New Reactor Technologies for the Future of Nuclear Power

Jon W. Ball
28th Annual NUPIC Vendor Meeting
June 19-20, 2019

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Advanced Nuclear … significant bi-partisan support!

Nuclear Energy Innovation Capabilities Act of 2017, S.97 (Public Law 115-248)

- Provides variety of research programs/funding for Ars
- Calls for versatile test reactor (VTR) by 2025
- Passed House and Senate by voice vote

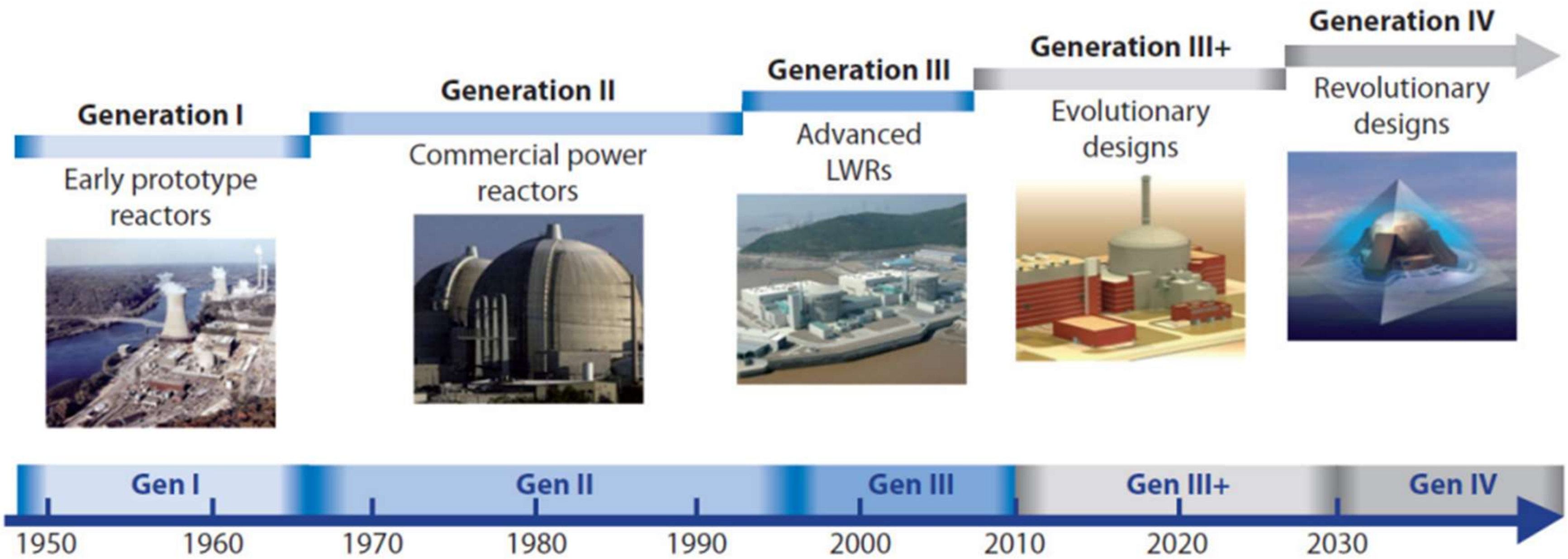
Nuclear Energy Innovation and Modernization Act, S.512 (Public Law 115-439)

- Prohibits NRC from seeking fees for AR preparation costs
- Requires NRC to prepare for licensing of advanced reactors
- Passed the Senate by voice vote and the House on a vote of 361-10 in 12/18

Nuclear Energy Leadership Act, S.903

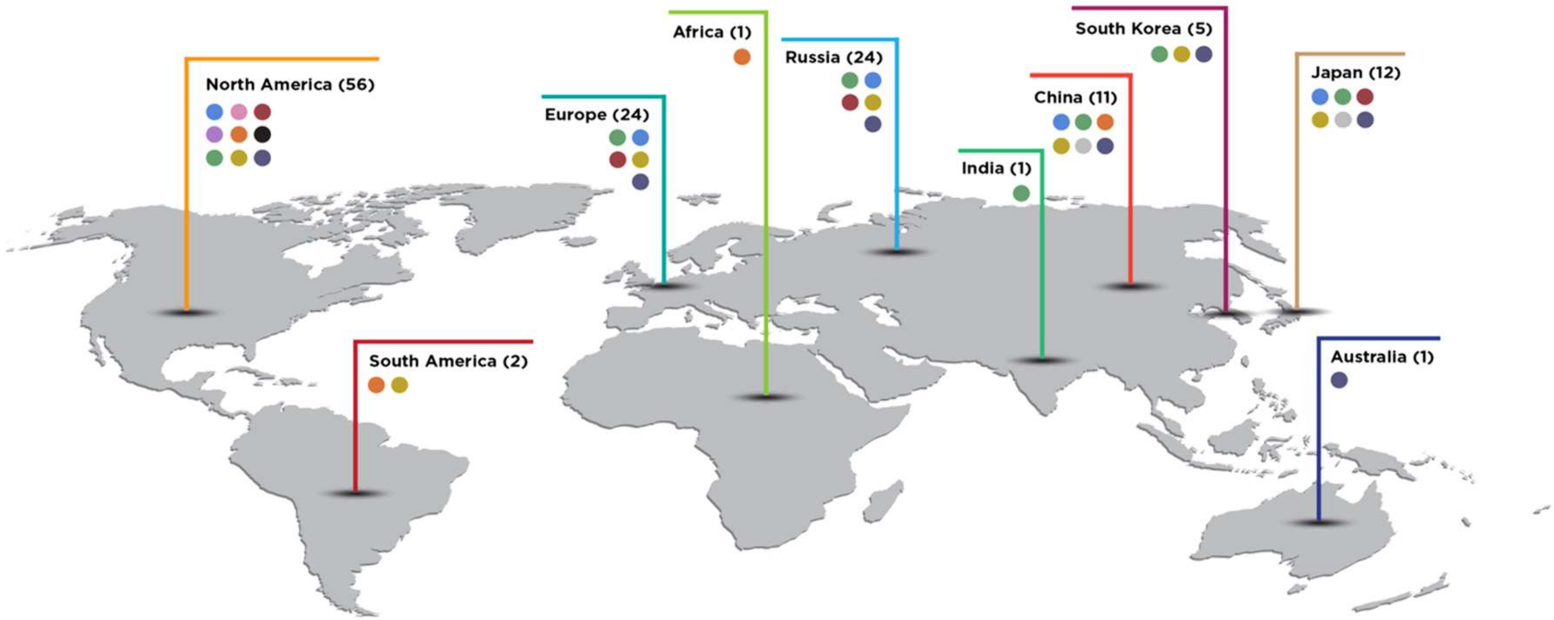
- Creates long-term PPA program and nuclear energy strategic plan
- Calls for deployment of 4 different advanced reactor technologies plus VTR
- Will be significant focus in 116th Congress

Generations and sizes of reactors … varies versions



- **Gen III** generally means advanced LWRs with <u>active</u> safety systems
- **Gen III+** generally means advanced LWRs with <u>passive</u> safety systems
- **Gen IV** are non-LWR reactors … normally referred to as Advance Reactors
- Now some LWR SMRs are being considered Advanced Reactors
- **Small Modular Reactors (SMRs)** are normally considered to be $\leq$ 300 MWe
- **Micro-reactors** generally considered < 10 MWe

