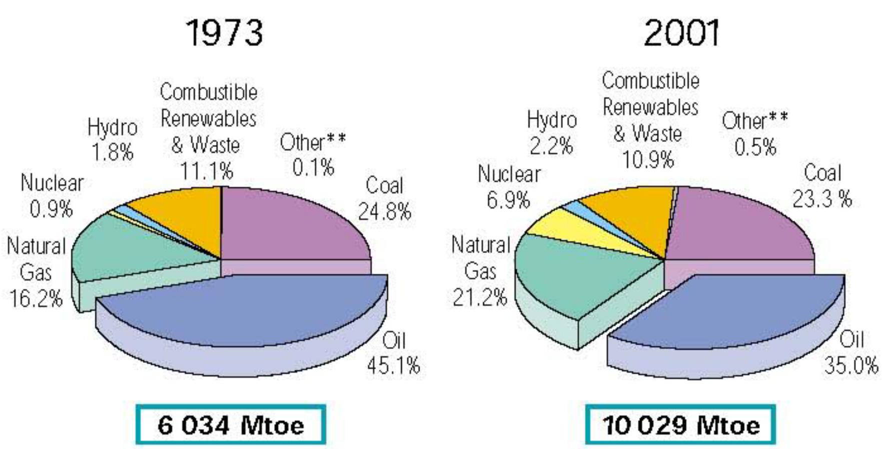
TOTAL PRIMARY ENERGY SUPPLY

The World

Evolution from 1971 to 2001 of World Total Primary Energy Supply* by Fuel (Mtoe)



1973 and 2001 Fuel Shares of TPES*



*Excludes international marine bunkers and electricity trade.
**Other includes geothermal, solar, wind, heat, etc.

Final Energy by Sector

(IIASA Scenario B)

	2000	2050	2100
Residential and Commercial	38%	31%	26%
Industry	37%	42%	51%
Transportation	25%	27%	23%
Total (TW-yr)	9.8	19.0	27.4

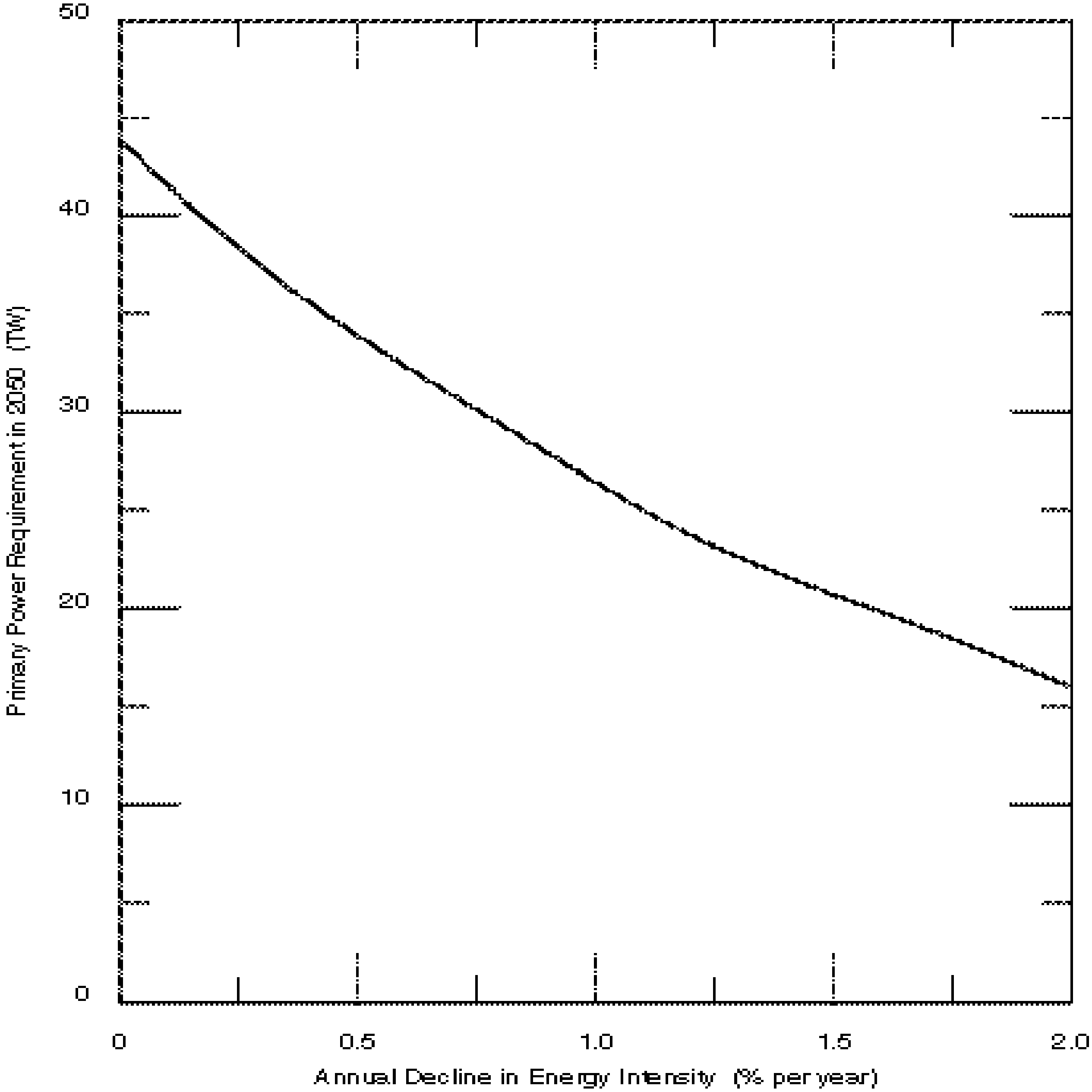
Large-Scale Energy Sources Without Greenhouse Gases

