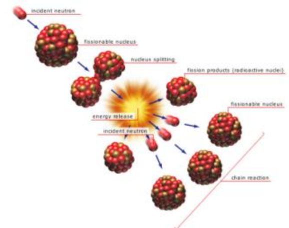
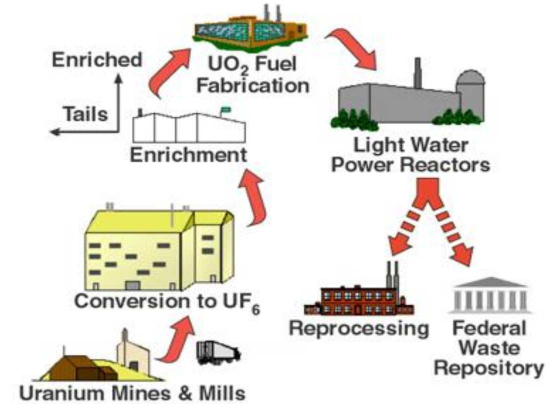




ANU Research School of Physics and Engineering, Director's Colloquium, September 2011

Advanced nuclear power systems for long-term energy and climate security

Professor Barry W. Brook

Sir Hubert Wilkins Chair of Climate Change* and *ARC Future Fellow

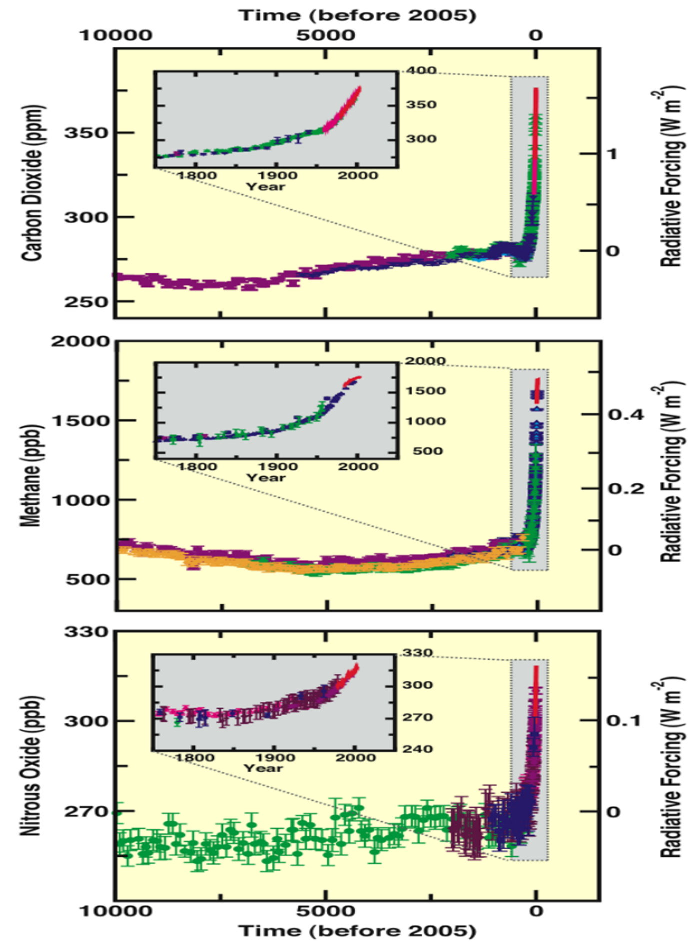
Director of Climate Science, Environment Institute

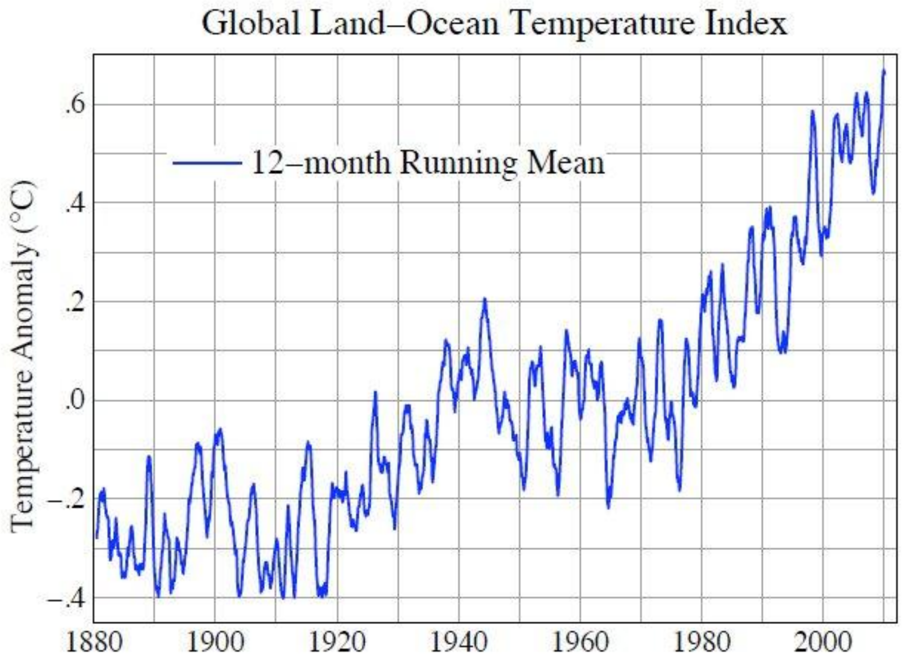
School of Earth and Environmental Sciences

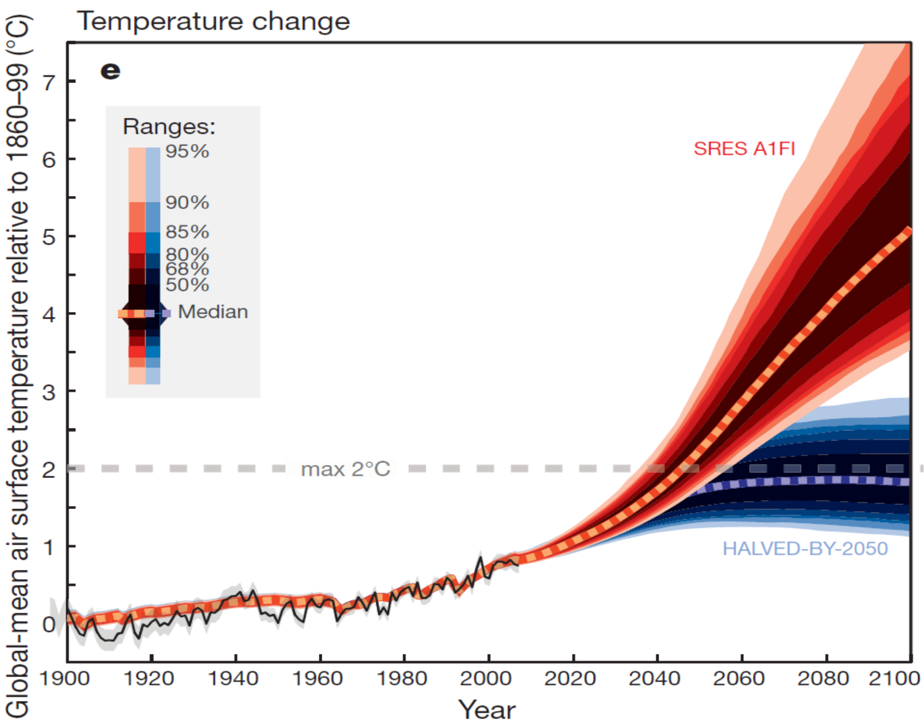
The University of Adelaide

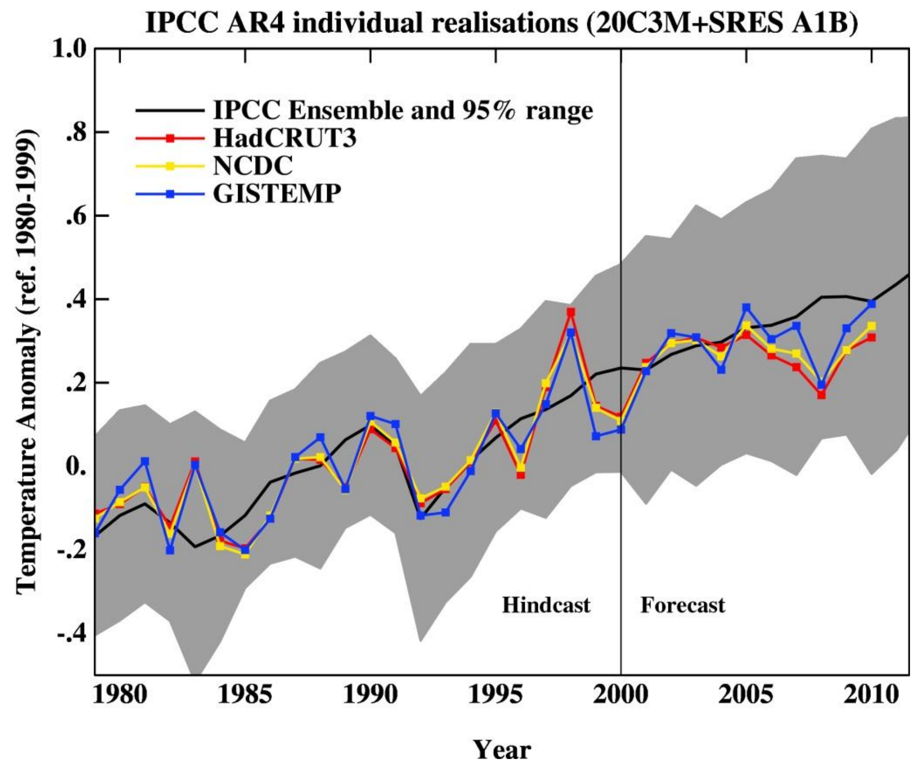
Email: barry.brook@adelaide.edu.au

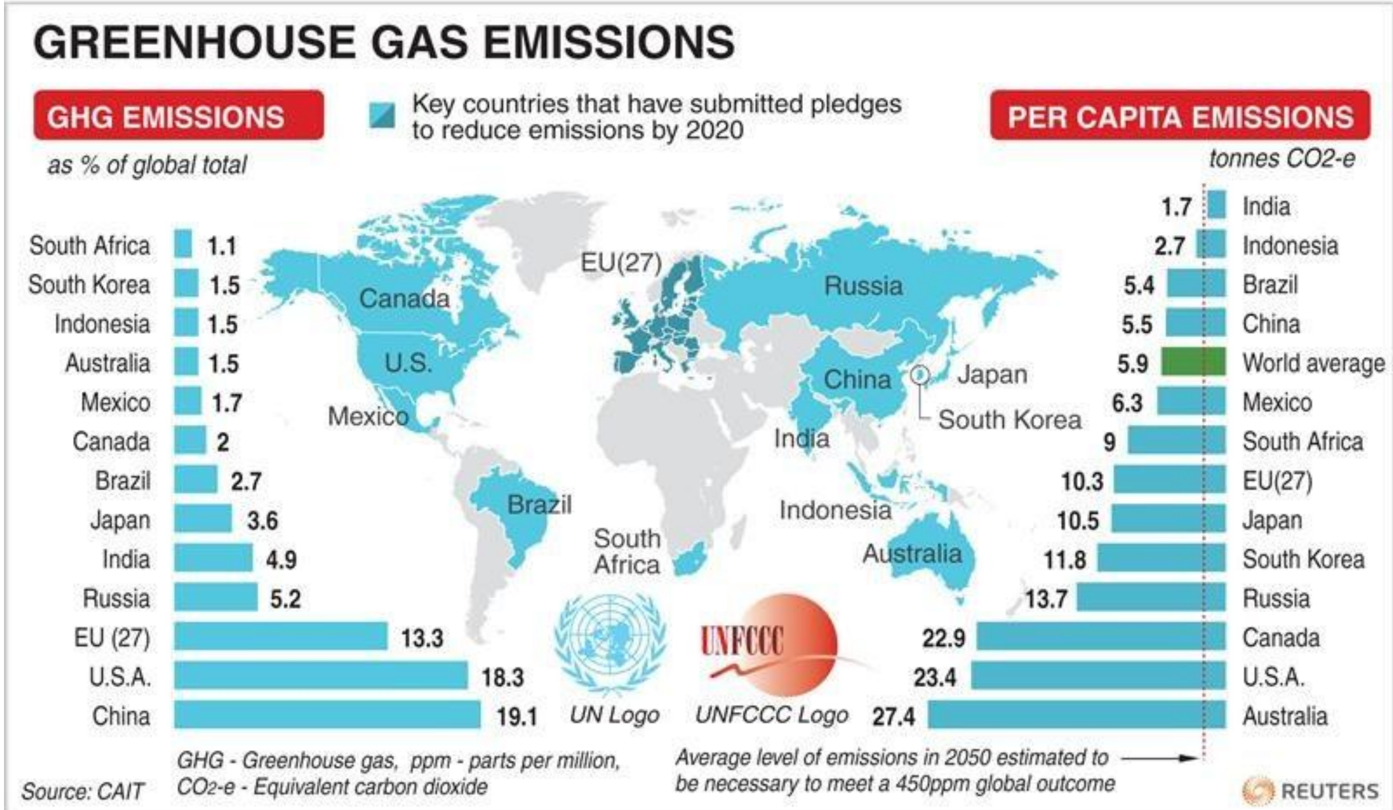

KEELEY OIL WELL, NEAR ROBINSON, ILL.


Time (before 2005)
10000
5000
0
Carbon Dioxide (ppm)
350
300
250
400
350
300
1800
1900
2000
Year
Radiative Forcing (W m^{-2})
1
0
Methane (ppb)
2000
1500
1000
500
2000
1500
1000
500
1800
1900
2000
Year
0.4
0.2
0
Radiative Forcing (W m^{-2})
Nitrous Oxide (ppb)
330
300
270
330
300
270
240
1800
1900
2000
Year
0.1
0
Radiative Forcing (W m^{-2})
10000
5000
0
Time (before 2005)


Global Land–Ocean Temperature Index
12–month Running Mean
Temperature Anomaly (°C)
.6
.4
.2
.0
–.2
–.4
1880
1900
1920
1940
1960
1980
2000


Temperature change
e
Ranges:
95%
90%
85%
80%
68%
50%
Median
SRES A1FI
max 2°C
HALVED-BY-2050
Global-mean air surface temperature relative to 1860–99 (°C)
0
1
2
3
4
5
6
7
1900
1920
1940
1960
1980
2000
2020
2040
2060
2080
2100
Year


IPCC AR4 individual realisations (20C3M+SRES A1B)
IPCC Ensemble and 95% range
HadCRUT3
NCDC
GISTEMP
Temperature Anomaly (ref. 1980-1999)
1.0
.8
.6
.4
.2
0.
-.2
-.4
Hindcast
Forecast
1980
1985
1990
1995
2000
2005
2010
Year

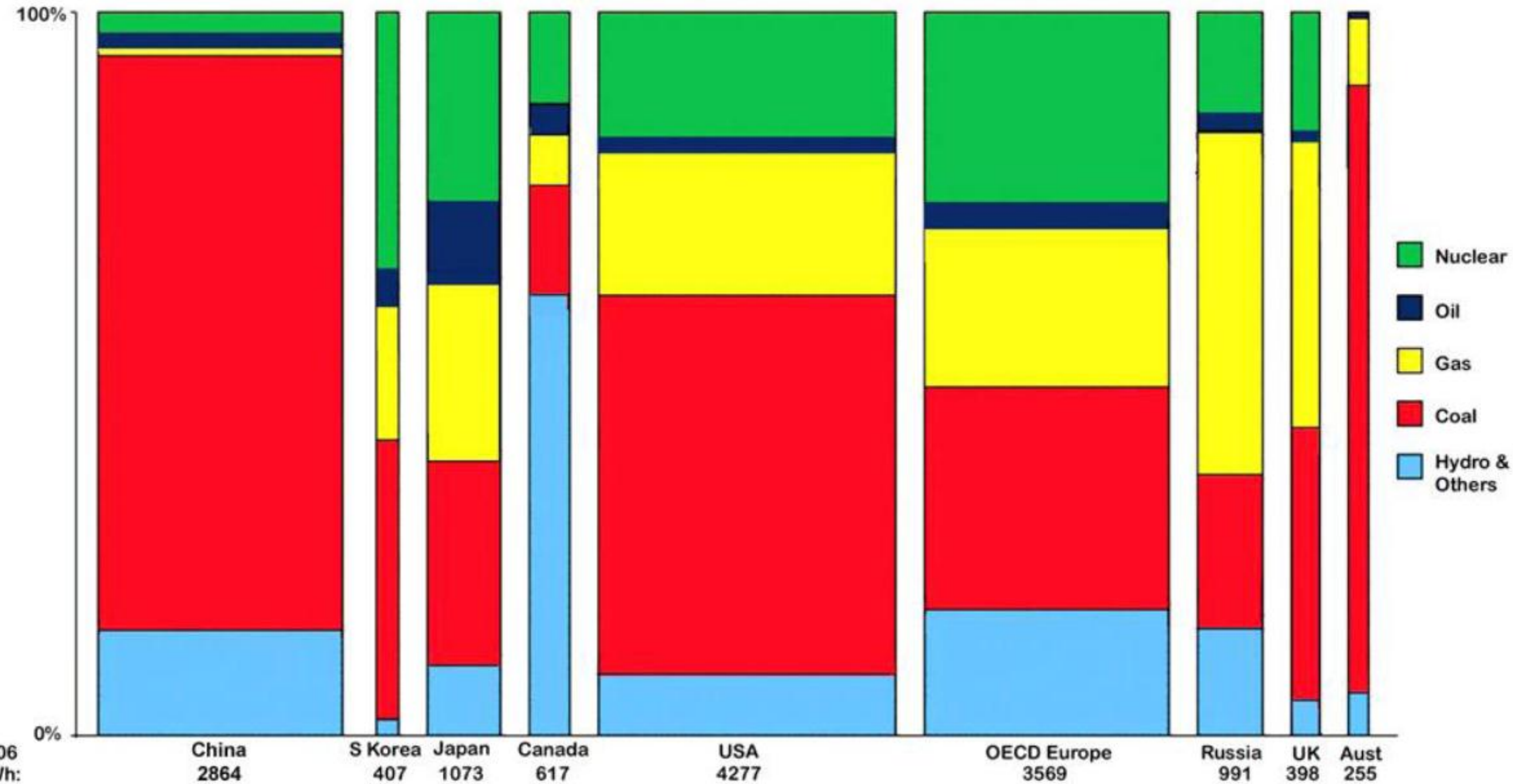


POLICY

NO POLICY

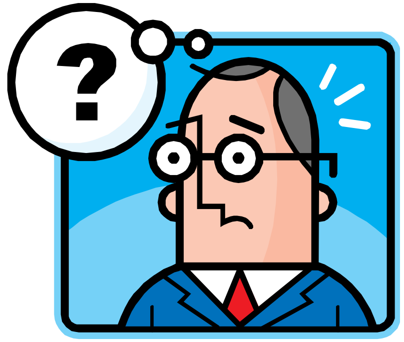
A challenging energy future…

Fuel for Electricity Generation (%)



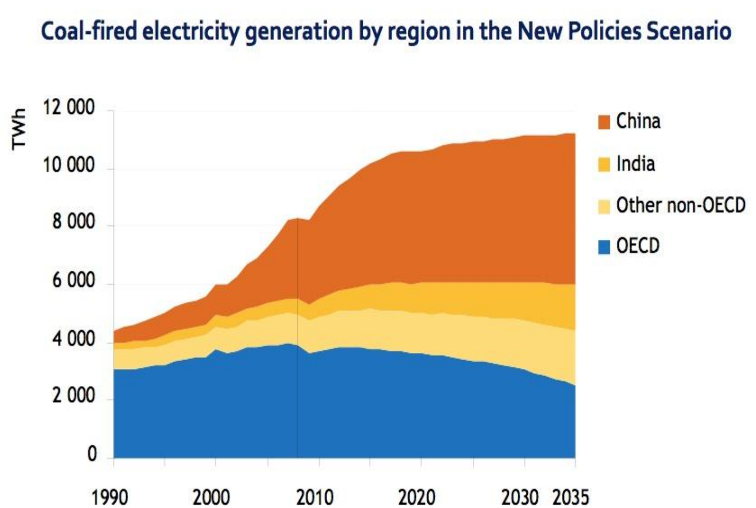
Width of each bar is indicative of gross power production

