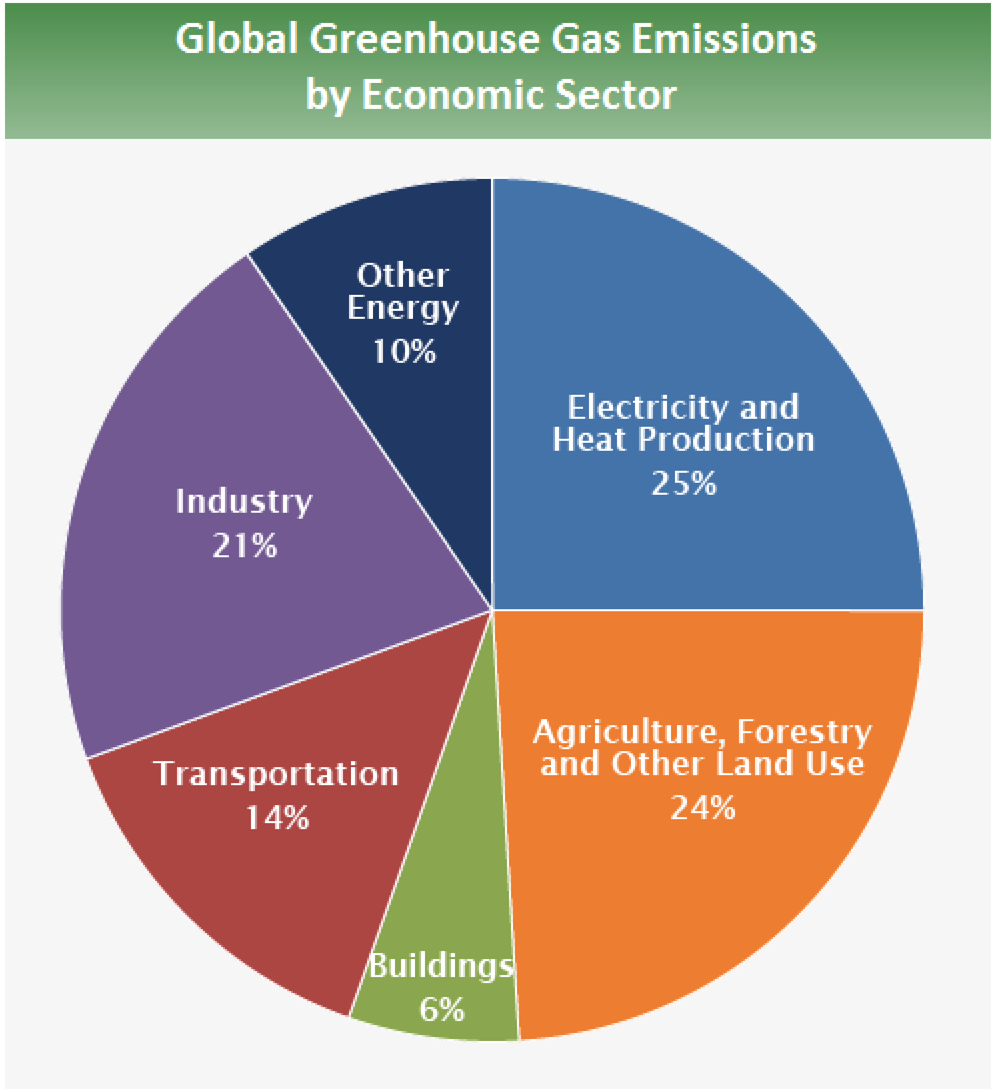
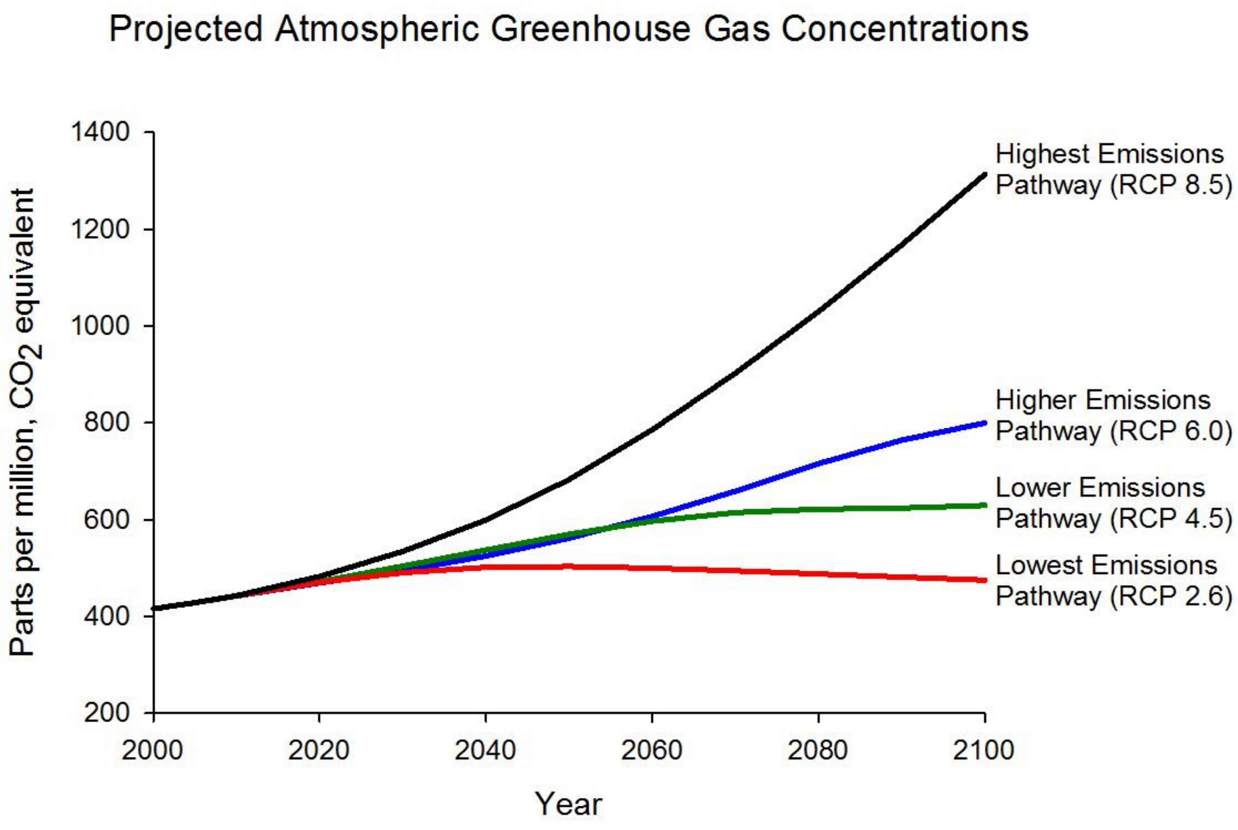
Once upon a time,
a Small Modular Reactor…

Outline

1. Why should we care?
2. What are SMRs?
3. What does the future hold?

Emissions Problem

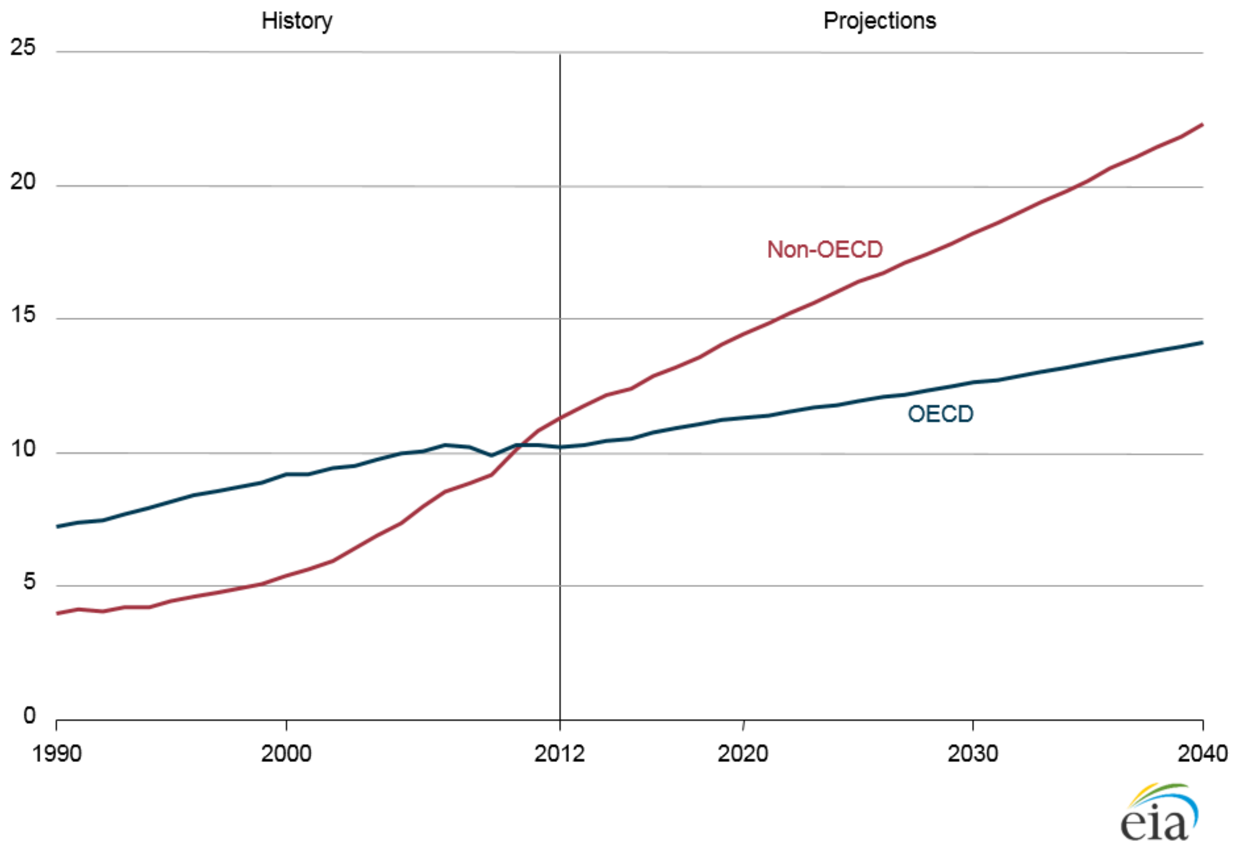




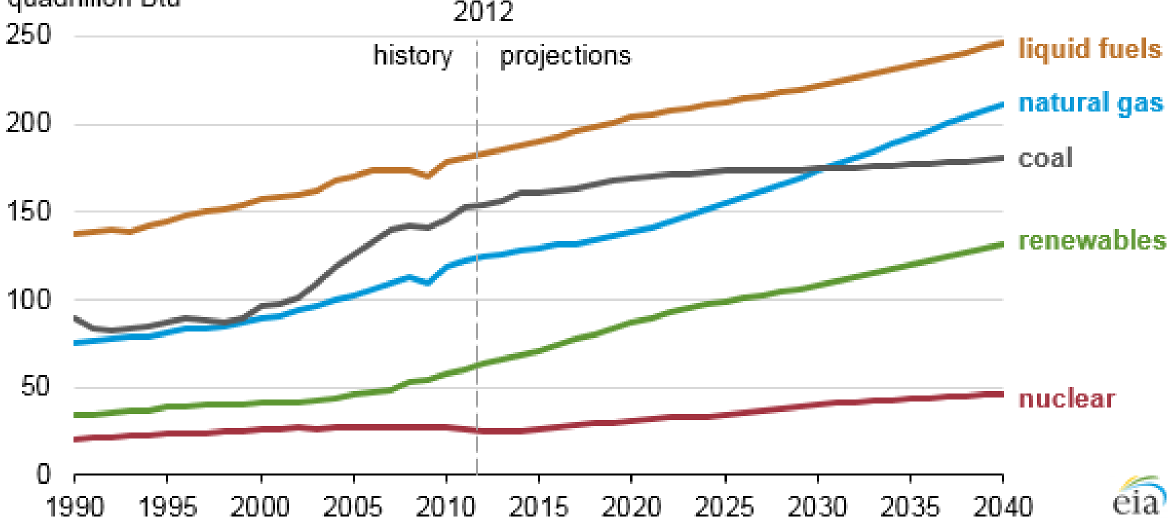
IPCC (2014) based on 2010 data, https://www3.epa.gov/climatechange/

