

# **SUSTAINABLE NUCLEAR POWER**

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# **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.**
- 4. Assurance of public safety.**

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

- e.g. The present USA SNF 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 requirements exist in Europe, Japan, Russia and elsewhere.
- 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.
- The IFR metal-fueled, pool-type sodium-cooled fast reactor technology for pyro-processing and re-fabricating spent fuel on-site and burning transuranics in inherently safe reactors has been demonstrated, but not yet implemented. The plutonium and higher actinides are recycled together, further reducing any proliferation risk.
- 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 AFTER MID-CENTURY**

- **The “Once-Thru” nuclear fuel cycle in the USA and elsewhere only utilizes < 1% of the potential energy content of uranium. This OTC (even augmented by Pu recycle) will not sustain a significant expansion of nuclear power beyond mid-century.**
- **Fast “breeder” reactors can transmute U-238 into Pu-239 and Th-232 into U-233, both of which are fissionable in LWRs. Such fast “breeder” reactors will be needed in the second half of the century to sustain a significant expansion of nuclear power.**
- **Sub-critical operation with an external neutron source also may be advantageous for fast “breeder” reactors.**

# WORLD ELECTRICITY DEMAND & PROVEN WORLD FUEL RESOURCES

- The world's electricity demand in 2050 will require an annual fuel consumption of  $0.42 \times 10^{21}$  Joules/yr<sup>a</sup>.
- The world's proven energy resources are

Fuel	Coal	Oil	Nat Gas	Uran OTC 1%	Uran 90%	Thor 90%	Lith D-T fus	HDO D-D fus
Proven Reserve (10 <sup>21</sup> J)	28.8 <sup>b</sup>	6.0 <sup>b</sup>	5.5 <sup>b</sup>	1.8 <sup>b</sup>	162 <sup>b</sup>	180 <sup>c</sup>	2650 <sup>c</sup>	unlimit
"2050" years	68.6	14.3	13.1	4.3	386	429	6310	forever

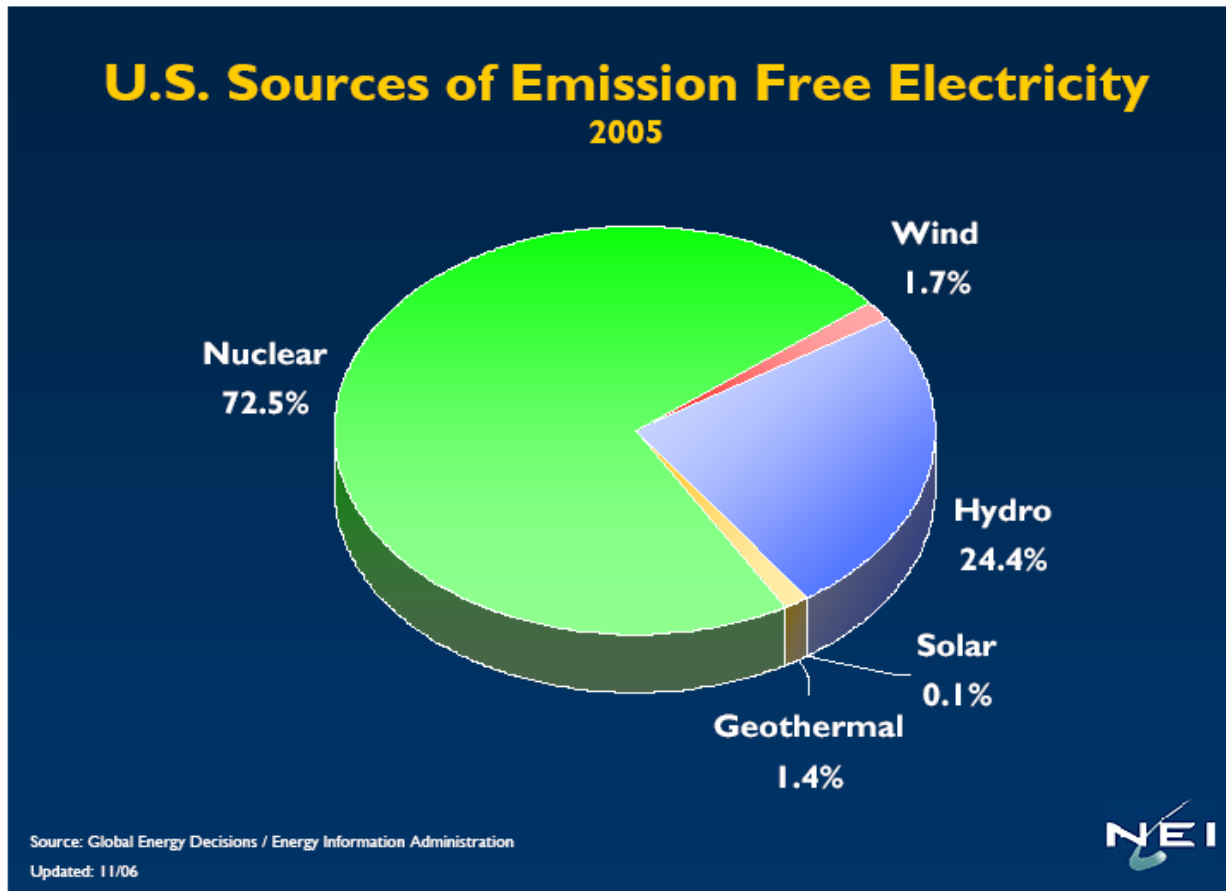
a) MIT "Future of Nucl. Energy" (2005); b) World Energy Inst. (1999); c) US Geological Survey Mineral Commodities(2005)

