Supercritical CO_2 Power Cycles in the Context of Advanced Nuclear Design

A Pragmatic Review of Opportunities and Areas for Development

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Contents

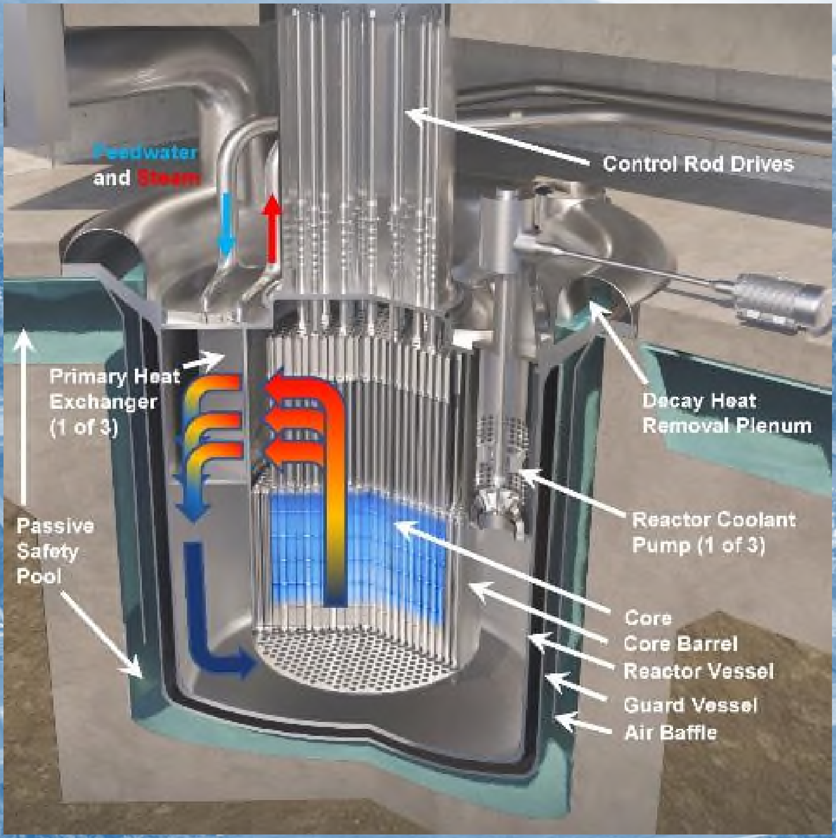
- A brief overview of the lead fast reactor (LFR) for context
- Genesis of sCO_2 development work on LFR
- Early, promising scoping studies
- The devil is in the details
- Comparisons to advanced steam cycles
- Switching decision specific to LFR
- Pros of each

Westinghouse LFR

Overview and History

- LFR was Westinghouse’s next generation of choice for utility scale applications
- Development occurred between 2015-2023
- Product was paused to focus on nearer-term priorities
- **Clean-sheet approach: no legacy from the past**
- Simple, compact, passively-safe, high-temperature, modular-construction pool-type fast reactor leveraging Westinghouse’s 60+ years of experience in NPP commercialization

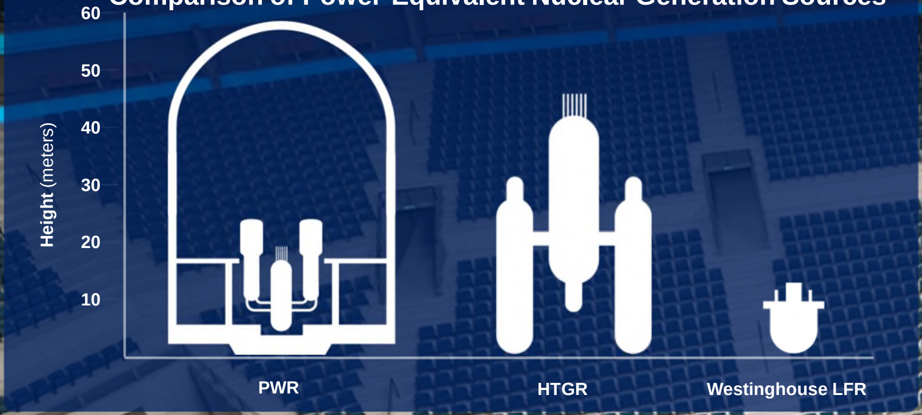
Reactor power	**450 MWe Net**
Primary / secondary coolant	**Liquid lead / Supercritical water**
Number of pumps / HXs	**3 / 3**
Ultimate heat sink	**Atmosphere, through air-cooled condensers. No water bodies required in the vicinity of the plant**
Load following	**600 MWe peak output through thermal energy storage system**
Fuel	**Oxide (near-term); Advanced fuel (nitride) (long-term)**
Fuel cycle	**Capable to accommodate closed cycle**
Operating pressure, MPa	**0.1 (primary) / ~34 (secondary)**
Lead coolant min/max temperature, ˚C	**390 / up to 530 (Phase 1); 390 / up to 650 (Phase 2)**



