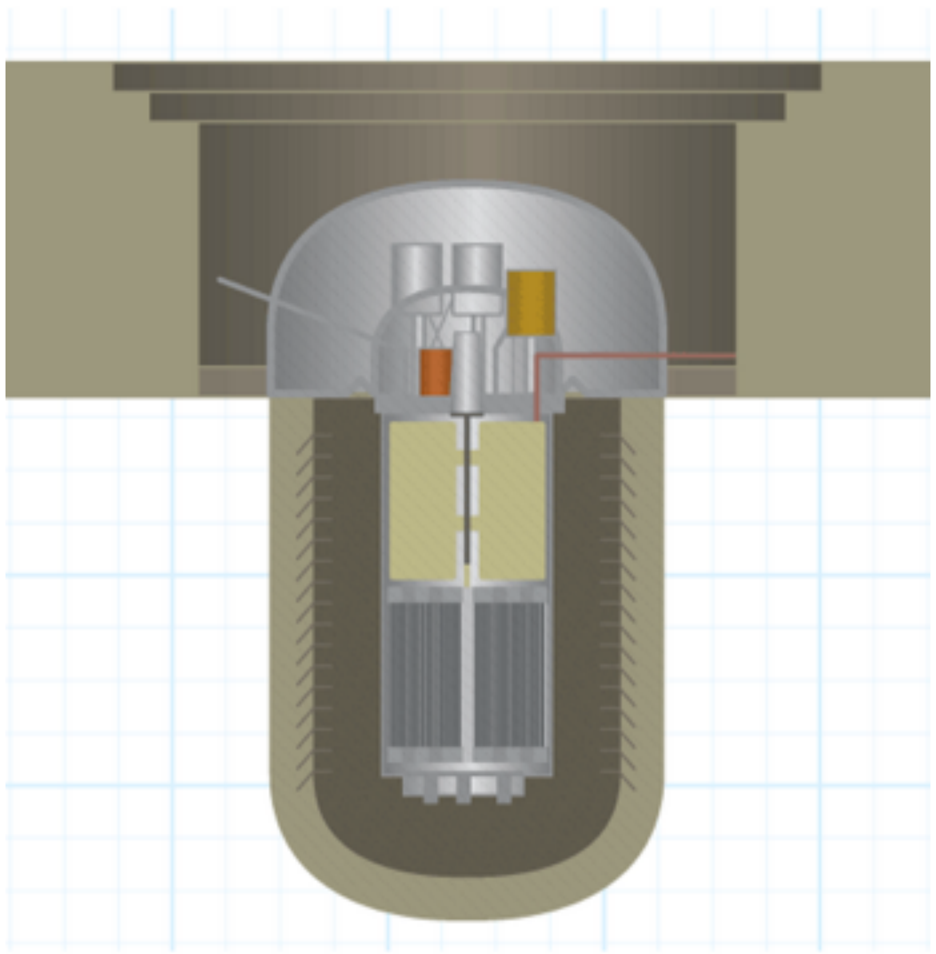

Source: terrestrialenergy.com

Small Modular Reactors

Technology and Deployment Choices

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Briefing for the U.S. Nuclear Regulatory Commission
Rockville, Maryland, November 5, 2014

Revision 4b

Princeton Project on Small Modular Reactors

funded by the MacArthur Foundation, Carnegie Corporation of New York,
and the Princeton Carbon Mitigation Initiative

SCOPE OF PROJECT

Review and analyze proposed SMR designs and their associated nuclear fuel cycles

Examine the implications of a large-scale deployment of SMRs
with a particular focus on resource requirements and proliferation risks

(Research supported by neutronics calculations for notional SMRs)

OUTLINE OF THIS TALK

Part I: Technology Choices for SMRs

Part II: Siting and Deployment Choices for SMRs

PART I: Technology Choices for SMRs

Integral Pressurized Water Reactors

(“Leveraging the First-to-Market Advantage”)

Most Concepts Considered Today Are Based on Standard Light-water Reactor Technology

