Deliberately Small Reactors and the Second Nuclear Era

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June 3, 2010
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U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
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Suppose you need to buy a new car…

H1 Hummer

EPR
(1600 MWe)

Cadilac
Escalade

AP-1000
(1150 MWe)

Smart Car

?

Some basic terminology

IAEA definitions:

Small:	**< 300 MWe**	*Small and Medium-sized Reactors (SMR)*
Medium:	**300-700 MWe**	
Large:	**> 700 MWe**	

Related but less precise terms:

Grid-Appropriate Reactors (GAR)

Small Modular Reactors (SMR)

Right-Sized Reactors (RSR)

Deliberately Small Reactors (DSR)

The U.S. began developing small nuclear reactors for naval propulsion

USS Nautilus
Launched 1954

USS Enterprise
Launched 1960

The U.S. Air Force explored nuclear powered aircraft

Nuclear Test Aircraft
1955-57

Heat Transfer Reactor Experiment

The U.S. Army built 6 small stationary power plants and 2 mobile plants

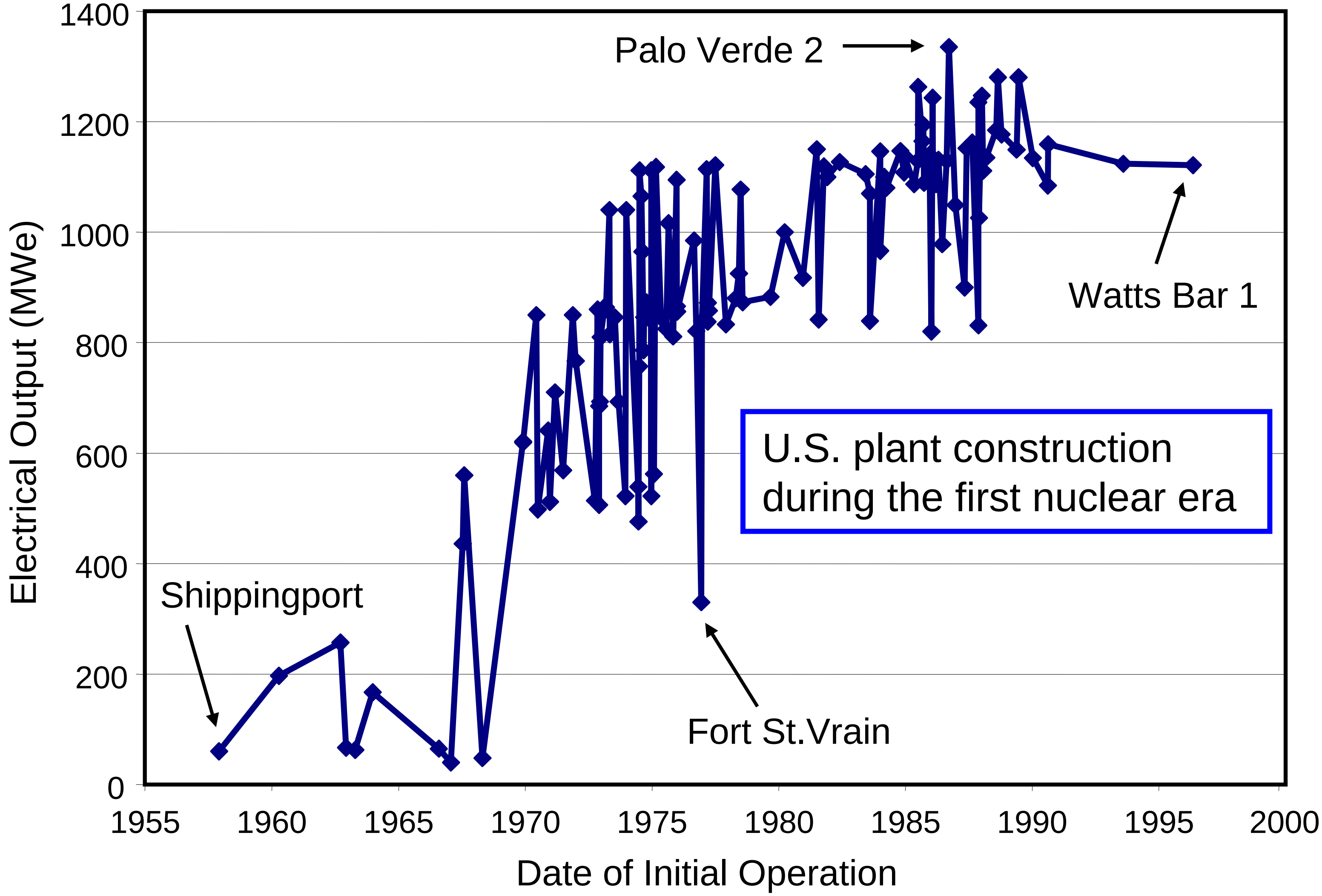
Ft. Belvoir

Camp Century

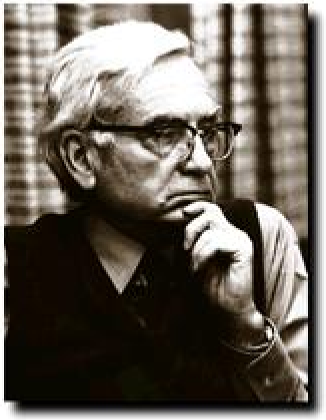
USS Sturgis

Reactor	Power (MWe)	Type	Location	Startup	Shutdown
SM-1	2	PWR	Fort Belvoir, Virginia	1957	1973
SM-1A	2	PWR	Fort Greely, Alaska	1962	1972
PM-1	1	PWR	Sundance, Wyoming	1962	1968
PM-2A	1	PWR	Camp Century, Greenland	1960	1962
