Where in the World Can We Find Clean, Safe, Long Lasting, and Economical Energy Sources for the 21st Century and Beyond?

Gerald L Kulcinski

Associate Dean-Engineering Research

University of Wisconsin

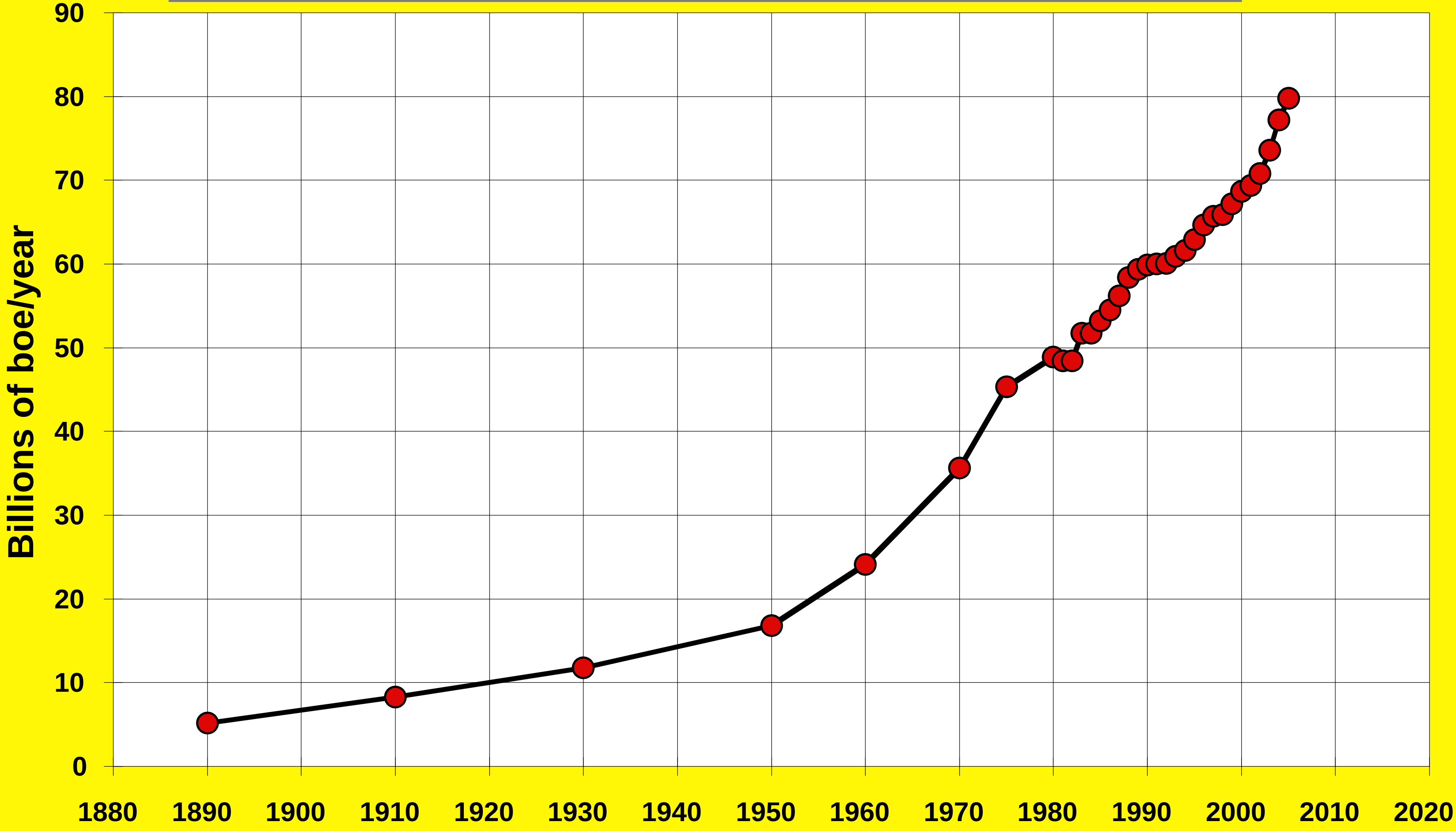
UCLA

November 6, 2007

Outline of Presentation

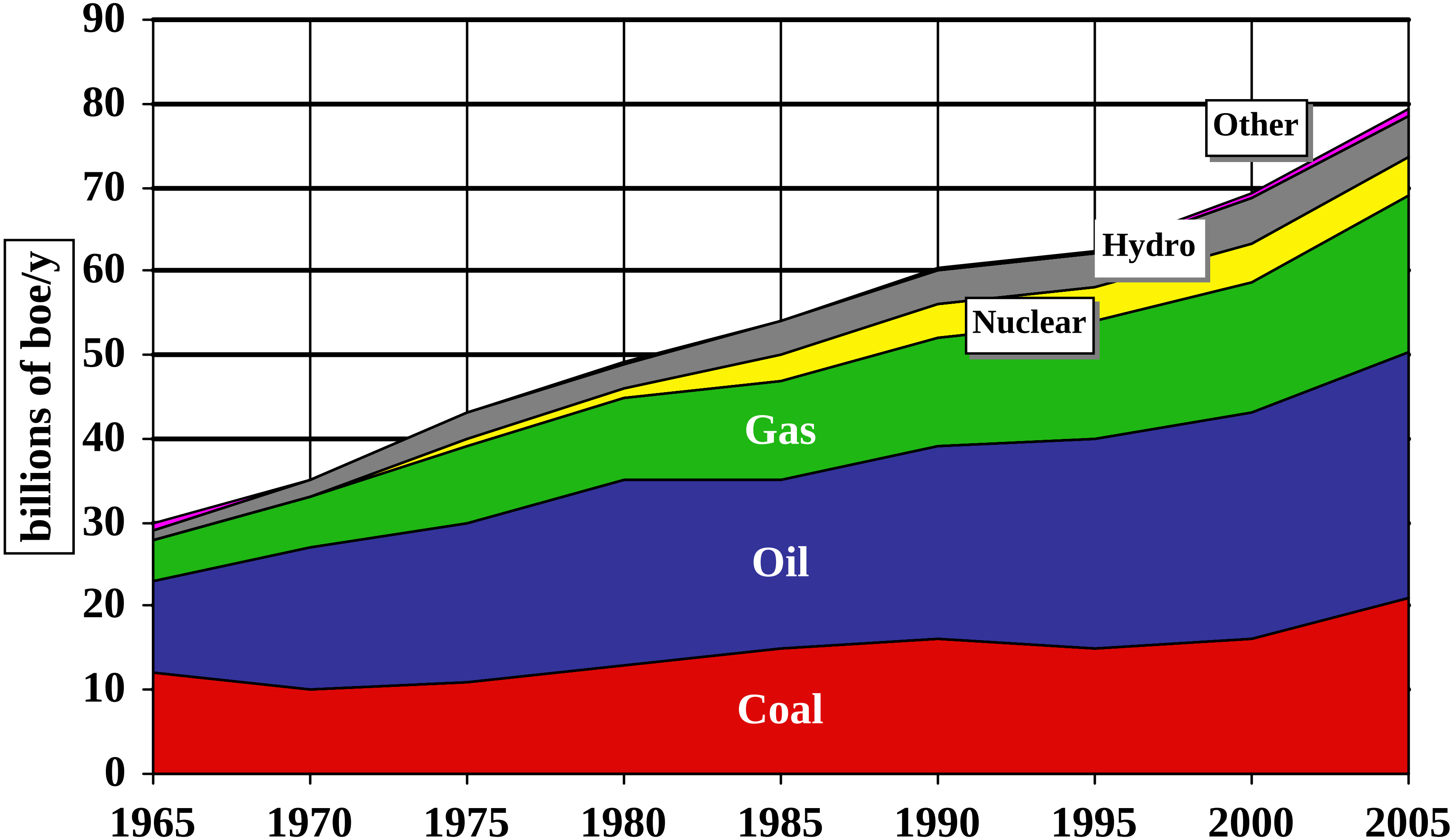
- Where we have been?--(History)
- Where we are now?--(Fact)
- Where are we going in the next ≈20-30 years?--(Projection)
- Where will we be in 100 years?--(Speculation)

The Total Energy Use in the World Has Increased by Over a Factor of 5 Since World War II



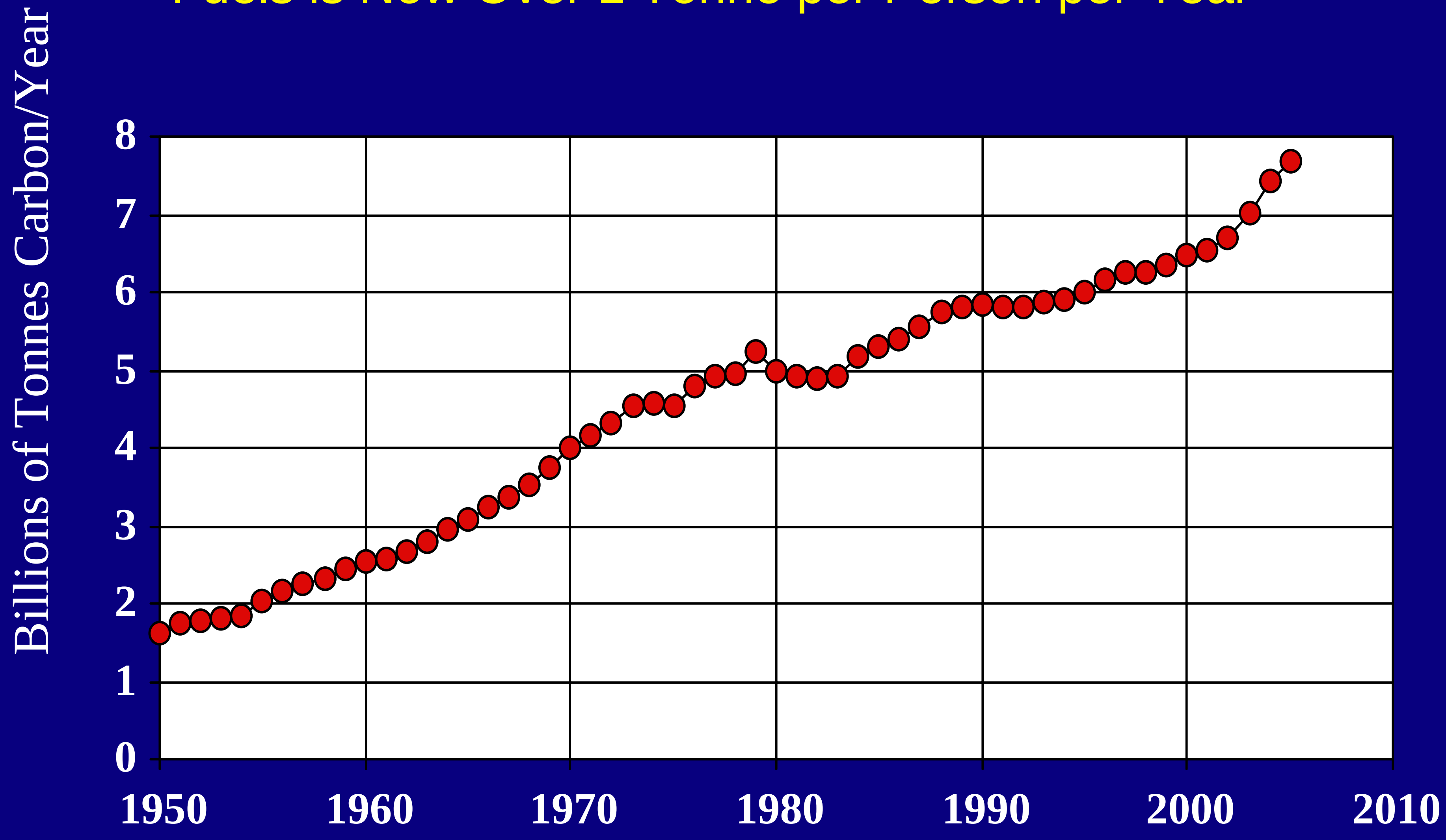
Sources: Hafele, Holdren, International Energy Annual Report-2005

Fossil Fuels Still Account for Over 85% of the Primary Energy Consumed in the World



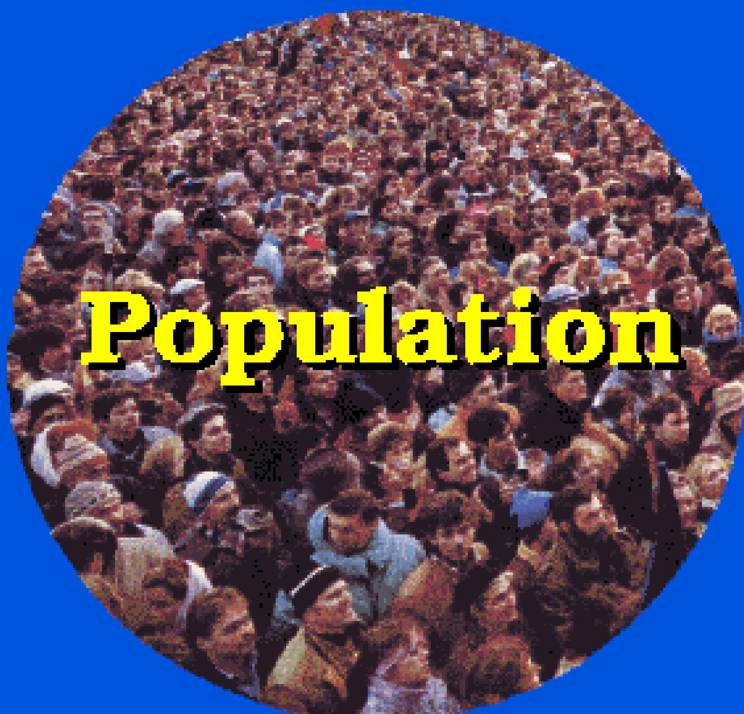
Source -International Energy Annual-2005, Publ. 2007

The Worldwide Emissions of Carbon from the Burning of Fossil Fuels is Now Over 1 Tonne per Person per Year



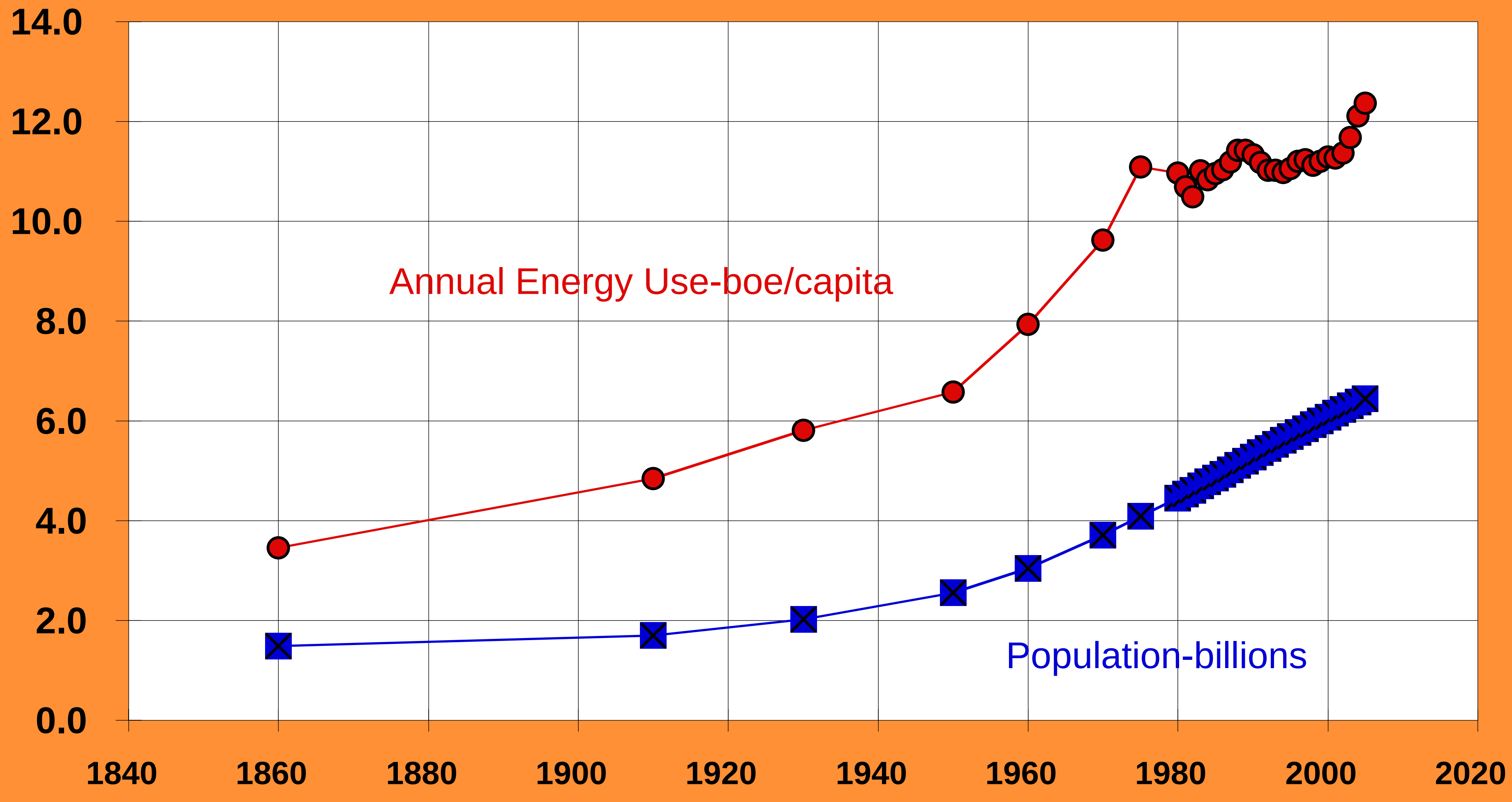
Energy Information Agency-International Energy Annual-2005, Table H-1, Publ. 2007

The World Energy Demand is the Product of Two Simple Numbers



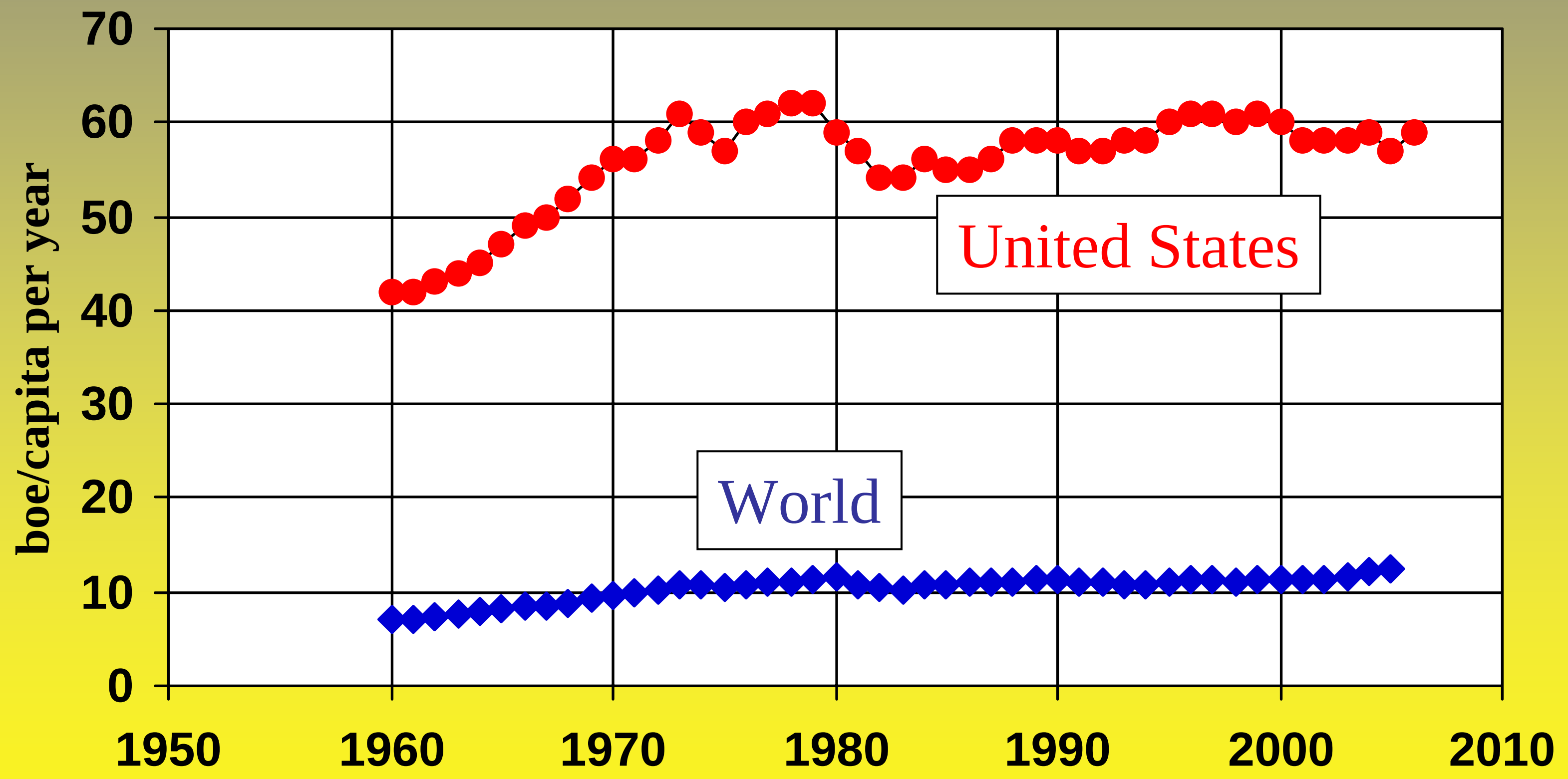
x

Annual World Energy Use Per Capita Has Started to Rise Again After Having Been Essentially Constant Since the 1973 Oil Crisis