Power Dense Solution

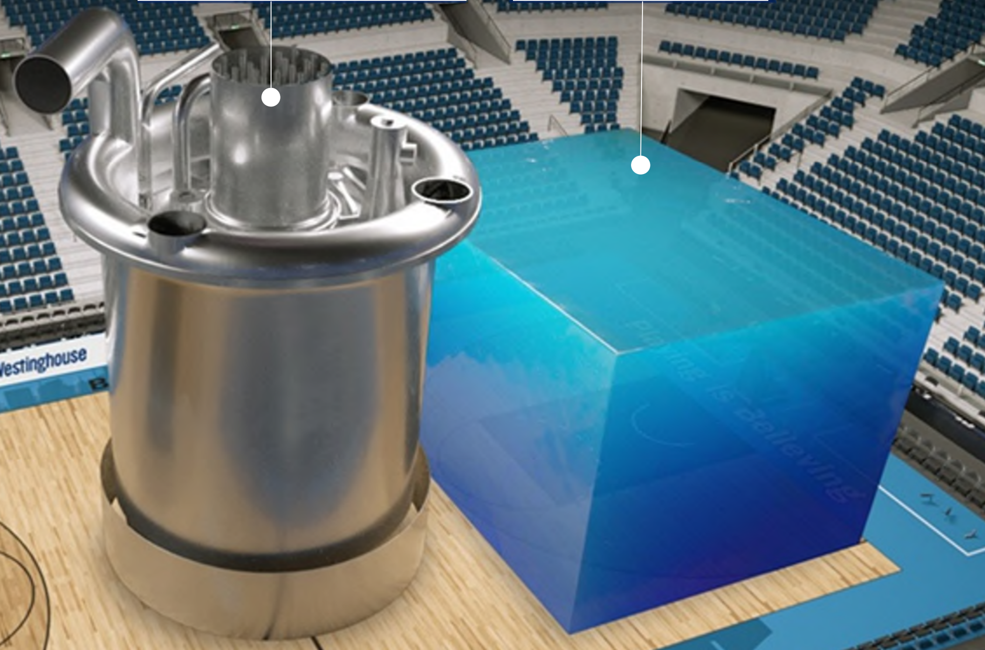
Extremely compact NSSS and proportional safety water volume, no safety heat exchangers & no spent fuel pool