- **Conservation and Efficiency**
  - ✓ No emissions from what you don't use.
- **Fossil**
  - ✓ If CO_2 can be sequestered, it is useable.
  - ✓ Reserves of:
    - Coal are huge
    - Oil are limited
    - Gas are large (but uncertain) in Methane Hydrates.
- **Nuclear**
  - ✓ Climate change problem is reviving interest.
  - ✓ 400 plants today equivalent to about 1-TW primary.
  - ✓ Major expansion possible IF concerns about radiation, waste disposal, proliferation, can be relieved.
- **Fusion**
  - ✓ Not for at least fifty years.

Renewables

- **Geothermal**
  - ✓ Cost effective in limited regions.
- **Hydroelectric**
  - ✓ 50% of potential is used now.
- **Solar Photovoltaic and Thermal**
  - ✓ Expensive but applicable in certain areas, even without storage. Photovoltaic is $5 per peak watt now; expected to be down to $1.5 by 2020.
- **Wind**
  - ✓ Cost effective with subsidy (U.S. 1.5¢, Australia 3¢, Denmark 3¢ per kW-hr). Intermittent.
- **Biomass**
  - ✓ Two billion people use non-commercial biomass now. Things like ethanol from corn are a farm subsidy, not in energy source.
- **Hydrogen**
  - ✓ It is a storage median, not a source. Electrolysis ~85% efficient. Membrane fuel cells ~65% efficient.

Power (TW) Required in 2050 Versus Rate of Decline in Energy Intensity



4-2001
9538/1

Power (TW) Required in 2050 vs Rate of Decline in Energy Intensity

CO_2 Sequestration

- Most study has been on CO_2 injection into underground reservoirs.
- Capacity not well known

Option	Gigaton CO_2	Fraction of Integrated Emissions to 2050
Depleted Gas Fields	690	34%
Depleted Oil Fields	120	6%
Deep Saline Aquifers	400 - 10,000	20% - 500%
Unmineable Coal	40	2%

CO_2 Sequestration (Continued)

- Norway does this on a medium scale.
- Costs estimates ≈ 1– 2¢/kW-hr or ≈ \$100/ton CO_2.
- Leak rates not understood.
- DOE project FutureGen on Coal + $H_20 \rightarrow H_2 + CO_2$ with CO_2 sequestrated.
- Alternative solidification (MgO – $MgCO_2$) in an even earlier state.

