International Atomic Energy Agency

Generation IV Reactor Systems

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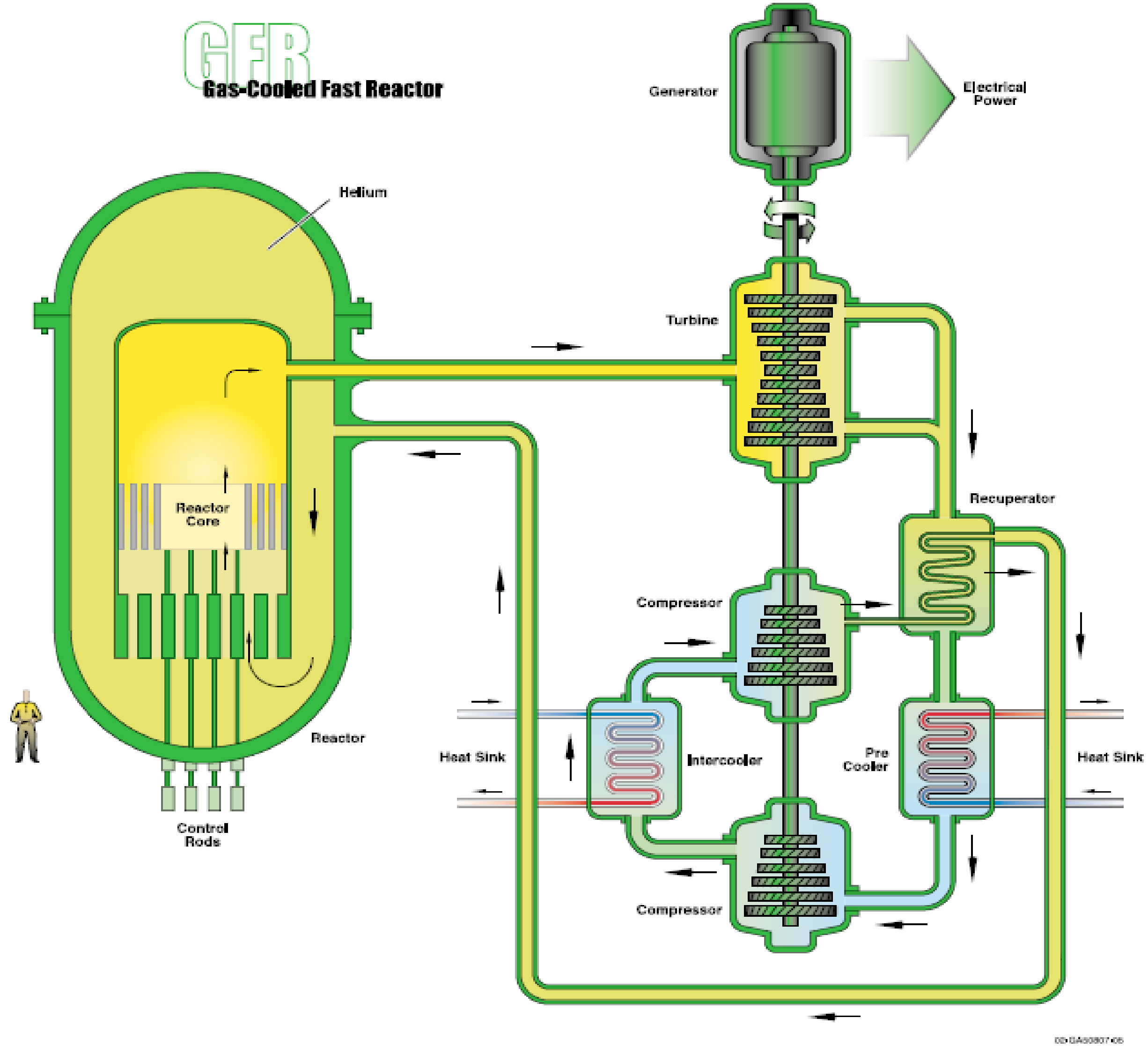
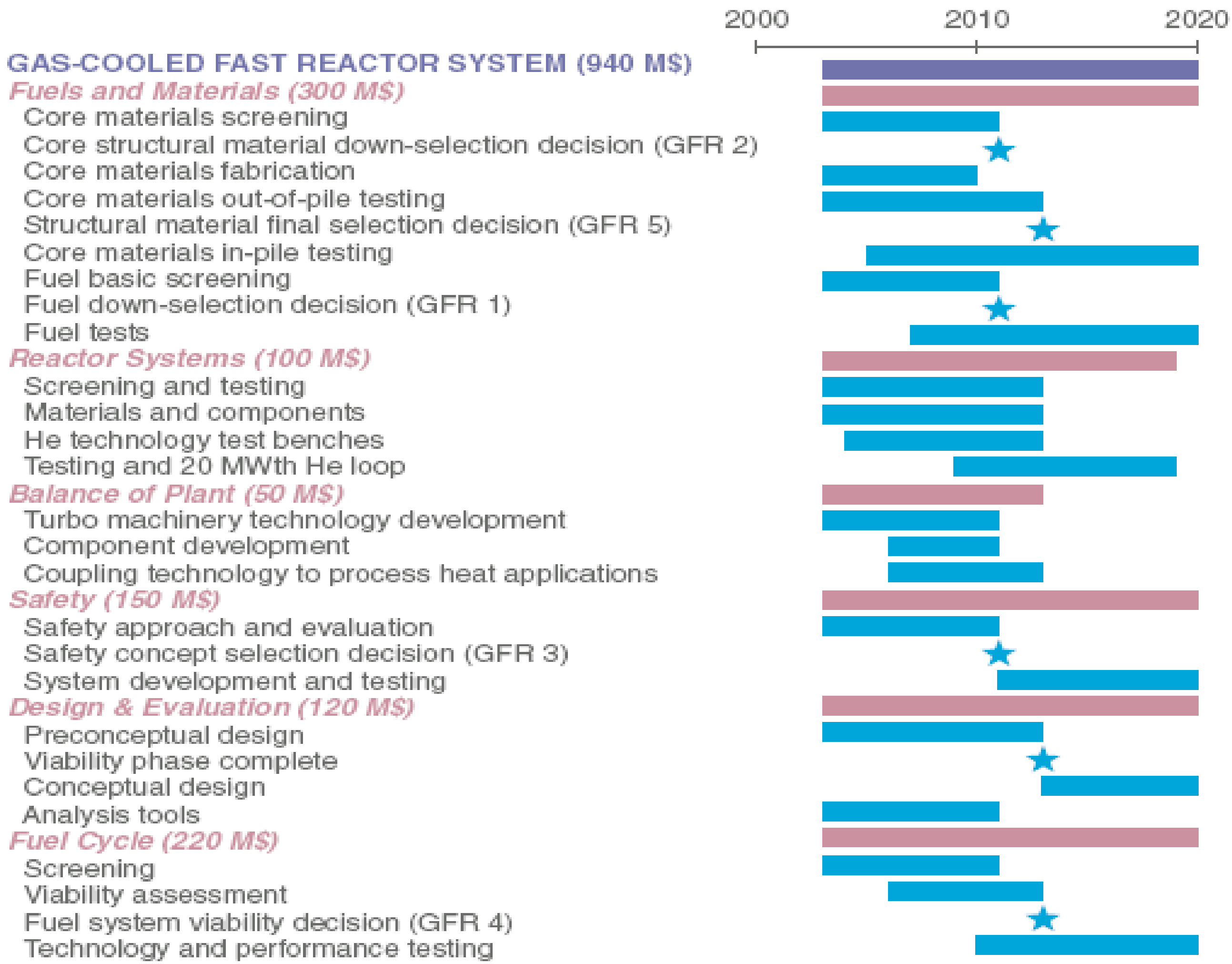
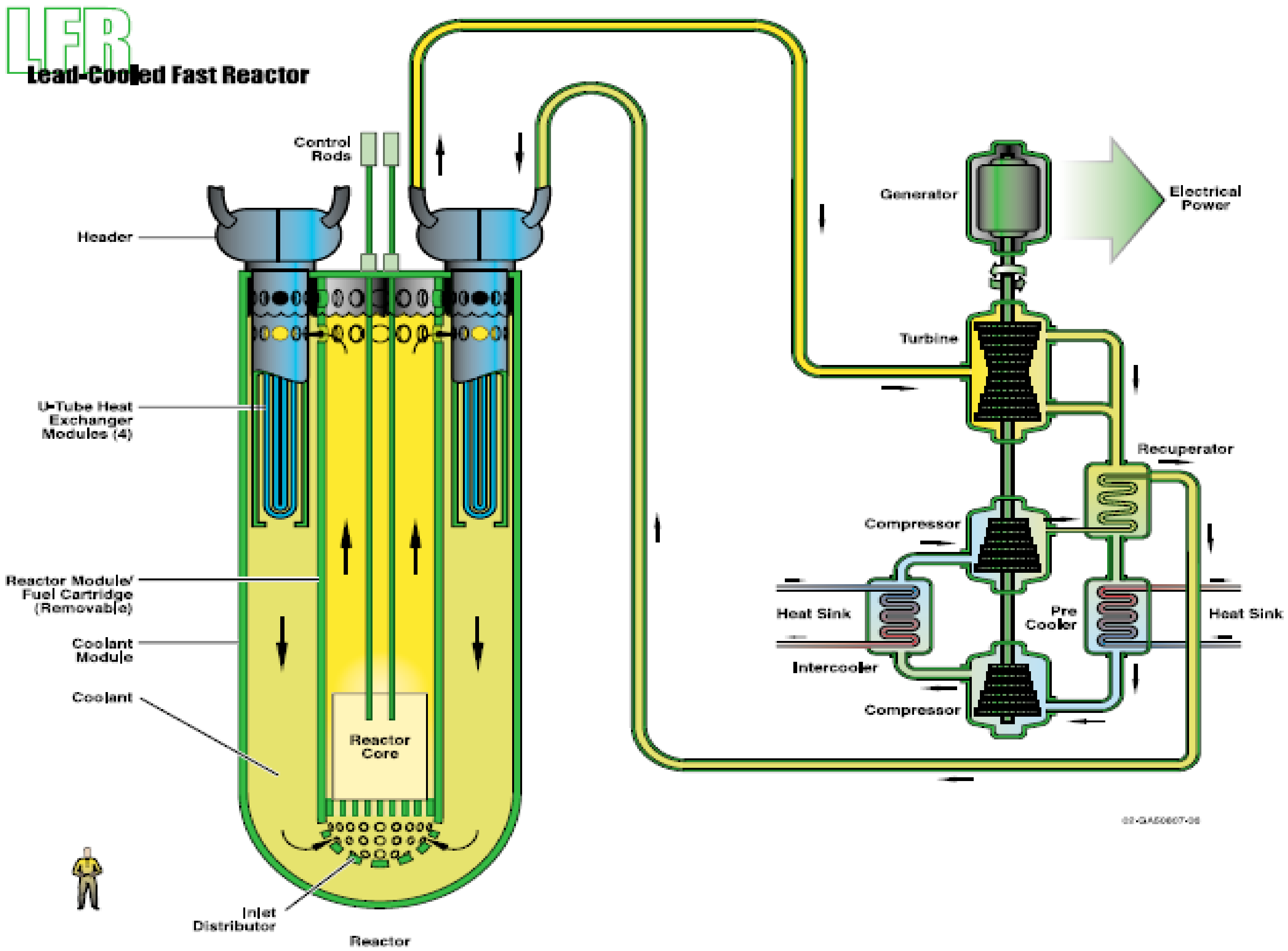