Comparison of Power-Equivalent Nuclear Generation Sources



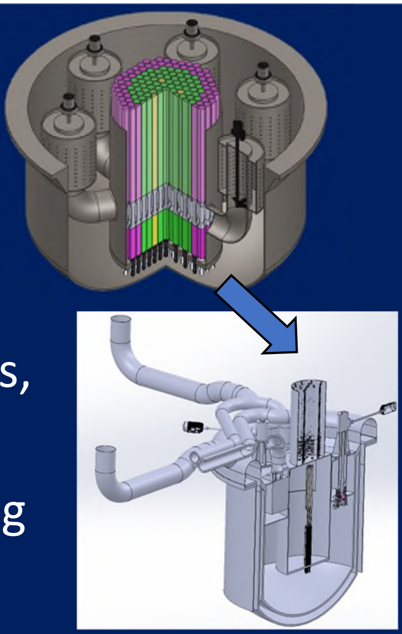
Compact & Simplified NSSS / Containment

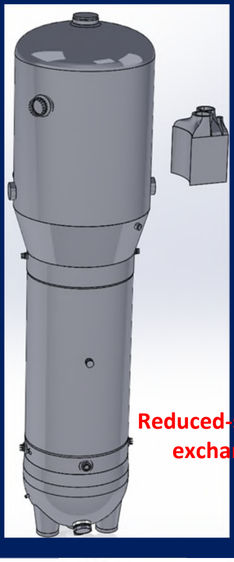
Safety Water Volume

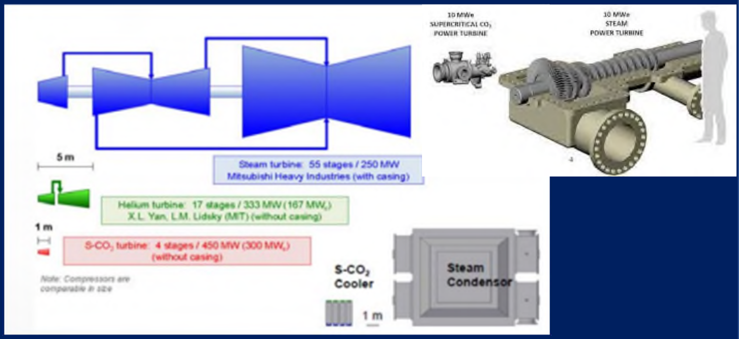


Genesis of Original sCO_2 Decision

- LFR Started with a conventional superheated water / tube SG design at 480°C – 530°C (530-580°C lead)
- sCO_2 was believed to deliver large performance benefits, generically, above 550°C
- A transformative LFR layout was then envisioned, having PCHE as key enabling technology
  - Edict at the time was “thou shalt not put water in a PCHE”
  - Steam cycles were limited to about 615°C and 300 bar
  - Claims of substantial size improvements were made, citing turbomachinery size
  - Decided that moving to next generation cycle technology would enable this configuration, bolster output, and shrink plant size



