Future Directions for Nuclear Energy

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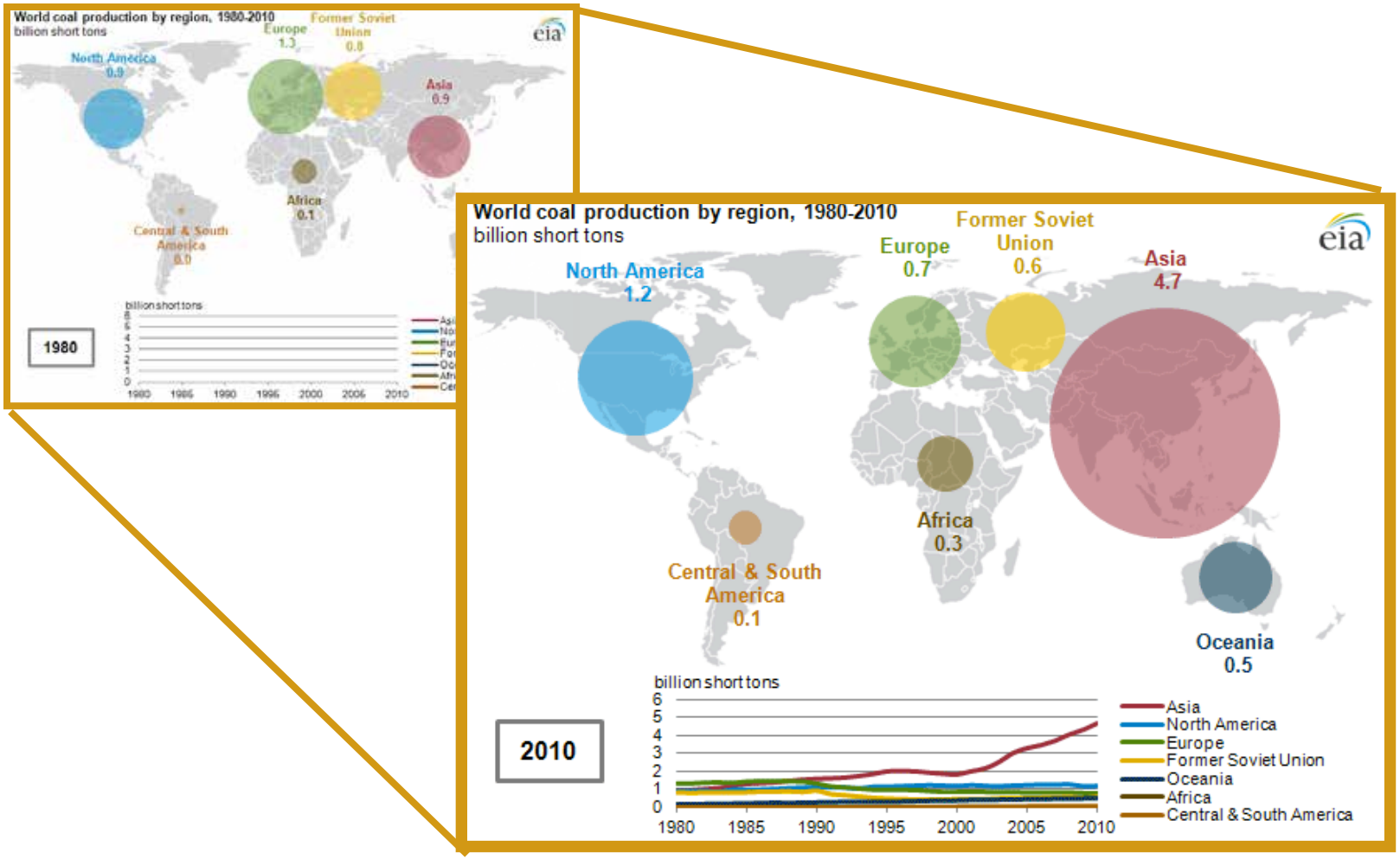
Nuclear Pioneers Lecture
April 24, 2014

Nuclear energy: Issues and comparison with other energy alternatives

Life-cycle impacts of energy production include effects on workers and on public health

Coal mine worker, China, 2004

World coal use is growing rapidly



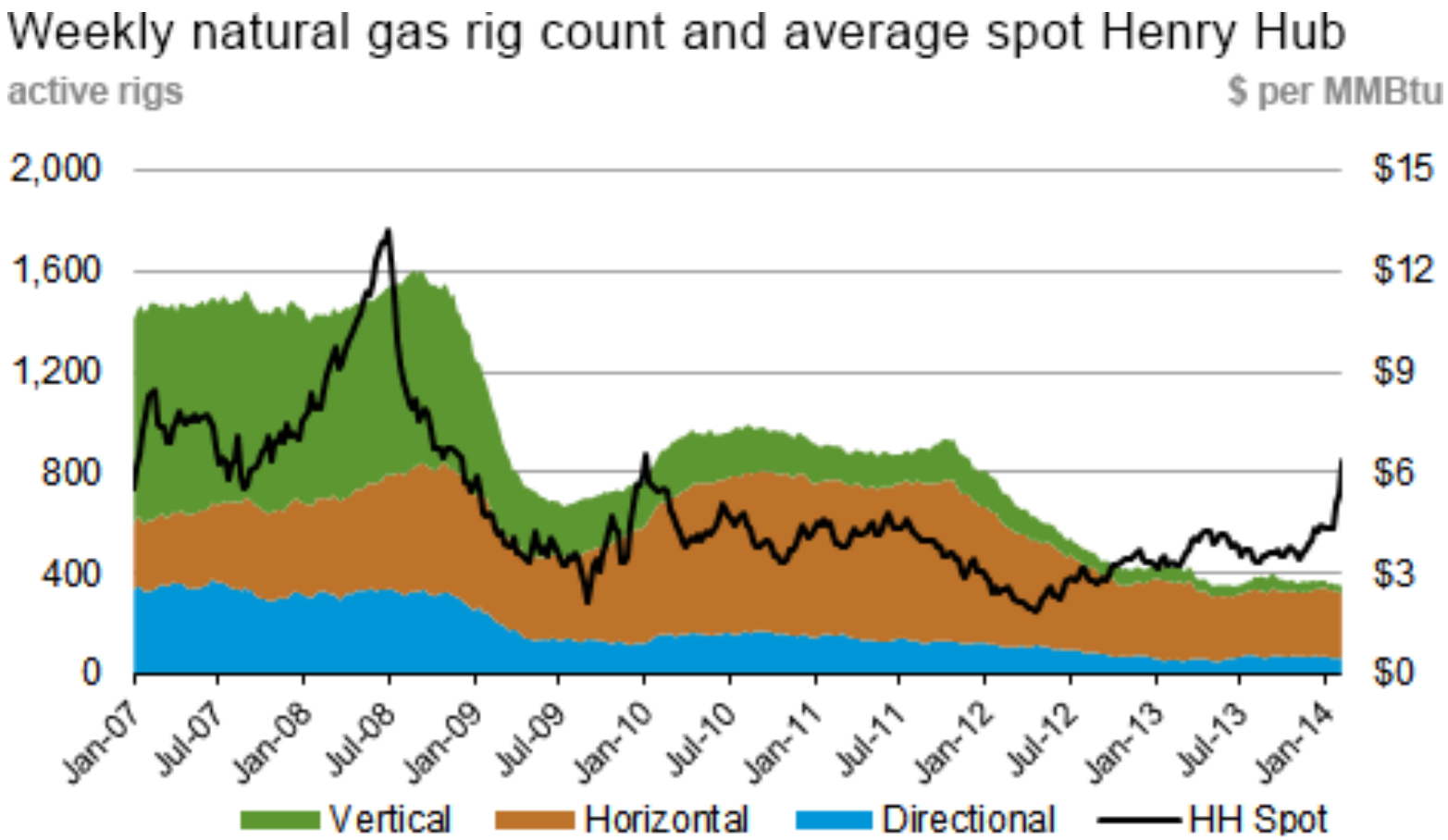
Humans have **failed** to slow our expanding use of coal

http://www.eia.gov/todayinenergy/detail.cfm?id=4210

U.S. natural gas prices are currently low

- Tight oil
  - Oil contains ~5.2 MMBtu/barrel
  - Oil at $100/bbl is equivalent to $17.2/MMBtu
  - U.S. tight oil production at the beginning of 2012
    - » 1.2 million bbl/day = 8.1 MMBtu/day
    - » Worth $140 million per day at $100/bbl
- Shale gas
  - U.S. shale gas production at the beginning of 2012
    - » 25 MMBtu/day
      - ~3 times more energy than tight oil
    - » Worth $100 million per day at $4.0/MMBtu
      - ~2/3 the net revenues of tight oil
- U.S. natural gas prices are now inversely coupled to global oil prices

Natural gas production will remain volatile because shale wells deplete rapidly



eia Source: Baker Hughes

http://www.eia.gov/naturalgas/weekly/#tabs-prices-4

Using natural gas for load following reduces combined-cycle power plant efficiency significantly

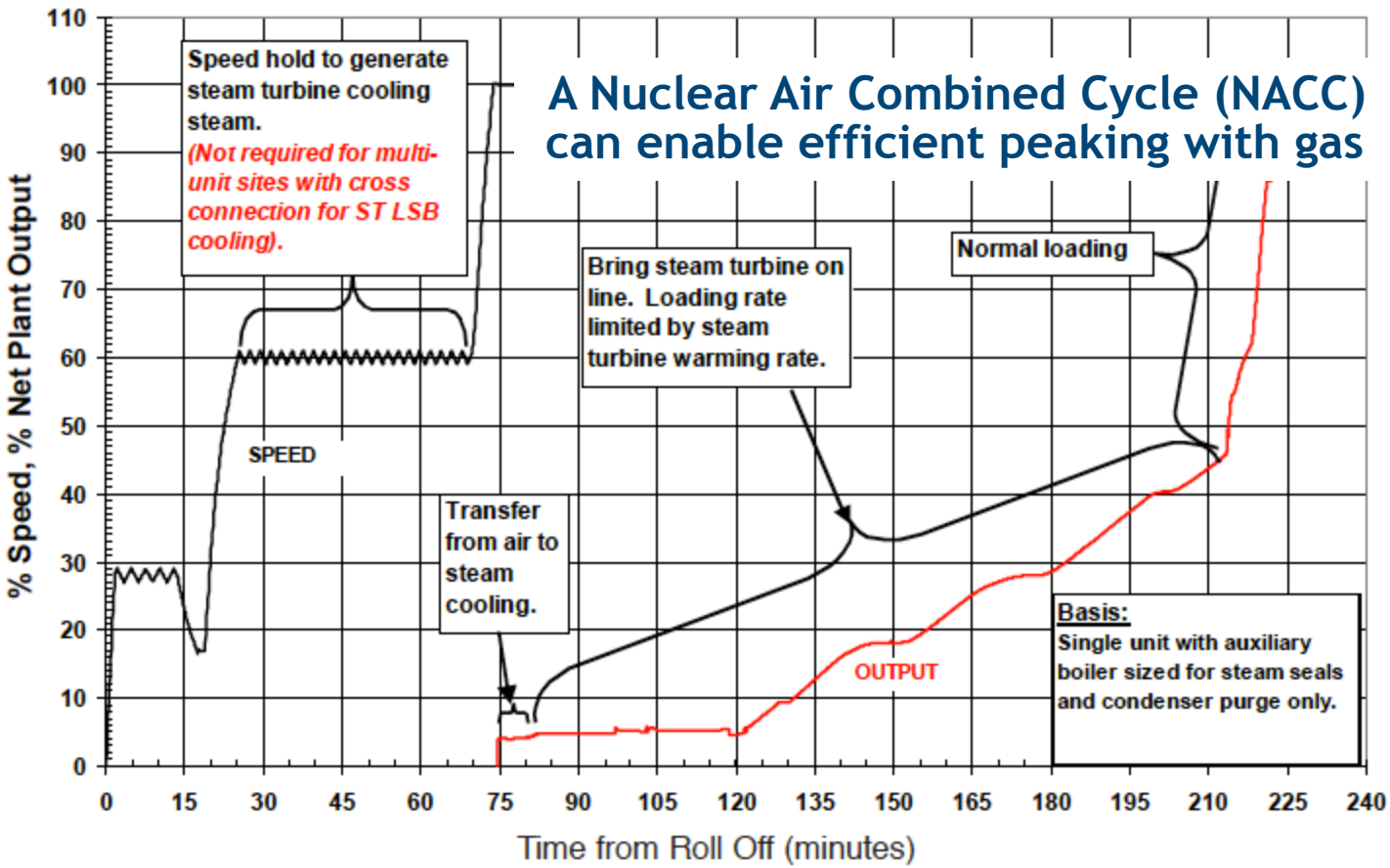
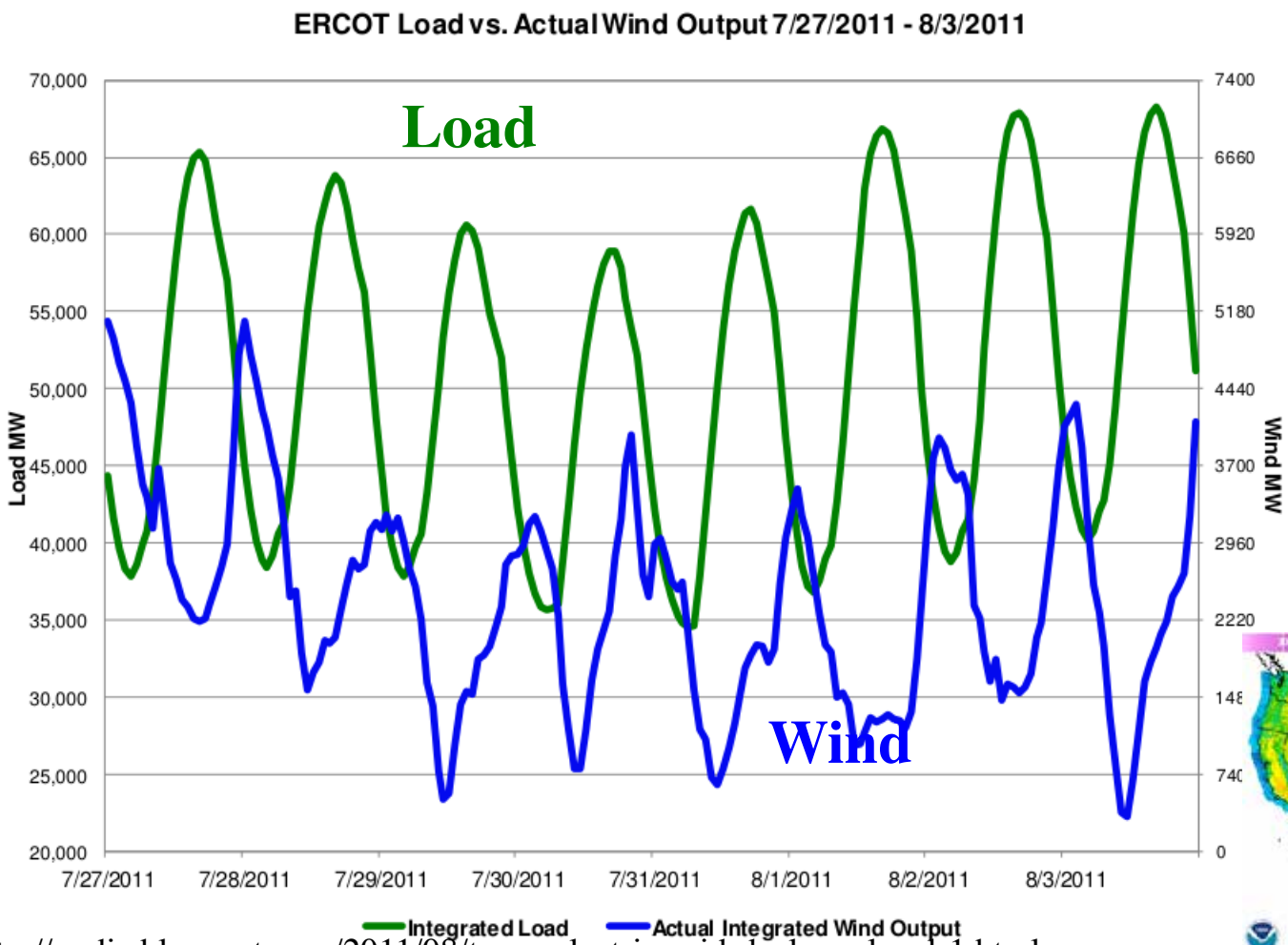


