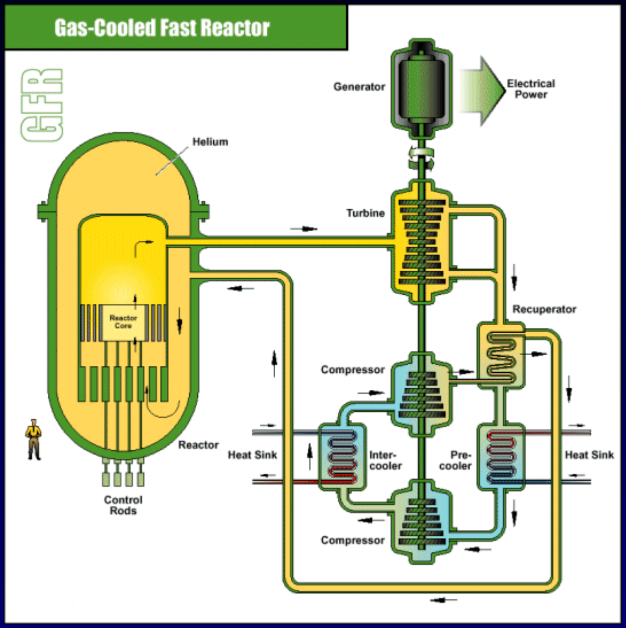

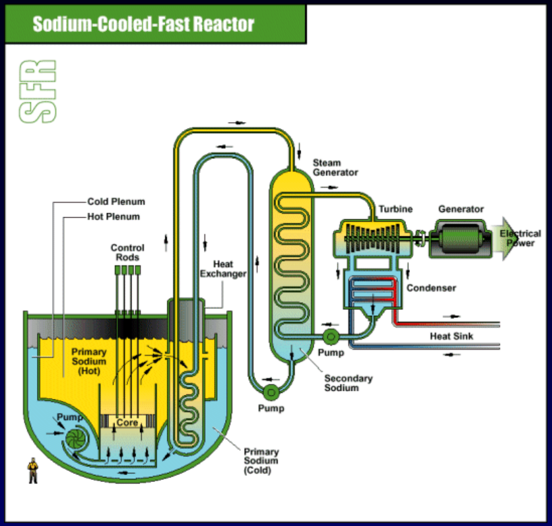

Module 12
Generation IV Nuclear Power Plants

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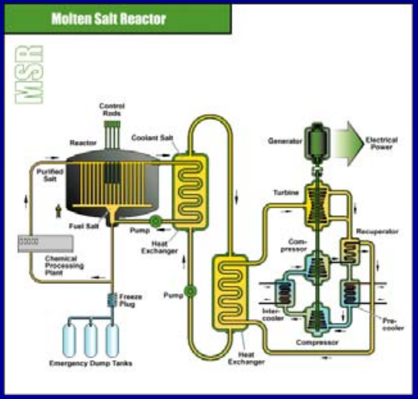
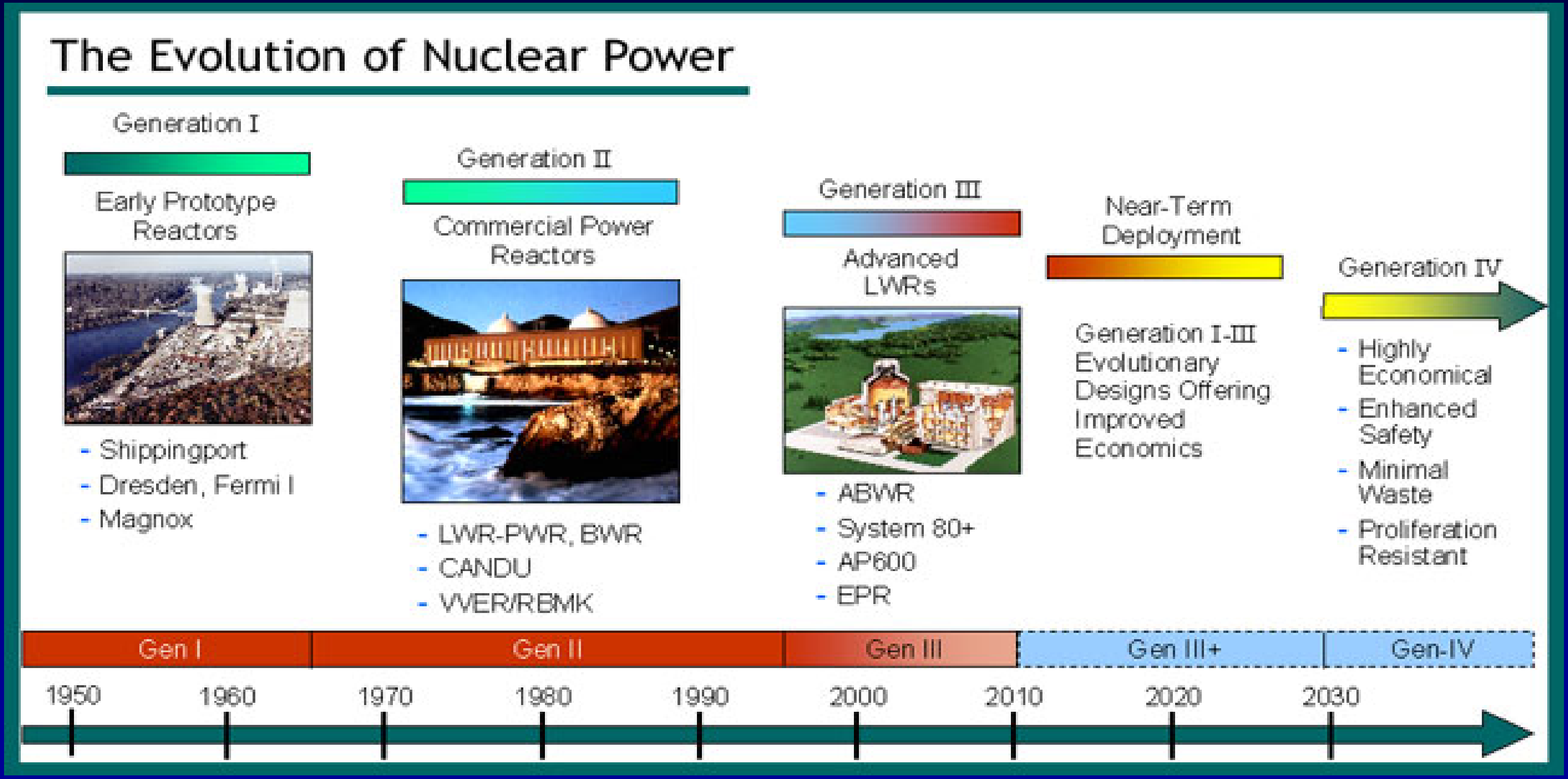


Generation IV Participants

Evolution of Nuclear Power Plants



Gen IV: Criteria and Goals

Roll Up of Metrics, Criteria, Goals and Goal Areas

4 Goal Areas	8 Goals	15 Criteria	24 Metrics
Sustainability	SU1 Resource Utilization	SU1-1 Fuel Utilization	• Use of fuel resources
	SU2 Waste Minimization and Management	SU2-1 Waste minimization	• Waste mass • Volume • Heat load • Radiotoxicity
		SU2-2 Environmental impact of waste management and disposal	• Environmental impact
Economics	EC1 Life Cycle Cost	EC1-1 Overnight construction costs	• Overnight construction costs
		EC1-2 Production costs	• Production costs
		EC2-1 Construction duration	• Construction duration
	EC2 Risk to Capital	EC1-1 Overnight construction costs	• Overnight construction costs
		EC2-1 Construction duration	• Construction duration
Safety and Reliability	SR1 Operational Safety and Reliability	SR1-1 Reliability	• Forced outage rate
		SR1-2 Worker/public - routine exposure	• Routine exposures
		SR1-3 Worker/public - accident exposure	• Accident exposures
	SR2 Core Damage	SR2-1 Robust safety features	• Reliable reactivity control • Reliable decay heat removal
		SR2-2 Well-characterized models	• Dominant phenomena - uncertainty • Long fuel thermal response time • Integral experiments scalability
	SR3 Offsite Emergency Response	SR3-1 Well-characterized source term/energy	• Source term • Mechanisms for energy release
		SR3-2 Robust mitigation features	• Long system time constants • Long and effective holdup
Proliferation Resistance and Physical Protection	PR1 Proliferation Resistance and Physical Protection	PR1-1 Susceptibility to diversion or undeclared production	• Separated materials • Spent fuel characteristics
		PR1-2 Vulnerability of installations	• Passive safety features

Goals of Generation IV

- Sustainability:
  - Generation IV nuclear energy-systems will provide sustainable energy generation that meets clean air objectives and promotes long-term availability of systems and effective fuel utilization for worldwide energy production.
  - Generation IV nuclear energy-systems will minimize and manage their nuclear waste and notably reduce the long-term stewardship burden, thereby improving protection for the public health and the environment.
- Economics:
  - Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy sources.
  - Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.

