Advanced Reactor Technology

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Outline

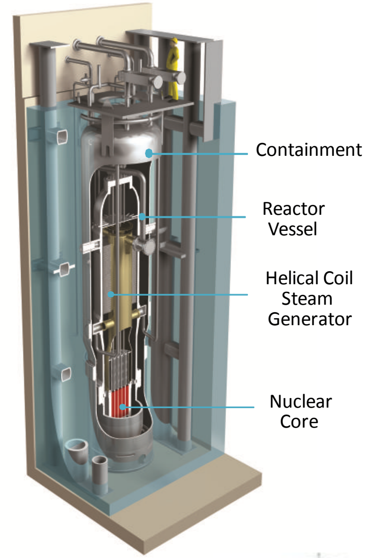
- Advanced Reactor Trends
  - Small Modular Reactors
  - Generation-IV Reactors

- Comparison of Reactor Conditions

- Goals and Objectives
  - Potential Nanotechnology Impacts
  - Example – Benefits and Issues

Attraction of Small and Medium Reactors (SMRs)

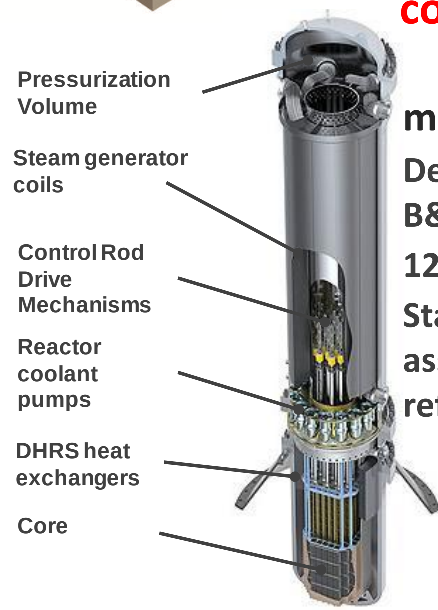
- **<u>Financing:</u> Lower absolute overnight capital cost for low power plant**
  - Economic viability is an issue; large monolithic reactors are priced in $5-10B range or higher
- **Fitness for small electricity grids, reduced design complexity, reduced impact of human factors and, perhaps, reduced infrastructure and staff requirements**
  - May be a good choice for developing countries
- **An option of incremental capacity increase**
- **Expand new site alternatives – near to load centers**
- **Option of operation without on-site refueling**
  - Attractive for nonproliferation regime
- **Potential for enhanced safety**



NuScale System

Developed by NuScale Power
45 Mwe capacity
Standard pin fuel assemblies; 3.5-yr refueling cycle
Multiple cores to meet demand

Integral PWR configurations



mPower System

Developed by B&W
125 MWe capacity
Standard pin fuel assemblies; 4.5-yr refueling cycle

Utility Perspective

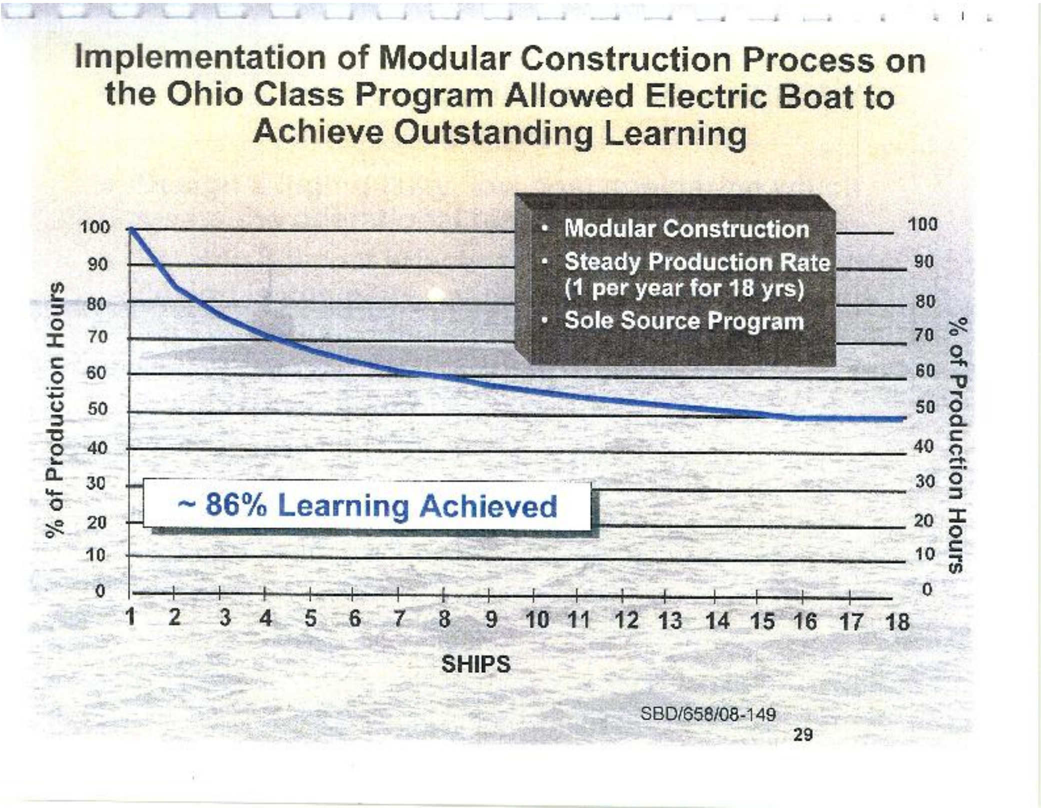
- **"Typical" nuclear company:**
  - $13 B per year revenues
  - $13 B outstanding debt
  - $40 B assets
  - $17 B market capitalization
  - Would rank 173 on the Fortune 500 list
- **Large nuclear power plant (~$10 B) a difficult challenge**