Sources: Hafele, Holdren, International Energy Agency Annual Report-2005

The U. S. Continues to Use a Large Amount of Energy Per Capita

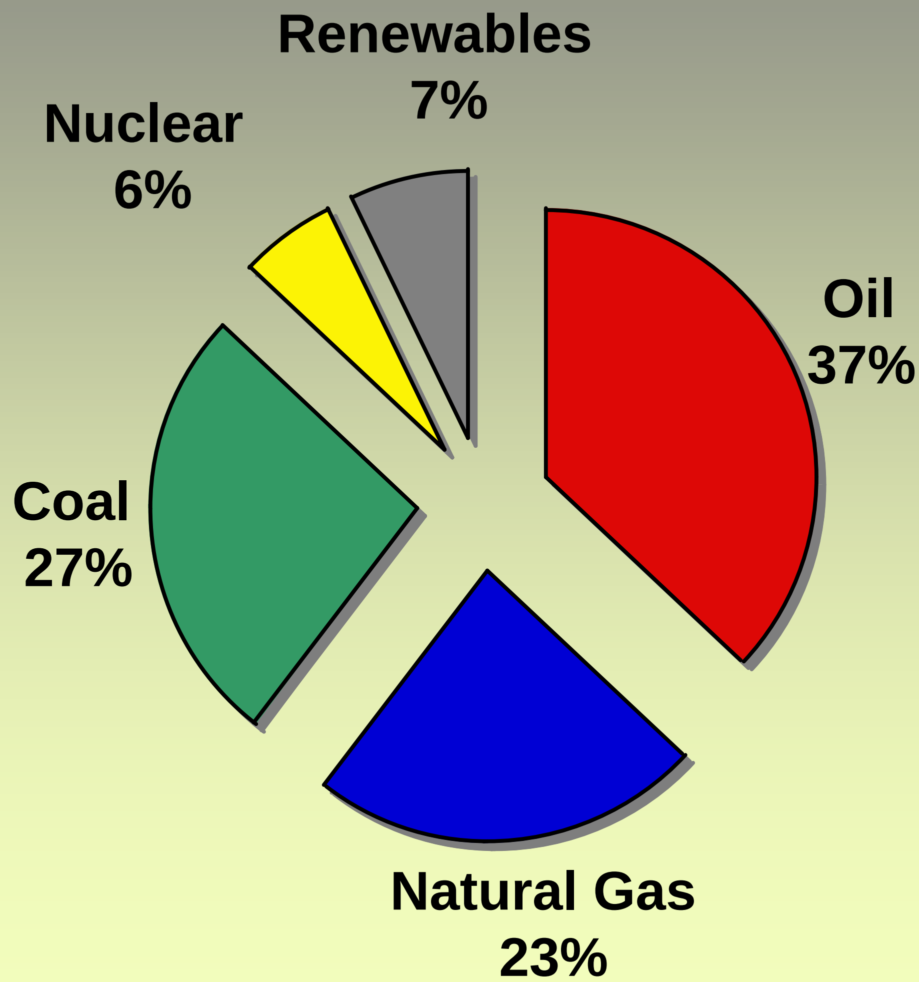


Source: EIA Monthly Energy Review-Dec 2006, U.S. Census Bureau , IEA-2005, Publ 2007

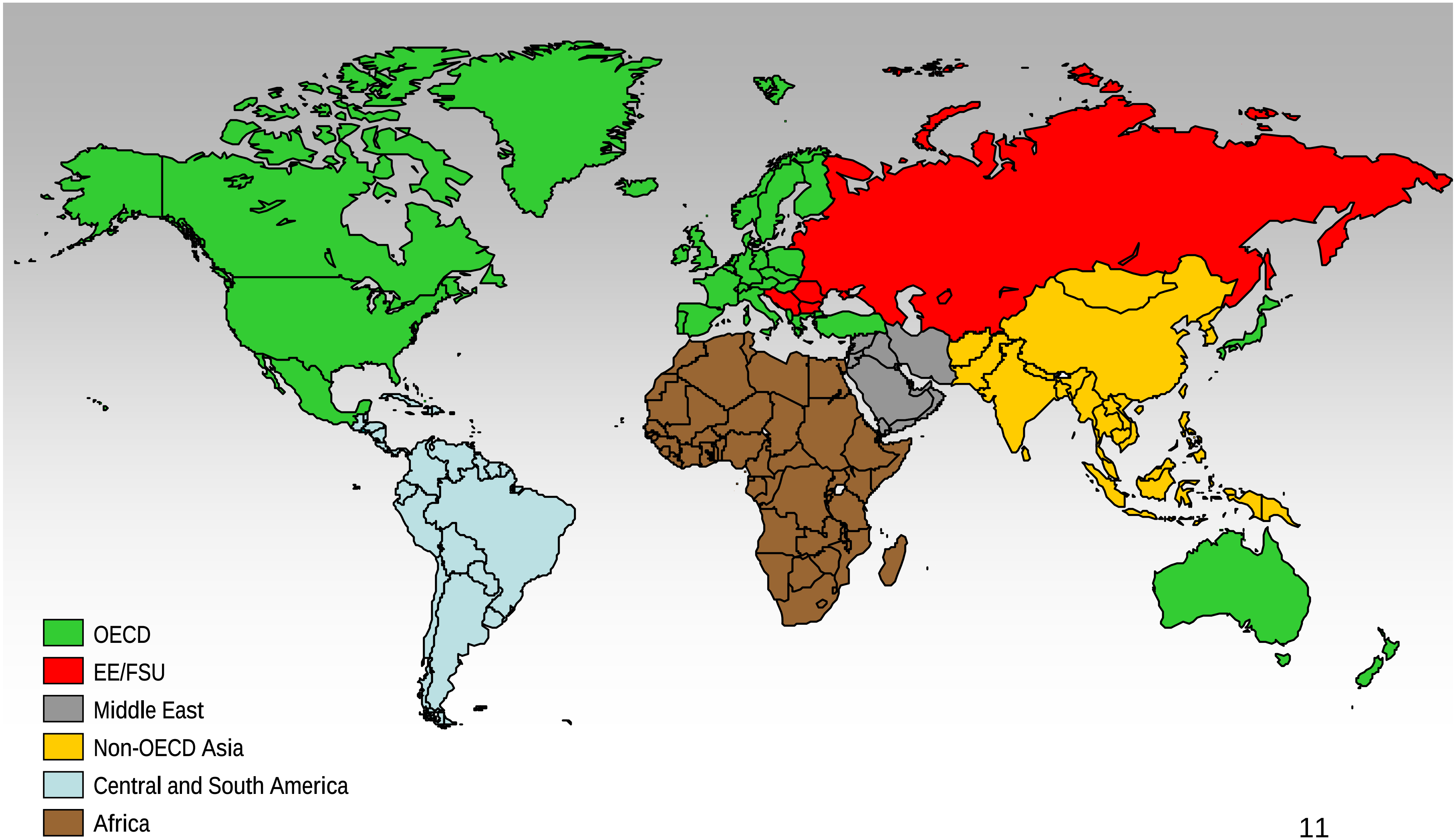
Outline of Presentation

- Where we have been?--(History)
- Where we are now?--(Fact)
- Where are we going in the next 20-30 years?--(Projection)
- Where will we be in 100 years?--(Speculation)

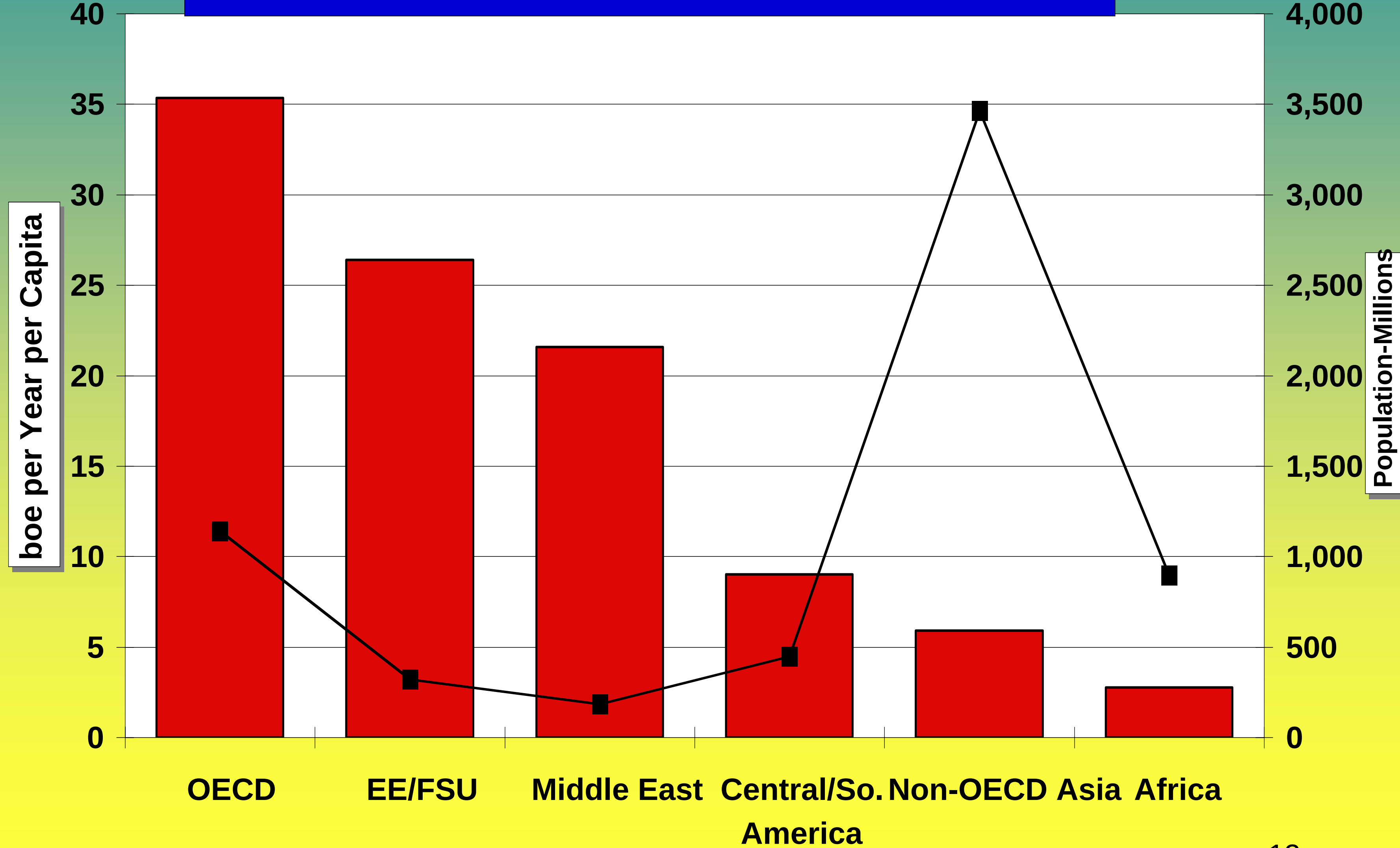
Currently, Fossil Fuels Provide 87% of the World’s Primary Energy



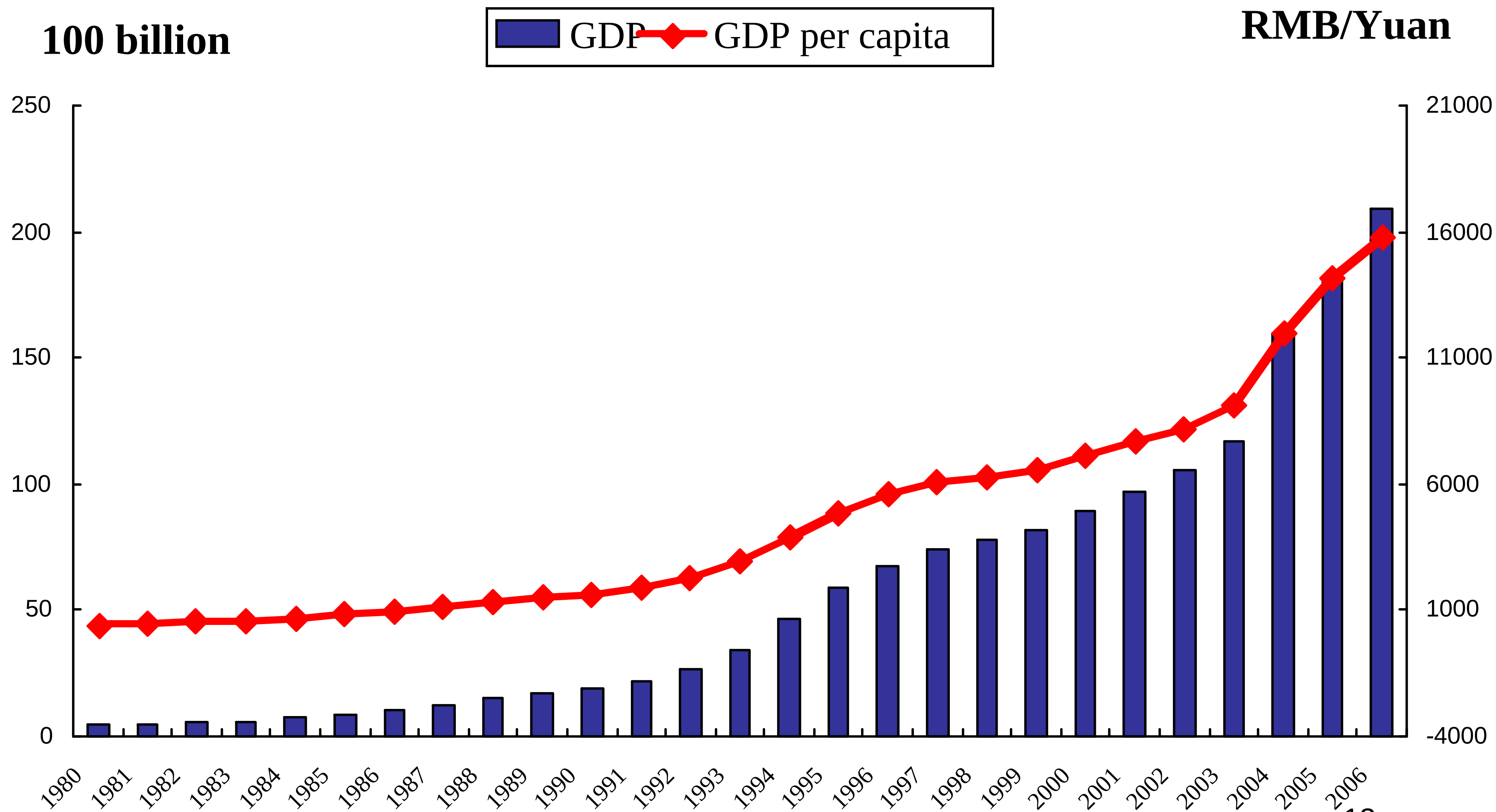
The World Can Be Broken Up into 6 Major Regions to Analyze World Energy Consumption



In 2005 the OECD Nations Comprised Less Than 18
World's Population But Consumed 50% of the World'

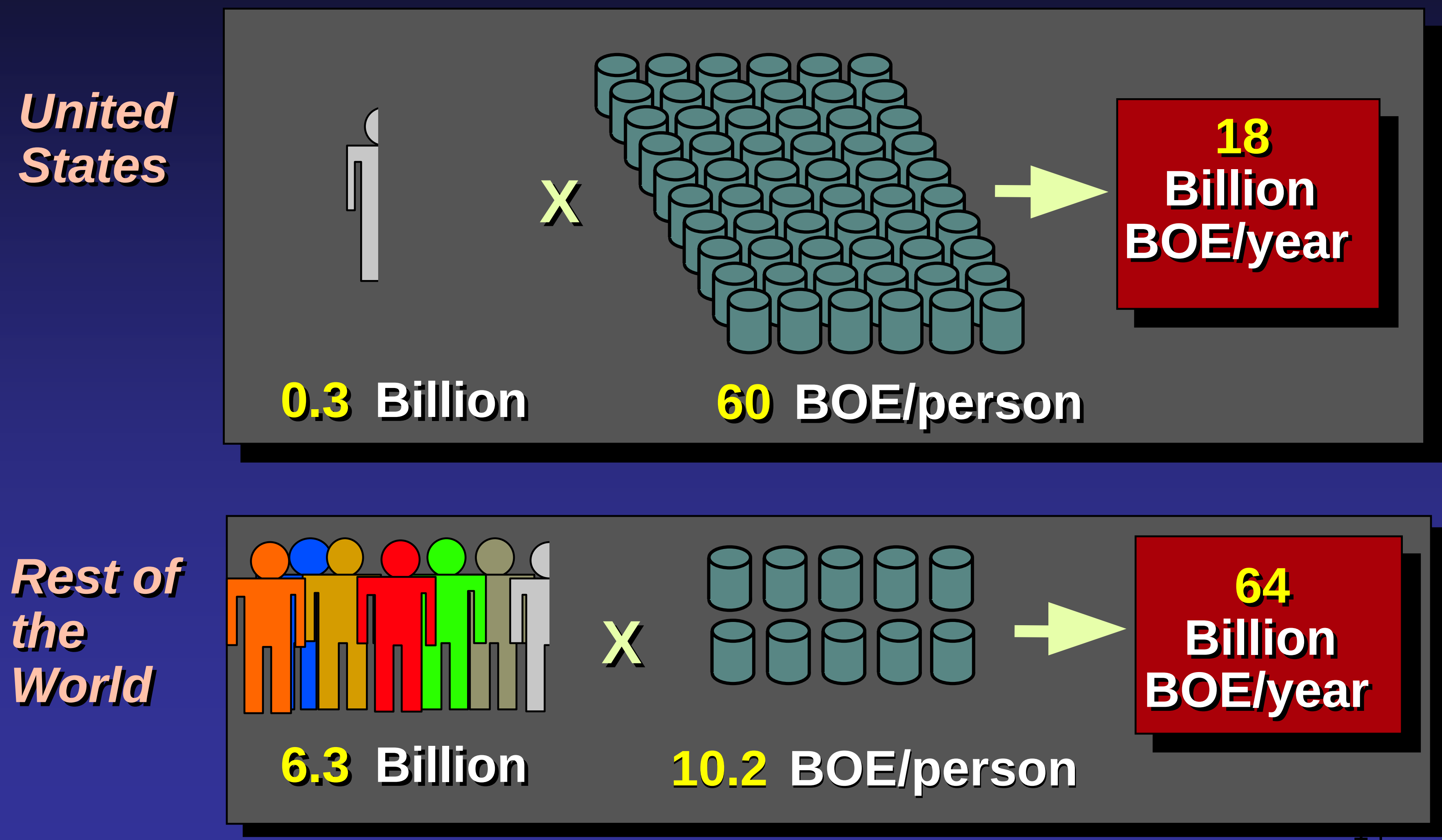


China's GDP Has Reached 20.9 Trillion Yuan RMB by the End of 2006 While GDP Per Capita Exceeds 2,000 USD



