United States Nuclear Regulatory Commission

Protecting People and the Environment

Presentations for September 13, 2018 Public Meeting
Regulatory Improvements for Advanced Reactors

In order of discussion, the meeting included the following topics and presentations

1) NRC Slides
2) Future of Nuclear Energy in a Carbon Constrained World
   (and potential insights to prioritize activities) – M Corradini (UWisc)
3) Consensus Codes and Standards – ASME Section III, Div 5
4) Fast Reactor Working Group, Metal Fuels Report – C Cochran (Oklo)
5) Licensing Modernization

Public Meeting on Possible Regulatory Process Improvements for Advanced Reactor Designs

September 13, 2018

Telephone Bridge
(888) 793-9929
Passcode: 2496308

Public Meeting

- Telephone Bridge

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  Passcode: 2496308
- Opportunities for public comments and questions at designated times

Outline

- Introductions
- Status of Activities: NRC, NEI
- Report on Future of Nuclear Energy in a Carbon-Constrained World and Potential Insights to Prioritize Activities (M. Corradini, UWisc)
- Consensus Codes and Standards
  - ASME Section III, Division 5
- Fast Reactor Technology Working Group (C. Cochran, Oklo)
- Licensing Modernization Project Guidance, Draft Regulatory Guide & Related Draft Commission Paper

Implementation Action Plans

Strategy 1
Knowledge, Skills and Capability
- ONRL Molten Salt Reactor Training
- Knowledge Management
- Competency Modeling

Strategy 2
Computer Codes & Review Tools
- Identification & Assessment of Available Codes

Strategy 3
Flexible Review Processes
- Regulatory Roadmap ✓
- Prototype Guidance ✓
- Non-LWR Design Criteria ✓
- Environmental Reviews
- Licensing Modernization Project

Strategy 4
Consensus Codes and Standards
- ASME BPVC Section III Division 5
- ANS Standards 20.1, 20.2 30.2, 54.1
- Non-LWR PRA Standard

Strategy 5
Policy and Key Technical Issues
- Siting near densely populated areas
- Insurance and Liability
- Consequence Based Security
- EP for SMRs and ONTs
- Functional Containment

Strategy 6
Communication
- NRC DOE Workshops ✓
- Periodic Stakeholder Meetings
- NRC DOE GAIN MOU
- International Coordination

- Potential First Movers
- Micro-Reactors

Advanced Reactor Program

NRC Status

- Developing Additional Staff Training (HTGRs, LMFRs)
- Continuing Computer Code Assessments (Future Meeting Topic)
- Interactions with Licensing Modernization Project (DG 1353)
- Environmental Review Working Group
- ASME Div 5, ANS Design Standards, non-LWR PRA Standard
- Policy Issues
  - Siting, PAA, Security, EP, Functional Containment, RIPB Licensing
- "Micro-Reactors"

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NEI / ARRTF Updates

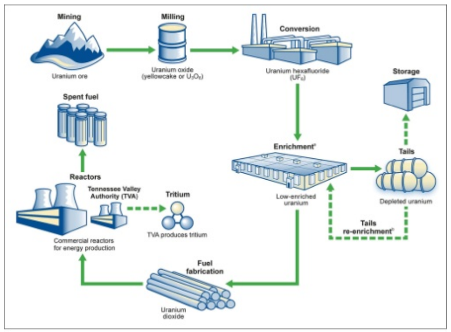
Advanced Reactor Program

Report on Future of Nuclear Energy in a Carbon-Constrained World and Potential Insights to Prioritize Activities

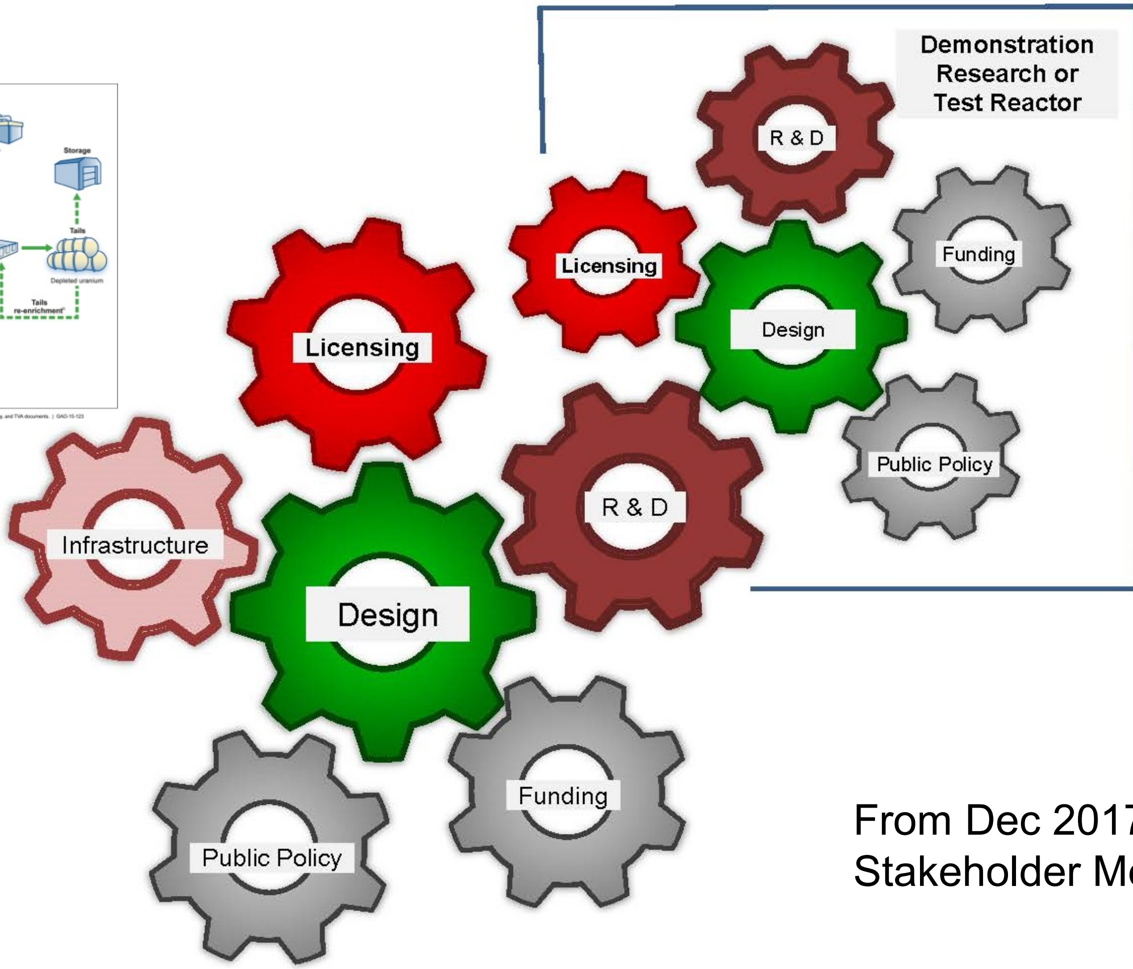
M. Corradini, University of Wisconsin

[Report Slides]

Licensing as Part of Overall Development Programs



Sources: GAO analysis of International Atomic Energy Agency, Nuclear Regulatory Commission, Congressional Research Service, Department of Energy, and TVA documents. | GAO-15-123



From Dec 2017 Stakeholder Meeting

Break

Meeting/Webinar will begin shortly

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Consensus Codes and Standards

- ASME Section III, Division 5

ASME Slides

Technology Working Groups

Fast Reactor Working Group

- C. Cochran, Oklo

FRWG Report

Future Stakeholder Meetings Topics ?

Sept 13	TWG – Fast Reactors, Metallic Fuel
	Prioritization of Issues Considering Capital Costs
	Consenus Codes & Standards (ASME § 3, Div 5)
	Licensing Modernization/DG 1353
Wed Oct 24	TWG - HTGRs
	Policy Table
	Licensing Modernization/DG 1353
Dec 13	TWG - ?
	Seismic Isolation
	Strategy 2 – Computer Codes

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Public Comments / Questions

Lunch

Meeting/Webinar will begin at 1:00pm

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Licensing Modernization Project

DG 1353

Policy Paper

Break

Meeting/Webinar will begin shortly

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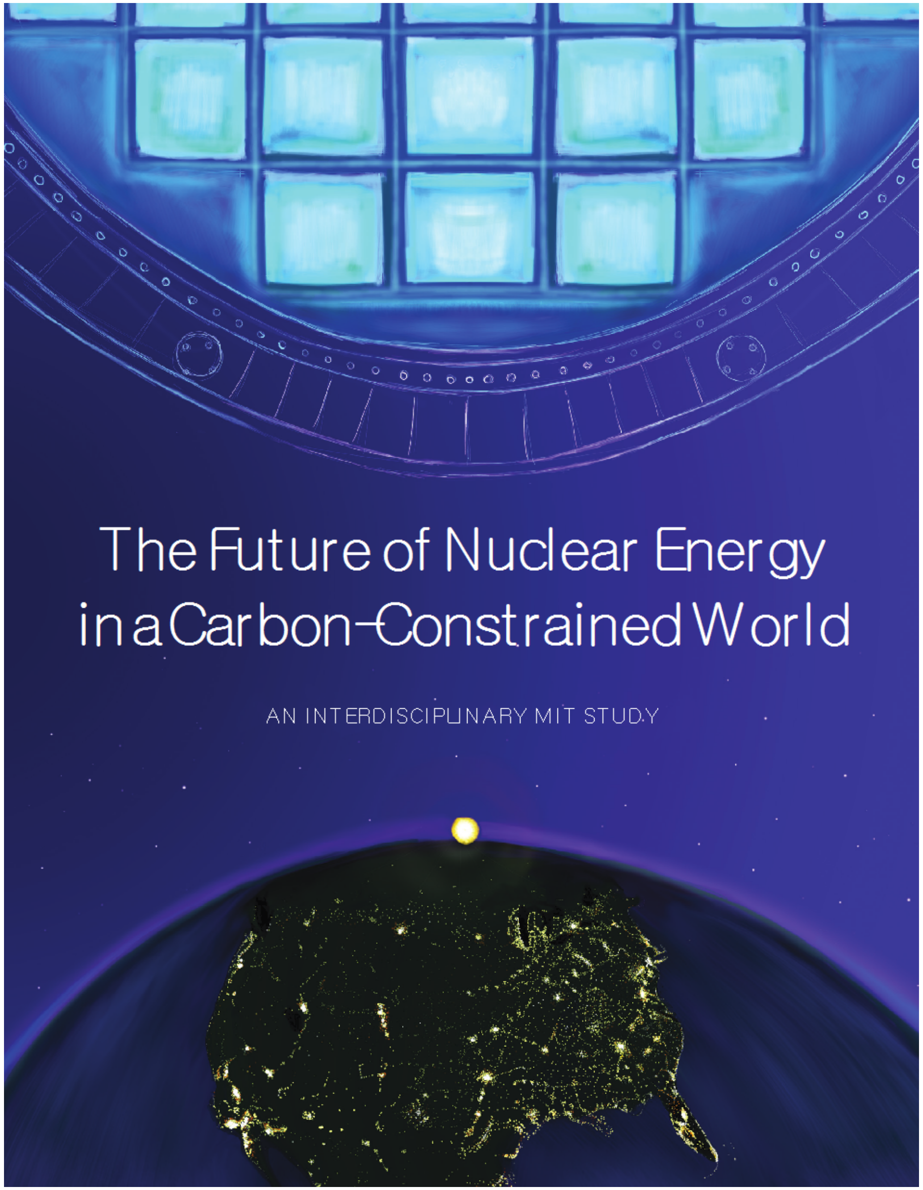


David Petti
Executive Director, INL

Jacopo Buongiorno
Co-Director, MIT

Michael Corradini
Co-Director, U-Wisconsin

John Parsons
Co-Director, MIT

MITei
MIT Energy Initiative

NSE
Nuclear Science and Engineering
science : systems : society

Key Questions Analyzed in the Study

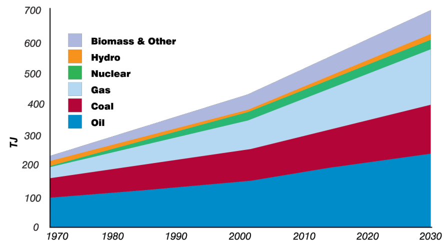
For the period present-2050:

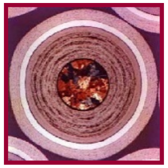
- Do we need nuclear to de-carbonize the power sector?
- What is the cost of new nuclear and how to reduce it?
- What is the value proposition of advanced nuclear technologies?
- What is the appropriate role for the government in the development and demonstration of new nuclear technologies?

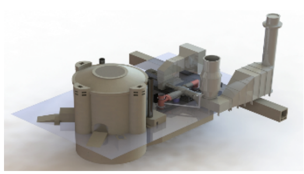
TAKE-AWAY MESSAGES

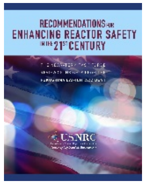
- Nuclear is an important option to keep average electricity costs reasonably low in a decarbonized economy
- The bulk of capital costs of new nuclear is in civil works, structures and buildings and indirect costs
- Innovative design/build approaches (not necessarily new reactor designs) have potential to reduce cost of nuclear
- Advanced reactors offer enhanced safety and are positioned to take advantage of the innovative approaches
- New government policies that level the playing field for all low-carbon energy technologies are needed

Five Major Themes









1. Opportunities

2. Cost

3. Advanced Reactor Evaluation

4. Policy and Business Models

5. Regulatory Assessment

What is *not* in the study
- Fuel Cycle -

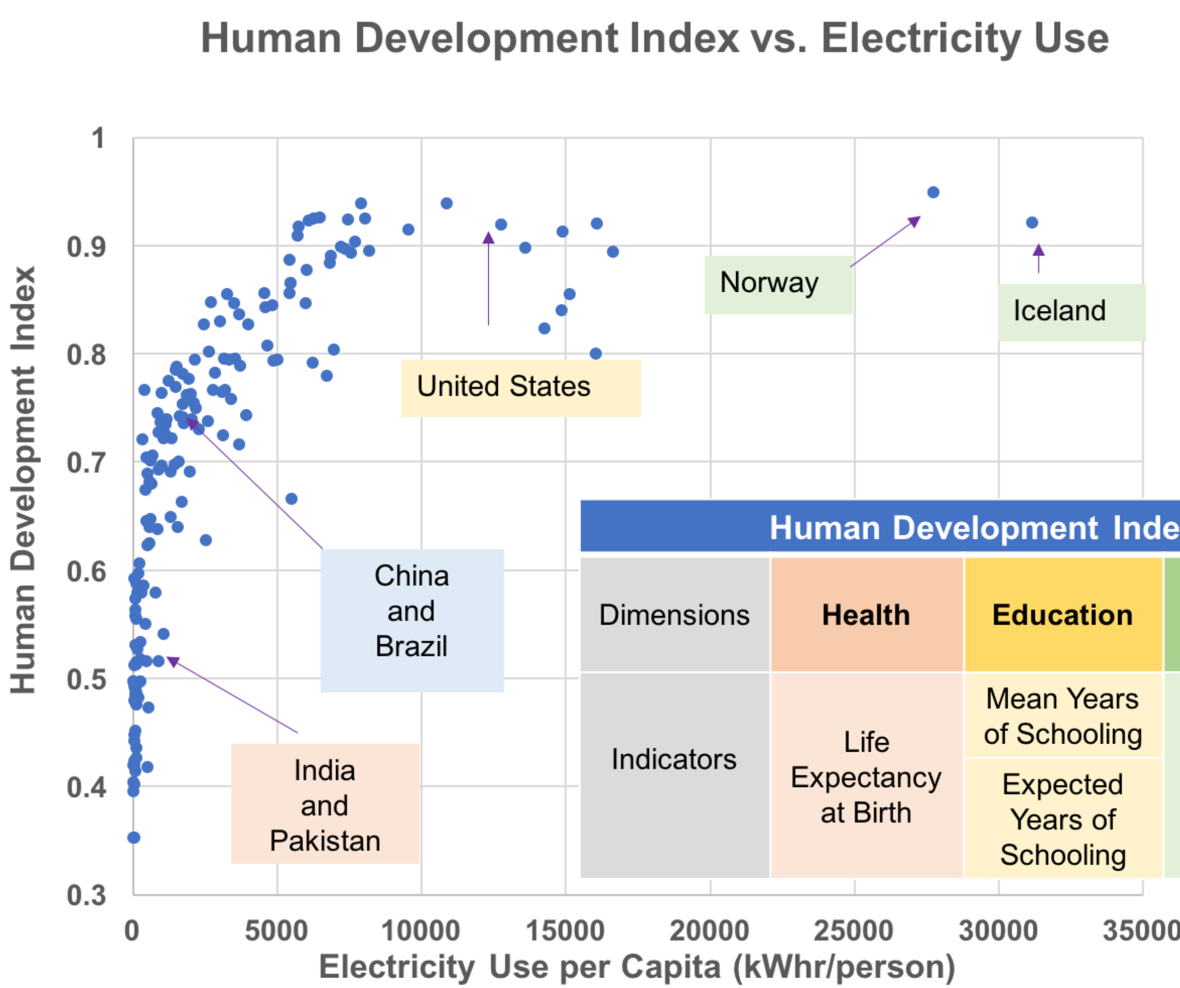
Results from the MIT 2009 study on the future of the nuclear fuel cycle remain valid today:

- Fuel utilization is not a significant cost issue given current resources,
- Technically viable options exist for the HLW disposal challenge, but must be implemented in a socially and politically acceptable manners, which has not happened in most countries with few exceptions (Finland, Sweden),
- There are approaches (e.g. centralized spent fuel repositories) that can make civilian fuel cycle an unattractive path to proliferation.

Solutions to these political problems will be found if society will decide that nuclear technology is essential. If the value of nuclear as a central contributor to deep decarbonization is not recognized, waste and proliferation will continue to be issues used to reject nuclear energy.

The big picture

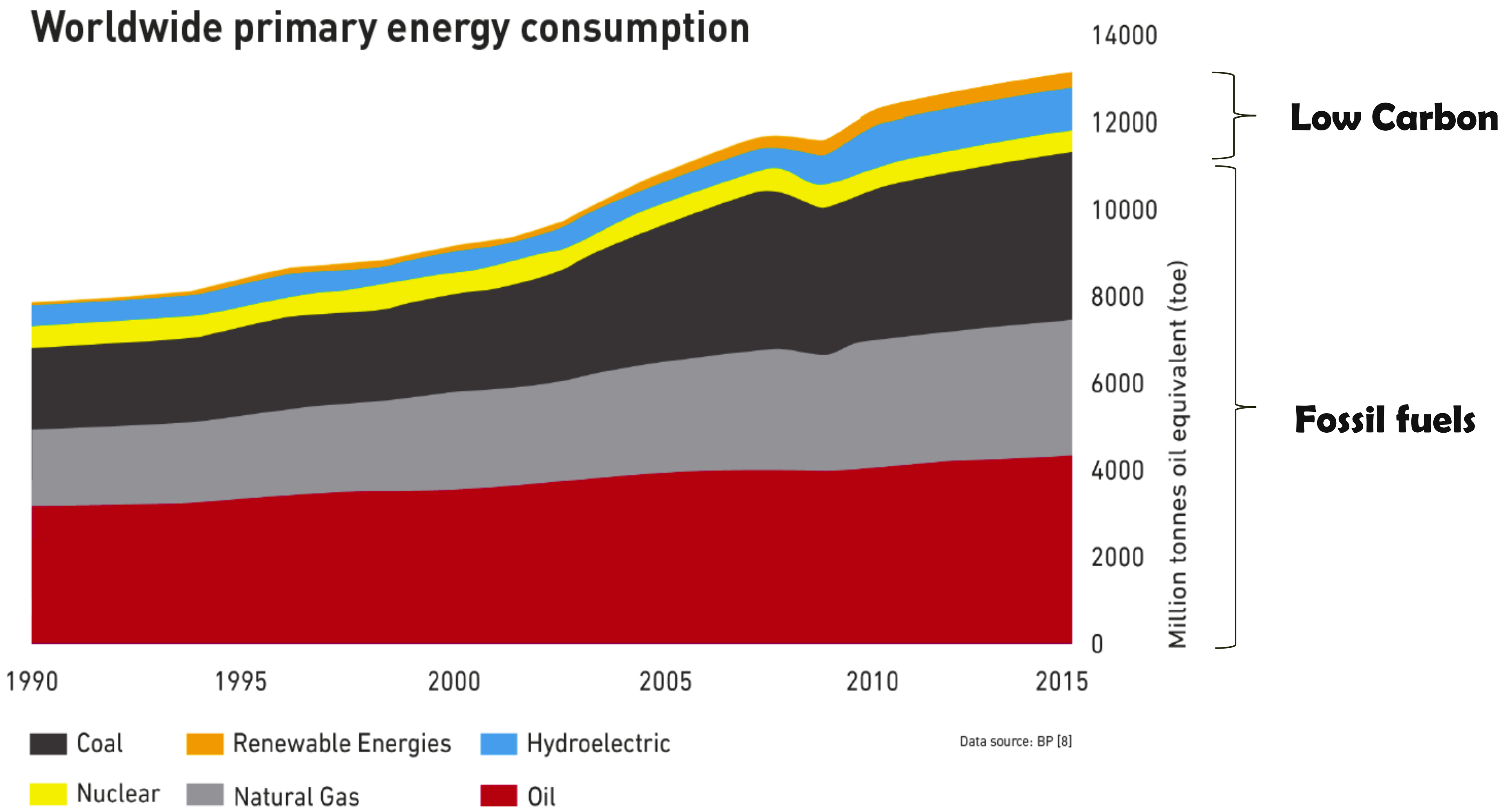
The World needs a lot more energy



Human Development Index			
Dimensions	**Health**	**Education**	**Living Standards**
Indicators	Life Expectancy at Birth	Mean Years of Schooling Expected Years of Schooling	Gross national income per capita

World's electricity consumption is projected to grow by 45% by 2040

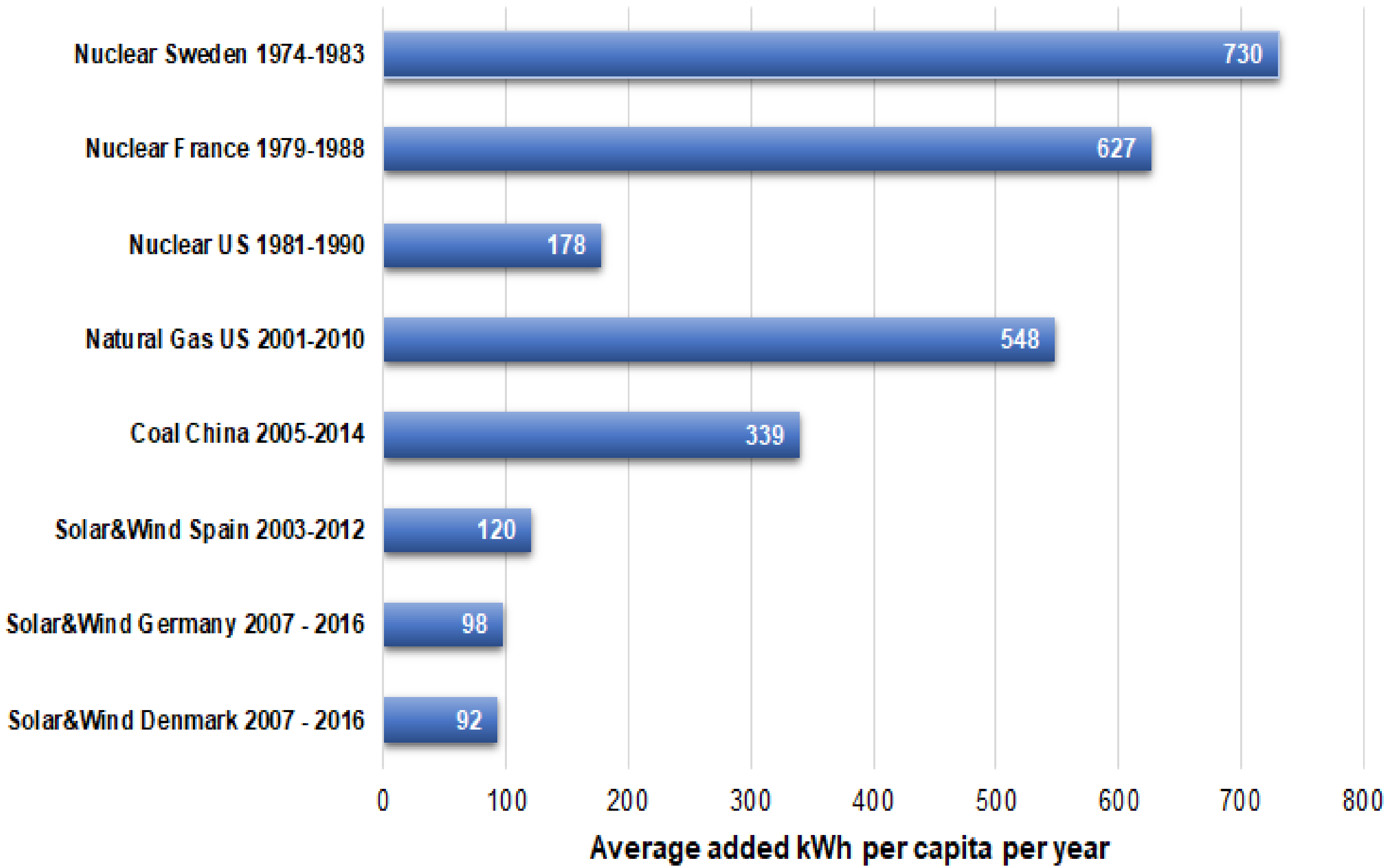
The key dilemma is how to increase energy generation while limiting global warming



CO_2 emissions are actually rising… we are NOT winning!