Emissions Problem

Figure 5-1. OECD and non-OECD net electricity generation, 1990–2040
trillion kilowatthours



World energy consumption by source, 1990-2040
quadrillion Btu

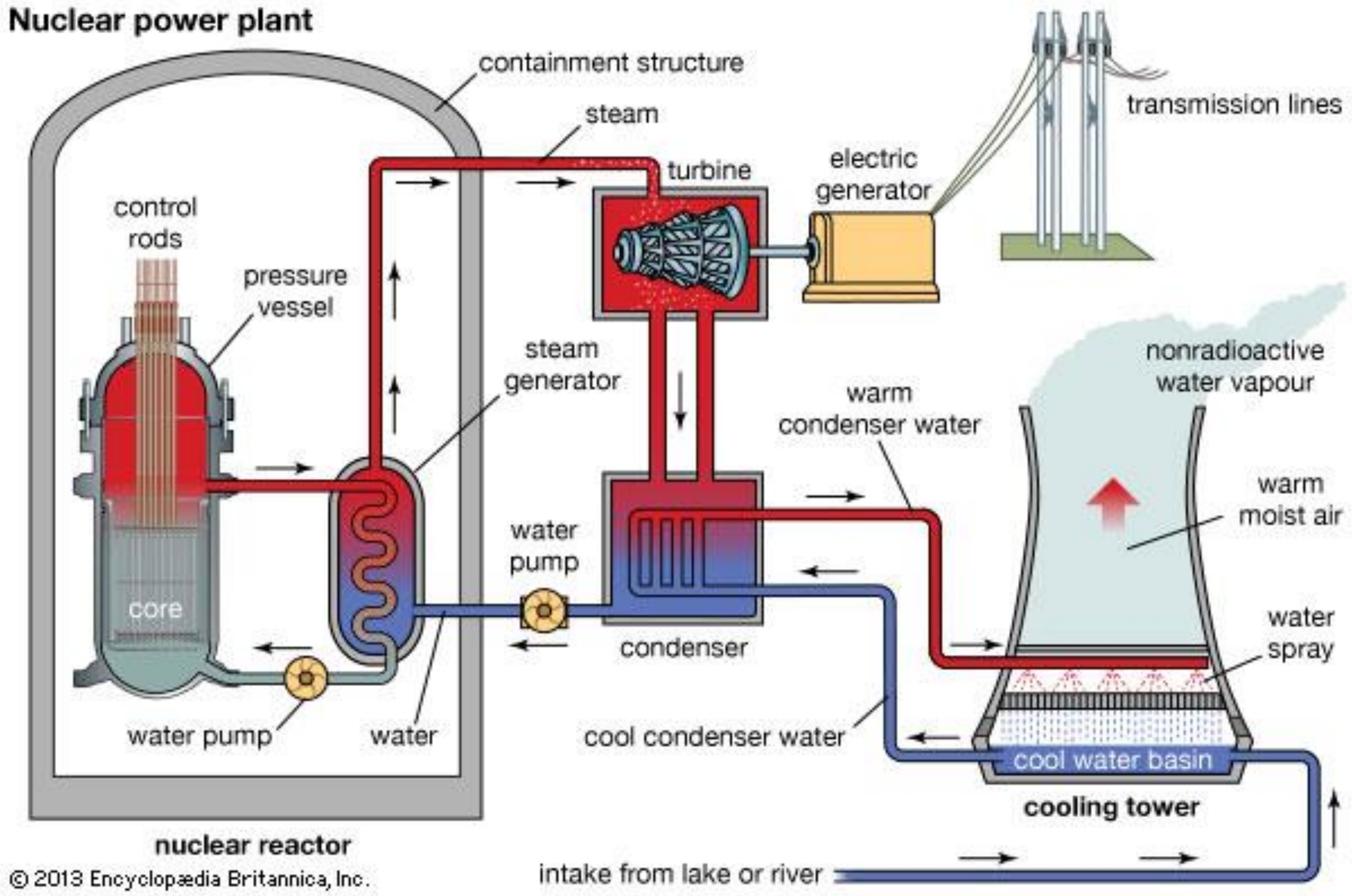


Issues with nuclear energy

What are your concerns re: nuclear energy?

- Safety
- Public perception
- Cost
- Time to build
- Nuclear waste
- Proliferation
- Crisis management

Conventional nuclear power



- Single reactor
- Large capacity (~1 GWe)
- Assembled on-site
- No load following*
- Long restart times
- Current fleet of LWR are near end of permits

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third way
fresh thinking

http://www.thirdway.org/report/the-advanced-nuclear-industry

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Company	Location	Design Type
Transatomic (TAP)	Cambridge, MA	Molten Salt Reactor
Terrestrial Energy (Integral MSR)	Mississauga, Canada	Molten Salt Reactor
Martingale Inc (Thorcon)	Stuart, FL	Molten Salt Reactor
Flibe Energy (LFTR)	Huntsville, AL	Molten Salt Reactor
Oak Ridge National Laboratory (SmATHR)	Oak Ridge, TN	Molten Salt Reactor
Massachusetts Institute of Technology (FHR)	Cambridge, MA	Molten Salt Reactor
University of California, Berkeley (PB-FHR)	Berkeley, CA	Molten Salt Reactor
General Electric-Hitachi (PRISM)	Wilmington, NC	Liquid Metal-cooled Fast Reactors
Advanced Reactor Concepts (ARC-100)	Reston, VA	Liquid Metal-cooled Fast Reactors
Thorenco	San Francisco, CA	Liquid Metal-cooled Fast Reactors
Argonne National Laboratory (STAR)	Lemont, IL	Liquid Metal-cooled Fast Reactors
LakeChime (L-ESSTAR)	Williamsburg, VA	Liquid Metal-cooled Fast Reactors
Gen4 Energy (G4M)	Denver, CO	Liquid Metal-cooled Fast Reactors
Virginia Tech and ADNA Corp. (GEMSTAR)	Blacksburg, VA	Liquid Metal-cooled Fast Reactors
University of California, Berkeley (ENHS)	Berkeley, CA	Liquid Metal-cooled Fast Reactors
Westinghouse	Pittsburgh, PA	Liquid Metal-cooled Fast Reactors
Terrapower (TWR)	Bellevue, WA	Liquid Metal-cooled Fast Reactors (Variant)
Starcore Nuclear	Montreal, Canada	High Temperature Gas Reactor
General Atomics (EM2 and MHR)	San Diego, CA	High Temperature Gas Reactor
Areva (SC-HTGR)	Bethesda, MD	High Temperature Gas Reactor
DOE Next Generation Nuclear Plant	Bethesda, MD	High Temperature Gas Reactor (Collaborative Project)
Hybrid Power Technologies (Hybrid)	Kansas City, KS	High Temperature Gas Reactor (Variant)
X-Energy	Greenbelt, MD	Pebble Bed Modular Reactor
Northern Nuclear (Leadir-PS100)	Cambridge, Canada	Pebble Bed Modular Reactor (Lead Cooled)
UPower	Mountain View, CA	Nuclear Battery (Solid State)
University of Missouri	Columbia, MO	Nuclear Battery
CityLabs (NanoTritium)	Homestead, FL	Nuclear Battery
Dunedin (SMART)	Toronto, Canada	Nuclear Battery
Widetronix	Ithaca, NY	Nuclear Battery
SuperCritical Technologies	Seattle, WA	Super-Critical CO2 Reactor
Lightbridge	Tysons Corner, VA	Designs Advanced Nuclear Fuels

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B&W Company and Bechtel Power Corp. (mPower)	Charlotte, NC	Small Modular Reactor (PWR)
NuScale Power (NuScale)	Corvallis, OR	Small Modular Reactor (PWR)
Radix Power and Energy Corp. (RADIX)	Setauket, NY	Small Modular Reactor (PWR)
Holtec (SMR-160)	Jupiter, FL	Small Modular Reactor (PWR)
Westinghouse (SMR)	Fulton, MO	Small Modular Reactor (PWR)
General Atomics (TPS)	San Diego, CA	Small Modular Reactor (PWR)
Helion Energy	Redmond, WA	Fusion
National Ignition Facility	Livermore, CA	Fusion
General Fusion	Burnaby, Canada	Fusion
Lawrenceville Plasma Physics	Middlesex, NJ	Fusion
Lockheed Martin	Bethesda, MD	Fusion
General Atomics	San Diego, CA	Fusion
Tri Alpha	Foothill Ranch, CA	Fusion
Princeton Plasma Physics Laboratory	Princeton, NJ	Fusion
Fusion Science Center	Rochester, NY	Fusion
Z Machine	Albuquerque, NM	Fusion

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Small reactors operating

Name	Capacity	Type	Developer
CNP-300	300 MWe	PWR	CNNC, operational in Pakistan & China
PHWR-220	220 MWe	PHWR	NPCIL, India
EGP-6	11 MWe	LWGR	at Bilibino, Siberia (cogen)

Small reactor designs under construction

Name	Capacity	Type	Developer
KLT-40S	35 MWe	PWR	OKBM, Russia
CAREM-25	27 MWe	integral PWR	CNEA & INVAP, Argentina
HTR-PM, HTR-200	2x105 MWe	HTR	INET, CNEC & Huaneng, China

Advanced Nuclear Power

Name	Capacity	Type	Developer
EM2	240 MWe	HTR, FNR	General Atomics (USA)
VK-300	300 MWe	BWR	RDIPE, Russia
AHWR-300 LEU	300 MWe	PHWR	BARC, India
CAP150	150 MWe	integral PWR	SNERDI, China
ACPR100	140 MWe	integral PWR	CGN, China
IMR	350 MWe	integral PWR	Mitsubishi Heavy Ind, Japan
PBMR	165 MWe	HTR	PBMR, South Africa*
SC-HTGR (Antares	250 MWe	HTR	Areva, France
Xe-100	48 MWe	HTR	X-energy, USA
Gen4 module	25 MWe	FNR	Gen4 (Hyperion), USA
MCFR	unknown	MSR/FNR	Southern Co, USA
TMSR-SF	100 MWt	MSR	SINAP, China
PB-FHR	100 MWe	MSR	UC Berkeley, USA
Integral MSR	192 MWe	MSR	Terrestrial Energy, Canada
Moltex SSR	150 MWe	MSR/FNR	Moltex, UK
Moltex SSR global	40 MWe	MSR	Moltex, UK
Thorcon MSR	250 MWe	MSR	Martingale, USA
Leadir-PS100	36 MWe	lead-cooled	Northern Nuclear, Canada

Small (25 MWe up) reactor designs at earlier stages
(or shelved)

Advanced Nuclear Power

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SMR Advantages

	Light Water Reactor	Small Modular Reactor	Advanced Reactor
Design Features	Uses water to cool uranium fission reactions	Most are similar to LWRs but have been reduced in size and complexity	There is a range of designs with coolants ranging from water to molten salt to liquid metal and even gases
Size[2]	A range of 800 MWe to 1600 MW[3]	Many designs are less than 300 MWe[4]	Scalable from 2 MWe[5] to 1200 MWe
Cost to Construct ($/kWe)[6]	$2600 to $6600[7] with averages at around $4000[8]	Estimated at $3200 to $16300[9] with average at $4,000[10]	Estimated between $2500[11] to $3900[12] though early in estimation
Time to Construct	4.5 years[13] to 6 years[14] on site with large modules	Estimated at 1.5 to 2.5 years[15] in factory modules	Estimated at 1 to 5 years[16] with factory or on-site modules

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SMR Advantages

Spent Fuel (MT/year)[17]	An average of 20 MT[18]	Similar but slightly higher at 33.6 MT[19]	Some produce 0.5 to 1 MT and can use 55 MT[20]
Operations	Existing reactors need an operator to shut-down the reactor. Some being built won't need immediate operator intervention	Some SMRs can shut down without an operator and some won't need immediate operator intervention	Many designs can be "walk away safe" without operator intervention
Proliferation Risk	Requires uranium enrichment	Requires slightly more fuel with uranium enrichment[21]	Can use enriched uranium, depleted uranium,[22] or used nuclear fuel[23]

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NuScale Power: Overview

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Simple

- Factory-built containment
- Modular constructability
- Fewer systems to construct and maintain
- Load following