# NUCLEAR POWER REACTORS TODAY

(Source Nuclear News , March, 2011)

	# operating	# forthcoming	MWe operating	MWe forthcoming
Developed world (US <sup>a</sup> , 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
<b>TOTAL</b>	<b>444</b>	<b>109</b>	<b>378,313</b>	<b>108,867</b>
<small>a) US--20% electricity, 104 reactors operating , 9 reactors under construction, 20 new application NRC</small>				

# 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 <sup>9</sup> W)
Could be provided by	
# of 1 GWe <sup>a</sup> nuclear reactors	3,325
or # of 3 MWe <sup>a</sup> wind turbines	1,110,000
or # of km <sup>2</sup> of solar panels <sup>b</sup>	166,250 <sup>c</sup>
a) GWe=10 <sup>9</sup> We, MWe=10 <sup>6</sup> Watt electrical b) 24 hr av solar intensity 200W/m <sup>2</sup> , conversion efficiency 10%.	c) land area of Georgia 153,910 km <sup>2</sup>



**ASSURANCE OF PUBLIC SAFETY IS A PREREQUISITE FOR  
SUSTAINABLE EXPANSION OF NUCLEAR POWER,  
AND SUCH ASSURANCE PROBABLY REQUIRES THE  
ELIMINATION OF THE POSSIBILITY OF HYDROGEN EXPLOSIONS.**

- Hydrogen explosions following “beyond design basis” events led to the dispersal of radioactive material in the major nuclear accidents at Chernobyl and Fukushima Daiichi, and were a major threat at Three-Mile Island.
- Replacement of water coolant would seem to be the only way to eliminate the possibility of a hydrogen explosion caused by “non-design basis” events.

# FAST REACTORS

- The neutron cross sections for fissioning the transuranic isotopes in spent nuclear fuel and for producing fissionable material from U238 (>99% natural U) are much more favorable in a fast neutron spectrum than in a thermal spectrum.
- Fast reactors can close the nuclear fuel cycle by i) using the transuranics in spent nuclear fuel as fuel and ii) producing their own fuel by transmuting U238 into Pu239 and higher transuranics.
- Subcritical operation may be optimal for fast reactors intended primarily for burning the transuranics in spent LWR fuel.