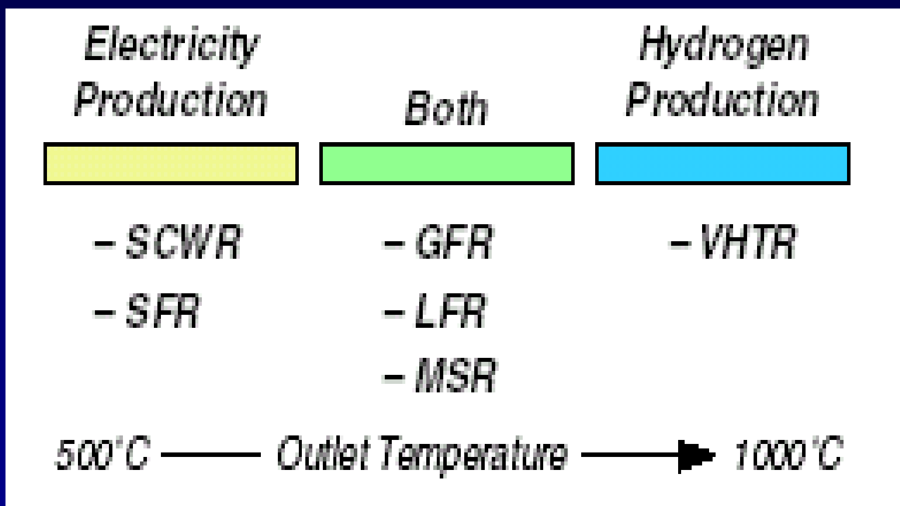
Goals of Generation IV

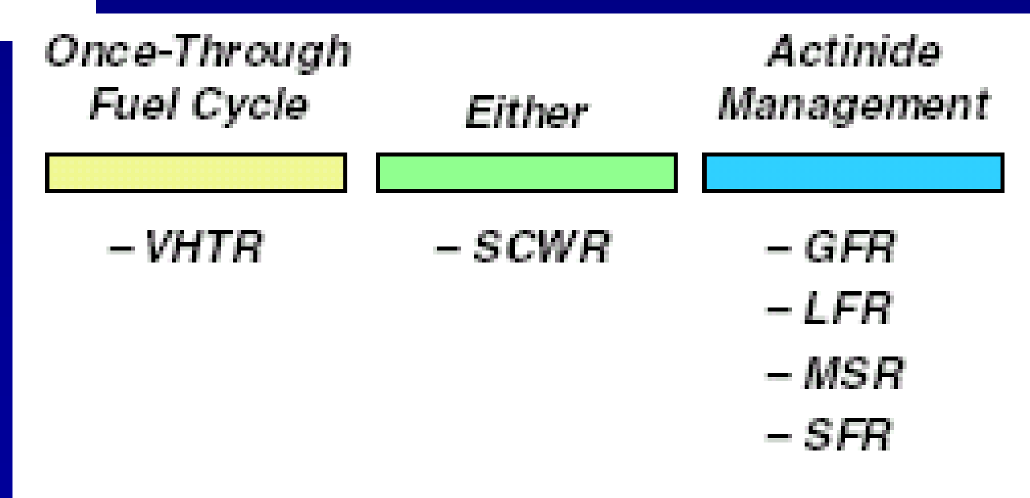
- Safety and Reliability:

  Generation IV nuclear energy systems operations will excel in safety and reliability, they will have a very low likelihood and degree of reactor core damage and

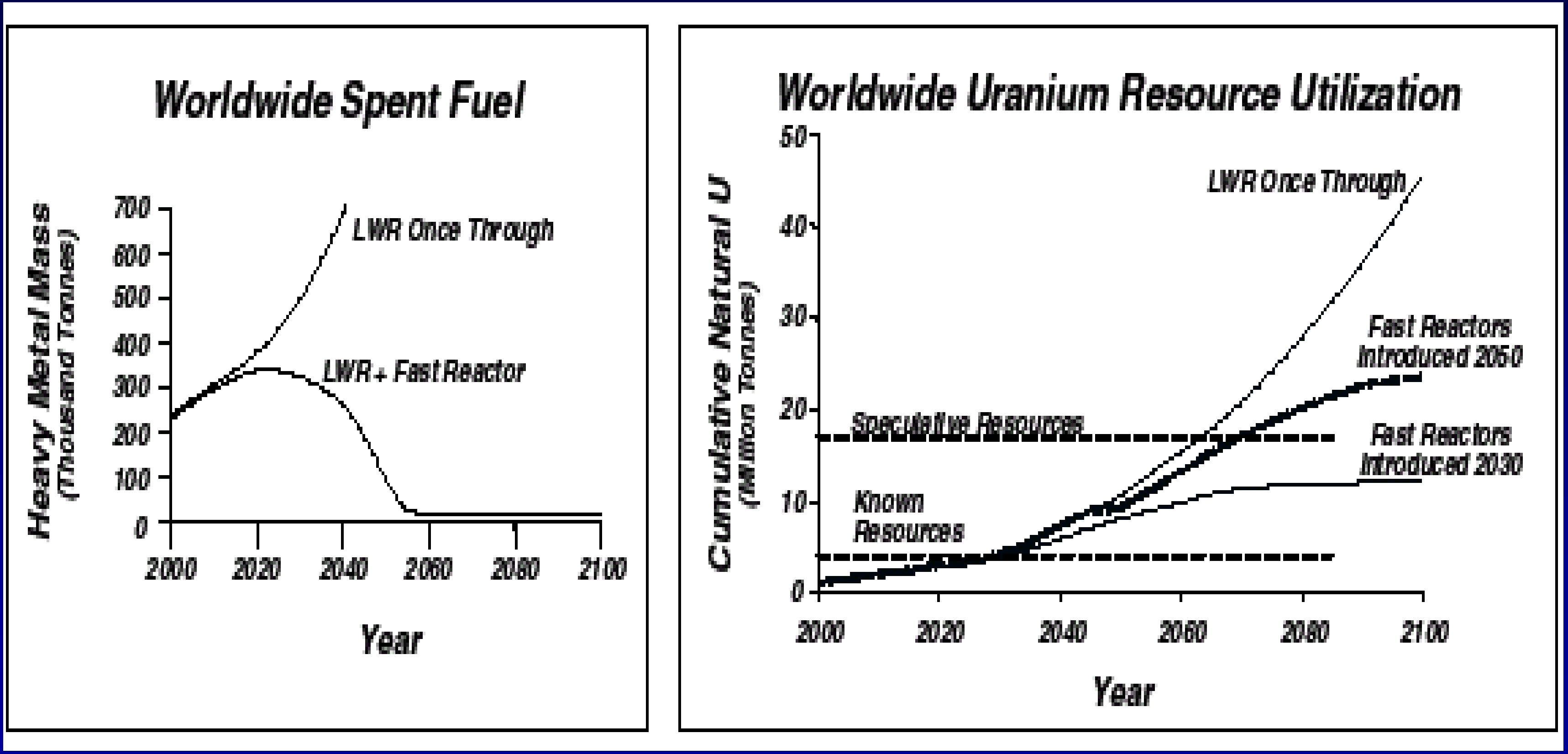
  Generation IV nuclear energy systems will eliminate the need for offsite emergency response.
- Proliferation Resistance and Physical Protection:
  Generation IV nuclear energy systems will increase the assurance that they are very unattractive and the least desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