PM-3A	1.5	PWR	McMurdo Station, Antarctica	1962	1972
SL-1	1	BWR	Arco, Idaho	1958	1960
MH-1	10	PWR	Panama Canal (Sturgis)	1967	1976
ML-1	0.5	GCR	Arco, Idaho	1961	1966

Commercial nuclear power plants escalated rapidly in size



Weinberg study* (1985) explored merits of smaller, simpler, safer reactors



Motivated by lessons learned from the *first nuclear era*

Main findings:

- **Incrementally-improved, post-TMI LWRs pose very low risks to the public but high investor risks and uncertain capital cost may limit market viability**
- **Large LWRs are too complex and sensitive to transients**
- **Inherently safe concepts are possible and should be pursued, such as:**
  - **The Process Inherent Ultimately Safe (PIUS) reactor**
  - **The Modular High-Temperature Gas-Cooled Reactor (MHTGR)**

*A. M. Weinberg, et al, *The Second Nuclear Era*, Praeger Publishers, 1985

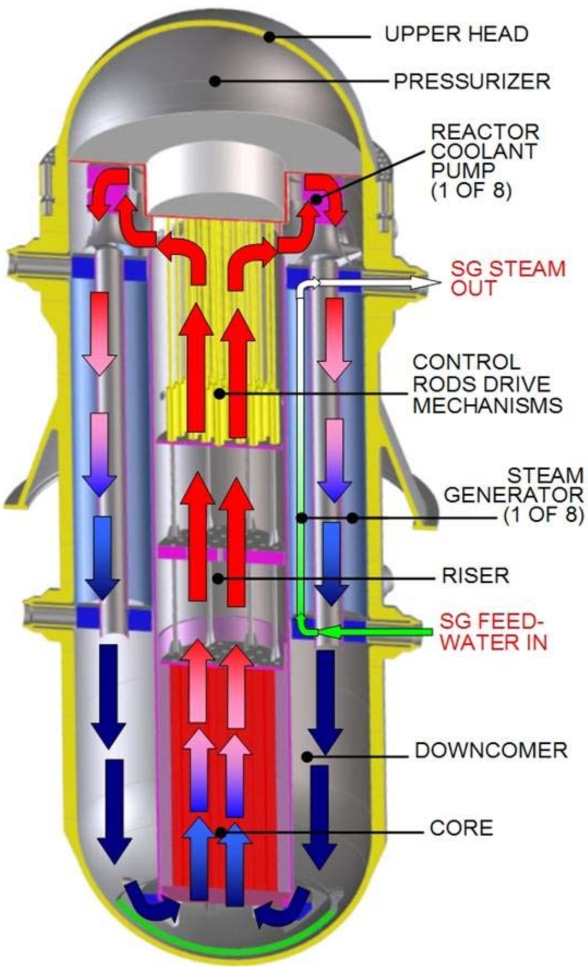
Interest in smaller sized reactor designs are beginning to (re)emerge

- **Benefits**
  - **Cheaper (capital outlay)**
  - **Improved fabrication and construction logistics (especially domestic)**
  - **Enhanced safety (robustness)**
  - **Operational flexibilities (broader applications)**
- **Applications**
  - **Smaller utilities**
  - **Countries with financing or infrastructure constraints**
  - **Distributed power needs (e.g. military base islanding)**
  - **Non-electrical (process heat) customers**