Main Source: OECD Electricity Information 2007

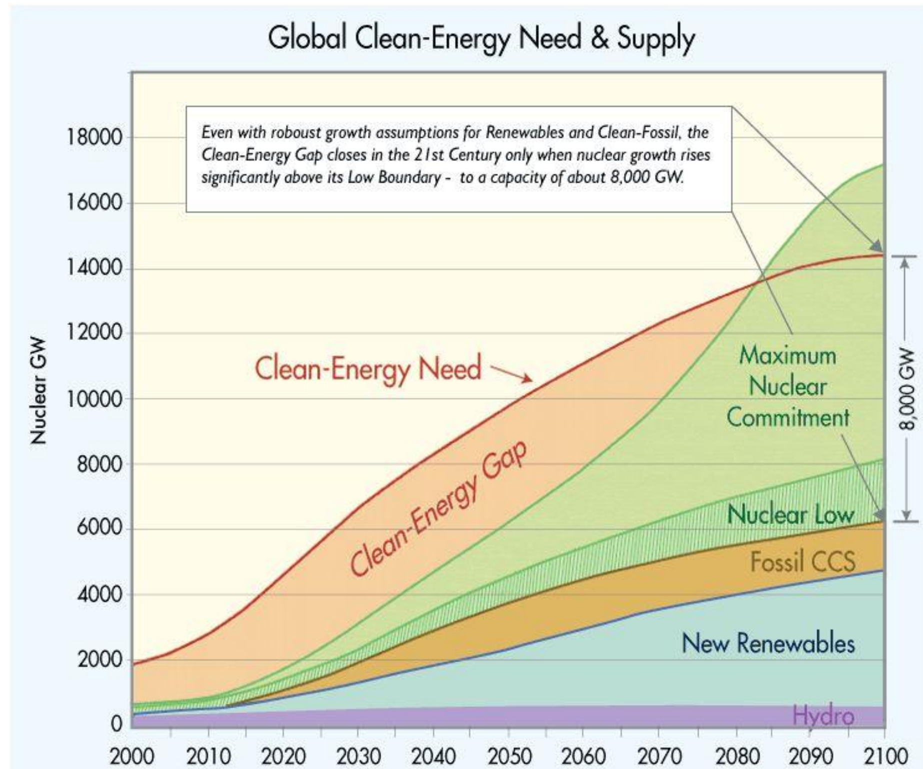


Coal remains the backbone of global electricity generation

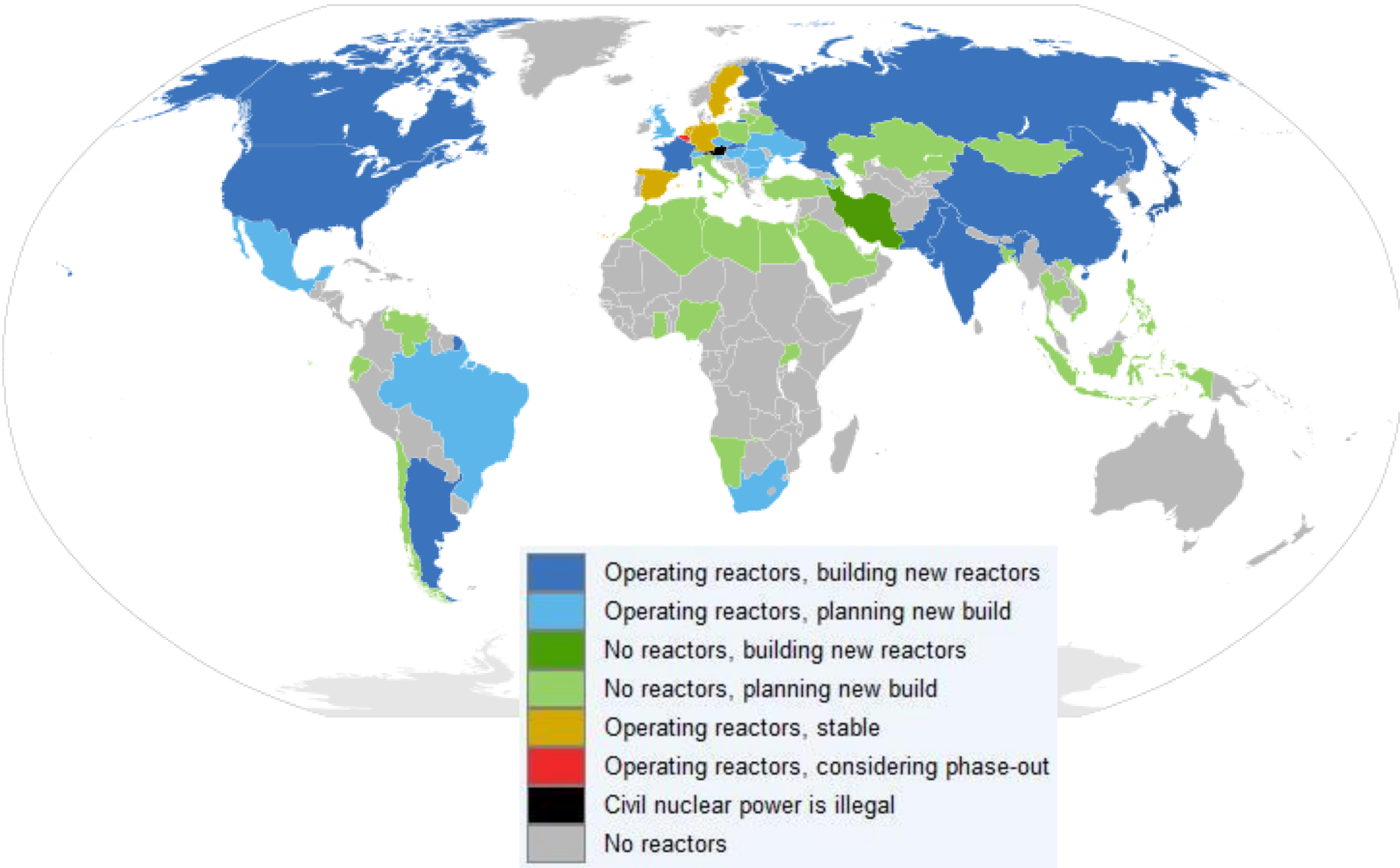
World Energy Outlook 2010

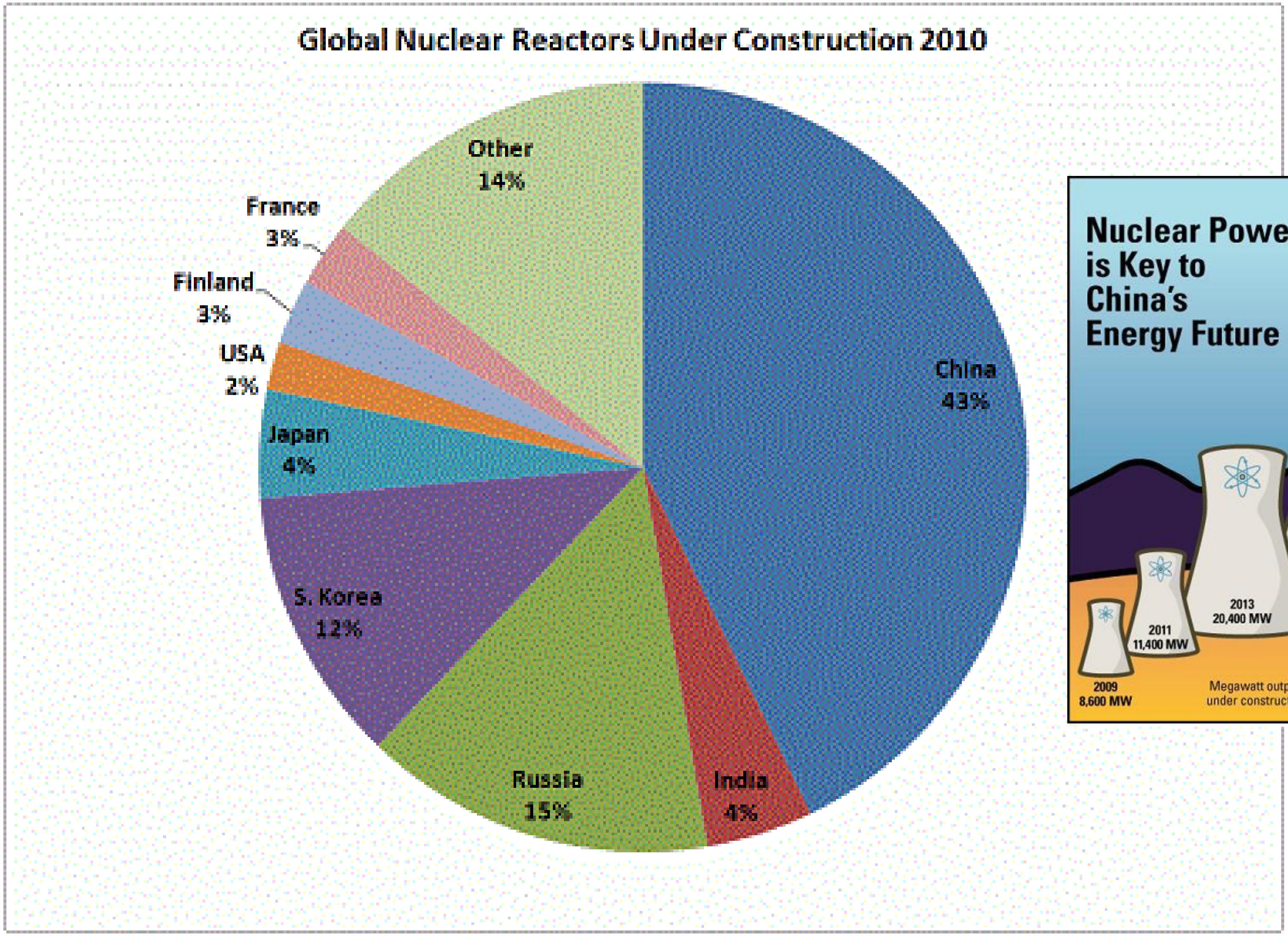


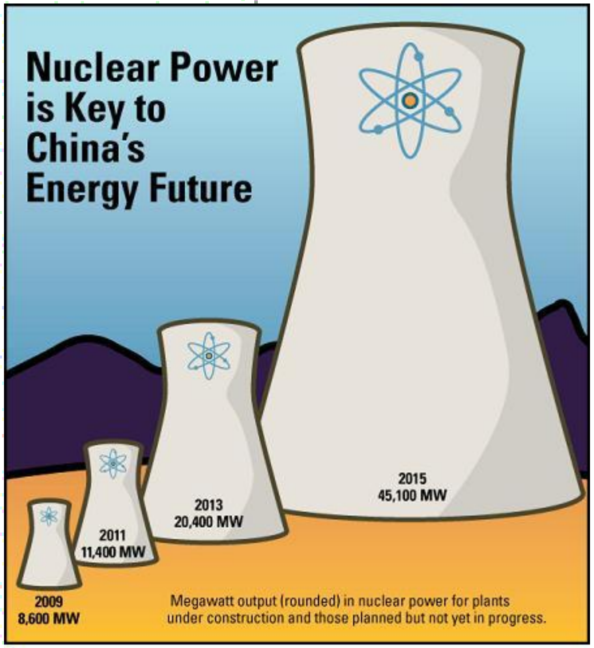
A drop in coal-fired generation in the OECD is offset by big increases elsewhere, especially China, where 600 GW of new capacity exceeds the current capacity of the US, EU & Japan



Nuclear’s current status


Operating reactors, building new reactors
Operating reactors, planning new build
No reactors, building new reactors
No reactors, planning new build
Operating reactors, stable
Operating reactors, considering phase-out
Civil nuclear power is illegal
No reactors

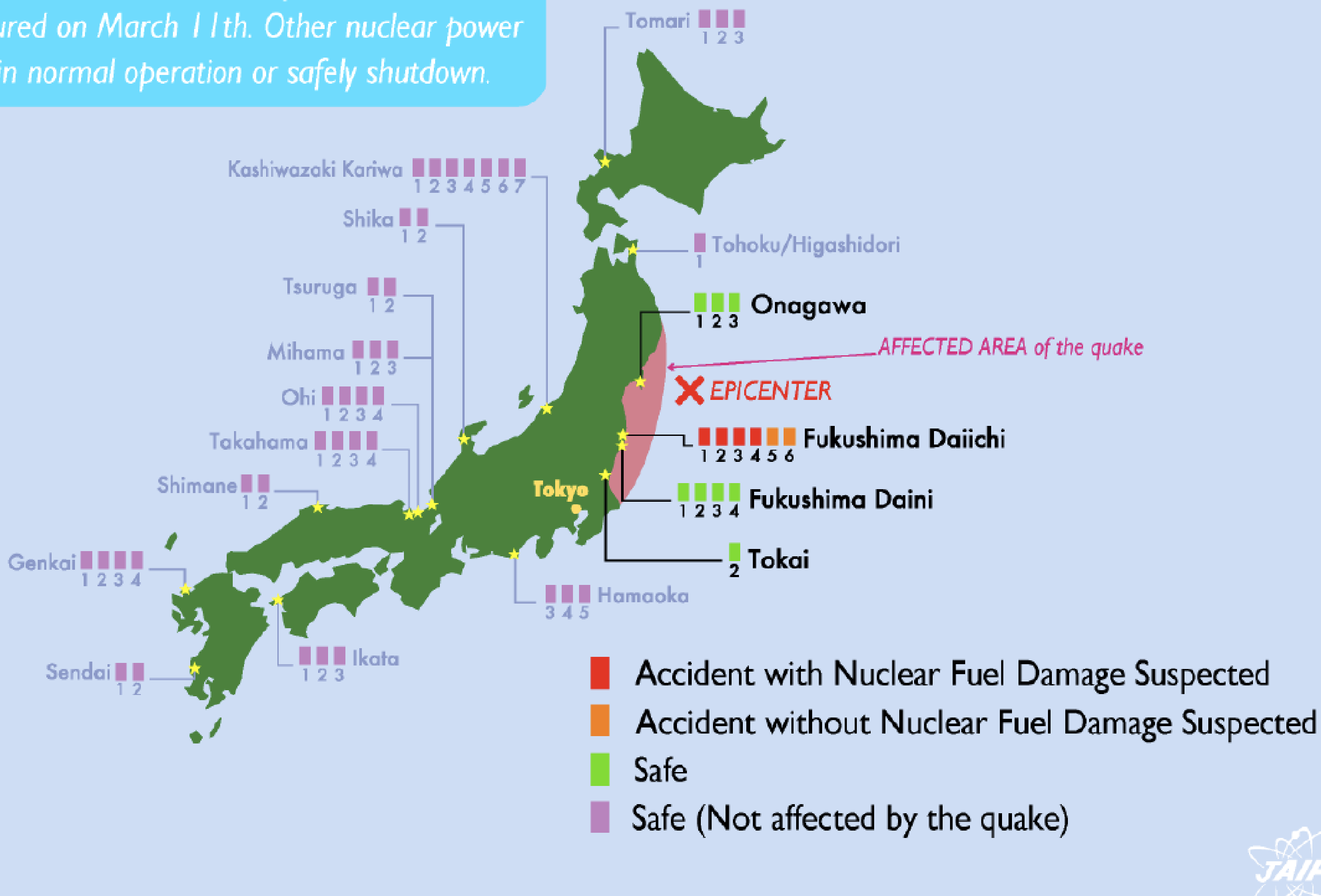

Global Nuclear Reactors Under Construction 2010
Other
14%
France
3%
Finland
3%
USA
2%
Japan
4%
S. Korea
12%
Russia
15%
India
4%
China
43%


Nuclear Power
is Key to
China's
Energy Future
2009
8,600 MW
2011
11,400 MW
2013
20,400 MW
2015
45,100 MW
Megawatt output (rounded) in nuclear power for plants
under construction and those planned but not yet in progress.

Yesterday’s vs Today’s technology

Status of the Nuclear Power Plants after the Earthquake

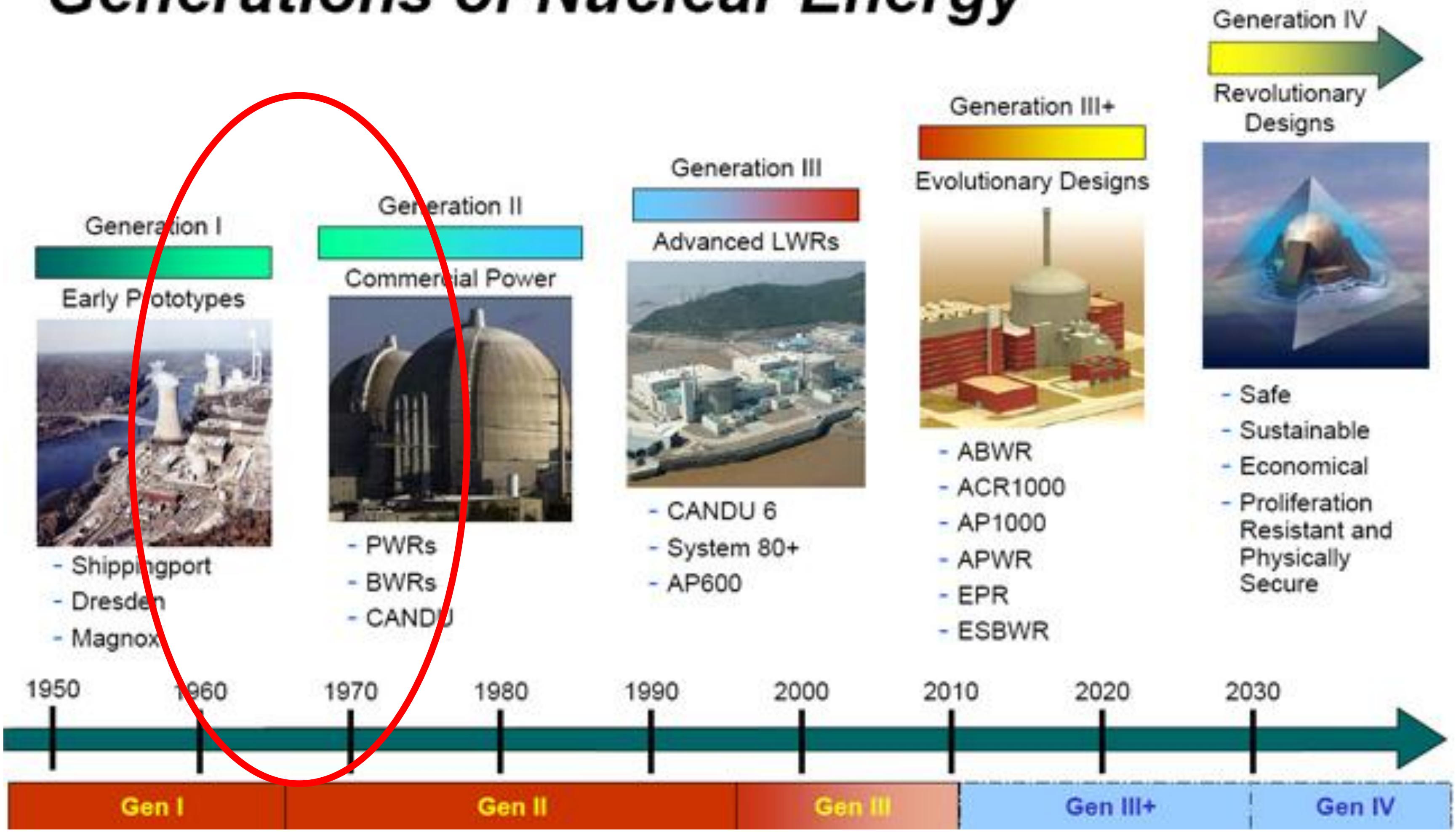
The accident that brings environmental impact is going on at several units in Fukushima Daiichi nuclear power Station after the earthquake occured on March 11th. Other nuclear power plants in Japan are in normal operation or safely shutdown.