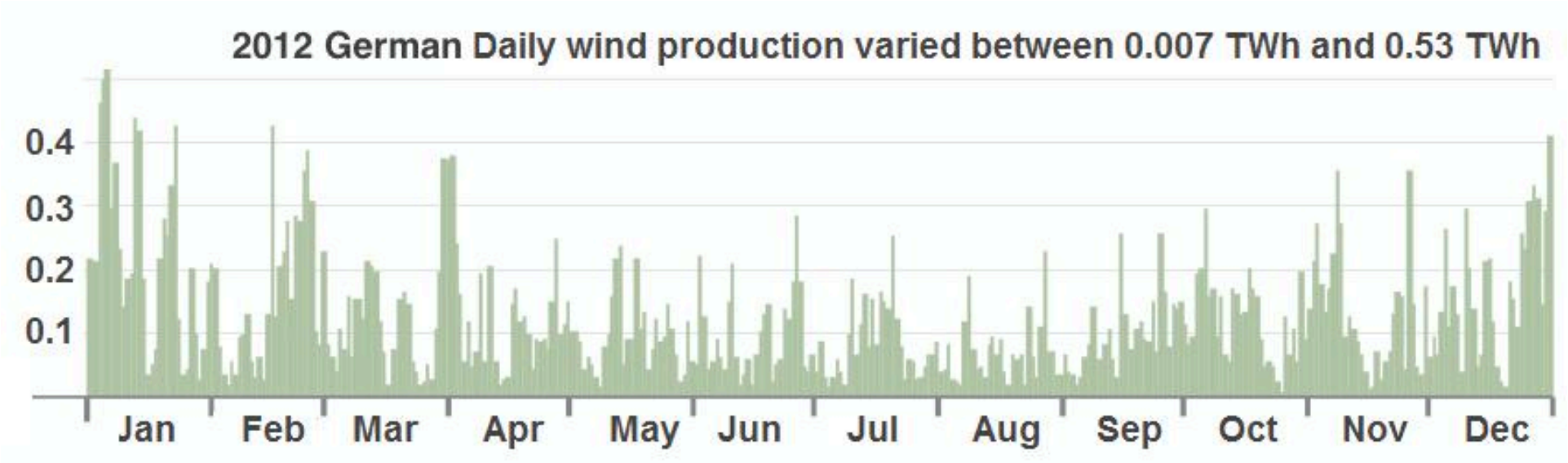
Figure 10. Typical S107H/S109H cold start loading profile, single unit

2011 major heat wave in Texas (4 reactors ran at 100%)



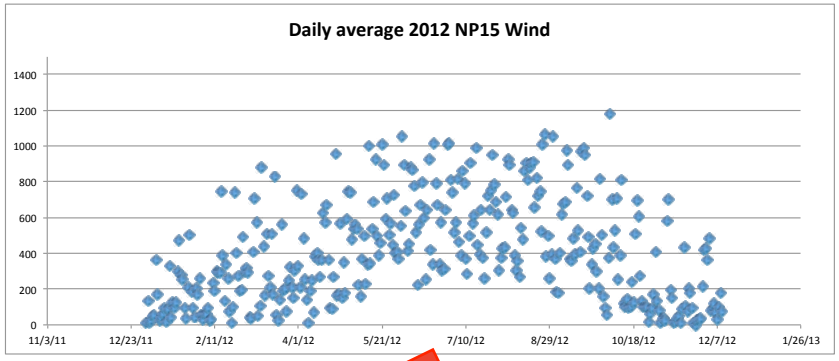
http://uvdiv.blogspot.com/2011/08/texas-electric-grid-declares-level-1.html

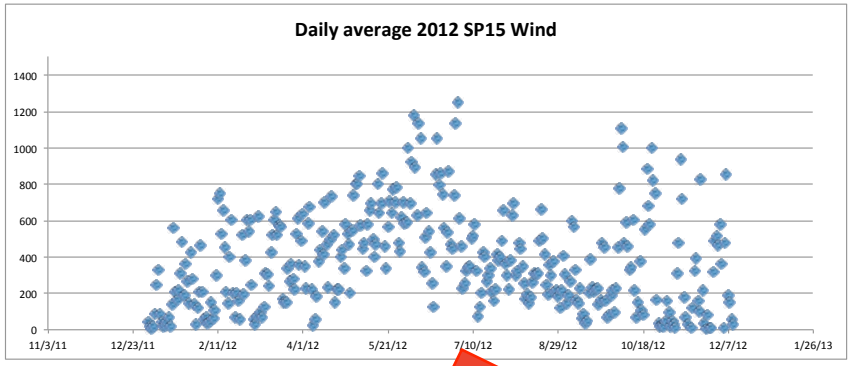
German wind production has high intermittency

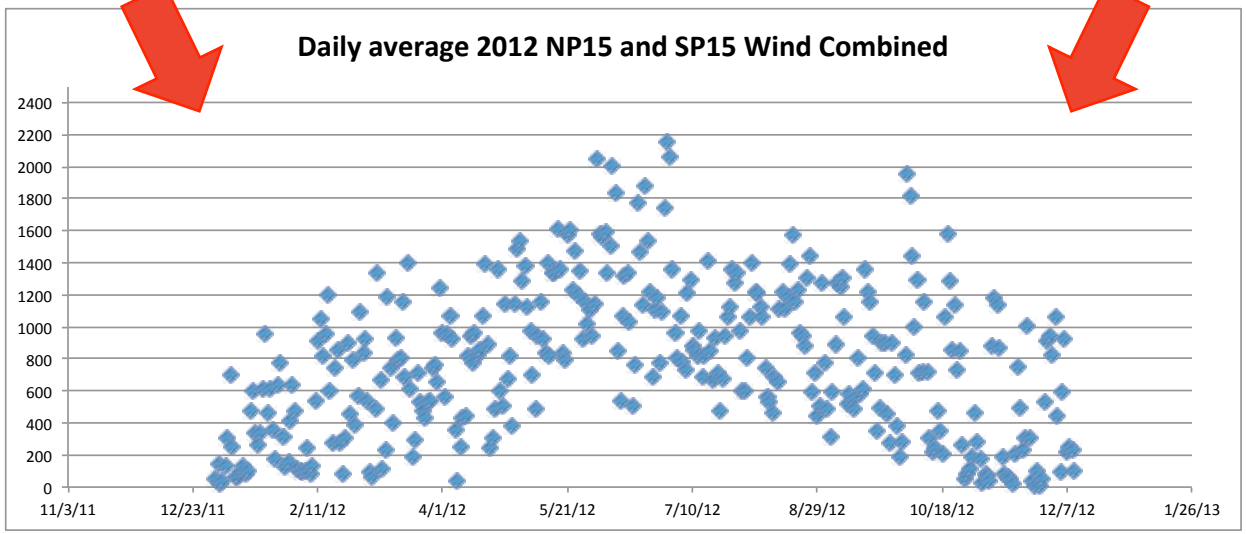


http://www.energybiz.com/article/13/11/wind-energys-production-tax-credit-crosshairs

California wind production also has high intermittency



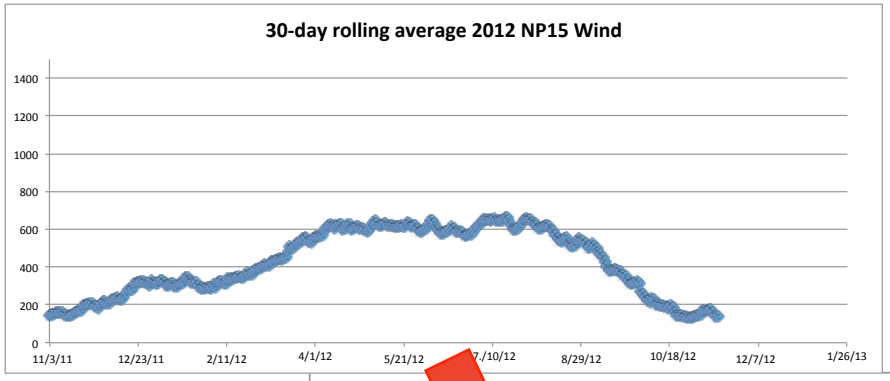


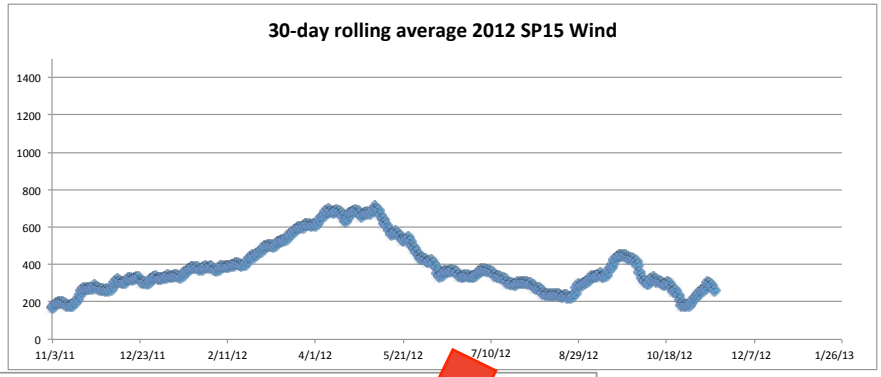


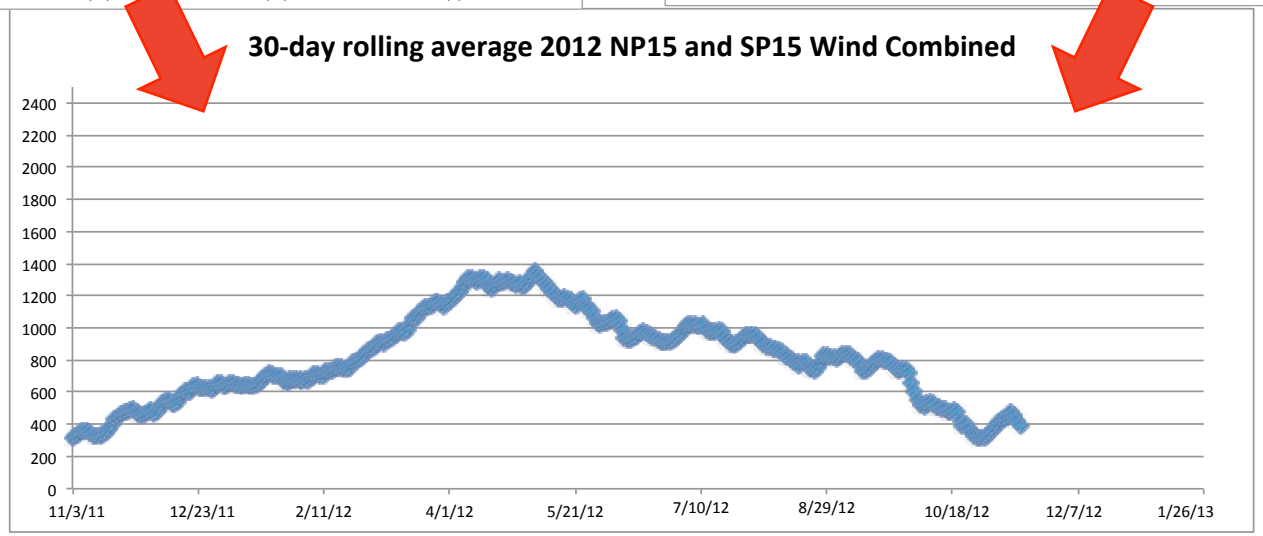
- Average daily wind production was highly intermittent in 2012
- Combining 2012 wind production from northern and southern California does not help, because bad wind days correlate significantly even over the entire length of the state

