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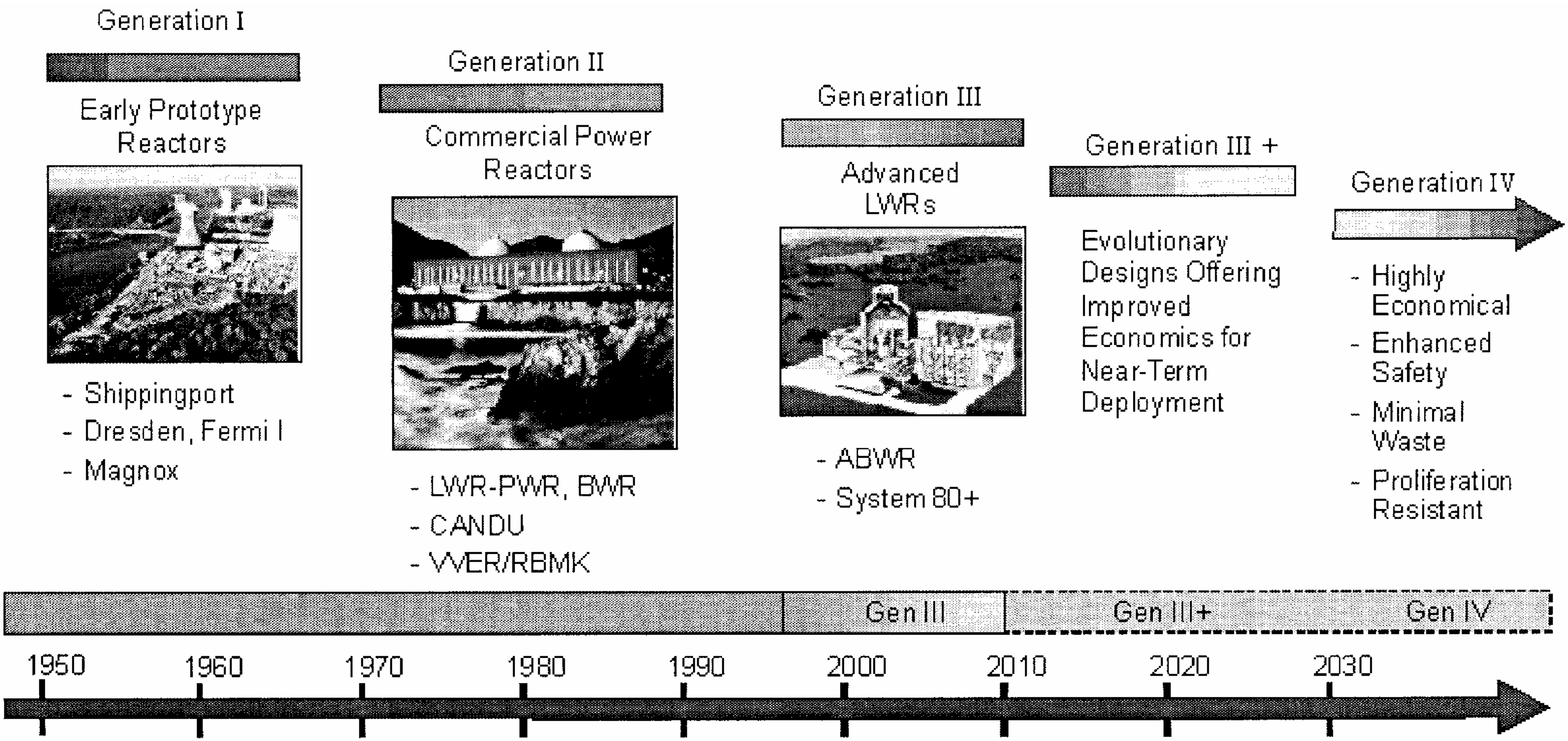
SUSTAINABLE ENERGY

Prof. Michael W. Golay

Nuclear Engineering Dept.

GENERATION-IV AND THE FUTURE OF NUCLEAR POWER

GENERATION IV TIMELINE



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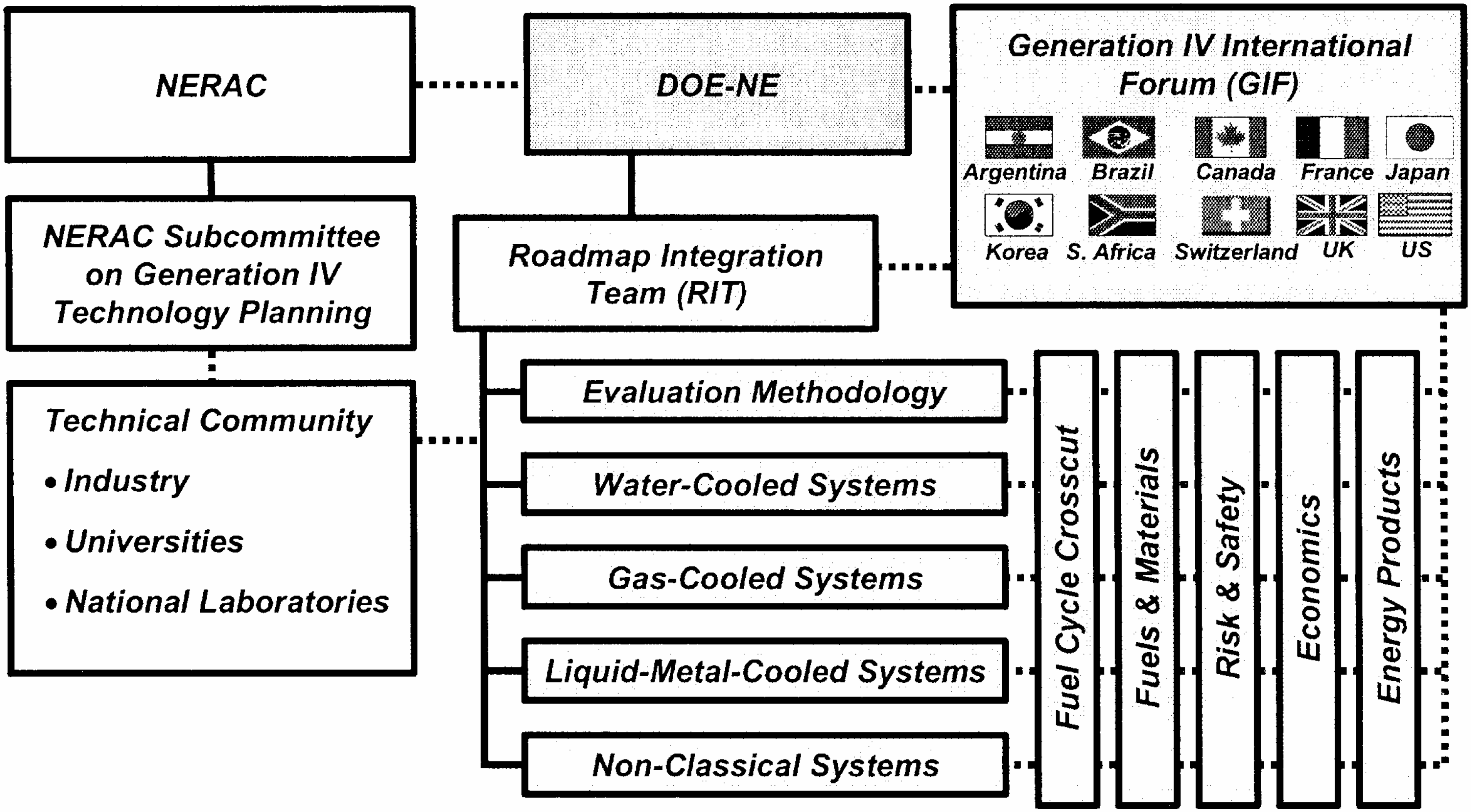
GOALS FOR GENERATION IV NUCLEAR ENERGY SYSTEMS

- **Sustainability-1** 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.
- **Sustainability-2** 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-1** Generation IV nuclear energy systems will have a clear life-cycle cost advantage over other energy systems.
- **Economics-2** Generation IV nuclear energy systems will have a level of financial risk comparable to other energy projects.

GOALS FOR GENERATION IV NUCLEAR ENERGY SYSTEMS, continued

- **Safety and Reliability-1** Generation IV nuclear energy systems operations will excel in safety and reliability.
- **Safety and Reliability-2** Generation IV nuclear energy systems will have a very low likelihood and degree of reactor core damage.
- **Safety and Reliability-3** Generation IV nuclear energy systems will eliminate the need for offsite emergency response.
- **Proliferation Resistance and Physical Protection-1** Generation IV will increase the assurance that they are a very unattractive and the leave desirable route for diversion or theft of weapons-usable materials, and provide increased physical protection against acts of terrorism.

THE GENERATION IV ROADMAP PROJECT



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ROLLUP 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 – low 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*

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GENERATION IV
NUCLEAR ENERGY SYSTEMS

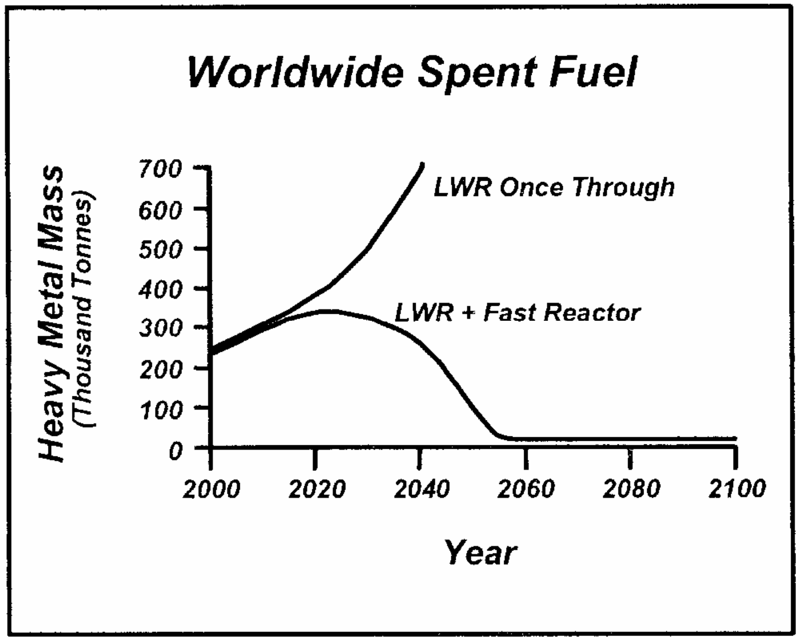
The Motivation for the Selection of Six Systems is to

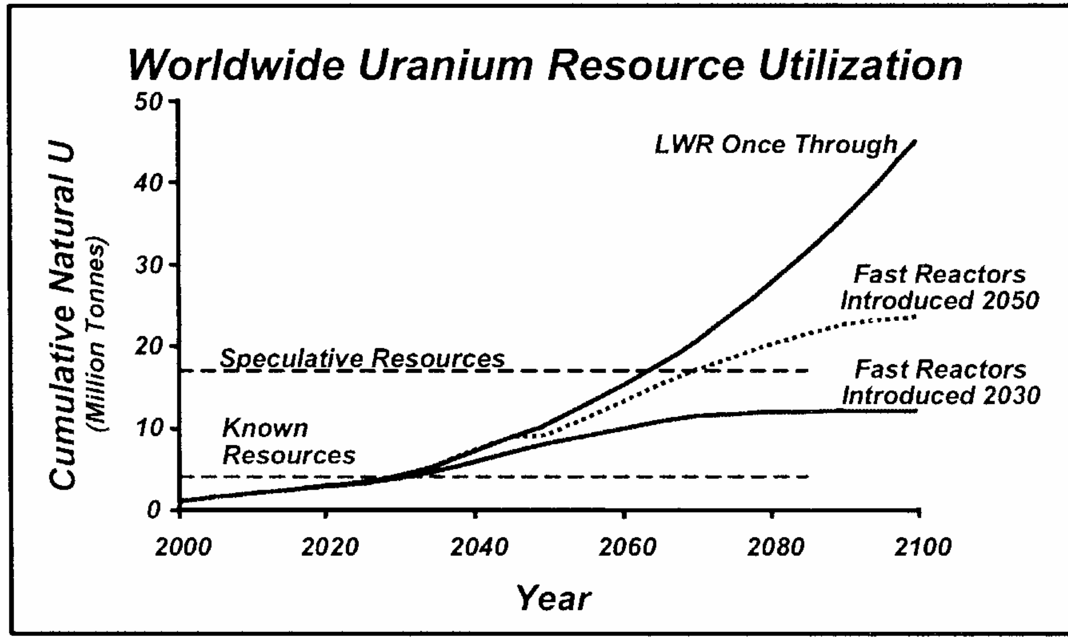
- Identify systems that make significant advances toward the technology goals
- Ensure that the important missions of electricity generation, hydrogen and process heat production, and actinide management may be adequately addressed by Generation IV systems
- Provide some overlapping coverage of capabilities, because not all of the systems may ultimately be viable or attain their performance objectives and attract commercial deployment.
- Accommodate the range of national priorities and interest of the GIF countries.