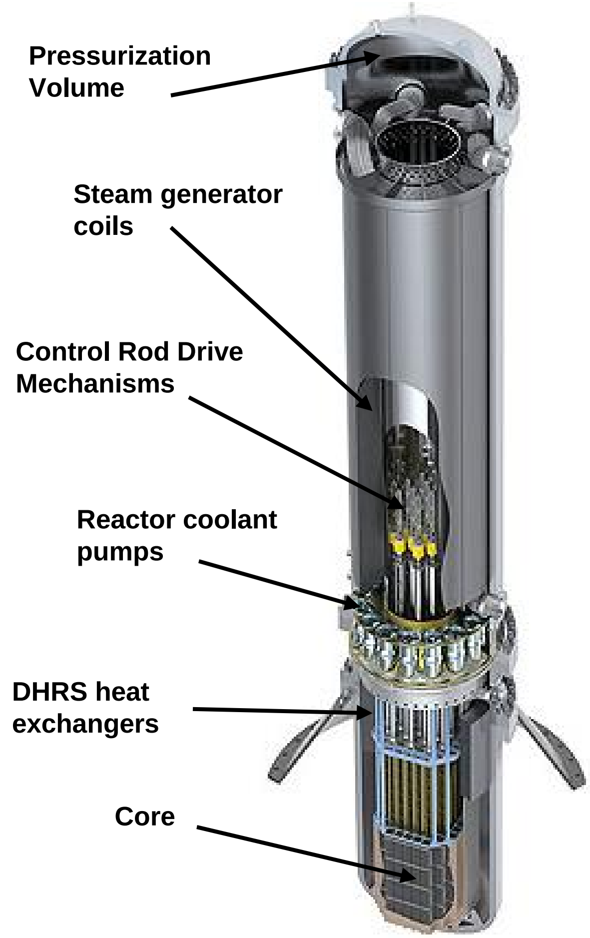
Sampling of SMR concepts under development world-wide

- **Integral PWR:** CAREM (Ar), IMR (Jp), IRIS (US), NuScale (US), mPower (US), SCOR (Fr), SMART (RoK)
- **Marine derivative PWR:** ABV (RF), KLT-40S (RF), NP-300 (Fr), VBER-300 (RF)
- **BWR/PHWR:** AHWR (In), CCR (Jp), MARS (It)
- **Gas-cooled:** GT-HTR-300 (Jp), GT-MHR (US), HTR-PM (Ch), PBMR (SA)
- **Sodium-cooled:** 4S (Jp), BN-GT-300 (RF), KALIMER (RoK), PRISM (US), RAPID (Jp)
- **Lead/Pb-Bi-cooled:** BREST (RF), ENHS (US), LSPR (Jp), STAR/SSTAR (US), SVBR-75/100 (RF)
- **Non-conventional:** AHTR (US), CHTR (In), Hyperion (US), MARS (RF), MSR-FUJI (Jp), TWR (US)

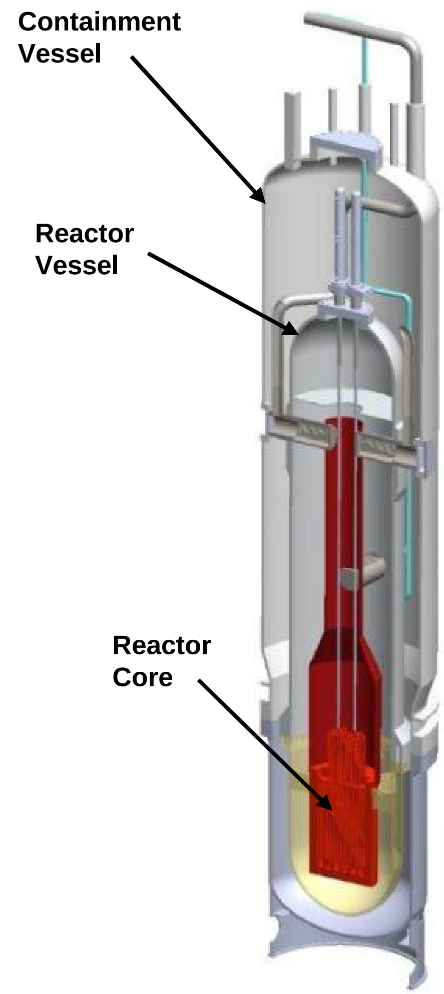
LWR-based SMR designs under development in U.S.



IRIS (Westinghouse)



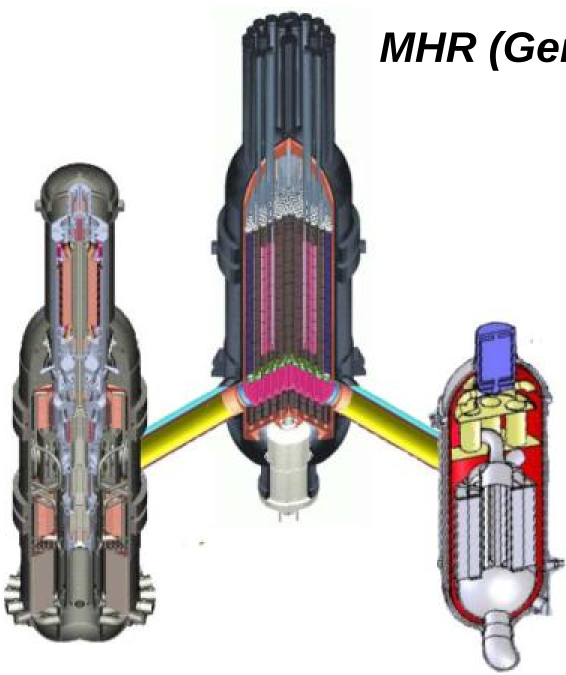
mPower (Babcock & Wilcox)