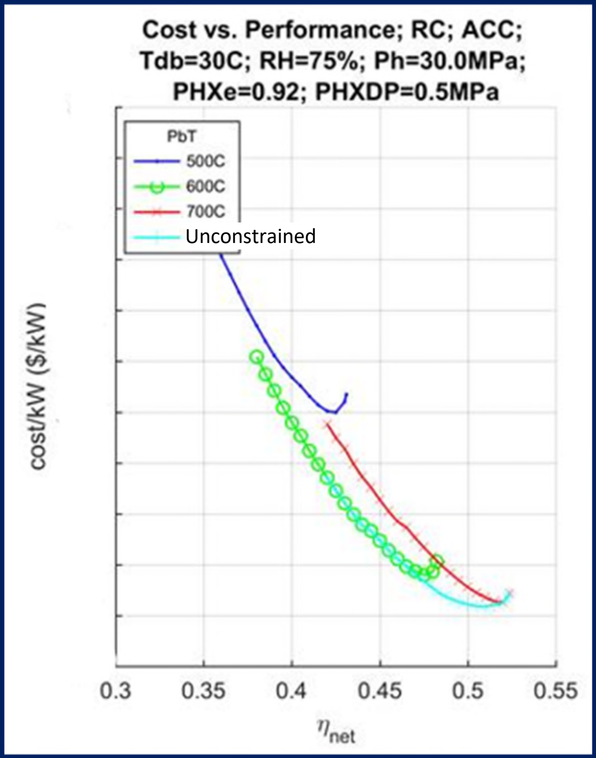




A View Worth the Climb

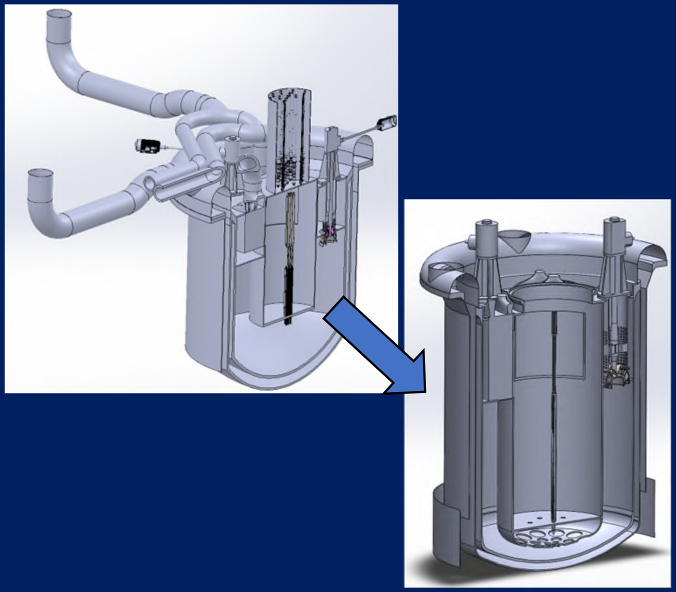
Initial CO_2 Cycle Work

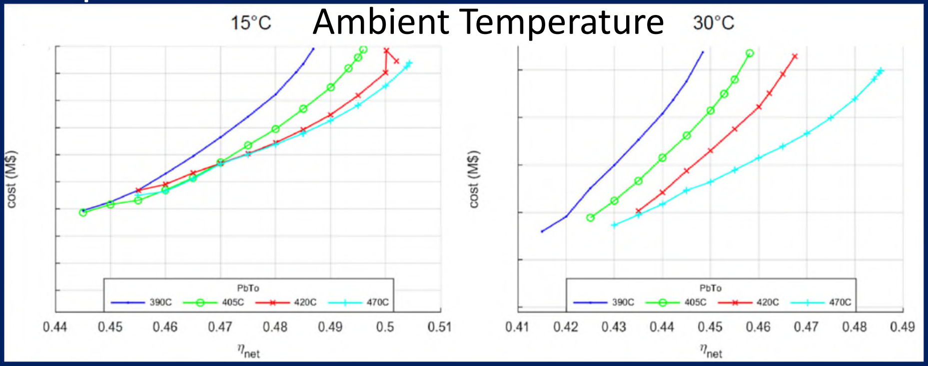
- LFR is 950 MWt
- Initially targeted 250-300 bar working pressure
- Evaluated conditions with Pb temperatures ranging from 500°C to 700°C with unconstrained return (Feed)
- In concert with detailed parametric cost / LCOE models, determined that 700°C was “best” of evaluated points
- However, 600°C was still quite good and ~650°C was basically identical to 700°C on LCOE
- This was good news, as it gave superb efficiency and cost at a temperature bordering on the believable
  - 50% thermal efficiency
  - Air cooled condenser
  - Compatible with lead-focused materials



More Detailed Evaluations with sCO_2

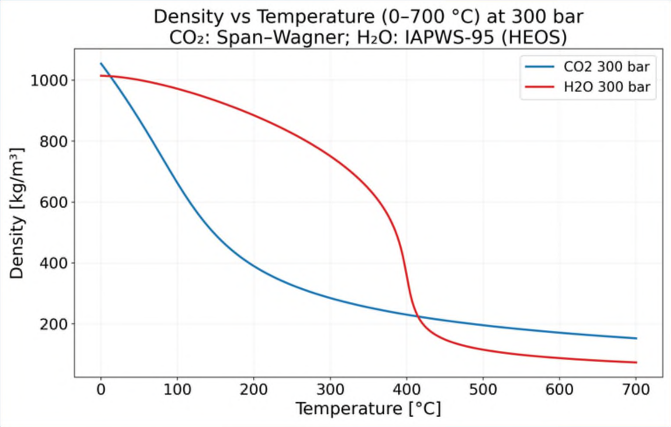
- Reactor considerations started to drive certain performance parameters
  - Reactor vessel shrunk again
  - LFR “wanted” a very high dT core
  - Early accident scenarios showed release of noble gasses would be the most pressing concern, challenging filtered vent solutions
- Started to look at non-design-day conditions
  - Found compromise return temperature
  - Modified cycle design to better tolerate lower return temperature
  - Evaluated at different ambient conditions
  - Continued to track piping and recuperator costs
- Compromise position was close on nominal, but hurt on hot days AND drove up costs notably
- Lost about 10-15 MWe vs. early predictions