GFR
Gas-Cooled Fast Reactor
Generator
Electrical Power
Helium
Turbine
Reactor Core
Recuperator
Compressor
Heat Sink
Intercooler
Pre Cooler
Heat Sink
Reactor
Control Rods
Compressor

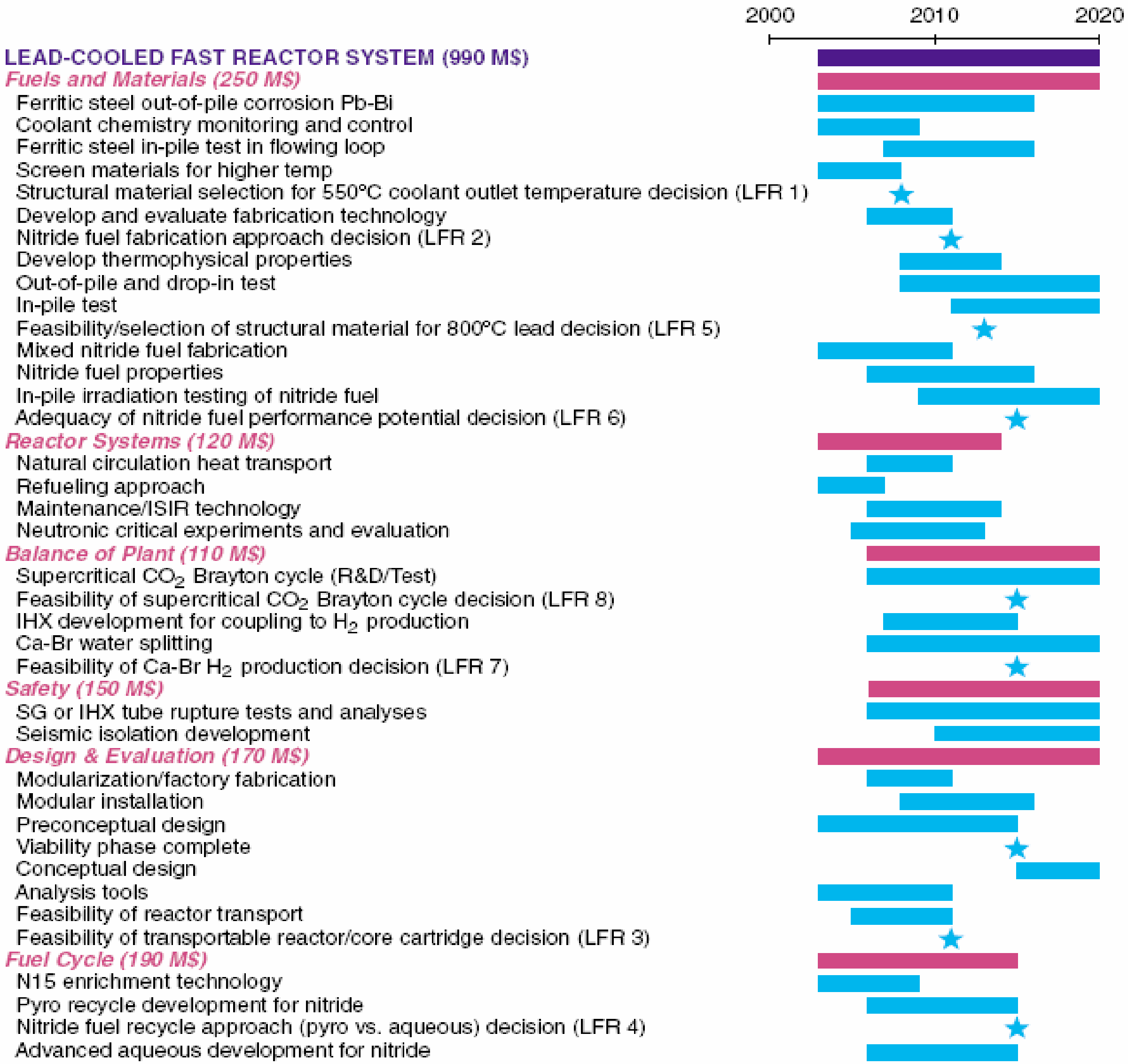
Reactor Parameters	Reference Value
Reactor power	600 MWth
Net plant efficiency (direct cycle helium)	48%
Coolant inlet/outlet temperature and pressure	490°C/850°C at 90 bar
Average power density	100 MWth/m3
Reference fuel compound	UPuC/SiC (70/30%) with about 20% Pu content
Volume fraction, Fuel/Gas/SiC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