Should nuclear play a role in decarbonizing the power sector?

The scalability argument

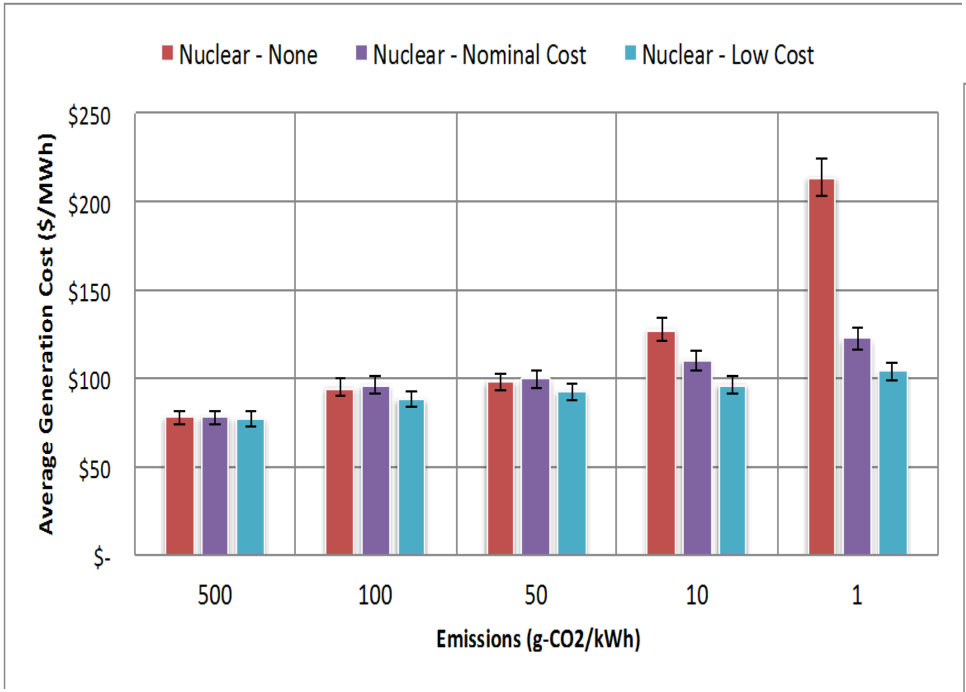


Nuclear electricity can be deployed as quickly as coal or gas at a time of need

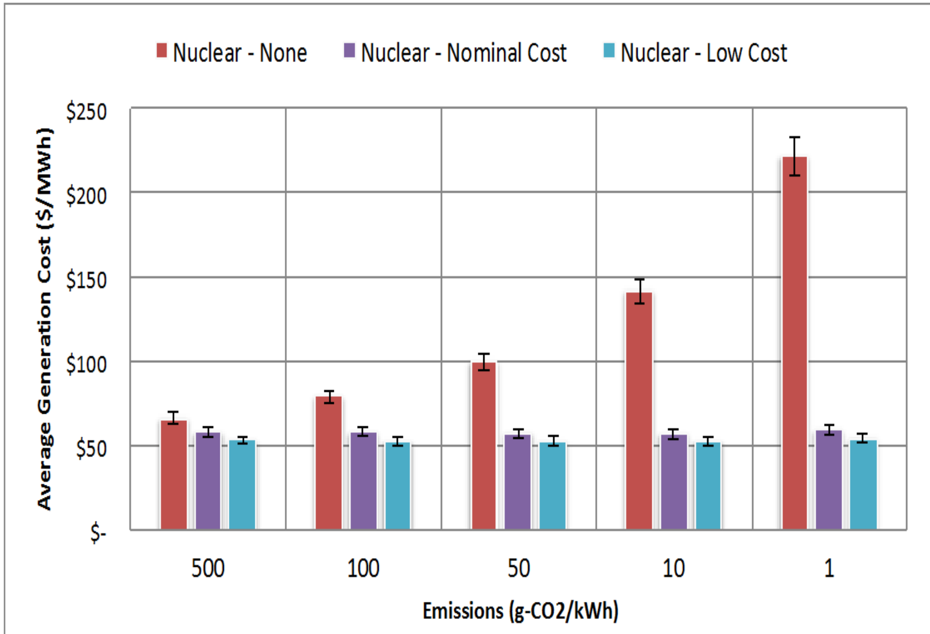
The economic argument

Excluding nuclear energy drives up the cost of electricity in low-carbon scenarios (U.S., Europe and China)

New England ISO
Nominal – 5500 $/kWe Low – 4100 $/kWe



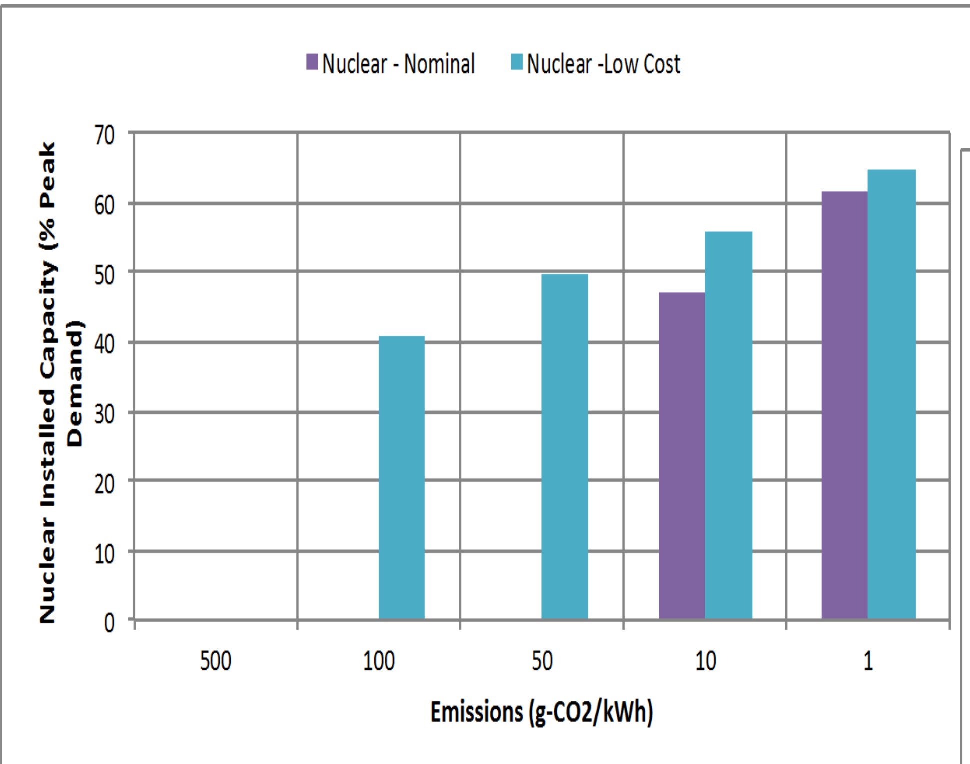
Tianjin-Beijing-Tangshan
Nominal – 2800 $/kWe Low – 2100 $/kWe



Simulation of optimal generation mix in power markets
MIT tool: hourly electricity demand + hourly weather patterns + capital, O&M and fuel costs of power plants, backup and storage + ramp up rates

The economic argument (2)

New England ISO
Nominal – 5500 $/kWe Low – 4100 $/kWe



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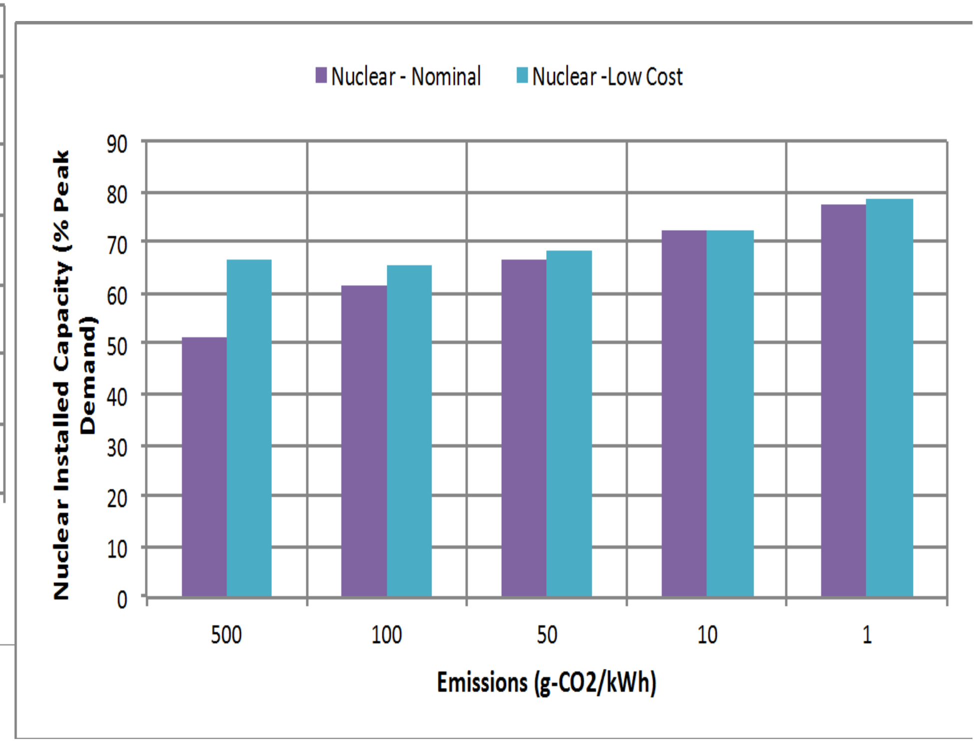
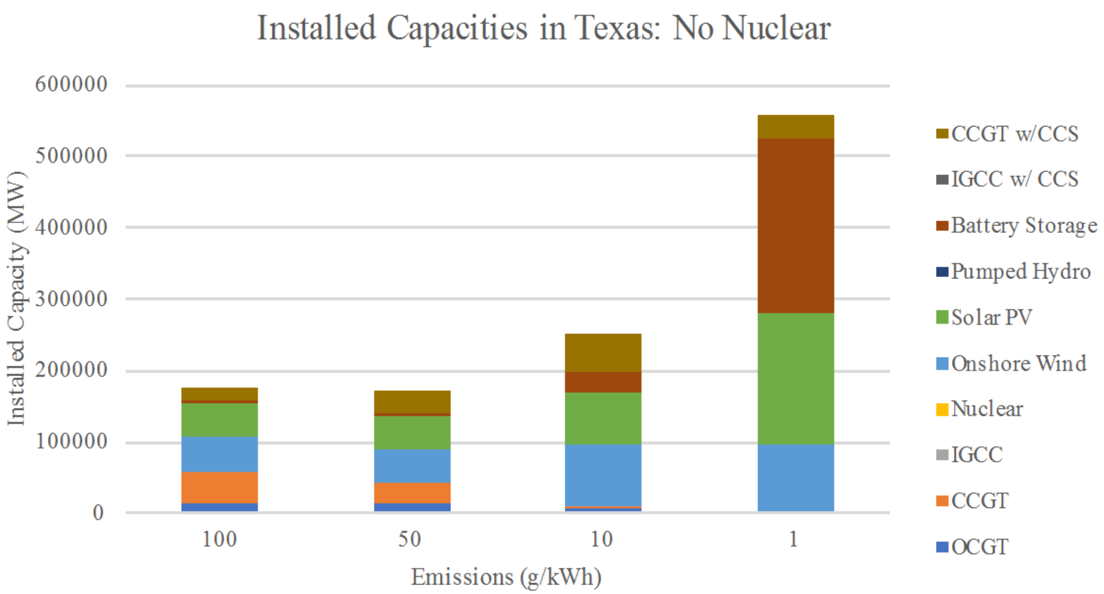


Capital cost matters!

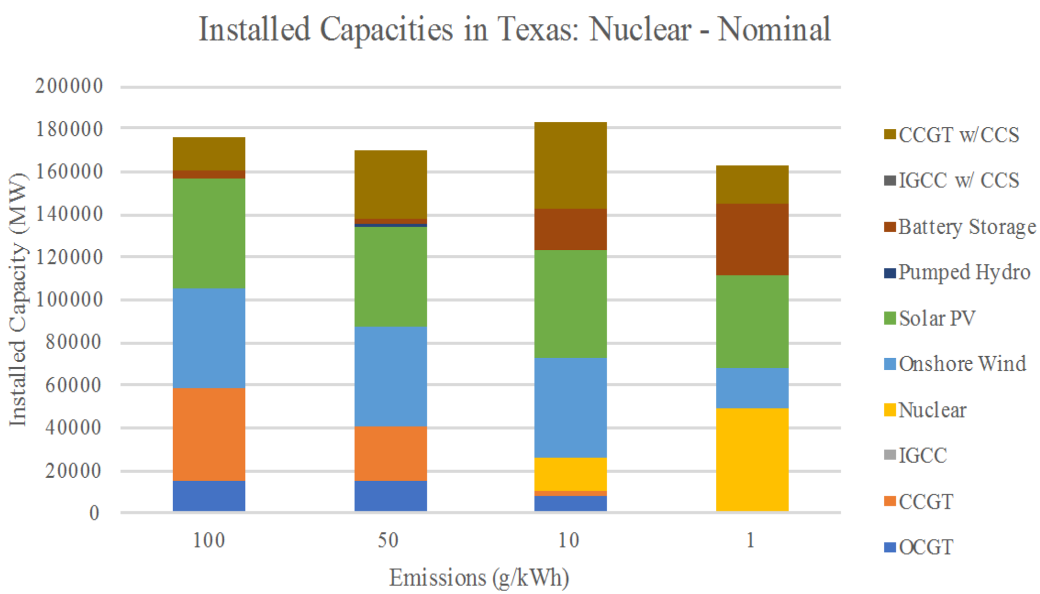
(markets can expand for nuclear even at modest decarbonization)

ERCOT and Europe Results are similar

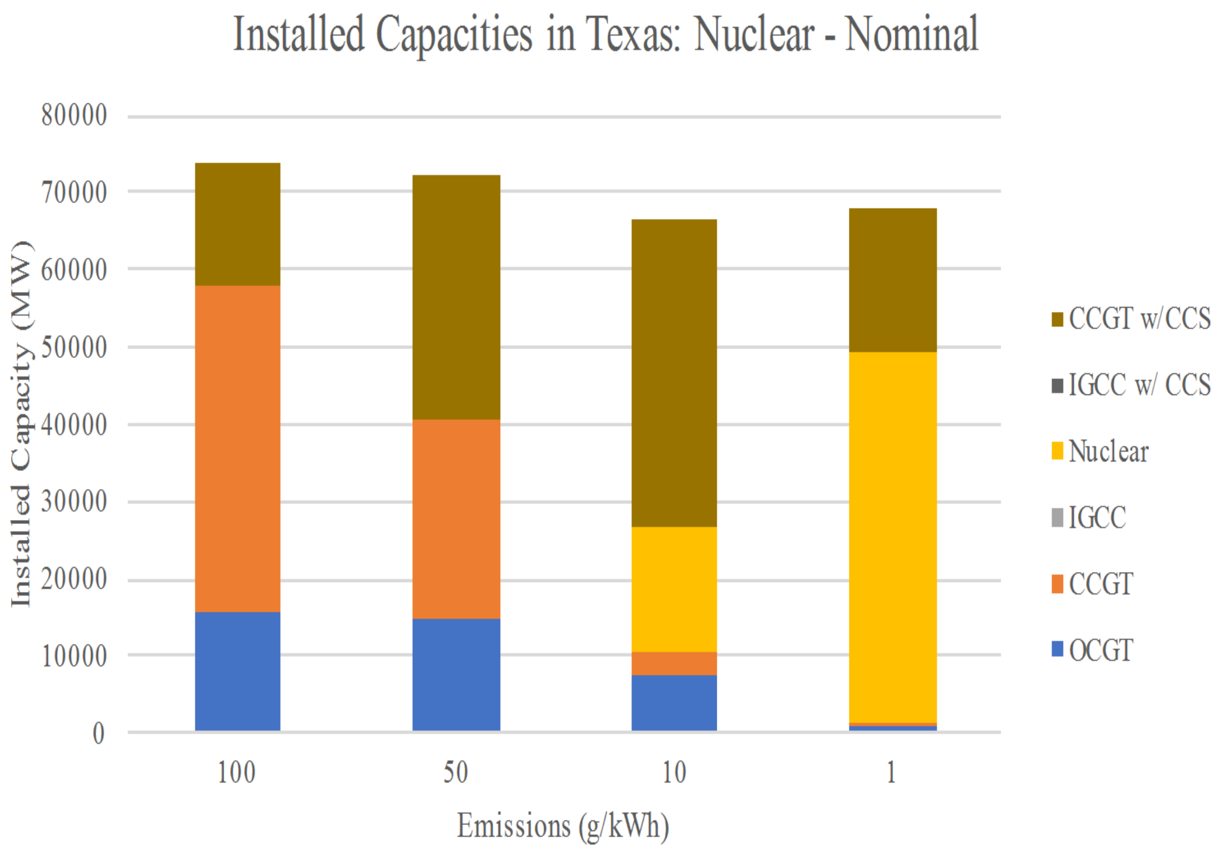


To meet constraint w/o nuclear requires major build-out of renewables

By contrast, installed capacity is relatively constant with nuclear allowed

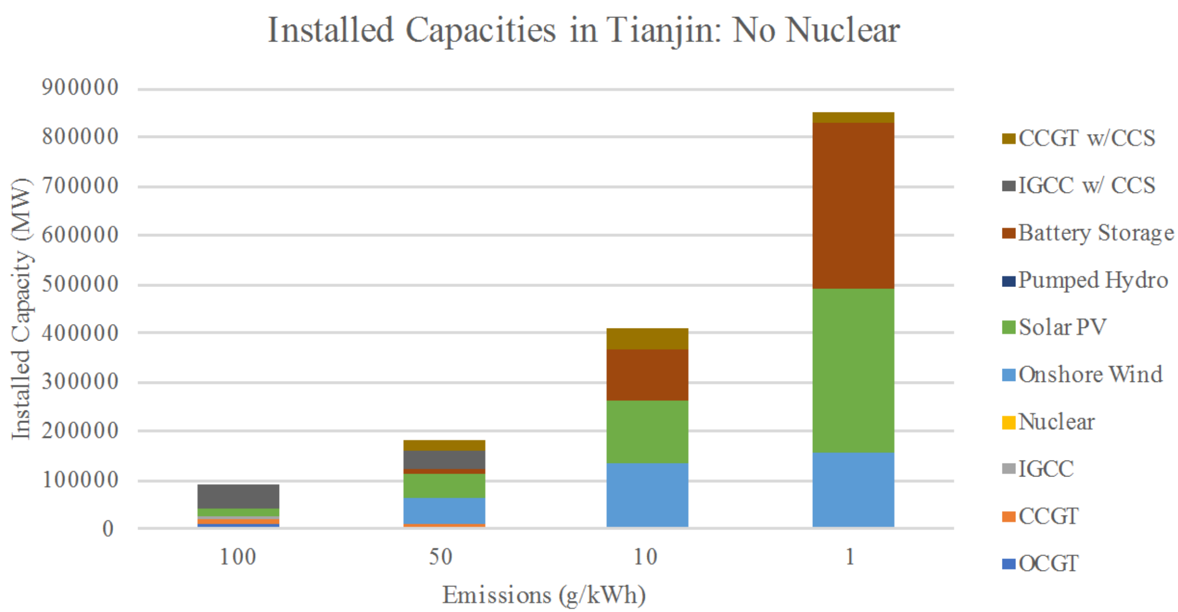


ERCOT Dispatchable Generation Competition



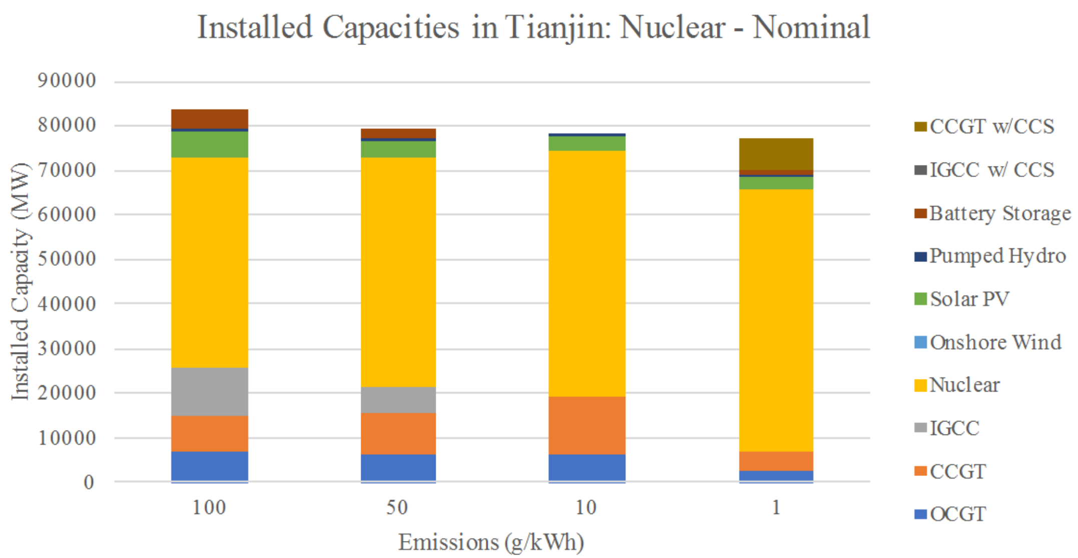
- Coal with CCS is never selected
- NG with CCS is selected over nuclear until 10 g/kWhr
- <10 g/kWhr, nuclear is chosen over NG with CCS
- Renewables add 10% to energy generated