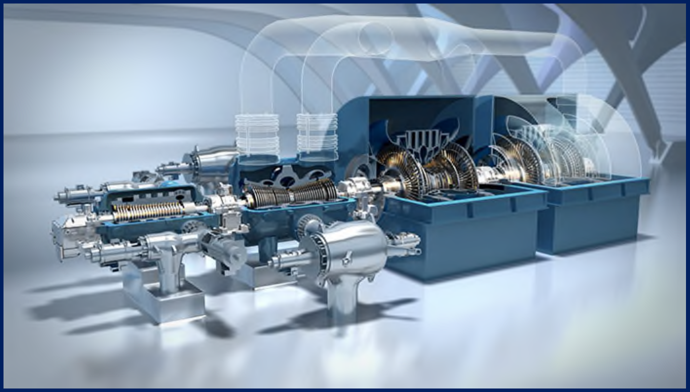




Final Realized Challenges and Steam's Resurgence

- Further divergence between nuclear wants / PCS desires
  - High T_{cold} greatly impacted outlet temperature of PHE at given ϵ
  - Extremely high flowrates challenged by shrinking vessel
    - dP would have been extremely high, further hurting performance
    - Drove very large feed and outlet piping to PHE
  - Some concern about CO_2 having carburation risks
  - Additional life safety concerns with CO_2 leaks
- Steam improvements?
  - Commercial introduction of GE STF-D1250
  - Comfort in water within PCHEs, especially when supercritical
  - Significant progress in ACCs
  - PCHEs could be smaller AND have higher effectiveness
  - Upon accidental release, water can be condensed and this is transformative to safety





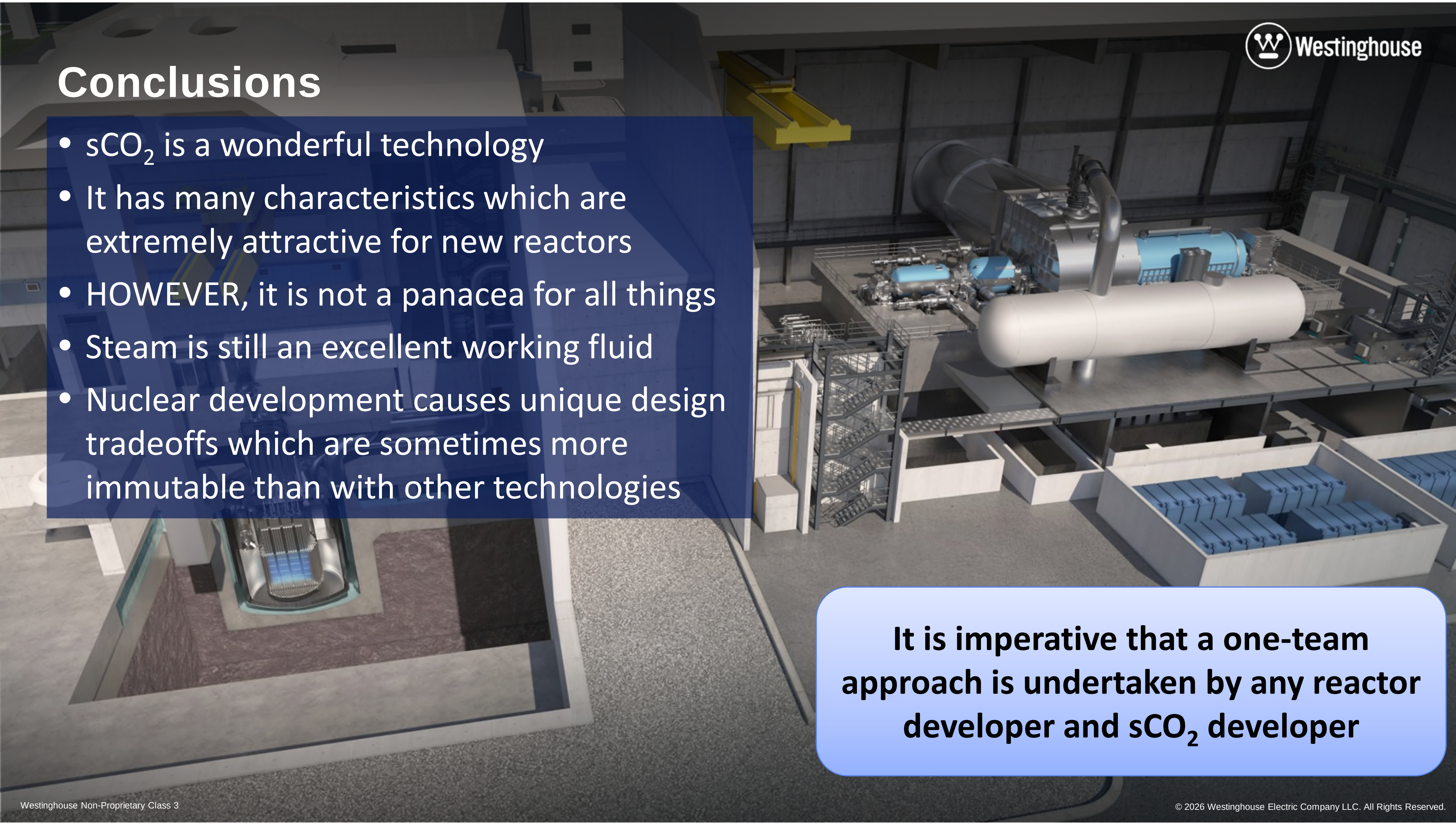
Pros of Each when Considering Mission Specific vs. Generic