Radiation Exposures

Source	Radiation Dose Millirem/year
Natural Radioactivity	240
Natural in Body (75kg)*	40
Medical (average)	60
Nuclear Plant (1GW electric)	0.004
Coal Plant (1GW electric)	0.003
Chernobyl Accident (Austria ~1988)	24
Chernobyl Accident (Austria 1996) ***Included in the Natural Total**	7

Public Health Impacts per TWh*

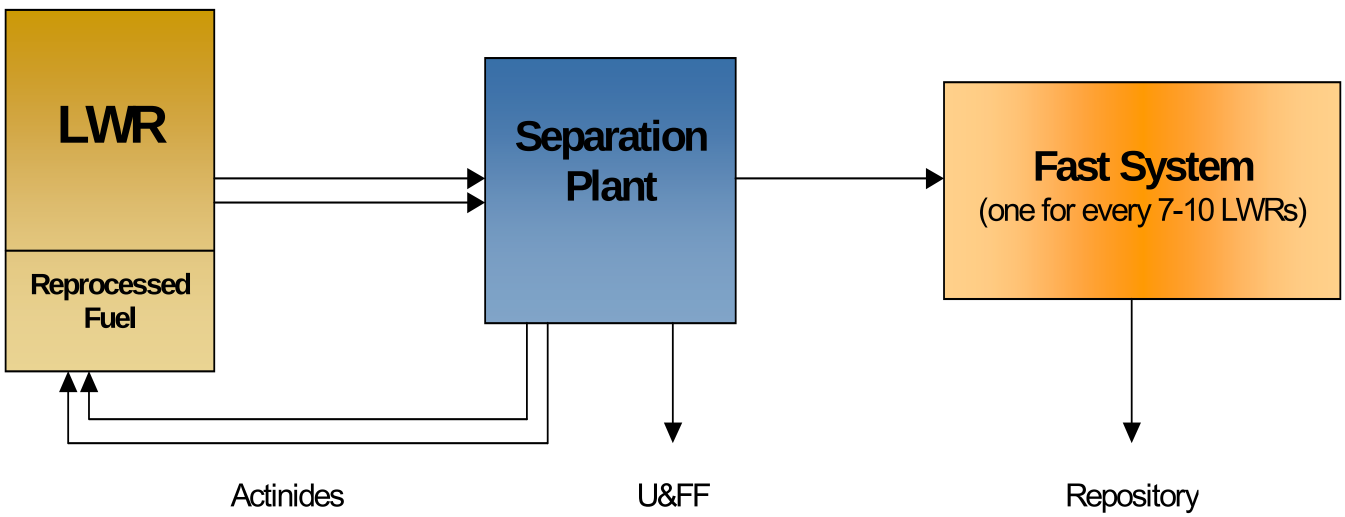
	Coal	Lignite	Oil	Gas	Nuclear	PV	Wind
Years of life lost: Nonradiological effects	138	167	359	42	9.1	58	2.7
Radiological effects: Normal operation					16		
Accidents					0.015		
Respiratory hospital admissions	0.69	0.72	1.8	0.21	0.05	0.29	0.01
Cerebrovascular hospital admissions	1.7	1.8	4.4	0.51	0.11	0.70	0.03
Congestive heart failure	0.80	0.84	2.1	0.24	0.05	0.33	0.02
Restricted activity days	4751	4976	12248	1446	314	1977	90
Days with bronchodilator usage	1303	1365	3361	397	86	543	25
Cough days in asthmatics	1492	1562	3846	454	98	621	28
Respiratory symptoms in asthmatics	693	726	1786	211	45	288	13
Chronic bronchitis in children	115	135	333	39	11	54	2.4
Chronic cough in children	148	174	428	51	14	69	3.2
Nonfatal cancer					2.4		

*Kerwitt et al., “Risk Analysis” Vol. 18, No. 4 (1998).

