THE 21st CENTURY

RISE OF NUCLEAR POWER

PHYSOR-2004

The Physics of Fuel Cycles
And Advanced Nuclear Systems

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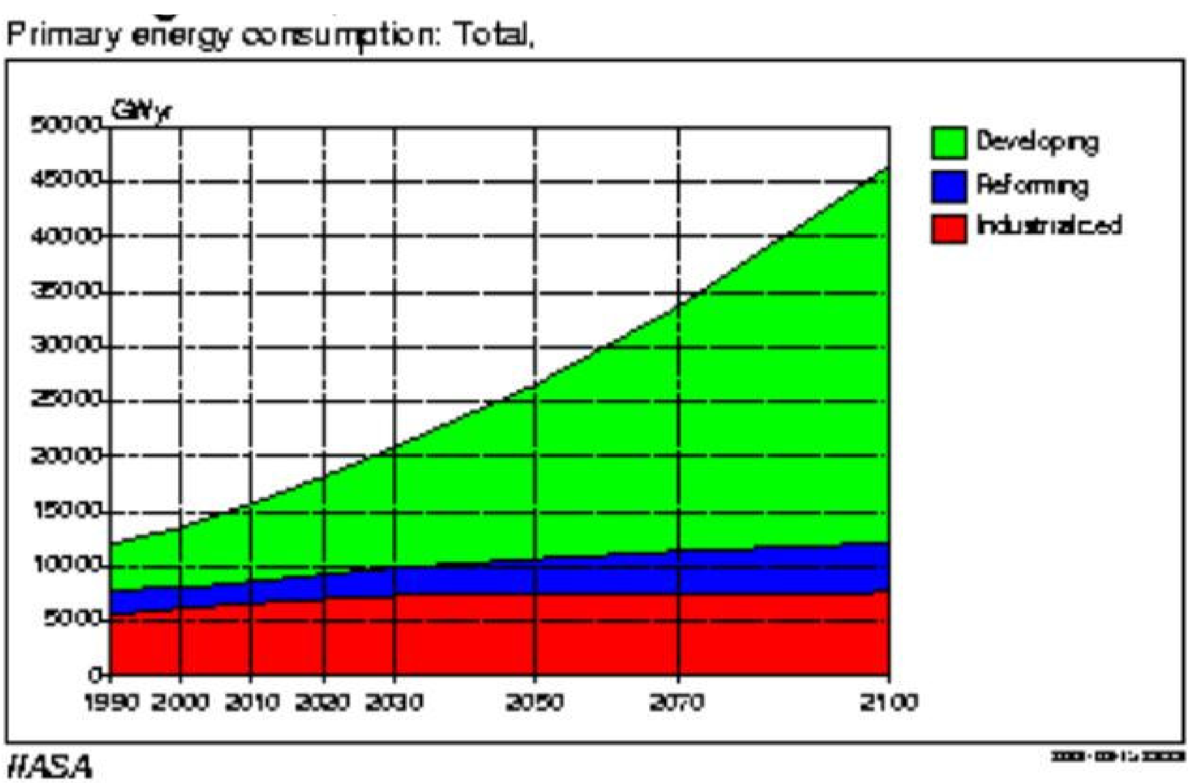
Outline

- Energy Forecasts:
  - How they are done.
- Climate Change:
  - What can we predict.
- Energy Supply:
  - Options for the future.
- Nuclear:
  - Issues and possible resolution
- Summary