# MAINLINE FAST REACTORS

COUNTRY	REACTOR	MWth	OPERATION
USA	EBR-I	1	1951-63
	EBR-II	63	1964-94
	FERMI-I	200	1965-72
	FFTF	400	1980-92
RUSSIA	BR-5/10	8	1958-02
	BOR-60	60	1969-
	BN-350	1000	1973-99
	BN-600	1470	1980-
FRANCE	RAPSODIE	40	1967-83
	PHENIX	590	1974-99
	SUPER PHENIX	3000	1985-97
JAPAN	JOYO	140	1978-
	MONJU	714	1994-
UK	DFR	72	1963-77

# INTEGRAL FAST REACTOR<sup>a</sup>

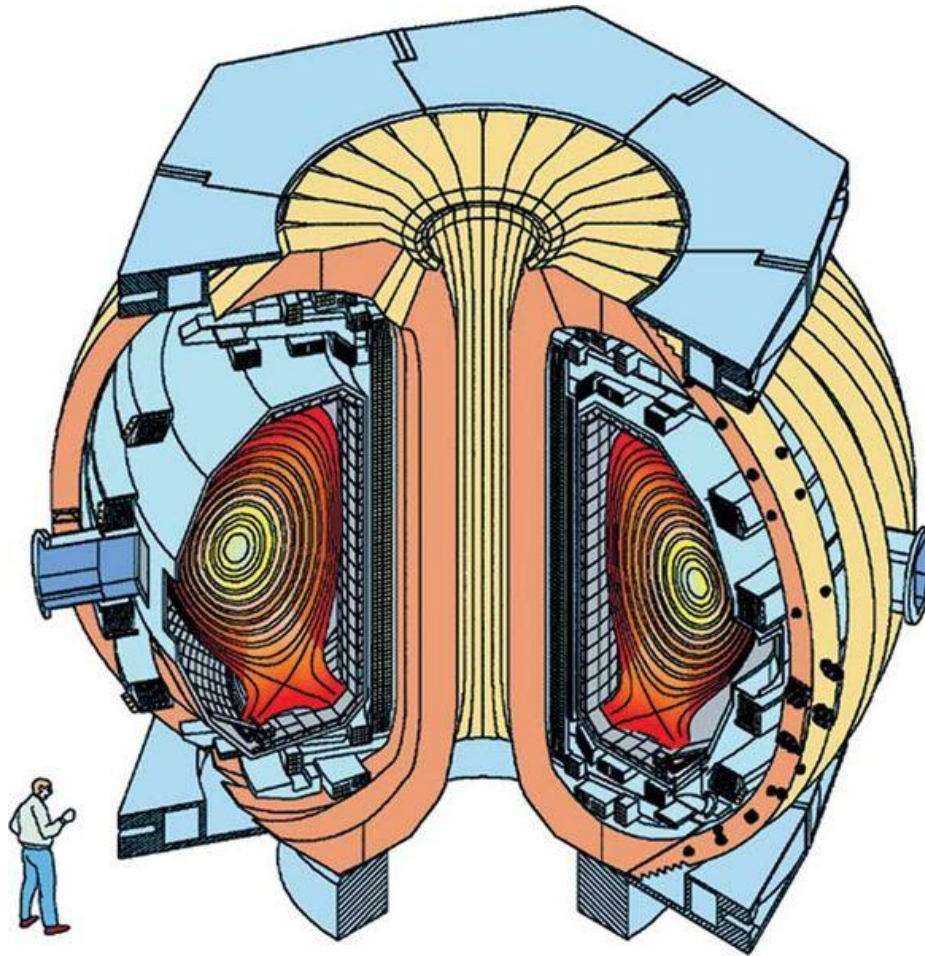
- Metal-fueled, Na-cooled, pool-type fast reactor based on the EBR-I and EBR-II operating experience and extensive subsequent development.
- On-site pyro-processing of spent fuel separates fission products, which go to HLWR, from a metal fuel mixture of all transuranics (Pu is never separated) which can be relatively simply re-fabricated into fuel rods.
- Negative reactivity feedback under all conditions insures inherent safety. Self-shutdown of EBR-II demonstrated in response to loss-of-coolant and loss-of-heat-sink conditions.
- Prototype IFR system could be online in 20-25 years.

a) C. E. Till and Y. I. Chang, "PLENTIFUL ENERGY The Story of the Integral Fast Reactor" (2012).