SIX SYSTEMS SELECTED TO GENERATION IV BY THE GIF

GENERATION IV SYSTEM	ACRONYM
Gas-Cooled Fast Reactor System	GFR
Lead-Cooled Fast Reactor System	LFR
Molten Salt Reactor System	MSR
Sodium-Cooled Fast Reactor System	SFR
Supercritical Water-Cooled Reactor System	SCWR
Very-High-Temperature Reactor System	VHTR

FUEL CYCLES AND SUSTAINABILITY





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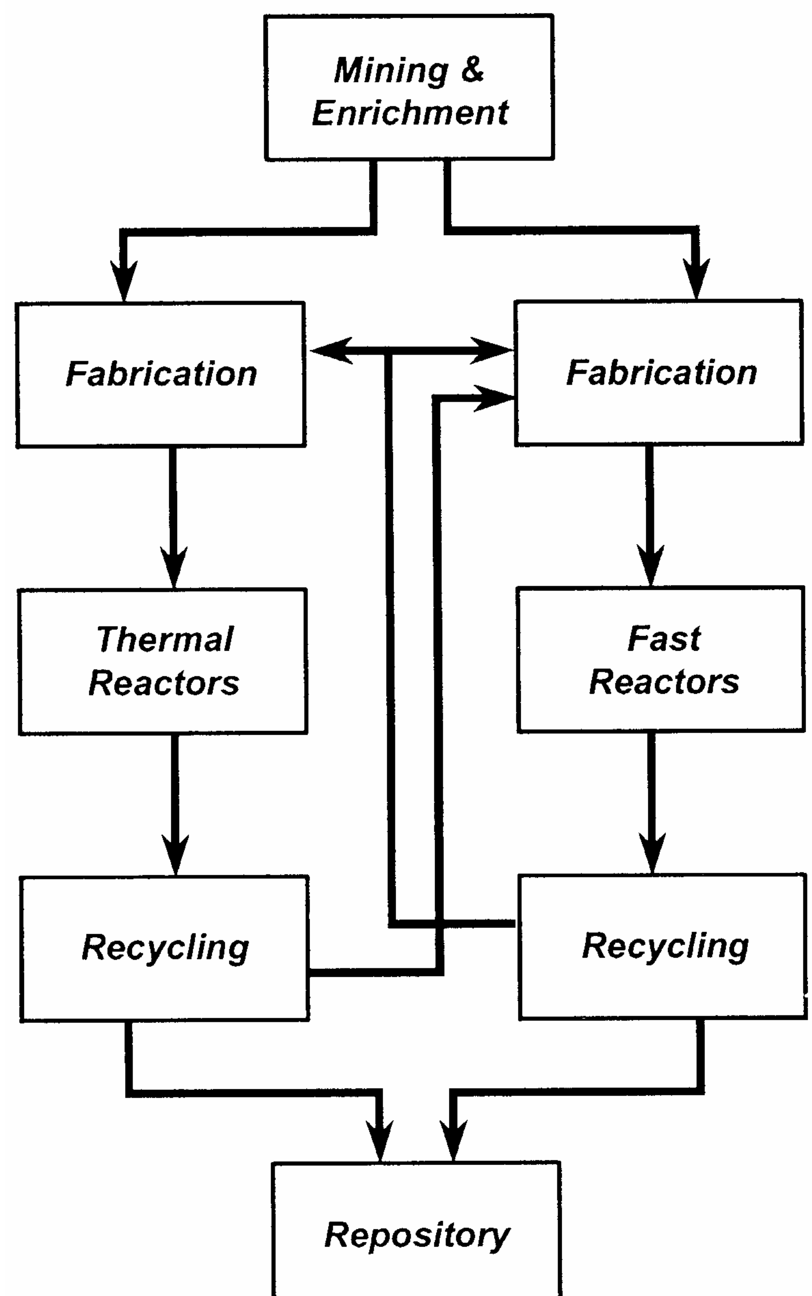
SYMBIOTIC FUEL CYCLES



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MISSIONS AND ECONOMICS FOR GENERATION IV

Electricity Production	**Both**	**Hydrogen Production**
• SCWR • SFR	• GFR • LFR • MSR	• VHTR

500°C ——— Outlet Temperature ———→ 1000°C

MISSIONS AND ECONOMICS FOR GENERATION IV, continued

Once-Through Fuel Cycle

- VHTR

Either

- SCWR

Actinide Management

- GFR
- LFR
- MSR
- SFR

MISSIONS AND ECONOMICS FOR GENERATION IV, continued

Large Monolithic

- LFR*
- MSR
- SFR*
- SCWR

Mid-size

- GFR
- VHTR
- SFR*

Small Modular

- LFR*

* Range of options

U.S. NEAR-TERM DEPLOYMENT (NTD)

- ABWR (Advanced Boiling Water Reactor)
- AP1000 (Advanced Pressurized Water Reactor 1000 MWe)
- ESBWR (European Simplified Boiling Water Reactor)
- GT-MHR (Gas Turbine-Modular High Temperature Reactor)
- PBMR (Pebble Bed Modular Reactor)
- SWR-1000 (Siedewasser Reactor-1000)

U.S. Near-Term Deployment (by 2010)
ABWR AP1000 ESBWR GT-MHR PBMR SWR-1000

INTERNATIONAL NEAR-TERM DEPLOYMENT

Advanced Boiling Water Reactors

- ABWR II (Advanced Boiling Water Reactor II)
- ESBWR (European Simplified Boiling Water Reactor)
- HC-BWR (High Conversion Boiling Water Reactor)
- SWR-1000 (Siedewasser Reactor-1000)

Advance Pressure Tube Reactor

- ACR-700 (Advanced CANDU Reactor 700)

Advanced Pressurized Water Reactors

- AP600 (Advanced Pressurized Water Reactor 600)
- AP1000 (Advanced Pressurized Water Reactor 1000)
- APR1400 (Advanced Power Reactor 1400)
- APWR+ (Advanced Pressurized Water Reactor Plus)
- EPR (European Pressurized Water Reactor)

International Near-Term Deployment (by 2015)
ABWR II ACR-700 AP600 AP1000 APR1400 APWR+ CAREM EPR ESBWR GT-MHR IMR IRIS PBMR SMART SWR-1000

Integral Primary Systems Reactors

- CAREM (Central Argentina de Elementos Modulares)
- IMR (International Modular Reactor)
- IRIS (International Reactor Innovative and Secure)
- SMART (System-Integrated Modular Advanced Reactor)

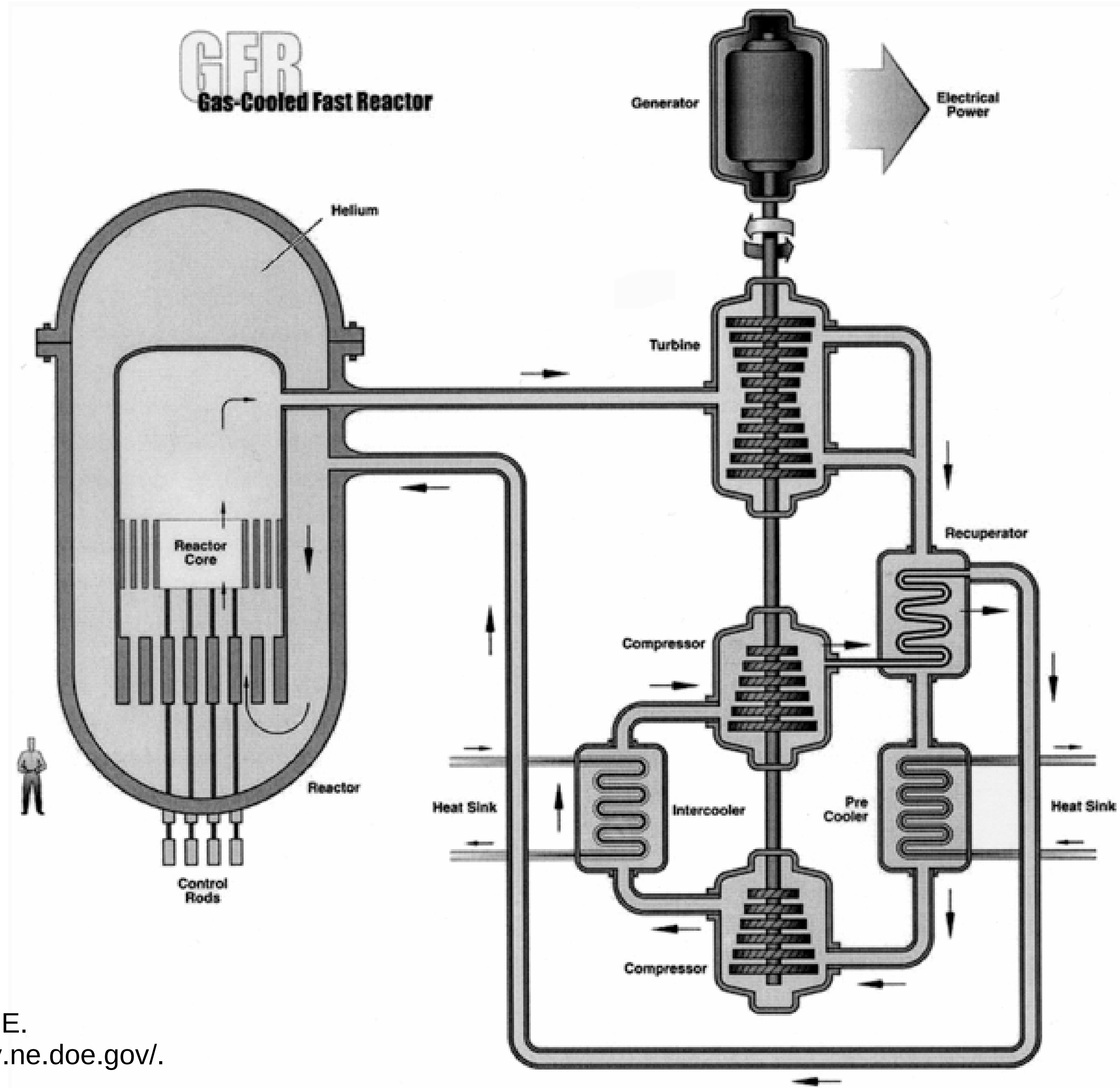
Modular High Temperature Gas-Cooled Reactors

- GT-MHR (Gas Turbine-Modular High Temperature Reactor)
- PBMR (Pebble Bed Modular Reactor)

GENERATION IV DEPLOYMENT

Generation IV System	Best Case Deployment Date
SFR	2020
VHTR	2020
GFR	2025
MSR	2025
SCWR	2025
LFR	2025

GAS-COOLED FAST REACTOR



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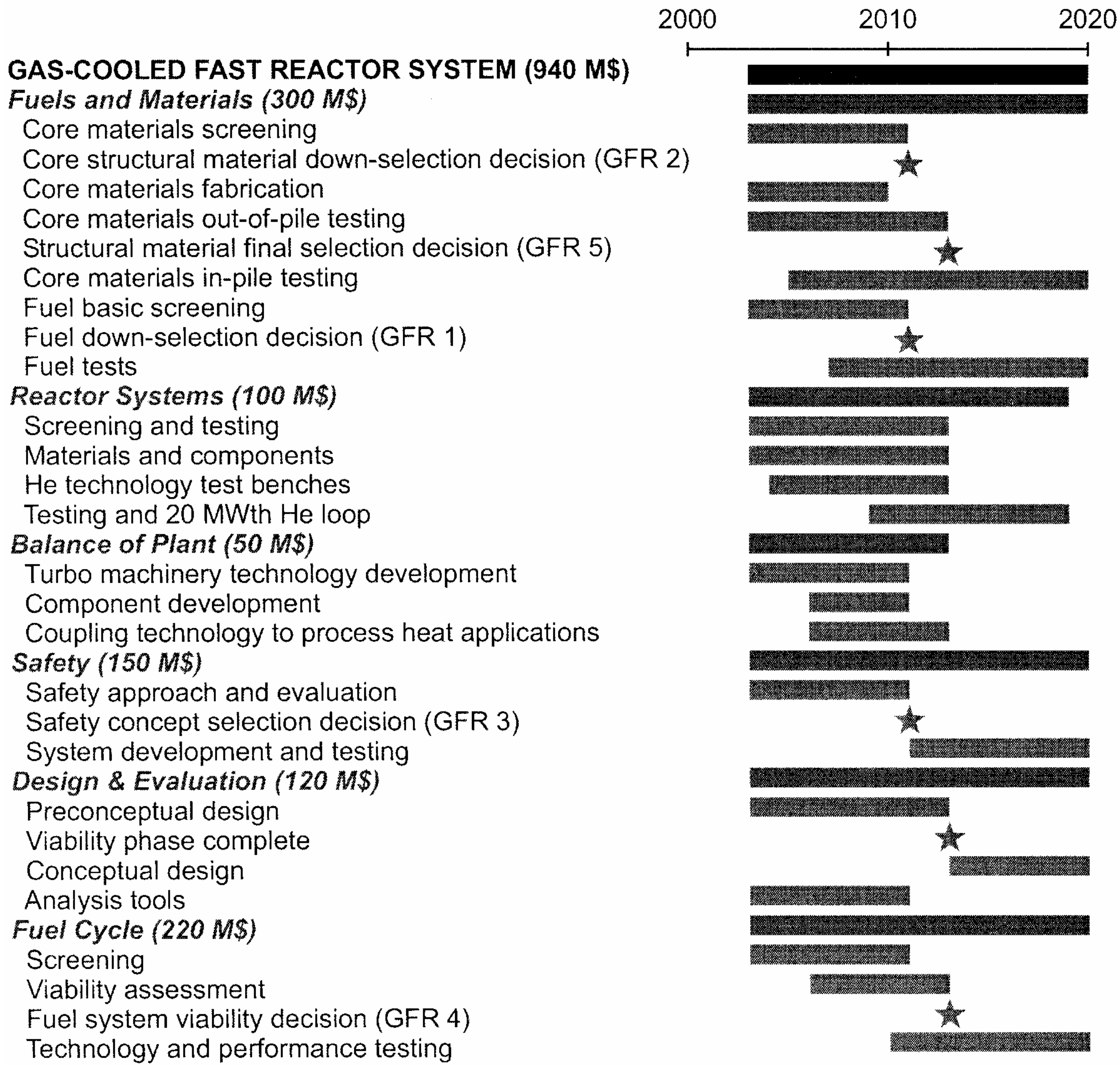
DESIGN PARAMETERS FOR THE GFR SYSTEM