Three Regions, Scenario B

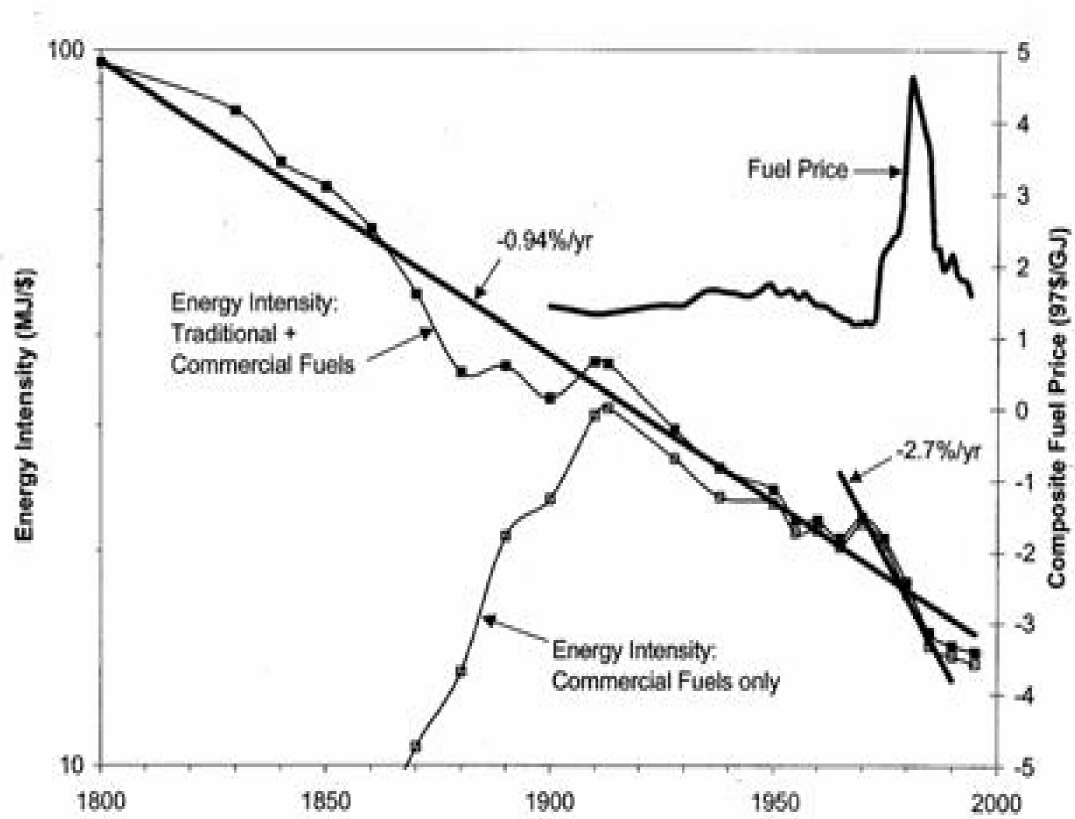


Projecting Energy Requirements

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

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

