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HELIUM-3 FUSION REACTORS – A CLEAN AND SAFE SOURCE OF ENERGY IN THE 21ST CENTURY

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Technical Report

Wisconsin Center for
Space Automation and Robotics
•
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Helium-3 Fusion Reactors - A Clean and Safe Source of Energy in the 21st Century

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Introduction

There is no doubt that one of the most difficult problems that a peaceful world will face in the 21st century will be to secure an adequate, safe, clean, and economical source of energy. Energy is essential to feed, clothe, house, and protect the billions of people that are now living on this planet. The United States and Russia have used their energy resources to become the leaders of nations and we can expect that others will try to follow our example. In addition, many other developing nations will be under great pressure to raise the standard of living for an exploding world population. Today, I want to tell you about one vision of how we can provide the enormous amounts of energy we will need on Earth in the future as well as in Space.

Energy Needs

First we need to have some idea of just how much energy we now use, what might be required in the future, and how that compares to the resources presently available to us. We can get a reasonable estimate of the future needs if we knew just two numbers (Figure 1); the population as a function of time and the annual energy use per capita. The product of these two numbers will give us an idea of the future demands to place on the energy resources of the world.

The world population (Figure 2) has grown from 1 billion in 1830 to 2 billion in 1930, 3 billion in 1960, 4 billion in 1975 and 5 billion in 1987. We are well on our way to 6 billion people before the turn of the century. Demographers tell us that **<u>if</u>** we can cut the birth rate around the world by almost a factor of 2, the world population will asymptote out at 10 billion by the middle of the next century. If we keep on at the current birth rate, the asymptotic world population may reach 12 to 14 billion.

The energy use per person shows a somewhat different behavior (Figure 3). In 1960, the <u>average</u> world energy use, expressed in the energy contained in an equivalent barrel of oil, was 6 BOE/person per year. Today that number has increased to over 11 BOE/person per year. For comparison, the per capita energy use of energy in the U.S. today is 55 BOE. In Russia, Europe, and in Japan it is ≈30 BOE. Over 80% of the world population uses less than the average value and as the developing nations "bootstrap" themselves into a standard of living that still is far below that of the developed nations, the average energy use per capita is predicted to rise by another 50% in the middle of the next century. This prediction already accounts for considerable conservation in the energy use patterns of the US, Europe, Russia, and Japan, who together now use over 70% of the world's energy resources.

The previous 2 charts can be used to predict the energy use well into the 21st century. Today (Figure 4) over 5 billion people use an average of 11 BOE/person per year to account for a world energy use rate of nearly 60 billion barrels of oil equivalent per year. With a conservative estimate, 10 billion people on the earth in the year 2050, and an equally conservative 15 BOE/capita per year usage in the middle of the next century, our annual energy use could easily rise to 3 times that of today.

What does this level of energy use imply when compared against our reserves of energy? The cumulative amount of energy used up through the next century, assuming that we reach an equilibrium value in the year 2050, is shown in Figure 5. We can see that even with this conservative picture we will have to provide the energy equivalent of at least 10 trillion BOE barrels of oil in the next century to maintain even a modest standard of living around the world (roughly 1/4 of that now enjoyed in the U.S.). The level of economically recoverable fossil fuels (coal, oil, and natural gas) is also listed on this figure. While the number is our best estimate of today, whether it is 7 trillion BOE or 8, or 6, does not make much difference to the general conclusion that is forced on us. Somewhere, in the middle of the 21st century we will exhaust our economically recoverable fossil fuels and we will have to look to another major source of energy to support a world population that is at least twice that of today, and it is easy to imagine that the world population may even be 3 times our present level.

There are two important observations that need to be made at this point. First, we will not run out of fuels overnight. Some areas of the world will run out before others and this could lead to global instabilities such as we observed in the recent Gulf War. Second, the year 2050 may seem far in the future, especially to the attendees at this conference. Let me remind you that if every student in high school today lives to the average life expectancy, he or she will be alive in the year 2050! Over 20% of the present US population will be alive in the year 2050! Therefore, it is not too soon to prepare for that time of adjustment with serious planning today.

What form of energy could fuel the engines of industry, commerce, transportation, and residential life after the fossil fuels are largely exhausted? At the present time it appears that only some form of nuclear energy, either fission or fusion, can fill that void. While nuclear fission now provides 20% of the world's electricity (more than 70% in France), this option is being avoided by many countries and has lost favor in many industrial nations around the world. Today, I want to discuss the nuclear fusion option.

Before we get into the fusion option, let me point out that there are at least two reasons why we may have to solve our worsening energy situation faster than by the middle of the 21st century. The first (Figure 6) is that we are currently dumping greenhouse gases into the atmosphere at an alarming rate. This figure shows that we are currently releasing over 5 billion tonnes of C into the atmosphere by the burning of fossil fuels (approximately 1 tonne per year for every man, woman, and child in the world). We do not know exactly what the effect of this rapid increase in CO_2 will have around the world, but more and more studies are predicting significant temperature increases and consequences to agriculture which may require premature curtailment of our voracious appetite for energy from fossil fuels.

If the resource and environment issues were not enough, the nonuniform distribution of fossil fuel resources could promote global instabilities which could lead to military conflicts all too familiar to us in the 20th century.

Fusion Physics

There currently are 3 main fusion fuel cycles being studied around the world and one fuel cycle which has only received attention recently (Figure 7). The first cycle, and the one which has received the most attention, is the fusion of deuterium (D) and tritium (T). This reaction produces a neutron and a ^{4}He nucleus releasing 17.6 MeV of energy. The deuterium is a common, nonradioactive isotope of hydrogen found in water all around the world. Tritium, on the other hand, is radioactive and must be made from lithium in a fusion reactor.

The second reaction is the fusion of two D nuclei which, half the time, produces a neutron and a ^{3}He nucleus, and the other half of the time the reaction produces a proton and a tritium nucleus. The T nucleus can burn with other D nuclei via the first reaction.

The third reaction is that of D and ^{3}He to produce a proton and a normal ^{4}He nucleus. On the surface, this is a perfect nuclear reaction because it uses no radioactive fuel and it produces no radioactive isotopes. However, some of the D nuclei in the plasma react via the DD chain and can produce a small amount of radioactivity.

The fourth reaction is that between two ^{3}He nuclei to produce 2 protons and a normal ^{4}He nucleus. This reaction is a perfect nuclear reaction in that it starts with no radioactivity, produces no radioactivity, and there are no side reactions that can produce radioactive isotopes. Obviously, if this was all there was to it, we would opt for the ^{3}He^{3}He reaction. Even though all of the above reactions have a positive Q value (that is, they release more energy than required to cause them to fuse), the rate at which they react is also an important consideration.

The reaction rate, times the energy released per reaction, is plotted in Figure 8 as a function of the temperature of the plasma. This figure shows that the DT reaction has the highest reaction rate and can be made to burn at the lowest plasma temperature. Therefore, is it is easy to see why this is the reaction most studied by plasma physicists around the world today. The other reactions need temperatures 3 to 10 times those necessary for the DT reaction. Incidentally, the highest temperature achieved thus far in the laboratory is ≈35 keV.

Another way to view these fuel cycles is to concentrate on the form of the energy release (Figure 9). Over 80% of the energy in the DT cycle is emitted in the form of neutrons, the rest is divided between transport (particle), synchrotron (photon), and bremsstrahlung (photon) losses. The kinetic energy of the neutrons must be converted to heat and in the process of slowing down, the neutrons can cause considerable damage as well as inducing substantial amounts of radioactivity in the surrounding material.

On the other hand, the D^{3}He reaction produces relatively few neutrons and a much larger fraction of the energy released can be converted directly into electricity electrostatically (particle transport losses) and electromagnetically (photons impinging directly on rectenna).

Finally, the ^{3}He^{3}He reaction in an electrostatic device, produces energy almost entirely in charged particles that can be converted directly to electricity at efficiencies of 70-80%. Even more importantly, notice the lack of neutron production. This means that there will be no radioactive waste to dispose of after the reactor is decommissioned, and there will be no radioactive material to deal with in the event of an accident or even in a maintenance situation.

What would we expect of fusion reactors utilizing these fuels? Any fusion reactor, regardless of the fuel cycle, would not emit any greenhouse gases. In addition, compared to fission reactors, the amount of long-lived radioactivity generated would be less and there is no possibility of any runaway nuclear reactions.

If we compare the fusion fuel cycles among themselves (Figure 10) we arrive at an interesting conclusion. As we said earlier, the DT cycle burns at the lowest temperature but at the same time generates the most radioactivity. After 100 years, the steel structural materials in a power reactor would have 1000 times less radioactivity per kWh generated than a fission reactor. Using the D^{3}He reaction would reduce that radioactivity by another factor of 30 and of course, if we used the ^{3}He^{3}He reaction there would be no residual radioactivity at all to dispose of.

The neutrons characteristic of the DT cycle can also damage the structural components of the reactors such that even after an extensive materials development program they will probably last only 3 to 4 full power years. The development requirements would be much smaller for the D^3He cycle and the materials will probably last the full reactor lifetime without a requirement to be replaced. Of course, since there are no neutrons in the $^3He^3He$ cycle, off-the-shelf materials could be used for the life of the plant.

The worst case scenario for an accident in fusion devices varies from no off-site fatalities (DT), to no evacuation required (D^3He) to no external effects at all with $^3He^3He$.

Because most of the energy in the DT cycle is in neutrons, the net electrical efficiency will be the same as for fission reactors. Since roughly half of the D^3He reaction products can be converted directly to electricity at ≈70-80% efficiency, we would expect to get at least 50% higher efficiencies. Finally, essentially all the products from the $^3He^3He$ can be converted directly allowing the ultimate efficiency of the reactor to be twice that of a fission system.

Thus far, the cost of electricity from DT fusion plants is projected to be ≈50% higher than from fission plants. The environmental and efficiency advantages of the D^3He reaction should improve the situation somewhat but it is expected that only the $^3He^3He$ reaction has the possibility to produce electricity at a lower cost than fission power plants.

At this point you are probably asking the question; "If the use of ^3He fuel is so attractive, why has it not been pursued more vigorously?" There are two answers to that question. First, there must be a conclusive demonstration that the fuel can be confined in a stable manner and that more energy can be released than required to contain the plasma. Second, there is the question of the ^3He fuel supply. Dr. Schmitt will address the latter and I will say more about the first question.