Before Explosion
After Explosion


DIGITALGLOBE

Generations of Nuclear Energy



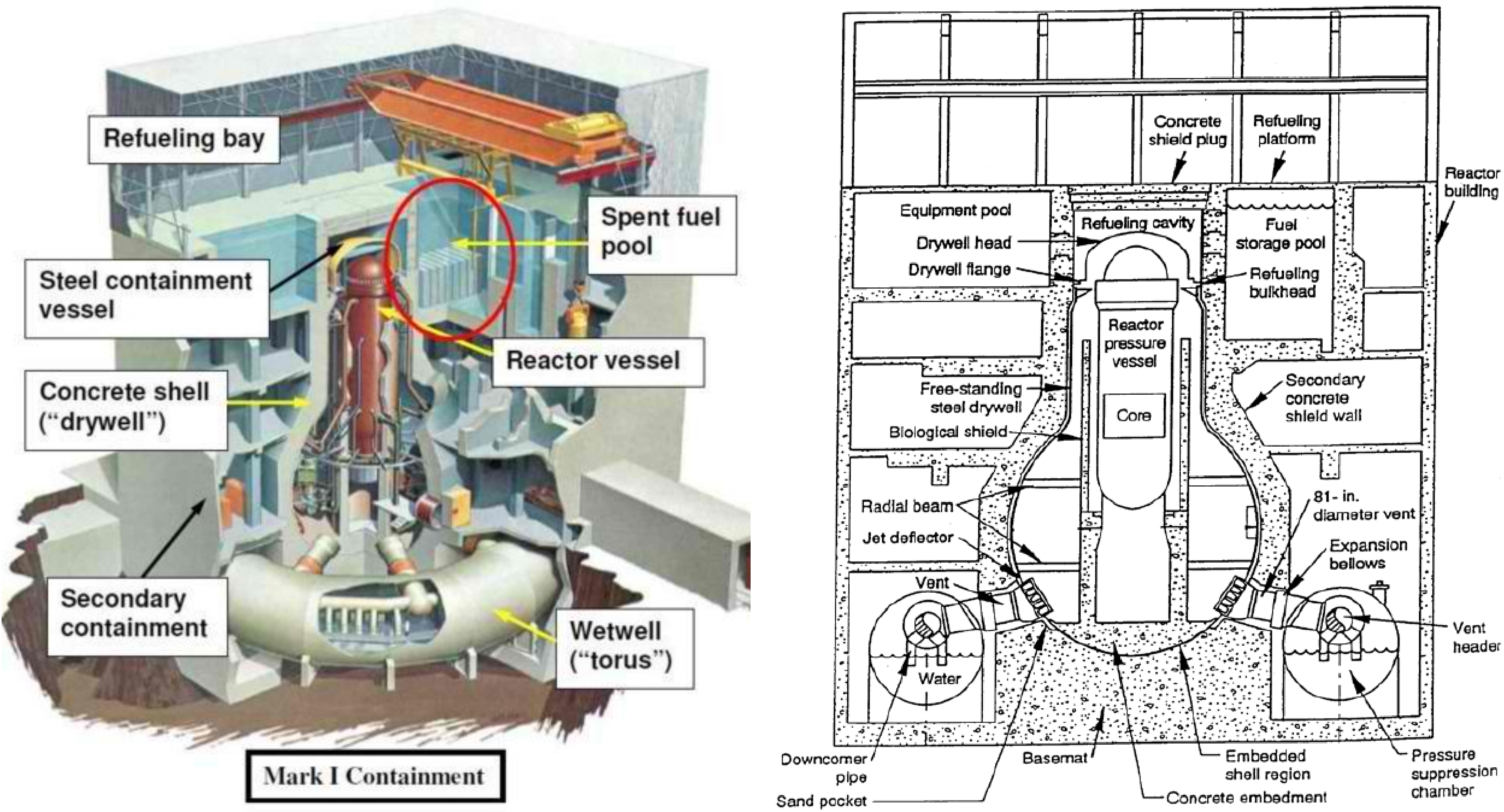
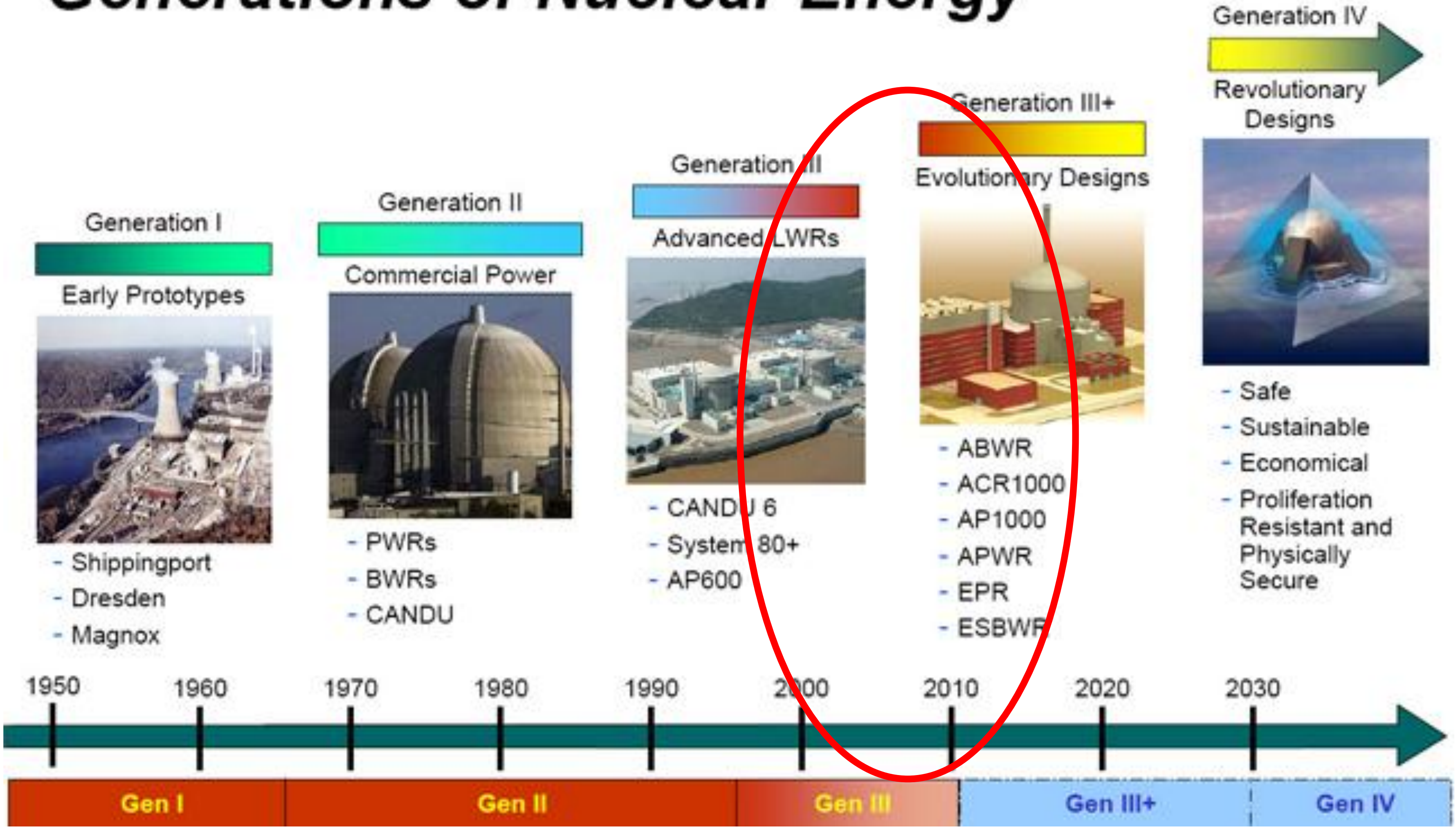


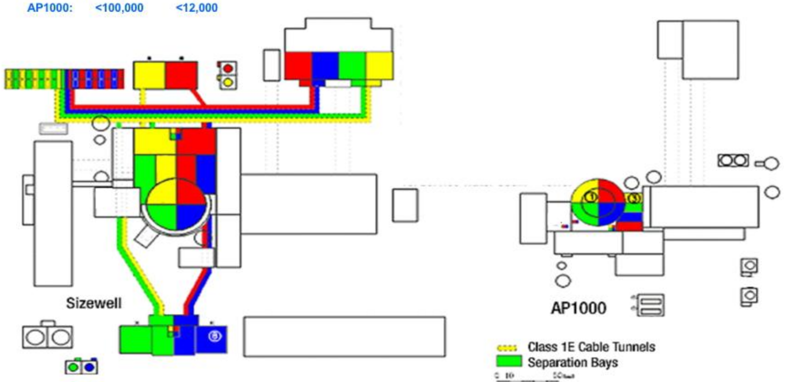
Figure 20. Mark I General Electric,GE BWR Containment.

Generations of Nuclear Energy



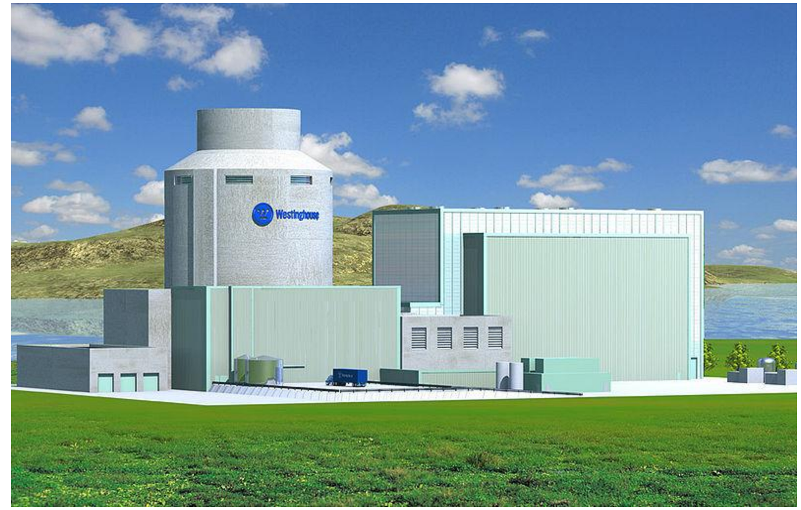
Simplification: Smaller Footprint

	Concrete, m³	Rebar, metric tons
Sizewell B:	520,000	65,000
Olkiluoto:	400,000	60,000
AP1000:	<100,000	<12,000

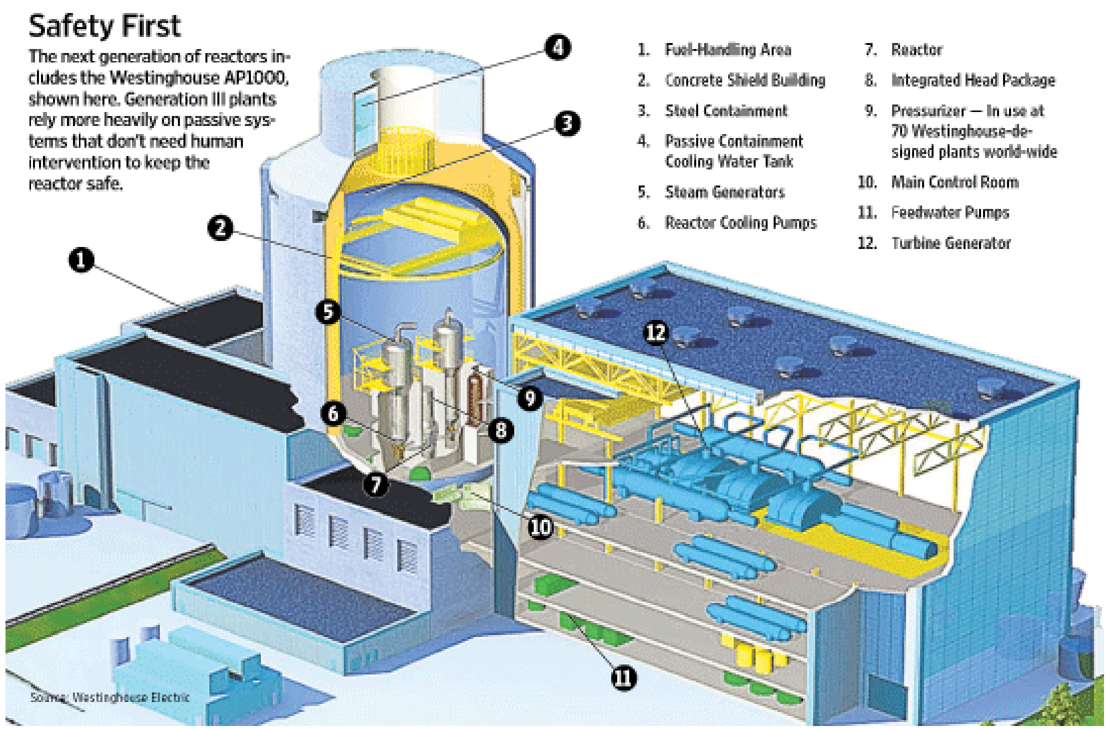


Evolutionary PWR

Size Matters



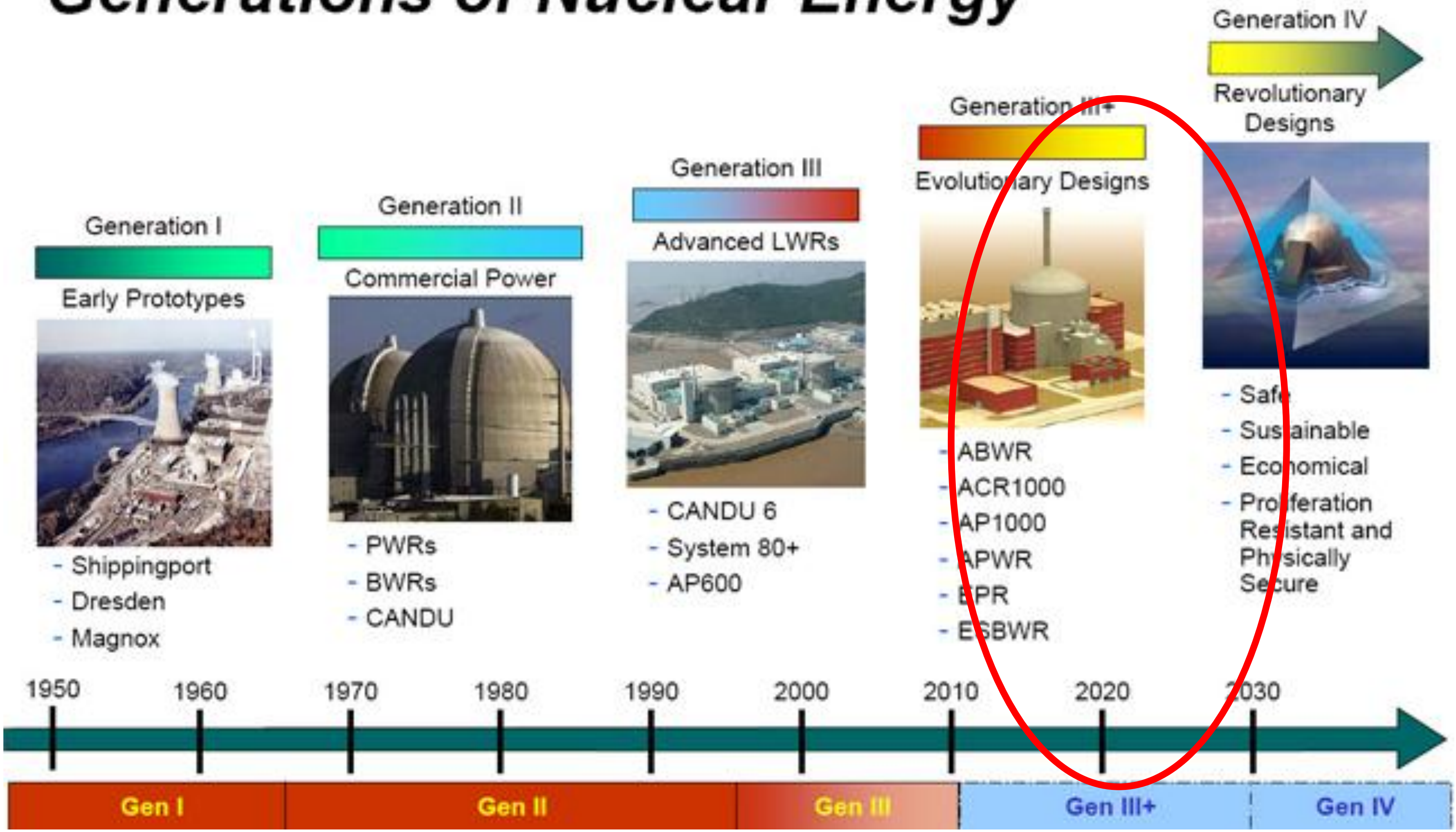
AP1000



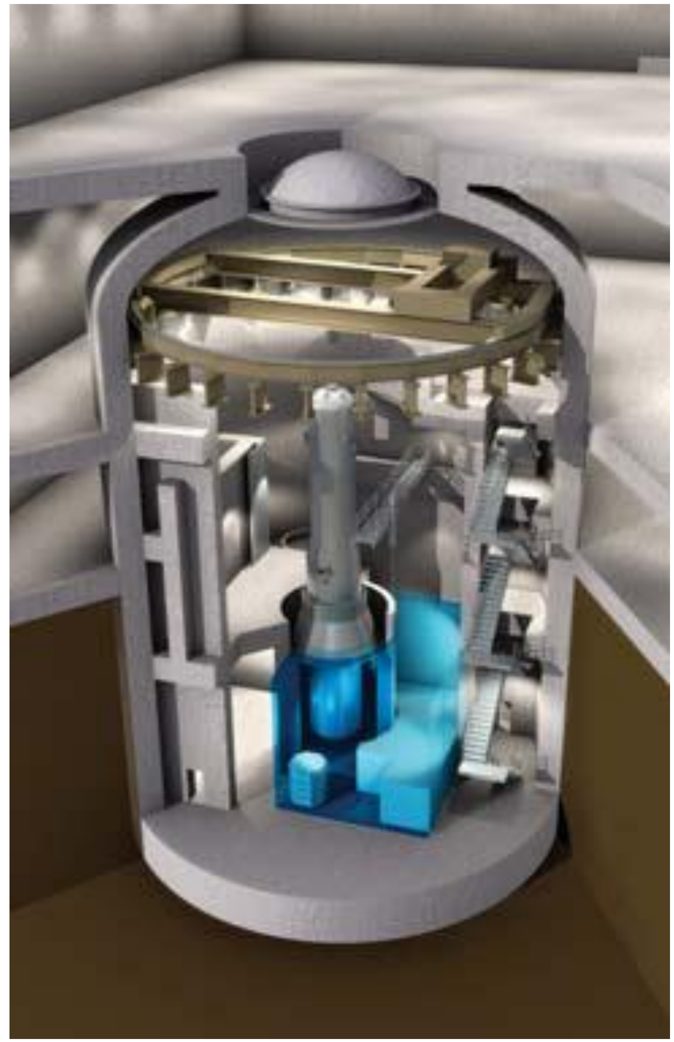

SNPTC
安全第一 质量第一 一次做好 持续改进
COI
安全发展 集约发展

Small Modular Reactors (SMR)

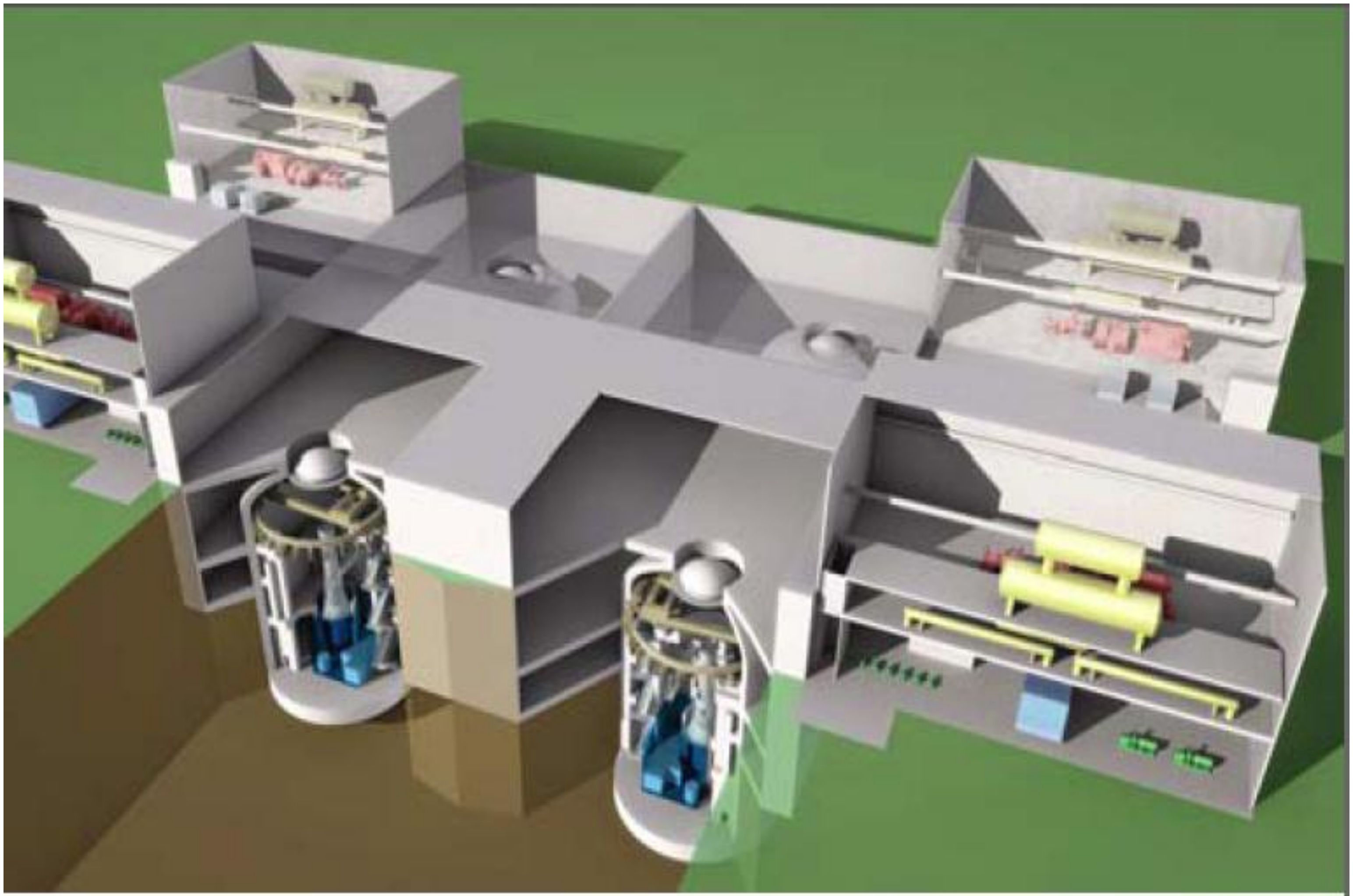
Generations of Nuclear Energy



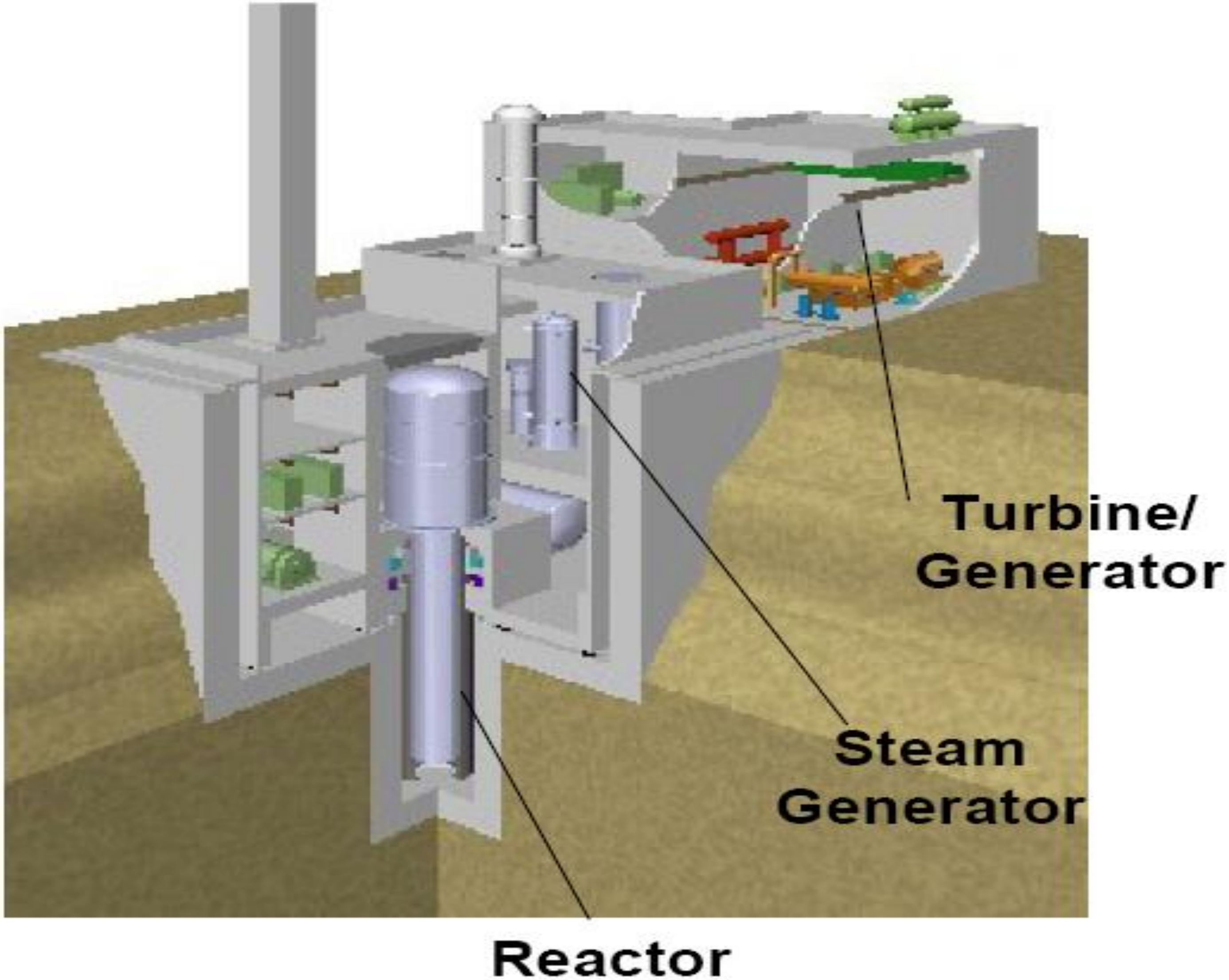
B&W 125MWe *mPower* reactor and underground containment vessel