Holding Company	MWe	Units	Maj.	Full	Mkt Cap	Revenue	Debt	Assets
Exelon	16,715	19	17	13	$ 27.1	$ 17.3	$ 12.7	$ 49.2
Entergy	10,129	11	11	10	$ 14.3	$ 10.7	$ 12.0	$ 37.4
Dominion Resources	5,691	7	7	4	$ 24.6	$ 15.1	$ 18.0	$ 42.6
FPL Group	5,470	8	8	5	$ 21.5	$ 15.6	$ 18.9	$ 48.5
Duke Energy	5,173	6	5	5	$ 22.2	$ 12.7	$ 17.0	$ 57.0
Constellation Energy Group	3,874	5	5	4	$ 6.8	$ 15.6	$ 4.9	$ 23.5
FirstEnergy	3,862	12	3	3	$ 11.4	$ 13.0	$ 14.2	$ 34.3
Progress Energy	3,771	5	5	1	$ 11.6	$ 9.9	$ 12.8	$ 31.2
Southern	3,644	6	4	2	$ 28.7	$ 15.7	$ 19.9	$ 52.1
PSEG	3,612	5	5	1	$ 16.9	$ 12.4	$ 8.7	$ 28.7
PG&E	2,240	2	2	2	$ 15.9	$ 13.4	$ 13.0	$ 43.0
American Electric Power	2,069	2	2	2	$ 16.6	$ 13.5	$ 17.6	$ 48.4
Xcel Energy	1,668	3	3	3	$ 9.9	$ 9.6	$ 8.9	$ 25.5
Edison International	2,236	5	2	-	$ 10.8	$ 12.4	$ 11.1	$ 41.4
PPL	2,093	2	2	-	$ 9.8	$ 7.6	$ 7.8	$ 22.2
Ameren	1,190	1	1	1	$ 5.9	$ 7.1	$ 8.2	$ 23.8
Pinnacle West	1,147	3	-	-	$ 4.2	$ 3.3	$ 3.8	$ 11.8
NRG Energy	1,126	2	-	-	$ 5.8	$ 9.0	$ 8.7	$ 23.4
DTE Energy	1,122	1	1	1	$ 8.0	$ 8.0	$ 8.4	$ 24.2
SCANA	644	1	1	-	$ 4.7	$ 4.2	$ 4.9	$ 12.1
El Paso Electric	623	3	-	-	$ 0.9	$ 0.8	$ 0.9	$ 2.2
Great Plains Energy	545	1	-	-	$ 2.4	$ 2.0	$ 3.7	$ 8.5
Westar Energy	545	1	-	-	$ 2.6	$ 1.9	$ 2.8	$ 7.5
Berkshire Hathaway	434	2	-	-	$ 196.6	$ 112.5	$ 37.9	$ 297.1
Sempra Energy	430	2	-	-	$ 12.2	$ 8.1	$ 8.7	$ 28.5
PNM Resources	402	3	-	-	$ 1.0	$ 1.7	$ 1.8	$ 5.4
Total All Nuclear Companies	**80,454**	**118**	**84**	**57**	**$ 492**	**$ 353**	**$ 287**	**$ 1,029**
"Typical" Nuclear Utility	**67,917**	**91**	**77**	**55**	**$ 17.5**	**$ 13.4**	**$ 13.7**	**$ 40.1**