The leading magnetic fusion concept is the tokamak (Figure 11), invented by Andrei Sakharov, among others in the former Soviet Union. This approach relies on heating all the atoms in a magnetically confined plasma to very high temperature. Since the particles are in equilibrium, there is a Maxwellian distribution with only those particles at the higher temperatures fusing. That is, we must heat up a large number of particles to fill up the Maxwellian so that only a few will react. This is not too much of a problem for the DT and D^3He cycles, but it is impractical for the $^3He^3He$ cycle. That is why only the DT, DD, and to some degree the D^3He cycle have been studied in the tokamak. You can also see in this figure an actual photo inside the worlds largest tokamak, the JET device in the UK. It is already operating and experiments have already released 1.7 MW_{th} with DT and next year they hope to reach close to 40 MW_{th}.

One can get a sense of the progress made in this field from Figure 12 where the actual fusion power released in tokamaks is plotted as a function of time. Note that 20 years ago we had released less than 1 watt of thermal fusion power. This level has been steadily increased, using DD fuel until the late 80's when helium-3 fuel was introduced. Those D^3He experiments released 100,000 watts of power in 1990. In 1992, the JET device conducted the first DT burn and released 1,700,000 watts. Later this year, the TFTR device in Princeton hopes to increase that by another factor of 10 to more than 10,000,000 watts and as was pointed out earlier, the JET experimentalists expect to produce ≈40,000,000 watts in a year or two. Beyond that, there is currently a 250 million dollar per year worldwide collaborative program between the US, Russia, European, and Japanese scientists to build a 1,000,000,000 watt reactor to operate shortly after the turn of the century.

Turning back our attention to the $^3He^3He$ cycle we find considerable progress on that front as well. Figure 13 shows a schematic of an entirely different approach to fusing plasmas. Instead of heating up a plasma so that only the particles in the "tail" of the Maxwellian react, an idea originally invented by Farnsworth (who invented television), and later improved upon by Hirsch and Bussard, cause the fuel atoms to fuse by falling through a spherically negative potential well. The positively charged fuel ions are contained within an electrostatic potential well in which they are accelerated toward the center and eventually fuse. The reaction products, being on the order of MeV's, escape the virtual cathode and can be converted directly to electricity outside the reaction zone. The experimental device in Figure 13, built for DARPA, has already demonstrated the formation of the potential well inside the virtual cathode and is now being readied for experiments to improve the confinement time. A device like this would be much more effective than a tokamak for the D^3He fuels and is the only way we know to make the $^3He^3He$ cycle work.

Fusion Propulsion

Fusion reactors are not only attractive for terrestrial electric power production, but they can also produce very powerful and efficient rockets. The exhaust of 14 MeV protons in the D^3He cycle can result in a specific impulse of over 1,000,000 seconds (Figure 14). Such performance is gained at the expense of thrust and by simply adding cold mass in the exhaust, we could lower the specific impulse and increase the thrust. Finally, the fusion rockets could also run in a NERVA mode (that is, heat hydrogen gas to high temper-atures to develop high thrusts and low specific impulses). The attractive feature of this concept is that one engine could operate in a range of modes using high thrust to get off a gravity well and later it could shift to higher and higher specific impulse operation once the spacecraft is in zero gravity.

The effect of such variable I_{sp} operation would be a significant shorten-ing of the trip time to Mars (Figure 15) and the farther out one goes, the greater the effect of the variable specific impulse operating mode. As recently stated by Santarius, "Fusion will be to space propulsion what fission is to the submarine".

Development Scenario

What is a reasonable timetable for the development of fusion energy especially that based on the ^3He fuel cycle? The response to that must first consider how much ^3He fuel is currently available for experimentation. The terrestrial supplies of ^3He (Figure 16) come from 2 sources. First, there is the primordial ^3He left over from the formation of the earth. Unfortunately, there is very little of that left and what is available is associated with natural gas resources. It has been estimated that if we extracted all the natural gas from under ground and separated out all the ^3He, there would be only ≈200 kg of ^3He available. This is clearly not practical. Fortunately, there is another source of ^3He which comes from the decay of tritium in thermonuclear weapons. If we collect the ^3He produced from the tritium in weapons, we would have on the order of 300 kg by the turn of the century. (There would be an equivalent amount from Russia.) Since 1 kg ^3He ≈ 19 MW_{th}, there is enough ^3He to:

- Fuel all the test facilities up to and including a 500 MW_e power plant.
- Fuel a 200 MW_e orbiting power plant continuously.

However, there is not enough ^3He for a large scale electric power economy as there is less than 5000 MW_e-years of energy in all the ^3He available today.

Considering the present US magnetic fusion program plans, we can construct a possible development schedule for ^3He fusion power plants (Figure 17). The US has recently proposed and has funding for the preliminary design of a 100 MW_{th} device called TPX (Toroidal Plasma Experiment). This device could be used to expand the tokamak database for D^3He fusion which could be tested to breakeven and ignition in a slightly modified ITER. Before the ITER gets too radioactive, the blanket and shield currently designed for DT operation could be replaced by a more efficient shield for D^3He. Power generating modules could be added and electricity generated by 2010. Meanwhile, based on successful physics results from ITER, the design and construction of a commercial prototype could begin, with operation in the 2015 time frame. This date tells us when we might need more ^3He than that available from the US (and possibly Russian) weapons programs.

A similar development schedule for the Inertial Electrostatic Confinement approach is given in Figure 18. This schedule would build on the previous DARPA work and aim at a small (10 MWth) breakeven experiment by the turn of the century. The next step would be an energy multiplication experiment to operate a 100 MW_{th} system around the 2005 period. If this is successful, the design and construction could begin of the first commercial electrical power plant to operate in the year 2015. It might be a small power plant by today's standards (≈100-200 MW_e). The next reactor would be the first reactor requiring an external source of ^3He.

Conclusions

From this brief presentation we can see 4 major conclusions:

- The world needs a new source of safe and clean energy by the middle of the 21st century.

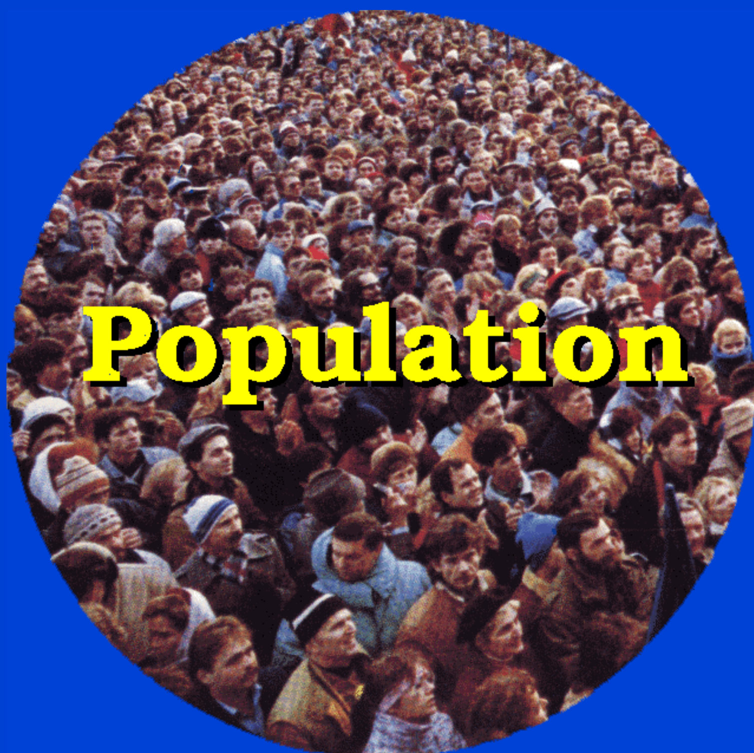
- Fusion fuel cycles containing ^3He (D^3He, $^3He^3He$, etc.,) could provide that energy safer, cleaner, and probably cheaper than present nuclear fission systems.

- Fusion rockets based on the ^3He fuel cycle could open up the Solar System to "Rapid Transit" through high I_{sp} rockets.

- The present world fusion program needs to investigate the use of electrostatic confinement as a means to use advanced fusion fuels.

If we start now, we just might be to help those students presently in school look forward, with confidence, to a productive life in the middle of the 21st century and beyond. If we delay, we will be handing over a world to our grandchildren with little remaining fossil fuels, one with an enormous environmental headache, and one in which global conflicts for the last remaining scraps of fossil fuels could dwarf the recent events in the Persian Gulf.

The World Energy Demand is the Product of Two Simple Numbers



X

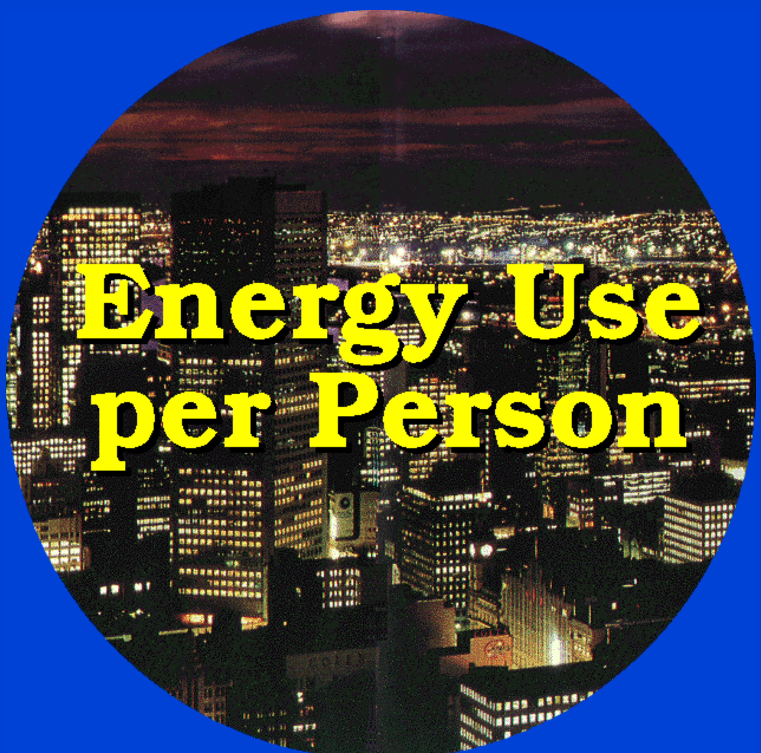


Figure 1

The World Population is Expected to Reach 10 Billion by the Middle of the Next Century

