ROLE OF FUSION IN THE SUSTAINABLE EXPANSION OF NUCLEAR POWER

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at

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World Electricity Needs

(Annual Fuel Consumption[a], Units 10^{21} Joules/yr, Source MIT Nuc Pwr Study 2005)

		2000	2050
Developed Nations[b] (USA*, West Europe, Japan...)		0.089 (*0.039)	0.171[c] (*...0.090)
Former Soviet Union (Russia, East Europe..)		0.013	0.017
Developing Nations (Asia, S. America, Africa..)		0.046	0.230[d]
World		0.147	0.418

a) 33% conversion efficiency b)>4000 kWh/person c)population growth 0.1-1.0%/yr d) population growth 1%/yr

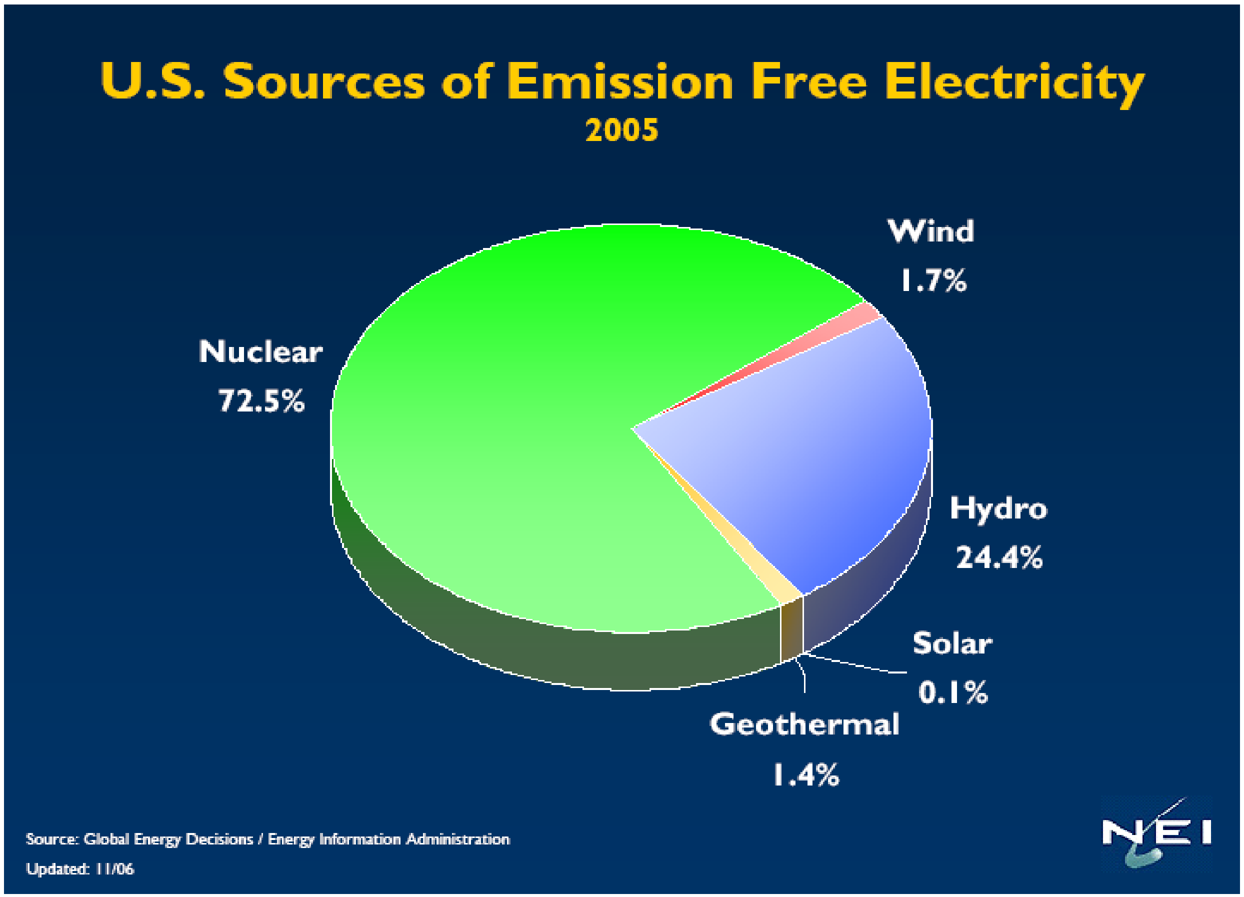
WORLD ELECTRICITY DEMAND & PROVEN WORLD FUEL RESOURCES

- The world's electricity demand in 2050 will require an annual fuel consumption of 0.42×10^{21} Joules/yr[a].
- The world's proven energy resources are inadequate to meet this increasing demand with carbon-free power unless the nuclear fuel cycle is closed and fusion power is developed, both within the present century.

Fuel	Coal	Oil	Nat Gas	Uran OTC 1%	Uran 90%	Thor 90%	Lith D-T fus	HDO D-D fus
Proven Reserve (10^{21} J)	28.8[b]	6.0[b,d]	5.5[b,e]	1.8[b]	162[b]	180[c]	2650[c]	unlimit[f]
"2050" years	68.6	14.3	13.1	4.3	386	429	6310	forever

a) MIT "Future of Nucl. Energy" (2005); b) World Energy Inst. (1999); c) US Geological Survey Mineral Commodities(2005); d) Heavy oil & bitumen would double this, but recovery is questionable; e) Methane hydrates would double this, but recoverability questionable; f) 1 in every 10.000 molecules of water.