Four B&W *mPower* reactor modules generating 500 MWe



Toshiba 4S reactor module 10 – 50 MWe



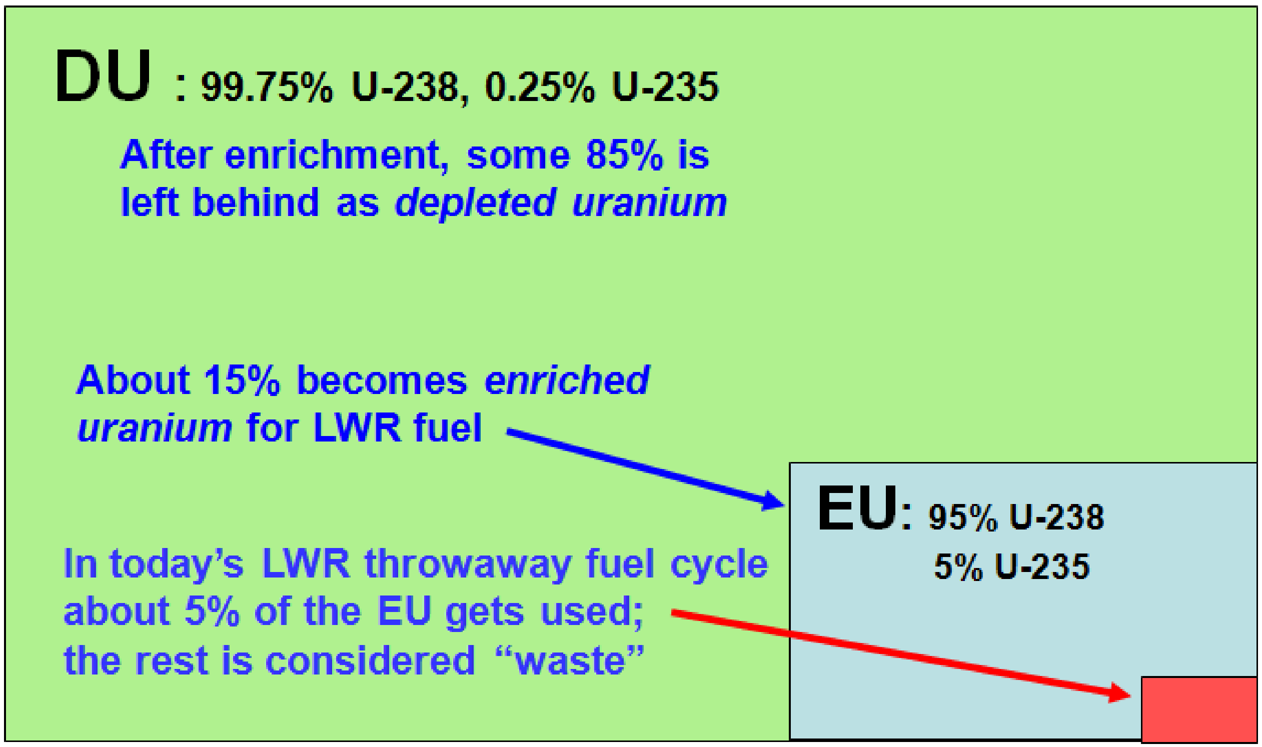
Integral Fast Reactor:
Safely closing the nuclear fuel cycle

THE FATE OF THE MINED URANIUM

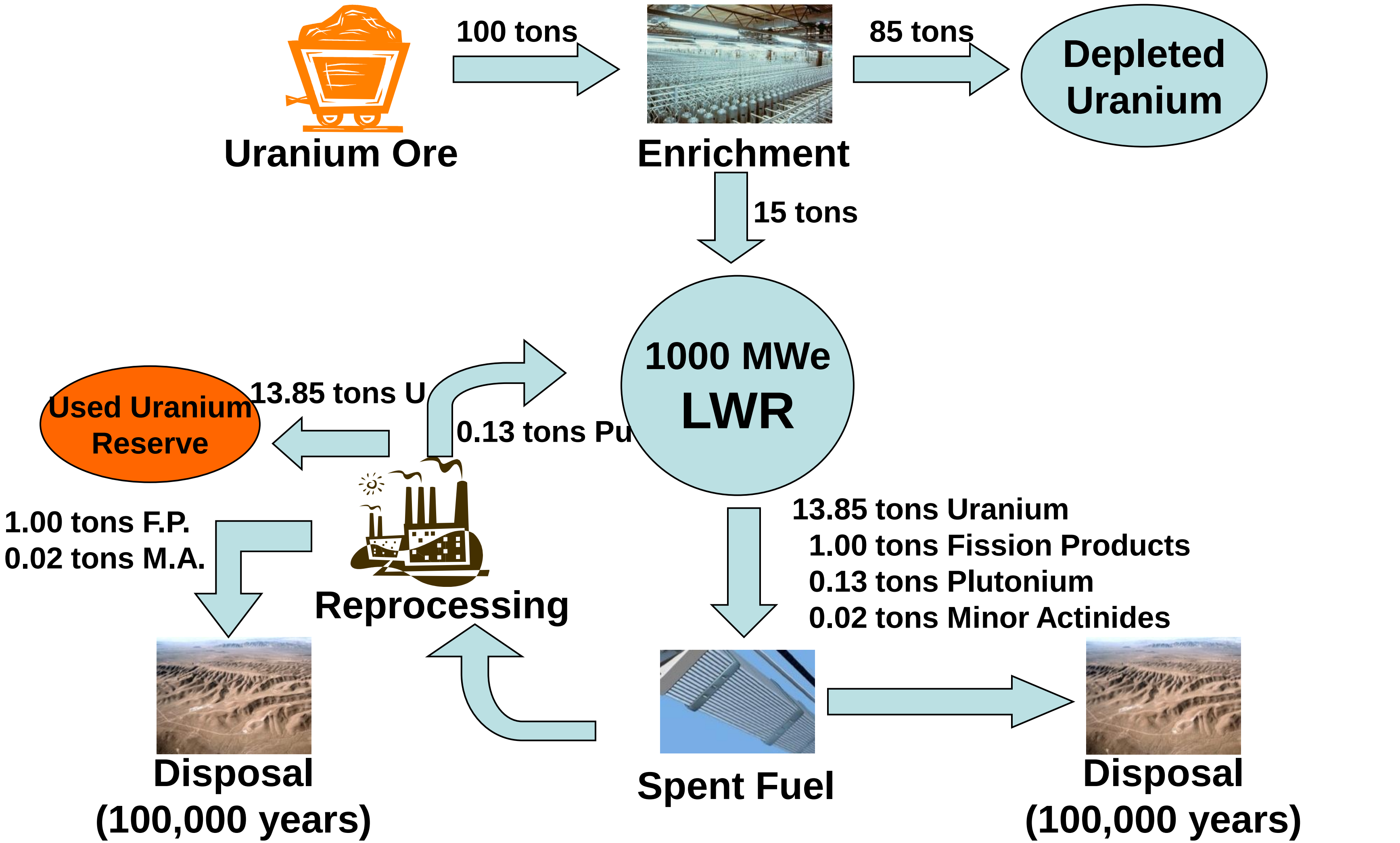
TODAY, LESS THAN 1% OF ITS ENERGY IS BEING USED

As mined, uranium is 99.3% U-238, 0.7% U-235. For LWR fuel, the uranium first goes to an enrichment plant

Mined uranium (after the enrichment process)



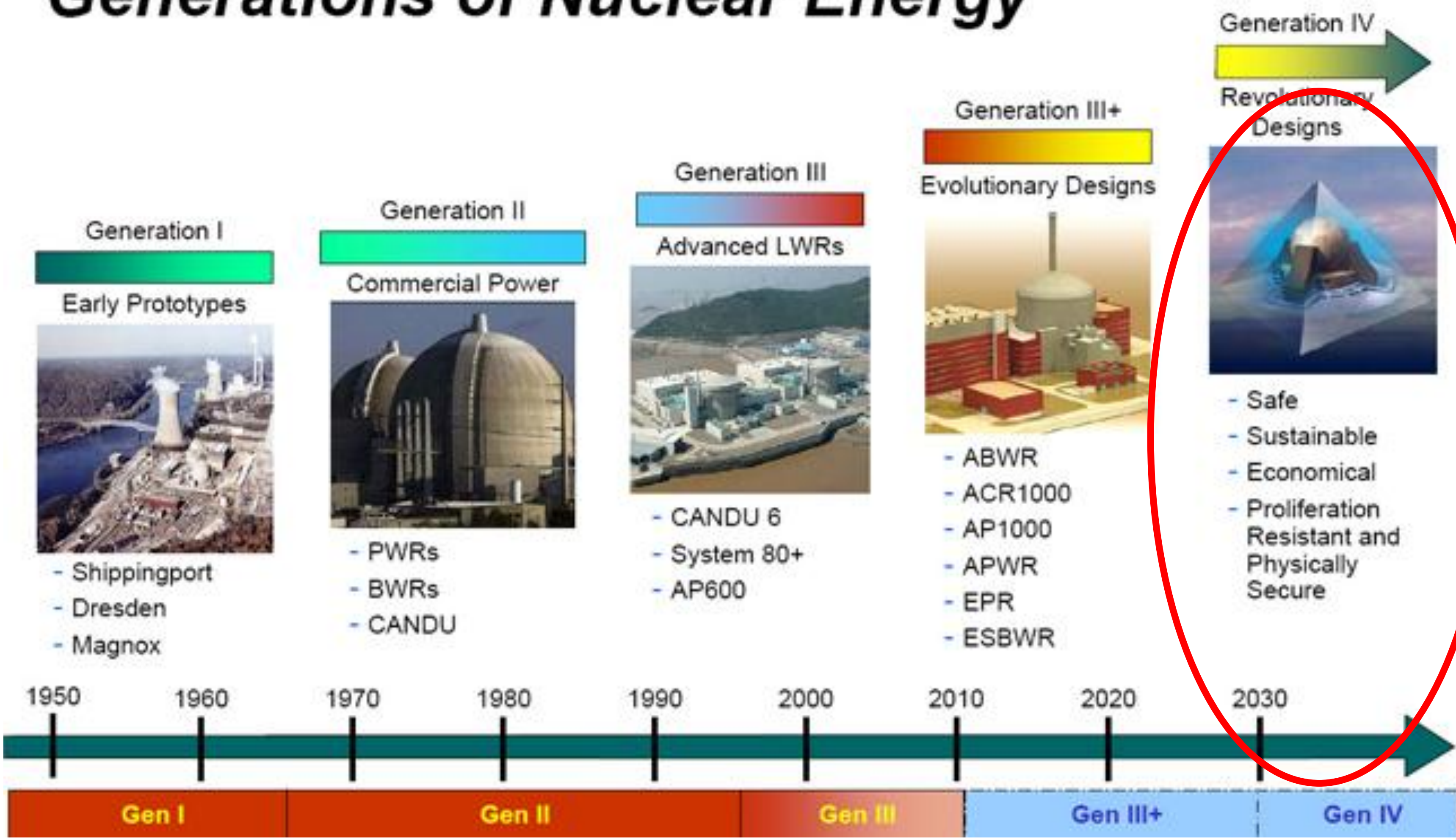
Annual Mass Flow for LWR

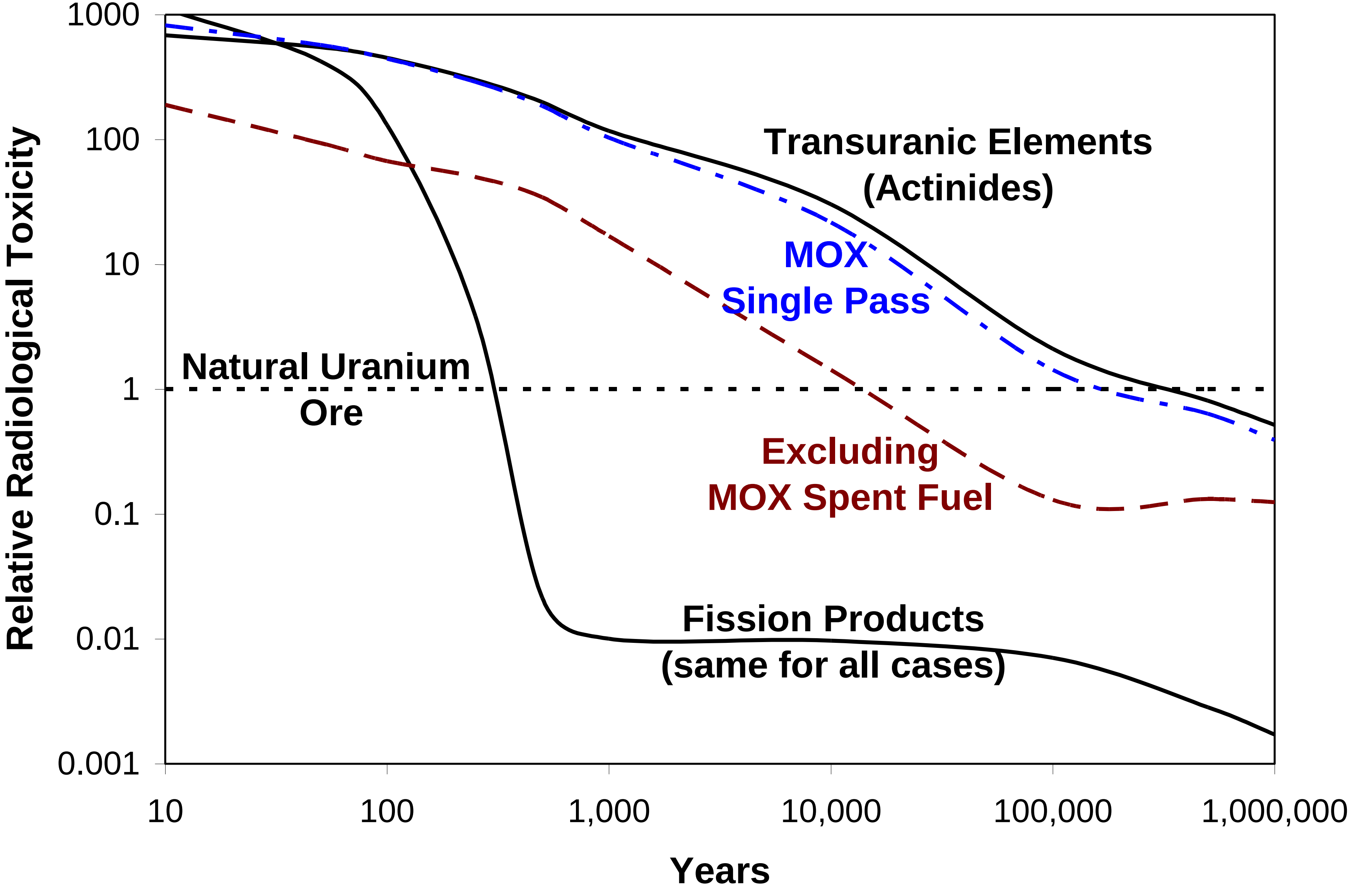


European recycle
- Saves 15% uranium
- But no reduction in waste life

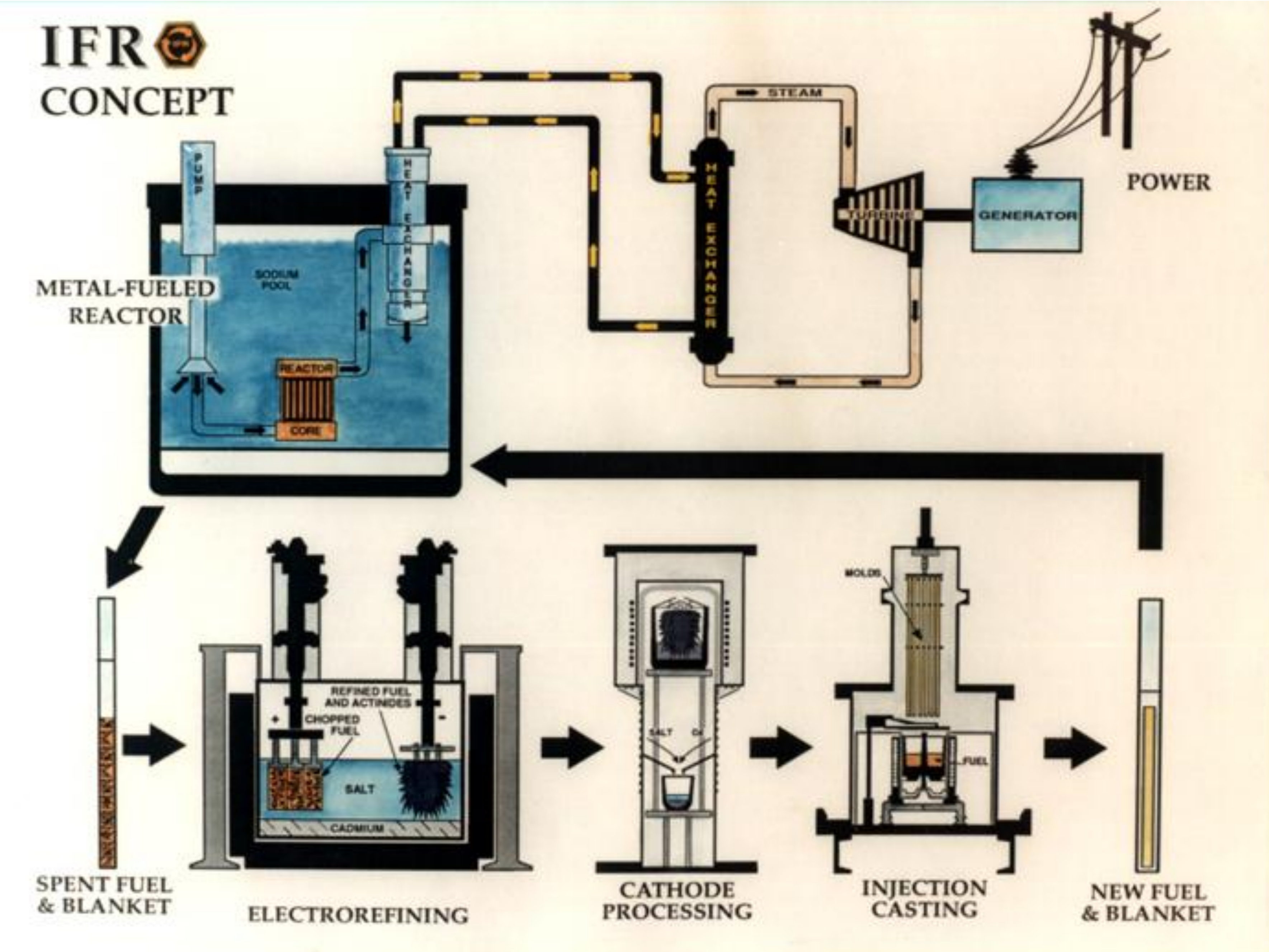
Direct disposal is
the current U.S. policy

Generations of Nuclear Energy



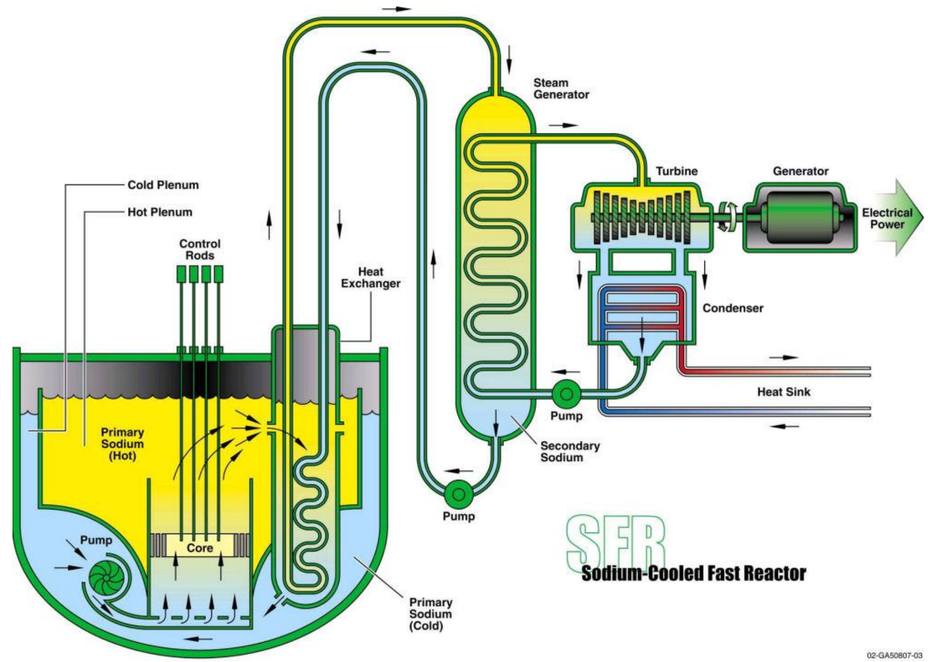


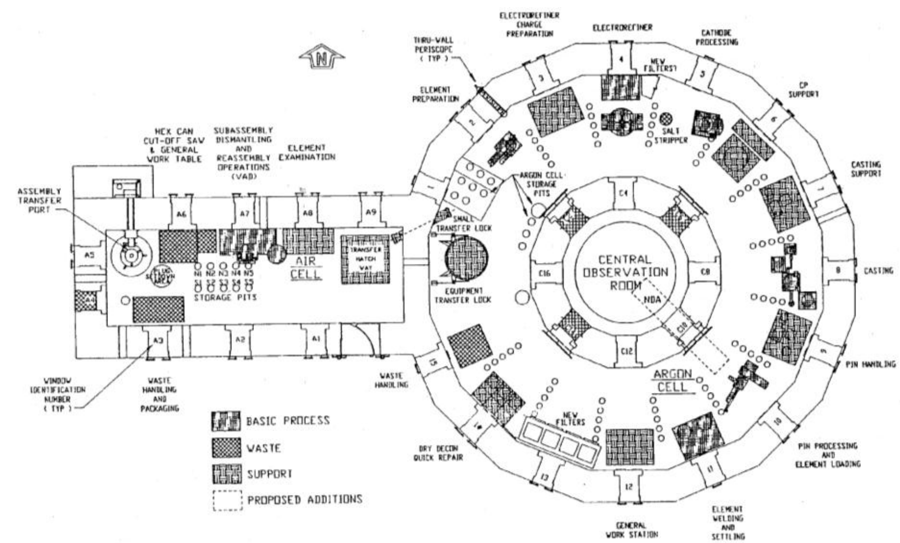
Relative radiological toxicity of spent fuel constituents