T-B-T Province Results

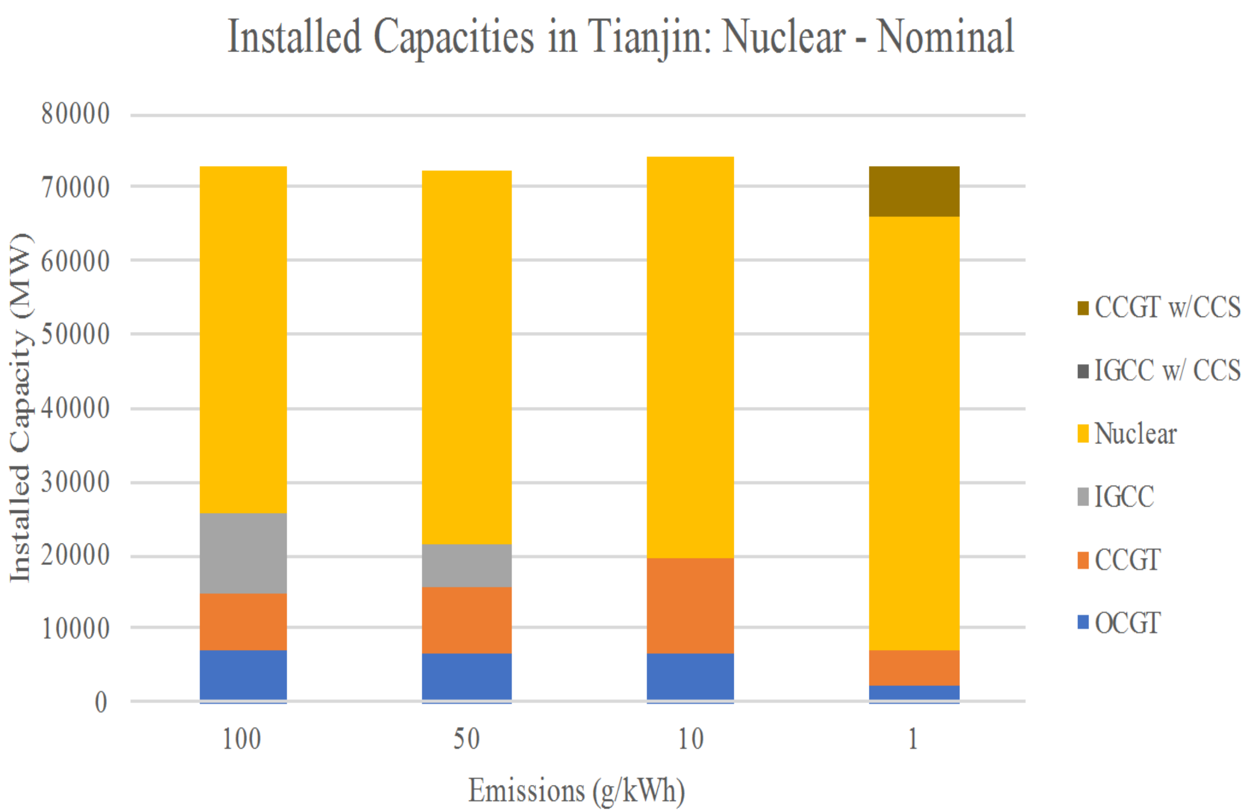


To meet constraint w/o nuclear requires significant build-out of renewables

By contrast, installed capacity is relatively constant with nuclear allowed



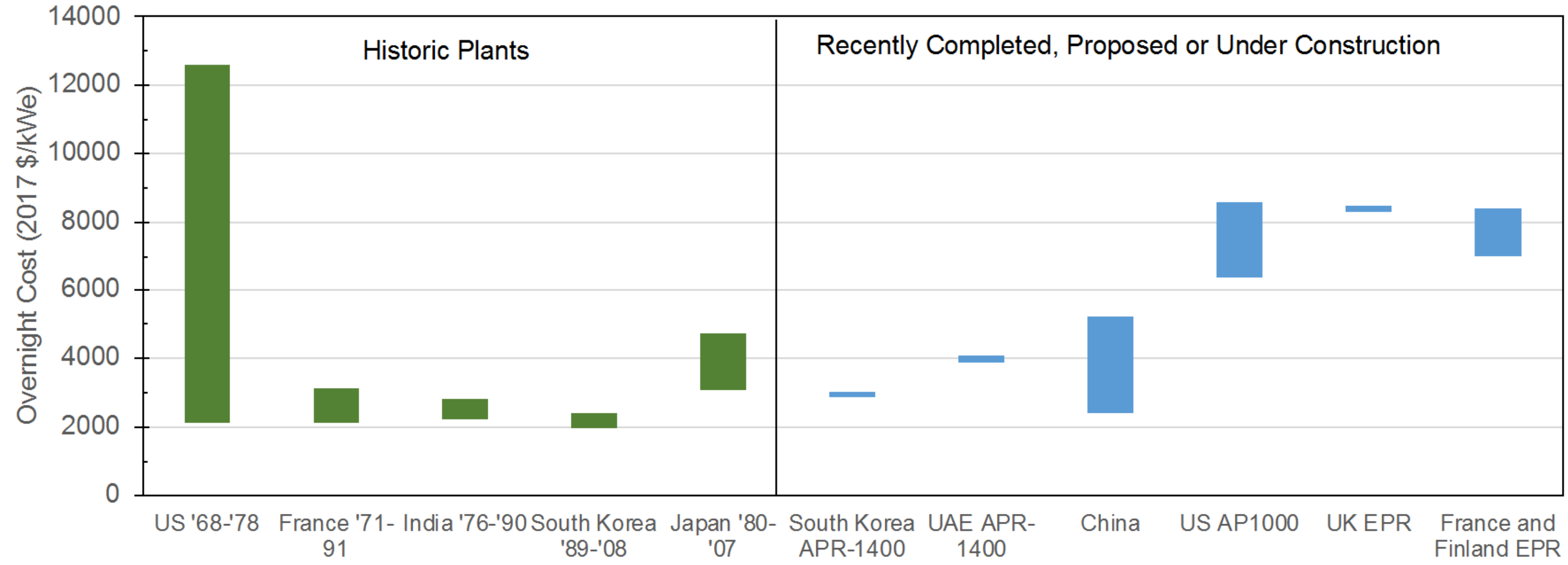
T-B-T Dispatchable Generation Competition



- NG with CCS is only selected in Tianjin between 10 g/kWh and 1g/kWh
- Nuclear is always selected at 100 g/kWh and below
- Renewables add ~5% to energy generated

The cost issue

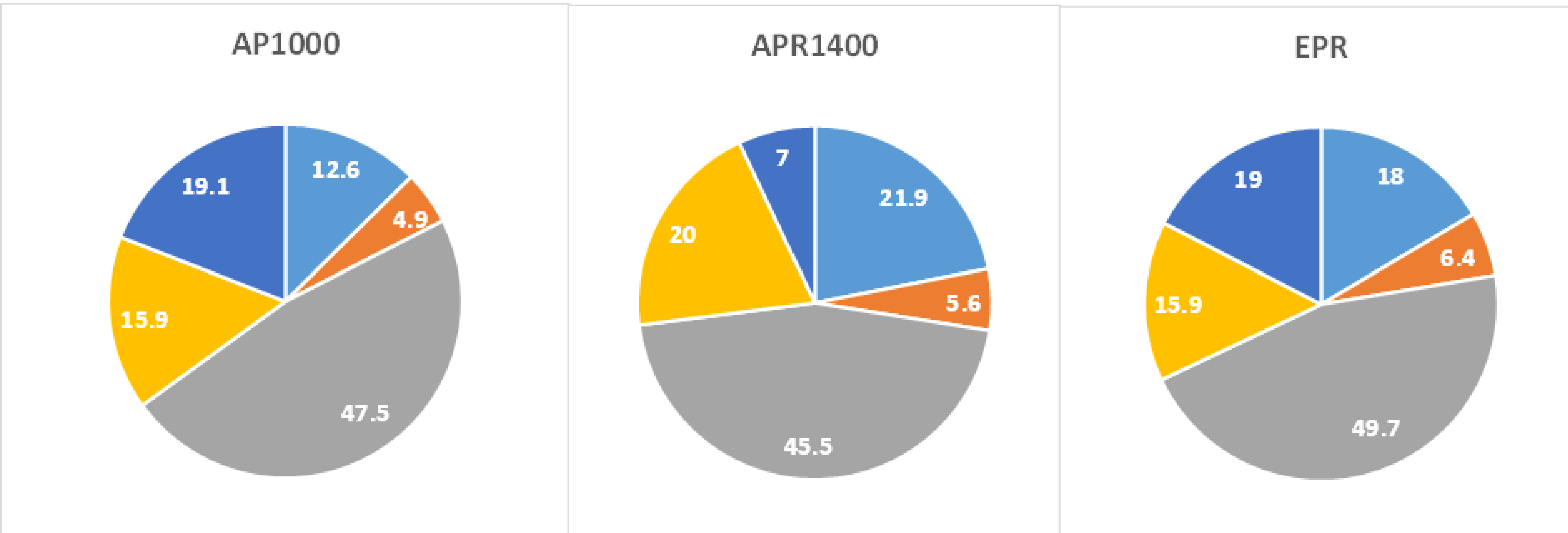
Nuclear Plant Cost



An increased focus on using proven project management practices will increase the probability of success in execution/delivery of new nuclear NPPs

- Complete design before starting construction,
- Develop proven NSSS supply chain and skilled labor workforce,
- Include fabricators and constructors in the design team,
- Appoint a single primary contract manager,
- Establish a successful contracting structure,
- Adopt a flexible contract administrative processes to adjust to unanticipated changes,
- Operate in a flexible regulatory environment that can accommodate changes in design and construction in a timely fashion.

Nuclear Plant Cost (2)

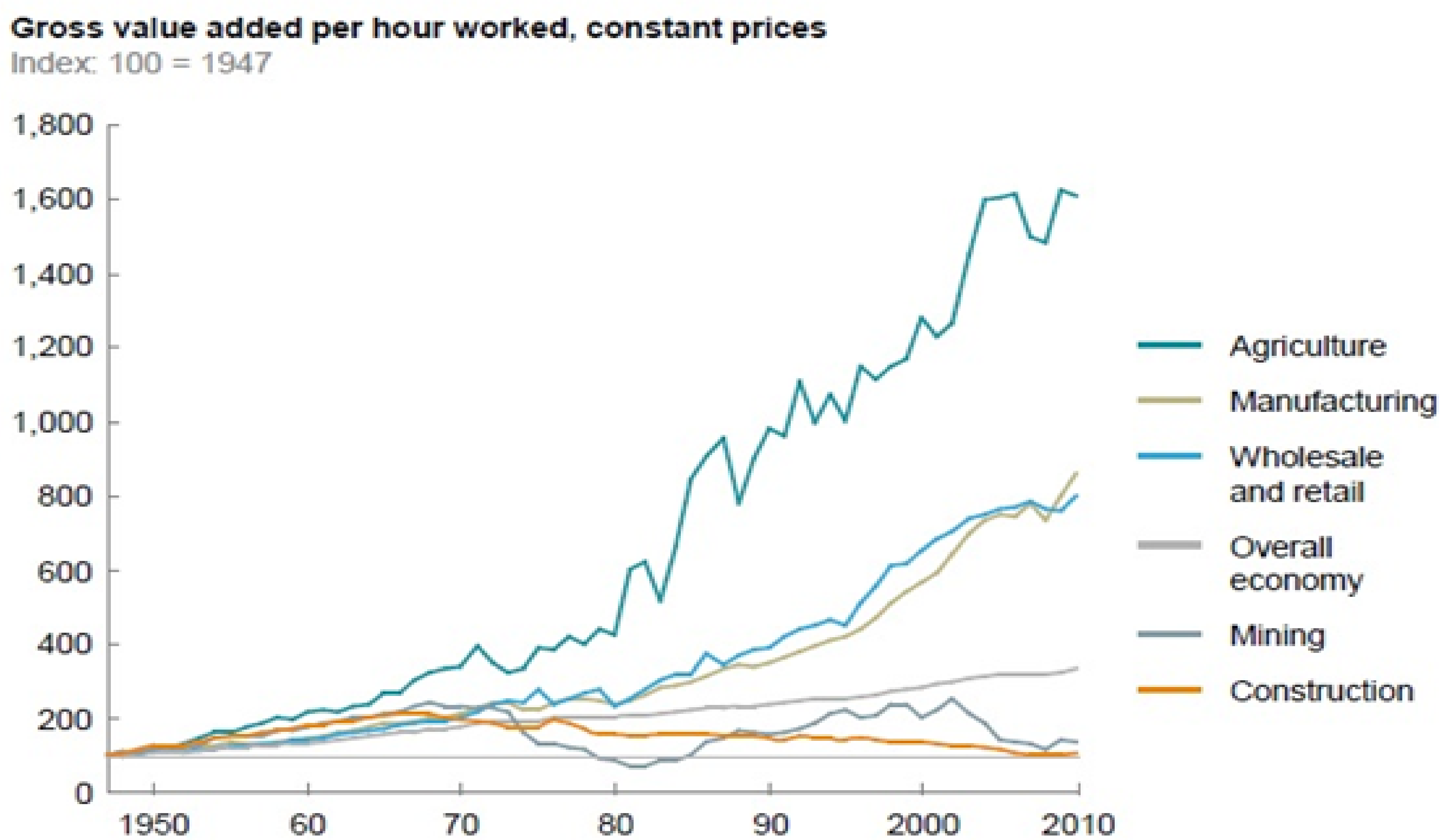


- Nuclear Island Equipment
- Turbine –Gen. Equipment
- Yard, Cooling and Installation
- Engineering, Procurement and Construction Cost
- Owner's cost

Sources:
AP1000: Black & Veatch for the National Renewable Energy Laboratory, *Cost and Performance Data for Power Generation Technologies*, Feb. 2012, p. 11
APR1400: Dr. Moo Hwan Kim, POSTECH, personal communication, 2017
EPR: Mr. Jacques De Toni, Adjoint Director, EPRNM Project, EDF, personal communication, 2017

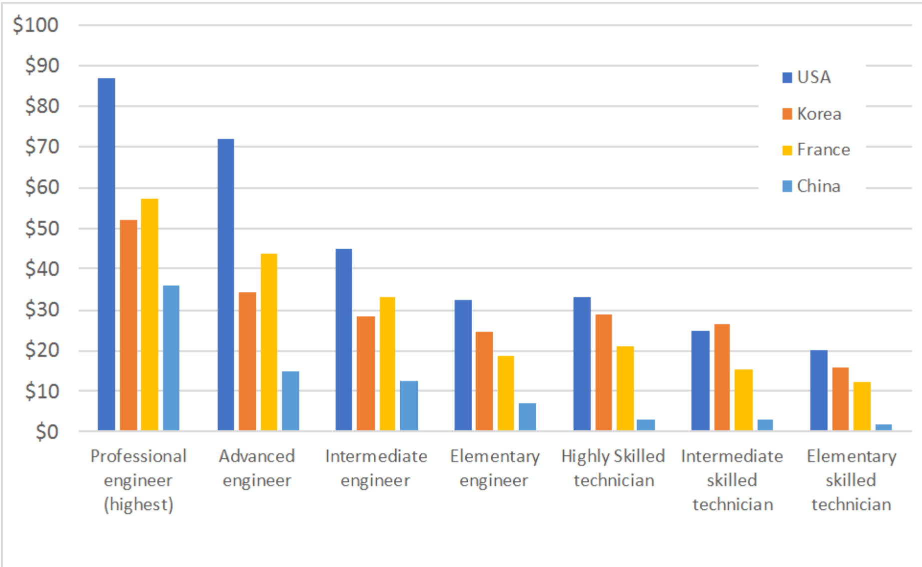
Civil works, site preparation, installation and indirect costs (engineering oversight and owner's costs) dominate

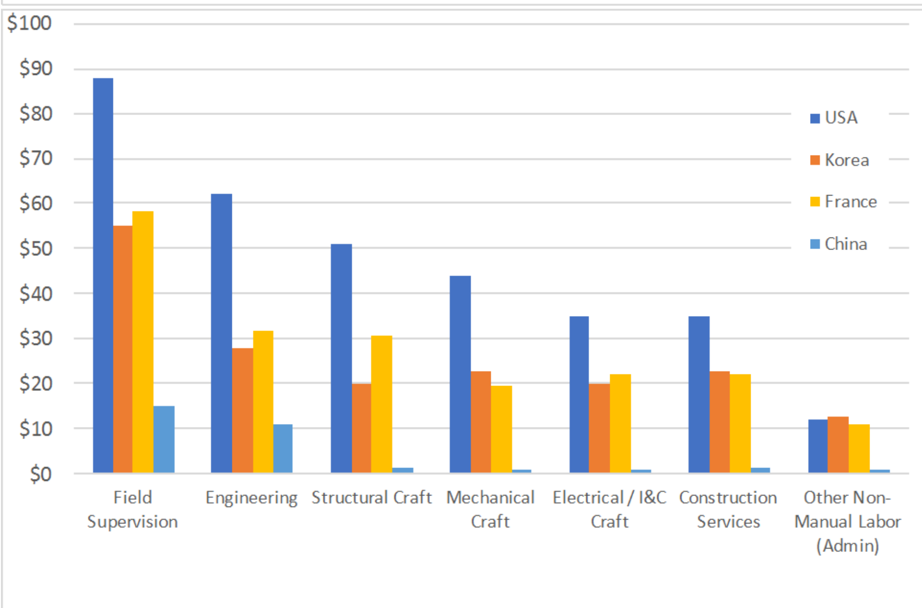
Why are nuclear construction projects in the West particularly expensive?



Construction labor productivity has decreased in the West

Why are nuclear construction projects in the West particularly expensive? (2)





Construction and engineering wages are much higher in the US than China and Korea

Estimated effect of construction labor on OCC (wrt US):
-$900/kWe (China)
-$400/kWe (Korea)

Source: Bob Varrin, Dominion Engineering Inc.

What innovations could make a difference?

Emphasis should be put on cross-cutting technologies that can reduce the indirect costs

<table>
<tr><th colspan="2">Reduce Capital Cost</th><th>Reduce O&M and Fuel Costs</th><th>Boost Revenues</th><th>Boost Efficiency</th></tr>
<tr><td>Modular Construction</td><td>Advanced Concrete</td><td>Robotics</td><td>Energy Storage</td><td>Hydro-phobic/hydro-philic Coatings</td></tr>
<tr><td>Seismic Isolation, Embeddment</td><td>Accident Tolerant Fuels</td><td>Advanced Informatics and I&C (AI, machine learning)</td><td colspan="2">Brayton Cycles</td></tr>
<tr><td>3D Printing</td><td>Advanced Decommissioning</td><td>Oxide Dispersion-Strengthened Alloys</td><td>Chemicals Production</td><td>Supercritical CO_2</td></tr>
</table>

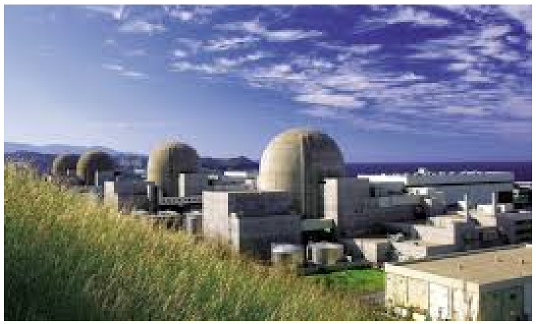
Must focus:

- **Shift labor from site to factories $\Rightarrow$ reduce installation cost**
- **Relentless push towards standardization $\Rightarrow$ reduce licensing and engineering costs**
- **Shorten construction schedule $\Rightarrow$ reduce owner's costs**

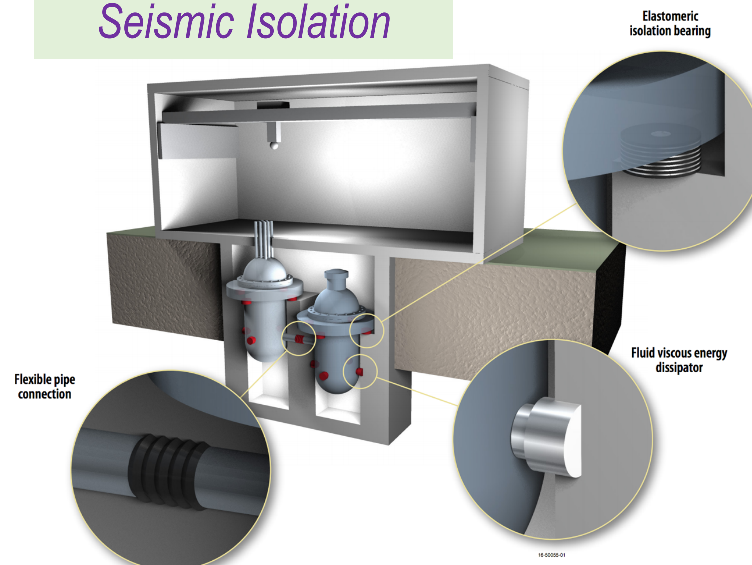
A shift away from primarily field construction of highly site-dependent plants to more serial manufacturing of standardized plants

(True for all plants and technologies. Without this, inherent technological features will NOT produce the level of cost reduction necessary)

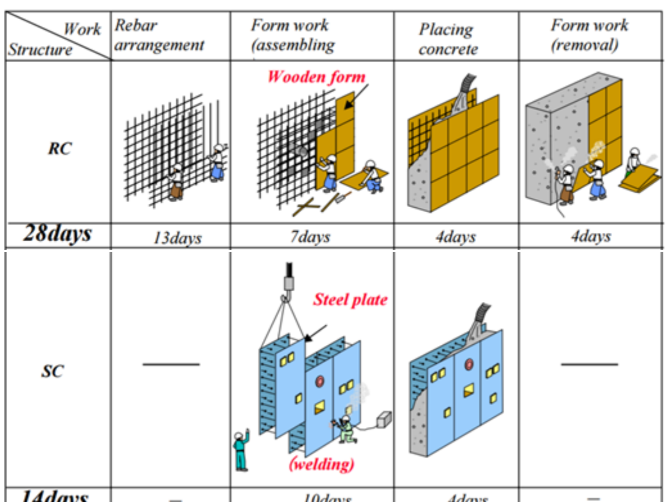
Standardization on multi-unit sites



Seismic Isolation



Advanced Concrete Solutions



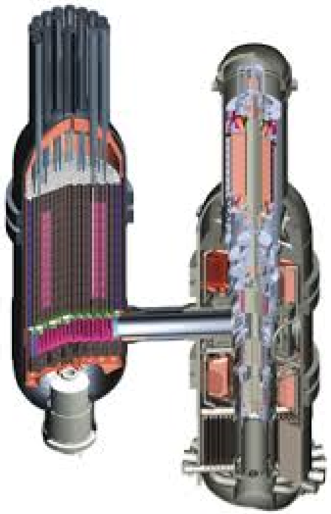
Work / Structure	Rebar arrangement	Form work (assembling	Placing concrete	Form work (removal)
RC				
28days	13days	7days	4days	4days
SC	—			—
14days	–	10days	4days	–

Modular Construction Techniques and Factory Fabrication

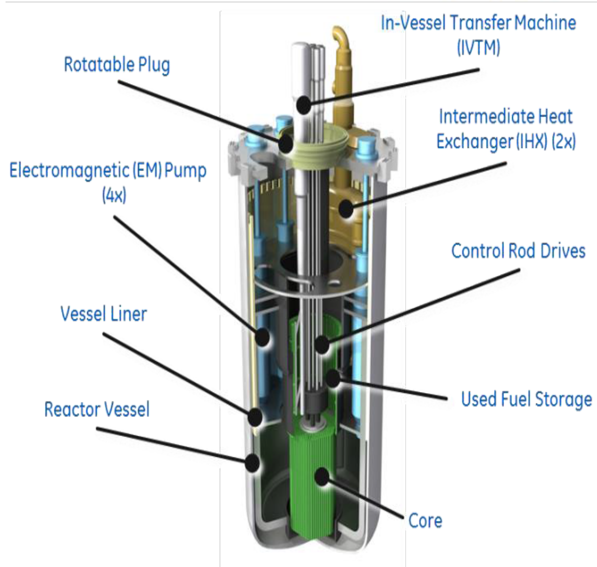
Advanced reactors

Advanced Reactors (Generation-IV)

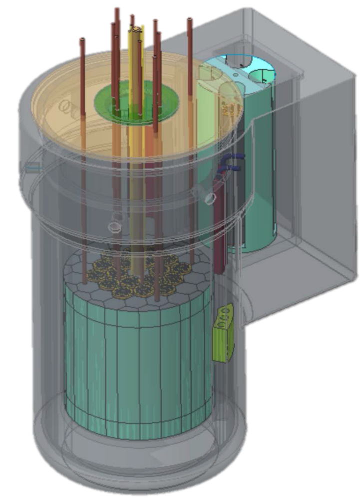
High Temperature Gas-Cooled Reactors



Sodium Fast Reactors

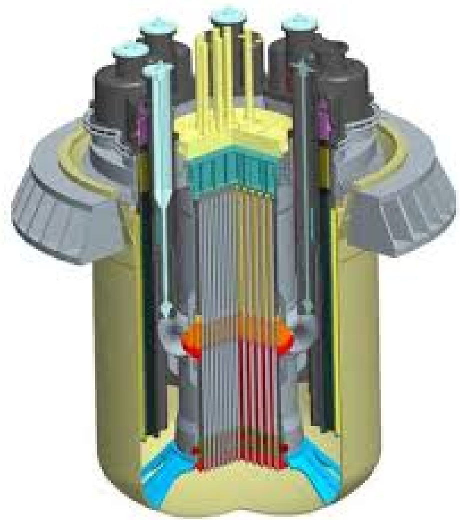


Fluoride High Temperature Reactors

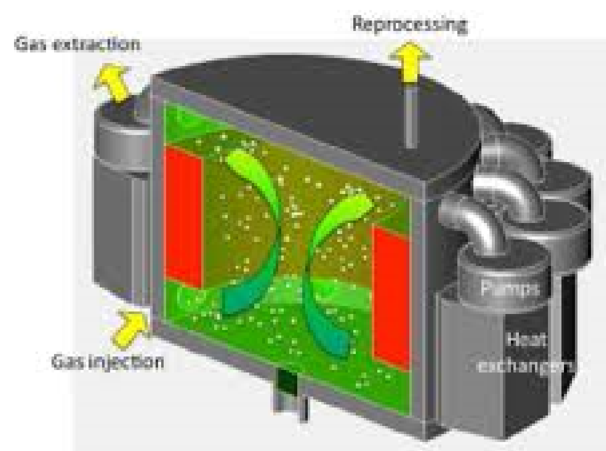


Gas-Cooled Fast Reactors

Lead-Cooled Fast Reactors



Molten Salt Reactors



What is the value proposition for advanced reactors?