FUTURE POWER SOURCES SHOULD NOT FURTHER DAMAGE THE ENVIRONMENT?



NUCLEAR POWER IS THE MOST REALISTIC OPTION FOR ENVIRONMENTALLY FRIENDLY, CARBON-FREE ELECTRICITY ON THE SCALE NEEDED

25% OF THE WORLD'S ELECTRICITY IN 2050	3325 GWe (1 GWe=10^9 W)
Could be provided by	
# of 1 GWe[a] nuclear reactors	3,325
or # of 3 MWe[a] wind turbines	1,110,000
or # of km^2 of solar panels[b]	166,250[c]
a) GWe=10^9 We, MWe=10^6 Watt electrical b) 24 hr av solar intensity 200W/m^2 , conversion efficiency 10%.	c) land area of Georgia 153,910 km^2

NUCLEAR POWER REACTORS TODAY

(Source Nuclear News , March, 2011)

	# operating	# forthcoming	MWe operating	MWe forthcoming
Developed world (US[a], W. Eur, Japan)	309	14	287,704	16,679
Russia & East Eur.	67	22	47,430	18,080
Developing world (Asia, Mideast, SA)	68	73	43,179	74,108
TOTAL a) US--20% electricity, 104 reactors operating , 9 reactors under construction, 20 new application NRC	444	109	378,313	108,867

SUSTAINABLE EXPANSION OF NUCLEAR POWER REQUIRES

1. In the near-term, dealing responsibly with the accumulating inventory of spent nuclear fuel.
2. In the intermediate term, utilization of a much greater fraction of the potential energy content of uranium (and thorium).
3. In the longer term, the production of power from nuclear fusion.

THE ACCUMULATING SPENT NUCLEAR FUEL INVENTORY IS THE MAJOR IMMEDIATE IMPEDIMENT TO THE SIGNIFICANT EXPANSION OF NUCLEAR POWER

- **e.g. The present USA inventory would almost fill the Yucca Mountain high-level waste repository (HLWR) (and there are no official plans for Yucca Mountain.) The present USA production of spent fuel would require a new Yucca Mountain HLWR about every 30 years. Similar situations exist in Europe, Japan, Russia and elsewhere.**

- **There is a solution. The long-lived transuranics in spent nuclear fuel (Pu,Np,Am,Cm,Cf) could be separated and fissioned in fast "burner" reactors, thereby reducing the HLWR requirements by a factor of 10-50.**

- **Sub-critical operation of these fast "burner" reactors, with a large external neutron source, may be necessary in order to achieve a factor of 10 reduction in required HLWRs and to reduce the number of burner reactors and separations facilities needed. The feasible neutron sources are D-T fusion and accelerator-spallation.**

INADEQUATE FUEL RESOURCES MAY BE THE MAJOR IMPEDIMENT TO THE SUSTAINABLE EXPANSION OF NUCLEAR POWER BY MID-CENTURY

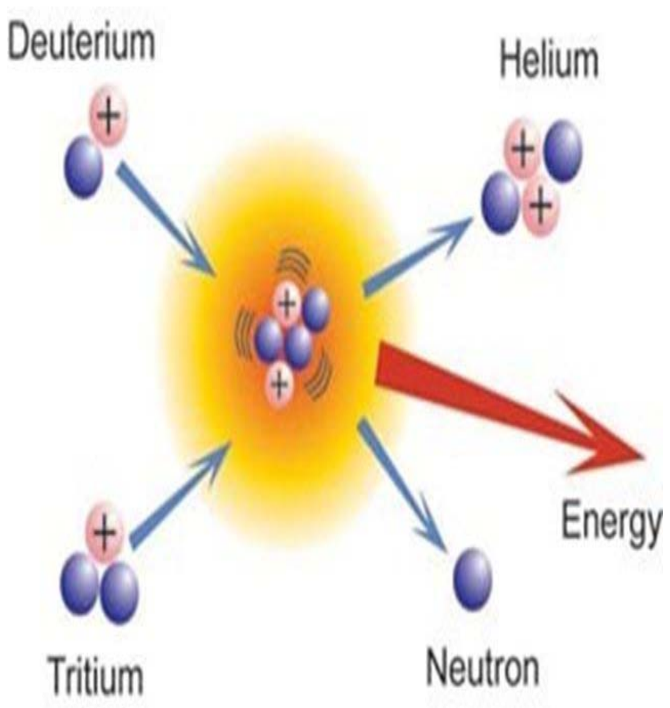
- **The "Once-Thru" nuclear fuel cycle in the USA and elsewhere only utilizes about 1% of the potential energy content of uranium. This OTC (even augmented by Pu recycle) will not sustain an expansion of nuclear power beyond mid-century.**