Safe

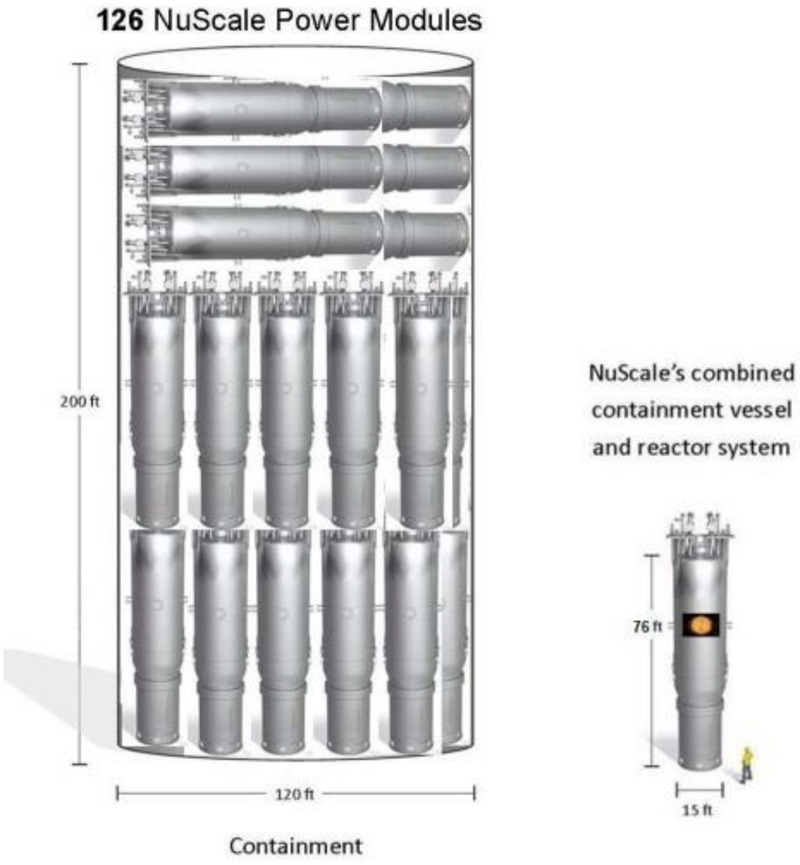
- Indefinite cooling in station blackout
- Unprecedented nuclear safety (Core Damage Frequency 10^{8})
- Fewer safety-related systems

Economic

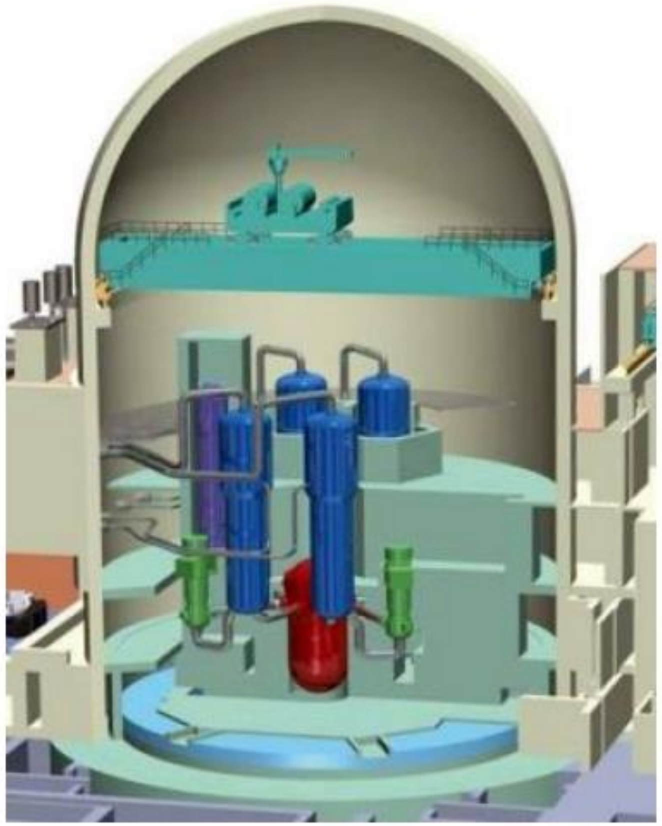
- < $3B EPC cost for FOAK 570MWe (net) plant (~$2.5B cost for NOAK)
- LCOE below $100/MW
- Scalable
- USDOE SMR awardee

NuScale Power: Overview

Comparison size envelope of new nuclear plants currently under construction in the United States



Typical Pressurized Water Reactor



*Source: NRC

NuScale Power: Overview

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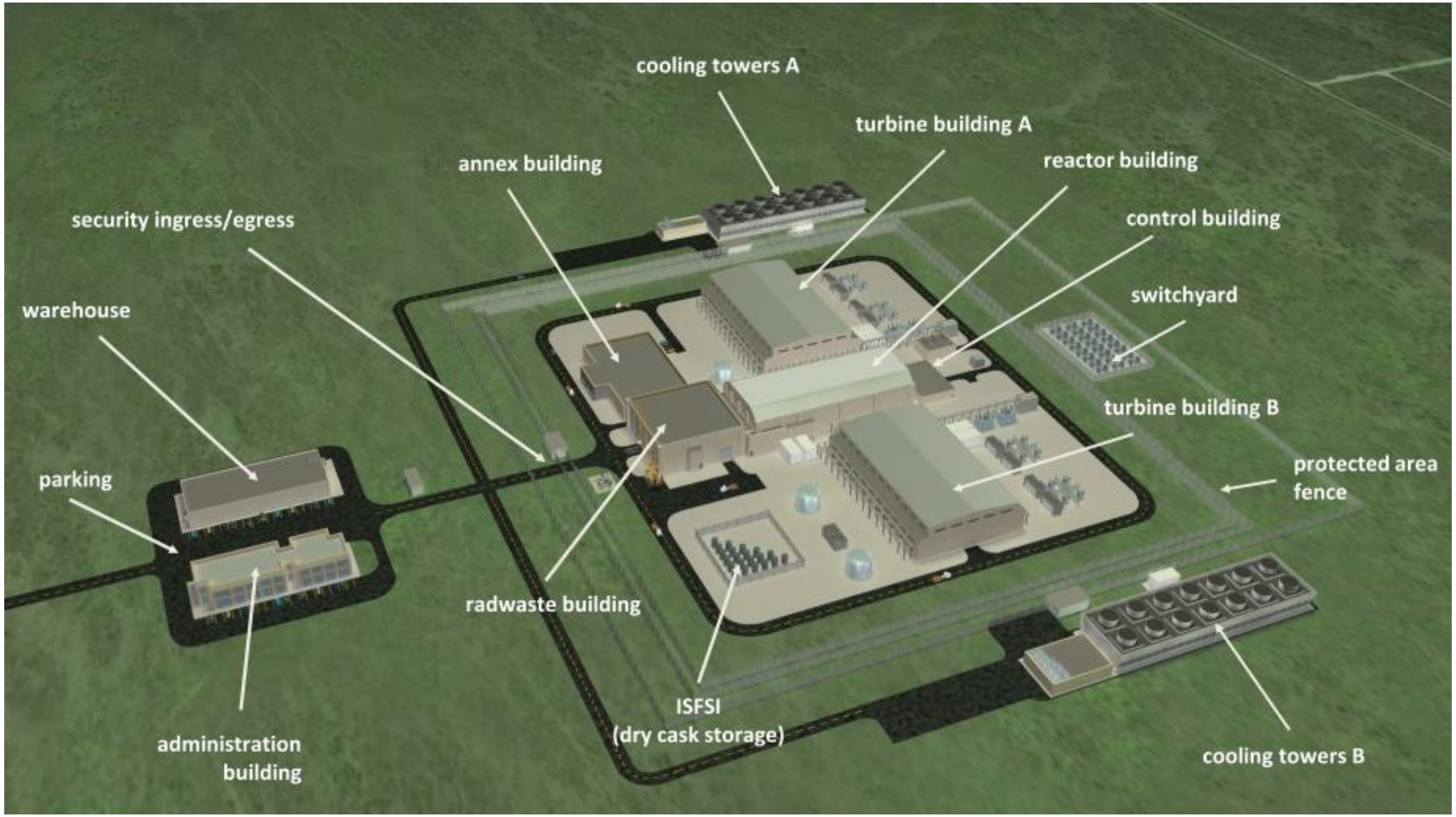
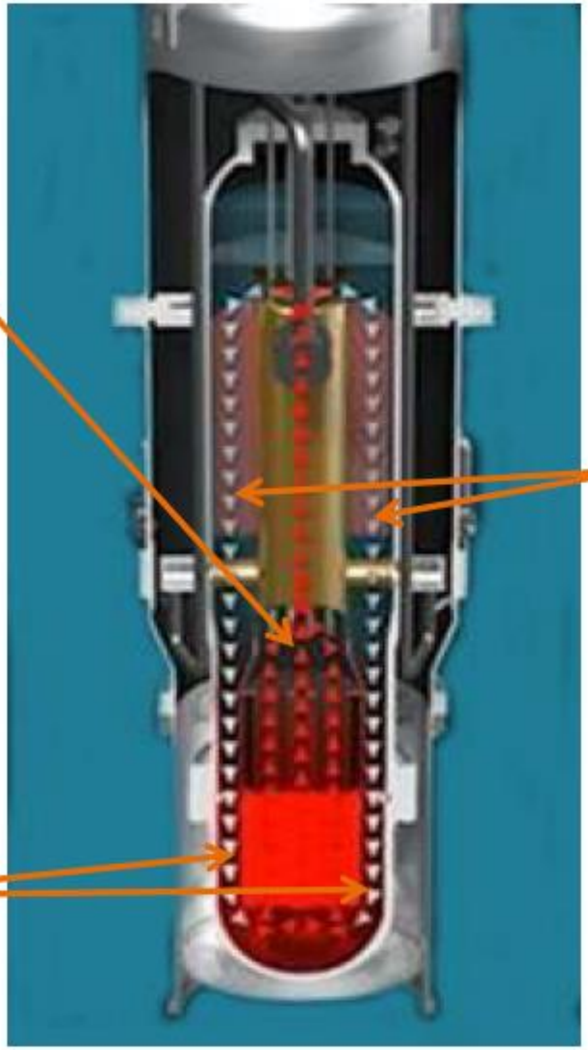


NuScale Power: Technology

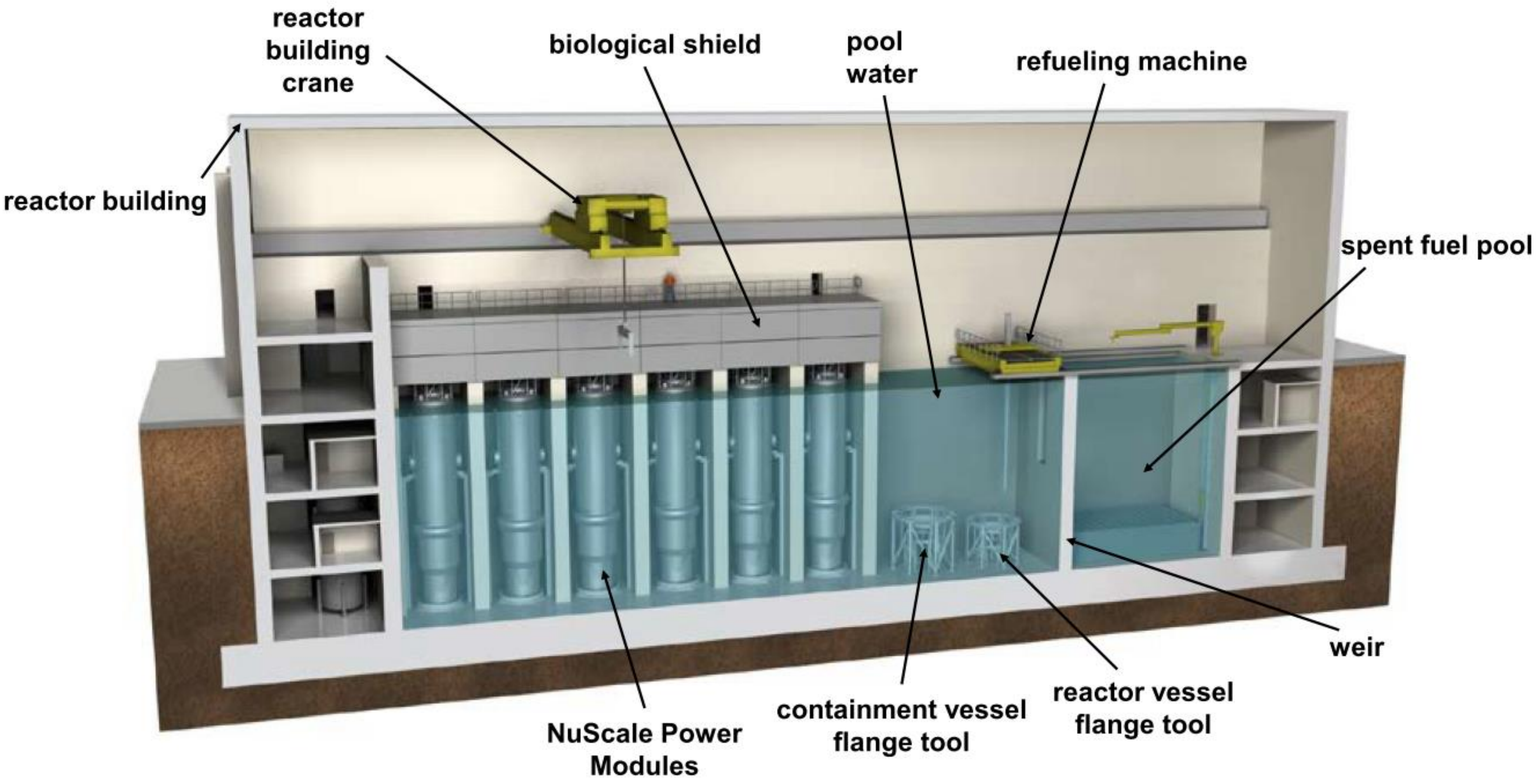
Convection **– energy from the nuclear reaction heats the primary reactor coolant causing it to rise by convection and natural buoyancy through the riser, much like a chimney effect**