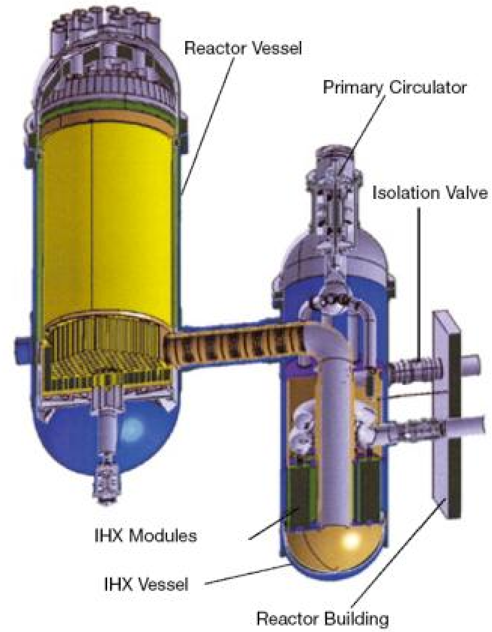
NuScale (NuScale)

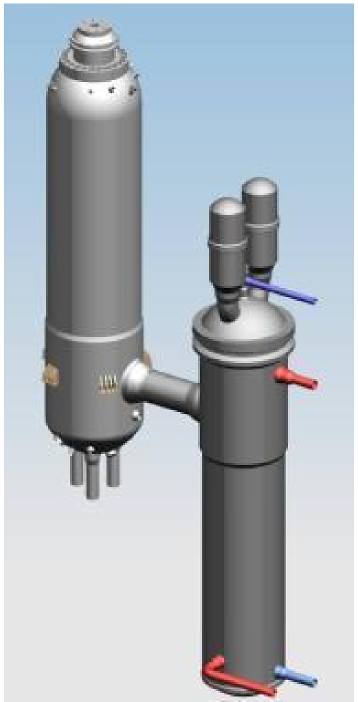
Gas-cooled SMRs (NGNP options)

MHR (General Atomics)



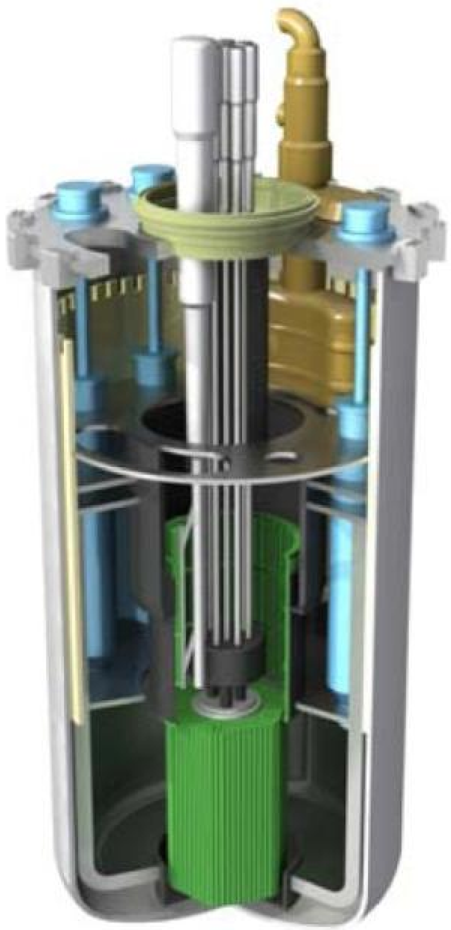
ANTARES (Areva)



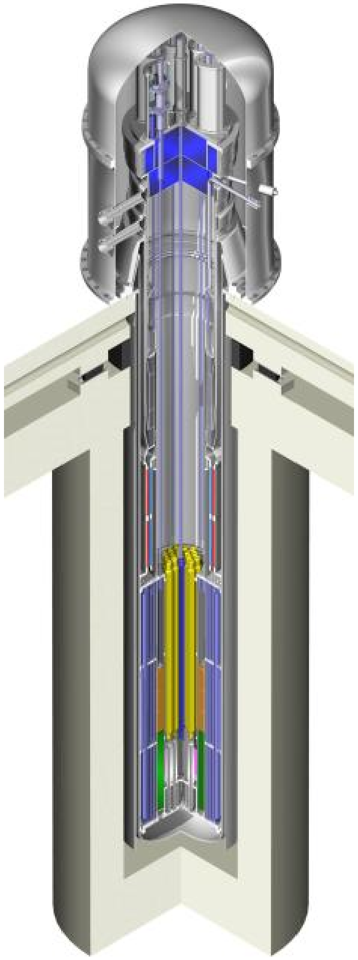


PBMR (Westinghouse)

Liquid-metal-cooled SMRs



PRISM (General Electric)