Application of Gen IV Reactors





Spent Fuel and Uranium Resources



Generation IV Deloyment Schedule

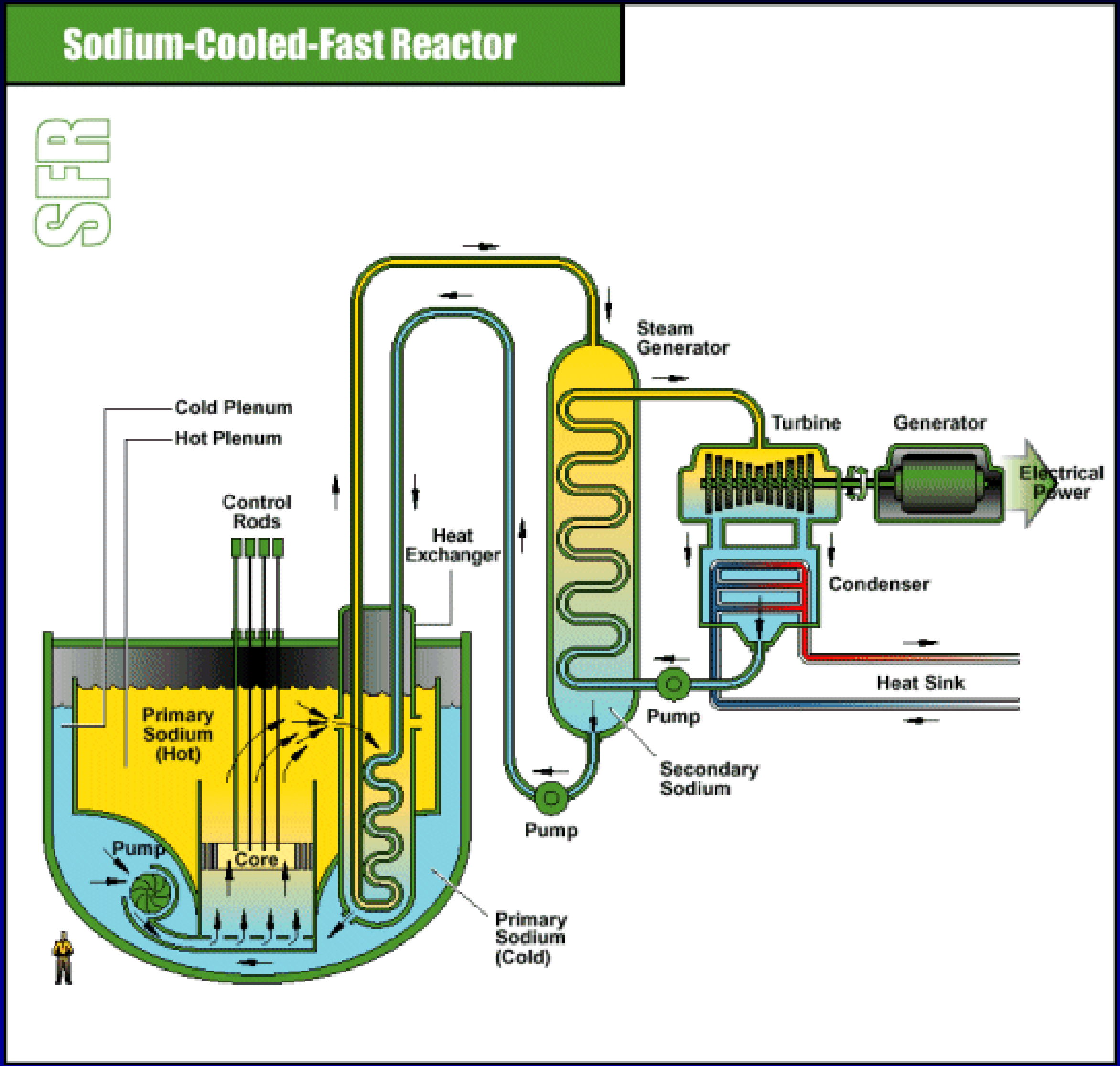
Generation IV System	Estimated deployment date
Sodium Cooled Fast Breeder (SFR)	2015
Very High Temperature Reactor (VHTR)	2020
Gas cooled Fast Reactor (GCR)	2025
Molten Salt Reactor (MSR)	2025
Super Critical Water Reactor (SCWR)	2025
Lead Cooled Fast Reactor (LFR)	2025

Generation IV General Design

(ATW 12/06)

	Neutron spectrum	Coolant	Temp. (^{0}C)	Fuel	Fuel cycle	Size(s) (MWe)
Sodium-cooled Fast Reactors (SFR)	fast	sodium	550	U-238 & MOX	closed	150 1,500
Very High Temperature Gas Reactors (VHTR)	thermal	helium	1,000	UO_2 prism or pebbles	open	275
Gas-cooled Fast Reactors (GFR)	fast	helium	850	U-238	closed	275
Supercritical Water-cooled Reactors (SCWR)	thermal or fast	water	500	UO_2 or MOX	open (thermal) or closed (fast)	10-100 600
Lead-cooled Fast Reactors (LFR)	fast	Pb or Pb-Bi	480-800	U-238	closed	10-100 600
Molten Salt Reactors (MSR)	epithermal	fluoride salts	700-800	UF in salt	closed	1,000