Design	Company	Power	Status
mPower	Babock & Wilcox	2 x 180 MWe	Detailed design
NuScale	NuScale Power	12 x 45 MWe	Detailed design
W-SMR*	Westinghouse	225 MWe	Basic design
HI-SMUR (SMR-160)	Holtec	145 MWe	Basic design
SMART	KAERI	100 MWe	Licensed
KLT-40S	OKBM, Russia	2 x 32 MWe	Under construction

*Project currently suspended

(Babcock & Wilcox (mPower) and NuScale Power have been selected by DOE's cost-sharing program)

General Observations About Integral Pressurized Water Reactors

Technology is mature

(compared to all other SMR concepts currently being considered)

Characteristics compared to existing gigawatt-scale light-water reactors

Significantly higher uranium/fuel demand (55–65%)
(and respective increase in volume of spent fuel)

Significantly higher demand for enrichment capacities

Comparable attractiveness of spent fuel for reprocessing or diversion
(total plutonium production increases by 30–40%, but lower concentration in spent fuel)

A. Glaser, L. Berzak Hopkins, M. V. Ramana, "Resource Requirements and Proliferation Risks Associated with Small Modular Reactors," *Nuclear Technology*, 184, October 2013, pp. 121–129

PART I: Technology Choices for SMRs

Reactors with Lifetime Cores

(“Offering the Nuclear Battery”)

Early Interest in SMRs was Often Motivated by the Vision of Lifetime-Core Reactors

A 2007 IAEA report discussed 30 reactor concepts without on-site refueling

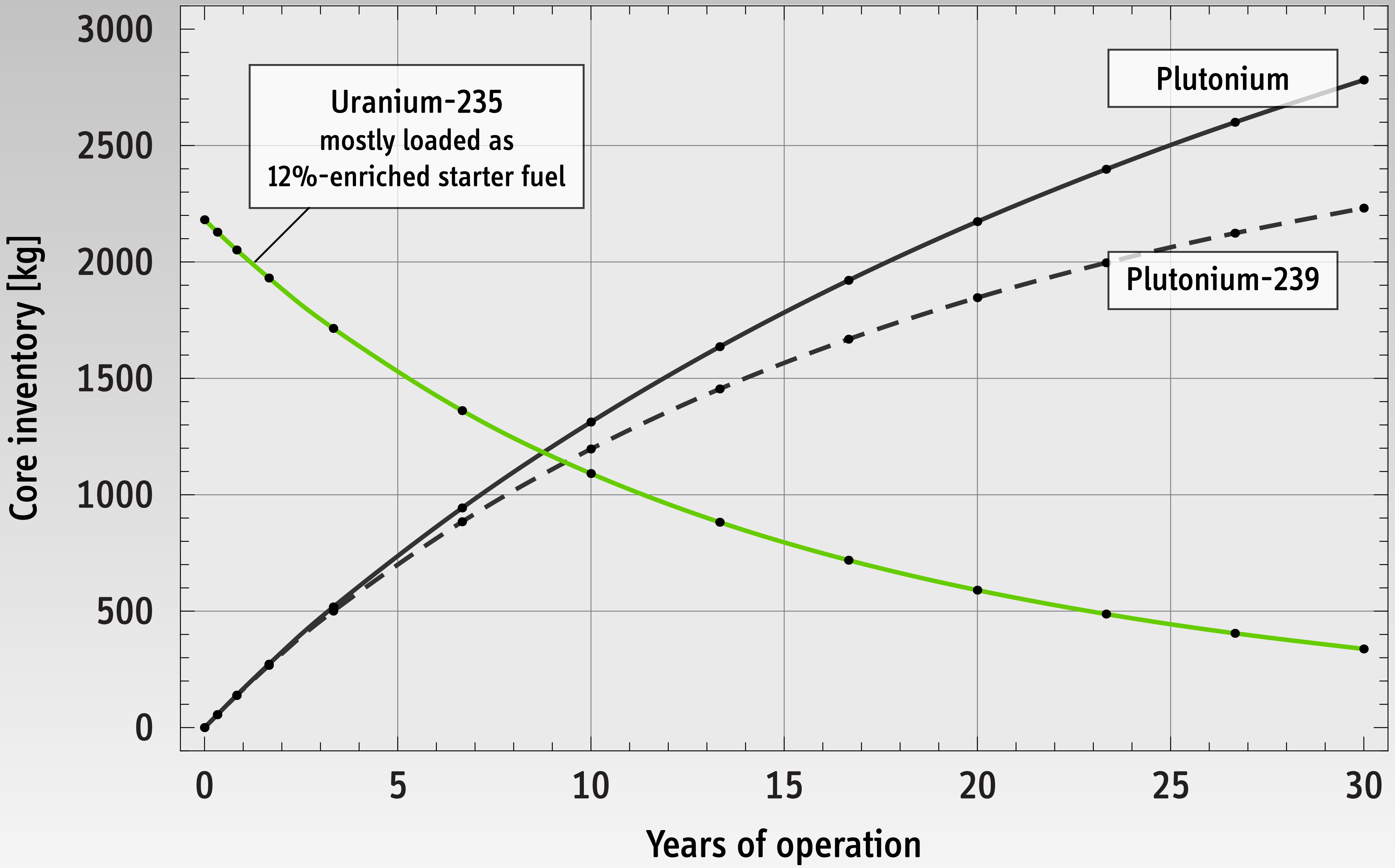
but very few projects in this category retain (some) momentum today