- **Moody's 2009:**
  - "We view new nuclear generation plants as a 'bet the farm' endeavor for most companies, due to the size of the investment and length of time needed to build a nuclear power facility."
  - Utilities should consider partnering with larger energy companies

Potential for Learning

- **Navy industrial experience part of SMR business case**
  - Assembly line replication optimizes cost, schedule, and quality through greater standardization of components and processes
  - Analysis of shipbuilding validates “*nth”* of a kind optimization
  - Increased skilled workforce retention with order backlog and diverse jobs



Challenges Facing LWR SMRs

- **Business prospects predicated on three premises**

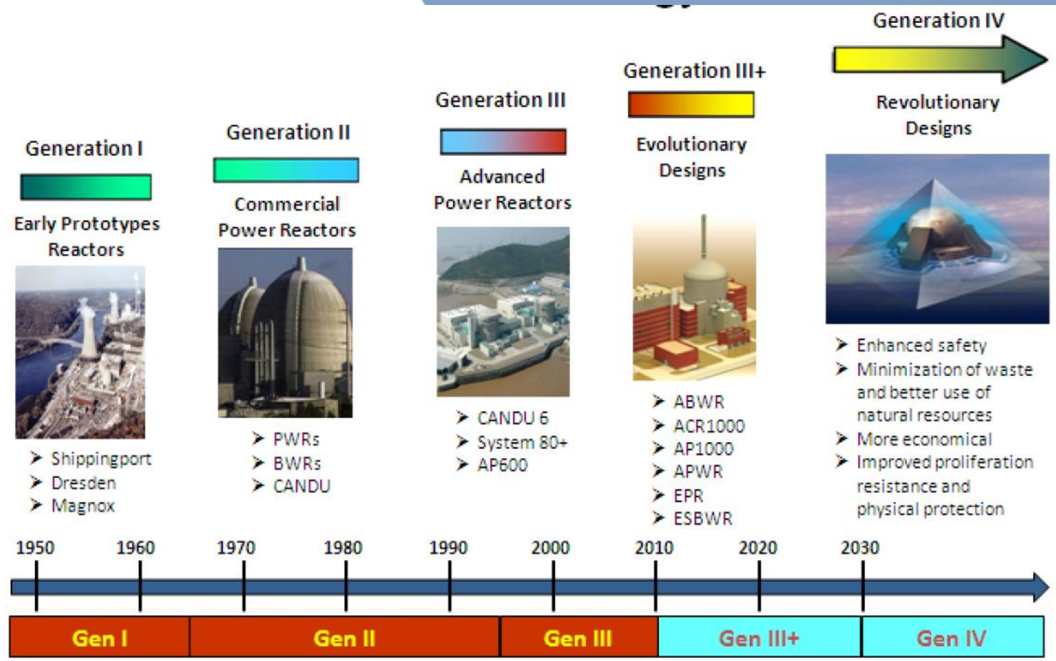
- **Significant investment needed to reach commercialization**
  - On the order of $500 M per design

- **Can the plants be built cheaply enough?**
  - Economies of replication > economies of scale?
  - Need a factory to make the price attractive, need an attractive price to produce the orders to warrant building the factory

- **Can the operations and maintenance costs be kept down?**
  - How will simplified “inherently safe” designs translate into smaller workforce and operation costs?
  - Must engage NRC to modify current regulations

Generation IV Nuclear Systems

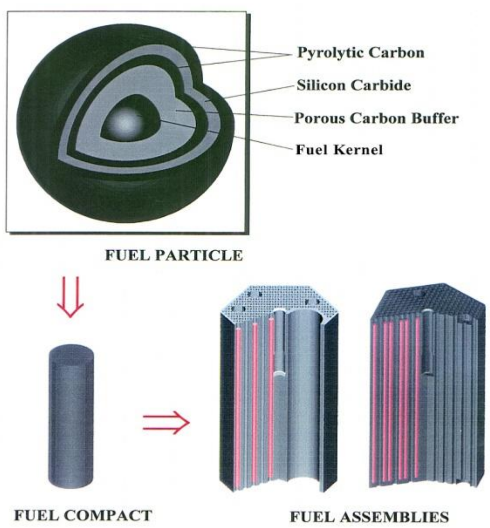
- **Six Generation IV Systems considered internationally**
- **Other systems, including non-reactor being explored**
  - Accelerator-driven systems
  - Fusion-fission hybrids