The Global Race for Advanced Nuclear



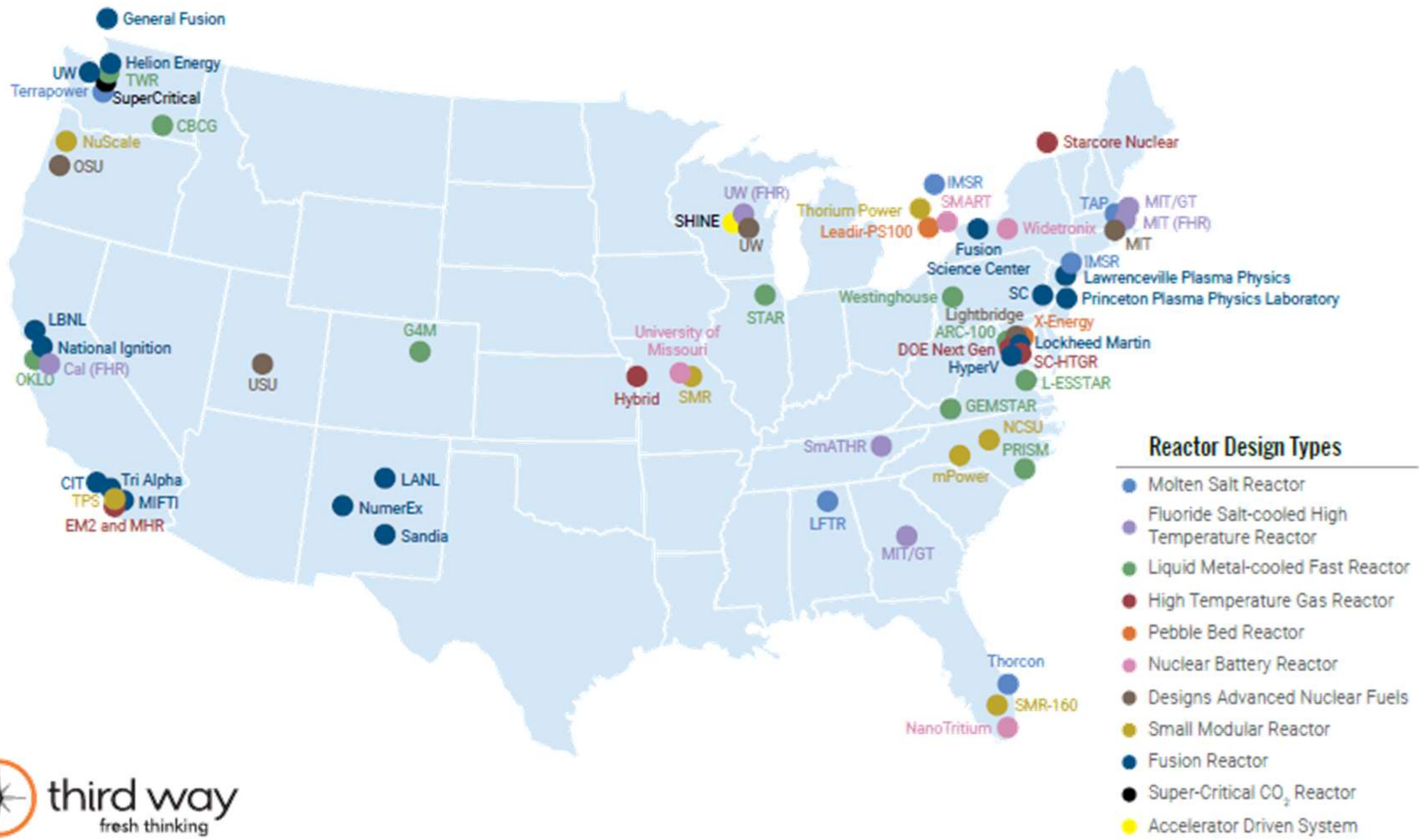
>100 Advanced Reactors/SMRs globally

Reactor Design Types

- Molten Salt Reactor
- Fluoride Salt-cooled High Temperature Reactor
- Liquid Metal-cooled Fast Reactor
- High Temperature Gas Reactor
- Pebble Bed Reactor
- Nuclear Battery Reactor
- Small Modular Reactor
- Fusion Reactor
- Super-Critical CO_2 Reactor
- Super-Critical Water-Cooled Reactor

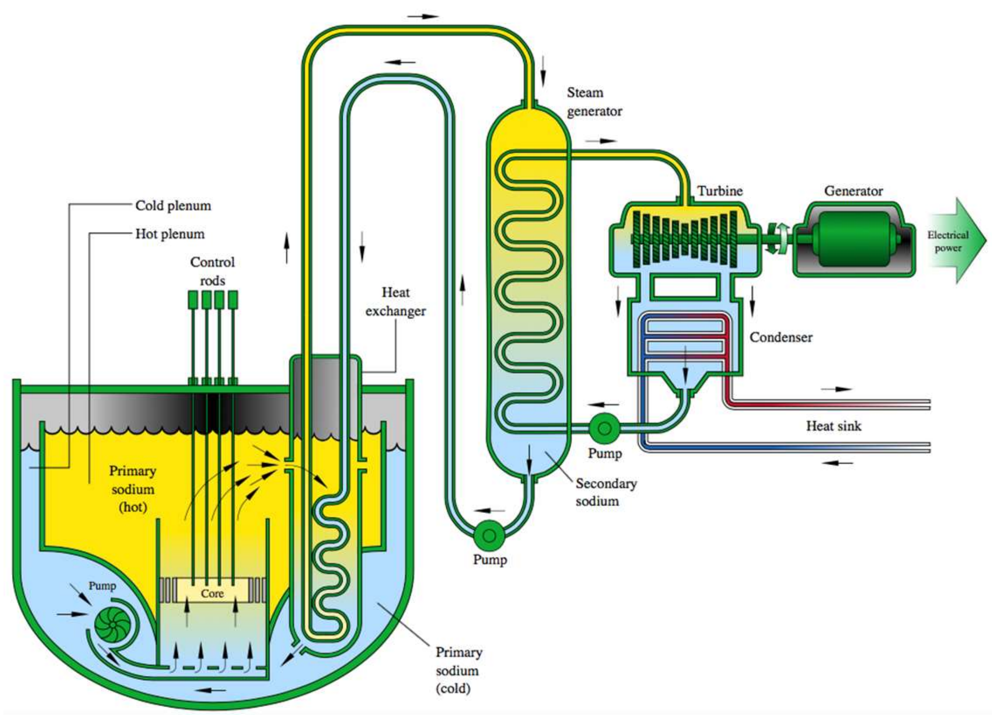
third way
fresh thinking

Next generation nuclear development



third way
fresh thinking

Sodium fast reactors (SFRs)