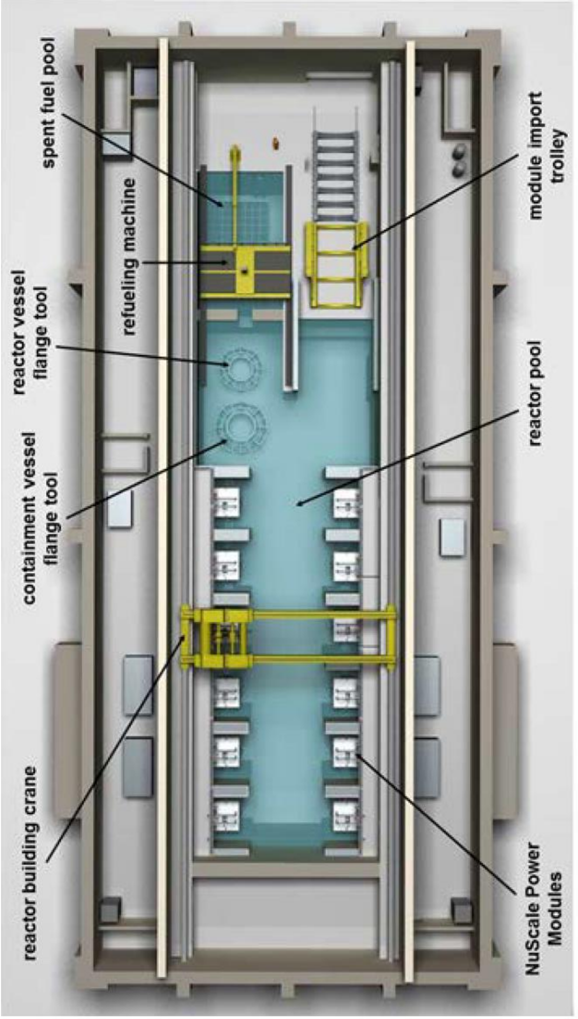
Gravity **– colder (denser) primary coolant "falls" to bottom of reactor pressure vessel, cycle continues**



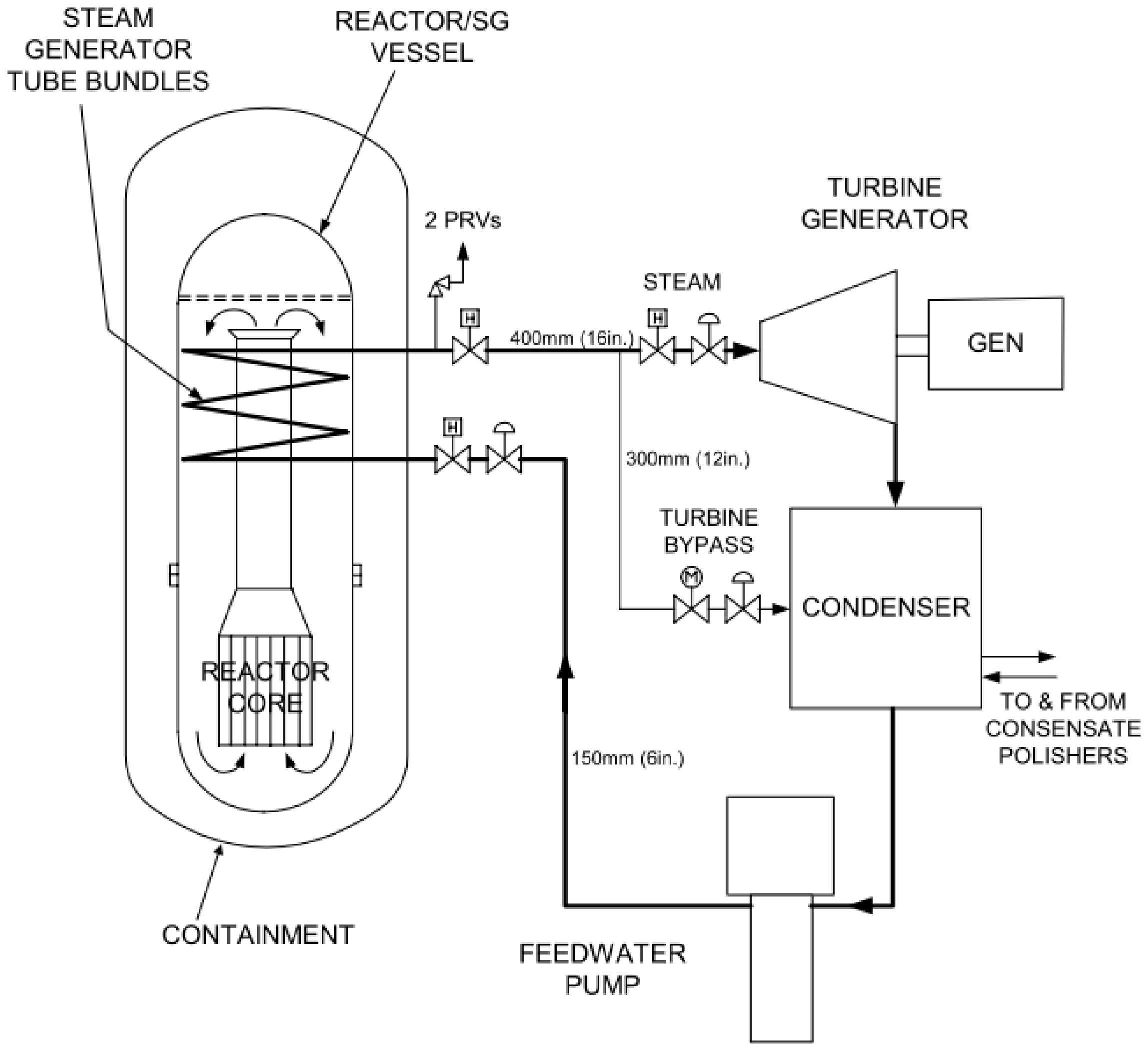
Conduction **– heat is transferred through the walls of the tubes in the steam generator, heating the water (secondary coolant) inside them to turn it to steam. Primary water cools.**

NuScale Power: Technology





NuScale Power: Technology



- **Thermal capacity** – 160 MWt
- **Electrical capacity** – 50 MWe (gross)
- **Capacity factor** – >95 percent
- **Dimensions** – 76′ x 15′ cylindrical containment vessel module containing reactor and steam generator
- **Weight** – ~ 700 tons as shipped from fabrication shop
- **Transportation** – Barge, truck or train
- **Cost** – Numerous advantages due to simplicity, off-the-shelf standard items, modular design, shorter construction times, <$5,100/KW
- **Fuel** – Standard LWR fuel in 17 x 17 configuration, each assembly 2 meters (~ 6 ft.) in length; 24-month refueling cycle with fuel enriched less than 4.95 percent

NuScale Power: Technology

Overall Plant

Net Electrical Output	1050 Mwe
Net Station Efficiency	23%
Number of Power Generation Units	30
Nominal Plant Capacity Factor	95%

Power Generation Unit

Number of Reactors	One
Net Electrical Output	35 Mwe
Steam Generator Number	One
Steam Generator Type	Vertical helical tube
Steam Cycle	Slightly superheated
Turbine Type	3600 rpm, single pressure, Two-Flow
Turbine Throttle Conditions	13.8 bars abs./204°C (200 psia/400°F)
Steam Flow	56 kg/s (445000 lb/hr)
Feedwater Temperature	33.3°C (92°F)

Reactor

Thermal Power (Core)	150 MWt
Cold Leg/Hot Leg Temperature	489.6°K/560.2°K
Coolant Mass Flow Rate	424 kg/s

Reactor Core

Fuel	UO_2, 8% enriched
Refueling Intervals	5 years

NuScale Power: Technology

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Table 3.2. Plutonium isotopics at 11MWd/kg burnup.

	UO_2 ($300MW_{th}$)	UO_2 ($950MW_{th}$)	UO_2 - ThO_2 ($950MW_{th}$)
Burnup (MWd/kg)	11	11	11
	Plutonium Production (g/kg ihm)		
Pu-238	0.010	0.010	0.010
Pu-239	5.026	5.079	2.005
Pu-240	0.578	0.593	0.270
Pu-241	0.268	0.285	0.153
Pu-242	0.017	0.018	0.011
Total Pu	**5.899**	**5.984**	**2.448**
Composition	Fraction of Total Pu		
Pu-238	0.2%	0.2%	0.4%
Pu-239	85.2%	84.9%	81.9%
Pu-240	9.8%	9.9%	11.0%
Pu-241	4.6%	4.8%	6.2%
Pu-242	0.3%	0.3%	0.5%

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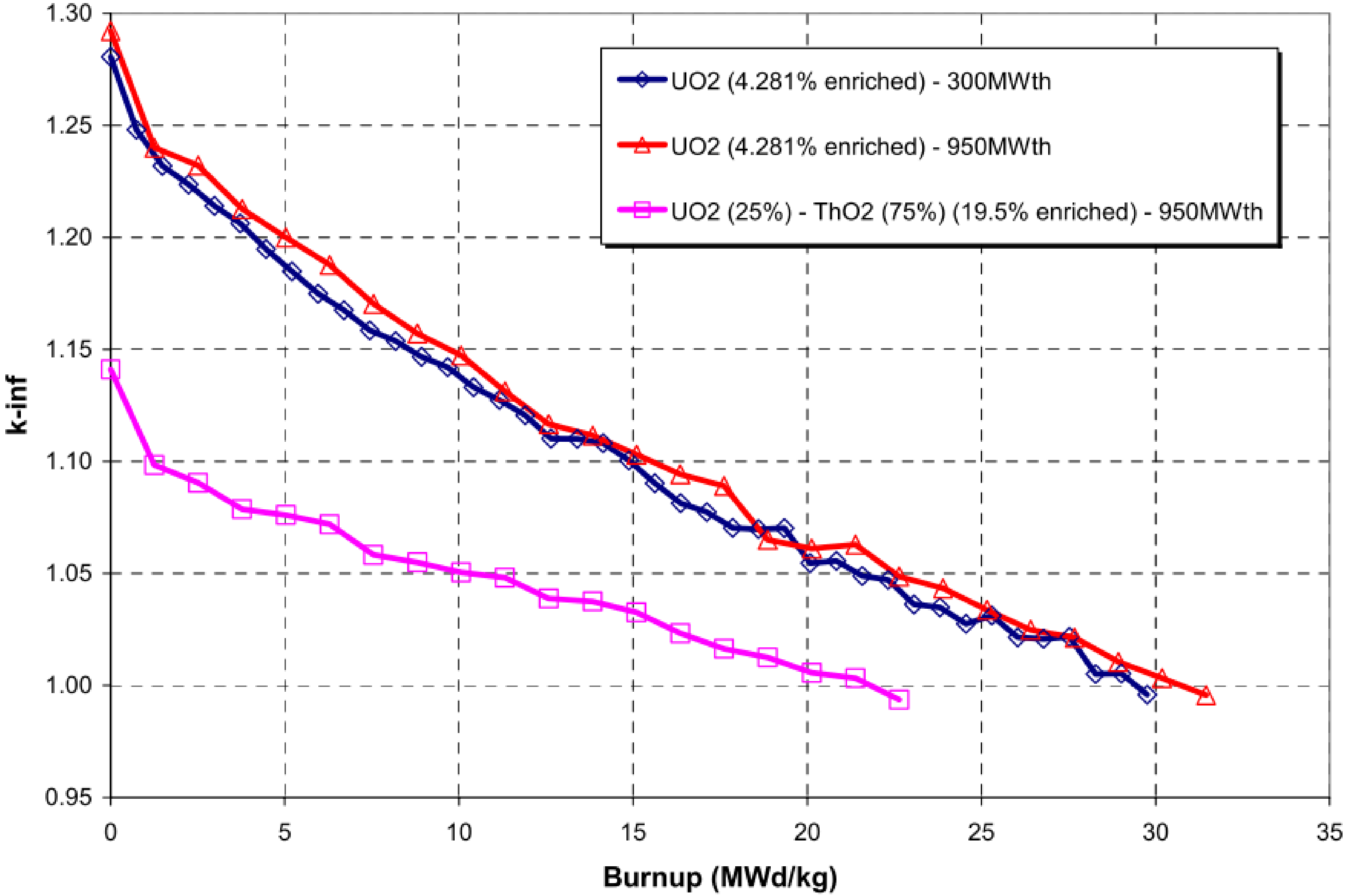