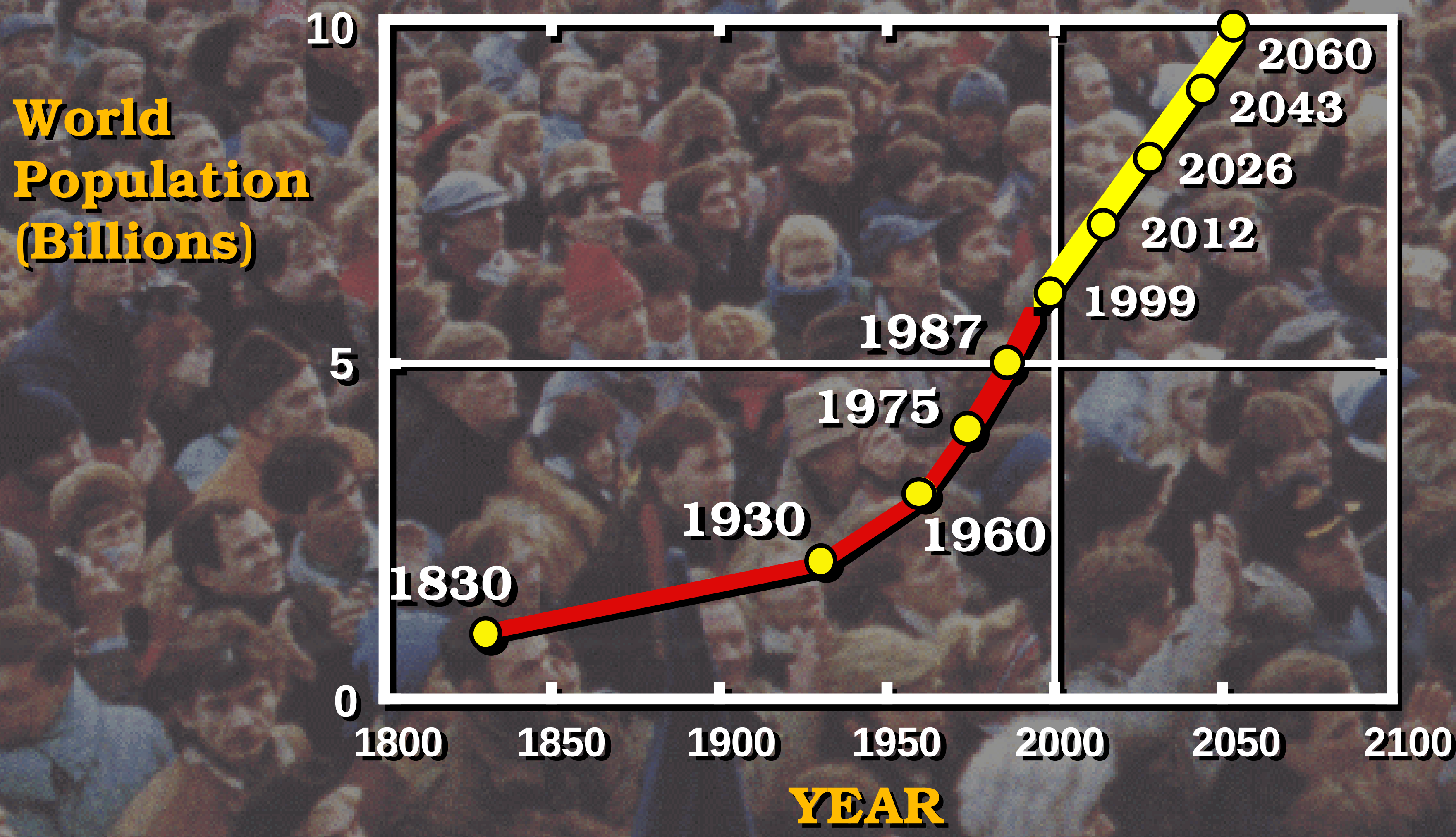


Figure 2

Growth of World Energy Use Per Capita

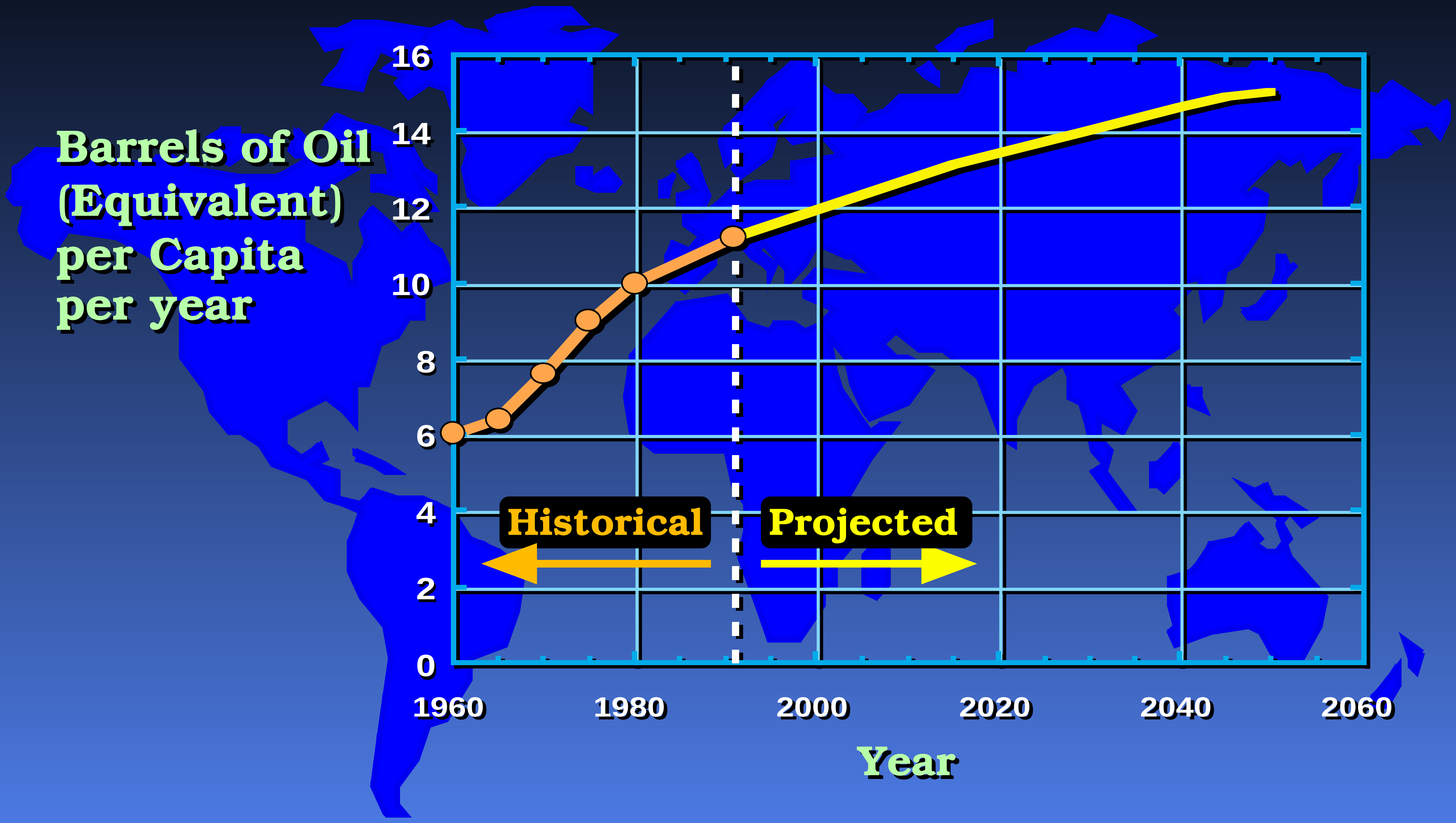


Figure 3

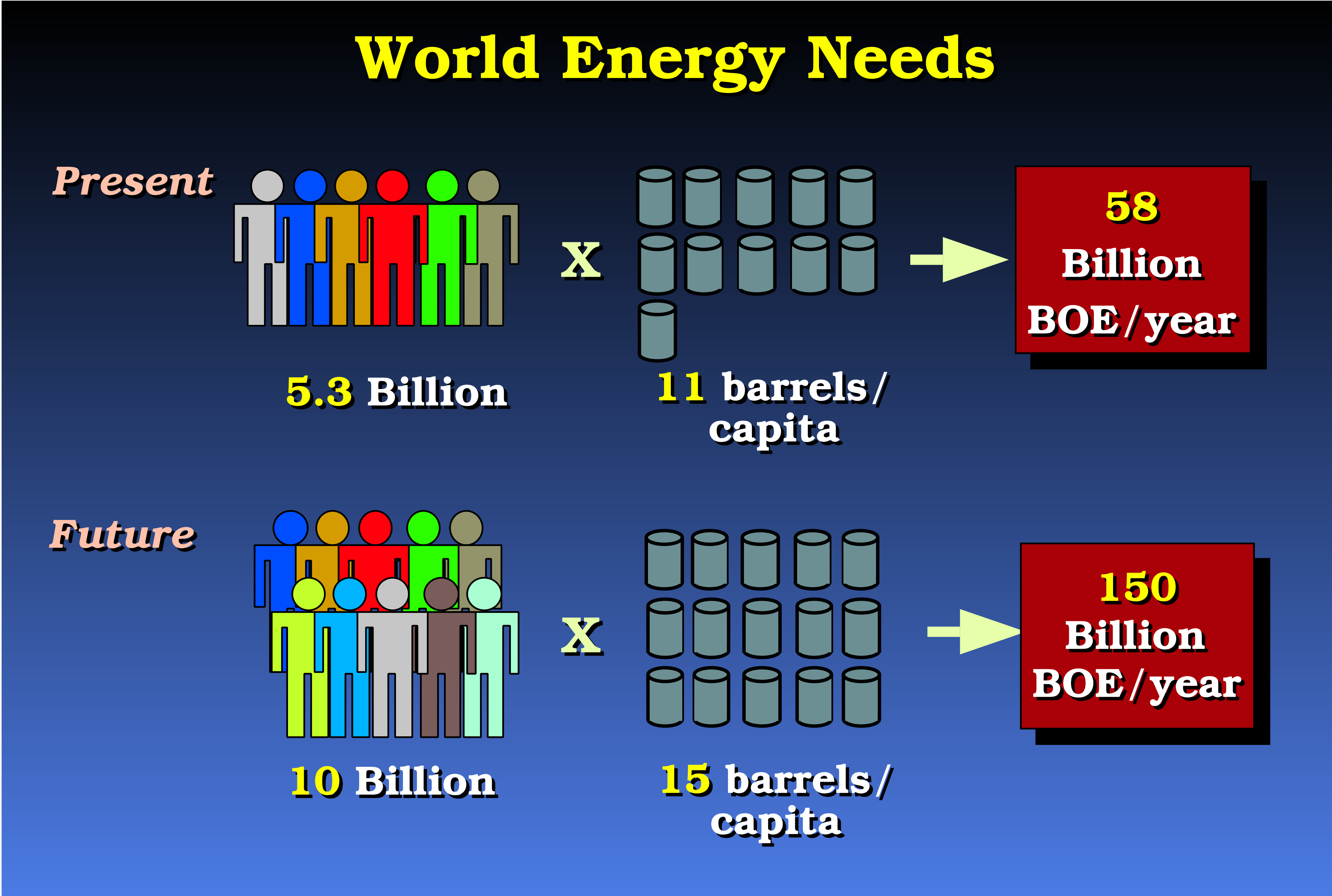

World Energy Needs
Present
x
58
Billion
BOE/year
5.3 Billion
11 barrels/
capita
Future
x
150
Billion
BOE/year
10 Billion
15 barrels/
capita