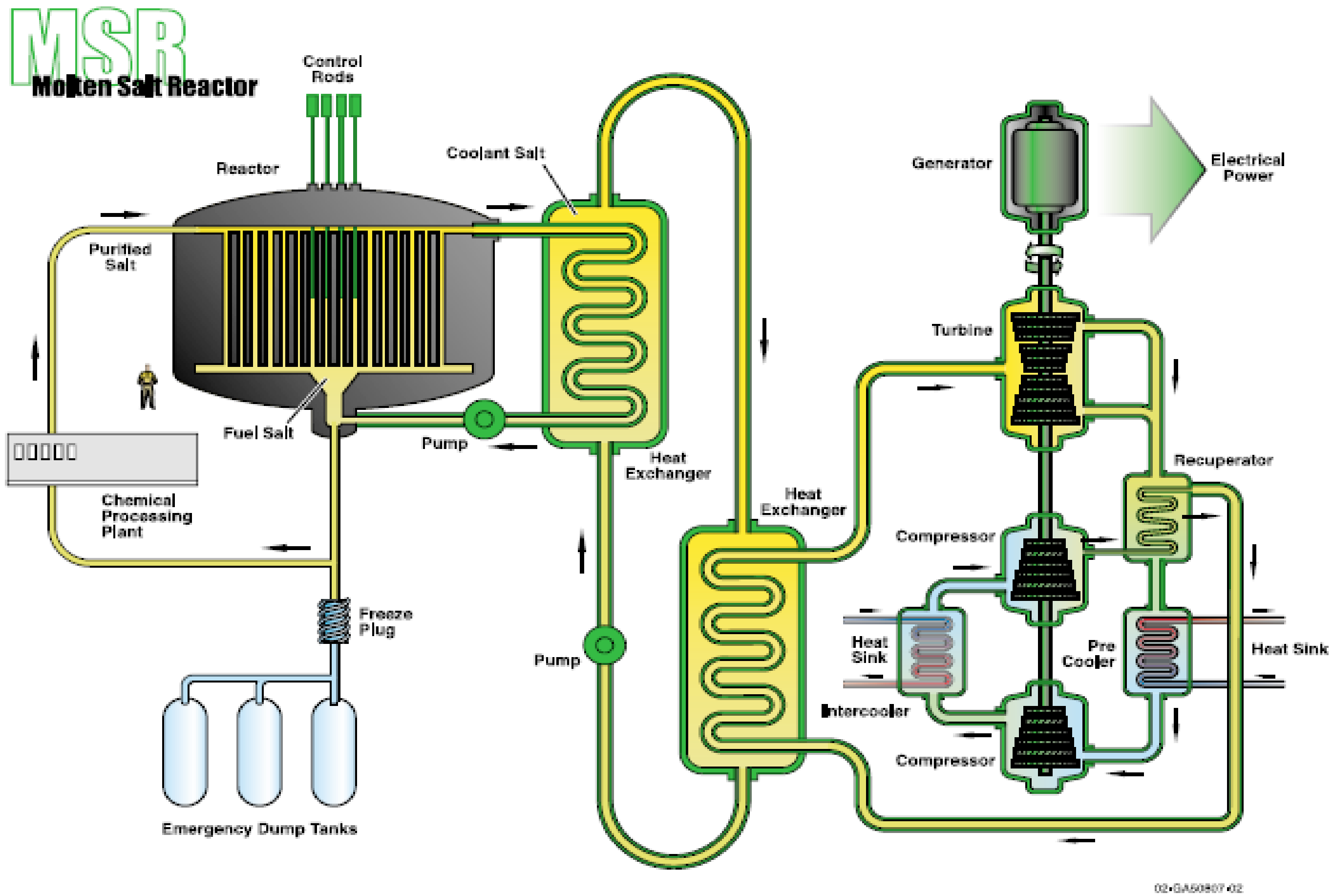

2000
2010
2020
GAS-COOLED FAST REACTOR SYSTEM (940 M$)
Fuels and Materials (300 M$)
Core materials screening
Core structural material down-selection decision (GFR 2)
Core materials fabrication
Core materials out-of-pile testing
Structural material final selection decision (GFR 5)
Core materials in-pile testing
Fuel basic screening
Fuel down-selection decision (GFR 1)
Fuel tests
Reactor Systems (100 M$)
Screening and testing
Materials and components
He technology test benches
Testing and 20 MWth He loop
Balance of Plant (50 M$)
Turbo machinery technology development
Component development
Coupling technology to process heat applications
Safety (150 M$)
Safety approach and evaluation
Safety concept selection decision (GFR 3)
System development and testing
Design & Evaluation (120 M$)
Preconceptual design
Viability phase complete
Conceptual design
Analysis tools
Fuel Cycle (220 M$)
Screening
Viability assessment
Fuel system viability decision (GFR 4)
Technology and performance testing


LFR
Lead-Cooled Fast Reactor
Control Rods
Header
U-Tube Heat Exchanger Modules (4)
Reactor Module/ Fuel Cartridge (Removable)
Coolant Module
Coolant
Reactor Core
Inlet Distributor
Reactor
Generator
Electrical Power
Turbine
Recuperator
Compressor
Heat Sink
Pre Cooler
Intercooler
Compressor
Heat Sink

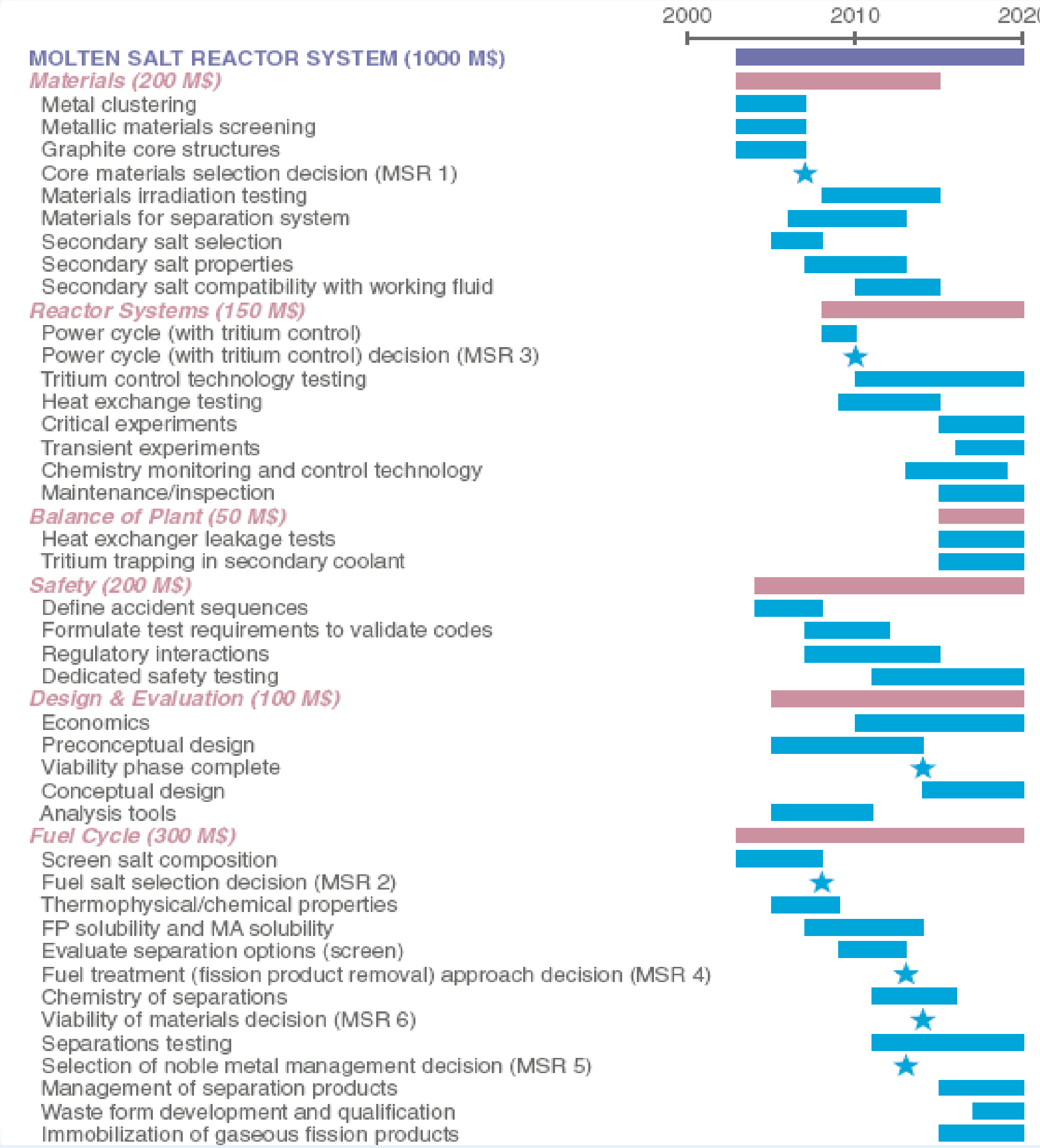
Reactor Parameters	Reference Value			
	Pb-Bi Battery (nearer-term)	Pb-Bi Module (nearer-term)	Pb Large (nearer-term)	Pb Battery (far-term)
Coolant	Pb-Bi	Pb-Bi	Pb	Pb
Outlet Temperature (ºC)	~550	~550	~550	750–800
Pressure (Atmospheres)	1	1	1	1
Rating (MWth)	125–400	~1000	3600	400
Fuel	Metal Alloy or Nitride	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