http://www.caiso.com/Documents/2012Report-Wind-SolarResources.xls

Even with 30-day storage, California wind production has seasonal intermittency



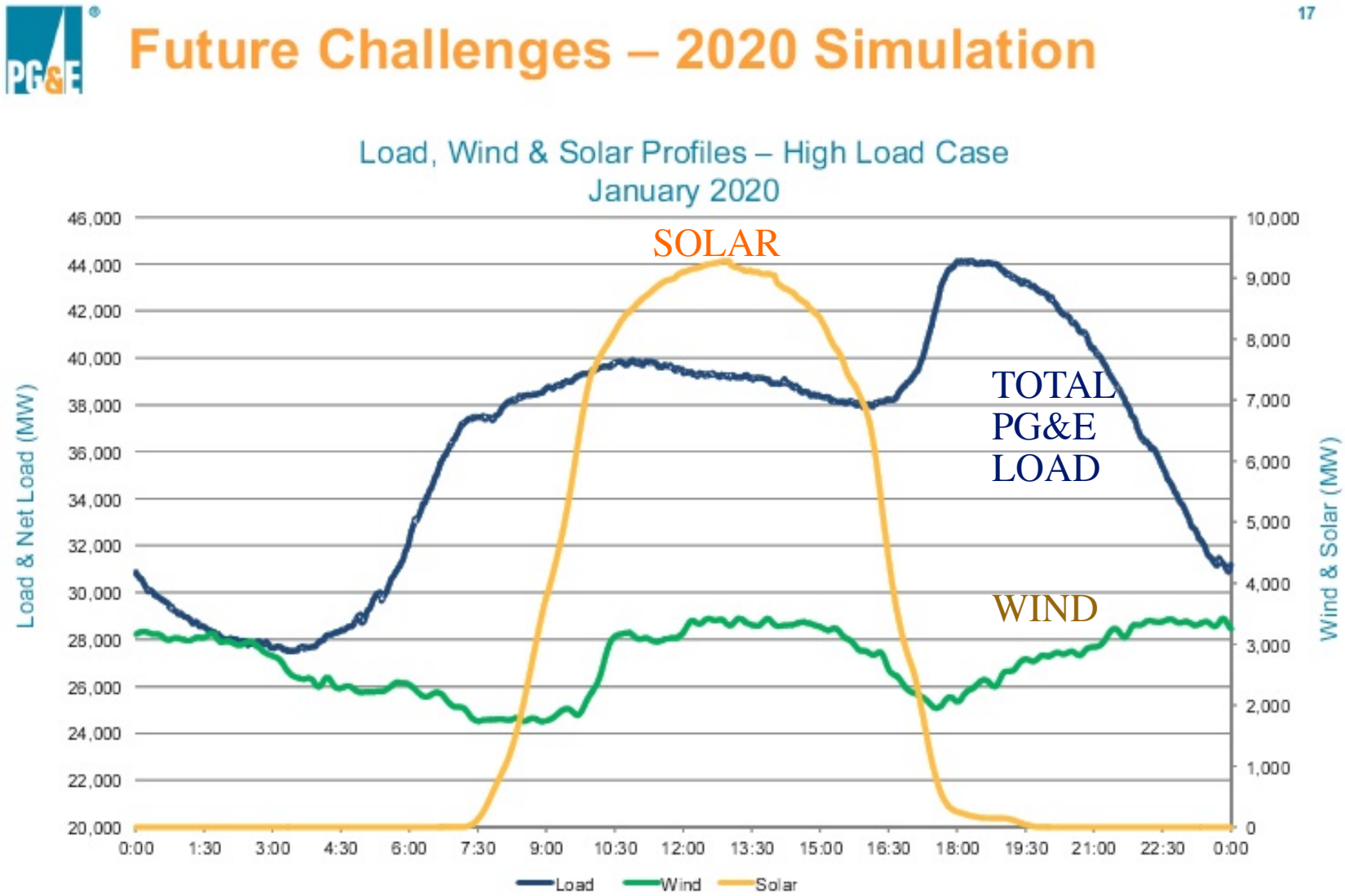




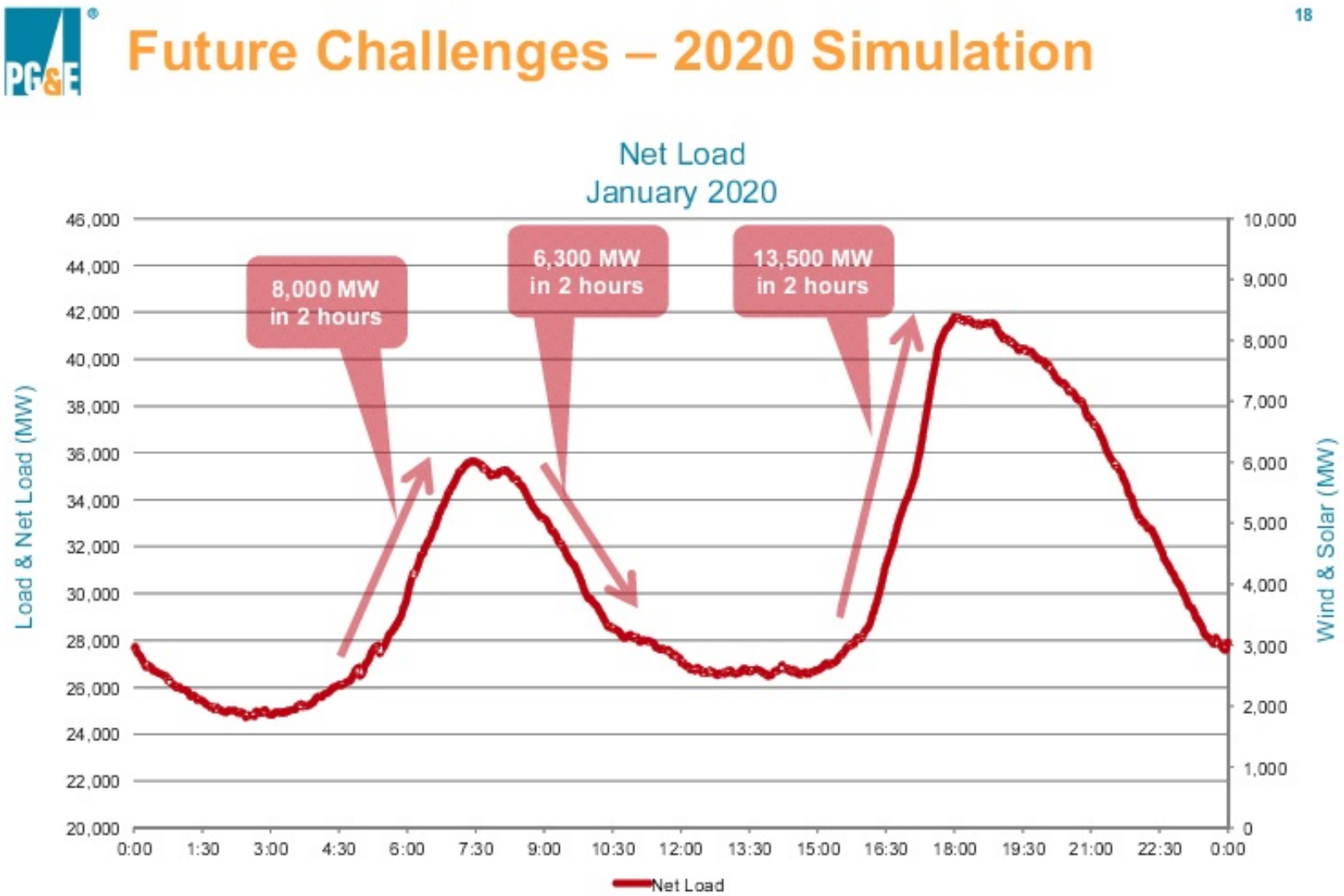
- Combining 2012 wind production from northern and southern California does not help, significant annual intermittency may also exist
- 30-day duty cycle is too long for efficient storage methods to be economic, so no practical method exists to address this monthly intermittency

http://www.caiso.com/Documents/2012Report-Wind-SolarResources.xls

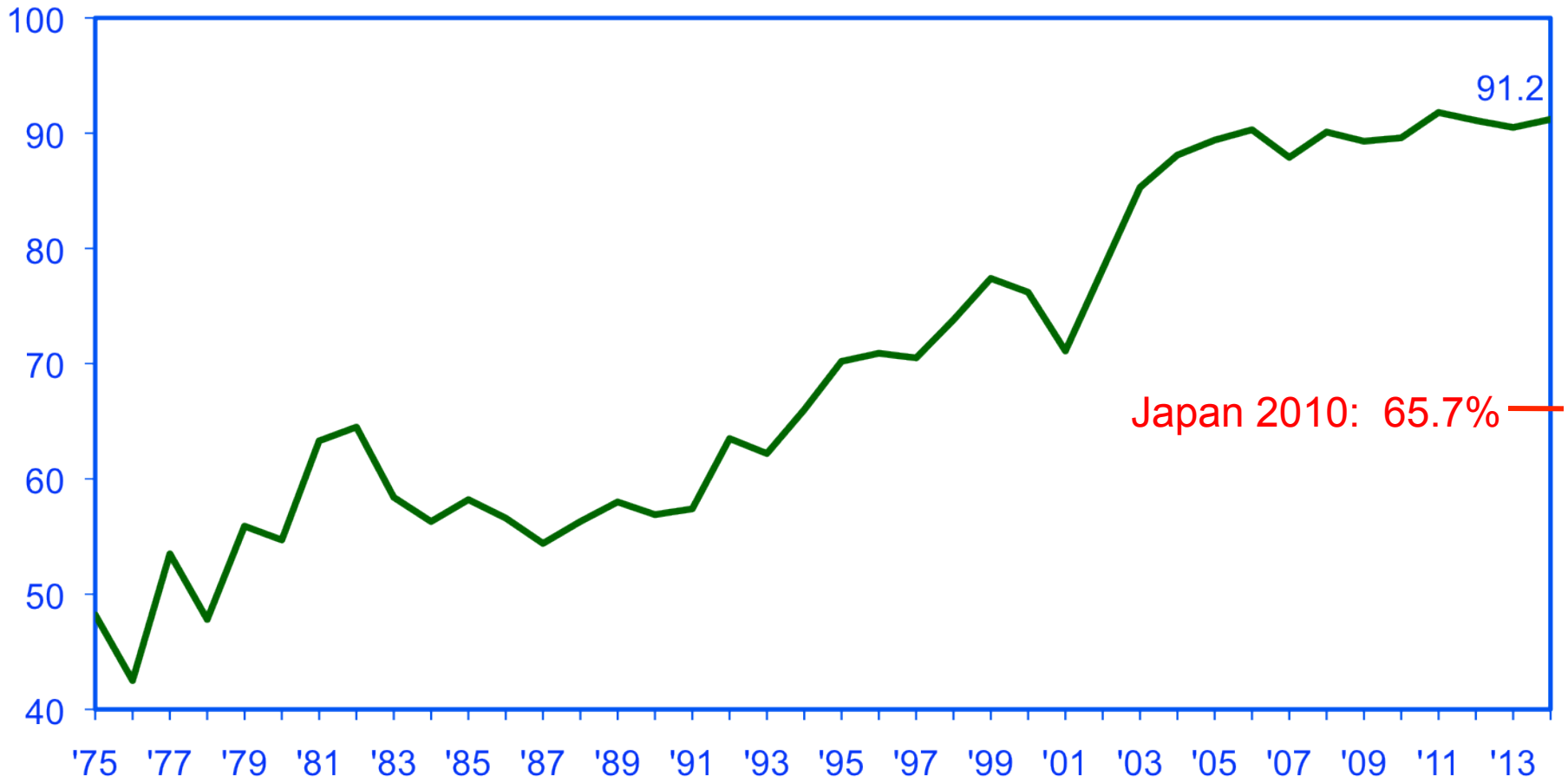
Wind and solar growth is expected in California



The net (non solar/wind) load may vary widely



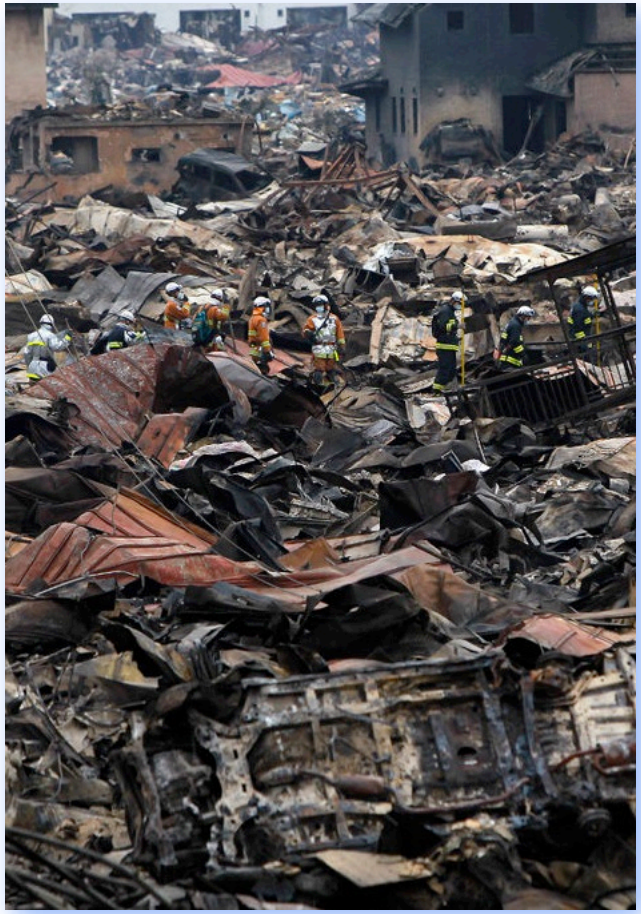
Nuclear plant reliability ("capacity factor") has changed greatly since the 1970's



The accident at Fukushima Daiichi

The Fukushima: What Happened?