Dr. Xu Kuangdi, President of Chinese Academy of Engineering-Oct., 2007

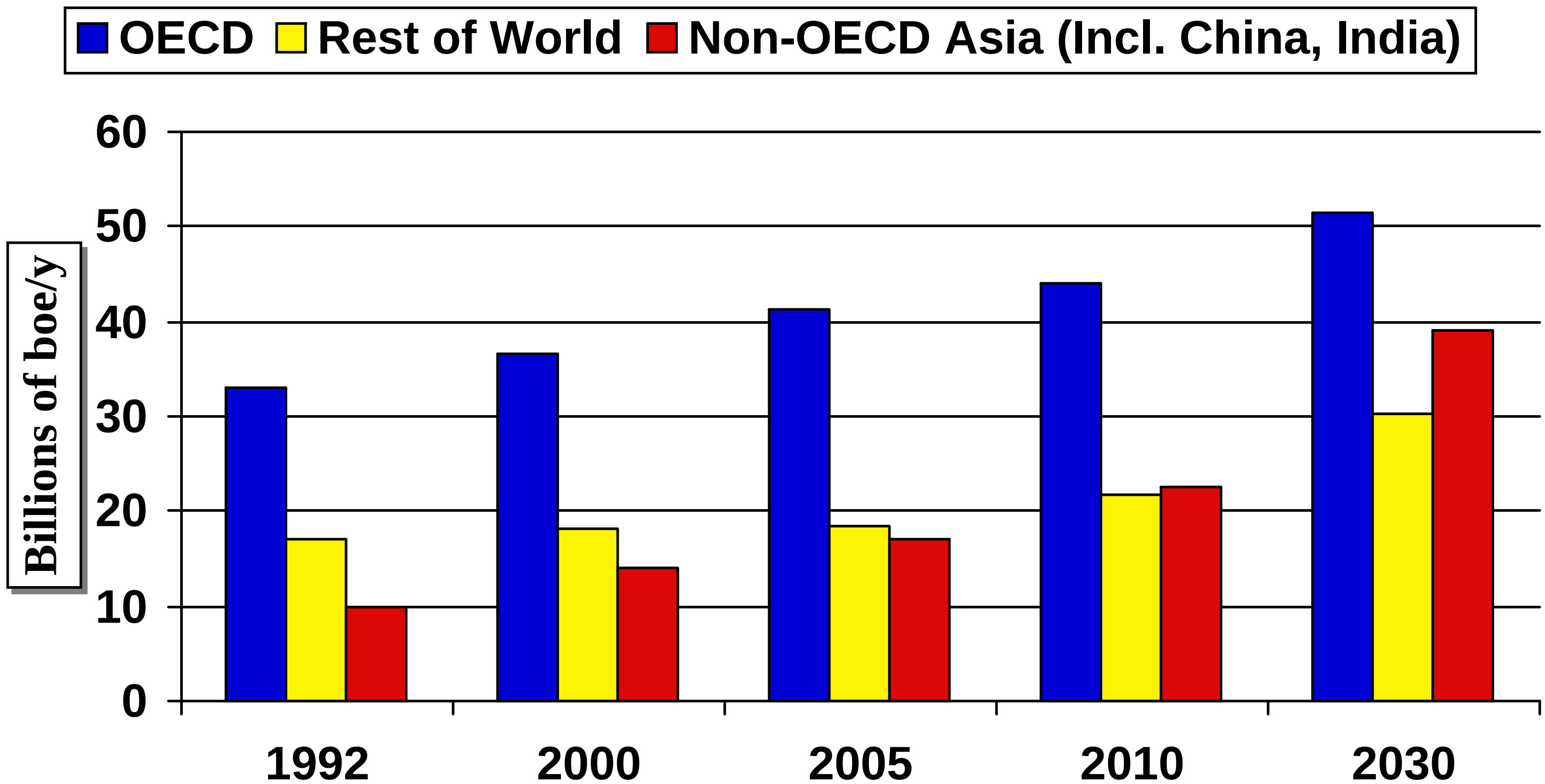
The Current Energy Use per Person in the U.S. is Much Larger Than in the Rest of the World



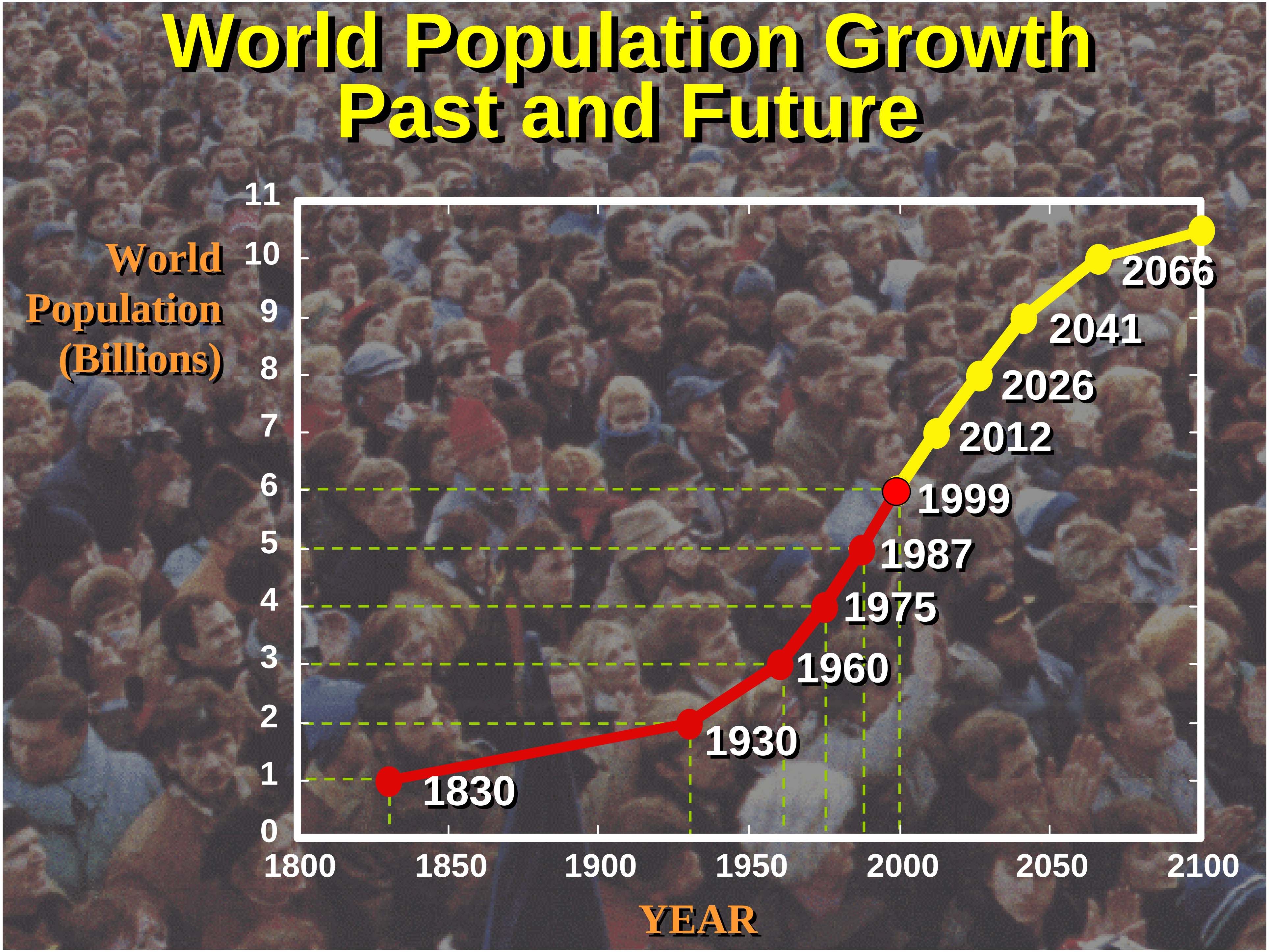
Outline of Presentation

- Where we have been?--(History)
- Where we are now?--(Fact)
- Where are we going in ≈ 20-30 years?--(Projection)
- Where will we be in 100 years?--(Speculation)

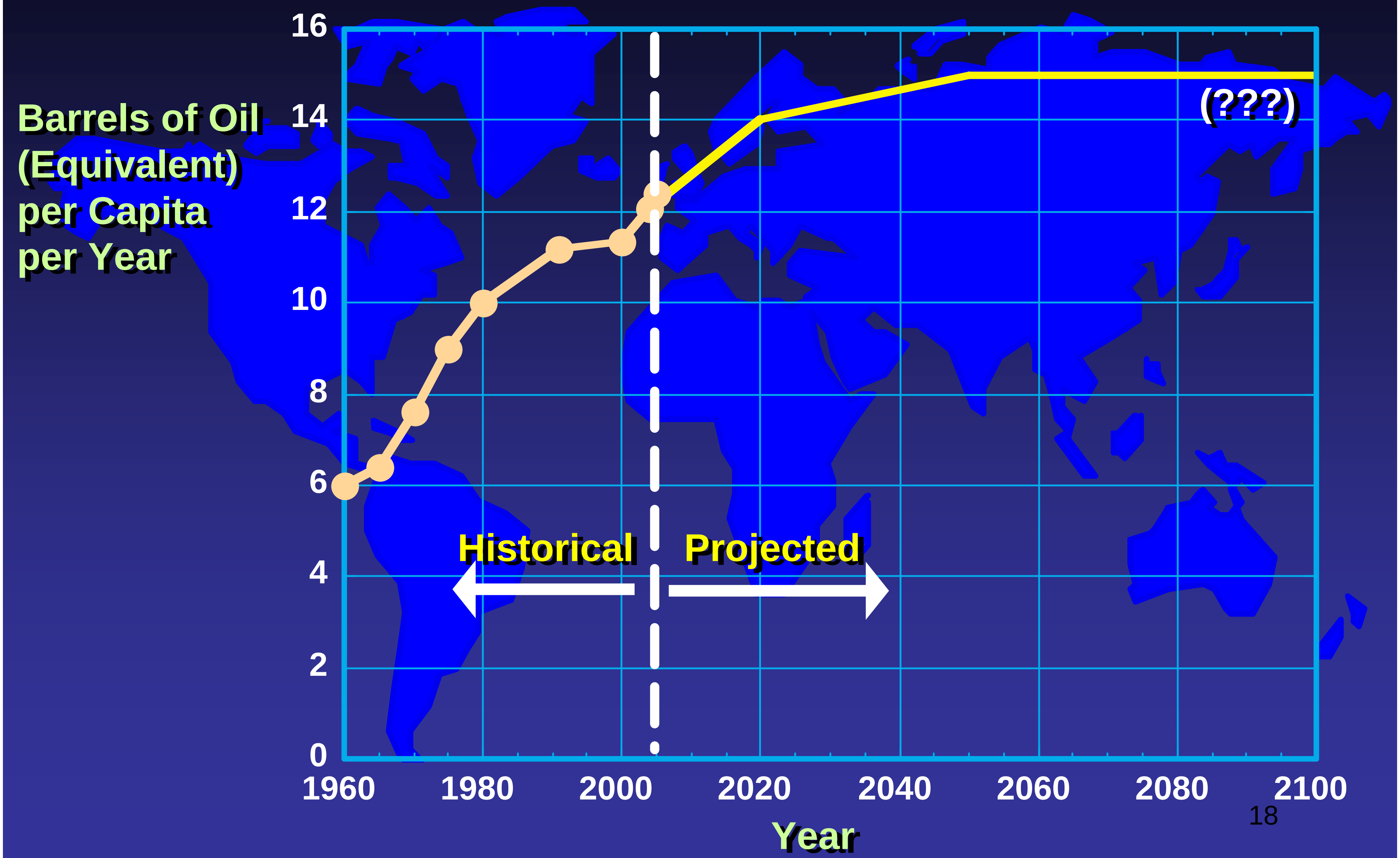
Over the Next 25 Years the Rate of Increase in Energy Consumption of the Non-OECD Asian Nations is Projected to be 5-6 Times that of the OECD Nations



Source: International Energy Outlook-2007, IEA Key World Energy Statistics-2006

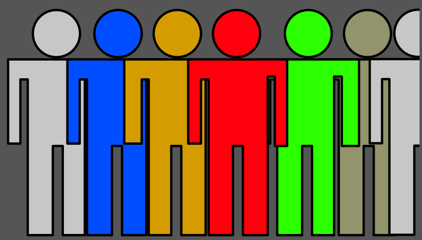

World Population Growth
Past and Future
World Population (Billions)
11
10
9
8
7
6
5
4
3
2
1
0
1800
1850
1900
1950
2000
2050
2100
YEAR
1830
1930
1960
1975
1987
1999
2012
2026
2041
2066

Growth of World Energy Use Per Capita

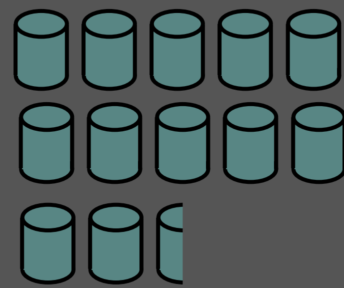


Annual World Energy Needs

Present



X

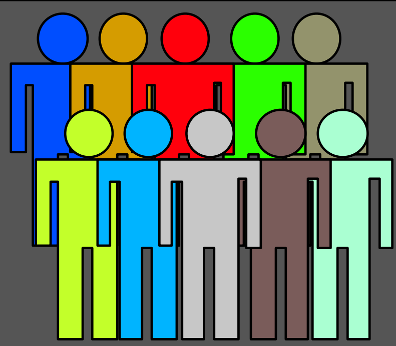


82 Billion BOE/year

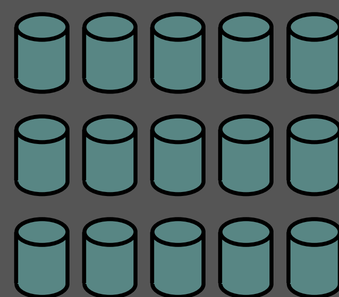
6.6 Billion

12.4 barrels/ capita

Future



X



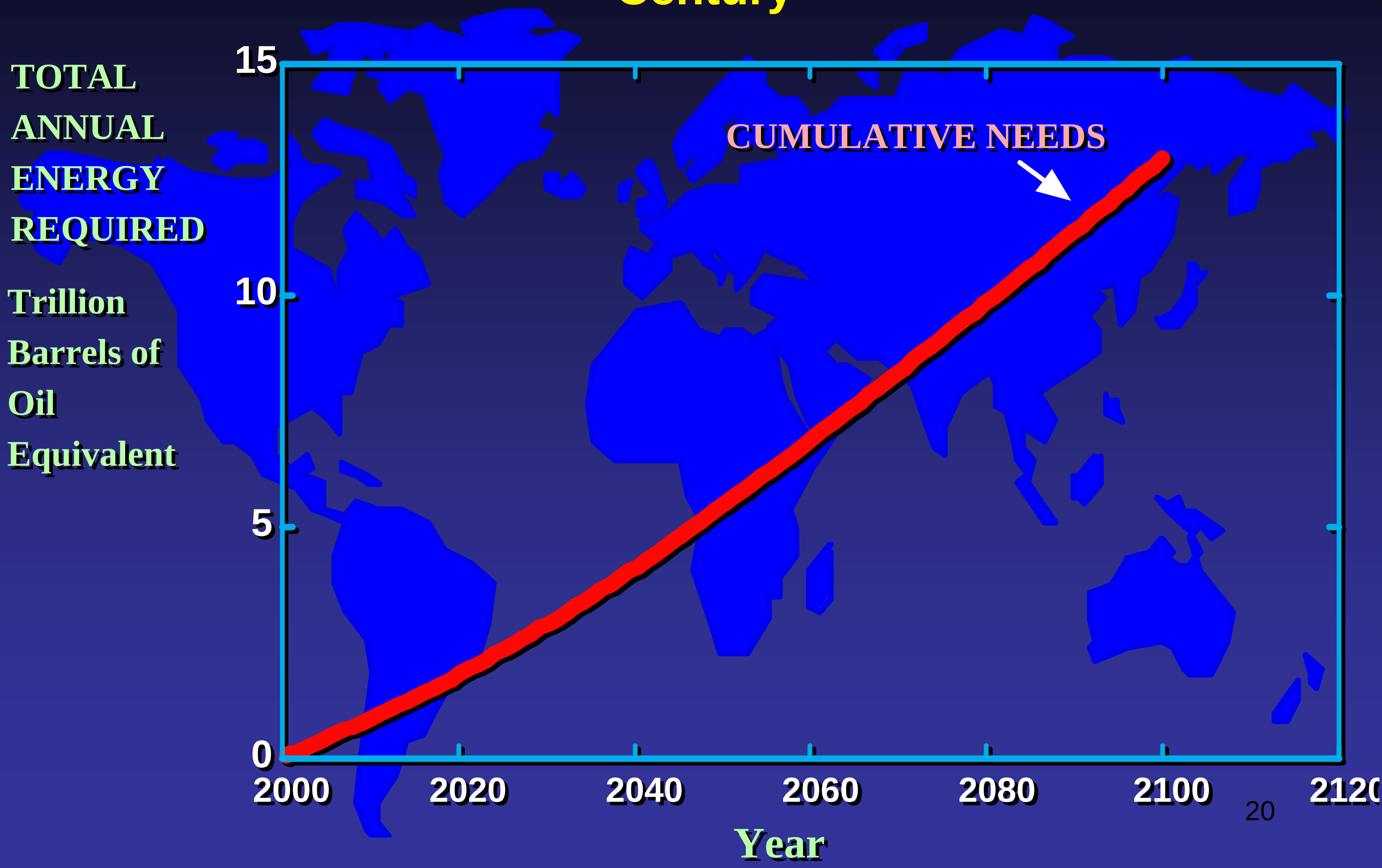
150 Billion BOE/year

10 Billion

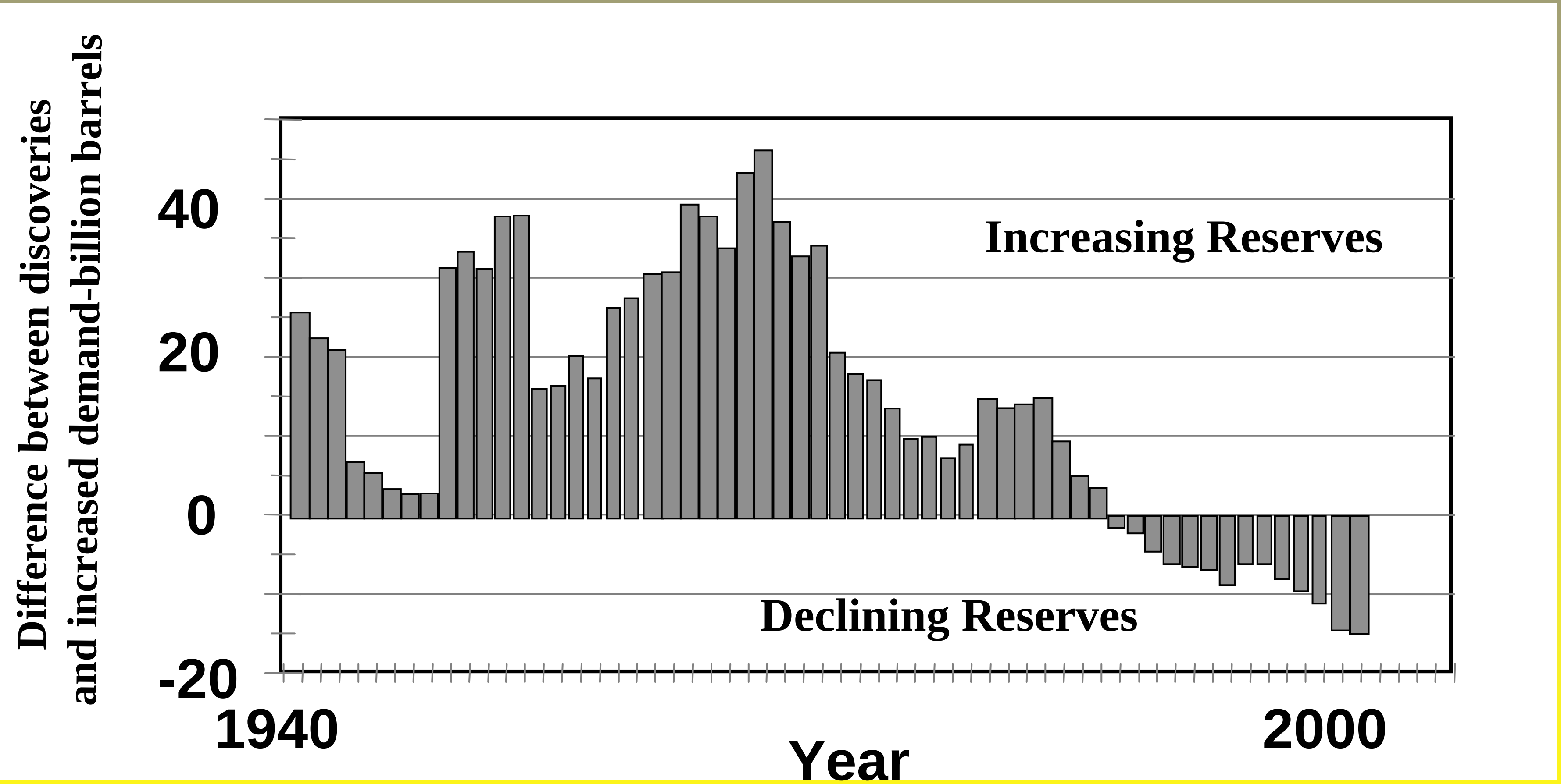
15 barrels/ capita

Over 10 trillion boe in energy is needed in this century.