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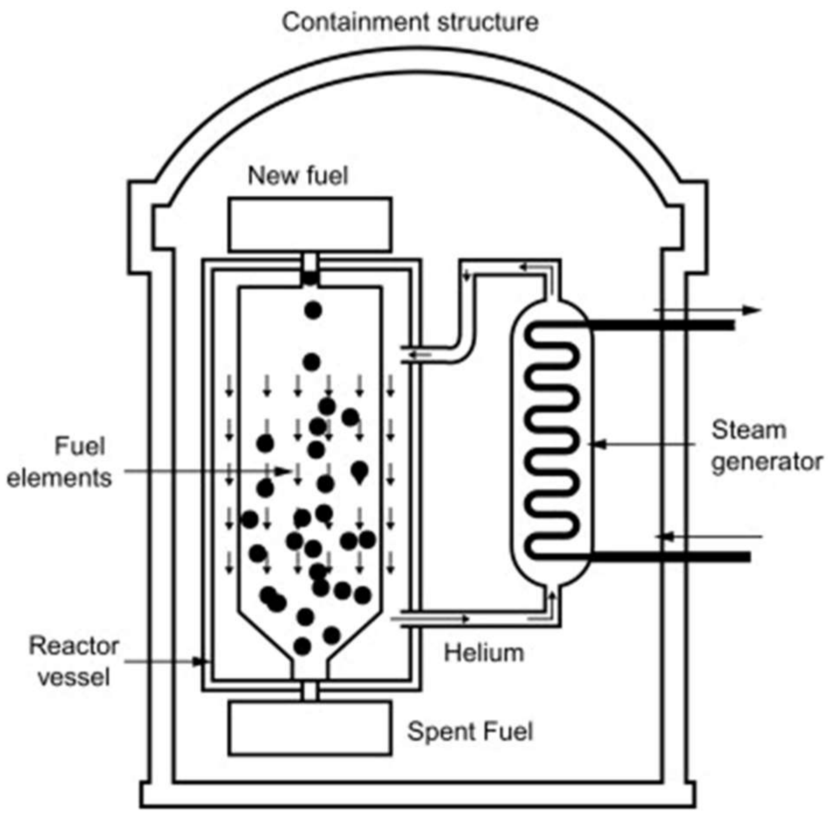
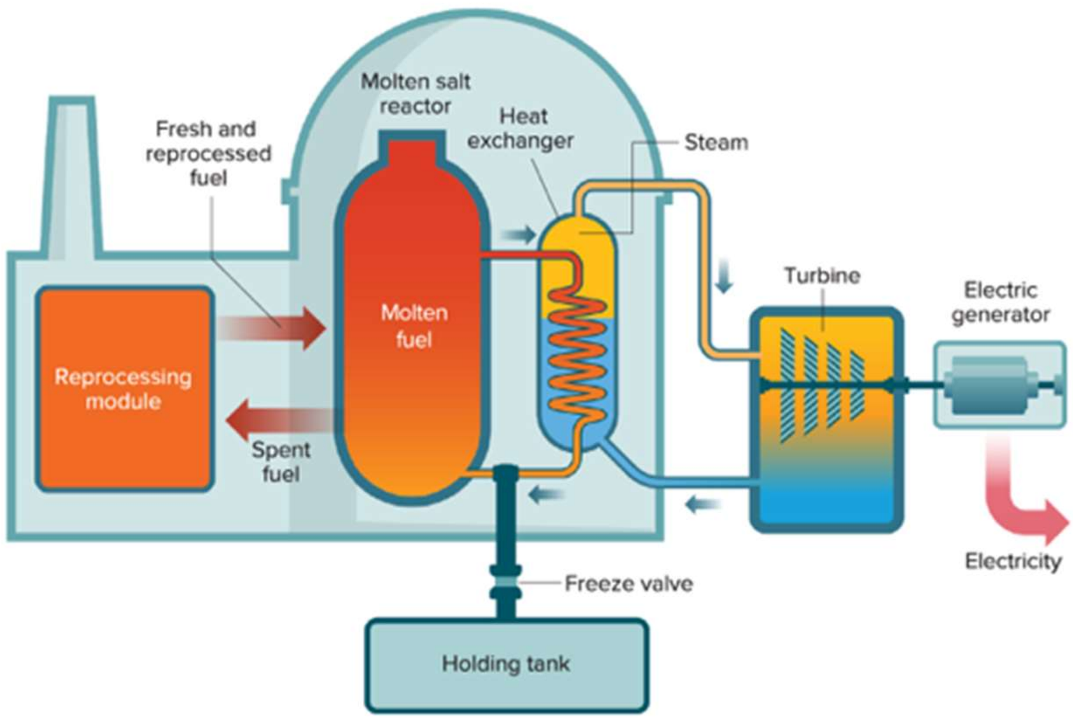
TerraPower
ARC
ADVANCED REACTOR CONCEPTS, LLC

High temperature gas reactors (HTGR)



Molten salt reactors (MSRs)



TerraPower

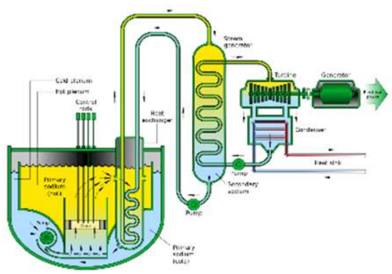
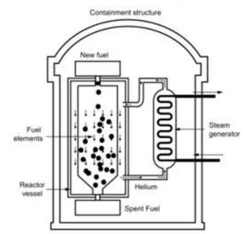
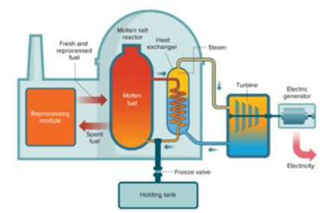
moltex energy
safer, cheaper, nuclear

TERRESTRIAL ENERGY

Common types of advanced reactors

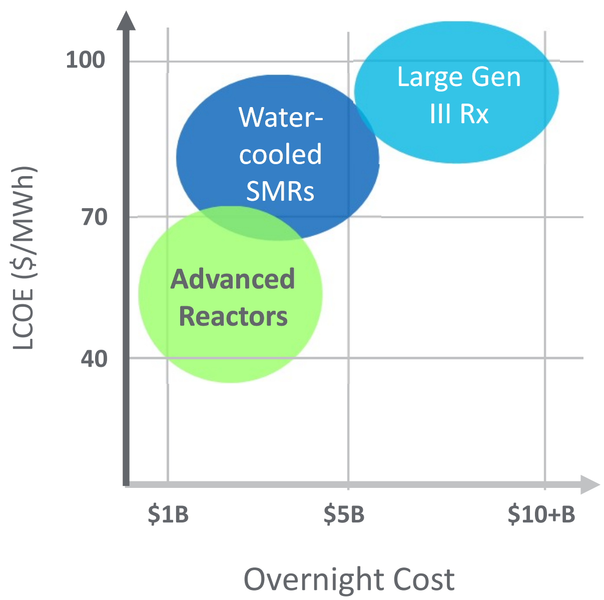
○ ◔ ◑ ◕ ●

Inferior ← → Superior

	Sodium Fast Reactor (SFR)	High Temperature Gas Rx (HTGR)	Molten Salt Reactor (MSR)
			
Pressure	●	◑	●
Temperature	◕	●	●
Fuel Flexibility & Utilization	●	◑	◕
Maturity/experience	● Most mature / 22 reactors	◕ Next / 5 reactors	◔ Least mature / 1 reactor

>100 Advanced Reactors/SMRs globally

Why advanced reactors?