- Previous major reactor accidents have resulted from combinations of equipment failures and human error
  - TMI and Chernobyl
  - Improvement in human and equipment reliability have greatly reduced the risk of internally initiated accidents
- Fukushima is the first major reactor accident to be initiated by a severe external event
  - Beyond design basis (BDB) event (although should have been in the design basis)
    - » NRC 90-day report recommended that U.S. reactors update natural hazard assessments every 10 years
  - Defense in depth measures are key to mitigating consequences



Lessons for U.S. reactor safety (highlights)

- Periodic review of natural hazards for nuclear plants (update every 10 years)
- Responsibility and authority to depart from procedures and enter into guidelines must be delegated at the plant level
  - 10 CFR 50.54(x) gives licensees legal authority to depart from procedures in an emergency, when they judge such action is needed to protect the public health and safety
- U.S. Extensive Damage Mitigation Guidelines (EDMGs) can be strengthened further
  - Value of preparation and capability to connect portable instruments, pumps and power supplies clearly demonstrated
- Diverse lessons for extensive damage mitigation, severe accident management and emergency response (FLEX) for current plants
- Passive safety (AP-1000, LWR-SMRs, Gen IV) eliminates concerns about station-blackout accidents

Recommendations from the Blue Ribbon Commission on America's Nuclear Future

Current Major Legal Actions

- DC Court of Appeals: Lawsuits against DOE seeking payments for interim storage costs resulting from partial breach of contract
  - Lawsuits ongoing, $21 billion liability by 2020.
- DC Court of Appeals: Lawsuit against DOE seeking suspension of the collection of the Nuclear Waste Fund Fee
  - On Nov. 19, 2013, the court ordered DOE to suspend collection of the fee (DOE letter sent to Congress Jan. 3, 2014)
- DC Court of Appeals: Lawsuit resulting in mandamus order to NRC to restart of Yucca Mountain License Review
  - NRC now plans to publish the YM Safety Evaluation Report
  - NRC has asked DOE to complete the Environmental Impact Statement
- NRC Nuclear Waste Confidence Rule
  - Currently licensing of new reactors is suspended
  - NRC plans to publish Final Waste Confidence Rule Oct. 3, 2014

Waste Isolation Pilot Plant, January 27, 2011

Blue Ribbon Commission

- The Blue Ribbon Commission on America's Nuclear Future established by the President's Memorandum for the Secretary of Energy on January 29, 2010

- Charge to the Commission: Conduct a comprehensive review of policies for managing the back end of the nuclear fuel cycle and recommend a new strategy

- Delivered final report with recommendations to the Secretary of Energy on January 29, 2012

Members

- *Lee Hamilton*, Co-Chair - Director of The Center on Congress at Indiana University, former Member of Congress (D-IN)
- *Brent Scowcroft*, Co-Chair – President, The Scowcroft Group, and former National Security Advisor to Presidents Gerald Ford and George H.W. Bush
- *Mark Ayers*, President, Building and Construction Trades Department, AFL-CIO
- *Vicky Bailey*, Former Commissioner, Federal Energy Regulatory Commission; Former Indiana PUC Commissioner; Former DOE Assistant Secretary for Policy and International Affairs
- *Albert Carnesale*, Chancellor Emeritus and Professor, UCLA
- *Pete V. Domenici*, Senior Fellow, Bipartisan Policy Center; former U.S. Senator (R-NM)
- *Susan Eisenhower*, President, Eisenhower Group, Inc.
- *Chuck Hagel*, Distinguished Professor at Georgetown University, Former U.S. Senator (R-NE)
- *Jonathan Lash*, President, World Resources Institute
- *Allison Macfarlane*, Assoc. Professor of Environmental Science and Policy, George Mason Univ.
- *Richard A. Meserve*, President, Carnegie Institution for Science, and former Chairman, U.S. NRC
- *Ernie Moniz*, Professor of Physics and Cecil & Ida Green Distinguished Professor, MIT
- *Per Peterson*, Professor and Chair, Dept. of Nuclear Engineering, Univ. of California – Berkeley
- *John Rowe*, Chairman and Chief Executive Officer, Exelon Corporation
- *Phil Sharp*, President, Resources for the Future; former Member of Congress (D-IN)

Overview of 8 Key Recommendations

1. A new, consent-based approach to siting and development

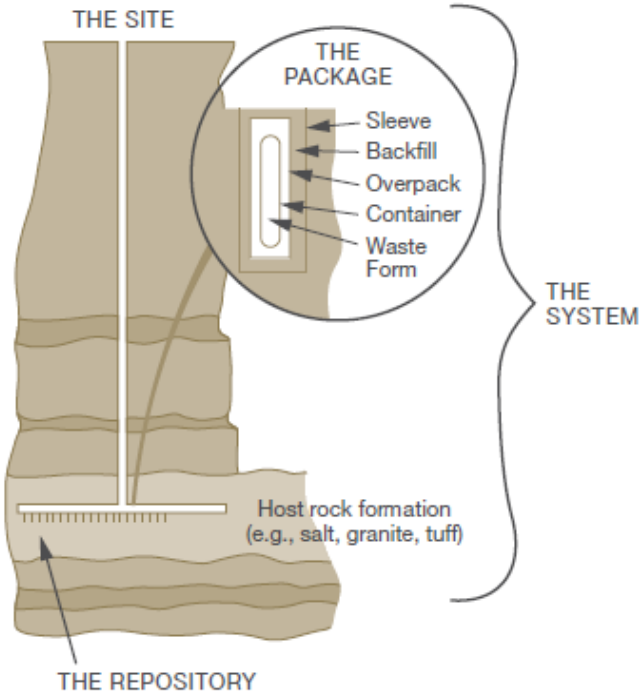
2. A new organization dedicated solely to implementing the waste management program and empowered with the authority and resources to succeed

Overview of 8 Key Recommendations

3. Access to the funds nuclear utility ratepayers are providing for the purpose of nuclear waste management

4. Prompt efforts to develop one or more geologic disposal facilities

5. Prompt efforts to develop one or more consolidated storage facilities



Overview of 8 Key Recommendations

6. Prompt efforts to prepare for the eventual large-scale transport of spent nuclear fuel and high-level waste to consolidated storage and disposal facilities when such facilities become available

7. Support for continued U.S. innovation in nuclear energy technology and for workforce development

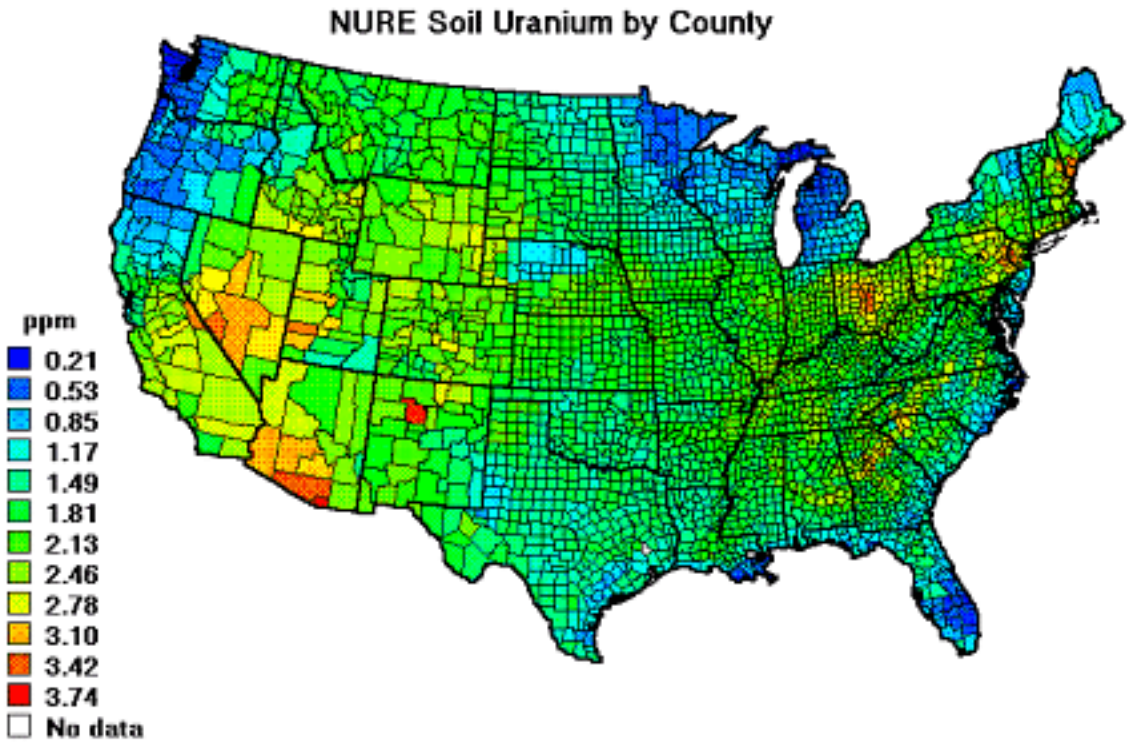
8. Active U.S. leadership in international efforts to address safety, waste management, non-proliferation, and security concerns

Senators Wyden, Murkowski, Alexander and Feinstein released a discussion-draft bill in 2013

- This "Nuclear Waste Administration Act of 2013" would:
  - Create a new Nuclear Waste Administration agency
    - » Administrator serves for a 6-year term and can be reappointed
    - » Oversight by a Nuclear Waste Oversight Board
  - Authorize the agency to enter into consent agreements with state, local, and tribal governments, subject to ratification by Congress
  - Create an new Working Capital Fund to hold future Nuclear Waste Fund receipts
  - Direct the agency to initiate a consent based process to site new consolidated storage and geologic disposal facilities
  - Does not fund any additional work for Yucca Mountain (not an appropriations bill), but also did not preclude any future decision by Congress to restart the Yucca Mountain project

Nuclear Economics and Life Cycle Assessment

Uranium, the fuel for fission energy, is abundant in the environment, as are the fuels for fusion

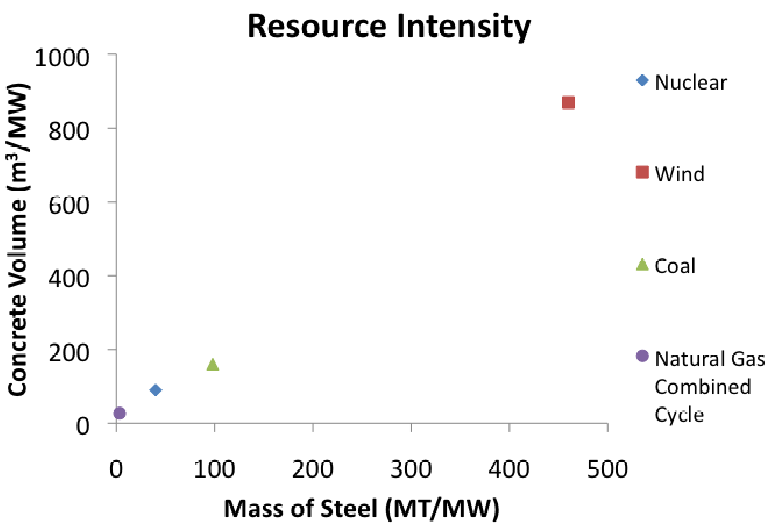


Natural uranium (99.3% ^{238}U, 0.7% ^{235}U) concentrations in U.S. soils, from USGS aerial surveys (1970 to 1980) using gamma-ray spectrometry to record the radioactivity of the isotope bismuth-214 in upper 50 cm of soil.

National average: 1.8 parts per million by weight
= 6 tons/mile^2 in top yard of soil

Resource inputs will affect future capital costs and competition

- **Nuclear:** 1970's vintage PWR, 90% capacity factor, 60 year life [1]
  - 40 MT steel / MW(average)
  - 90 m^3 concrete / MW(average)
- **Wind:** 1990's vintage, 6.4 m/s average wind speed, 25% cap. factor, 15 year life [2]
  - 460 MT steel / MW (average)
  - 870 m^3 concrete / MW(average)
- **Coal:** 78% cap. factor, 30 year life [2]
  - 98 MT steel / MW(average)
  - 160 m^3 concrete / MW(average)
- **Natural Gas Combined Cycle:** 75% cap. factor, 30 year life [3]
  - 3.3 MT steel / MW(average)
  - 27 m^3 concrete / MW(average)



Concrete + steel are >95% of construction inputs, and become more expensive in a carbon-constrained economy

1. R.H. Bryan and I.T. Dudley, "Estimated Quantities of Materials Contained in a 1000-MW(e) PWR Power Plant," Oak Ridge National Laboratory, TM-4515, June (1974)
2. S. Pacca and A. Horvath, *Environ. Sci. Technol.*, **36**, 3194-3200 (2002).
3. P.J. Meier, "Life-Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis," U. WisconsinReport UWFDM-1181, August, 2002.