Figure 4

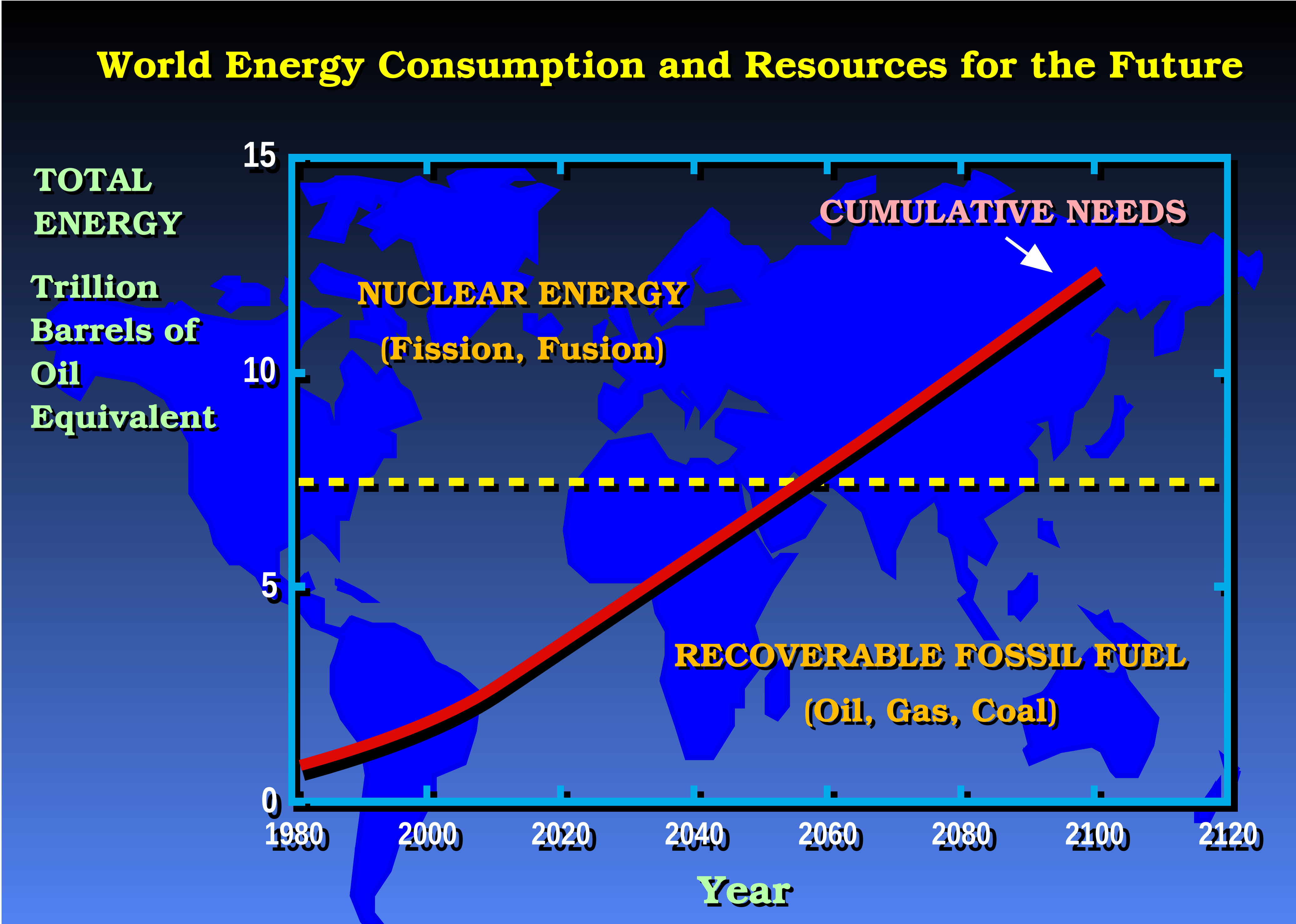

World Energy Consumption and Resources for the Future
TOTAL ENERGY
Trillion Barrels of Oil Equivalent
15
10
5
0
CUMULATIVE NEEDS
NUCLEAR ENERGY
(Fission, Fusion)
RECOVERABLE FOSSIL FUEL
(Oil, Gas, Coal)
1980
2000
2020
2040
2060
2080
2100
2120
Year