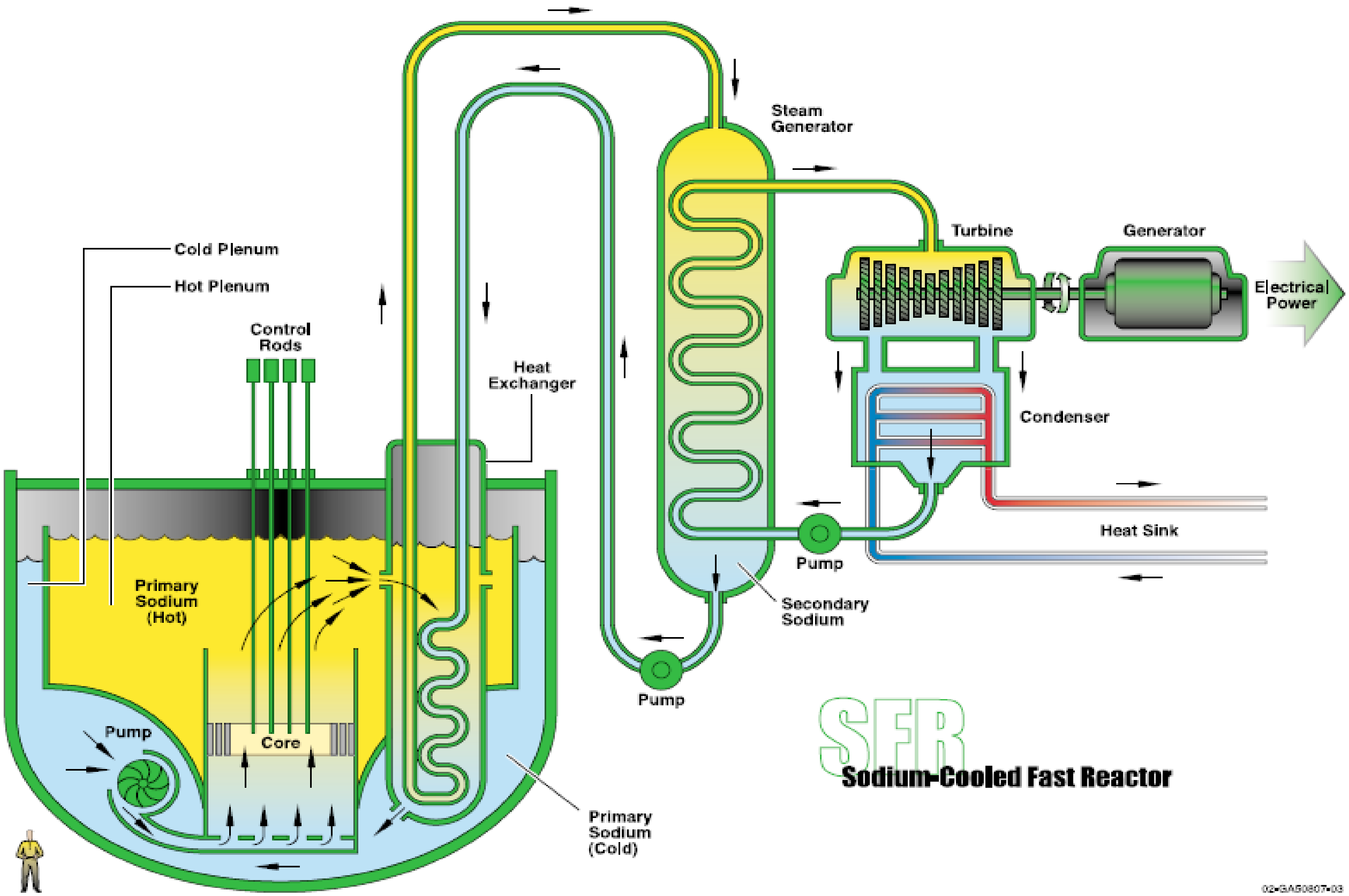
Major R&D Areas	Pb-Bi Battery (nearer-term)	Pb-Bi Module (nearer-term)	Pb Large (nearer-term)	Pb Batter (far-term)
Metal Alloy or Nitride Fuel (esp. for higher temperature range)	x	x	x	x
High-Temperature Structural Materials				x
Natural Circulation Heat Transport in Open Lattice	x	x	x	x
Forced Circulation Heat Transport in Open Lattice	x	x	x	x
Coolant Chemistry Control	x	x	x	x
Innovative Heat Transport	x	x	x	x
Internals Support and Refueling	x	x	x	x
Energy Conversion:				
Supercritical CO_2 Brayton	x	x		x
Supercritical Water Rankine		x	x	
Ca-Br Water Cracking				x
Desalinization Bottoming	x	x		x
Economics:				
Modularization	x	x	x	x
Modularization & Site Assembly	x	x	x	x
Metal Fuel Recycle/Refabrication	x	x		
Nitride Fuel Recycle/Refabrication	x	x	x	x


2000
2010
2020
LEAD-COOLED FAST REACTOR SYSTEM (990 M$)
Fuels and Materials (250 M$)
Ferritic steel out-of-pile corrosion Pb-Bi
Coolant chemistry monitoring and control
Ferritic steel in-pile test in flowing loop
Screen materials for higher temp
Structural material selection for 550°C coolant outlet temperature decision (LFR 1)
Develop and evaluate fabrication technology
Nitride fuel fabrication approach decision (LFR 2)
Develop thermophysical properties
Out-of-pile and drop-in test
In-pile test
Feasibility/selection of structural material for 800°C lead decision (LFR 5)
Mixed nitride fuel fabrication
Nitride fuel properties
In-pile irradiation testing of nitride fuel
Adequacy of nitride fuel performance potential decision (LFR 6)
Reactor Systems (120 M$)
Natural circulation heat transport
Refueling approach
Maintenance/ISIR technology
Neutronic critical experiments and evaluation
Balance of Plant (110 M$)
Supercritical CO_2 Brayton cycle (R&D/Test)
Feasibility of supercritical CO_2 Brayton cycle decision (LFR 8)
IHX development for coupling to H_2 production
Ca-Br water splitting
Feasibility of Ca-Br H_2 production decision (LFR 7)
Safety (150 M$)
SG or IHX tube rupture tests and analyses
Seismic isolation development
Design & Evaluation (170 M$)
Modularization/factory fabrication
Modular installation
Preconceptual design
Viability phase complete
Conceptual design
Analysis tools
Feasibility of reactor transport
Feasibility of transportable reactor/core cartridge decision (LFR 3)
Fuel Cycle (190 M$)
N15 enrichment technology
Pyro recycle development for nitride
Nitride fuel recycle approach (pyro vs. aqueous) decision (LFR 4)
Advanced aqueous development for nitride

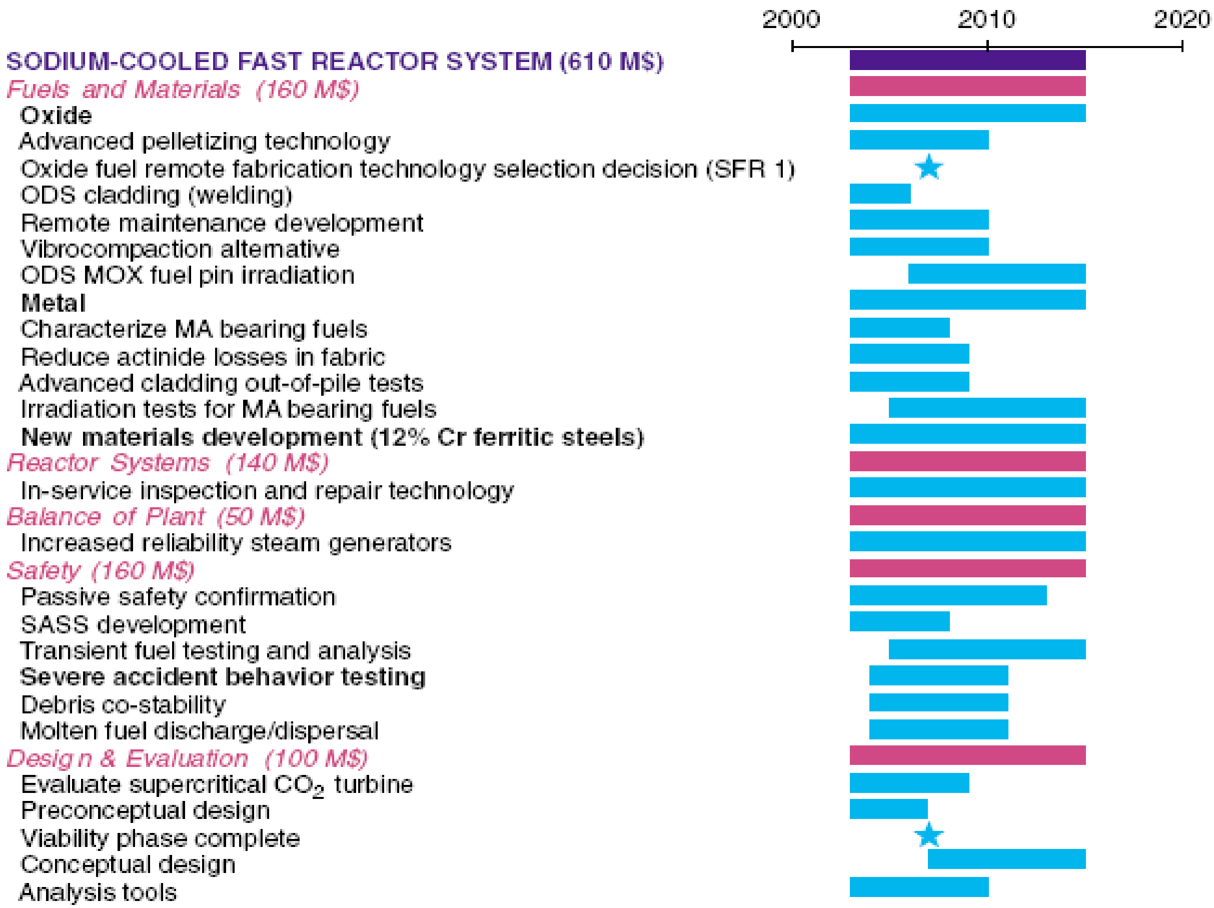

MSR
Molten Salt Reactor
Control Rods
Reactor
Coolant Salt
Purified Salt
Generator
Electrical Power
Turbine
Fuel Salt
Pump
Heat Exchanger
Chemical Processing Plant
Heat Exchanger
Recuperator
Compressor
Freeze Plug
Heat Sink
Pre Cooler
Heat Sink
Pump
Intercooler
Compressor
Emergency Dump Tanks
02-GA50807-02