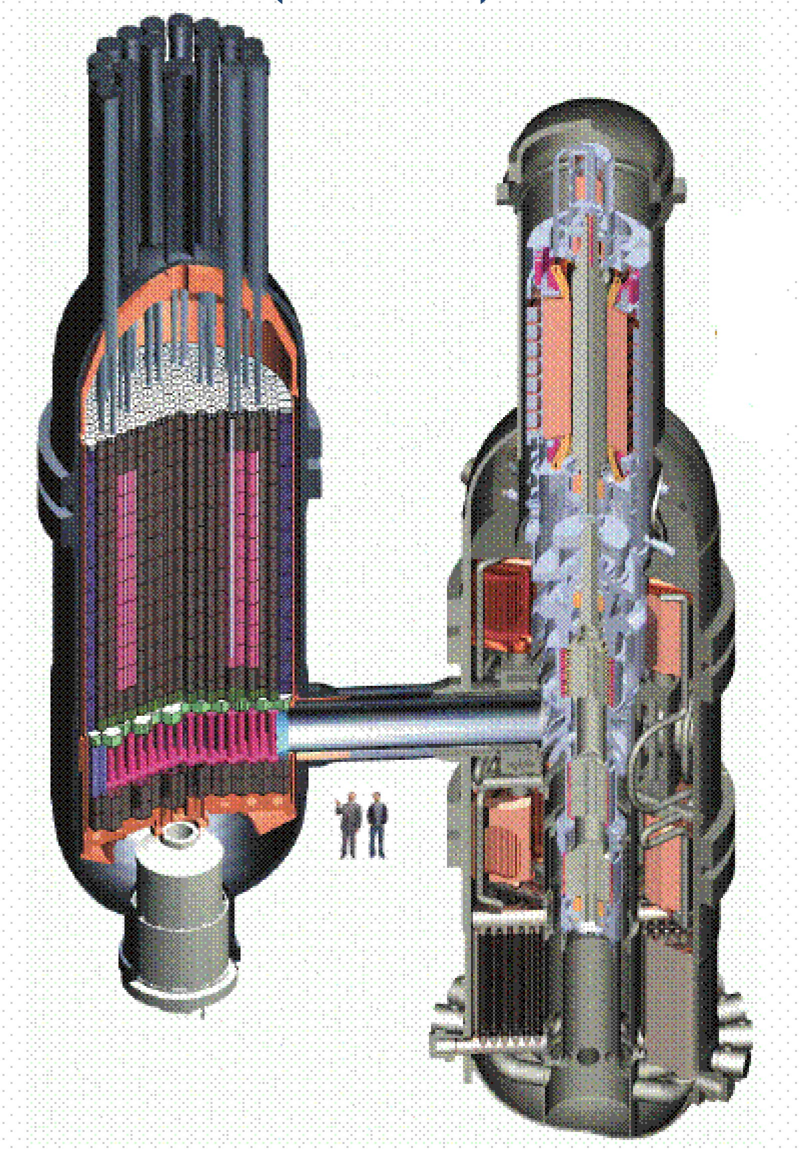


System	Neutron spectrum	Coolant	Outlet coolant Temp. °C	Fuel cycle	Size (MWe)
VHTR (Very high temperature reactor)	thermal	helium	900-1 000	open	250-300
SFR (Sodium-cooled fast reactor)	fast	sodium	550	closed	30-150, 300-1 500, 1 000-2 000
SCWR (Supercritical water cooled reactor)	thermal/fast	water	510-625	open/closed	300-700 1 000-1 500
GFR (Gas-cooled fast reactor)	fast	helium	850	closed	1200
LFR (Lead-cooled fast reactor)	fast	lead	480-800	closed	20-180, 300-1 200, 600-1 000
MSR (Molten salt reactor)	Epithermal/fast	fluoride salts	700-800	closed	1 000

Very High Temperature Reactor (VHTR)

