Nuclear Power and Sustainable Development

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Introductory Remarks on Energy and Nuclear Power

Energy use

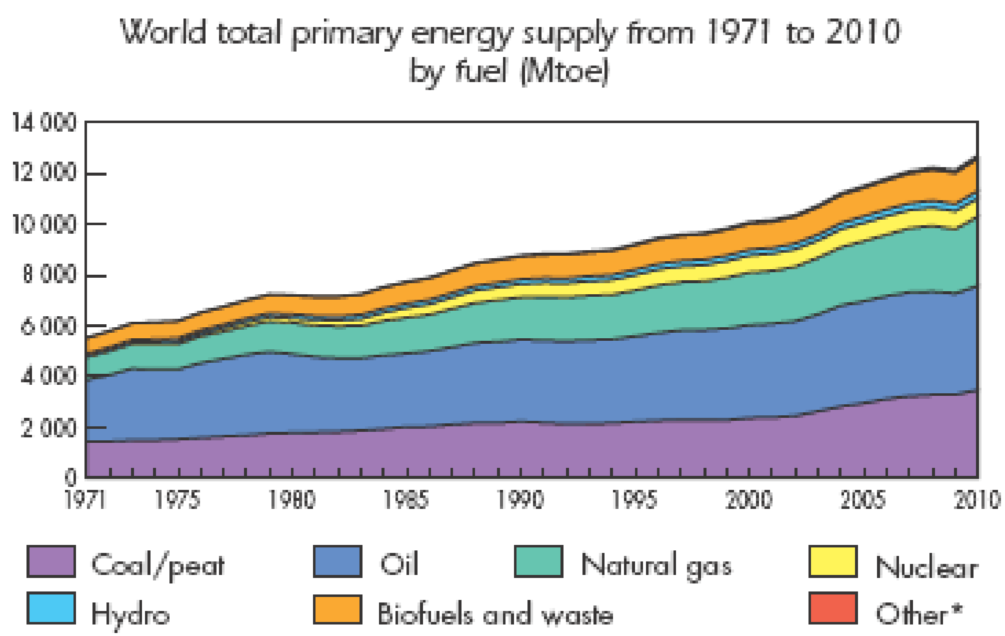
Energy is necessary for development

(well-known strong correlation between GDP/HDI and energy production)

ANNUAL PRIMARY ENERGY CONSUMPTION:

~12 Gtoe (billions ton of oil equivalent) or ~475 QBTU (BTU x 10^{15})

Prediction for 2050: 14-24 Gtoe (depending on the scenario)



(Source: IEA)

Meeting the growing energy needs

- **Energy security** – necessary for national security
- Energy **conservation** OR **new sources**? → need **BOTH** (Conserve as much as practical, but we still need more; in particular, developing nations.)
- **Hydro/fossil** OR **nuclear** OR **renewable/alternative**? → need **ALL** Each as much as justified. A reasonable mix.
  Cannot afford otherwise.
- What is the best option/mix?
  - **No free lunch** – each option has advantages/disadvantages!
  - Need **responsible decision process** – technical comparison of different options (based on well-defined metrics), rather than on pre-conceived opinion

Worldwide use of nuclear power

- 2012: 435 reactors, 370.0 GWe (NN 3/2012)
- 2013: 433 reactors, 371.5 GWe (NN 3/2013)
- About 1/6-th world electricity
- Over 60 new reactors in 14 countries under construction (WNA, 2/2013)
- Major source of electricity in several countries

NUCLEAR POWER UNITS BY NATION

POWER REACTORS BY TYPE, WORLDWIDE

Reactor Type	# Units (in operation)	Net MWe (in operation)	# Units (forthcoming)	Net MWe (forthcoming)	# Units (total)	Net MWe (total)
Pressurized light-water reactors (PWR)	267	246 555.1	89	93 014	356	339 569.1
Boiling light-water reactors (BWR)	84	78 320.6	6	8 056	90	86 376.6
Gas-cooled reactors, all models	17	8 732	1	200	18	8 932
Heavy-water reactors, all models	51	25 610	8	5 112	59	30 722
Graphite-moderated reactors, all models	15	10 219	0	0	15	10 219
Liquid-metal-cooled reactors, all models	1	560	4	1 516	5	2 076
Totals	**435**	**369 996.7**	**108**	**107 898**	**543**	**477 894.7**

March 2012 NUCLEAR NEWS 79

(source: ANS, Nucl. News 3/2012)

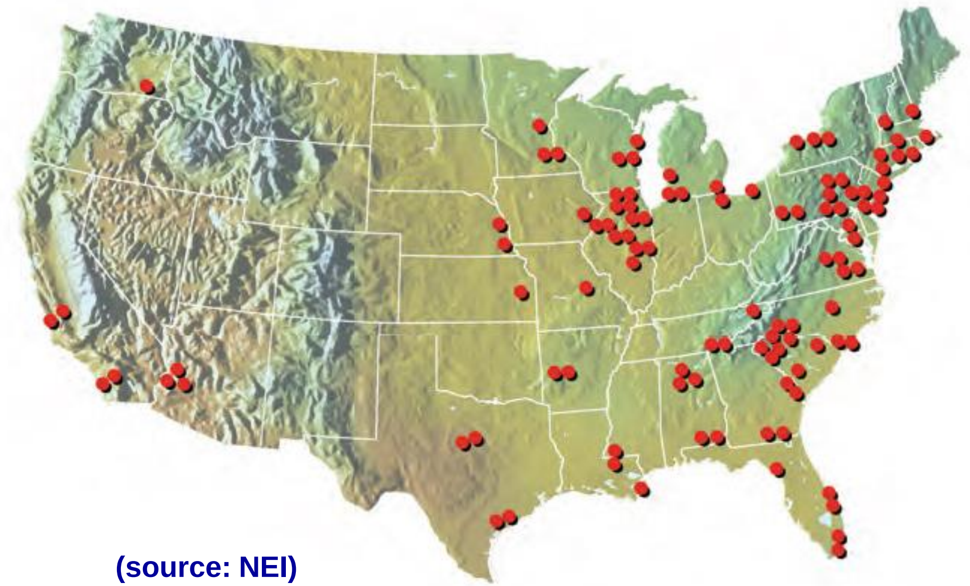
Worldwide use of nuclear power by country

Nation	# Units	Net MWe	# Units	Net MWe	# Units	Net MWe
	(in operation)		(forthcoming)		(total)	
Argentina	2	935	1	692	3	1 627
Armenia	1	375	0	0	1	375
Belgium	7	5 885	0	0	7	5 885
Brazil	2	1 901	1	1 275	3	3 176
Bulgaria	2	1 906	2	2 000	4	3 906
Canada	22	15 137	0	0	22	15 137
China	14	11 048	43	42 450	57	53 498
Czech Republic	6	3 678	0	0	6	3 678
Finland	4	2 716	1	1 600	5	4 316
France	58	63 130	1	1 600	59	64 730
Germany	9	12 058	0	0	9	12 058
Hungary	4	1 889	0	0	4	1 889
India	20	4 391	7	4 894	27	9 285
Iran	0	0	1	915	1	915
Japan	50	44 104	3	3 002	53	47 106
Mexico	2	1 300	0	0	2	1 300
Netherlands	1	487	0	0	1	487
Pakistan	3	725	1	300	4	1 025
Romania	2	1 300	3	1 860	5	3 160
Russia	32	22 693	12	10 560	44	33 253
Slovakia	4	1 816	2	810	6	2 626
Slovenia	1	666	0	0	1	666
South Africa	2	1 800	0	0	2	1 800
South Korea	21	18 697	7	8 600	28	27 297
Spain	8	7 514	0	0	8	7 514
Sweden	10	9 303	0	0	10	9 303
Switzerland	5	3 238	0	0	5	3 238
Taiwan	6	4 884	2	2 600	8	7 484
Turkey	0	0	4	4 600	4	4 600
Ukraine	15	13 107	3	2 850	18	15 957
United Arab Emirates	0	0	4	5 600	4	5 600
United Kingdom	18	9 920	0	0	18	9 920
United States	104	103 393.7	10	11 690	114	115 083.7
Totals	**435**	**369 996.7**	**108**	**107 898**	**543**	**477 894.7**

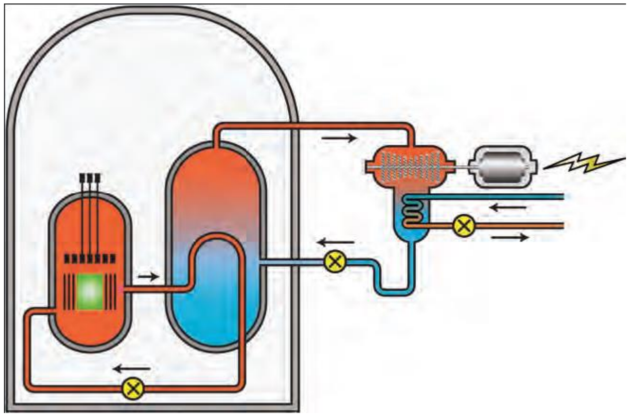
(source: ANS, Nucl. News 3/2012)

Nuclear power plants in the U.S. – status report

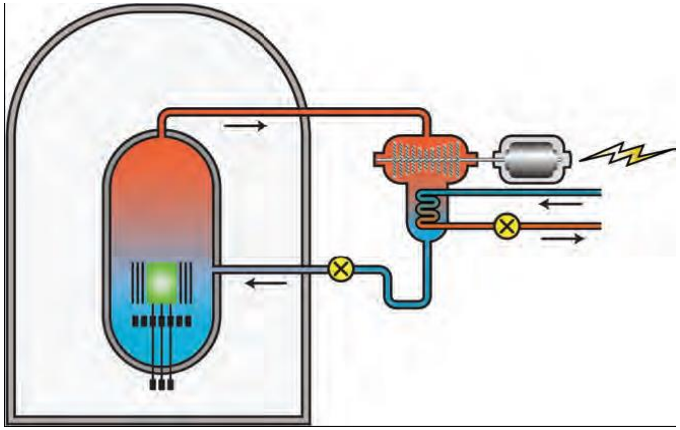
- 103 operating reactors in 31 states
- Close to 20% electricity produced
- 68 PWRs (+8), 35 BWRs (+2)
- 103,200 MWe (+11,700)



(source: NEI)



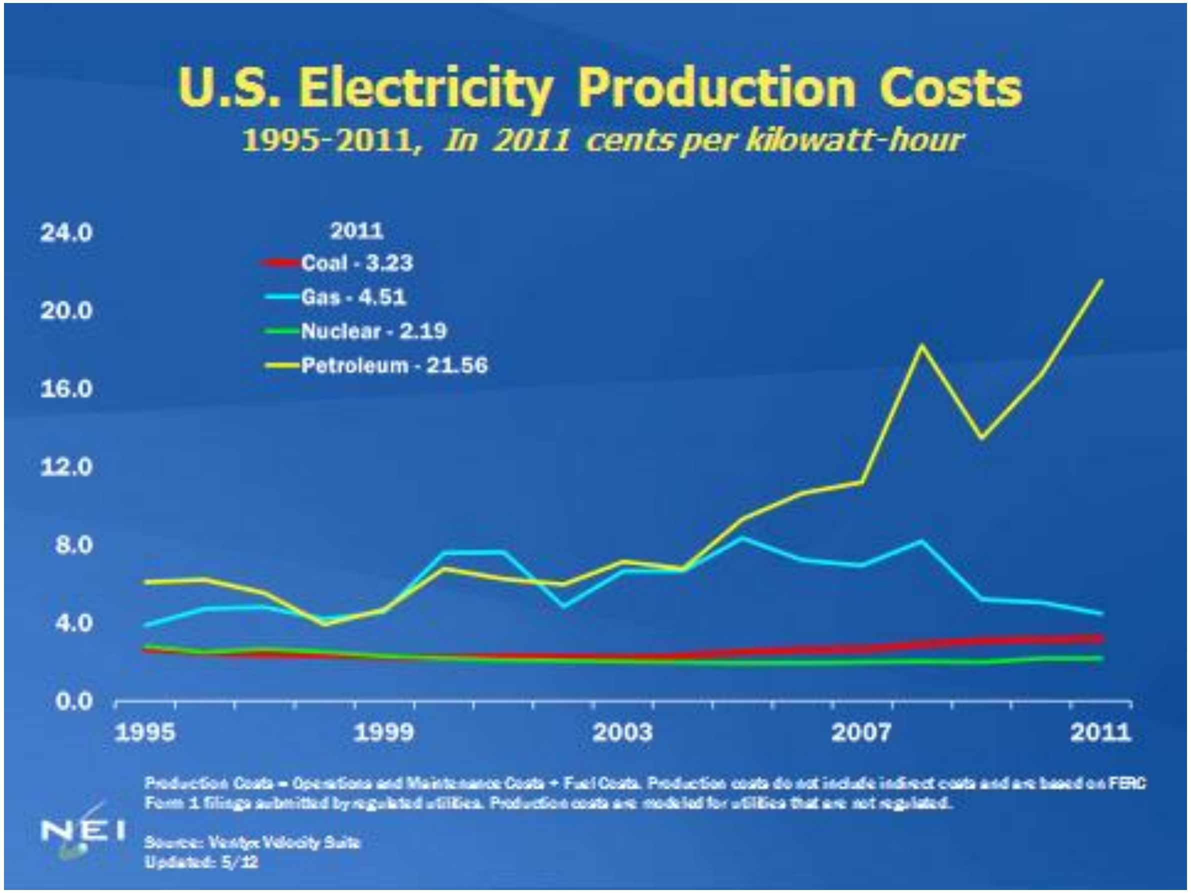
Pressurized Water Reactor (PWR)



Boiling Water Reactor (BWR)

Nuclear Power Plants – Most Expensive Electricity?

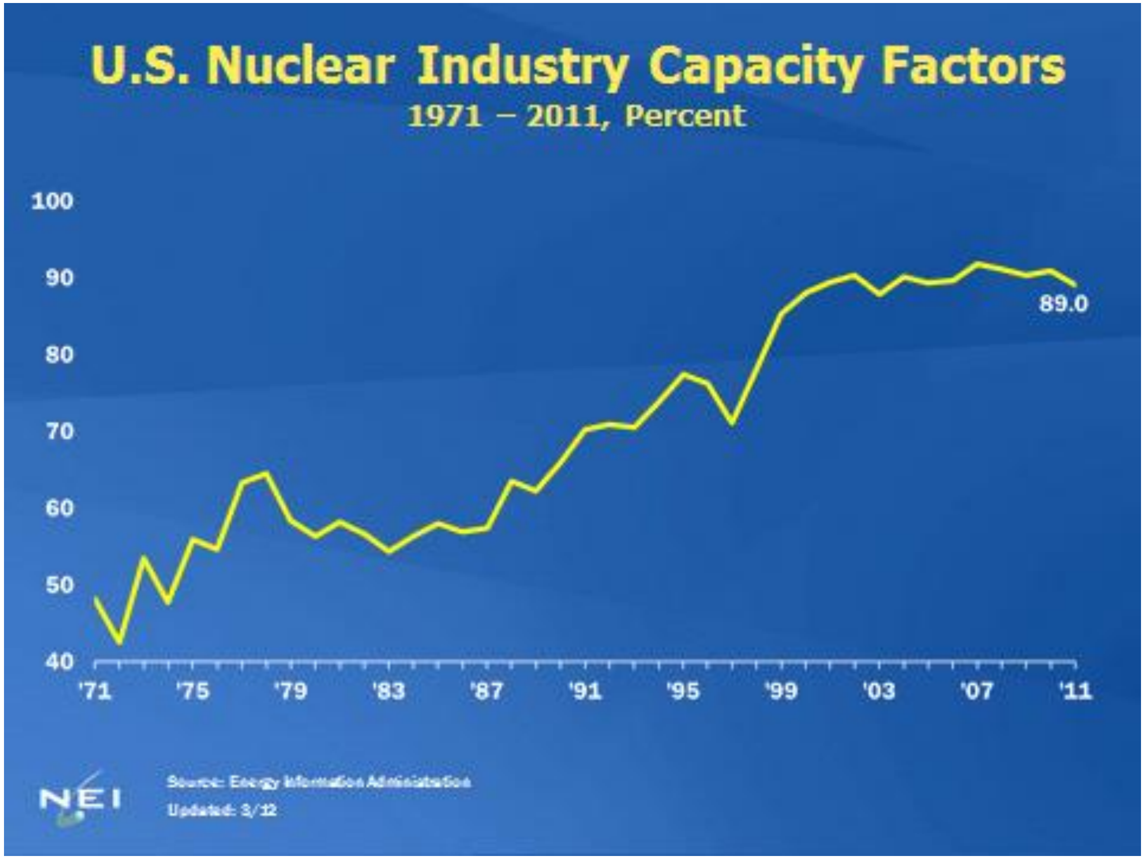
Energy production cost



Nuclear power has low electricity production cost
(lowest-cost source of electricity over the past 10+ years;
it will be initially higher but still competitive for the newly constructed NPPs)

(Source: NEI)

NPPs – Capacity Factor



Nuclear power has high capacity factor (which offsets high capital cost)

(Source: NEI)

Nuclear power – What is new?

