

~~Makes Folly here as info to
summarize exploitation of oil~~

So, how much have we used and how much is left?

Consumption best viewed in context of energy use as a whole.

Units — simplest to convert everything to energy units.

Some conversion factors are handy:

1 BTU = energy required to raise one pound of water 1°F — quart

$$1 \text{ BTU} = 1055 \text{ J}$$

$$1 \text{ quad} = 1 \text{ quadrillion BTU}$$

$$= 10^{15} \text{ BTU} = 1.055 \text{ EJ}$$

exajoule

unit commonly used for global accounting

$$= 1.055 \cdot 10^{18} \text{ J}$$

$$\approx 1 \text{ EJ}$$

oils differ but we adopt a nominal average



$$1 \text{ bl oil (upon burning)} = 5.8 \text{ MBTU} = 6.1 \text{ GJ}$$

$$1 \text{ bbo} \approx 6 \text{ quads}$$

10^{1/2}



To make matters more confusing:

Natural gas resources measured in

tcf = trillions of cubic ft!

$$1000 \text{ cu ft} = 1 \text{ MBTU} = 1 \text{ GJ}$$

so $1 \text{ tcf} = 1 \text{ quad}$

Finally, coal ~~consumption is~~ ^{consumption is} measured
in tons

$$1 \text{ Gt} = ~~27.8~~ 27.8 \text{ quads}$$

A typical electrical power plant has
~~capacity~~ a full capacity of $\sim 1 \text{ GW}$

Typically, operate at \sim ~~60%~~ 60%
capacity, producing $\sim 0.6 \text{ GW}$

World consumption currently (1996)

350 ~~quads~~ quads/yr \leftarrow 87% fossil fuel

Increasing at 2.7% / year — almost
twice (1.7 times) as fast as
world population

NPGL = natural gas pressurized liquid (propane, etc.)

One more source of confusion - utility companies charge by the kilowatt-hr

1 kWh = 3.6 MJ = 3412 BTU

So 1 barrel oil produces 1700 kWh

A coal-burning power plant requires ~ 10,000 BTU to produce 1 kWh
=> efficiency of electrical conversion about 33%

~~about 33%~~

Current US consumption rate 82 quads/yr

Fossil fuels ~ 95%

Coal & nuclear are the fastest growing

World consumption rate ~ 350 quads/yr
~~this in 1992 - now 350 quads/yr~~

oil 21 bbl/yr = 120 quads/yr
137 in 1992

~~oil 21 bbl/yr = 120 quads/yr~~

Coal 2.7 Gt/yr = 75 quads/yr
88 in 1992

gas 60 tcf/yr = 60 quads/yr
74 in 1992

not same as Fig. 8.31 (1992)

Problems :

- How does fossil fuel consumption compare to food consumption?

fossil fuel

$$\left(\cancel{350} \cdot 10^{18} \text{ J} \right) \left(\cancel{8500} \text{ fossil fuel} \right)$$

~~3.5e20 J/yr~~

$$3 \cdot 10^{20} \text{ J/yr}$$

this is $10^{13} \text{ W} \approx \frac{1}{4} \times \text{heat flow from } \oplus$

- food

$$(2700 \text{ kcal/day}) (365 \text{ days/yr})$$

$$\times (4184 \text{ J/kcal}) \left(\cancel{57} \cdot 10^9 \text{ people} \right)$$

$$= 2.4 \cdot 10^{19} \text{ J/yr} = 8 \cdot 10^{11} \text{ W}$$

~~10~~¹² times as much fossil fuel (nonrenewable) as food (renewable)

terrestrial NPP is $8 \cdot 10^{13} \text{ W}$

NPP is
~ twice
x heat flow
from \oplus so
fossil fuel

This makes sense : fossil fuel consumption release $\underline{6 \text{ Gt C/yr}}$ into atmosphere

This ~~1000~~^{12%} of NPP and human food consumption is about 1% of NPP
↑ terrestrial

~~consumption~~
is $\sim \frac{1}{8}$ NPP - checks →

Great inequities —

US: 5% of population
20% of energy consumption

China: 20% of population
< 10% of energy

per capita
US = 8x China

US oil "production" (funny word — nature produced it)

18 ~~quads~~ quads/yr

Consumption 33 quads/yr
24% of world total

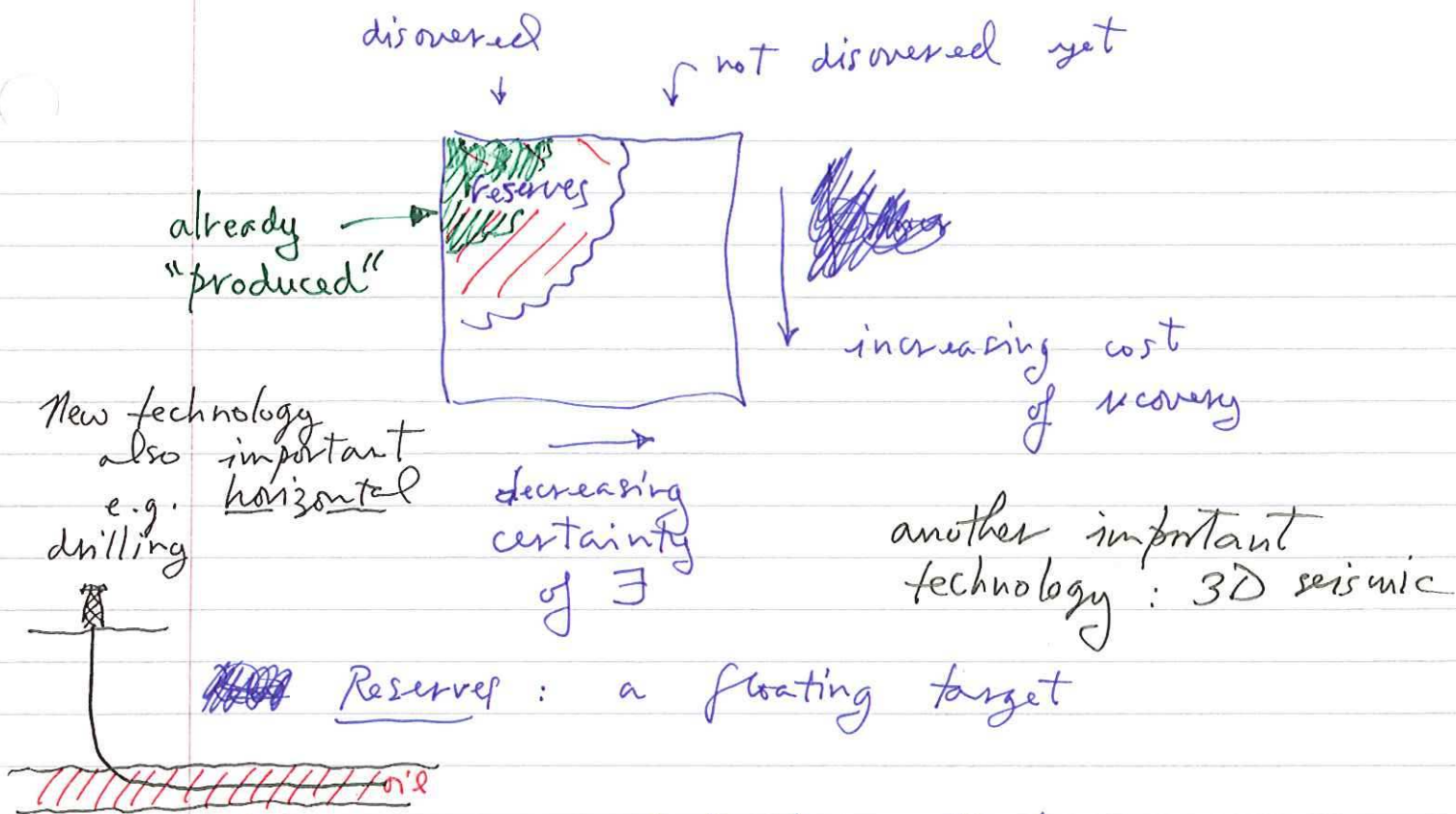
Produces only ~ half of what it
consumes.

So, how much is left?

Very difficult to estimate — not a
strictly scientific question

As with any nonrenewable resource:

~~increasing~~
~~increasing~~
~~certainty of~~



US reserves relatively well known (well explored) but small

Original	226	bbbl	
Already consumed	142	bbbl	
Remaining	84		
Estimated undiscovered	46		} 130 total ↑ 2 estimates

Have consumed ~~oil~~ ~ 3/4 of all pumpable oil in ground in US since time of Drake's folly — 130 years ago

in Holland & Petersen say ~ 155 bbl

World reserves more uncertain

About ~~1000 bbl~~ 1200 bbl — out of 1900 original

About 3/4 of known reserves in the Middle East — reason for US interest in political & economic stability of this region

Total reserves, including undiscovered, could be up to 2000 bbl = 12,000 quads

Current production 20 bbl / ~~yr~~ ⇒

About 100 more years

But remember that consumption is increasing at 3% per year

World reserves of natural gas: ~~1000~~

World-wide 8100 tcf = 8100 quads

Also about 100 years supply at current rates

Coal: even greater reserves

US richest in this case

Fig 8.37 adds to 1100 ~~1000~~ Gt but could be as high as 3000 Gt

some estimates of "ultimately recoverable" coal as high as 6700 Gt

3000 Gt coal = 80,000 quads

↑ Bodansky says 10,000 - 12,000 quads

Most coal in Russia, US, China
(in that order)

15

At current consumption rate will last

$$\frac{3000}{5.2} = \underline{500-600 \text{ years}}$$

~~But, however~~

~~3000 years~~

For US alone ($\sim 1/4 - 1/5$ of world supply)

Proven reserves

$$\frac{276 \text{ Gt}}{0.9 \text{ Gt/yr}} \sim \frac{300}{\cancel{100}} \text{ years}$$

Subeconomic sources — petroleum
that has not been cooked
enough to be pumped.

Too viscous, or may be trapped in
original impermeable shale source rock.

Tar sands, oil shales, heavy oils

New extraction techniques required

But reserves are huge.

Current production rates miniscule
because of expense.

But will become more important in future

Estimates vary — but maybe as high as

~~10,000~~ ^{20,000} bbl oil equivalent

This ~~10 times~~ ^{10 times} times as much as pumpable oil = ~~10,000~~ ^{120,000} quads

Total remaining — all sources:

oil	12,000	quads	
gas	8,000	quads	
coal	80,000	quads	← some say its
other	120,000	quads	4x this
<hr/>			
	220,000	quads	

Current consumption rate

350 quads/yr \Rightarrow ~~370~~ ⁶⁰⁰ years

So — the bottom line — are we about to run out of fossil fuel energy?

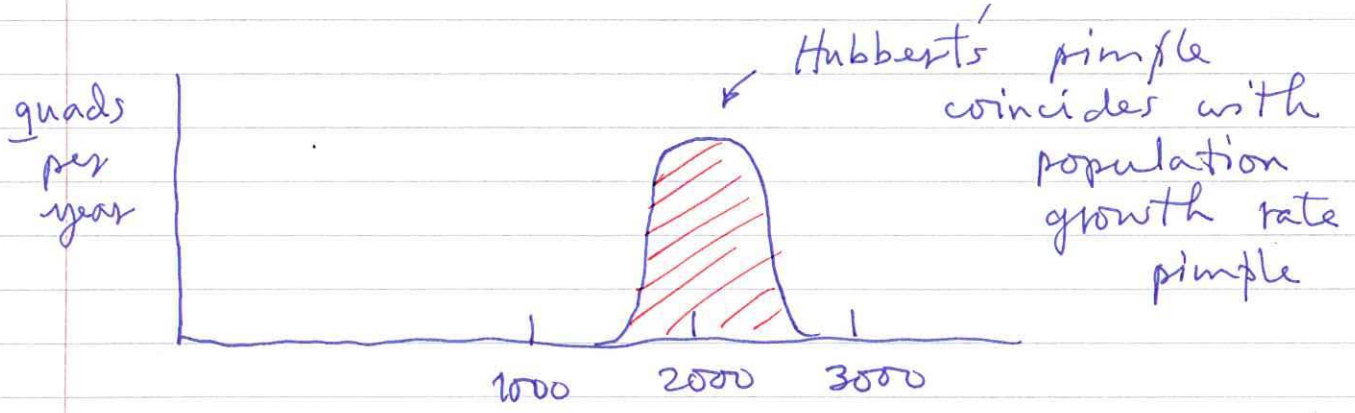
No, though projections are uncertain

~~150,000~~ ^{220,000} ← both uncertain

350 ← may increase due to rising GNP or decrease by conservation measures

A few years ago, projections (by environmentalists) were much more dire.

M. King Hubbert - plot of energy consumption



Hubbert thought the peak would be before now - writing in 1976. He thought would peak at $55 \cdot 10^{12}$ kW/yr = 190 quads/yr. Now known that we have a few hundred years to adapt to a non-fossil-fuel world.

He thought oil consumption would peak at more than 40 bbo/yr about now - in fact demand has stayed at 1976 levels 22 bbo/yr

From a ~~geological~~ geological perspective Hubbert's ~~pimple~~ pimple is a reality

In a few hundred years we will completely deplete the fossil fuel resources that the \oplus took 1 billion years to produce

~~resources~~

In fact Hubbert made a much more pessimistic estimate.

He based his analysis on the recovery cost per barrel.

On this basis he thought the oil production was showing signs of decline in 1974-76 when he did his work

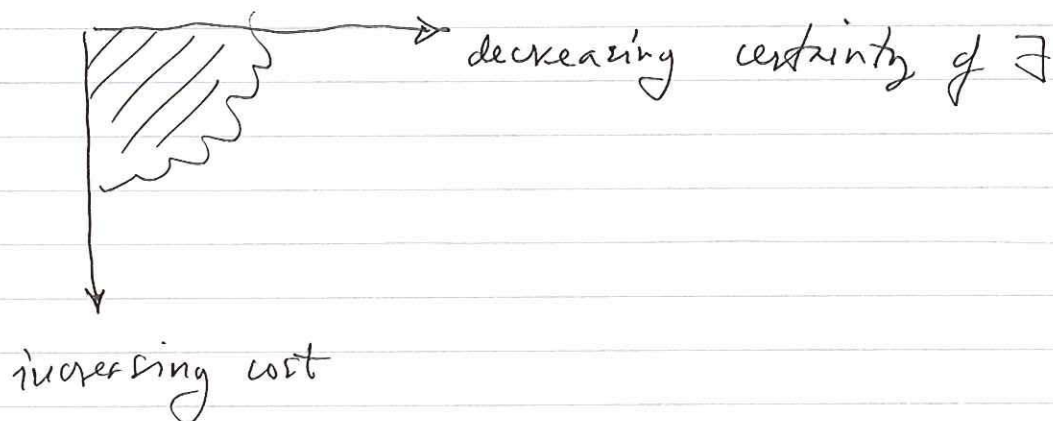
He thought the maximum production rate would bend over in 1995

Thought we would "run out" in 2025-2050.

Total supply remaining in 1996, according to his analysis, ~ 1000 bbls

More recent estimates ~ 2000 bbls.

It all depends on where you draw the line "recoverable resources"



Oil shale — again it all depends on how much effort it is to recover.

the extraction process — we simply cook it some more

Yields — ~~to~~ using retort methods (heat the shale and extract the organic component in liquid form in an above-ground retort — also can heat in situ) range from 5-100 gallons of oil per ton of shale

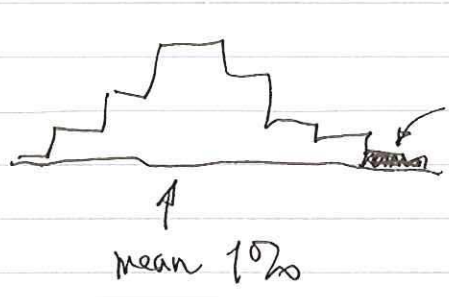
The US is rich in these shale oil resources

Most intensively explored is Green River Formation in Colo, Utah, Wyoming

Show Table 4 & Table 5 from article by Hinman

If it could be extracted shale oil in US reserves would supply US needs for centuries

25 gallons of oil / ton of shale
⇒ 8% organic matter by weight



just this — about ~~10%~~ ^{1%} of total

Let's view this — in closing — in the context of the global C cycle as a whole.

At present ~ 65 Gt of C fixed / yr
 0.1-0.2 Gt of C buried per year

Total amount of organic C in shales:

x 75% ← % of organic matter that is C-est is mostly th

$$1\% \times \text{total mass of shales} = \text{~~2.10^7~~} 2 \cdot 10^7 \text{ Gt}$$

By comparison CaCO_3 in limestones ~ $5 \cdot 10^7$ Gt
 ↑
 inorganic carbon

$$\text{CaCO}_3 = 40 + 12 + 3(16) = 100$$

C is 12% of CaCO_3

Shales are ~ 95% of all sediments

$$(0.95) (0.01) (\text{~~2.10^7~~} \frac{2}{7})$$

↑ $\frac{2}{7}$ of C in shale

← $\frac{30\%}{\text{~~2.10^7~~}}$ of all sedr are limestone + dolomite

$$\approx (0.03) (.12) (\text{~~2.10^7~~} \frac{5}{7})$$

Not bad!

↑ $\frac{5}{7}$ of all C in ~~shales~~ carbonates

According to ~~Stumm~~ Jasmiento & Siegenthaler
The repository of buried carbon in
the \oplus 's crust is:

organic C (coal + oil shale)	^{mostly →} $2 \cdot 10^7$ GtC
(Ca, Mg)CO ₃ (limestone + dolomite)	$50 \cdot 10^7$ GtC

See the calculation on page 18
showing that this checks

How much total C in oil shale (and
coal)?

$$\begin{aligned} \text{Total} &= 2 \cdot 10^7 \text{ GtC} = \frac{2}{0.75} \cdot 10^7 \text{ Gt oil} \\ &= 2.7 \cdot 10^7 \text{ Gt oil} \end{aligned}$$

$$= \underline{2 \cdot 10^8 \text{ } ~~\text{bbl}~~ \text{ bbl}} \quad 1 \text{ barrel} = 0.137 \text{ ton}$$

$$= 2 \cdot 10^{17} \text{ barrels}$$

top 10% in grade amounts
to $2 \cdot 10^5$ bbl

Conventional estimates of the amount that
can be exploited commercially more like

20,000 bbl — with ~ 3000 in NAM
 $2 \cdot 10^4$ bbl

↑ only about 10% of the top 1%

Present-day erosion — and thus organic C burial — rates are ~~probably~~ higher ~~than~~ than in the past due to anthropogenic effects — recall study of Huang He River in China.

Today's erosion rates ~ twice pre-human rates \Rightarrow 200 million years — consistent with Fig. 11.2 showing use distribution of oil-bearing rocks 58% are Cenozoic (< 70 m.y old)

But if today's rate were typical, it would have taken this is the residence time $\frac{2 \cdot 10^7 \text{ GtC}}{0.2 \text{ GtC/yr}} = 100 \text{ million years}$ to bury all the organic C at today's rates
also some of it must be unburied: oil seeps, etc.
(Jorge says this better)

This looks about right — if today's rates are a factor of 10 higher than pre-human we get 10 billion years.

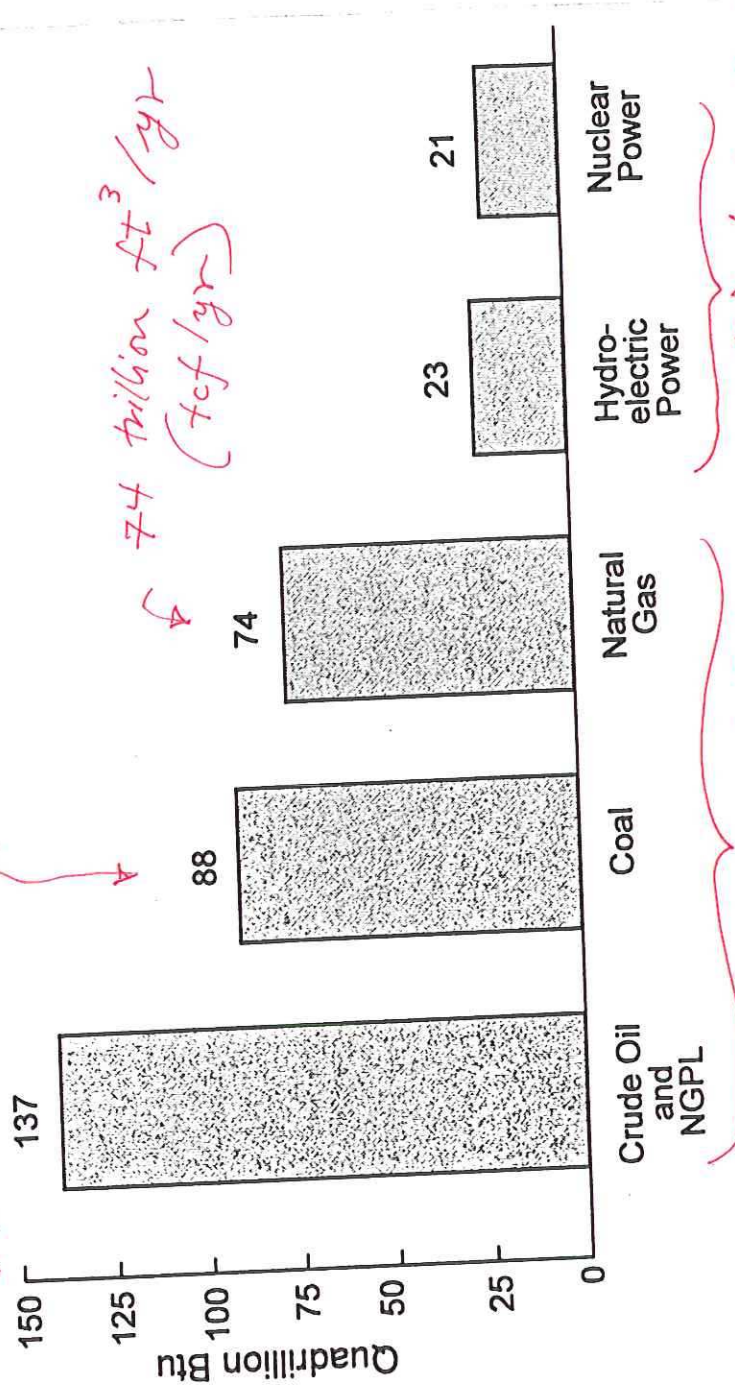
Roughly:

- $\frac{1}{\text{every } 500}$ C atoms fixed by phytoplankton each year are buried
- $\frac{1}{\text{every } 100,000}$ of those get "cooked" just right and are trapped in pumpable reservoirs of oil
- however $\frac{1}{\text{every } 10,000}$ reside in commercially exploitable oil shale

22 billion
oil barrels/yr
(22 bbl/yr)

3 Gt coal/yr

74 trillion ft³/yr
(7cf/yr)



13% hydroelectric & nuclear

87% fossil fuel

Figure 8.31.
The major sources of world energy in 1992. (Annual Energy Review 1993)

sum to 343
quads/yr

increasing at 2.7% (yr)

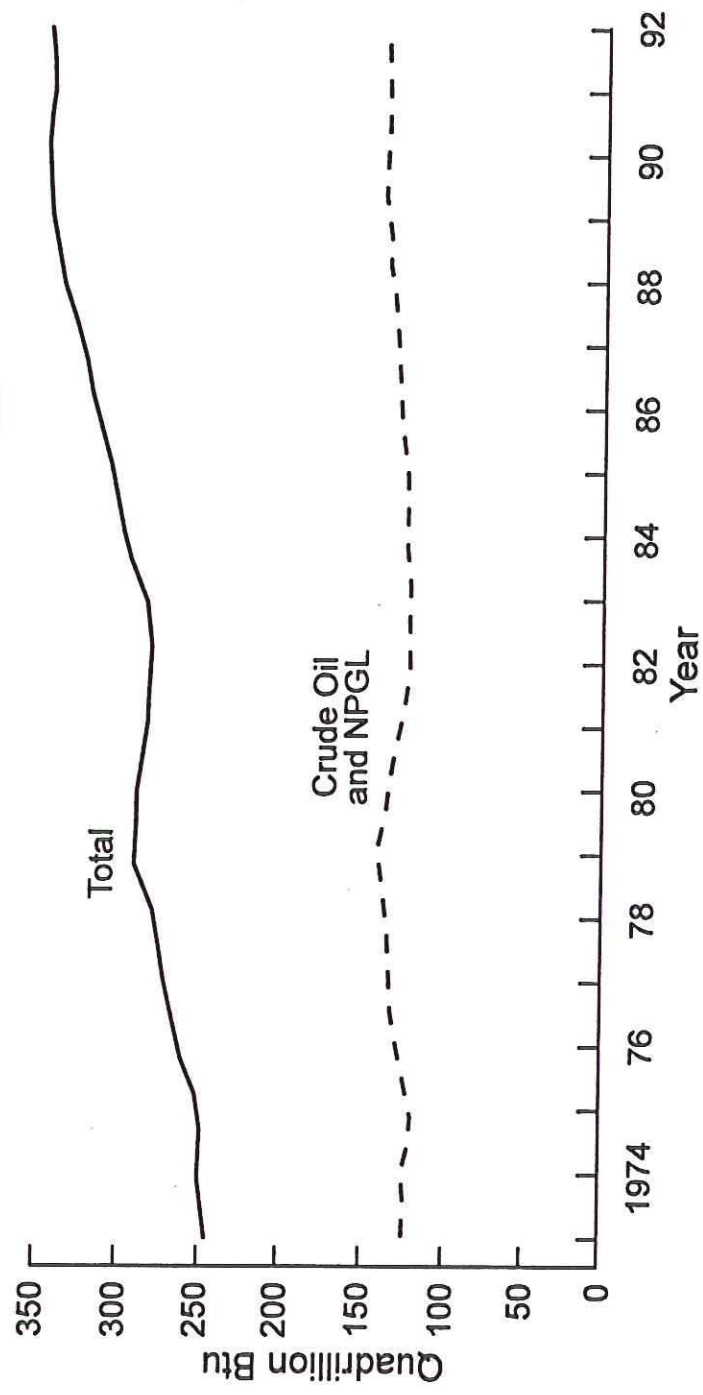


Figure 8.30.
World primary energy production between 1973 and 1992. (Annual Energy Review 1993)

nuclear power is the fastest growing world-wide — slowed to a standstill in US.