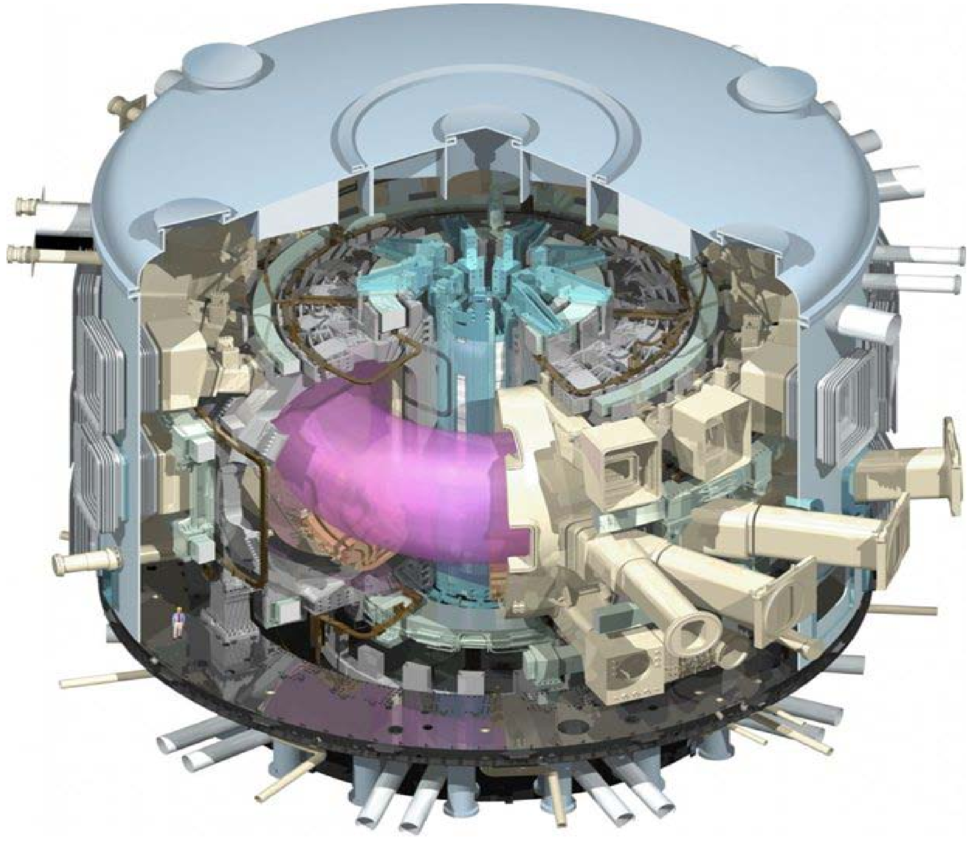
- **There is a solution. Fast "breeder" reactors can transmute U-238 into Pu-239 and Th-232 into U-233, which are fissionable in LWRs. Fast "breeder" reactors will be needed in the second half of the century to sustain an expansion of nuclear power.**

- **Sub-critical operation with a D-T fusion neutron source also may be advantageous for fast "breeder" reactors.**

POWER FROM FUSION

The conversion of mass into energy by the fusion of light nuclei takes place naturally in the sun and other stars to provide the energy of the universe. Terrestrially, we are working to create and confine a very small star to produce the same energy for the benefit of mankind.

