Commodication of advanced and micro reactors: an invested civil engineer’s perspective

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For our conversation today

• The 10 TWe moonshot
• Commodifying nuclear energy
• Right-sizing external hazards and risk
• Earthquake load case and seismic isolation
• REPOWER
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Nuclear: great idea but far too expensive?

• Major impediments to deployment of new LLWRs in the US
  • High OCC and LCOE, long time to deploy and to ROI
  • No learning from doing = NoaK

Plant Vogtle, 2+ GWe, $32B USD

<table>
<thead>
<tr>
<th>Total Capital Cost (2017 USD)</th>
<th>FoaK plants</th>
<th>Multiple plants</th>
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<tbody>
<tr>
<td>$14,000 /kW</td>
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<td>$0 /kW</td>
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</tbody>
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(ETI 2018)
Nuclear: great idea but far too expensive?

- Preconstruction (8+ years)
  - FEED studies
    - Geotechnical studies
    - PSHA
    - SSI analysis
    - Scheme design
  - DD + CD
  - Internal and external events PRA
  - Licensing
- Construction (12+ years)
- 20+ years to ROI = no customers
- Seismic load case → FoaK
- Civil/structural engineering: 50+% of OCC
- FoaK = no nuclear supply chain
- ROI = 5 years @ $2,500/kWe
Commodifying nuclear energy: changing the paradigm

Figure 1. Schematic Characterization of Different Energy Technologies Based on Their Design Complexity and Need for Customization

- Type 1 (yellow) technologies require no special design measures and can be mass-produced globally.
- Type 2 (blue) technologies require design measures that can be adapted to local needs, including small and modular designs.
- Type 3 (red) technologies require extensive design customization and often benefit from international coordination.

The figure illustrates how different technologies cluster in terms of their design complexity and need for customization. The axes represent a continuum along each of these two dimensions, and the locations of technologies within this framework are relative to each other. Based on this characterization, the technologies are grouped into three types, each requiring different roles of national and international innovation and deployment policy.
Advanced and micro reactors

TerraPower and GEH

Lucid Catalyst

Example Case Study
Natrium™ Power Production and Storage System
(TerraPower and GEH Hitachi Nuclear Energy)
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Right-sizing external hazards and risk

- Cost and safety impacts
- Load effects
  - Wind-borne missile impact
  - Aircraft impact
  - Extreme ground shaking
- Acceptable risk

Stephenson, 1977

- 2008 Mt. Carmel, IL, 0.2 g
- 2011 Greenbrier, AR, 0.4 g
- 1982 Miramichi, 0.4 g
- 2011 Mineral, VA, 0.2 g
Right-sizing external hazards and risk

- **Load effects: wind-borne missiles**
  - Regulatory Guides
    - Tornadoes (RG 1.76), hurricanes (RG 1.221)
  - **Normal** impact of high-velocity missiles
    - Schedule 40 steel pipe, 150 mm dia, 5 m long, 130 kg
      - 41 m/s (tornado), 94 m/s (hurricane)
      - *Simple* but why normal impact?
    - Automobile, 1820 kg, specific size
      - 41 m/s (tornado), 113 m/s (hurricane)
  - Any evidence of such damage?
    - Non-nuclear sectors: no

Stephenson, Terranova et al.
Right-sizing external hazards and risk

- Load effects: aircraft impact
  - Aircraft cockpits secured for 20 years
  - Hijacking of aircraft in US since 2001 = 0
  - Strike a RC box and not a political target? No.
  - Could you hit the RC box if you wanted to? No.
  - MAF of aircraft impact on a RC box in the US = 0
  - Guaranteed fatalities from an aircraft strike?
    - 250+ dead on B787, all on the plane
Right-sizing external hazards and risk

- Load effects: *incredible* ground shaking
  - Consider Seismic Design Category 4, Clinch River
    - 100% DRS (PHA=0.53g, RP=5,300 years), 200% DRS (1.06g, 25,000), 400% DRS (2.12g, 150,000), 600% DRS (3.18g, 490,000), 800% DRS (4.24g, 1,250,000)
Right-sizing external hazards and risk

- Tolerable risk
  - MAF of death in a car accident?
    - 1/10000 (1E-4)
  - MAF of building collapse?
    - 1/5000 (2E-4) from ground shaking
  - MAF of death due to dam failure
    - 1/10000 (1E-4), existing dam
    - 1/100000 (1E-5), new, major dam
- Need to right size the F-C chart
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Earthquake load case. Always FoaK?