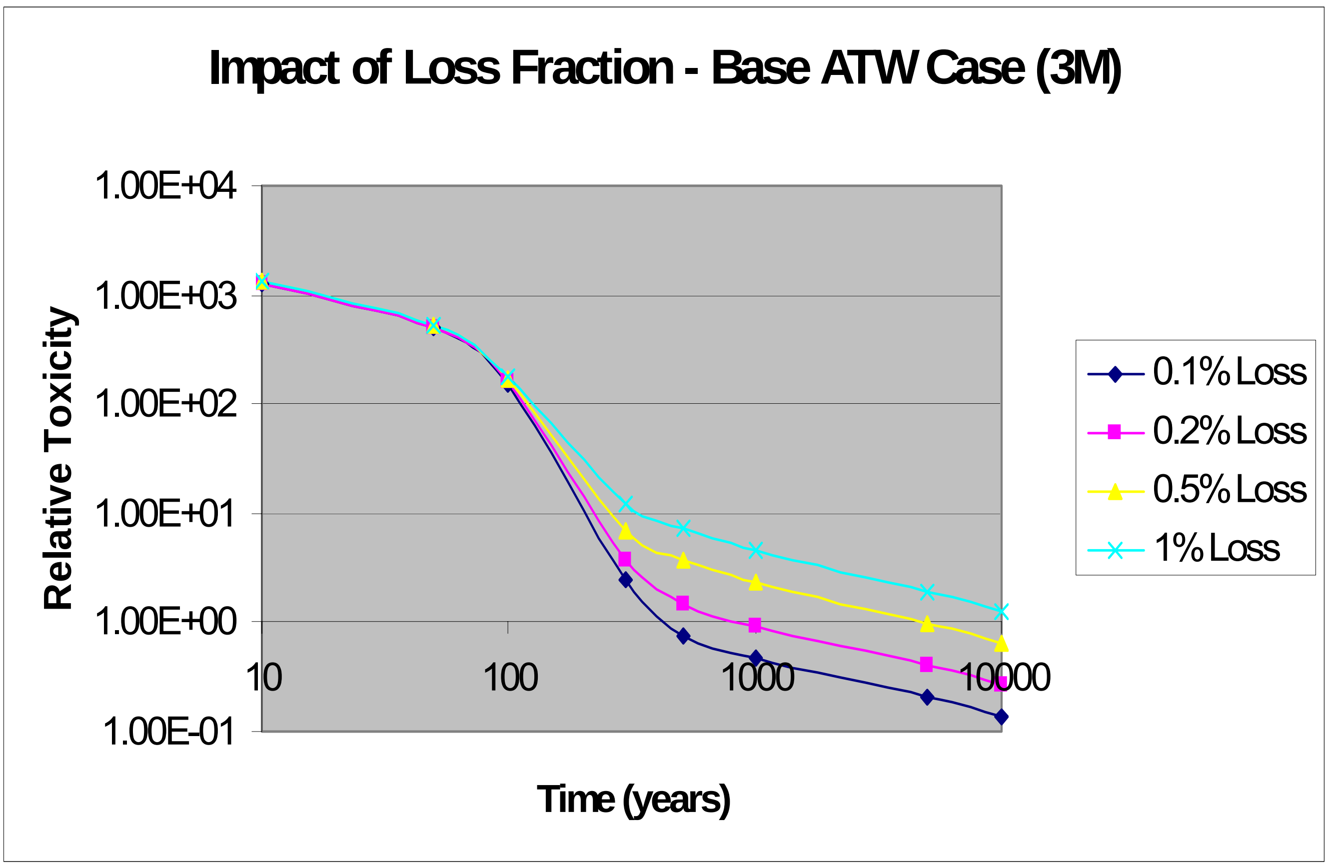
The Spent Fuel Problem

Component	Fission Fragments	Uranium	Long-Live Component
Per Cent Of Total	4	95	1
Radio-activity	Intense	Negligible	Medium
Untreated required isolation time (years)	200	0	300,000