Sodium Cooled Fast Reactor



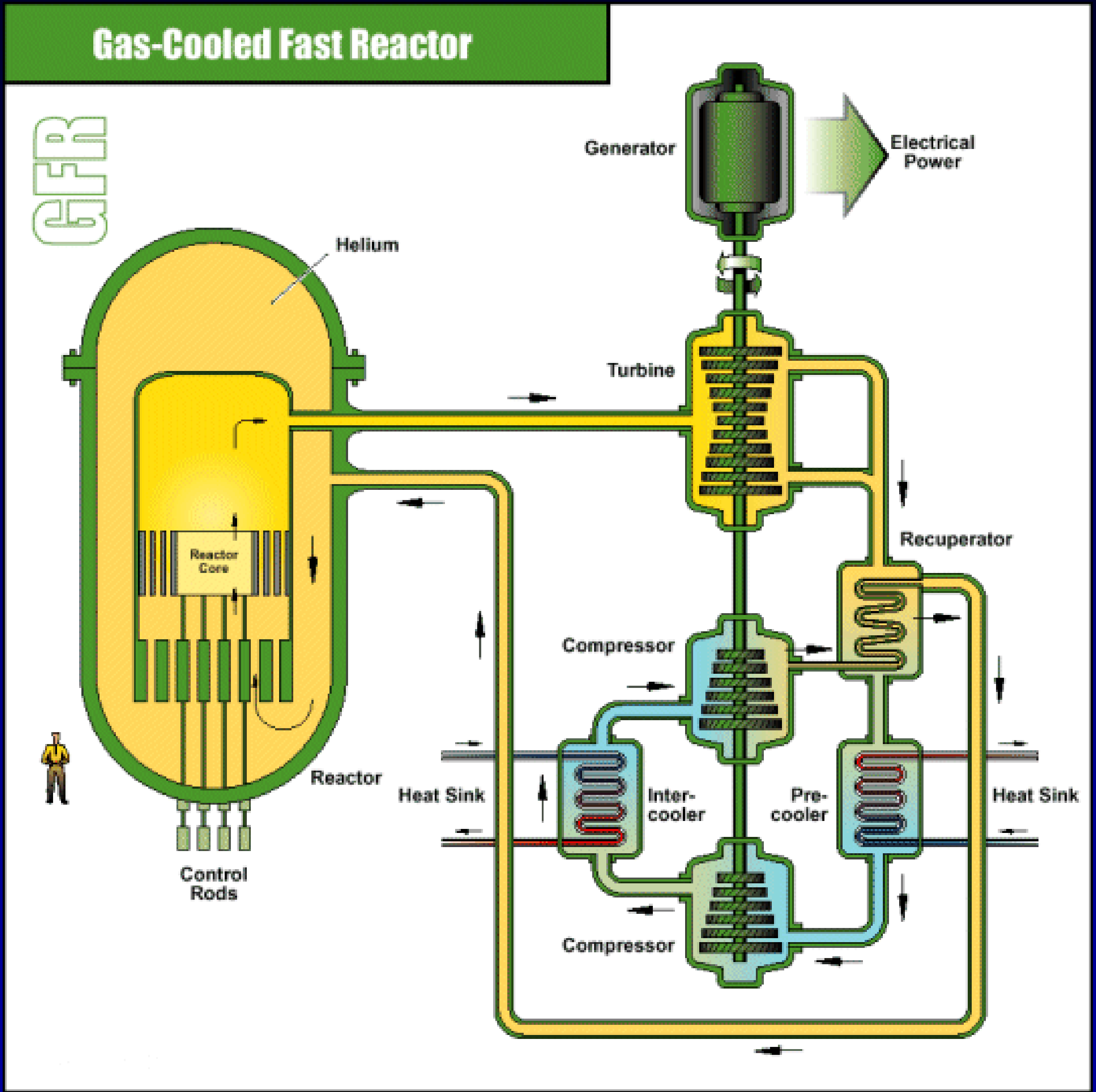
Sodium Cooled Fast Reactor

Reactor Parameters	Reference Value
Outlet Temperature	530-550 °C
Pressure	~1 Atmospheres
Rating	1000-5000 MWth
Fuel	Oxide or metal alloy
Cladding	Ferritic or ODS ferritic
Average Burnup	~150-200 GWD/MTHM
Conversion Ratio	0.5-1.30
Average Power Density	350 MWth/m^3

Sodium Cooled Fast Reactor System

- The Sodium-Cooled Fast Reactor (SFR) system features a fast-spectrum reactor and closed fuel recycle system.
- Power may range from a few hundred MWe to large monolithic reactors of 1500–1700 MWe.
- Sodium core outlet temperatures are typically 530–550ºC.
- Either pool layout or compact loop layout is possible.
- Large margin to coolant boiling is achieved by design, and is an important safety feature of these systems. Another major safety feature is that the primary system operates at essentially atmospheric pressure, pressurized only to the extent needed to move fluid.
- Sodium reacts chemically with air, and with water, and thus the design must limit the potential for such reactions and their consequences. To improve safety, a secondary sodium system acts as a buffer between the radioactive sodium in the primary system and the steam or water. If a sodium-water reaction occurs, it does not involve a radioactive release.

Gas Cooled Fast Reactor



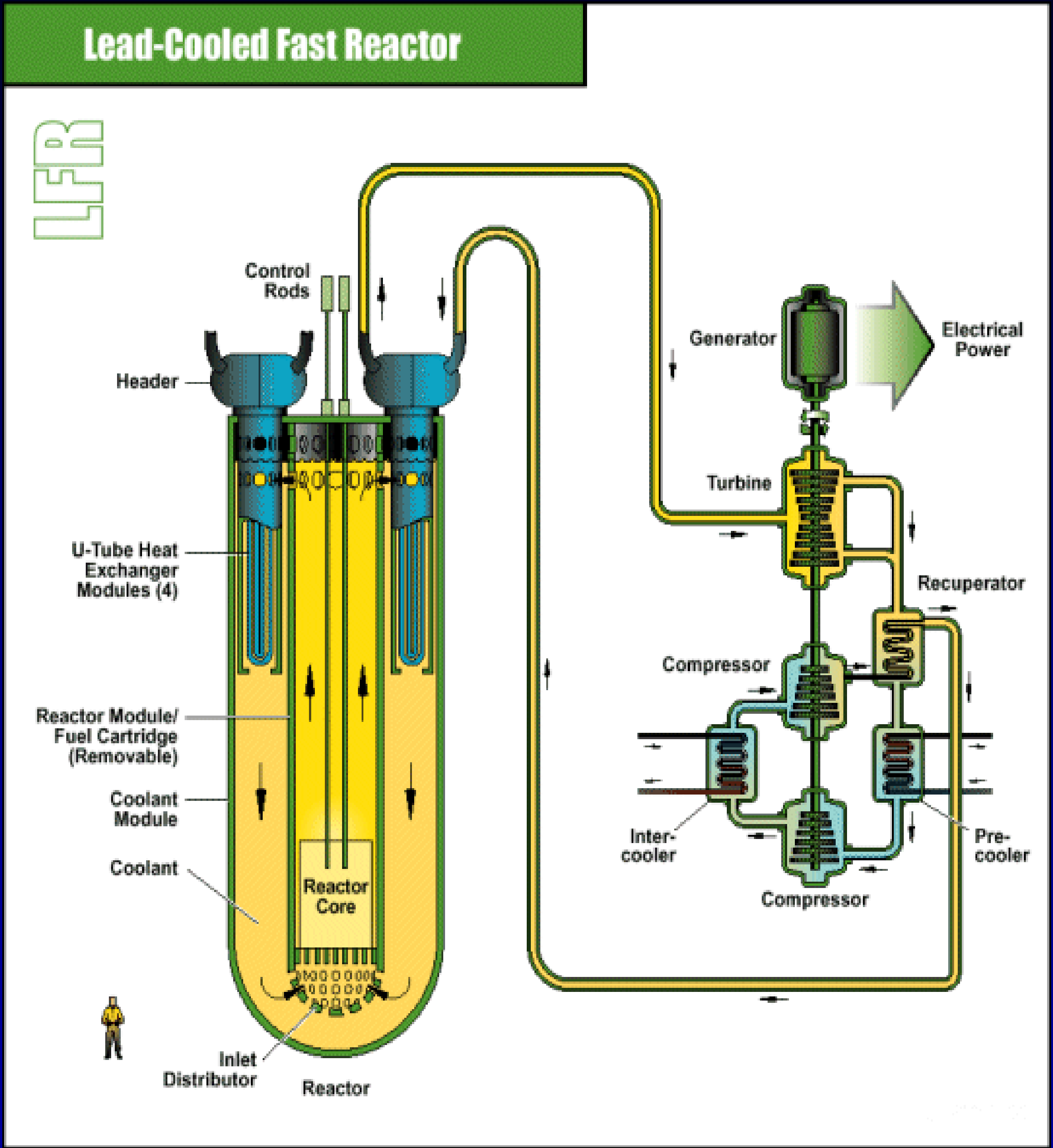
Gas Cooled Fast Reactor

Reactor Parameters	Reference Value
Reactor power	600 MWth
Net plant efficiency (direct cycle helium)	48%
Coolant inlet/outlet temperature and pressure	490xC/850xC at 90 bar
Average power density	100 MWth/m3
Reference fuel compound	UPuC/SiC (70/30%) with about 20% Pu content
Volume fraction, Fuel/Gas/SiC	50/40/10%
Conversion ratio	Self-sufficient
Burnup, Damage	5% FIMA; 60 dpa

Gas-Cooled Fast Reactor System

- The GFR system features a fast-spectrum helium-cooled reactor and closed fuel cycle.
- The high outlet temperature of the helium coolant makes it possible to deliver electricity, hydrogen, or process heat with high conversion efficiency.
- The GFR uses a direct-cycle helium turbine for electricity and can use process heat for thermo-chemical production of hydrogen.
- The GFR's fast spectrum also makes it possible to utilize available fissile and fertile materials (including depleted uranium from enrichment plants) two orders of magnitude more efficiently than thermal spectrum gas reactors with once-through fuel cycles.
- The GFR reference assumes an integrated, on-site spent fuel treatment and re-fabrication plant.