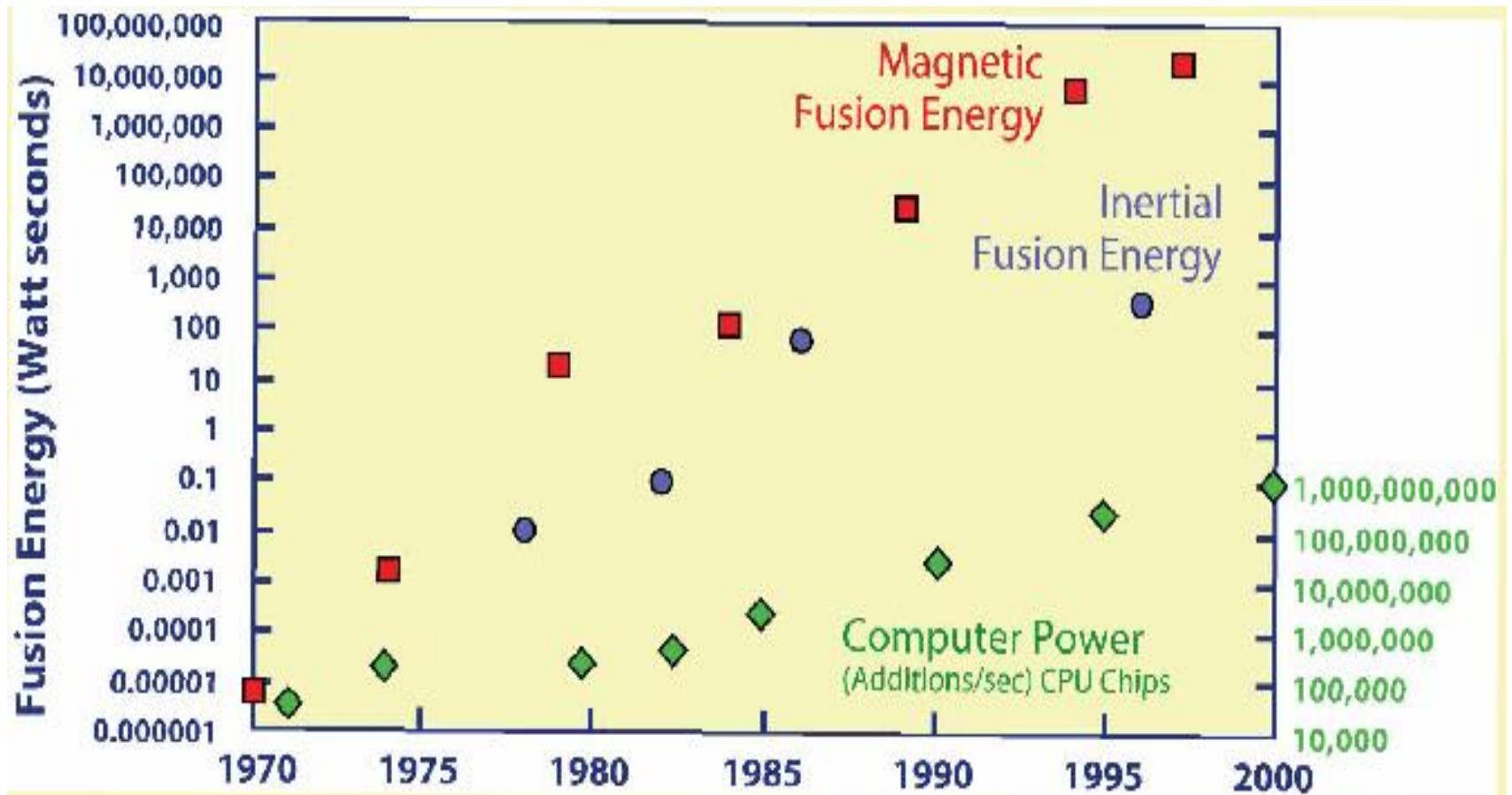
# POWER FROM FUSION

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

# DIII-D TOKAMAK FUSION FACILITY



# PROGRESS IN FUSION ENERGY PRODUCTION

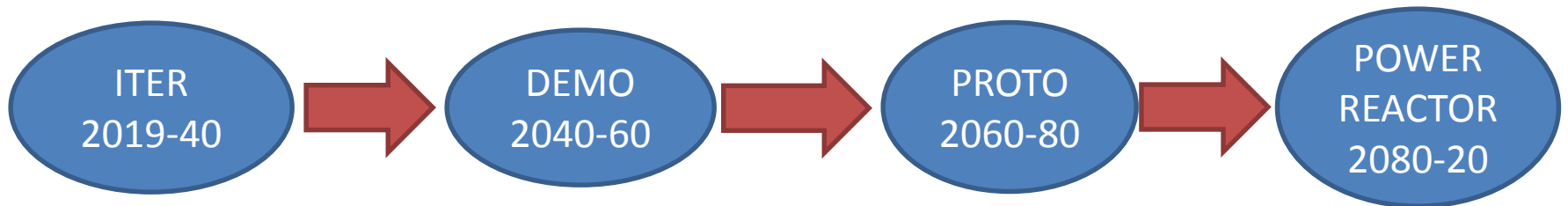


# An Unofficial Fusion Development Schedule

## Canonical



## More Likely?



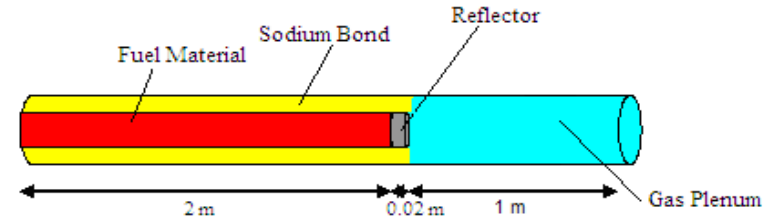
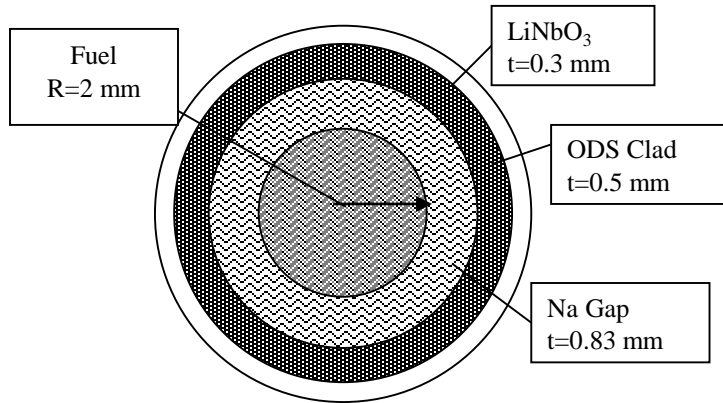


# **PROPOSAL--A SUBCRITICAL IFR FAST BURNER REACTOR WITH A FUSION NEUTRON SOURCE BASED ON ITER PHYSICS & TECHNOLOGY**

- **Prototype IFR “burner” reactor and separations/re-fabrication facilities could be online in 20-25 years. Subcritical reactor 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<sup>a</sup> for a fast “burner” reactor based on an IFR metal fuel, Na-cooled reactor combined with a neutron source based on the ITER design concept (scaled down to half volume and adapted for sodium coolant) has been developed.**

a) Nuclear Technology 162, 53 (2008); 172, 48 (2010). See also “transmutation reactor” link on [www.frc.gatech.edu](http://www.frc.gatech.edu)