Source: graph estimated from multiple public reports
* Not all Advanced Reactors

Advanced vs. water cooled reactors

- ✓ Lower pressure
- ✓ Higher temperature
- ✓ Improved fuel utilization
- ✓ Smaller EPZ

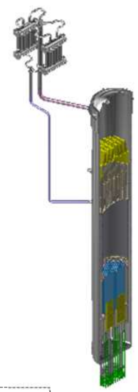
= Lower costs

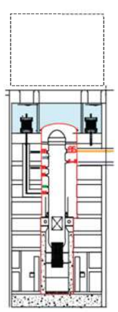
Aiming to be simpler … safer … lower cost

Leading light water SMRs

BWRX300

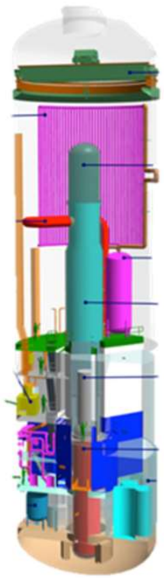
300 MW

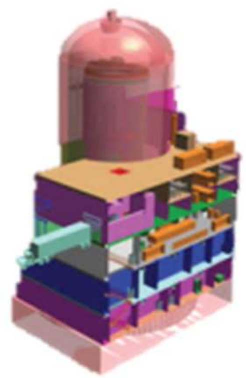




HOLTEC INTERNATIONAL

160 MW





NUSCALE™ Power for all humankind

720 MW

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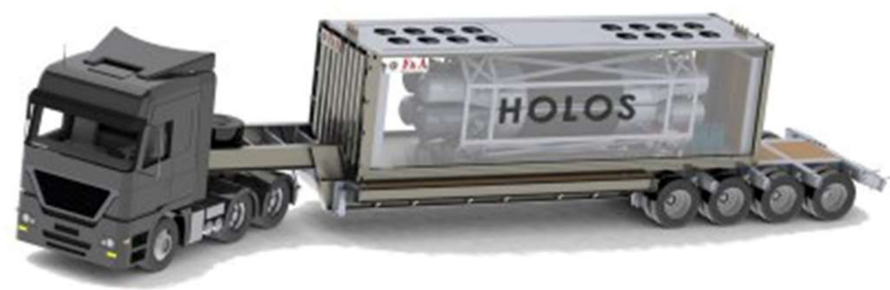
Sources: NuScale: public information and NRC DCD Application
Holtec: "Holtec SMR-160 Technical Bulletin" Rev 8 5/2013, https://smrllc.com/technology/smr-160-overview/

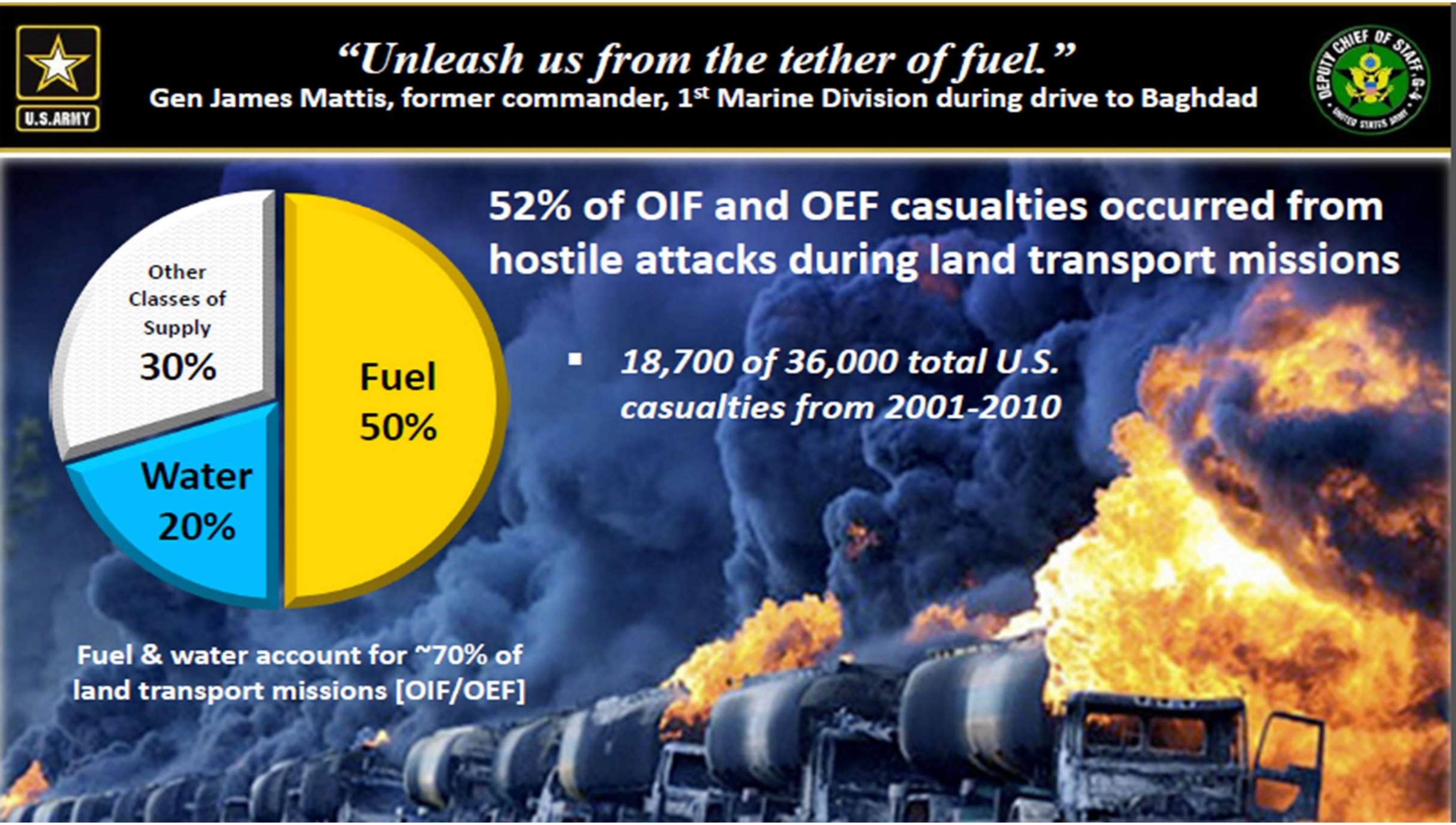
Micro Reactors

Various vendors/designs:

- Oklo
- Westinghouse eVinci
- U-Battery (Urenco)
- HolosGen
- X-energy
- General Atomics
- Ultra Safe Nuclear Corp
- StarCore Nuclear

- Canada and Alaska considering for remote communities currently powered by diesel generation
- Army and DoD applications




"Unleash us from the tether of fuel."
Gen James Mattis, former commander, 1st Marine Division during drive to Baghdad
U.S.ARMY
DEPUTY CHIEF OF STAFF, G-4
UNITED STATES ARMY
52% of OIF and OEF casualties occurred from hostile attacks during land transport missions
18,700 of 36,000 total U.S. casualties from 2001-2010
Other Classes of Supply 30%
Fuel 50%
Water 20%
Fuel & water account for ~70% of land transport missions [OIF/OEF]