World Energy Consumption and Resources for the 21st Century

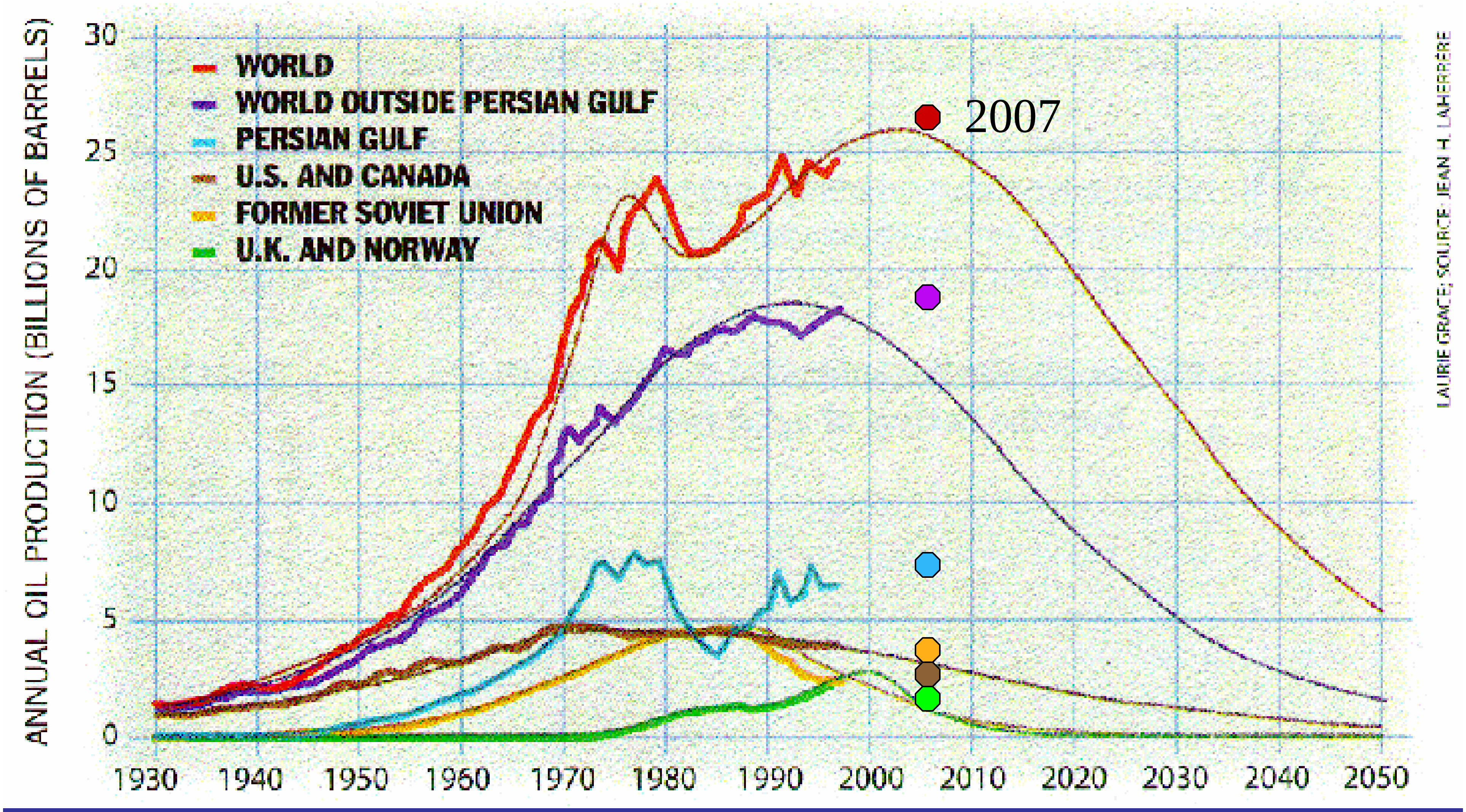


The World is Already Increasing its Oil Consumption Faster Than it is Discovering New Reserves

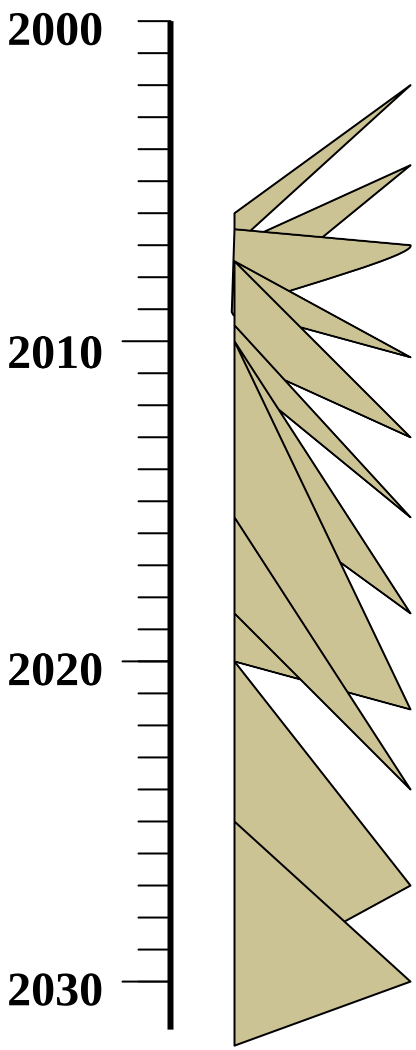


After Hirsch-2005

The worldwide production of oil is predicted by Campbell et. al., (Scientific American, March 1998) to peak about now!.

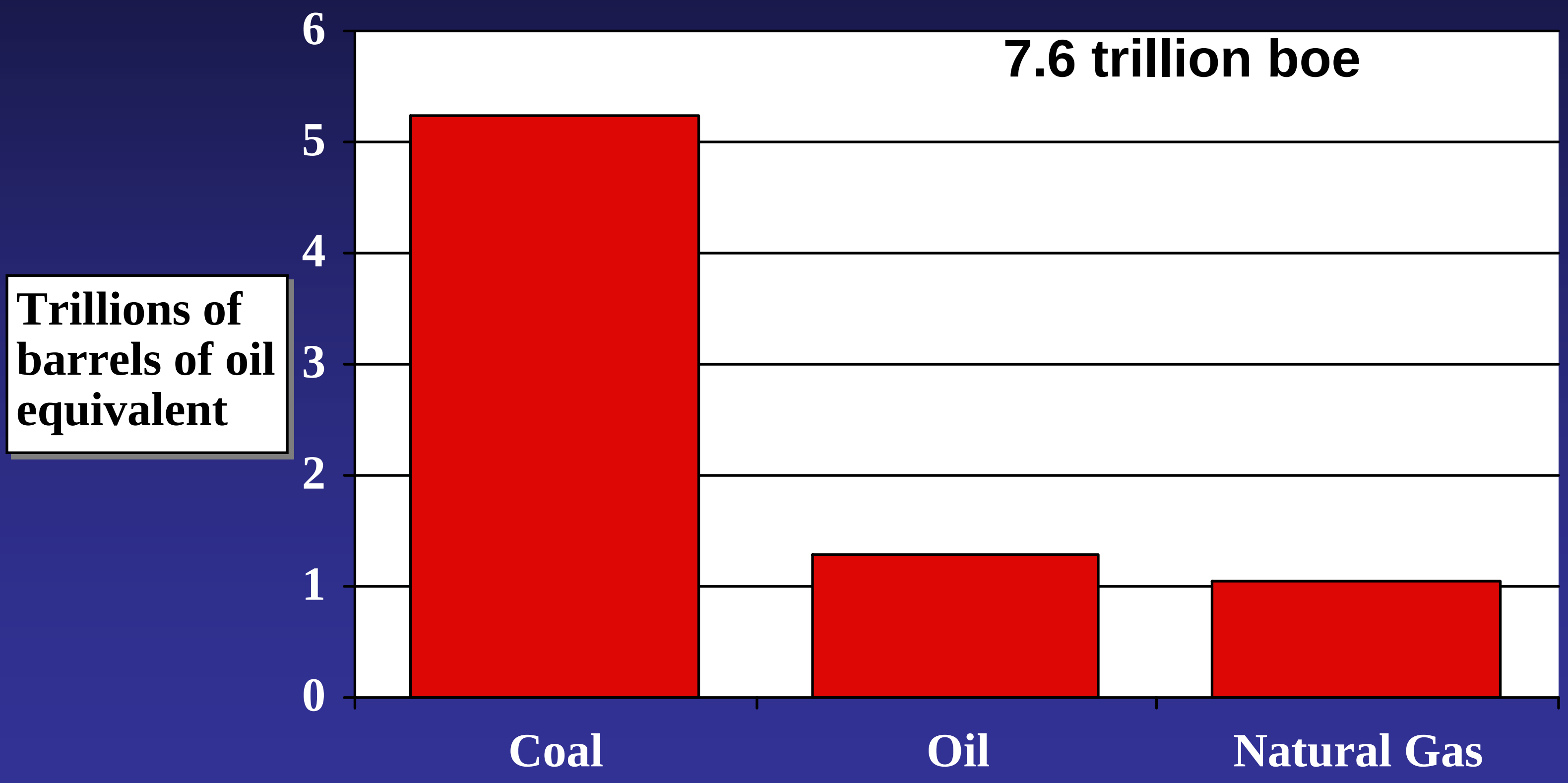


RECENT PROJECTIONS OF WORLD OIL PRODUCTION PEAKING



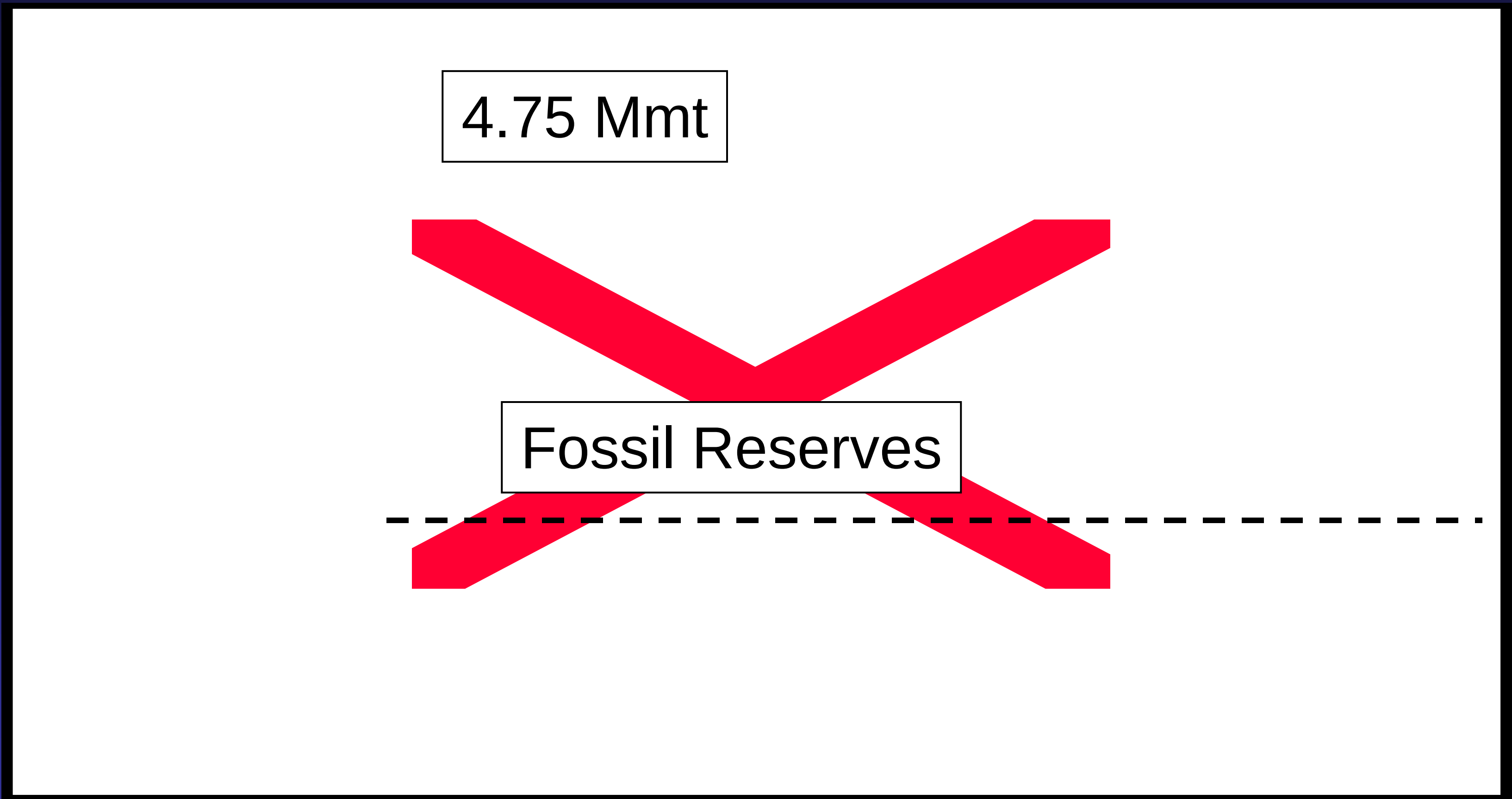
Projection	Source
2006-2007	Bakhitari, A.M.S.
2007-2009	Simmons, M.R.
After 2007	Skrebowski, C.
Before 2009	Deffeyes, K.S.
Before 2010	Goodstein, D.
Around 2010	Campbell, C.J.
After 2010	World Energy Council
2010-2020	Laherrere, J.
2016	EIA nominal case
After 2020	CERA
2025 or later	Shell
No visible peak	Lynch, M.C.

The World Reserves of Fossil Fuel are Dominated by Coal (January 1, 2006)



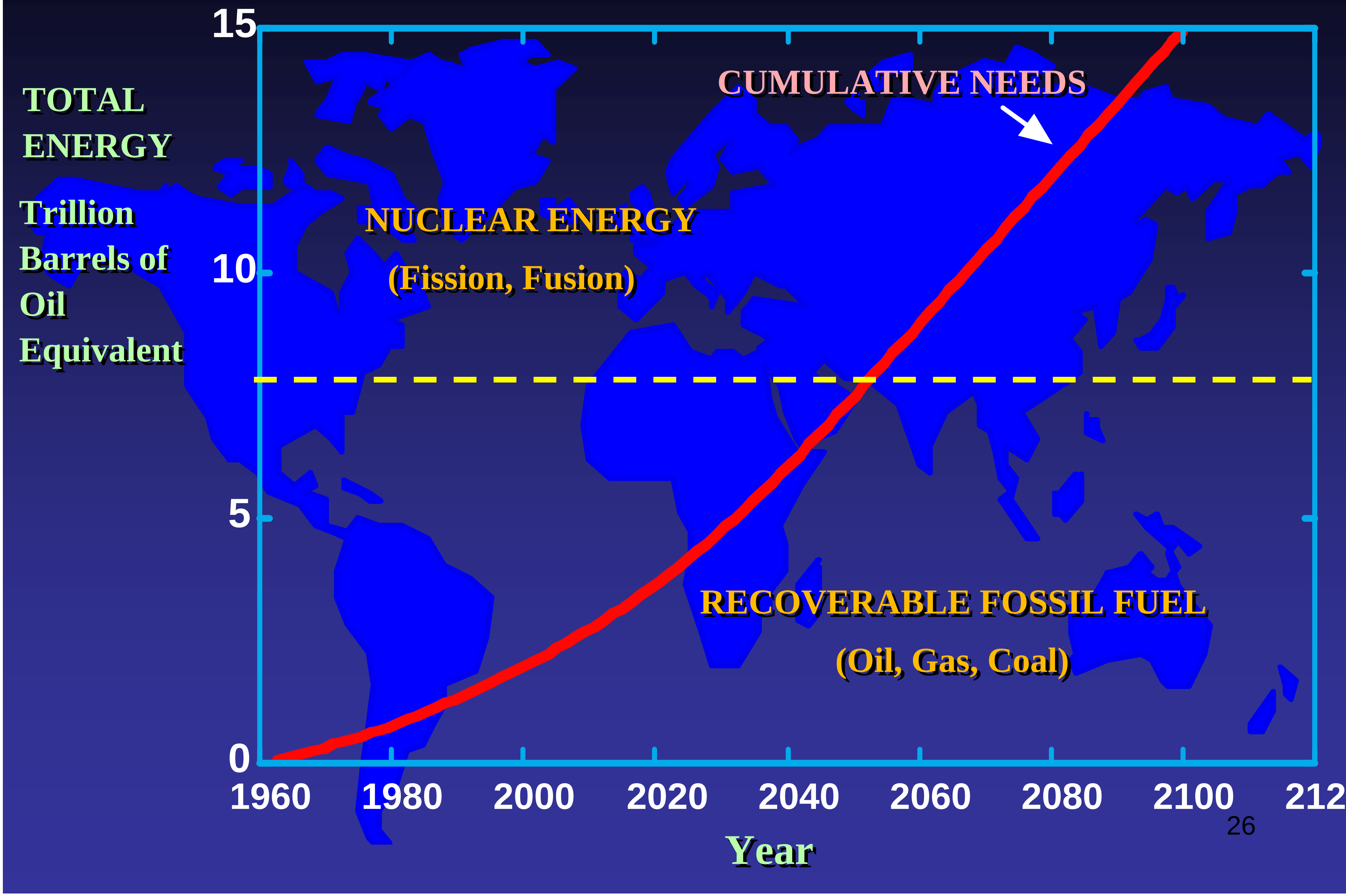
Source: International Energy Annual 2005, Published June, 2007

There is 5 Times as Much Energy in the World's Reserves of Uranium Used in Breeder Reactors Than in All the Fossil Fuel Reserves in the World



Source: OECD/NEA-IAEA "Red Book"-2006

World Energy Consumption and Resources for the Future



Technical Maximum Potential of Renewable Resources

Resource	Annual Energy Potential (billion boe/y)	Comment
Biomass	30	Requires cultivation of a large fraction the productive land in the world
Hydro power	15	Includes minor contribution from glaciers
Wind	15	High quality but utilization must deal with energy storage
Geothermal	10	Technology not available for large scale heat "mining".
OTEC	5	Potential is great if ocean heat can be diverted on a large scale
Tidal	0.2	Very localized
Total	≈ 75	

Source: W. Hafele, ENERGY IN A FINITE WORLD-A Global Systems Analysis

Technical Potential of Solar Energy Used Collected on the Earth

1.) Solar energy has the same level of potential to provide essentially inexhaustible long-term energy source for society as does the LMFBR.

2.) A global solar option would exhibit enormous heterogeneity

3.) No more than 5-10 billion boe/y should be expected before 2030.

4.) Solar Power Satellites are a potential solution for >2050

5.) Large scale storage capacity will probably turn out to be the key barrier

6.) Environmental effects are not entirely benign (risks in material intensive industries, GaAs, etc.)