Energy Intensity and Composite Fuel Price in North America



Climate Change 2001: Synthesis Report

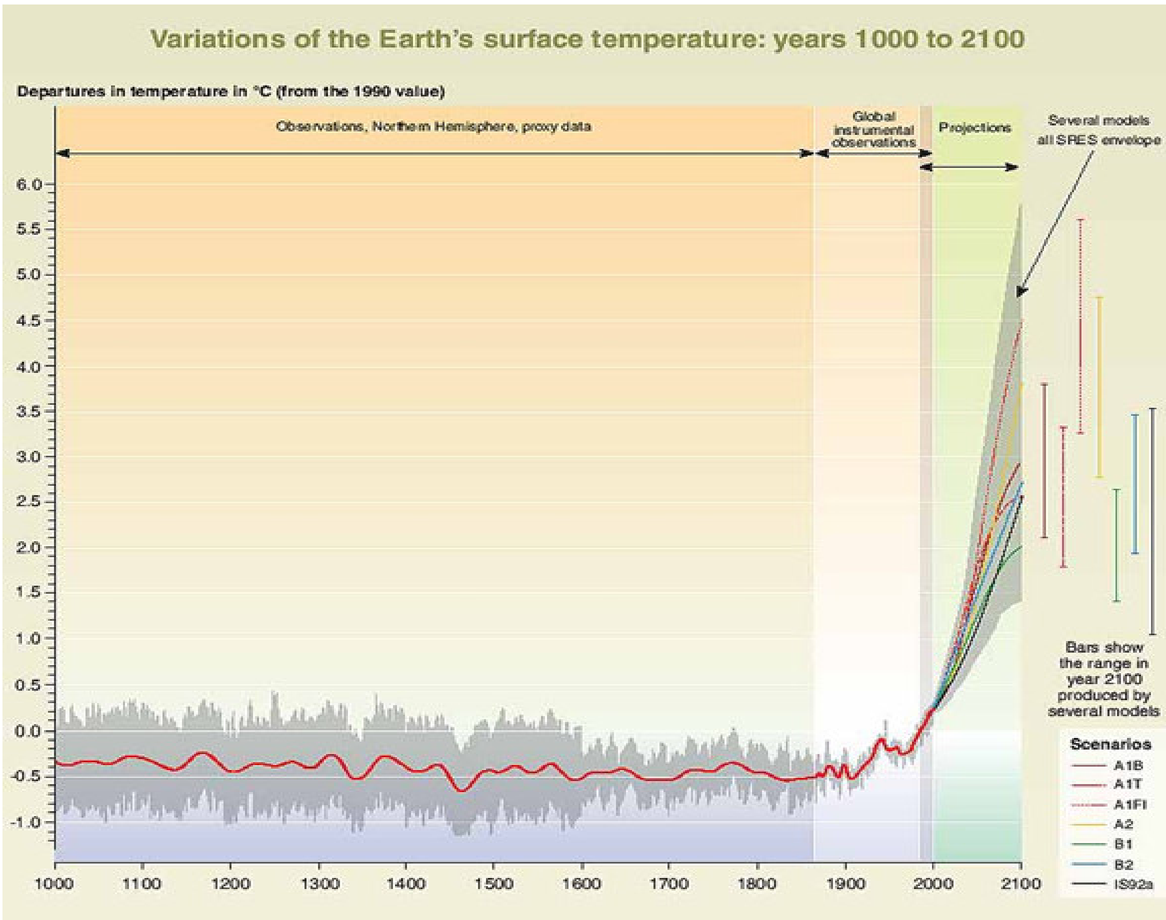
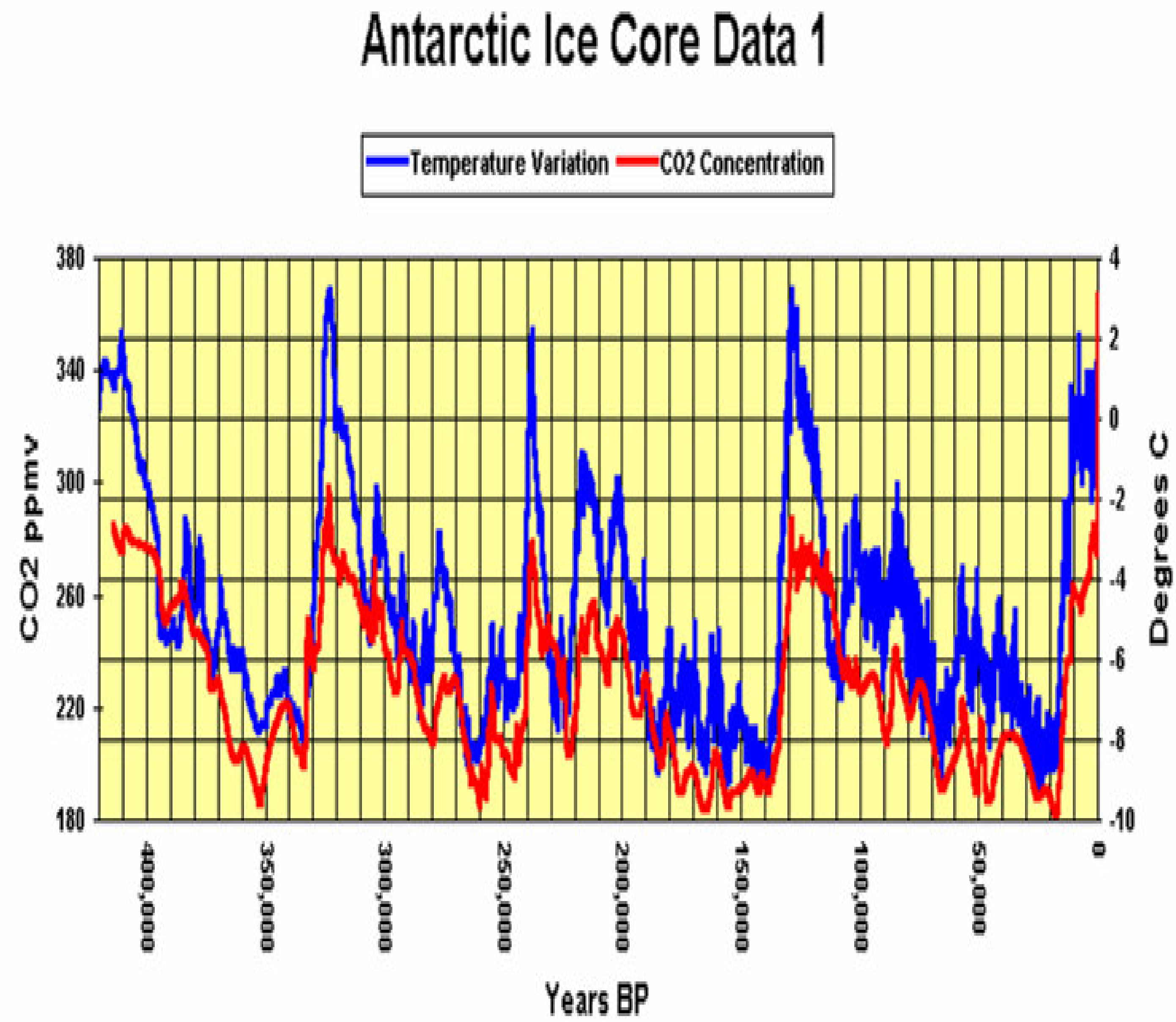