Lead-Cooled Fast Reactor System



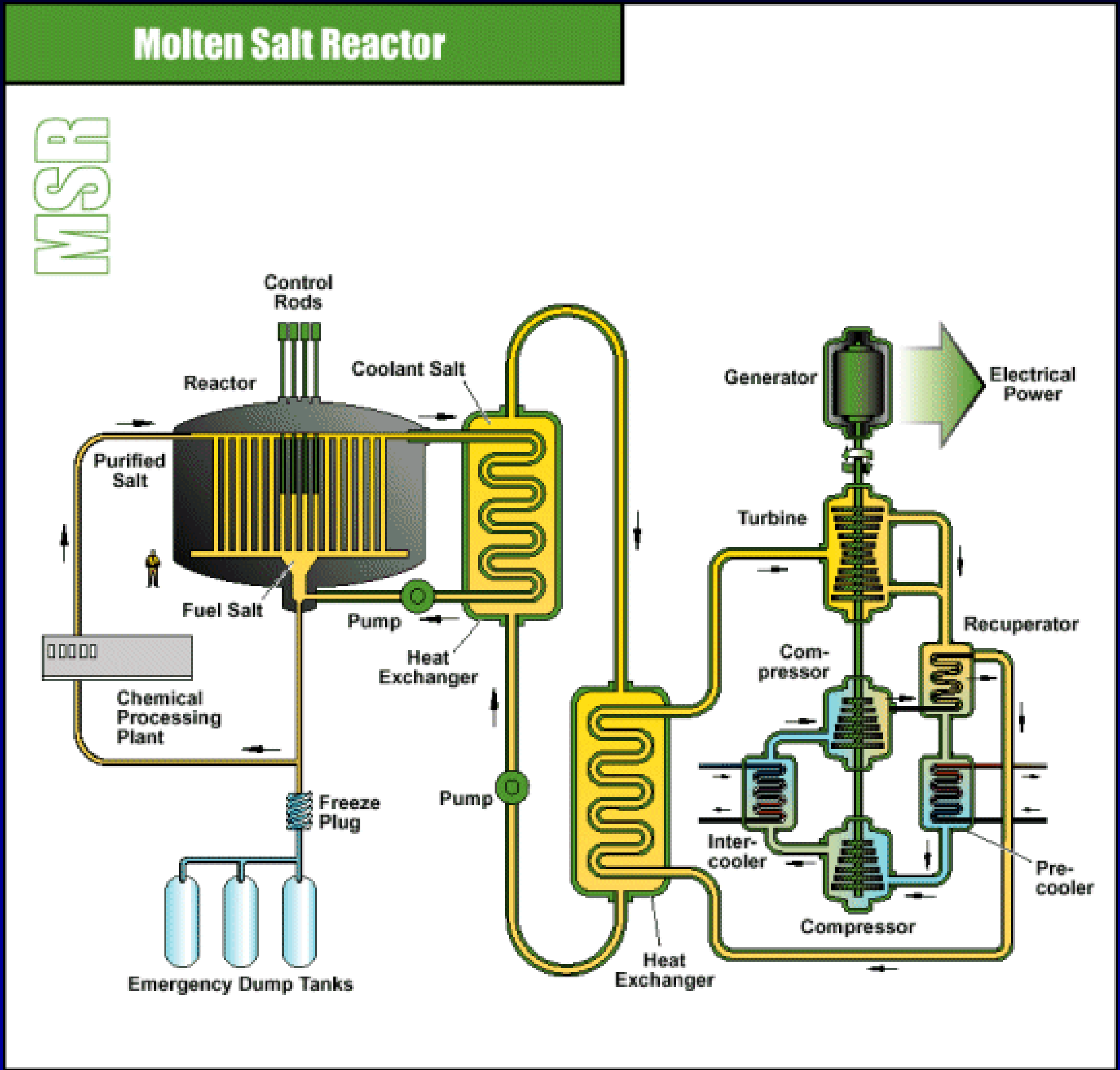
Lead Cooled Fast Reactor Reference values

Reactor Parameters	Reference Value			
	Pb-Bi Battery (nearer-term)	Pb-Bi Module (nearer-term)	Pb Large (nearer-term)	Pb Battery (far-term)
Coolant	Pb-Bi	Pb-Bi	Pb	Pb
Outlet Temperature (°C)	–550	–550	–550	750–800
Pressure (Atmospheres)	1	1	1	1
Rating (MWth)	125–400	–1000	3600	400
Fuel	Metal Alloy or Nitride	Metal Alloy	Nitride	Nitride
Cladding	Ferritic	Ferritic	Ferritic	Ceramic coatings or refractory alloys
Average Burnup (GWD/MTHM)	–100	–100–150	100–150	100
Conversion Ratio	1.0	d≥1.0	1.0–1.02	1.0
Lattice	Open	Open	Mixed	Open
Primary Flow	Natural	Forced	Forced	Natural
Pin Linear Heat Rate	Derated	Nominal	Nominal	Drated

Lead-Cooled Fast Reactor System

- LFR systems are Pb or Pb-Bi alloy-cooled reactors with a fast-neutron spectrum and closed fuel cycle.
- Options include a range of plant ratings, including a long refueling interval battery ranging from 50–150 MWe, a modular system from 300–400 MWe, and a large monolithic plant at 1200 MWe.
- It had the highest evaluations to the Generation IV goals among the LFR options, but also the largest R&D needs and longest development time.
- The nearer-term options focus on electricity production and rely on more easily developed fuel, clad, and coolant combinations and their associated fuel recycle and refabrication technologies.
- The longerterm option seeks to further exploit the inherently safe properties of Pb and raise the coolant outlet temperature sufficiently high to enter markets for hydrogen and process heat, possibly as merchant plants.