IFR
CONCEPT
PUMP
HEAT EXCHANGER
SODIUM POOL
METAL-FUELED REACTOR
REACTOR
CORE
STEAM
HEAT EXCHANGER
TURBINE
GENERATOR
POWER
MOLDS
REFINED FUEL AND ACTINIDES
CHOPPED FUEL
SALT
CADMIUM
SALT
Cd
FUEL
SPENT FUEL & BLANKET
ELECTROREFINING
CATHODE PROCESSING
INJECTION CASTING
NEW FUEL & BLANKET

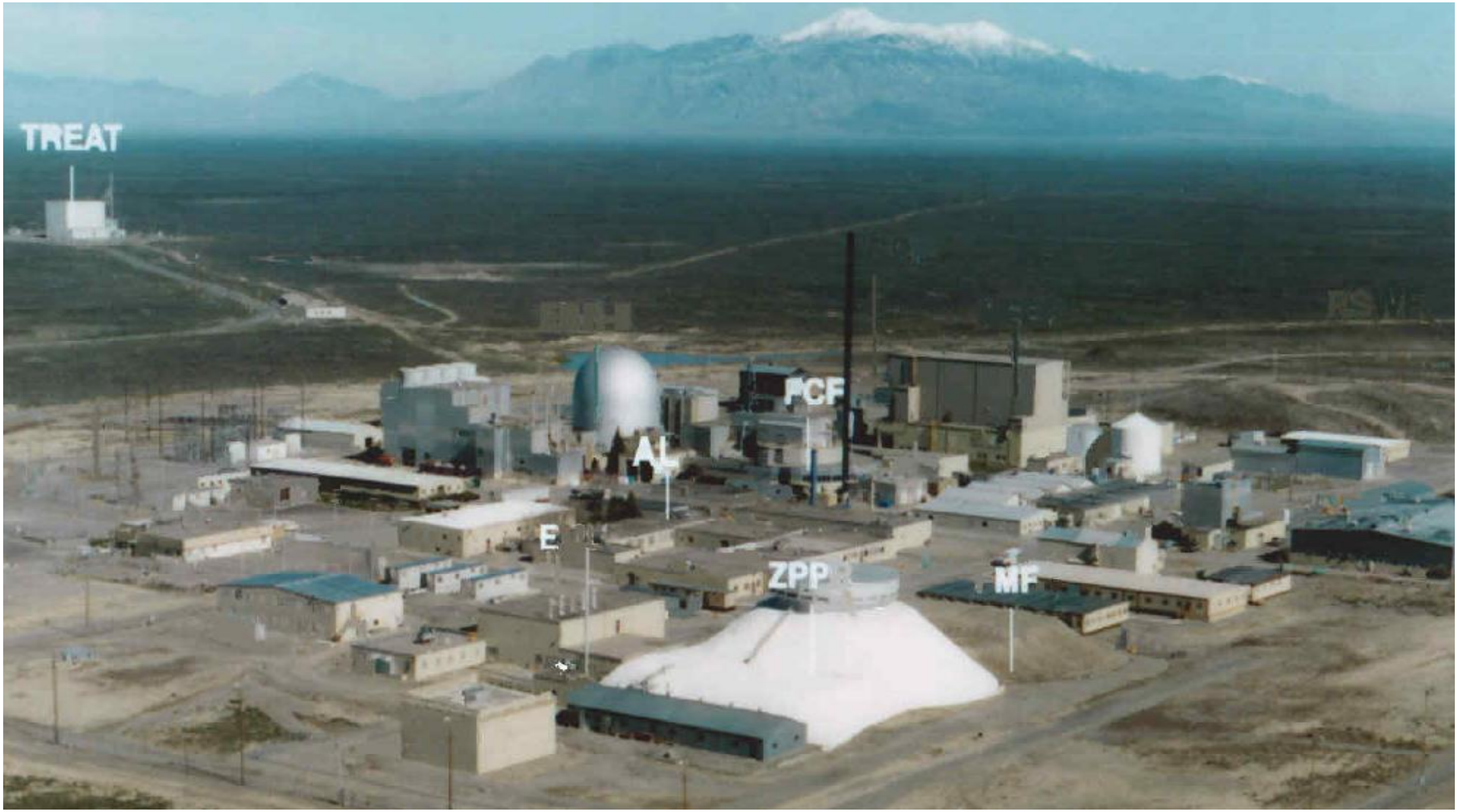

EBR-II
REACTOR PLANT 767


Steam Generator
Turbine
Generator
Electrical Power
Cold Plenum
Hot Plenum
Control Rods
Heat Exchanger
Condenser
Heat Sink
Pump
Secondary Sodium
Primary Sodium (Hot)
Pump
Core
Pump
Primary Sodium (Cold)
SFR
Sodium-Cooled Fast Reactor
02-GA50807-03

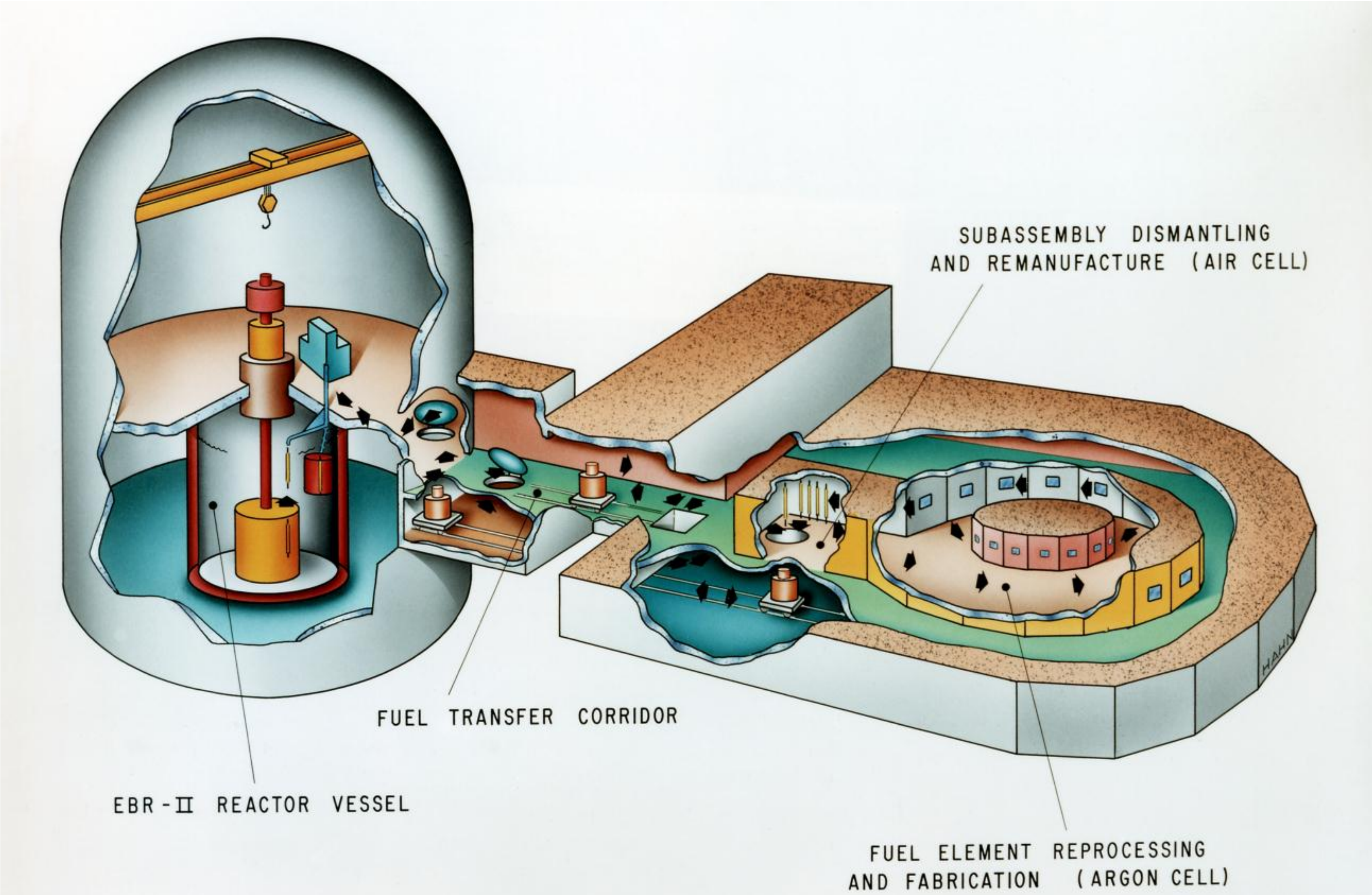

ELECTROREFINER CHARGE PREPARATION
ELECTROREFINER
CATHODE PROCESSING
THRU-WALL PERISCOPE (TYP)
ELEMENT PREPARATION
CP SUPPORT
HEX CAN CUT-OFF SAW & GENERAL WORK TABLE
SUBASSEMBLY DISMANTLING AND REASSEMBLY OPERATIONS (VAB)
ELEMENT EXAMINATION
ASSEMBLY TRANSFER PORT
ARGON CELL STORAGE PITS
SALT STRIPPER
CASTING SUPPORT
SMALL TRANSFER LOCK
AIR CELL
STORAGE PITS
CENTRAL OBSERVATION ROOM
CASTING
EQUIPMENT TRANSFER LOCK
PIN HANDLING
WINDOW IDENTIFICATION NUMBER (TYP)
WASTE HANDLING AND PACKAGING
WASTE HANDLING
ARGON CELL
BASIC PROCESS
WASTE
SUPPORT
PROPOSED ADDITIONS
DRY DECON QUICK REPAIR
PIN PROCESSING AND ELEMENT LOADING
GENERAL WORK STATION
ELEMENT WELDING AND SETTLING

What is Integral Fast Reactor (IFR)?

	Current Generation LWR	Next Generation IFR	Principal Impacts
Coolant	Water	Liquid sodium	Non-pressurized system
Neutron energy	Thermal (<1 eV)	Fast (>100 keV)	Breeding capability
Fuel type	Oxide	Metal	Inherent passive safety
Fuel Cycle	Aqueous reprocessing	Pyro-processing	Waste management solution, proliferation-resistance, economics

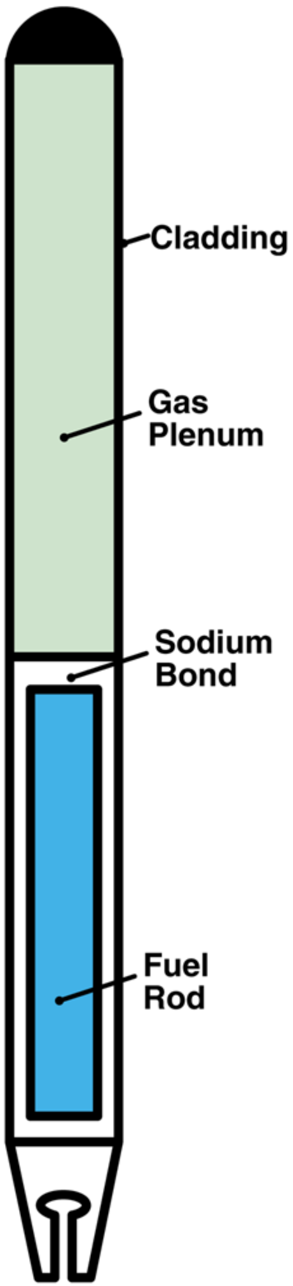


The Argonne West National Lab (now part of INL) ~50 km west of Idaho Falls



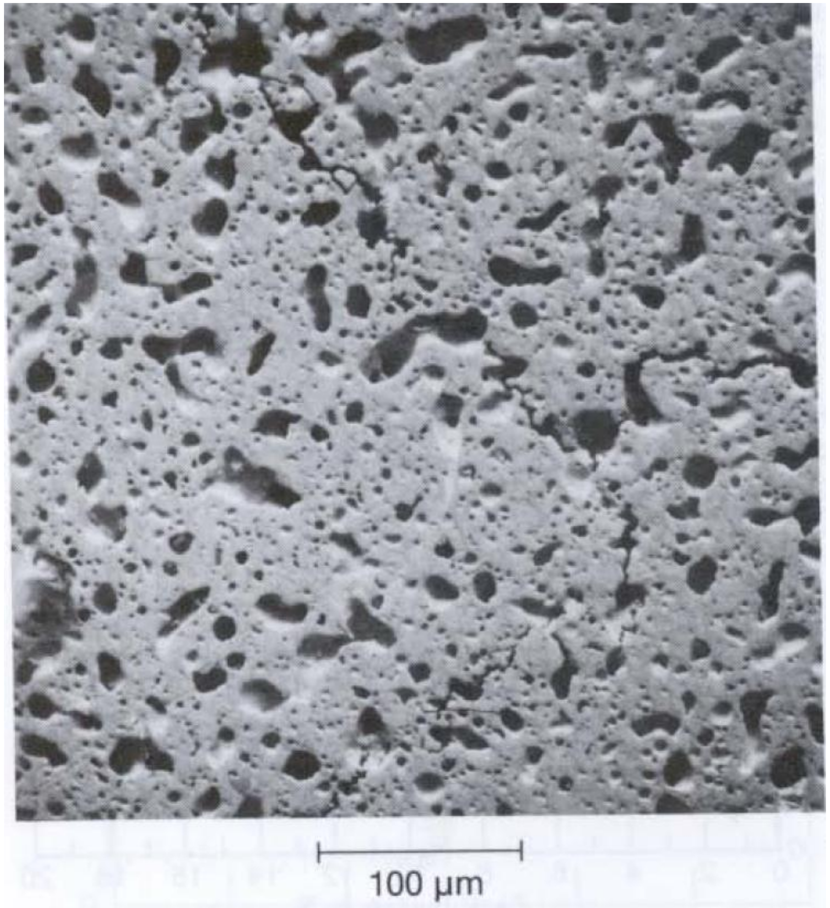
EBR-II and Fuel Cycle Facility showing reactor vessel, fuel transfer tunnel, air cell, and argon cell

EBR-II Metallic Fuel

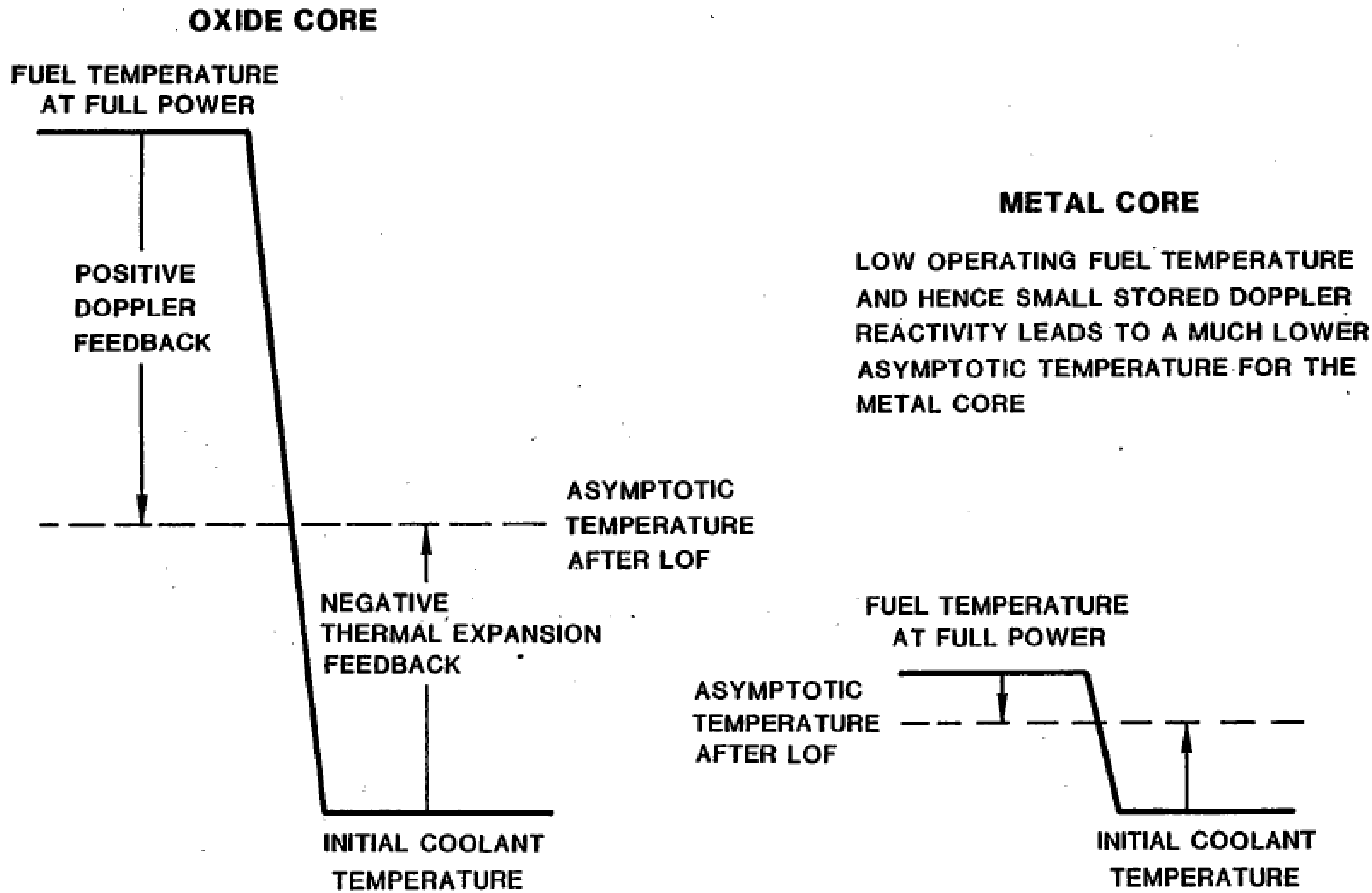


- EBR-II used a sodium bonded metallic fuel..
  - Highly enriched uranium in driver fuel (63-75% U-235).
  - Fuel rod immersed in sodium encased in a stainless-steel tube
  - Large plenum collected fission gas

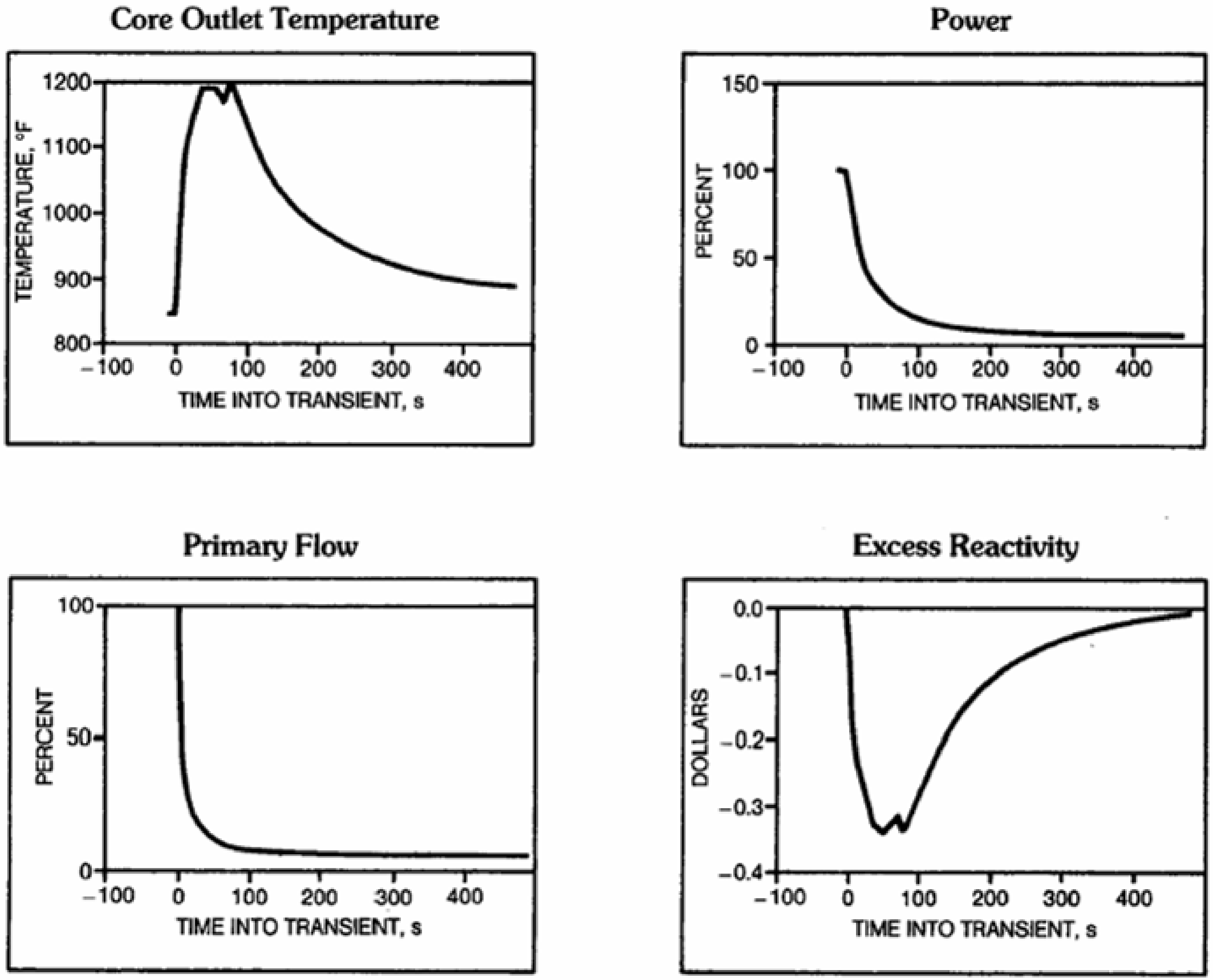
Schematic Drawing of EBR-II Fuel Element