Steam Pros for LFR

- **Steam has much higher TRL at similar efficiency**
- **Many tens of millions cheaper (much in piping)**
- Matches primary conditions perfectly
- No life safety issues from inhalation of humid air
- **Equipment size for steam is compact where it counts**
  - Smaller PCHE
  - Smaller connecting piping
  - Reduced high pressure piping in system
- Actual overall layout size may not be very different
  - sCO_2 has small power turbine, but much larger feed equipment
  - sCO_2 has large recuperation requirement relative to feedwater heaters
- Integrated energy storage options easier on steam cycles
- Steam has lower loads in break scenarios
- Steam is more able to use water, at-site, if available (optionality)

CO_2 Pros for Advanced Reactors in general

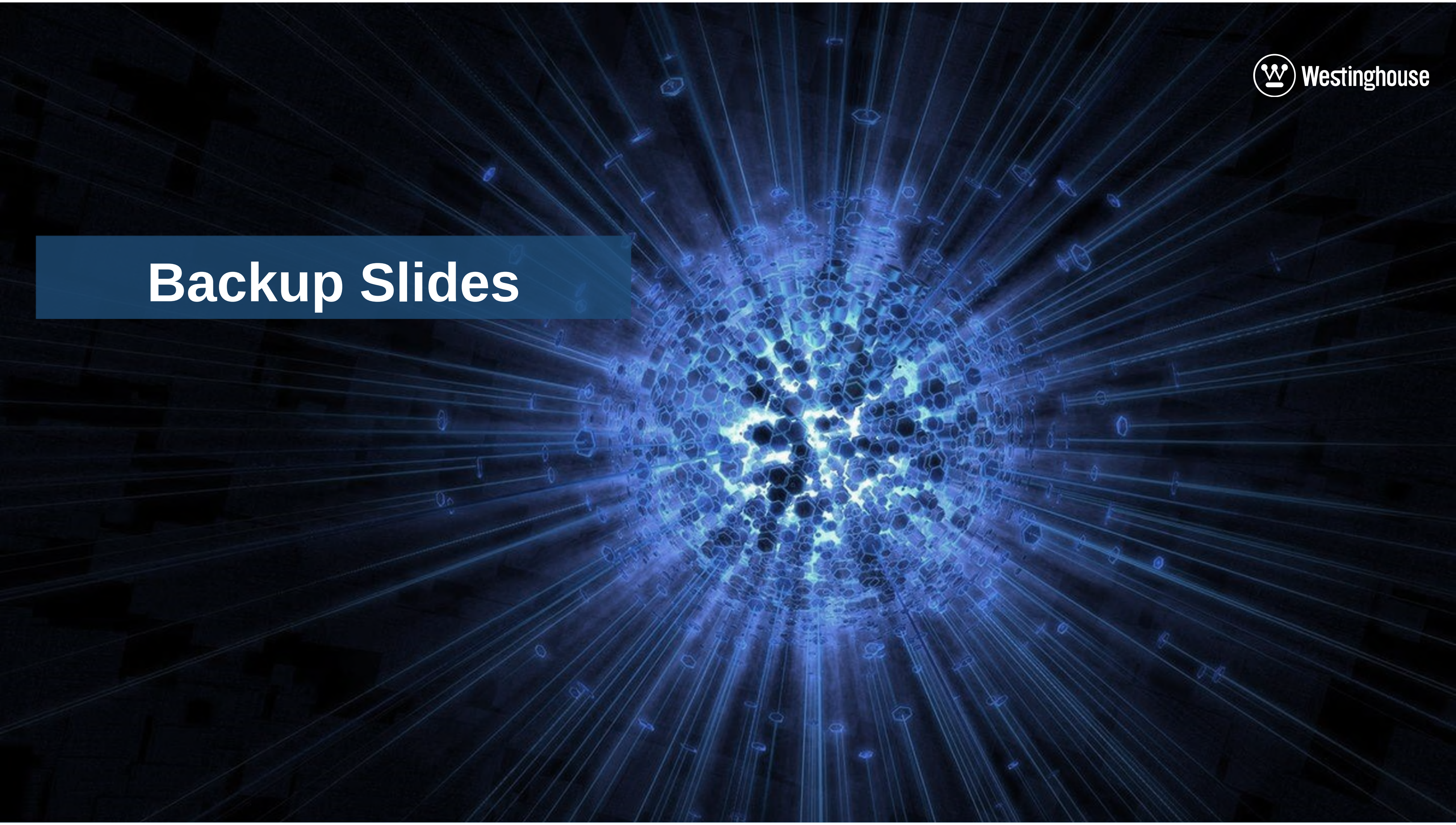
- Higher theoretical efficiencies at a given heat provision
- **MUCH easier tritium separation from secondary, should diffusion be a concern (notable in fusion, especially)**
- **Lower chemical reactivity with some primary coolants**
- **Material compatibility is better at high temperatures with some classes of reactor alloys**
- CO_2 equipment may be compact enough to permit novel layouts in nuclear island + blade throw risk is eliminated
- LACK of condensation may permit certain types of filtering
- Opportunities to reach marginally higher temperatures within material turbomachinery limits
- CO_2 is a better cycle for many sensible heat storage technologies for decoupled energy storage applications