Material inputs are a small fraction of the construction cost of a nuclear power plant

Commodity	Quan. (1)	Price 3/20/08	Cost ($/kW)
Aluminum (metric tons) (2)	18	$2,794	$0.05
Brass (metric tons) (2)	10	$4,950	$0.05
Bronze (metric tons) (3)	25	$4,950	$0.12
Carbon steel (metric tons) (2)	32731	$601	$19.67
Concrete (m^3) (3)	75026	$98	$7.36
Copper (metric tons) (2)	694	$7,634	$5.30
Galvanized iron (metric tons) (2)	1257	$721	$0.91
Iconel (metric tons) (2)	124	$7,000	$0.87
Insulation (thermal) (m. tons) (3)	922	$1,000	$0.92
Lead (metric tons) (2)	46	$2,640	$0.12
Nickel (metric tons) (2)	1	$28,446	$0.03
Paint (gal) (3)	17500	$20	$0.35
Total commodities cost			**$35.75**

Nuclear energy costs are not sensitive to construction material costs, just as nuclear energy costs are not sensitive to uranium costs…

(1) R.H. Bryan and I.T. Dudley, "Estimated Quantities of Materials Contained in a 1000-MW(e)PWR Power Plant," Oak Ridge National Laboratory, TM-4515, June (1974)
2. Prices for 3/20/08 downloaded from http://www.metalprices.com/FreeSite/metals/cu/cu.asp
3. Assumed price

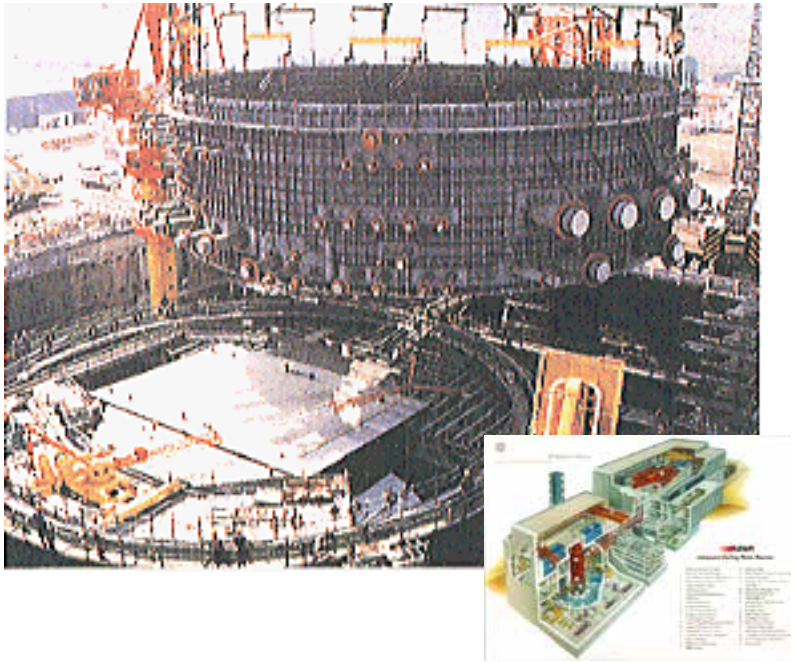
It is expensive to build new nuclear plants if the specialized manufacturing and skilled workforce are used inefficiently

Construction Costs for U.S. Nuclear Reactors by Year of Completion

http://energyathaas.wordpress.com/2014/02/18/a-small-bet-with-big-stakes

"Modular" design no longer requires "cookie cutter" construction

Modern cruise-ship construction using 3-D computer aided design and automated manufacturing

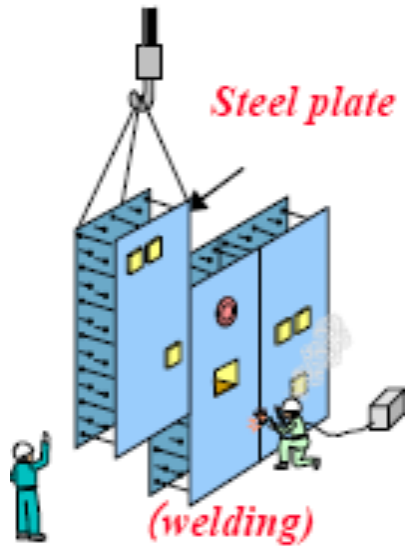


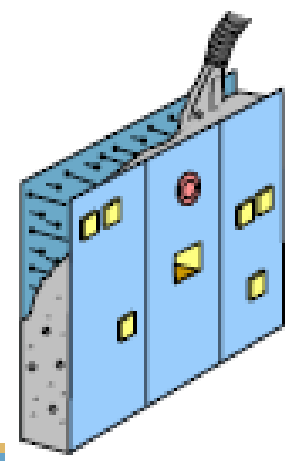
1990's ABWR onsite modular assembly reduce construction time to 52 months

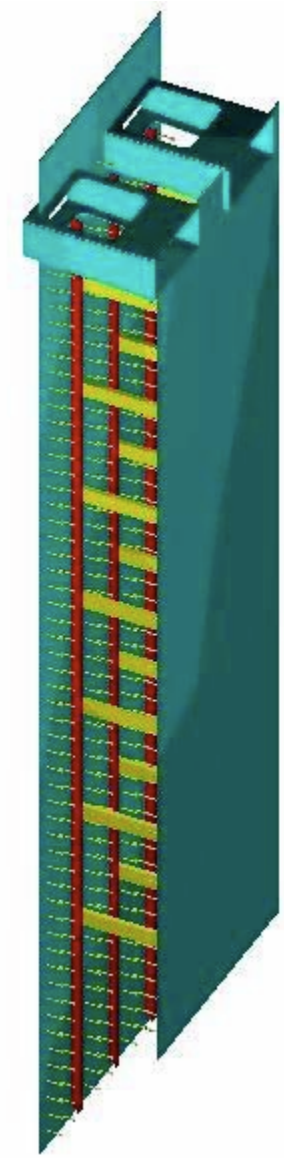
New nuclear construction approach: Factory modular fabrication

Steel-plate sandwich wall construction facilitates modular, rapid fabrication

- Steel plate used as:
  - Form
  - Reinforcement
- Modular, prefabricated components
- Rapid construction
  - Eliminates set up and tear down of plywood framing



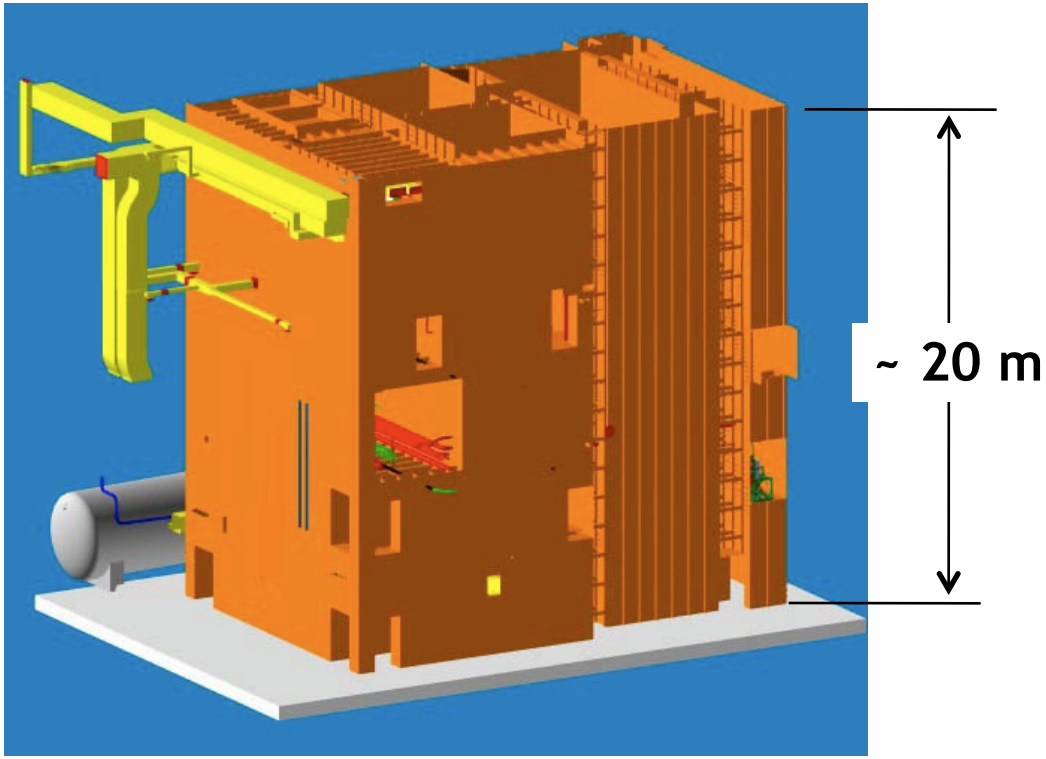




AP-1000 Structural Submodule

Automated factory fabrication of AP-1000 building structural modules in China (A similar CB&I plant is now operating in Lake Charles, LA)

The first AP-1000 under construction in Sanmen, China



770-ton AP-1000 auxiliary building module, assembled from factory prefabricated plate components, being set in place onto foundation, Sanmen, China, July 2009

U.S. Vogtle site August 2013

October 2011

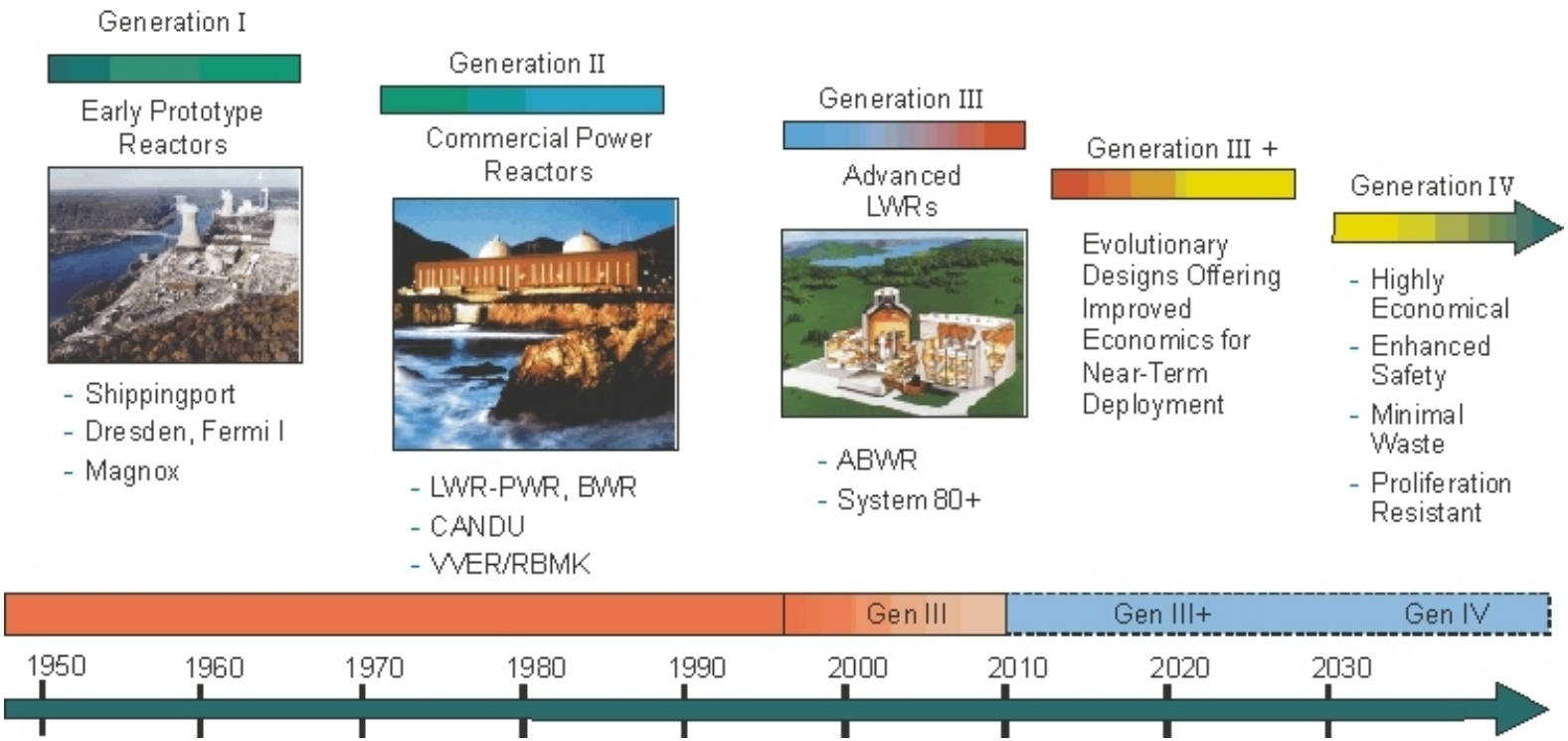
Unit 4

Unit 3

Unit 3

Future Nuclear Energy Systems

The Generations of Nuclear Energy



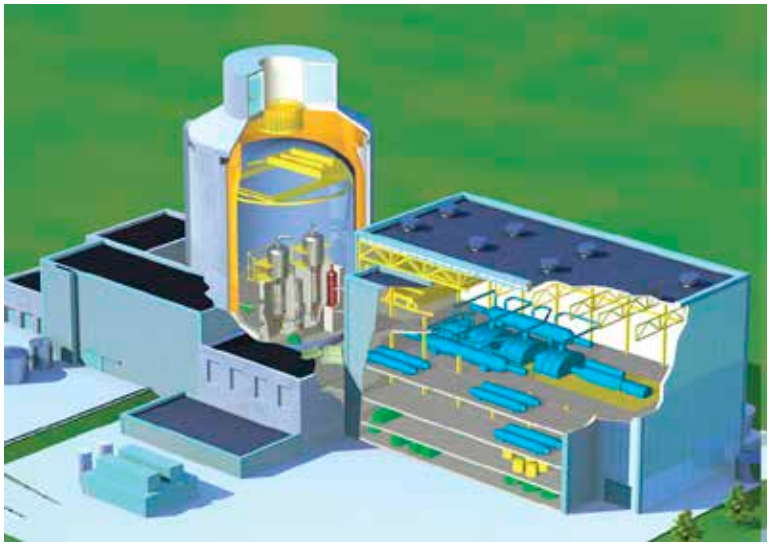
Source: DOE Generation IV Project

Fission energy continues to evolve

PG&E Diablo Canyon Plant

- Existing Nuclear Plants
  - 20% U.S. electricity
  - 70 % U.S. total non-fossil energy production
  - Average capacity factors now ~ 90%