Figure 5

World Carbon Emissions from Burning Fossil Fuels

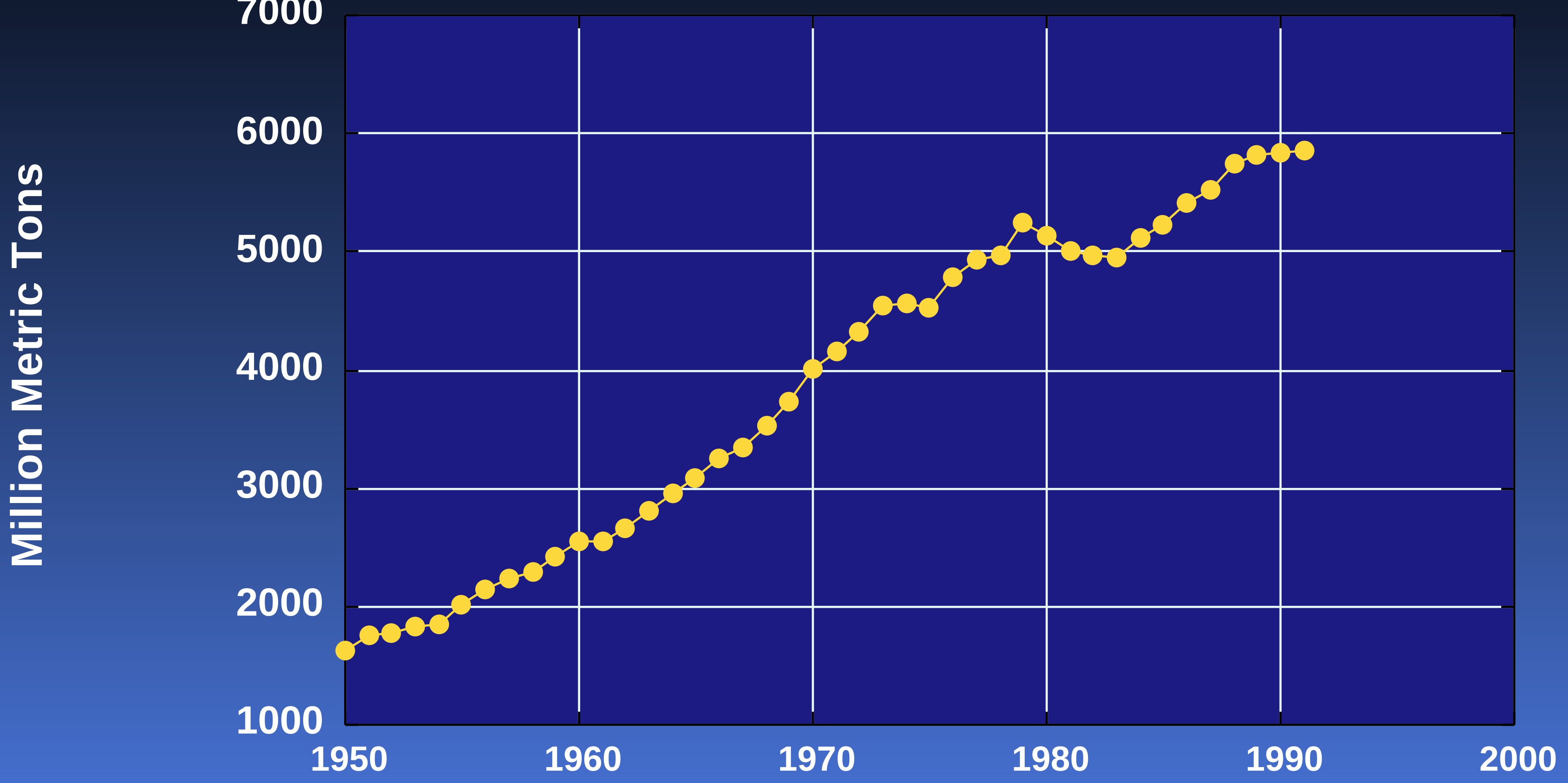


Figure 6

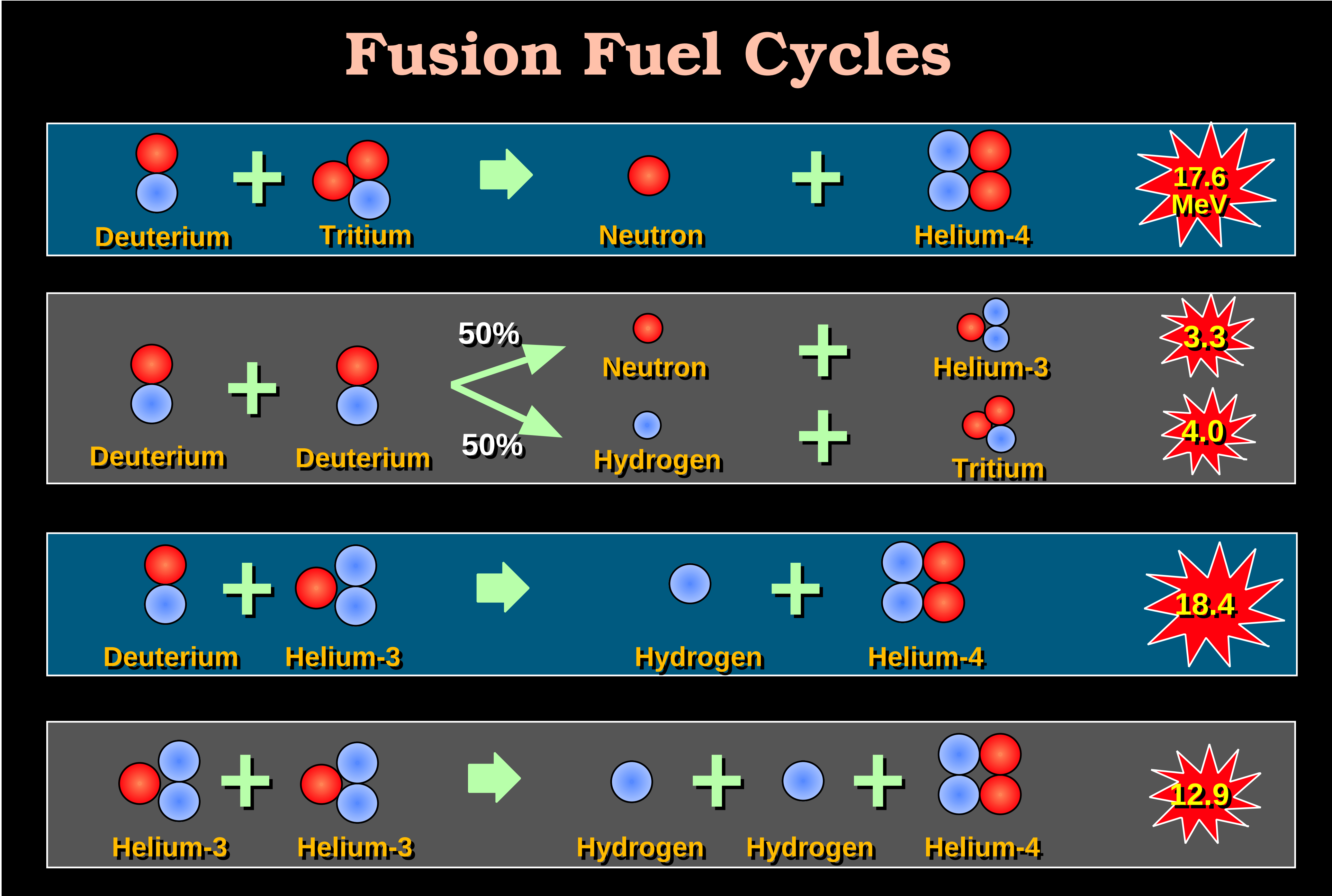

Fusion Fuel Cycles
Deuterium
Tritium
Neutron
Helium-4
17.6 MeV
50%
50%
Deuterium
Deuterium
Neutron
Helium-3
3.3
Hydrogen
Tritium
4.0
Deuterium
Helium-3
Hydrogen
Helium-4
18.4
Helium-3
Helium-3
Hydrogen
Hydrogen
Helium-4
12.9

Figure 7

Fusion Fuel Cycle Power Density Depends on Plasma Temperature

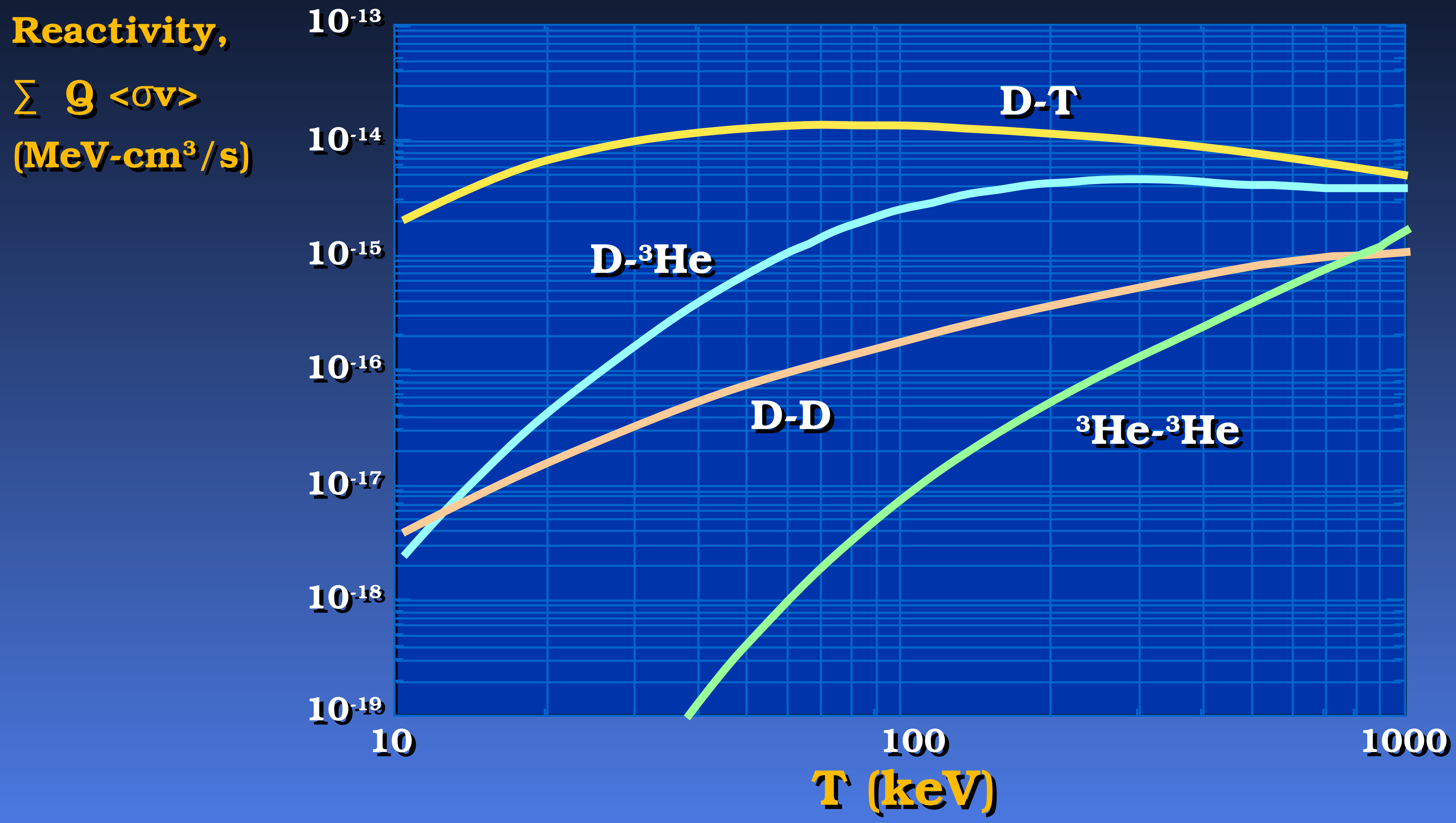


Figure 8

The Form of Energy Release is Quite Different in DT, DD, D^{3}He and ^{3}He-^{3}He Fuel Cycles