Figure SPM-10b: *From year 1000 to year 1860 variations in average surface temperature of the Northern Hemisphere are shown (corresponding data from the Southern Hemisphere not available) reconstructed from proxy data (tree rings, corals, ice cores, and historical records). The line shows the 50-year 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*

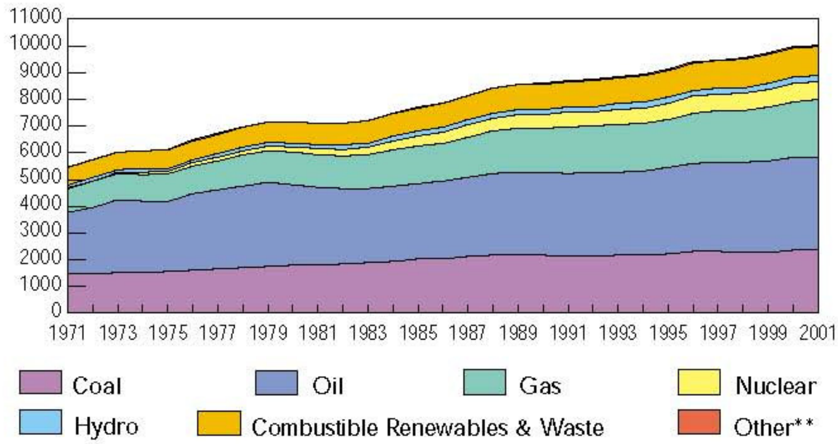


Antarctic Ice Core Data 1
Temperature Variation
CO2 Concentration
380
340
300
260
220
180
CO2 ppmv
4
2
0
-2
-4
-6
-8
-10
Degrees C
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
Years BP