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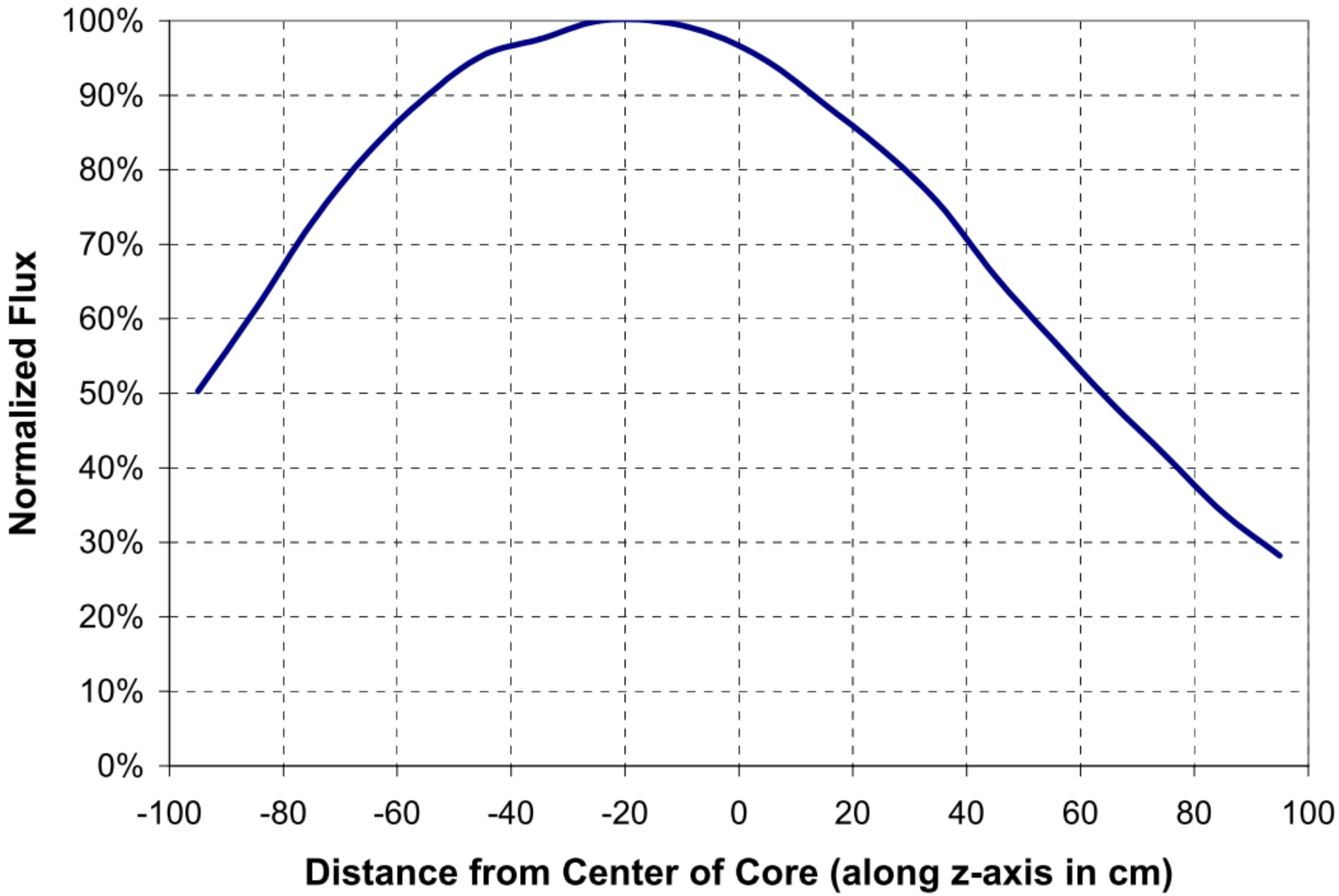
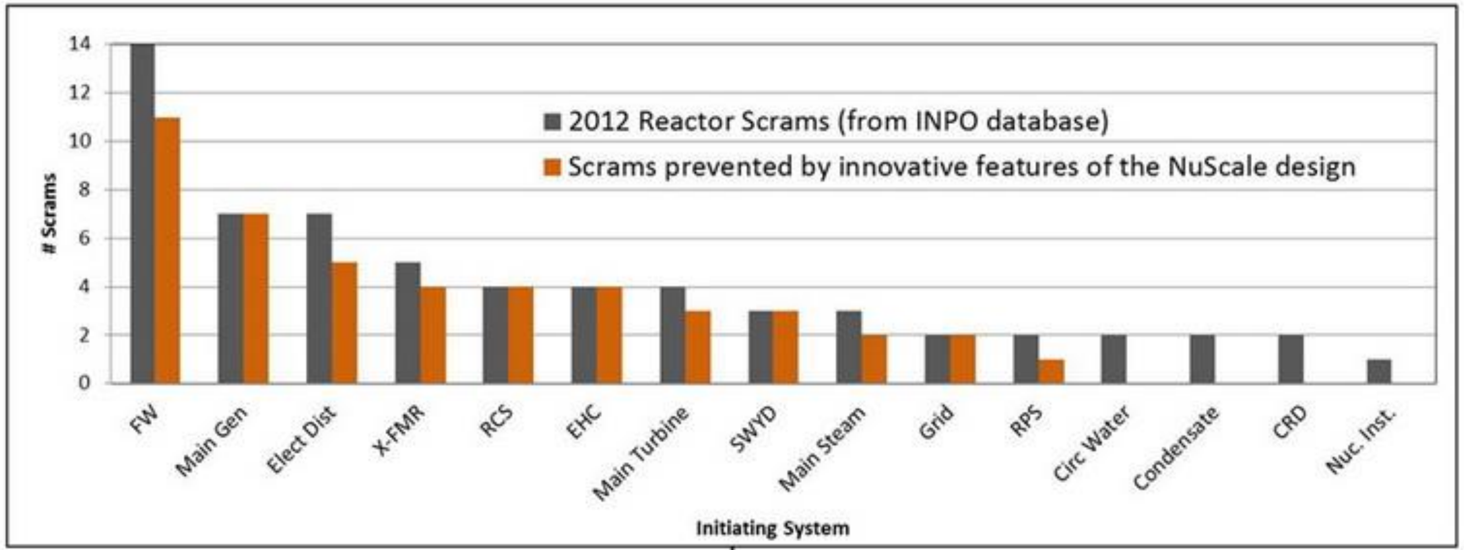


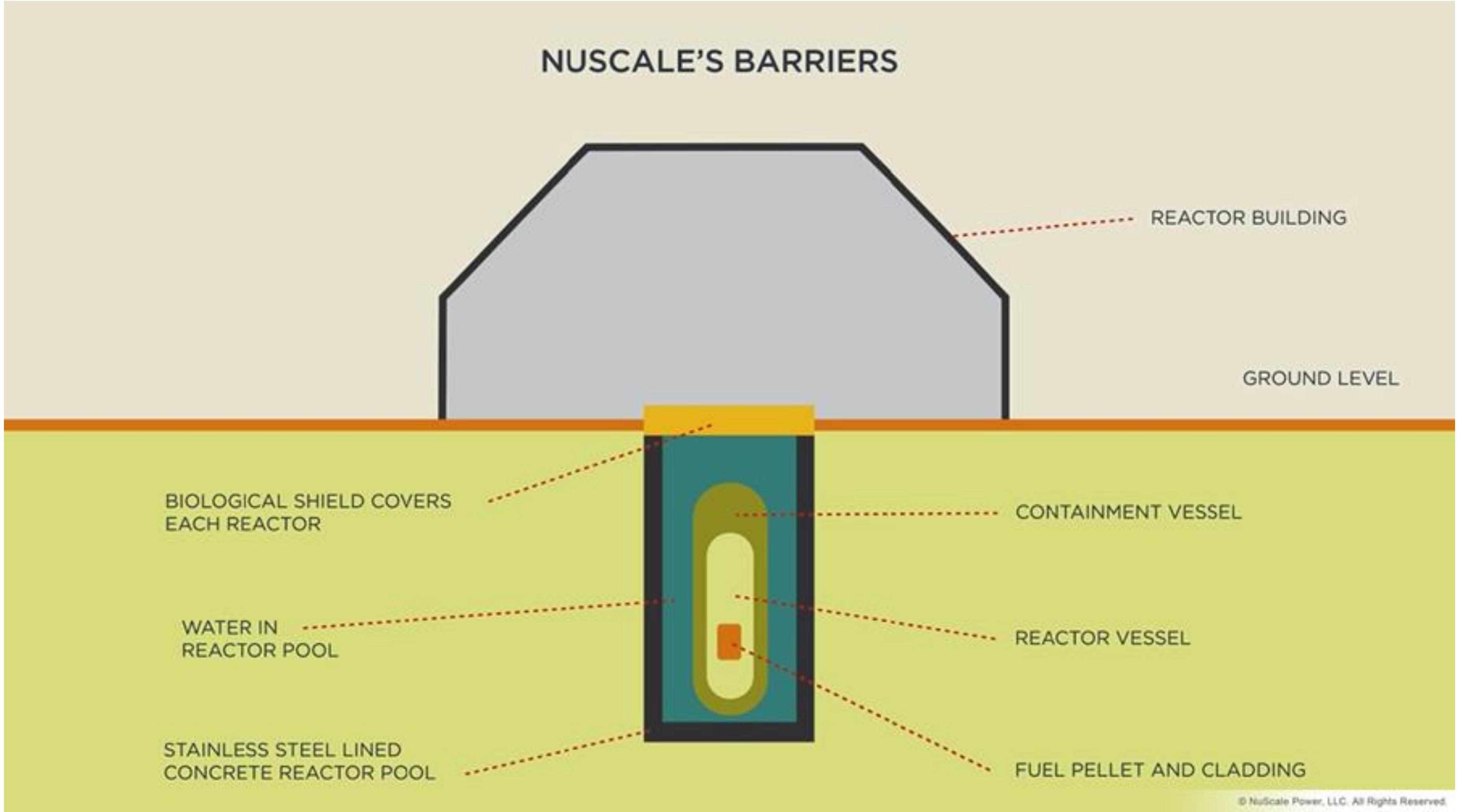
NuScale Power: Safety

Fewer Systems, 73% Fewer SCRAMS



58% of events cause by power conversion systems	27% of events caused by electrical distribution system
86% of power conversion related scrams prevented by NuScale design	82% of electrical related scrams prevented by NuScale design