Two-Tier Schematic



Impact of Loss Fraction



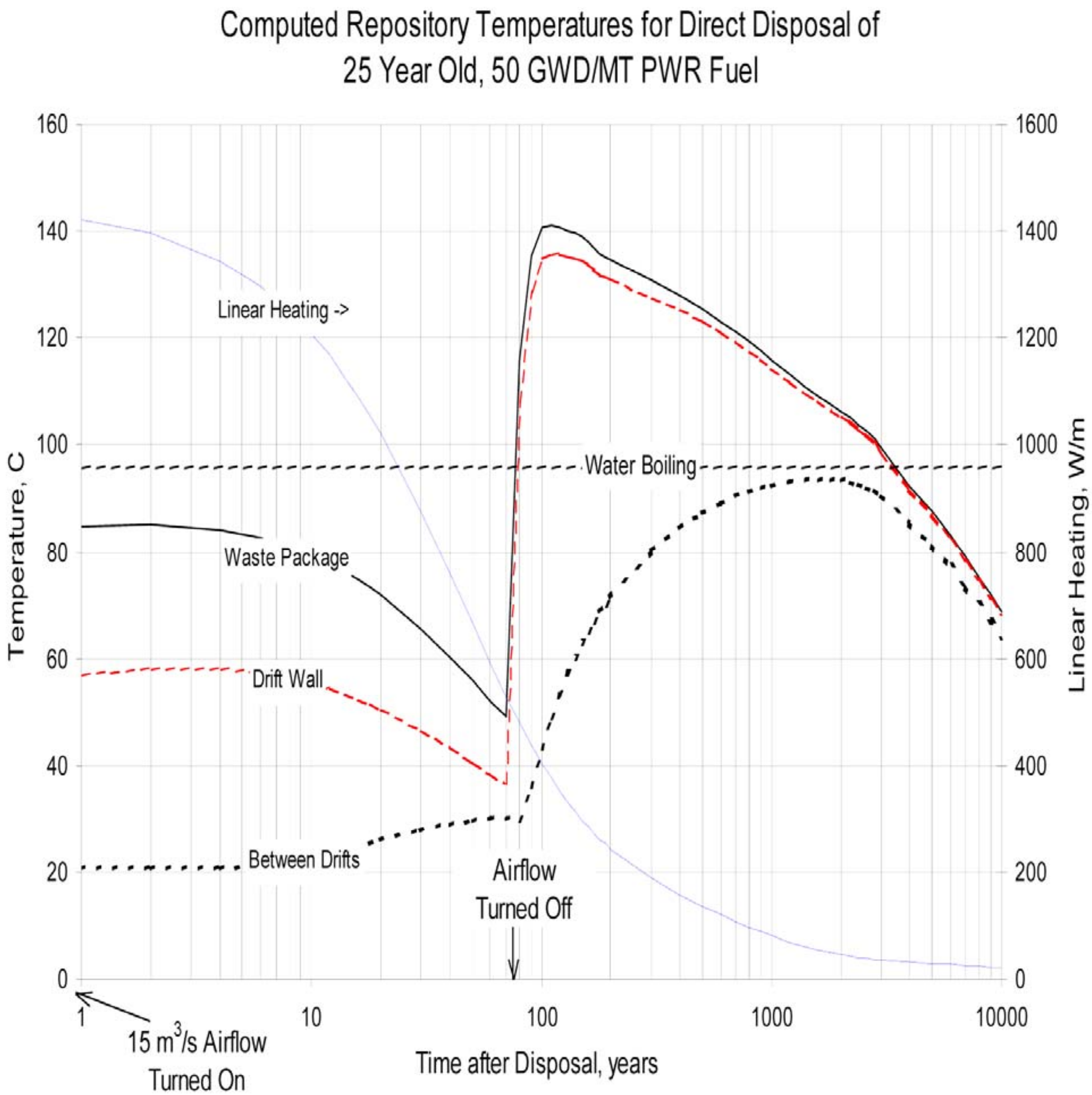
- Technical issues controlling repository capacity.
  - ✓ Tunnel wall temperature ≤ 200°C.
  - ✓ Temperature midway between adjacent tunnels ≤ 100°C.

- Fission fragments (particularly Cs and Sr) control in early days, actinides (Pu and Am) in the long term.

- Examples:
  - ✓ Removal of all fission fragments does nothing to increase capacity.
  - ✓ Removal of Cs and Sr (to separate short-term storage) and Pu and Am (to transmutation) increase capacity sixty fold.

- Note: Yucca Mountain is estimated to cost about $50 Billion to develop and fill.

