CHANGING WHAT'S POSSIBLE

Safe and Secure Micro Modular Reactors

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ARPA-E Safe and Secure Megawatt-Size Nuclear Power Workshop
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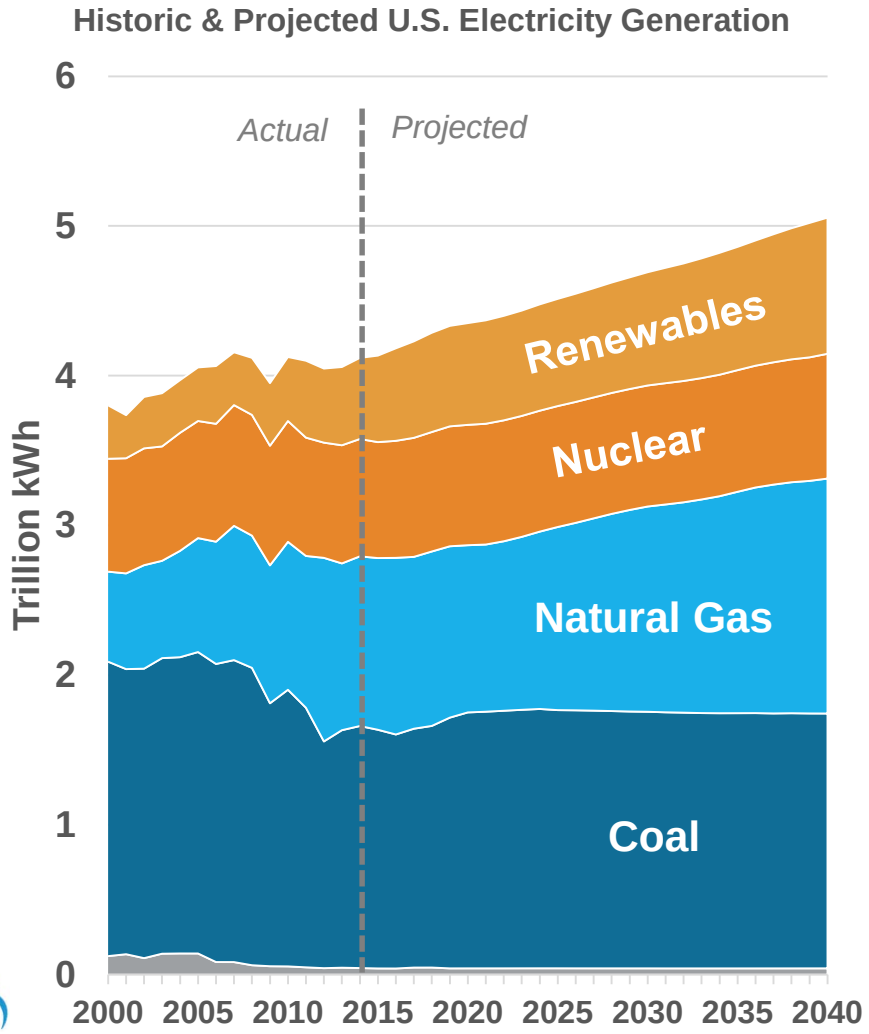
Why nuclear is essential?



eia

The New York Times
The New Atomic Age We Need

Forbes
Paris COP21 and the Urgent Need for More Nuclear Energy

Four top climate scientists *James Hansen, Tom Wigley, Ken Caldeira*, and *Kerry Emanuel* urged a major expansion of nuclear power.