Fission gas pore structure of irradiated U-10Zr fuel

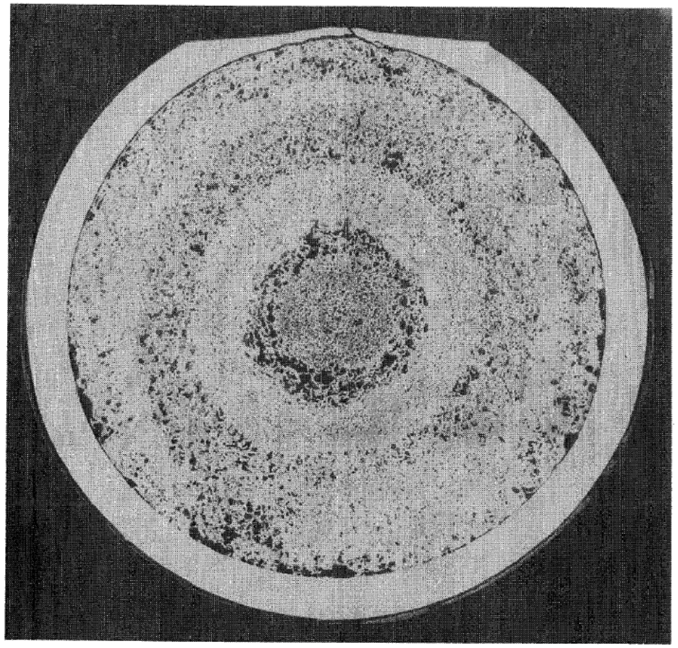


Asymptotic temperature reached during unprotected loss-of-flow event is determined by reactivity balance: comparison of oxide and metal cores

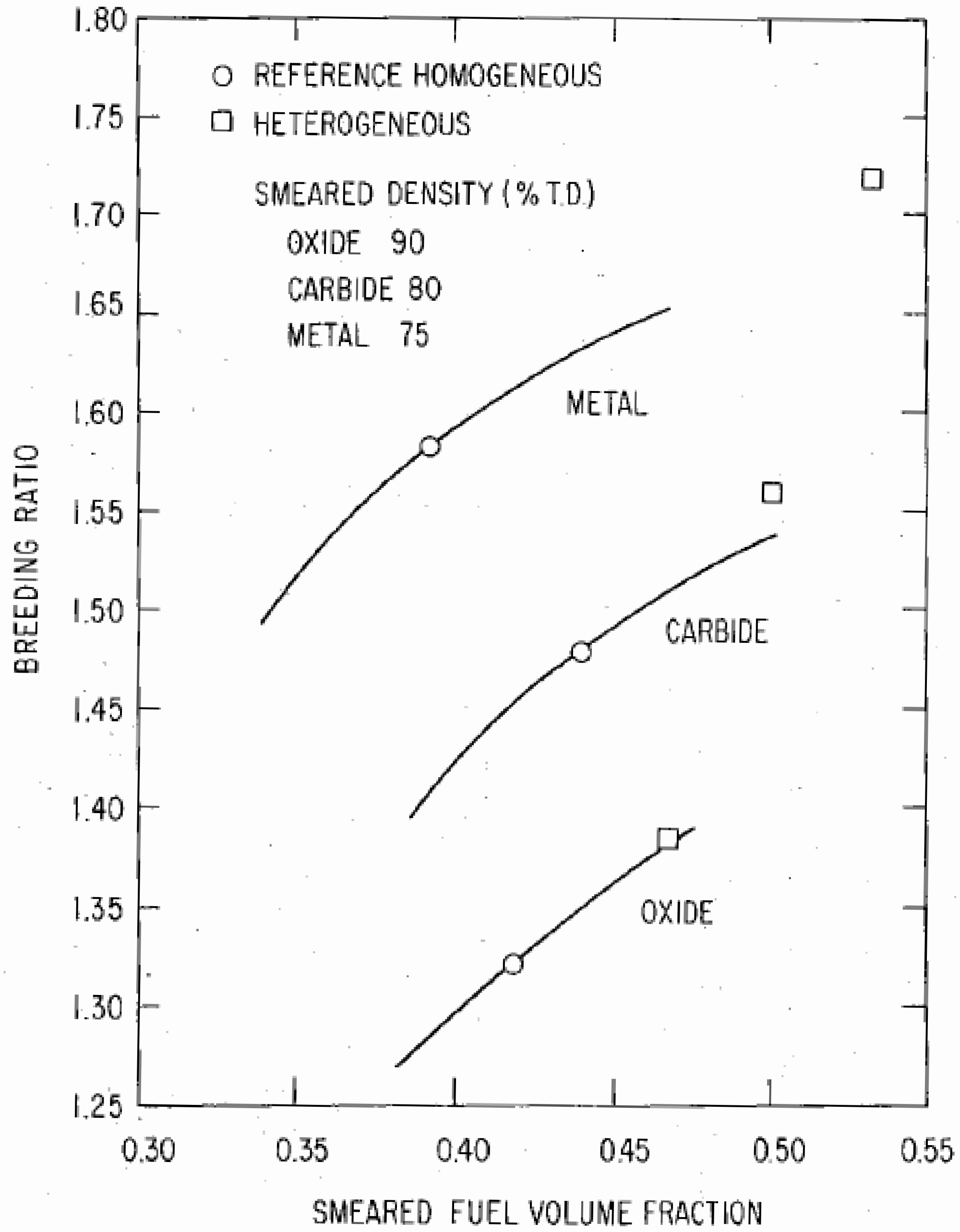


Unprotected loss-of-flow test results

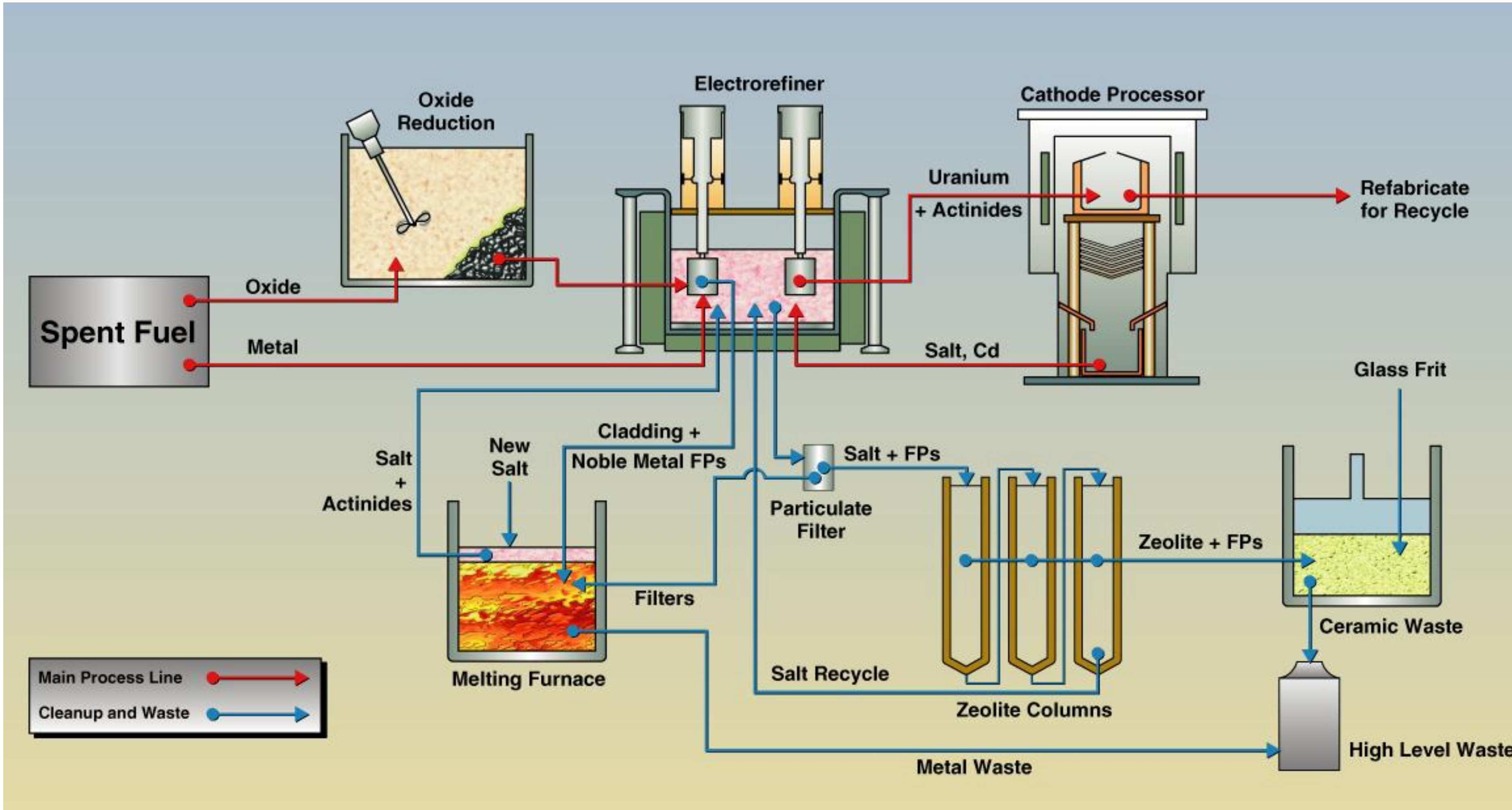
Oxide fuel (9% burn-up)



Metal fuel (12% burn-up)



Breeding ratio as a function of fuel volume fraction for various fuel types

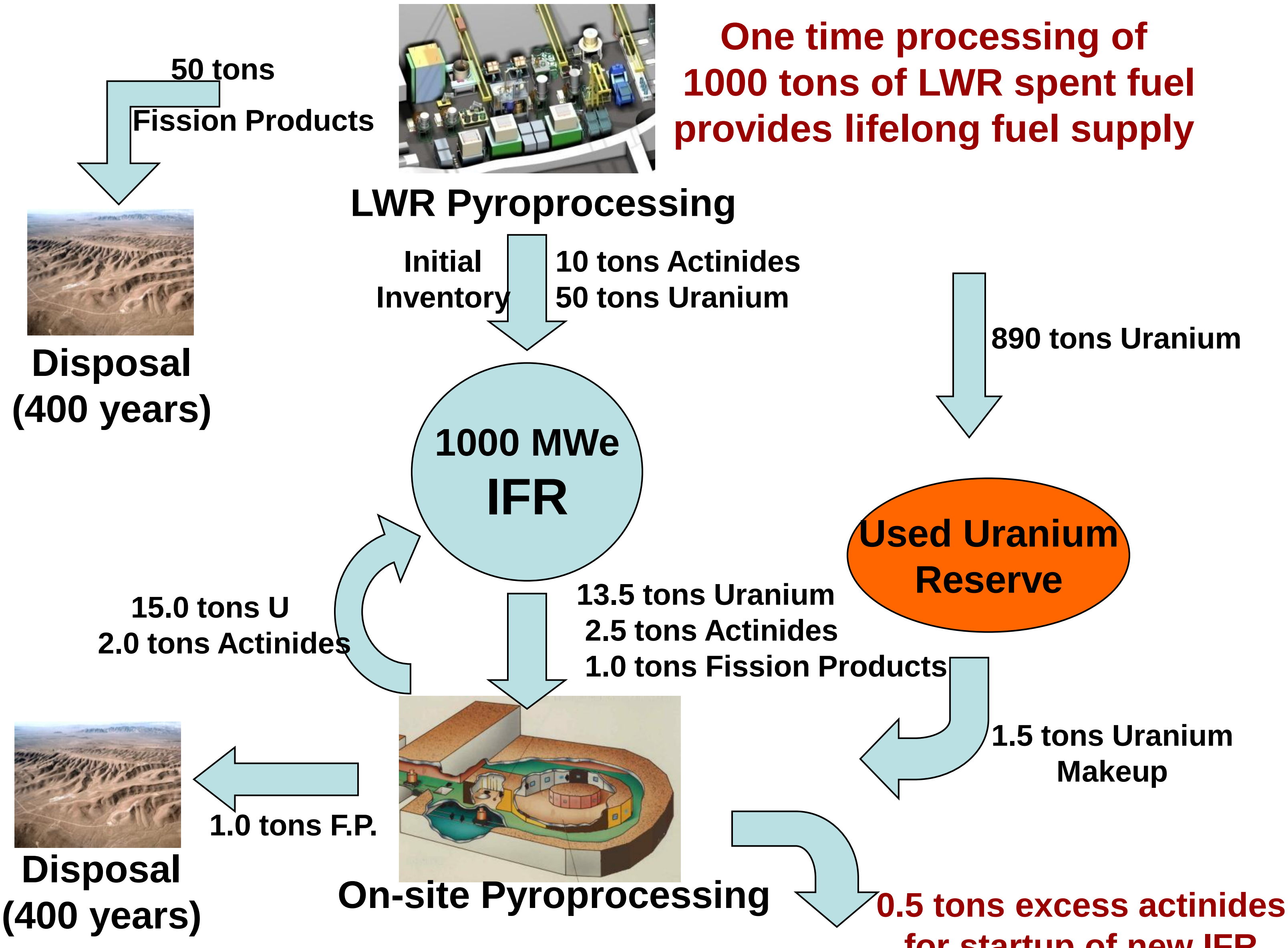


Schematic flow sheet of electro-refining based spent fuel treatment

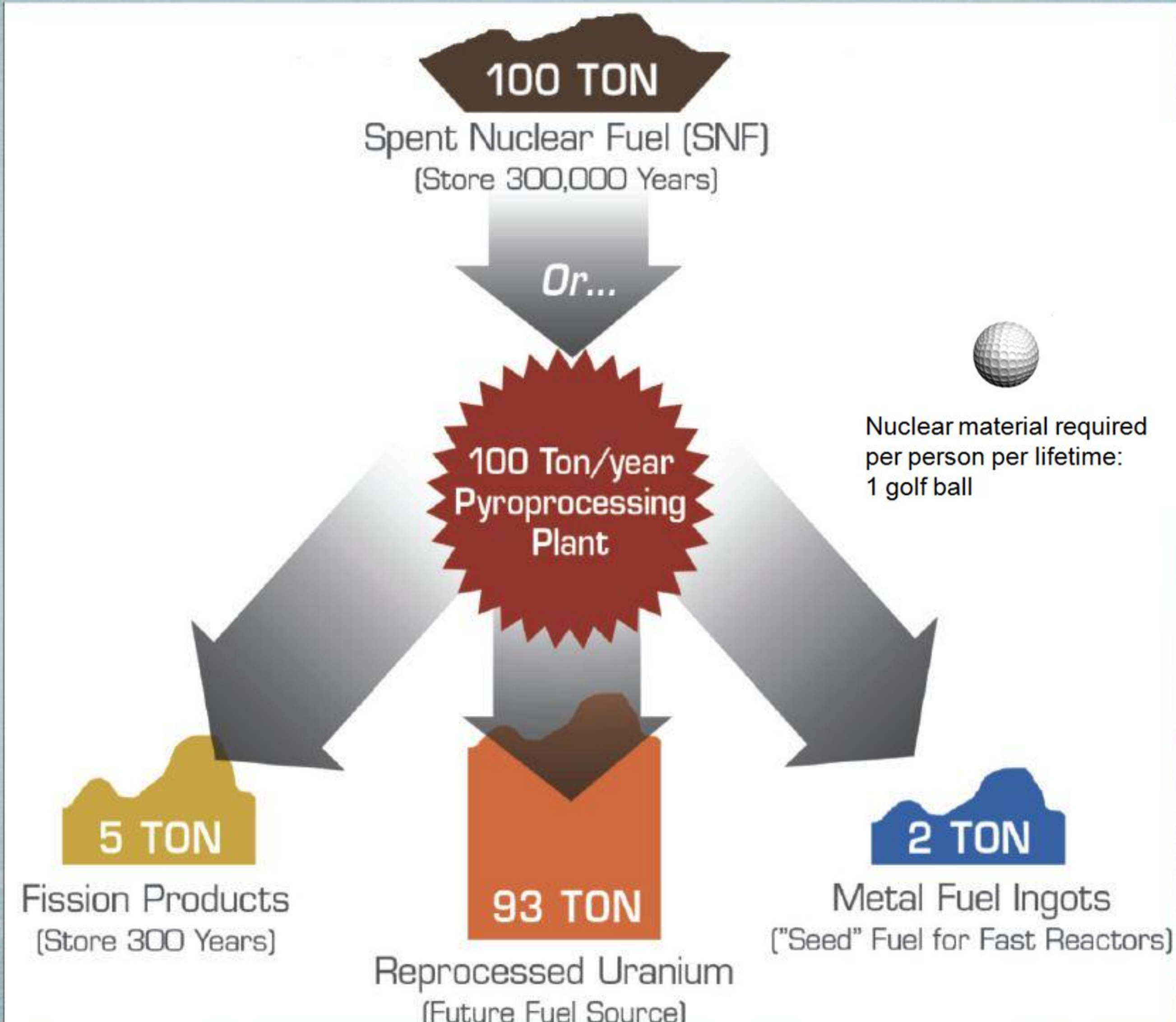
Comparison of IFR with Conventional SFR

	IFR	Conventional SFR	Advantages
Fuel	Metal	Oxide	Superior performance
Safety	Inherent Safety	Engineered Systems	Easy licensibility Low cost
Fabrication	Injection Casting	Powder Pellet	Simple remotization
Repro-cessing	Pyro-processing	Aqueous Reprocessing	Economics Proliferation-resist. Waste management

Annual Mass Flow for IFR



ALL THE SPENT FUEL IN THE WORLD CAN BE RECYCLED INTO IFR FUEL



Nuclear material required per person per lifetime: 1 golf ball

Volume of waste per person generated for their lifetime. These fission products remain radioactive for only 300 years.

Weapons Usability Comparison

	Weapon Grade Pu	Reactor Grade Pu	IFR Grade Actinide
Production	Low burnup PUREX	High burnup PUREX	Fast reactor Pyroprocess
Composition	Pure Pu 94% Pu-239	Pure Pu 65% Pu-fissile	Pu + MA + U 50% Pu-fissile
Thermal power w/kg	2 - 3	5 - 10	80 - 100
Spontaneous neutrons, n/s/g	60	200	300,000
Gamma radiation r/hr at ½ m	0.2	0.2	200

Commercialisation?