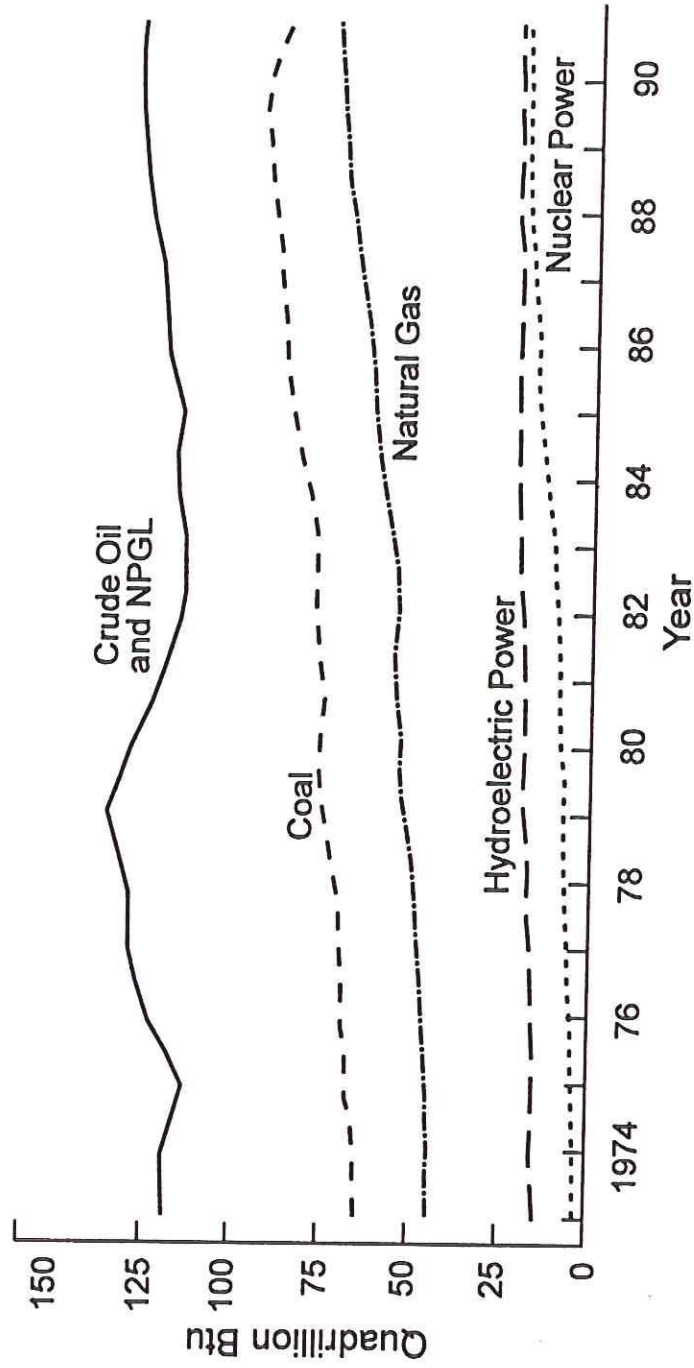


Figure 8.32. World primary energy production by source between 1973 and 1992. (Annual Energy Review 1993)

US with 5% of population consumes 20% of world's energy



Figure 8.33a.
The eleven major primary energy-producing countries in 1992. (Annual Energy Review 1993)

China 20% of world's population only 10% of world's energy - but increasing rapidly

US consumption of energy exceeds "production"

effect of oil embargo

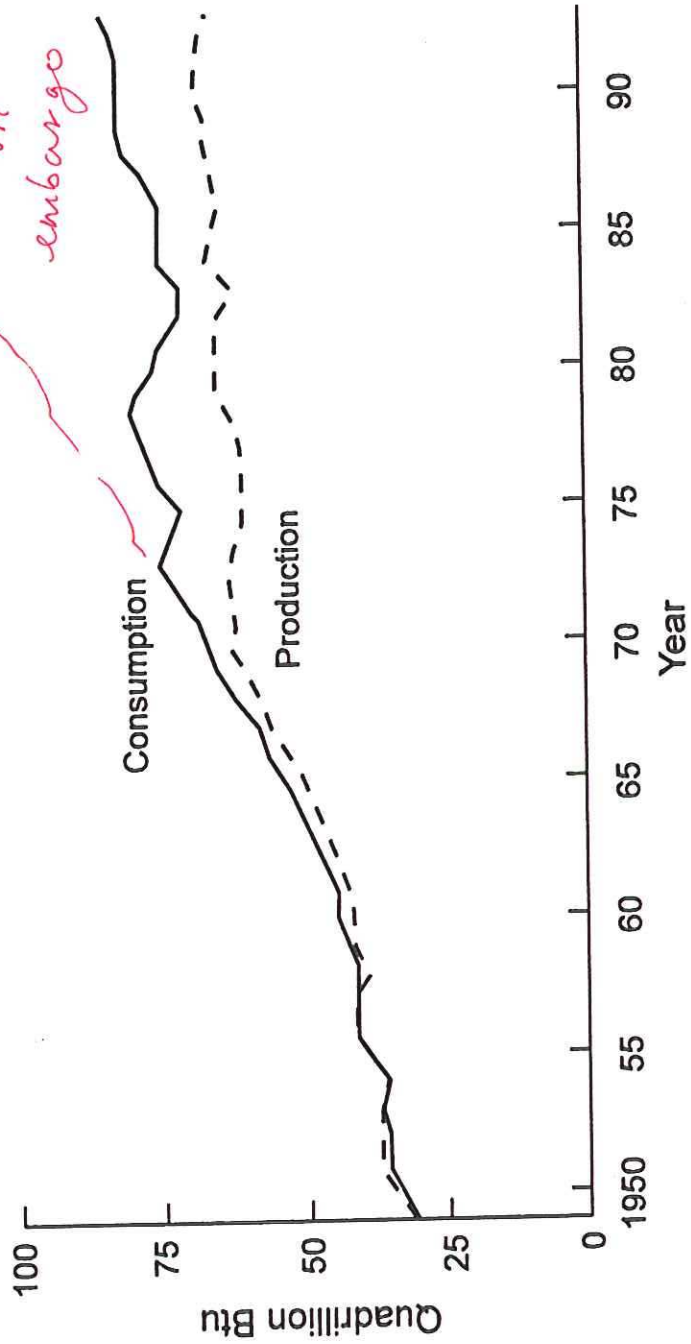
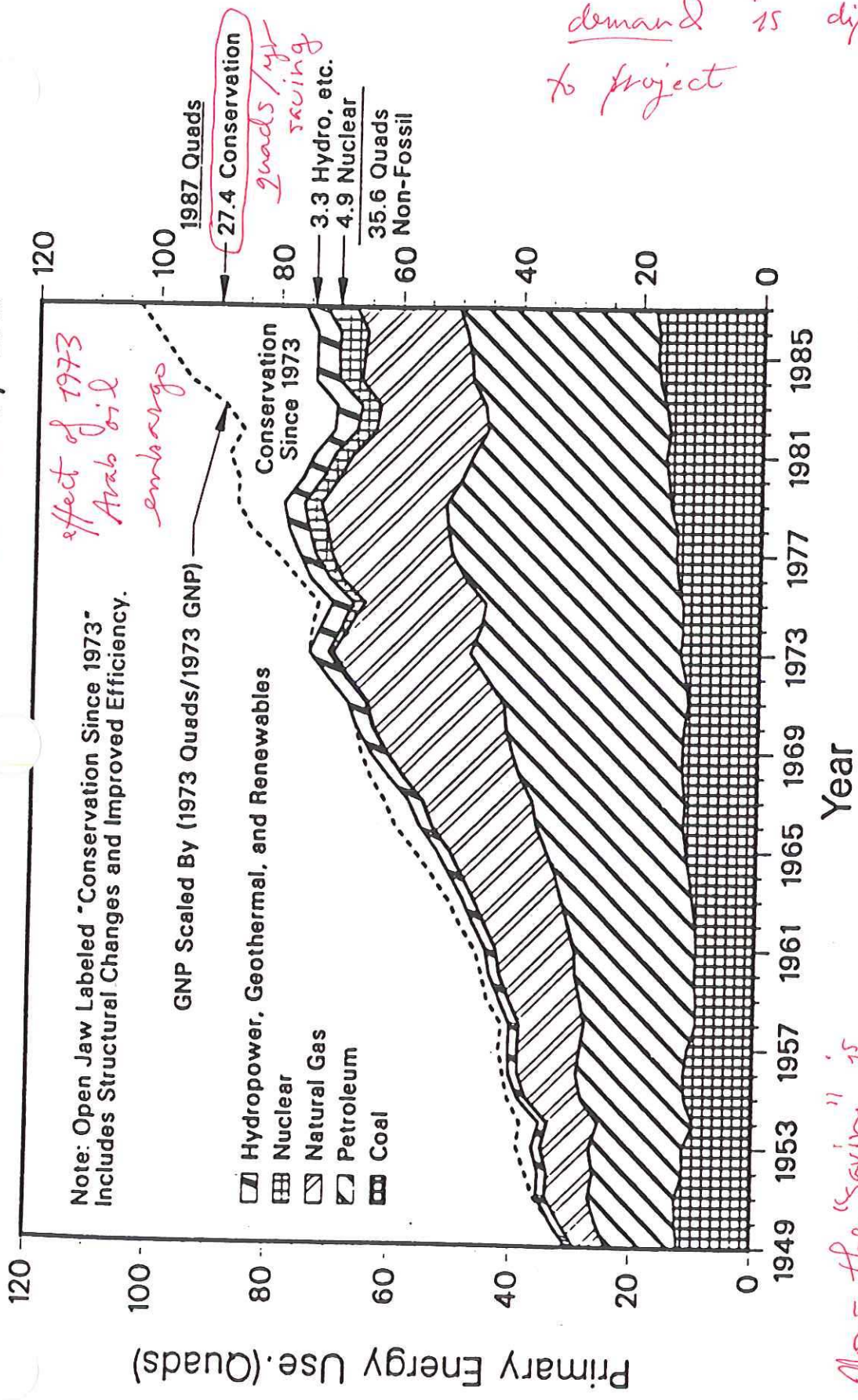


Figure 8.26.
The production and consumption of energy in the United States between 1949 and 1993. (Annual Energy Review 1993)

U.S. Primary Energy Use: Actual vs. Predicted by GNP



This shows that future demand is difficult to project

Source: *Economic Report of the President*, Council of Economic Advisors, January 1988, and *Annual Energy Review 1987*, EIA.

Figure 1. U.S. primary energy use: Actual vs predicted by GNP. (Source: Economic Report of the President, Council of Economic Advisors, January, 1988, and Annual Energy Review 1987, EIA. Figure courtesy of Lawrence Berkeley Laboratory, LBL.)

US oil consumption is twice this:
 27% of world total

6.9 ~~trillion~~ $\cdot 10^6$ barrels/day
 = 2.5 billion barrels/year \leftarrow call this 3 billion
 = 15 quads/yr produced

Saudi Arabia major supplier of oil

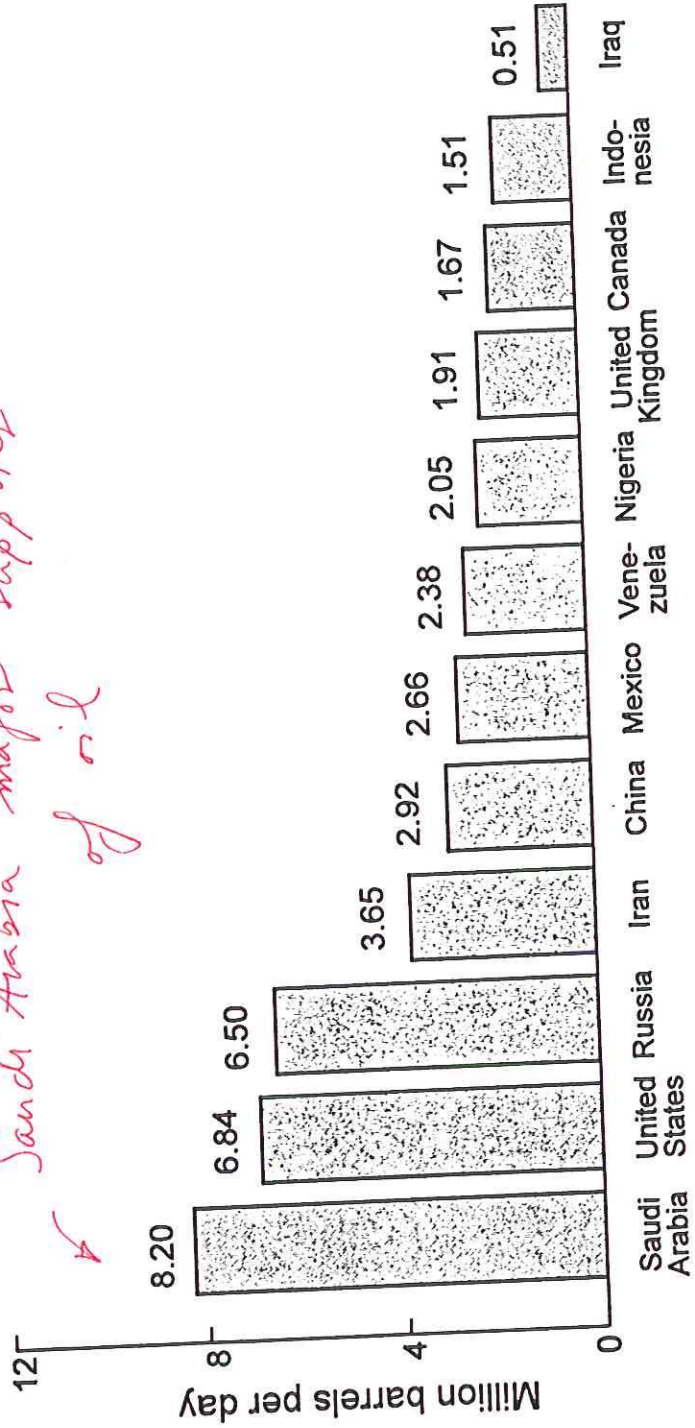


Figure 8.40. 1993 oil production by the twelve most important oil-producing countries. (Annual Energy Review 1993)

Most natural gas is consumed locally

Figure 8.42.
The major producers of natural gas in 1991.
(Annual Energy Review 1993)

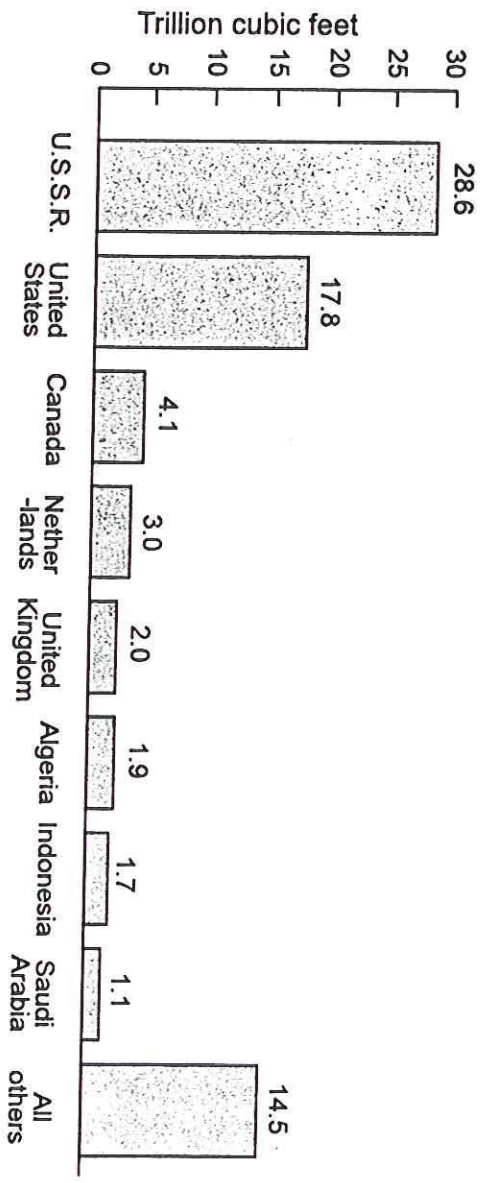
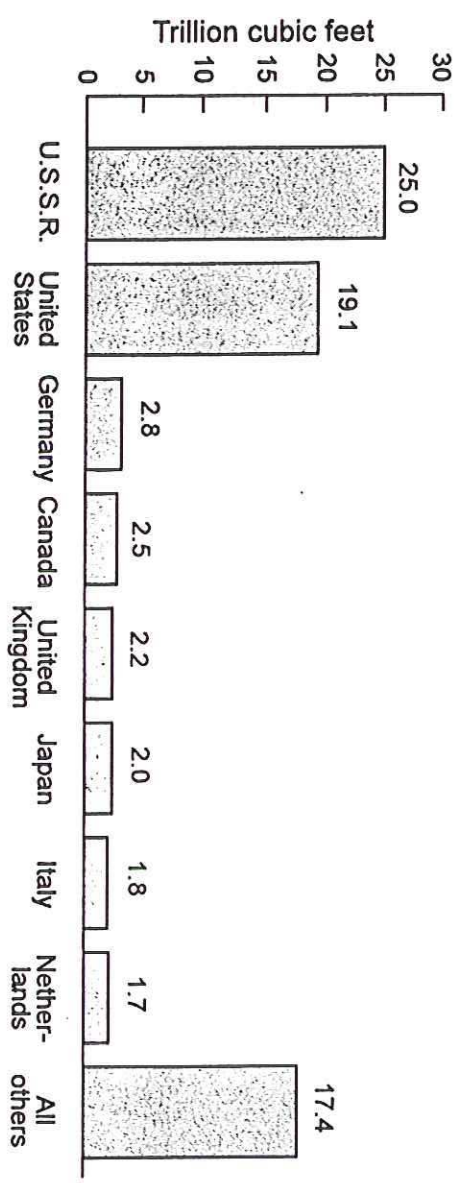


Figure 8.43.
The major consumers of natural gas in 1991.
(Annual Energy Review 1993).



ditto coal

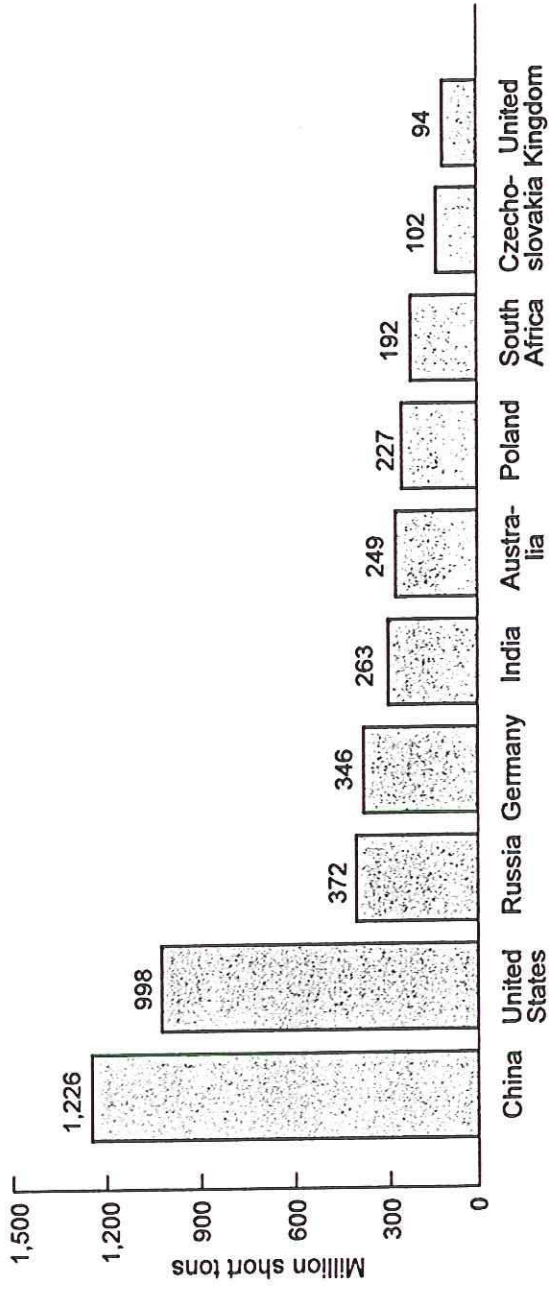


Figure 8.34. 1992 production of coal in the ten leading countries. (*Annual Energy Review 1993*)

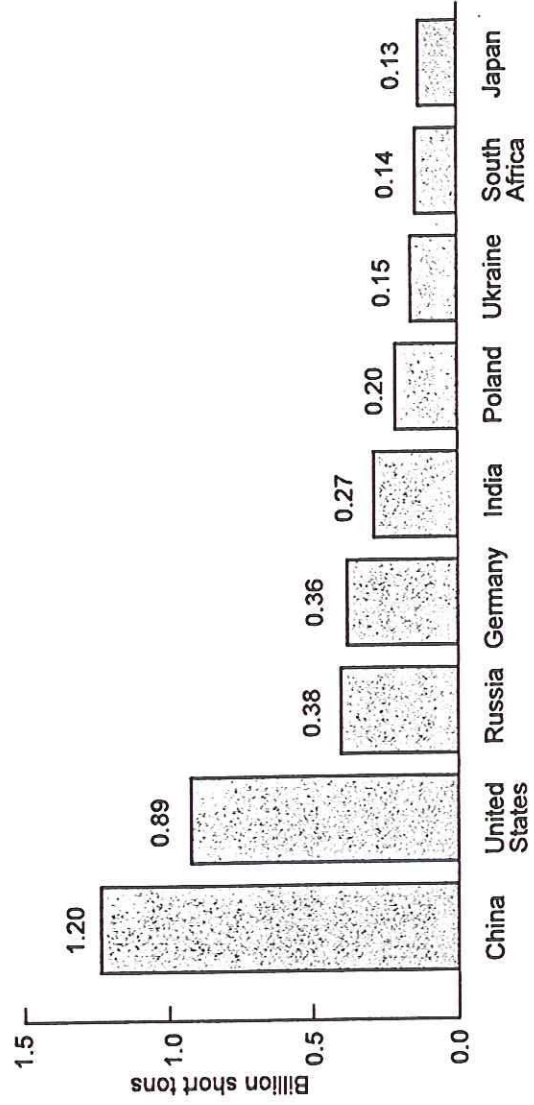


Figure 8.35. 1992 consumption of coal in the nine most coal-consuming countries. (*Annual Energy Review 1993*)