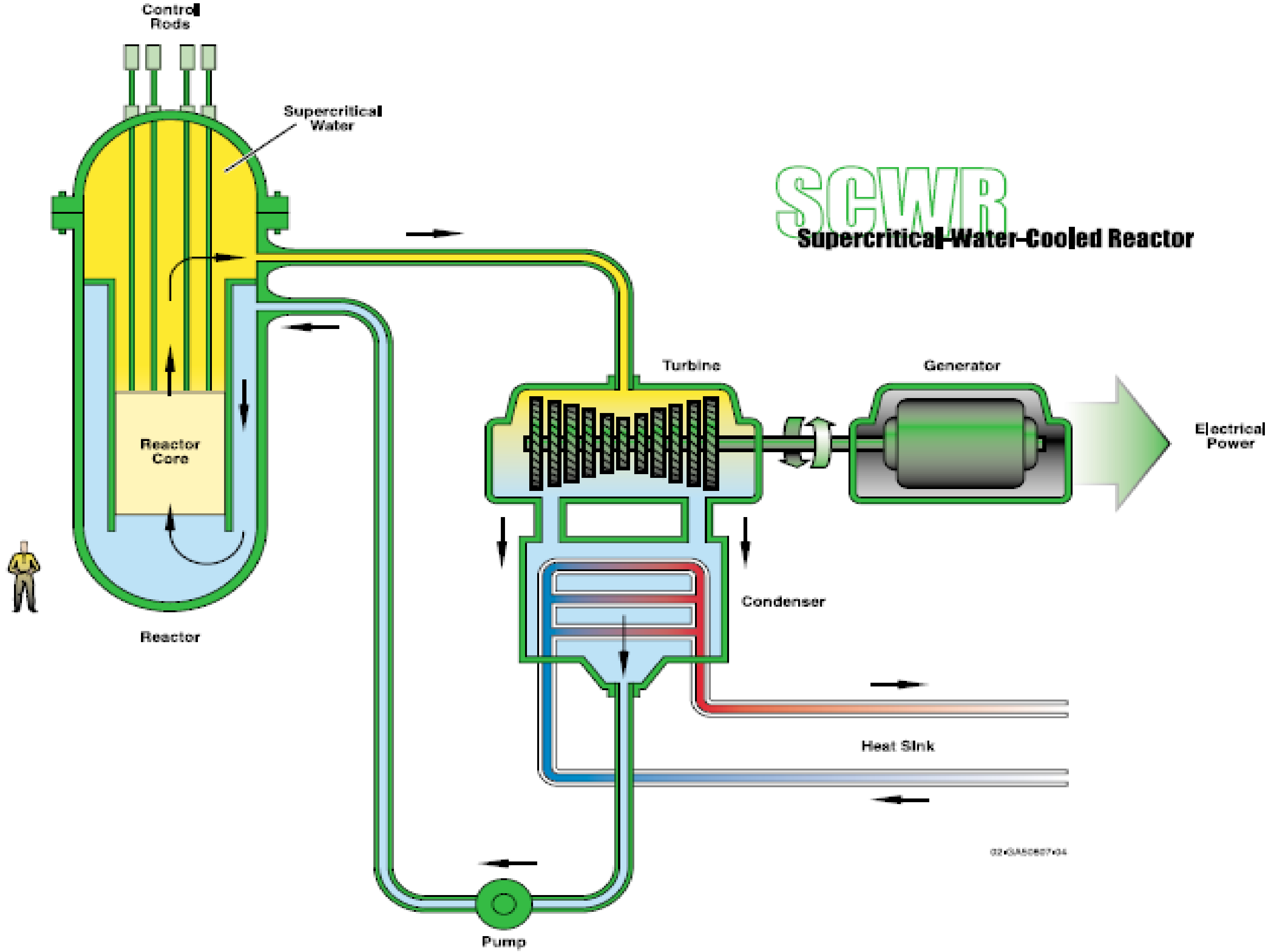
Reactor Parameters	Reference Value
Net power	1000 MWe
Power density	22 MWth/m^3
Net thermal efficiency	44 to 50%
Fuel-salt – inlet temperature	565°C
– outlet temperature	700°C (850°C for hydrogen production)
– vapor pressure	<0.1 psi
Moderator	Graphite
Power Cycle	Multi-reheat recuperative helium Brayton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


2000
2010
2020
MOLTEN SALT REACTOR SYSTEM (1000 M$)
Materials (200 M$)
Metal clustering
Metallic materials screening
Graphite core structures
Core materials selection decision (MSR 1)
Materials irradiation testing
Materials for separation system
Secondary salt selection
Secondary salt properties
Secondary salt compatibility with working fluid
Reactor Systems (150 M$)
Power cycle (with tritium control)
Power cycle (with tritium control) decision (MSR 3)
Tritium control technology testing
Heat exchange testing
Critical experiments
Transient experiments
Chemistry monitoring and control technology
Maintenance/inspection
Balance of Plant (50 M$)
Heat exchanger leakage tests
Tritium trapping in secondary coolant
Safety (200 M$)
Define accident sequences
Formulate test requirements to validate codes
Regulatory interactions
Dedicated safety testing
Design & Evaluation (100 M$)
Economics
Preconceptual design
Viability phase complete
Conceptual design
Analysis tools
Fuel Cycle (300 M$)
Screen salt composition
Fuel salt selection decision (MSR 2)
Thermophysical/chemical properties
FP solubility and MA solubility
Evaluate separation options (screen)
Fuel treatment (fission product removal) approach decision (MSR 4)
Chemistry of separations
Viability of materials decision (MSR 6)
Separations testing
Selection of noble metal management decision (MSR 5)
Management of separation products
Waste form development and qualification
Immobilization of gaseous fission products

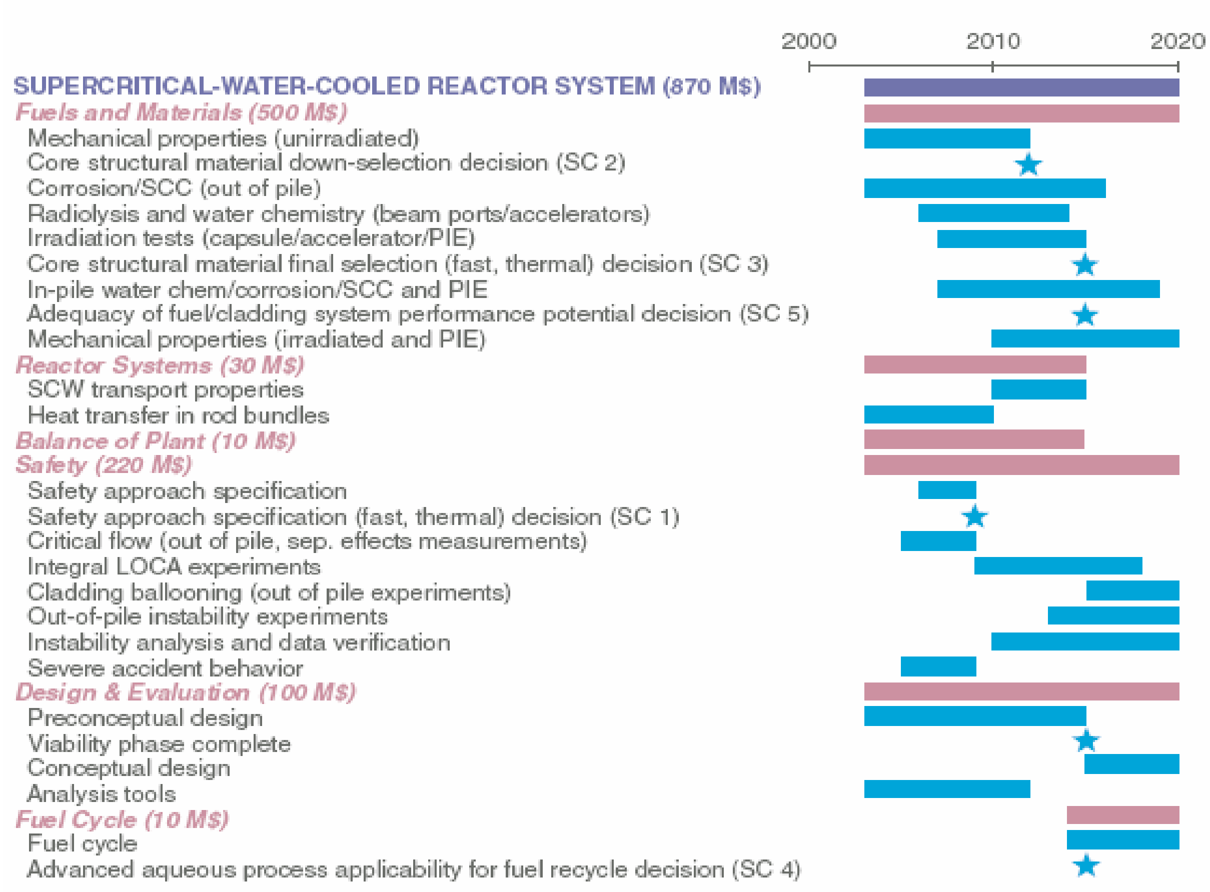

Steam
Generator
Turbine
Generator
Electrical
Power
Cold Plenum
Hot Plenum
Control
Rods
Heat
Exchanger
Condenser
Heat Sink
Pump
Secondary
Sodium
Primary
Sodium
(Hot)
Pump
Core
Pump
Primary
Sodium
(Cold)
SFR
Sodium-Cooled Fast Reactor
02-GA50807-03