The CEFR buildings

CEFR (China)

20 MWe (2010)

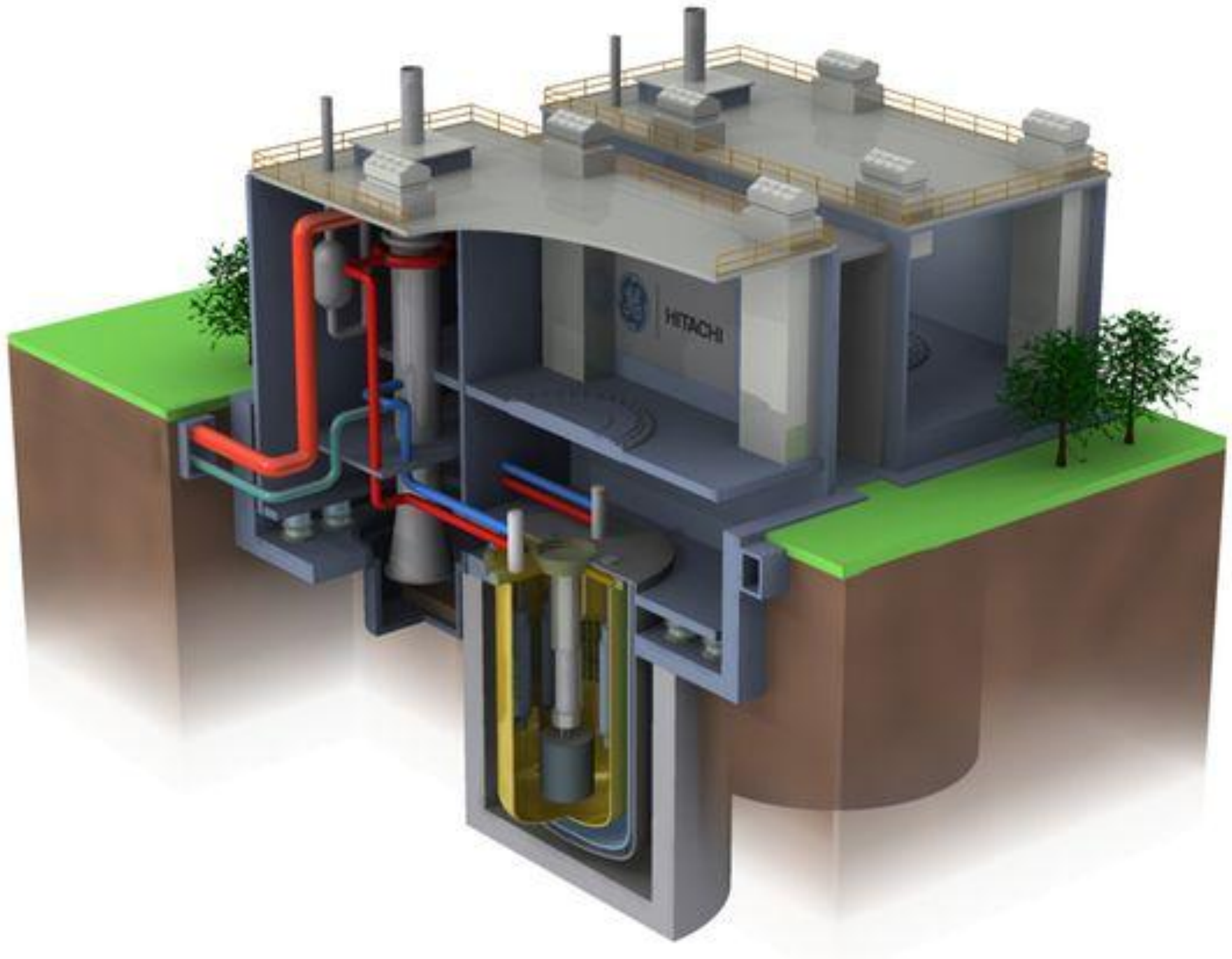
Technicians at work atop the reactor

Inside the control room

PFBR (India)

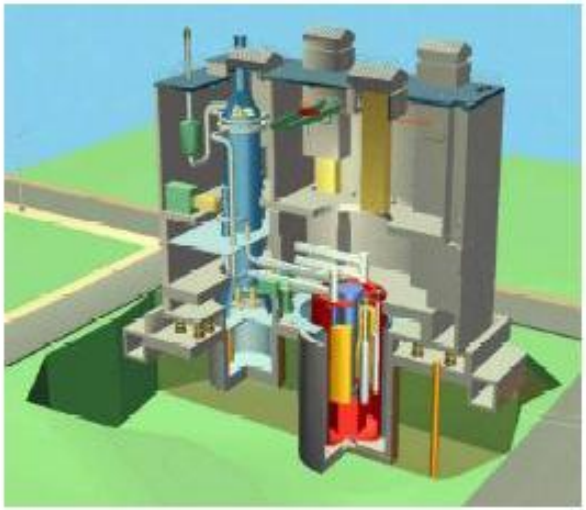
500 MWe (2012)

GEH S-PRISM 311 MWe IFR module



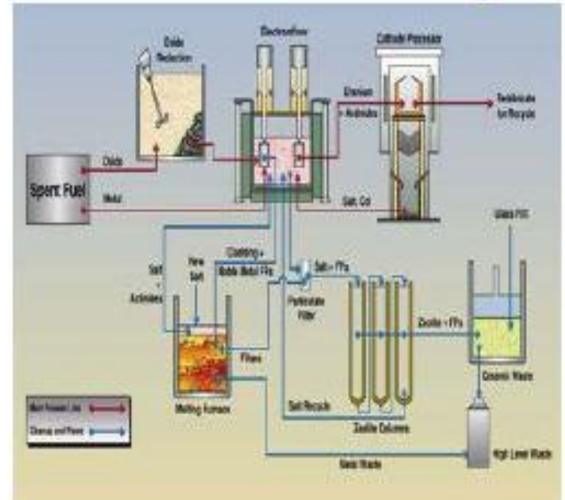
ARC Technology Solution

PRISM



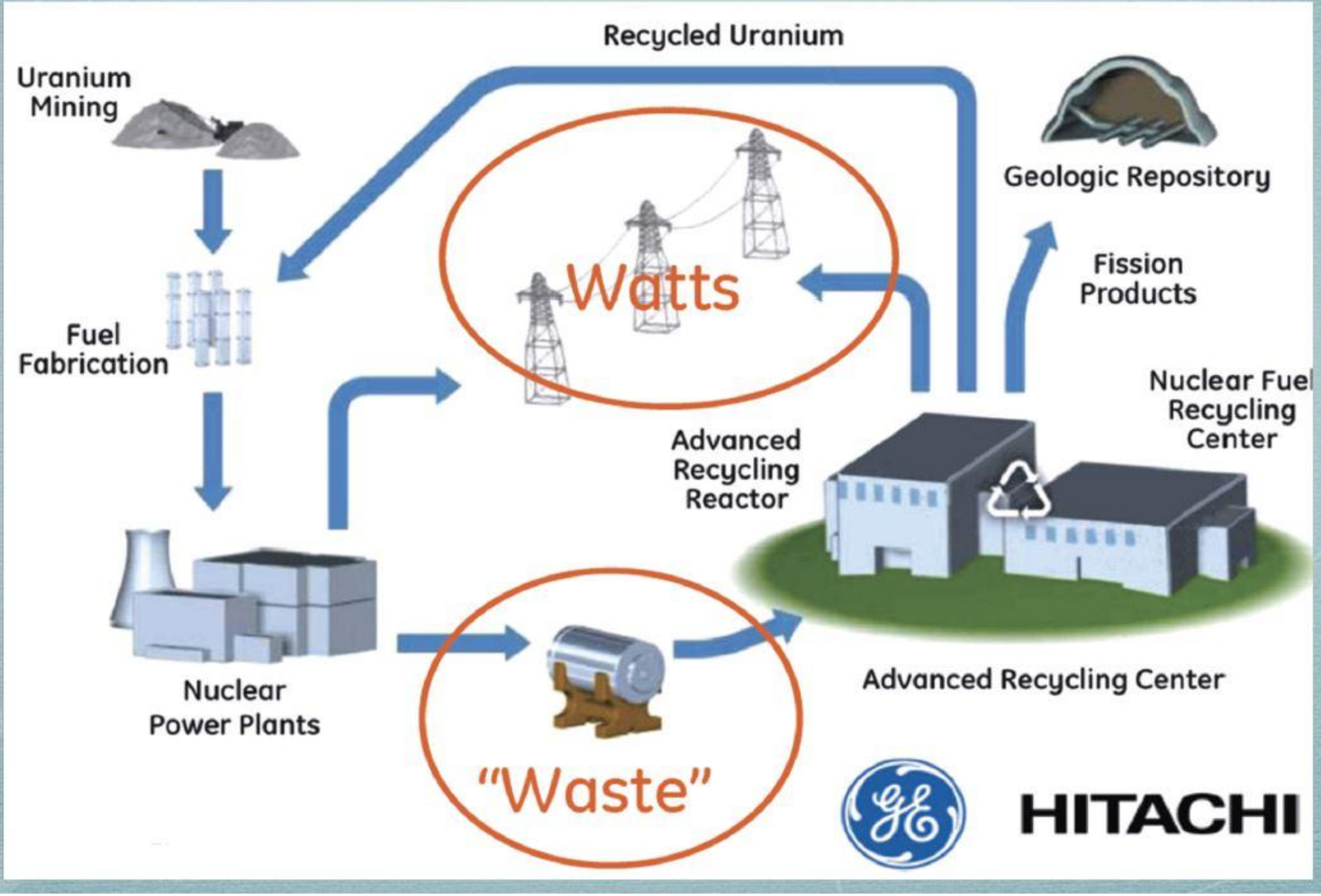
- 840 MWth & 311 MWe
- Na cooled fast reactor
- Passive safety
- Modular/scalable
- Factory built
- Flexible fuel cycle (broad input composition)
- Metal or oxide fuel (metal pref.)
- Extensive component testing

Electro Refining



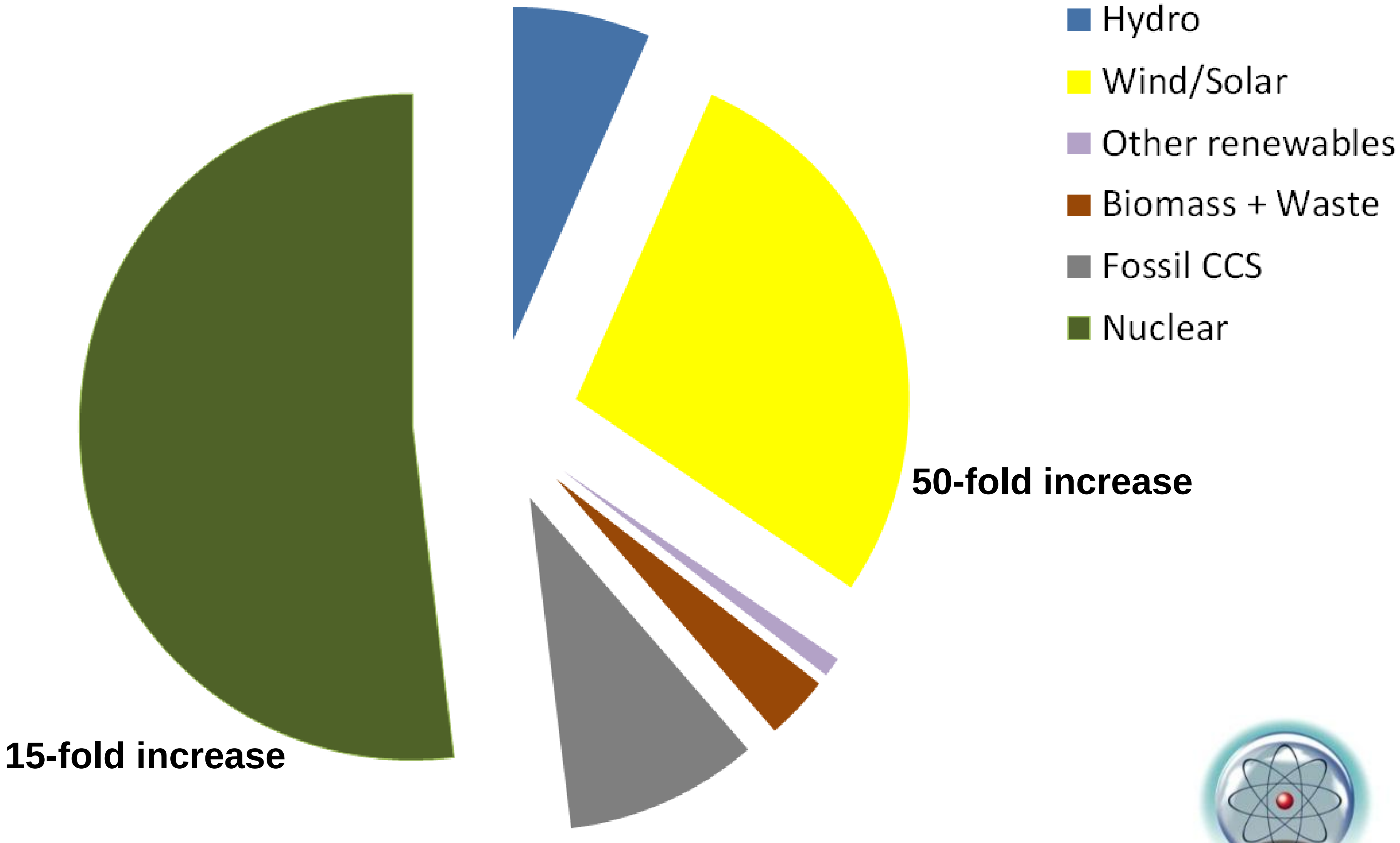
- Modular/scalable
- Sized to support ABR
- Proliferation resistant
- Removal of volatile FP through voloxidation
- Continuous or batch process
- Extensive testing in the U.S., Russia, Japan, and Korea
- Used by industrial refiners

GE-Hitachi is prepared to build the first commercial-scale IFR (labeled "Advanced Recycling Center" in the diagram below) to lead the world into an era of unlimited clean energy. Efforts are underway to build the first PRISM (the reactor portion) and the first pyroprocessing facility. If the political will can be mustered, IFRs could quickly begin to turn the energy tide for the entire planet.



Gen III+ / IV / renewables synergy

Realistic low-carbon 2060 energy mix?



Realistic low-carbon 2060 energy mix?

Supply source	EJ	GW_e av	Nameplate	% Share	% GR/yr
Hydro	18.5	587	1332	6.7	0.8
Wind/Solar	77.3	2449	8164	27.9	8.1
Other renewables	2.6	84	167	1.0	4.7
Biomass + Waste	8.6	273	321	3.1	4.7
Fossil CCS	26.0	824	970	9.4	N/A
Non-nuclear*	133	4217	10955	48	4.5
Nuclear	144	4566	5372	52	5.5
World total supply	277	8783	16327	100	

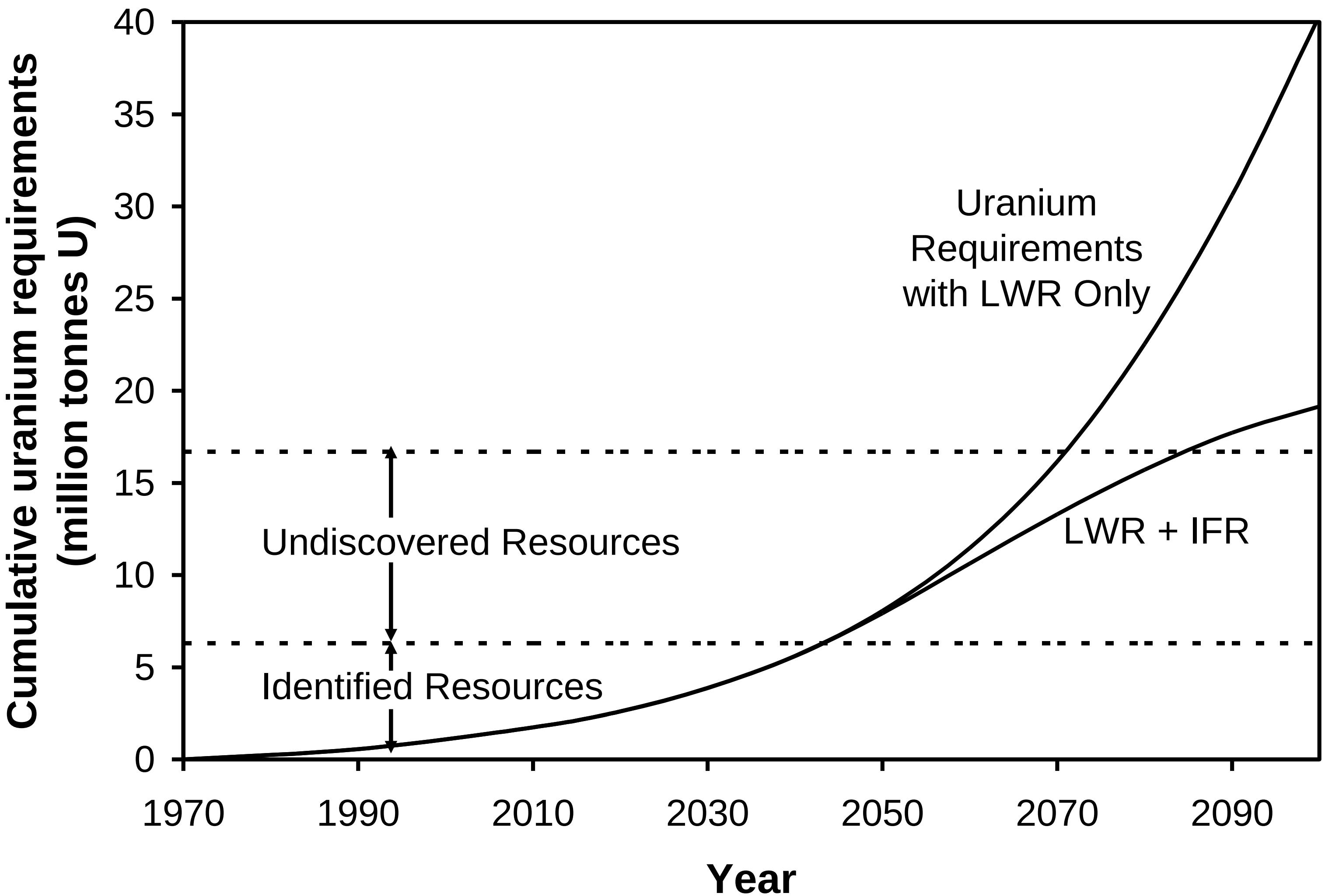
*Excludes fossil fuels without CCS

Can we really get 5+ TWe by 2060?

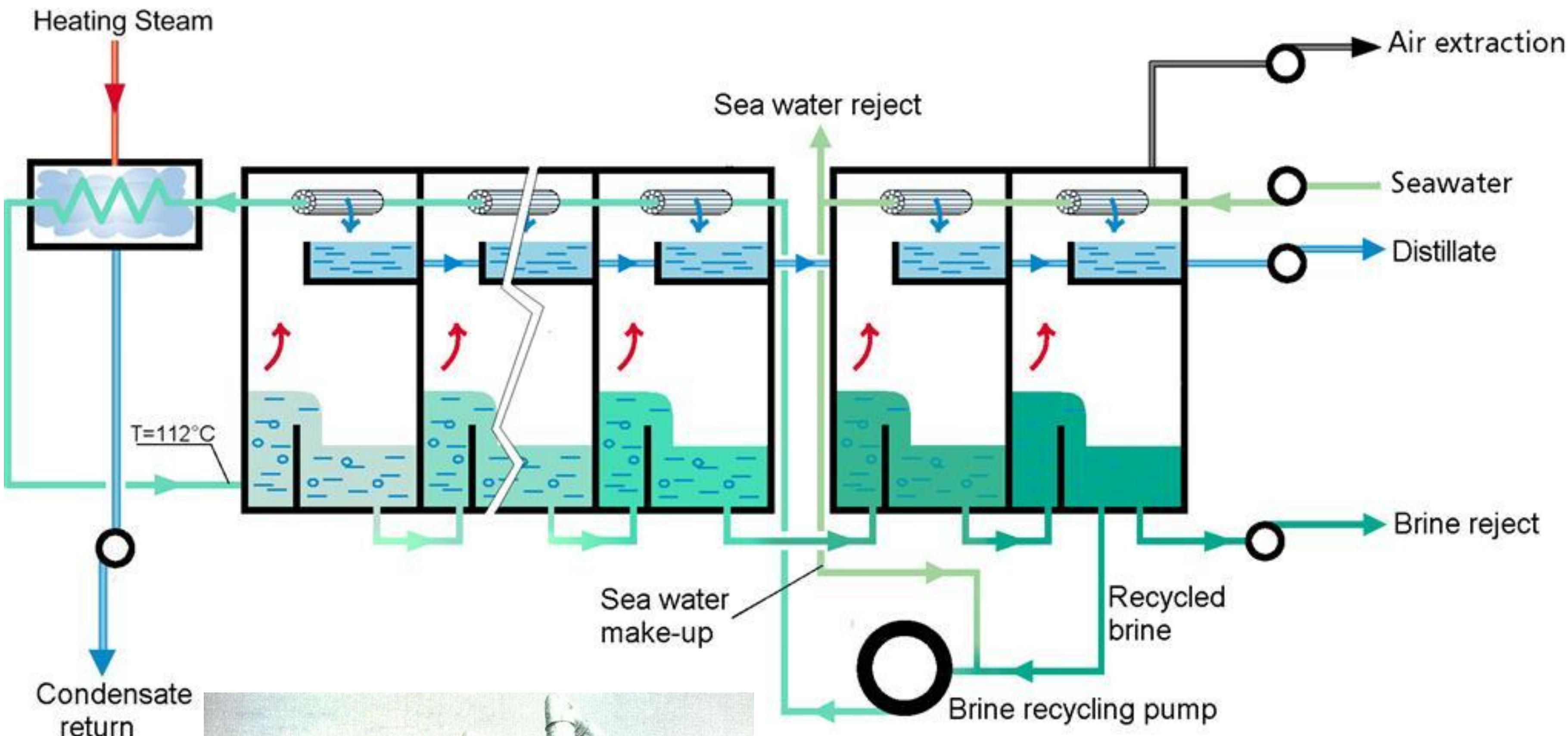
— **Gen III alone = difficult, will run low on fissile fuel**

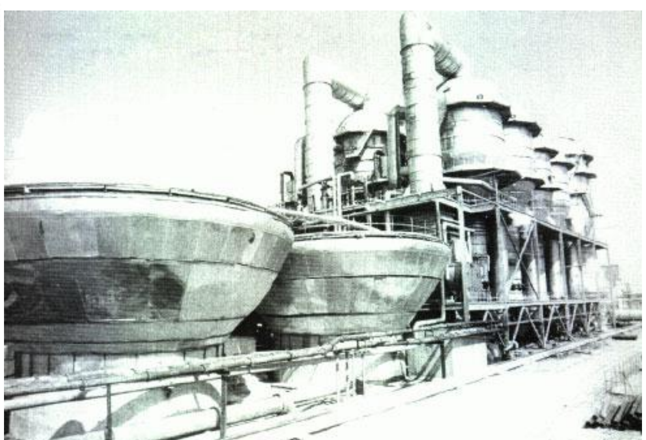
— **Gen IV alone = too slow to ramp up**

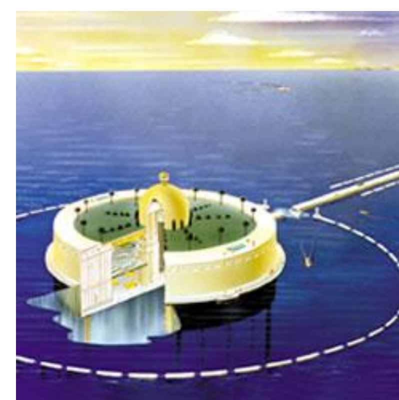
— **Gen III and Gen IV in partnership = perfect synergy**