China is using its plentiful coal reserves to fuel its industrial expansion

China - electricity consumption increasing 10% / yr

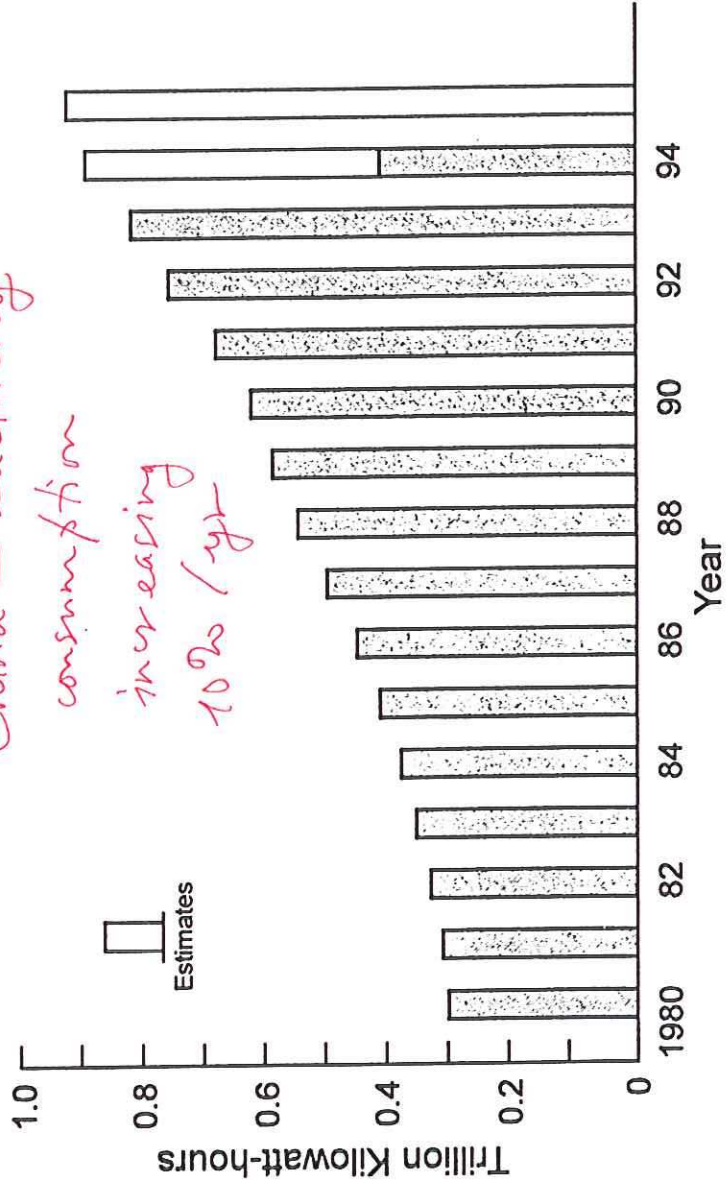
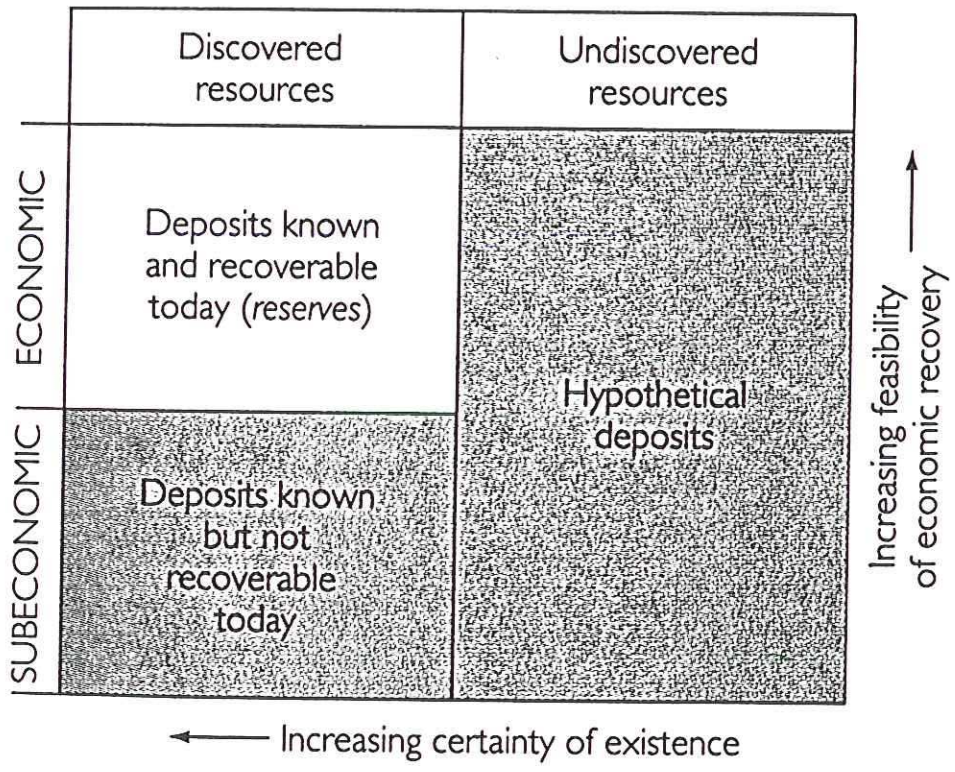


Figure 8.33b.
Electricity generation in
China since 1980.
(New York Times,
November 7, 1994)

TOTAL RESOURCES



US consumes 6 bbo/yr

Petrobrás Finds Big Deep-Water Oilfield

By AGIS SALPUKAS

Petrobrás, the state-owned Brazilian oil company, said yesterday that an oilfield in very deep water contained reserves of about 1.3 billion barrels of oil, more than double previous estimates, making it one of the largest discoveries in recent years.

"This is a major field," said Mary Quinn, an analyst who follows the oil industry in Latin America for SBC Warburg Inc.

She said that if the field was brought into production, this could further help cut Brazil's need to import oil. That, in turn, would add to world supplies. But she noted that the field was beneath about 6,100 feet of water, so pumping oil to the surface would pose a major technological challenge.

Petrobrás, however, has been a pioneer in producing oil from deep water off the coast of Brazil and has teamed up with the Shell Oil Compa-

ny, a pioneer in deep-water development and a unit of the Royal Dutch/Shell Group, to meet the technological challenges.

The increasing flow of oil from Latin America, particularly from Venezuela and Colombia, has blunted efforts by the Organization of Petroleum Exporting Countries to keep up the price by keeping its production quota at 25 million barrels a day.

Latin America has become increasingly important as a supplier to the United States, whose dependence on imports has been rising as domestic production, particularly from Prudhoe Bay in Alaska, has been declining.

The Petrobrás field is about 80 miles off the coast of the state of Rio de Janeiro.

With an estimated 1.3 billion barrels in reserves, the Petrobrás field is the largest discovery since the Cusiana and Cupiagua fields were discovered in Colombia in 1991. That

find, in turn, was the largest since Prudhoe Bay in 1968.

Petrobrás, whose formal name is Petróleo Brasileiro S.A., had estimated last month that the field could hold reserves of 400 million to 600 million which it now has more than doubled.

"This is a new frontier for Petrobrás," said Daniel Oliveira, the financial manager in New York of the oil company. He said it was too early to say whether Petrobrás would go ahead with the huge costs and technical challenges of bringing the field into production.

"The prospects are very good," he said, since the oil is of much higher quality than the heavy crude oil from neighboring fields in the Campos Basin, where Petrobrás has brought up oil from wells deep under water.

The higher-quality oil commands a higher price in world markets, providing an added incentive for Petrobrás to make the investment needed to bring the field into production.

Table 1. United States oil resources (in billions of barrels).

Original proven conventional recoverable resources	226
Already produced	142
Remaining	84
Estimated undiscovered resources	46
Domestic production (per year)	3
Domestic consumption, including imports (per year)	5.5
Years left. under current production conditions, and no increase in imports	28-43

note imbalance

Note 1: If imports decrease or use increases, the number of years left will be smaller.

Note 2: As supplies shrink, increasing costs will decrease use, so reserves will increase number of years left.

rate at which US is finding new gas "plays"

Table 2. United States natural gas resources (in trillions of cubic feet).

Proven conventional recoverable resources (including Alaska, and at less than \$5 per thousand cubic feet)	384
Production rate (per year)	17
Recent yearly addition to proven recoverable resources	14-15
Estimated total remaining conventionally recoverable resources (lower 48)	400-900
Estimated unconventional recoverable resources (price of recovery not determined, but probably high)	140-700
Total estimated resources	540-1600
Years left at current rate	35-95
Years left at double current rate	17-47

Note: Current cost of natural gas is about \$1.70 per thousand cubic feet.

Table 3. Global resources.

Oil (in billions of barrels)	
Original resources	1900
Produced	673
Remaining	1227
Production (per year)	21
Years left at current rate	60

Many say 2000 bbo (12,000 quads) left →

Note: Undiscovered and unconventional resources could approximately double the total supplies, but at undetermined cost.

Natural gas (in trillion of cubic feet)	
Estimated remaining resources	8100
Production rate (per year)	10,000 tcf (10,000 quads) →
Years left at current rate	120

Many say more than 10,000 tcf (10,000 quads) left

Table 3. Global resources.

Natural gas (in trillion of cubic feet)	
Estimated remaining resources	8100
Production rate (per year)	
Years left at current rate	120

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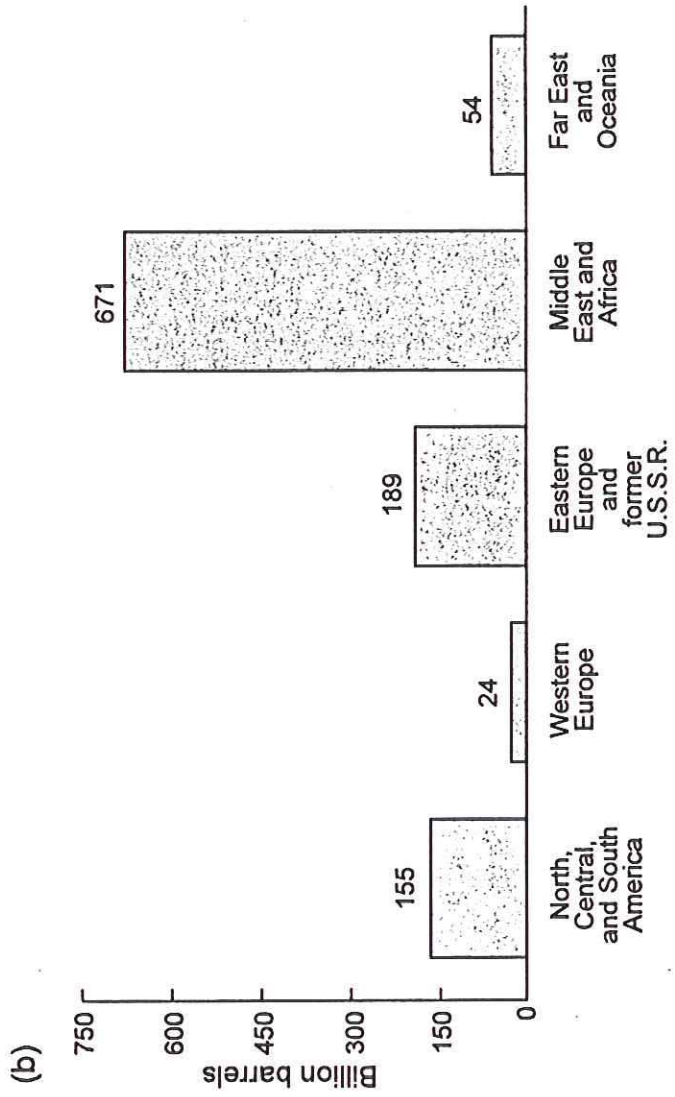
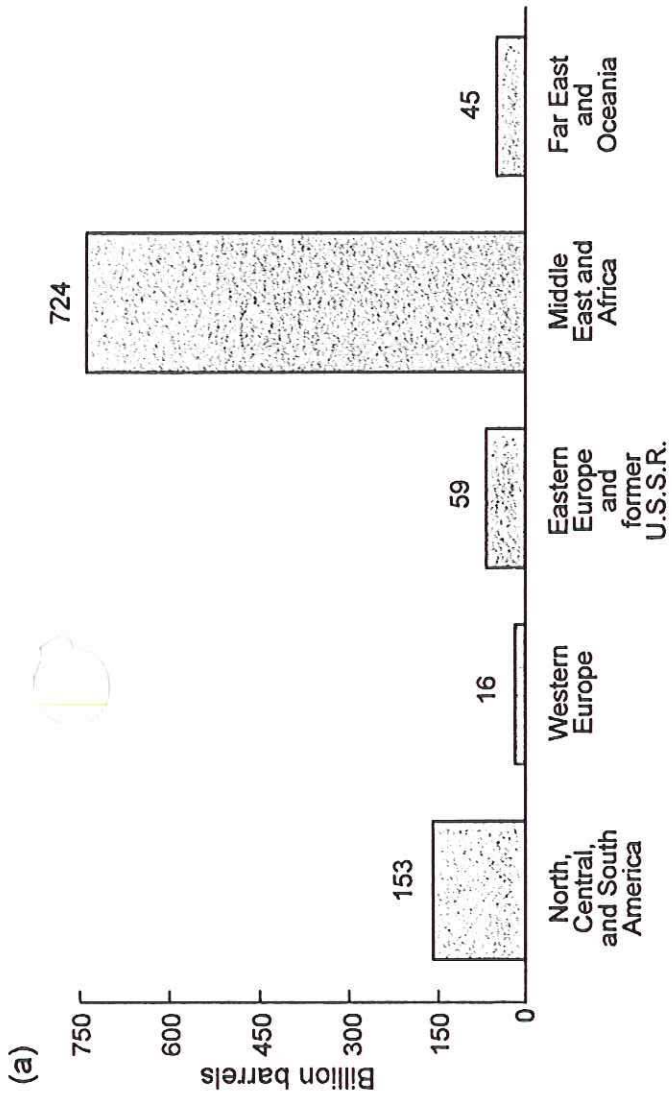


Figure 8.41.

The distribution of world oil reserves in 1993.

Sources (a) *Oil and Gas Journal*; (b) *World Oil*.

(*Annual Energy Review 1993*)

The New York Times

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America's Energy Independence

The worldwide scramble to develop new and existing energy sources has become a driving force in contemporary foreign policy. The Clinton Administration, building on America's dual role as the world's largest energy producer and largest energy consumer, has made itself a main player in this new world energy game, promoting increased production at home and abroad. Its sensible goal is to lessen the country's vulnerability to pressures from energy exporters and protect Washington's freedom to make foreign policy based on larger American and global interests.

Global energy supplies are not tight now, but demand is rising quickly, especially in areas of robust economic growth, like the United States, China and Southeast Asia. Last year, the world consumed just over 70 million barrels of oil every day. That is projected to rise to nearly 105 million barrels by 2015. Proven worldwide reserves are now about one trillion barrels, a figure that tends to rise over time with new exploration, cheaper extraction methods and changes in price.

America's daily oil consumption was just over 18 million barrels last year, up nearly 10 percent from 1991. Without significant new gains in conservation and efficiency, the United States can be expected to consume more than 22 million barrels by 2015. Imports have been rising even more sharply, and now account for just over half the oil the country uses.

The Administration is right to emphasize developing new low-cost foreign sources. The United States learned the perils of overdependence on Persian Gulf supplies during the 1970's Arab oil embargo.

But there is no strategic justification for the favors, like reduced royalty payments, that the Administration and Congress have been lavishing on domestic producers. The United States can retain its energy independence while relying on foreign sources of supply, leaving much of its own

untapped wealth in the ground as a strategic reserve. The Administration has also failed to focus on more efficient use of existing energy supplies and on stronger conservation efforts, whether through taxes, regulation or market-based incentives.

Diversification is not the only motive behind the race for new supplies. There is worry that prices will rise if global consumption grows as rapidly as predicted. Meanwhile, the investment climate has been transformed by political changes in oil regions, like the collapse of Communism in Russia and the Caspian Basin and Latin America's more welcoming attitude toward foreign investment.

The Administration's policies have produced good results in Venezuela, from which the United States now imports more oil than it does from Saudi Arabia. Since 1995, American companies have helped Venezuela sharply increase its production capacity. Washington has promoted business partnerships with Russia's oil and gas industry, in the hope that American technology will help Russia pump more energy at lower cost from aging wells.

Washington has also been wooing the newly independent governments of the Caspian Basin, like Azerbaijan, Georgia, Kazakhstan and Turkmenistan, all of which sit astride rich energy deposits or vital pipeline routes. Rightly, it has pressed the case of American companies seeking a share of Caspian energy rights, encouraged the removal of regulatory obstacles and sought consistent standards for cross-border pipeline routes.

But except for Georgia, Caspian area governments have shown scant tolerance for democracy and human rights and have tried to use their leverage with Washington to deflect American pressures on these issues. The Administration should be cautious about the tradeoffs it makes to smooth access to oil. One aim of energy independence is to gain more freedom to pursue larger national goals. Washington should not subordinate these goals to a mindless rush for new energy suppliers.

NYT data
1997
70x365 =
26 bbl/day
US alone
7 bbl/day
proven
reserves
1000 bbl

U.S. has $\frac{1}{4}$ to $\frac{1}{5}$ of world's supply

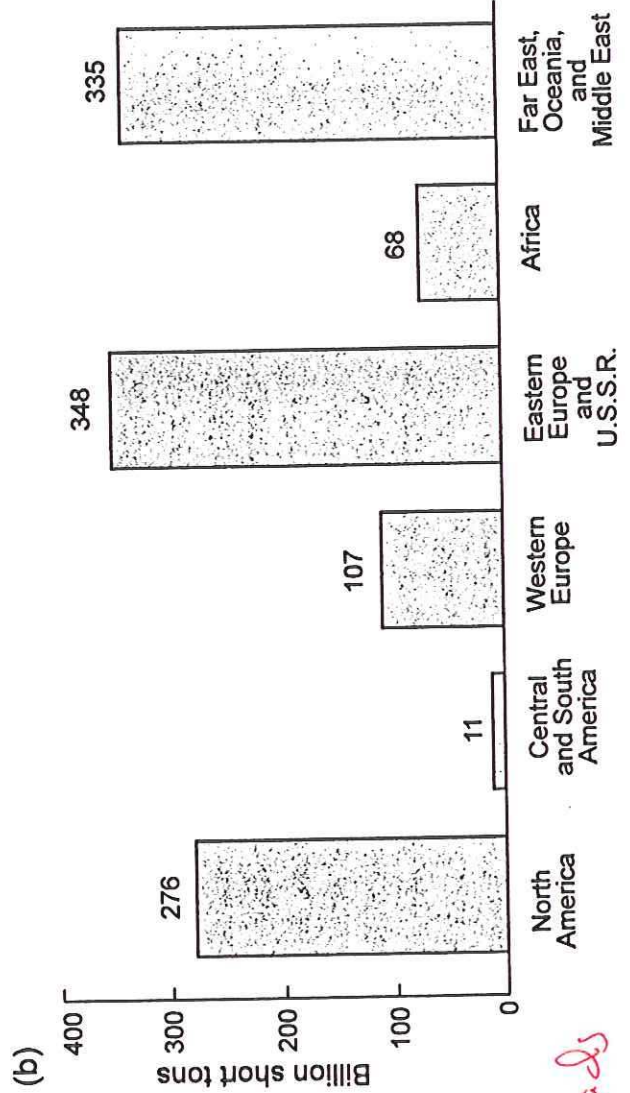
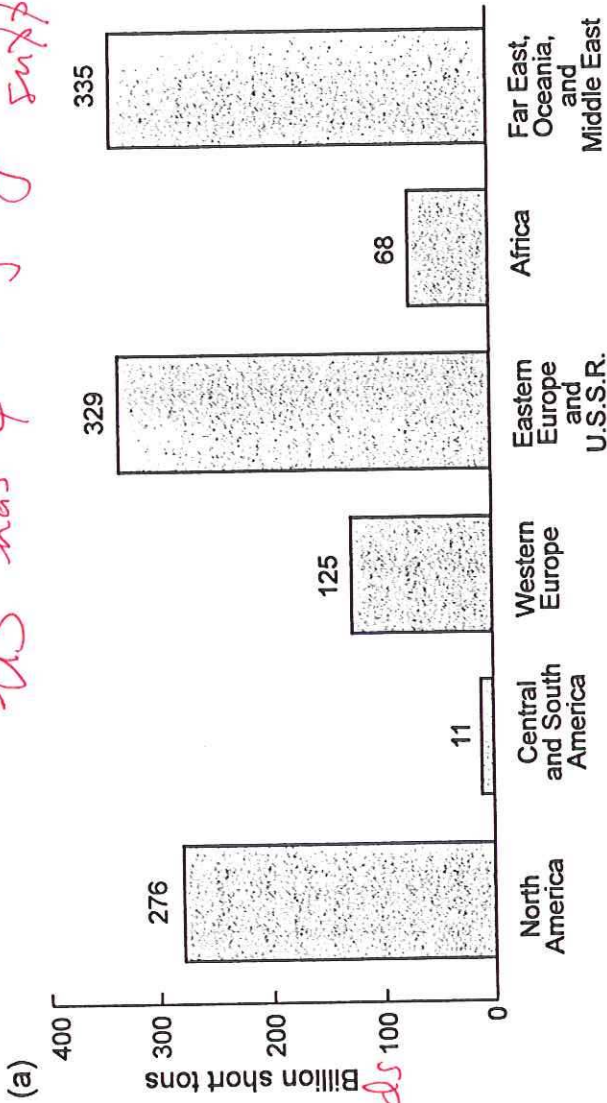


Figure 8.37.

World reserves of coal estimated by

(a) the World Energy Council, 1991;

(b) British Petroleum, 1992. (Annual Energy Review 1993)

↘ 30,000 quads

adds to 1100 Gt of coal but some estimates of "ultimately recoverable" coal are

as high

as ~~3000-4000~~ 3000-4000 Gt of coal

⇒ 80,000 - 110,000 quads

⇒ 80,000 - 110,000 quads

World Petroleum Assessment 2000:

Excluding the United States, the estimated mean (expected) volumes of undiscovered resources are 649 billion barrels of oil (BBO), 778 billion barrels of oil equivalent (BBOE) or 4,669 trillion cubic feet of gas (TCFG), and 207 billion barrels of natural gas liquids (BBNGL).

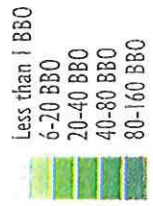
The estimated mean additions to reserves from discovered fields (potential reserve growth) are 612 BBO, 551 BBOE or 3,305 TCFG, and 42 BBNGL. Compared to the 1994 USGS world petroleum assessment, undiscovered volumes from the 2000 assessment are 20 percent greater for oil, 14 percent smaller for gas, and 130 percent greater for natural gas liquids. This study offers the first USGS assessment of large estimated volumes of oil, gas, and natural gas liquids from reserve growth at the world level.

The estimated volume of undiscovered oil is more than that of the 1994 assessment, due in part to larger estimates for the Middle East and Atlantic offshore portions of South America and Africa. However, in some areas the estimated volumes of undiscovered oil were smaller, particularly for Mexico and China.

