Commodification of advanced and micro reactors: an invested civil engineer's perspective

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Chair, ASCE Nuclear Standards Committee

For our conversation today

- The 10 TWe moonshot
- Commodifying nuclear energy
- Right-sizing external hazards and risk
- Earthquake load case and seismic isolation
- REPOWER

NASA

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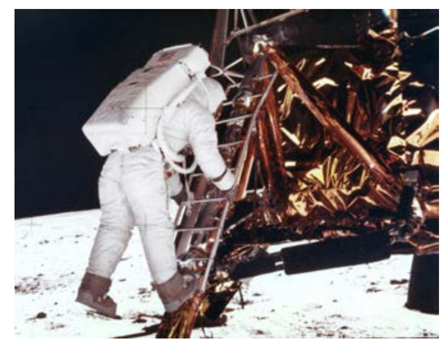

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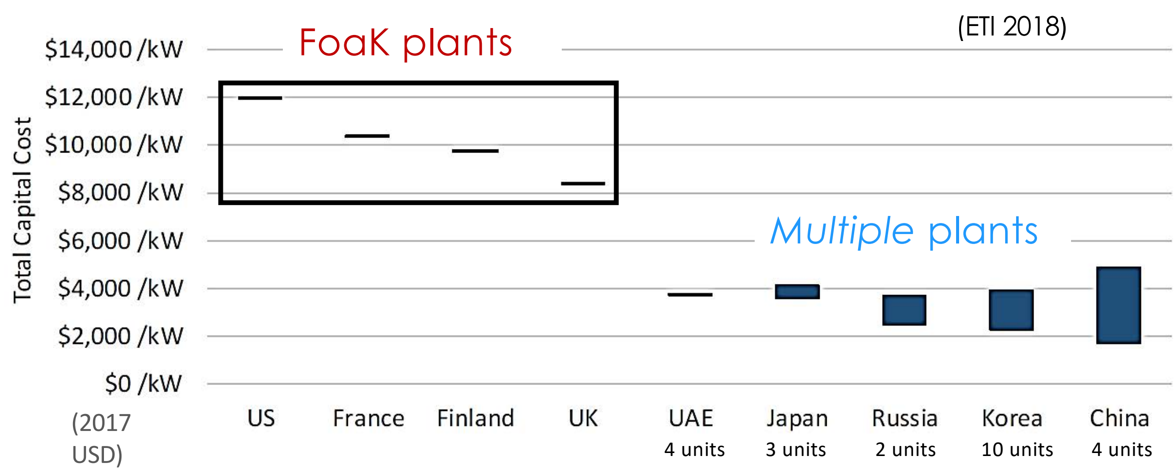
Nuclear: great idea but far too expensive?

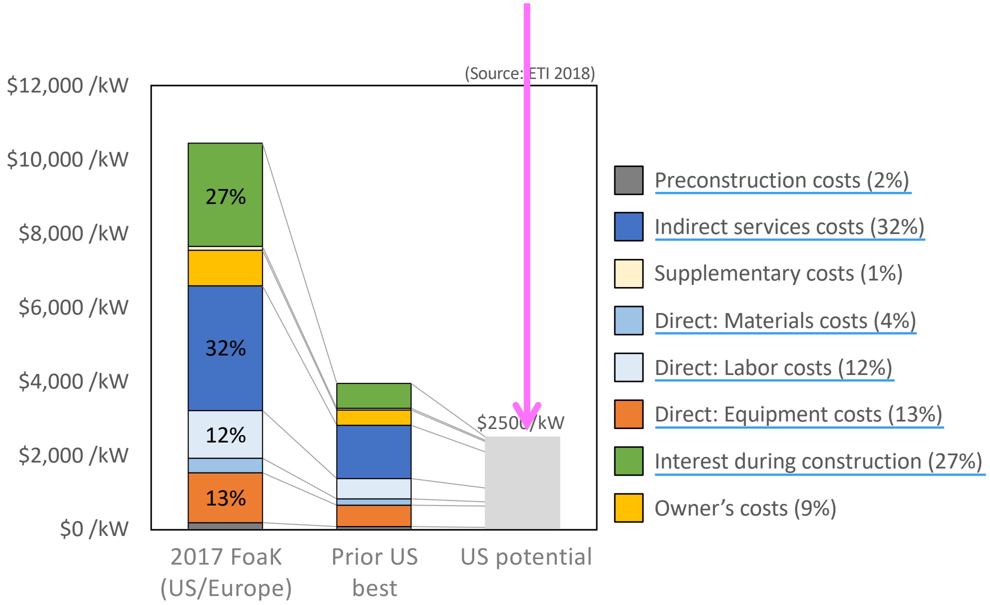
- Major impediments to deployment of new LLWRs in the US
  - High OCC and LCOE, long time to deploy and to ROI
  - No *learning from doing* = NoaK