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/m^3
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 pda

GFR R&D SCHEDULE AND COSTS



★ = decision points

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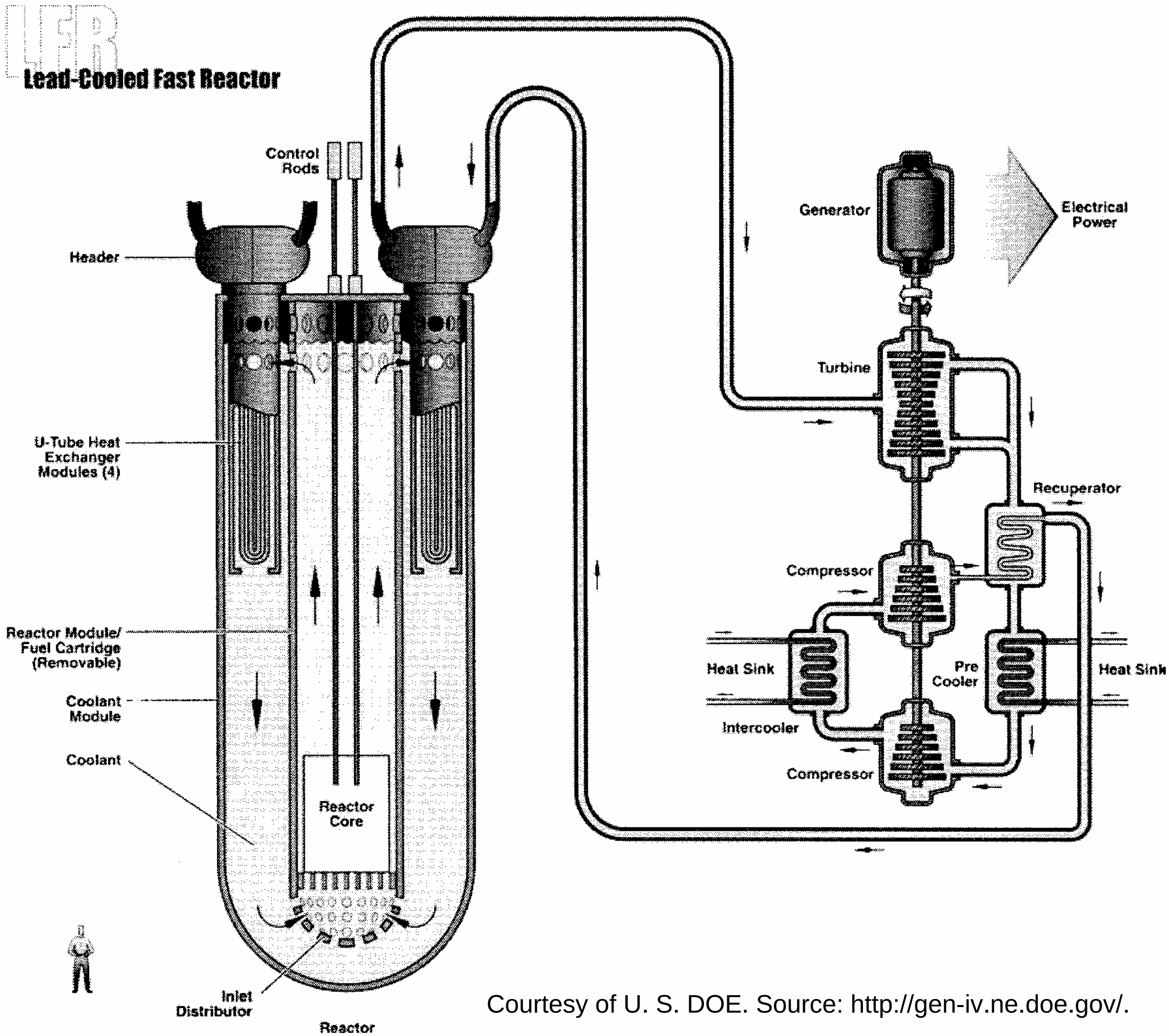
LEAD-COOLED FAST REACTOR



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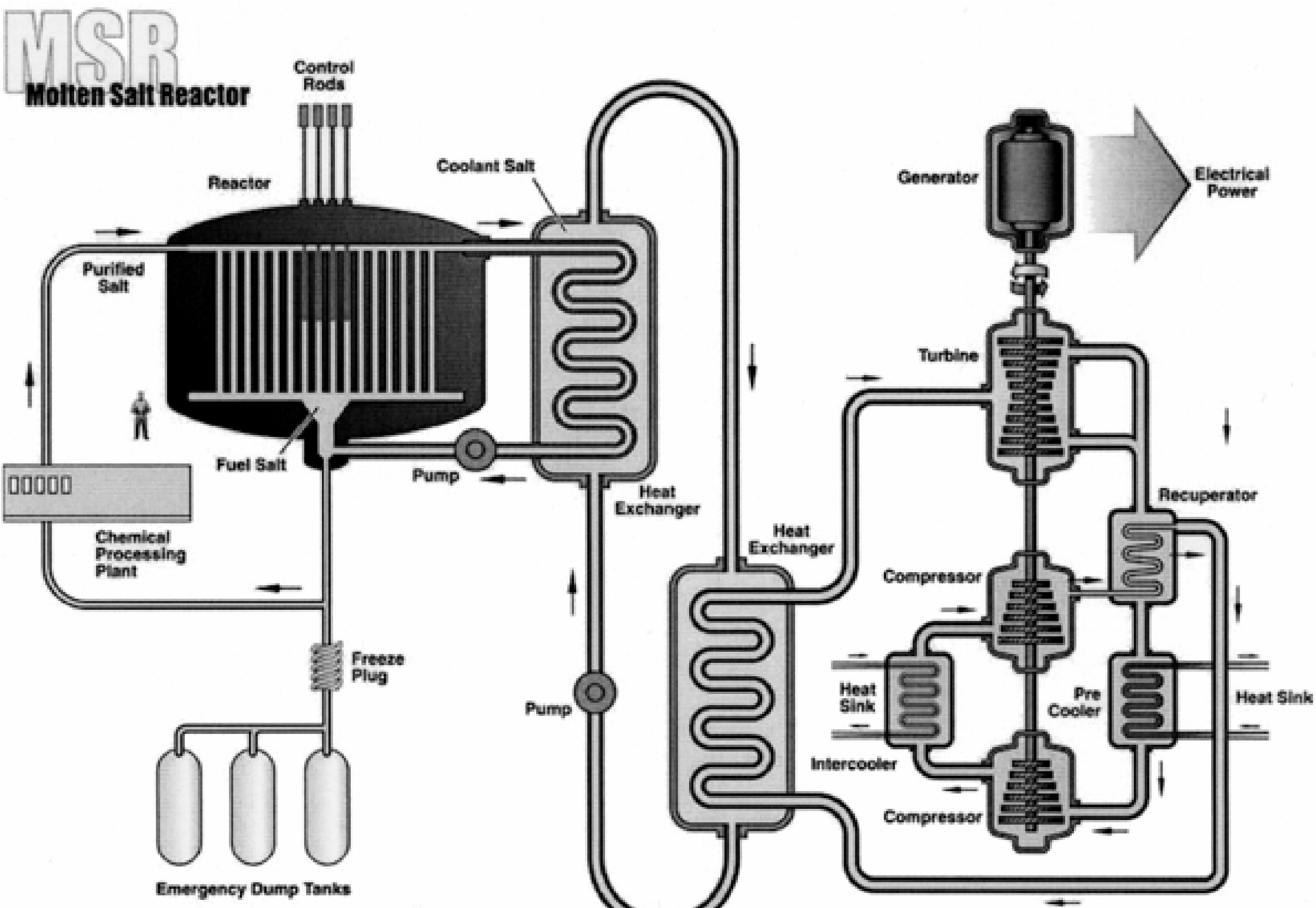
DESIGN PARAMETERS FOR THE LFR SYSTEM

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	≤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	Derated

IMPORTANT R&D AREAS FOR EACH OPTION

Major R&D Areas	Pb-Bi Battery (nearer-term)	Pb-Bi Module (nearer-term)	Pb Large (nearer-term)	Pb Battery (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:				
Factory Fabrication	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

MOLTEN SALT REACTOR



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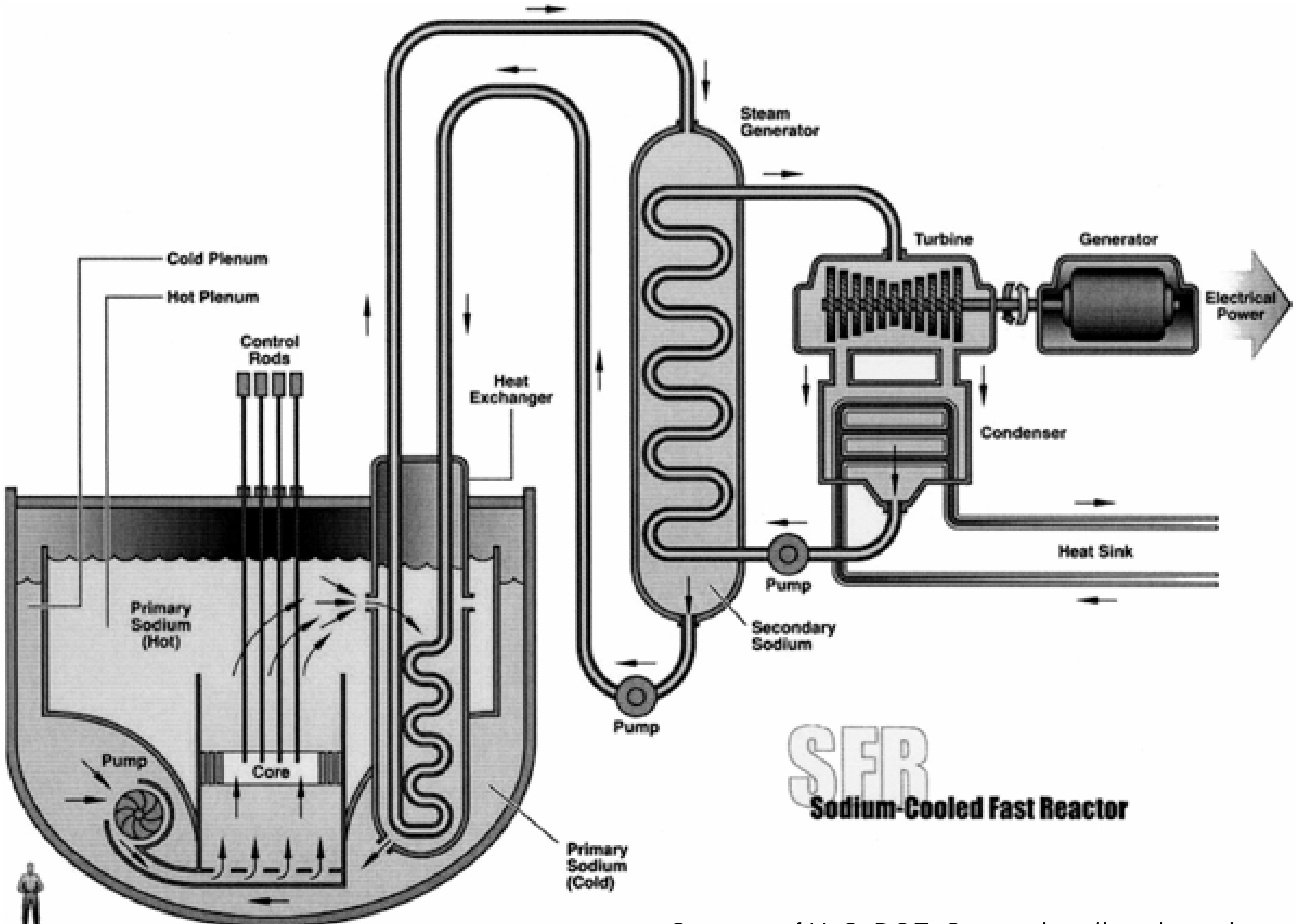
REFERENCE DESIGN PARAMETERS FOR THE MSR