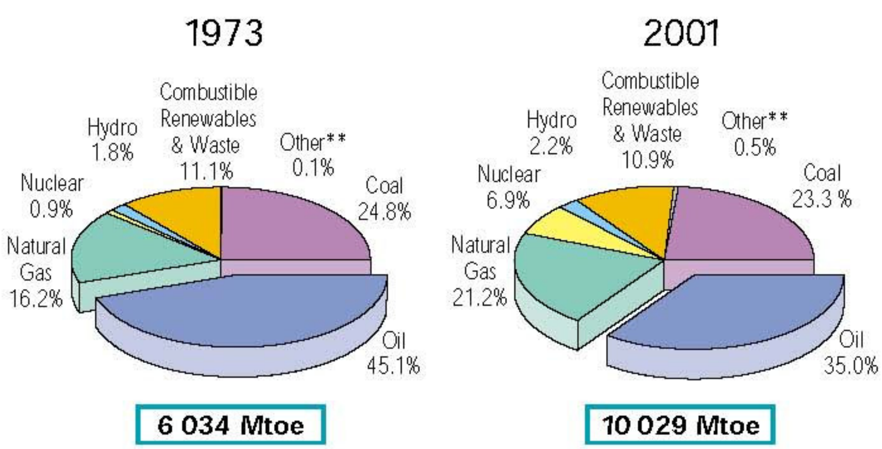
TOTAL PRIMARY ENERGY SUPPLY

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.*

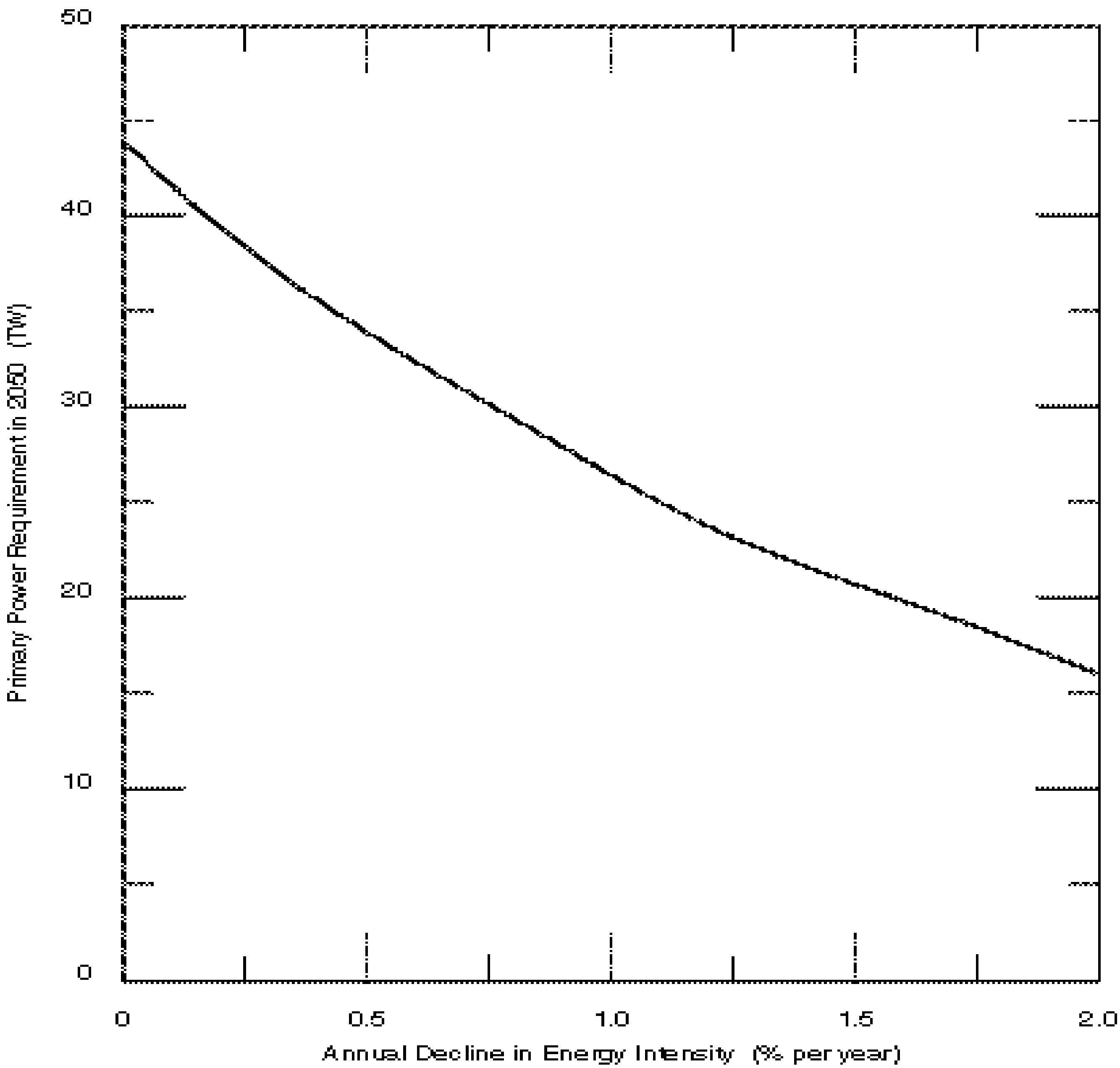
Final Energy by Sector
(IIASA Scenario B)

	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.