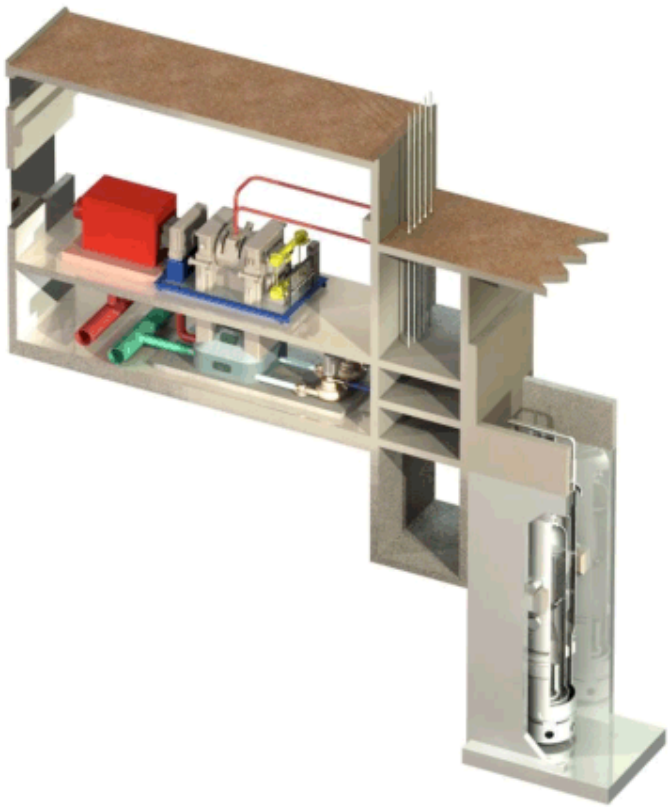
- Near-term New Plants
  - Construction of four U.S. AP-1000 reactors started in 2012



Westinghouse AP-1000

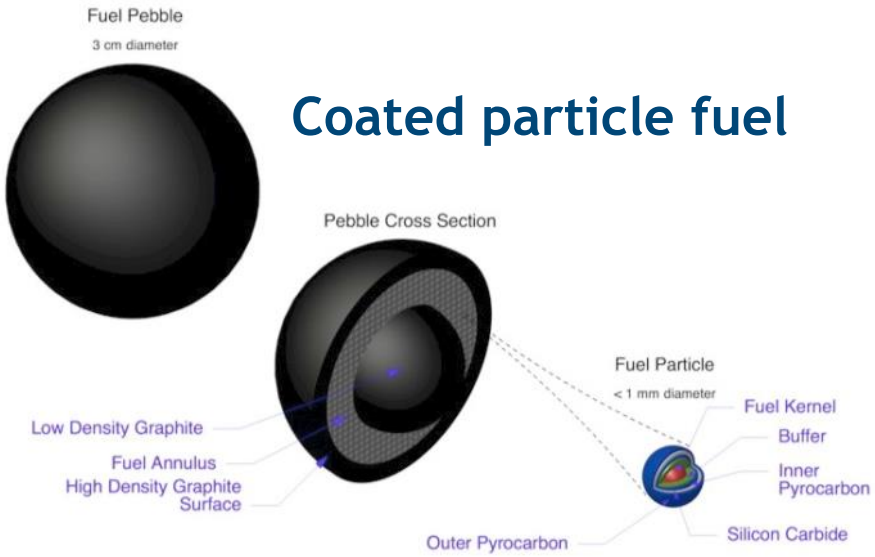
Small modular reactors (SMRs) based upon LWR technology now have commercial interest and investment

- Financing difficulty is reduced greatly
  - Commercial prototype plant
  - Subsequent plants
  - Technology is appropriate for process heat applications
- New designs reduce economy of scale issues
  - Nuscale plants use less steel and concrete, per MW, than the AP1000
- Commercial first movers face important licensing risks
  - Competitors can free-ride on NRC licensing decisions

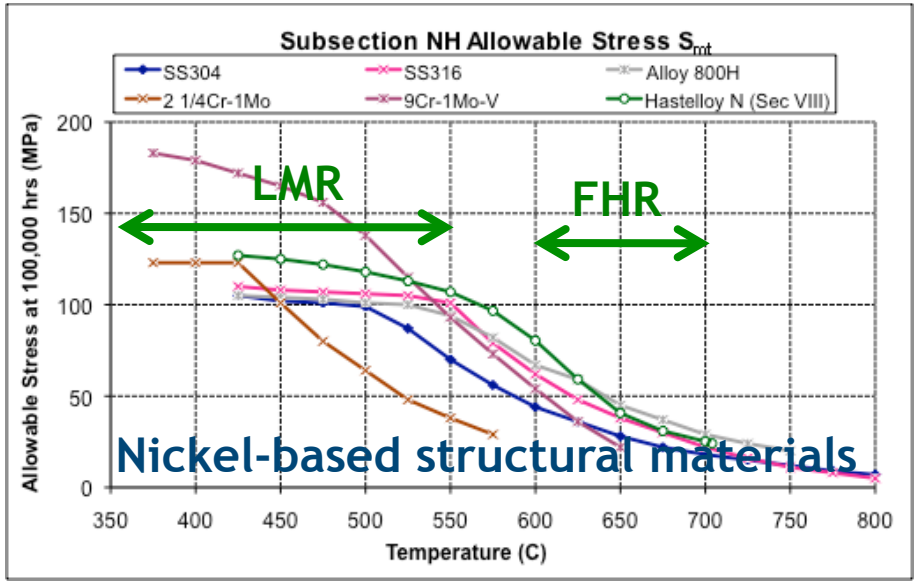


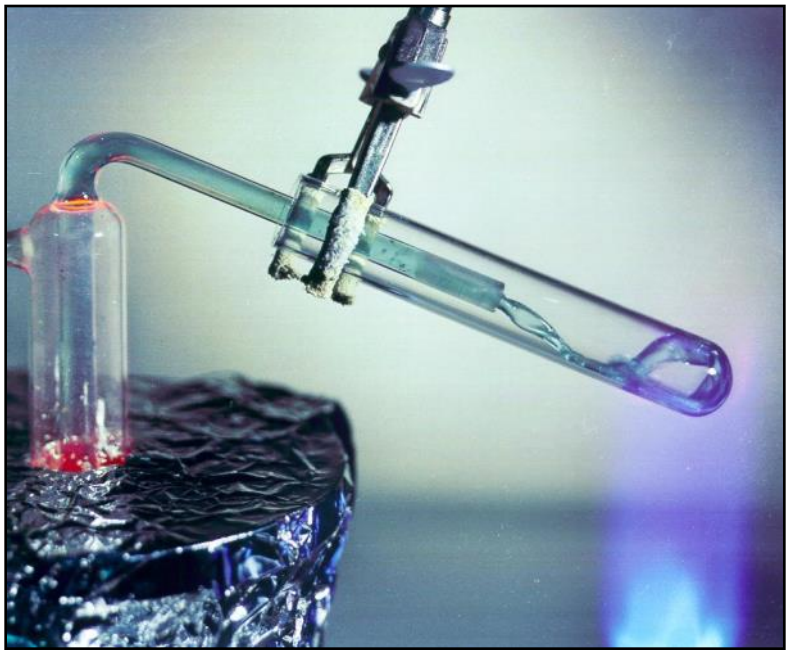
NuScale reactor module
Pressurized Water Reactor
45 MW electric

Fluoride Salt Cooled High Temperature Reactors (FHRs) use a novel combination of fuel and coolant



Coated particle fuel

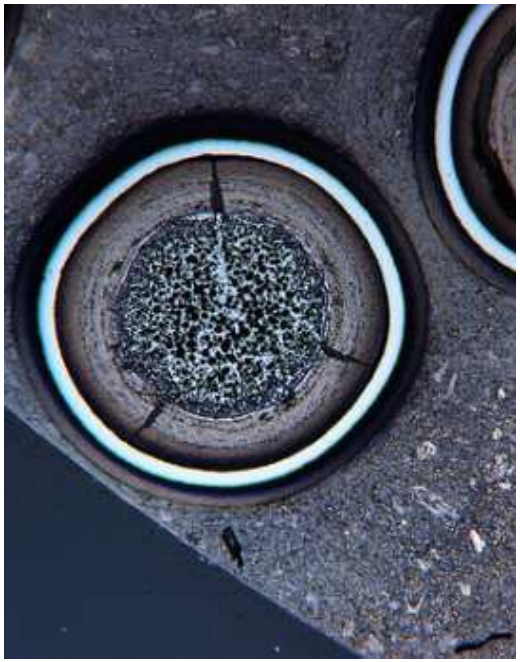




Liquid fluoride salt coolants

Recent studies for FHR materials and fuels are encouraging

- INL testing of NGNP TRISO fuel shows excellent fission product retention up to 1800°C



http://www.world-nuclear-news.org/ENF-Triso_fuel_triumphs_at_extreme_temperatures-2609137.html

- UW static corrosion tests show low corrosion rates for 316 SS and Alloy N in flibe at 700°C (1000 hr)

FHRs have remarkably small Cs-137 inventories

	Mk1 PB-FHR	ORNL 2012 AHTR	Westing-house 4-loop PWR	PBMR	S-PRISM
Reactor thermal power (MWt)	236	3400	3411	400	1000
Reactor electrical power (MWe)	100	1530	1092	175	380
Fuel enrichment †	19.90%	9.00%	4.50%	9.60%	8.93%
Fuel discharge burn up (MWt-d/kg)	180	71	48	92	106
Fuel full-power residence time in core (yr)	1.38	1.00	3.15	2.50	7.59
Power conversion efficiency	42.4%	45.0%	32.0%	43.8%	38.0%
Core power density (MWt/m3)	22.7	12.9	105.2	4.8	321.1
Fuel average surface heat flux (MWt/m2)	0.189	0.285	0.637	0.080	1.13
Reactor vessel diameter (m)	3.5	10.5	6.0	6.2	9.0
Reactor vessel height (m)	12.0	19.1	13.6	24.0	20.0
Reactor vessel specific power (MWe/m3)	0.866	0.925	2.839	0.242	0.299
Start-up fissile inventory (kg-U235/MWe) ††	0.79	0.62	2.02	1.30	6.15
EOC Cs-137 inventory in core (g/MWe) *	30.8	26.1	104.8	53.8	269.5
EOC Cs-137 inventory in core (Ci/MWe) *	2672	2260	9083	4667	23359
Spent fuel dry storage density (MWe-d/m3)	4855	2120	15413	1922	-
Natural uranium (MWe-d/kg-NU) **	1.56	1.47	1.46	1.73	-
Separative work (MWe-d/kg-SWU) **	1.98	2.08	2.43	2.42	-

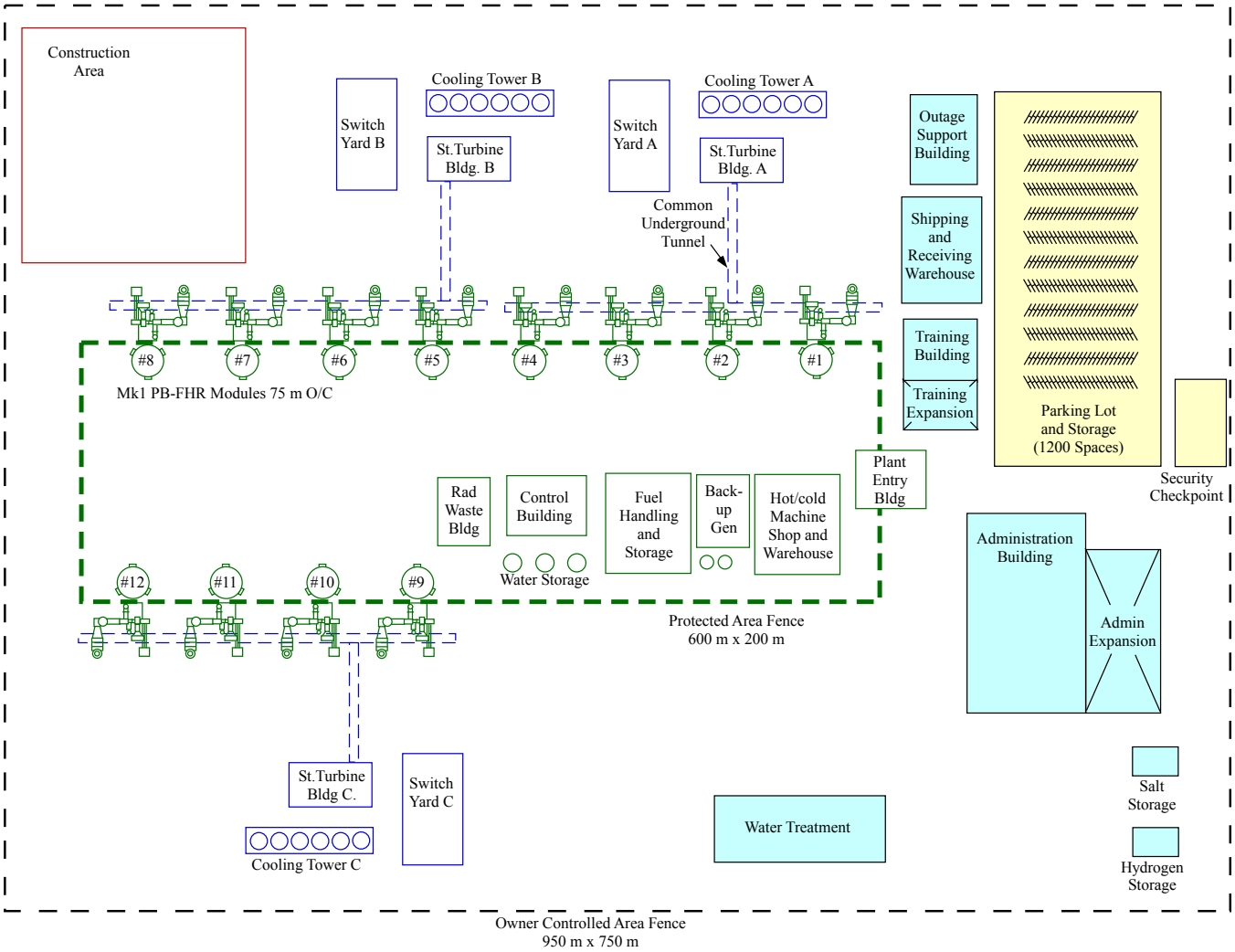
† For S-PRISM, effective enrichment is the Beginning of Cycle weight fraction of fissile Pu in fuel