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

SODIUM-COOLED FAST REACTOR



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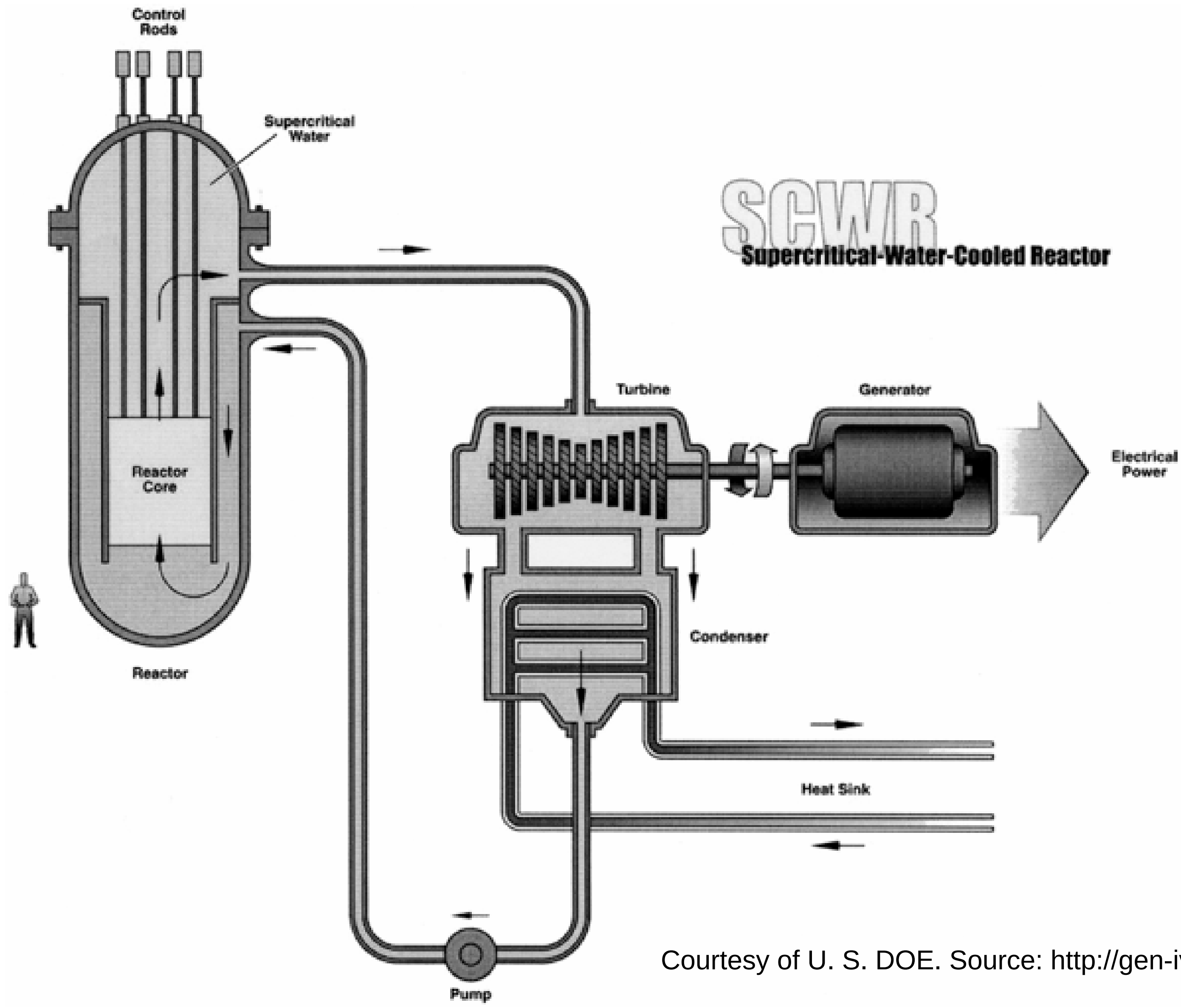
DESIGN PARAMETERS FOR THE SFR SYSTEM

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	340 MWth/m^3

SUPERCRITICAL-WATER-COOLED REACTOR



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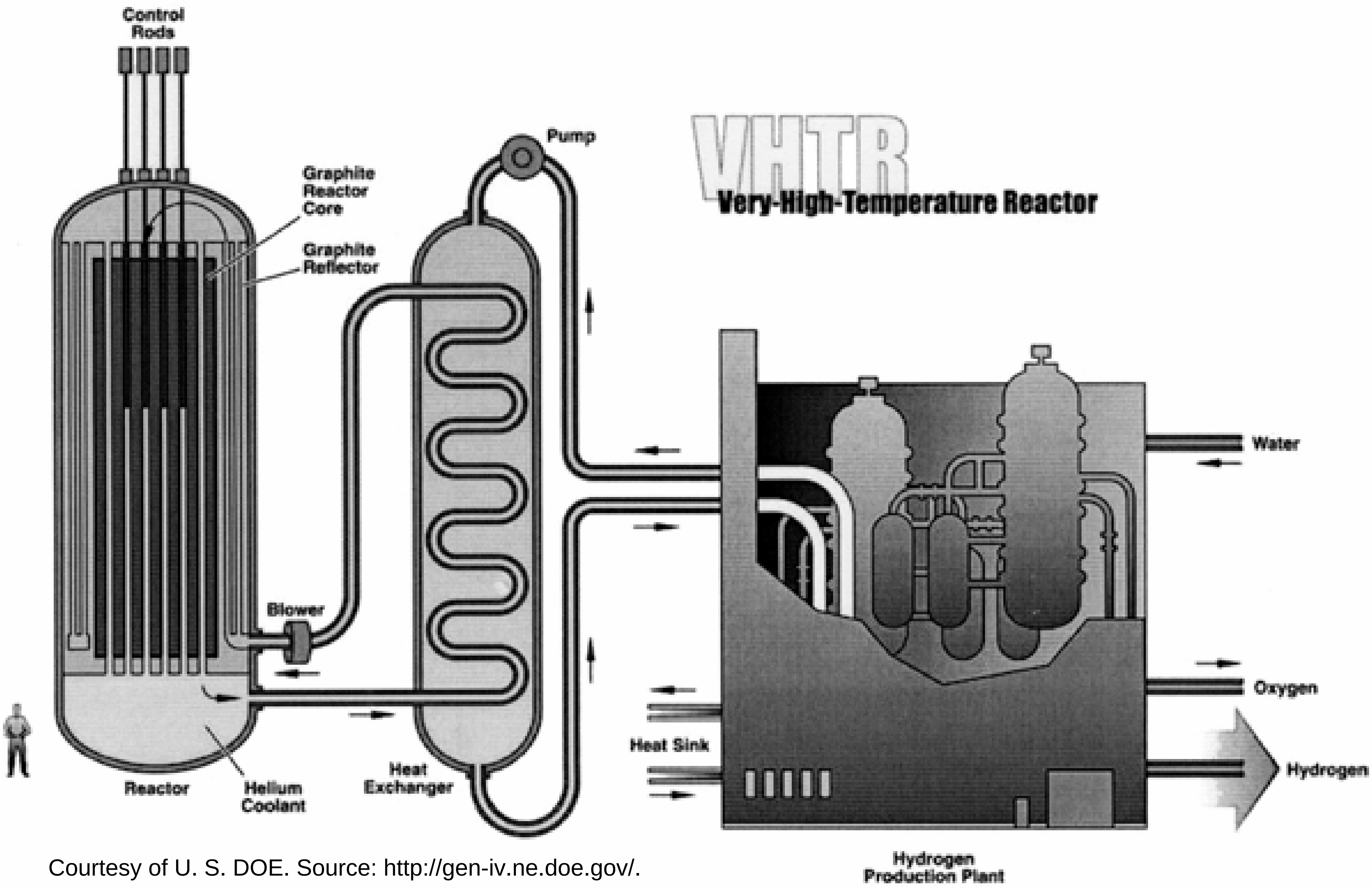
DESIGN PARAMETERS FOR THE SCWR SYSTEM

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	280ЕC/510ЕC/25 MPa
Average power density	~100 MWth/m^3
Reference fuel	UO2 with austenitic or ferritic-martensitic stainless steel, or Ni-alloy cladding
Fuel structural materials cladding structural materials	Advanced high-strenght metal alloys are needed
Burnup/Damage	~45 GWD/MTHM; 10-30 dpa
Safety approach	Similar to ALWRs

VERY-HIGH-TEMPERATURE REACTOR



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DESIGN PARAMETERS CONSIDERED FOR THE VHTR

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%

RECOMMENDED CROSSCUTTING R&D

- Fuel Cycle
- Fuels and Materials
- Energy Products
- Risk and Safety
- Economics
- Proliferation Resistance and Physical Protection

OPTIONS FOR FUEL AND RECYCLE TECHNOLOGY DEVELOPMENT

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

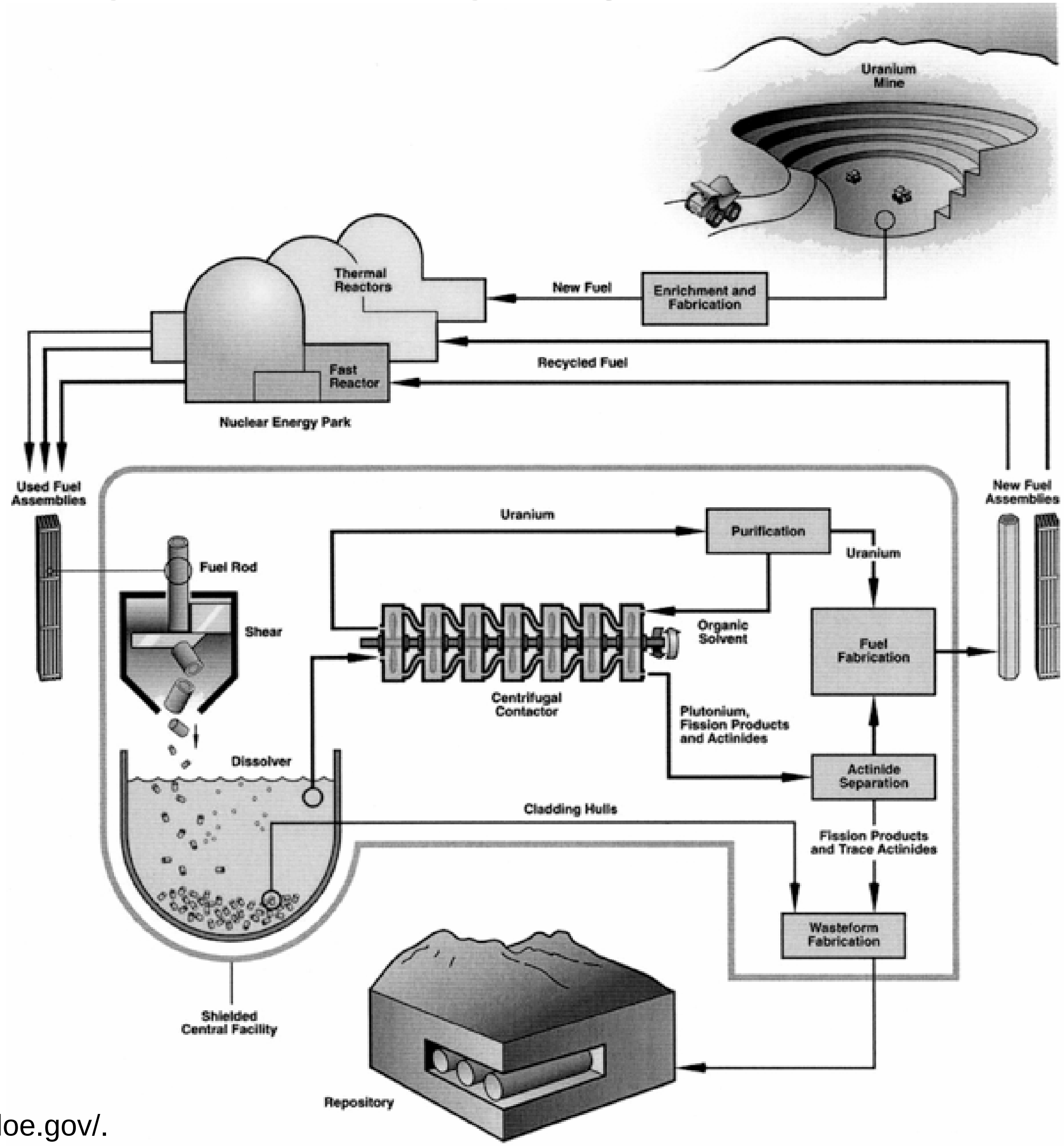
1 The GFR proposes (U,Pu)C in ceramic-ceramic (cercer), coated particles or ceramic-metallic (cermet).