ThirdWay Nuclear Reimagined


Remote Arctic Community


Data Center


Clean Transit Hub


High Temperature Reactor for Industry

CNSC Vendor Design Review (VDR)

Phase 1 – Assess intent to comply with requirements

Phase 2 – Identify potential fundamental barriers to licensing

Phase 3 – Undertake pre-construction follow-up

VDR No.	Country of origin	Company	Reactor type
1	Canada/U.S.	Terrestrial Energy (IMSR-400)	Molten salt / 200 MWe
2	U.S.	Ultra Safe Nuclear/Global First Power	High-temperature gas prismatic block / 5 MWe
3	Sweden / Canada	LeadCold	Molten lead pool fast spectrum / 3-10 MWe
4	U.S.	Advanced Reactor Concepts	Sodium pool fast spectrum / 100 MWe
5	UK	U-Battery	High-temperature gas prismatic block / 4 MWe
6	UK	Moltex Energy	Molten salt fast spectrum / ~300 MWe
7	Canada/U.S.	StarCore Nuclear	High-temperature gas prismatic block / 10 MWe
8	U.S.	SMR, LLC. (a Holtec International Company)	Pressurized water / 160 Mwe
9	U.S.	NuScale Power	Integral pressurized water / 50 Mwe
10	U.S.	Westinghouse Electric Co.	eVinci micro reactor / <25 MWe
11	U.S.	GE Hitachi Nuclear Energy (BWRX-300)	Boiling Water Reactor / 300 MWe

Source: CNSC, https://nuclearsafety.gc.ca/eng/reactors/power-plants/pre-licensing-vendor-design-review/index.cfm

GE Hitachi Innovation in Advanced Nuclear

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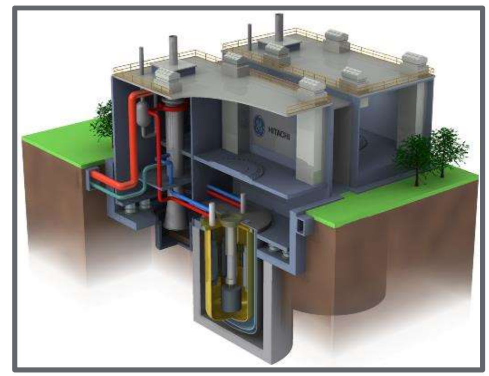
New Plant Innovation

Past, Present and into the Future

Rich history of nuclear innovation ready to support advanced reactor market



Over 60 years of nuclear experience & innovation

- 1939 – First GE involvement in nuclear physics
- 1951 – Aircraft nuclear propulsion
- 1955 – GE Atomic Division established
- 1957 – Vallecitos BWR AEC License #1
- 1981 – PRISM development commences
- 1996 – 1st ABWR built on time on budget
- 2014 – ESBWR NRC License
- 2017 – BWRX-300 launched & ABWR licensed in 4th country
- 2018 – VTR Contract PRISM

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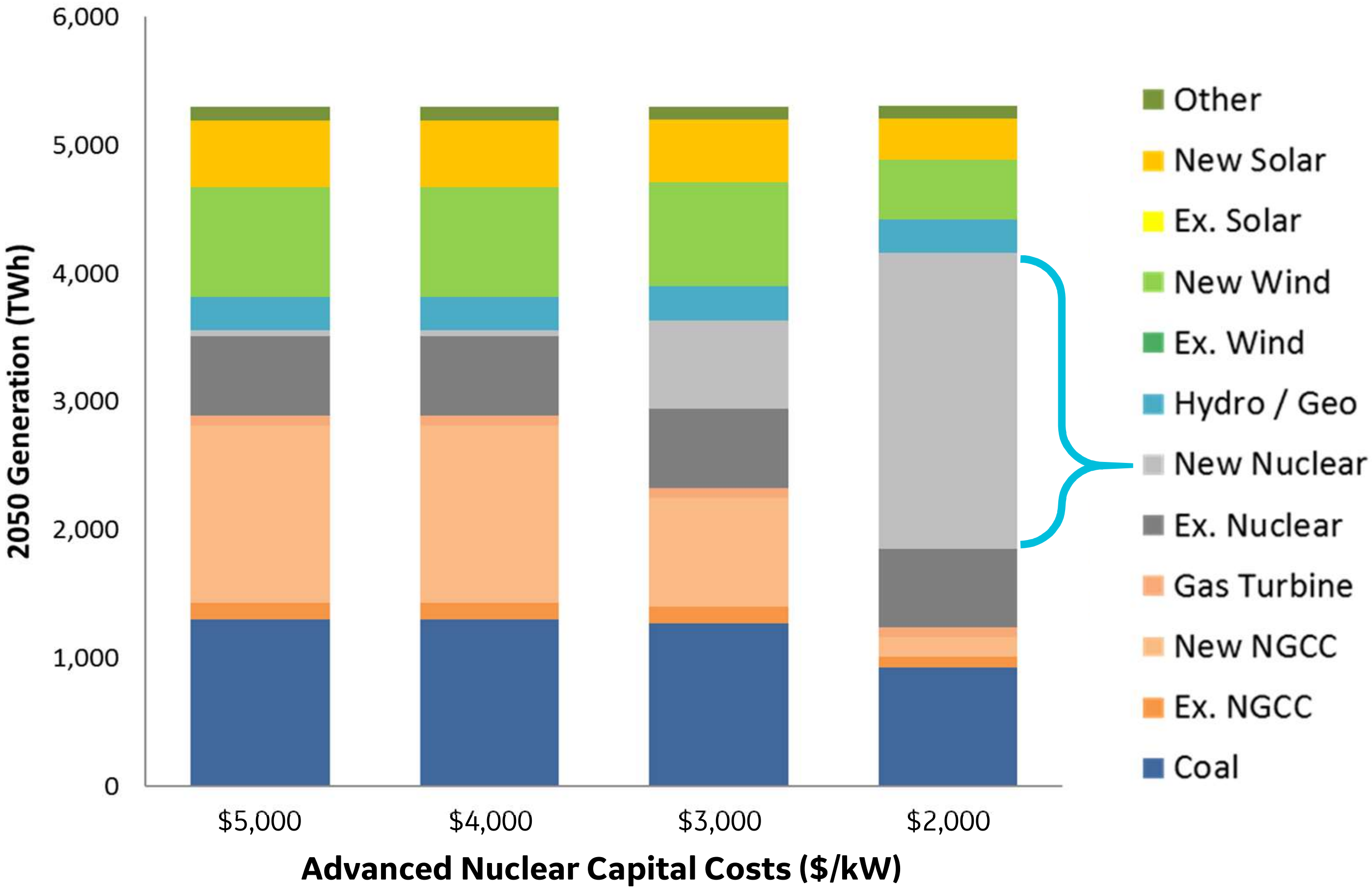
Solving the Cost Challenge