- New build in US
- New build worldwide

- New/advanced reactor designs

- Yucca Mountain (intended site of deep geological nuclear waste repository)
  and
  Blue Ribbon Commission on America's Nuclear Future – Final Report

- New/old fuel cycle options
  - Thorium fuel

- The Great East Japan Earthquake (Fukushima)

New construction in the U.S.

- 2 new units (AP1000) under construction in Georgia, Vogtle 3 and 4 (2x1,170 MWe)

Aerial photograph of Vogtle 3 and 4 construction site. Unit 3 is located at left and top of photo and Unit 4 to the right and bottom. Heavy lift derrick crane foundation in center. August 11, 2011

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- 1 unit to be completed at TVA
  Bellefonte 1, AL (1,260 MWe)
  Project started in 1974, suspended in 1988
  8/2011 approved, targeting 2018-2020

Considering new construction in the US

Reference

New Power Reactor Projects in the United States
(Applications docketed by the Nuclear Regulatory Commission through Dec. 31, 2012)

License Applicant	Reactor(s)	Location[1]	Model[2]	Startup Target	Licensing Status	Commercial Status
Ameren Missouri	Callaway-2	Fulton, Mo. (R)	TBD	Indefinite	Suspended at applicant's request	No current activity
Dominion	North Anna-3	Mineral, Va. (R)	US-APWR	2022	NRC to revise schedule (E)	Term sheet with vendor
DTE Electric	Fermi-3	Monroe, Mich. (R)	ESBWR	6/2020	NRC to revise schedule	Vendor negotiations
Duke Energy	Harris-2, -3	New Hill, N.C. (R)	AP1000	1Q2026, 3Q2027	NRC to revise schedule	Vendor negotiations
	Lee-1, -2	Gaffney, S.C. (C)	AP1000	2022 or later	NRC to revise schedule	Vendor negotiations
	Levy-1, -2	Levy County, Fla. (G)	AP1000	2024, 2025–26	NRC to revise schedule	EPC contracts signed
Entergy	River Bend-3	St. Francisville, La. (R)	TBD	Indefinite	Suspended at applicant's request	No current activity
FPL Energy	Turkey Point-6, -7	Florida City, Fla. (R)	AP1000	2022, 2023	NRC to revise schedule	Vendor negotiations
Luminant	Comanche Peak-3, -4	Glen Rose, Texas (R)	US-APWR	2Q2021, 3Q2022	COL target 2015–16	Term sheet with vendor
NINA/STPNOC	South Texas-3, -4	Palacios, Texas (R)	ABWR	2018, 2019	COL target indefinite	EPC contracts signed
NuStart/Entergy	Grand Gulf-3	Port Gibson, Miss. (R)	TBD	Indefinite	Suspended at applicant's request (E)	No current activity
NuStart/TVA	Bellefonte-3	Scottsboro, Ala. (C)	AP1000	Indefinite	Suspended at applicant's request	No current activity
PPL	Bell Bend	Berwick, Pa. (R)	U.S. EPR	12/2018	NRC to revise schedule	Vendor negotiations
SCANA/Santee Cooper	Summer-2, -3	Parr, S.C. (R)	AP1000	Late 2016, mid-2018	COLs issued 3/30/2012	EPC contracts signed
Southern Nuclear	Vogtle-3, -4	Waynesboro, Ga. (R)	AP1000	2017, 2018	COLs issued 2/10/2012 (E)	EPC contracts signed
UniStar Nuclear	Calvert Cliffs-3	Lusby, Md. (R)	U.S. EPR	Indefinite	Denied by licensing board	Term sheet with vendor
	Nine Mile Point-3	Scriba, N.Y. (R)	U.S. EPR	Indefinite	Suspended at applicant's request	Vendor negotiations

[1]C indicates a site where a plant was canceled, but a construction permit had previously been approved. G indicates greenfield, with no reactor siting ever before considered. R indicates a site where reactors are now in operation. Levy is shown as greenfield (it is about eight miles from Crystal River), but Bell Bend is shown as an existing site, because its land is adjacent to Susquehanna. Summer-2 and -3 are on hard-rock terrain roughly one mile from Summer-1, and this is considered part of an existing site.

[2]ABWR: Boiling water reactor available from either GE Hitachi Nuclear Energy or Toshiba; South Texas-3 and -4 are by Toshiba, and this version of the design was certified by the NRC in 2012. AP1000: Westinghouse pressurized water reactor, design certified by the NRC in 2011. ESBWR: GE Hitachi BWR, design certification application under review by the NRC. US-APWR: Mitsubishi PWR, design certification application under review by the NRC. U.S. EPR: Areva PWR, design certification application under review by the NRC.

Other abbreviations: COL, combined construction and operating license; E, early site permit issued; EPC, engineering, procurement, and construction; TBD, to be determined.

The NRC will not take final action on pending license applications until after a federal court finds that the agency has remedied shortcomings in the waste confidence rule. The NRC is preparing an environmental impact statement to submit to the court, and it will be finished no sooner than September 2014.

(source: ANS, Nucl. News 3/2013)

New construction worldwide

- Over 60 new reactors in 13 countries under construction (WNA, 3/2013) http://www.world-nuclear.org/info/inf17.html
- Power reactors under construction, or almost so

Commercial Operation*		REACTOR	TYPE	MWe (net)
2013	Iran, AEOI	Bushehr 1*	PWR	950
2013	India, NPCIL	Kudankulam 1	PWR	950
2013	India, NPCIL	Kudankulam 2	PWR	950
2013	China, CGNPC	Hongyanhe 1*	PWR	1080
2013	China, CGNPC	Ningde 1*	PWR	1080
2013	Korea, KHNP	Shin Wolsong 2	PWR	1000
2013	Korea, KHNP	Shin-Kori 3	PWR	1350
2013	Russia, Rosenergoatom	Leningrad II-1	PWR	1070
2013	Argentina, CNEA	Atucha 2	PHWR	692
2013	China, CGNPC	Ningde 2	PWR	1080
2013	China, CGNPC	Yangjiang 1	PWR	1080
2013	China, CGNPC	Taishan 1	PWR	1700
2013	China, CNNC	Fangjiashan 1	PWR	1080
2013	China, CNNC	Fuqing 1	PWR	1080
2013	China, CGNPC	Hongyanhe 2	PWR	1080
2014	Russia, Rosenergoatom	Novovoronezh II-1	PWR	1070
2015	Russia, Rosenergoatom	Rostov 3	PWR	1070
2014	Slovakia, SE	Mochovce 3	PWR	440
2014	Slovakia, SE	Mochovce 4	PWR	440
2014	Taiwan Power	Lungmen 1	ABWR	1300
2014	China, CNNC	Sanmen 1	PWR	1250
2014	China, CPI	Haiyang 1	PWR	1250
2014	China, CGNPC	Ningde 3	PWR	1080
2014	China, CGNPC	Hongyanhe 3	PWR	1080
2014	China, CGNPC	Yangjiang 2	PWR	1080
2014	China, CGNPC	Taishan 2	PWR	1700
2014	China, CNNC	Fangjiashan 2	PWR	1080
2014	China, CNNC	Fuqing 2	PWR	1080
2014	Korea, KHNP	Shin-Kori 4	PWR	1350
2014?	Japan, Chugoku	Shimane 3	ABWR	1375
2014	India, Bhavini	Kalpakkam	FBR	470
2014	Russia, Rosenergoatom	Beloyarsk 4	FNR	750

New construction worldwide (cont.)

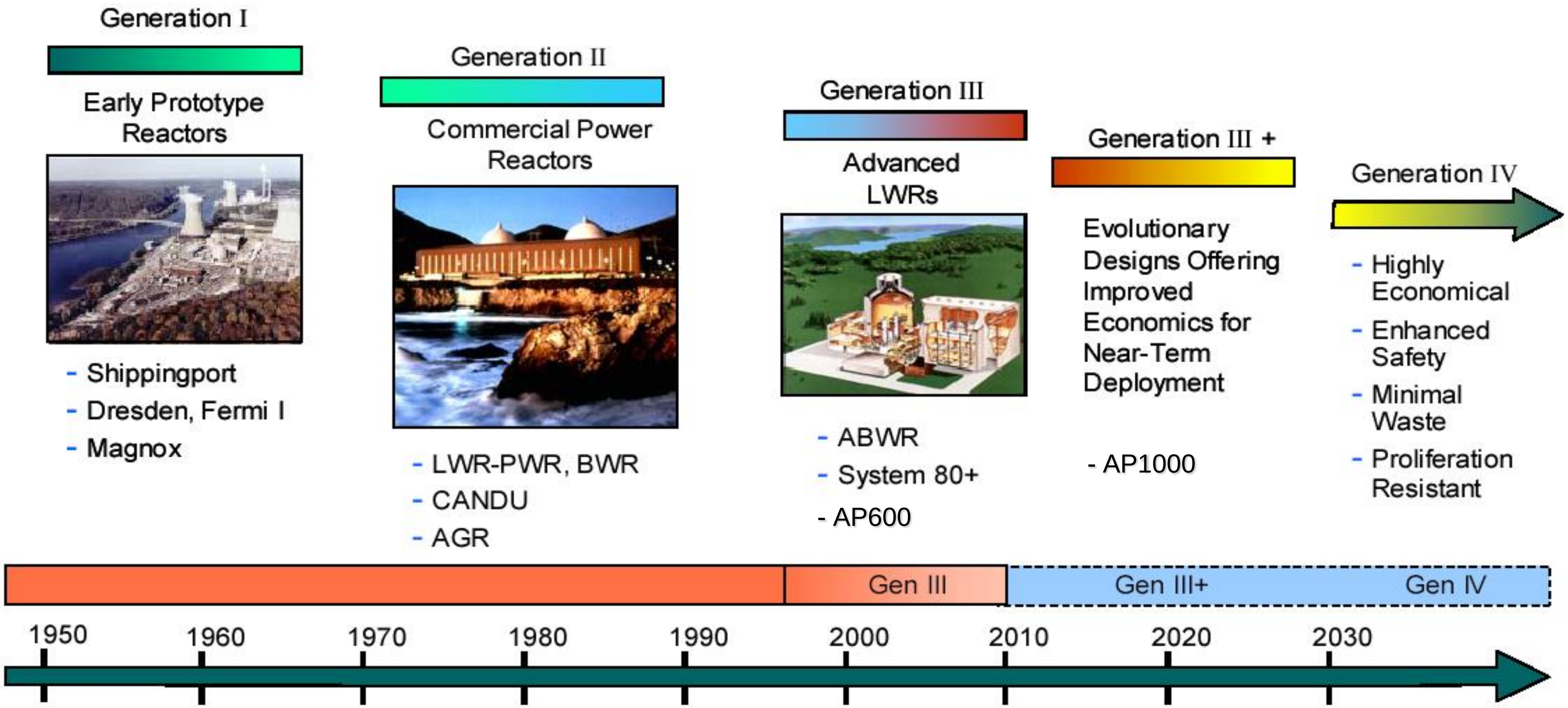
- Over 60 new reactors in 13 countries under construction (WNA, 3/2013) http://www.world-nuclear.org/info/inf17.html
- Power reactors under construction, or almost so

Commercial Operation*		REACTOR	TYPE	MWe (net)
2015	USA, TVA	Watts Bar 2	PWR	1180
2015	Taiwan Power	Lungmen 2	ABWR	1300
2015	China, CNNC	Sanmen 2	PWR	1250
2015	China, CGNPC	Hongyanhe 4	PWR	1080
2015	China, CGNPC	Yangjiang 3	PWR	1080
2015	China, CGNPC	Ningde 4	PWR	1080
2015	China, CGNPC	Fangchenggang 1	PWR	1080
2015	China, CNNC	Changjiang 1	PWR	650
2015	China, CNNC	Changjiang 2	PWR	650
2015	China, CNNC	Fuqing 3	PWR	1080
2015	India, NPCIL	Kakrapar 3	PHWR	640
2015?	Japan, EPDC/J Power	Ohma 1	ABWR	1350
2016	Finland, TVO	Olkilouto 3	PWR	1600
2016	France, EdF	Flamanville 3	PWR	1600
2016	Russia, Rosenergoatom	Novovoronezh II-2	PWR	1070
2016	Russia, Rosenergoatom	Leningrad II-2	PWR	1200
2016	Russia, Rosenergoatom	Vilyuchinsk	PWR x 2	70
2016	India, NPCIL	Kakrapar 4	PHWR	640
2016	India, NPCIL	Rajasthan 7	PHWR	640
2016	Pakistan, PAEC	Chashma 3	PWR	300
2016	China, China Huaneng	Shidaowan	HTR	200
2016	China, CPI	Haiyang 2	PWR	1250
2016	China, CGNPC	Yangjiang 4	PWR	1080
2016	China, CGNPC	Hongyanhe 5	PWR	1080
2015	China, CNNC	Hongshiding 1	PWR	1080
2015	China, CGNPC	Fangchenggang 2	PWR	1080
2016	China,	several others	PWR	
2017	USA, Southern	Vogtle 3	PWR	1200
2017	Russia, Rosenergoatom	Baltic 1	PWR	1200
2017	Russia, Rosenergoatom	Rostov 4	PWR	1200
2017	Russia, Rosenergoatom	Leningrad II-3	PWR	1200
2017	Ukraine, Energoatom	Khmelnitsky 3	PWR	1000
2017	Korea, KHNP	Shin-Ulchin 1	PWR	1350
2017	India, NPCIL	Rajasthan 8	PHWR	640
2017	Romania, SNN	Cernavoda 3	PHWR	655
2017?	Japan, JAPC	Tsuruga 3	APWR	1538
2017	Pakistan, PAEC	Chashma 4	PWR	300
2017	USA, SCEG	Summer 2	PWR	1200
2017	China,	several		
2018	Korea, KHNP	Shin-Ulchin 2	PWR	1350

New/advanced designs

- New/advanced designs
  - "Gen-IV" (Generation IV nuclear power plants) – 6 types, see Appendix
- New/advanced designs pursued at GT NRE
  - SMR (Small Modular Reactors), up to several hundred MWe
    Reduces the required investment from several billion $ to <$1B
    Extremely high interest recently
  - I2S-LWR
  - Liquid-salt cooled reactors (LSCR)
    High temperature, high efficiency, low reject heat, low pressure
    ORNL
  - Hybrid Advanced Nuclear-Solar EneRgy (ANSER) system
  - Fusion-fission hybrid