Plant Vogtle, 2+ GWe, $32B USD

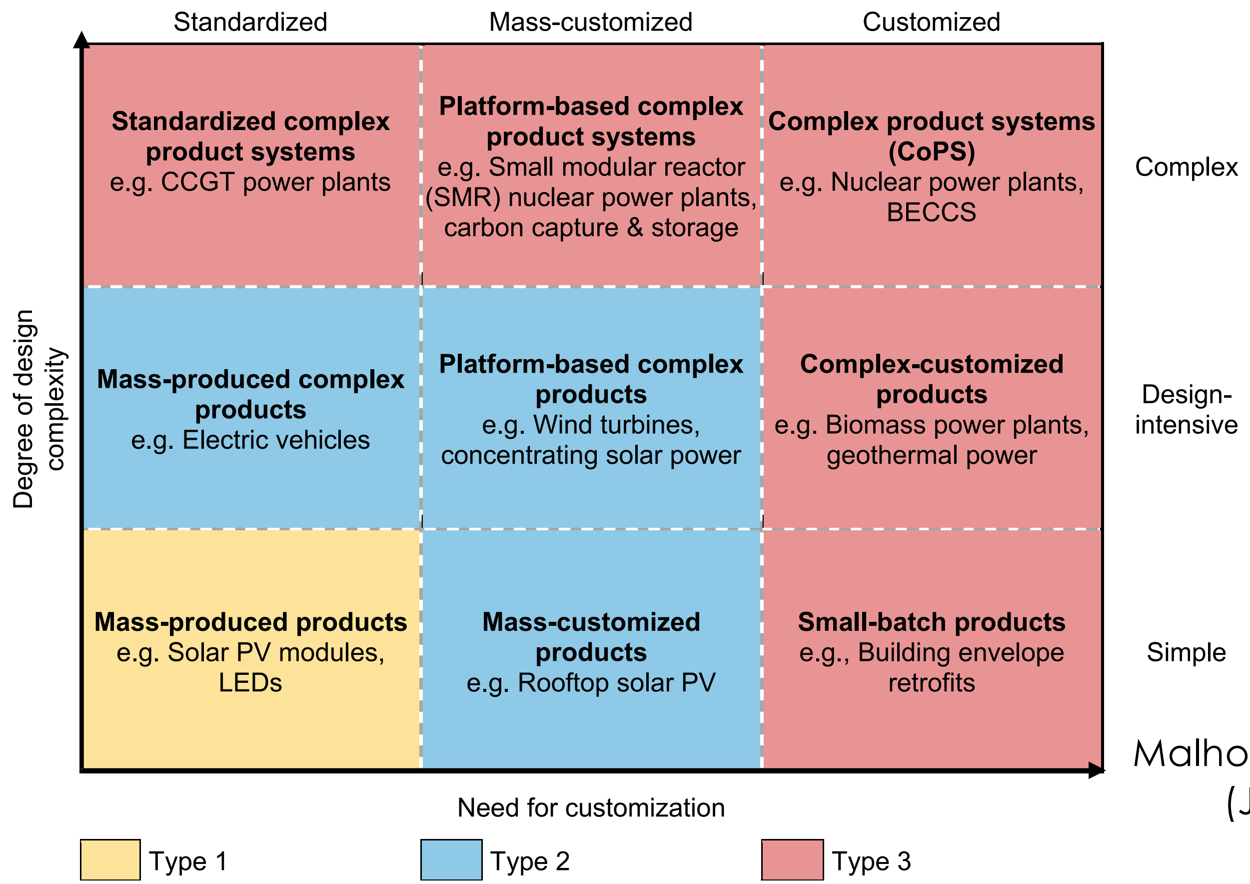


Nuclear: great idea but far too expensive?