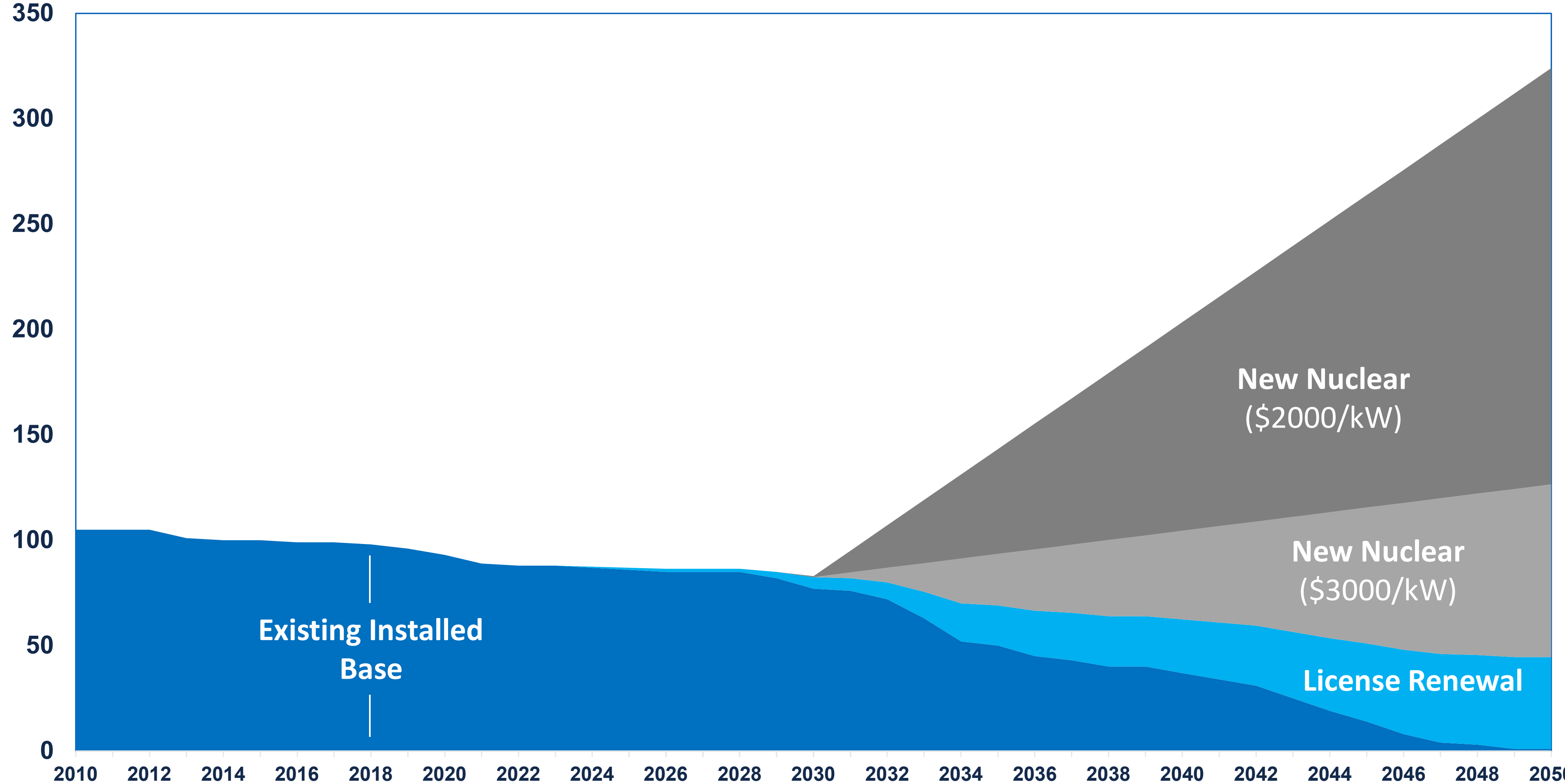
Importance of Cost



Nuclear could become a major source of U.S. power generation at $2000/kW

Source: Figure 3.2 from EPRI Report 3002011803: Exploring the Role of Advanced Nuclear in Future Energy Markets

Nuclear Inflection Point



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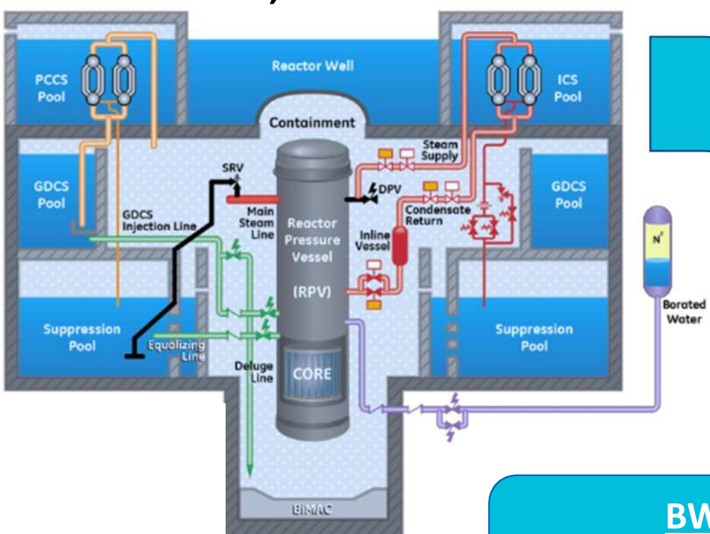
BWRX300

- 10th generation BWR
- 300 MWe SMR
- World class safety
- LCOE competitive with gas
- Up to 60% capital cost reduction per MW
- Scaled from licensed ESBWR
- Designed to eliminate LOCA
- Reduced on-site staff and security
- Design-to-cost approach: <$1B total & <$2,250/kW
- Proven components, fuel, and supply chain
- Constructability integrated into design

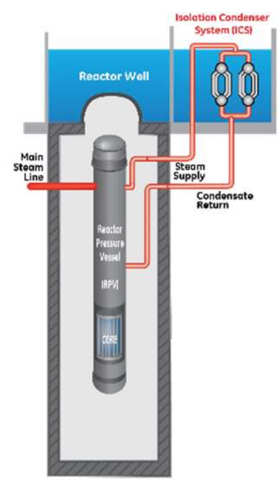
Deployable by 2028

BWRX-300
Optimized and simplified structures

ESBWR
161,000 m^3



90% volume reduction



BWRX300

15,500 m^3

- Mitigation of Large LOCAs … eliminates multiple systems
- Metal containment … small, simple, robust
- Underground containment … reduced staff and staff
- TI & BOP off-the-shelf

<u>BWRX-300 compared to ESBWR:</u>
>50% building volume reduction/MW
>50% less concrete/MW

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BWRX300

Industry collaboration

Investor

Dominion Energy®

http://www.world-nuclear-news.org/NN-Dominion-Energy-invests-in-GE-Hitachi-SMR-2105187.html