- <u>High Temperature Applications</u>
  - Direct gas Brayton cycle
- System Configuration
  - TRISO fuel particles
  - Low Power Density
  - Prismatic or Pebble Bed





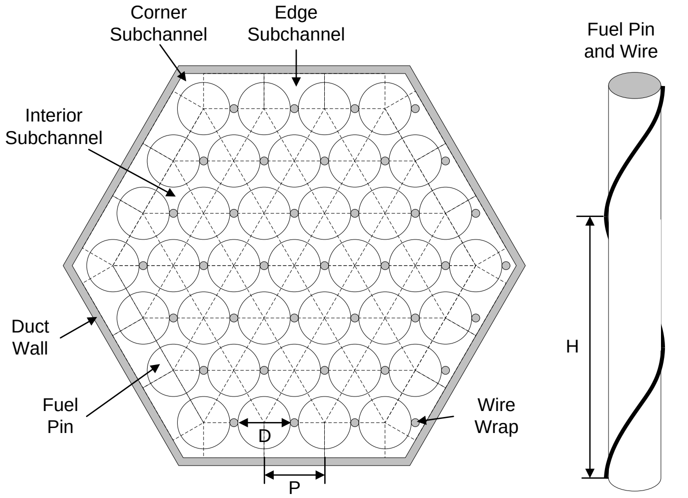
Safety Behavior of VHTR

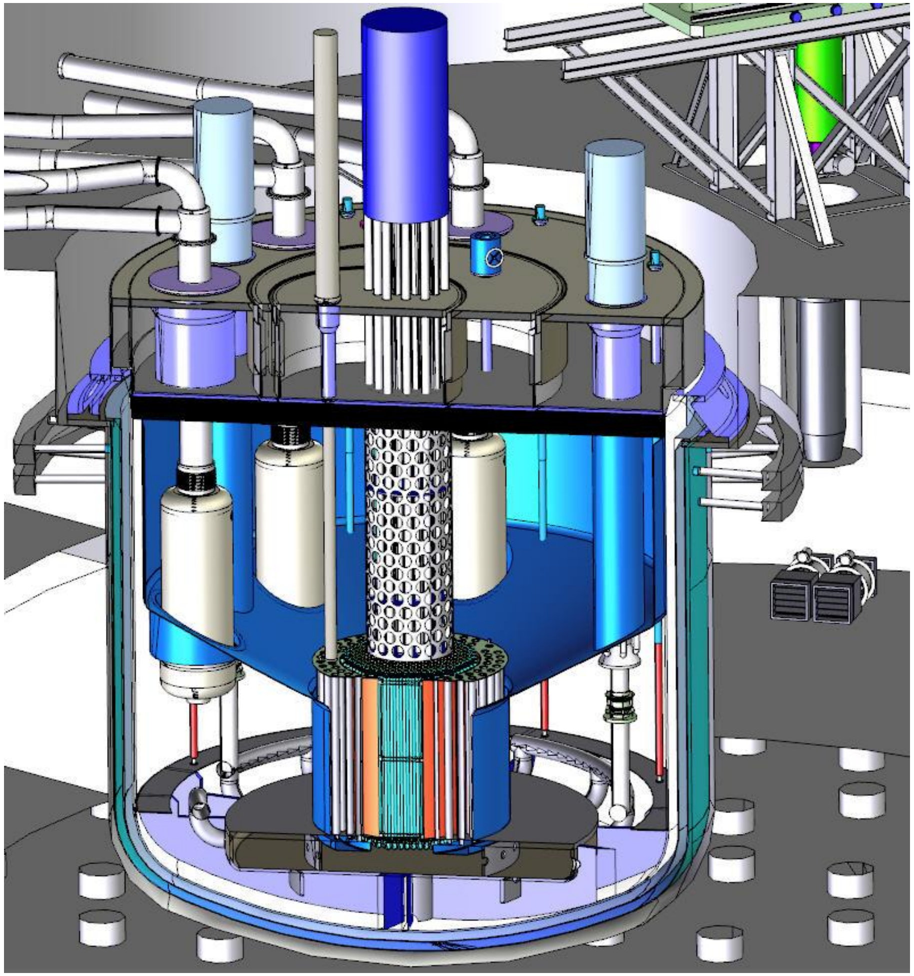
- Inherent characteristics
  - Inert, single phase helium coolant
  - Refractory coated robust fuel particles prevent releases
  - High temperature stable graphite structure and moderator