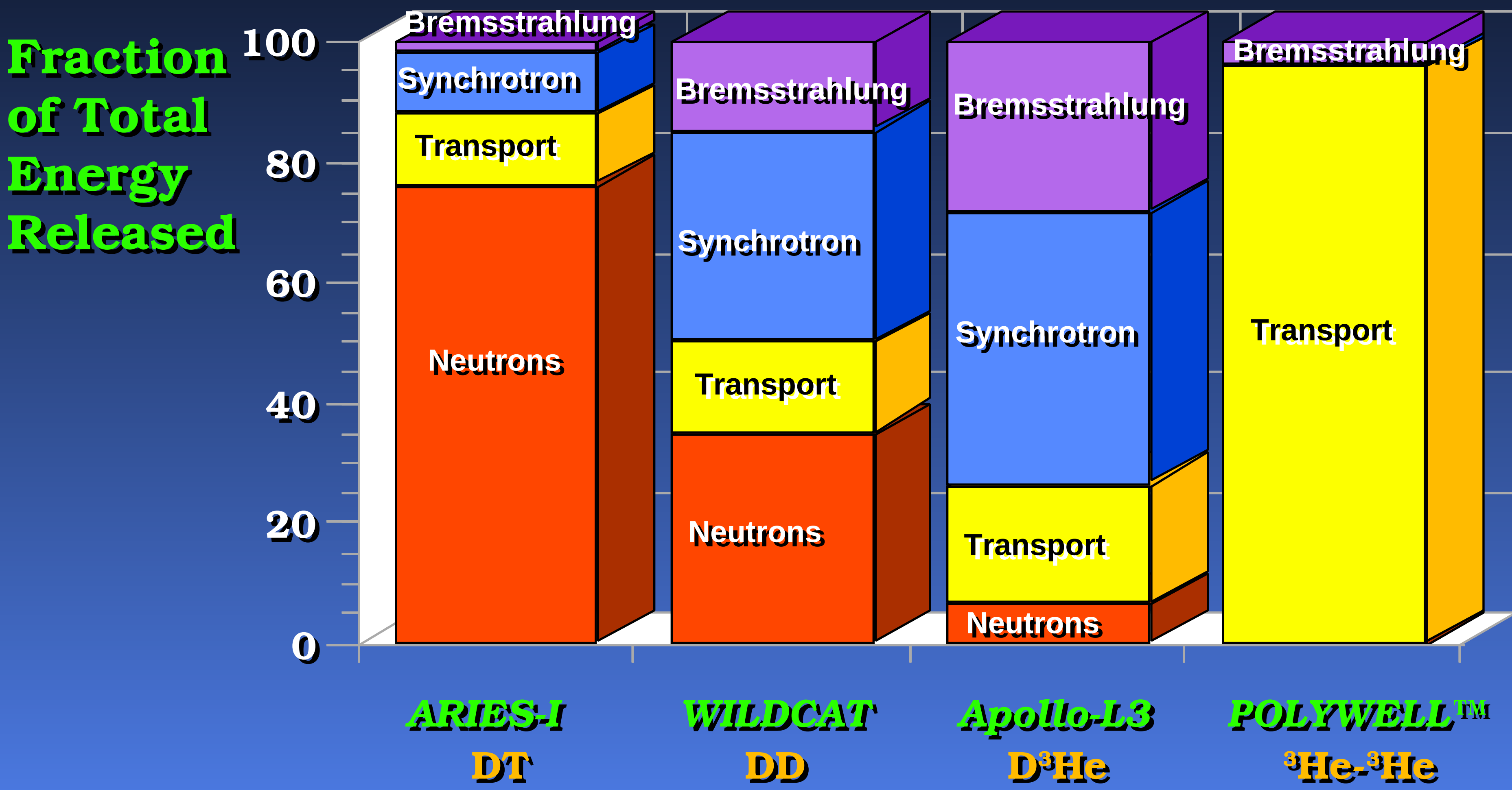


Figure 9

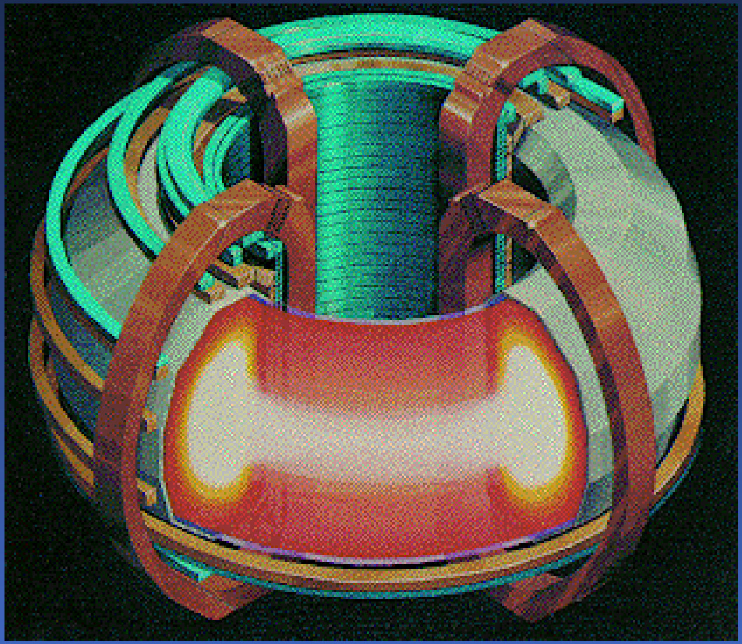
Key Technological Features of Fusion Power Plants

	DT	D^3He	$^3He^3He$
Physics	Easiest (20 keV)	Harder (60 keV)	Hardest (200 keV)
Radioactivity (vs. Fission)	Same (1 day) 0.1% (100 yr)	3% (1 day) 0.003% (100 yr)	None (1 day) None (100 yr)
First Wall Life (Matls. Development)	3–4 FPY's (Extensive)	Full Lifetime (Small)	Full Lifetime (Off-the-Shelf)
Worst Accident Scenario	No Offsite Fatalities	No Evacuation Required	Inherently Safe
Electrical Efficiency (vs. Fission)	≈ same	1.5–2X Higher	2X Higher
Projected Cost of Electricity (vs. Fission)	≈ 1.5 X	≈ 1–1.5 X	< Fission

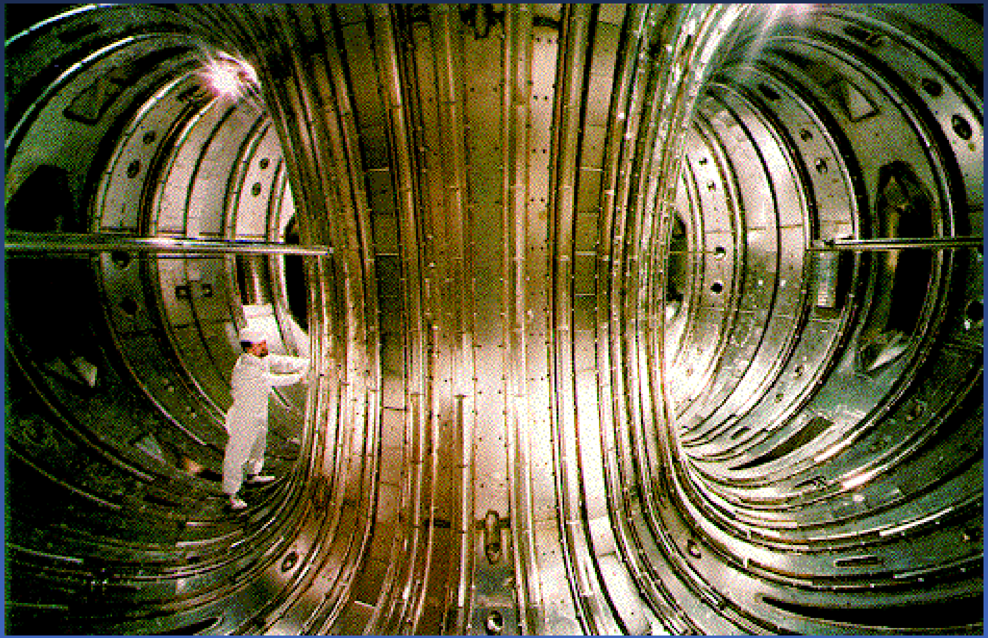
Figure 10

The Tokamak is the Leading Magnetic Fusion Concept for the DT Fuel Cycle

D + T –> n (14 MeV) + ^{4}He (3.5 MeV)