7.) High capital costs are the immediate barrier to commercialization

After: W. Hafele, ENERGY IN A FINITE WORLD-A Global Systems Analysis

Outline of Presentation

- Where we have been?--(History)
- Where we are now?--(Fact)
- Where are we going in ≈ 20-30 years?--(Projection)
- Where will we be in 100 years?--(Speculation)

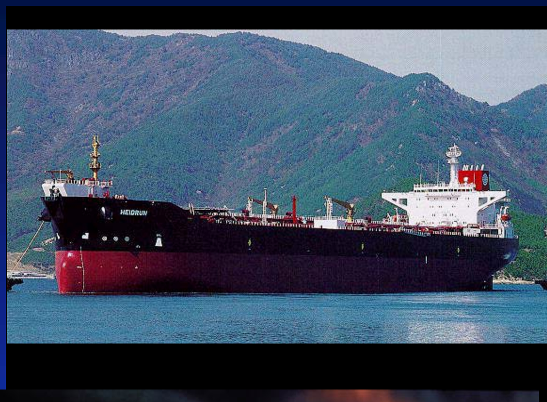
Framework

- Look out 100 years from now (≈ 2100)
- Assumptions
  - China, India, and other developing countries continue economic growth
  - No major catastrophes of the several billion people scale

How Much Energy Will be Needed to Get Through the Next 100 Years?

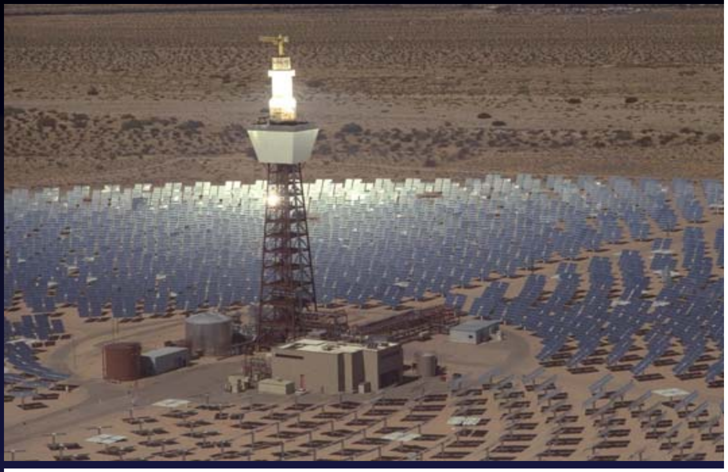
- *Assume energy use between 2000-2050 rises from 80 to an "equilibrium" of 150 billion boe/y*
- *Assume "equilibrium" energy use between 2050-2100 is 150 billion boe/y*
- Energy Consumption between 2000 and 2050 is 5,500 billion boe.
- Energy needed between 2050 and 2100 is 7,500 billion boe.

What Will the Status of Energy Sources be in 2100?



- Oil-Essentially gone for use as a major energy source, used only for special applications.
- Natural Gas-Essentially gone for use as a major energy source, used only for special applications.
- Coal-Approaching the end of economically retrievable resources

What Will the Status of Energy Sources be in 2100? (cont.)



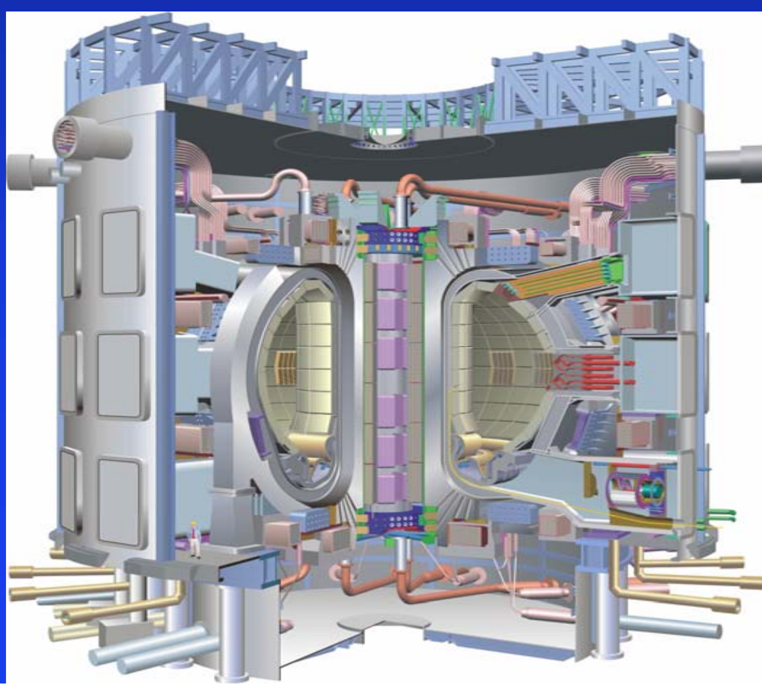
- Renewables-

If developed to 50% of their potential, they could provide 25% of required energy (<40 billion boe/y, or < half of world energy demand today)

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

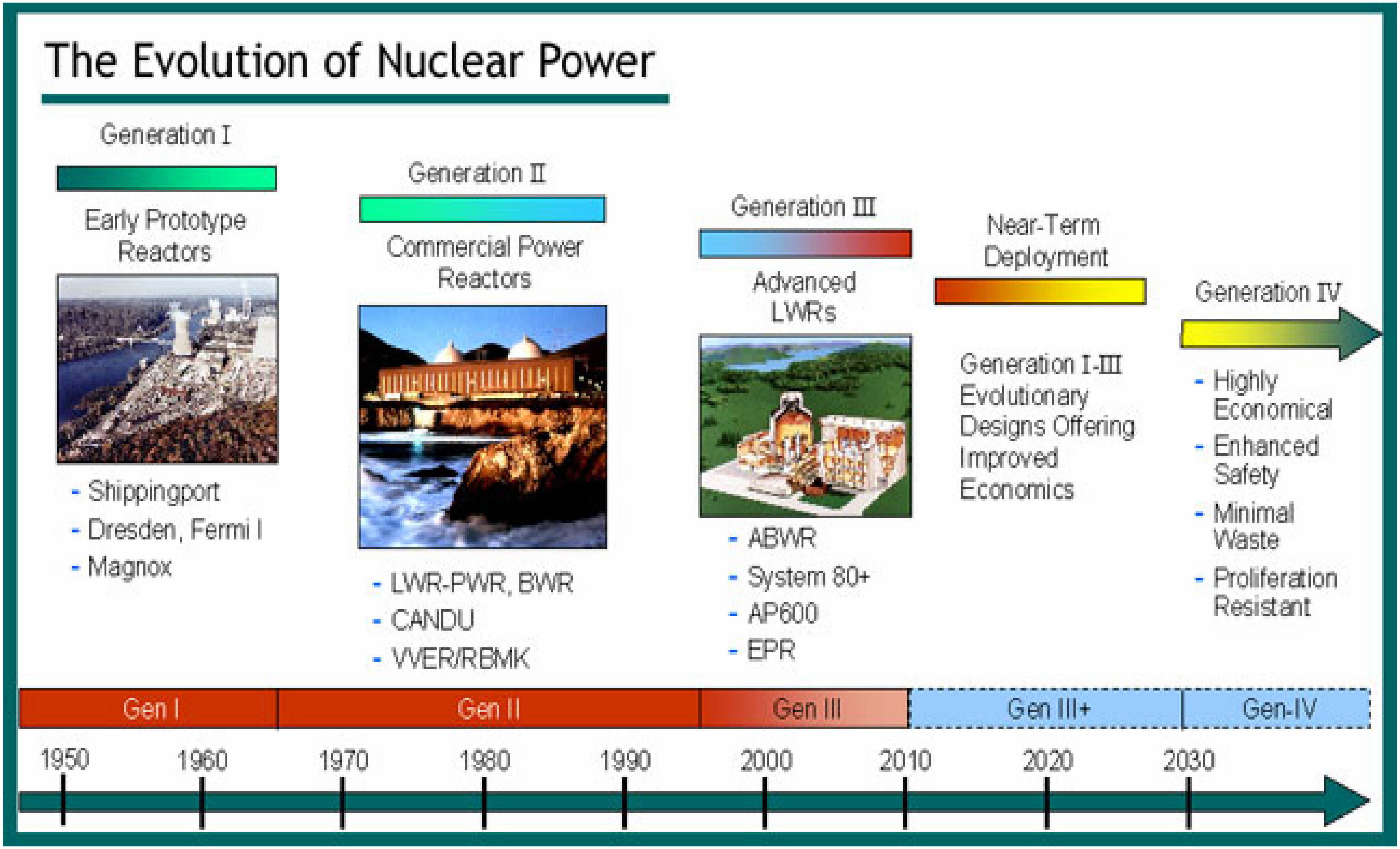
QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

What Will the Status of Energy Sources be in 2100? (cont.)



- Fission-Could satisfy <u>total</u> demand if the present fleet of ≈ 450 Gw_e in LWR's is increased by 30 times in Breeder Reactors (≈ 13,500 GW_e)

  - Fusion-Could be competitive with fission if the fusion reactors produce << less long half life radioactivity per kW_eh than current DT designs <u>and</u> show reasonable economics.


The Evolution of Nuclear Power
Generation I
Early Prototype Reactors
- Shippingport
- Dresden, Fermi I
- Magnox
Generation II
Commercial Power Reactors
- LWR-PWR, BWR
- CANDU
- VVER/RBMK
Generation III
Advanced LWRs
- ABWR
- System 80+
- AP600
- EPR
Near-Term Deployment
Generation I-III Evolutionary Designs Offering Improved Economics
Generation IV
- Highly Economical
- Enhanced Safety
- Minimal Waste
- Proliferation Resistant
Gen I
Gen II
Gen III
Gen III+
Gen-IV
1950
1960
1970
1980
1990
2000
2010
2020
2030

Required Attributes of Major Energy Sources in the Latter Half of the 21st Century and Beyond

- Satisfy the needs of ≈10 billion people
  - Energy equivalent to 7.5 trillion barrels of oil @ >150 bboe/y from 2050-2100
- Have minimal impact on environment
  - Greenhouse gases, nuclear waste, etc
- Produce energy safely without side effects and international conflicts
  - i. e., proliferation of weapons grade material
- Be affordable

The Public Developed a Resistance to Nuclear Fission Power in the Late 20th Century

The resistance seems to be largely based on:

1) Fear of radioactivity releases
2) Uneasiness with long-term nuclear waste storage
3) Fear of proliferation of nuclear weapons grade material

All of the above problems stem from the nuclear reaction:

1) Radioactive fuel
2) Radioactive reaction products
3) Neutrons

The Use of Fusion Fuels May Evolve in the Future to Address the Radioactive Waste Problem

1st Generation

$$D + T \rightarrow n\ (14.07\ MeV) + {}^{4}He\ (3.52\ MeV)$$

$$D + D \rightarrow n\ (2.45\ MeV) + {}^{3}He\ (0.82\ MeV) \quad \{50\%\}$$

$$\rightarrow p\ (3.02\ MeV) + T\ (1.01\ MeV) \quad \{50\%\}$$

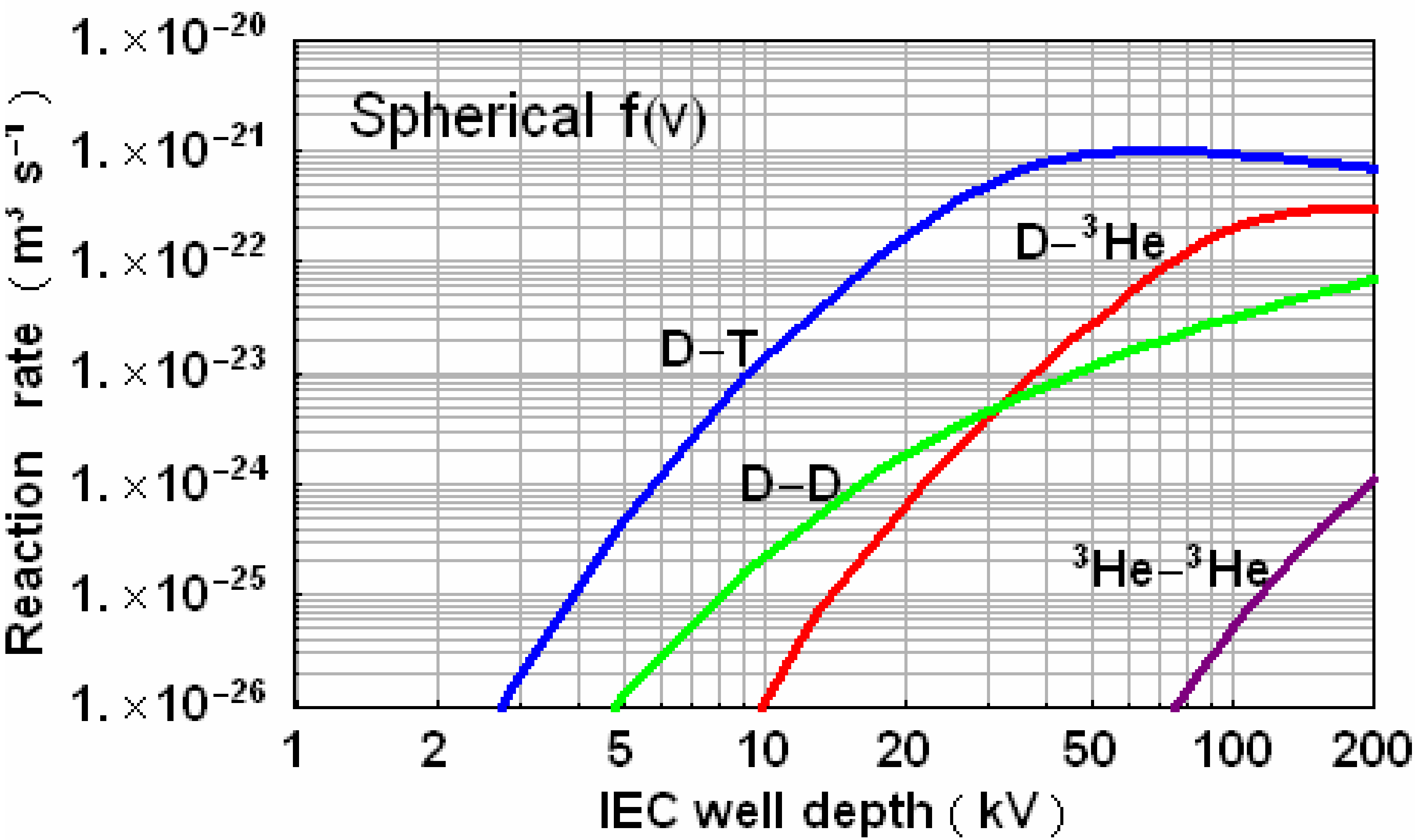
2nd Generation

$$D + {}^{3}He \rightarrow p\ (14.68\ MeV) + {}^{4}He\ (3.67\ MeV)$$

3rd Generation

$${}^{3}He + {}^{3}He \rightarrow 2p + {}^{4}He \quad (12.9\ MeV)$$

Advanced Fusion Fuels are More Difficult to “Burn”



The 20th Century Approach to Fusion Only Partly Alleviates Public Concerns About Nuclear Fission Power

Public Concern	How DT Fusion Addresses Concern
Radioactive Releases	Avoid runaway reactions and "meltdown" scenarios However, still have gigacuries in reactor in the event of an accident
Long Term Radioactive Waste Storage	Choice of fuel and structural material can reduce effective half life to < 100's years However, radiation damage and replacement of components can produce large volumes of radioactive waste
Proliferation	FusionReactor does not require fissile or fertile material However, excess neutrons can be used to breed fissile fuel

How Do Fission and Fusion Stack Up Against Our Criteria For 21st Century Energy Sources?

- Satisfy the needs of 6-10 billion people (Energy equivalent to 13 trillion barrels of oil over 100 years)
  - Land resources of U contain more than 35 trillion boe (LMFBR)
  - Current DT is limited by Li (more >15 trillion boe of Li resources)
  - D is essentially unlimited (longer than the sun will last)
  - 1.5 x 10^5 tonnes of ^{3}He used in fusion contain ≈ 15 trillion boe
- Have minimal impact on environment (Greenhouse gases, nuclear waste, etc)
  - Both fission and fusion have low GHG emissions during operation
  - Advanced fusion fuels can greatly reduce or even eliminate nuclear wastes

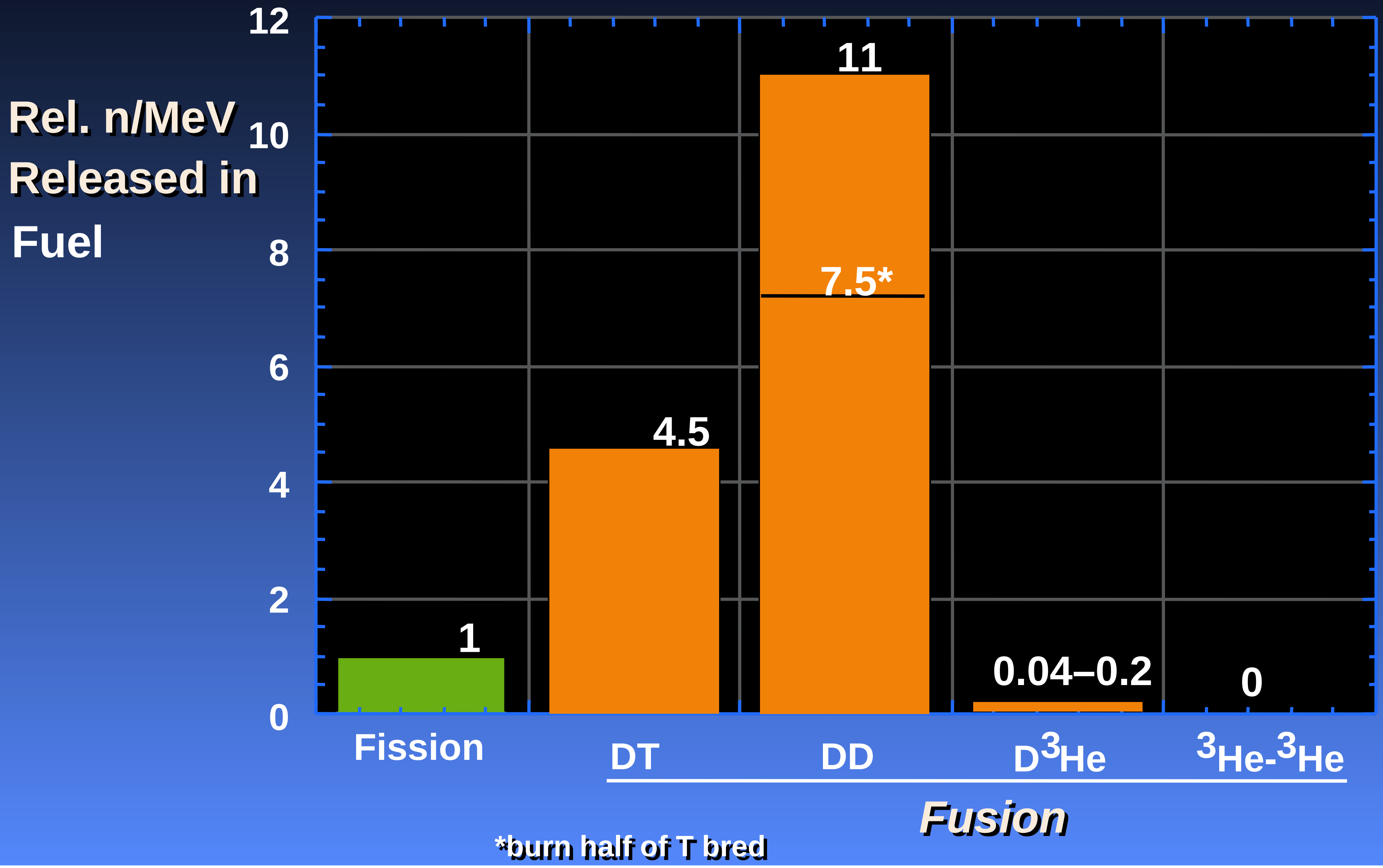
How Do Fission and Fusion Stack Up Against Our Criteria For 21st Century Energy Sources? (cont)

- Produce energy safely without side effects and international conflicts (i. e., proliferation of weapons grade material)
  - -Fission inherently produces material that can be used for weapons
  - -Today's fusion (DT) can also produce weapons grade material
  - -^{3}He fuels cannot be used to produce fissile material

- Be affordable (Consume no more than 10% of the World GNP)
  - Fission is already the most economical way to produce electricity in many countries
  - Fusion ??? (@ $1 billion dollar a tonne, ^{3}He increases the COE by 1¢/kWh)

Why Are We Interested in the Advanced Fusion Fuel Cycles if DT Fusion is Easier?