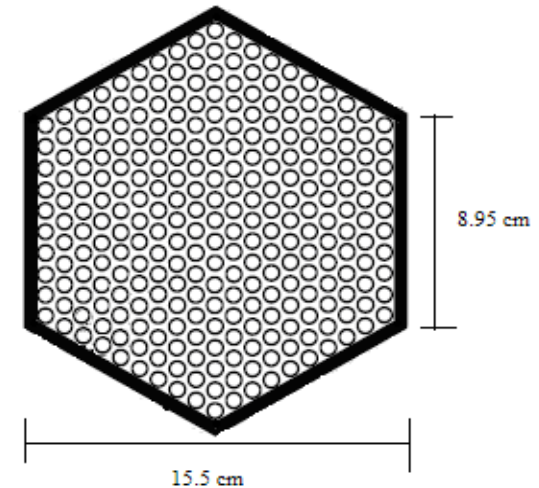
# SABR Fast Reactor



Axial View of Fuel Pin

**Fuel Composition 40Zr-10Am-10Np-40Pu (w/o)**  
(Under development at ANL)

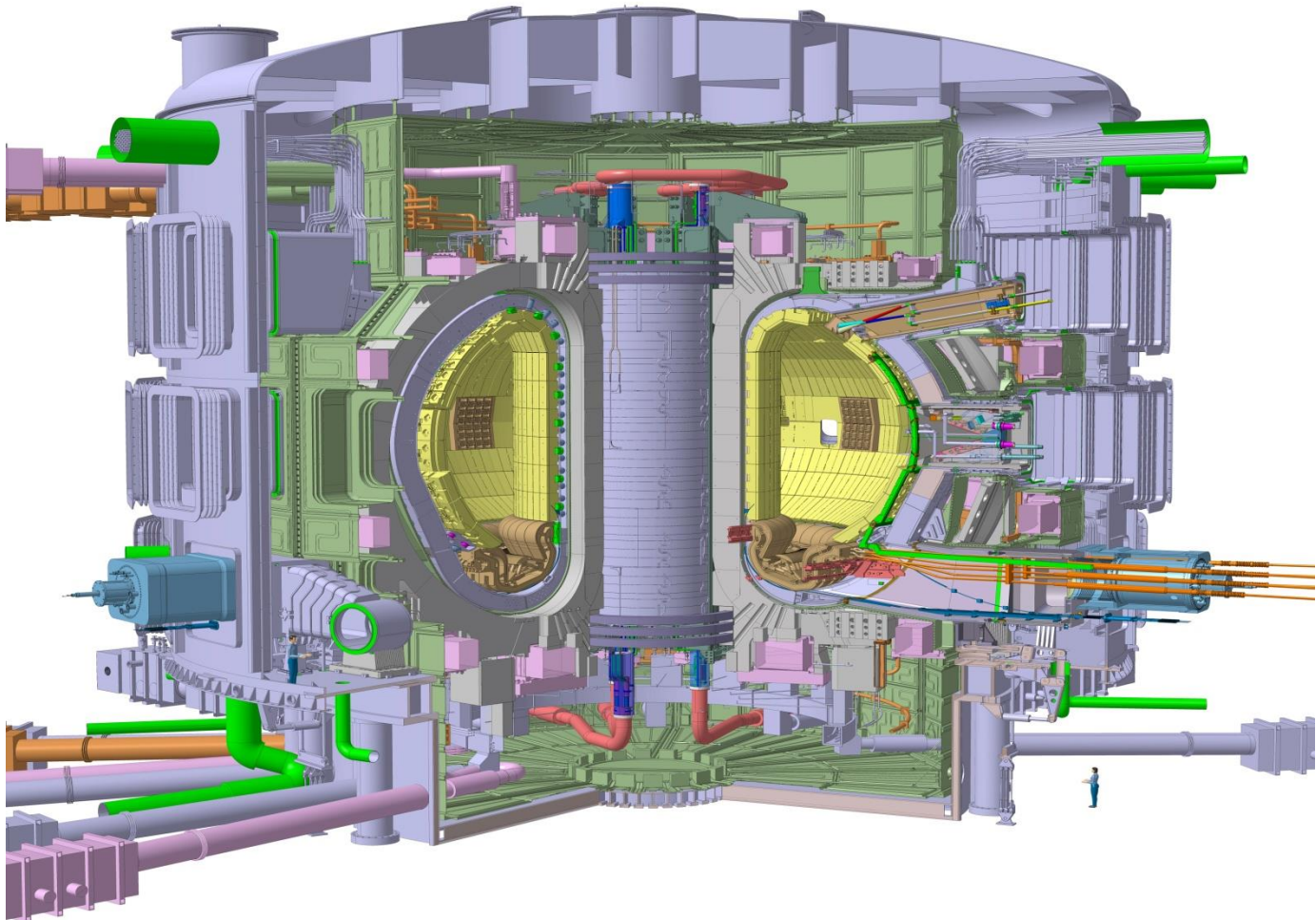
**Design Configuration of Fuel Pin Assemblies**  
**271 pins per assembly**  
**918 assemblies arranged into annular core**