2 The MSR employs a molten fluoride salt fuel and coolant, and a fluoride based pyroprocess 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.

ADVANCED AQUEOUS PROCESS AND REMOTE CERAMIC FUEL FABRICATION



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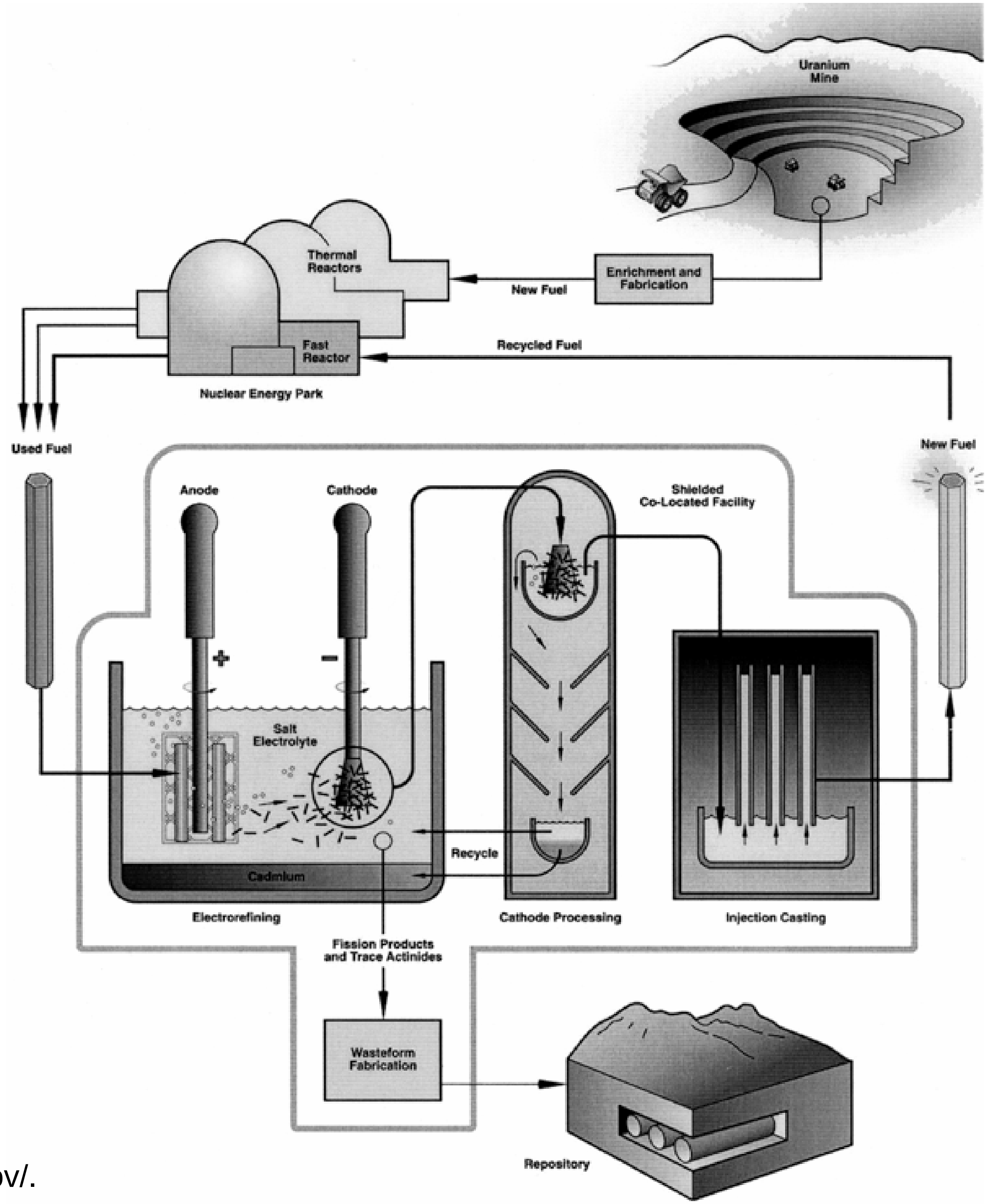
PYROPROCESS AND REMOTE METAL FUEL FABRICATION



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R&D ENDPOINTS

Viability Phase Objective:	**Performance Phase Objective:**
Basic concepts, technologies and processes are proven out under relevant conditions, with all potential technical *show-stoppers* identified and resolved.	Engineering-scale processes, phenomena, and materials capabilities are verified and optimized under prototypical conditions

Viability Phase Endpoints:	**Performance Phase Endpoints:**
1. Preconceptual design of the entire system, with nominal interface requirements between subsystems and established pathways for disposal of all waste streams	1. Conceptual design of the entire system, sufficient for procurement specifications for construction of a prototype or demonstration plant, and with validated acceptability of disposal of all waste streams
2. Basic fuel cycle and energy conversion (if applicable) process flowsheets established through testing at appropriate scale	2. Processes validated at scale sufficient for demonstration plant
3. Cost analysis based on preconceptual design	3. Detailed cost evaluation for the system
4. Simplified PRA for the system	4. PRA for the system
5. Definition of analytical tools	5. Validation of analytical tools
6. Preconceptual design and analysis of safety features	6. Demonstration of safety features through testing, analysis, or relevant experience
7. Simplified preliminary environmental impact statement for the system	7. Environmental impact statement for the system
8. Preliminary safeguards and physical protection strategy	8. Safeguards and physical protection strategy for system, including cost estimate for extrinsic features
9. Consultation(s) with regulatory agency on safety approach and framework issues	9. Pre-application meeting(s) with regulatory agency

DECISION MILESTONES AND THEIR PROJECTED DATES

System	Viability Phase Decisions	Date
GFR	• Fuel down-selection (GFR 1)	2010
	• Core structural materials down-selection (GFR 2)	2010
	• Safety concept specification (GFR 3)	2010
	• Fuel recycle viability (GFR 4)	2012
	• Structural material final selection (GFR 5)	2012
LFR	• Structural material selection (550EC outlet temperature) (LFR 1)	2007
	• Nitride fuel fabrication method (LFR 2)	2010
	• Feasibility of transportable reactor/core cartridge (LFR 3)	2010
	• Feasibility/selection of structural material for 800EC Pb (LFR 5)	2012
	• Nitride fuel recycle method (LFR 4)	2014
	• Adequacy of nitride fuel performance potential (LFR 6)	2014
	• Ca-Br hydrogen production process (LFR 7)	2014
	• Supercritical CO_2 Brayton cycle (LFR 8)	2014
MSR	• Core materials selection (MSR 1)	2006
	• Fuel salt selection (MSR 2)	2007
	• Power cycle (with tritium control) (MSR 3)	2009
	• Fuel treatment (fission product removal) approach (MSR 4)	2012
	• Noble metal management (MSR 5)	2012
	• Viability of materials (MSR 6)	2013

DECISION MILESTONES AND THEIR PROJECTED DATES, continued

System	Viability Phase Decisions	Date
SFR	• Oxide fuel remote fabrication technology selection (SFR 1)	2006
SCWR	• Safety approach specification (SC 1)	2008
	• Core structural material down-selection (SC 2)	2011
	• Core structural material final selection (SC 3)	2014
	• Advanced aqueous process application to recycle (SC 4)	2014
	• Fuel/cladding system viability (SC 5)	2014
VHTR	• Reactor/hydrogen production process coupling approach (VH 1)	2010
	• Identification of targeted operating temperature (VH 2)	2010
	• Fuel coating material and design concept VH 3)	2010
	• Adequacy of fuel performance potential (VH 5)	2010
	• Reactor structural material selection (VH 4)	2010

DECISION MILESTONES AND THEIR PROJECTED DATES, continued

Crosscut	Viability Phase Decisions	Date
Fuel Cycle	• Adequacy of actinide fraction (advanced aqueous) (FC 1) • Pyroprocess recycle for LWR spent fuel (FC 2) • Adequacy of actinide recovery fraction (pyroprocess) (FC 3) • Recommendation on separate management of Cs, Sr (FC 4) • Integrated management of once-through cycle (FC 5) • Group extraction of actinides in aqueous process (FC 6)	2006 2006 2006 2007 2007 2009
Fuels and Materials	• Requirements for irradiation and transient test facilities (FM 1)	2005
Energy Products	• Requirements for hydrogen production (EP 1) • Hydrogen thermochemical production demonstration (EP 2)	2006 2011
Economics	• Viability of modular fabrication and installation technologies (EC 1)	2008

PRODUCTION PHASE R&D ACTIVITIES

System	Prioritized Performance Phase R&D Issues
GFR	• Fuel and materials performance • Safety performance • Recycle performance • Economics performance • Balance-of-plant performance
LFR	• Fuel and materials performance • Recycle performance • Economics performance • Balance-of-plant performance • Safety performance • Inspection and maintenance methods
MSR	• Fuel treatment performance • Balance-of-plant performance • Safety performance • Materials performance • Reliability performance • Economics performance • Inspection and maintenance methods
SFR	• Economics performance • Recycle performance at scale • Passive safety confirmation
SCWR	• Fuels and materials performance • Safety performance • Economics performance • Recycle performance
VHTR	• Fuel and materials performance • Economics performance • Safety performance • Balance-of-plant performance

A Window of Opportunity has Reopened

EXISTING U.S. NUCLEAR FLEET

- Enhanced Operations
- Power Uprates
- License Extension
- NRC Oversight & Risk Informed Regulation

ENERGY FUTURE

- Air Quality & Global Warming
- Economics - Natural Gas Prices
- Energy Demand

NUCLEAR POWER 2010 PROGRAM

Courtesy of U. S. DOE. Source: http://gen-iv.ne.doe.gov/.

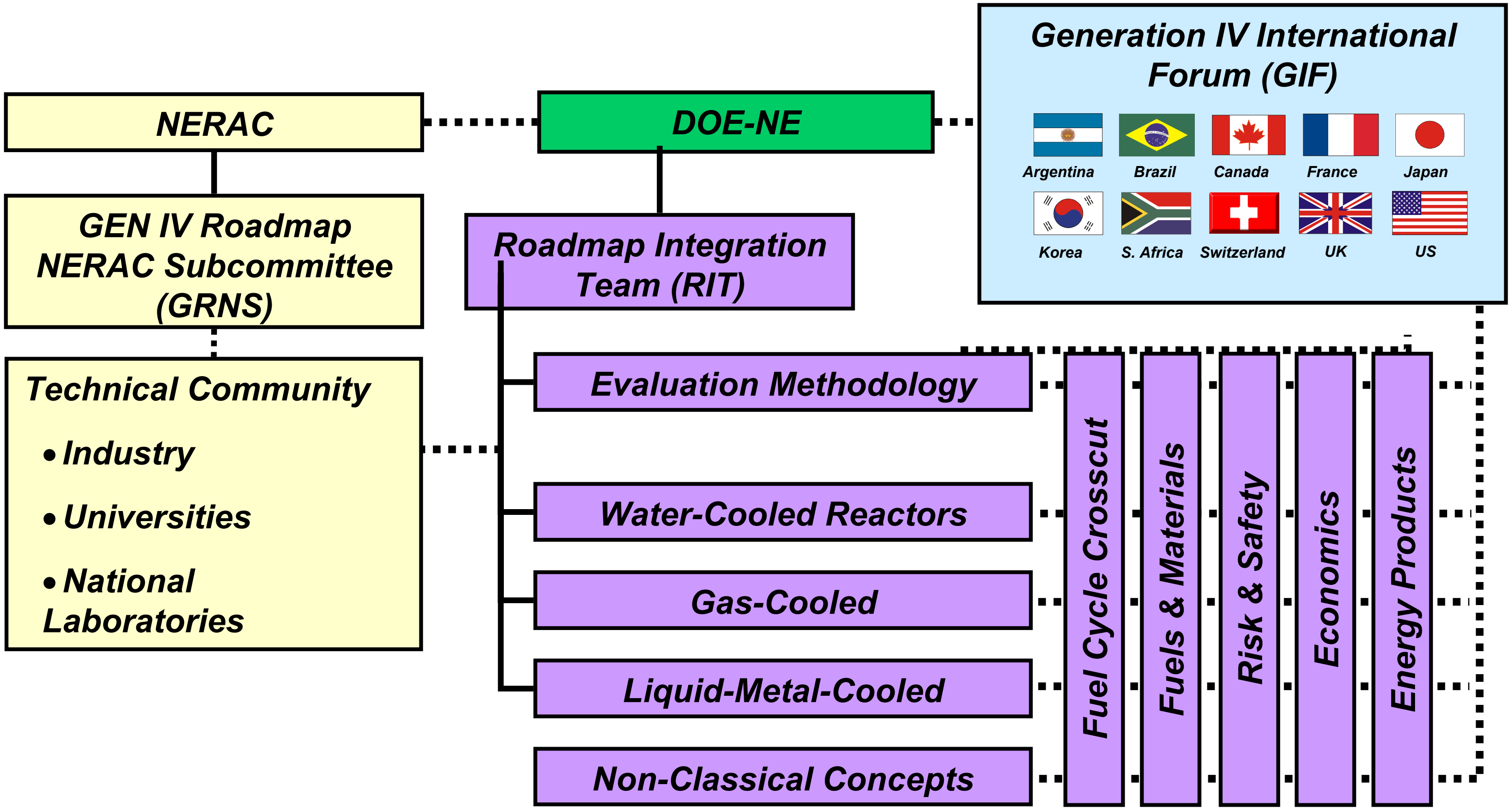
What is the GENIV Program?