World Oil Assessment 2000



Conventional Natural Oil Endowment in billions of barrels of oil (BBO)



World Gas Assessment 2000



Conventional Natural Gas Endowment in Trillions of Cubic Feet (TCF)



- 1 Former Soviet Union
- 2 Middle East and North Africa
- 3 Asia Pacific
- 4 Europe
- 5 North America
- 6 Central and South America
- 7 Sub-Saharan Africa and Antarctica
- 8 South Asia

Table 6. Composition and pyrolysis products of typical Colorado oil shale.^a

Mineral constituents	
Mineral	Weight percent of minerals
Dolomite	32
Calcite	16
Quartz	15
Illite	19
Low-albite	10
Adularia	6
Pyrite	1
Acalcime	1
Total	100

Ultimate analysis of organic constituent	
Element	Weight percent of organics
Carbon	76.5
Hydrogen	10.3
Nitrogen	2.5
Sulfur	1.2
Oxygen	9.5
Total	100.0

Yields from Fischer assay pyrolysis		
Decomposition product	Weight percent of organic constituent in raw shale	Weight percent of total raw shale
Oil	63	10.4
Noncondensable gas	15	2.5
Fixed-carbon residue	13	2.2
Water vapor	9	1.4
Total	100	16.5

15% organic matter by weight

^aPyrolyzed by the standard Fischer assay at 932 F: oil yield = 26.7 gal/ton.

Source: T.A. Sladek, "Recent Trends in Oil Shale—Part 1," *Mineral Industries Bulletin*, Vol. 17, No. 6, November, 1974, pp. 4–5. As reported in Reference 10, Table 16.

Figure 7.8.
 Plot of the burial efficiency, BE, of organic carbon with marine sediments vs. the sedimentation rate (S), in centimeters per 1,000 years. (Betts and Holland 1991)

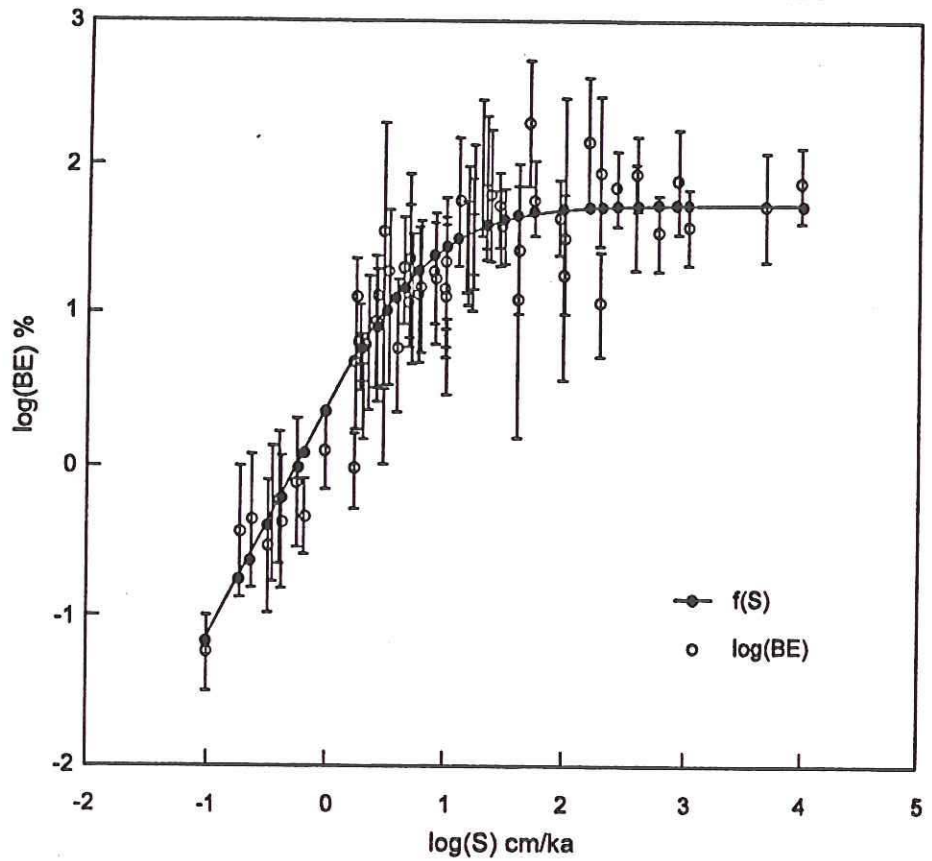


Figure 7.9.
 The total organic carbon content of recent and ancient limestones and shales. (Gehman 1962)

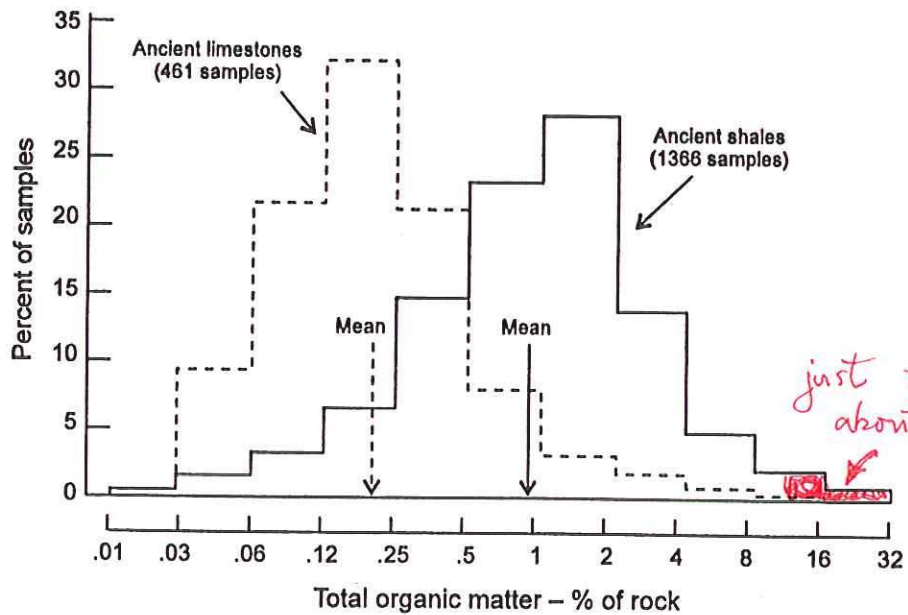


Table 4. Potential shale oil in place in the oil shale deposits of the United States (billions of barrels).

Location	Range of shale oil yields (gallons per ton ³)		
	5-10	10-25	25-100
Colorado, Utah, and Wyoming (the Green River formation)	4,000	2,800	1,200
Central and eastern states (includes Antrim, Chattanooga, Devonian, and other shales)	2,000	1,000	(?)
Alaska	Large	200	250
Other deposits	134,000	22,000	(?)
Total	140,000+	26,000	2,000(?)

³Order of magnitude estimate. Includes known deposits, extrapolation and interpolation of known deposits, and anticipated deposits.

Source: Reference 1 as reported in Reference 2.

Table 5. Potential shale oil resources of the Green River formation (billions of barrels).

Location	Resource class ^a				Total
	1	2	3	4	
Piceance basin (Colorado)	34	83	167	916	1200
Uinta basin (Colorado & Utah)	...	12	15	294	321
Wyoming basins	4	256	260
Total	34	95	186	1466	1781

^a1 Deposits at least 30 ft thick and average 35 gal/ton.

2 Deposits at least 30 ft thick and average 30 gal/ton.

3 Similar to 1 & 2 but less well defined and not as favorably located.

4 Poorly defined, ranging down to 15 gal/ton.

Source: "An Initial Appraisal by the Oil Sale Task Group 1971-1985." U.S. Energy Outlook—

An Interim Report, The National Petroleum Council, Washington, DC, 1972. Reported in Reference 2.

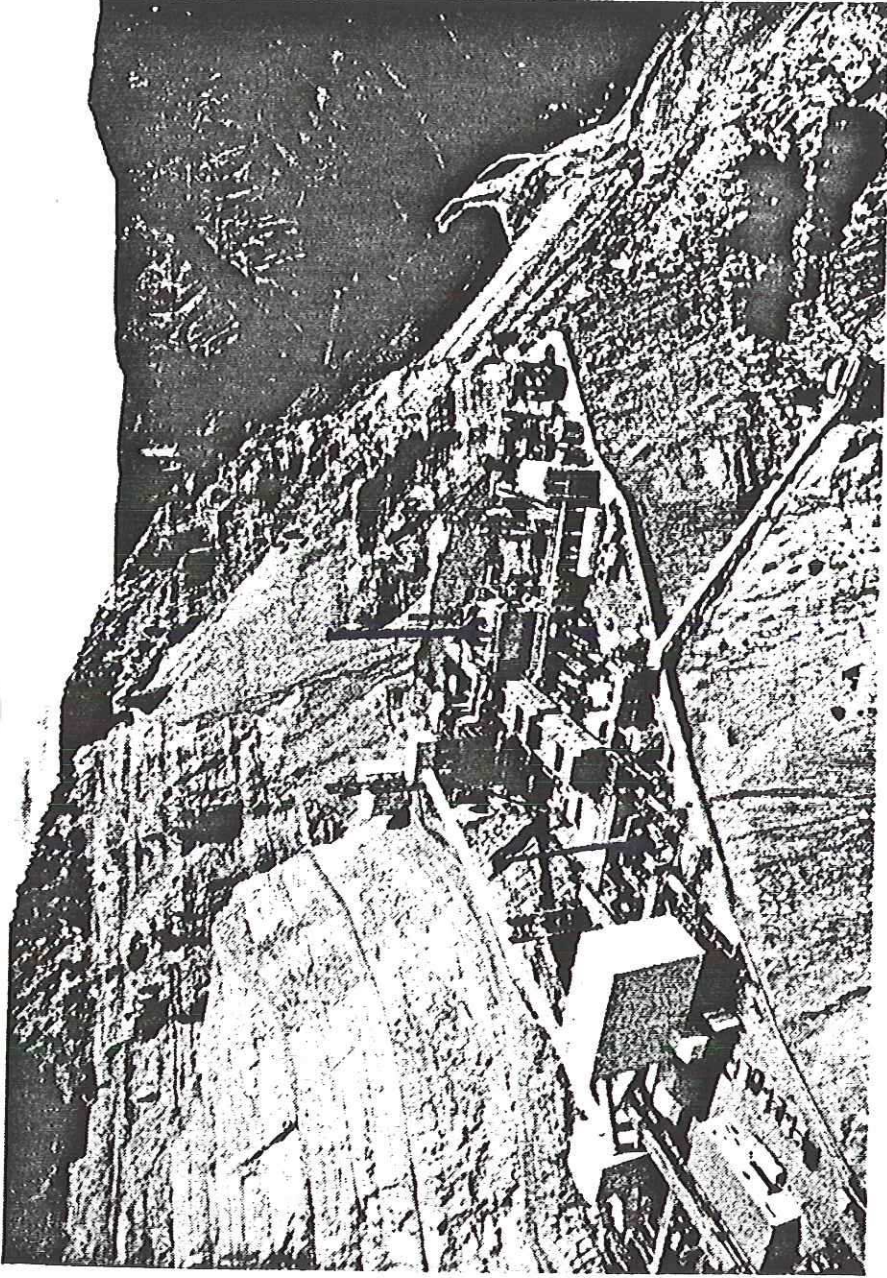
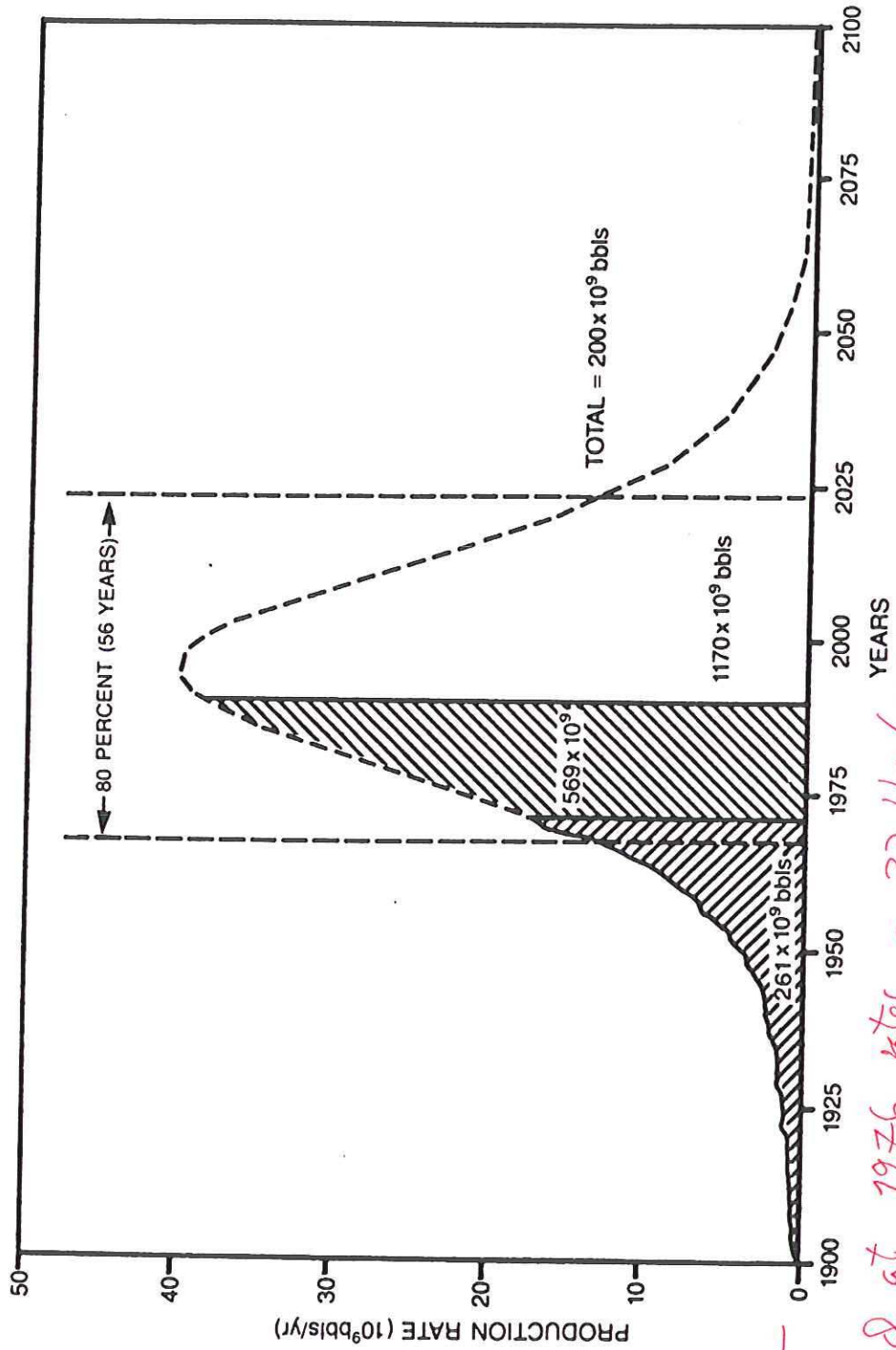


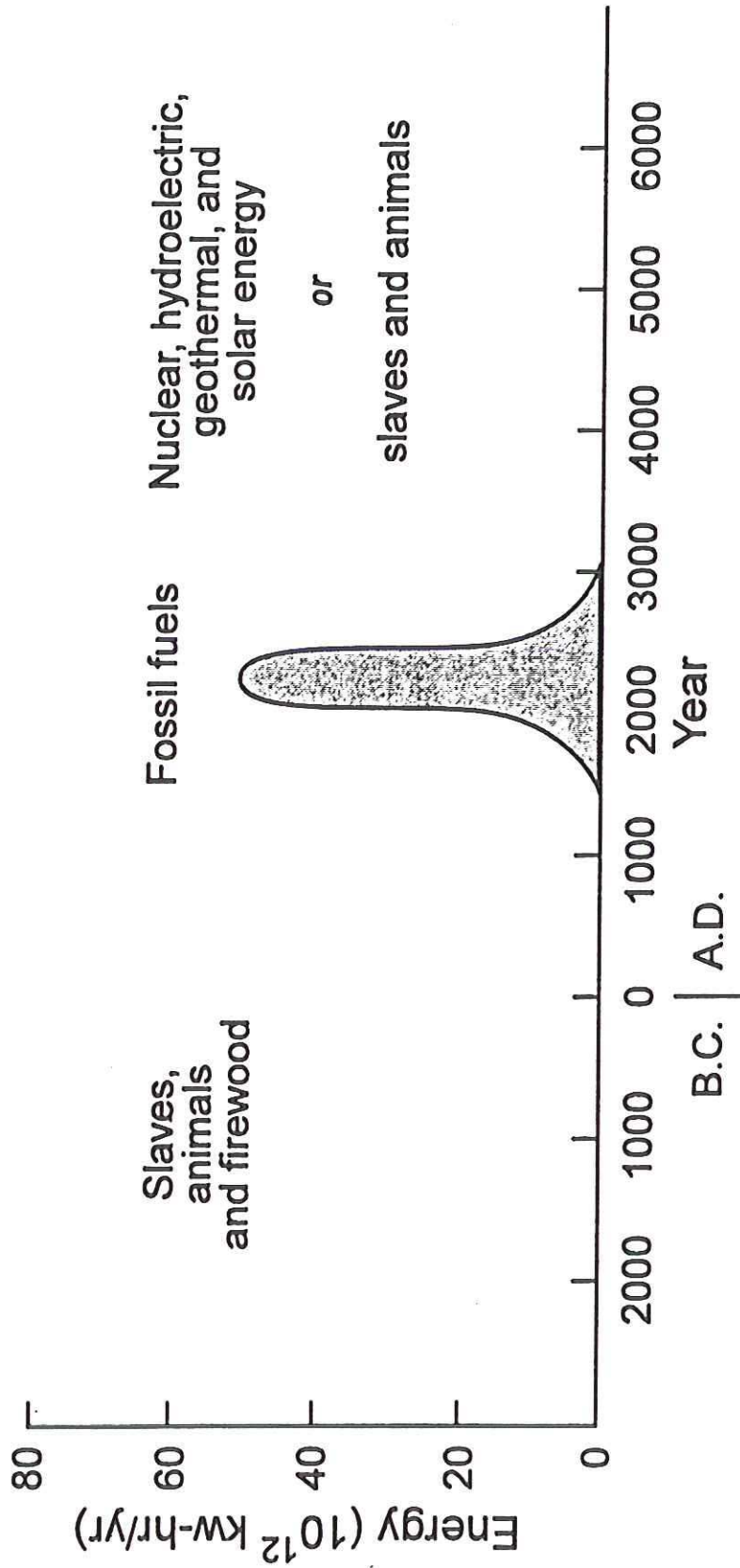
Figure 3. Photograph courtesy of Unocal.

*Oil field of the future
Strip mine → above ground retort*



Hubbert
 thought
 consumption
 would
 peak at
 more than
 40 bbl/yr
 about now—
 in fact
 has remained at 1976 rates ~ 22 bbl/yr

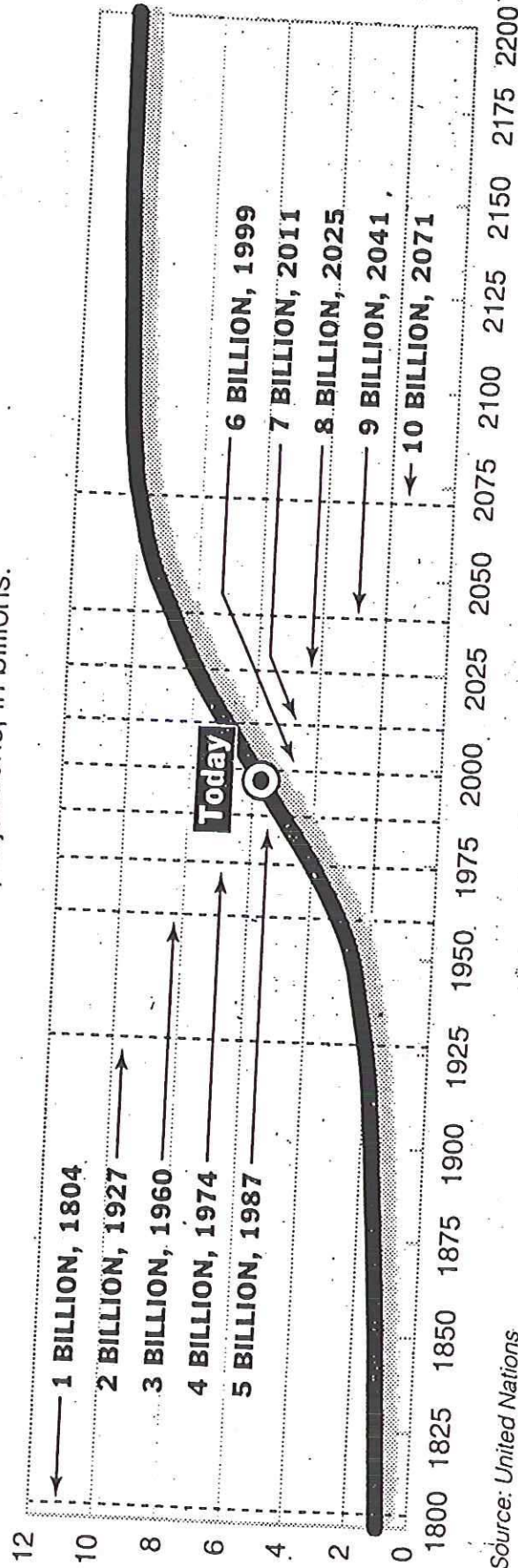
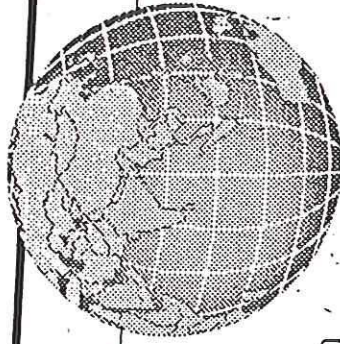
Figure 14-1. Complete lifetime curve for world petroleum "production." (After Hubbert, 1974.)



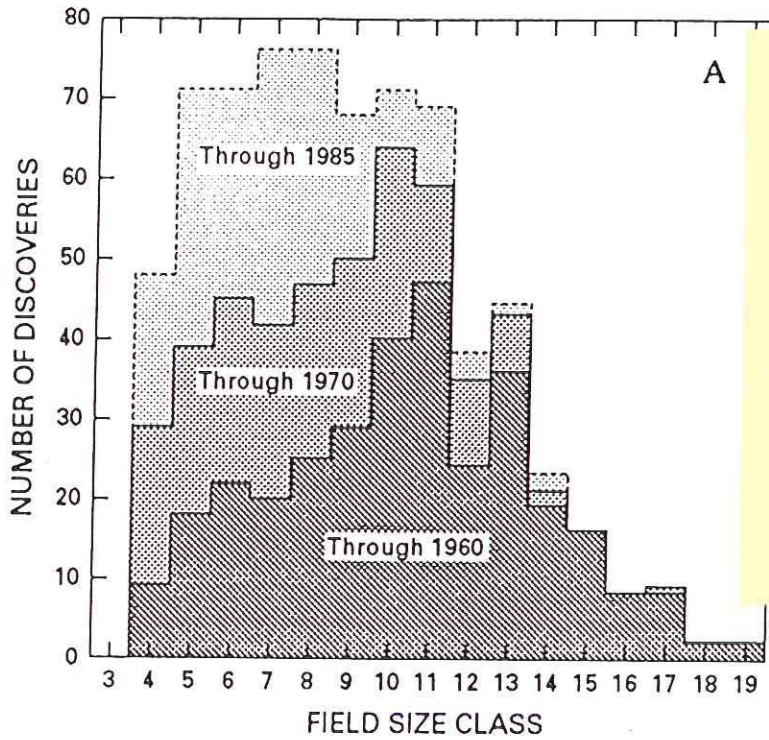
STATUS REPORT

The Population Explosion Slows Down

A new United Nations study has found that the world's population is growing more slowly than was expected. This suggests that the world's population, now 5.77 billion, will stabilize just after the year 2200 at 10.73 billion. Shown is the world population from 1800 to stabilization based on United Nations projections, in billions.