- 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



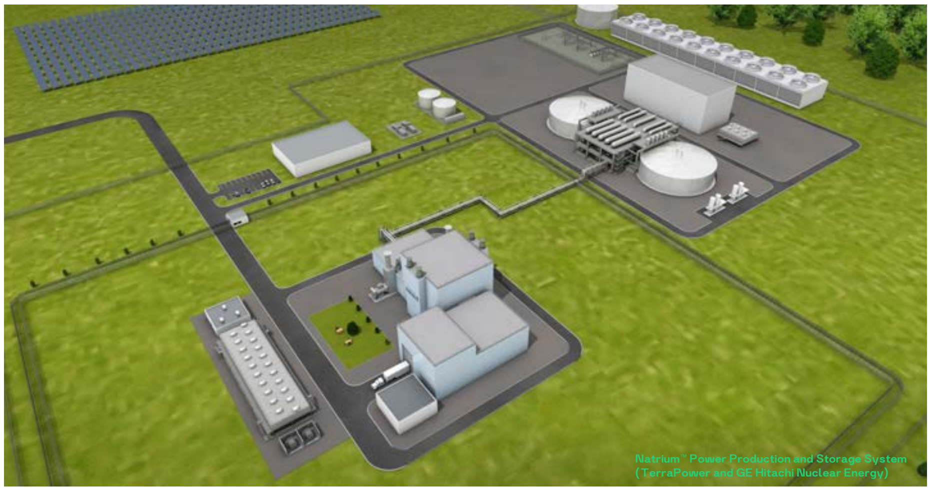
Commodifying nuclear energy: changing the paradigm



Malhotra and Schmidt (Joule, 2020)

Advanced and micro reactors

TerraPower and GEH



Lucid Catalyst

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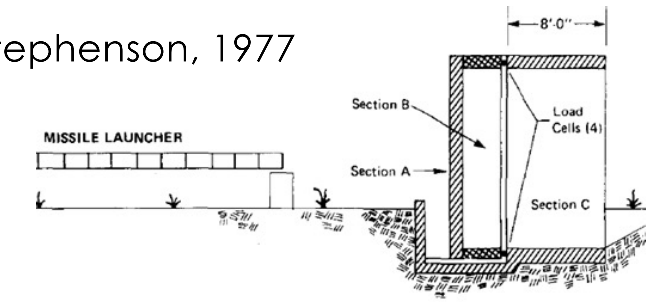
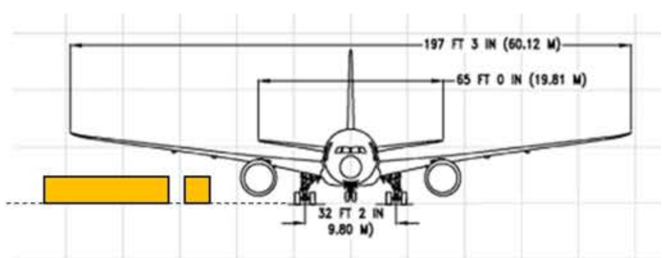
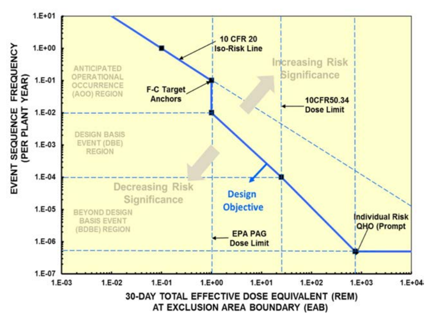
Right-sizing external hazards and risk

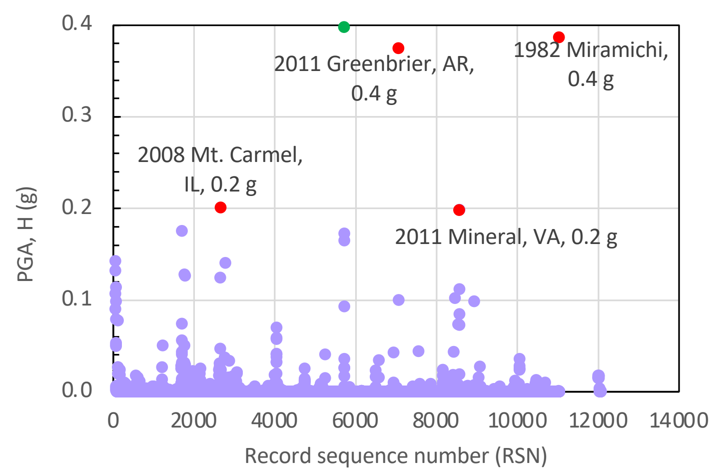
- Cost and safety impacts
- Load effects
  - Wind-borne missile impact
  - Aircraft impact
  - Extreme ground shaking
- Acceptable risk