NuScale Power: Safety



http://www.nuscalepower.com/

NuScale Power: Safety

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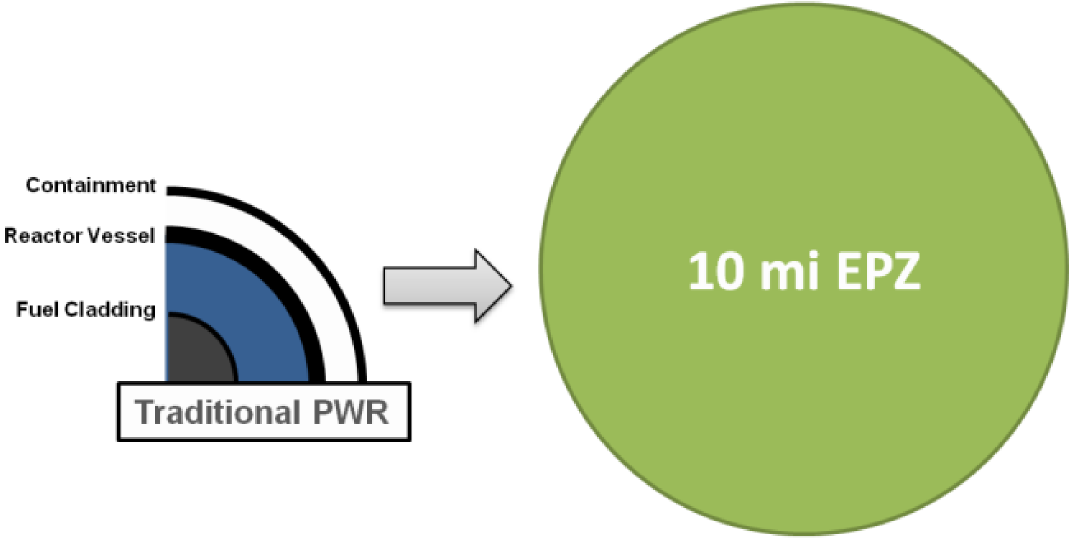
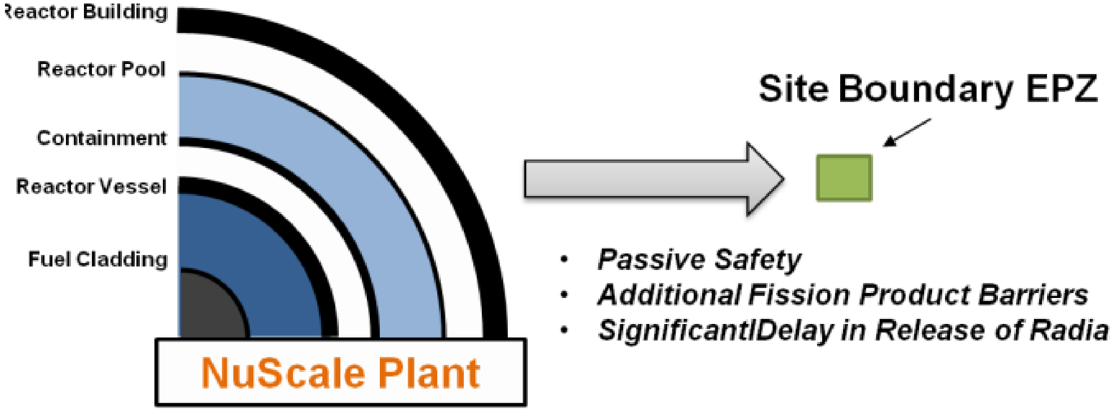
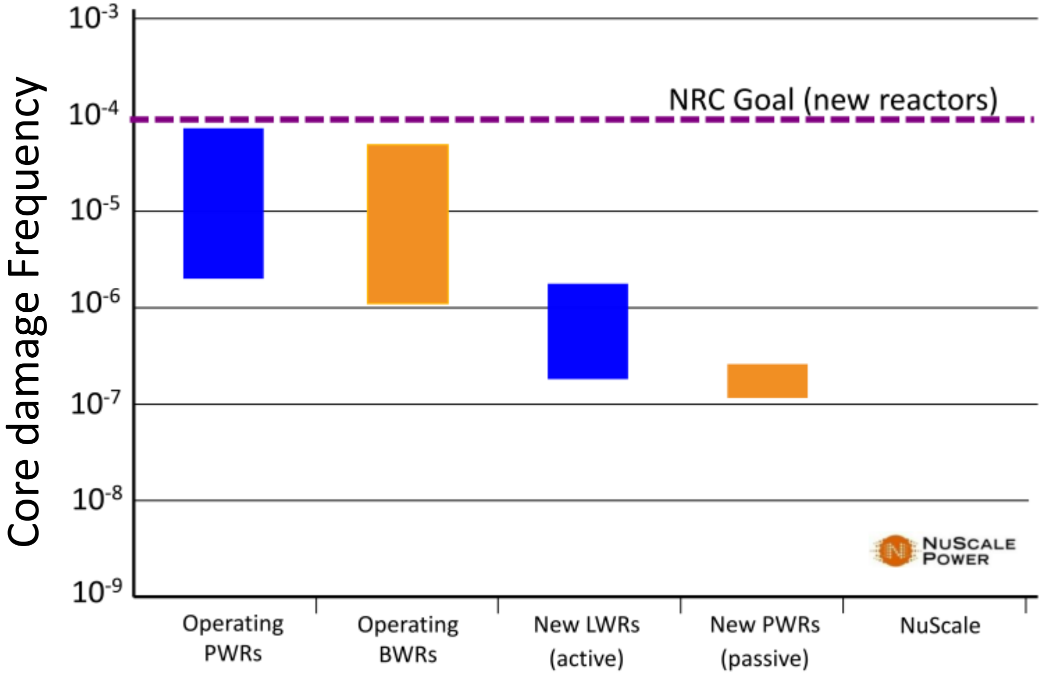


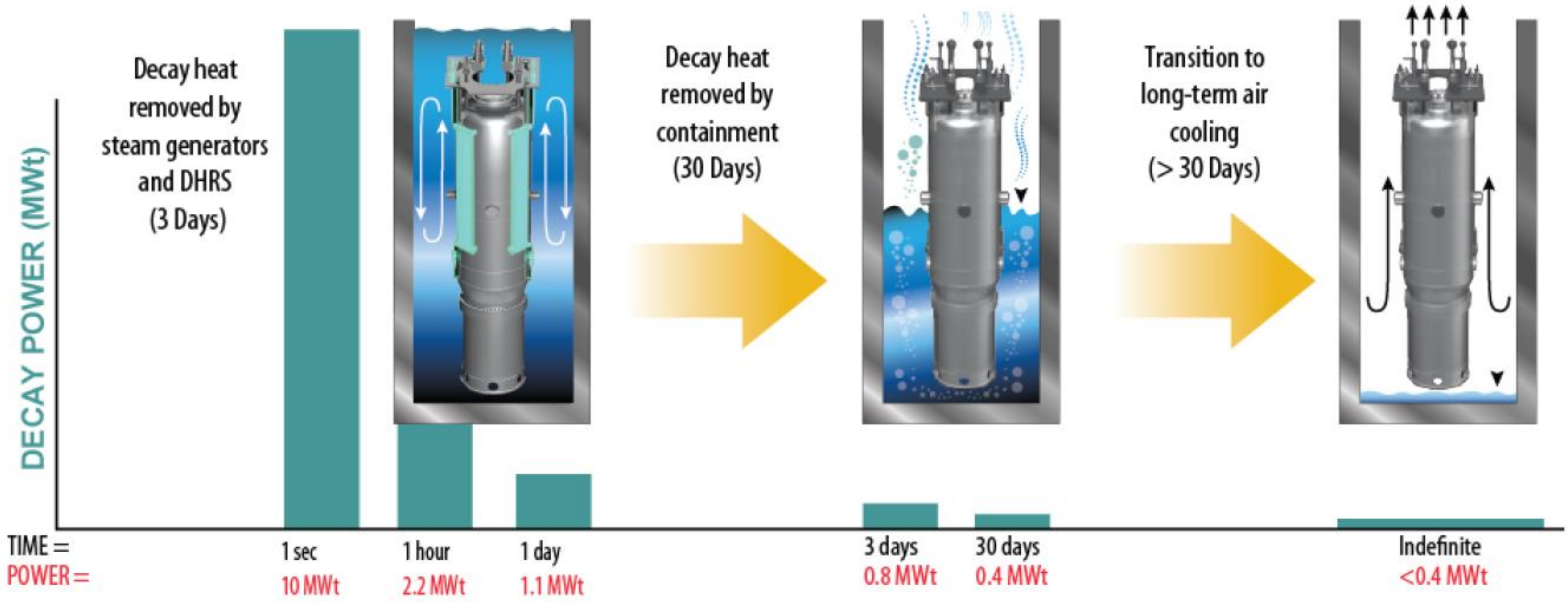


- *Passive Safety*
- *Additional Fission Product Barriers*
- *SignificantlDelay in Release of Radiation*



Source: NRC White Paper, D. Dube; basis for discussion at 2/18/09 public meeting on implementation of risk matrices for new nuclear reactors

NuScale Power: Safety



NuScale Power: Safety

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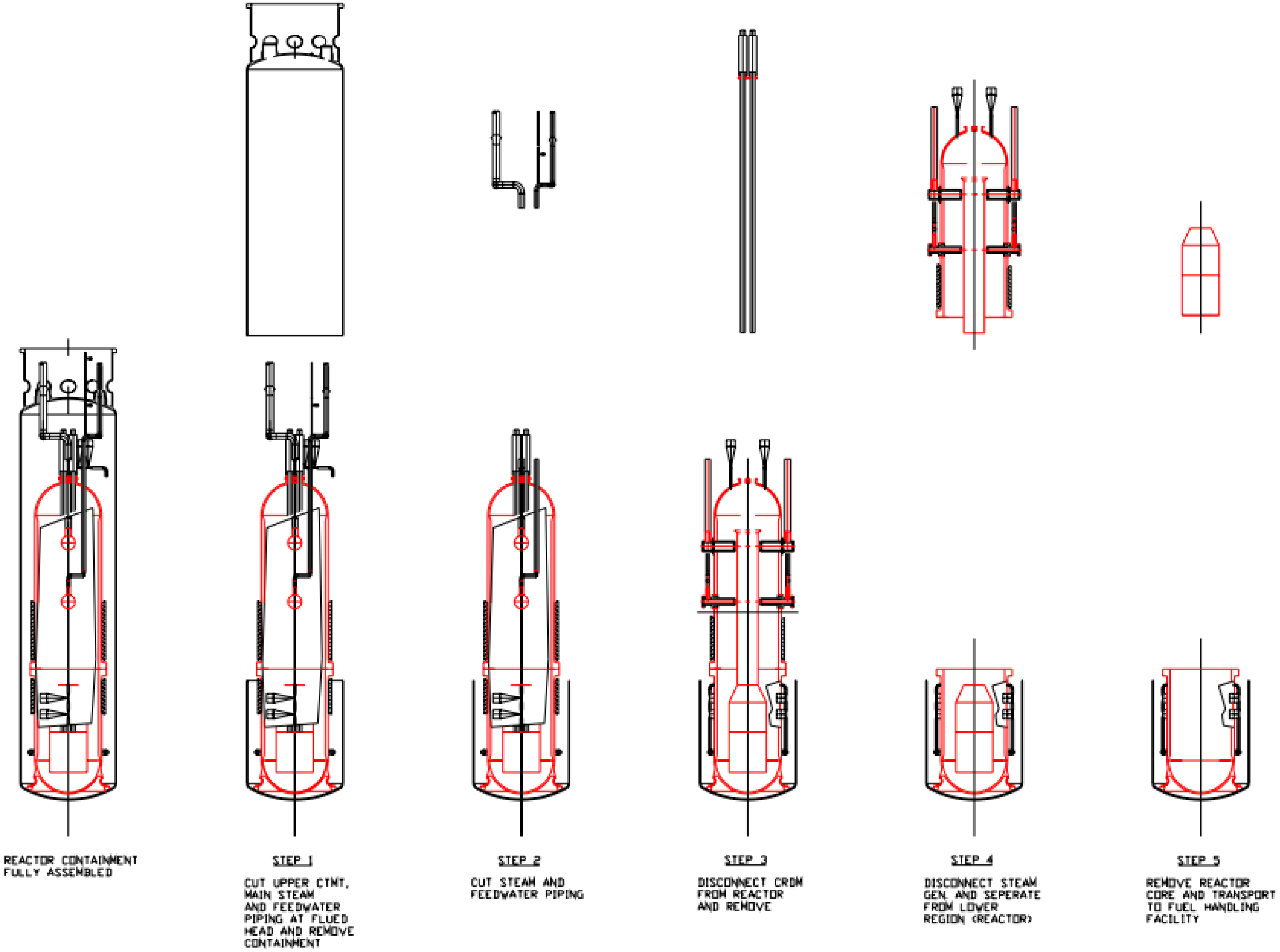