Design	Company	Power	Status
Gen4 Module (G4M)	Gen4 Energy (USA)	25 MWe	Conceptual design
4S	Toshiba (Japan)	10 MWe	Detailed design
EM^2	General Atomics	200 MWe	Conceptual design

Status of Small Reactor Designs Without On-Site Refuelling, IAEA-TECDOC-1536, International Atomic Energy Agency, January 2007

SMRs with Lifetime Cores Can Have Significant Inventories of Fissile Material

Neutronics calculations for a notional design, 200 MWe, 30-year core life, 300 days per year



A. Glaser, L. Berzak Hopkins, M. V. Ramana, "Resource Requirements and Proliferation Risks Associated with Small Modular Reactors," *Nuclear Technology*, 184, October 2013, pp. 121–129

General Observations About (Small) Reactors with Lifetime Cores

Characteristics compared to existing gigawatt-scale light-water reactor

Significantly decreased resource demand
(when operated as a break-even breeder, e.g. with a fast-neutron spectrum)

In principle, compatible with once-through operation
(but large plutonium inventory in spent fuel potentially “attractive” for reprocessing)

Overall proliferation risks strongly depend on design choices and fuel-cycle architectures

Significant technology gaps remain

(especially with regard to irradiation performance of fuels and materials)

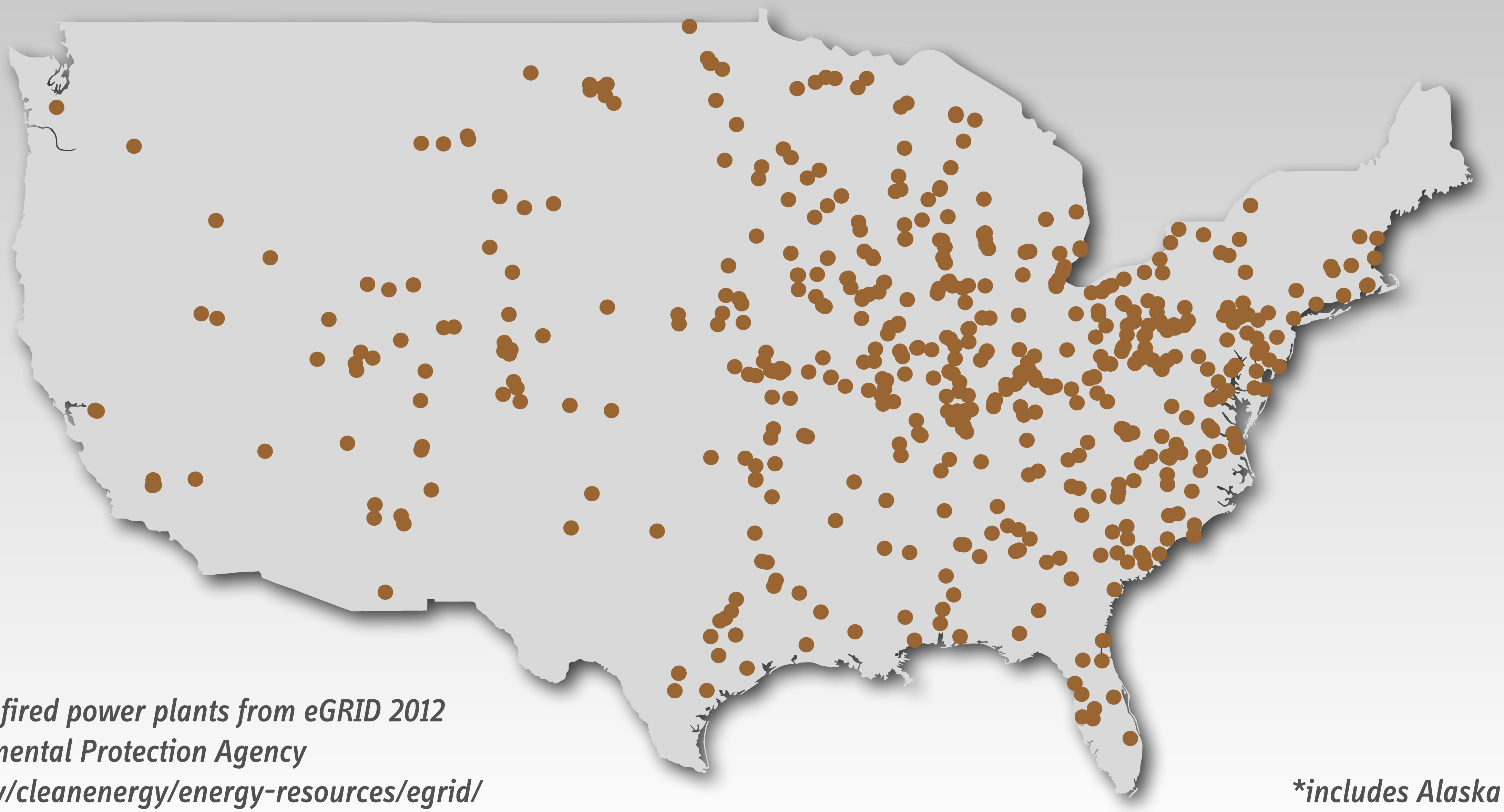
PART II

Siting and Deployment Choices

Could Small Modular Reactors Be Deployed at Sites That Previously Hosted Coal-fired Plants?

In the United States, 560 coal sites (1370 generators) with an installed capacity of 330 GWe*

250 sites (with about 600 generators and a cumulative capacity of 115 GWe)
could be considered candidate sites for SMR deployment (pre-1980 and 40–500 MWe)



Data on coal-fired power plants from eGRID 2012
U.S. Environmental Protection Agency
www.epa.gov/cleanenergy/energy-resources/egrid/

**includes Alaska and Hawaii*

Siting Small Modular Reactors

Coal-fired power plants are generally closer to urban areas

No U.S. nuclear power plant has population of more than 300,000 within 10 miles of the plant

whereas 30% of U.S. small/old coal plants have population of more than 300,000 within that range

But large numbers of coal-plants are still in relatively remote areas

60% of U.S. small/old coal plants have population of less than 100,000 within 10 miles

(compared to 75% of all U.S. nuclear power plants)

This corresponds to about 150 sites with 70 GWe (i.e., hypothetically 200–300 SMRs)