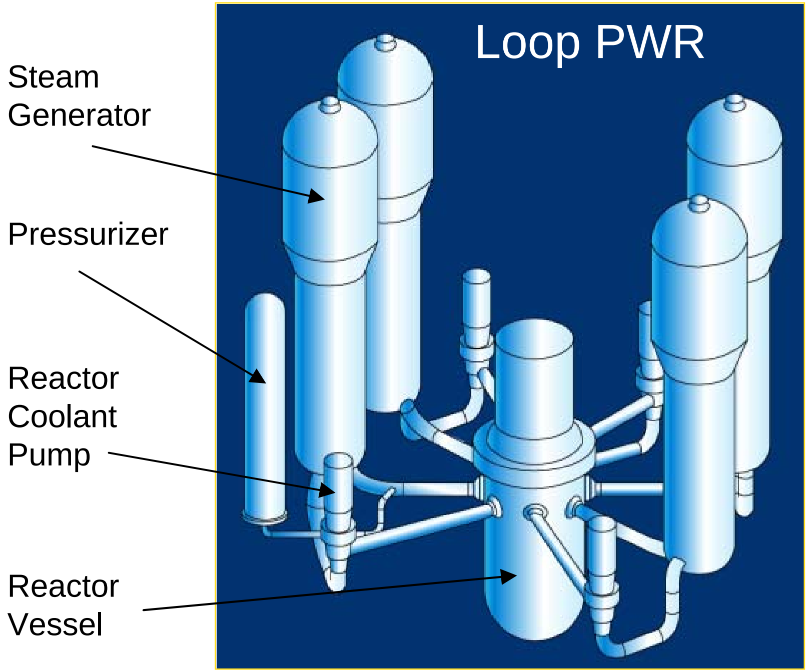
4S (Toshiba/W)

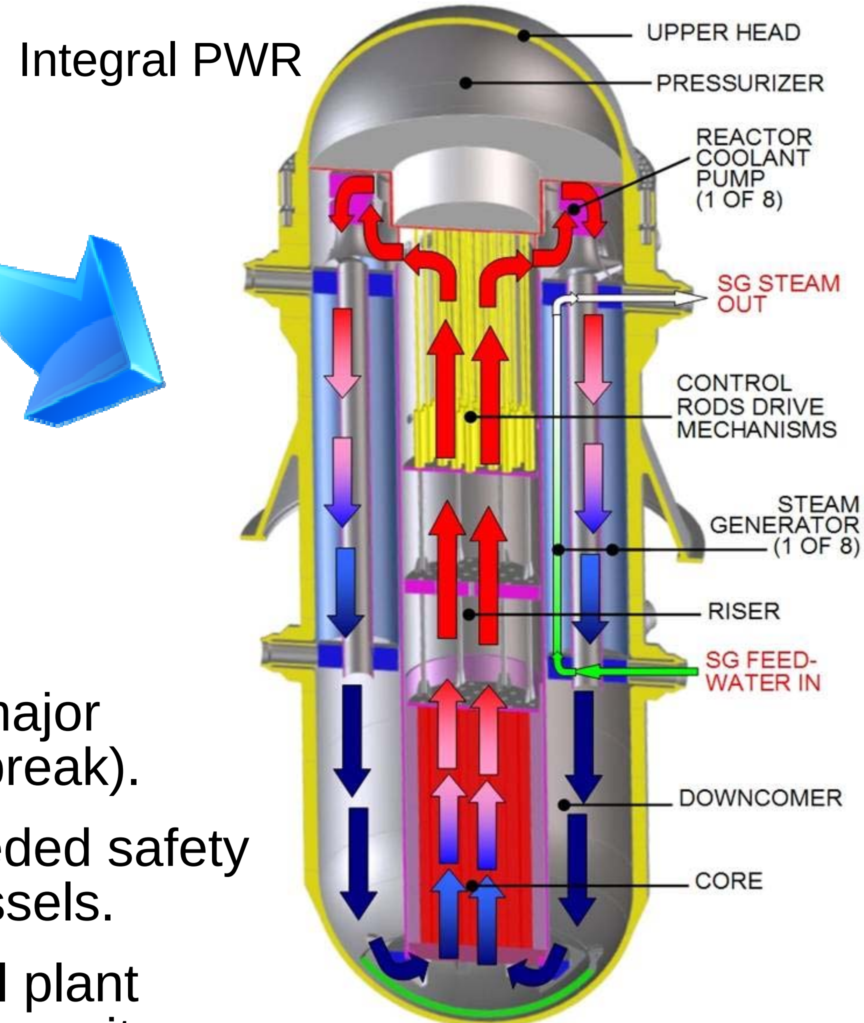
HPM (Hyperion)

Safety benefits of DSRs

- **Reduced source term**
  - **Lower power means fewer fission products produced**
  - **Can allow for increased margin, or reduced shielding, site radius, emergency planning zone, etc.**
- **Improved decay heat removal**
  - **Lower decay heat generated in the reactor core**
  - **More efficient passive decay heat removal from reactor vessel (volume-to-surface area ratio effect)**
- **Elimination of accident initiators (e.g., integral designs)**
  - **No large pipes in primary circuit means no large-break loss-of-coolant accidents**
  - **Increased water inventory means slower system response to power transients**