Nuclear power plants – past/present/future



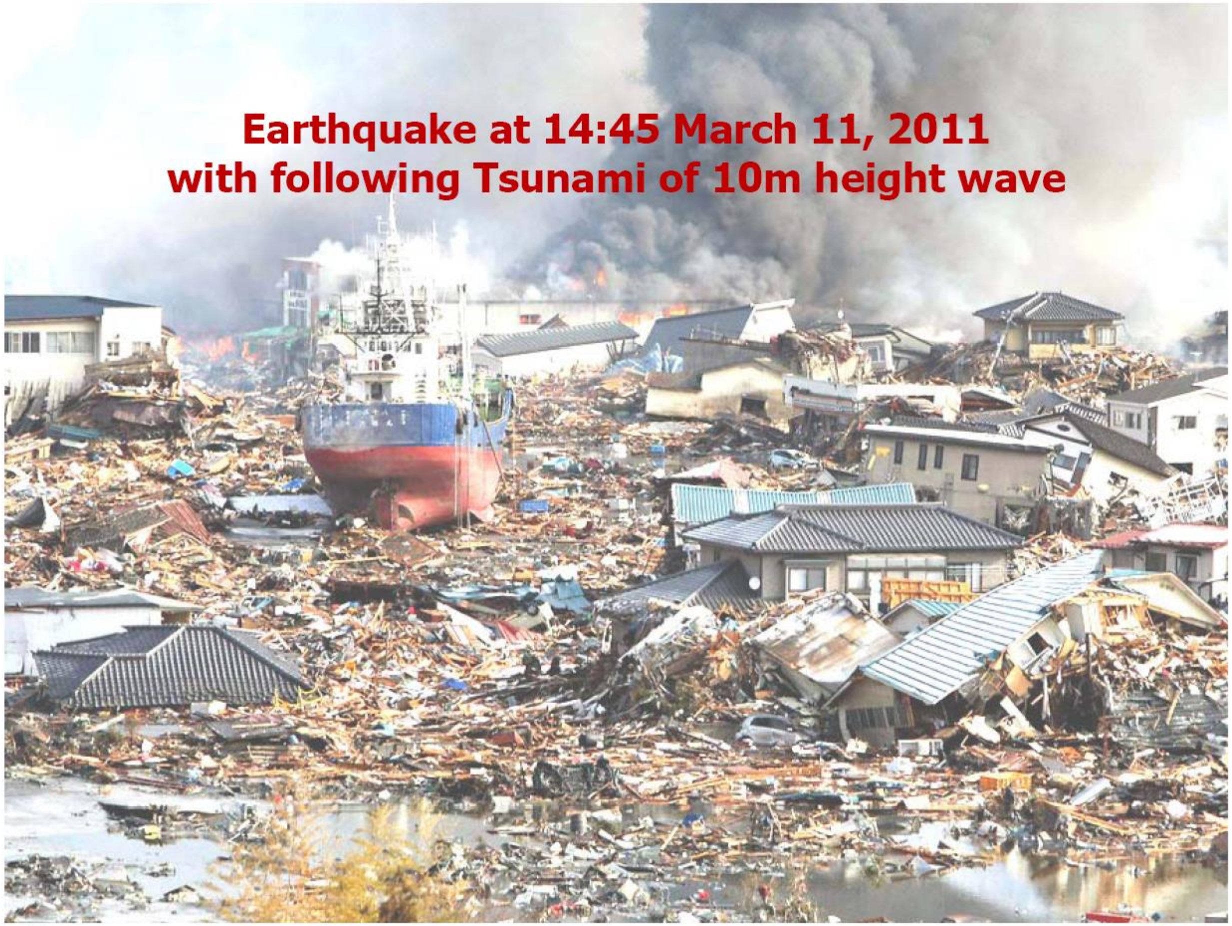
Fukushima?

Fukushima Dai-ichi

- Sequence of events

- March 11 – 9.0 Richter earthquake (much stronger than historically predicted)
- Reactors shut down (or already shut down)
- Decay heat continues to be generated and needs to be removed
- Loss of offsite power (multiple power lines), diesel generators started
- Tsunami (14 m vs. designed for 5.7 m) – diesel generators failure
- Limited cooling time on batteries
- ....

Fukushima


Earthquake at 14:45 March 11, 2011
with following Tsunami of 10m height wave

Fukushima Event

- Need to put in perspective:
  - Design basis and performance
  - Media attention given to Fukushima vs. all other consequences of the earthquake
- Impact
  - 2 tsunami fatalities at Fukushima Dai-ichi
  - Large economic damage
  - Contaminated area
- We need to openly evaluate all implications and lessons learned to improve future plants
- Nuclear remains a safe option to produce energy

→ Article by W. Allison

Energy and Environment

Sustainable development – some considerations

Energy is necessary for development.

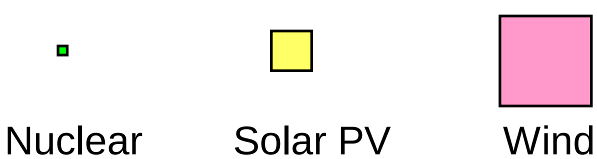
At the same time attention is needed with respect to:

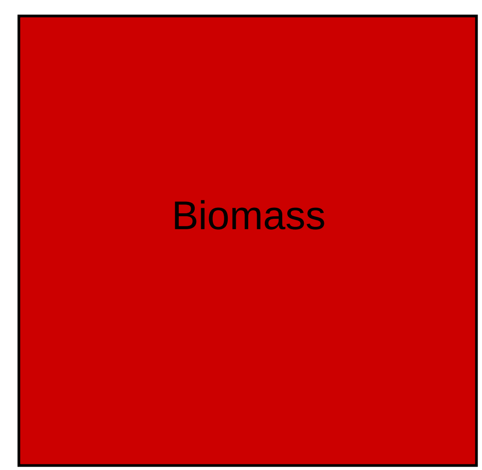
- Environmental impact
- Emission of CO_2 → climate impact
- Particulates emission → health impact
- Resources
- Cost
- Waste
- Land area use
- ….

Environmental impact: Footprint (Land use)

- Energy produced by one 1 GWe nuclear power plant is ~8TWh/year
  (Range of land use area estimated using several references and data for representative installations)
  - Nuclear power plant 1-2 (2) km^2
  - Solar PV 20-80 (40) km^2
  - Wind 50-800 (200) km^2
  - Biomass 4,000-6,000 (5,000) km^2

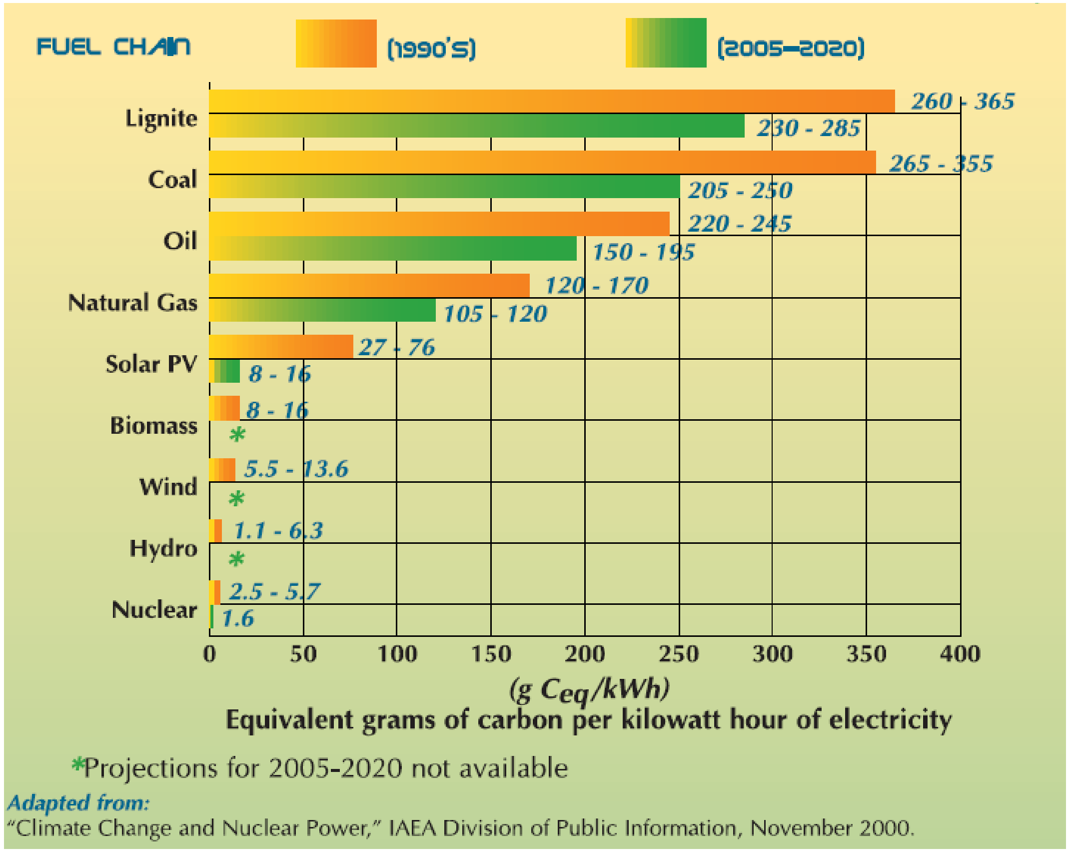
NOTE: Diluted energy density may present some limitations.
For example, the total world production of corn, if all converted to ethanol, would substitute about 1/3 of the U.S. current gasoline consumption …..





Nuclear power requires limited land area

GHG emissions



Total GHG Emission Factors for the production of Electricity

(source: ANS)

Nuclear reactors generate electricity with very low emissions

Each year, U.S. nuclear power plants prevent 5.1 million tons of sulphur dioxide, 2.4 million tons of nitrogen oxide, and 164 million tons of carbon from entering the earth atmosphere

Energy efficiency –
Life-Cycle Energy Ratio (Output/Input) for Energy Technologies

Energy Technology	Lifetime Energy Ratio Output/Input	Lifetime Energy Input as Percent of Output	Reference
Solar PV (utility)	5	20	Uchiyama, 1996
LNG	6	17	Uchiyama, 1996
Wind	6	17	Uchiyama, 1996
Solar PV (roof top)	9	11	Uchiyama, 1996
Coal	17	6	Uchiyama, 1996
Nuclear (diffusion enrichment)	21	5	ERDA, 1976; Perry, 1977
Natural Gas-pipe	26	4	Kivisto, 2000
Wind	34	3	Kivisto, 2000
Hydro	50	2	Uchiyama, 1996
Nuclear (centrifuge enrichment)	59	2	ERDA, 1976; Perry, 1977

Adapted from:
UIC Nuclear Issues Briefing Paper #57, May 2000

References:

ERDA (1976) A national plan for energy research, development and demonstration: creating energy choices for the future. Appendix B: Net energy analysis of nuclear power production, ERDA 76/1.

Kivisto, A. (1995) Energy Payback Period & CO2 emissions in different power generation methods in Finland, and (2000) personal communications.

Perry, A.M., et.al. (1977) Net Energy from Nuclear Power, IAEA Proceedings.

Uchiyama, Y. (1996) Life cycle analysis of electricity generation and supply systems, IAEA Proceedings.

Notes:
Estimates of the Energy Ratios vary depending on the assumptions made in the analysis and on real operating conditions. For example, the significant difference between the two estimates of Energy Ratio for wind power represents, among other factors, significant differences in utilization factors related to site characteristics.

(source: ANS)

Nuclear power has very favorable output/input ratio

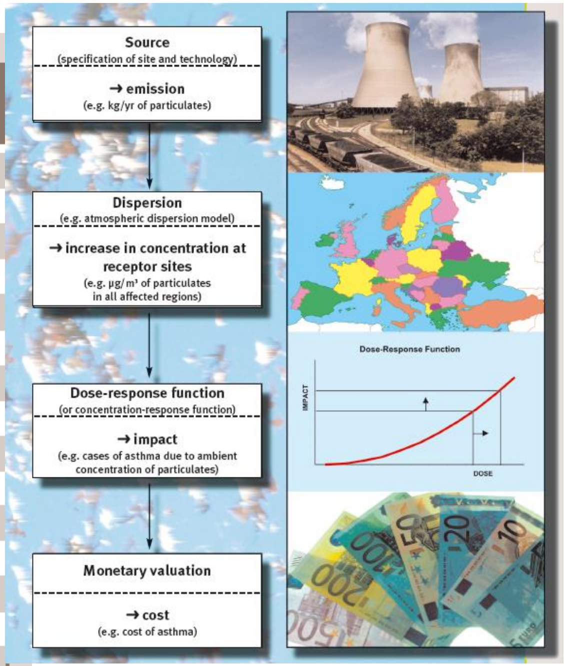
True cost of generating electricity – including externalities

Study ExternE, performed in Europe (European Commission), examined external costs of electricity production

External cost figures for electricity production in the EU for existing technologies[1] (in € cent per kWh*)

Country	Coal & lignite	Peat	Oil	Gas	Nuclear	Biomass	Hydro	PV	Wind
AT				1-3		2-3	0.1		
BE	4-15			1-2	0.5				
DE	3-6		5-8	1-2	0.2	3		0.6	0.05
DK	4-7			2-3		1			0.1
ES	5-8			1-2		3-5**			0.2
FI	2-4	2-5				1			
FR	7-10		8-11	2-4	0.3	1	1		
GR	5-8		3-5	1		0-0.8	1		0.25
IE	6-8	3-4							
IT			3-6	2-3			0.3		
NL	3-4			1-2	0.7	0.5			
NO				1-2		0.2	0.2		0-0.25
PT	4-7			1-2		1-2	0.03		
SE	2-4					0.3	0-0.7		
UK	4-7		3-5	1-2	0.25	1			0.15

* *sub-total of quantifiable externalities (such as global warming, public health, occupational health, material damage)*
** *biomass co-fired with lignites*



Source: EU / EUR 20198

Take Away: Nuclear power and renewable sources have significantly lower external costs than fossil plants

Nuclear power characteristics

- High energy density; low emission; low land area use; favorable output/input energy factor
- Competitive cost - low external cost, thus **low true total cost**
- U/Th resources sizeable (on the order of hundred(s) years for once through fuel cycle, thousands years with reuse of irradiated fuel)
- Waste must be addressed (technologically manageable, however….)
- Several prominent "founding fathers" of the environmental movement, based on evaluating feasible alternatives, came to the position that nuclear power offers a valid option to address environmental concerns
  - Patrick Moore - Greenpeace founder
  - Stewart Brand - Whole Earth Catalog founder
  - James Lovelock - Gaia theorist
  - Recent UN IPCC report (May 2007) acknowledges the potential role of nuclear power
- **Nuclear power has a role to play in sustainable development. Otherwise, it is difficult to imagine satisfying energy needs without exhausting resources and significantly impacting environment.**
- **But, is Nuclear Power itself sustainable?**

Sustainable Nuclear Power

Sustainable Nuclear Power

- Safety
  - Inherent safety features
- Economics
  - Long-term competitive
- Fuel cycle:
  - Better use of nat. resources (uranium, thorium)
  - Long-term nuclear waste management

→ Sustainability & Public Acceptance

Sustainability Viewed through Nuclear Fuel Cycle

- Front end → Sufficient Resources?
  - Mining, Enrichment
  - (Use Recycled)
  - Fuel fabrication
- In-core residence time → Safety?
  - Energy production
  - Irradiation
  - Isotopic change
- Back end → Acceptable Waste Management?
  - Waste management
  - (Reprocessing)
  - Short/intermediate storage
  - Ultimate disposal of (residual) waste

Safety

State-of-the-art: Safe enough?

- Gen. III+ Advanced Passively Safe Nuclear Power Plants
- Safety systems operate based on laws of nature (gravity, natural circulation), thus don’t require external power, and much less likely to fail than active systems

- Is it safe enough?
- Can it be safer?

Personal perspective:

- Extremely safe for all planned/foreseen events
- Inherent safety may (significantly?) improve response to unforeseen events (Fukushima-type scenario?)