Stephenson, 1977



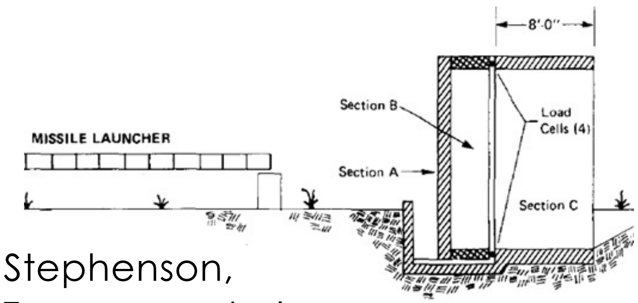




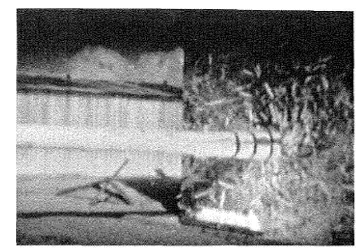


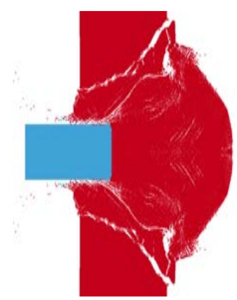
Right-sizing external hazards and risk

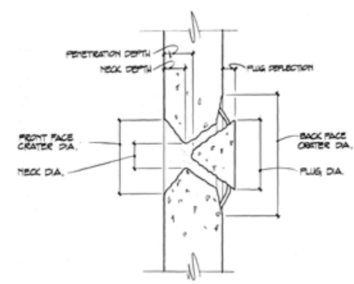
- Load effects: wind-borne missiles
  - Regulatory Guides
    - Tornadoes (RG 1.76), hurricanes (RG 1.221)
  - **Normal** impact of high-velocity missiles
    - Schedule 40 steel pipe, 150 mm dia, 5 m long, 130 kg
      - 41 m/s (tornado), 94 m/s (hurricane)
      - *Simple* but why *normal* impact?
    - 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.