Schematic of a Tokamak

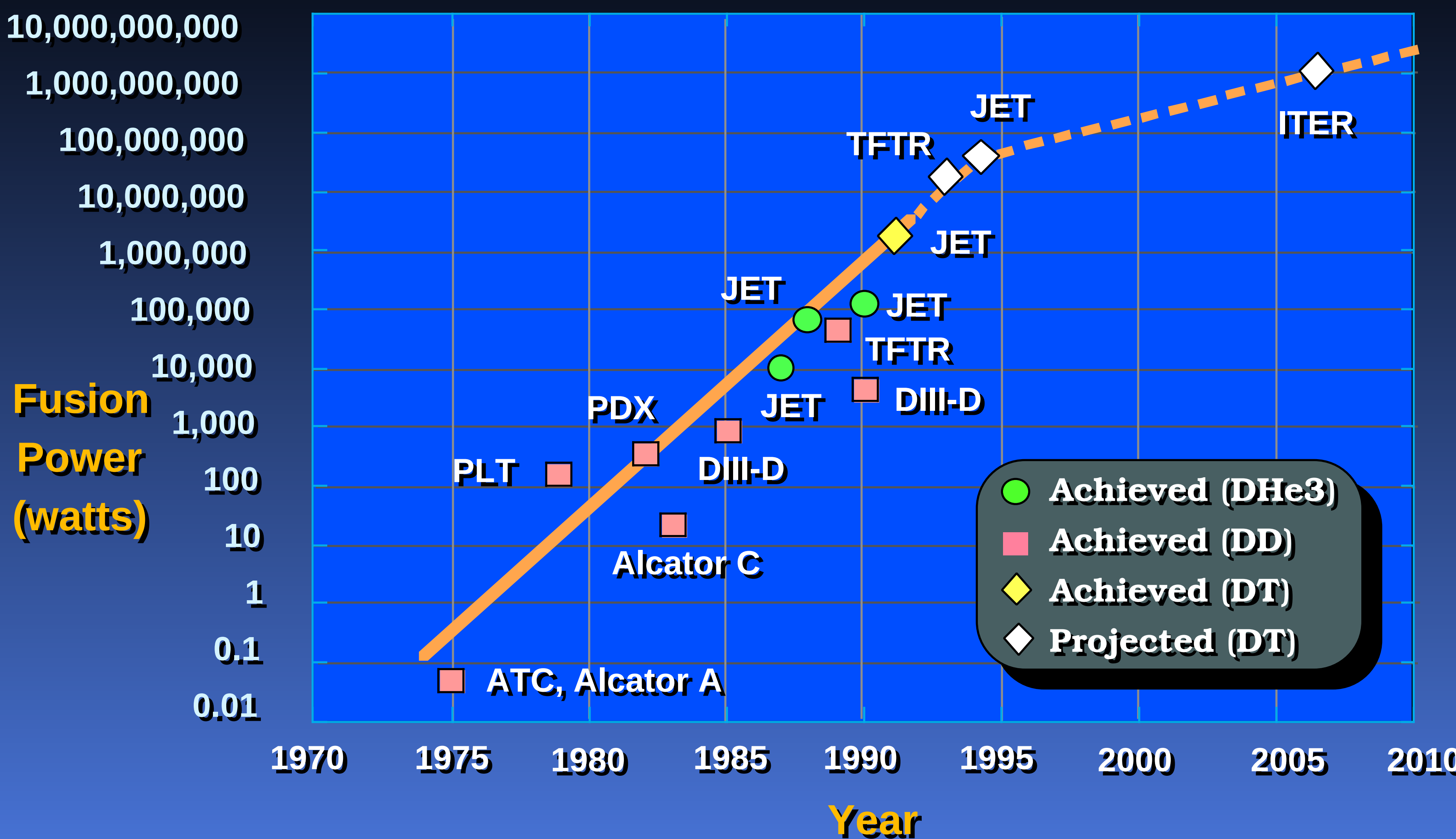


Joint European Torus – JET

~ 40 MW

Figure 11

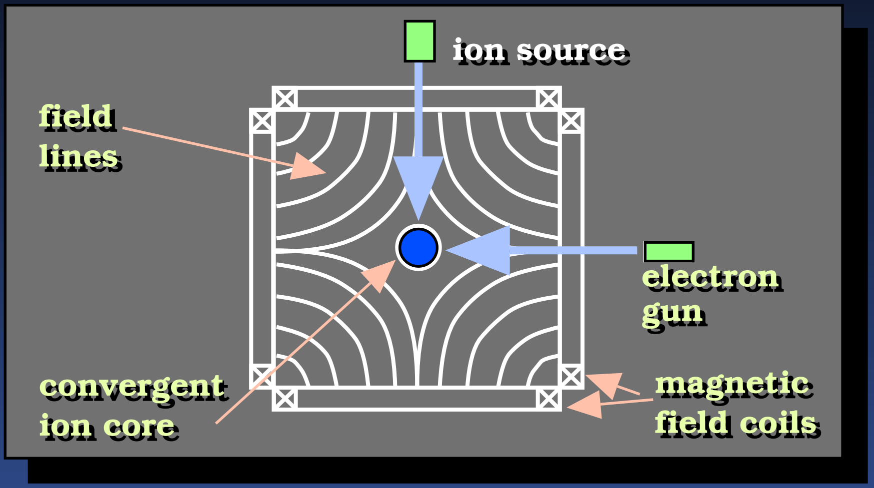
Progress in Magnetic Fusion Power

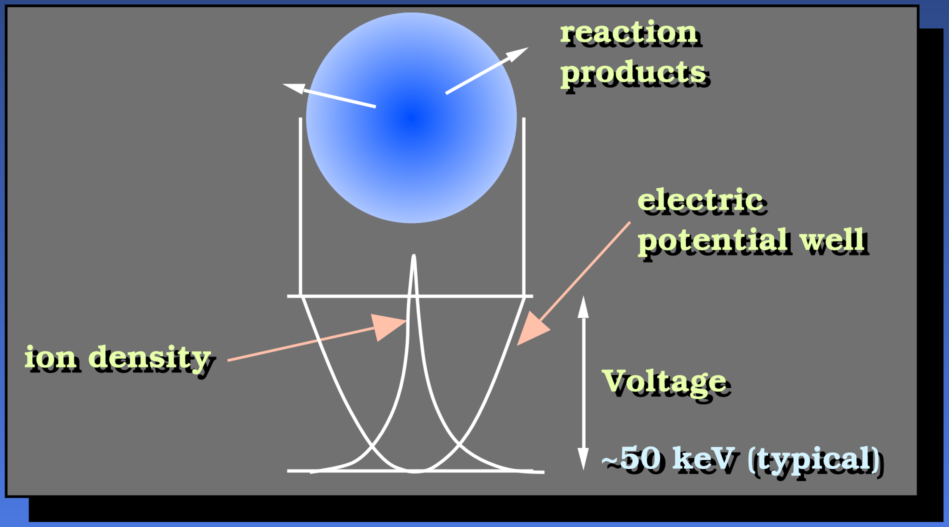


PLT	Princeton Large Tokamak
PDX	Princeton Divertor Experiment
JET	Joint European Torus
ITER	International Thermonuclear Experimental Reactor
DIII & DIII-D	General Atomics Tokamak Experiments
ATC & TFTR	Princeton Plasma Physics Laboratory
Alcator A, C	Massachusetts Institute of Technology

Figure 12

Magnetostatic Confinement Would be Ideal for Advanced Fuels (D^3He, ^3He-^3He, etc.)