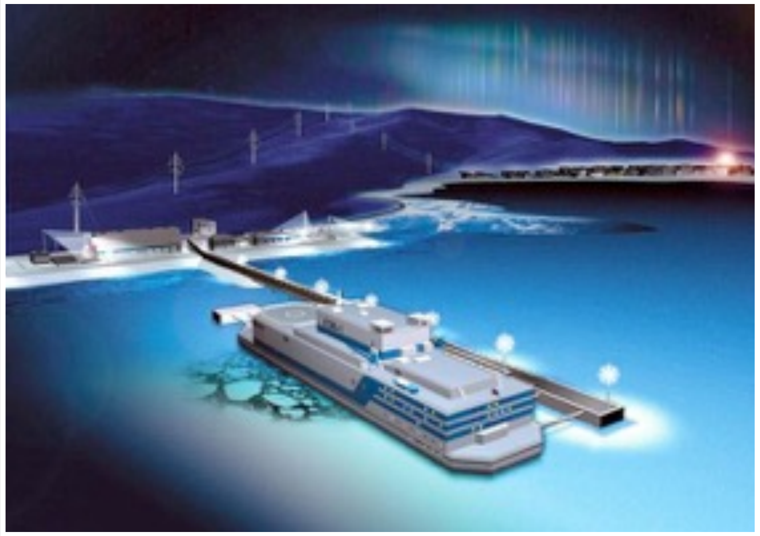
Many opportunities to site SMRs at locations similar to typical nuclear sites

(Moreover, 62 additional sites with operating nuclear power plants)

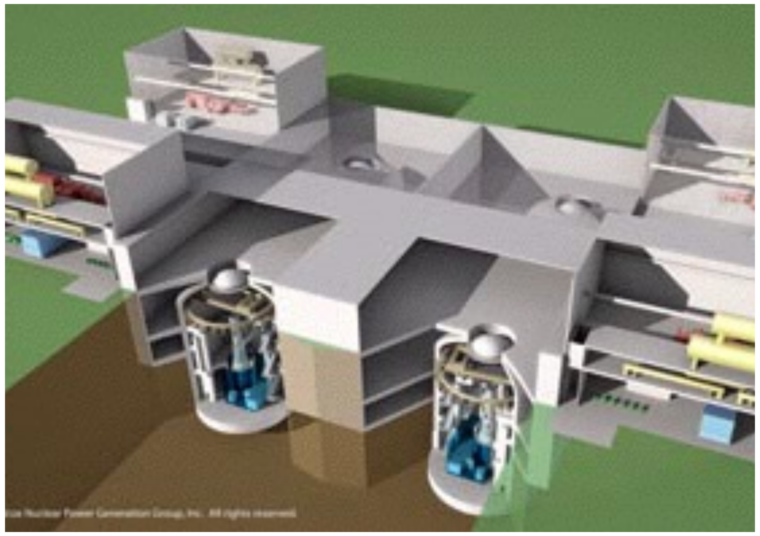
Based on population data from the United States 2010 Population Census; Digital Map and Geospatial Information Center, Princeton University