Alliance Partner

HITACHI GE

Collaborators

Exelon Generation

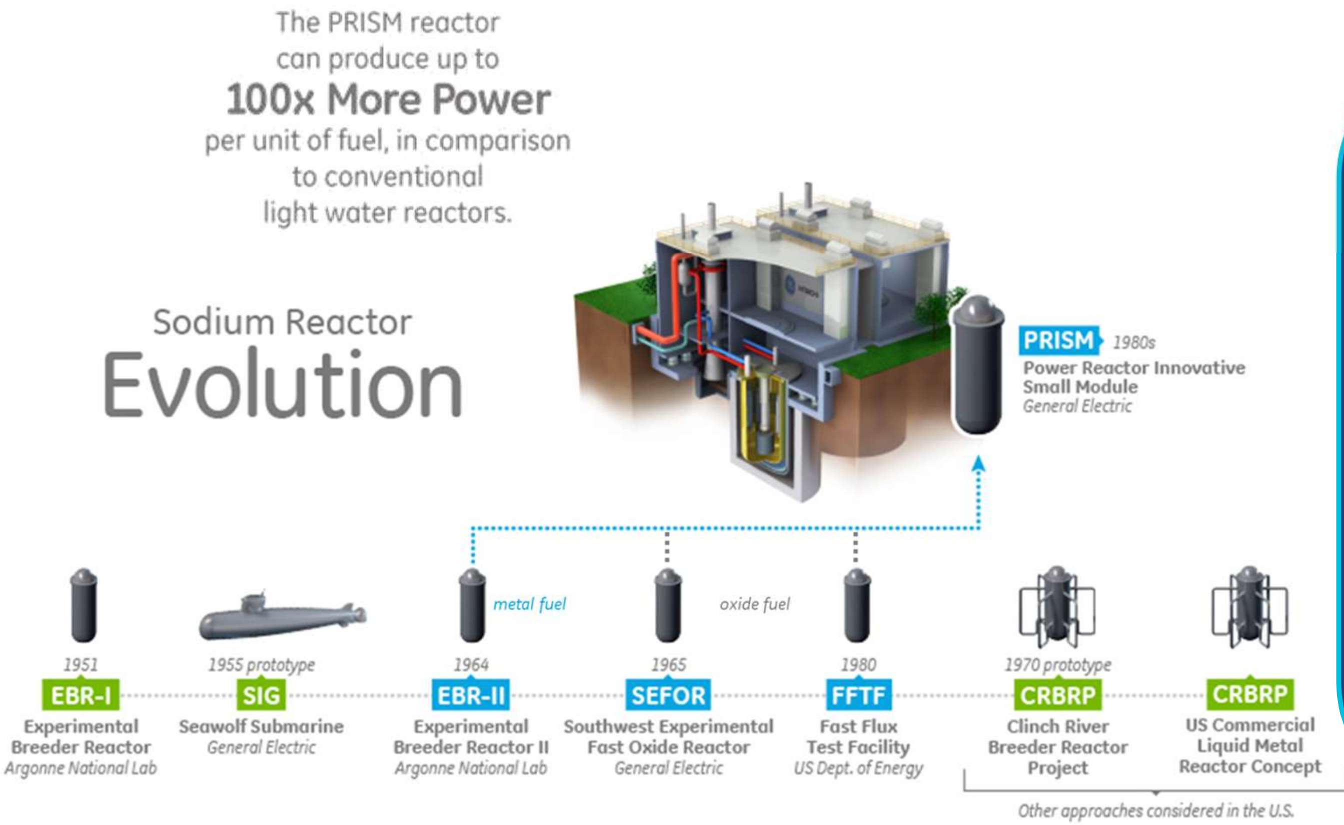
BECHTEL

MIT

GE HITACHI

PRISM and VTR

Sodium Fast Reactor Solution
PRISM



- Sodium cooled fast reactor … Gen IV
- 165 and 311 MWe options
- Compact pool-type … atmospheric pressure, eliminates LOCA
- Passive safety … air cooling
- Proven metal fuel … inherently safe
- Superheated steam … plant efficiency
- Modular design … quality & efficiency
- High temperature … industrial process heat applications
- Advanced Recycling Center application … 99% fuel utilization

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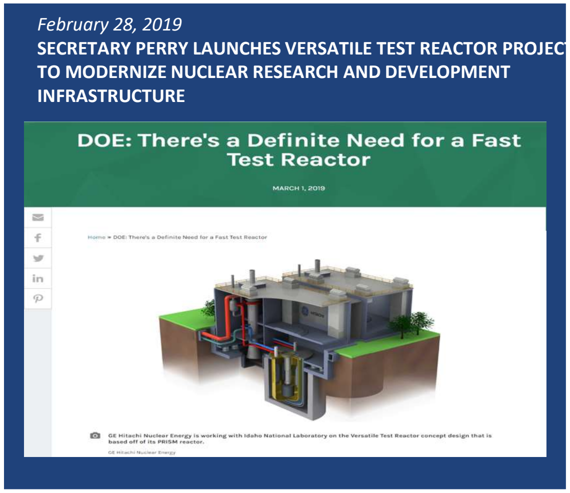
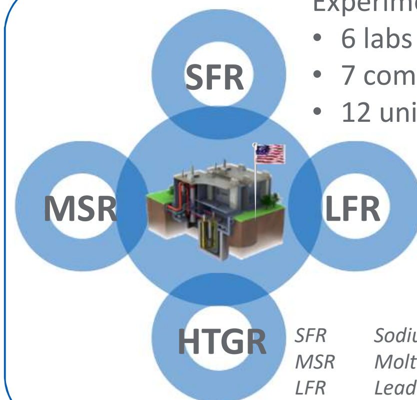
VTR Initial Phase Summary



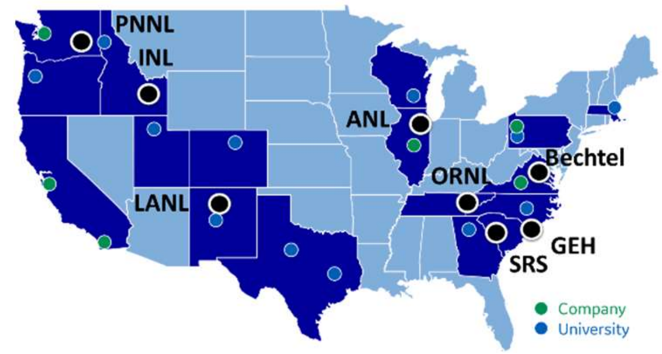
GEH Deliverables

- **Advance** conceptual **design**
- **Adapt** PRISM for VTR … add & remove Structures, Systems and Components
- High confidence **cost assessment**
- High confidence **schedule assessment**

Inclusive



Experiments:
- 6 labs
- 7 companies
- 12 universities



SFR Sodium Fast Reactor
MSR Molten Salt Reactor
LFR Lead Fast Reactor
HTGR High Temp. Gas Reactor

ANL Argonne National Lab
INL Idaho National Lab
LANL Los Alamos National Lab

ORNL Oak Ridge National Lab
PNNL Pacific Northwest National Lab
SRS Savannah River Site

Scope

INL / ANL / ORNL / LANL / PNNL/SRS		GEH/Bechtel
Integration (INL Lead)	Core Design Concept	Reactor Facility Concept
Licensing	Transient Analysis	Heat Rejection Concept
Fuel Design/Manufacturing	Safety Analysis	Virtual Design & Construction
Site Infrastructure	Risk Analysis	Cost Estimate
413.3B Acquisition Process	Probabilistic Risk Assessment	Schedule Estimate
Experiments		Supply Chain Plan