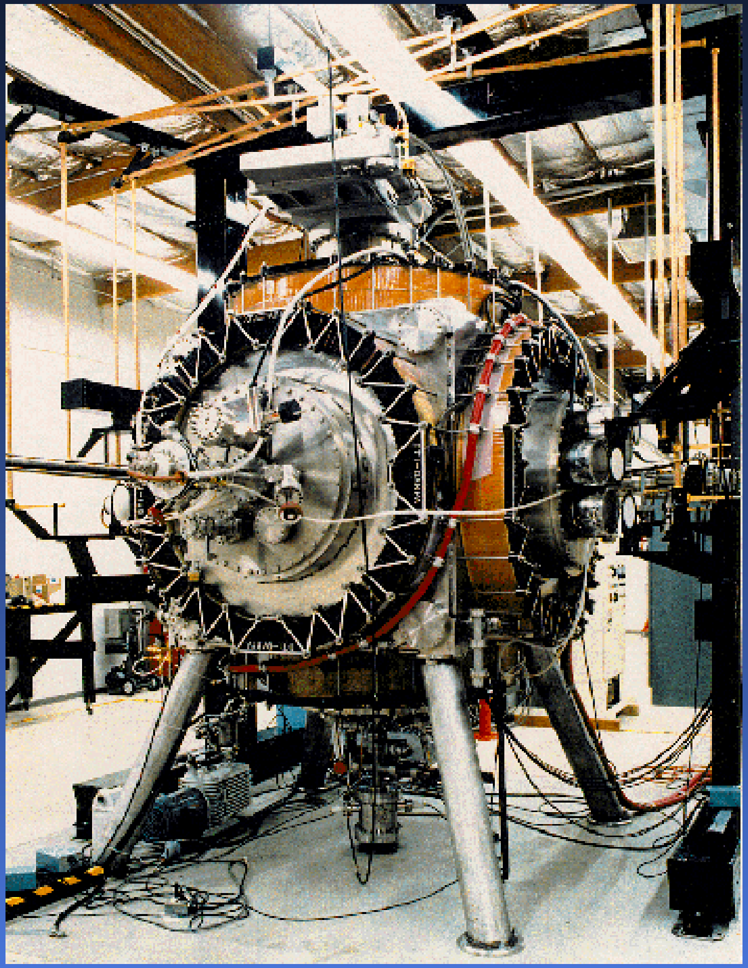


Figure 13

D-^{3}He Fusion Rockets Would Provide Very Flexible Thrust Parameters

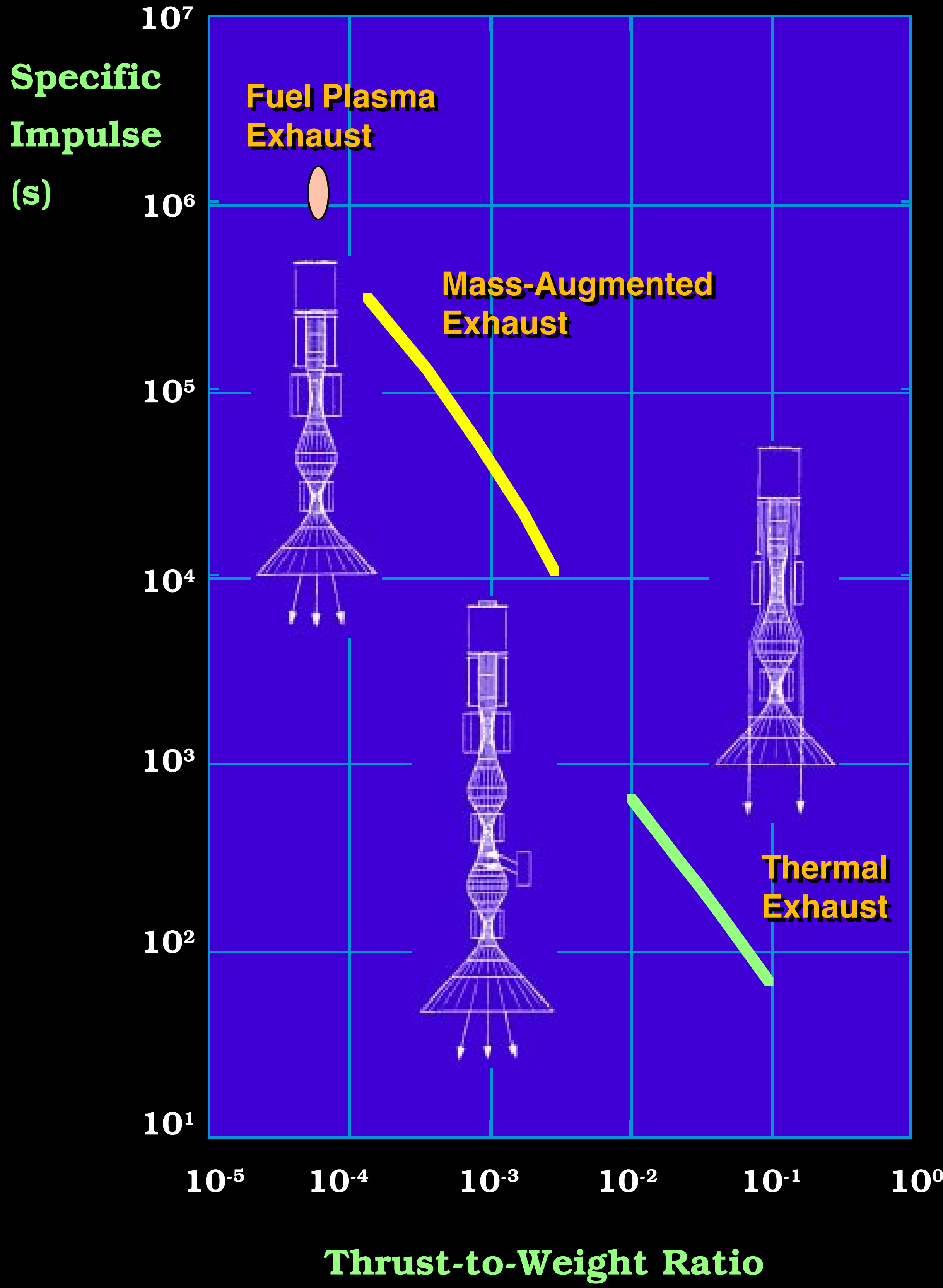


Figure 14

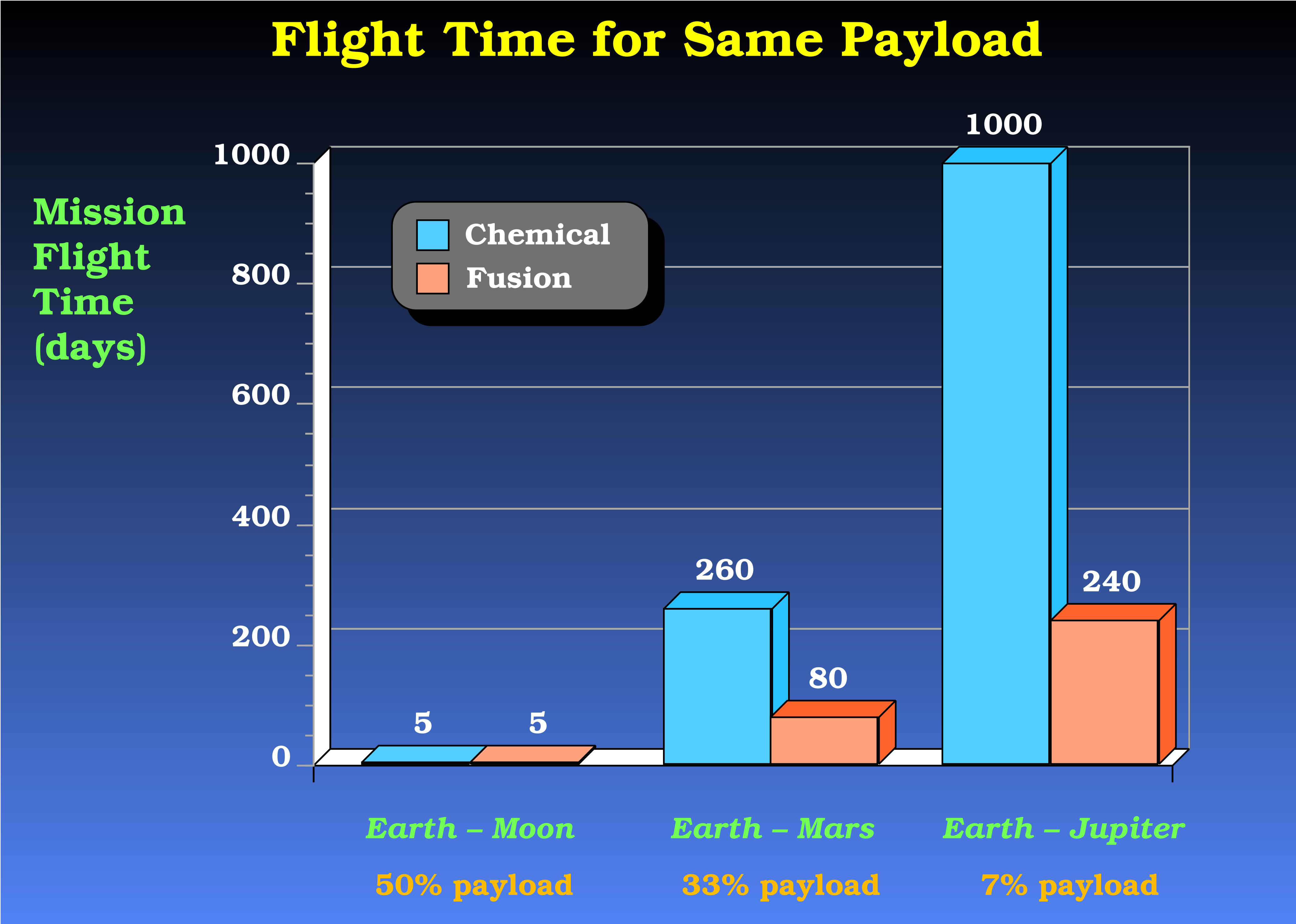

Flight Time for Same Payload
Mission Flight Time (days)
1000
800
600
400
200
0
Chemical
Fusion
5
5
260
80
1000
240
Earth – Moon
Earth – Mars
Earth – Jupiter
50% payload
33% payload
7% payload

Figure 15

Reasonably Assured Reserves of He3 That Could Be Available in the Year 2000

Source	Cumulative Amount (kg)	Production Rate Post 2000 (kg/y)
TRITIUM DECAY		
•U.S. Weapons	300	15
•CANDU Reactors	10	2
PRIMORDIAL		
•He Storage	29	–
•Natural Gas	187	–
	>500	~17

Figure 16

Ambitious Development Schedule for ^3He Fusion

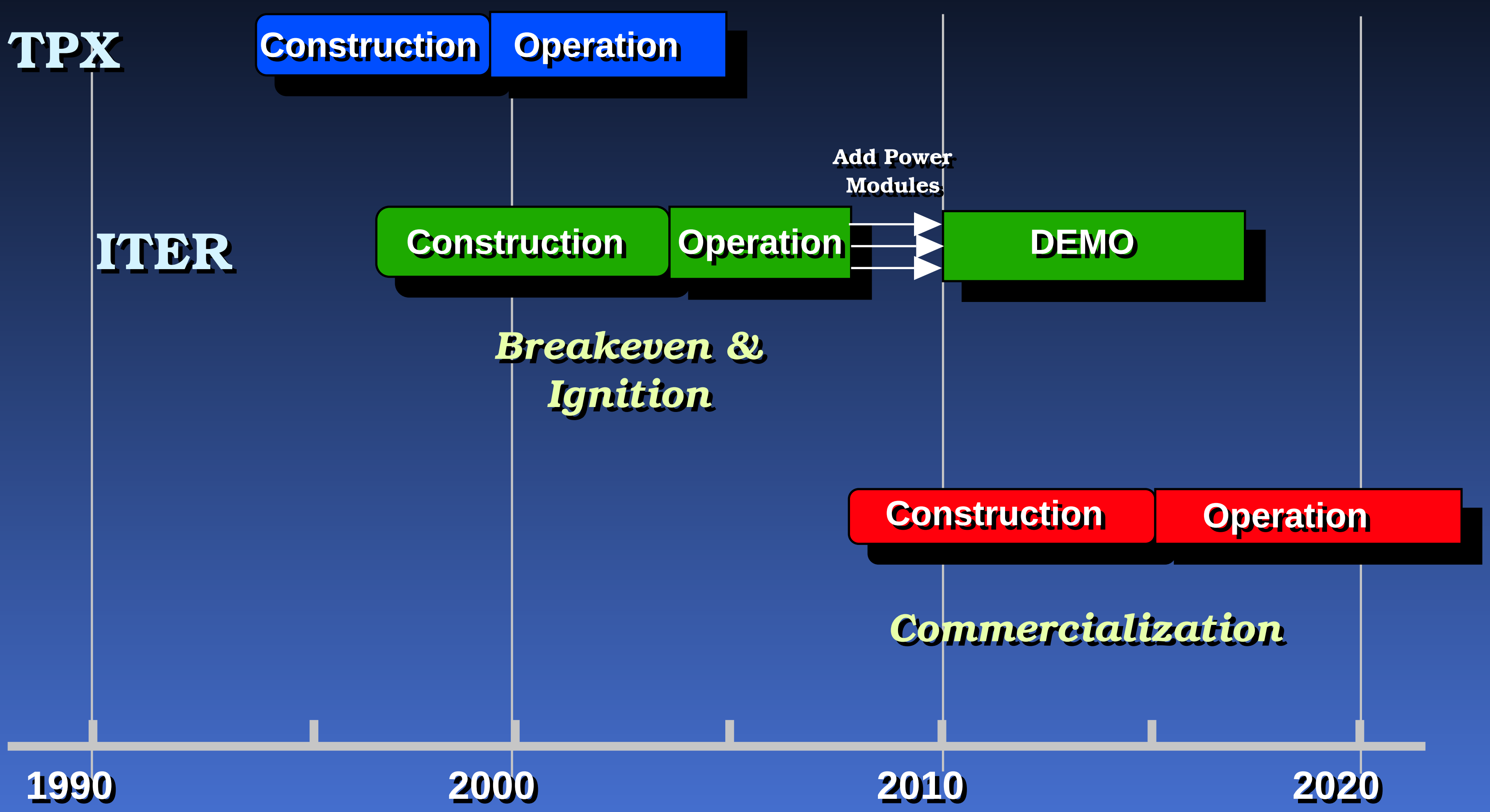


Figure 17

Success With the Polywell™ Concept Could Require Lunar ^{3}He by 2015

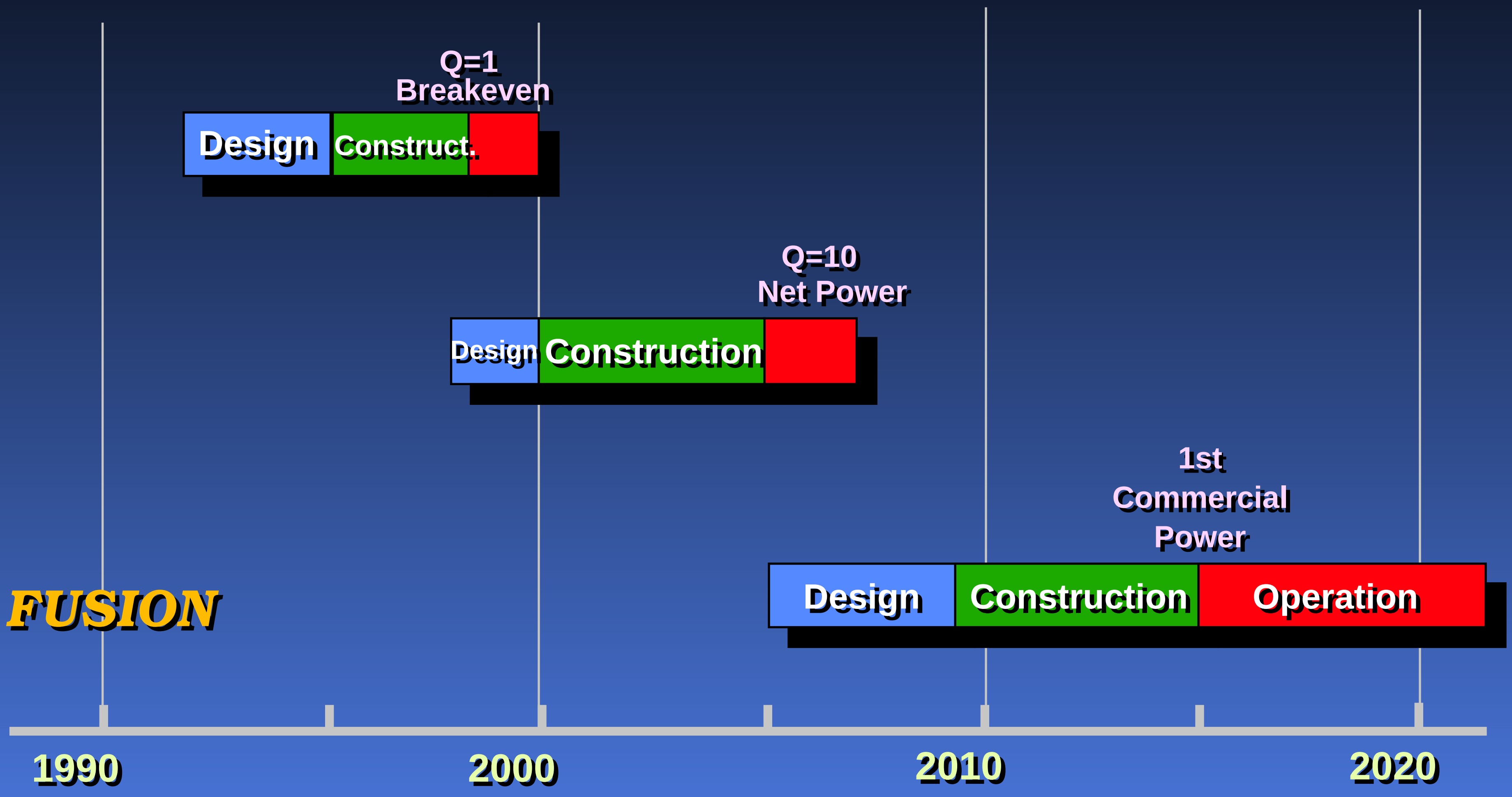


Figure 18