- Passively safe design
  - Slow heat-up of large graphite structures
    - In combination with low power density, implies long response times
  - Passive decay heat removal by radiation to cavity cooling
  - Annular core with negative temperature coefficients
  - No coolant voiding and/or change in moderation with temperature

Sodium-Cooled Fast Reactor (SFR)

- Fuel Cycle Applications
  - Actinide Management
- System Configuration
  - Metal Alloy or Oxide Fuel
  - Pool or Loop Configuration
  - High Power Density





Safety Implications of SFR Design Approach

- Superior heat transfer properties of liquid metals allow:
  - Operation at high power density and high fuel volume fraction
  - Low pressure operation with significant margin to boiling
  - Enhanced natural circulation for heat removal
- Inherent safety design
  - Multiple paths for passive decay heat removal envisioned
  - Tailored reactivity feedbacks to prevent core damage
- High leakage fraction implies that the fast reactor reactivity is sensitive to minor geometric changes
  - As temperature increases and materials expand, a net negative reactivity feedback is inherently introduced
- Favorable inherent feedback in sodium-cooled fast reactors (SFR) have been demonstrated
  - EBR-2 and FFTF tests for double fault accidents

Comparison of Key Reactor Characteristics

	Gen III ALWR	*Gen IV VHTR*	*Gen IV SFR*
Applications	electricity generation	electricity generation, heat supply	electricity generation, actinide management
Power, MW_{th}	3000-4500	600-800 (block) 300-400 (pebble)	800-3500 (loop or pool plant)
Power Density, W/cm^3	50-100	≤ 6.5	200-400
Primary Coolant (T_{Outlet}, ºC)	H_2O (300-350)	He (850-1000)	Na (510-550)
Primary System Pressure (MPa)	15.5	7.1	0.1
Fuel Material	UO_2	UO_2, $UC_{0.5}O_{1.5}$	(U,TRU) oxide, metal alloy
Fuel Form	pellet	Triso coated particle	pellet or slug
Fuel Element / Assembly	square pitch pin bundle	hex block, pebble	triangular pitch pin bundle with duct
Moderator	light water	graphite	none
Number of coolant circuits	2	1 or 2	3
Core Structural Material	zirconium alloy	graphite	ferritic steel
Power Conversion Cycle	steam Rankine	direct or indirect He Brayton	superheated steam Rankine, or S-CO_2 Brayton