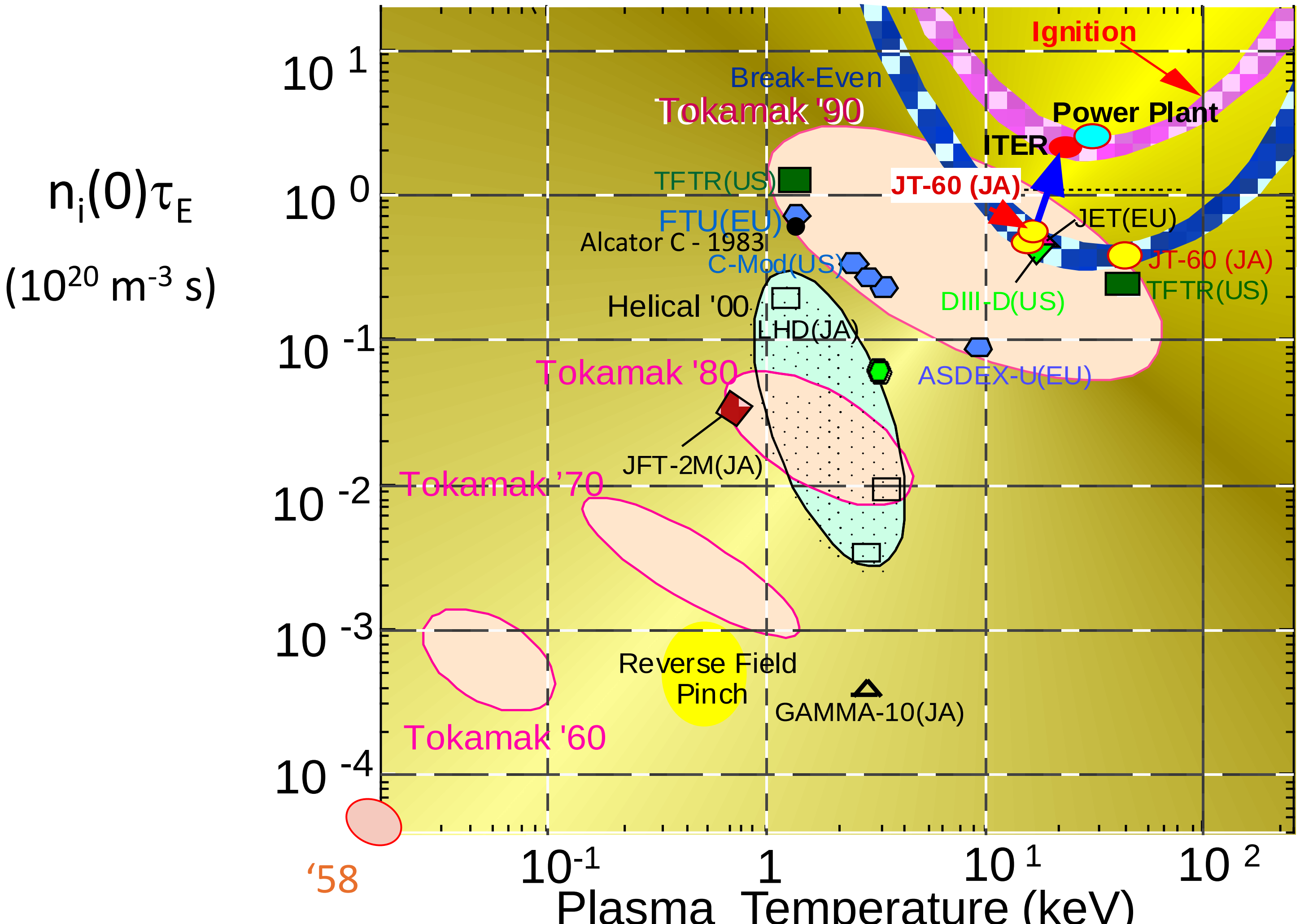




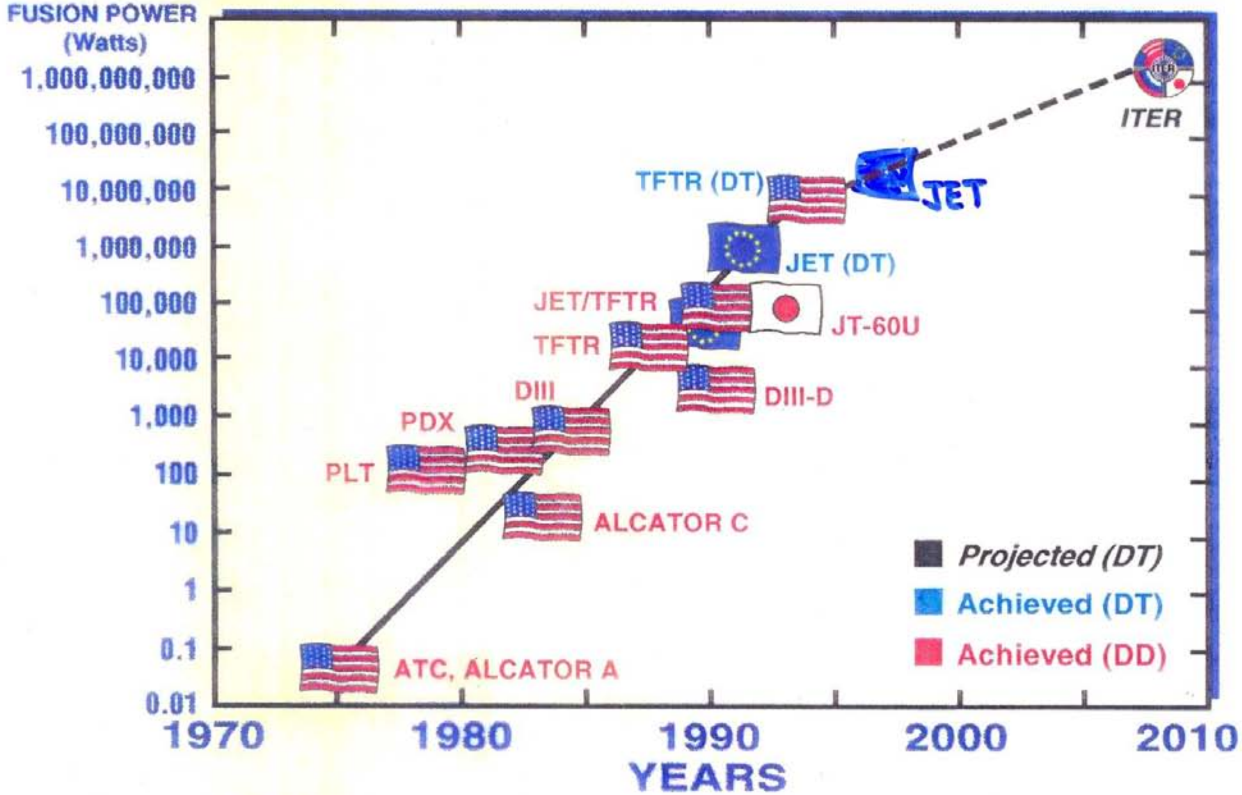
STATUS OF FUSION

- MAJOR ADVANCES HAVE BEEN MADE OVER THE PAST HALF CENTURY IN FUSION PHYSICS AND THE SUPPORTING TECHNOLOGY, BOTH FOR MAGNETIC (TOKAMAK) AND INERTIAL (LASER) FUSION.
- AN EXPERIMENTAL FUSION POWER REACTOR (ITER-TOKAMAK) IS UNDER CONSTRUCTION TO OPERATE INTERNATIONALLY (FRANCE) IN 2021-40.
- FURTHER ADVANCES IN FUSION PHYSICS AND SUPPORTING TECHNOLOGY, DEVELOPMENT OF FUSION NUCLEAR TECHNOLOGY AND DEVELOPMENT OF A RADIATION-RESISTANT STRUCTURAL MATERIAL ARE NEEDED FOR AN ECONOMICALLY COMPETITIVE FUSION POWER REACTOR BY THE 2ND HALF OF THE CENTURY.