Inherent safety - examples

Small power reactor (one of drivers toward SMRs)

- Large surface-to-power ratio
- Decay heat removal by conduction

Integral primary circuit configuration

- All primary circuit components within the reactor vessel
- Eliminates large external piping
- Since it does not exist, cannot break it
- No possibility for LB-LOCA

SMR
Small Modular Reactors

SMRs

- Smaller power modules, up to a few hundred MWe
- In the focus (again) starting about 15 years ago

  [B. Petrovic et al., "The Pioneering Role of IRIS in Resurgence of Small Modular Reactors (SMRs), *Nuclear Technology*, **178**, 126-152 (2012)]
- This time may actually succeed in licensing/building
- Water-cooled designs (shorter-term)
- Other coolants Gen IV SMRs (longer term)

Pro

- More feasible to finance (in particular for smaller markets/utilities)
- More conducive to inherent safety

et contra

- Need to demonstrate economic competitiveness
- Perceived as more novel technology, thus more difficult to license

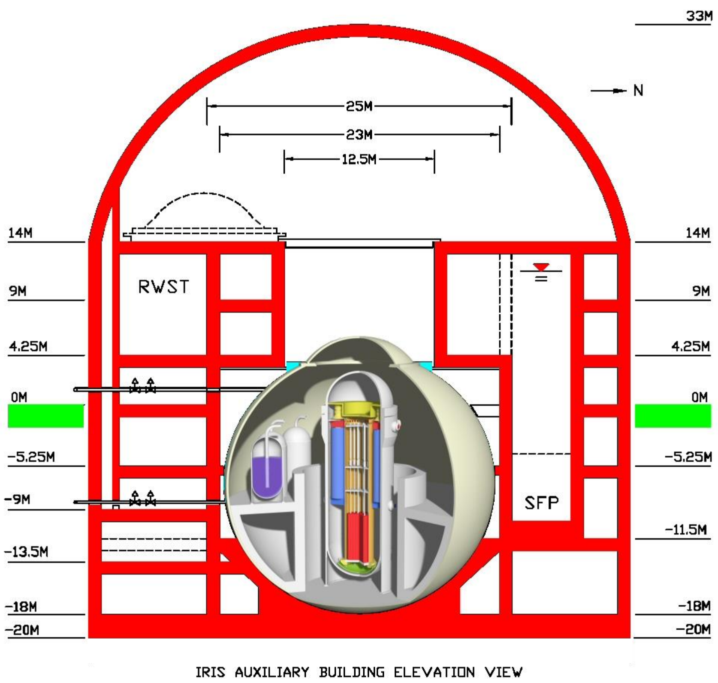
Representative recent SMRs

- IRIS, 335 MWe (1999 to ~2009, Intl. team)
- Babcock & Wilcox mPower, 2 x 180 MWe
- Westinghouse SMR, 225+ MWe
- NuScale, 12 x 45 MWe
- ….

- IRIS design will be used to illustrate certain safety features found in SMRs

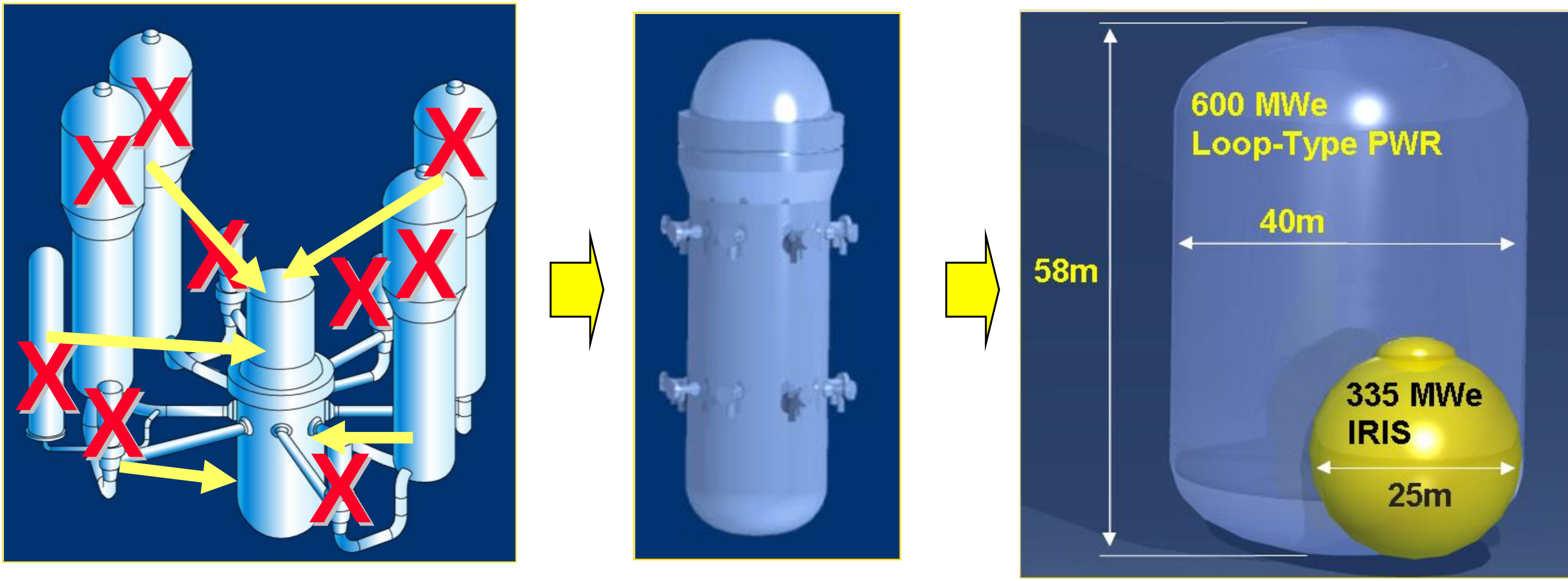
IRIS main design features

- Advanced integral light water reactor
- Innovative, simple design
- Safety-by-design™ eliminates a number of accidents
- Capability of being licensed without off-site emergency response requirements
- International team
- Anticipated competitive economics
- Cogeneration (desalination, district heating, synthetic fuel)
- NRC pre-application started
- Design Certification testing program started
- Interest expressed by several countries
- Very compact design on seismic isolators



335 MWe/module

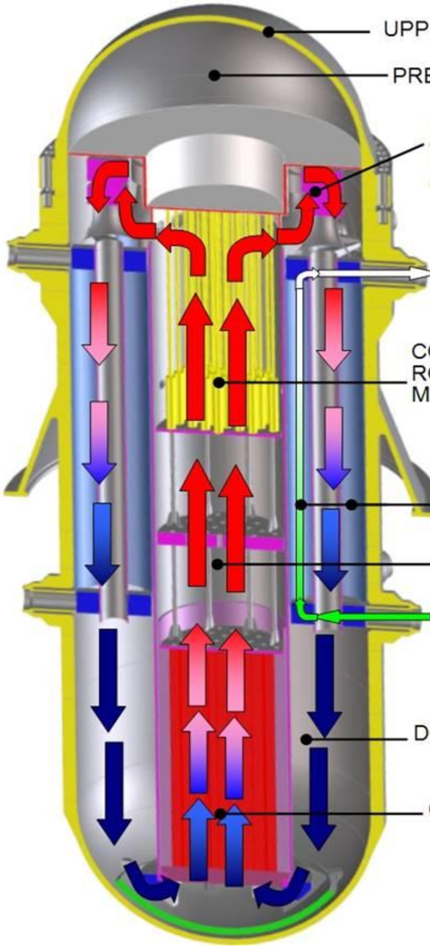
Integral Primary System Reactor



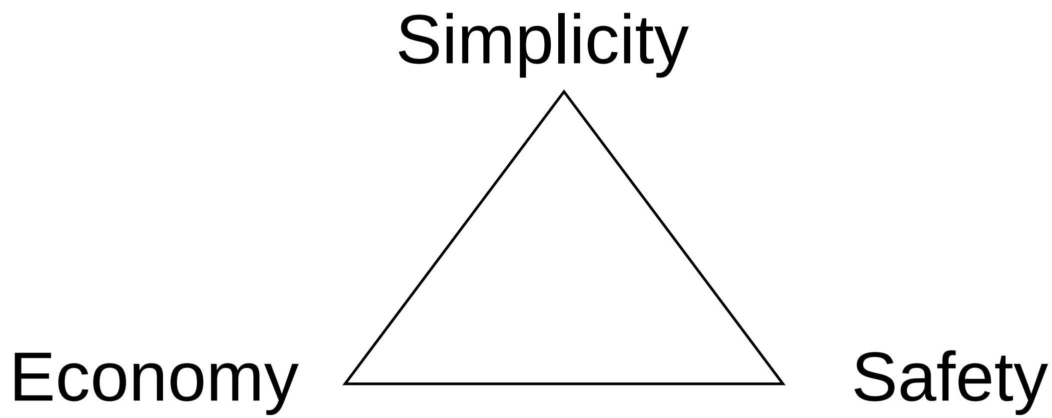
- Simplifies design by eliminating loop piping and external components
- Enhances safety by eliminating major classes of accidents
- Compact containment (small footprint) enhances economics and security

IRIS Design Features

- 335 MWe PWR
- Long Life core: up to 4 years without refueling
- Required maintenance intervals: 4 years
- 8 helical-coil steam generators
- 8 axial flow fully immersed primary coolant pumps
- Internal control rod drive mechanisms
- Integral pressurizer with large volume-to-power ratio



IRIS Design Philosophy



- Simplicity enables both economy <u>and</u> safety
- Proven light water reactor technology
- Implements engineering innovation, but does not require new technology development

IRIS Enhanced (Three-Tier) Safety

1. **Safety-by-Design™**
   Aims at eliminating by design possibility for accidents to occur. Eliminates systems/components that were needed to deal with those accidents.

2. **Passive Safety Systems**
   Protect against still remaining accidents and mitigate their consequences. Fewer (only five) and simpler than in passive LWRs.

3. **Active Systems**
   No active safety-grade systems are required. Active non-safety-grade systems contribute to reducing CDF (core damage frequency).

IMPROVED SAFETY WITH SIMPLIFIED DESIGN AND LOWER COST

IRIS "Safety-by-Design"™ Approach (First Tier)

- Exploit to the fullest what is offered by IRIS design characteristics (chiefly integral configuration) to:
  - Physically eliminate possibility for some accidents to occur.
  - Decrease probability of occurrence of most remaining accident scenarios.
  - Lessen consequences if an accident occurs.
- Intrinsically, without dedicated safety systems

Examples:

No external primary loops → no large break LOCA

Internal CRDMs → no CR ejection

Eventually:

Out of 8 Class IV accidents (most severe ones), 7 eliminated or reduced severity

SMR summary

- Attractive safety (promoted through integral configuration)

- Economic competitiveness yet to be demonstrated

Integral Inherently Safe Light Water Reactor (I2S-LWR)

Recently Awarded: DOE NEUP IRP

Integral Inherently Safe Light Water Reactor – I^2S-LWR

Only one IRP awarded each year for a new reactor concept

FY2012 IRP FOA requirements:

- Large (~1,000 MWe) PWR for US market - economics
- Inherent safety

Awarded to a GT-led team

Multi-institutional, multi-disciplinary:

Georgia Tech (B. Petrovic, PI), F. Rahnema, Co-PI;

NRE/ME/MSE faculty

Nine other partnering organizations: Industry (Westinghouse), Utility (Southern Nuclear), National Lab (INL), US universities (U. of Michigan, U. of Tennessee, U. of Idaho, Morehouse College) and Int'l (U. of Cambridge, UK; Politecnico di Milano, Italy)

3-year program

I2S-LWR approach to advanced, safe and economical nuclear power plant

Advanced, passively safe, large LWRs

Demonstrated economics

+

Inherently safe SMRs

Credible inherent safety features

Economics (through modularity)

yet to be demonstrated

→

I²S-LWR

Integral inherently safe LWR

- 1,000 MWe class (economics)
- Integral primary circuit
- Inherent safety features
- Indefinite passive decay heat removal (under LOOP)
- Seismic isolators

+

Fuel with Enhanced Accident Tolerance

Nuclear Fuel Cycle
and Nuclear Waste Management

Nuclear Fuel Cycle Sustainability

- Front end → Sufficient Resources?
  - Mining, Enrichment
  - (Use Recycled)
  - Fuel fabrication

Yes

- **Uranium, once through fuel cycle → of the order of 70 years**
- **Thorium**
- **Non-traditional U sources**
- **Breeder reactors with recycle → thousands of years**

- In-core residence time
  - Energy production
  - Irradiation
  - Isotopic change

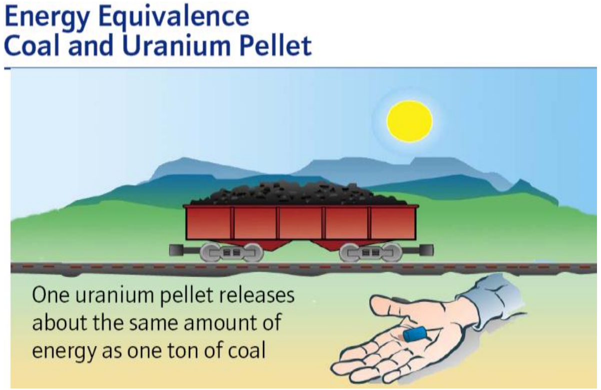
- Back end → Acceptable Waste Management?
  - Waste management
  - (Reprocessing)
  - Short/intermediate storage
  - Ultimate disposal of (residual) waste

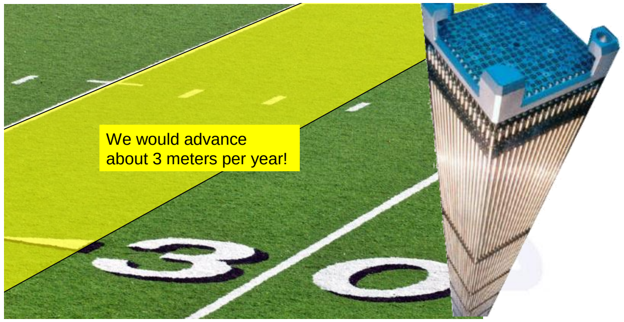
Need to demonstrate

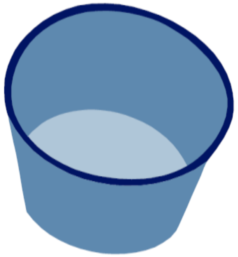
- "Nuclear Waste" is a concern (Used Nuclear Fuel – UNF, and, if recycling, High Level Waste – HLW)
- Understanding/addressing the problem:
  - » Technical
  - » Public acceptance

Used/spent Nuclear Fuel and High Level Waste Management (cartoon level)

- Any energy production generates waste
- Nuclear plant waste lasts long time but is a relatively small quantity (concentrated energy, concentrated waste → may be viewed as advantageous)
- Waste is confined (while burning fossil fuel spreads wastes into the atmosphere)
- All high-level waste since the beginning of commercial nuclear power in the U.S. would by volume occupy less space than a football field piled 15 feet high
- If over your entire lifetime all electricity was generated by a modern PWR, your share of the HL wastes would fit comfortably into a 2-gallon wastepaper basket .







Source:

Used nuclear fuel in US

1. Legacy UNF

- ~65,000 tons
- In spent fuel pools, at NPP sites, mostly filled up
- In dry storage (casks - vertical; horizontal vault)

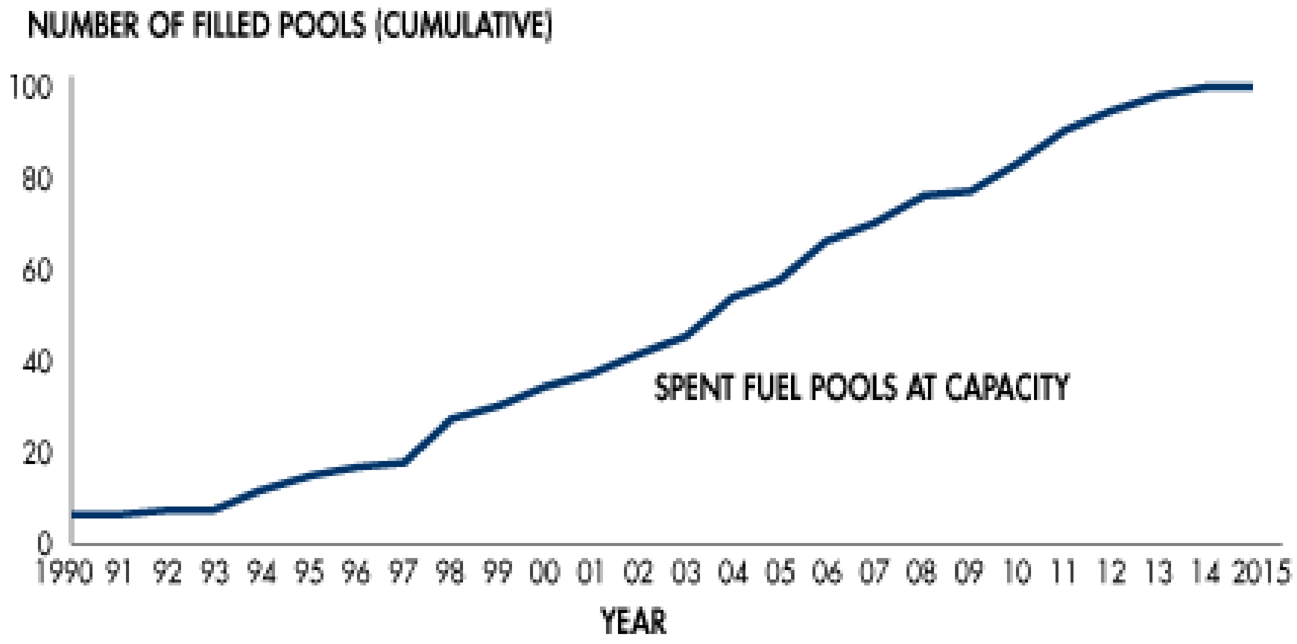
- Interim off-site (centralized) storage facility?
- Permanent disposal?