Demonstrated inherent safety attributes:

- No coolant boiling
- High thermal capacity
- Strong negative temperature/power coefficients
- Strong fission product retention in fuel, coolant and moderator
- Low chemical reactivity

+

Engineered passive safety systems:

- Heat removal
- Shutdown

=

- ✓ No need for emergency AC power
- ✓ Long coping times
- ✓ Simplified design and operations
- ✓ Emergency planning zone limited to site boundary

Leading Gen-IV systems exploit inherent and passive safety features to reduce the probability of accidents and their offsite consequences.

***Their economic attractiveness is still uncertain*.**

We judge that advanced LWR-based SMRs (e.g. NuScale), and mature Generation-IV concepts (e.g., high-temperature gas-cooled reactors and sodium-cooled fast reactors are now ready for commercial deployment.

What is the value proposition for advanced reactors? (2)

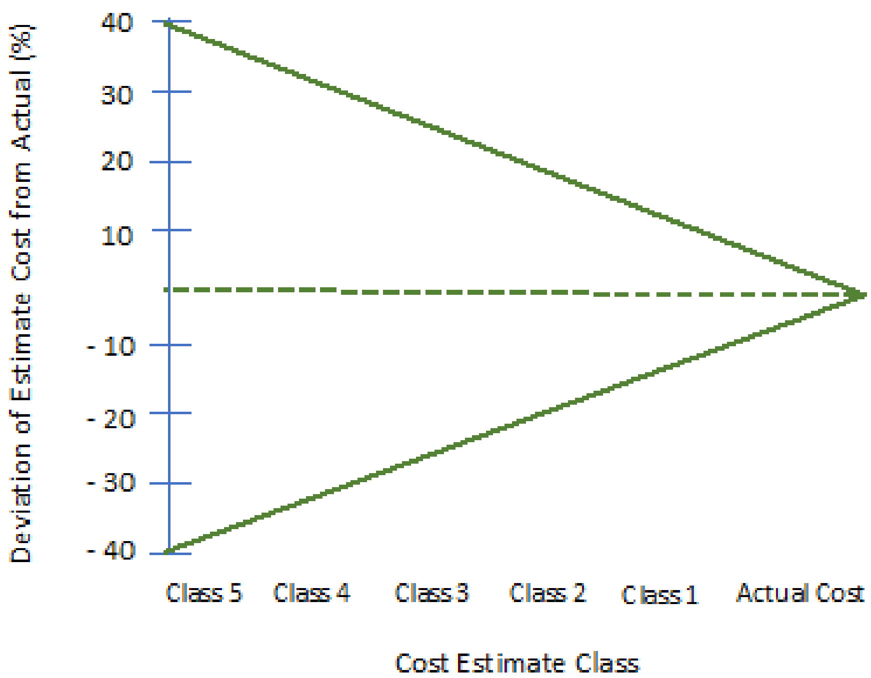
Cost ($/kWe)	HTGR	SFR	FHR (Large)	FHR (Small)	MSR
Machine Size	4 x 600 MWth	4 x 840 MWth	3400 MWth	12 x 242 MWth	2275 MWth
Design Stage	Conceptual approaching Preliminary	Conceptual approaching Preliminary	Early conceptual	Early conceptual	Early conceptual
Direct Cost	2400	2500	2100	2300	2500
Indirect Cost	1400	1600	1400	1300	1700
Contingency	800	800	1100	1100	1200
Total Overnight Cost	4600	4900	4600	4700	5400
Interest During Construction	600	700	600	700	700
Total Capital Invested	5200	5600	5200	5400	6100

1. E. Ingersoll, "International Nuclear Project Costs, Proprietary and Confidential
2. F. Ganda et al., "Reactor Caital Costs Breakdown and Statistical Analysis of Historical US Construction Costs," ICAPP 206
3. A. M. Gandrik, "Assessment of High Temperature Gas-Cooled Reactor (HTGR) Capital and Operating Costs," TEV-1196, Jan. 2012
4. F. Ganda, "Economcis of Promising Options," FCRD-FCO-2015-000013, Sept. 2015
5. D. E. Holcomb et al., "Advanced High Temperature Reactor Systems and Economic Analysis,' Sept. 2011
6. J. Engle et al., "Conceptual Design Characteristics of a Denatured Molten-Salt Reactor with Once-through Fuelings, ORNL/TM-7207, July 1980
7. C. Andreades, "Nuclear AirBrayton Combined Cycle Power Conversion Design, Physical Performance Estimation and Economic Assessment," UC Berkely Thesis, 2015

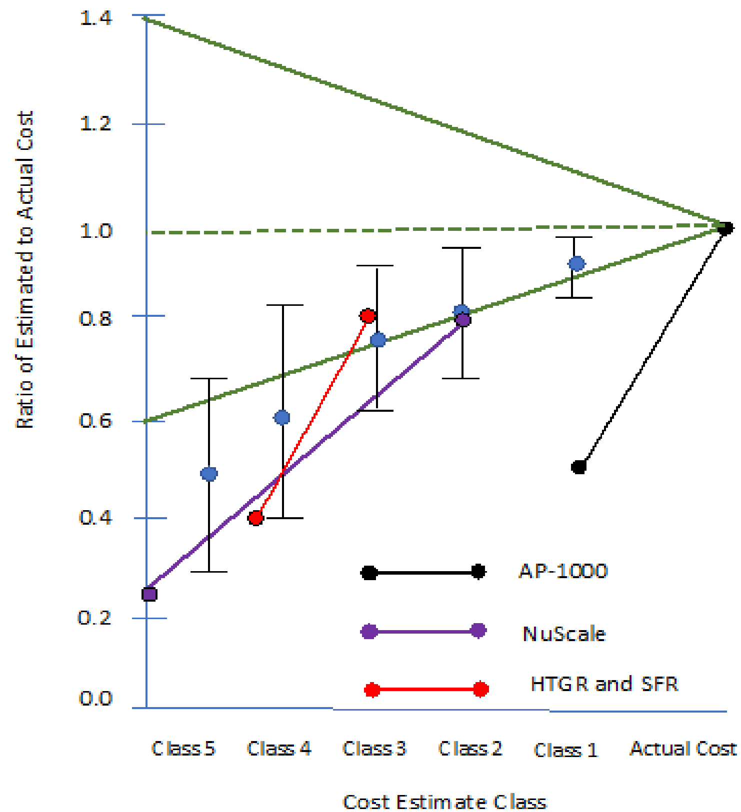
Independent cost estimates for advanced reactors confirm importance of civil works (buildings and structures) and indirect costs, and do not suggest significant cost reduction with respect to LWRs

Uncertainty in cost estimates for large, complex projects

Conventional View



Reality



Early-stage cost estimates are unreliable predictors of the eventual cost of mega-projects. This is valid across large non-nuclear mega-projects and also for all nuclear technologies.

What is the value proposition for advanced reactors? (3)

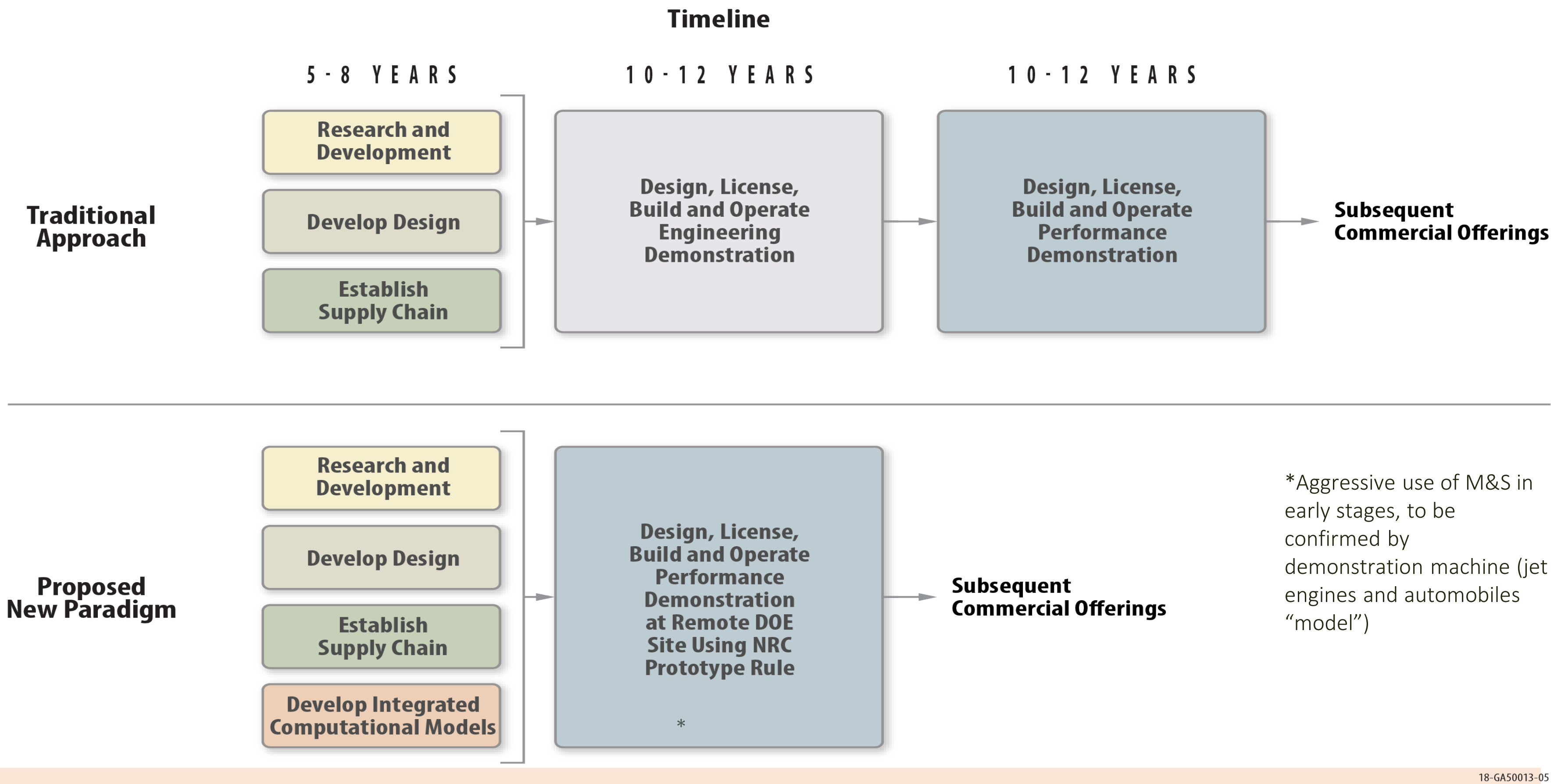
There exists a small (but not insignificant) potential market for nuclear heat

Industry	300 MW_{th} Reactor		150 MW_{th} Reactor	
	U.S. Capacity (MW_{th} Installed) (%)	Global Capacity (MW_{th} Installed) (%)	U.S. Capacity (MW_{th} Installed) (%)	Worldwide Capacity (MW_{th} Installed) (%)
Co-Generation Facilities	82,800 (61.7%)	340,800 (59.8%)	86,250 (57.5%)	355,050 (55.7%)
Refineries	15,600 (10.4%)	76,800 (12.1%)	17,250 (11.5%)	84,750 (13.3%)
Chemicals	7,800 (5.2%)	36,600 (5.7%)	7,050 (4.7%)	34,200 (5.4%)
Minerals	2,100 (1.4%)	8,700 (1.4%)	2,100 (1.4%)	8,700 (1.4%)
Pulp and Paper	12,600 (8.4%)	51,900 (8.1%)	21,300 (14.2%)	87,750 (13.8%)
Other	13,200 (8.8%)	55,200 (8.7%)	16,050 (10.7%)	66,450 (10.4%)
Total	**134,100 (100%)**	**570,000 (100%)**	**150,000 (100%)**	**636,900 (100%)**

Methodology:

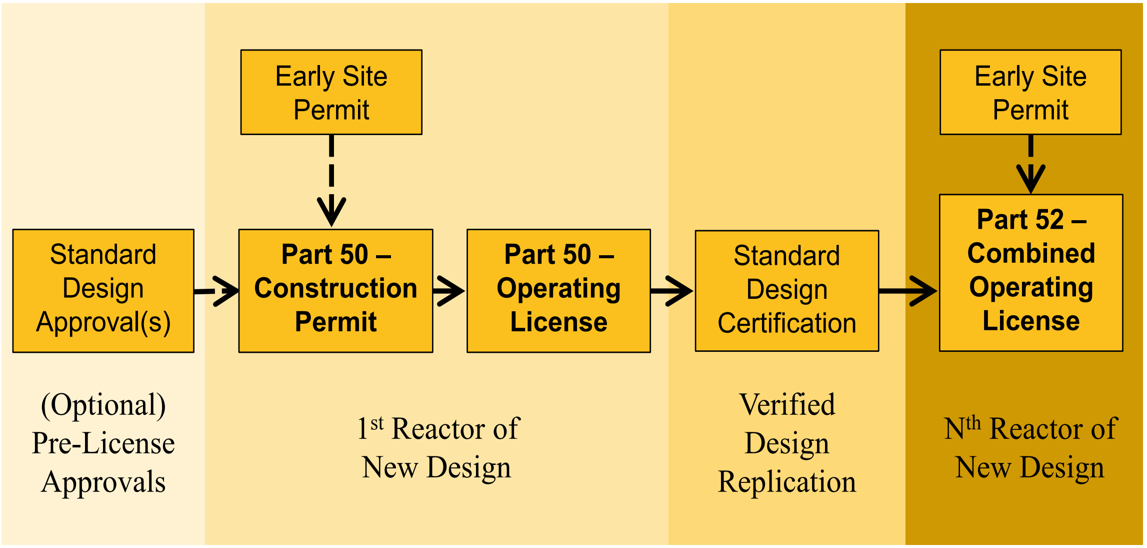
- EPA database for US sites emitting 25,000 ton-CO_2/year or more
- Site must need at least 150 MW_{th} of heat
- Nuclear heat delivered at max 650°C (with HTGR technology)
- At least two reactors per site for assured reliability
- Heat from waste stream not accessible
- Costs not evaluated

Can we accelerate commercialization of the less mature advanced reactors?



By combining the engineering demonstration machine (traditionally a small-scale machine) with the at-scale performance demonstration machine, and using the NRC prototype rule at a "forgiving" site, it may be possible to accelerate the commercial deployment of the less mature advanced reactors (i.e. molten salt-cooled and lead-cooled designs) by over 10 years

Can we license advanced reactors?



Adapted from *Advanced Demonstration and Test Reactor Options Study*, Chapter 7, INL

Finding: *Regulatory agencies in other nations have similar basic principles as described in IAEA policies and as embodied in NRC regulations, but vary widely in the detailed application of these policies and principles.*

Finding: *Advanced reactor concepts should consider NRC prototype option (10CFR50.43(e)) to license less mature designs to accelerate these concepts toward commercialization*

Finding: *Current NRC regulatory structure is flexible and can be adapted to accommodate licensing of (mature) advanced reactors (such as SFRs and HTGRs), without a new regulatory paradigm. NRC has sufficient and diverse tools at hand to provide a stepwise process with intermediate licensing decisions without unnecessary delays, given required design information.*

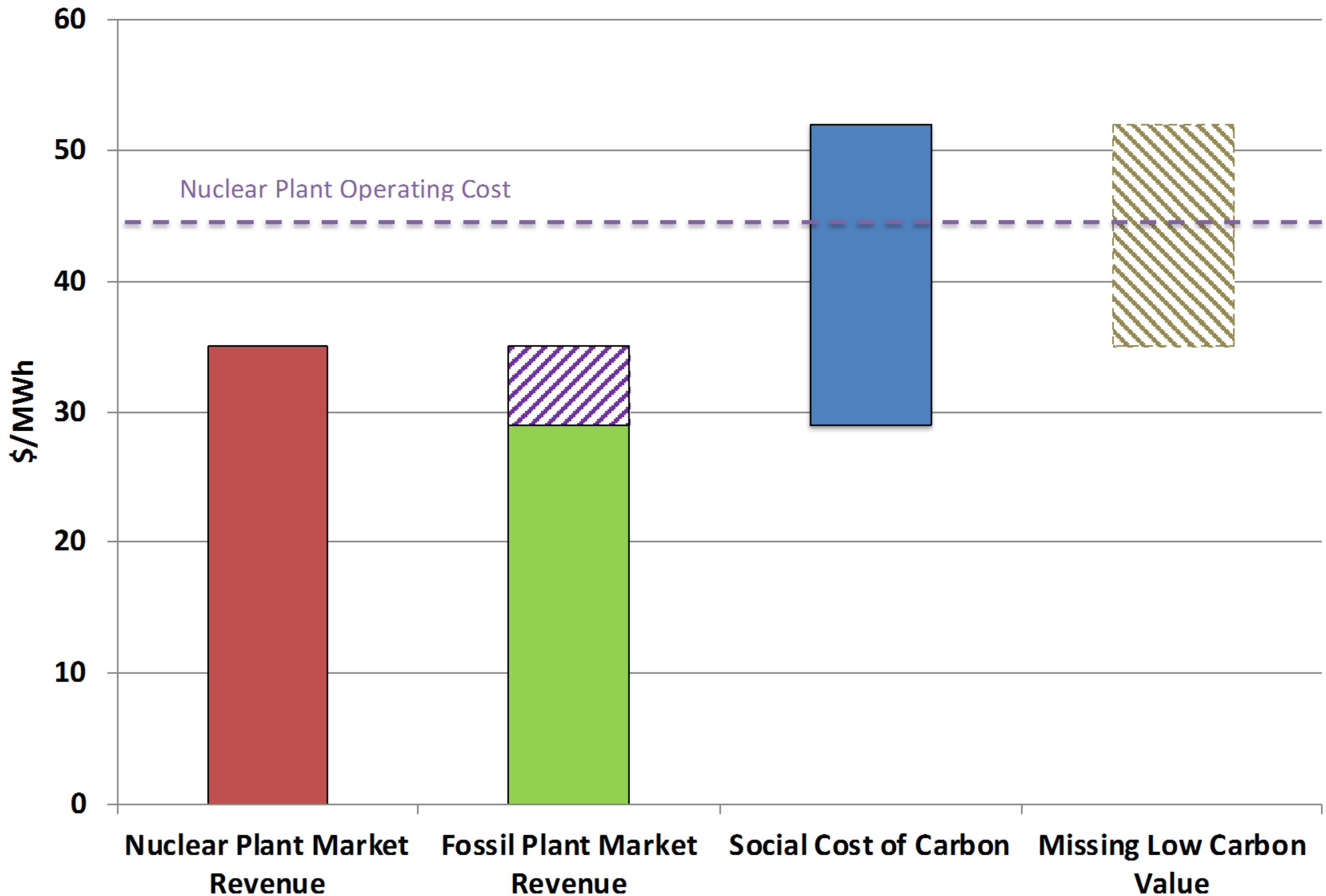
Government role

Preserve the existing fleet

An essential bridge to the future to:

- **Avoid emission increases:**
  - Keeping current NPPs is the lowest cost form of constraining carbon emissions
  - A $12-17/MWh credit would be enough to keep US nuclear power plants open
  - *Zero Emission Credits* are doing the job in NY, IL and NJ
- **Retain key technical expertise** needed to operate the nuclear systems of the future

US Electricity Markets



Global Nuclear Market

- Growth in electricity demand is primarily in the non-OECD.

- Plenty of choice of vendors.
  - Korea has been successful.
  - Russia is extremely active globally.
  - China has built a domestic foundation to become an exporter.

- US success as a nuclear innovator must be won in this new context.

New Reactor Designs

Electricity sector remains the major energy product

- Bigger than ever on a global scale, and
- with electrification of transportation and other energy services in the offing

Cost is the driver

- That means cutting the capital cost of the entire plant.
- $5,500 overnight is only competitive when carbon constraints are very tight
- $2,000 overnight is required without carbon constraints

How can the government help to deploy new nuclear technologies?

Improve the design of competitive electricity markets

- Decarbonization policies should create a level playing field that allows all low-carbon generation technologies to compete on their merits.
- Ensure technology neutrality in capacity markets
- Enable investors to earn a profit based on full value of their product (include reducing CO2 emissions)
- Would enable current plants to compete in the market

- Focus government research spending on innovations that lower capital cost of NPPs vs. fuel cycle innovations, reductions in waste streams and recycling
- Develop a durable political solution for spent fuel disposal to spur private investment

How can the government help to deploy new nuclear technologies? (2)

Governments should establish reactor sites where companies can deploy prototype reactors for testing and operation oriented to regulatory licensing.