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



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

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.

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*

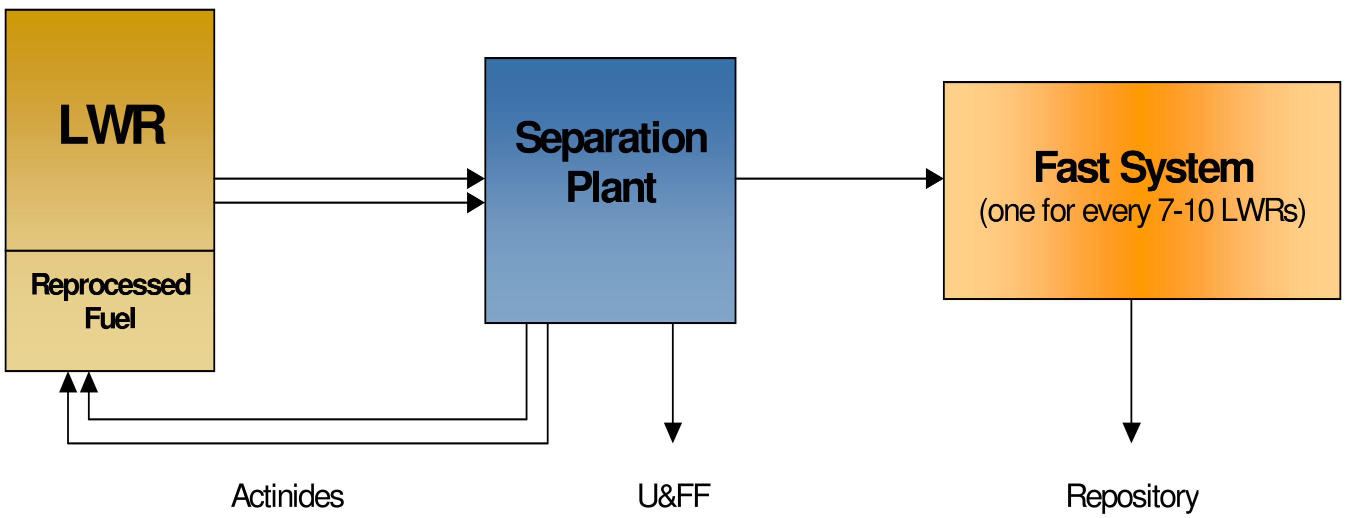
	Coal	Lignite	Oil	Gas	**Nuclear**	PV	Wind
Years of life lost: Nonradiological effects	138	167	359	42	**9.1**	58	2.7
Radiological effects: Normal operation					**16**		
Accidents					**0.015**		
Respiratory hospital admissions	0.69	0.72	1.8	0.21	**0.05**	0.29	0.01
Cerebrovascular hospital admissions	1.7	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).