Cross-Sectional View Fuel Assembly

# ITER

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



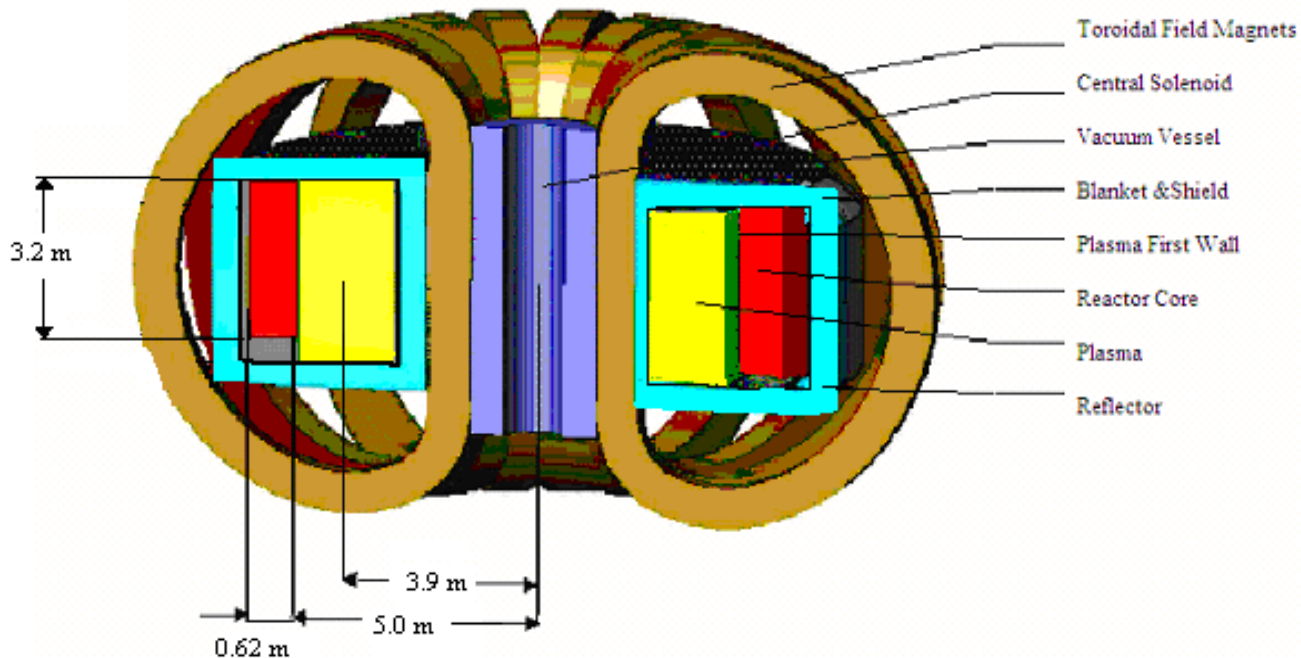
# SUB-CRITICAL ADVANCED BURNER REACTOR (SABR)