- Government provides site security, cooling, oversight, PIE facilities, etc.
- Government provides targeted objectives, e.g. production of low-cost power or industrial heat, for which it is willing to provide production payments as an incentive

- Government takes responsibility for waste disposal
- Companies using the sites pay appropriate fees for site use and common site services
- Supply high assay LEU and other specialized fuels to enable tests of advanced reactors

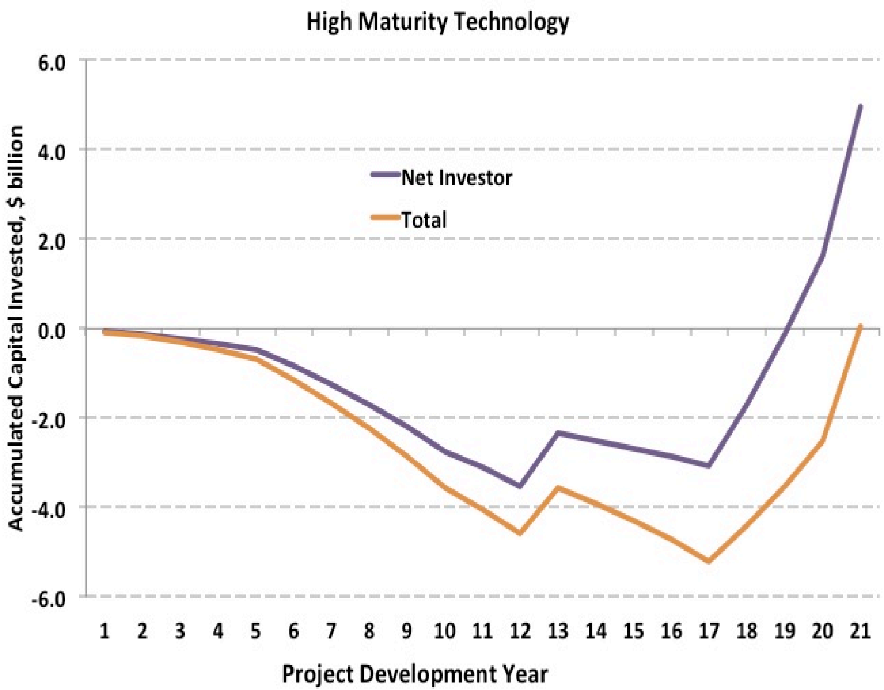
How can the government help to deploy new nuclear technologies? (3)

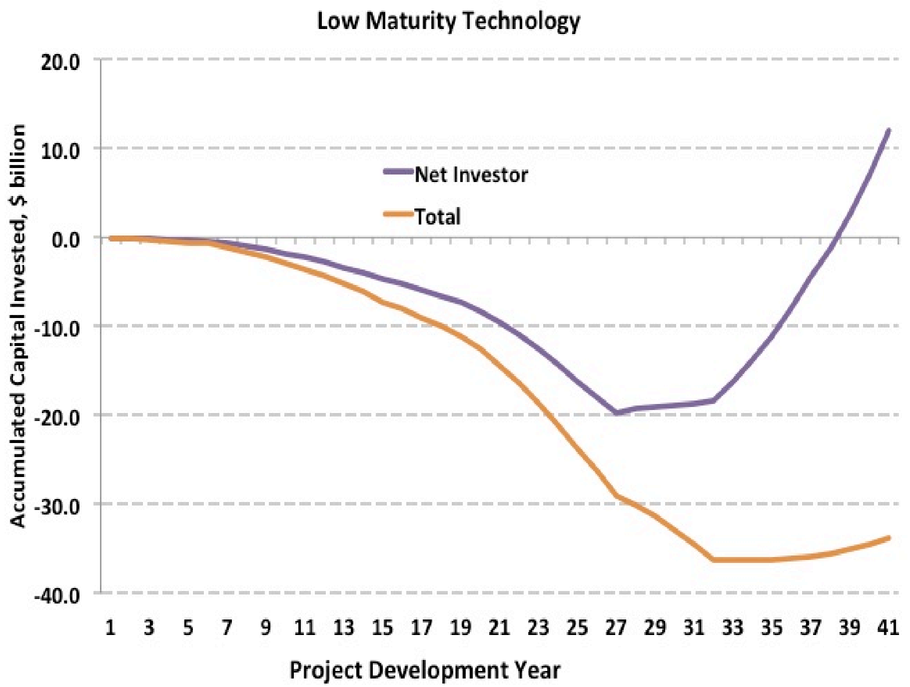
- Cost sharing for Research and Development
- Licensing support cost sharing for a demonstration reactor
- Commercial contracts to support construction of demonstration reactors that have key attribute
  - milestone payments (similar to NASA COTS program)
- Supplemental production for generated electricity

	Higher Maturity Technology	Lower Maturity Technology
Government Funding Program		
Rate for R&D cost sharing	50%	50%
Rate for Licensing cost sharing	50%	50%
Rate for Milestones	20%	31%
Production Credit, $/MWh	27	27

How can the government help to deploy new nuclear technologies? (4)

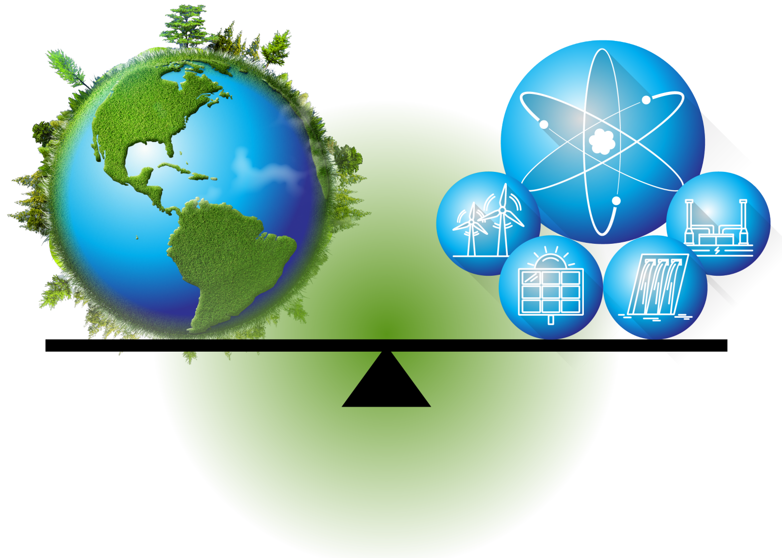
High upfront costs and long time to see return on investment (more so for less mature technologies, e.g. FHR, MSR, LFR, GFR, than more mature technologies, i.e. HTGR, SFR)





Take-away messages

- **The opportunity is carbon emissions**
- **The major issue is cost**
- **There are ways to reduce cost**
- **Adv. Reactors: enhance safety, reduce cost**
- **Government help needed to make it happen**



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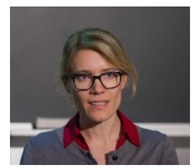

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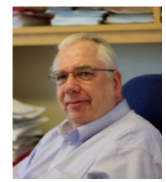

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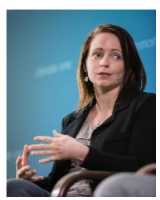

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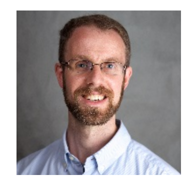

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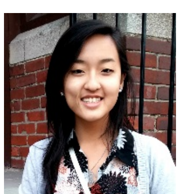

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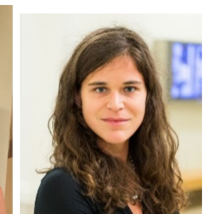

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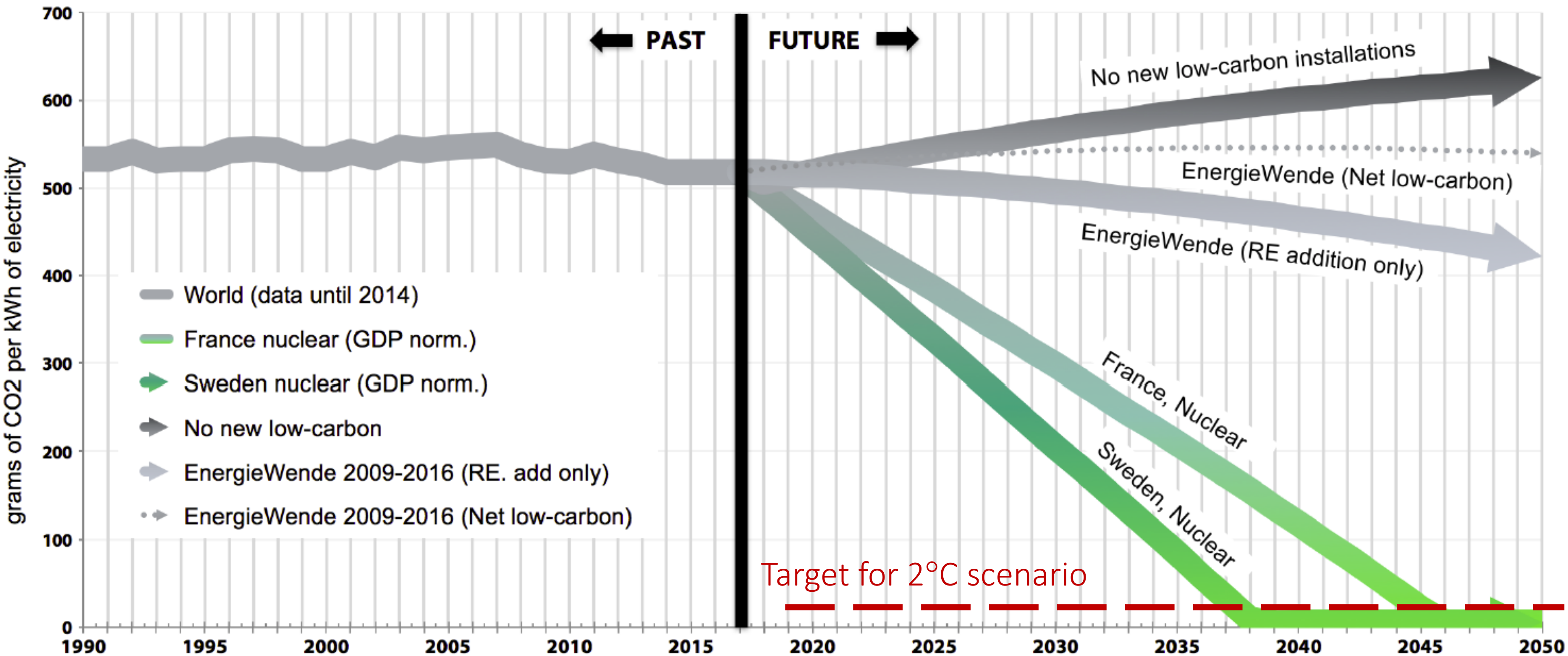
DISCLAIMER: MIT is committed to conducting research work that is unbiased and independent of any relationships with corporations, lobbying entities or special interest groups, as well as business arrangements, such as contracts with sponsors.

BACKUP SLIDES

The scalability argument



Source: Staffan Qvist, 2018

A nuclear build-up (at historically feasible rate) can completely decarbonize the World's power sector within 30 years

Opportunities for Nuclear Energy

Opportunities for Nuclear Energy

Objective: *Analyze need for nuclear given goal of deep decarbonization*

Approach: For time periods from present to beyond 2050:

- What is the current status and the plan for nuclear energy development internationally (e.g., China, India, Korea…)?
- What are the long-term prospects for decarbonization with different energy technology scenarios for nuclear electricity? Does nuclear have a role and under what conditions?
- What are the energy markets to which nuclear energy can contribute to (e.g., process heat, desalination..)?

Findings [Market Dependent]:

- Without a decarbonization constraint, new nuclear is not cost competitive today because of the low cost of fossil fuels without CCS.
- Given a low-carbon emissions constraint, nuclear technology, when part of the electrical generation system mix, produces the least expensive option.
- Average cost of electricity may escalate dramatically when nuclear is excluded from low-carbon scenarios

Opportunities (long term view)

What are the long-term prospects for decarbonization with different energy scenarios with and without nuclear? What role does nuclear energy have and under what conditions?

- Determine the electricity system mix of technologies for various scenarios in US (e.g. ERCOT, ISO-NE) and international (e.g., China and Europe).
- For 2050 timeframe pick a constraint on CO_2 release (e.g., 50 gm/kWhr)
- Use cost-minimization simulation tool (GenX benchmarked by JuiceBox)
- Minimize overall electricity system cost for an optimal technology mix

Simulation of optimal capacity mix in each specific market:

- Capital costs, O&M costs and fuel costs for each power plants, energy storage + startup-ramp rates + hourly electricity demand + hourly weather patterns: limited by the CO_2 emissions target

Modeling: Technology Choices

Pathway 1: "With Nuclear"	Pathway 2: "Without Nuclear"
<u>Carbon "Free" Options</u> • Photovoltaic Solar • On-Shore Wind • LWR Nuclear • Coal (IGCC) with CCS (90% Efficient) • Natural Gas with CCS (90% Efficient) <u>Carbon Options</u> • OCGT and CCGT Natural Gas • Coal (current technology) <u>Storage Options</u> • Battery Storage • Hydro-electric Storage (fixed & small)	<u>Carbon "Free" Options</u> • Photovoltaic Solar • On-Shore Wind • ~~*LWR Nuclear*~~ • Coal (IGCC) with CCS (90% Efficient) • Natural Gas with CCS (90% Efficient) <u>Carbon Options</u> • OCGT and CCGT Natural Gas • Coal (current technology) <u>Storage Options</u> • Battery Storage • Hydro-electric Storage (fixed & small)

US Overnight Cost Assumptions

Resource	Low Cost	Nominal Cost	High Cost
OCGT [A]		$805/kW	
CCGT [A]		$948/kW	
Coal [A]		$3,515/kW	
Nuclear	$4,100[C]/kW	$5,500[A]/kW	$6,900/kW
Wind [A]	$1,369/kW	$1,553/kW	$1,714/kW
Solar [A]	$551/kW	$917/kW	$1,898/kW
Battery Storage [B]	$429/kW ($215/kWh)	$715/kW ($358/kWh)	$1,430/kW ($715/kWh)
Coal IGCC+CCS [A]		$5,876/kW	
Gas CCGT+CCS [A]		$1,720/kW	$2,115/kW

[A] NREL-ATB report (2016)

[B] Lazard.com report (2015)

[C] OECD (2015)

GenX Results

Simulated Texas-ERCOT and NE-ISO with GenX; similar analyses for China (Tianiin, Zhejaing province) and UK and France with a range of carbon constraints (500-nominal, 100, 50, 10, 1 gm-CO2/kWh)

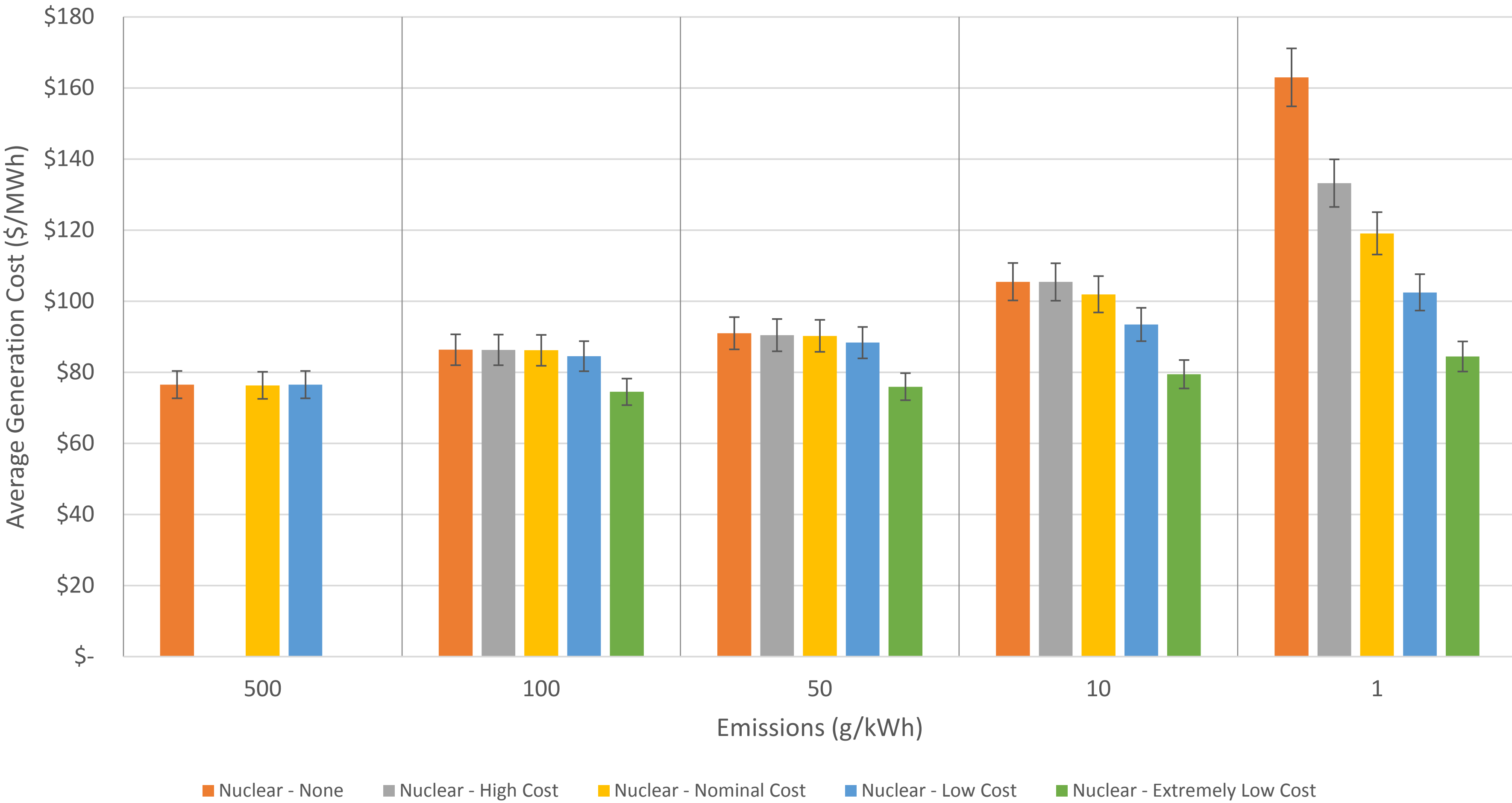
Performed a range of sensitivity studies on:

- Renewables plus battery storage cost (hi-nominal-low)
- Nuclear capital cost (nominal – low with improvements)
- Natural gas price (hi-nominal-low)
- CCS Cost and Efficiency (nominal-hi; 90% and 99%)
- Demand-Side Response (with and without)
- Extreme Weather (clouds/low-wind for a time period)

Texas – ERCOT ISO

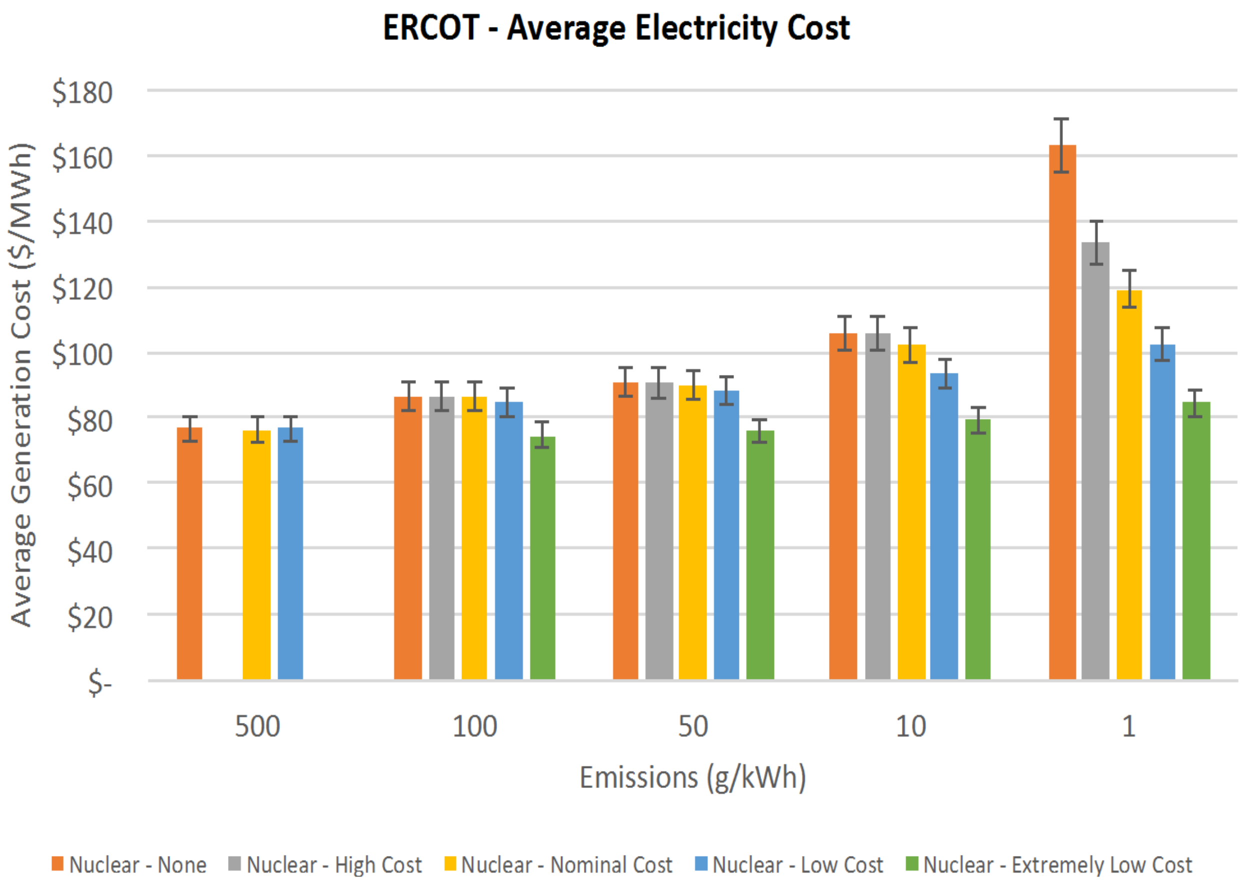
Simulation of optimal generation mix in power markets

MIT tool: hourly electricity demand + hourly weather patterns + capital, O&M and fuel costs of power plants, backup and storage + ramp up rates



Similar results were found for Europe (U.K. and France)

Texas - ERCOT Results

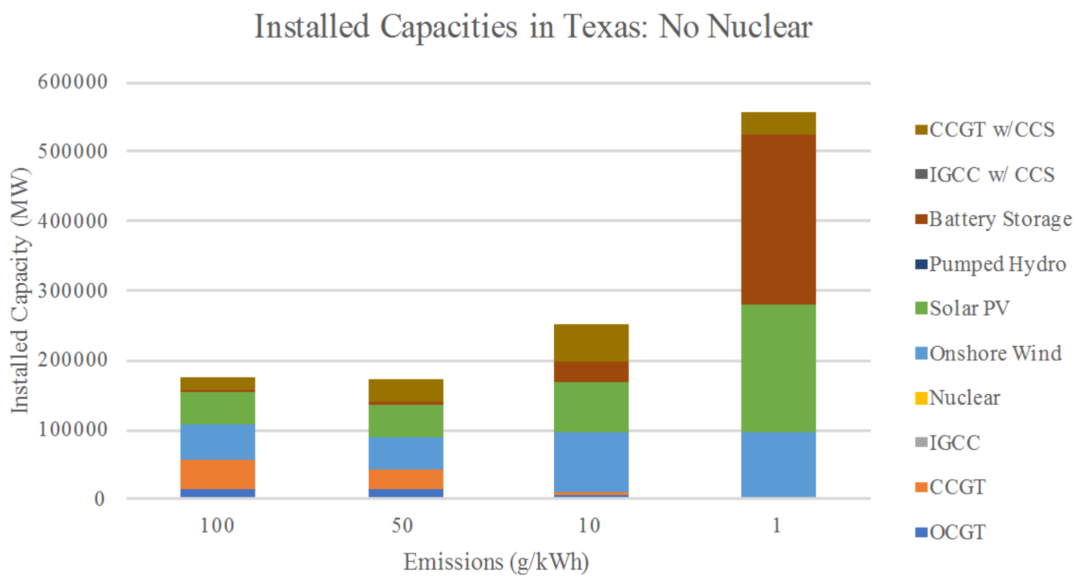


Nuclear option makes a difference btw 50 g/kWhr and 10 g/kWhr for nominal cost case

Nuclear always part of the system mix for lower cost nuclear with improvements due to enabling technologies