Transmutation Benefits Repository Transient Thermal Response



Decay Heating of Spent Fuel

Heat generation in watts per metric ton initial heavy metal after cooling for 30 years (for all radionuclides producing more than 1 watt)

Fission Product	Watts/tIHM
Sr-90	65
Y-90	305
Cs-137	85
Ba-137m	304
Eu-154	21

Actinide	Watts/tIHM	g/t
Pu-238	116	207
Pu-239	10	5000
Pu-240	15	2200
Pu-241	2	438
Am-241	159	1390
Am-243	4	537
Cm-243	2	1
Cm-244	179	63

Half-lives

Y-90: 64 hours

Ba-137m: 2.6 minutes

12

Pioneering Science and Technology

Office of Nuclear Energy, Science and Technology U.S. Department of Energy

Proliferation

- The "spent fuel standard" is a weak reed. Repositories become potential Pu mines in about 100-150 years.
- For governments, the only barrier to "going nuclear" is international agreements.
- Reprocessed material is difficult to turn into weapons and harder to divert.

Isotope	Isotopic Percentage		
	LWR	MOX	Non-fertile Pu
Pu 238	2	4	9
Pu 239	60	41	8
Pu 240	24	34	38
Pu 241	9	11	17
Pu 242	5	9	27

Costs

- The report, "Nuclear Waste Fund Fee Adequacy: An Assessment, May 2001, DOE/RW-0534" concludes 0.1¢ per kW-hr remains about right for nuclear waste disposal.

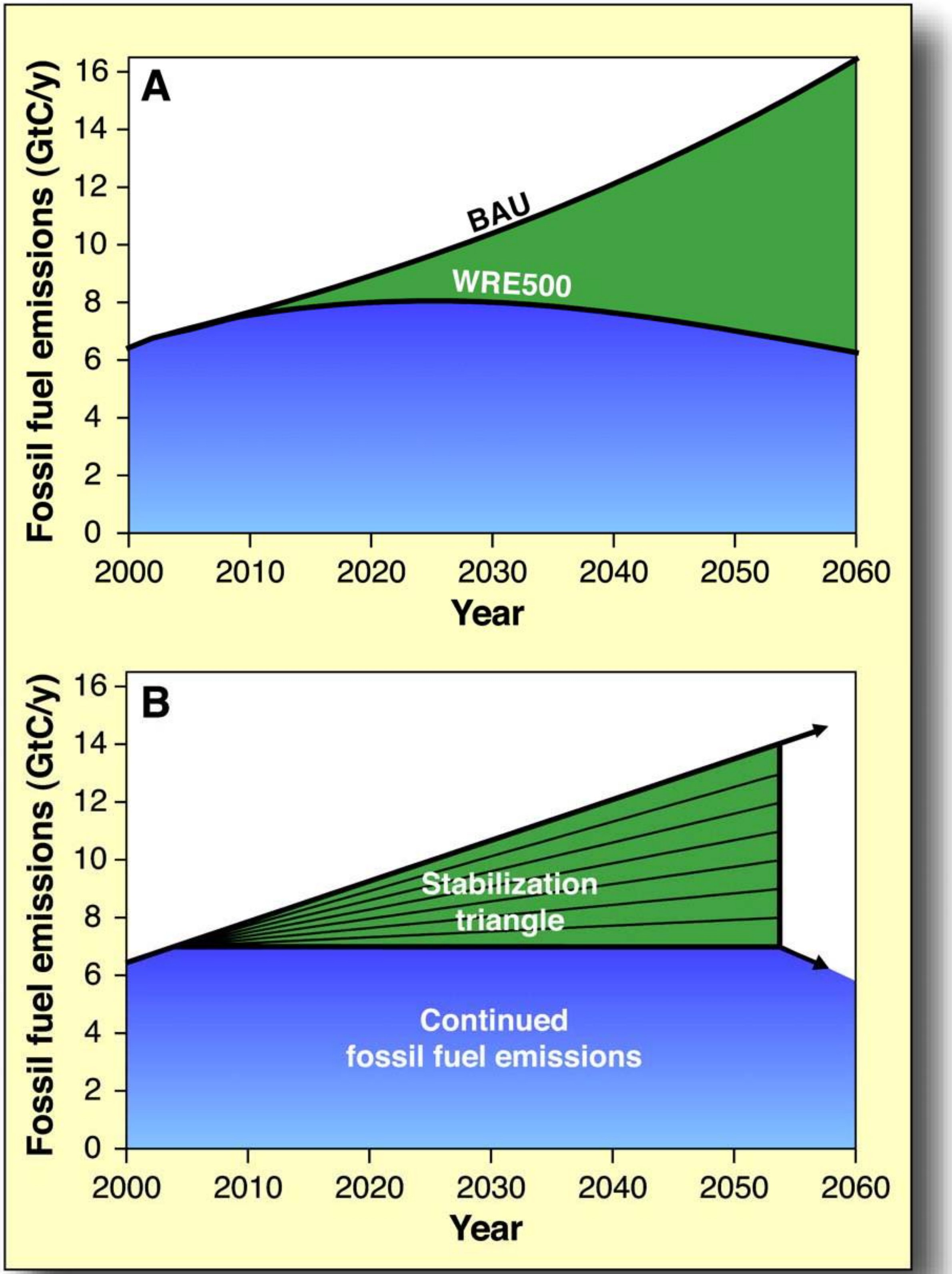
- CO-2 sequestration is estimated to cost 1-1.5¢ per kW-hr for gas-fired plants and 2-3¢ per kW-hr for coal-fired plants (Freund & Davison, *General Overview of Costs*, Proceedings of the Workshop on Carbon Dioxide Capture and Storage, http://arch.rivm.nl/env/int/ipcc/ccs2002.html).