†† Assume start-up U-235 enrichment is 60% of equilibrium enrichment; for S-PRISM startup uses fissile Pu

* End of Cycle (EOC) life value (fixed fuel) or equilibrium value (pebble fuel)

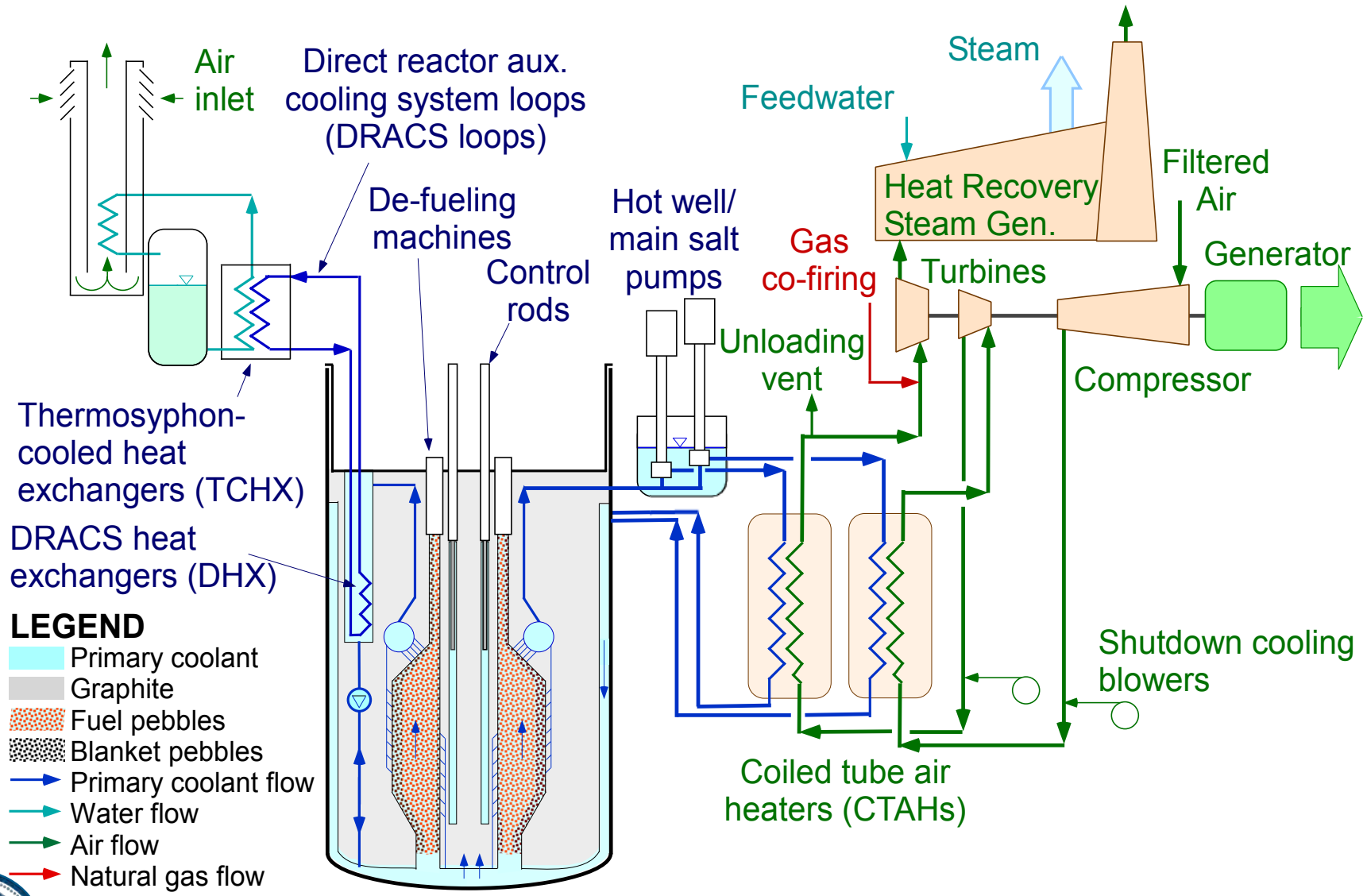
** Assumes a uranium tails assay of 0.003.

Under DOE IRP support, UCB is developing a new, Mk1 PB-FHR design using NACC



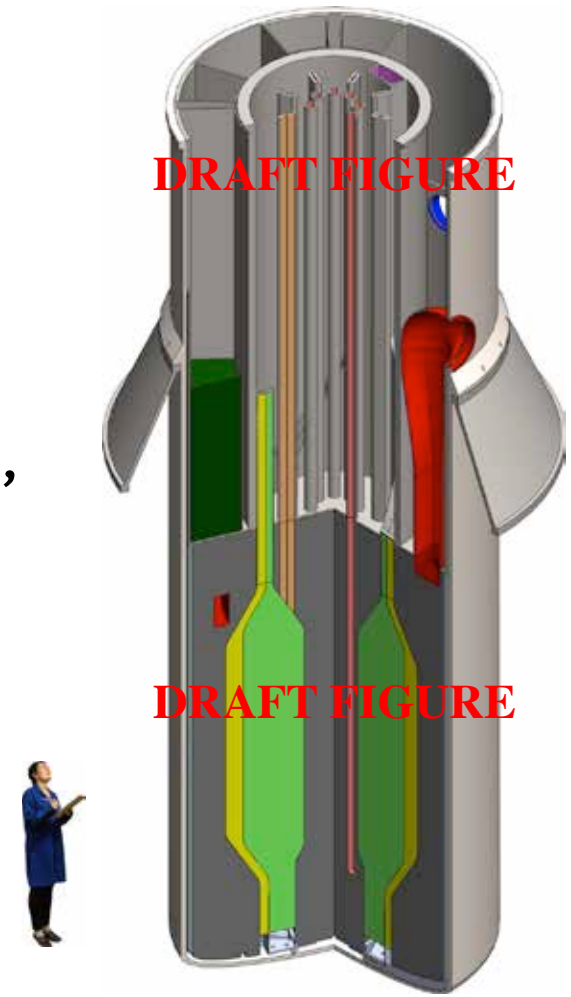
- **1200 MWe base load, 2900 MWe peak Mk1 station design**

Mk1 PB-FHR flow schematic



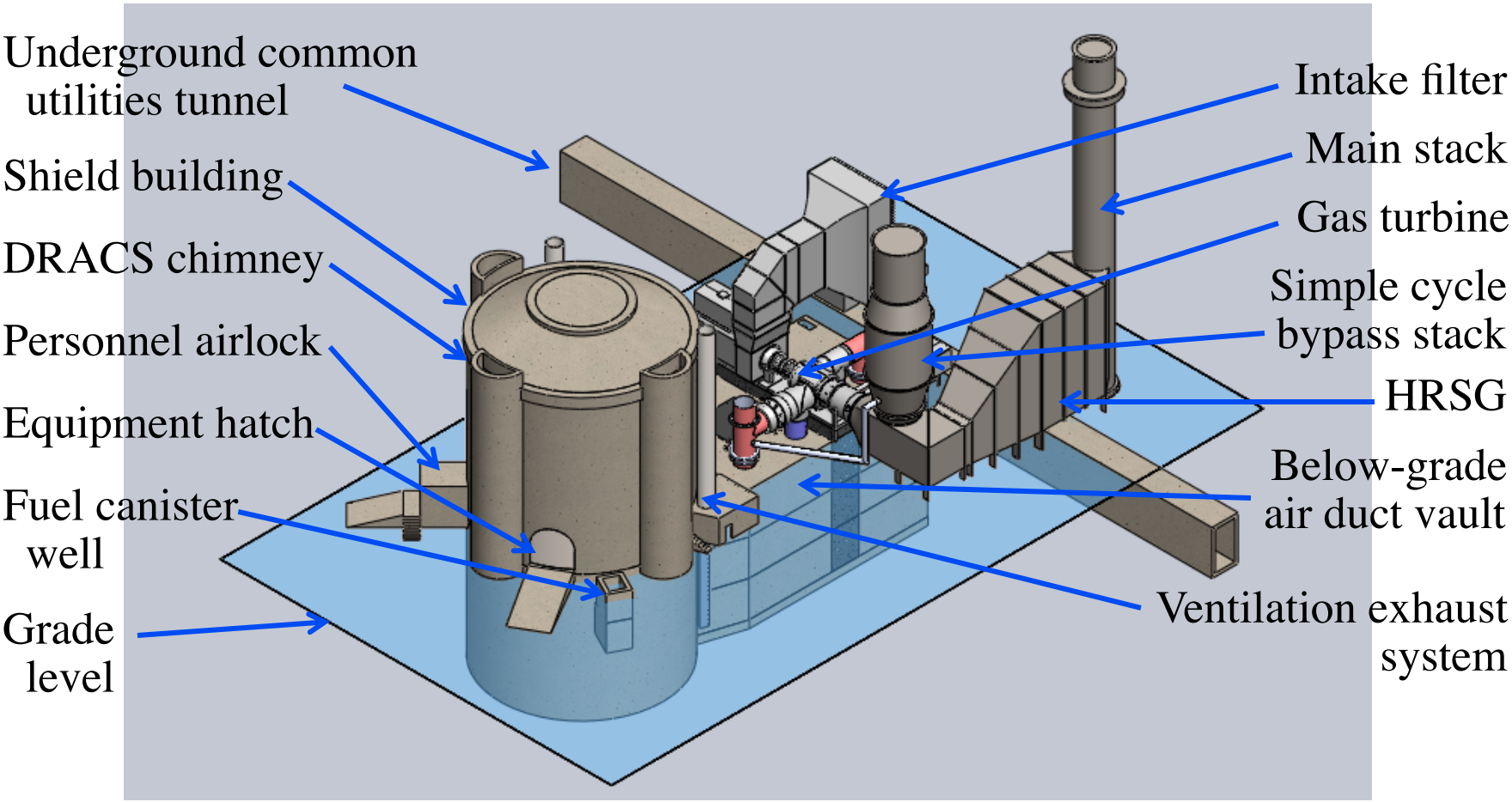
Nominal Mk1 PB-FHR Design Parameters

- Annular pebble bed core with center reflector
  - Core inlet/outlet temperatures 600°C/700°C
  - Control elements in channels in center reflector
  - Shutdown elements cruciform blades insert into pebble bed
- Reactor vessel 3.5-m OD, 12.0-m high
  - Vessel power density 3 x higher than S-PRISM & PBMR
- Power level: 236 MWth, 100 MWe (base load), 242 MWe (peak w/ gas co-fire)
- Power conversion: GE 7FB gas turbine w/ 3-pressure HRSG
- Air heaters: Two 3.5-m OD, 10.0-m high CTAHs, direct heating
- Tritium control and recovery
  - Recovery: Absorption in fuel and blanket pebbles
  - Control: Kanthal coating on air side of CTAHs