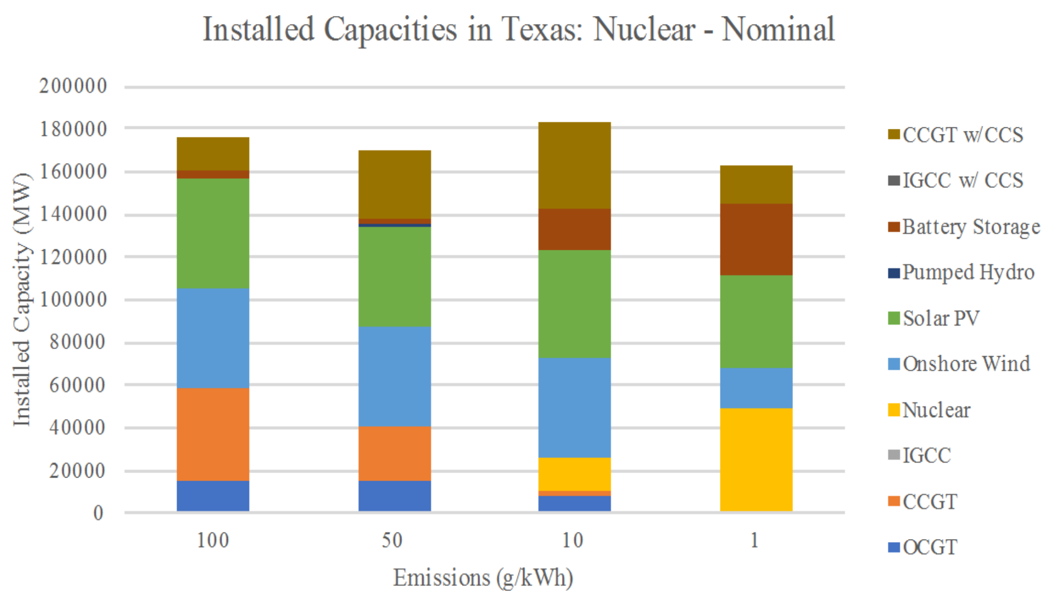
Extremely Low Nuclear Cost is Advanced Reactor Stretch Goal - $2500/kWe ONC

Texas - ERCOT Results



To meet constraint w/o nuclear requires major build-out of renewables

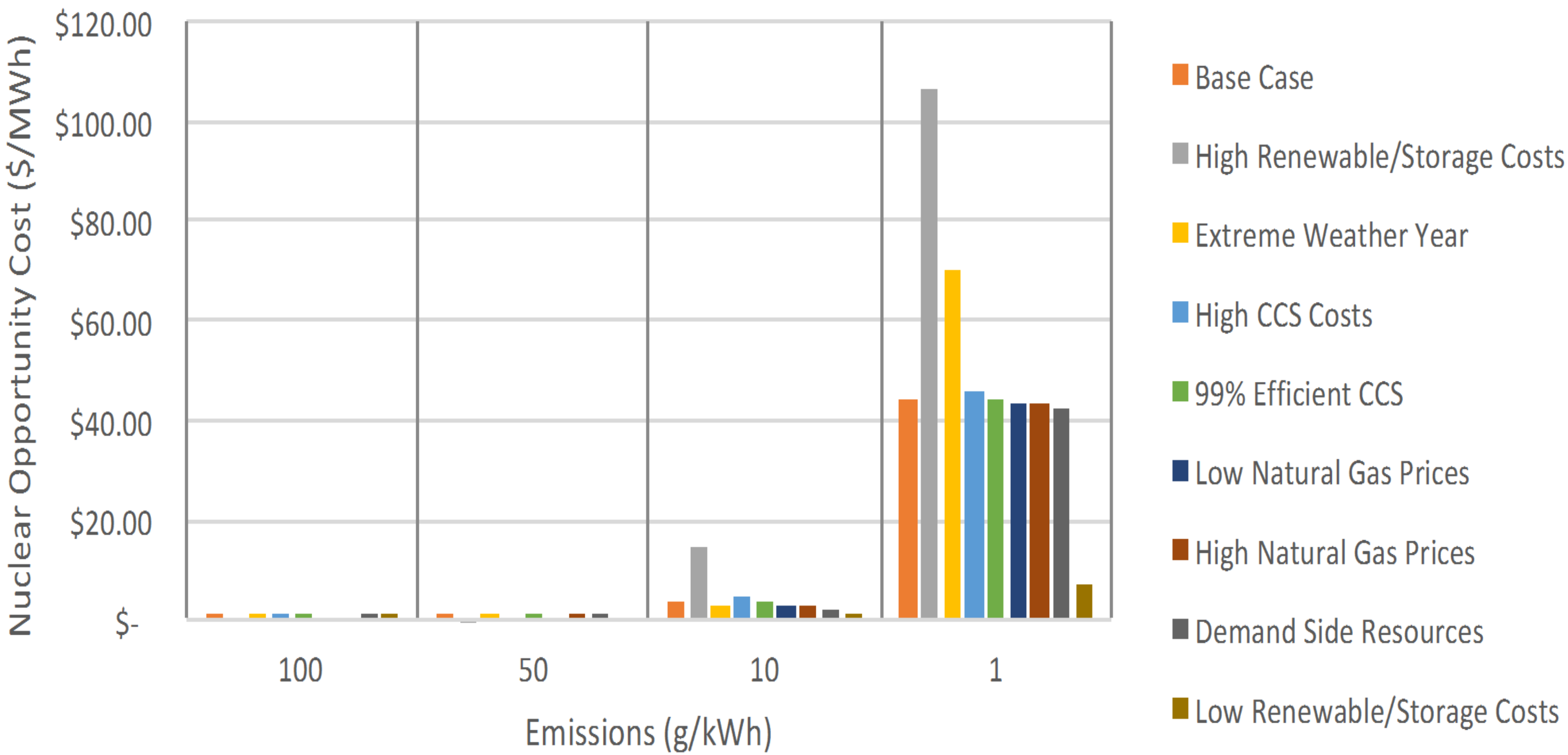
In contrast, installed capacity is relatively constant w nuclear allowed



GenX Sensitivity Nomenclature

- No nuclear case: All costs at nominal conditions w/o nuclear
- Nuclear-nominal: Nuclear included w nominal conditions
- Nuclear-low cost: Lower cost w improved enabling technology
- Renewable/Battery Low cost: Nominal w low cost renewables
- Renewable/Battery High cost: Nominal w hi cost renewables
- High Nat.Gas cost: Nominal w high natural gas fuel cost
- Low Nat.Gas cost: Nominal w low natural gas fuel cost
- 99% CCS: Nominal costs with 99% Carbon-capture efficiency
- Demand-side response allowed (DSM + DR)
- Extreme weather year: Nominal w 1wk-Low-Renew Cap.Fac.

Texas ERCOT Sensitivity Results

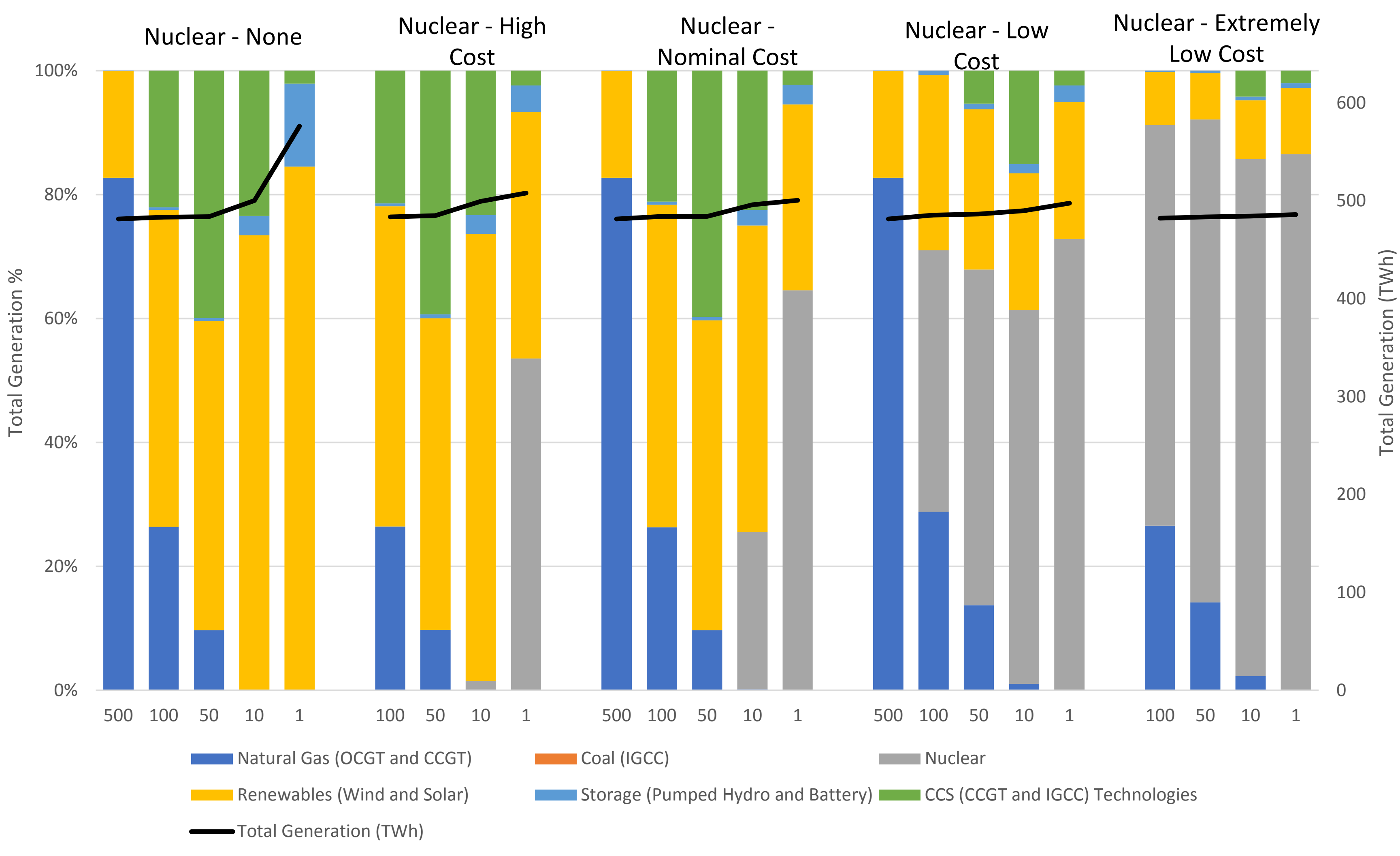


Opportunity Cost = [Systems cost w/o Nuclear – Systems cost w Nuclear]

At a high renewables and battery storage cost, opportunity cost is much larger

At a low renewables and battery storage cost, nuclear is not selected until 1 g/kWhr

ERCOT Electricital Energy Generation

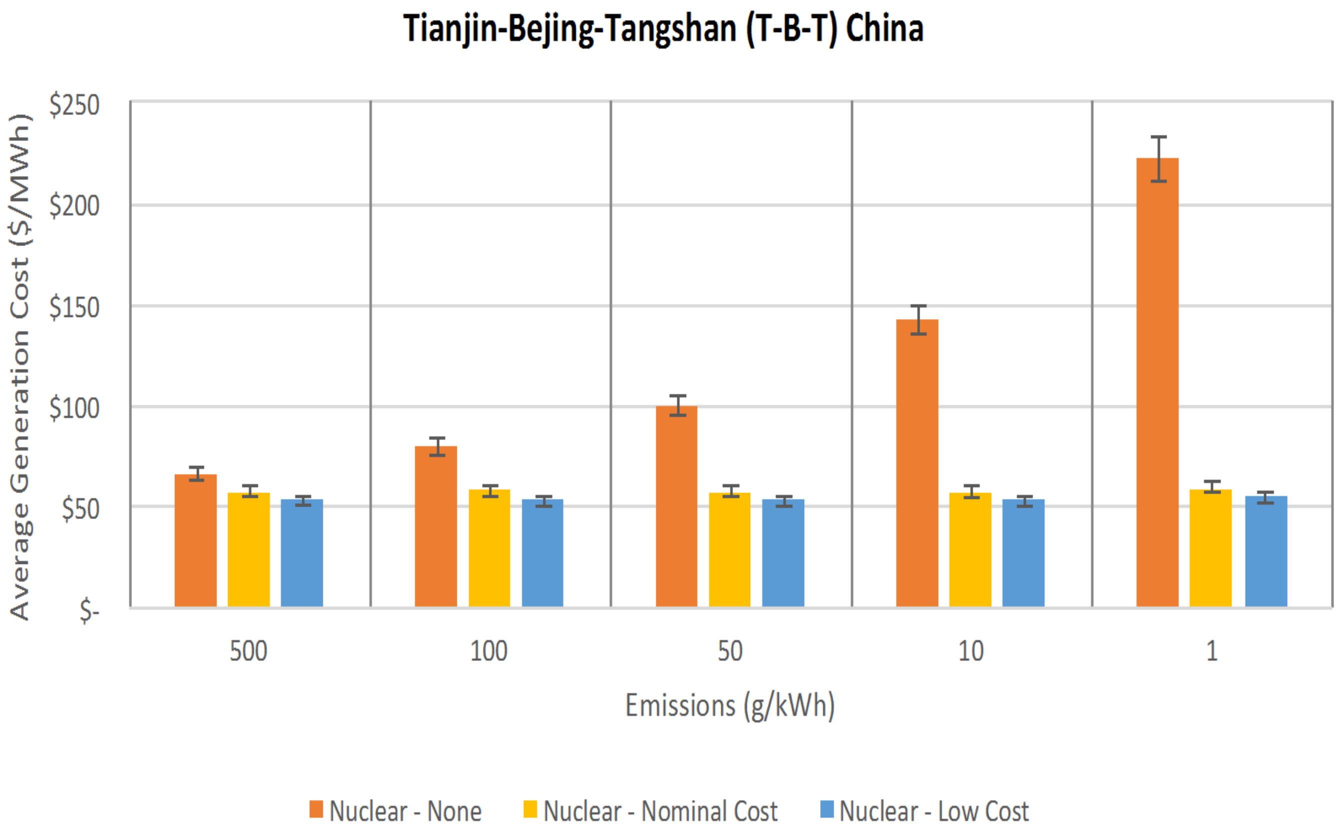


China Overnight Cost Assumptions

Resource	Low Cost	Base Cost	High Cost
OCGT		$421/kW	
CCGT		$496/kW	
Coal		$1,160/kW	
Nuclear	$2,084/kW	$2,796/kW	
Wind	$1,117/kW	$1,267/kW	$1,398/kW
Solar	$404/kW	$671/kW	$1,389/kW
Battery Storage	$429/kW ($215/kWh)	$715/kW ($358/kWh)	$1,430/kW ($715/kWh)
Coal IGCC+CCS		$1,940/kW	
Gas CCGT+CCS		$900/kW	$1,159/kW

NOTE: Study used the relative costs for each technology from the 2015 OECD Report with NREL U.S. cost values used as cost basis for scaling to other countries

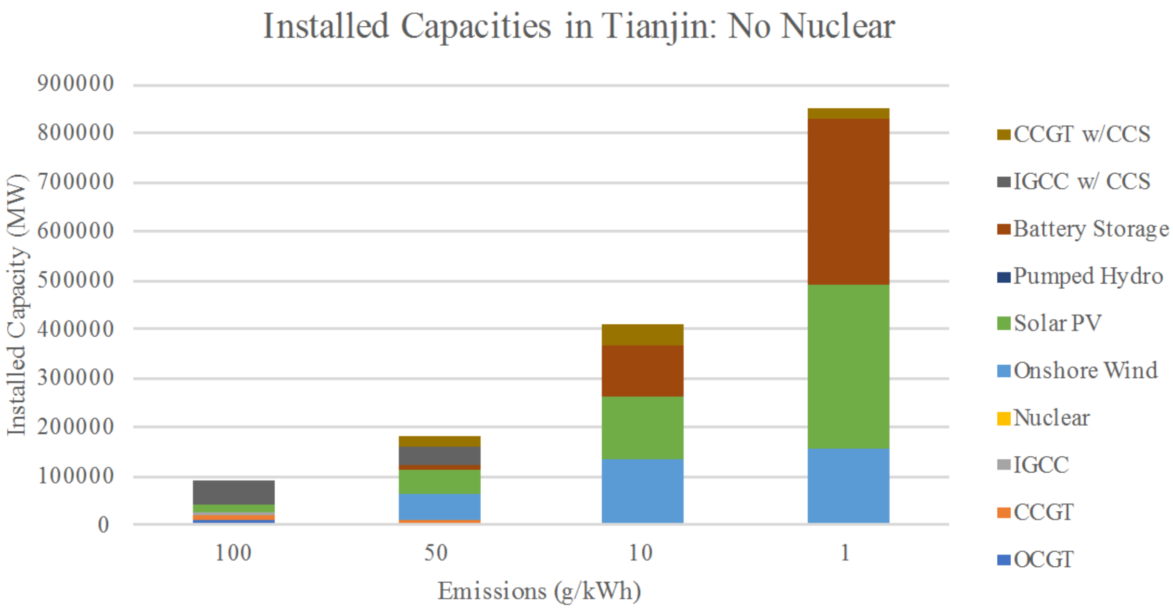
T-B-T Province Results



Due to its low relative cost, having nuclear as an option always decreases overall system cost

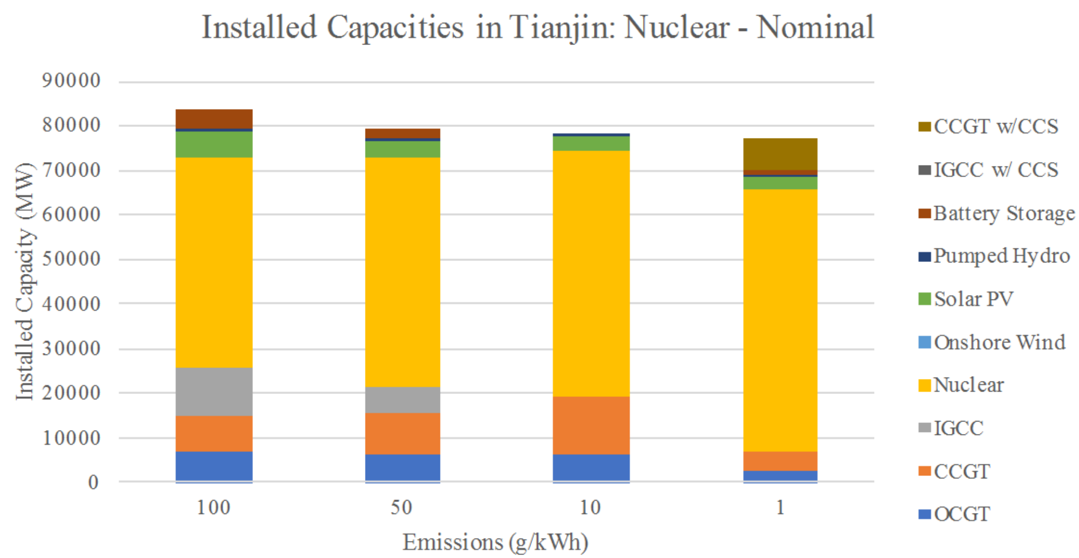
This decrease in system cost is dramatic for low carbon scenarios

T-B-T Province Results

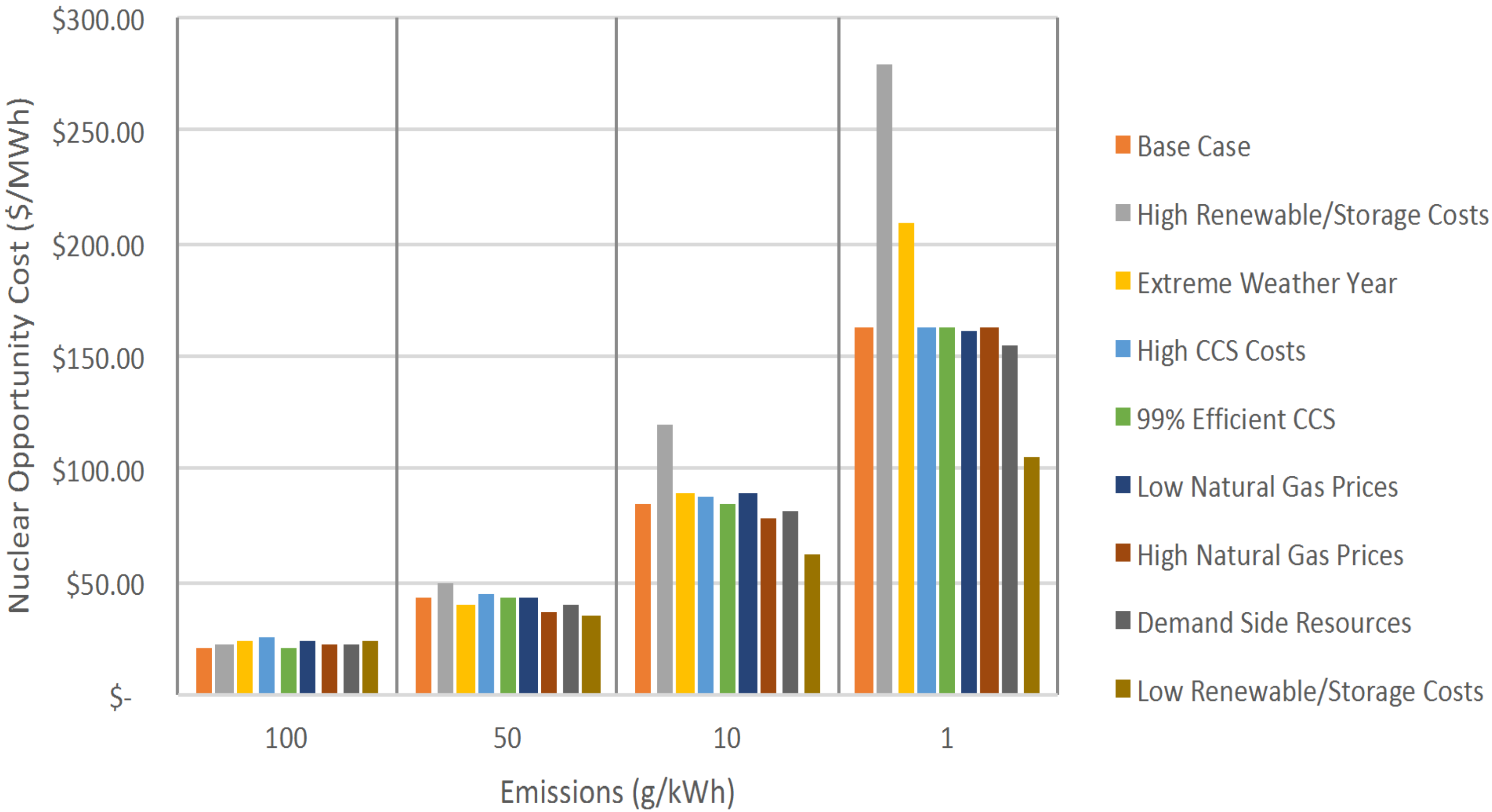


To meet constraint w/o nuclear requires significant build-out of renewables

In contrast, installed capacity is relatively constant w nuclear allowed

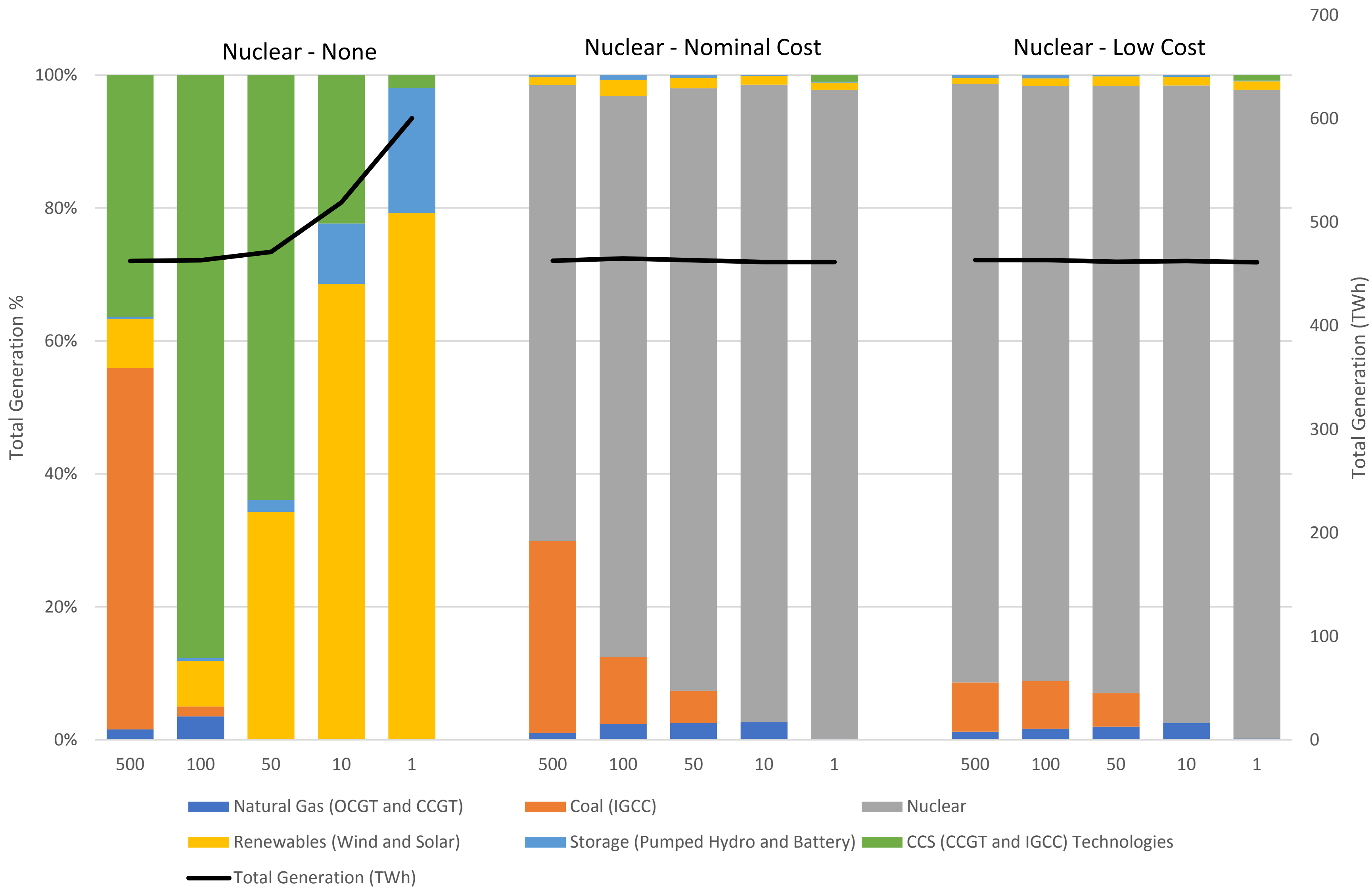


T-B-T Cost Sensitivity Results



Even with low renewables/storage cost, nuclear is still chosen for all constraints