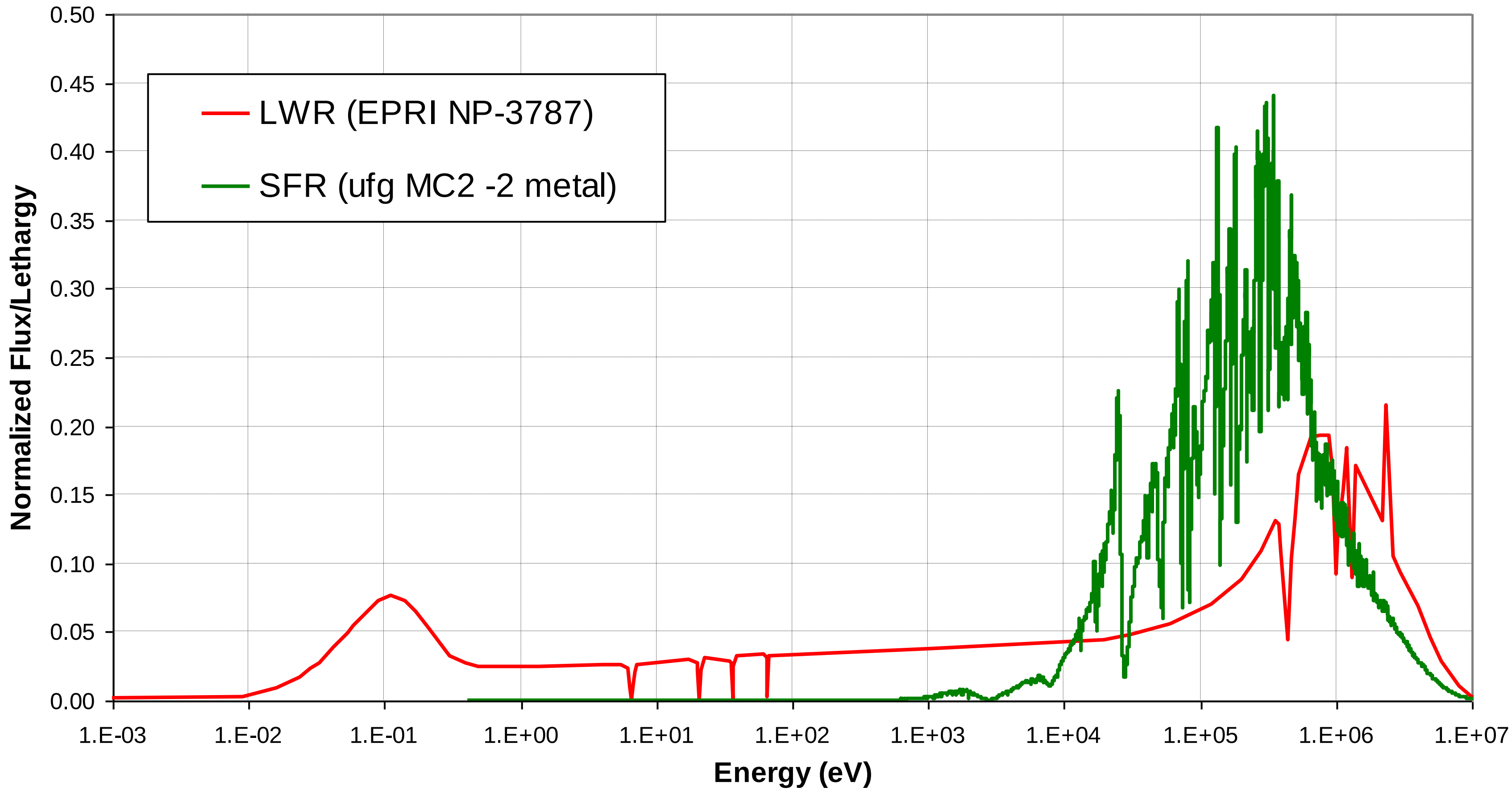
Advanced Reactor Objectives

- **For all three technology options (LWR, VHTR, SFR), a major emphasis is improved cost of electricity**
  - Reactor capital cost is the dominant cost component for nuclear energy
    - Reduce the commodity requirements
    - Reduce the physical footprint
  - Improve the energy conversion (more MWe per MWt)
  - Technology innovations being explored in current DOE-NE R&D
- **Enhanced safety is another important goal**
  - Following Fukushima, behavior of system in severe conditions
    - Passive decay heat removal
    - Seismic response
  - Inherent safety a major feature of Generation-IV designs
- **Enhanced reliability can improve system energy production**
  - Extended lifetime for the reactor plant
  - Improved capacity factor with simple maintenance

Potential Technical Areas for Nanotechnology Impact

- **Advanced nuclear fuels**
  - Improve thermal transport (lower operating temperatures)
  - Control fission gas release (extend burnup)
- **Advanced materials**
  - Improved strength (translates to reduced commodity mass)
  - Corrosion resistance
  - High temperature applications for VHTR/SFR
    - Creep resistance
  - Radiation resistance for SFR (following example)
- **Coolant and Heat Transfer**
  - Nanofluids could improve basic properties (thermal conductivity, heat capacity, boiling temperature, overall heat transfer coefficient)
  - Improved chemical properties (corrosion or other reactions)
- **Energy Conversion**
  - Improved thermal efficiency (enable higher T)
  - Again, improved heat transfer of working fluids

Radiation Damage of SFR In-Core Components



- Higher energy neutrons can cause more radiation damage
- Furthermore, flux level roughly an order of magnitude higher
  - Power density high and fission cross sections low
- Net result is within-core damage of ~200 dpa for 20% burnup

Radiation Resistant Materials

- **Basic structures have significant impact on radiation tolerance**
  - Initial austenitic steels exhibited void swelling
  - Significant improvement with ferritic steels
    - Attributed to body-centered cubic crystal structure
    - Demonstrated to 200 dpa in FFTF without void swelling
  - Some issues encountered with reduced strength

- **Nanodispersion particles may further improve radiation resistance and strength properties**
  - ODS steels being evaluated in international SFR R&D Programs
  - Several key issues must be demonstrated
    - Stability of the nanostructure in nuclear environment
    - Simplicity and consistency of fabrication
    - Ability to weld/join for reactor structures
    - Relative cost (commensurate with improved performance?)