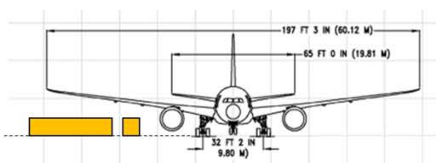


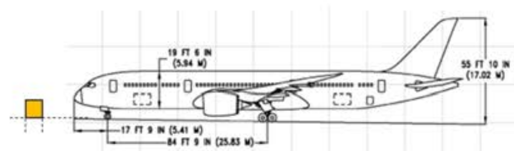




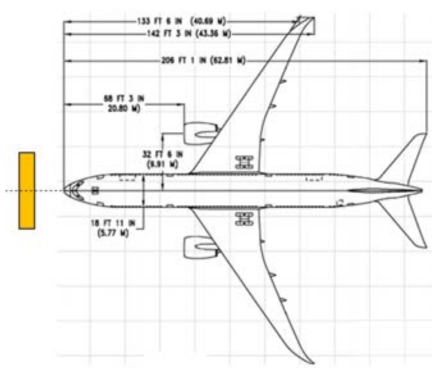
Right-sizing external hazards and risk

- 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



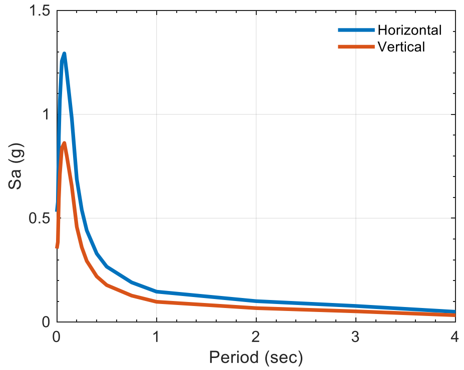


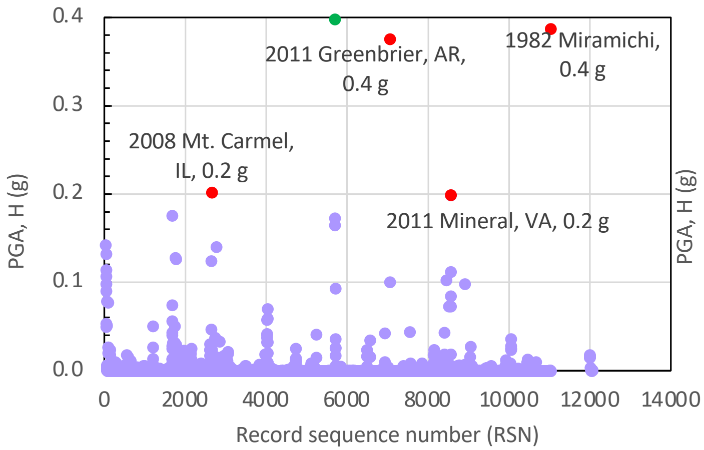
Boeing

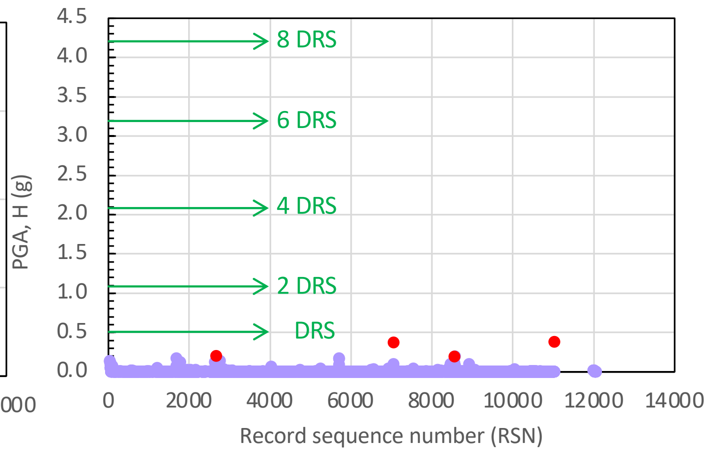


Right-sizing external hazards and risk

- 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)