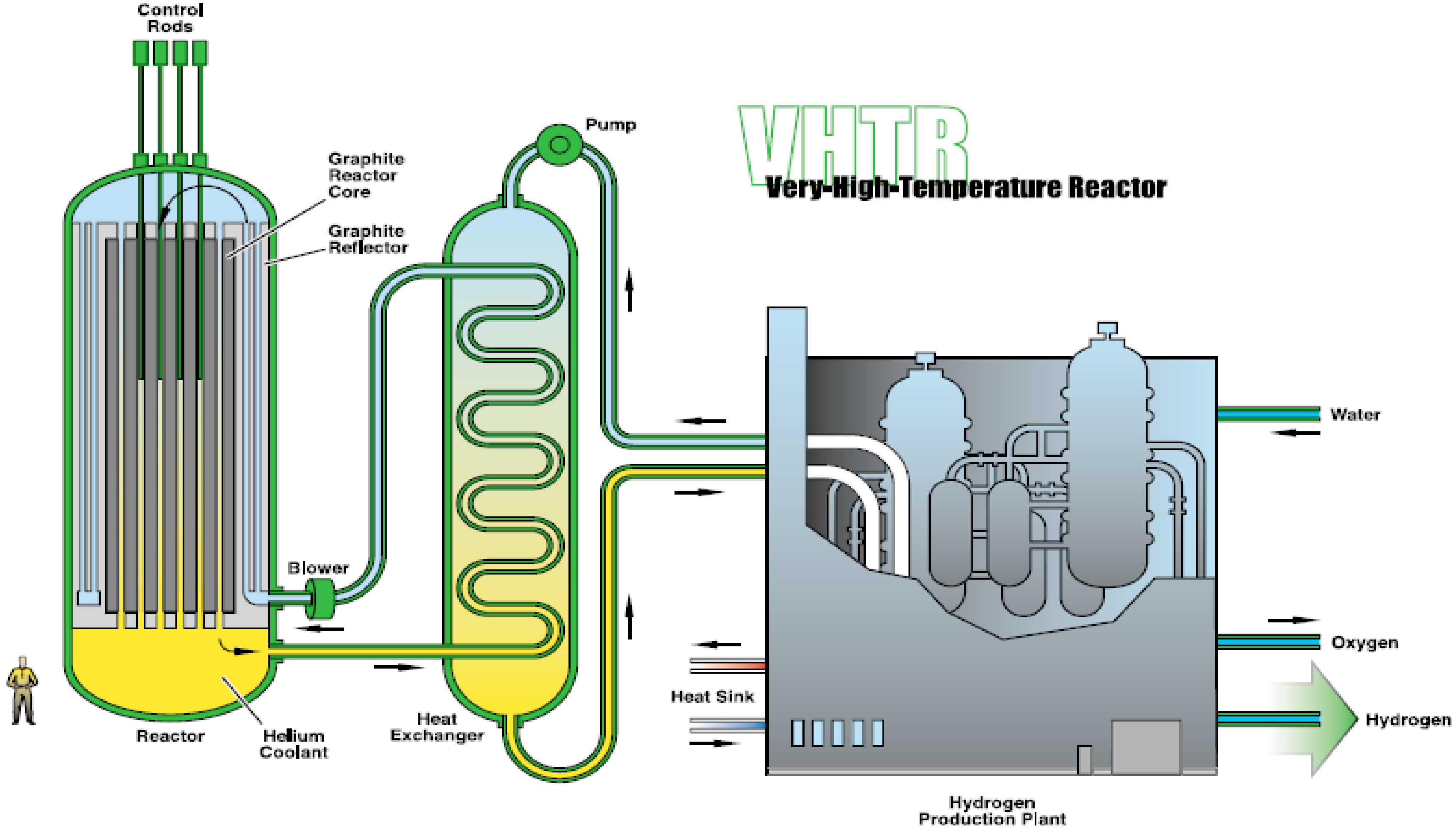
Reactor Parameters	Reference Value
Outlet Temperature	530-550°C
Pressure	~1 Atmospheres
Rating	1000-5000 MWth
Fuel	Oxide or metal alloy
Cladding	Ferritic or ODS ferritic
Average Burnup	~150-200 GWD/MTHM
Conversion Ratio	0.5-1.30
Average Power Density	350 MWth/m^3


2000
2010
2020
SODIUM-COOLED FAST REACTOR SYSTEM (610 M$)
Fuels and Materials (160 M$)
Oxide
Advanced pelletizing technology
Oxide fuel remote fabrication technology selection decision (SFR 1)
ODS cladding (welding)
Remote maintenance development
Vibrocompaction alternative
ODS MOX fuel pin irradiation
Metal
Characterize MA bearing fuels
Reduce actinide losses in fabric
Advanced cladding out-of-pile tests
Irradiation tests for MA bearing fuels
New materials development (12% Cr ferritic steels)
Reactor Systems (140 M$)
In-service inspection and repair technology
Balance of Plant (50 M$)
Increased reliability steam generators
Safety (160 M$)
Passive safety confirmation
SASS development
Transient fuel testing and analysis
Severe accident behavior testing
Debris co-stability
Molten fuel discharge/dispersal
Design & Evaluation (100 M$)
Evaluate supercritical CO_2 turbine
Preconceptual design
Viability phase complete
Conceptual design
Analysis tools