Integral primary system configuration





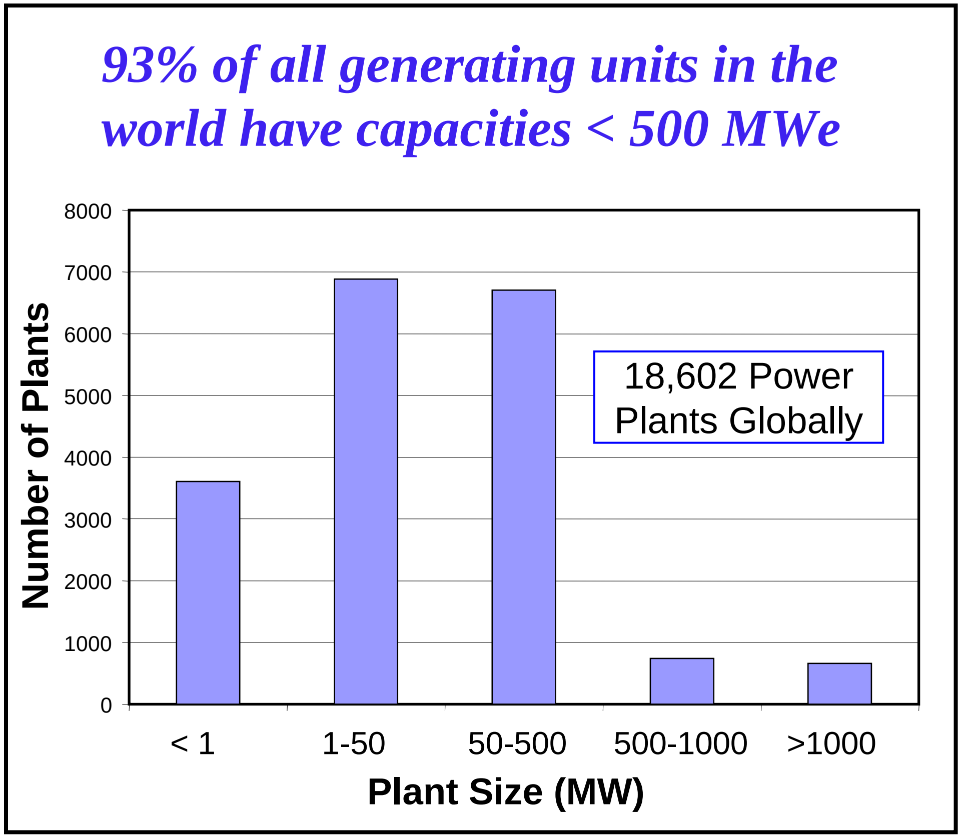
- Enhances robustness by eliminating major classes of accidents (e.g., large pipe break).
- Simplifies design by eliminating unneeded safety systems, large piping and external vessels.
- Allows for compact containment (small plant footprint) to enhance economics and security.

Fabrication and construction benefits

- **Physically smaller components**
  - **Eliminate or reduce number of large forgings**
  - **More in-factory fabrication; less site-assembly**
    - **Reduces schedule uncertainty**
    - **Improves safety/quality**
    - **Reduces cost (as much as 8-fold)**
  - **Reduce size and weight for easier transport to site**
    - **Access to a greater number of sites**
    - **Well suited for remote or undeveloped sites**
- **Smaller plant footprint**
  - **Place nuclear system further below grade to improve resistance to external events and sabotage**