Molten Salt Reactor



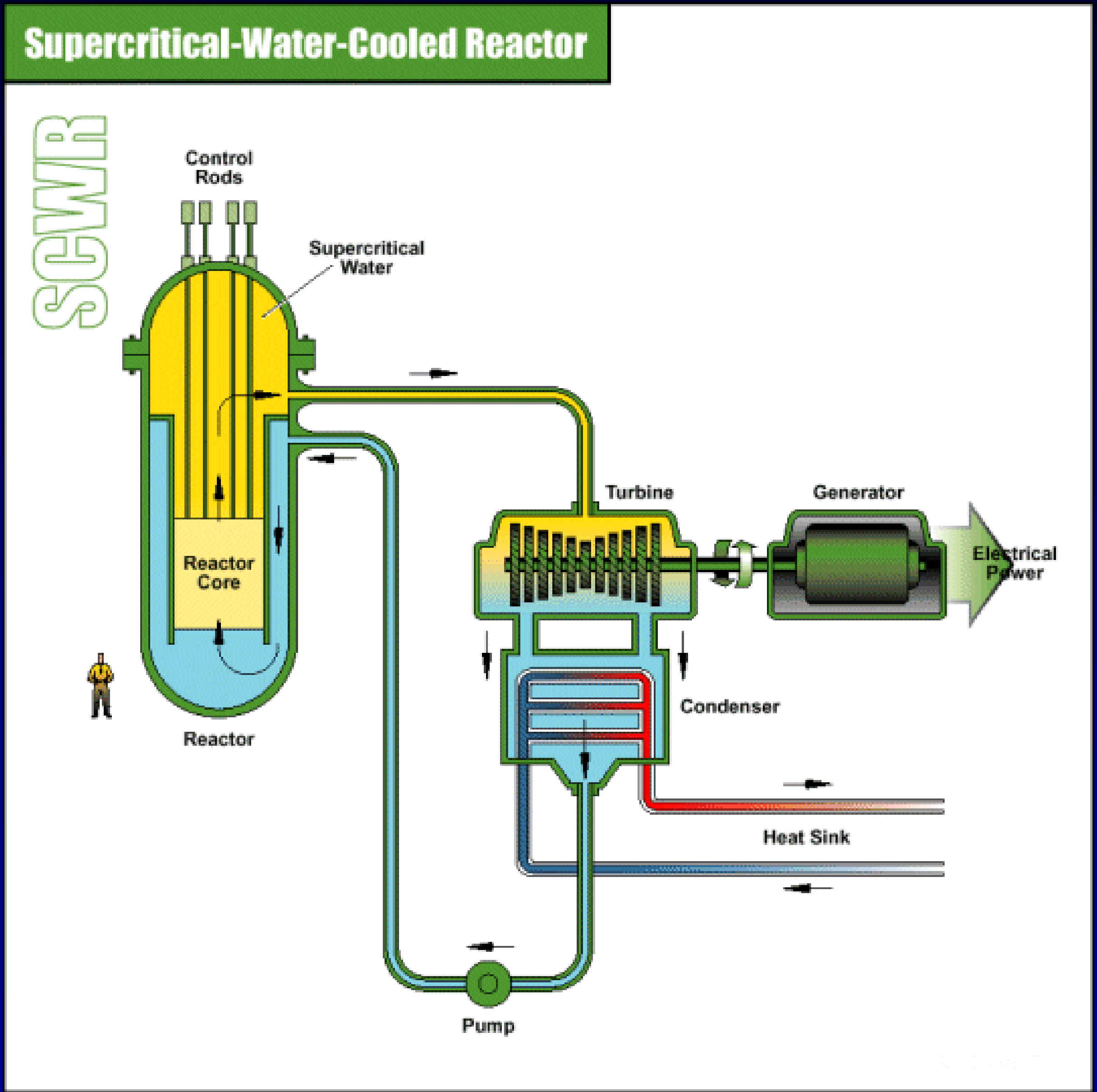
Molten Salt Reactor

Reactor Parameters	Reference Value
Net power	1000 MWe
Power density	22 MWth/m^3
Net thermal efficiency	44 to 50%
Fuel-salt – inlet temperature	565°C
– outlet temperature	700°C (850°C for hydrogen production)
– vapor pressure	<0.1 psi
Moderator	Graphite
Power Cycle	Multi-reheat recuperative helium Brayton cycle
Neutron spectrum burner	Thermal–actinide

Molten Salt Reactor System

- The MSR produces fission power in a circulating molten salt fuel mixture fuelled with uranium or plutonium fluorides dissolved in a mixture of molten fluorides, with Na and Zr fluorides as the primary option.
- MSRs have good neutron economy, opening alternatives for actinide burning and/or high conversion
- High-temperature operation holds the potential for thermo-chemical hydrogen production
- Molten fluoride salts have a very low vapour pressure, reducing stresses on the vessel and piping
- Inherent safety by fail-safe drainage, passive cooling low inventory of volatile fission products in the fuel
- Refuelling, processing, and fission product removal performed online, potentially yielding high availability
- MSRs allow the addition of actinide feeds to the homogenous salt solution without blending and fabrication needed by solid fuel reactors.

Supercritical Water Cooled Reactor



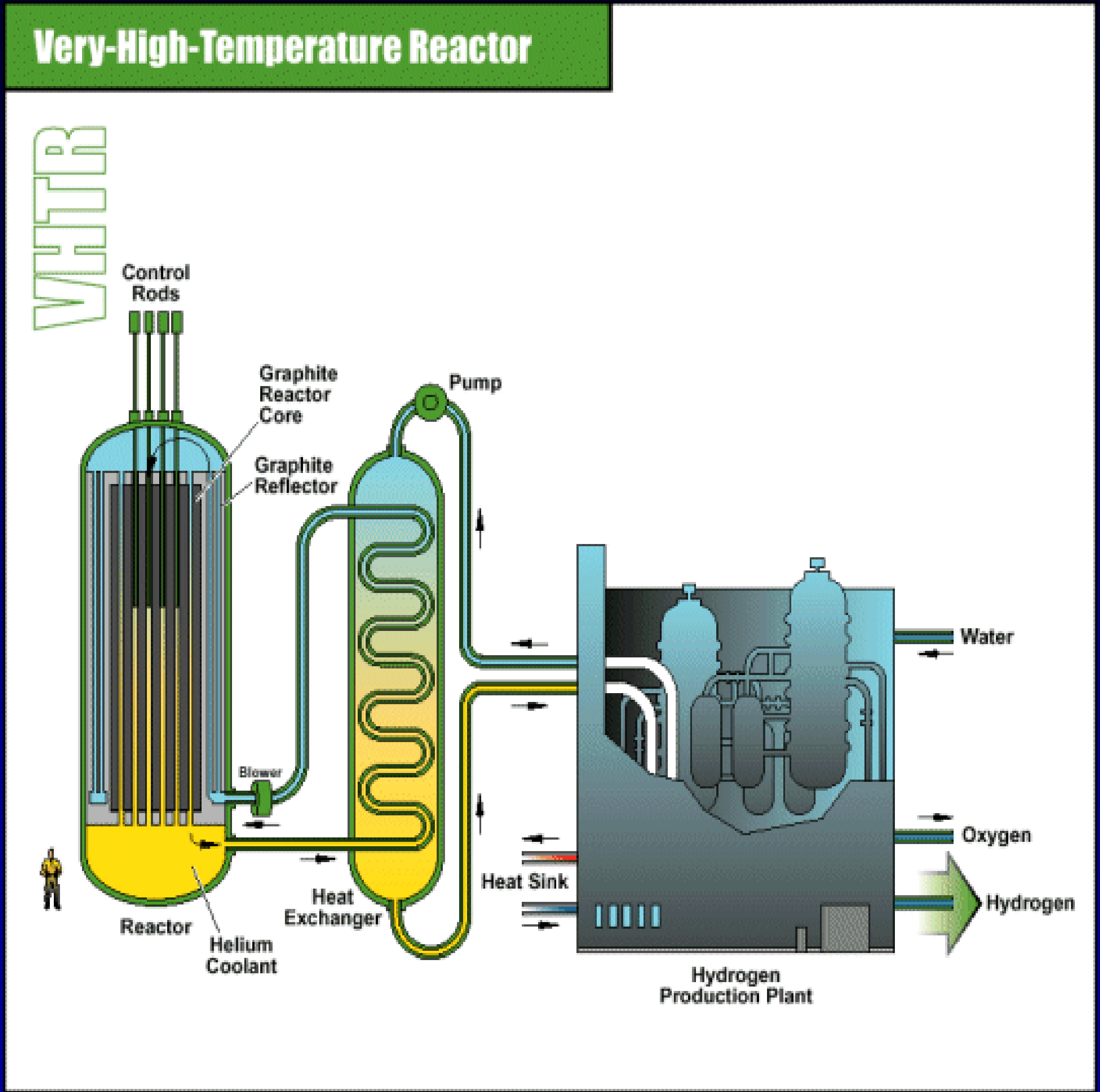
Supercritical Water Cooled Reactor

Reactor Parameters	Reference Value
Plant capital cost	$900/KW
Unit power and neutron spectrum	1700 MWe, thermal spectrum
Net efficiency	44%
Coolant inlet and outlet temperatures and pressure	280ºC/510ºC/25 MPa
Average power density	–100 MWth/m^3
Reference fuel	UO_2 with austenitic or ferritic-martensitic stainless steel, or Ni-alloy cladding
Fuel structural materials cladding structural materials	Advanced high-strength metal alloys are needed
Burnup / Damage	–45 GWD/MTHM; 10ñ30 dpa
Safety approach	Similar to ALWRs

Supercritical-Water-Cooled Reactor System

- SCWRs are high-temperature, high-pressure water- cooled reactors that operate above the thermodynamic critical point of water (374°C, 22.1 MPa)
- These systems may have a thermal or fast-neutron spectrum, depending on the core design.
- SCWRs offer increases in thermal efficiency relative to current-generation LWRs. The efficiency of a SCWR can approach 44%, compared to 33–35% for LWRs.
- A lower-coolant mass flow rate per unit core thermal power .This offers a reduction in the size of the reactor coolant pumps, piping, and associated equipment, and a reduction in the pumping power.
- Steam dryers, steam separators, recirculation pumps,

Very High Temperature Reactor



Very High Temperature Reactor

Reactor Parameters	Reference Value
Reactor power	600 MWth
Coolant inlet/outlet temperature	640/1000°C
Core inlet/outlet pressure	Dependent on process
Helium mass flow rate	320 kg/s
Average power density	6–10 MWth/m^3
Reference fuel compound	ZrC-coated particles in blocks, pins or pebbles
Net plant efficiency	>50%