FUSION TEMPERATURE ACHIEVED, CONFINEMENT IS A STEP AWAY



Progress in Magnetic Fusion Power



PLT	Princeton Large Torus	ITER	International Thermonuclear Experimental Reactor
PDX	Princeton Divertor Experiment	DIII & DIII-D	General Atomics Tokamak Experiments
JET	Joint European Torus	ATC & TFTR	Princeton Plasma Physics Laboratory
JT-60	Japan	ALCATOR A, C	Massachusetts Institute of Technology

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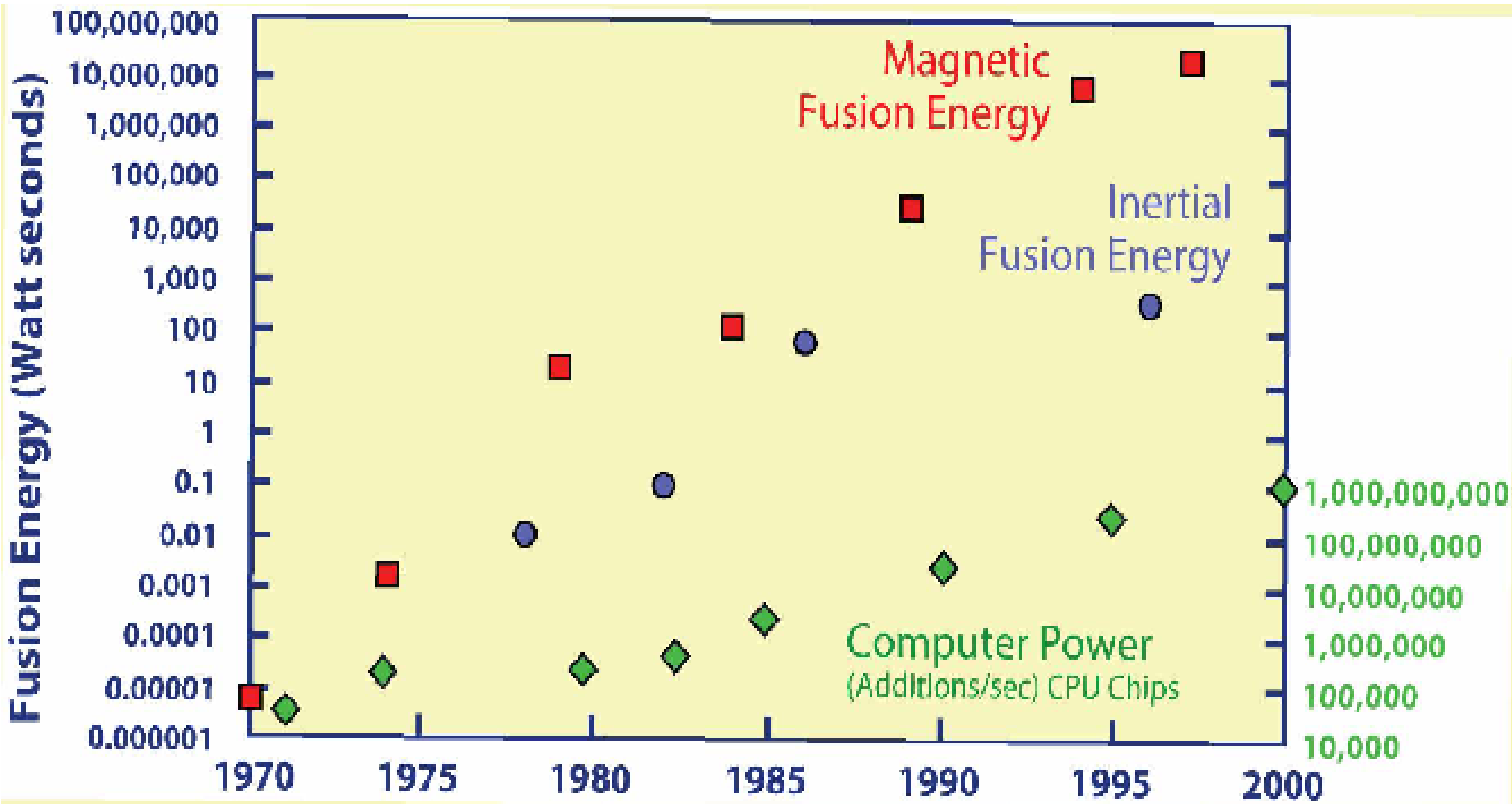
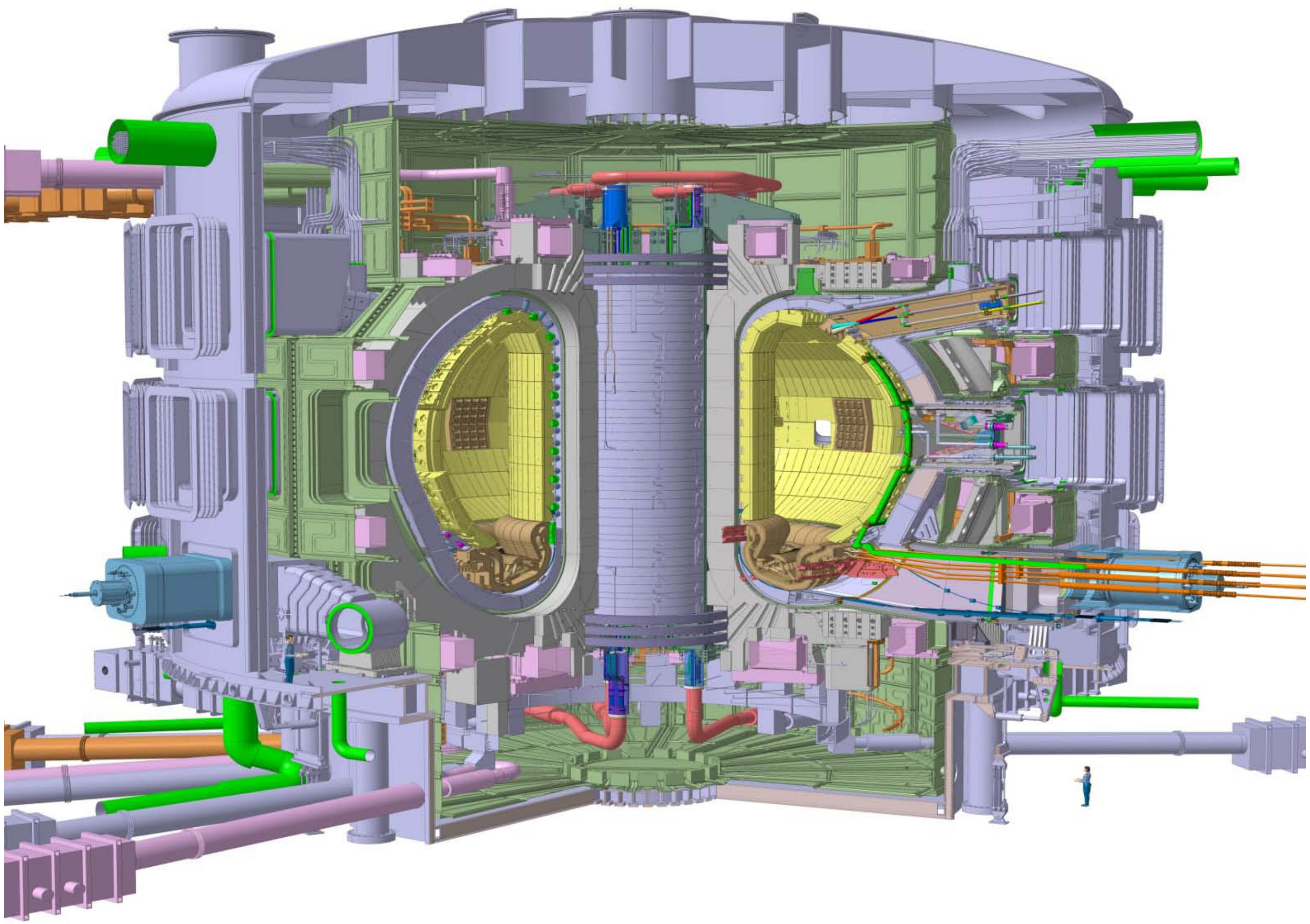
PROGRESS IN FUSION ENERGY PRODUCTION