Proposed Deployment Modes for SMRs

on barges, underground, underwater



FNPP, Rosatom



mPower, B&W

Flexblue, DCNS

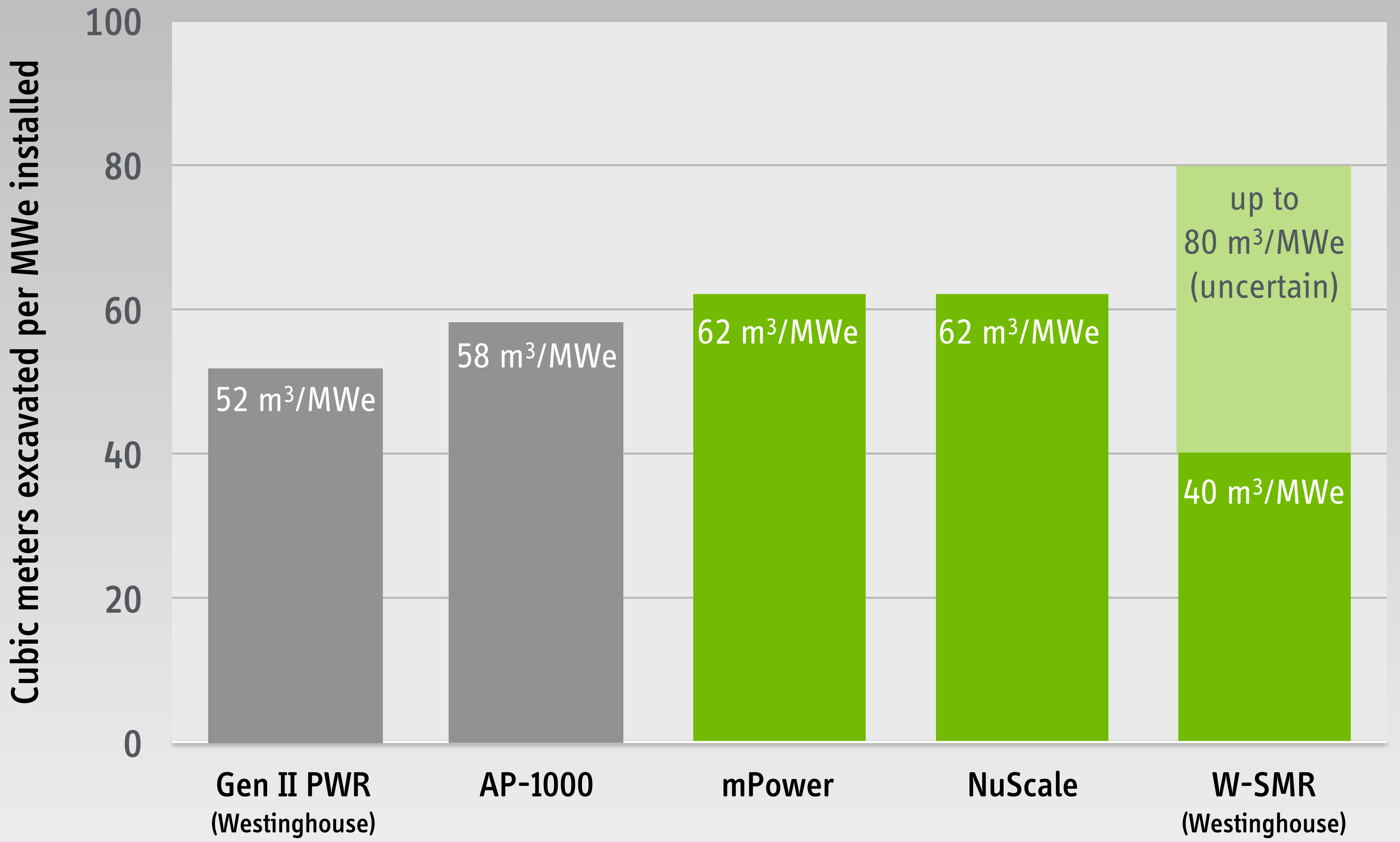
Essentially all SMR designs currently considered for near-term deployment in the United States would be built underground

Idea is not new but has attracted new attention since 9/11

C. W. Forsberg and T. Kress, Underground Reactor Containments: An Option for the Future?, CONF-970649-3, 1997
W. Myers and J. M. Mahar, Underground Siting of Small Modular Reactors: Rationale, Concepts, and Applications, ASME Symposium, 2011

Excavation Volumes for Underground Siting

(Based on the Containment Size of Different Reactor Types)



Per megawatt installed, underground siting of SMRs is not necessarily easier than for typical gigawatt-scale power reactors

Values for SMRs are estimates by Ali Ahmad (Princeton University, October 2014)

Underground vs Aboveground Siting

Underground siting may have important advantages … but also some drawbacks

Enhanced protection against aircraft impact and (possibly) earthquakes
(versus accessibility in emergencies or resistance to flooding)

Additional costs of underground siting are highly uncertain, somewhere between 20–60%

SMRs already challenged to compete with large reactors on levelized cost of electricity

Benefits of agreeing early on "standard" deployment modes

Standardization can "enhance plant safety, improve the efficiency and reduce the complexity and uncertainty in the regulatory process"

Nuclear Power Plant Standardization, Policy Statement
Nuclear Regulatory Commission, 10 CFR Part 50, 52 FR 34884, Washington DC, September 1987

Summary

Technology and Deployment Choices for SMRs

(Summary)

Technology Choices for SMRs

Current focus is on light-water reactor concepts for SMRs

Risk of technology lock-in by giving preference to first-to-market projects

Reactor design choices and fuel-cycle architectures determine resource requirements and proliferation risks of SMRs

Siting and Deployment

Many sites available in the United States that are comparable to typical nuclear sites

(with regard to population density near the plant)

Underground vs aboveground siting involves tradeoffs between security, safety, and economics