Carbon-free baseload/"standby" power to balance the intermittent solar & wind

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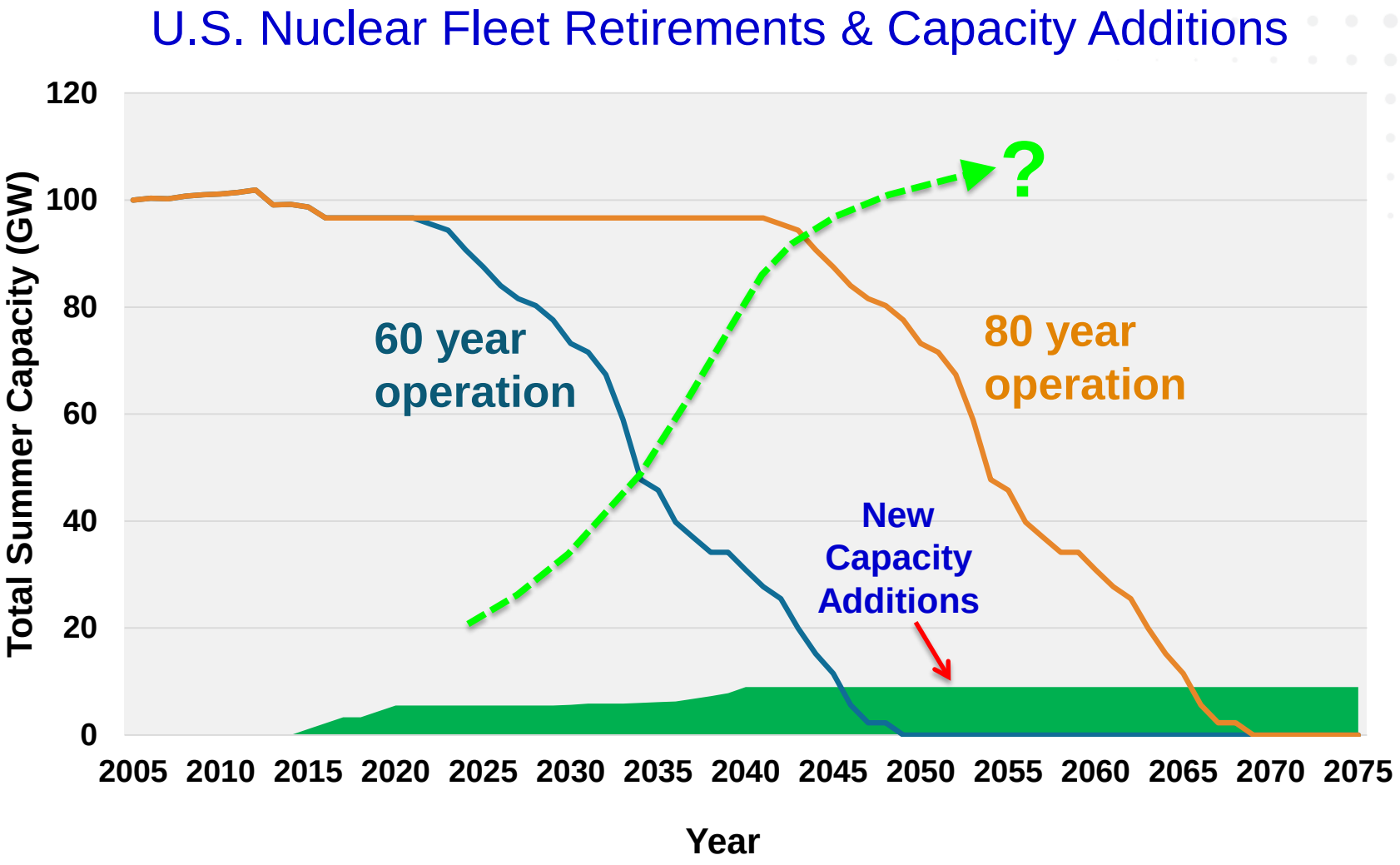
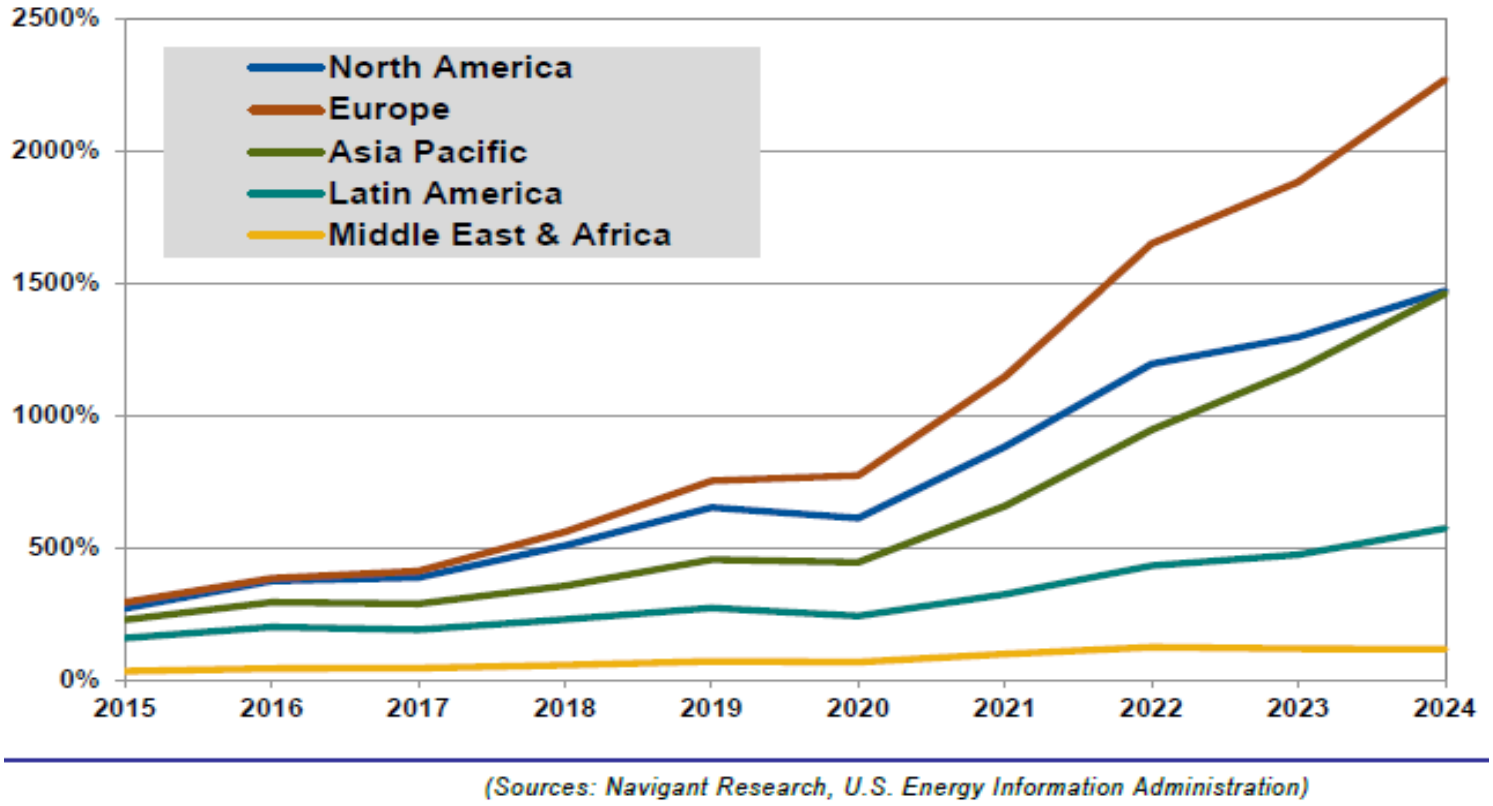
U.S. nuclear energy



Source: EIA (2015), NEI, NRC (2015), Capacity additions data from EIA

Decentralized Generation (DG)



Courtesy: Westinghouse

Forecast (Navigant Research & EIA)**:**

- Globally 1.2 TW of new DG is expected by 2023, valued at **$1.3 trillion**
- DG will displace at least 321 GW of new large-scale power plants by 2024

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Can nuclear be part of the DG growth opportunities?