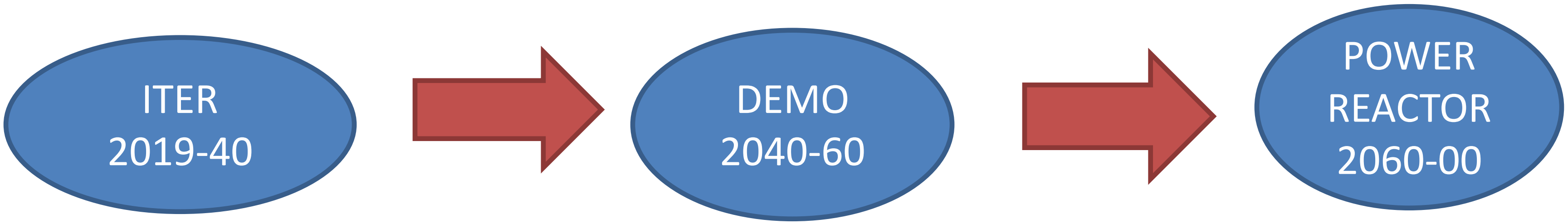
ITER

500 MWth Experimental Fusion Reactor Under Construction Internationally in France to Operate 2021-2040

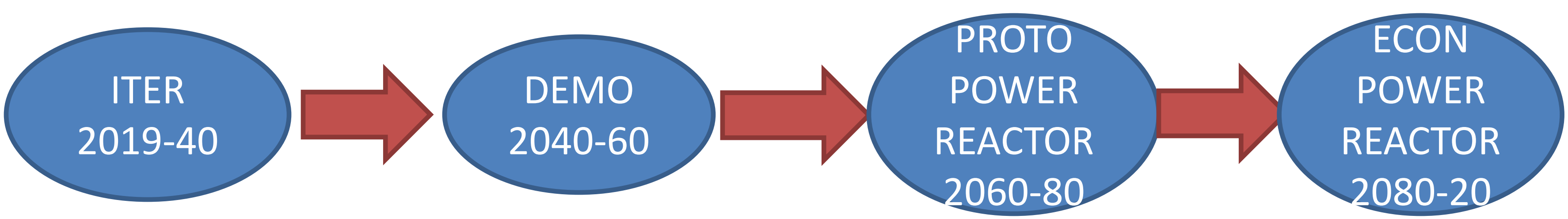


An Unofficial
Fusion Development Schedule

Canonical



More Likely?