Modified MIT Study Table

Item	**Power Costs (cents per kWe-hr)**		
	Nuclear	**Coal**	**Gas**
Capital & Operation	4.1 – 6.6	4.2	3.8 – 5.6
Waste Sequestration	0.1	2 – 3	1 – 1.5
Total	**4.2 – 6.7**	**6.2 – 7.2**	**4.8 – 7.1**

Conclusions and Recommendations

- Energy use will expand.
- There is no quick fix.
- A goal needs to be set.
- Driving down energy intensity should be first on the list of action items.
- Emissions trading and reforestation should be encouraged.
- Nuclear Power should be expanded.
- Bringing the renewables to maturity should be funded.
- Financial incentives and penalties need to be put in place.


A
Fossil fuel emissions (GtC/y)
16
14
12
10
8
6
4
2
0
BAU
WRE500
2000
2010
2020
2030
2040
2050
2060
Year
B
Fossil fuel emissions (GtC/y)
16
14
12
10
8
6
4
2
0
Stabilization
triangle
Continued
fossil fuel emissions
2000
2010
2020
2030
2040
2050
2060
Year

Energy and Environment Web Sites of Interest

- EPA's global warming resource center – an annotated list of resources
  http://yosemite.epa.gov/oar/globalwarming.nsf/content/ResourceCenterResourceGuide.html
- Department of Energy's Energy Information Administration – mostly energy information about the US with some international. http://www.eia.doe.gov/
- International Energy Agency's statistics home page – statistics by region, country fuel, etc. (IEA home page is http://www.iea.org/) – they have a particularly interesting new report on "Biofuels for Transport"
  http://www.iea.org/dbtw-wpd/Textbase/stats/index.asp
- World Energy Outlook 2004 – an update of long range projections due out at the end of October 2004 (many university libraries are subscribers to IEA publications and you may be able to down load this free). http://www.worldenergyoutlook.org/
- International Institute of Applied Systems Analysis and World Energy Council long range projection – this is from 1998 but remains particularly useful in allowing the user to chose different assumptions and see what happens.
  http://www.iiasa.ac.at/cgi-bin/ecs/book_dyn/bookcnt.py
- IIASA home http://www.iiasa.ac.at/
- Intergovernmental Panel on Climate Change – the international group responsible for projection on climate change under different scenarios. Their workshops address specific issues and are the source of much valuable information. http://www.ipcc.ch/
- Nuclear Energy Agency – an arm of the OECD on nuclear issues. http://www.nea.fr/
- US Climate Change Information Center – the latest report on the US program. http://www.climatescience.gov/