Conclusions

- sCO_2 is a wonderful technology
- It has many characteristics which are extremely attractive for new reactors
- HOWEVER, it is not a panacea for all things
- Steam is still an excellent working fluid
- Nuclear development causes unique design tradeoffs which are sometimes more immutable than with other technologies

It is imperative that a one-team approach is undertaken by any reactor developer and sCO_2 developer



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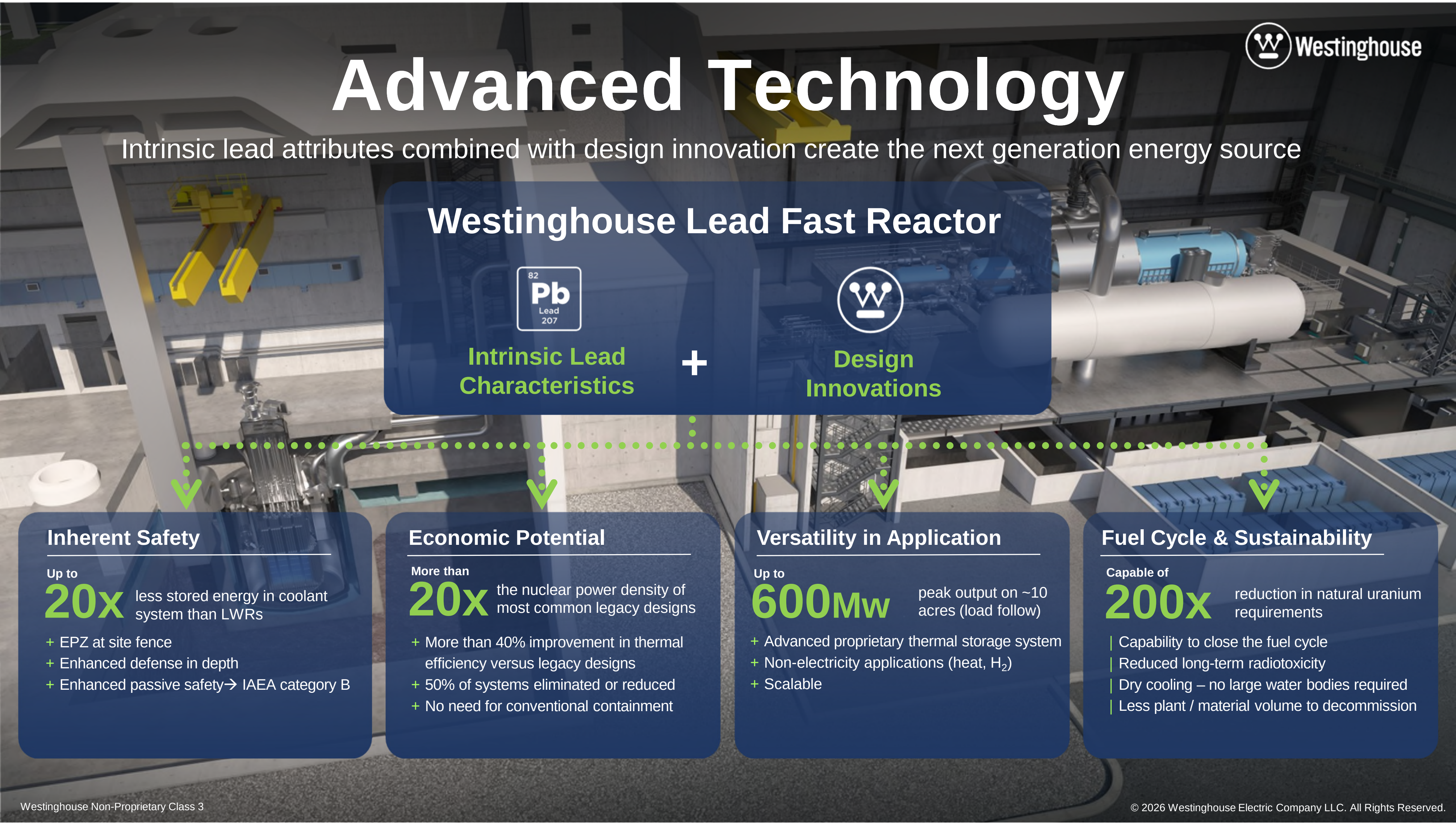
Backup Slides