T-B-T Electrical Energy Generation



Advanced Reactor Stakeholder Meeting: NRC Endorsement of ASME BPVC Section III, Division 5

Andrew Yeshnik

September 13, 2018

Background – FY16-17

Implementation Action Plans (July 2017) to support NRC Vision and Strategy (December 2016)

1. Acquire/develop sufficient staff knowledge, tech. skills, capacity to perform non LWR regulatory reviews
2. Acquire/develop sufficient computer codes/tools to perform non-LWR regulatory reviews
3. Establish a more flexible, RIPB non-LWR review process within the bounds of existing regulations, incl. CDAs, staged reviews
4. **Facilitate industry codes & standards development needed to support the non-LWR lifecycle, including fuels & materials**
5. Identify & resolve tech-inclusive non-LWR policy issues
6. Develop a structured, integrated communications strategy for internal and external stakeholders with non-LWR interests)

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

NRC Endorsement of ASME BPVC Section III, Division 5

- Current nuclear power designs operate within a thermal range of 275°C to 315°C.
- Advanced reactor designs have operating thermal ranges that vary widely between 480°C and 1000°C.
- There is no NRC-endorsed code of construction for nuclear reactors operating above 425°C (800°F).
- American Society of Mechanical Engineers Boiler and Pressure Vessel Code (ASME BPVC) Section III, Division 5 provides design, construction, certification, and quality assurance rules for metallic components operating in excess of 800°F, graphite core structures, and ceramic-composite components.
- A letter dated June 21, 2018 from ASME (ML18184A065) requested that the NRC review and endorse the 2017 Edition of ASME BPVC Section III, Division 5 (NRC Response Letter: ML18211A571)

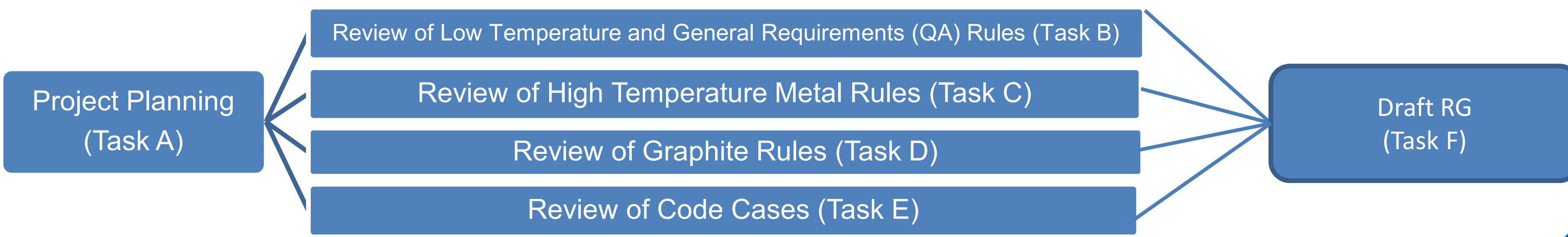
Review and Endorsement Process

- NRO-Lead with support from RES/DE and NRR/DE
- **Objective:** Official NRC Endorsement of the 2017 Edition of ASME BPVC Section III, Division 5
- **Anticipated Product (August 2020):** A draft regulatory guide for public comment that includes the 2017 ASME BPV Code Section III, Division 5 as an endorsed method of constructing Advanced Reactor Designs, subject to any conditions the staff deems necessary.
- The NRC is participating on two ASME/NRC task groups:
  - Metallic Materials
  - Graphite and Ceramics
- Contractors: PNNL, ORNL, ANL, Commercial
- Stakeholder engagement throughout the review

Review and Endorsement Process

Current Status:

- The endorsement team has started Task A, Project Planning
  - Establishing the scope, schedule, and NRC points of contact
- Process:



Metallic Fuel Experience in Sodium Cooled Fast Reactors

FRWG

September 13, 2018

Presentation Overview

- Presentation Purpose
- Metallic Fuel Experience
- Steady State Performance
- Transient Behavior
- EBR-II
- Notes on QA and legacy data work at Argonne and interest to other reactor types
- Summary

Presentation Purpose

- Familiarize the NRC and stakeholders with information on metallic fuel

Metallic Fuel Experience

Metallic Fuel History

- Over 30 years of irradiation experience
- EBR-I, Fermi-1, EBR-II, FFTF
- U-Fs*, U-Mo, U-Pu-Fs*, U-Zr, U-Pu-Zr, others
- EBR-II
  - > 40,000 U-Fs* pins, **> 16,000 U-Zr pins** & > 600 U-Pu-Zr pins irradiated, clad in 316 stainless steel, D9 & **HT9**
- FFTF
  - **> 1000 U-Zr pins**, mostly in HT9
  - Vast experience with HT9 cladding

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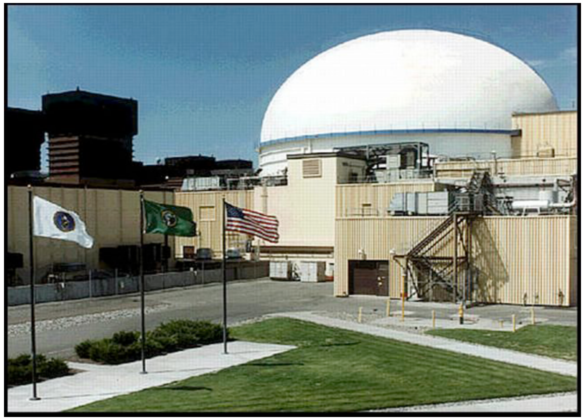
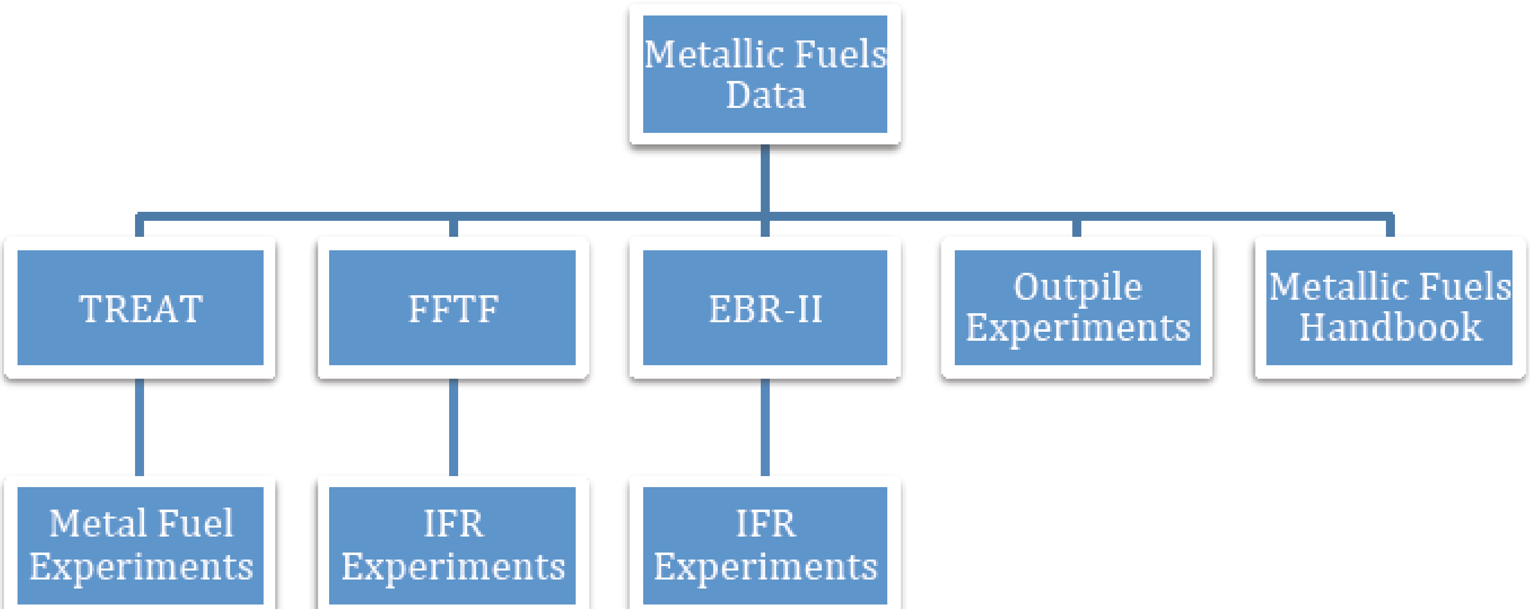
*Fs – Simulated Fission Products

EBR-II

FFTF



Sources of Metallic Fuel Data



Metallic Fuel Experimental Database (Steady State)

- EBR-II experiments to look at parameters and phenomena of interest to fuel performance
  - Prototype fuel behavior
  - RBCB* and failure mode
  - Fuel swelling and restructuring
  - Lead IFR** fuel test
  - Fabrication
  - Design parameters
  - High clad temperature
  - Large fuel diameter
  - Blanket safety
  - Fuel qualification
  - Fuel impurities

- FFTF experiments to look at
  - Fuel column length effects
  - Lead metal fuel tests
  - Metal fuel prototype
  - Metal fuel qualification

____

*RBCB – Run Beyond Cladding Breach

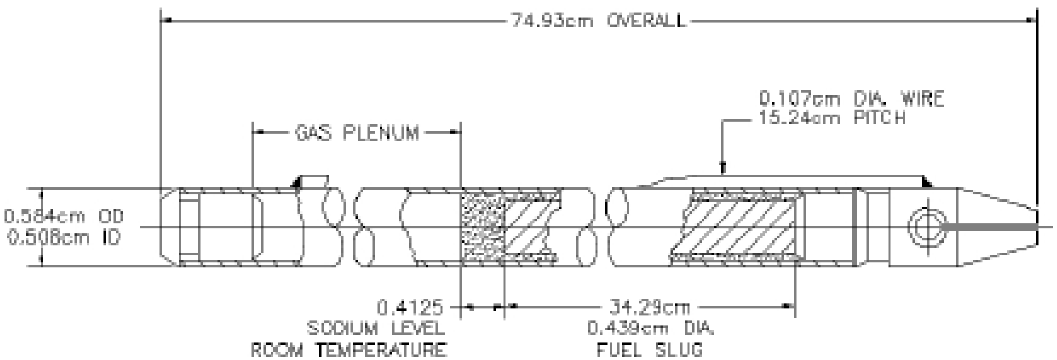
**IFR – Integral Fast Reactor

Metallic Fuel Experimental Database (Transient)

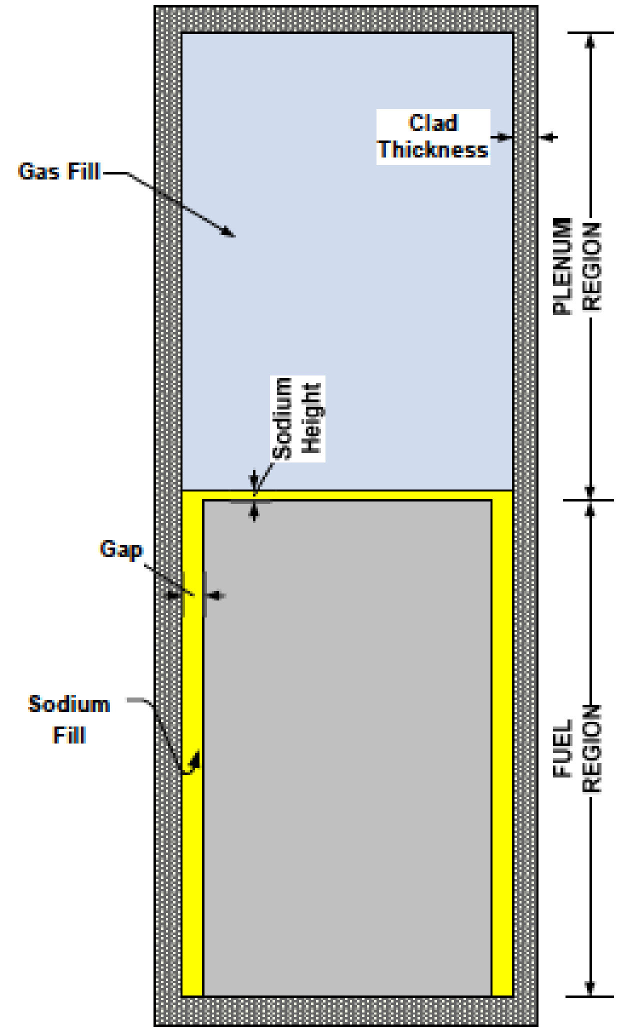
- In-Pile
  - Run Beyond Cladding Breach (RBCB) experiments:
    6 RBCB tests U-Fs &
    U-Pu-Zr/U-Zr
  - 6 TREAT tests:
    U-Fs in 316SS&
    U-Zr/U-Pu-Zr in D9/HT9

- Out-Pile
  - Whole Pin Furnace Tests (WPF)
  - Fuel Behavior Test Apparatus (FBTA)
  - Diffusion compatibility tests

Typical Metallic Fuel Design



Typical EBR-II Metallic Fuel Pin
(Pahl, et al., 1990)



Design Parameters (nominal) of EBR-II Fuel

Item	Mark-IA	Mark-II	Mark-IIC	Mark-IICS	Mark-III	Mark-IIIA	Mark-IV
Fuel alloy, wt %	U-5Fs	U-5Fs	U-10Zr	U-10Zr	U-10Zr	U-10Zr	U-10Zr
Enrichment weight, % ^{235}U	52	67	78	78	66.9	66.9	69.6
Fuel-slug mass, g	64	52	47	47	83	83	78
Fuel smeared density, %	85	75	75	75	75	75	75
Cladding-wall thickness, cm	0.023	0.030	0.030	0.030	0.038	0.038	0.046
Cladding-wall OD, cm	0.442	0.442	0.442	0.442	0.584	0.584	0.584
Length, cm	46.0	61.2	63.0	53.6	74.9	74.9	74.9
Cladding material	304L	316	316	316	CW D9	CW316	HT9
Spacer-wire diameter, cm	0.124	0.124	0.124	0.124	0.107	0.107	0.107

C. E. Lahm, et al., “Experience with Advanced Driver Fuels in EBR-II,” 1993.

Historical Fuel Design Parameters

Key Parameter	EBR-II/FFTF
Peak Burnup, 10^4MWd/t	5.0 – 20
Max. linear power, kW/m	33 – 50
Cladding hotspot temp., ^oC	650
Peak center line temp., ^oC	<700
Peak radial fuel temp. difference, ^oC	100 - 250
Cladding fast fluence, n/cm^2	up to 4 x 10^{23}
Cladding outer diameter, mm	4.4 - 6.9
Cladding thickness, mm	0.38 – 0.56
Fuel slug diameter, mm	3.33 – 4.98
Fuel length, m	0.3 (0.9 in FFTF)
Plenum/fuel volume ratio	0.84 to 1.45
Fuel residence time, years	1 - 3
Smeared density, %	75

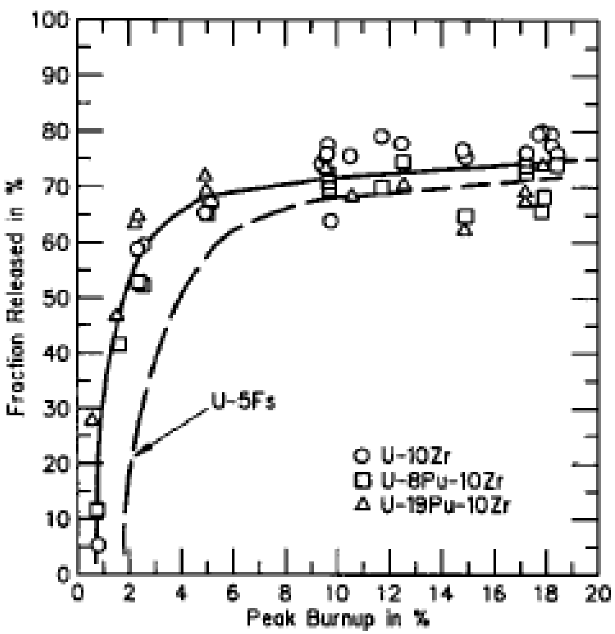
Steady State Metallic Fuel Performance

Steady State Performance Topics

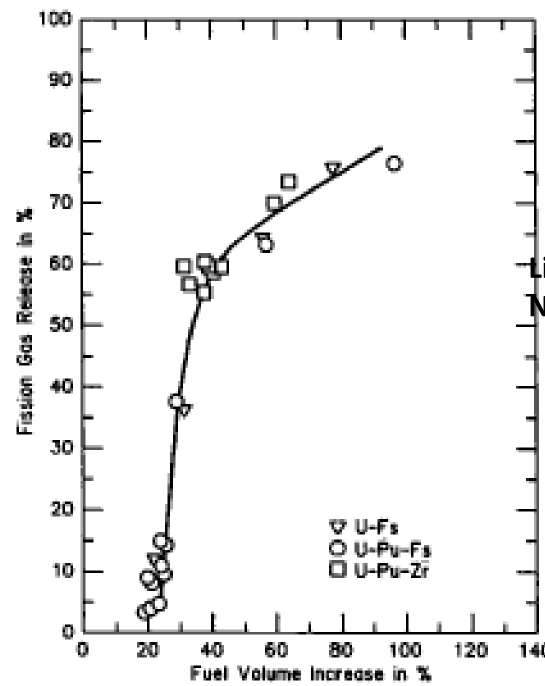
- Fission Gas Release (FGR)
- Fuel Swelling
- Constituent Redistribution and Zone Formation
- Fuel-Cladding Chemical Interaction (FCCI) & Rare Earth Migration
- Fuel-Cladding Mechanical Interaction (FCMI)
- Cladding Material Performance

Fission Gas Release (FGR)

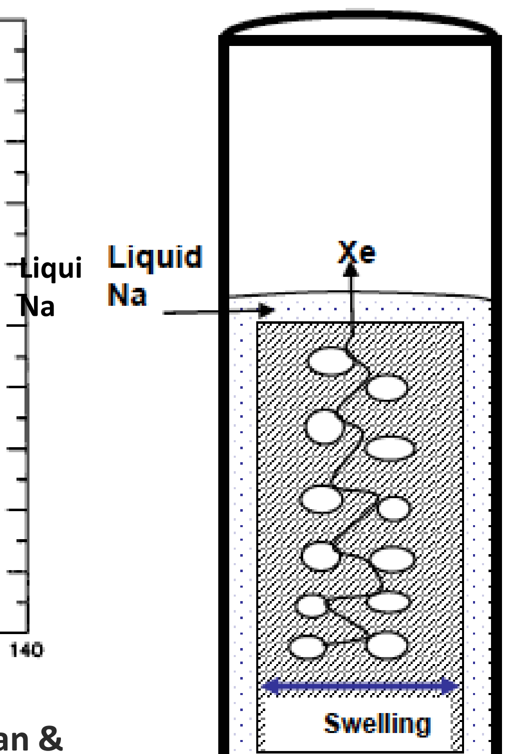
- Insoluble fission gases, Xe and Kr, accumulate in fuel until inter-linkage of porosity at sufficient burnup leads to release of large fraction of gas.
- The fission gases accumulate in plenum region and constitute the primary clad loading mechanism.



FGR vs. Burnup (Hofman & Walter, 1994): U-5Fs slightly lower because of beneficial effect of Si inclusion

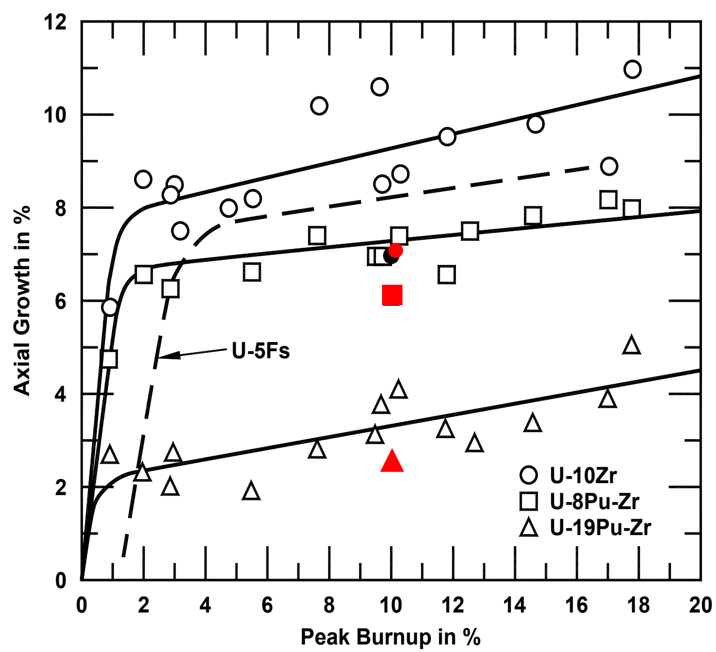


FGR vs. Fuel Swelling (Hofman & Walter, 1994): Independent of metal-fuel type



Fuel Swelling

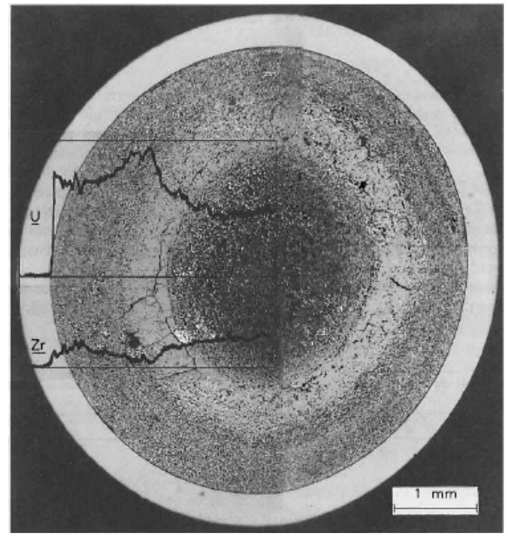
- Driven by nucleation and growth of immobile fission-gas bubbles
- Low fuel smeared density (~75%) combined with high swelling rate allow rapid swelling to ~33 vol% at ~2 at.% burnup where inter-linkage of porosity results in large gas release fraction which decreases the driving force for continued swelling



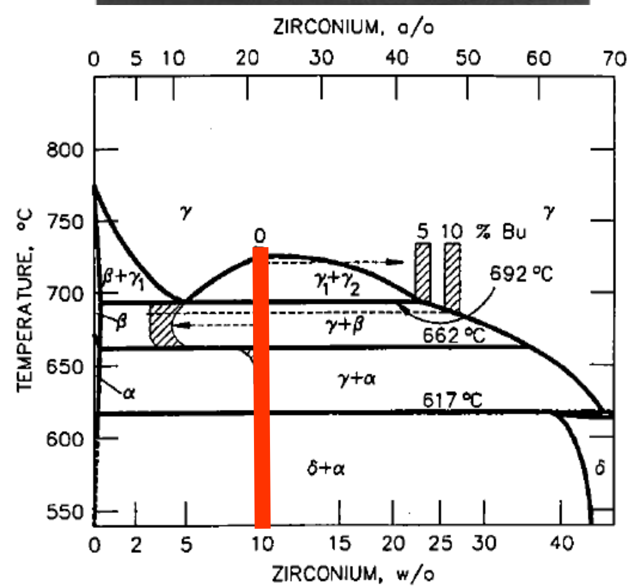
EBR-II fuel length increase in various metallic fuels as a function of burnup where closed symbols correspond to FFTF data (ANL-AFCI-211)

Constituent Redistribution & Zone Formation

- Fuel melting temp. decrease in Zr-depleted region (this zone happens off the fuel center).
- Local fission rate change.
- Changes in swelling characteristics.
- Reliable predictive model has been developed.