Very High Temperature Reactor Systems

- The VHTR is a next step in the evolutionary development of high-temperature gas-cooled reactors. It is a graphite-moderated, helium-cooled reactor with thermal neutron spectrum. and can supply nuclear heat with core-outlet temperatures of 1000°C. The core can be a prismatic block core such as the operating Japanese HTTR, or a pebble-bed core such as the Chinese HTR-10.
- The VHTR produce hydrogen from only heat and water using thermo-chemical iodine-sulfur (I-S) process It can yield over 2 million normal cubic meters of hydrogen per day. The VHTR can also generate electricity with high efficiency, over 50% at 1000°C, compared with 47% at 850°C in the GTMHR or PBMR.
- Core outlet temperatures higher than 1000°C would enable nuclear heat application to such processes as steel, aluminium oxide, and aluminium production.
- For electricity generation, the helium gas turbine system can be directly set in the primary coolant loop, which is called a **direct cycle**.
- For nuclear heat applications such as process heat for refineries, petro-chemistry, metallurgy, and hydrogen production, the heat application process is generally coupled with the reactor through an intermediate heat exchanger (IHX), which is called an **indirect cycle.**

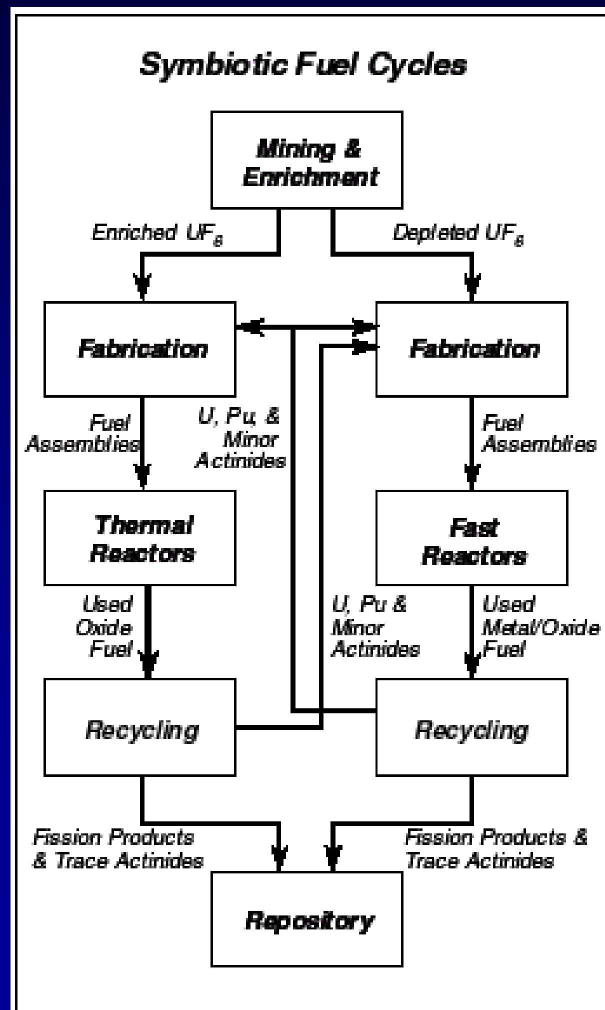
Candidate Materials

System	Fuel Materials					Structural Materials						
	Oxide	Metal	Nitride	Carbide	Fluoride (liquid)	Ferritic-martensitic Stainless Steel Alloys	Austenitic Stainless Steel Alloys	Oxide Dispersion Strengthened	Ni-based Alloys	Graphite	Refractory Alloys	Ceramics
GFR			S	P		P	P	P	P		P	P
MSR					P				P	P	S	S
SFR	P	P				P	P	P				
LFR		S	P			P	P	S			S	S
SCWR-Thermal	P					P	P	S	S			
SCWR-Fast	P	S				P	P	S	S			
VHTR	P					S			P	P	S	P