Operational flexibilities

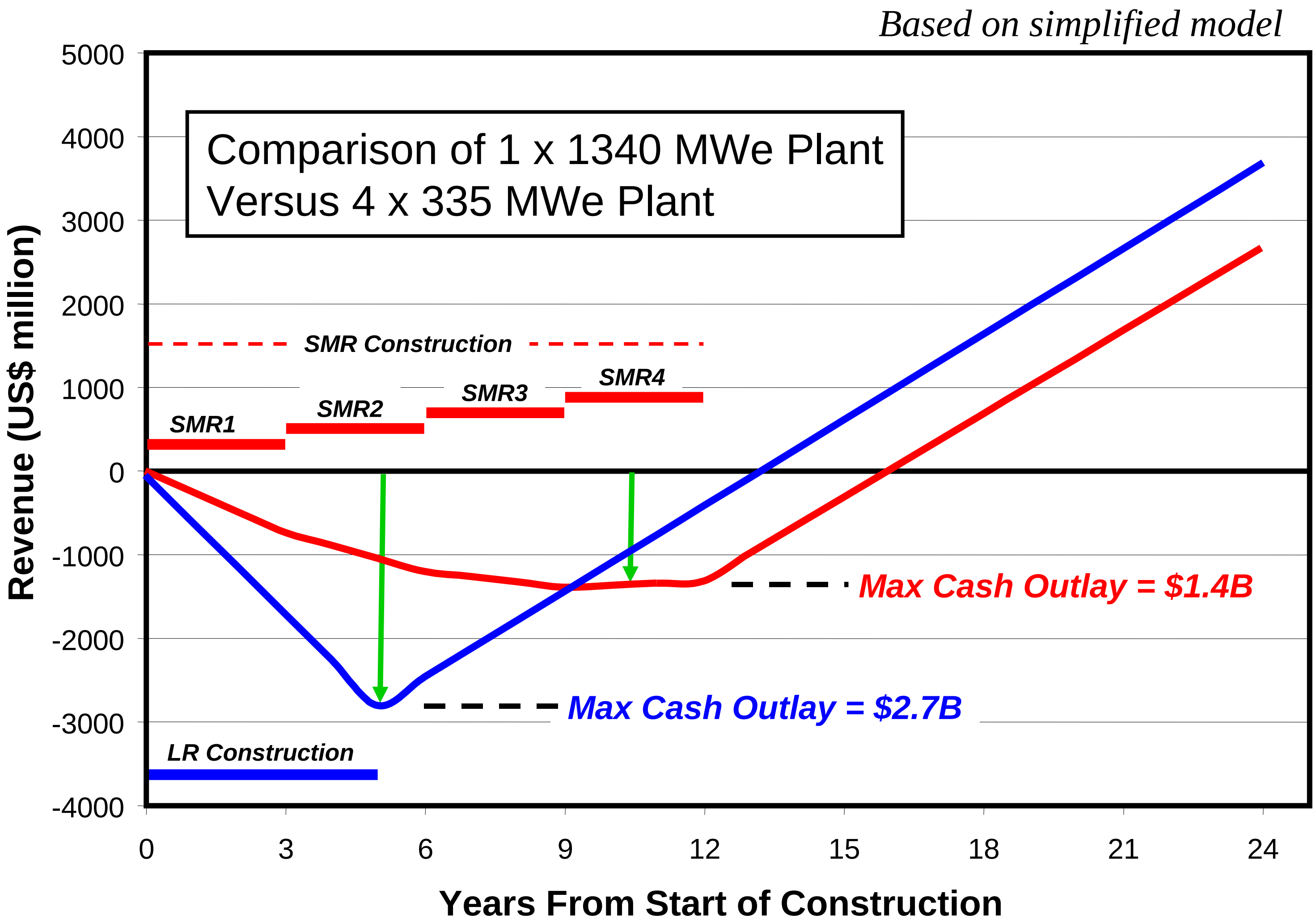
- **Site selection**
  - **Potentially reduced emergency planning zone**
  - **Use of seismic isolators**
  - **Lower water usage**
- **Load demand**
  - **Better match to power needs for many non-electrical applications**
- **Grid stability**
  - **Closer match to traditional power generators**
  - **Smaller fraction of total grid capacity**
- **Demand growth**
  - **Ability to add (and pay for) capacity as demand dictates**