Micro Modular Reactors (MMRs): <10 MW_e

In-factory certification

Make in factories
Certify in factories
Transport to sites

- Inherently safe
- Proliferation resistant
- Tow-away decommission
- Made to order

Micro Modular Reactors (MMRs)

- **Safety, safety, safety …**
- **Security, security …**
- **Non-proliferation …**

- **MMR enables more rigorous safety validation tests like jet engines**

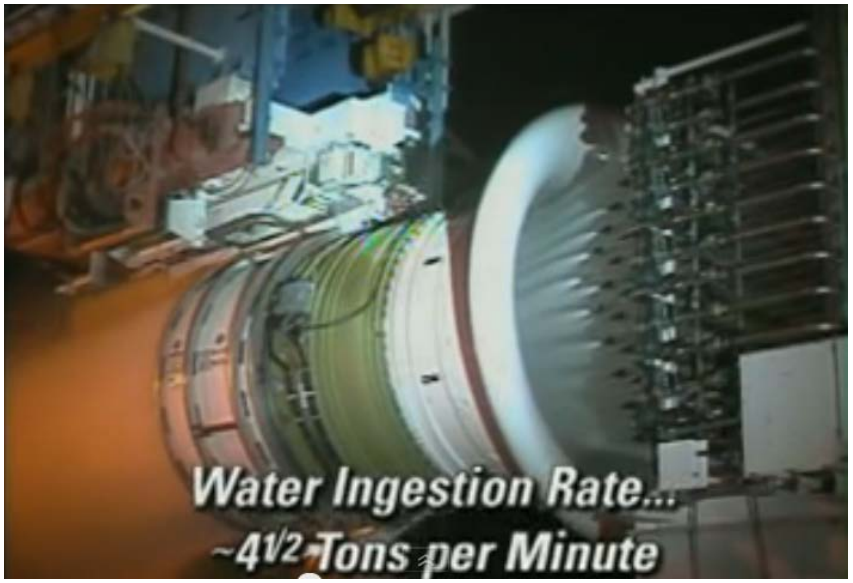
Design for safety → jet engine example

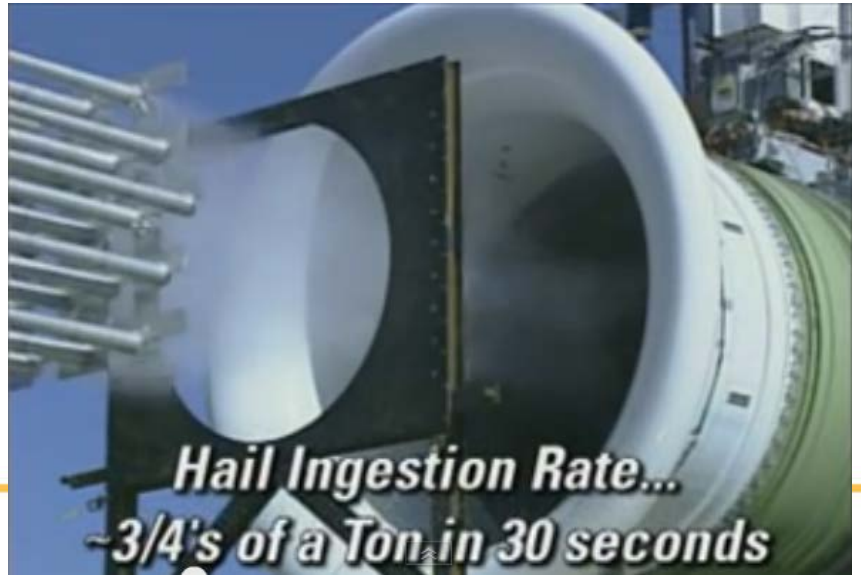
- Jet engine certification test examples
- Carbon fiber composite fan blades
- TiAl intermetallic blades