Source: United Nations



from John's lecture when I was at AGU

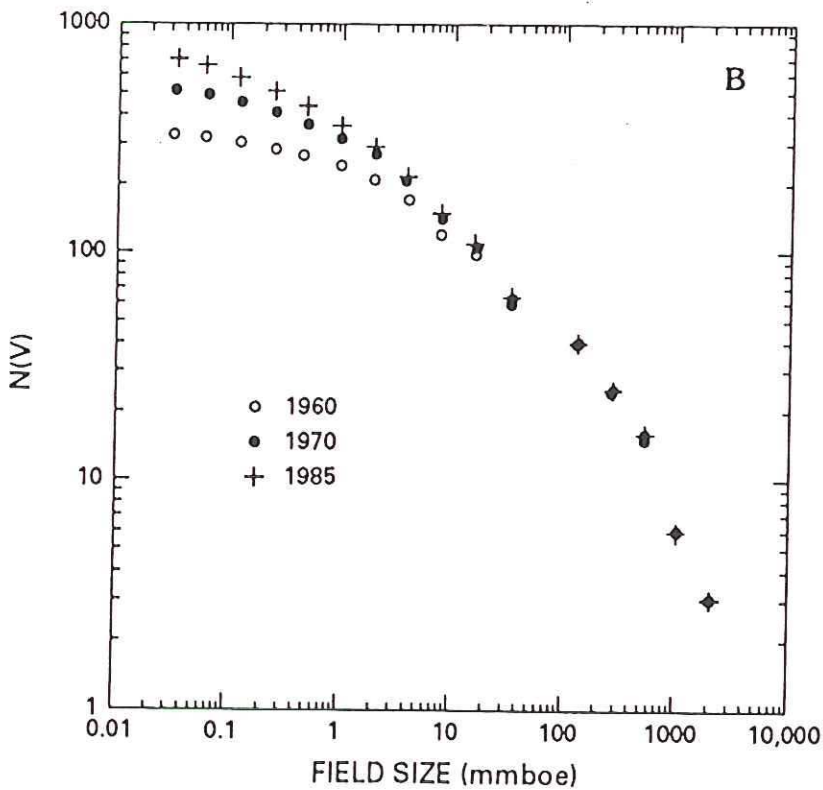


FIGURE 2.2. Observed field size distribution for oil and gas in the Frio Strand Plain exploration play, onshore Texas during three time periods; through 1960, through 1970, and through 1985. (a) The distribution's three discovery segments over time, when added, show the cumulative number of fields of a given size discovered through the specified year. (Taken from Drew, 1990, Fig. E.4). (b) Log-log plot by time segments of cumulative frequency of oil and gas fields, $N(V)$, versus field size.

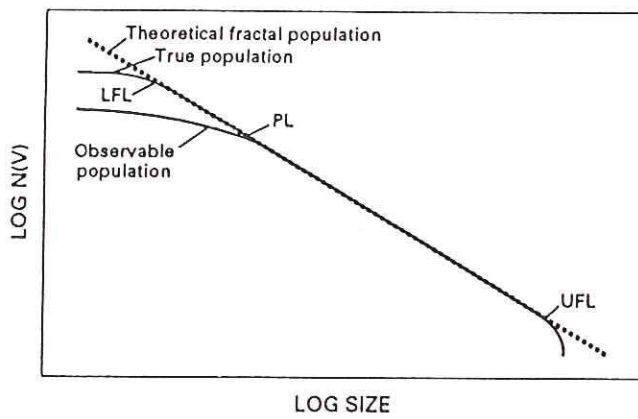
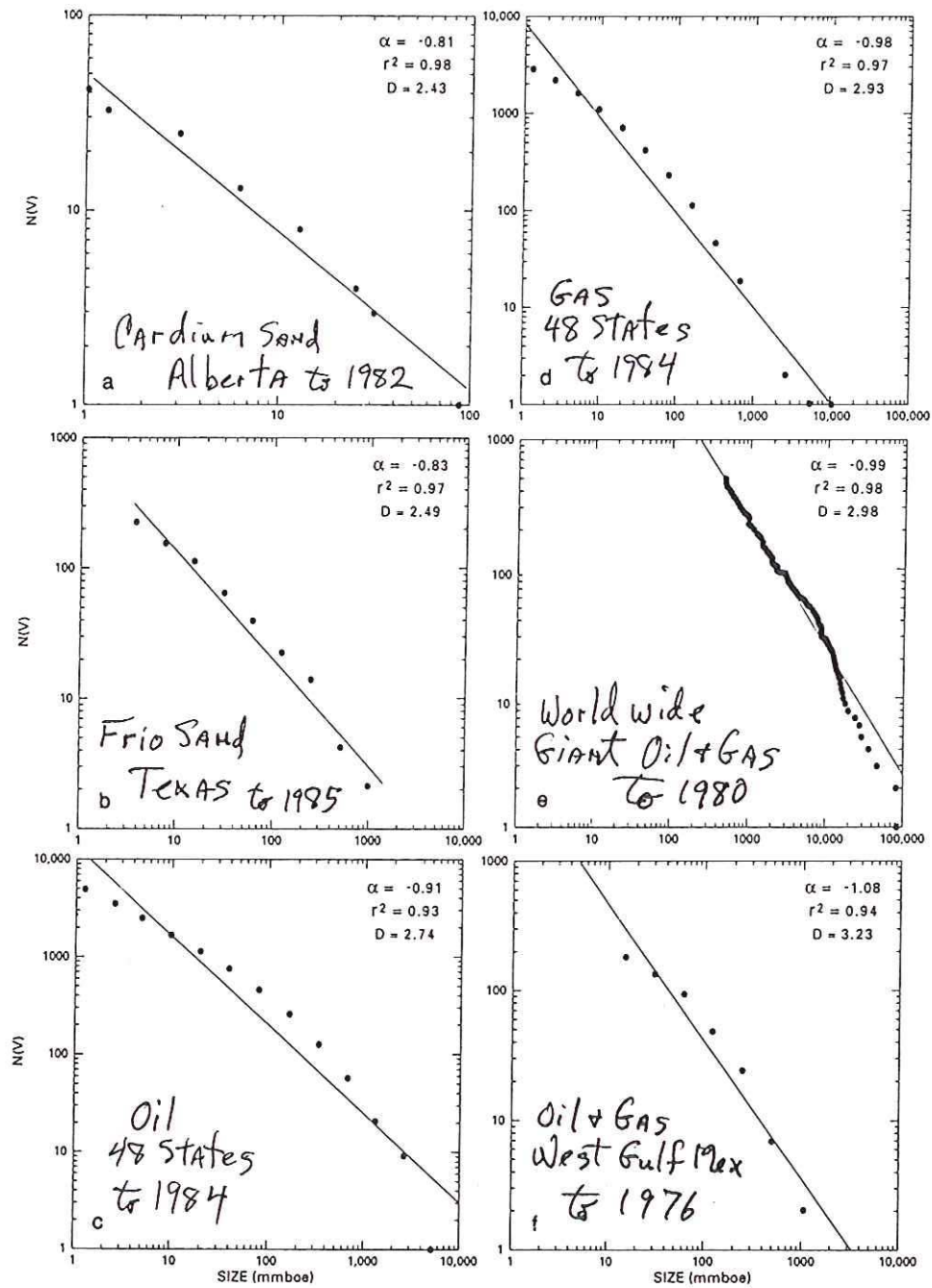


FIGURE 2.1. Schematic diagram, a log-log plot of cumulative frequency versus size, illustrating the differences between a theoretical fractal distribution (dashed line), a true fractal population, between upper and lower fractal limits (UFL and LFL), and an observable population, that is truncated by a perceptibility limit (PL).



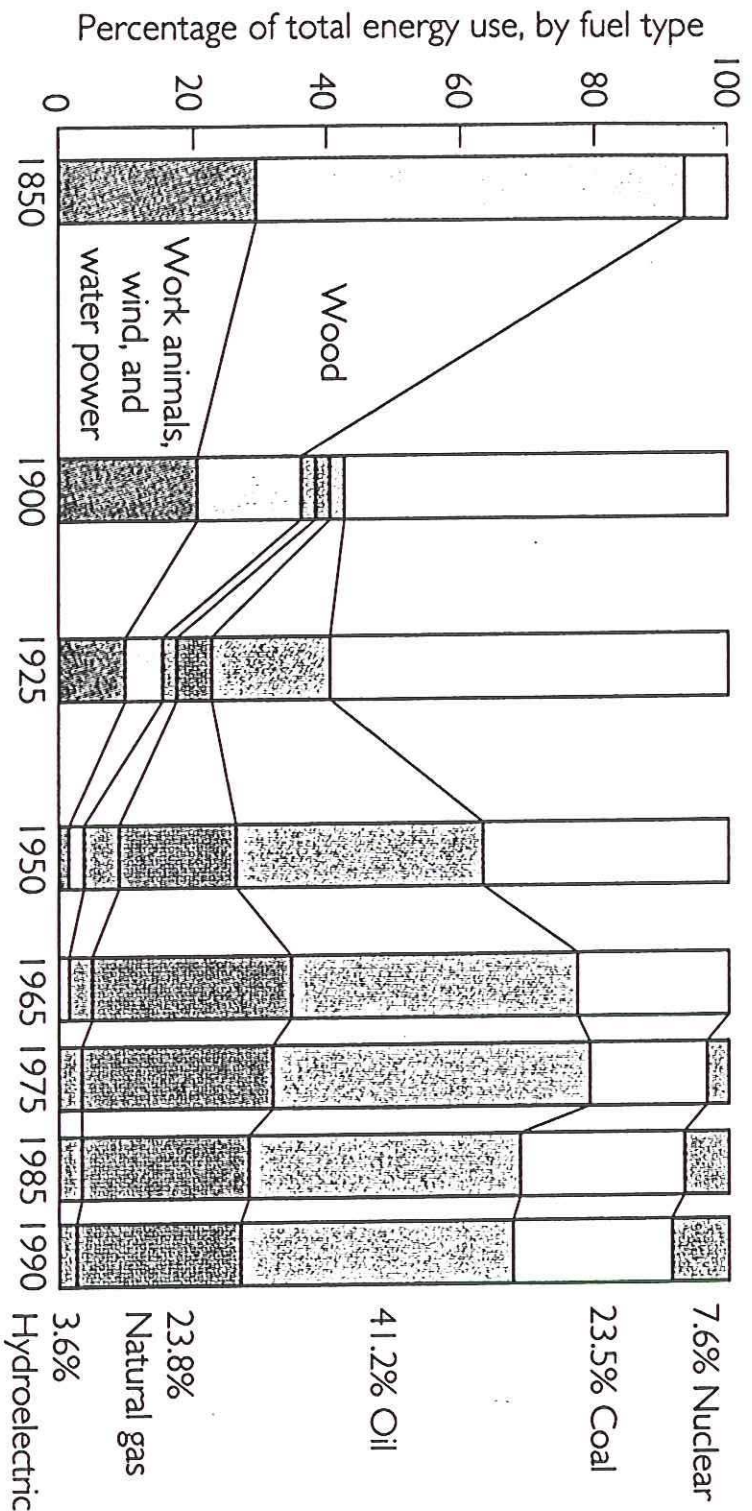


FIGURE 22.3 Percentages of various types of energy used in the United States from 1850 to 1990. (Data from U.S. Energy Information Agency, 1991.)

extra beyond here

Figure 8.27.
 The major sources of energy produced in the United States between 1949 and 1993. NPG = natural pressurized gas liquid. (Annual Energy Review 1993)

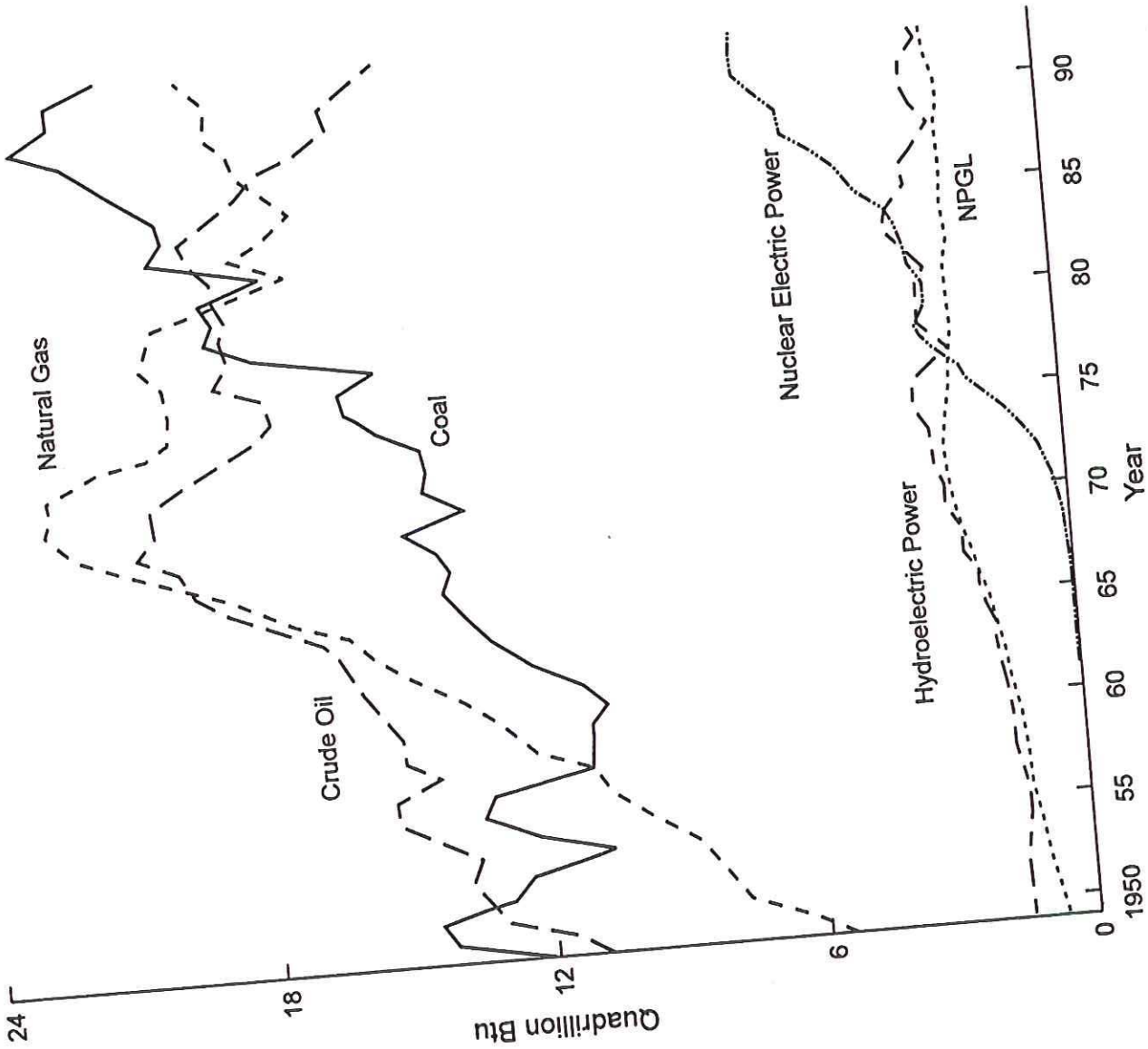
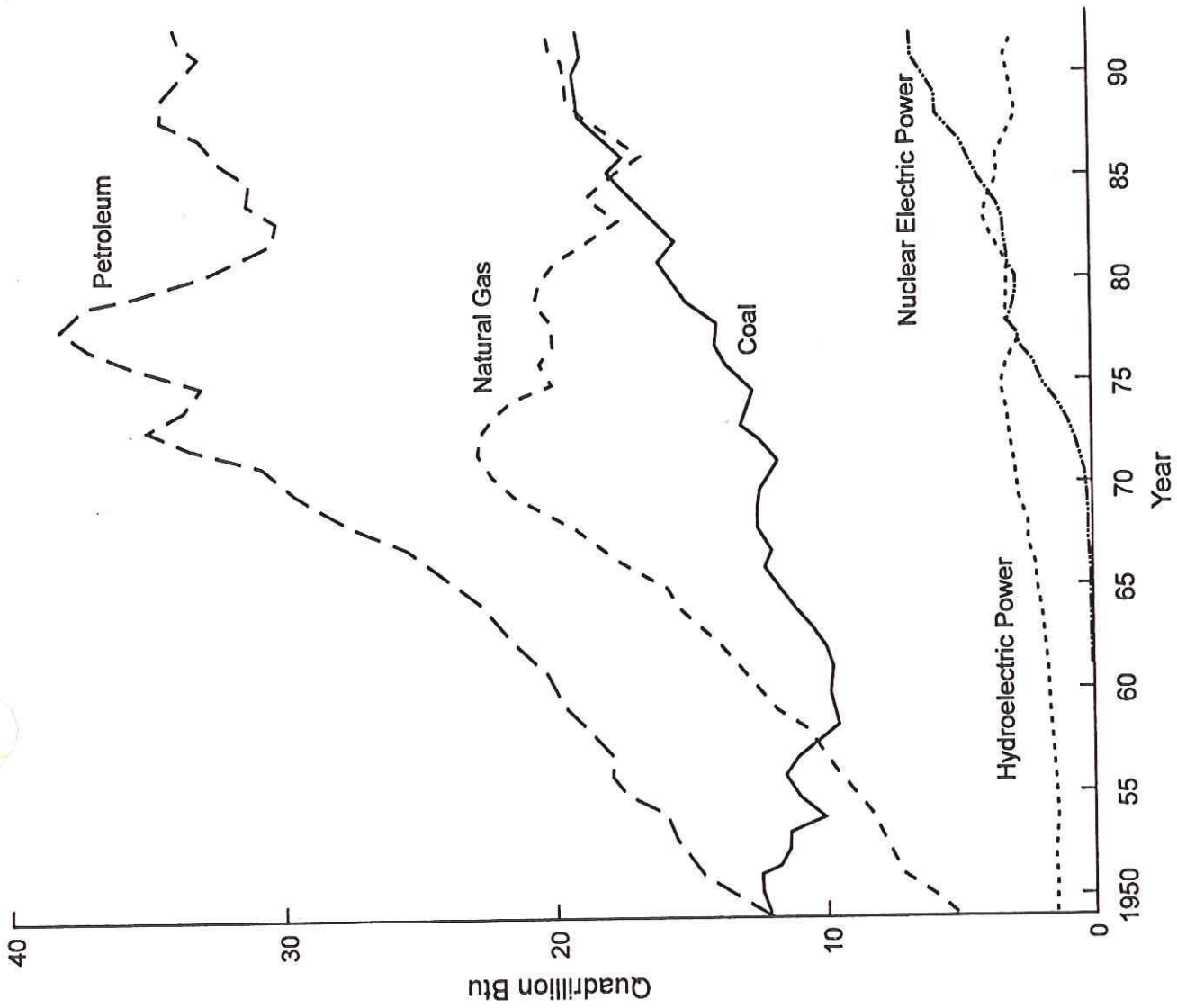


Figure 8.29.
 The major sources of
 energy consumed in the
 United States between
 1949 and 1993. (*Annual
 Energy Review 1993*)



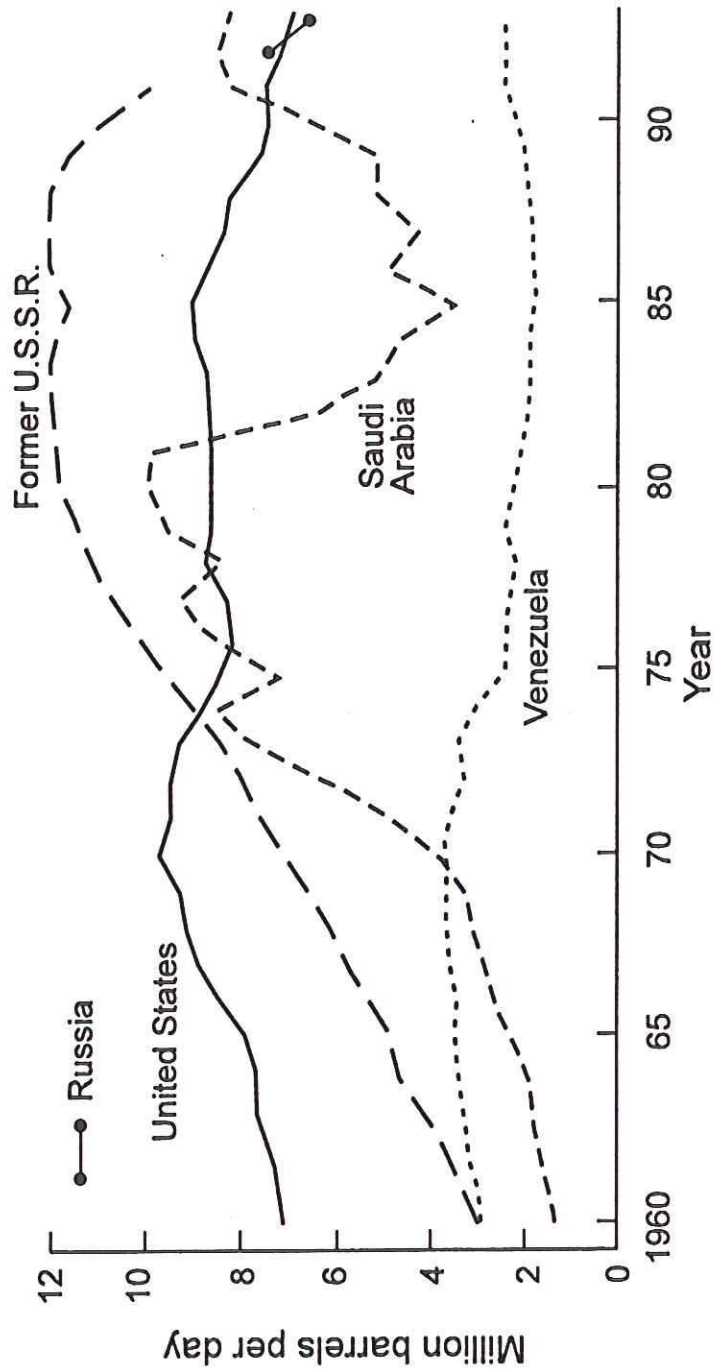
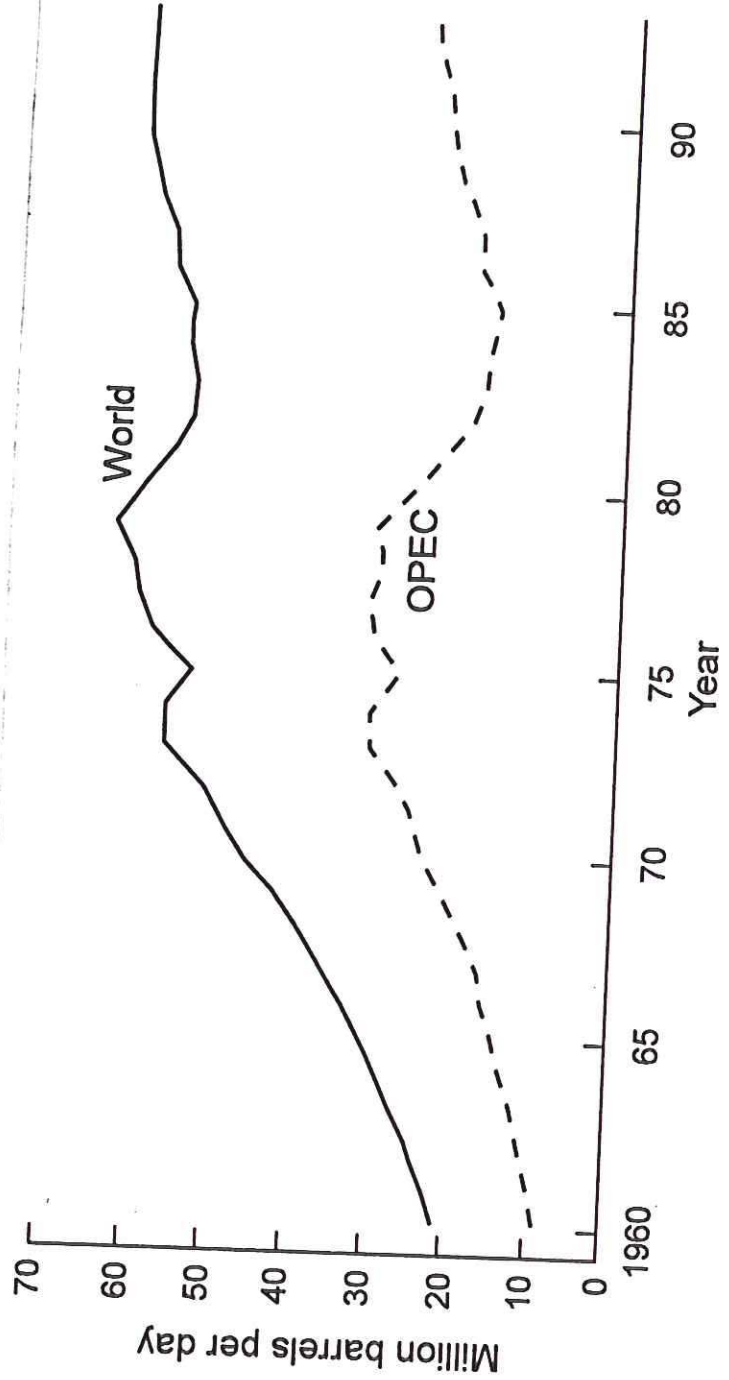