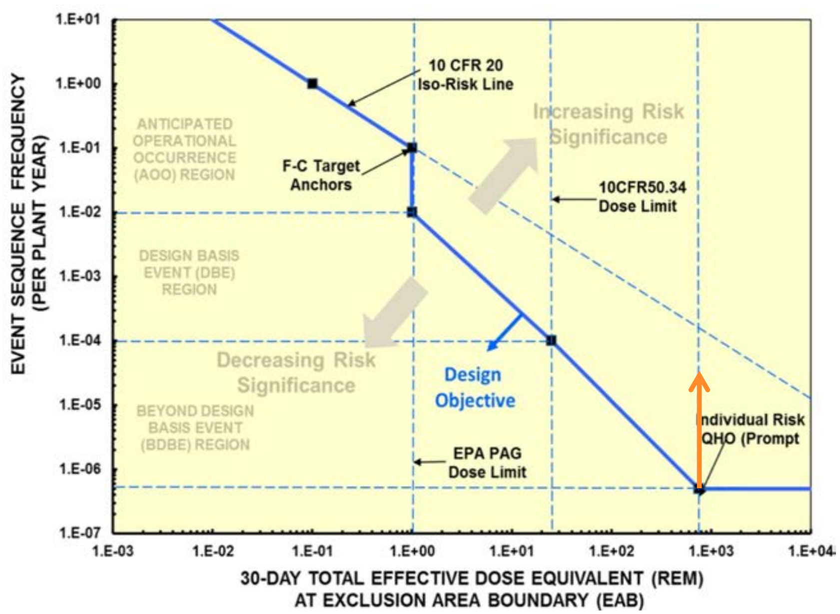






Right-sizing external hazards and risk

- 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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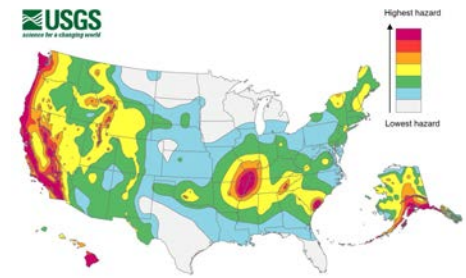
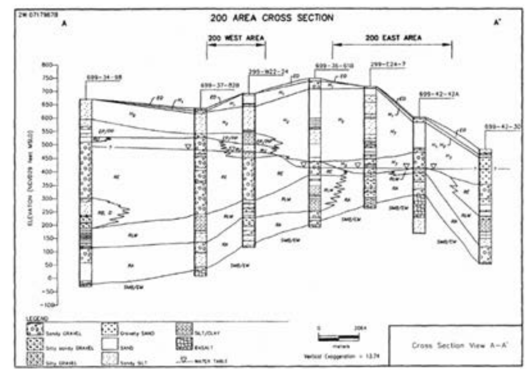
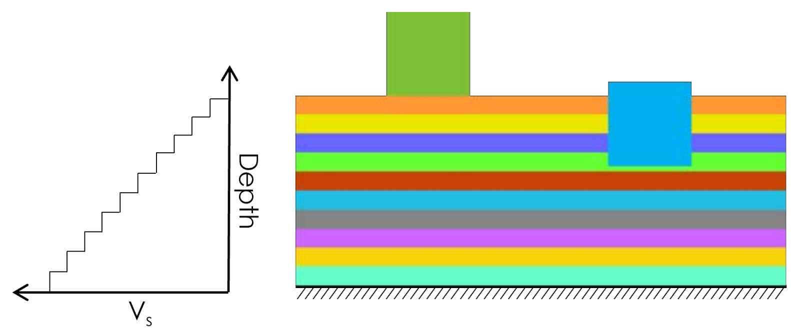
Earthquake load case. Always FoaK?

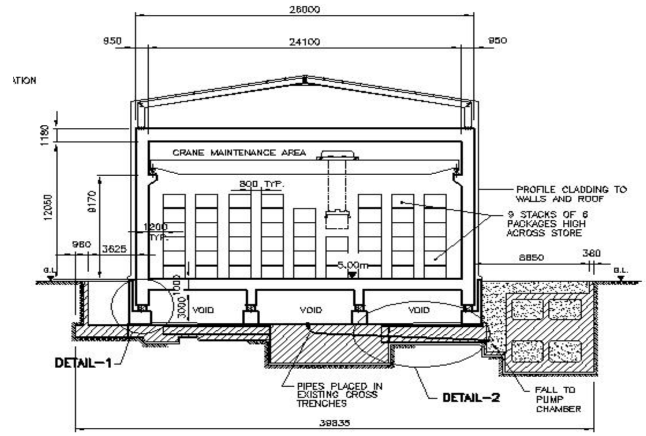


- Seismic hazard varies by
  - Proximity to faults (line, areal, point)
  - Soil conditions
  - How characterized now: SSHAC
- Soil-structure-interaction analysis
  - Nuclear cottage industry
  - Coupled dynamics of soil and structure
    - Surface mounted structures
    - Deeply embedded structures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



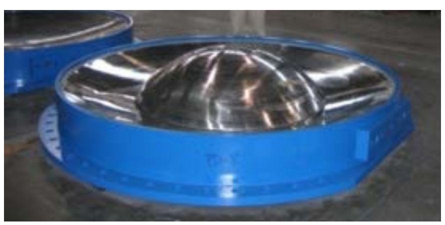


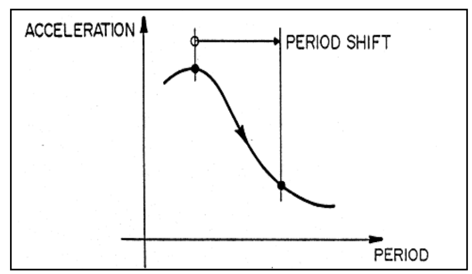
Seismic isolation. What is it? How does it work?