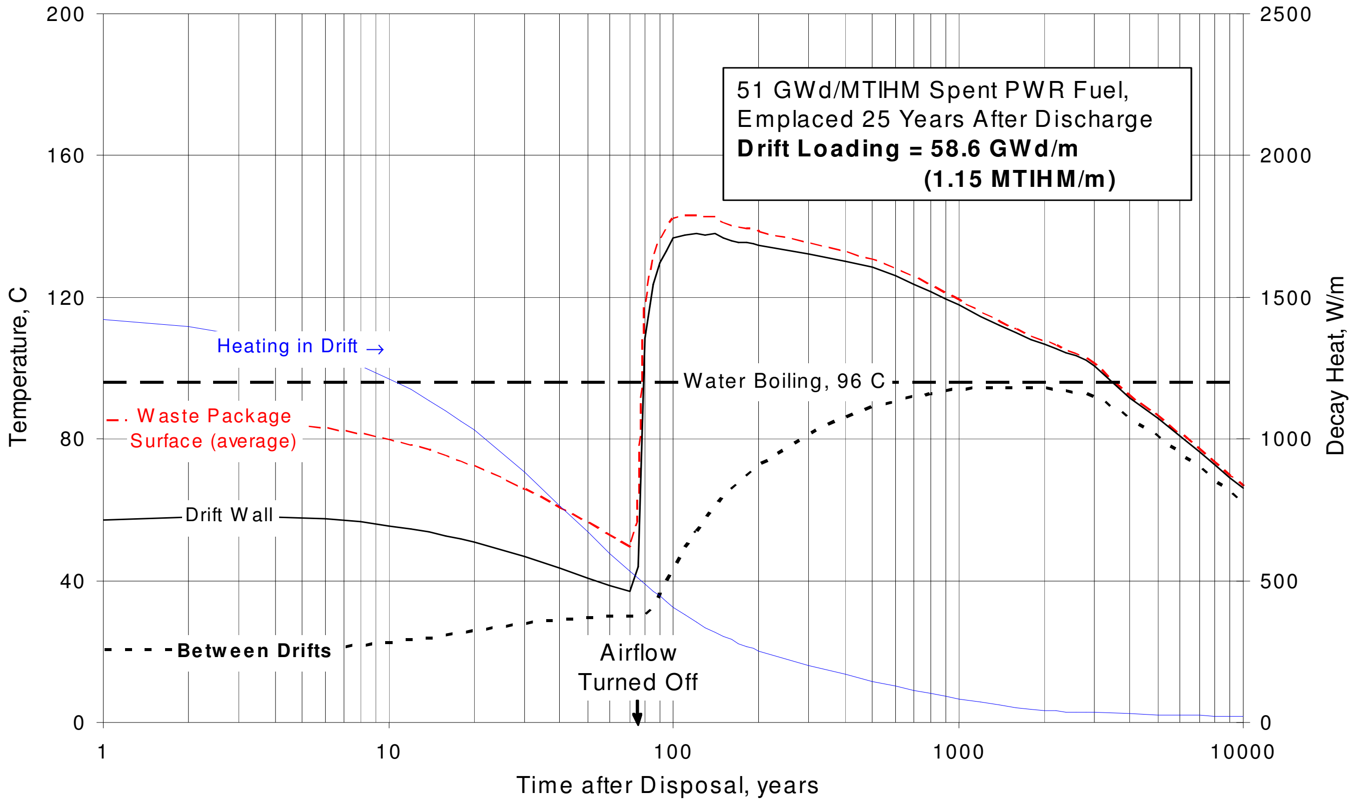
The Spent Fuel Problem

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



Transient thermal response of a repository at Yucca Mountain for reference loading conditions of SNF and 75 years of forced ventilation.



Repository Requirements in the U.S. by 2100*

Nuclear Futures	Legal Limit	Extended License for Current Reactors	Continued Constant Energy Generation	Constant Market Share	Growing Market Share
Total Discharged Fuel by 2100, MTHM	63,000	120,000	240,000	600,000	1,300,000
Repositories needed with current approach	1	2	4	9	21
Repository with expanded capacity		1	2	5	11
With thermal recycle only			1	2	5
With thermal and fast					1

*Adapted from Reference 2.

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**

Conclusion

- Nuclear is a necessary large-scale part of the world energy portfolio for the foreseeable future.

- Nuclear is safe with a rigorous and cooperative regulatory culture.

- Properly structured geological repositories are effective.

Conclusion (continued)

- Transmutation can reduce the isolation time required for nuclear waste and increase the capacity of **any** given repository.

- The proliferation issue has to be addressed honestly.

- When externalities are factored in, nuclear is the low-cost option.

Recommendations

1. Re-analyze the proliferation potential of spent fuel **after** one or more recycles of actinides.

2. We have had an international GEN-IV program.

Can we begin an international T-1(transmutation)?