Figure 8.39.
 Production by the
 leading crude oil
 producers, 1960-93.
 (Annual Energy
 Review 1993)

Figure 8.38.
Crude oil production,
1960-93; the world and
OPEC. (*Annual Energy
Review 1993*)



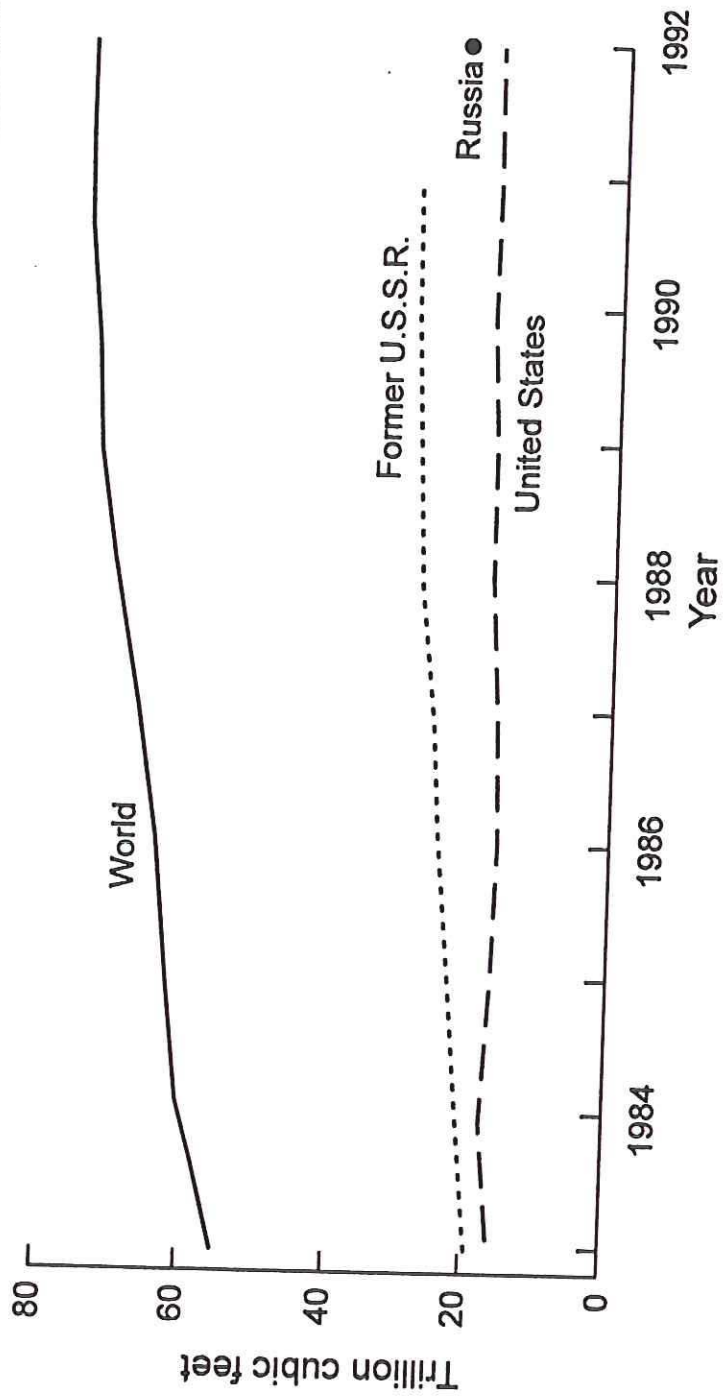
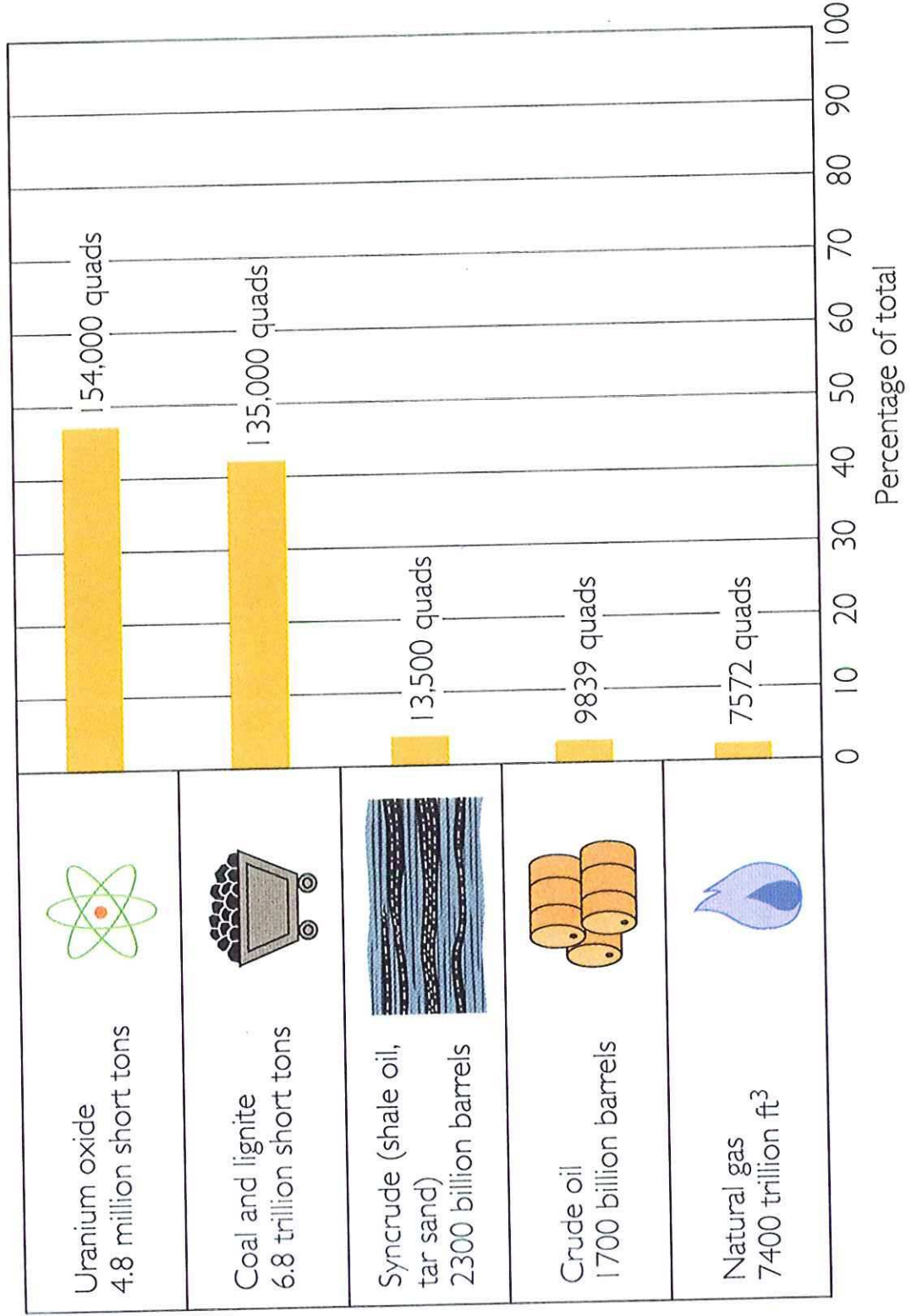


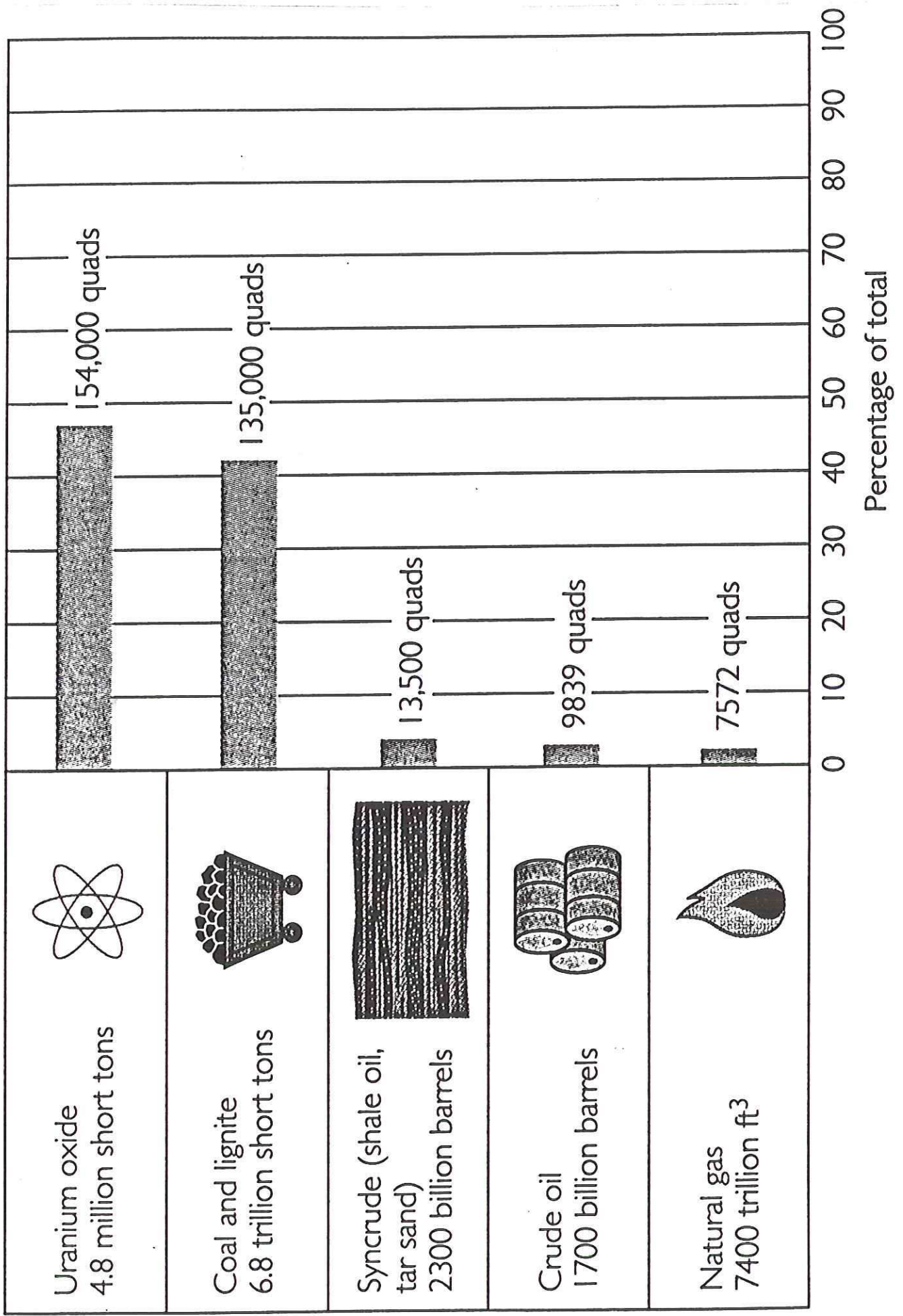
Figure 8.44.

Natural gas production in the United States, the former USSR, and the world as a whole between 1983 and 1992. (*Annual Energy Review 1993*)

TOTAL WORLD RESOURCES



TOTAL WORLD RESOURCES



In 1949, I was at Raffles College (now the University of Singapore) when their new library, not yet built, received a complete set (1662–1930's) of the *Philosophical Transactions of the Royal Society of London*. I took the beautiful calf-bound volumes into protective custody and set them in ten-year piles on the bedside bookshelves. For a year I read them cover to cover, thereby getting my initial education as a historian of science. As a side product, noting that the piles made a fine exponential curve against the wall, I counted all the other sets of journals I could find and discovered that exponential growth, at an amazingly fast rate, was apparently universal and remarkably long-lived.

Derek de Solla Price
1983

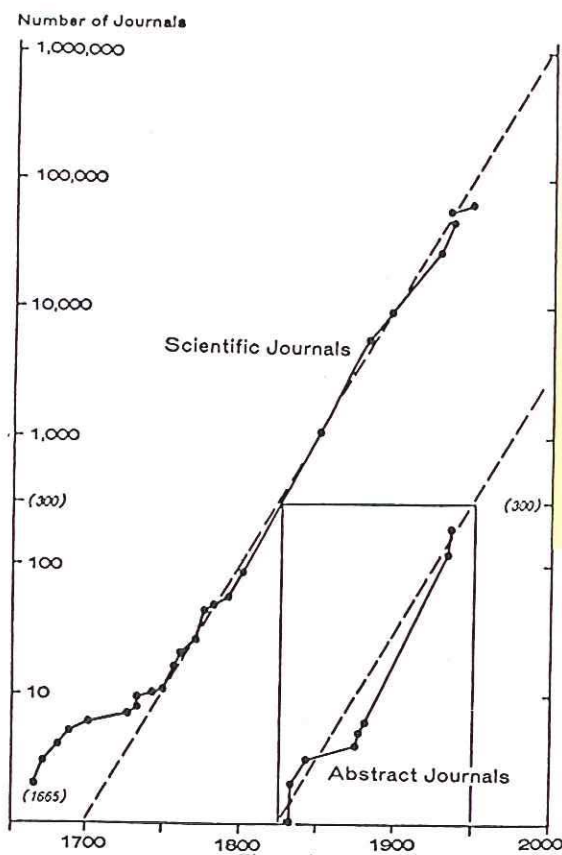


Figure 8.1
Number of journals founded (not surviving) as a function of date. The two uppermost points are taken from a slightly differently based list.

John on
growth
of science

Derek de Solla Price,
1961, *Science
Since Babylon*.
Yale Univ Press

"Geology" Publication Rates

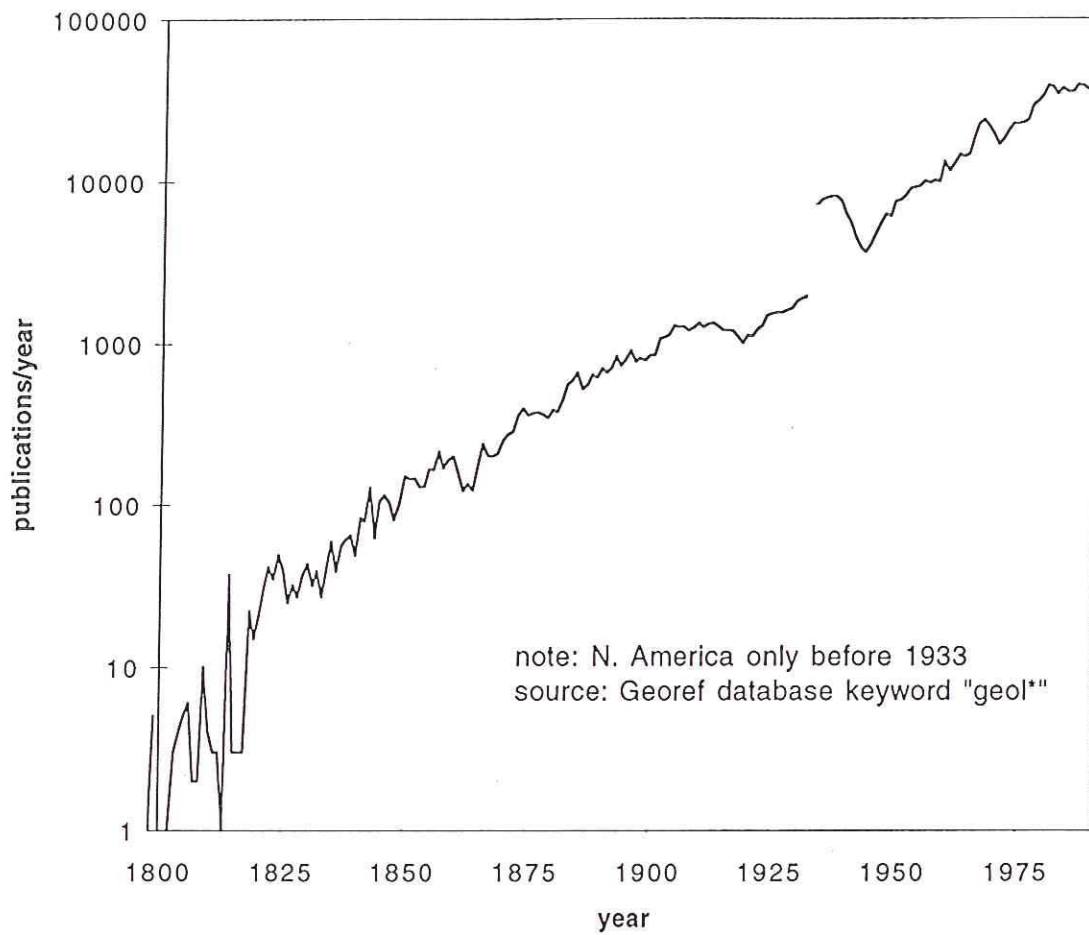
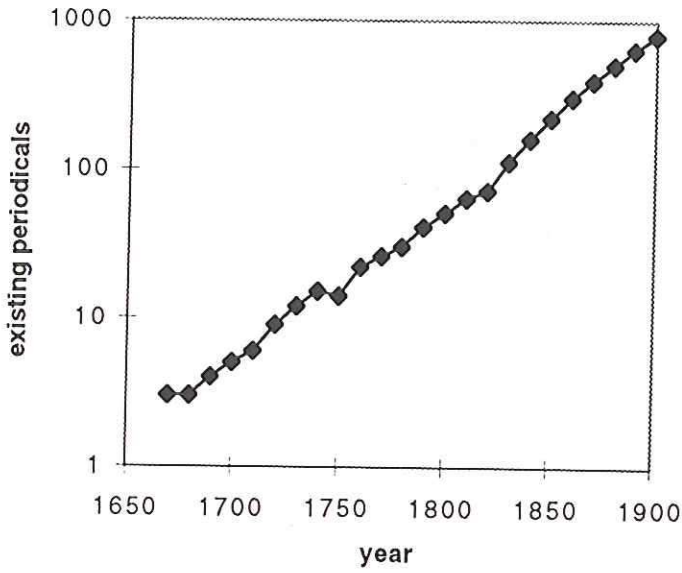


Table 1: The Doublings of North American & World Geologic Literature since 1818.

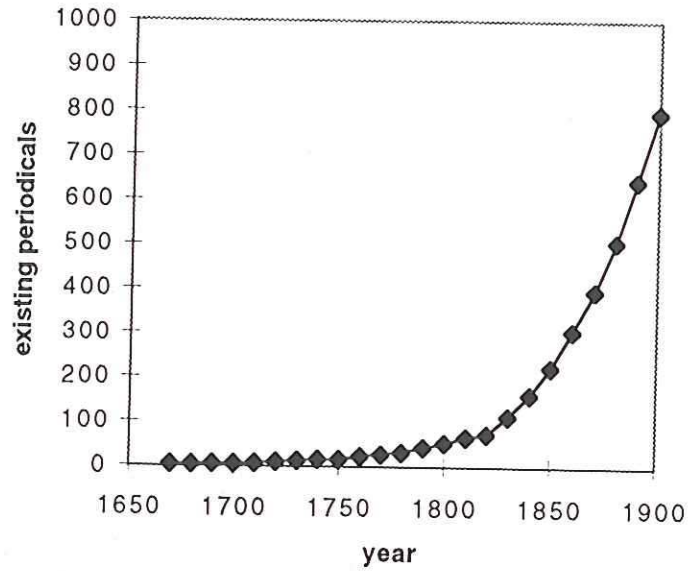
date	cumulative publications	cumulative percent
1818	134	0.01%
1823	277	0.02%
1830	530	0.04%
1840	999	0.08%
1850	2,012	0.16%
1863	3,961	0.32%
1878	8,306	0.65%
1892	16,155	1.3%
1909	33,219	2.6%
1932	65,479	5.2%
1941	131,362	10%
1959	261,893	21%
1974	530,291	42%
1990	1,066,976	84%
1998	1,270,537	100%

*Based on references to 'geology' in the comprehensive *Georef* digital database, published by the American Geological Institute. This database covers North American literature from 1785 until 1933, at which point it expands to worldwide coverage.

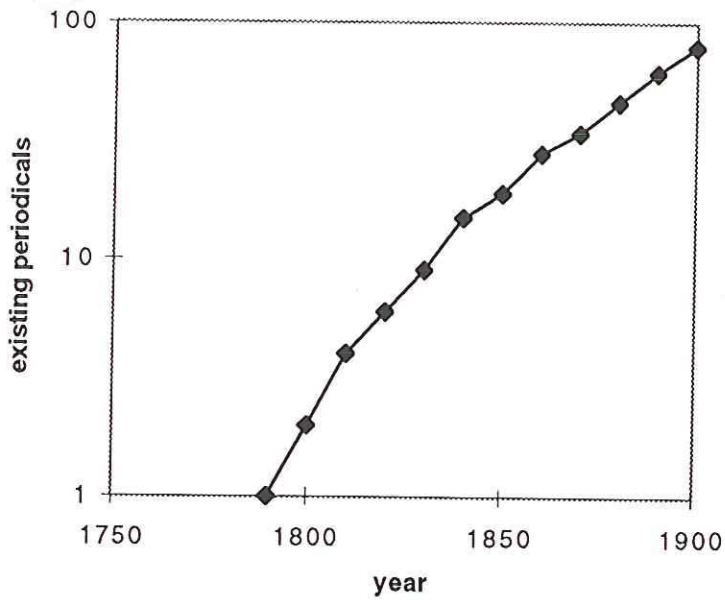
Gascoigne (1985): Scientific Periodicals



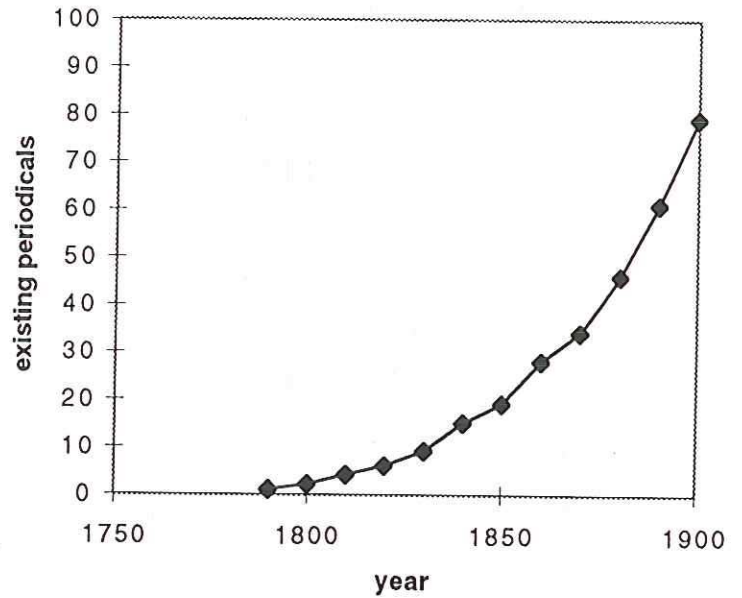
Gascoigne (1985): Scientific Periodicals



Gascoigne (1985): Geology Periodicals

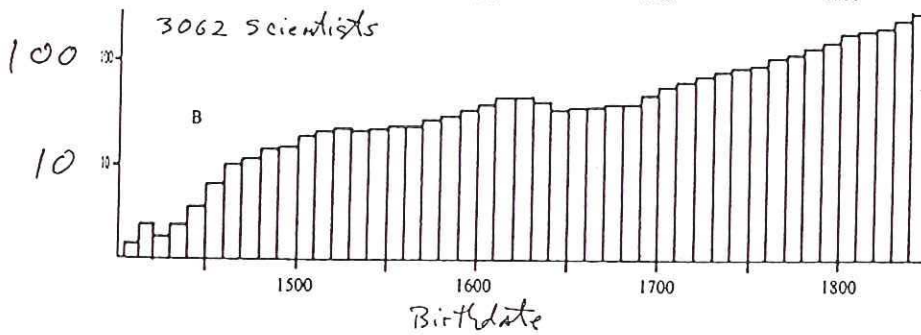
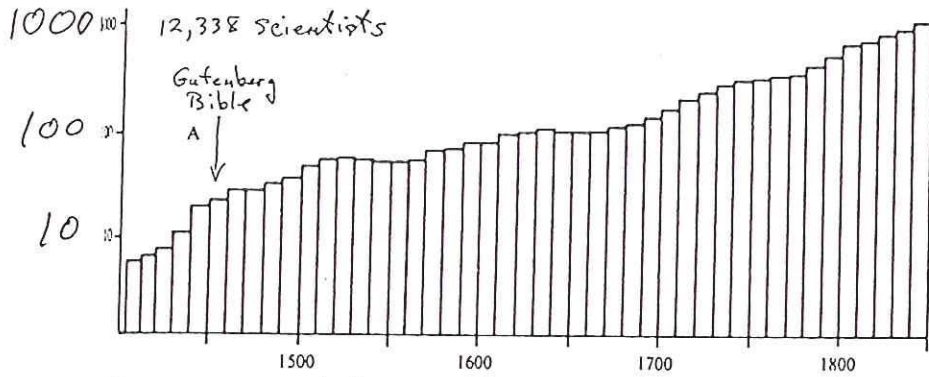


Gascoigne (1985): Geology Periodicals

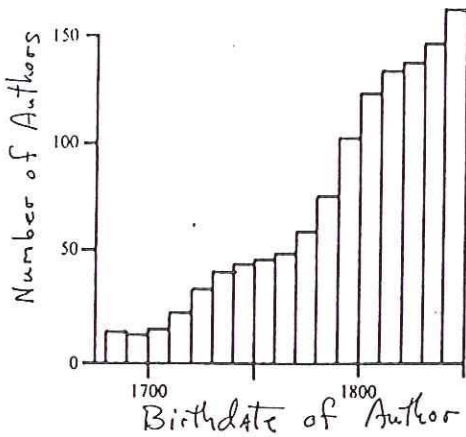


Gascoigne, R.M., 1985, A Historical Catalogue of Scientific Periodicals, 1665-1900. Garland, New York.