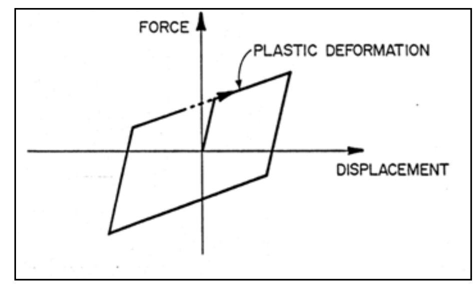


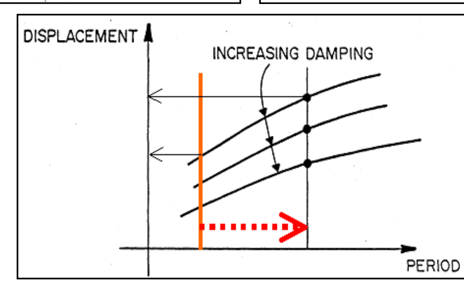
- 2D horizontal or 3D
  - Nearly all 10,000+ applications 2D horizontal





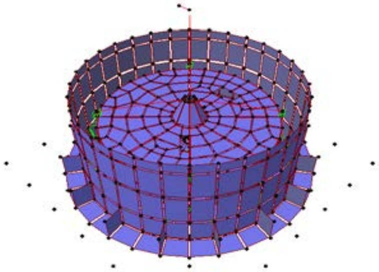


Seismic isolation. Asset protection only?

- Isolated LLWRs: Cruas and Koeberg
  - Synthetic rubber bearings

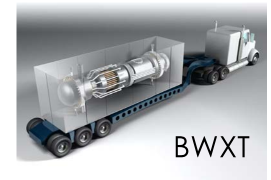




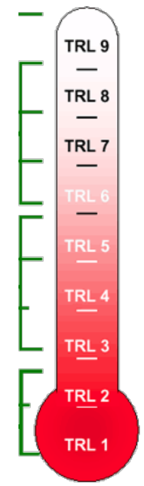

Arup, 2020

Seismic isolation, LLWRs, advanced and micro reactors

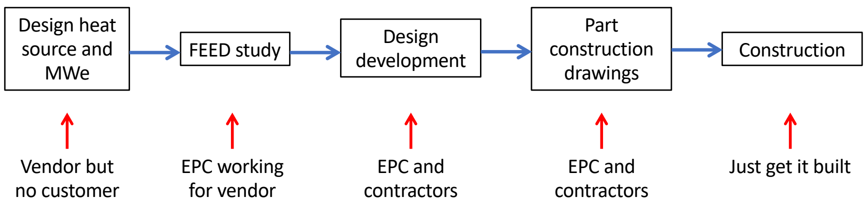


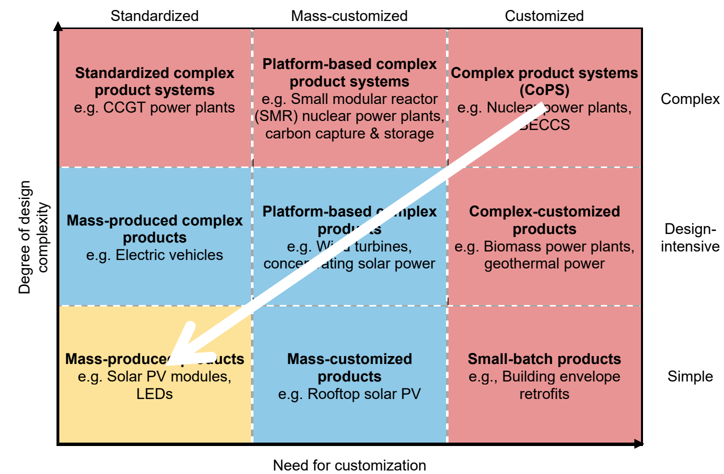
- USNRC (2008-2017): Seismic isolation of large light water reactors
- DOE (2014-2016): Seismic isolation of components in advanced nuclear reactors
- DOE (2016-2018): Evaluation of the potential effect of seismic risk at DOE facilities
- DOE (2017-2019): Seismic isolation of advanced reactors with considerations 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

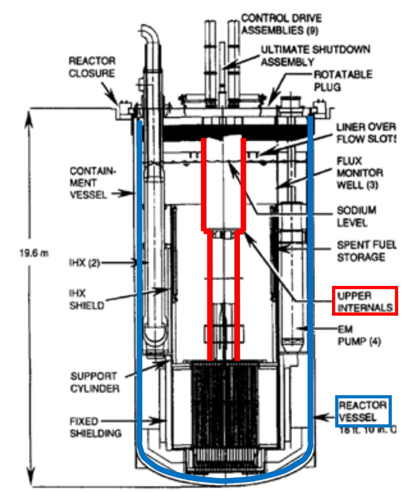


Why standardize? The role of isolation?