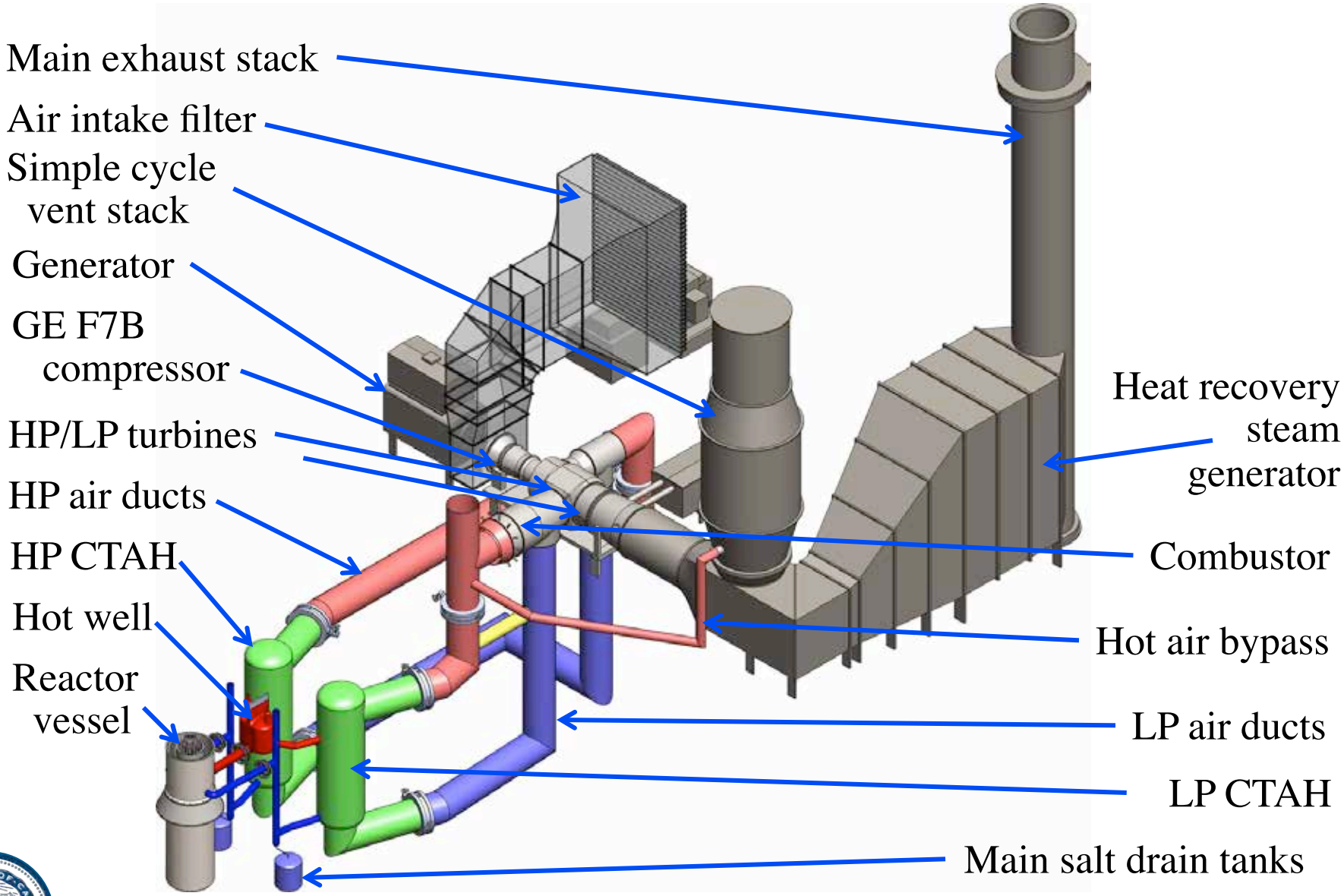


PB-FHR cross section

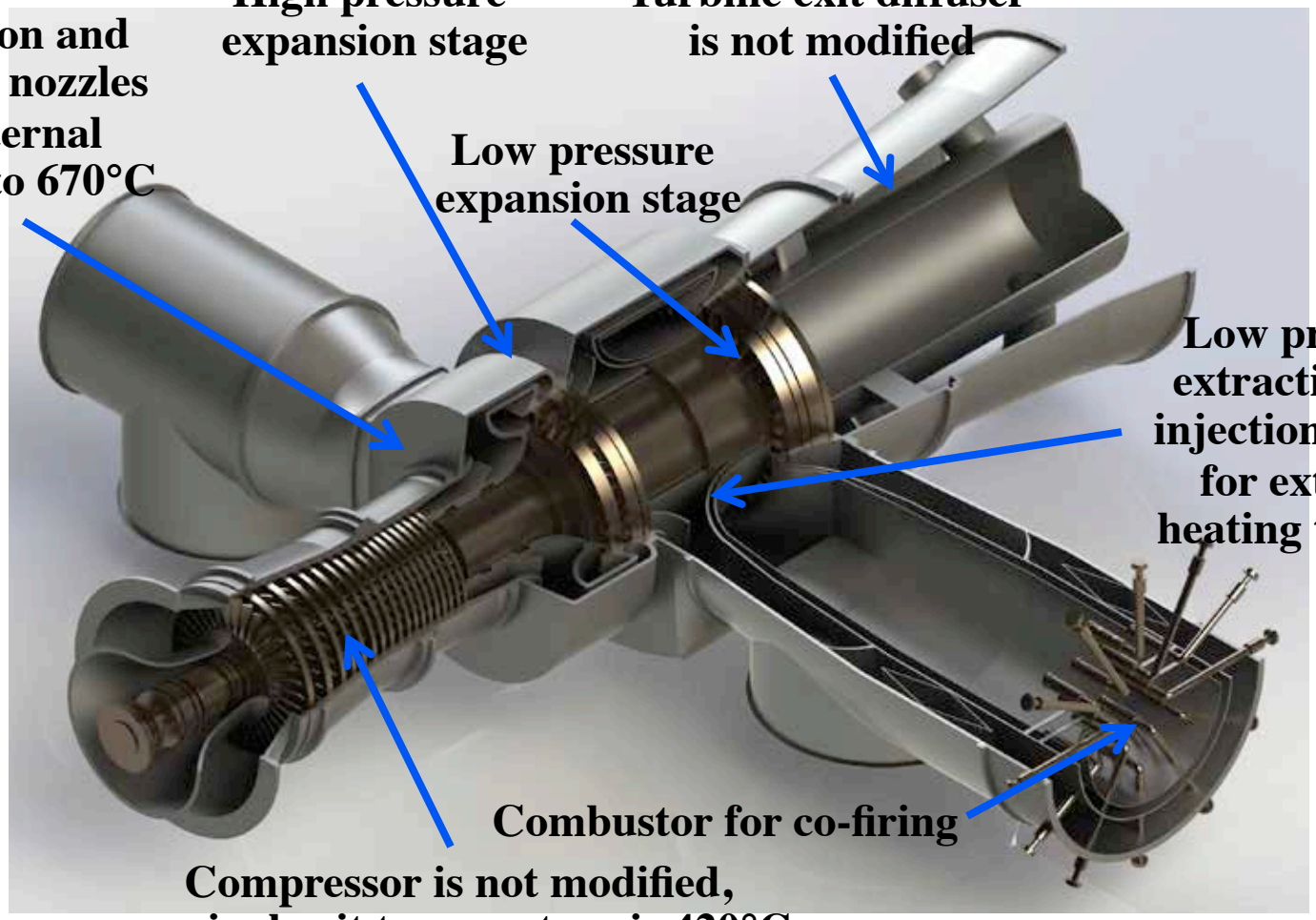
The Mk1 structures are designed for modular construction



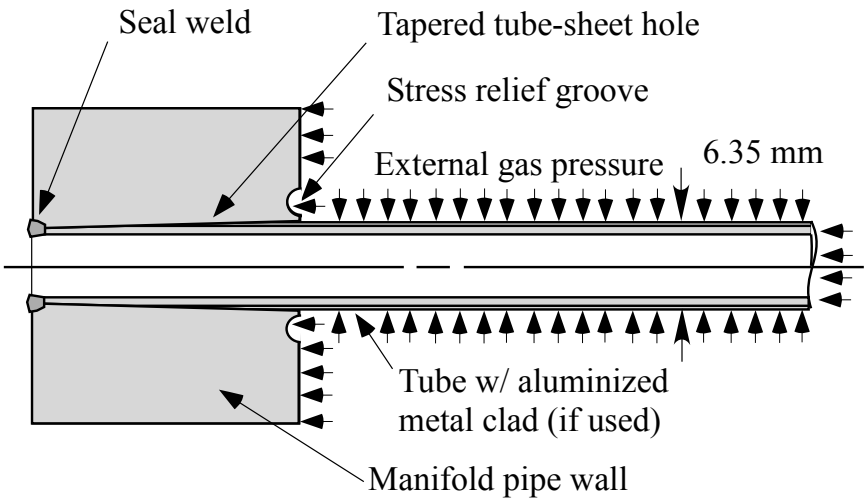
Mk1 NACC physical arrangement

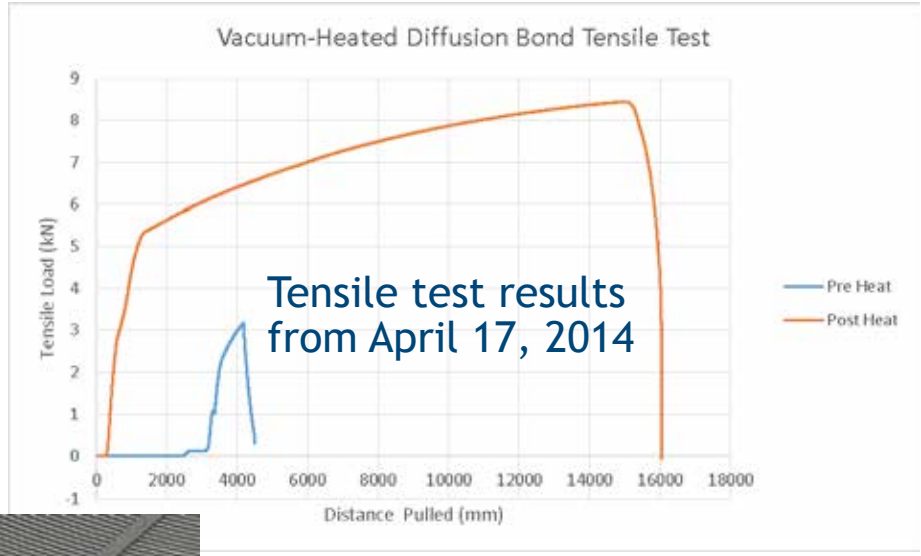


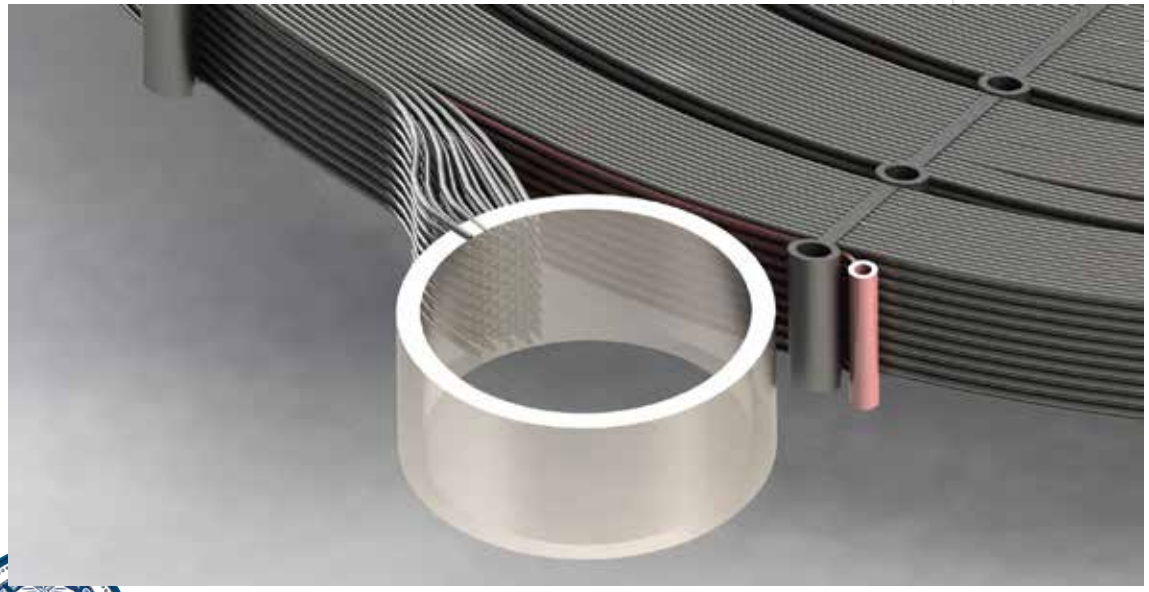
The GE 7FB turbine design has been modified to implement nuclear heating

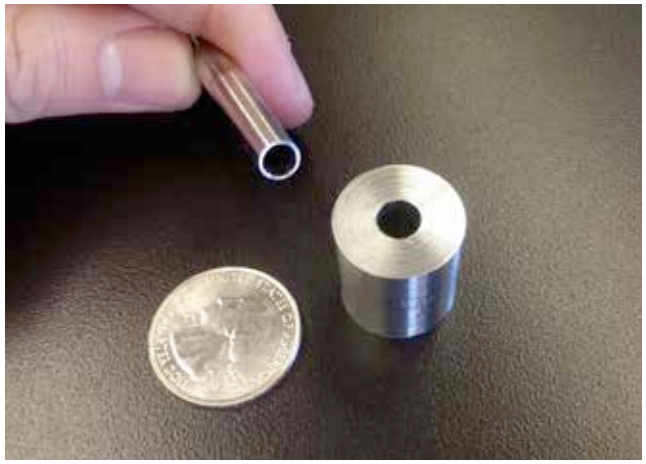


The Mk1 CTAH tube to tube-sheet joints use diffusion bonding









Conclusions

- The United States needs to rethink its overall strategy for nuclear energy
  - It is critical that Congress take action in the next year to restart the U.S. nuclear waste program
    - Need a strategy that recognizes that spent LWR fuel could be a future asset, and allows communities that host consolidated storage to capture this future value
  - Nuclear energy construction and operation use very small quantities of natural resources
    - Resource scarcity is unlikely to emerge as a future constraint
    - Major issues involve using expensive specialized manufacturing and skilled workforces efficiently
      - The airlines now do this—almost every seat is filled
  - With low but volatile natural gas prices, U.S. reactor vendors cannot recover development costs from domestic sales alone
    - The U.S. needs a strategy that gains access to international markets
    - USNRC Design Certification remains the gold standard