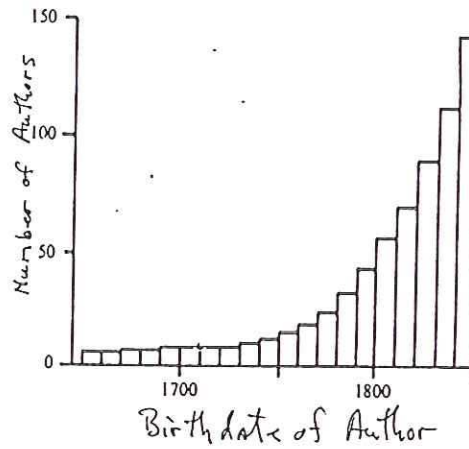
All Countries (Logarithmic Scale)
 A: Data from HCS (Hist Cat Sci + Sci Books)
 B: Data from DSB (Dict. Sci - Biography)



Geology: Data from HCS
 (Historical Catalogue of Scientists
 and Scientific Books)



United States: Data from HCS



Robert Gascoigne, 1992,
 "The historical demography
 of the scientific community,
 1450-1900"
 Social Studies of Science,
 v. 22, pp. 545-573.

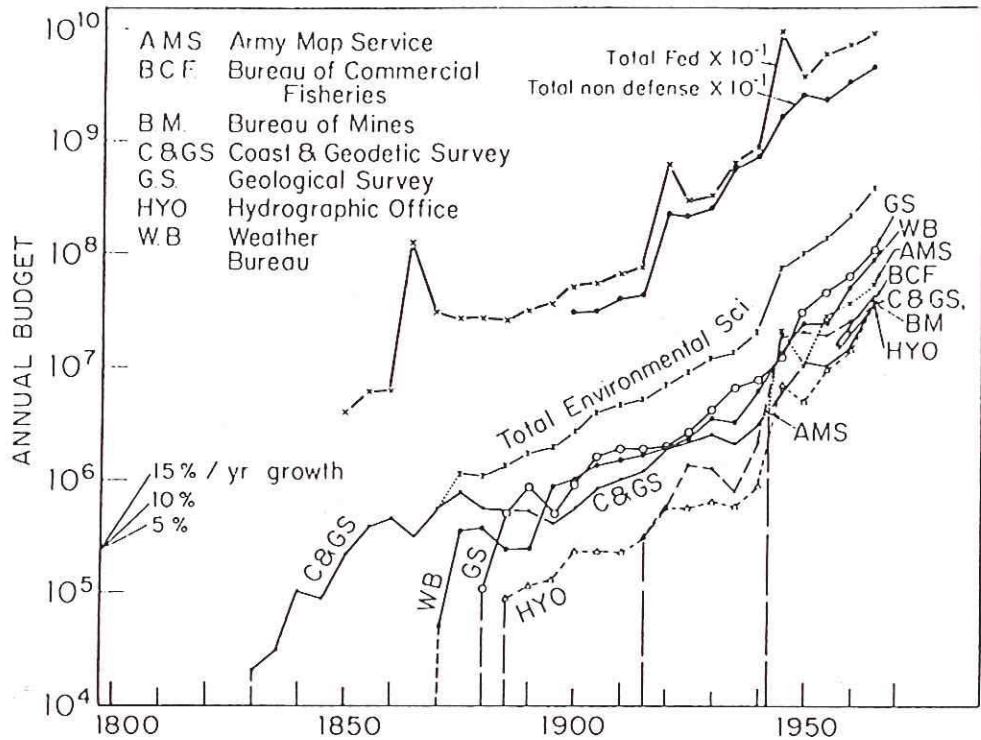
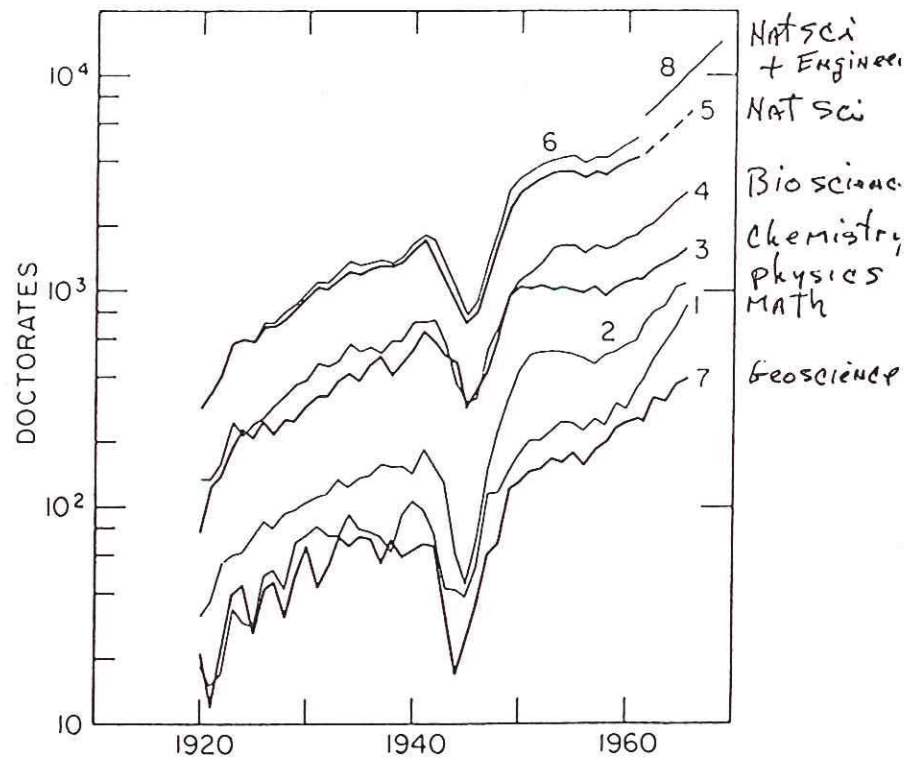
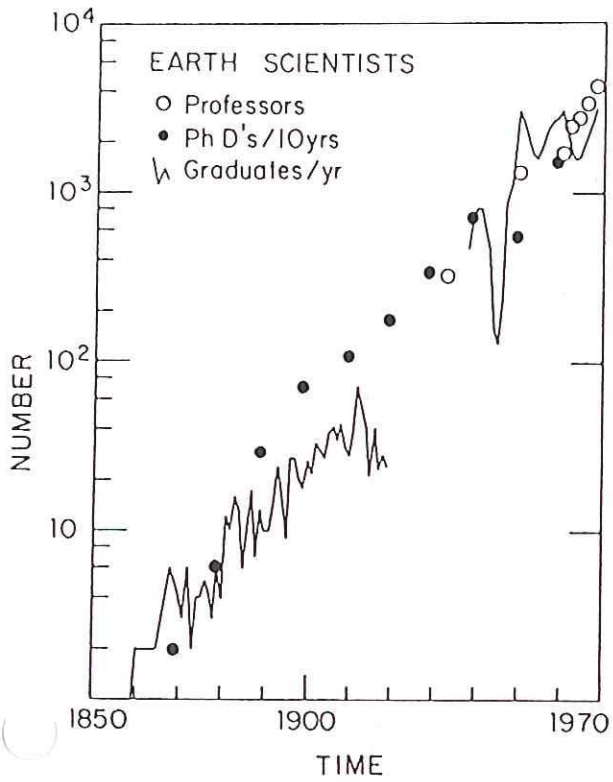


Fig. 8.1 Annual budgets of federal agencies concerned with the environmental sciences compared with the nondefense and total federal budget.



Menard, H., 1971, Science: Growth and Change. Harvard U. Press

Knowledge begets knowledge as money bears interest.

—A. CONAN DOYLE, *The Great Keinplatz Experiment*

I. ADAMS' LAW

By the end of the nineteenth century no clear-eyed observer could fail to remark the striking pace of scientific advance. But among the first to detail this phenomenon in exact terms—indeed to give it mathematical formulation—was Henry Brooks Adams (1838–1918), the American scholar, historian, and student of cultural affairs. (He was a grandson of John Adams, George Washington's successor as President.) Noting that scientific work increased at a rate fixed by a constant doubling-time—so that science has an *exponential* growth-rate—Adams characterized this circumstance as a “law of acceleration” governing the progress of science. He wrote:

Laplace would have found it child's play to fix a ratio in the progression in mathematical science between Descartes, Leibnitz, Newton and himself. . . . Pending agreement between . . . authorities, theory may assume what it likes—say a fifty or even a five-and-twenty year period of reduplication . . . for the period matters little once the acceleration itself is admitted.¹

¹ *The Education of Henry Adams* (Boston, 1918; privately printed already in 1907), chapter 34 (see p. 491). This chapter was written in 1904. The earliest anticipation of Adams' principle of exponential growth that I know of occurs in an *obiter dictum* in the 1901 Presidential Address to the British Association for the Advancement of Science by William Thomson (Lord Kelvin):

Scientific wealth tends to accumulate according to the law of compound interest. Every addition to knowledge of the properties of matter supplies the naturalist with new instrumental means for discovering and interpreting phenomena of nature, which in their turn afford foundations for fresh generalizations. (Reprinted in G. Basalla, William Coleman, and R. H. Kargon [eds.], *Victorian Science: A Self-Portrait Through the Presidential Addresses of the British Association for the Advancement of Science* [New York, 1970], pp. 101–128 [see p. 114], and compare p. 488.)

The idea occurs in embryonic form in A. Conan Doyle's 1894 short story *The Great Keinplatz Experiment*, in whose opening paragraph the professorial protagonist is described as follows:

As . . . the worthy professor's stock of knowledge increased—for knowledge begets knowledge as money bears interest—much which had seemed strange and unaccountable began to take another shape in his eyes. New trains of reasoning became familiar to him, and he perceived connecting links where all had been incomprehensible and startling.

Rescher, Nicholas, 1978,
Scientific Progress.
Univ. Pittsburgh Press

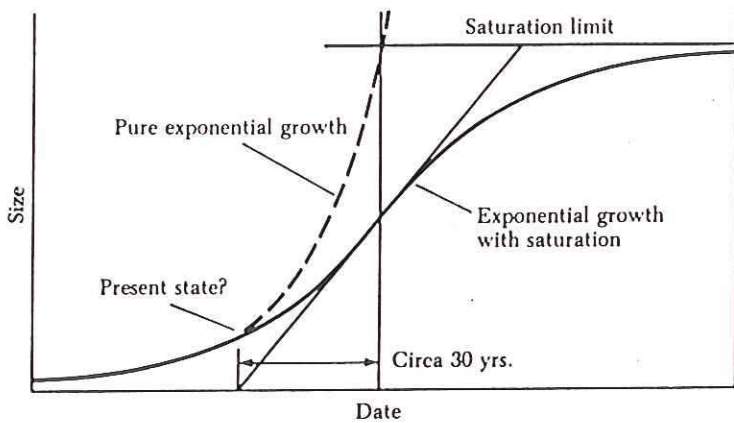


Figure 1.5. General Form of the Logistic Curve

From Derek J. de Solla Price, *Science Since Babylon* (New Haven, Yale University Press, 1961).

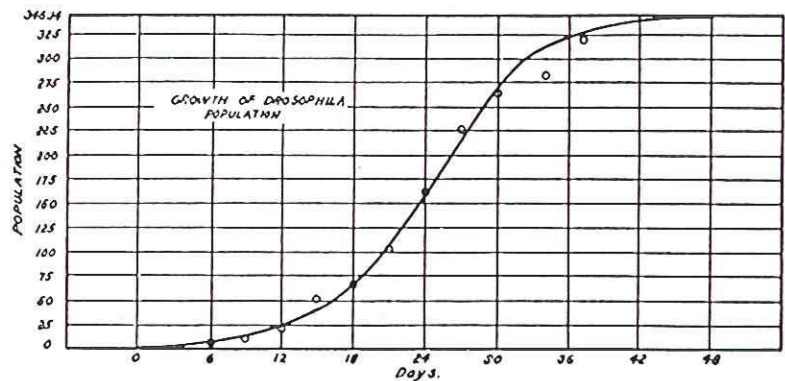


FIG. 5. GROWTH OF A POPULATION OF DROSOPHILA (FRUIT FLIES) UNDER CONTROLLED EXPERIMENTAL CONDITIONS, ACCORDING TO PEARL AND PARKER

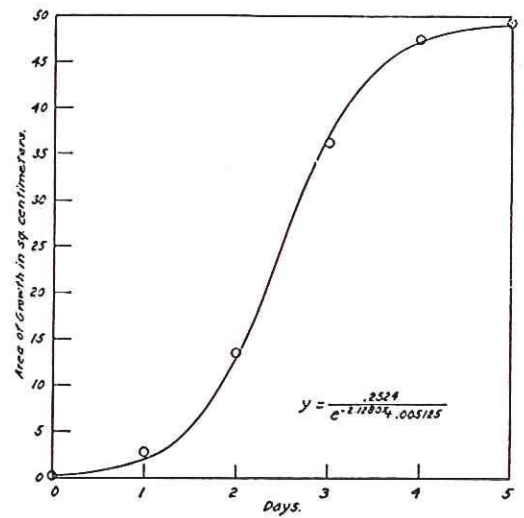


FIG. 6. GROWTH OF A BACTERIAL COLONY (*B. DENDROIDES*)
Observations by H. G. Thornton

Extrapolation of Logistic Curves

$$X = -\frac{\frac{a}{b}}{1 + e^{-at}} \quad (12)$$

the symbol t' denoting time reckoned from the origin indicated.⁵

Population of United States. Formula (12) has been applied by Pearl and Reed⁶ to the population growth of the United States.⁷ The calculated curve for the number N of the population fits the observed data over a long period of years (1790 to 1910) with remarkable faithfulness, as will be seen from table 2 and the graph shown in figure 4. Numerically the formula (12) here takes the form

$$N = \frac{197,273,000}{1 + e^{-0.03134t'}} \quad (14)$$

and the time t' (in years) is dated from April 1, 1914 (t' , being negative for dates anterior to this). This epoch is one of peculiar interest. It represents the turning point when the population passed from a progressively increasing to a progressively diminishing rate of growth. Incidentally it is interesting to note that if the population of the

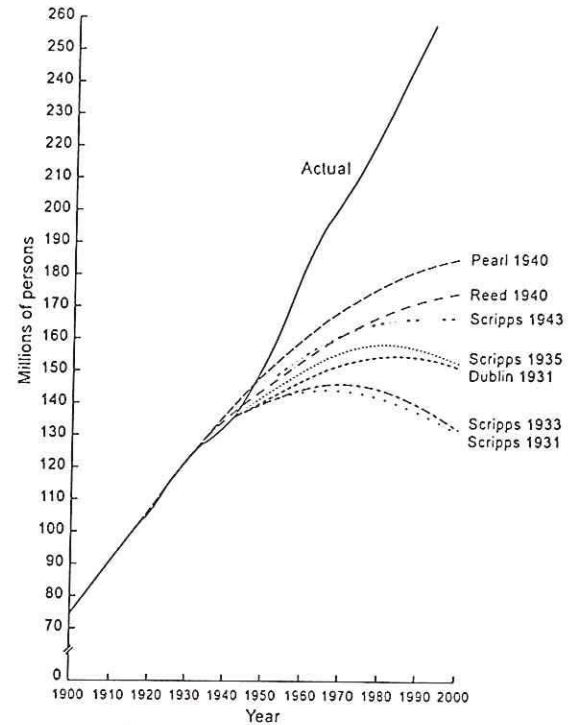


Figure 5.13. U.S. population forecasts made between 1931 and 1943, and the actual population increase during the twentieth century.

TABLE 2

Results of fitting United States population data 1790 to 1910 by equation (14)

YEAR	OBSERVED POPULATION	CALCULATED POPULATION BY EQUATION (14)	ERROR
1790	3,929,000	3,929,000	0
1800	5,308,000	5,336,000	+28,000
1810	7,240,000	7,228,000	-12,000
1820	9,638,000	9,757,000	+119,000
1830	12,866,000	13,109,000	+243,000
1840	17,069,000	17,506,000	+437,000
1850	23,192,000	23,192,000	0
1860	31,443,000	30,412,000	-1,031,000
1870	38,558,000	39,372,000	+814,000
1880	50,156,000	50,177,000	+21,000
1890	62,948,000	62,769,000	-179,000
1900	75,995,000	76,870,000	+875,000
1910	91,972,000	91,972,000	0

United States continues to follow this growth curve in future years, it will reach a maximum of some 197 million souls, about double its present population, by the year 2060 or so. Such a forecast as this, based on a rather heroic extrapolation, and made in ignorance of the physical factors that impose the limit, must, of course, be accepted with reserve.

Lotka Elements of
Mathematical Biology
1st pub 1923

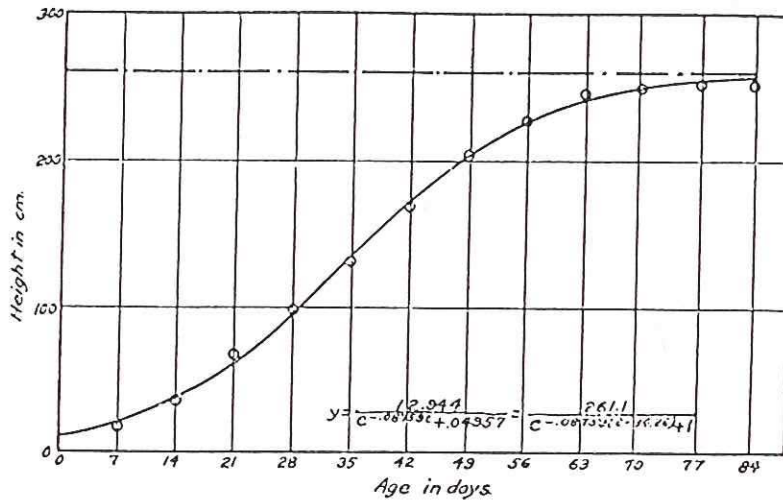


FIG. 8. GROWTH OF SUNFLOWER SEEDLINGS ACCORDING TO H. S. REED AND R. H. HOLLAND; COMPUTED CURVE BY L. J. REED

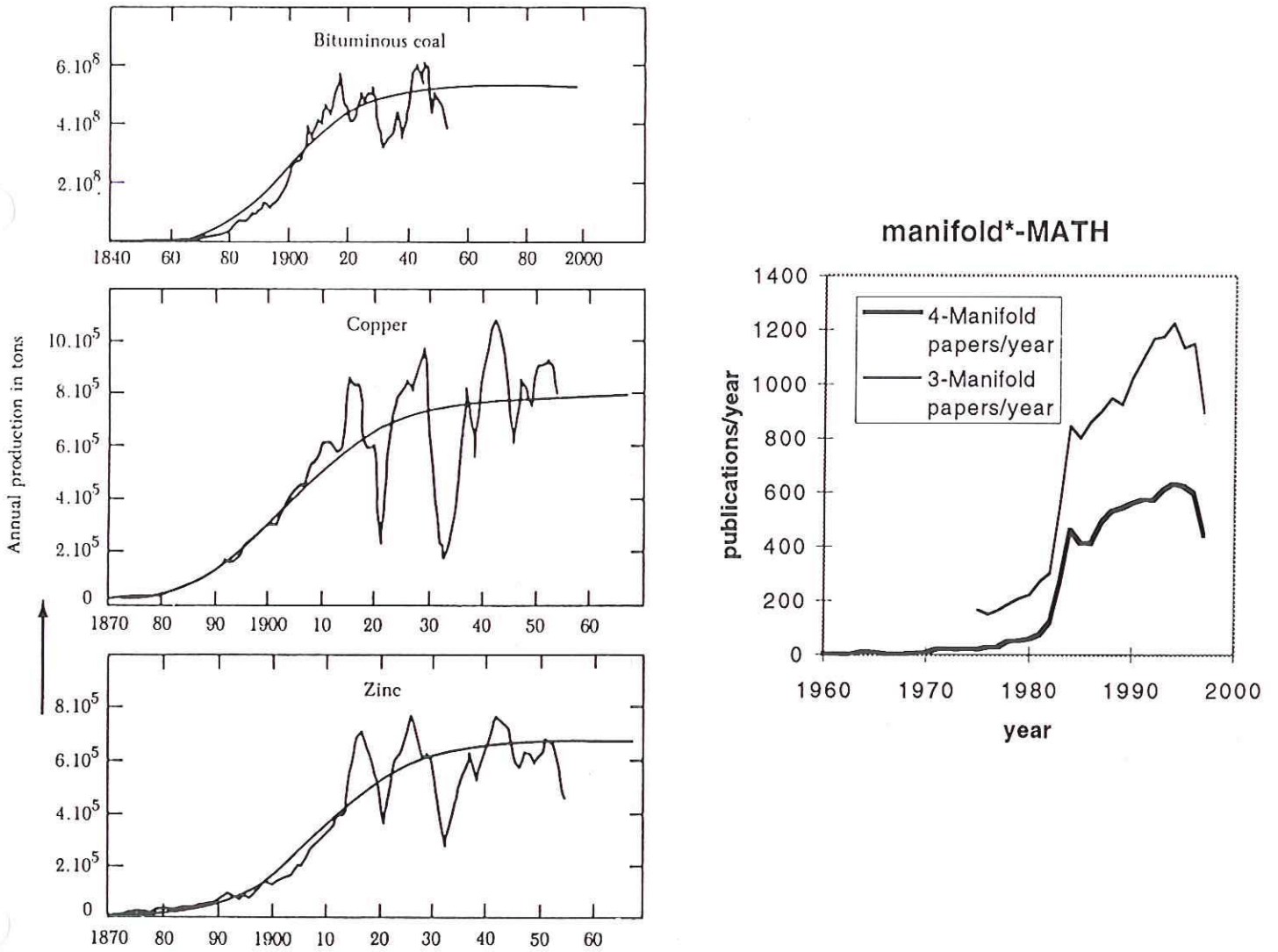
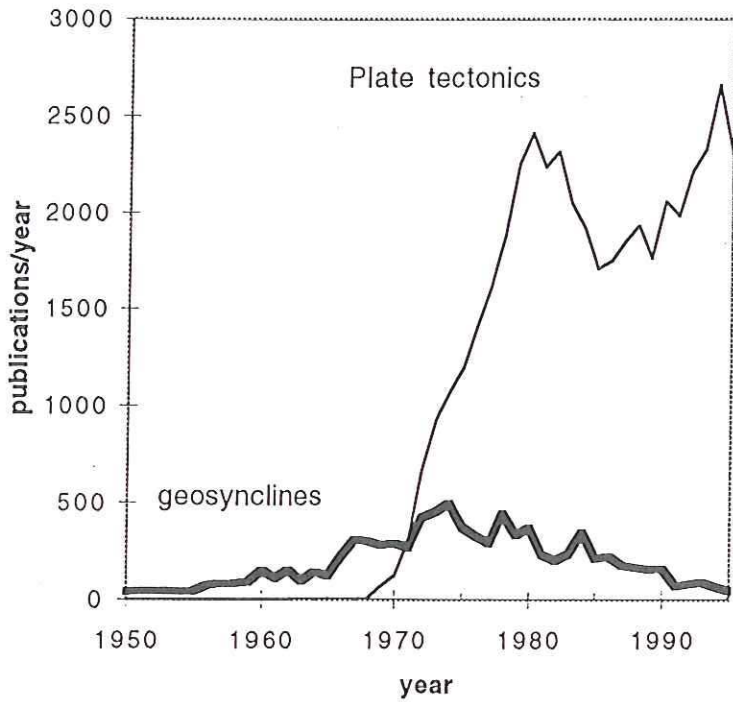