2. Future UNF and HLW (if reprocessing)

Thus, we need to take care of legacy UNF and develop/implement long-term solutions for future UNF and/or HLW

Source: NRC

Spent fuel pools status
(Source: NRC, as of 3/2011)



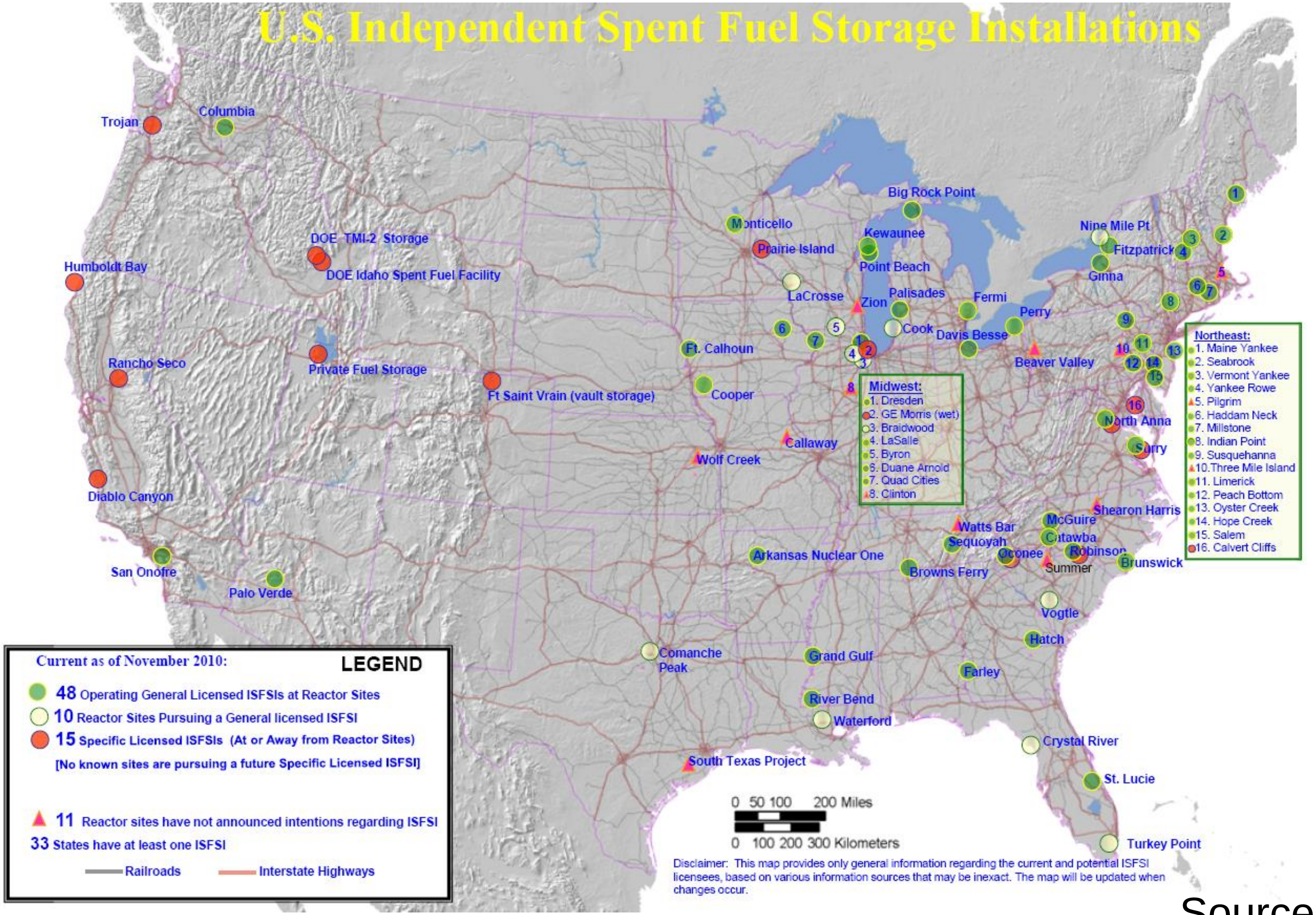
Note: All operating nuclear power reactors are storing used fuel under NRC license in spent fuel pools. Some operating nuclear reactors are using dry cask storage. Information is based on loss of full-core reserve in the spent fuel pools.

Source: Energy Resources International and DOE/RW-0431 – Revision 1

- Spent fuel pools approaching capacity
- Fukushima – requires further re-examination of spent fuel pools

Spent fuel storage installations –
Provide interim storage, but not a long term solution

•



Source: NRC

Used/spent nuclear fuel (once-through cycle) (some numbers….)

Representative used fuel (once through) composition (wt% in UNF)

- 93 wt% Uranium → Waste volume
- 5 wt% Fission Products → Heat generation, dose, small fraction long term
- <2 wt% Transuranics (Pu,Np,Am,Cm) → Long term dose, heat generation
  These TRUs (plutonium and "minor actinides") - main long-term concern
  - Plutonium – may be recycled to generate more energy
  - Remaining minor actinides <0.2% wt%

- Annual amount of used nuclear fuel from one 1,000 MWe Nuclear Plant
  - ~20t "heavy metal" (actinides) in spent fuel, mostly uranium, but also including:
  - ~300 kg plutonium
  - ~30 kg minor actinides (about half a gallon volume in metallic form)
- Your lifetime share (if all electricity produced by nuclear power) of minor actinides would be less than 5 grams! (less than the weight of a nickel) [Compare to all other wastes that we generate during out lifetime]

- Nuclear power generates very small amount of very concentrated waste – it is a feature, not necessarily a drawback (compare to difficulty of CCS – capturing and sequestering billions of tons of carbon)

A number of technical solutions, but no coherent long-term policy/approach

→ A separate talk…….

Summary

Summary and Conclusions

- New electricity/energy sources are and will be needed
- Impossible to meet the growing energy demand without nuclear power (in the mix)
- Nuclear power plants offer several attractive features
- Need to openly address all implications of the Fukushima event; nevertheless, nuclear has good safety record
- Need to address sustainability requirements
- The key concern (real/perceived) is nuclear waste management, and the related nuclear fuel cycle management

Thank you for your attention!
Questions?

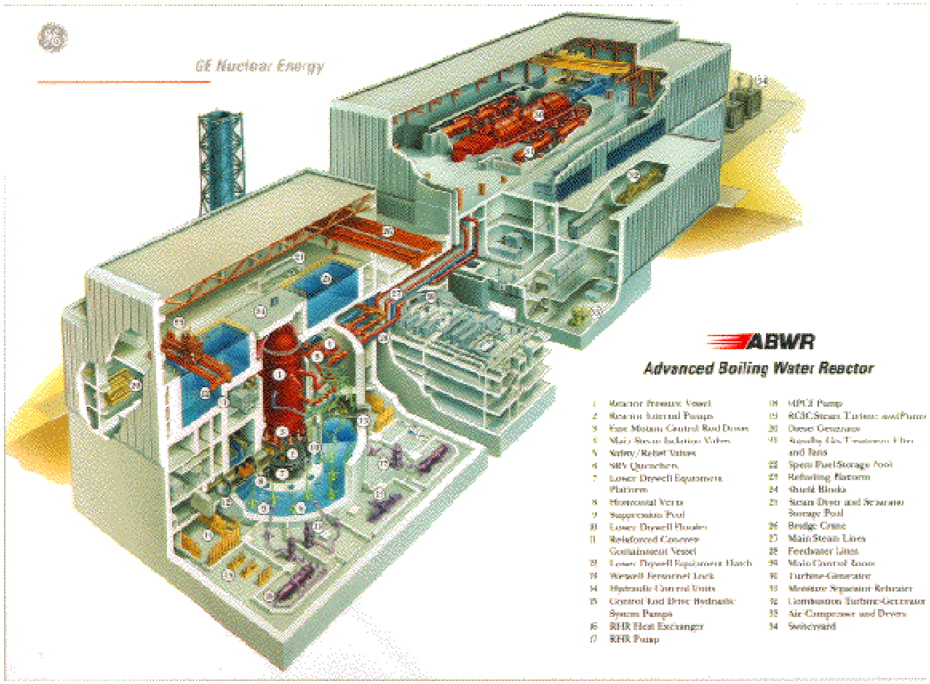
Additional Slides

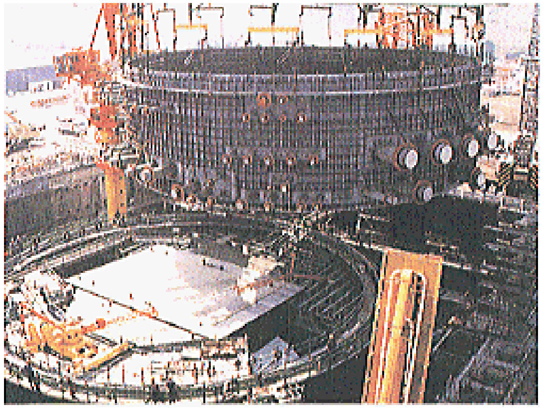
Generation III+ Reactor Designs

Examples:
ABWR → ESBWR
AP1000 – Advanced Passive PWR

Generation III: ABWR (Advanced Boiling Water Reactor)

- Advanced Boiling Water Reactor - ABWR
- Developed by General Electric, Hitachi and Toshiba
- 1,300-1,400 MWe capacity
- 4 units constructed in Japan
- 4 units under construction in Taiwan and Japan

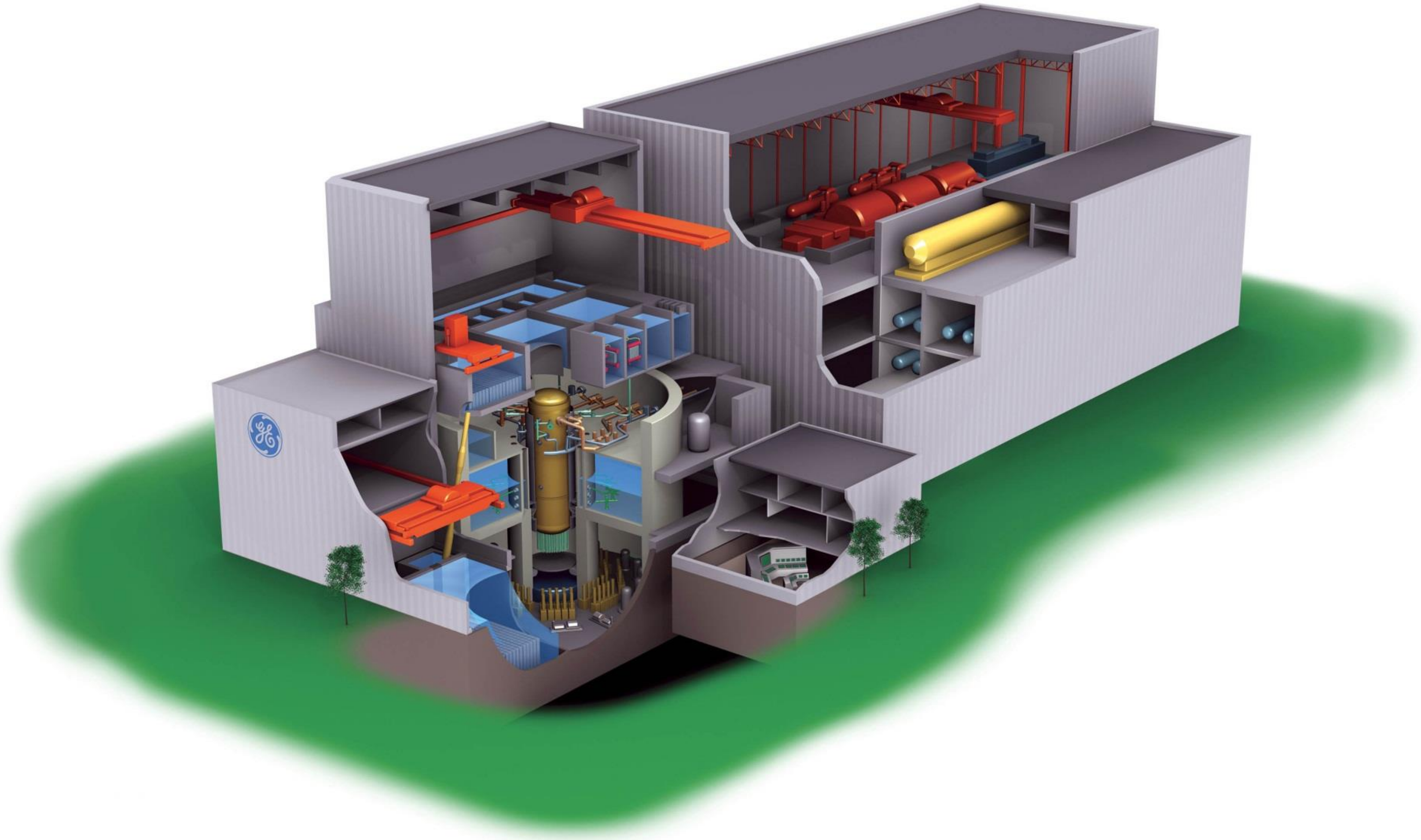




Demonstrated construction time 39 months

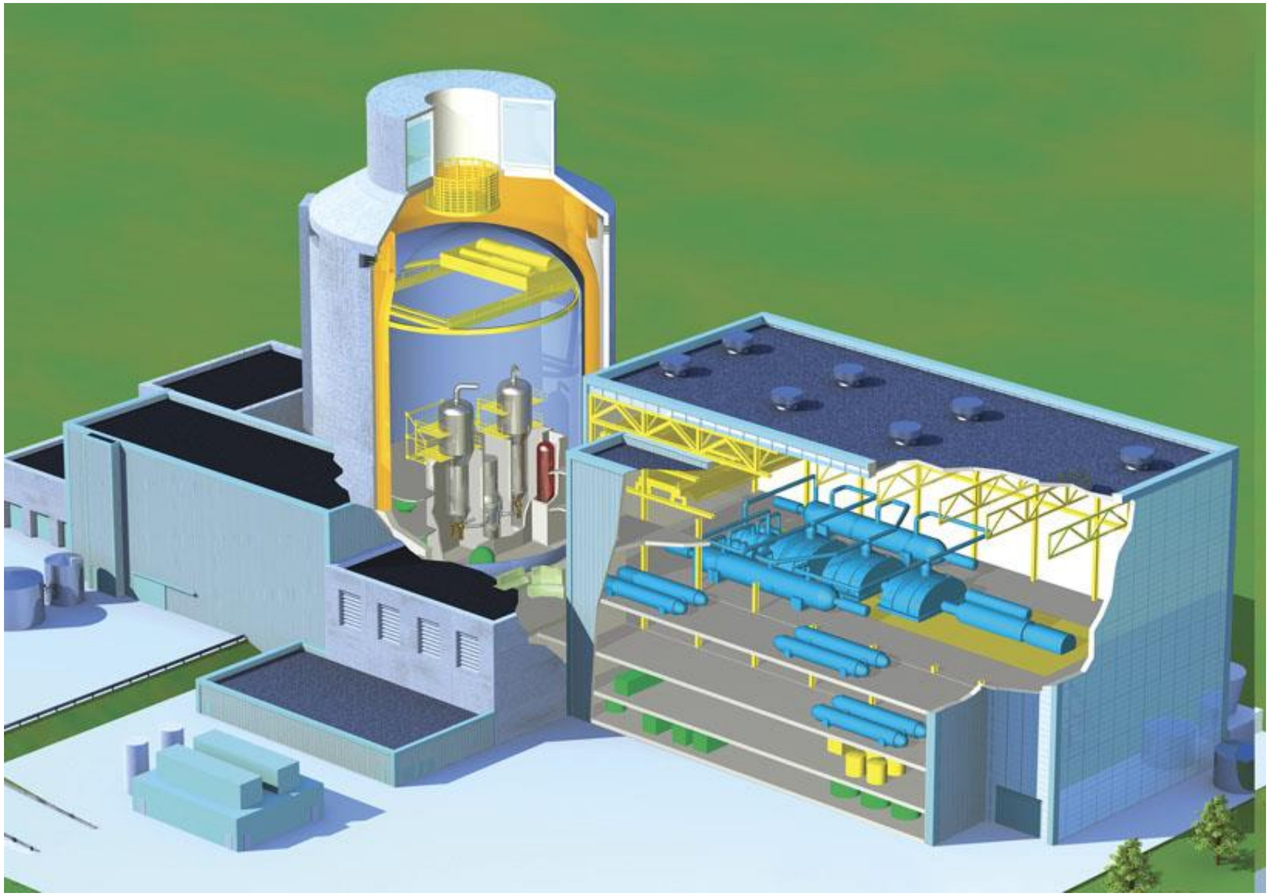
(source: GE / Hitachi)