GE90-115B

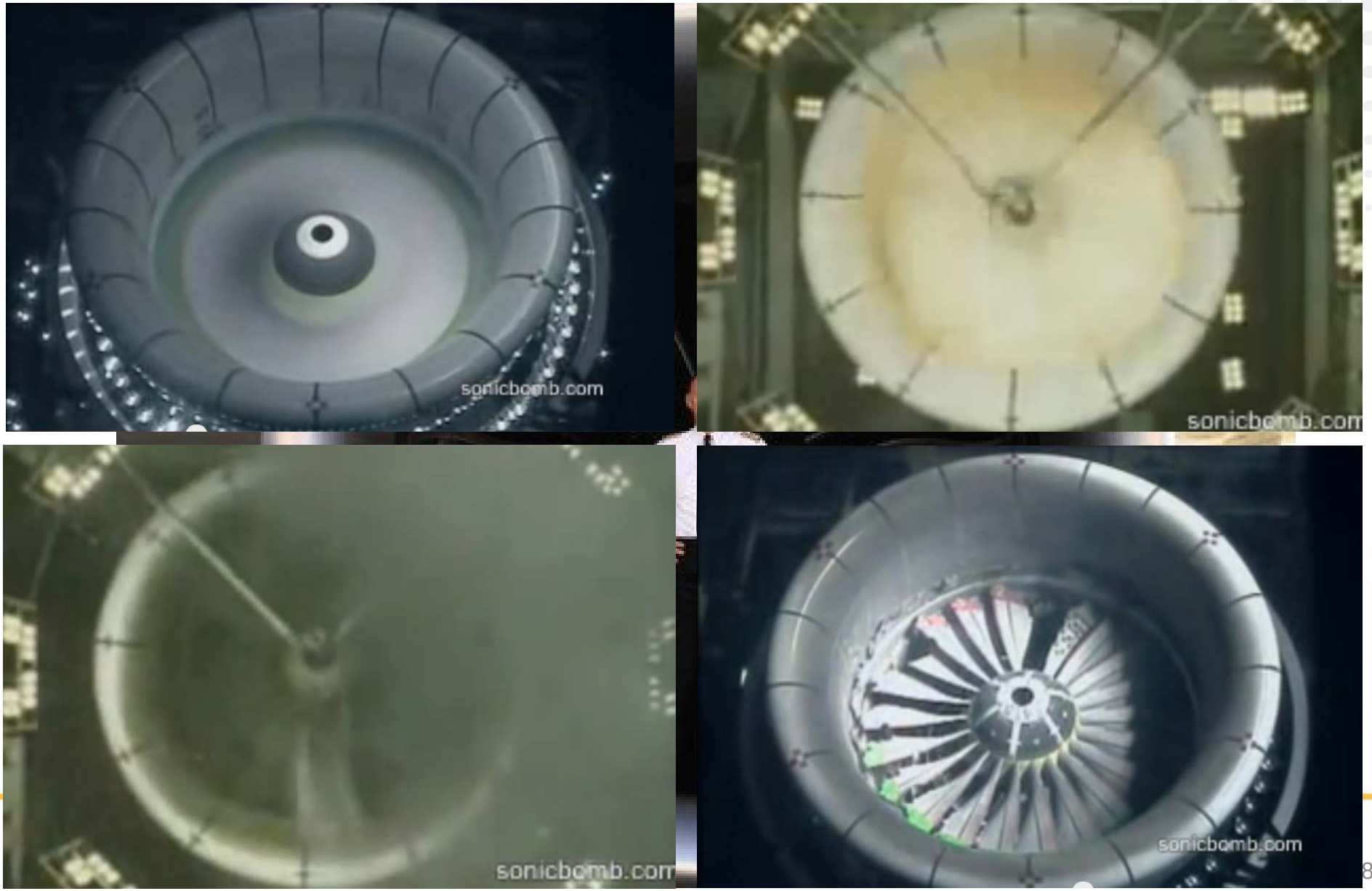
Jetpak.net

MMR enables more rigorous safety tests like jet engines



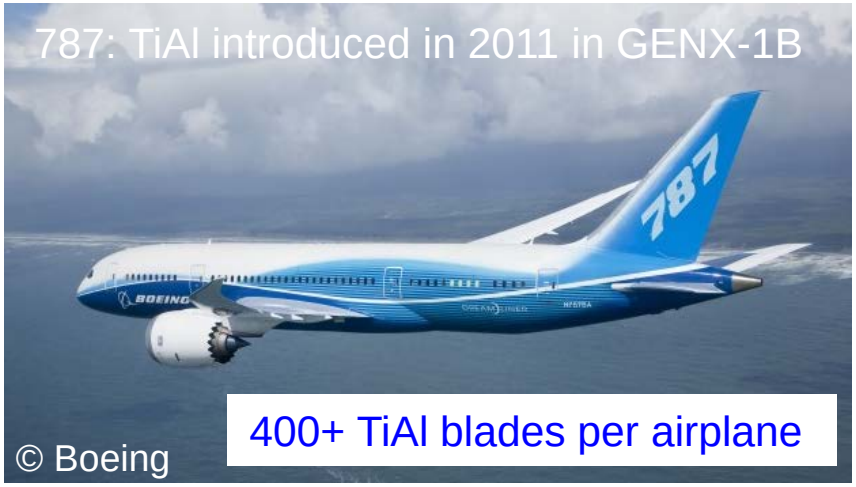


MMR enables more rigorous safety tests like jet engines



Example: Introduction of TiAl to jet engines

The first FAA certified intermetallic material for jet engine application



© GE

48Ti-48Al-2Nb-2Cr

- 150,000+ blades
- 750+ engines
- 4+ million hours of flawless operations

(as of April 2015)

TJ Kelly and MJ Weimer, "Bringing TiAl to Production as Low Pressure Turbine Blades", TMS Annual Meeting, New Orleans (2008)
Latest Information based on the 2014 Distinguished Lecture in Materials and Society by Robert Schafrik at MS&T 2014

Paramount rigor of safety in designs, validation tests & inspections, yet open to innovations

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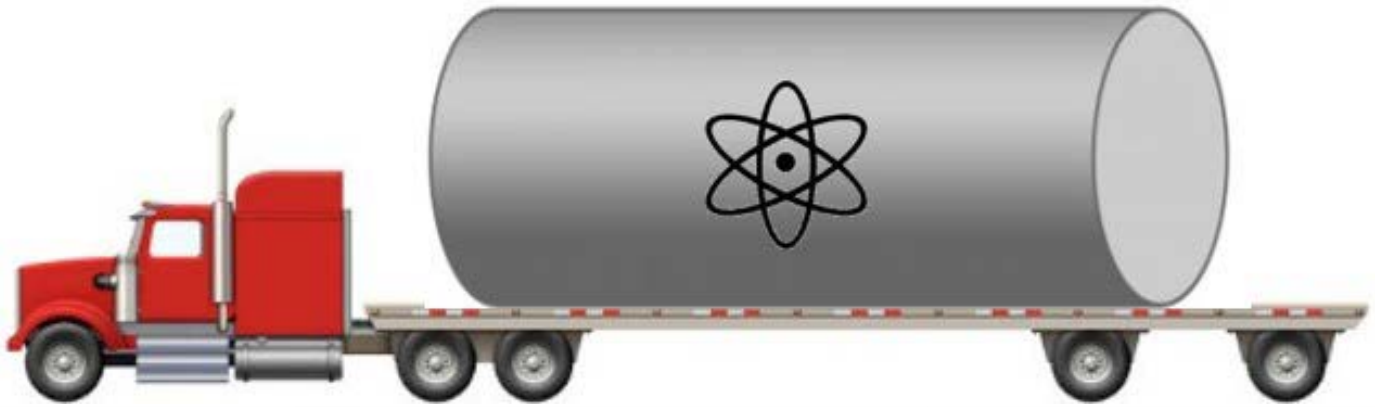
What are the equivalent safety validation tests for micro modular reactors?