Advanced Technology

Intrinsic lead attributes combined with design innovation create the next generation energy source

Westinghouse Lead Fast Reactor

82 Pb Lead 207

Intrinsic Lead Characteristics + **Design Innovations**

Inherent Safety

Up to

20x less stored energy in coolant system than LWRs

- EPZ at site fence
- Enhanced defense in depth
- Enhanced passive safety→ IAEA category B

Economic Potential

More than

20x the nuclear power density of most common legacy designs

- More than 40% improvement in thermal efficiency versus legacy designs
- 50% of systems eliminated or reduced
- No need for conventional containment

Versatility in Application

Up to

600MW peak output on ~10 acres (load follow)

- Advanced proprietary thermal storage system
- Non-electricity applications (heat, H_2)
- Scalable

Fuel Cycle & Sustainability

Capable of

200x reduction in natural uranium requirements

- Capability to close the fuel cycle
- Reduced long-term radiotoxicity
- Dry cooling – no large water bodies required
- Less plant / material volume to decommission

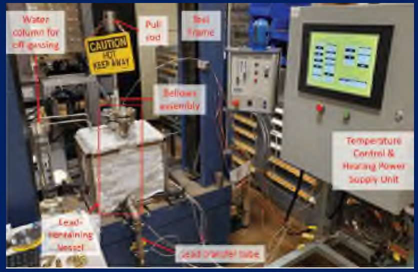
An impressive network of LFR test facilities recently built

Test facilities in the UK

Test facility	Location
Pb freezing and Under-Lead Viewing test facility (LEFREEZ)	Westinghouse (Springfields, UK)
Lead-to-water interaction test facility (LEWIN)	
Flowing Pb corrosion facility (MELECOR)	
Versatile Loop Facility (fuel bundle and HX testing) (VLF, in final phase of construction)	Ansaldo Nuclear (Wolverhampton, UK)
Passive Heat Removal testing facility (PHRF)	
Stagnant Pb corrosion facility	Jacobs (Warrington, UK)
Materials' mechanical property test facility	
Corrosion/erosion test facility (high-velocity) (BULLET)	Bangor Univ. (UK)

Test facilities in the US

Test facility	Location
Heavy Liquid Metal Embrittlement Test Facility (HELMET)	Westinghouse (Churchill, PA, USA)
Creep test facility (under procurement)	
Corrosion/erosion test facility (CORRERE)	Univ. of Pittsburgh (Pittsburgh, USA)
Corrosion test loop (LOBO)	Uni. Of New Mexico (NM, USA)
Facility for radioisotope retention capability of liquid Pb (under construction)	Virginia Tech (Blacksburg, VA, USA)



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