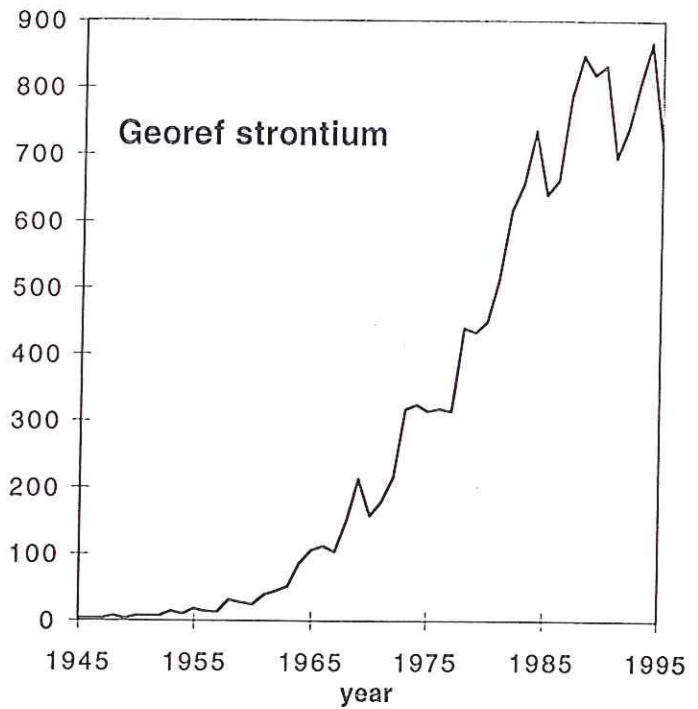
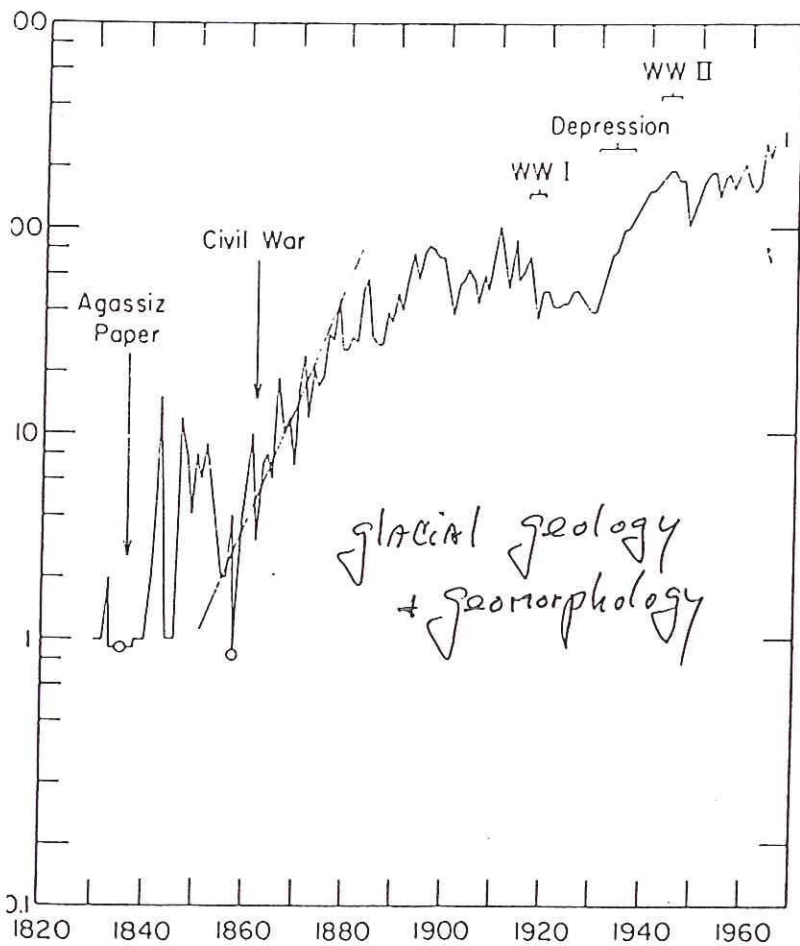
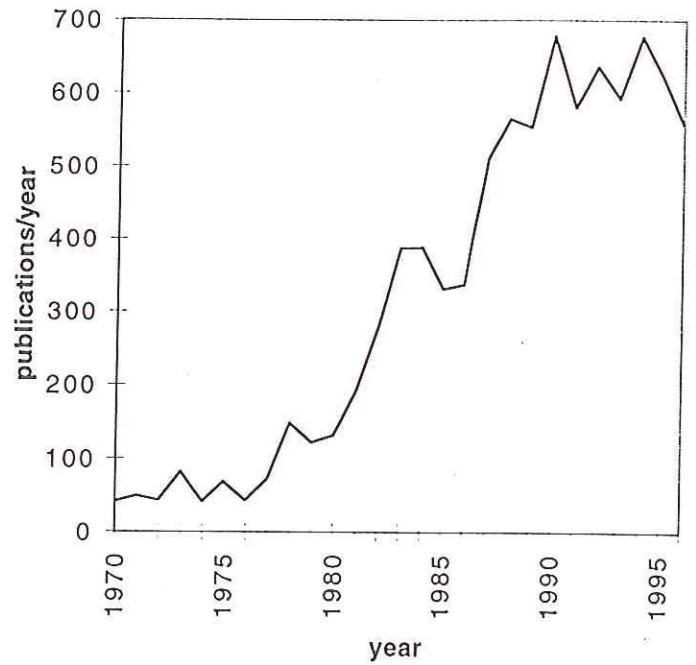
Figure 1.8. Logistic Growth of Raw Material Production, Showing Oscillation on Attaining Ceiling Conditions

Adapted from S. G. Lasky, "Mineral industry futures can be predicted," *Engineering and Mining Journal* (September 1955), Vol. 15b.

Plate tectonic revolution

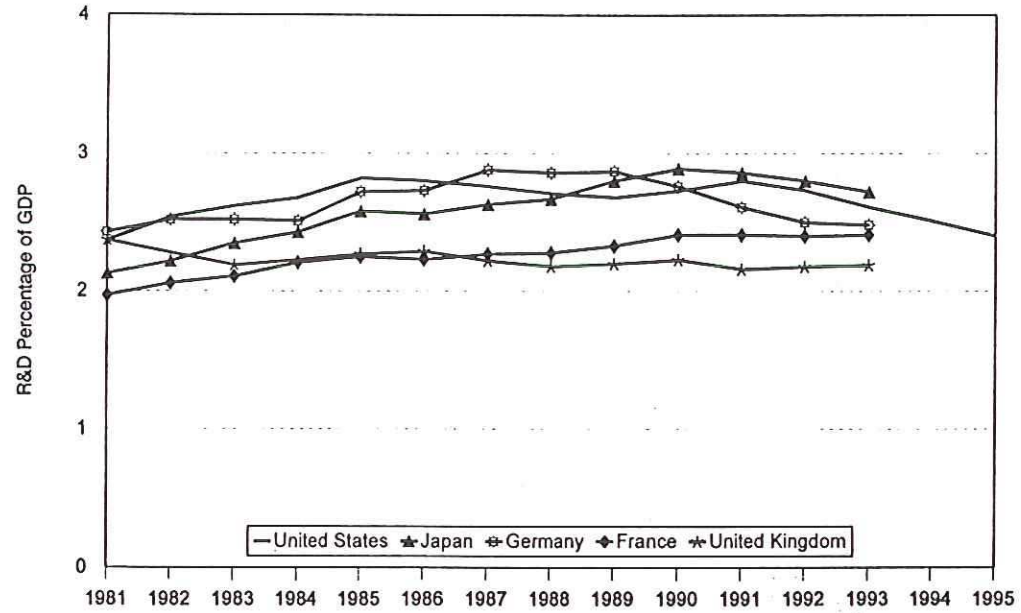
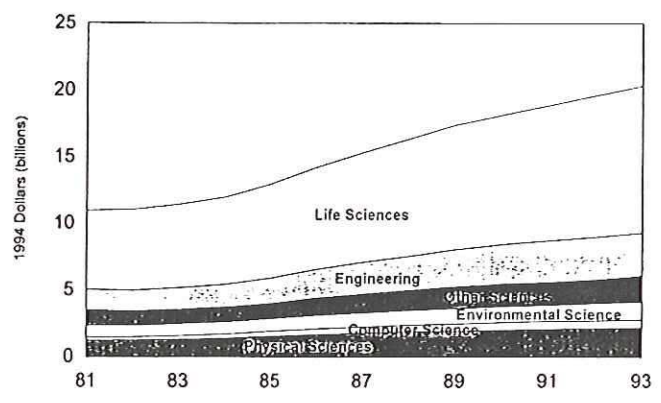
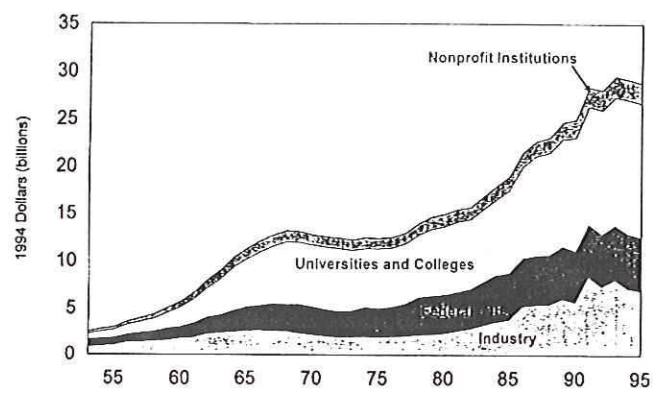


Neodymium georef citations

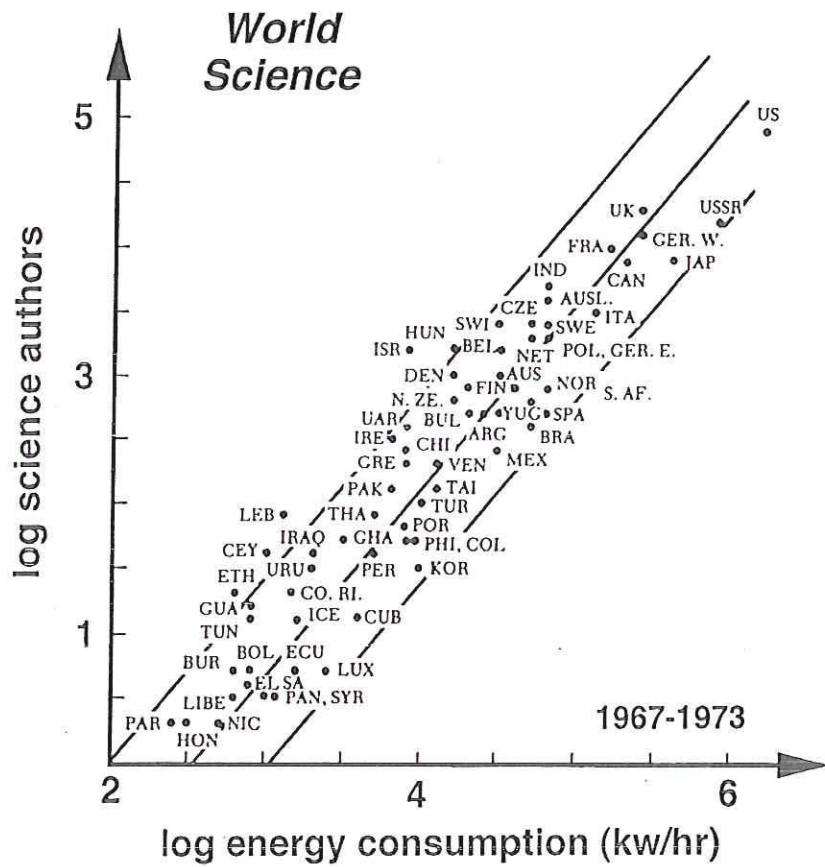


John Siegel

NATIONAL ACADEMY OF SCIENCES COLLOQUIUM:



SCIENCE, TECHNOLOGY AND THE ECONOMY



Derek J. de Solla Price, 1986

Do major discoveries in science grow linearly?

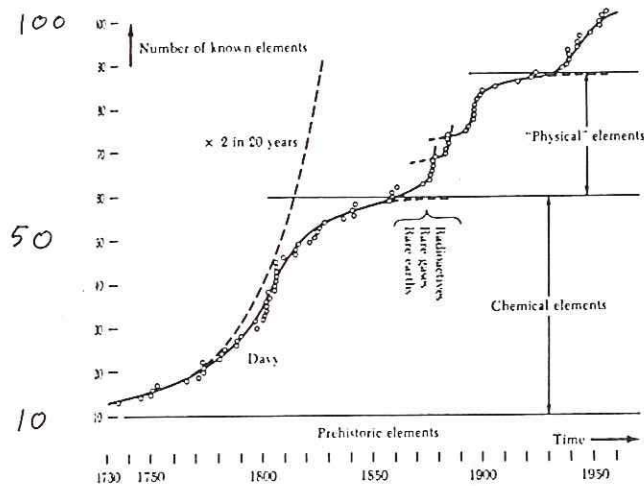


Figure 1.11. Number of Chemical Elements Known as a Function of Date

After the work of Davy there is a clear logistic decline followed by a set of escalations corresponding to the discovery of elements by techniques that are predominantly physical. Around 1950 is the latest escalation produced by the manufacture of transuranic elements.

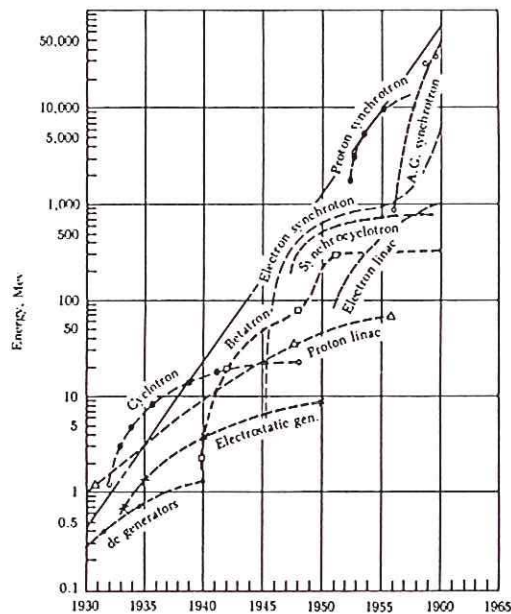
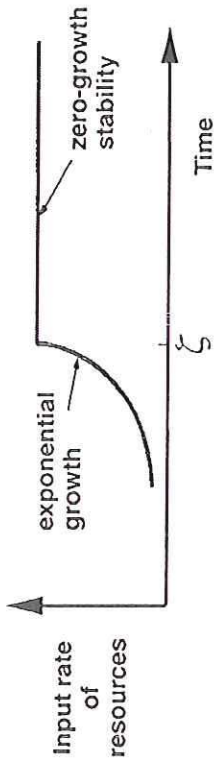


Figure 1.10. The Rate of Increase of Operating Energy in Particle Accelerators

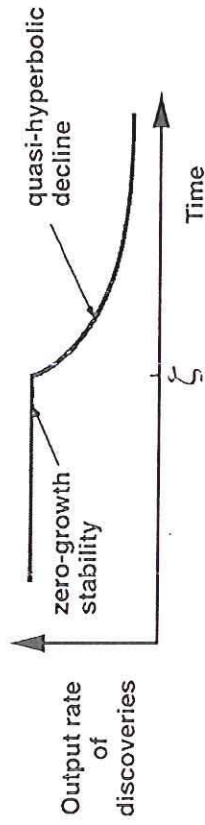
From M. S. Livingston and J. P. Blewett, *Particle Accelerators* (New York: McGraw-Hill, 1962), p. 6, figure 1.1, used by permission.

The Transition from Exponential Growth to Zero Growth in Resources for Scientific Discovery

A. Input History



B. Output History



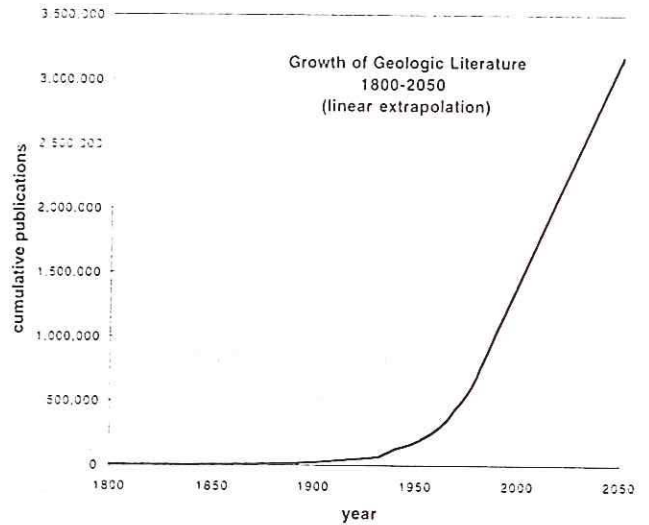
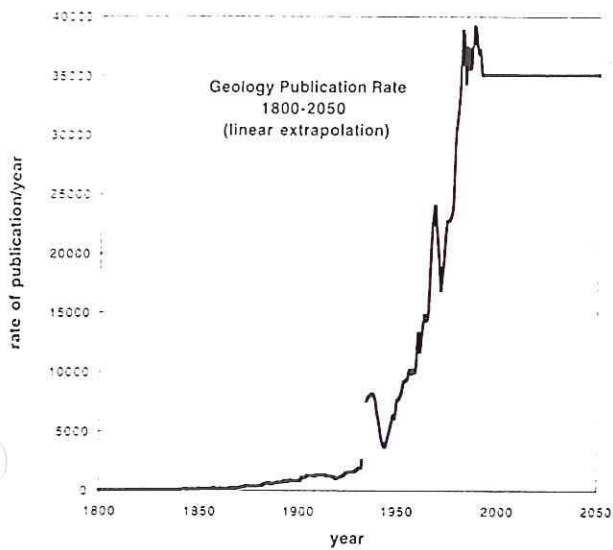
after Rescher, 1978

Observed

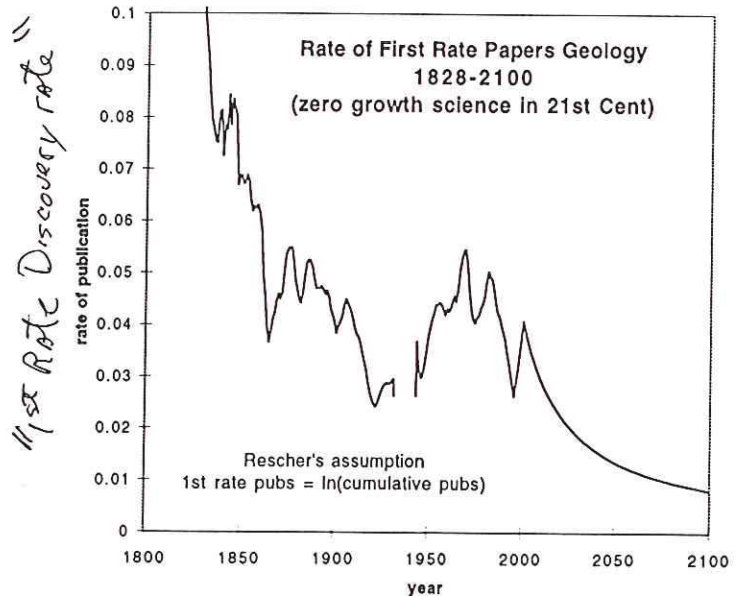
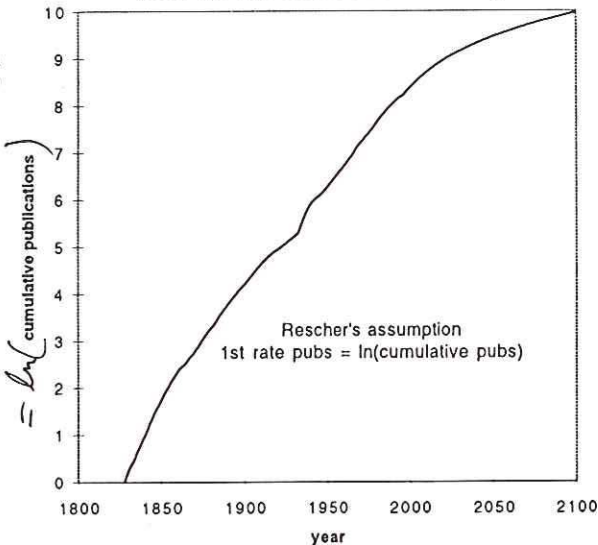
rate ordinary science \propto rate of resources

Idea (unsubstantiated)

First-Rate Discoveries \propto \ln cumulative resources
 \propto \ln cumulative ordinary science



first-rate publications geology
1828-2100
(zero growth science in 21st Cent)



1st Rate Discoveries

"1st Rate Discovery rate"

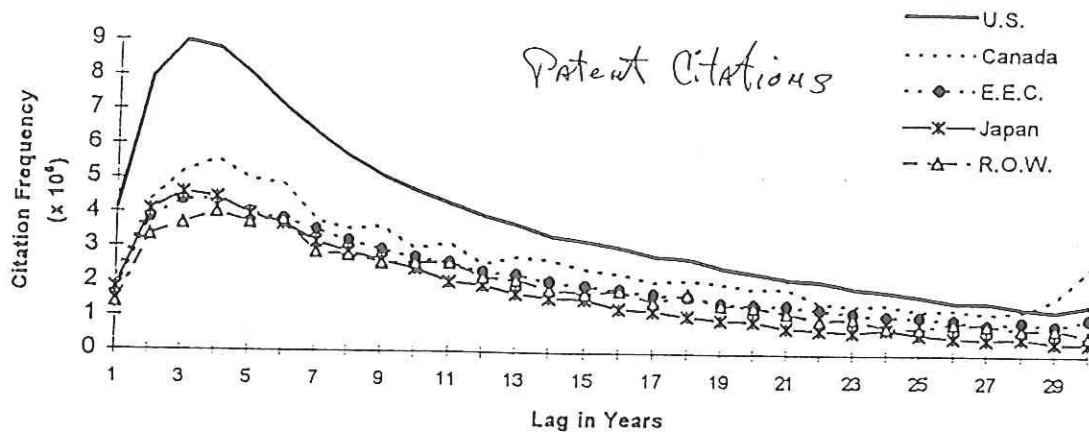


FIG. 1. Plot of the average citation functions for each of five geographic regions (citation frequency as a function of time elapsed from each potentially cited patent).

Citations to 1984 Nd isotope papers

pub/yr (years = 83, 84, 85, 90)