- Intentional fault tests
- Earthquake shaker table tests?
- Water submersion tests?
- Projectile penetration tests?

- Neutron/nuclear simulation expertise
- Crash-worthiness simulations (from auto industry)
- Projectile simulations (from the military)

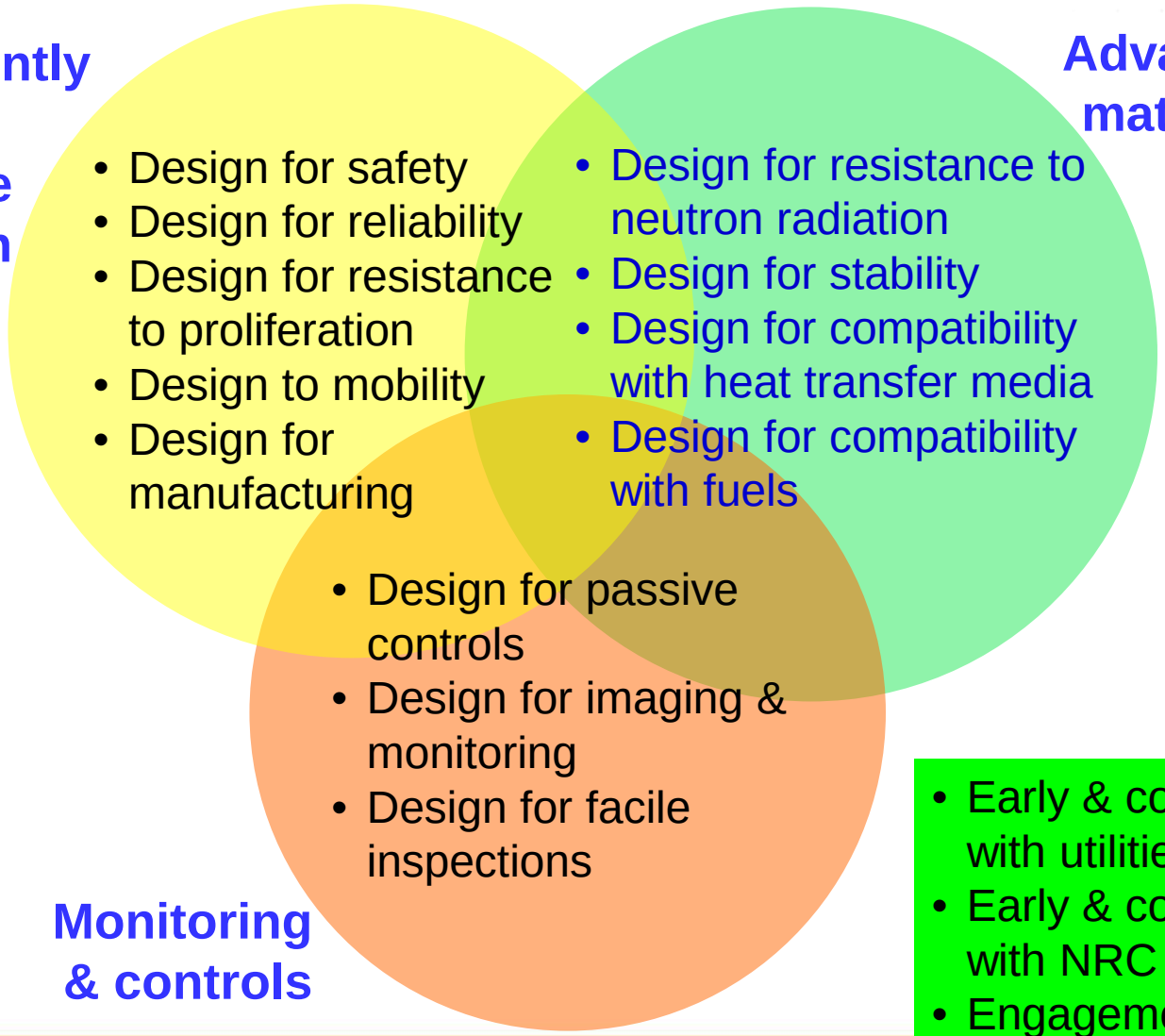
Do modeling & simulations tools have the fidelity to replace some costly experiments?