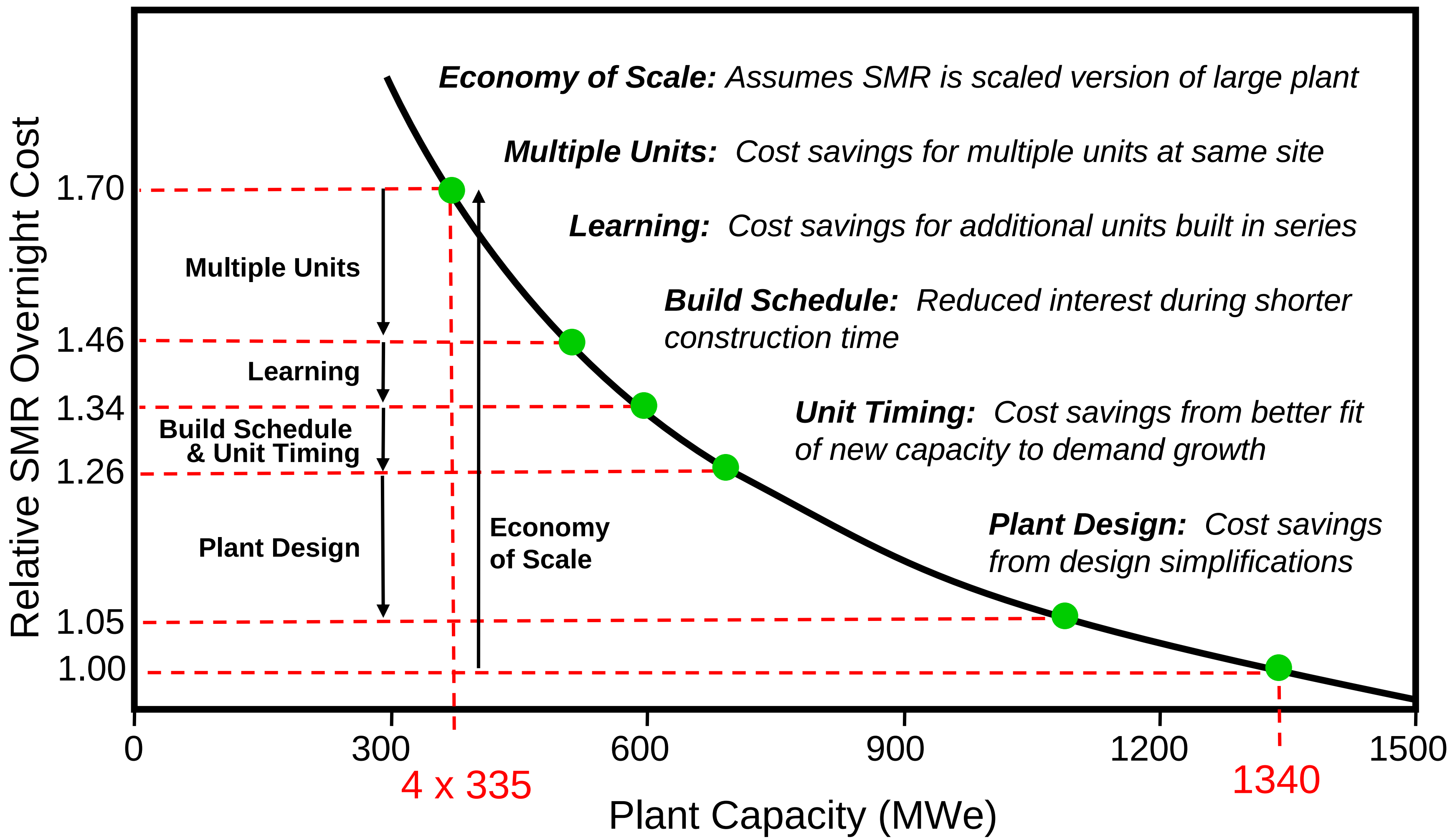
Economic benefits

- **Total project cost**
  - **Smaller plants should be cheaper**
  - **Improves financing options and lowers financing cost**
  - **May be the driving consideration in some circumstances**
- **Cost of electricity**
  - **Economy-of-scale (EOS) works against smaller plants but can be mitigated by other economic factors**
    - **Accelerated learning, shared infrastructure, design simplification, factory replication**
- **Investment risk**
  - **Maximum cash outlay is lower and more predictable**
  - **Maximum cash outlay can be lower even for the same generating capacity**

Staggered build of SMRs reduces maximum cash outlay (*Source: B. Petrovic, GaTech*)



Factors offsetting the economy of scale penalty (Source: C. Mycoff, WEC)



SMR challenges – technical

- **All designs have some degree of innovation in components, systems, and engineering, e.g.**
  - **Integral primary system configuration**
  - **Internal control rod drive mechanisms and pumps**
  - **Multiplexed control systems/interface**
- **Longer-term systems strive for increased utility/security**
  - **Long-lived fuels and materials for extended operation**
  - **Advanced designs for load-following and co-generation**
- **Sensors, instrumentation and controls development are likely needed for all designs**
  - **Power and flow monitoring in integral systems**
  - **Advance prognostics and diagnostics for remote operations**
  - **Control systems for co-generation plants**

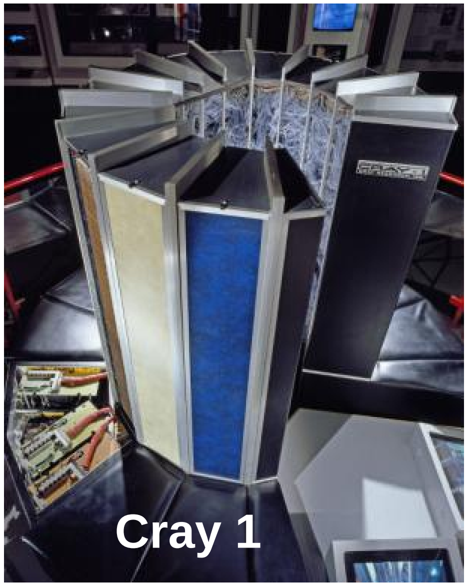
SMR challenges – institutional

- **Too many competing designs**
- **Mindset for large, centralized plants**
  - **Fixation on economy-of-scale**
  - **Economy-of-hassle drivers**
  - **Perceived risk factors for nuclear plants**
- **Traditional focus of regulators on large, LWR plants**
  - **Standard 10-mile radius EPZ (in the U.S.)**
  - **Staffing and security force size**
  - **Plant vs module licensing**
- **Fear of first-of-a-kind**
  - **New business model as well as new design must be compelling**

Summary

- **The U.S. started commercial nuclear power using smaller sized plants**
- **After initial experience with small units, plant size and complexity grew rapidly**
- **New SMRs offer many potential benefits**
- **SMRs do not compete directly with large plants—they offer customers a greater range of options**

Time for "cluster" power generation?



1 large processor

1 small processor

64 small processors

>224,000 small processors