Generation IV is a new generation of nuclear energy systems that can be made available to the market by 2030 or earlier, and that offer significant advances toward challenging Goals defined in the broad areas of sustainability, safety and reliability, and economics.

- **Systems** - includes the entire fuel cycle.
- **2030 or earlier** - how linked to deployment in next 10 years?
- **Made available to market** - but will not necessarily be commercialized.
- **Goals** - a major challenge which importantly involve fuel cycle options.

Organization of Working Groups

- *Technical Working Groups (horizontal)*
- *Crosscut Groups (vertical)*



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Guiding Principles

- ***Technology goals for Generation IV systems must be challenging and stimulate the development of innovative systems.***

- ***Generation IV systems must be responsive to energy needs worldwide.***

- ***Generation IV concepts must define complete nuclear energy systems, not simply reactor technologies.***

- ***All candidates should be evaluated against the goals on the basis of their benefits, costs, risks, and uncertainties, with no technologies excluded at the outset.***

Generation IV System Technology Goals

SUSTAINABILITY

Sustainability is the ability to meet the needs of present generations while enhancing and not jeopardizing the ability of future generations to meet society's needs indefinitely into the future.

Goals on: Fuel utilization, Waste stewardship

SAFETY AND RELIABILITY

Safety and reliability are essential priorities in the development and operation of nuclear energy systems.

Goals on: Reliability, low core damage frequency, eliminate need for offsite emergency response

Generation IV System Technology Goals

ECONOMICS

Economic competitiveness is a requirement of the marketplace and is essential for Generation IV nuclear energy systems.

Goals on: Life-cycle cost advantage, comparable level of financial risk

PROLIFERATION & PHYSICAL SECURITY

Proliferation resistance and physical protection are essential priorities in the expanding role of nuclear energy systems

Goals on: Unattractive and least desirable route for diversion/theft, increased physical protection against acts of terrorism

Courtesy of U. S. DOE. Source: http://gen-iv.ne.doe.gov/.

Six Generation IV Concepts Selected For Further Development

- **Once-through or MOX fuel cycle:**
  - **Supercritical-water-cooled reactor - SCWR - T**
  - **Very-high-temperature gas-cooled reactor - VHTR**

- **Full actinide recycle:**
  - **Sodium-cooled fast-spectrum reactor - SFR**
  - **Lead/bismuth-cooled fast-spectrum reactor - LFR**
  - **Gas-cooled fast-spectrum reactor - GFR**
  - **Molten salt reactor - MSR**

Generation IV System 'Portfolio'

Products

Electricity Production	*Both*	*Hydrogen Production*
– *SCWR*	– *GFR*	– *VHTR*
– *SFR*	– *LFR*	
	– *MSR*	

500°C → Outlet Temperature → 1000°C

Plant Size

Large Monolithic	*Mid-size*	*Small Modular*
– *LFR**	– *GFR*	– *LFR**
– *MSR*	– *VHTR*	
– *SFR**	– *SFR**	
– *SCWR*		

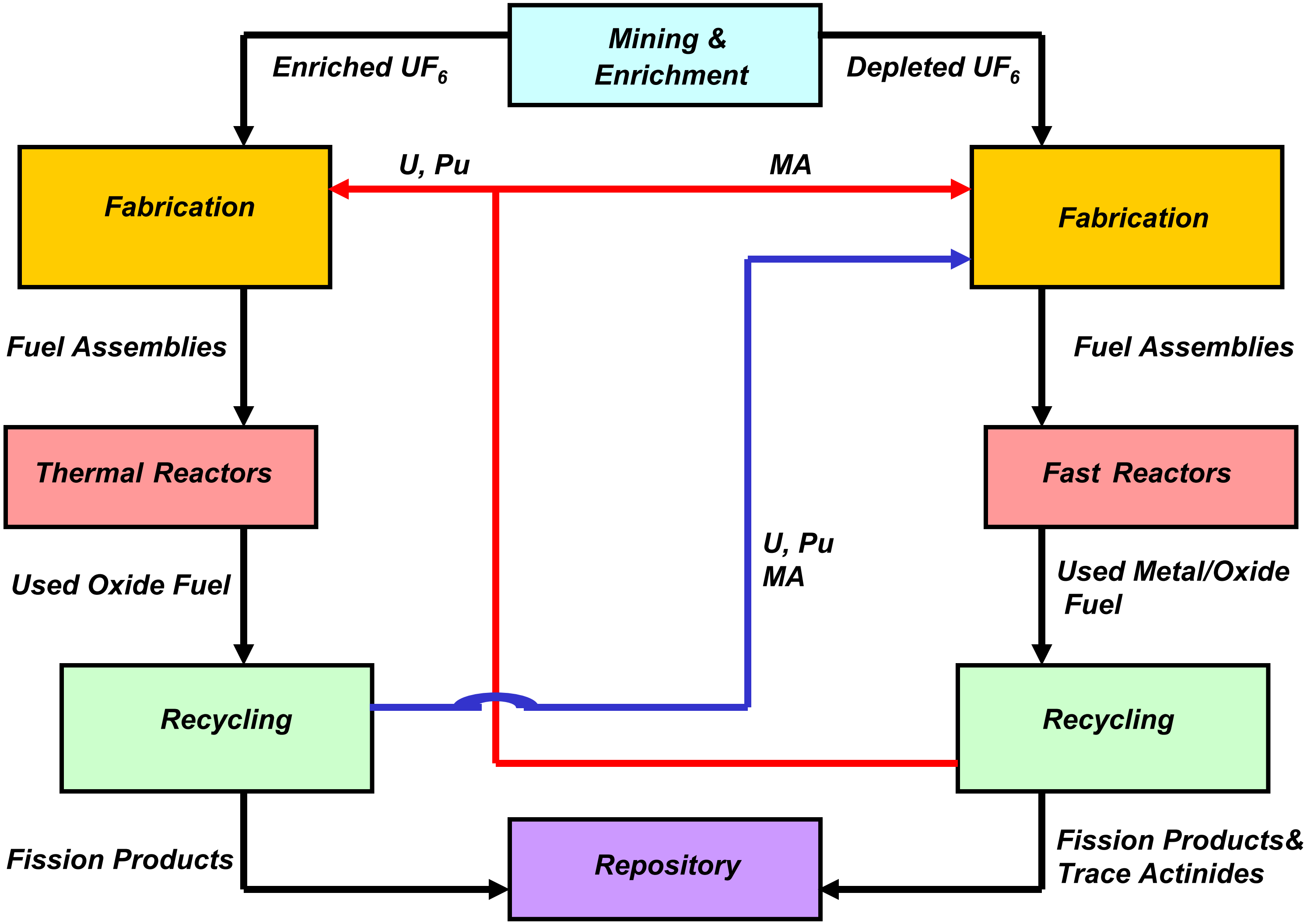
** Range of options*

Fuel Cycle

Once-Through Fuel Cycle	*Either*	*Actinide Management*
– *VHTR*	– *SCWR*	– *GFR*
		– *LFR*
		– *MSR*
		– *SFR*

Courtesy of U. S. DOE. Source: http://gen-iv.ne.doe.gov/.

The Portfolio Supports Symbiotic Fuel Cycles



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Future Challenges

1. **A Near Term Deployment program that leads to new construction.**

2. **A LWR concept that can serve as a bridge to future Generation IV concepts.**

3. **An R&D program that emphasizes fuel cycle activity.**

Prognosis

Factors that could significantly effect these Challenges

- **Air Quality & Global Climate Change are emerging as overriding issues.**
- **Sustainability issue may become dominant.**
- **Fuel Utilization - Scarcity - related price escalation should be far in the future.**
- **Economics eventually prevails (or does it?).**
- **Radiation Standards may be altered - Linear No Threshold Hypothesis.**

The Devil is in the details - Paper Reactors

Paper Reactors, Real Reactors

(H.G. Rickover, The Journal of Reactor Science & Engineering, June 1953)

Characteristics of an Academic Plant

- It is simple.
- It is small.
- It is cheap.
- It is light.
- It is can be built quickly.

- It is very flexible in its purpose.
- Very little development is required. It will use mostly off-the-shelf components.
- The reactor is in study phase. It is not being built now.

Characteristics of a Practical Reactor Plant

- It is being built now.
- It is behind schedule.
- It is very expensive.

- It is large.
- It is heavy.
- It is complicated.

- It is requiring an immense amount of development on apparently trivial items. Corrosion, in particular, is a problem.
- It takes a long time to build because of the engineering development problems.

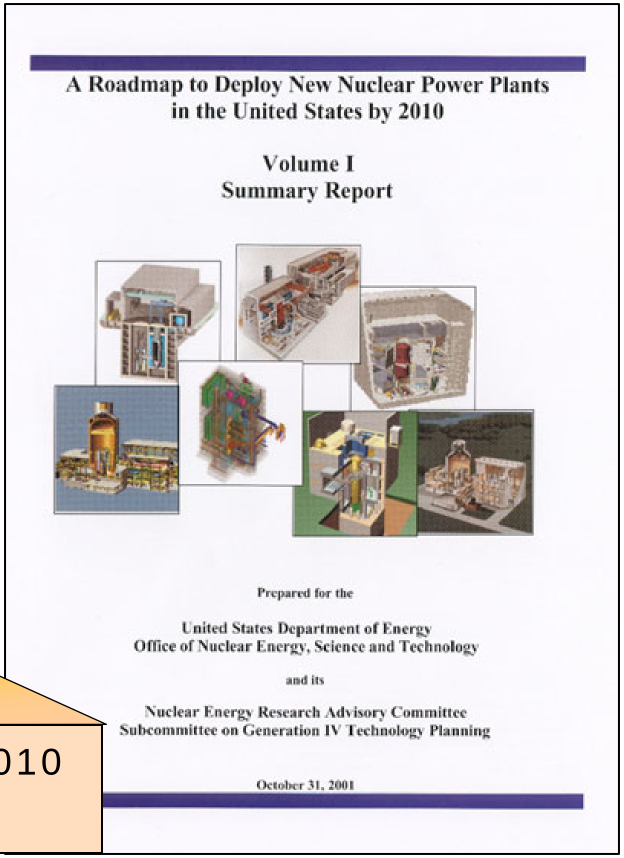
NTD Roadmap Conclusions

Can Be Deployed by 2010
- ABWR (General Electric)

Probably Can Be Deployed by 2010
- AP600 (Westinghouse)
- AP1000 (Westinghouse)
- PBMR (Exelon)

Possibly Can Be Deployed by 2010
- SWR-1000 (Framatone)
- ESBWR (General Electric)
- GT-MHR (General Atomics)

Cannot Be Deployed by 2010
- IRIS (Westinghouse)



Conclusions of the Expert Study:
A Roadmap to Deploy New Nuclear Power Plants in the United States by 2010

Courtesy of U. S. DOE. Source: http://gen-iv.ne.doe.gov/.