We have the foundations…



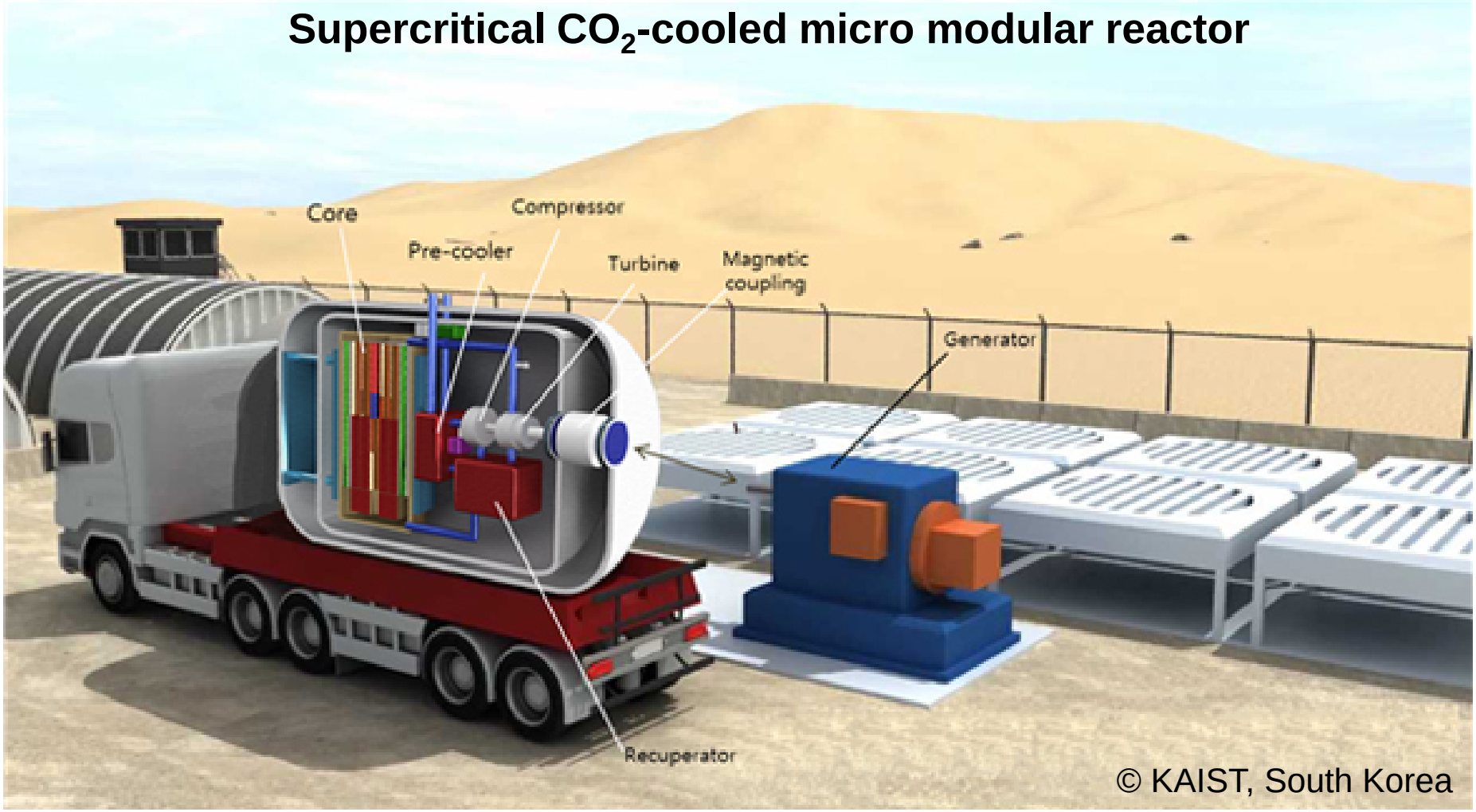
Test capabilities	Sensors, Controls & robotics technology	Simulation excellence
Nuclear excellence	Rigorous regulatory practice	Materials science excellence
Engineering prowess	Commercial aviation safety design & experience	Space technologies

Working together



- Early & constant engagement with utilities & OEMs
- Early & constant engagement with NRC
- Engagement with potential early adopters

Design for MMRs: *KAIST example*



Several submitted concepts will be discussed at this workshop

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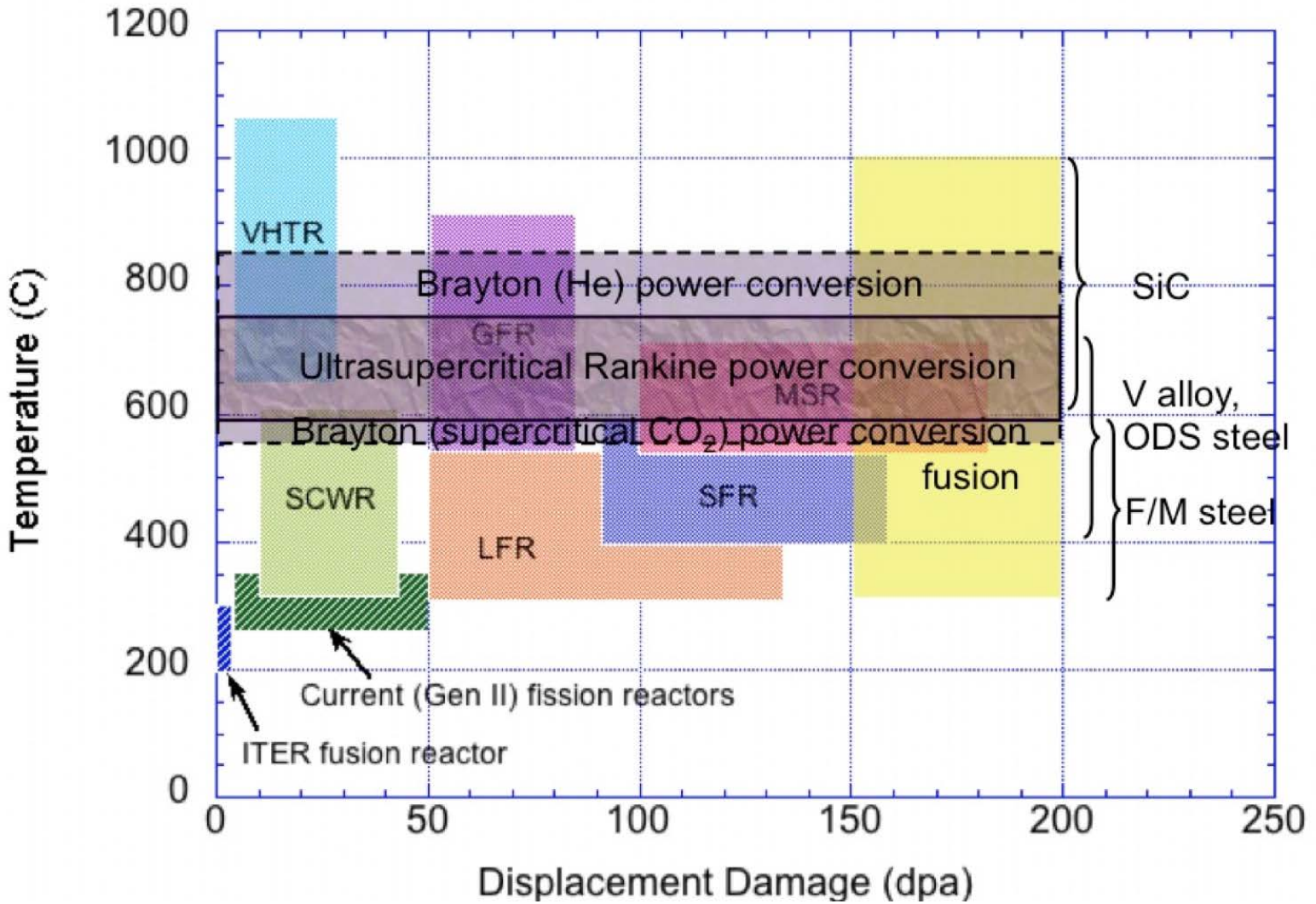
Materials for MMRs: *Zinkle talk*