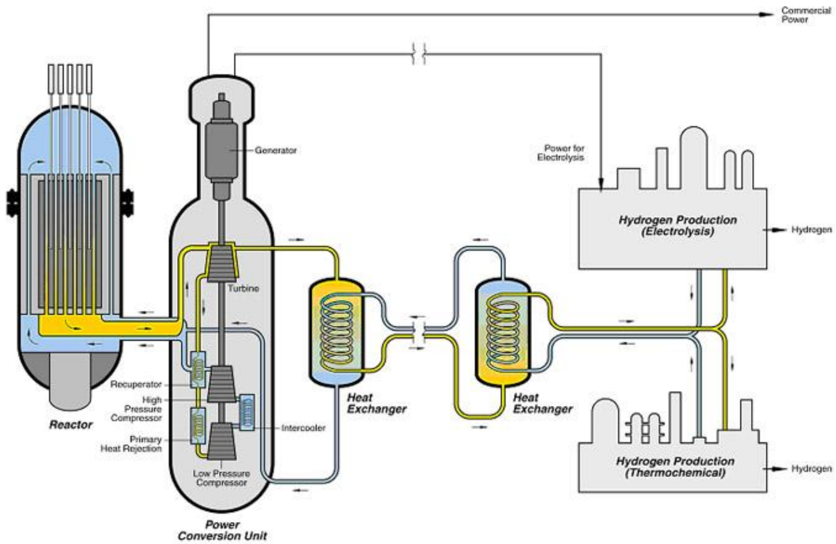


A sustainable energy-rich future

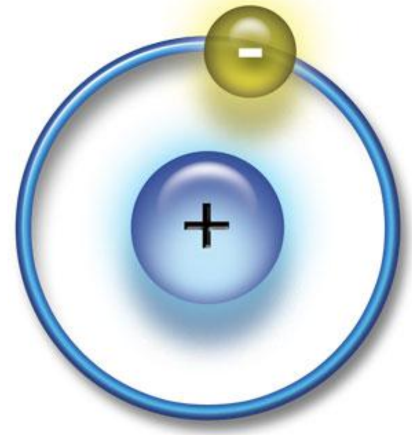

Heating Steam
Sea water reject
Air extraction
Seawater
Distillate
T=112°C
Brine reject
Sea water make-up
Recycled brine
Brine recycling pump
Condensate return







Commercial Power
Generator
Power for Electrolysis
Hydrogen Production (Electrolysis)
Hydrogen
Turbine
Heat Exchanger
Heat Exchanger
Recuperator
High Pressure Compressor
Primary Heat Rejection
Intercooler
Low Pressure Compressor
Reactor
Power Conversion Unit
Hydrogen Production (Thermochemical)
Hydrogen



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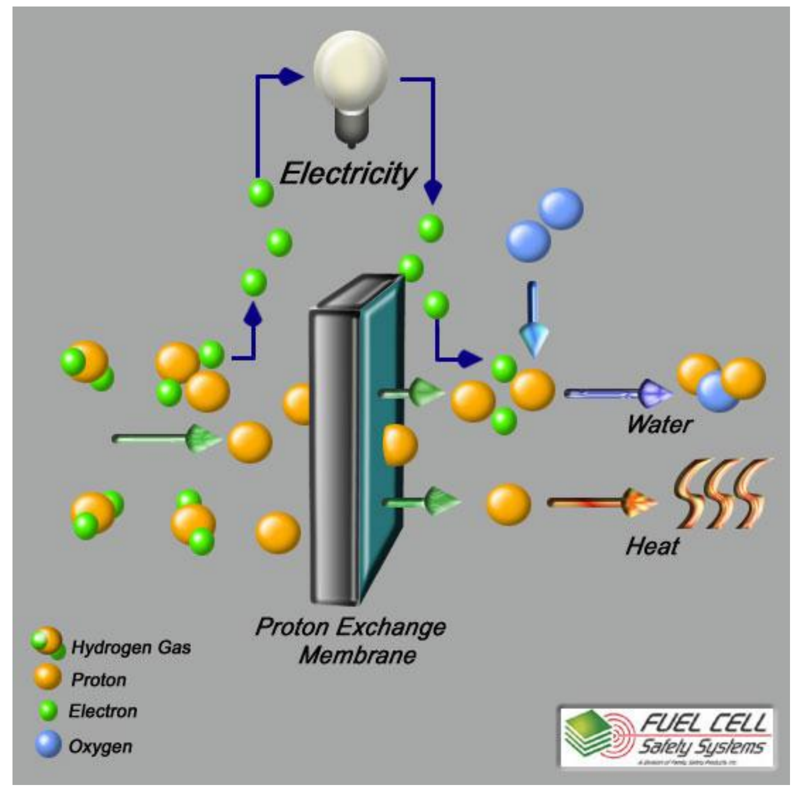
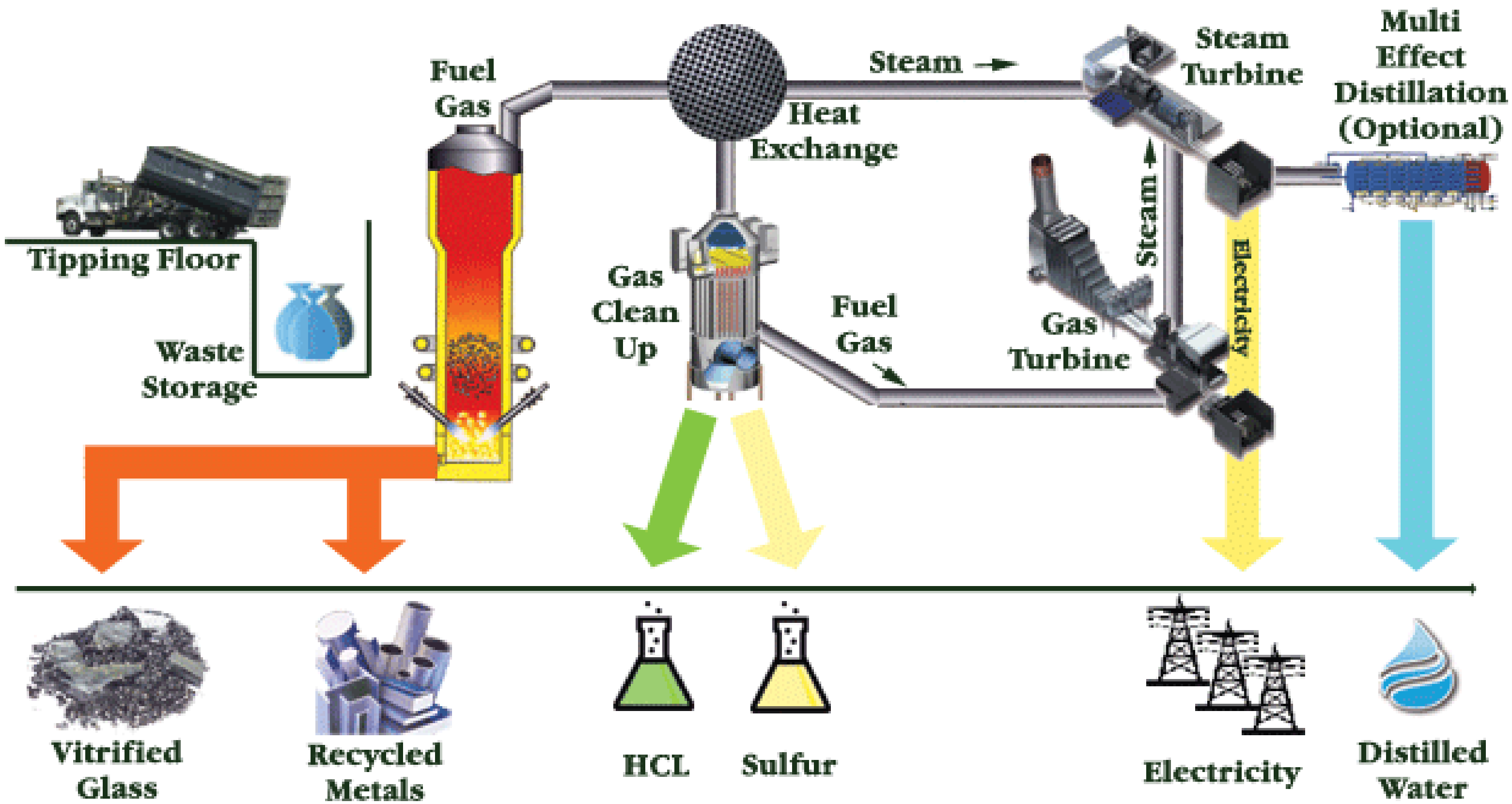


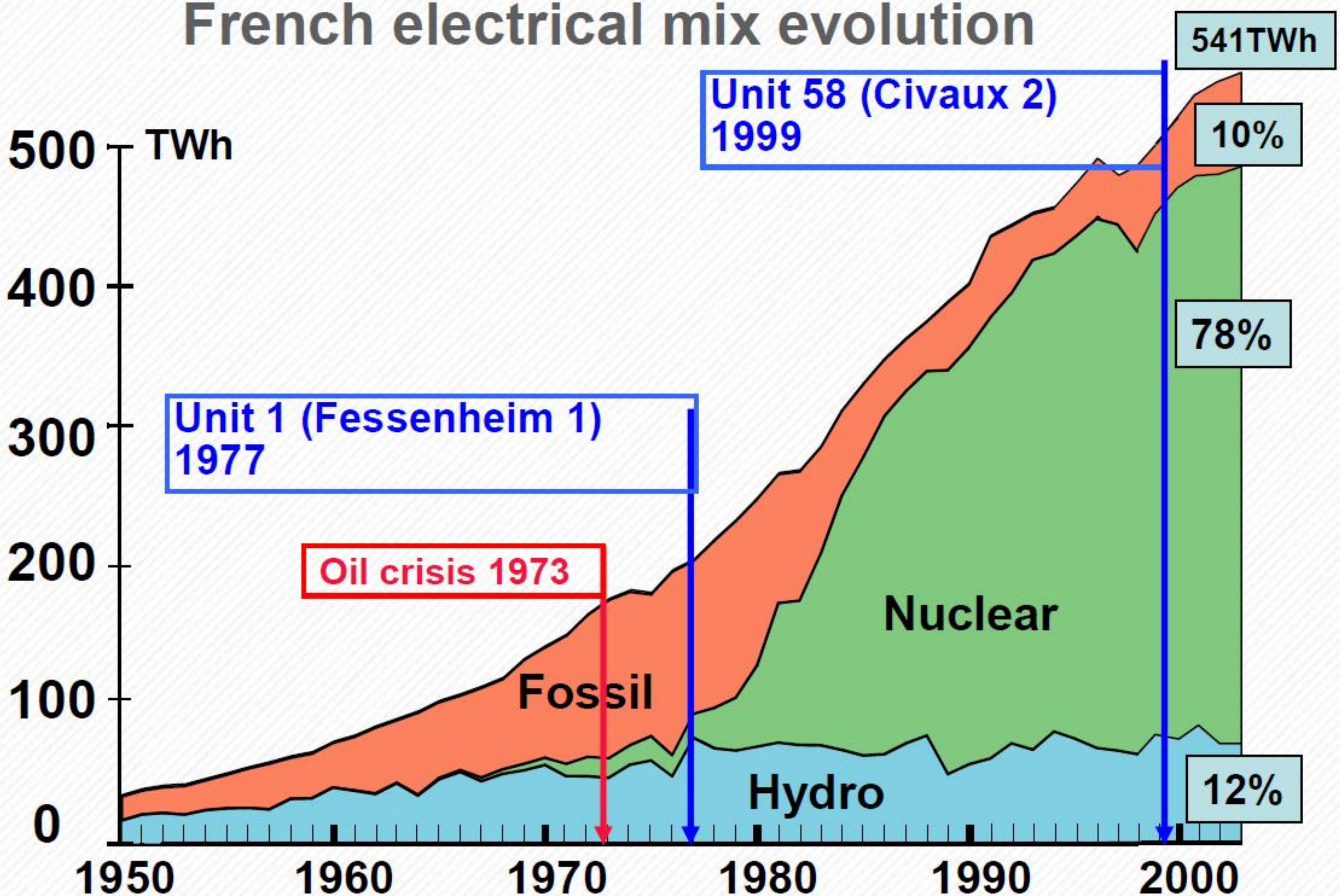
Electricity
Water
Heat
Proton Exchange Membrane
Hydrogen Gas
Proton
Electron
Oxygen
FUEL CELL Safety Systems

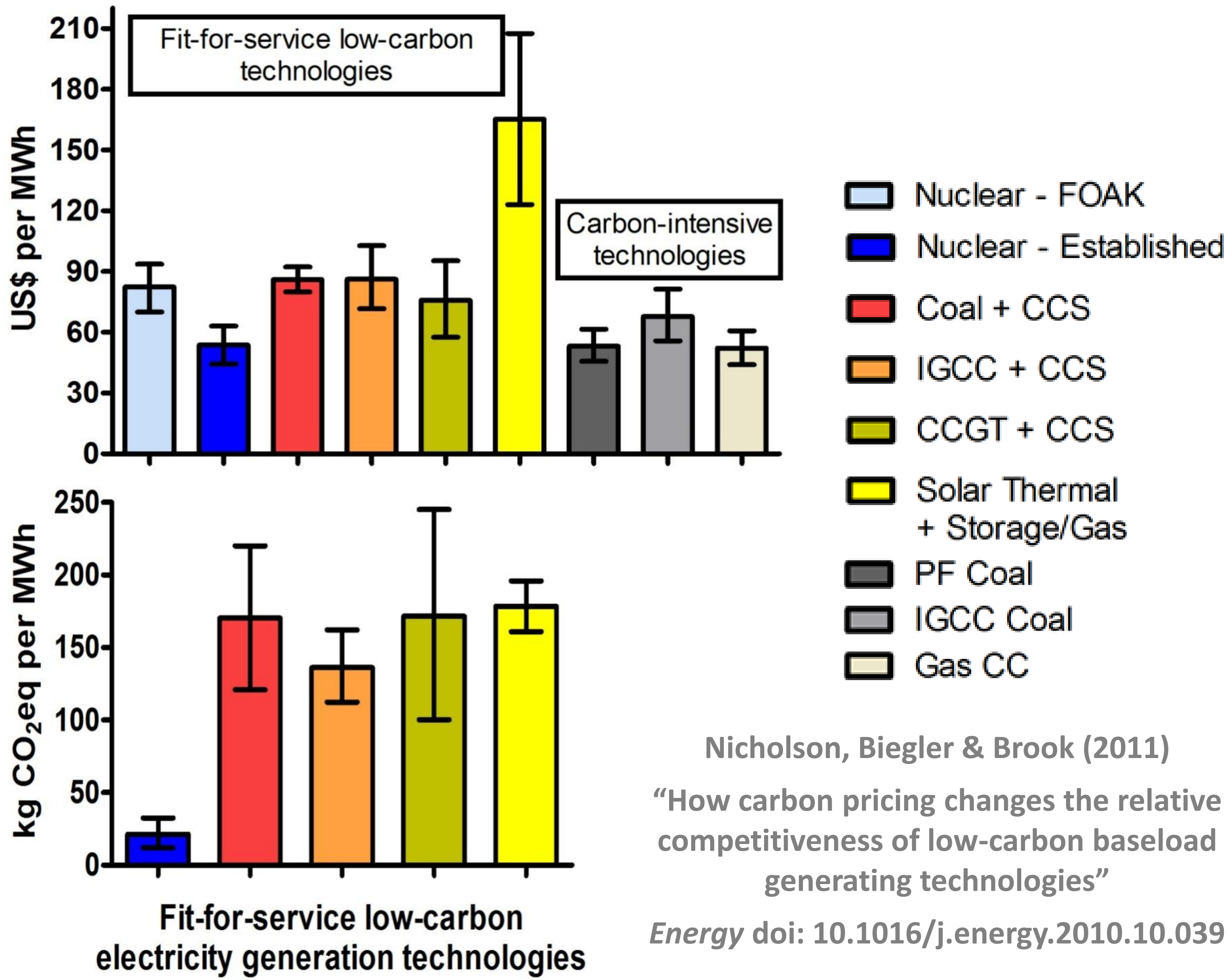


Fuel Gas
Heat Exchange
Steam
Steam Turbine
Multi Effect Distillation (Optional)
Tipping Floor
Waste Storage
Gas Clean Up
Fuel Gas
Steam
Electricity
Gas Turbine
Vitrified Glass
Recycled Metals
HCL
Sulfur
Electricity
Distilled Water

Final word on socio-economic realities

French electrical mix evolution

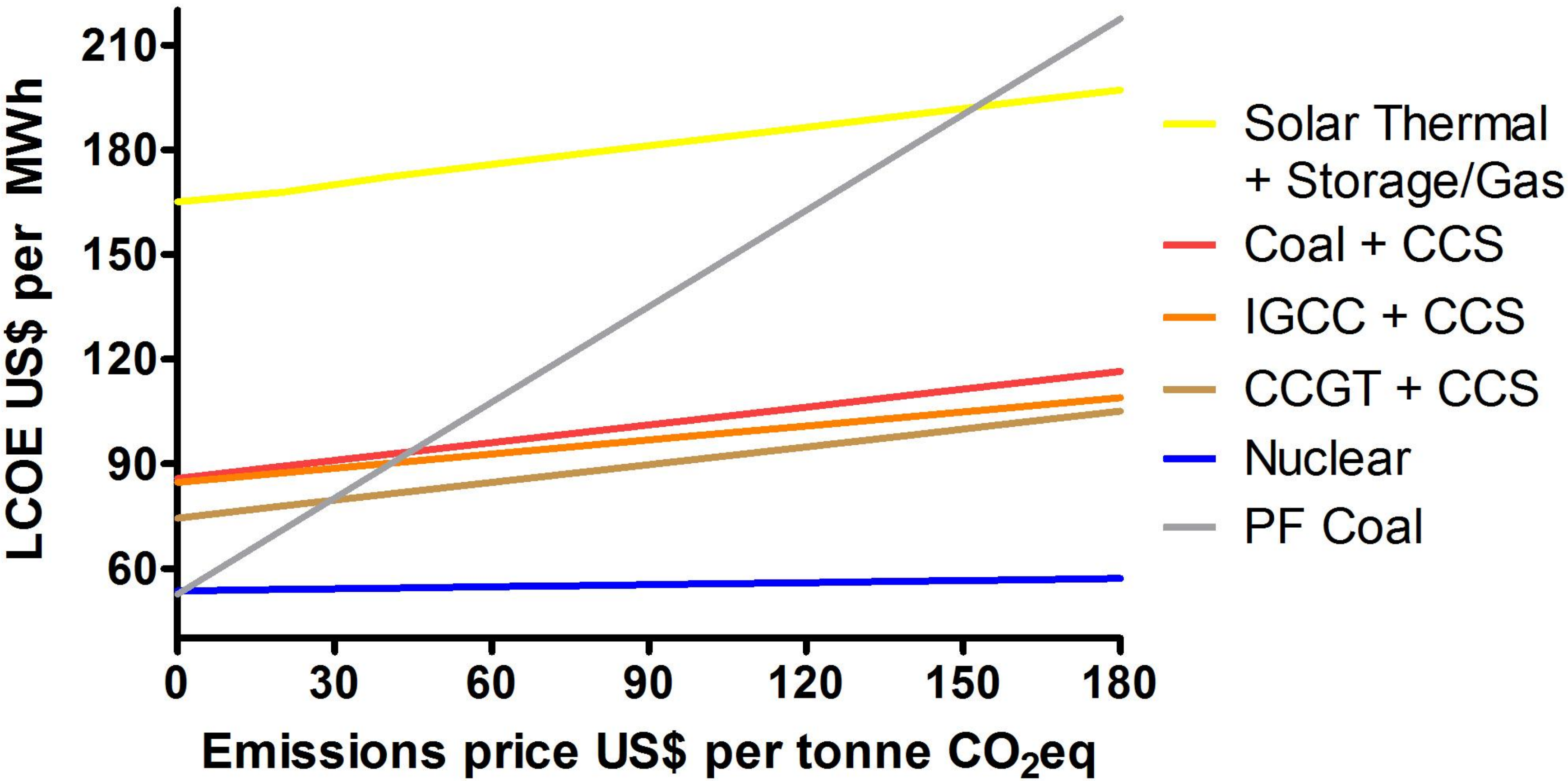




Nicholson, Biegler & Brook (2011)

"How carbon pricing changes the relative competitiveness of low-carbon baseload generating technologies"

Energy doi: 10.1016/j.energy.2010.10.039



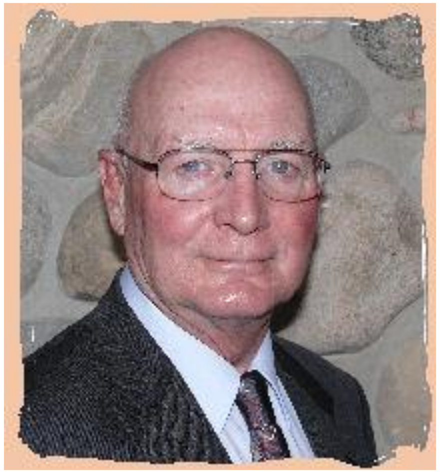
LCOE US$ per MWh
210
180
150
120
90
60
0
30
60
90
120
150
180
Emissions price US$ per tonne CO_2eq
Solar Thermal + Storage/Gas
Coal + CCS
IGCC + CCS
CCGT + CCS
Nuclear
PF Coal

Acknowledgements and More information

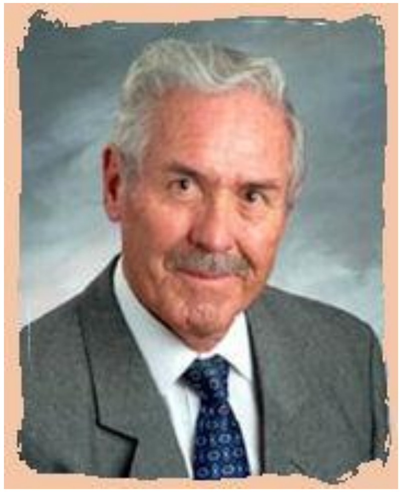
http://thesciencecouncil.com (Science Council for Global Initiatives)

Chuck Till

Yoon Chang



John Sackett



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More information, discussion, references for slides and presentation downloads:

bravenewclimate.com