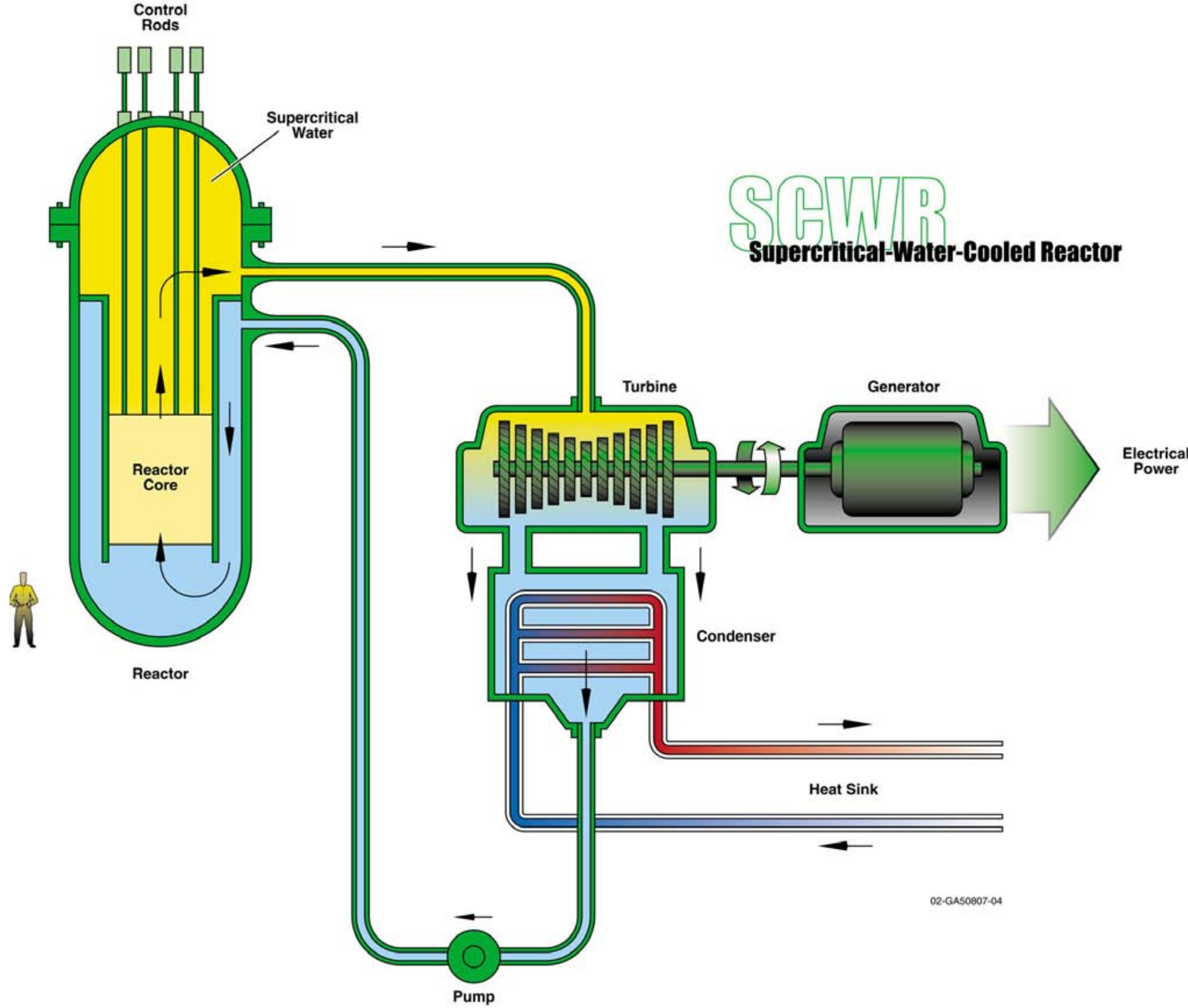
Supercritical Water Reactor (SCWR)

Characteristics

- **Water coolant at supercritical conditions**
- **500°C outlet temperature**
- **1700 MWe**
- **Simplified balance of plant**

Benefits

- **Efficiency near 45% with excellent economics**
- **Thermal or fast neutron spectrum**



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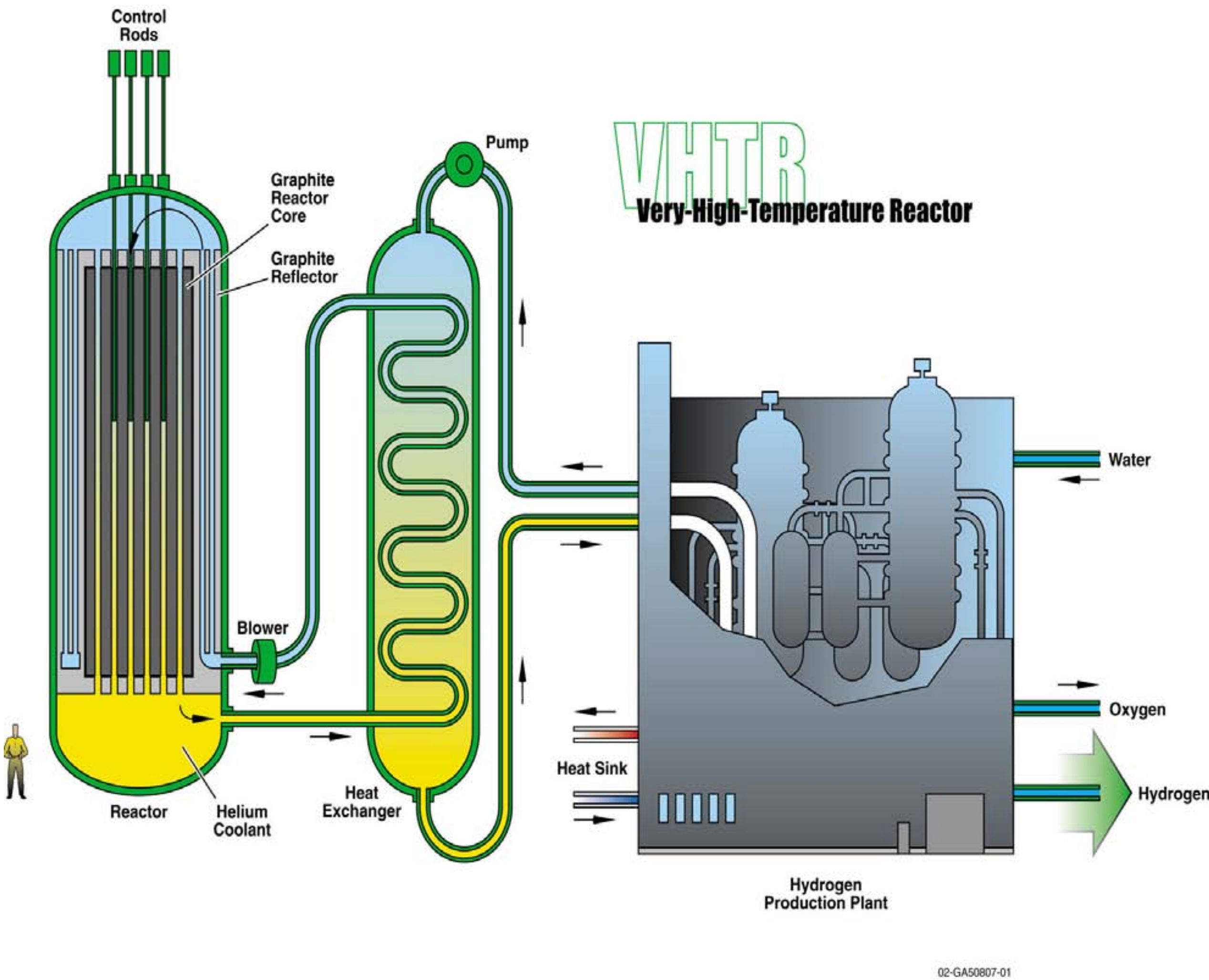
Very High-Temperature Reactor (VHTR)

Characteristics

- He coolant
- >1000°C outlet temperature
- 600 MWe
- Solid graphite block core based on GT-MHR

Benefits

- High thermal efficiency
- Hydrogen production
- Process heat applications
- High degree of passive safety



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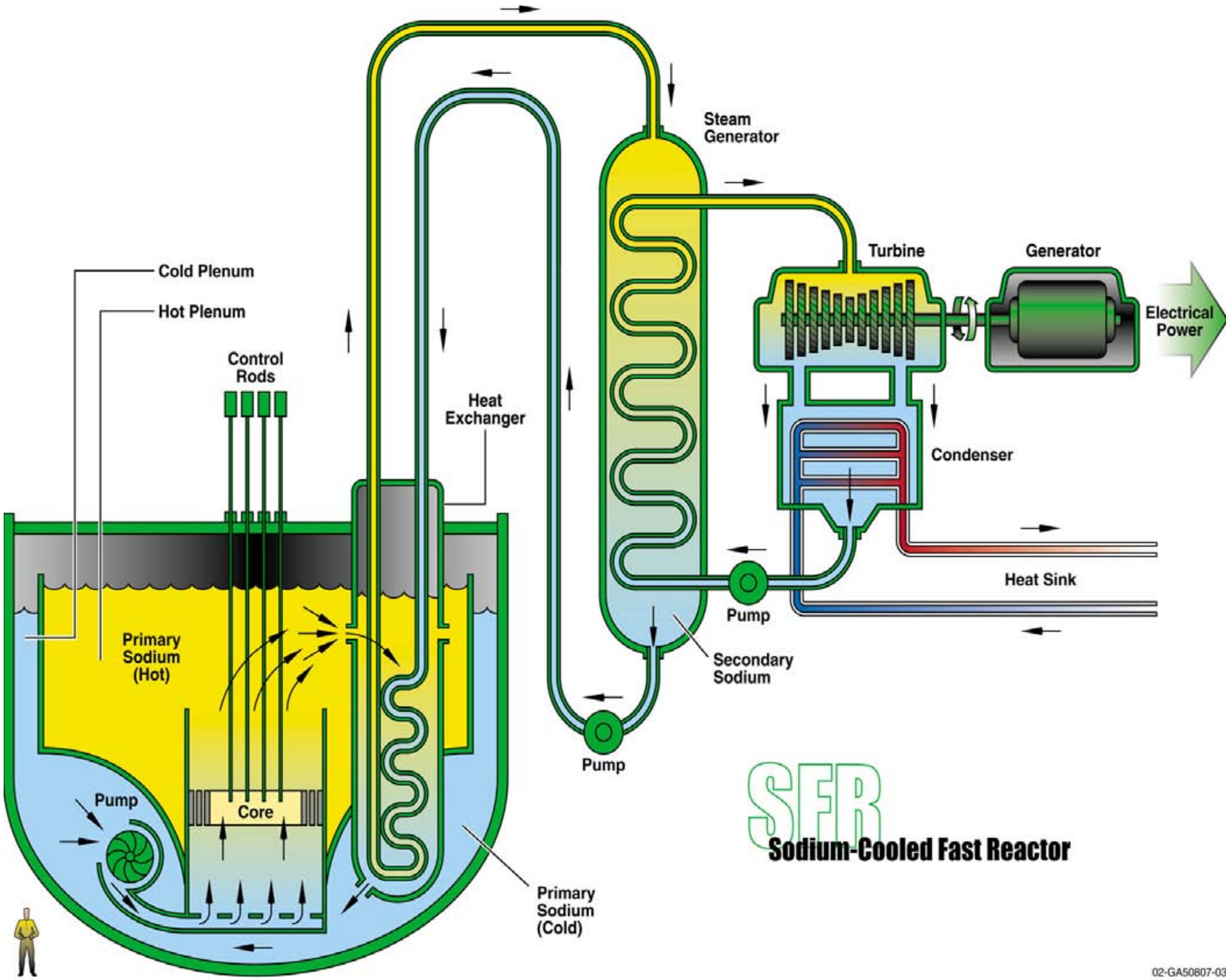
Sodium Liquid Metal-Cooled Reactor (Na LMR)

Characteristics

- Sodium coolant
- 150 to 500 MWe
- Metal fuel with pyro processing / MOX fuel with advanced aqueous