Sensors & Controls for MMRs: *EPRI report*

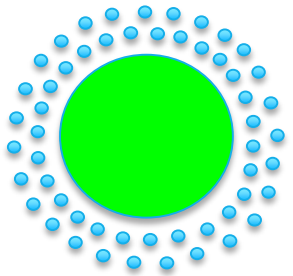
Next-generation sensors and their key characteristics

Sensor	Principle of Operation	Application	Development Status
Johnson noise thermometry	Uses an RTD; the noise voltage at the output of the RTD corresponds to temperature.	Measuring temperature with continuous on-line self calibration	Almost ready.
Solid-state neutron flux monitor	Monitors the flux-induced change in electric resistance of aluminum nitride solid.	In-core flux mapping	More R&D is needed.
Magnetic flowmeter	Conducting fluid passing through magnetic field generates voltage proportional to velocity of flow.	Measuring primary coolant flow in PWRs	More R&D is needed.
SiC neutron flux monitor	Material deposited on top of a thin SiC layer converts neutrons to charged particles.	Monitoring ex-core neutron flux	Prototype tested in research reactor; sensor is almost ready for use.
Hydrogen sensors	Uses palladium-sensing element. Palladium's resistance changes with hydrogen diffusion.	Post-accident hydrogen monitoring	Almost ready.
Virtual sensor	Uses sensor redundancy and analytical modeling technologies to provide virtual/empirical sensors.	OLM of nuclear power plant instruments, processes, and equipment	In use.
Nanotriodes	Follows the principle of vacuum tubes using nanotechnology.	High-radiation and temperature application	Fundamental research is underway. Long time before ready for use.
Gamma ray tomographic spectrometry	Uses the energy and time of Compton scatter events and photoelectric absorption events to project the arrival angle of an incident gamma ray.	Real-time characterization of radiation field	Almost ready.
Fuel mimic power monitor	Controls the input electric power to a fuel pellet to maintain constant temperature. The power to maintain constant temperature corresponds to reactor power.	Direct measuring of reactor power level	More R&D is needed.

Source: EPRI

Security & Safety: inherent design features

- Zero chance of core melting → passive safety
- Complete prevention of radiation leaks
- Zero Emergency Planning Zone (EPZ)
- Design for time-intensive removal from sites
- Limited and well-controlled radiological materials
- Safety protocols to transport MMRs from factories to operation sites
- Layered monitors & security measures to reduce security staff → sensors, cameras, robots, drones…
- Resistance to projectile attacks
- Cyber security of operations

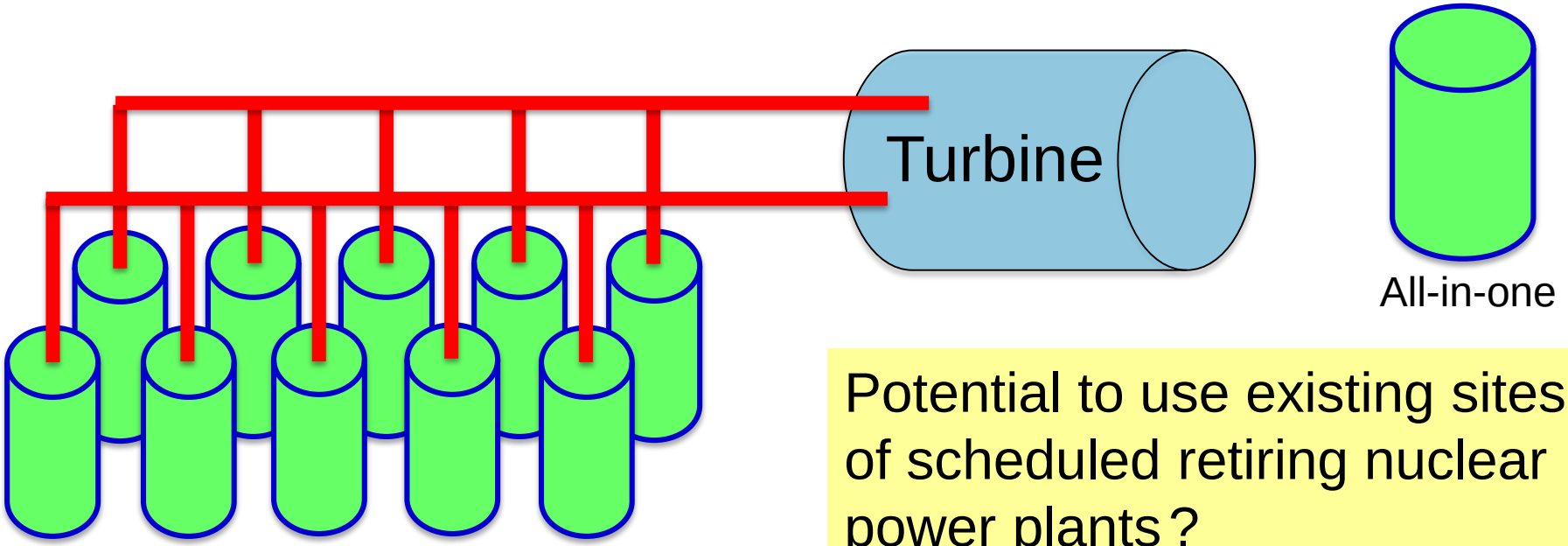


Non-proliferation

- Proliferation-resistant fuels → lessons from other nuclear operations?
- No refueling on site
- No on-site spent fuel storage
- Tow-away decommission
- … → Panel discussion tomorrow