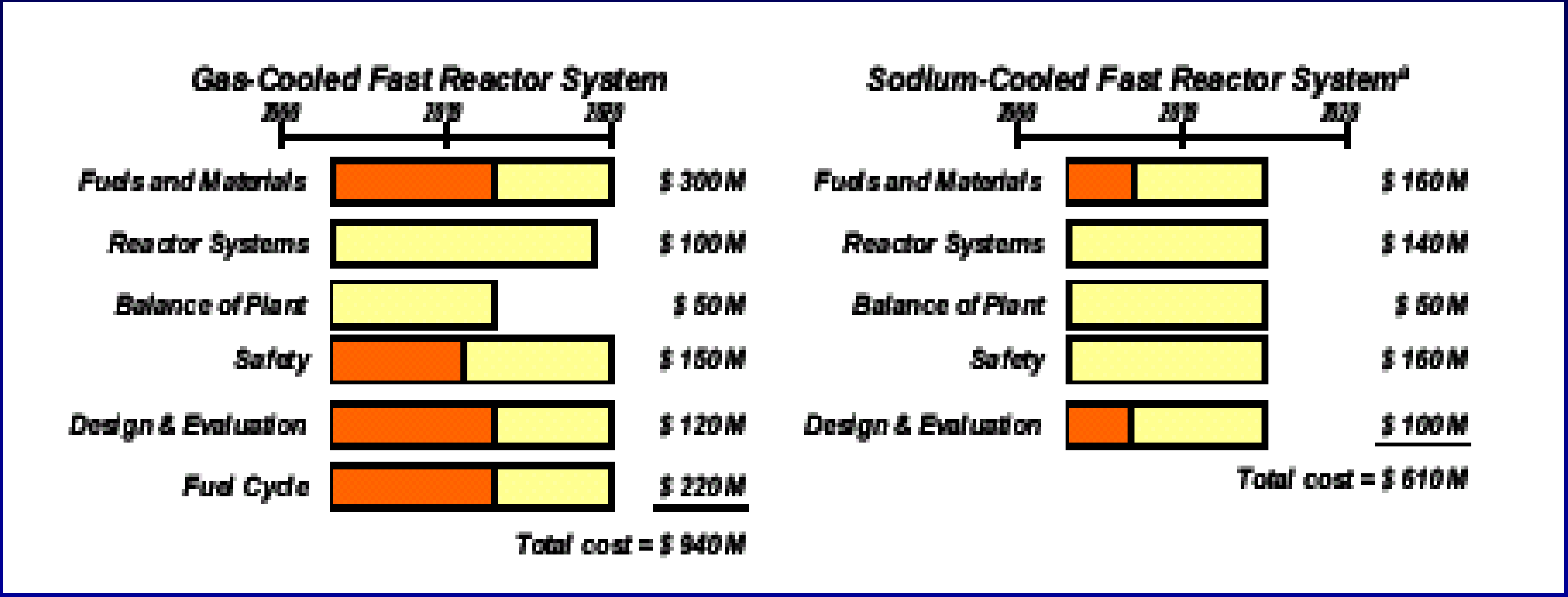
P: Primary Option

S: Secondary Option

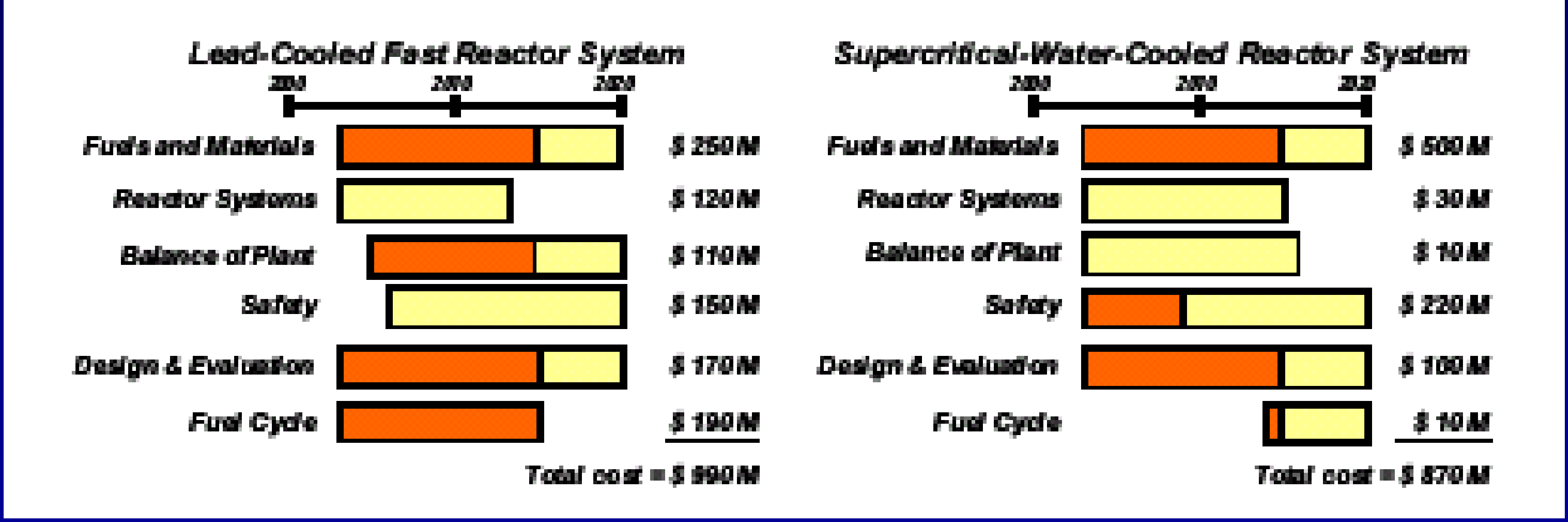
Combined Thermal and Fast Fuel Cycle



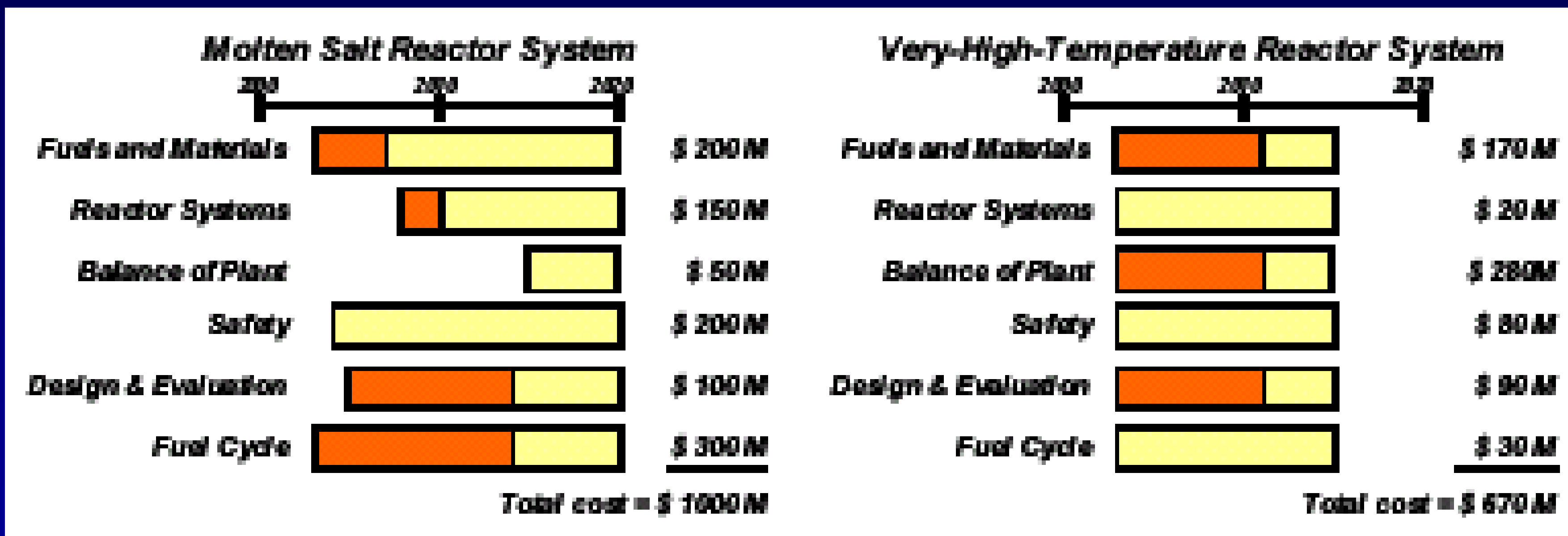
Development Costs for GCFR & SCFR



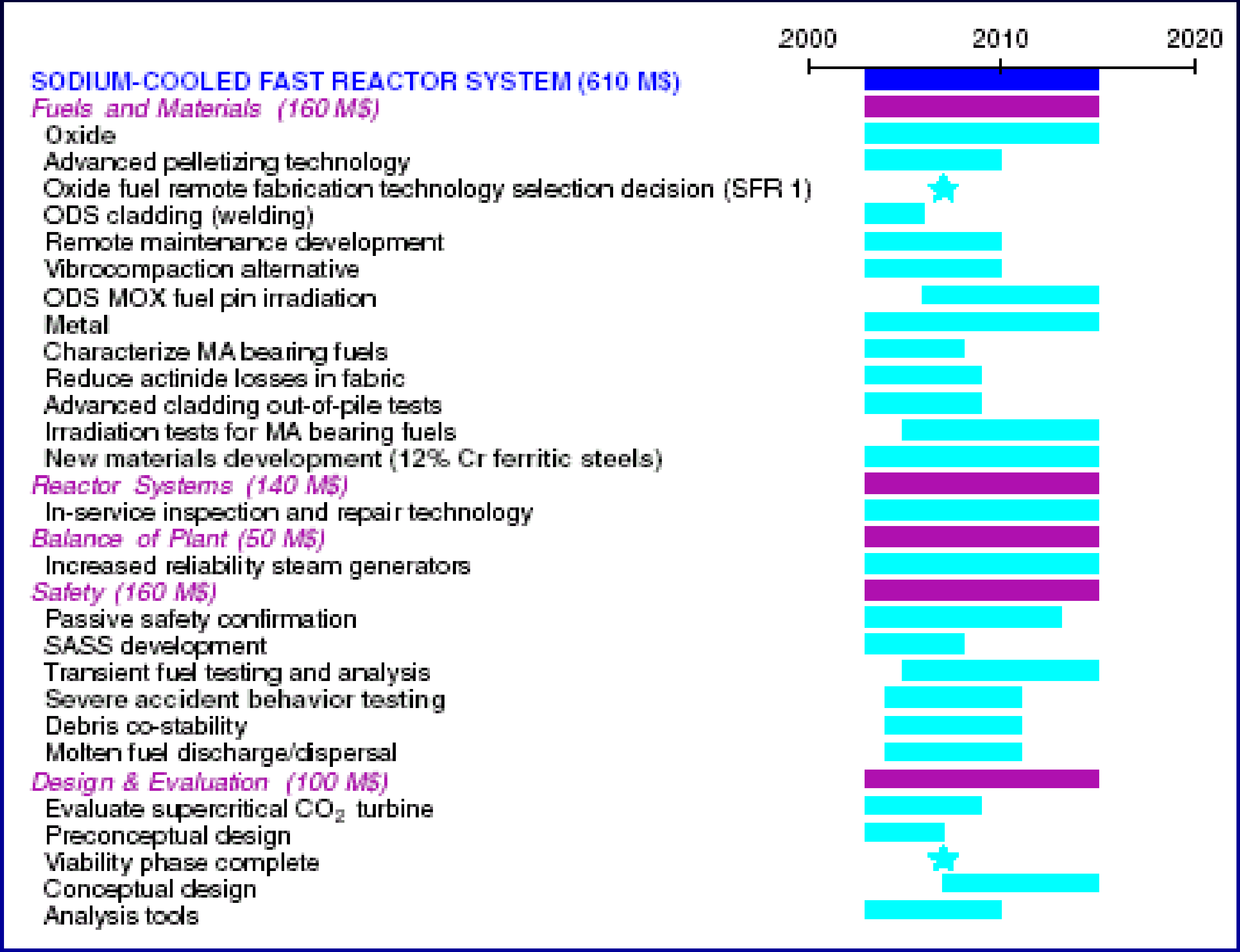
Development Costs for LCFR & SCWCR



Development Costs for MSR & VHTR



Schedule for SFR



References

http://energy.inel.gov/gen-iv/

www.world-nuclear.org

For SWR 1000, BWR+90, ABWR,AP 600;ALWR: see Atomwirtschaft 4/96