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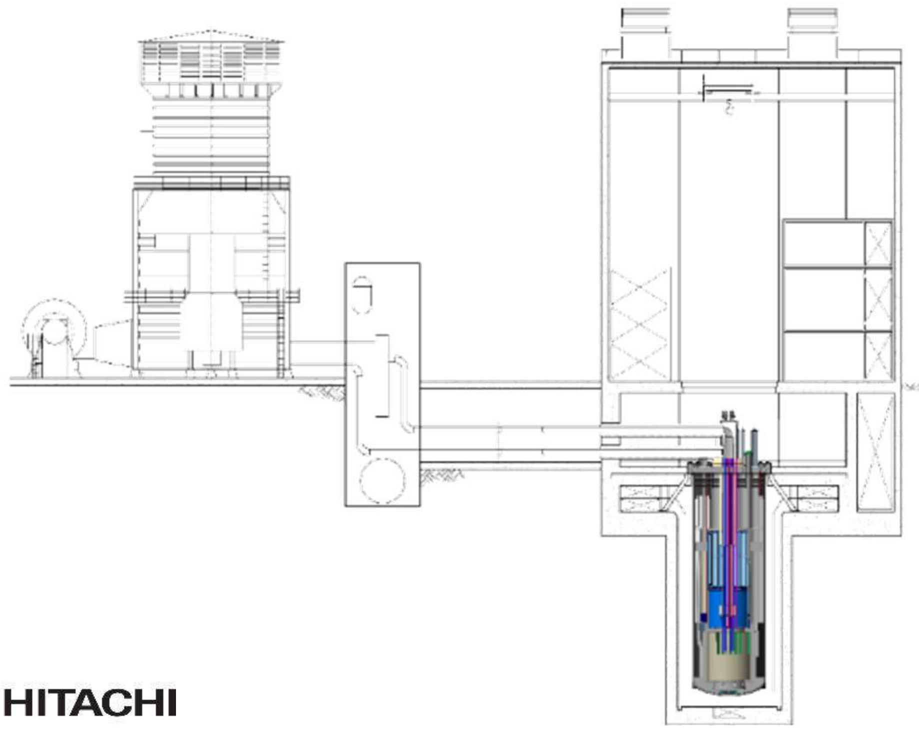
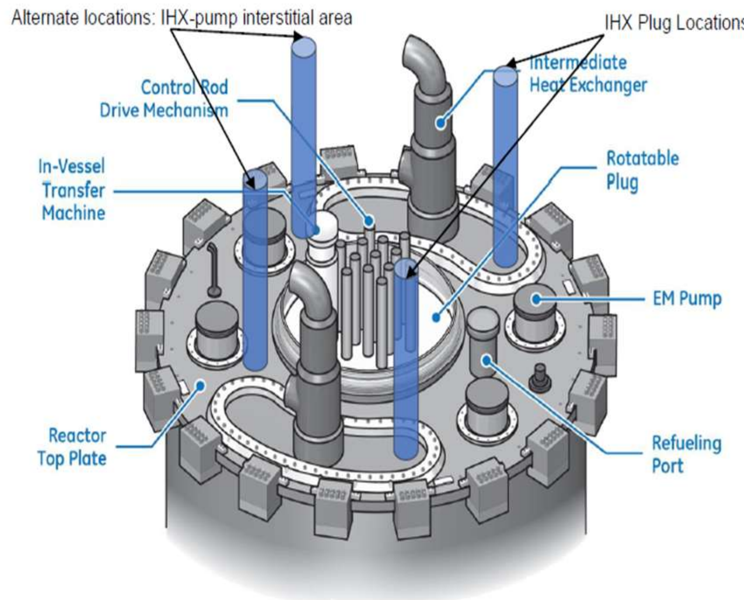
Versatile Test Reactor
PRISM adaptation

Sodium to air heat exchangers





Potential Extended Length Assembly In-Vessel Storage Locations

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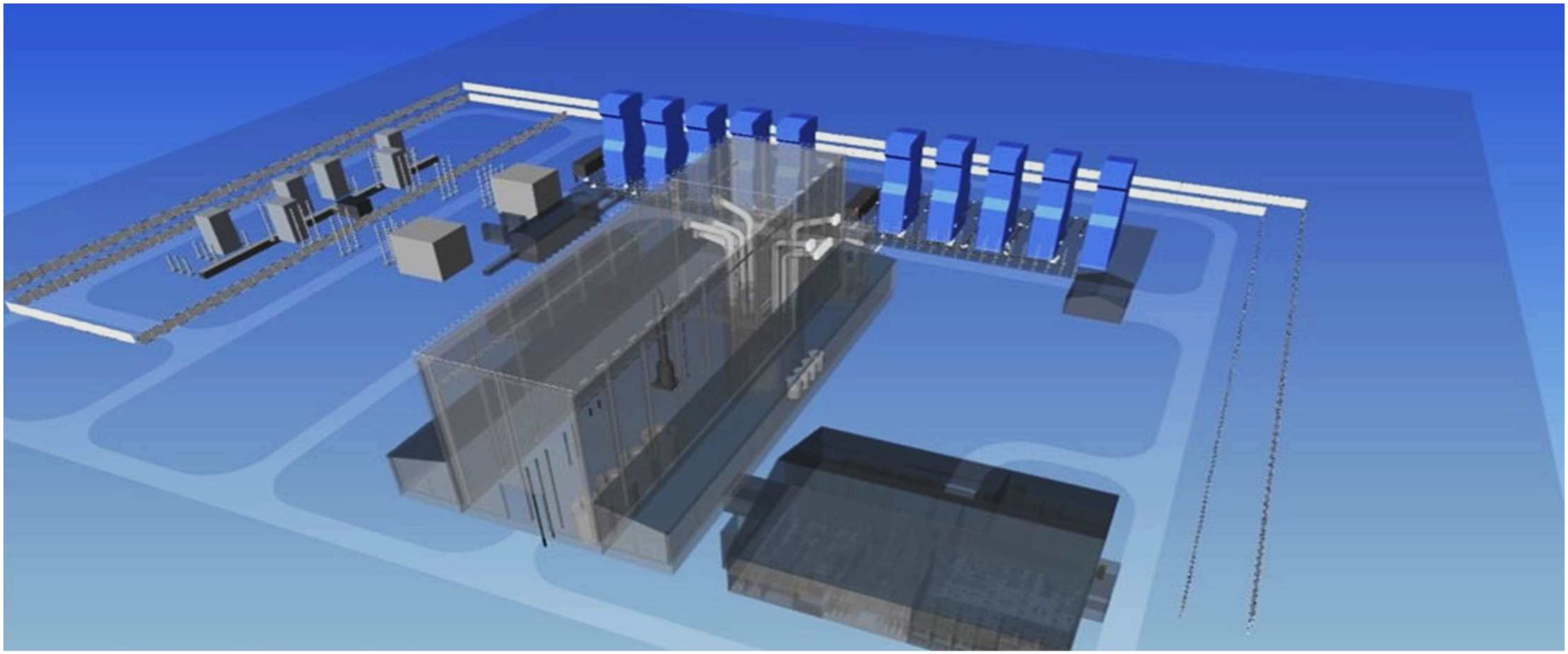
Versatile Test Reactor - Evolving Site Layout Concept



Thank You!

29