Benefits

- Consumption of LWR actinides



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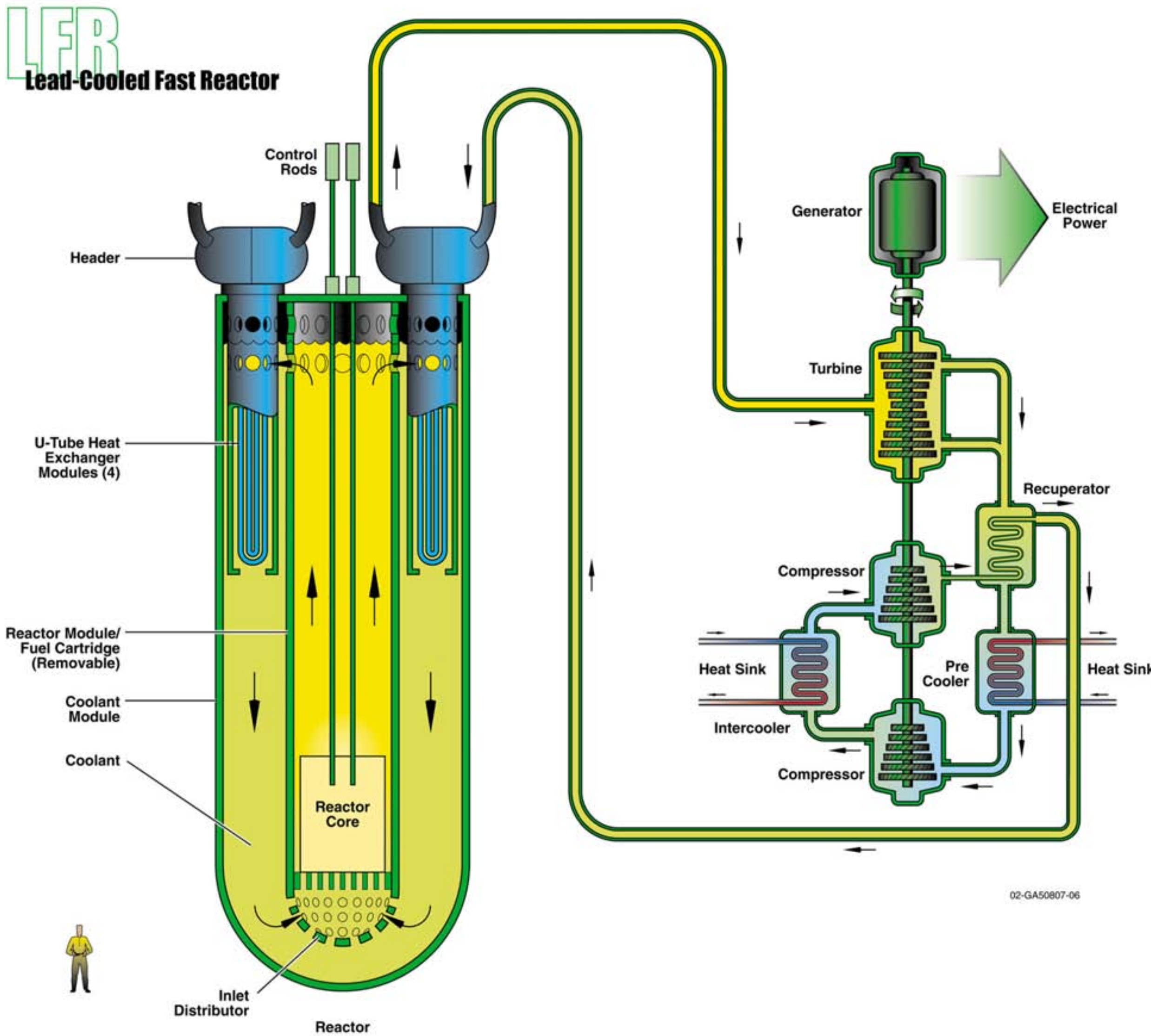
Pb/Bi Reactor – Cartridge Core (Pb/Bi Battery)

Characteristics

- Pb or Pb/Bi coolant
- 540°C to 750°C outlet temperature
- 120-400 MWe
- 15-30 year core life

Benefits

- Distributed electricity generation
- Hydrogen and potable water
- Cartridge core for regional fuel processing
- High degree of passive safety
- Proliferation resistance through long-life cartridge core



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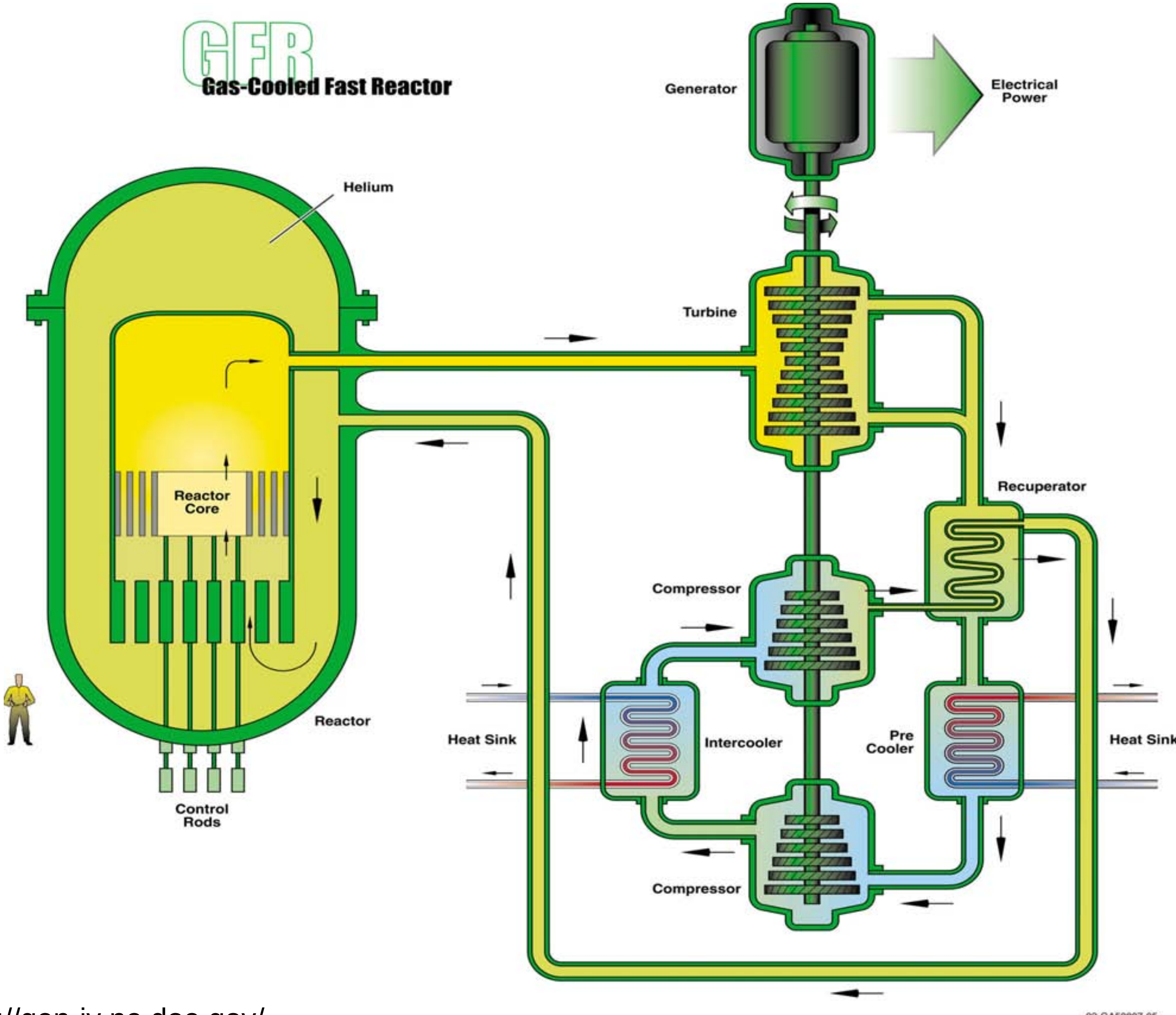
Gas-Cooled Fast Reactor (GFR)

Characteristics

- He coolant
- 850°C outlet temperature
- direct gas-turbine conversion cycle – 48% efficiency
- 600 MW_{th}/288 MW_e
- Several fuel options and core configurations

Benefits

- Waste minimization and efficient use of uranium resources



Courtesy of U. S. DOE. Source: http://gen-iv.ne.doe.gov/.

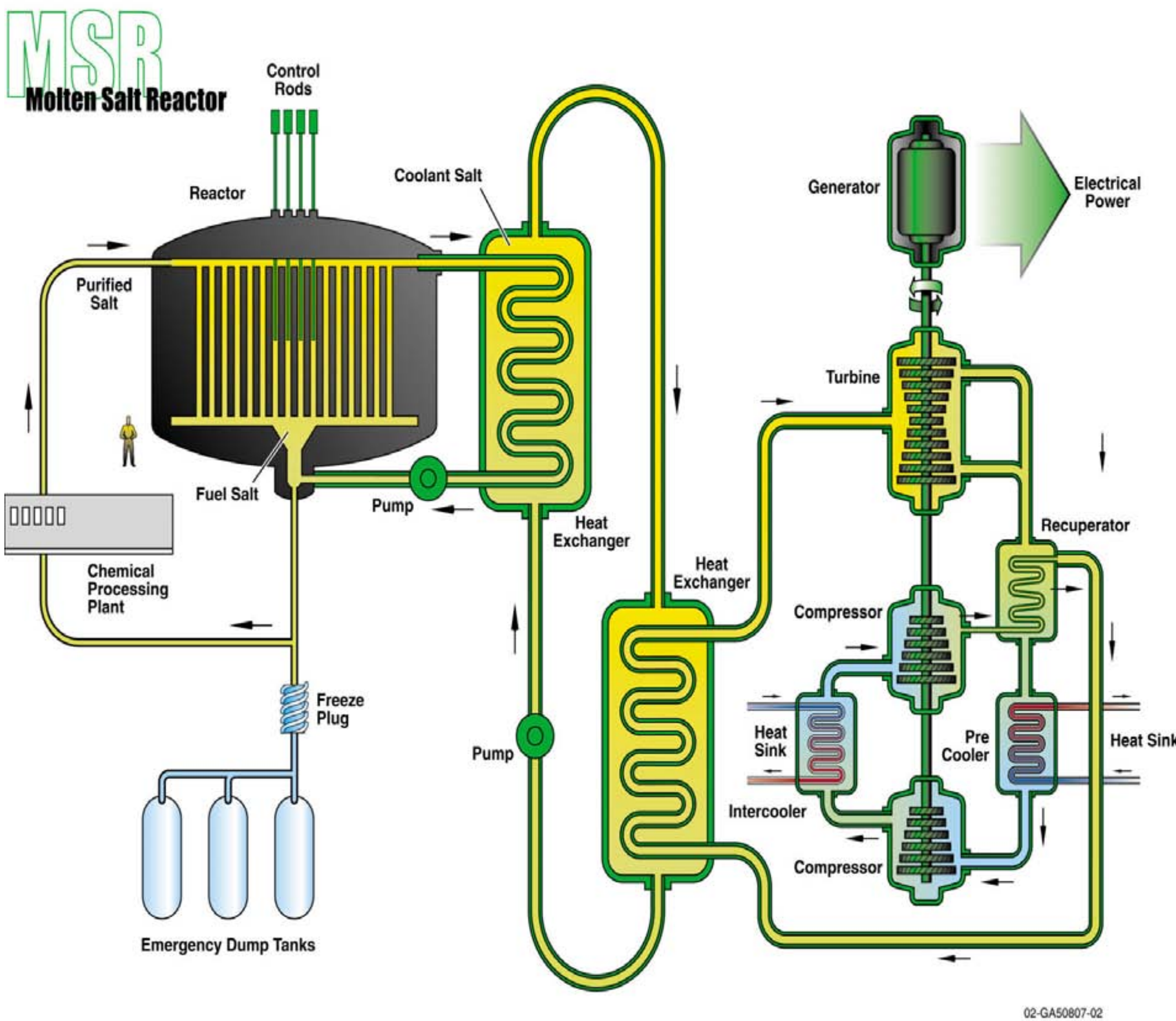
Molten Salt Reactor (MSR)

Characteristics

- **Fuel: liquid Li, Be, Th and U fluorides**
- **700°C outlet temperature**
- **1000 MWe**
- **Low pressure (<0.5 MPa) & high temperature (>700°C)**

Benefits

- **Low source term due to online processing**
- **Waste minimization and efficient use of uranium resources**
- **Proliferation resistance through low fissile material inventory**



Courtesy of U. S. DOE. Source: http://gen-iv.ne.doe.gov/.

METHODS OF HYDROGEN STORAGE TRANSPORT

- Compressed Gas
- Liquified Gas
- Metal Hydrides
- Borohydroxide ($NaBH_4 + 2H_2O \varnothing 4H_2 + NaBO_2$)
- Amonia ($2NH_3 \varnothing 3H_2 + N_2$)
- Cyclohexane ($2CH_4 + 2H_2 \varnothing C_2H_6$)
- Bucky Balls and Tubes Trapping

METHODS OF HYDROGEN PRODUCTION

- Electrolysis ($2H_2O \varnothing O_2 + 2H_2$)
- Metal-Water Reaction ($3Fe + 4H_2O \varnothing Fe_3O4 + 4H_2$)
- Hydrocarbon Stripping
- Steam Reforming ($CH_4 + 2H_2O \varnothing CO_2 + 4H_2$)
- Thermo Chemical

$$H_2SO_4 \varnothing H_2O + SO_2 + 1/2\ O_2$$
$$I_2 + SO_2 + 2H_2O \varnothing 2HI + H_2SO_4$$
$$2HI \varnothing H_2 + I_2$$