AN EARLIER USE OF FUSION?

A SUBCRITICAL FAST BURNER REACTOR WITH A FUSION NEUTRON SOURCE BASED ON ITER PHYSICS & TECHNOLOGY

- **Fast "burner" fission reactors could be online in 20-25 years. Subcritical operation with a neutron source is advantageous (maybe necessary) for fast "burner reactors.**

- **The physics and technology performance parameters upon which ITER is designed are adequate for a neutron source for a fast "burner" reactor, so to a large extent ITER operation (2021-40) will serve as a prototype for the neutron source for a fast "burner" reactor.**

- **The SABR design concept[a] for a fast "burner" reactor based on an "Integral Fast Reactor" metal fuel, Na-cooled fission reactor combined with a neutron source based on the ITER design (scaled down to half volume and adapted for sodium coolant) has been developed and evaluated.**

a) Nuclear Technology 162, 53 (2008); 172, 48 (2010). See also "transmutation reactor" link on www.frc.gatech.edu

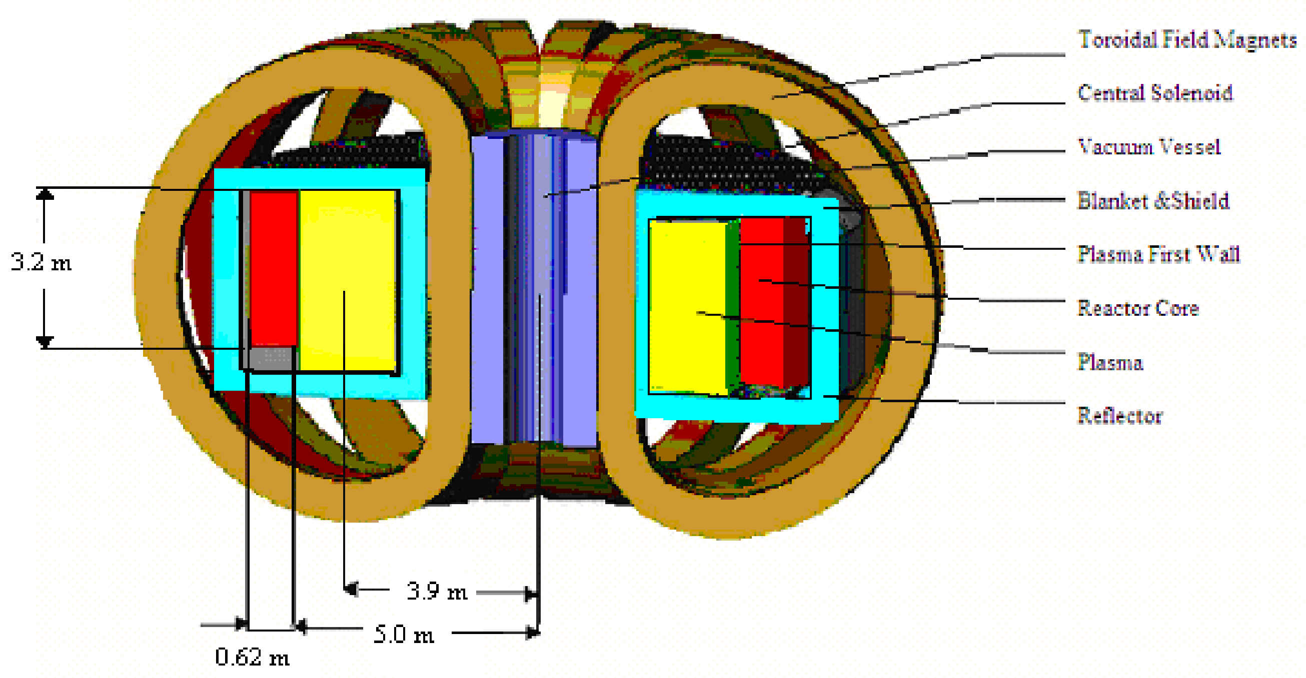
SUB-CRITICAL ADVANCED BURNER REACTOR (SABR)

ANNULAR FAST REACTOR (3000 MWth)

- Fuel—TRU from spent nuclear fuel. TRU-Zr metal being developed by ANL.
- Sodium cooled, loop-type fast reactor.
- Based on fast reactor designs being developed by ANL in Nuclear Program.

TOKAMAK D-T FUSION NEUTRON SOURCE (200-500 MWth)

- Based on ITER plasma physics and fusion technology.
- Tritium self-sufficient (Li_4SiO_4).
- Sodium cooled.