The Number of Neutrons Generated by Helium-3 Fusion Fuels is Very Small



Characteristics of D ^{3}He Fusion Power Plants

- **No Greenhouse or Acid Gas Emissions During Operation**
- **Very High Efficiencies (>70%)**
- **Greatly Reduced Radiological Hazard Potential Compared to Fission Reactors (<1/10,000)**
- **Low Level Waste Disposal After 30 y**
- **No Possible Offsite Nuclear Fatalities in the Event of Worst Possible Accident**

Characteristics of ^{3}He ^{3}He Fusion Power Plants

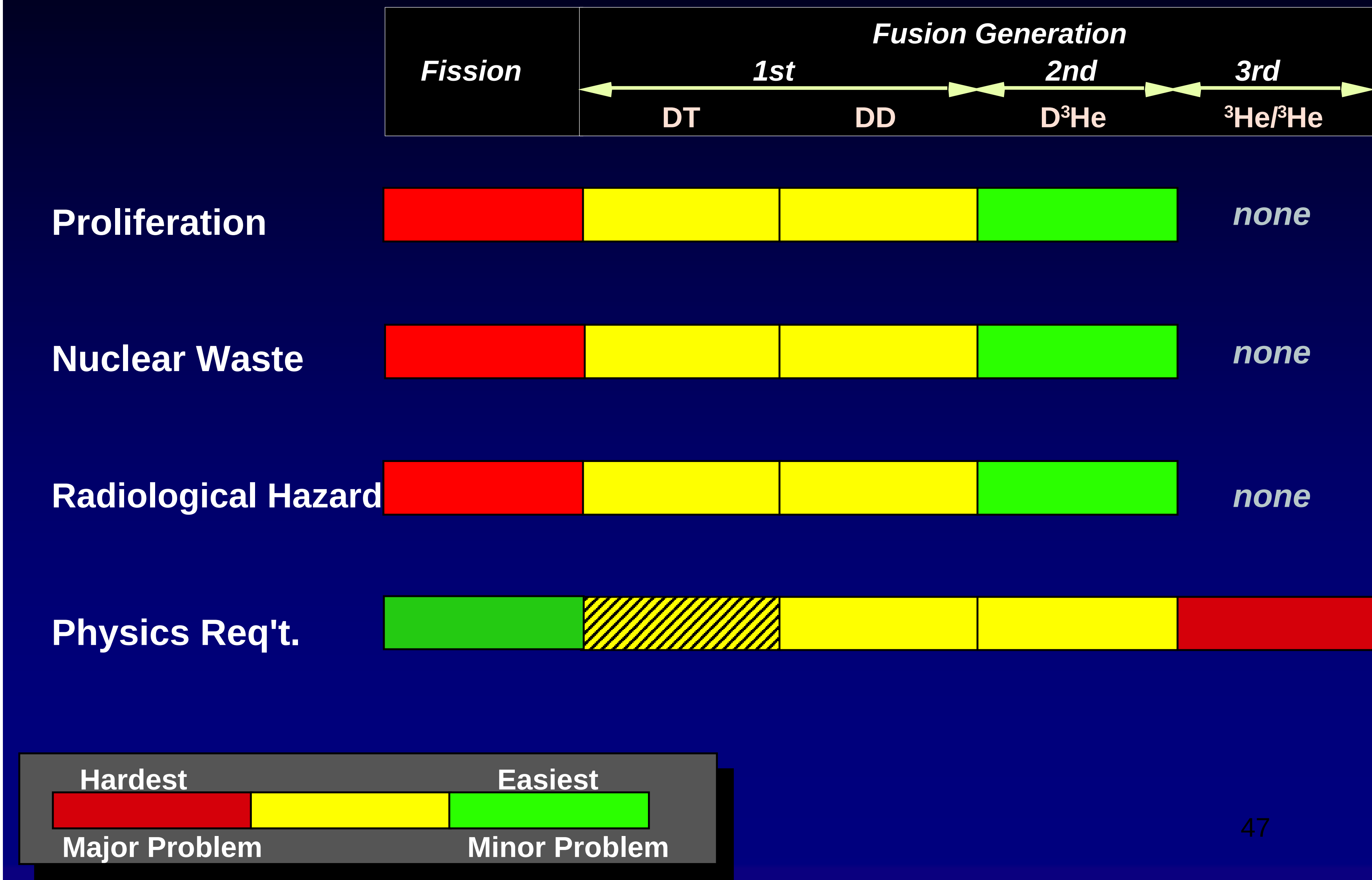
- **No Greenhouse or Acid Gas Emissions During Operation**

- **Very High Efficiencies Possible (>70%)**

- **No Residual Radioactivity After 30 Years of Operation (No Radioactive Waste or Nuclear Safety Hazard).**

Nuclear Energy Without Nuclear Waste !!

Major Societal and Technical Concerns of Nuclear Energy Options



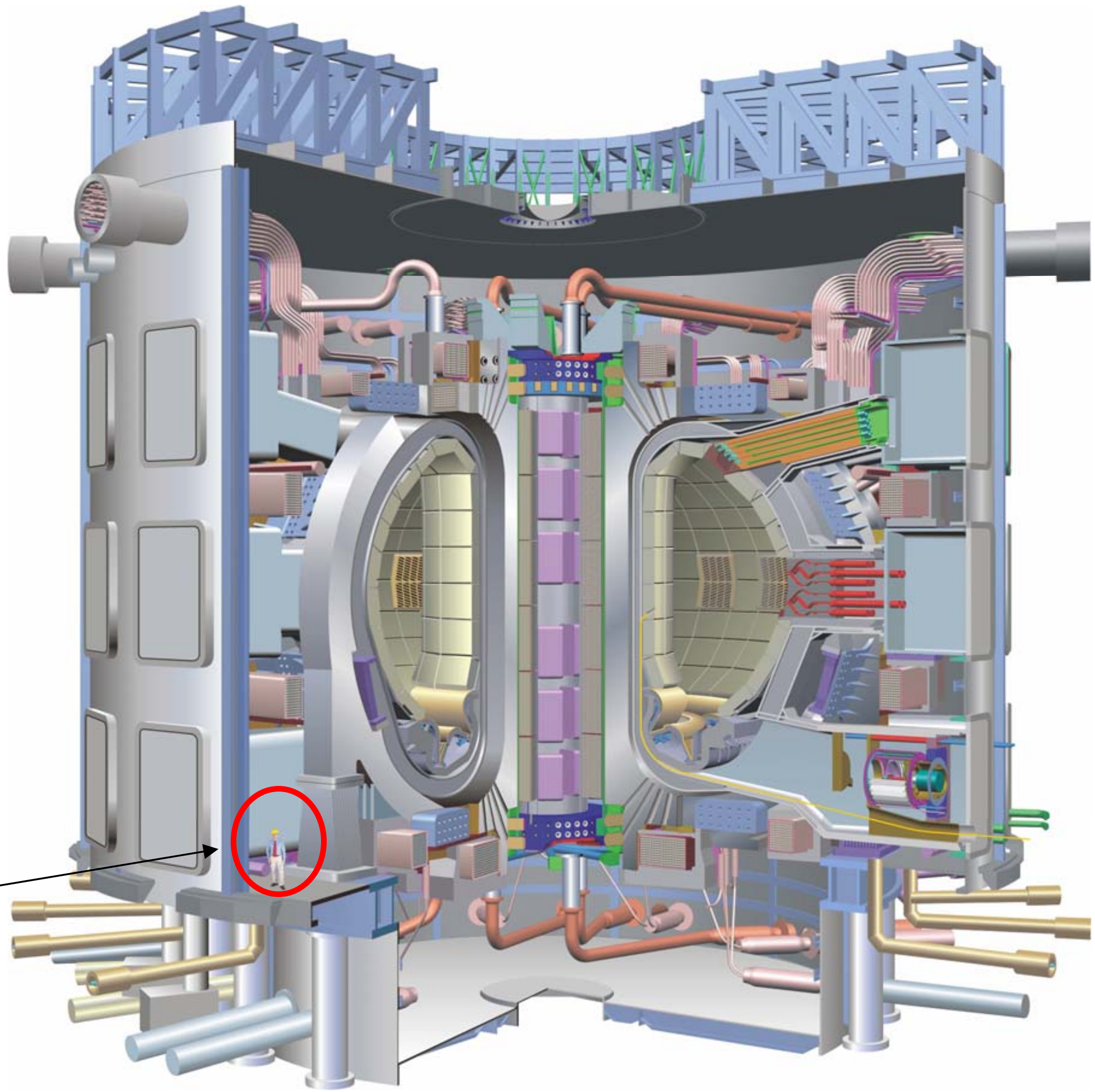
If Helium-3 Fusion is So Great, Why Has it Not Been Developed by Now?

- Need a demonstration of ^{3}He fusion physics
- Need a source of ^{3}He

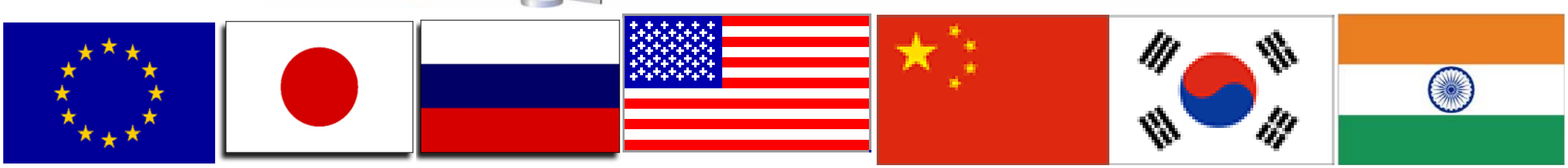
The ITER DT Facility is Presently (2008)Under Construction in France

Cost
10-20 $B

2 meter
Worker



First Plasma
2016
Full Power
500 MW
≈2022



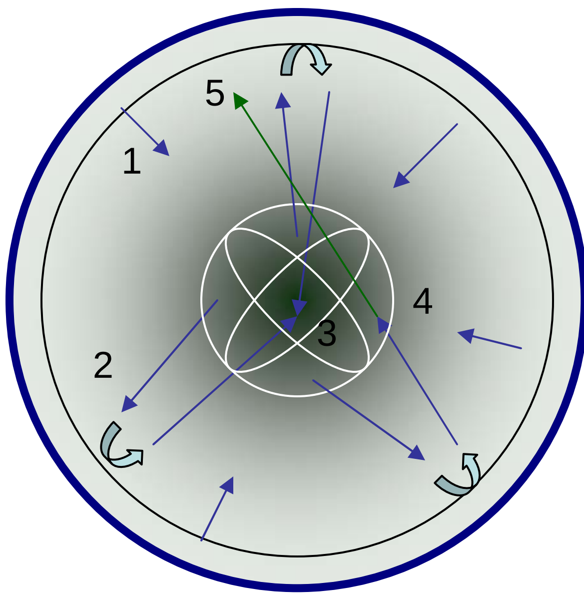
How Can We make the Advanced Fusion Fuel Cycles "Burn" More Efficiently?

To Avoid the Limitations of Maxwellian Plasmas, Farnsworth Invented the Inertial Electrostatic Concept

1. Positive ions are created from the fuel gas near the outer grid, and are accelerated towards the negativity charged inner grid.

2. The ions can oscillate through the inner grid several times, creating a concentration of high temperature ions.

3. The ions can collide, creating a fusion reaction.

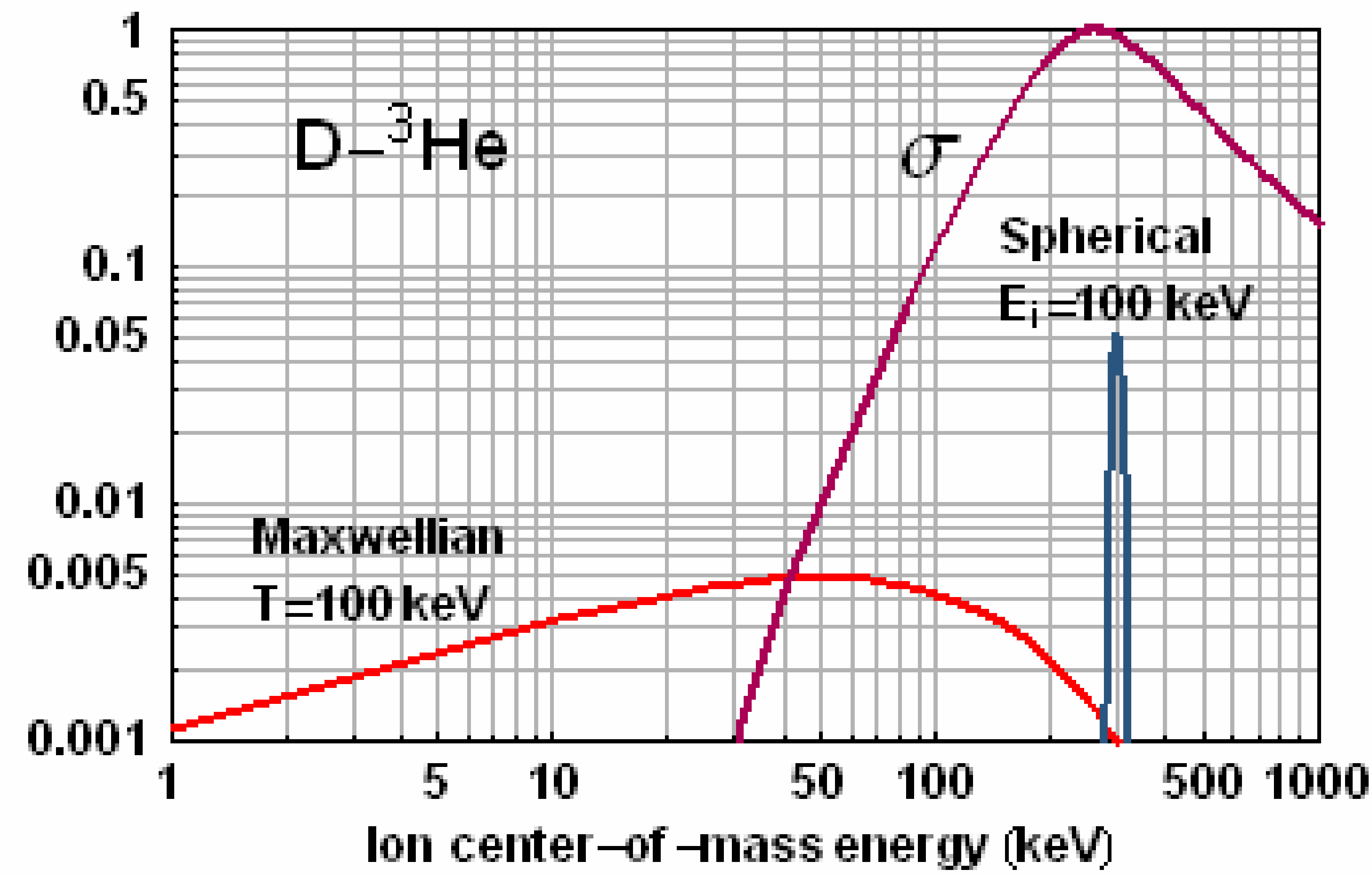


4. The ions can also undergo a charge exchange, creating a fast neutral.

5. Fast neutrals can collide with the neutral gas, also creating fusion reactions.

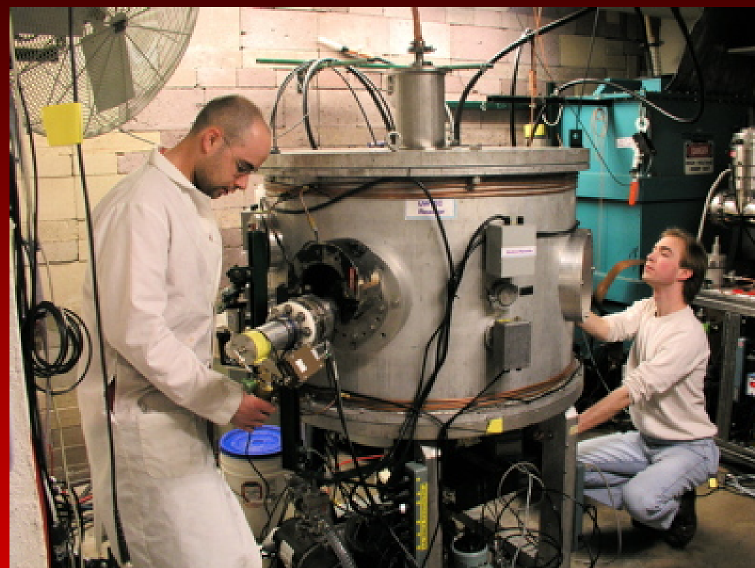
6. High energy fusion products, such as protons and neutrons, are created and can be used in many different applications.

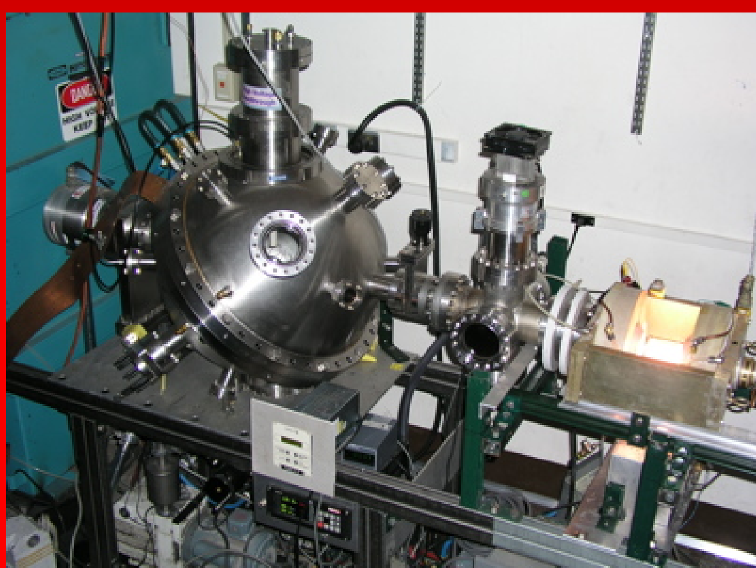
Using the IEC concept, accelerating ions to 100 keV makes much more efficient use of the input energy



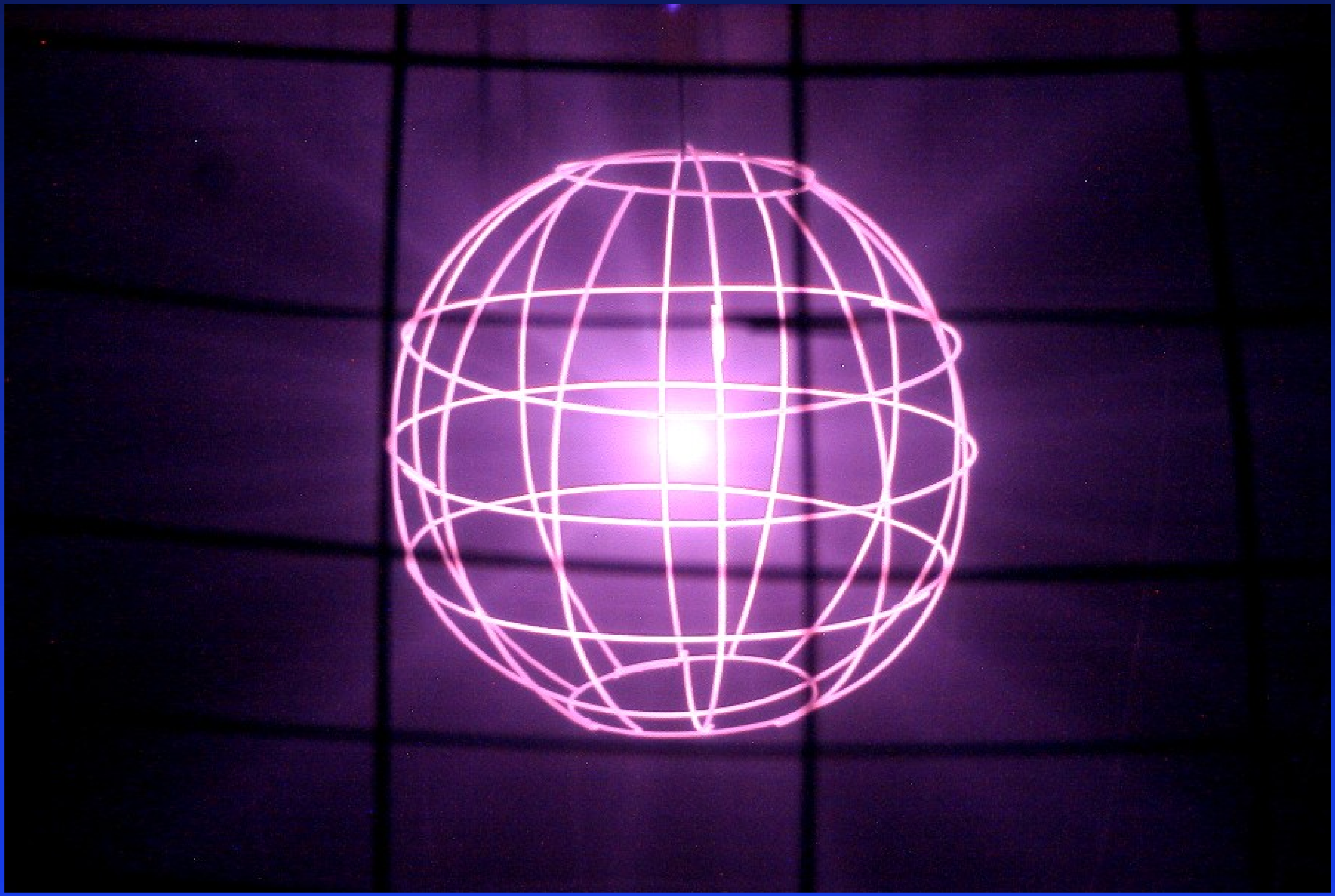
Source- J. F. Santarius

Steady State Helium-3 Fusion has Already Been Produced in Different Chambers at the University of Wisconsin