Gen III+: ESBWR
(Economic Simplified BWR)



(source: GE / Hitachi)

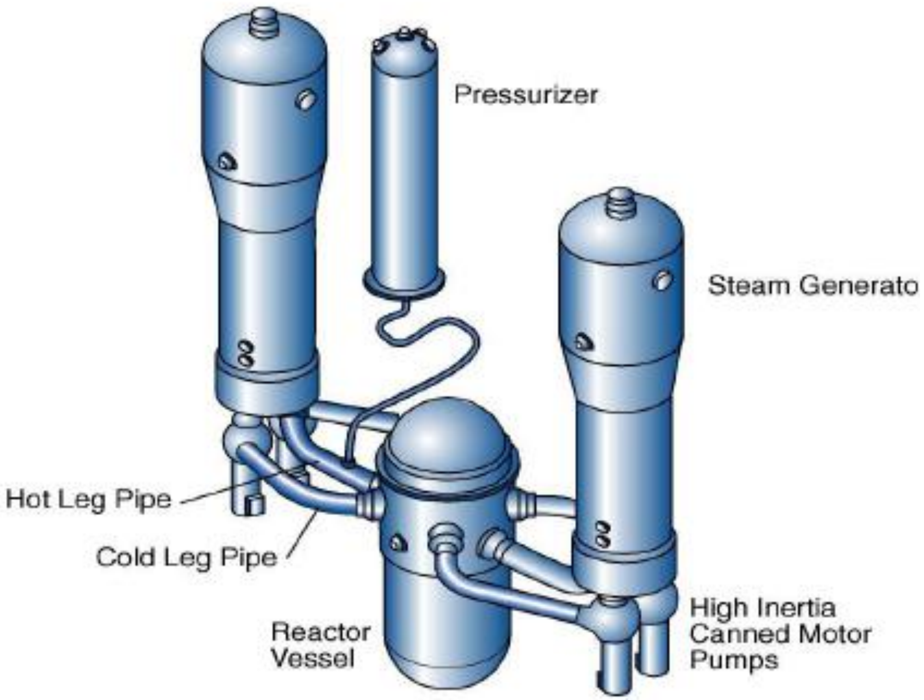
Gen III+: The AP-1000



(source: Westinghouse)

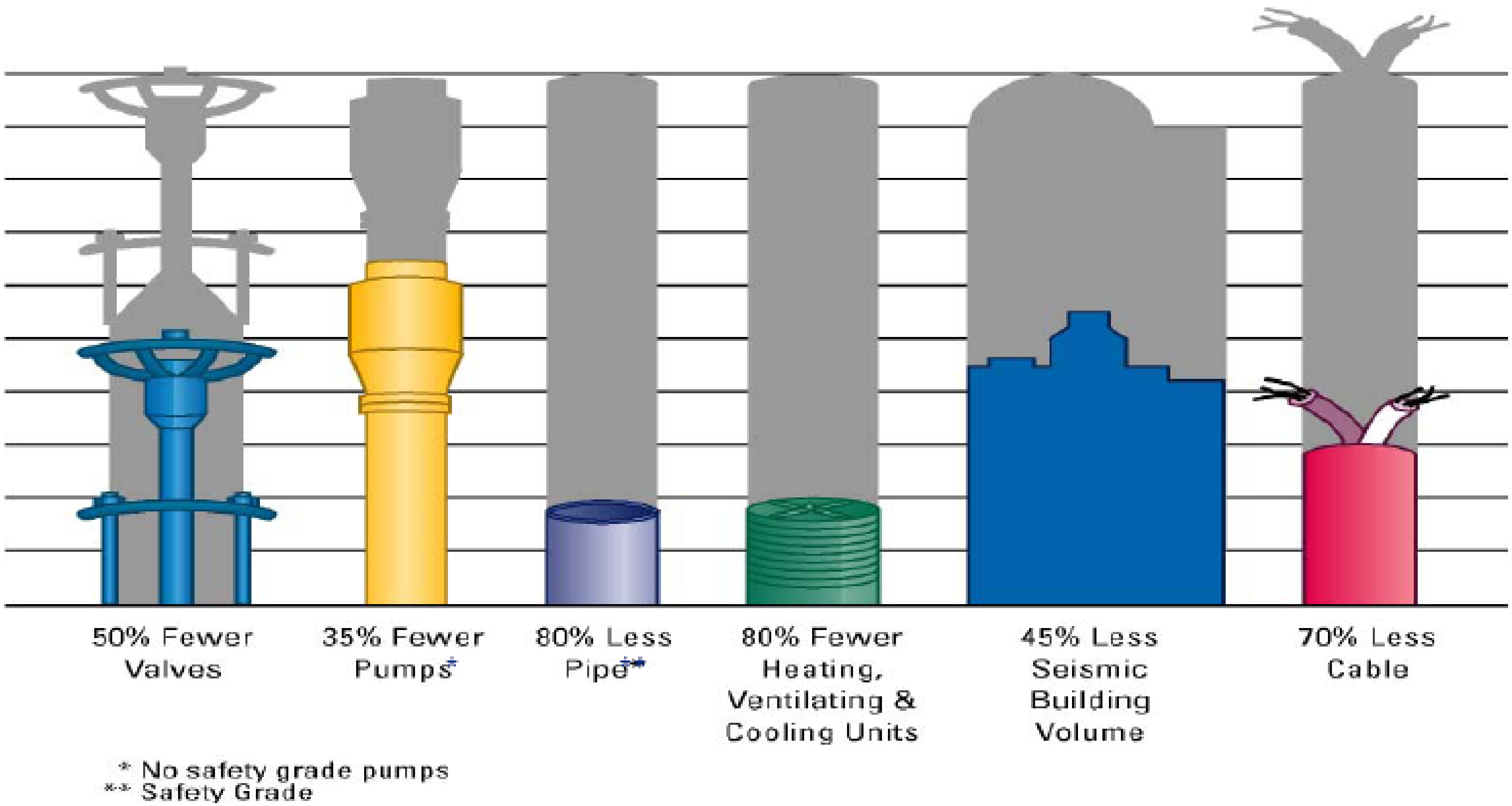
AP1000 reactor system

- Simpler system configuration
- Greater margins in materials selected and size of components
- No reliance on availability of AC electrical power for safety function
- More time for operators to take action if transient event occurs
- Improved economics



(source: Westinghouse)

Passive safety systems eliminate components

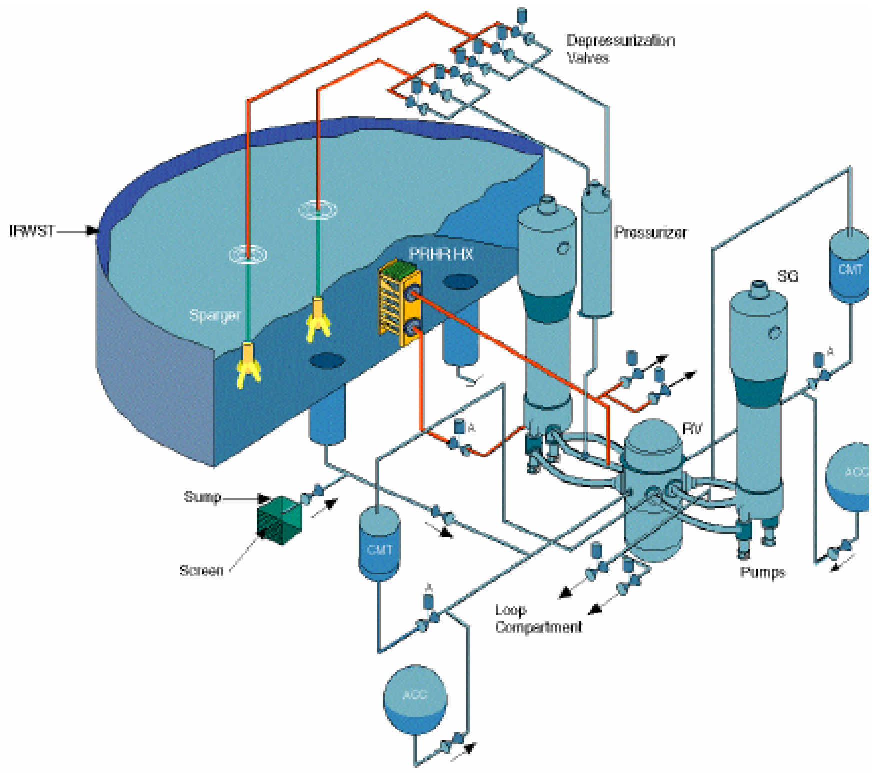


(source: Westinghouse)

AP1000 passive core cooling system

- **AP1000 has no reliance on AC power**
  - **Passive Decay Heat Removal**
  - **Passive Safety Injection**
  - **Passive Containment Cooling**

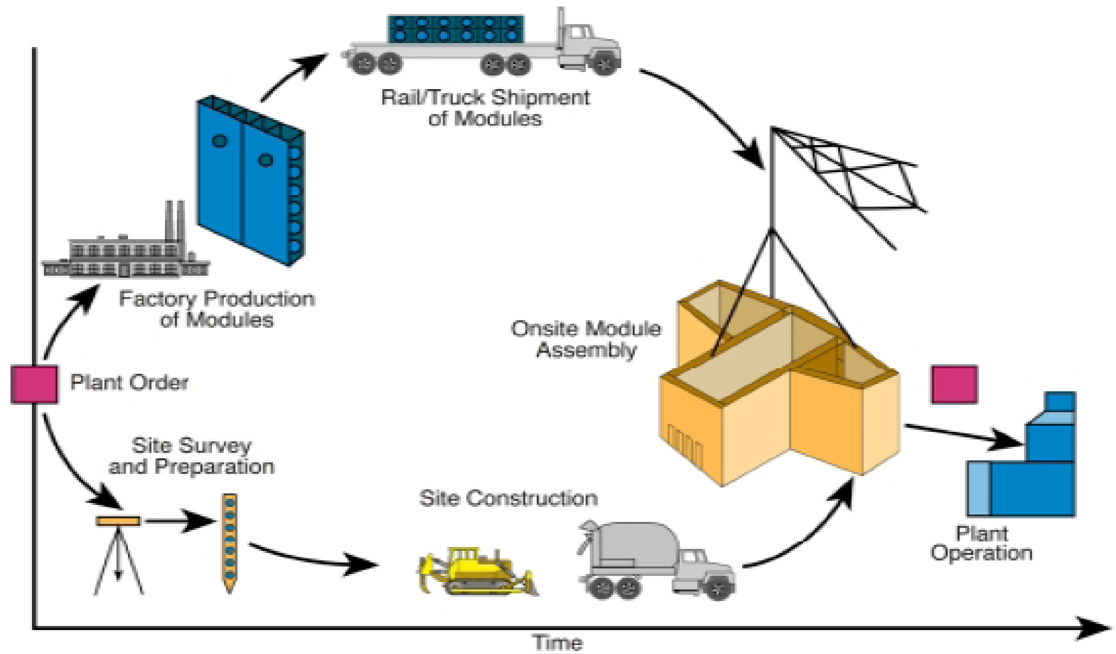
- **Long term safe shutdown state > 72 hours without operator action**



(source: Westinghouse)

Modular design for simplified construction

- Constructed with 300 large modules
- Factory manufacture and assembly of modules
- Pre-testing and inspection prior to shipment
- 36 month construction schedule independently supported



(source: Westinghouse)

Advanced SMRs
(Small/Medium Power Reactors)
(Small/Modular Power Reactors)

If interested:
Special issue of Nuclear Technology – May 2012

SMR / Grid-Appropriate Power Reactors

SMR = small/medium reactor = up to 300/700 MWe

- Why small/medium reactors (SMRs)?
- Rule of thumb: Largest size power plant shouldn't be larger than ~10% of the grid capacity
- For a large 1,600 MWe unit → grid larger than 15 GWe needed. Many countries don't have

- About 1/3 of currently operating reactors are SMRs
- About 1/3 of currently being built reactors are SMRs
- SMRs are performing safely and economically
- Large plants are not a feasible solution in all situations (countries/markets with limited grid or financial)

SMRs

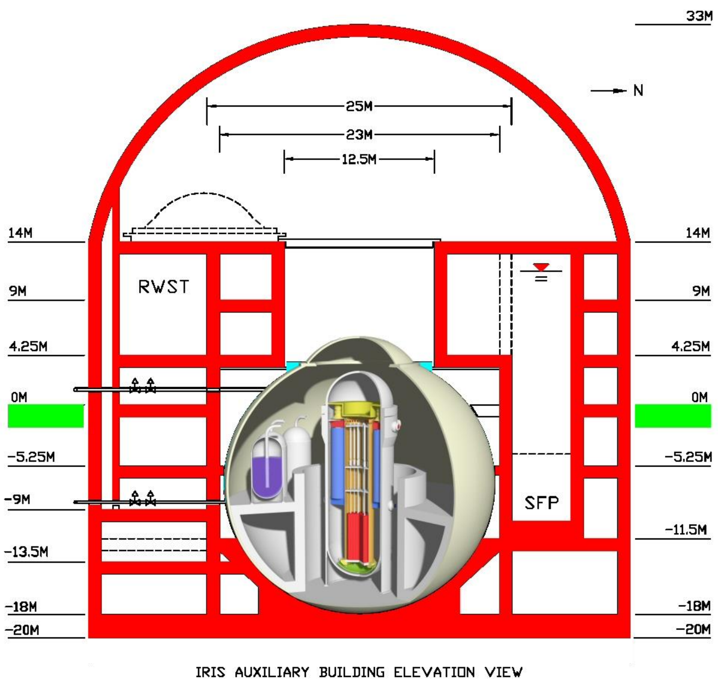
Small/medium reactors
Strong international interest, coordinated through IAEA
Range of technological options

- LWR (light-water cooled reactor)
  - IRIS
  - mPower
  - NuScale
  - Westinghouse
  - …..
- Non-LWR
  - 4S
  - PBMR
  - SVBR
  - …

EXAMPLE: IRIS

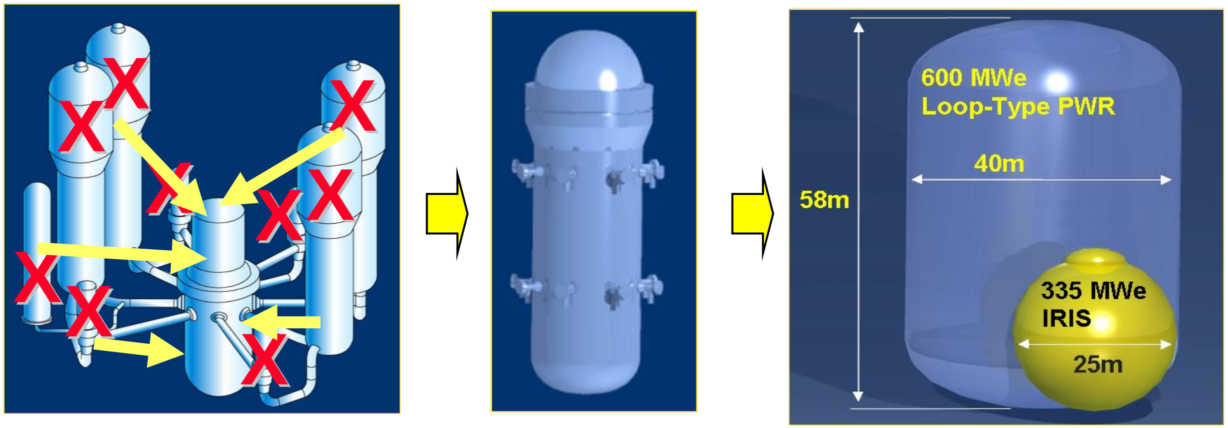
- Advanced integral light water reactor
- Innovative, simple design
- Safety-by-design™ eliminates a number of accidents
- Capability of being licensed without emergency response requirements
- International team
- Anticipated competitive economics
- Cogeneration (desalination, district heating, synthetic fuel)
- Very compact design on seismic isolators

More information: Nuclear Technology, May 2012

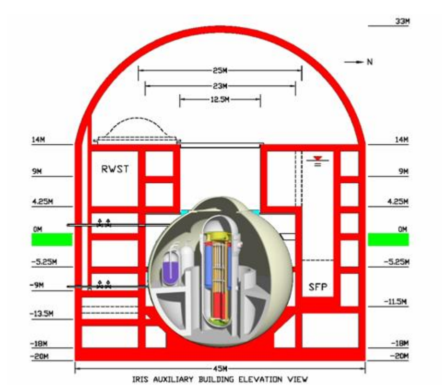


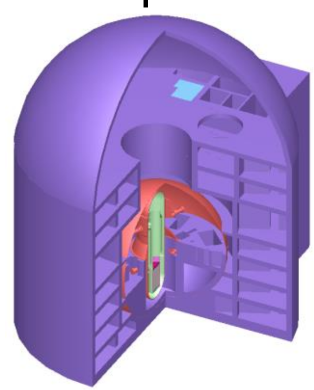
100-335 MWe/module

Integral Primary System Reactor



- Simplifies design by eliminating loop piping and external components.
- Enhances safety by eliminating major classes of accidents.
- Compact containment and small NPP footprint enhances economics and security.