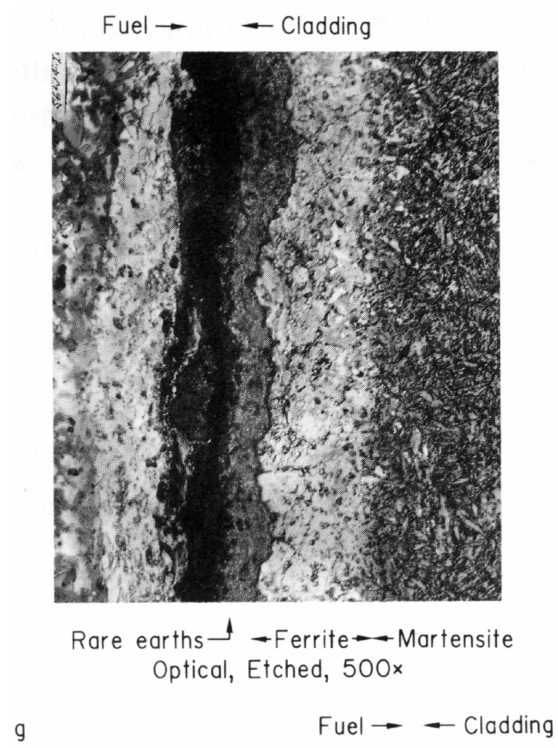
Metallographic cross section with superimposed radial microprobe scans at top of U-10Zr pin DP-81, experiment X447 (Hofman, et al., 1995)



U-Zr Phase Diagram

Fuel Cladding Chemical Interaction (FCCI) & Fission Product Migration

- At steady state FCCI is characterized by solid state interdiffusion
- Interdiffusion forms U/Fe alloys with lower eutectic temperature
- Decarburized zone at fuel-clad interface is expected in HT-9 cladding
- RE fission products (La, Ce, Pr, Nd) form a cladding brittle layer
- Penetration depth data are available from
  in and out-of-pile measurements



FCCI of U-10Zr/HT-9 due to inter-diffusion of fuel/cladding constituents after 6 at% burnup at 620ºC (Hofman & Walter 1994)

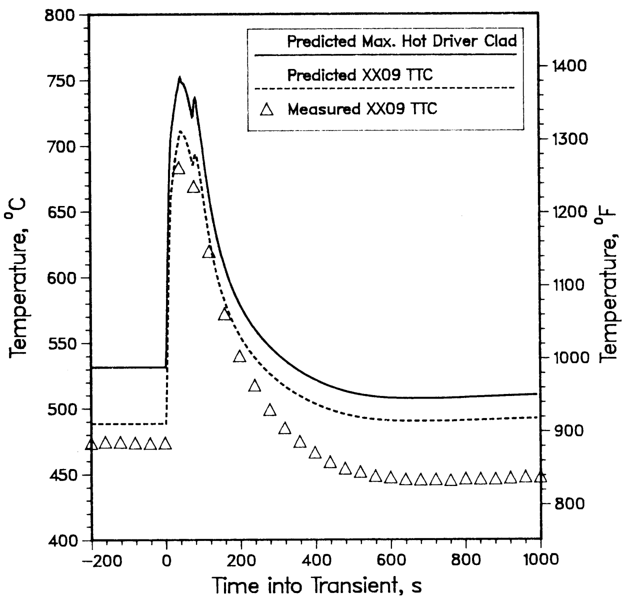
Transient Behavior

Metallic Fuel Characteristics

- Excellent transient capabilities
  - Does not impose restrictions on transient operations capabilities
  - Sample history of a typical driver fuel irradiated during the EBR-II inherent passive safety tests conducted in 1986;

  - *40 start-ups and shutdowns*
  - *5 15% overpower transients*
  - *3 60% overpower transients*
  - *45 loss-of-flow (LOF) and loss-of-heat-sink tests including a LOF test from 100% without scram*

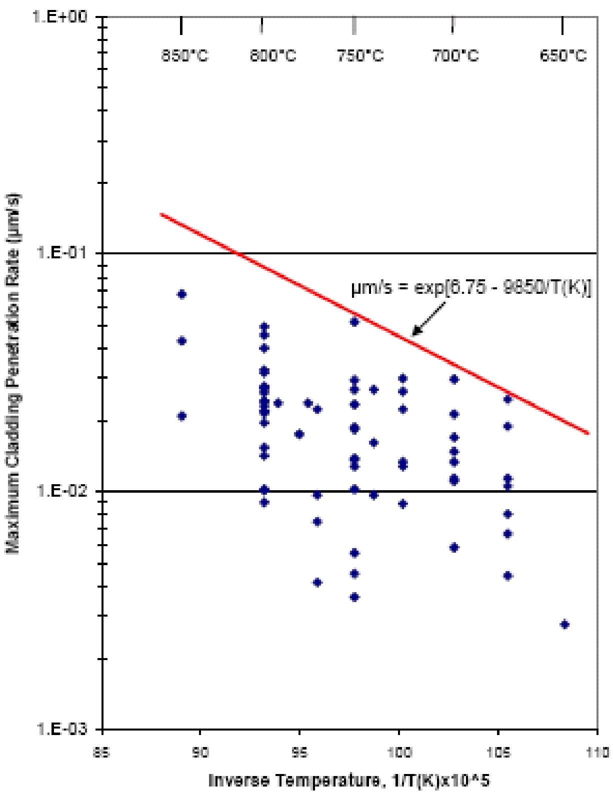
– **No fuel failures**



Unprotected loss-of-flow test in EBR-II demonstrated the benign behavior predicted (Mohr, et al., 1987)

Transient Tests

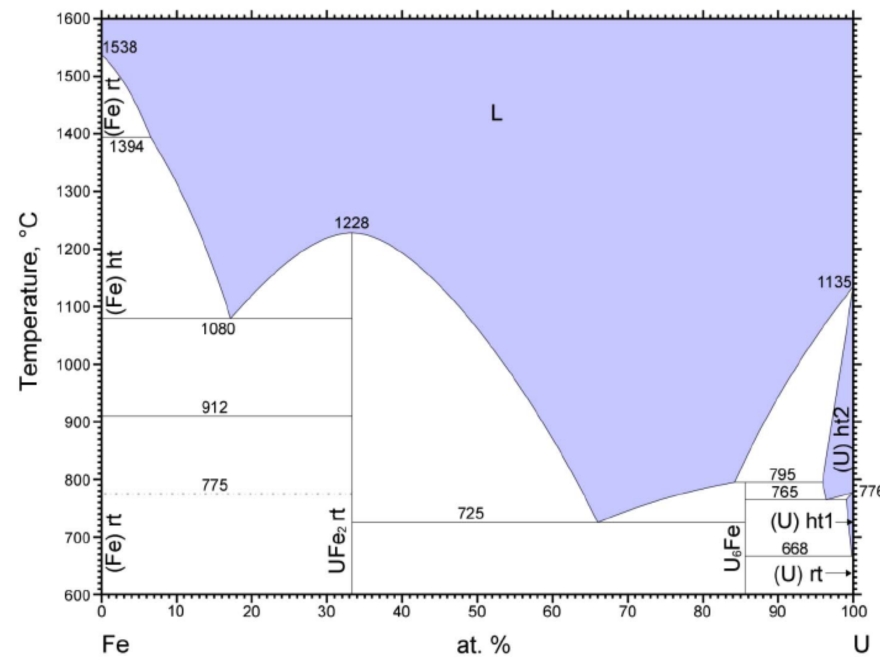
- In –pile TREAT (Transient Reactor Test Facility) tests evaluated transient overpower margin to failure, pre-failure axial fuel expansion, and post-failure fuel and coolant behavior
- Hot cell furnace testing of pin segments (Fuel Pin Test Apparatus), and full length pins (Whole Pin Furnace) showed **significant safety margin for particular transient conditions**.
  - Penetration depth data were measured and provided the basis for penetration depth correlations



Effective cladding penetration rates from FBTA tests for speciments tested for 1.0 hour (Tsai, et al., 2007)

Eutectic Formation Temperature between Fuel and Clad

- Critical parameter for metal fuel design
- Onset of eutectic formation occurs between 650 – 725 ^oC
- Rapid eutectic penetration at a much higher temperatures
- Places limits on the coolant outlet temperature to provide adequate margin to onset of eutectic formation



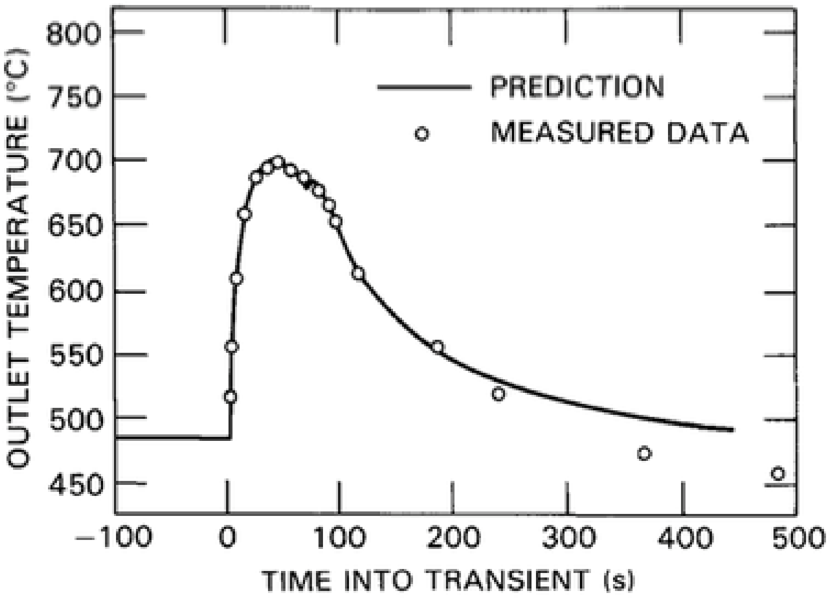
The Iron-Uranium Phase Diagram (Okamoto, 1990)

EBR-II shutdown heat removal tests (SHRT)

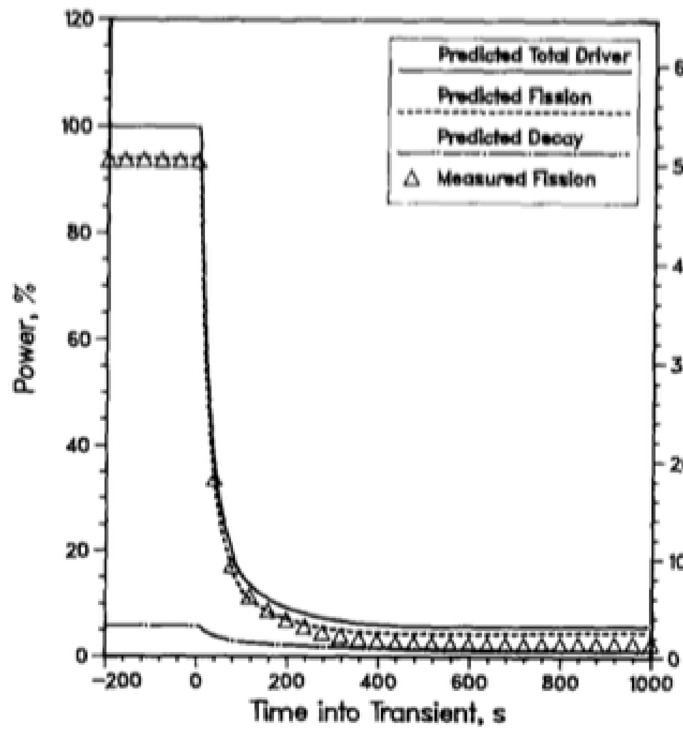
- Performed on the same day (April 3rd, 1986)
- Two types of unprotected loss-of-cooling accidents
  - Loss of Flow Without Scram
  - Loss of Heat Sink Without Scram
- Performed on the actual, operating reactor at full power!

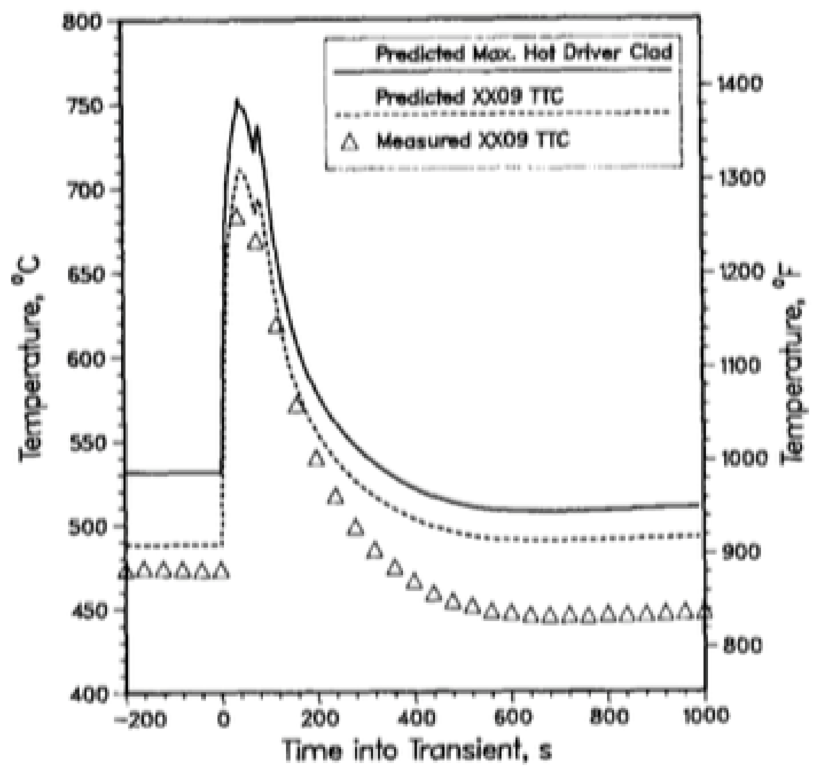
EBR-II Loss of Flow Without Scram

- Primary coolant pumps turned off while operating at full power
- Reactor shut down due to fuel thermal expansion feedbacks



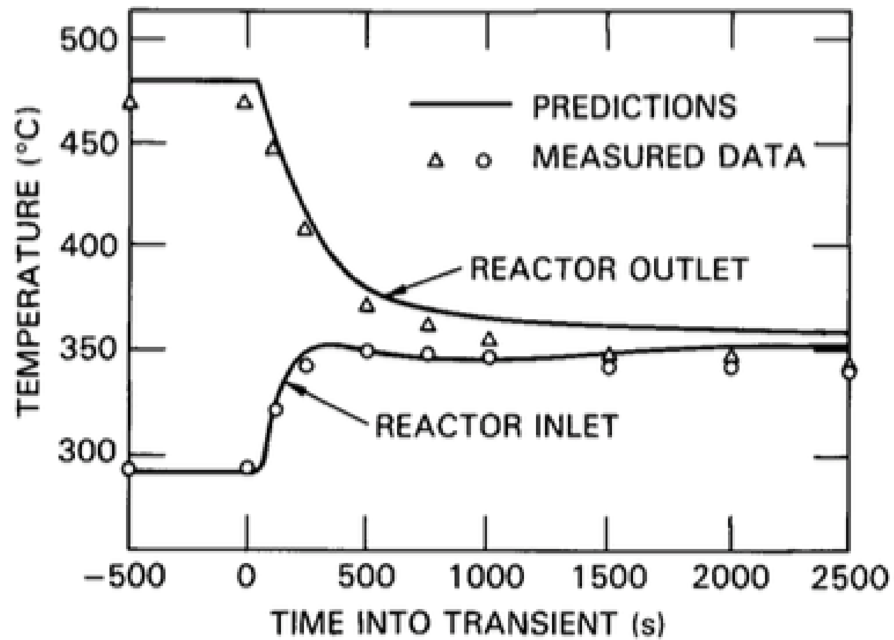
More EBRII LOFWS plots





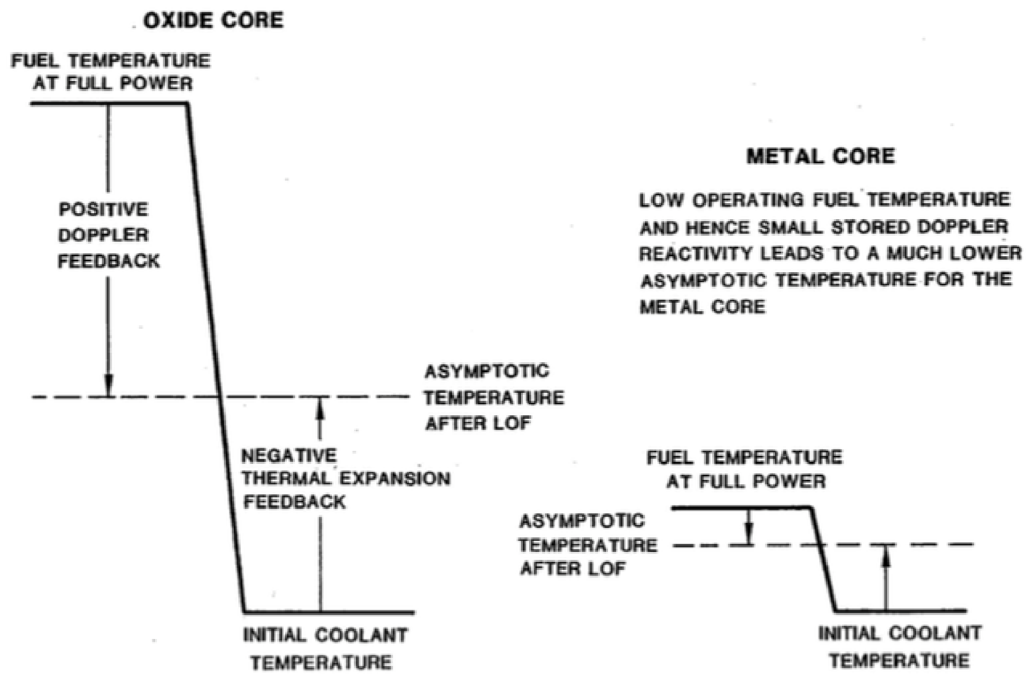
EBR-II Loss of Heat Sink Without Scram

- Intermediate coolant pumps turned off while operating at full power
- Again, reactor shuts down without scram due to thermal expansion feedbacks



EBRII passive safety

- Benign transient behavior enabled by lower stored Doppler reactivity of metal fuel
- Result of operating at lower nominal fuel temp (relative to oxide)



EBR-II safety test takeaways

- These are sensational results. Two of the most severe accidents that can threaten nuclear power systems have been shown to be of no consequence to safety or even operation of EBR-II. The reactor was inherently protected without requiring emergency power, safety systems, or operator intervention."
  -J.I. Sackett, "OPERATING AND TEST EXPERIENCE WITH EBR-II, THE IFR PROTOTYPE", Progress in Nuclear Energy 31, 1-2, pp. 111-129, 1997.

Notes on Laboratory Efforts and Interest to Other Reactor Types

- Presentation from Argonne at one of these meetings in June
- Efforts at Argonne
- Other technology types may want to follow or learn about

Southern Nuclear

NEI 18-04 - Licensing Modernization Project (LMP) Guidance Document Update

Jason Redd, PE
Southern Nuclear Development, LLC

September 13, 2018

NEI 18-04 LMP Guidance Document Updates

LMP Guidance Document Introduction

- The NEI 18-04 LMP Guidance Document represents a framework for the efficient licensing of advanced non-light water reactors (non-LWRs).
- It is the result of the LMP led by American nuclear utilities and cost-shared by the US Department of Energy (DOE).
- The LMP Team prepared this document for establishing licensing technical requirements to facilitate risk-informed and performance-based (RIPB) design and licensing of advanced non-LWRs.
- Such a framework acknowledges enhancements in safety achievable with advanced designs and reflects current states of knowledge regarding safety and design innovation, creating an opportunity for reduced regulatory complexity with increased levels of safety.

LMP Guidance Document Recent Activities

- June 19 – The LMP Guidance Document (Working Draft M) was reviewed and discussed by the Advisory Committee on Reactor Safeguards (ACRS) Future Plants Subcommittee. [transcript available at ML18184A148]

- August 21 – NRC-Industry Workshop regarding first draft of Draft Guide DG-1353 *Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Approach to Inform the Content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors.* [slides available at ML18242A447]

- September 13 – NRC stakeholder public meeting. [announcement available at ML18249A337]

LMP Guidance Document Upcoming Meetings and Milestones

- NLT September 28 – Near final draft of NEI 18-04 LMP Guidance Document submitted to the ACRS Future Plant Designs (FPD) Subcommittee chair in preparation for the October 30 ACRS FPD Subcommittee meeting.

- October 30 – ACRS FPD Subcommittee meeting to review and discuss the draft LMP Guidance Document, draft NRC SECY, and draft NRC Regulatory Guide DG-1353 addressing the LMP Guidance Document.

- December 6 or 7 – Full ACRS meeting to review and discuss the draft of the LMP Guidance Document, draft NRC SECY, and draft NRC Regulatory Guide DG-1353 addressing the LMP Guidance Document.

LMP Guidance Document Upcoming Opportunities for Industry and Public Participation

- By 2Q19 we expect between four and six advanced reactor designers to have exercised the LMP RIPB processes on their designs to obtain potential insights. The LMP team is interested in demonstrating the LMP RIPB processes with additional vendors.
  - X-energy has generously publicly shared their report on the LMP demonstration on a TRISO pebble-bed, high-temperature, gas-cooled reactor via NRC ADAMS at Accession Number ML18228A779.

- Anytime – The LMP team always welcomes questions, comments, and feedback. Please contact me at jpredd@southernco.com or 205-992-6435.

LMP Feedback on DG-1353 *Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Approach to Inform the Content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors* with associated draft SECY

DG-1353 and draft SECY Acknowledgement and Thanks

- LMP recognizes the extensive work by Bill Reckley and Amy Cubbage, along with the contributions and oversight from the NRC Staff and management, to prepare DG-1353 *Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Approach to Inform the Content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors* with its draft SECY.

Key Messages from the LMP Team on DG-1353 and draft SECY

- No significant deltas have been identified between the RIPB process proposed by the draft NEI 18-04 LMP Guidance Document and DG-1353 with draft SECY.

- The LMP Team is pleased to offer verbal feedback to the NRC Staff on DG-1353 and the draft SECY paper.

Questions?