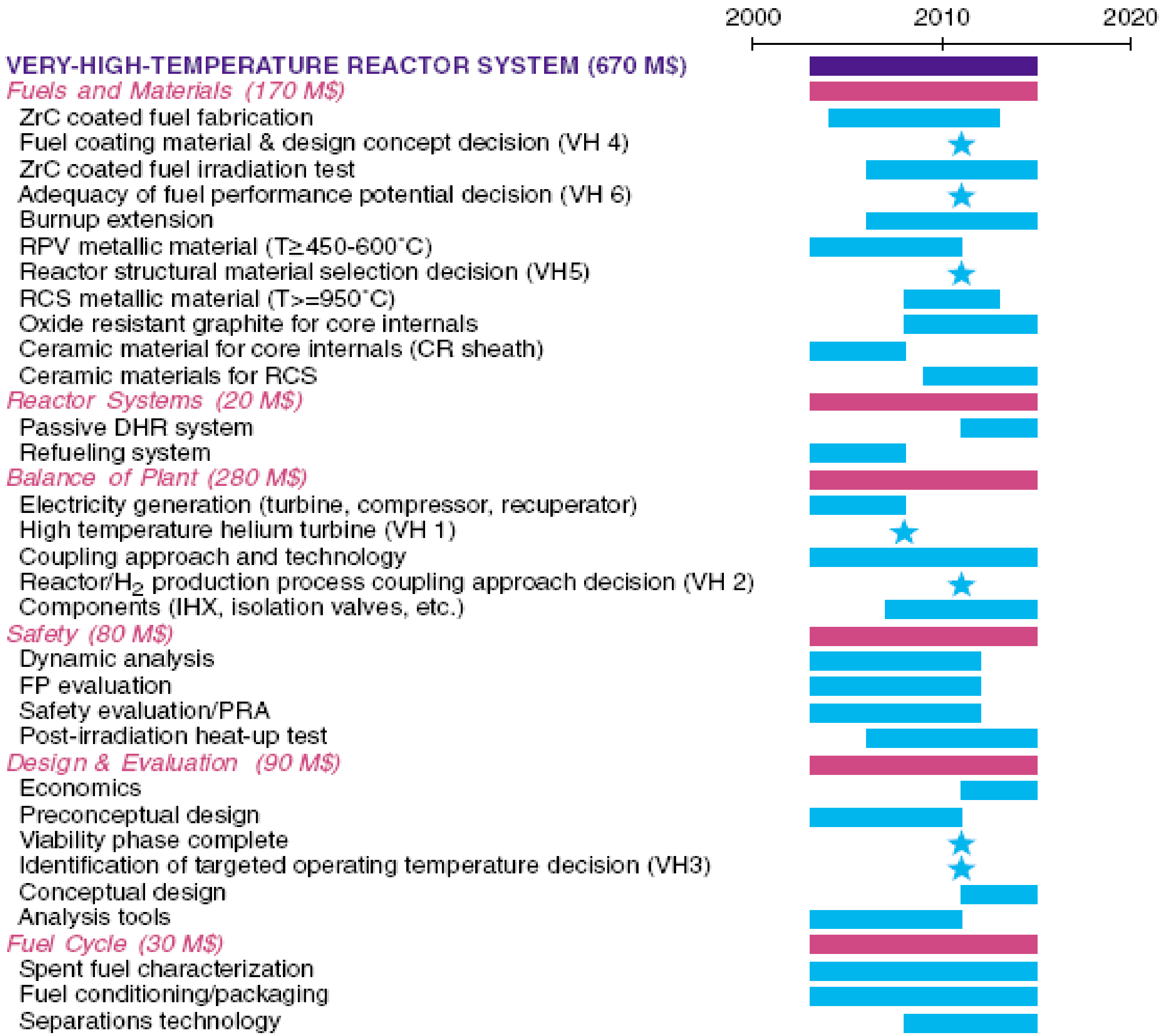

SCWR
Supercritical-Water-Cooled Reactor
Control Rods
Supercritical Water
Reactor Core
Reactor
Turbine
Generator
Electrical Power
Condenser
Heat Sink
Pump

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	280°C/510°C/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; 10–30 dpa
Safety approach	Similar to ALWRs


2000
2010
2020
SUPERCRITICAL-WATER-COOLED REACTOR SYSTEM (870 M$)
Fuels and Materials (500 M$)
Mechanical properties (unirradiated)
Core structural material down-selection decision (SC 2)
Corrosion/SCC (out of pile)
Radiolysis and water chemistry (beam ports/accelerators)
Irradiation tests (capsule/accelerator/PIE)
Core structural material final selection (fast, thermal) decision (SC 3)
In-pile water chem/corrosion/SCC and PIE
Adequacy of fuel/cladding system performance potential decision (SC 5)
Mechanical properties (irradiated and PIE)
Reactor Systems (30 M$)
SCW transport properties
Heat transfer in rod bundles
Balance of Plant (10 M$)
Safety (220 M$)
Safety approach specification
Safety approach specification (fast, thermal) decision (SC 1)
Critical flow (out of pile, sep. effects measurements)
Integral LOCA experiments
Cladding ballooning (out of pile experiments)
Out-of-pile instability experiments
Instability analysis and data verification
Severe accident behavior
Design & Evaluation (100 M$)
Preconceptual design
Viability phase complete
Conceptual design
Analysis tools
Fuel Cycle (10 M$)
Fuel cycle
Advanced aqueous process applicability for fuel recycle decision (SC 4)


VHTR
Very-High-Temperature Reactor
Control Rods
Graphite Reactor Core
Graphite Reflector
Pump
Blower
Reactor
Helium Coolant
Heat Exchanger
Heat Sink
Water
Oxygen
Hydrogen
Hydrogen Production Plant

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%


2000
2010
2020
VERY-HIGH-TEMPERATURE REACTOR SYSTEM (670 M$)
Fuels and Materials (170 M$)
ZrC coated fuel fabrication
Fuel coating material & design concept decision (VH 4)
ZrC coated fuel irradiation test
Adequacy of fuel performance potential decision (VH 6)
Burnup extension
RPV metallic material (T≥450-600˚C)
Reactor structural material selection decision (VH5)
RCS metallic material (T>=950˚C)
Oxide resistant graphite for core internals
Ceramic material for core internals (CR sheath)
Ceramic materials for RCS
Reactor Systems (20 M$)
Passive DHR system
Refueling system
Balance of Plant (280 M$)
Electricity generation (turbine, compressor, recuperator)
High temperature helium turbine (VH 1)
Coupling approach and technology
Reactor/H2 production process coupling approach decision (VH 2)
Components (IHX, isolation valves, etc.)
Safety (80 M$)
Dynamic analysis
FP evaluation
Safety evaluation/PRA
Post-irradiation heat-up test
Design & Evaluation (90 M$)
Economics
Preconceptual design
Viability phase complete
Identification of targeted operating temperature decision (VH3)
Conceptual design
Analysis tools
Fuel Cycle (30 M$)
Spent fuel characterization
Fuel conditioning/packaging
Separations technology

Generation IV System	Fuel				Recycle	
	Oxide	Metal	Nitride	Carbide	Advanced Aqueous	Pyroprocess
GFR[1]			S	P	P	P
MSR[2]						
SFR[3]	P	P			P	P
LFR		S	P		P	P
SCWR	P				P	
VHTR[4]	P				S	S