- Seismic hazard varies by
  - Proximity to faults (line, areal, point)
  - Soil conditions
  - How characterized now: SSHAC
- Soil-structure-interaction analysis
  - Nuclear cottage industry
  - Coupled dynamics of soil and structure
    - Surface mounted structures
    - Deeply embedded structures
  - Need to define ground motion at depth
    - Where, how? Body waves, surface waves?
- Cost impact of the seismic load case?
Seismic isolation. What is it? How does it work?

- 2D horizontal or 3D
  - Nearly all 10,000+ applications 2D horizontal
Seismic isolation. Asset protection only?

- Isolated LLWRs: Cruas and Koeberg
  - Synthetic rubber bearings
Seismic isolation, LLWRs, advanced and micro reactors

- DOE (2014-2016): Seismic isolation of components in advanced nuclear reactors
- DOE (2016-2018): Evaluation of the potential effect of seismic risk at DOE facilities
- DOE (2017-2019): Seismic isolation of advanced reactors with considerations of fluid structure interaction
- DOE (2018-2020): Seismic isolation of major advanced reactor systems for economic improvement and safety assurance
- EPRI (2018-2019): Cost basis for utilizing seismic isolation for nuclear power plant design
- ARPA-E (2018-2021): Reducing the overnight capital cost of advanced reactors using equipment-based seismic protective systems
- DOE via Southern Company (2021-2023): Topical report on seismic isolation of advanced reactors
- DOE ARDP via MIT (2021-2024): Horizontally configured high-temperature gas reactor
- DOE NEUP (2022-2025): Gamma irradiation effects on the mechanical properties of seismic protective devices
Technology readiness: seismic isolation
Why standardize? The role of isolation?

- Advanced Liquid Metal Reactor, 1992, Berkeley
- Standardize for needed cost reductions
  - Seismic isolation
  - Productized buildings, DfMA
  - COTS equipment
  - Separate nuclear island from the balance of plant
  - Web-based ground motion calculations (USGS)
  - One time licensing: building, equipment, isolation systems
  - Enable a nuclear supply chain: order books for parts
- Quantify the cost savings? Data for advanced reactors?
Quantify costs savings: isolation and standardization (NoaK)

EPRI, DOE
Seismic isolation and ARPA-E
Risk-based design of isolation systems: 2023 topical report

• Southern Company lead
  • Seismic isolation systems: technology, use, guidelines
  • Earthquake shaking definitions, performance expectations
  • Archetype reactor building, equipment, siting
  • Risk-based design of a seismic isolation system
  • Qualification, prototype, and production testing
  • Specifications for supply of isolators and dampers
  • Commercial grade dedication
  • Generating a displacement demand curve
  • Achieving a risk target, including derivation of fragility functions
  • Selecting a target performance goal: how to start?
  • Isolation-system options: judging different systems
Risk-based design of isolation systems: 2023 topical report

- Risk-based design of a seismic isolation system
- Seismic displacement demand curves
- Isolation-system fragility function
  - Increment F50 until target performance goal (TPG) achieved
  - Prototype testing
Standardization of design and licensing

1) Site selected. 2) Pick a licensed heat source (MWe). 3) Pick a licensed isolation solution. 4) Price time and construction. 5) Evaluate alternatives and iterate on 2, 3, and 4.
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Electric Power Research Institute: John Richards, Hasan Chakas
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Kairos Power, X-energy, TerraPower, Boston Atomics, BWXT-RR