The Steady State D-^{3}He Fusion Reaction is Routinely Produced in the UW IEC Device



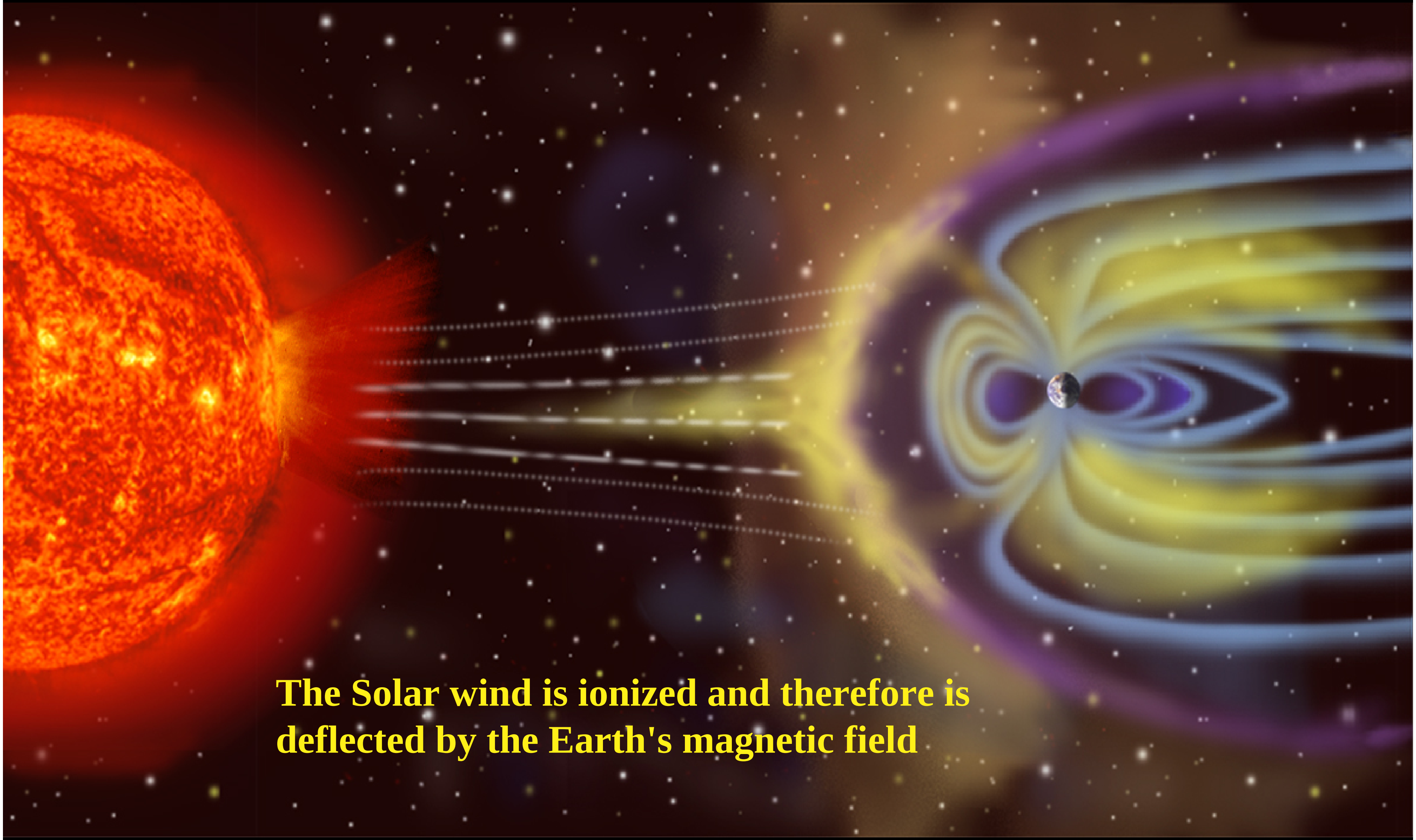
$^{3}He(^{3}He,2p)^{4}He$ Fusion Reactions Have Been Measured in a Fusion Device at UW-Madison

Where Can We Find a Large Source of ^3He?

There are only a few 100 kilograms of Helium-3 on the Earth

(from nuclear weapons programs)

The Solar Wind has been "blowing" on the planets (and Moons) of our solar system for some 4.5 billion years.



http://sec.gsfc.nasa.gov/sec_resources_imagegallery.htm

Solar Wind

$96\%\ H^+$

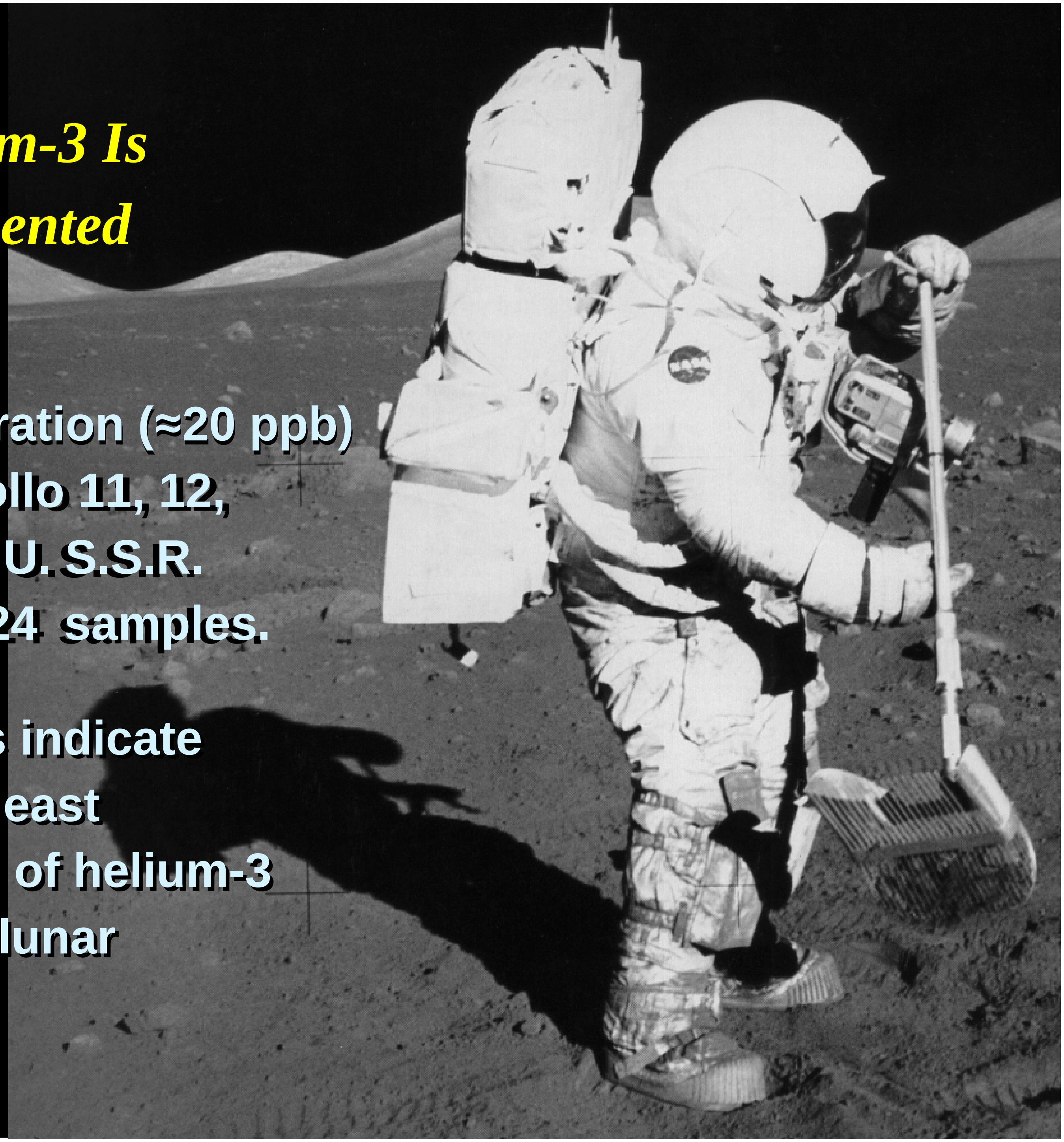
$4\%\ He^{++}$

Solar Wind

is deflected by any body that has a magnetic field or absorbed in an atmosphere around a planet

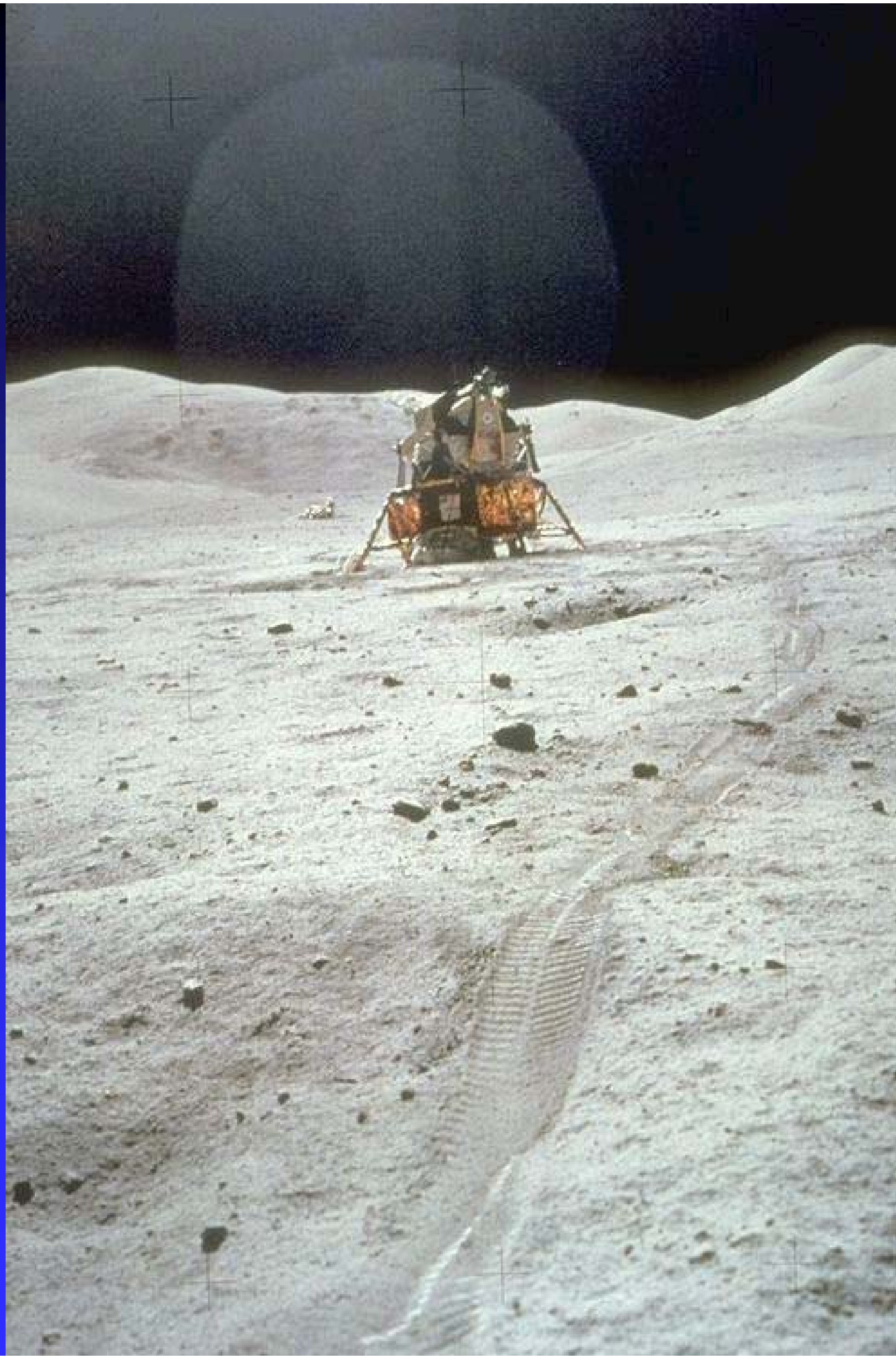
Total ^3He to hit the Moon is about 500 million tonnes over 4.5 billion years

Lunar Helium-3 Is Well Documented



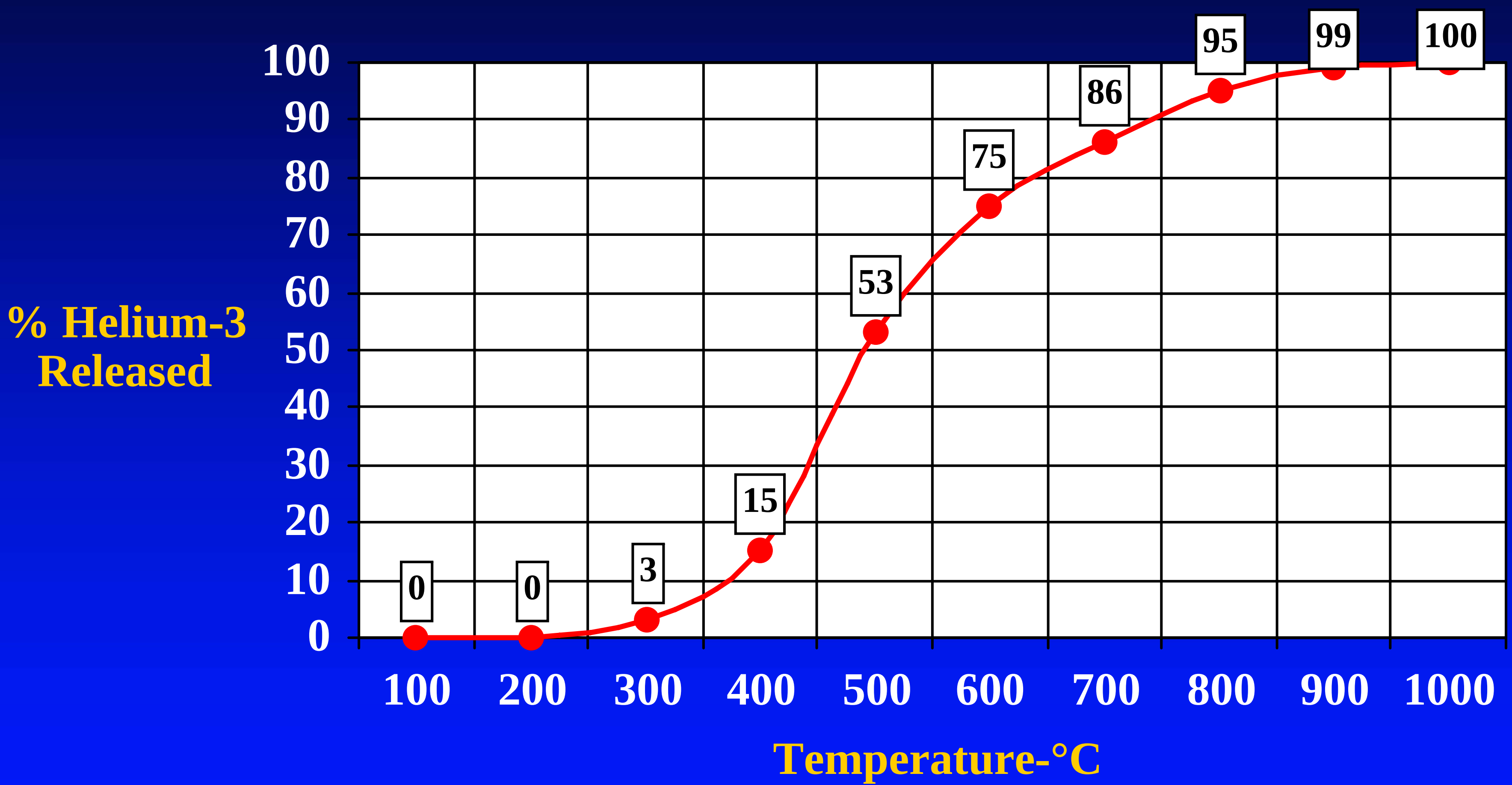
- **Helium-3 concentration (≈20 ppb) verified from Apollo 11, 12, 14, 15, 16, 17 and U. S.S.R. Luna 16, 20, and 24 samples.**

- **Current analyses indicate that there are at least 1,000,000 tonnes of helium-3 imbedded in the lunar soil (3m depth).**

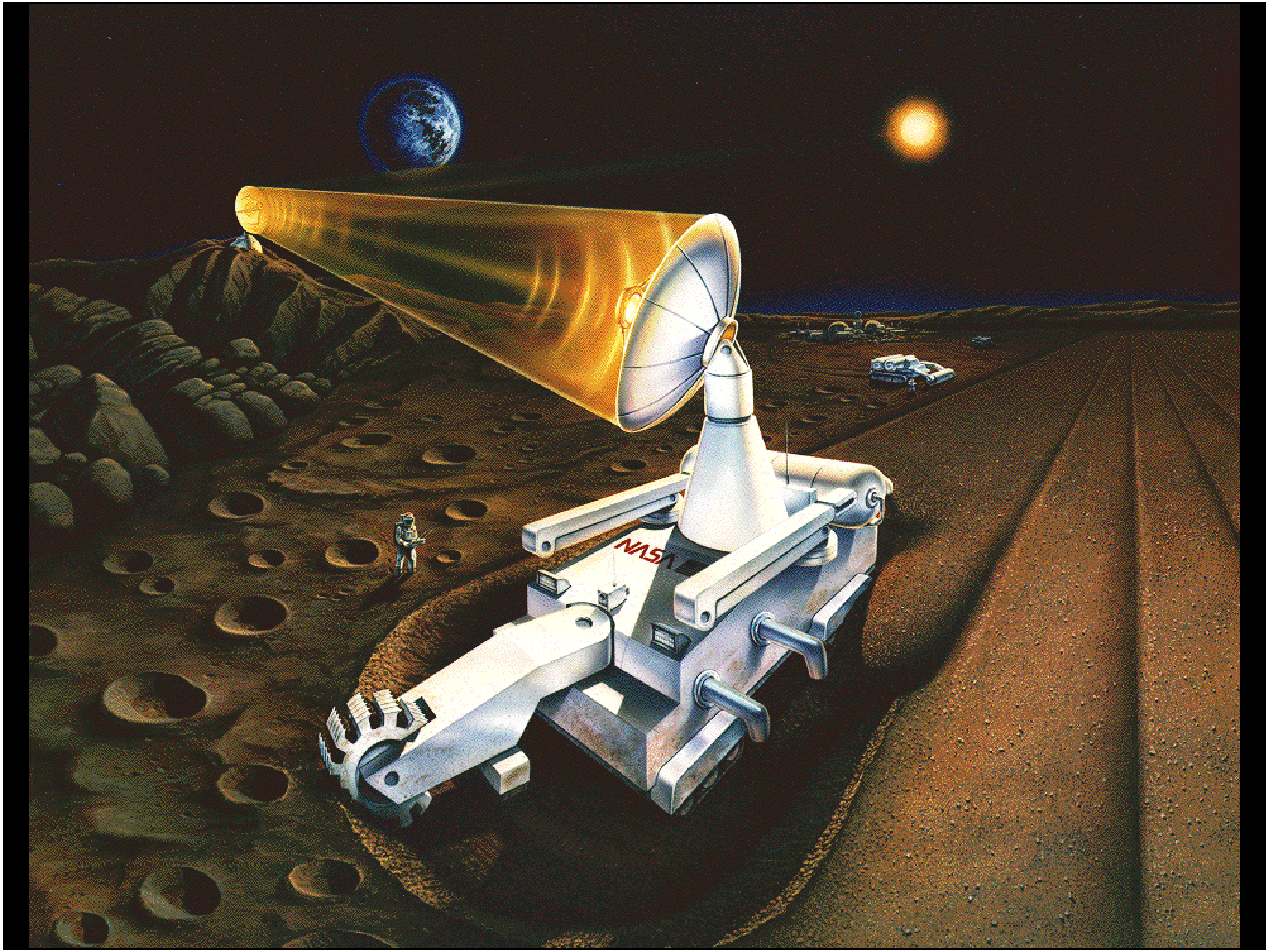


The regolith in those regions is made up of very fine grains which has been “gardened” by meteorites over billions of years (NASA Photo).