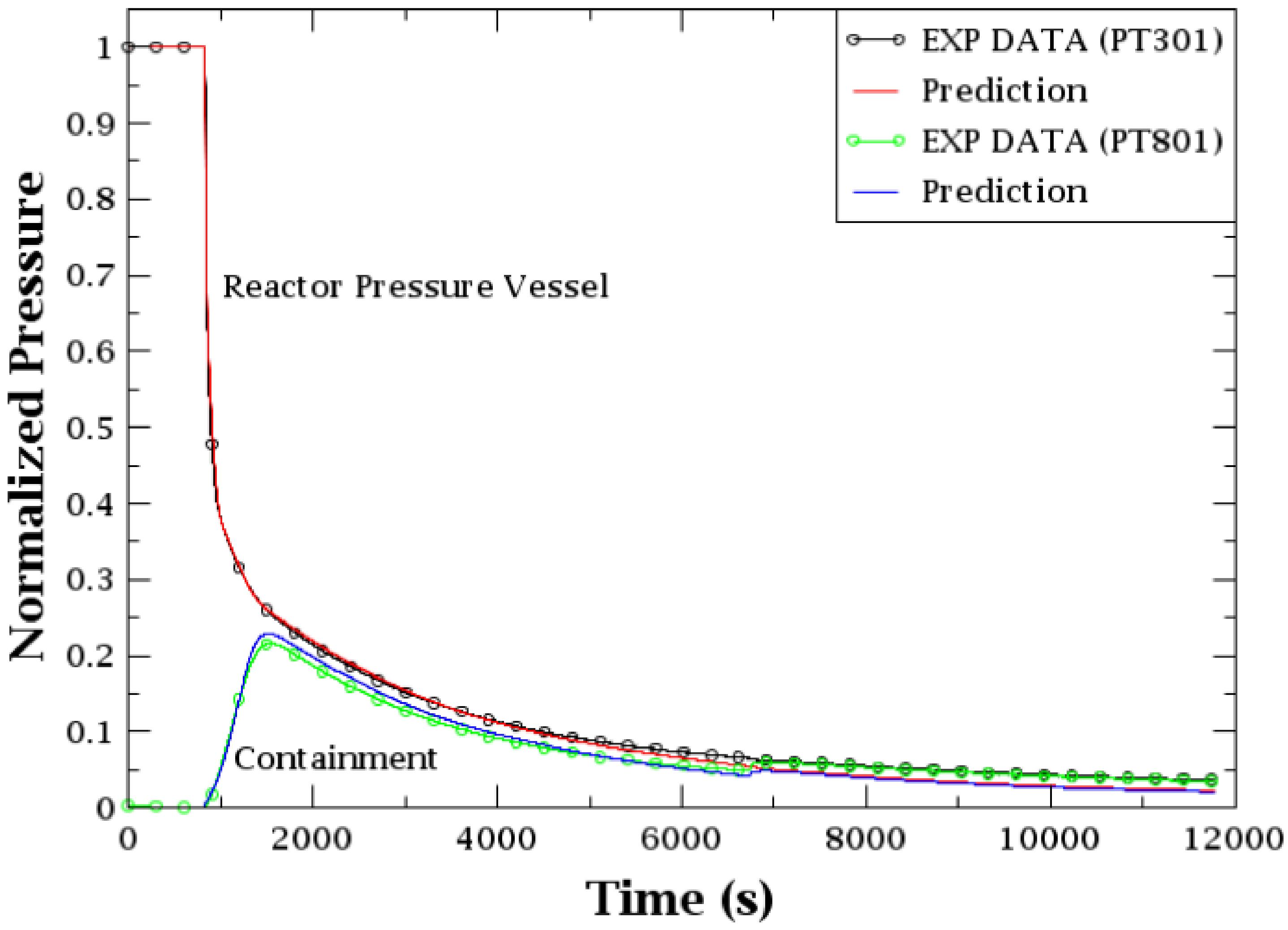
http://www.nuscalepower.com/

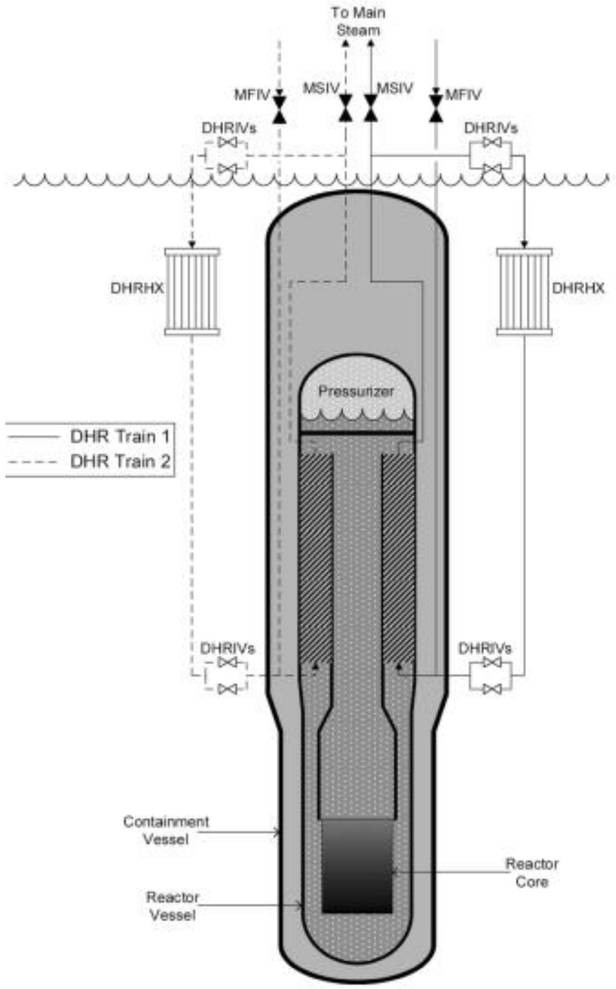
NuScale Power: Safety

NuScale Design Features Relevant to the Fukushima Cooling Issues

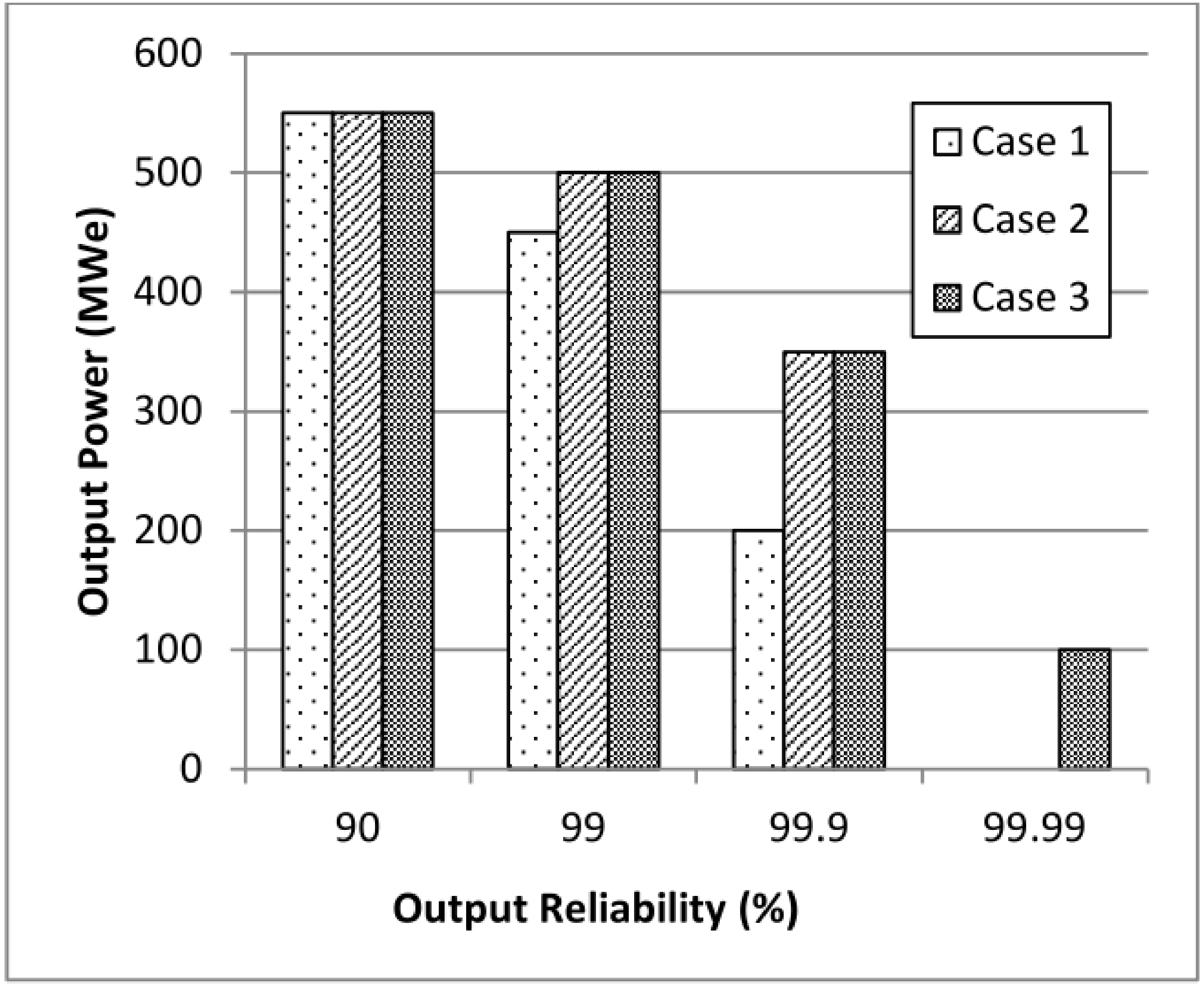
	Fukushima	NuScale Plant
Reactor and containment	Emergency diesel generators required	Emergency diesel generators not required
	External supply of water required	Containment immersed in 30-day supply of water
	Coolant supply pumps required	Coolant supply pumps not required
	Forced flow of water required for LTC	LTC (beyond 30 days) by natural convection to air
Spent fuel pool	Water cooling of spent fuel	Extended cooling capability: four times the water of conventional spent fuel pools per MW power
	Elevated SFP	Deeply embedded SFP
	Limited access to backup supply of water	Accessible backup supplies of water

NuScale Power: Safety





NuScale Power: Safety



Initiator Description	Frequency ($mcyr^{-1}$)	Error Factor
CVCS LOCA Inside Containment - Charging Line	2.60E-04	5.57
CVCS LOCA Outside Containment - Charging Line	3.00E-04	6.86
CVCS LOCA Outside Containment - Letdown Line	2.56E-04	13.18
Spurious Opening of an ECCS Valve	1.00E-05	3.11
Loss of DC Power	8.86E-05	33.44
Loss of Offsite Power	3.2E-02	3.46
Steam Generator Tube Failure	1.30E-03	3.40
LOCA Inside Containment	1.62E-03	1.78
Secondary Side Line Break	1.10E-02	3.62
Loss of Power Conversion System (PCS)	1.81E-01	1.10
Transient with PCS Available	1.16	1.04

NuScale Power: Cost

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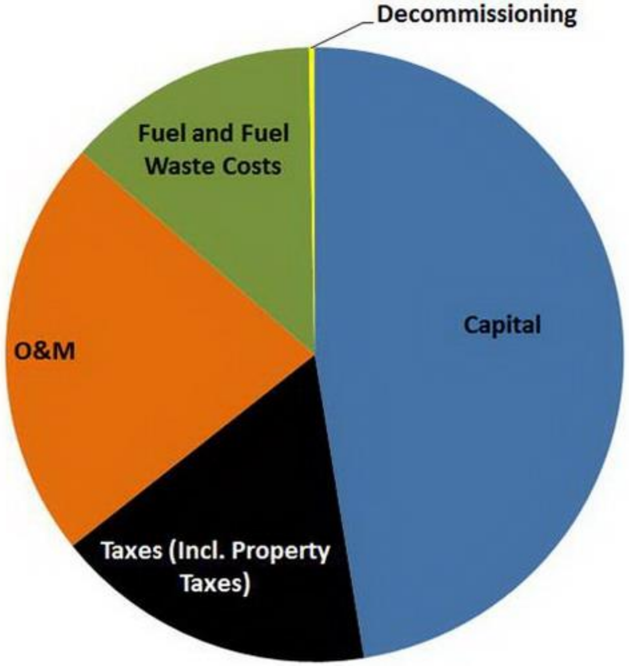
Overall EPC Overnight Plant Costs

($1,000,000)

ITEM	2014 Dollars	
Power Modules (FOAK Cost plus Fee, Transportation, & Site Assembly)	$	848
Home Office Engineering and Support	$	144
Site Infrastructure	$	60
Nuclear Island (RXB, RWB, MCR)	$	538
Turbine Island (2 buildings with 6 turbines each)	$	350
Balance of Plant (annex, cooling towers, etc)	$	225
Distributables (Temp. Bldgs., Field Staff, Const. Equip., etc.)	$	545
Other Costs	$	185
Total Overnight Price	**$**	**2,895**

$ 5,078 per kWe net



Note: Delivered costs shown are in 2014 $'s.