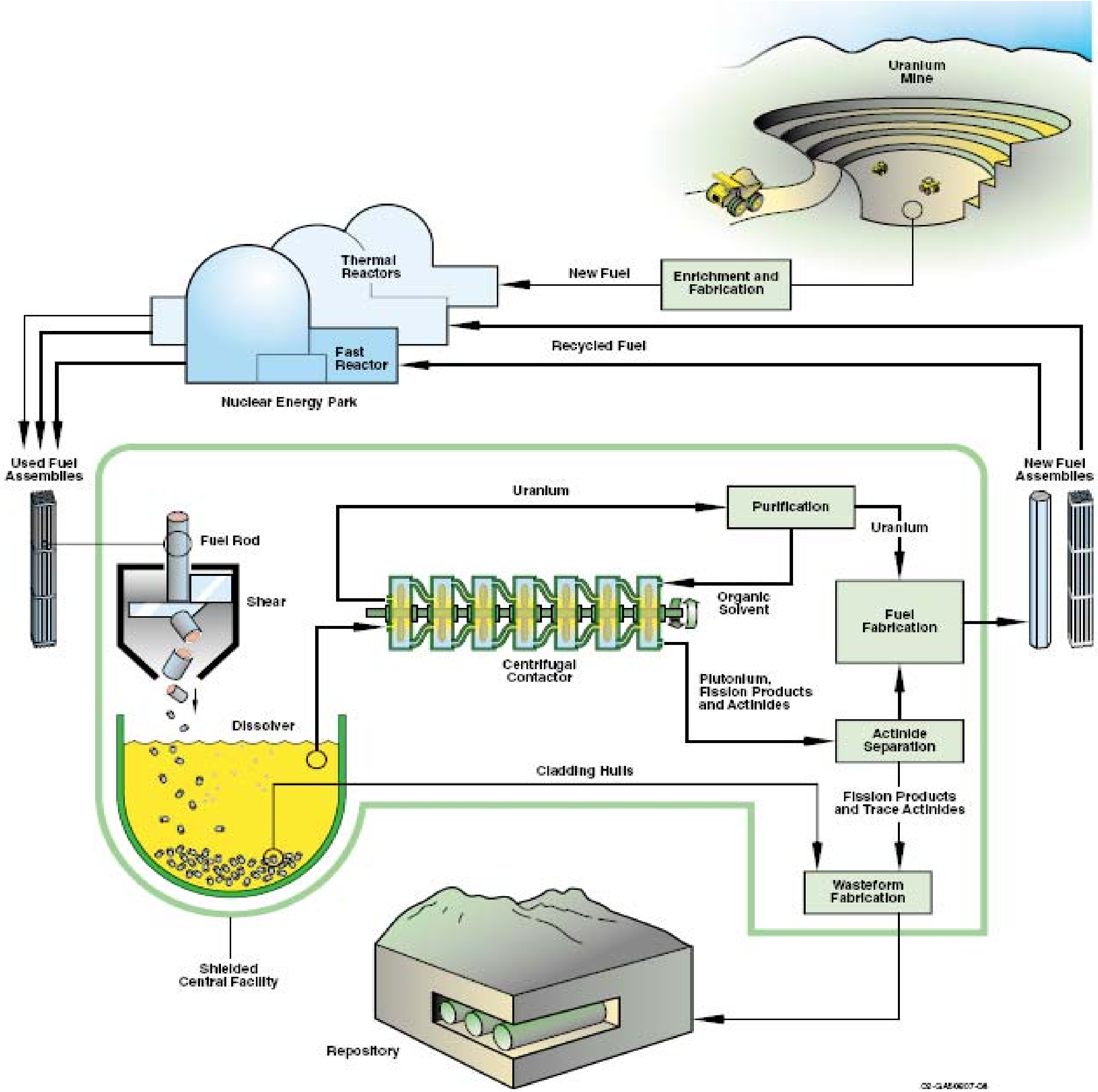
P: Primary option; S: Secondary option

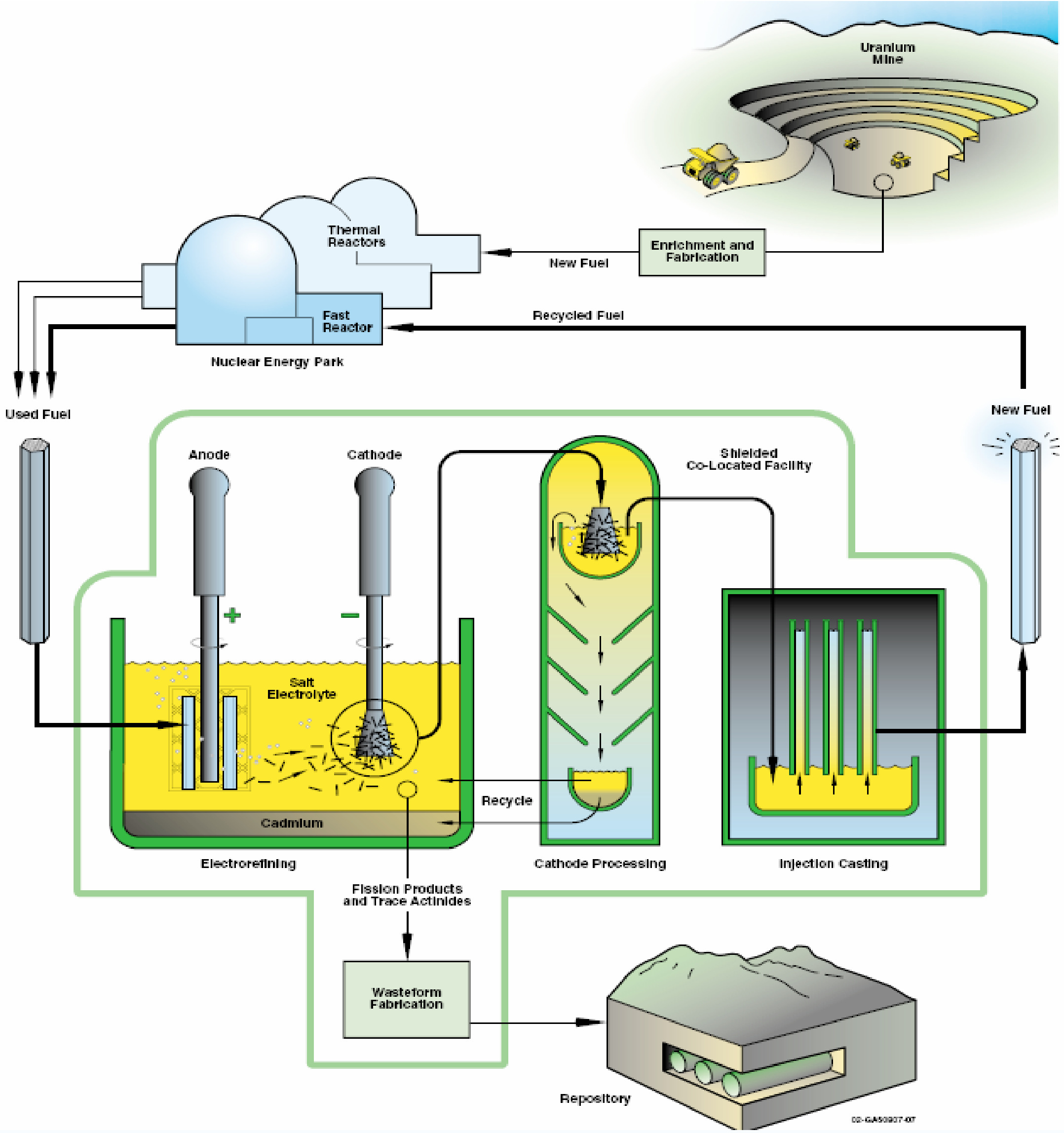
[1] The GFR proposes (U,Pu)C in ceramic-ceramic (cercer), coated particles or ceramic-metallic (cermet).

[2] The MSR employs a molten fluoride salt fuel and coolant, and fluoride-based processes for recycle.

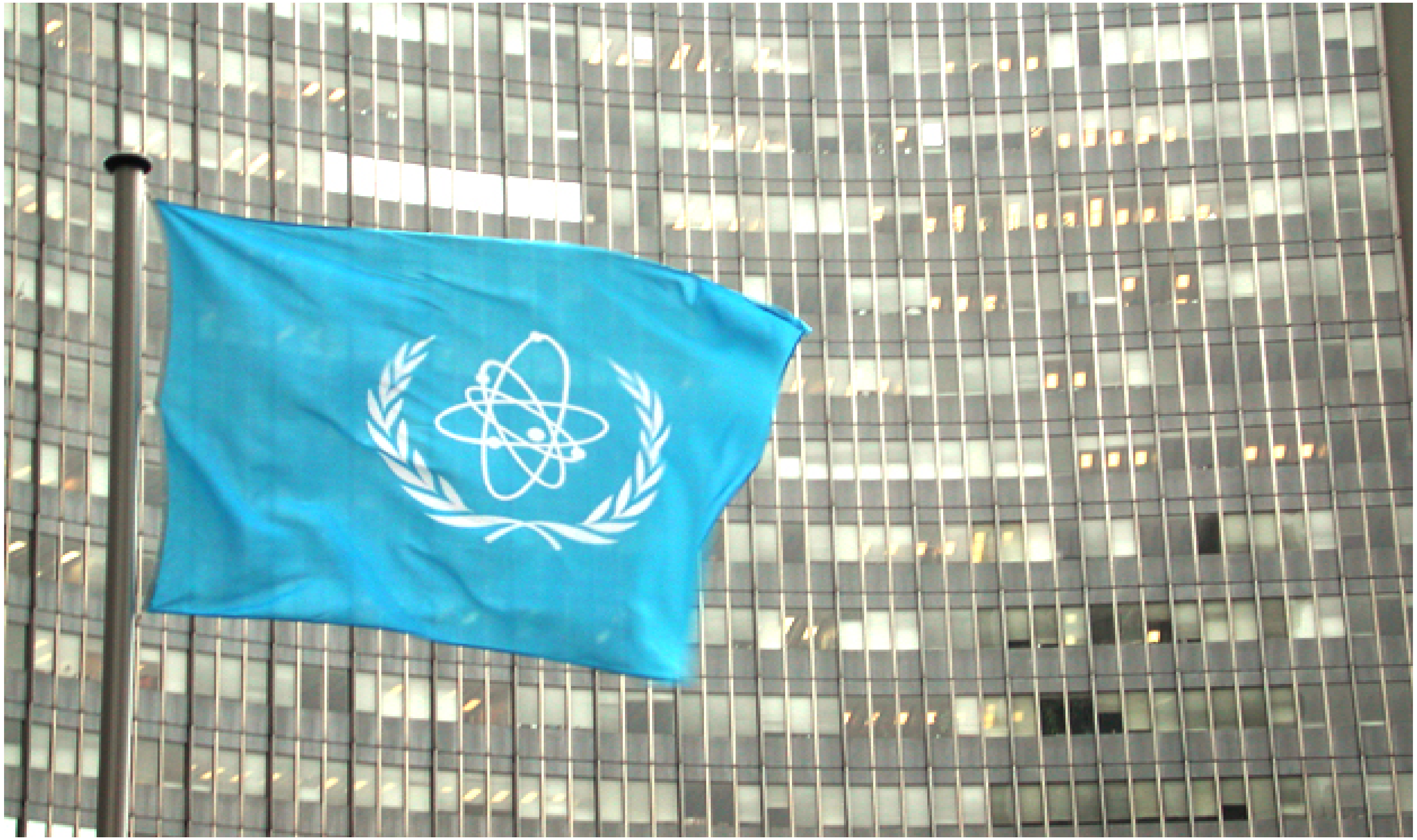
[3] The SFR has two options: oxide fuel with advanced aqueous, and metal fuel with pyroprocess.

[4] The VHTR uses a once-through fuel cycle with coated (UCO) fuel kernels, and no need for fuel treatment, as the primary option.


Uranium
Mine
Thermal
Reactors
New Fuel
Enrichment and
Fabrication
Recycled Fuel
Fast
Reactor
Nuclear Energy Park
Used Fuel
Assemblies
New Fuel
Assemblies
Uranium
Purification
Uranium
Fuel Rod
Shear
Organic
Solvent
Fuel
Fabrication
Centrifugal
Contactor
Plutonium,
Fission Products
and Actinides
Dissolver
Actinide
Separation
Cladding Hulls
Fission Products
and Trace Actinides
Wasteform
Fabrication
Shielded
Central Facility
Repository



Uranium Mine
Thermal Reactors
Enrichment and Fabrication
New Fuel
Fast Reactor
Recycled Fuel
Nuclear Energy Park
Used Fuel
New Fuel
Anode
Cathode
Shielded Co-Located Facility
Salt Electrolyte
Cadmium
Recycle
Electrorefining
Cathode Processing
Injection Casting
Fission Products and Trace Actinides
Wasteform Fabrication
Repository



…atoms for peace