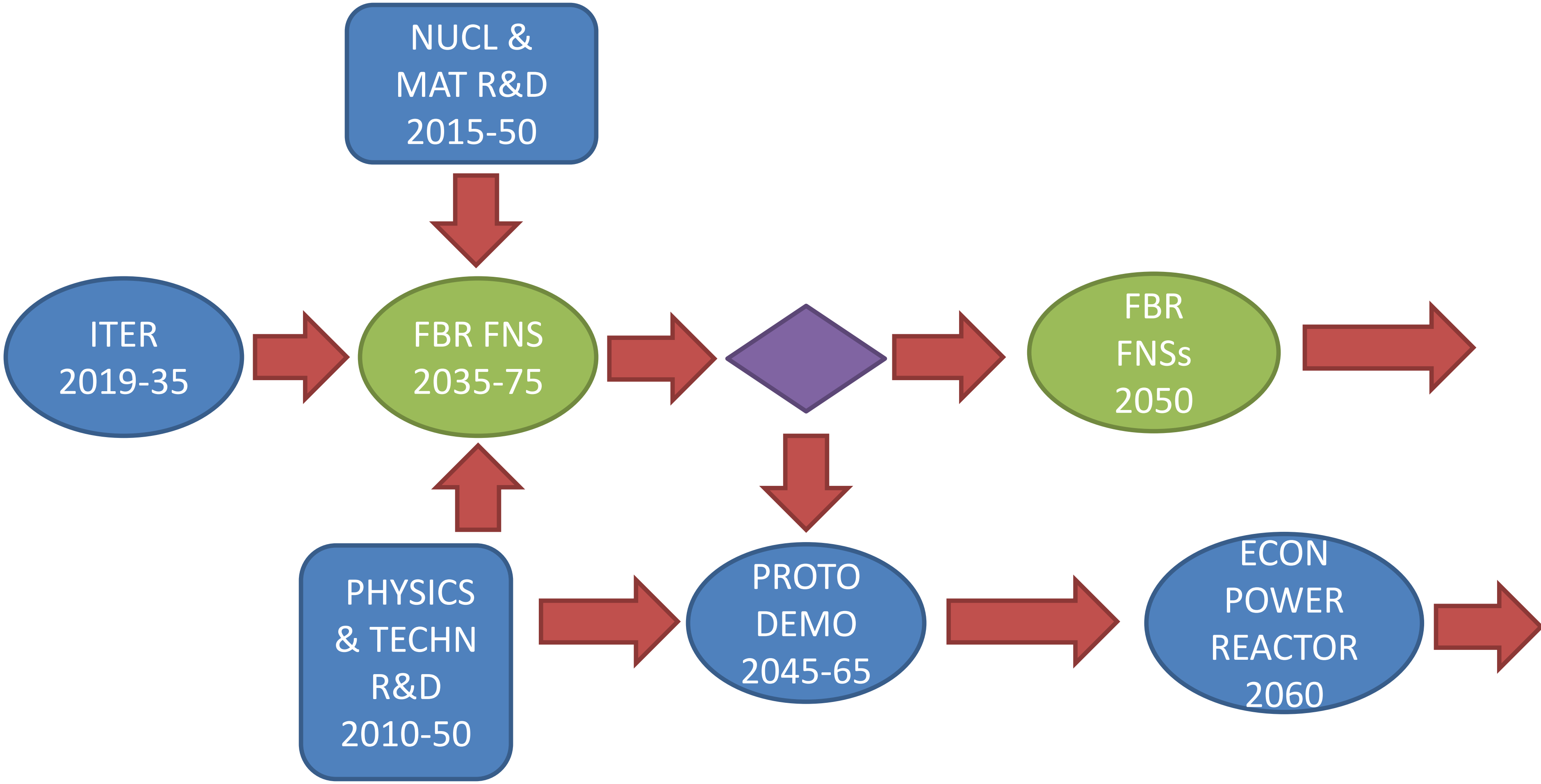


PERFORMANCE OF
SABR FAST BURNER REACTORS

- ***Scenario 1** Indefinite Continuation of LWRs***: **A SABR would be able to fission all of the transuranics produced in 3 LWRs of 1GWe. A nuclear fleet of 75% LWRs (% nuclear electric power) and 25% SABRs would reduce geological repository (HLWR) requirements by a factor of >10 relative to direct burial of spent fuel from a nuclear fleet of 100% LWRs.**

- ***Scenario 2** Transition from LWRs to Fast Reactors***: **If some Pu from spent fuel transuranics was set aside for future fast reactor fuel, a SABR would be able to fission the remaining Pu and minor actinides produced by 25 LWRs of 1 GWe. A nuclear fleet of 96% LWRs and 4% SABRs would reduce needed HLWRs by a factor of 10 relative to direct burial of the remaining Pu and minor actinides from the spent fuel.**

FUSION NEUTRON SOURCE DEVELOPMENT IS SYMBIOTIC WITH FUSION POWER DEVELOPMENT



SUMMARY

- Nuclear power is the most credible option for meeting the world's growing energy needs while reducing carbon emissions.

- Sustainable expansion of nuclear energy requires: i) now--dealing with spent nuclear fuel; ii) mid- century--utilizing a much greater fraction of the energy content of uranium (and thorium); and iii) 2nd half of century—producing power from nuclear fusion.

- A subcritical fast "burner" reactor with a fusion neutron source based on ITER could be online in 25-30 years to reduce by >10 the number of long term geological repositories needed for secured, long-term storage of spent nuclear fuel and fission products.

- Fusion electrical power reactors based on substantial physics and technology advances beyond ITER could be operational during the second half of the century.