## ANNULAR IFR FAST REACTOR (3000 MWth)

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

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

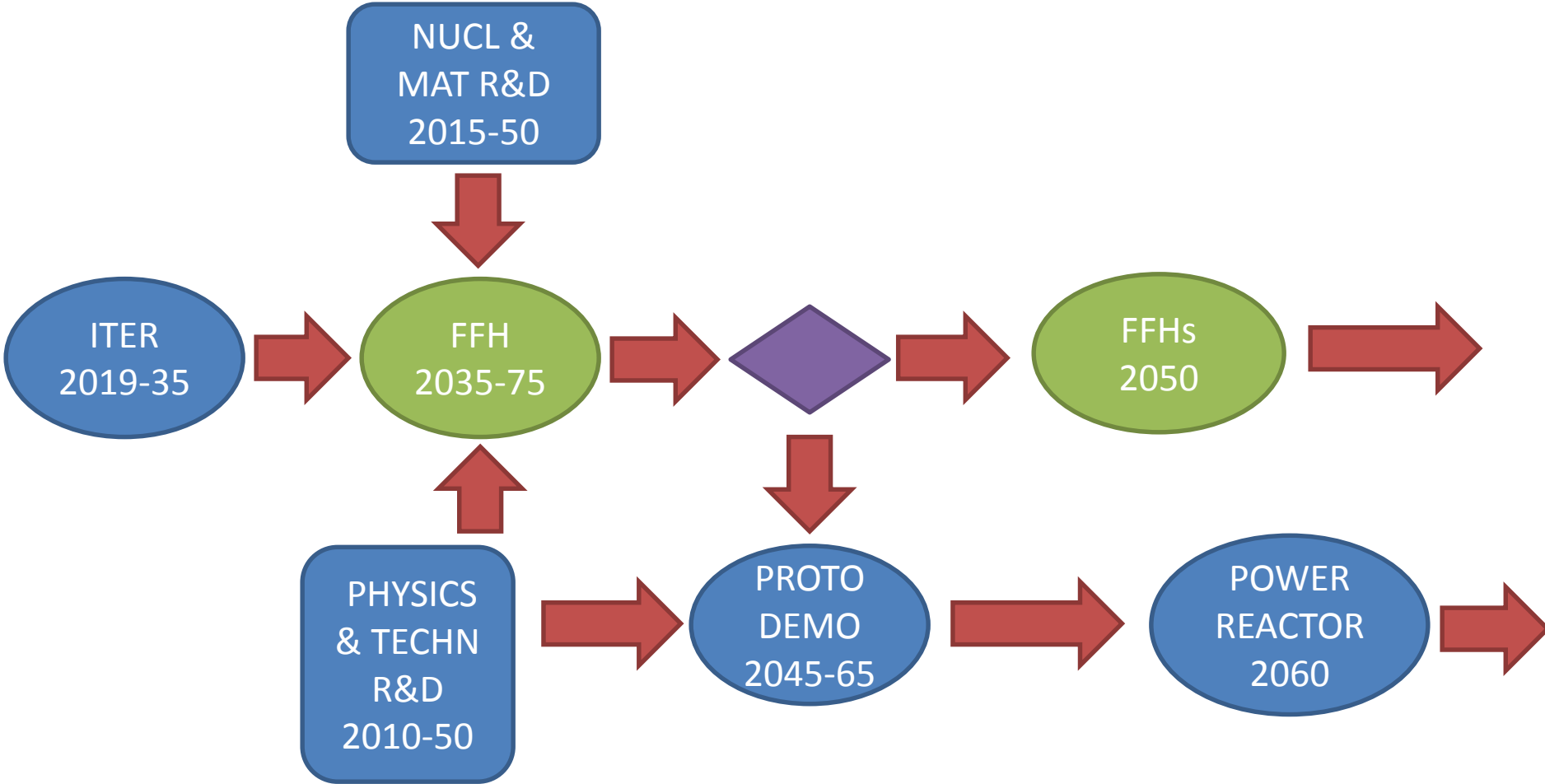
- Based on ITER plasma physics and fusion technology.
- Tritium self-sufficient ( $\text{Li}_4\text{SiO}_4$ ).
- Sodium cooled.



# TRANSMUTATION 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 requirements by a factor of >10 relative to direct burial of spent fuel from a nuclear fleet of 100% LWRs.
- *Scenario 2 Transition 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

- **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) 2<sup>nd</sup> half of century—producing power from nuclear fusion.
- **Innovation---**a subcritical IFR “burner” reactor with a fusion neutron source is proposed to reduce by >10 the number of long term geological repositories needed for secured, long-term storage of spent nuclear fuel and fission products.