IRIS Enhanced (Three-Tier) Safety Philosophy

1. **Safety-by-Design™**
   Aims at eliminating by design possibility for accidents to occur. Eliminates systems/components that were needed to deal with those accidents.

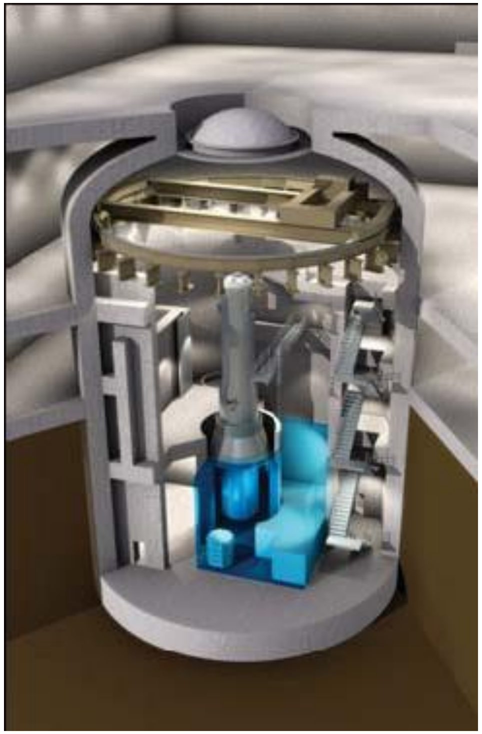
2. **Passive Safety Systems**
   Protect against still remaining accidents and mitigate their consequences. Fewer and simpler than in passive LWRs.

3. **Active Systems**
   No active safety-grade systems are required. But, active non-safety-grade systems contribute to reducing CDF (core damage frequency).

IMPROVED SAFETY WITH SIMPLIFYIED DESIGN

EXAMPLE: B&W mPower Reactor

- Babcock & Wilcox
- Modular
- Integral PWR
- 125 MWe
- 4.5 year cycle



EXAMPLE: Westinghouse SMR

Westinghouse Non-Proprietary Class 3

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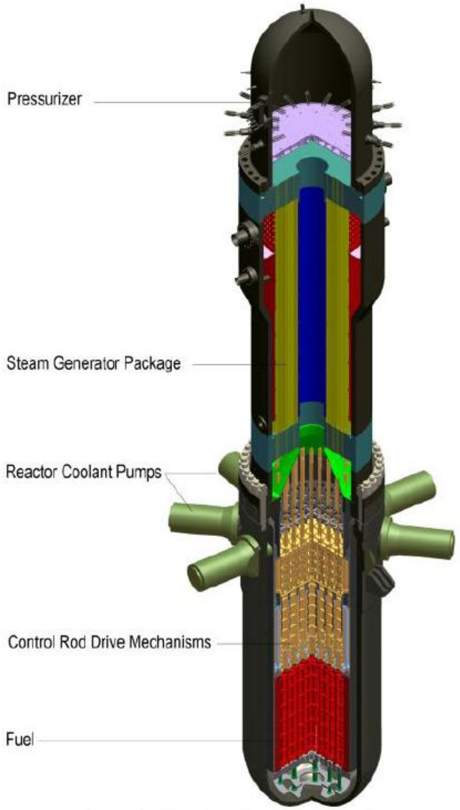
What It Is…

- An integral pressurized water reactor—single 225 MWe reactor (standalone plant design)
- Innovative packaging of proven components
- The highest levels of safety with fewer accident scenarios
- Industry-proven system designs
- Compact reactor coolant system and containment
- An engineered solution for today's clean energy challenges

The Most Economic SMR Design

Westinghouse



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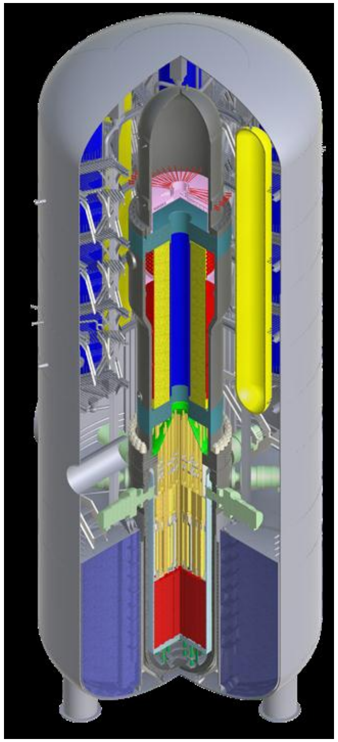
W-SMR Integral Reactor Vessel



(source: Westinghouse)

Generation IV

"Generation IV"

- Initiated by DOE about 10 years ago
- Key requirements evolved over time, focusing on the following characteristics
  - Economics
  - Safety, security
  - Improved use of uranium/thorium resources
  - Improved waste management
  - Ability to transmute ("burn") nuclear waste
  - Generally available after ~2030(?)

GIF

- Generation-IV International Forum (GIF)
  Thirteen members have signed the GIF Charter: Argentina, Brazil, Canada, People's Republic of China, Euratom, France, Japan, Republic of Korea, the Russian Federation, Republic of South Africa, Switzerland, the United Kingdom and the United States.

- Identified 6 types of reactor systems within Gen-IV of interest to GIF members:
  - VHTR – Very-High-Temperature Reactor
  - GFR – Gas-Cooled Fast Reactor
  - MSR – Molten-Salt Reactor
  - LFR – Lead-cooled Fast Reactor
  - SFR – Sodium-Cooled Fast Reactor
  - SCWR – Supercritical-Water-Cooled Reactor

- US interest primary in VHTR and SFR, and Fuel Cycle
- VHTR → NGNP (Next Generation Nuclear Plant)

Overview of Gen-IV Systems (source: OECD)

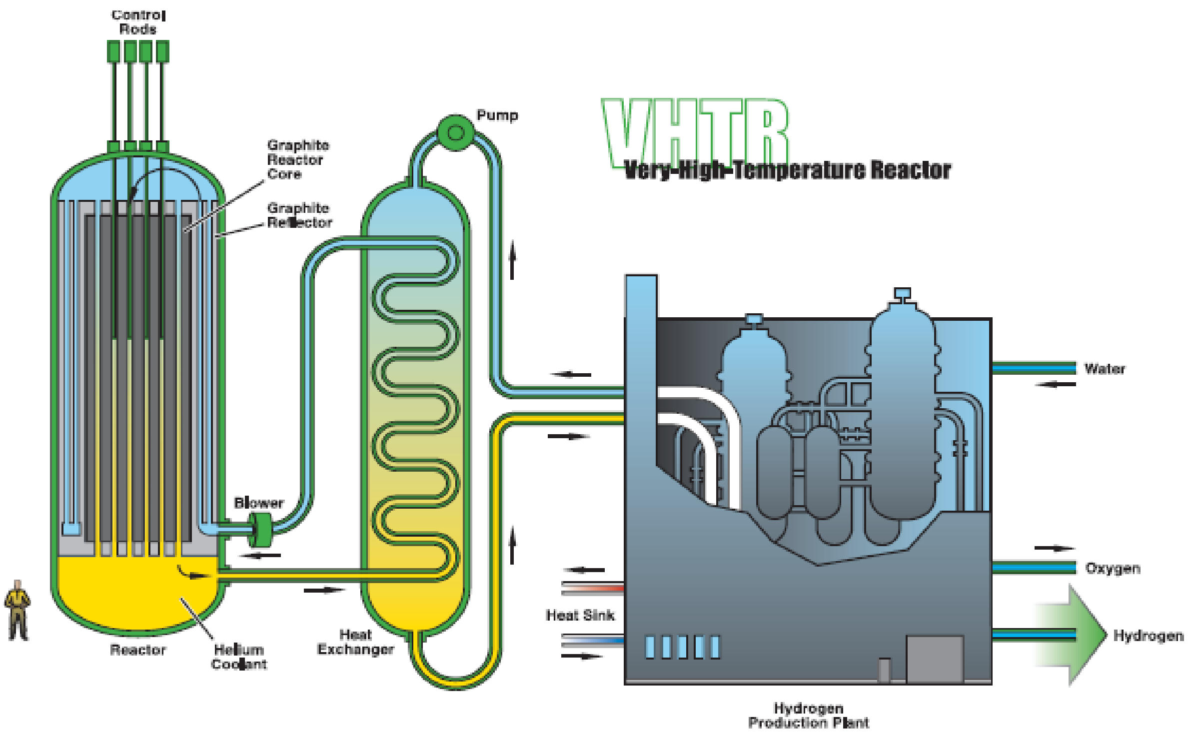
Table 6.1 Overview of Generation IV nuclear energy systems

System	Neutron spectrum	Coolant	Temp.	Fuel	Fuel cycle	Size (MWe)	Main uses
GFR (gas-cooled fast reactor)	fast	helium	850°C	^{238}U & MOX	closed, in-situ	288	electricity & hydrogen
LFR (lead-cooled fast reactor)	fast	PB or Pb-Bi	550-800°C	^{238}U & MOX	closed, regional	50-150, 300-400, 1 200	electricity & hydrogen
MSR (molten salt reactor)	epithermal	fluoride salts	700-800°C	UF_4 in salt	closed, in-situ	1 000	electricity & hydrogen
SFR (sodium-cooled fast reactor)	fast	sodium	550°C	^{238}U & MOX	closed	300-1 500	electricity
SCWR (supercritical water-cooled reactor)	thermal/ fast	water	510-550°C	UO_2	Open/ closed	1 500	electricity
VHTR (very high temperature gas reactor)	thermal	helium	1 000°C	UO_2	open	250	hydrogen & electricity

(source: OECD)

Georgia Tech

VHTR – Very High Temperature Reactor



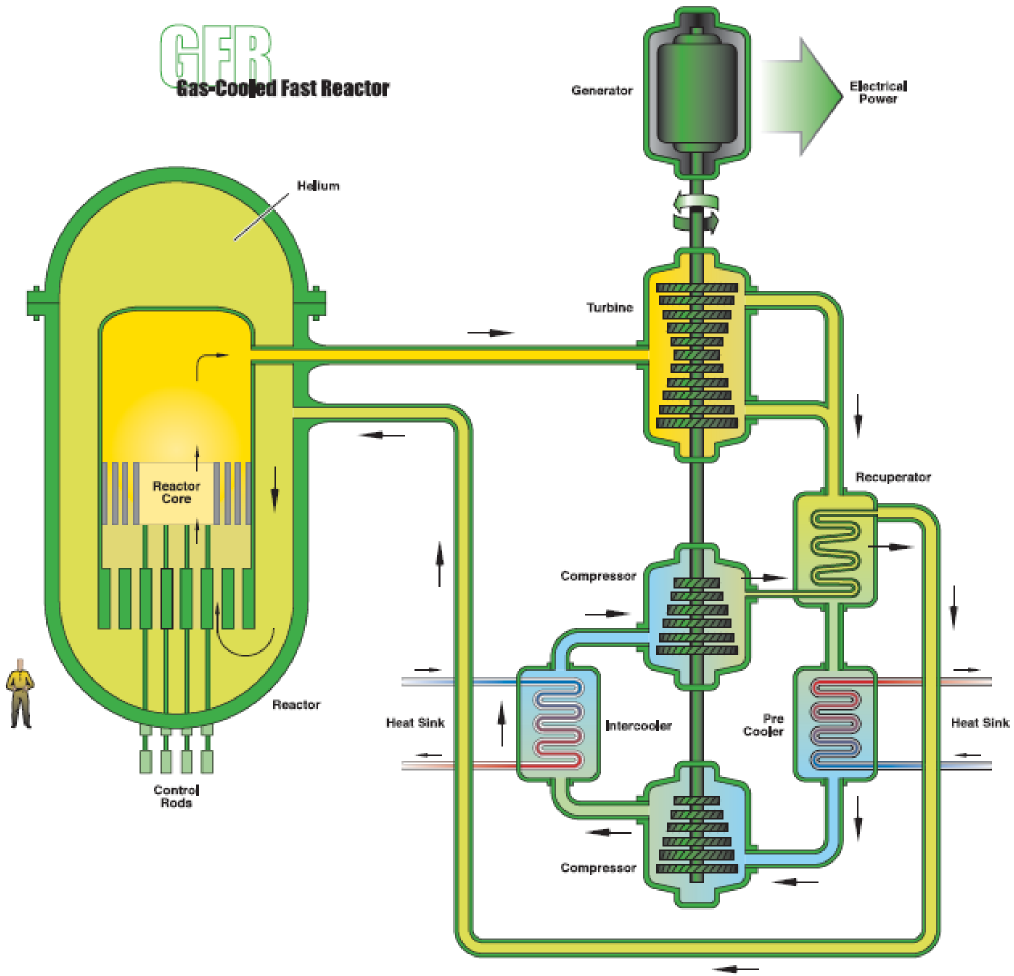
- Gas-cooled (He)
- Very high exit temperature: 1000°C or 850°C
- Two “flavors”:
  - prismatic fuel
  - pebble-like fuel
- High temperature process heat
- Hydrogen production
- High thermodynamic efficiency
- Thermal spectrum
- Deep burn option
- Technological basis (HTGR - PB, FSV, AVR, HTTR, HTR-10, …)

Very-High-Temperature Reactor System (VHTR)

The Very-High-Temperature Reactor (VHTR) system uses a thermal neutron spectrum and a once-through uranium cycle. The VHTR system is primarily aimed at nearer-term deployment of a system for high-temperature process heat applications with a focus on thermochemical hydrogen production at superior efficiency. The VHTR system has coolant outlet temperatures above 1000°C, which enables high efficiency thermochemical water-splitting without carbon emissions. The reference reactor concept has a 600-MWth helium-cooled core based on either the prismatic block fuel of the Gas Turbine–Modular Helium Reactor (GT-MHR) or the pebble fuel of the Pebble Bed Modular Reactor (PBMR). Operating at an efficiency of over 50%, such a plant would produce over 200 metric tonnes of hydrogen per day. This is the equivalent of over 300,000 gallons of gasoline per day.