NuScale Power: Cost

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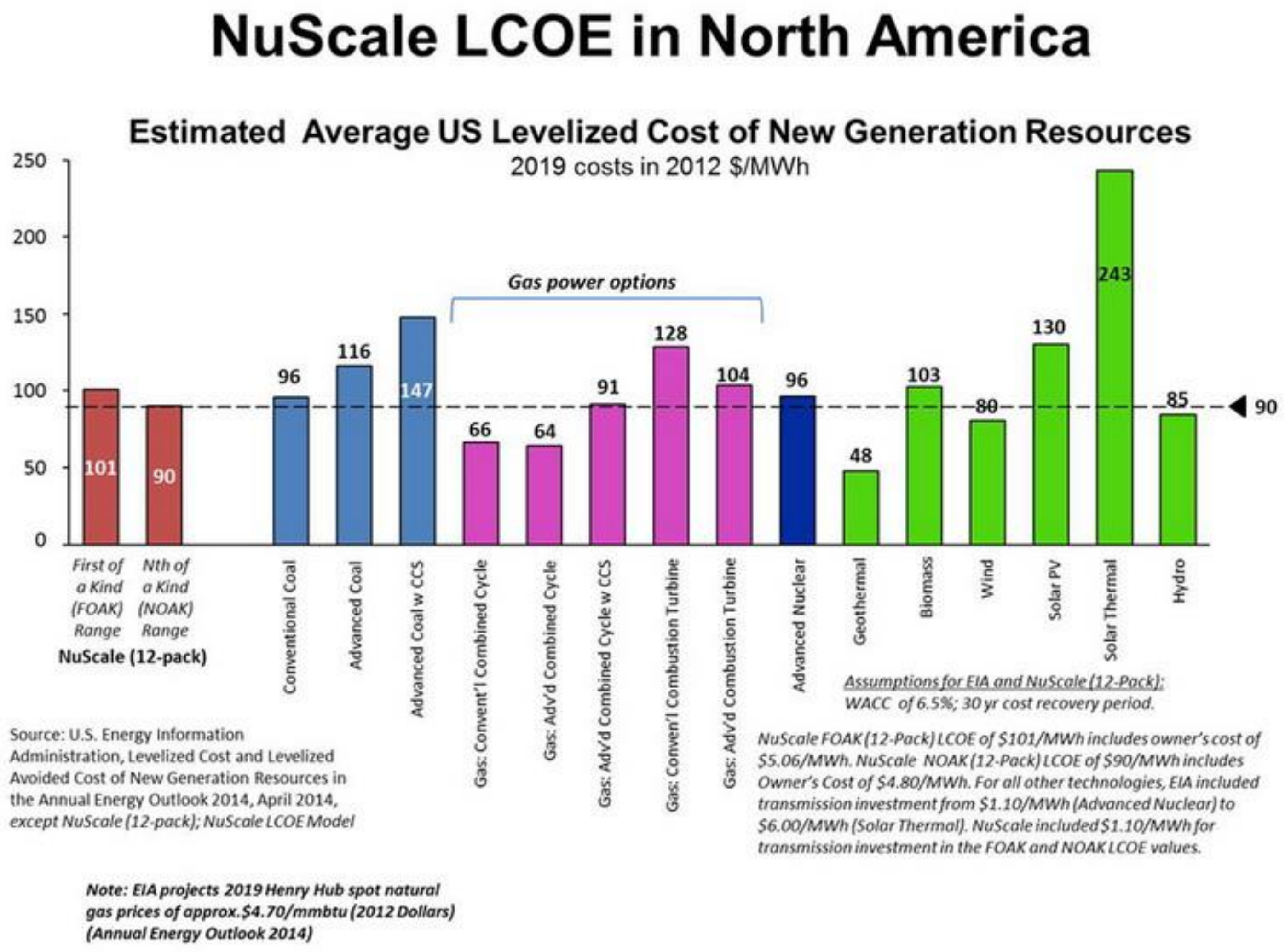


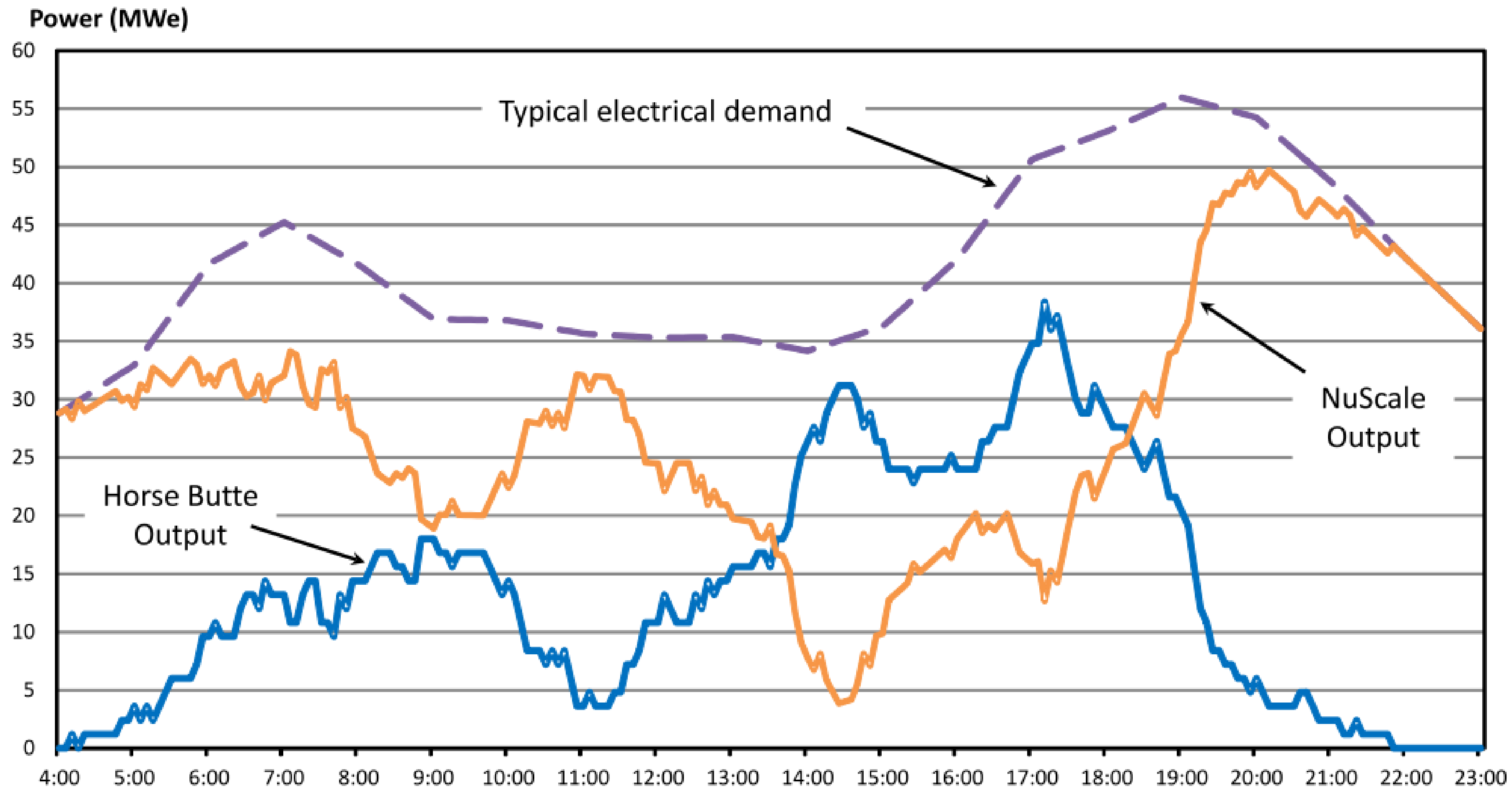
Integration with Renewables

Take modules offline

De-rate power to 40%

Bypass turbine

Integration with Renewables



Integration with Renewables

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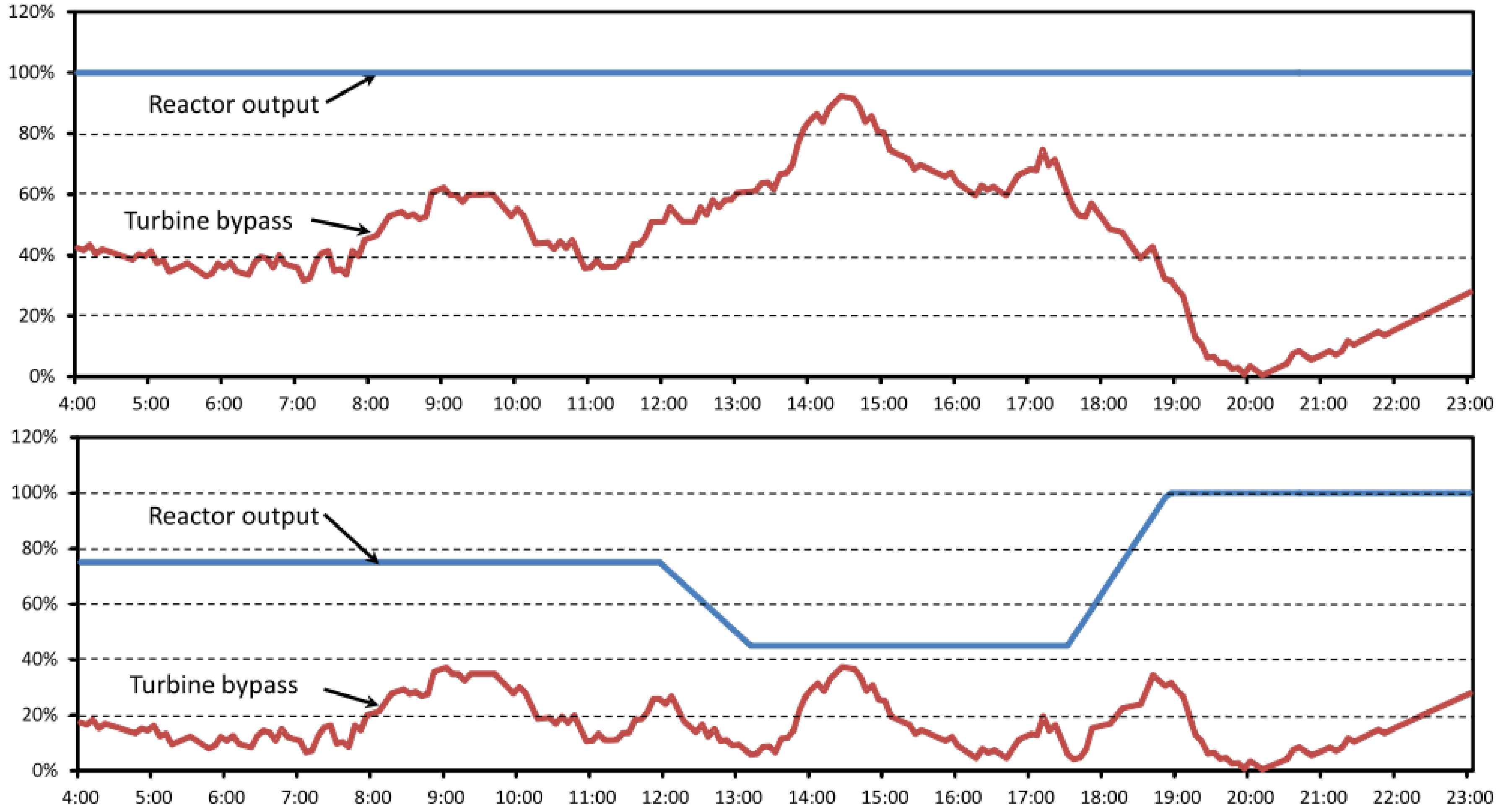

So, what do we think?

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