When Lunar Regolith is Heated the Helium-3 is Released



Pepin and Co-Workers, University of Minnesota, 1970

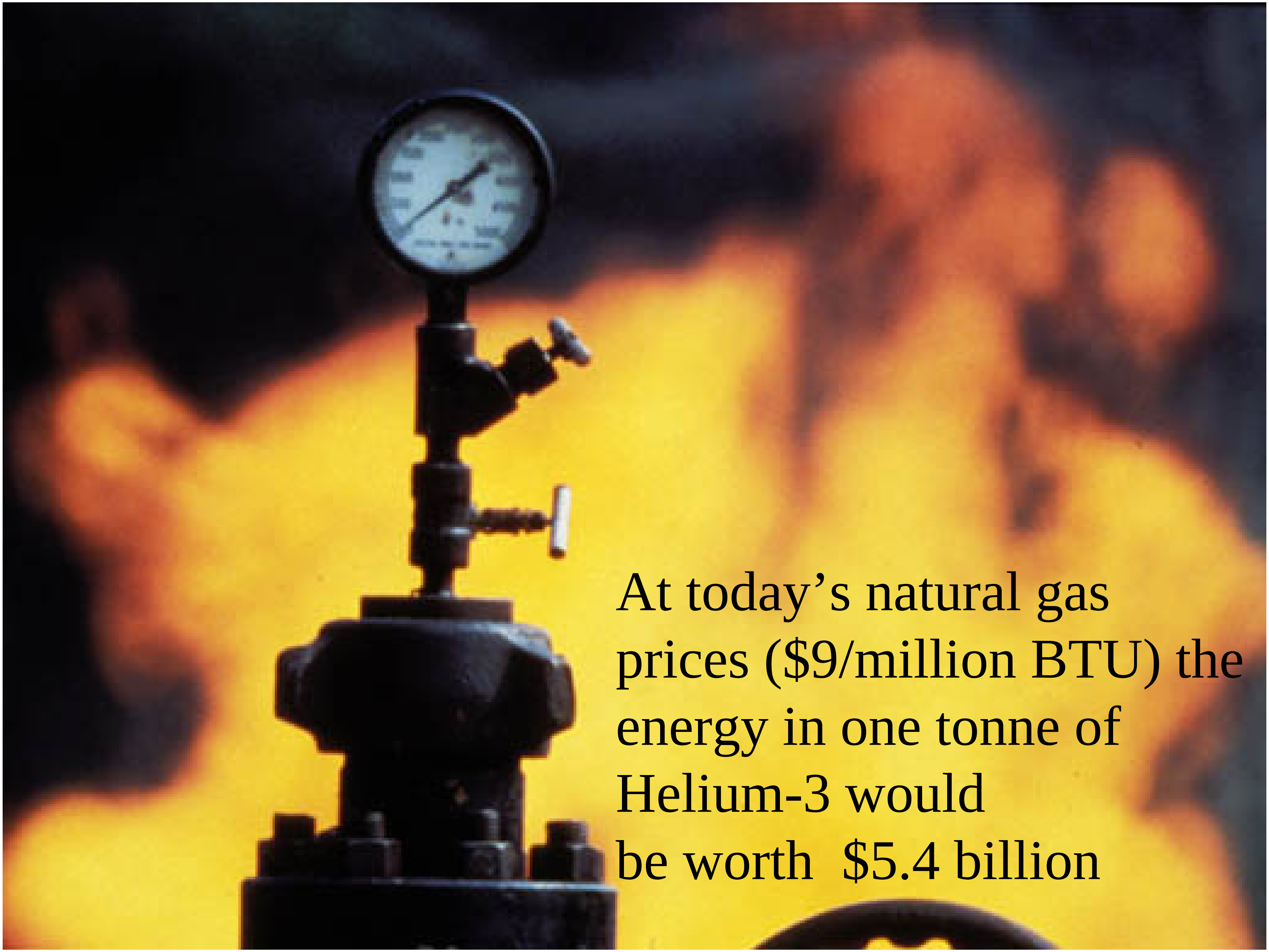

NASA

Significance of Lunar Helium-3

- 1 tonne of Helium-3 can produce enough electricity to fulfill the needs of 10 million Americans for a whole year

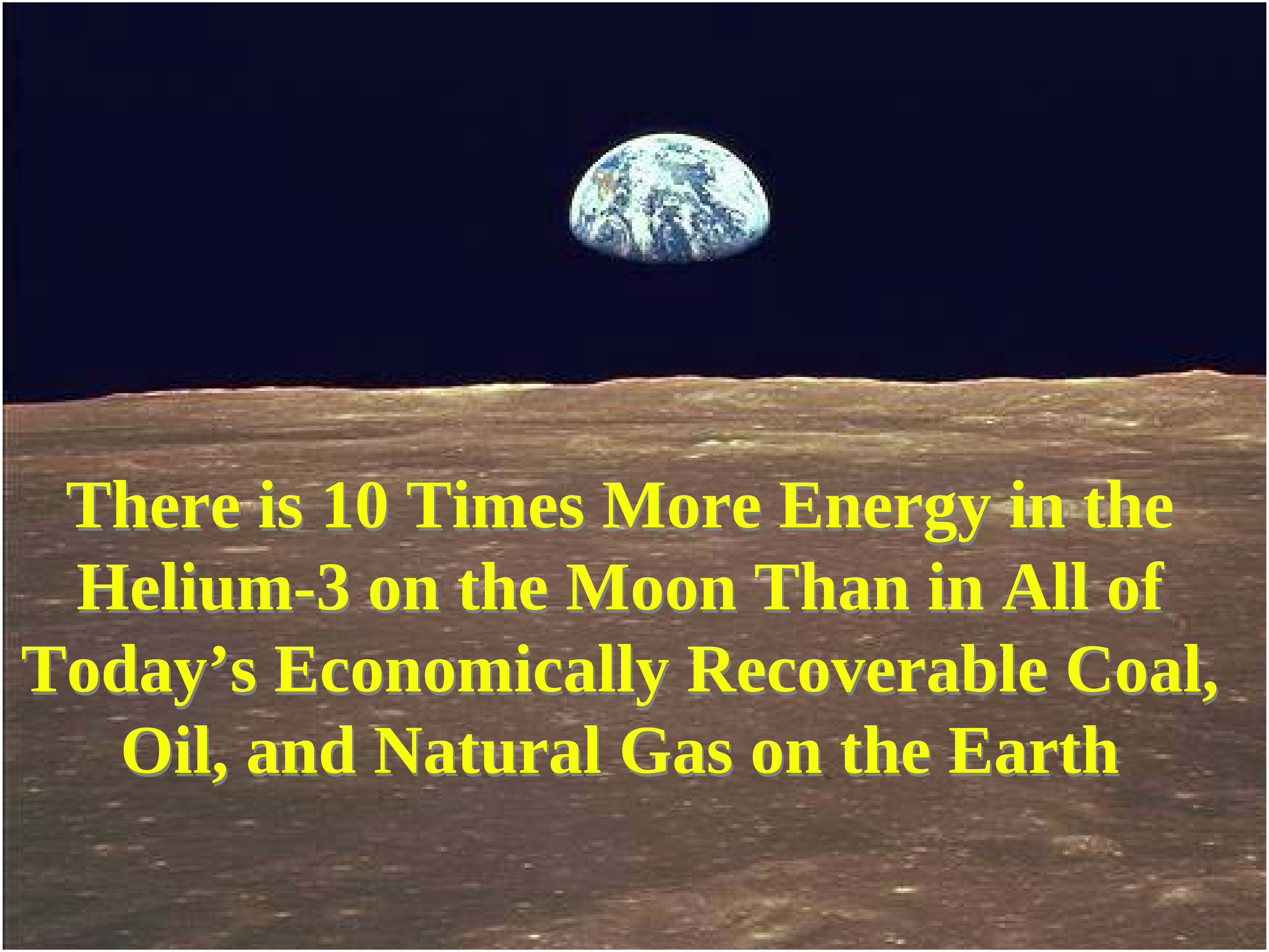
- 40 tonnes of Helium-3 will provide all the electricity used in the United States in 2007


At today's spot coal prices ($3/million BTU or $66/tonne) the energy in one tonne of Helium-3 would be worth $1.8 billion

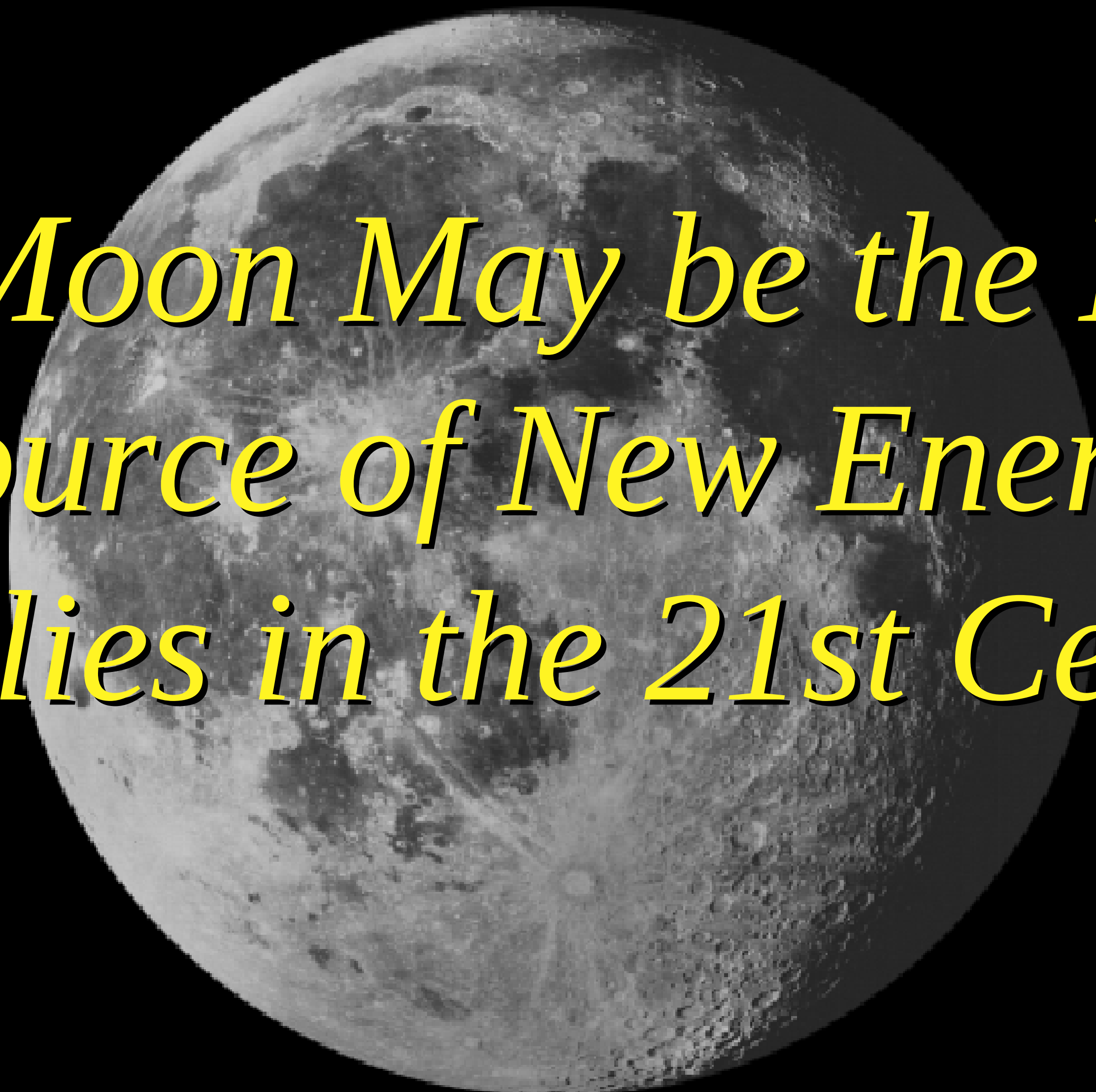


At today's natural gas prices ($9/million BTU) the energy in one tonne of Helium-3 would be worth $5.4 billion


At today's oil prices ($13/million BTU or $80/barrel)
the energy in one tonne of Helium-3 would
be worth $8 billion
HEIDRUN
One of today's U. S. shuttles could return a
"payload" worth over $150 billion.

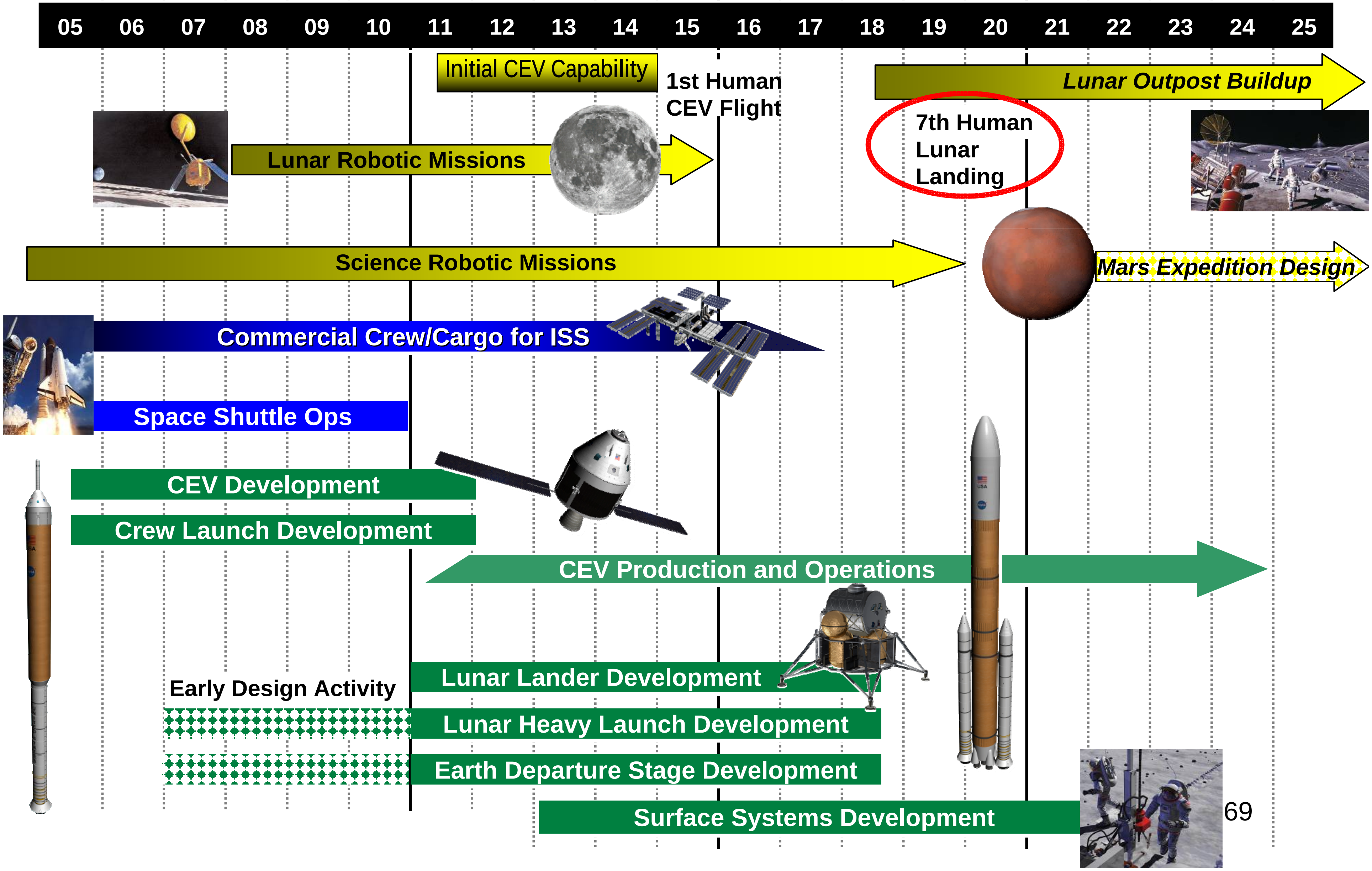

There is 10 Times More Energy in the
Helium-3 on the Moon Than in All of
Today’s Economically Recoverable Coal,
Oil, and Natural Gas on the Earth

The Moon May be the Major Source of New Energy Supplies in the 21st Century



This would make the investment in the Space program one of the largest payoffs in history.

NASA's Exploration Roadmap



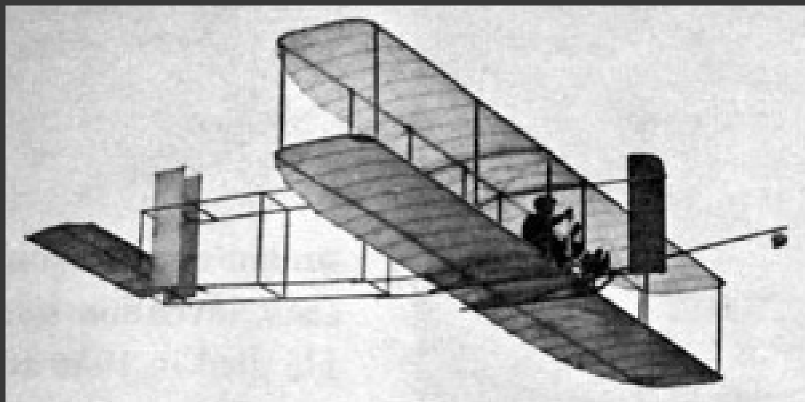
Conclusions

- We have an energy problem that requires immediate attention and new sources must be made available by 2050.
- Nuclear sources appear to be the only worldwide solution for the long run.
- Fusion has many advantages over fission.
- Advanced fusion fuels using ^3He have significant advantages over the DT cycle.

Conclusions(cont.)

- There are 2 main remaining issues before a ^3He based fusion economy can be realized:
  - Successful demonstration of breakeven and net energy gain
  - A resource base of > 10,000 tonnes of economically accessible ^3He
- The ^3He resources on the Moon (≈ 1,000,000 tonnes) can satisfy the world electricity demand for more than a 1,000 years.
- For fusion reactors based on the ^3He fuel cycle to be available by the 2040-2050 time frame, a significant worldwide effort in research is needed now.

They Said It Couldn't Be Done



"Man will not fly for fifty years."

–Wilbur Wright, 1901

"Heavier-than-air flying machines are impossible." **–Lord Kelvin, president, Royal Society, 1895**

"There is not the slightest indication that [nuclear energy] will ever be obtainable. It would mean that the atom would have to be shattered at will." **–Albert Einstein, 1932**

"Anyone who looks for a source of power in the transformation of the [nucleus of the] atom is talking moonshine." **–Ernest Rutherford, 1933**

"Airplanes are interesting toys but of no military value." **–Marshall Foch, future WWI French commander-in-chief, 1911**

"Space travel is utter bilge." **–Dr. Richard Wooley, Astronomer Royal, space advisor to the British government, 1956**


Where in the World Can We
Find Clean, Safe, Long Lasting,
and Economical Energy
Sources for the 21st Century
and Beyond?
Possibly Here!

Questions?