(source: DOE / GIF)

GFR – Gas-Cooled Fast Reactor



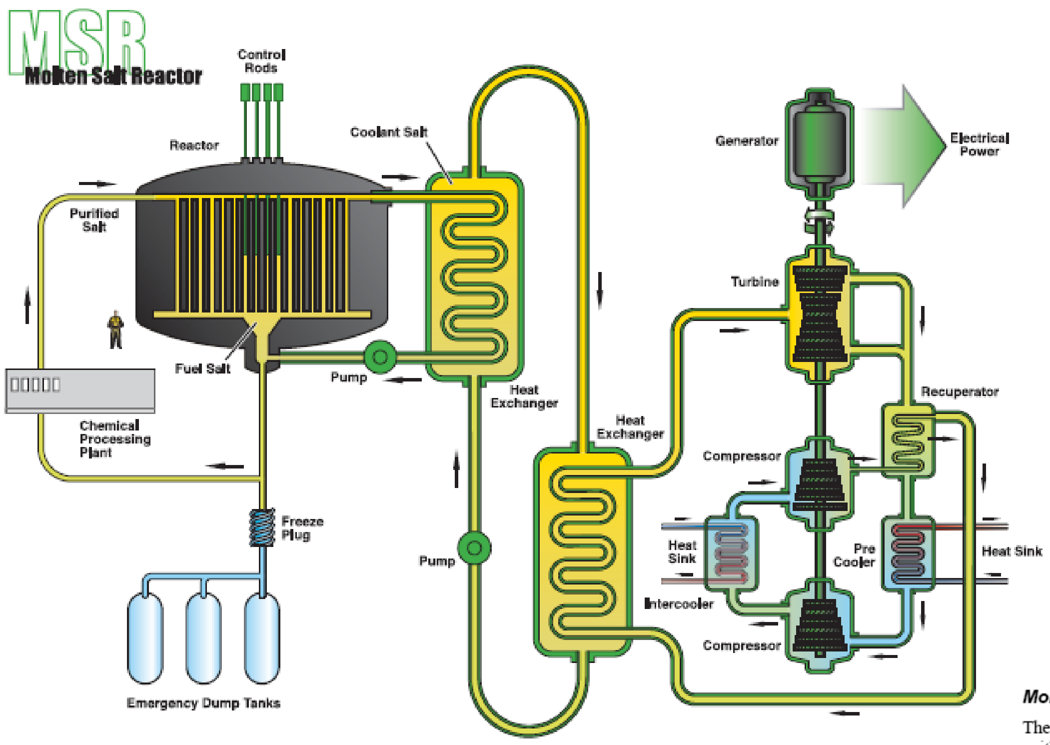
- Gas-cooled
- 300-600 MWe
- Fast spectrum
- Closed fuel cycle; management of actinides and/or conversion of fertile uranium → improved sustainability
- Potentially hydrogen production

Gas-Cooled Fast Reactor System (GFR)

The Gas-Cooled Fast Reactor (GFR) system features a fast neutron spectrum and closed fuel cycle for efficient management of actinides and conversion of fertile uranium.[2] Core configurations are being considered based on pin- or plate-based fuel assemblies or prismatic blocks, with a total core power of 300–600 MWe. The GFR system is strong in sustainability because of its closed fuel cycle and excellent performance in actinide management. It is rated good in safety, economics, and in proliferation resistance and physical protection. It is primarily envisioned for missions in electricity production and actinide management, although it may be able to economically support hydrogen production.

(source: DOE / GIF)

MSR – Molten Salt Reactor



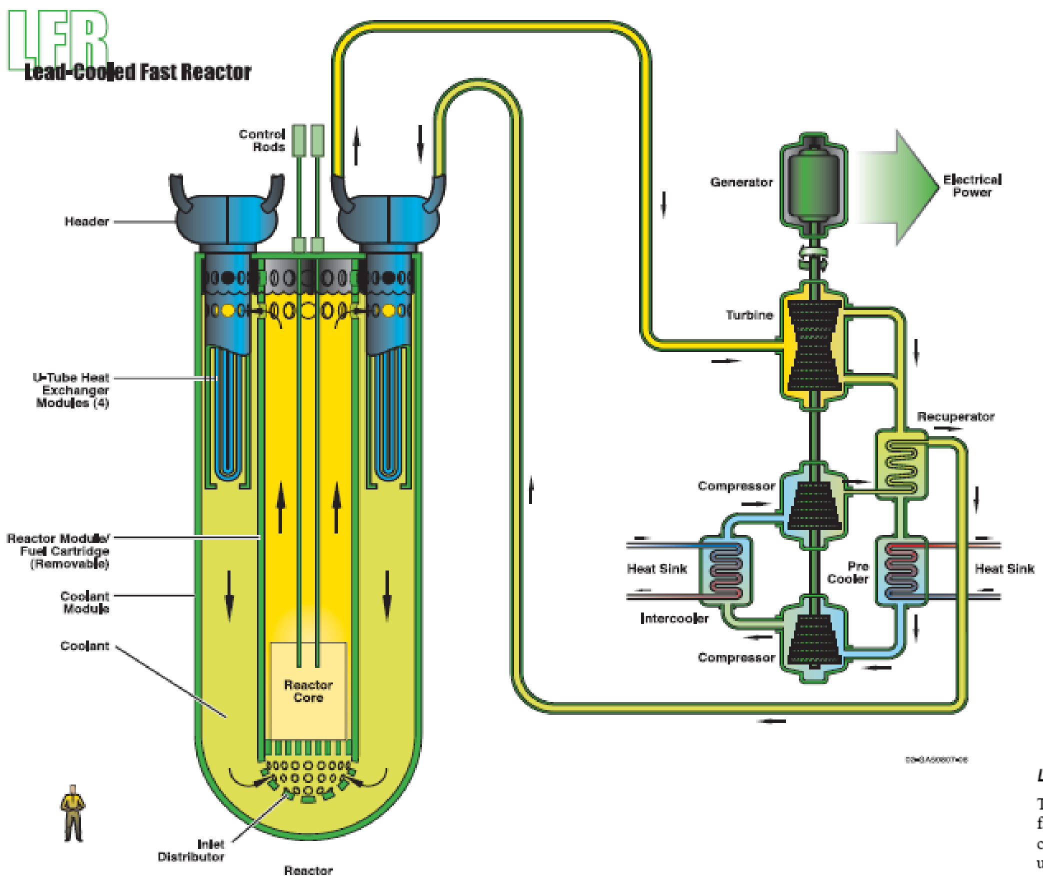
- Molten salt – coolant, fuel may also be dissolved
- 1000 MWe reference
- Thermal/epithermal spectrum
- High temperature (700-800°C) and efficiency
- Enhanced safety (small fissile content, low pressure)
- Closed fuel cycle – on-line reprocessing
- Effective for disposition/burn of Pu and MA
- Suitable for Th cycle

Molten Salt Reactor System (MSR)

The Molten Salt Reactor (MSR) system features an epithermal to thermal neutron spectrum and a closed fuel cycle tailored to the efficient utilization of plutonium and minor actinides. In the MSR system, the fuel is a circulating liquid mixture of sodium, zirconium, and uranium fluorides. The reference plant has a power level of 1000 MWe. The system operates at low pressure (about 5 atmospheres) and has a coolant outlet temperature above 700°C, affording improved thermal efficiency. The MSR system is strong in sustainability because of its closed fuel cycle and excellent performance in waste burndown. It is rated good in safety, and in proliferation resistance and physical protection, and it is rated neutral in economics because of its large number of subsystems for maintenance of the fuel and coolant. It is primarily envisioned for missions in electricity production and the final burn of plutonium and minor actinides.Sodium-Cooled Fast Reactor System (SFR)

(source: DOE / GIF)

LFR – Lead-Cooled Fast Reactor



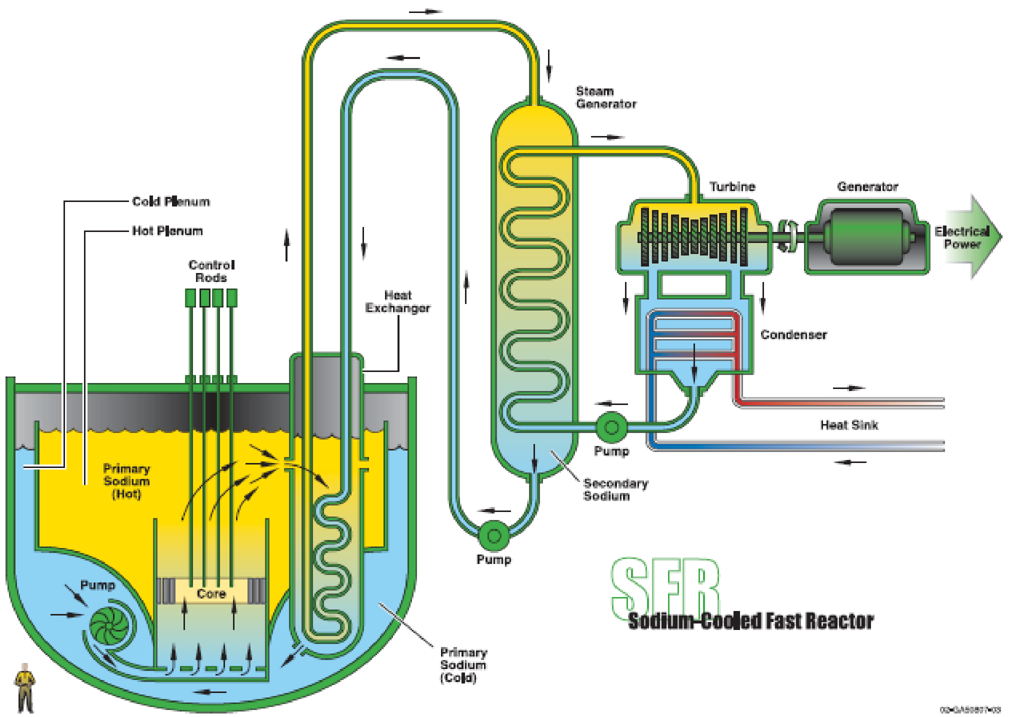
- Lead-cooled or LBE-cooled
- Range of power levels (50-1200 MWe)
- Fast spectrum
- High temperature and efficiency
- Enhanced safety (large thermal inertia, high boiling point)
- Management of actinides and/or conversion of fertile uranium → improved sustainability
- Potentially hydrogen production

Lead-Cooled Fast Reactor System (LFR)

The Lead-Cooled Fast Reactor (LFR) system features a fast neutron spectrum and a closed fuel cycle for efficient management of actinides and conversion of fertile uranium. The system uses a lead or lead/bismuth eutectic liquid-metal-cooled reactor. The reactor is cooled by natural convection and sized between 50–1200 MWe, with a reactor outlet coolant temperature of 550°C, possibly ranging up to 800°C, depending upon the success of the materials R&D. The LFR system is strong in sustainability because a closed fuel cycle is used, and in proliferation resistance and physical protection because it employs a long-life core. It is rated good in safety and economics. The safety is enhanced by the choice of a relatively inert coolant. It is primarily envisioned for missions in electricity and hydrogen production and actinide management with good proliferation resistance.

(source: DOE / GIF)

SFR – Sodium-Cooled Fast Reactor



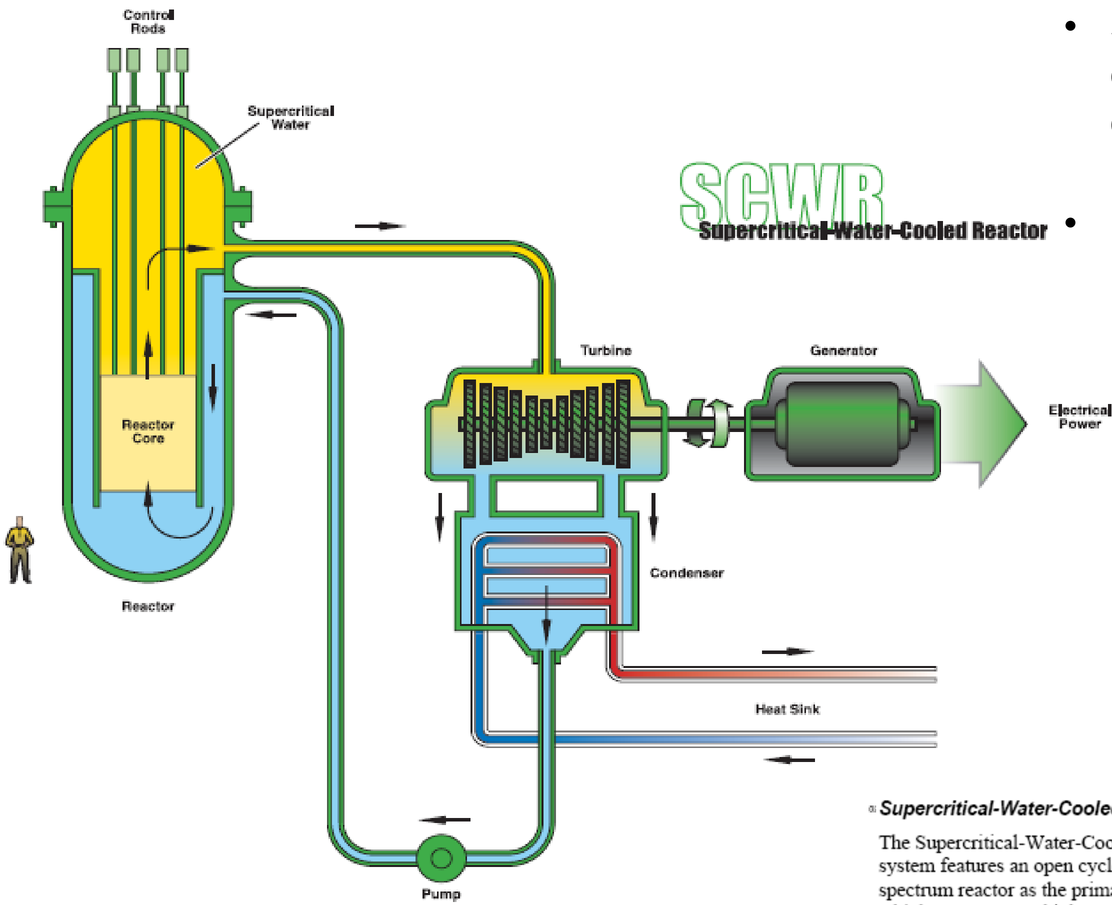
- Sodium-cooled
- Range of power levels 150-1500 MWe
- Fast spectrum
- Closed fuel cycle; aqueous or pyro-metallurgy processing; management of actinides
- Mid-high temperature (550C exit)

Sodium-Cooled Fast Reactor System (SFR)

The Sodium-Cooled Fast Reactor (SFR) system features a fast neutron spectrum and a closed fuel cycle for efficient management of actinides and conversion of fertile uranium. A full actinide recycle fuel cycle is envisioned with two major options: One is an intermediate size (150 to 500 MWe) sodium-cooled reactor with a uranium-plutonium-minor-actinide-zirconium metal alloy fuel, supported by a fuel cycle based on pyrometallurgical processing in collocated facilities. The second is a medium to large (500 to 1500 MWe) sodium-cooled fast reactor with mixed uranium-plutonium oxide fuel, supported by a fuel cycle based upon advanced aqueous processing at a central location serving a number of reactors. The outlet temperature is approximately 550°C for both. The SFR system is strong in sustainability because of its closed fuel cycle and excellent potential for actinide management. It is rated good in safety, economics, and proliferation resistance and physical protection. It is primarily envisioned for missions in electricity production and actinide management.

(source: DOE / GIF)

SCWR – Supercritical-Water-Cooled Reactor



- Supercritical-water cooled to increase efficiency compared to other water-cooled systems
  [Potential stability issues]
- 1700 MWe

Supercritical-Water-Cooled Reactor System (SCWR)

The Supercritical-Water-Cooled Reactor (SCWR) system features an open cycle with a thermal neutron spectrum reactor as the primary option. The system uses a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water to achieve a thermal efficiency approaching 44%. The reference plant has a 1700-MWe power level and a reactor outlet temperature of 550°C. The SCWR system is highly ranked in economics because of the high thermal efficiency and plant simplification. The SCWR is rated good in safety, and in proliferation resistance and physical protection. The SCWR is primarily aimed at electricity production, where its high thermal efficiency and plant simplification may provide a breakthrough in system economics.

(source: DOE / GIF)