MMRs provide flexibility & modularity

- Remote, energy-lean areas
- Backup power
- Rapid response needs
- Cogeneration (e.g., heat, desalination)
- Critical infrastructure
- **Hybrid with renewables**
- Maritime shipping
- **Micro-grids & decentralized generation**



Potential to use existing sites of scheduled retiring nuclear power plants?

Micro Modular Reactors (MMRs)

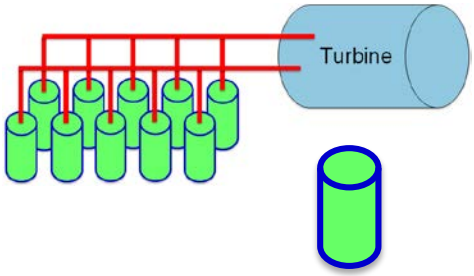
In-factory certification

Make in factories

- *Inherently safe & secure designs such as solid core*
- *Deployment of advanced materials, sensors & controls*
- *Assembly-line efficiency & strict quality controls*
- *Made to order - minimal delay & much reduced capital*

Certify in factories

- *Licensing/certification once only for each type of reactor*
- *Safety tests (earthquake shake tables…faulty tests)*
- *Much reduced certification/licensing cost*



Transport to sites

- *Minimal site requirements (emergency planning zone)*
- *No need for on-site spent fuel storage*
- *Much expanded use with size flexibility/modularity*
- *Tow-away decommission*

- Make & certify MMRs like jet engines
- Make MMRs safer than jet engines

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Imagine this:

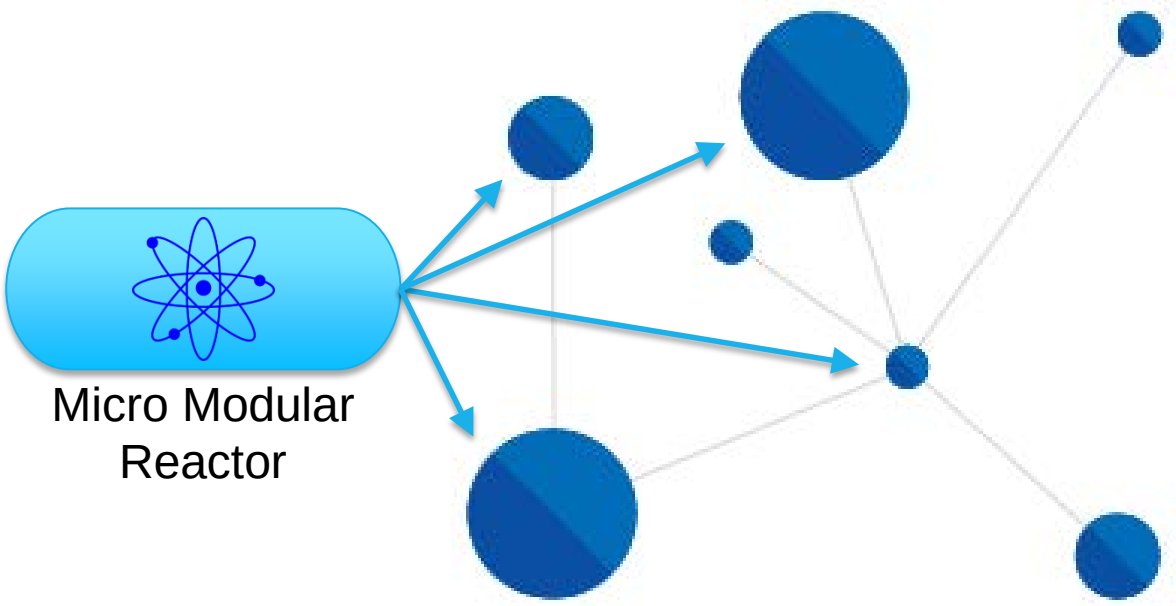
A drop-in replacement for current incumbent technologies

…with growing decentralized energy generation market

- Current: ~142 GW added/year*
- Projected: ~200 GW added/year*

Reciprocating Engines

Microturbines



Micro Modular Reactor

* GE report

Key metrics for discussion

- Physical size: each component fits in an **ISO container**
- Weight: **<59,000 lbs** (per component)
- Lifetime without refueling: **10-20 years**
- Fuels (e.g., enrichment: **<20%**, preferred 4-5%)
- **Load following** capability
- **No external cooling** towers
- **No water** usage
- Resistance to 9.0 magnitude **earthquakes, tsunami water submersion**
- **Inherent (passive) safety, security, and proliferation resistance** with sensors and controls

Key questions

- Are there inherently safe & secure designs at the MMR size?
- What tests & what operational metrics?
- How far do we need to go to demonstrate the safety and security to seed a pathway for the development & deployment of MMRs?
- How can a $30M ARPA-E program make a difference?
- What are the key enabling technologies and system integration innovations?

Design for safety, security & non-proliferation

Are you willing to put a MMR in your own backyard?

+ Security

+ Non-proliferation

In-factory certification

Make in factories
Certify in factories
Transport to sites

We seek your help in charting a path …

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If we do **this**, it will lead to …

Thank you !

JC Zhao
Ron Faibish
Ryan Umstattd
Colleen Nehl
Adam Fischer
Adrienne Little

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