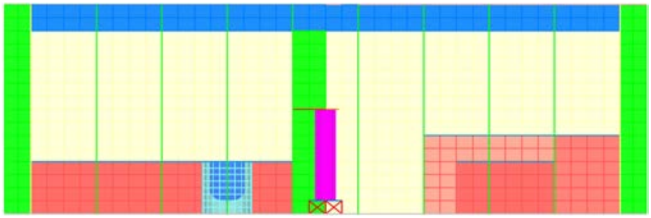


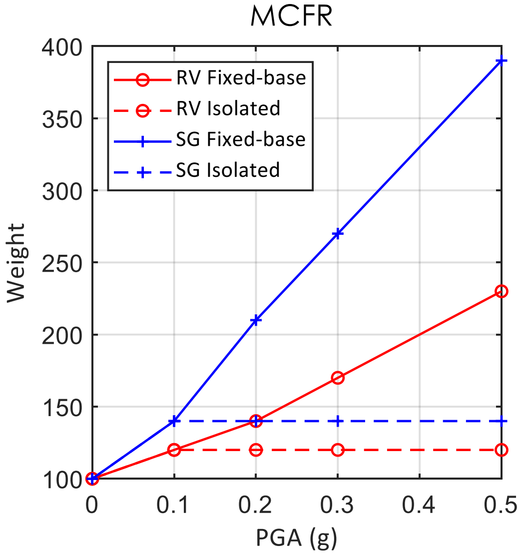
- Advanced Liquid Metal Reactor, 1992, Berkeley
- Standardize for needed cost reductions
  - Seismic isolation
  - Productized buildings, DfMA
  - COTS equipment
  - Separate nuclear island from the balance of plant
  - Web-based ground motion calculations (USGS)
  - One time licensing: building, equipment,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

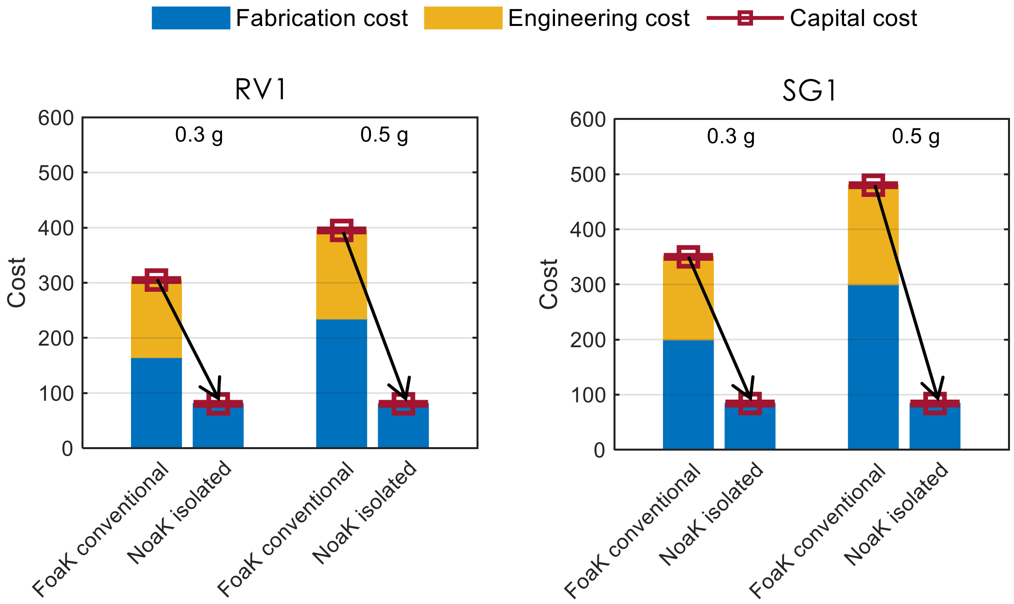


Quantify costs savings: isolation and standardization (NoaK)

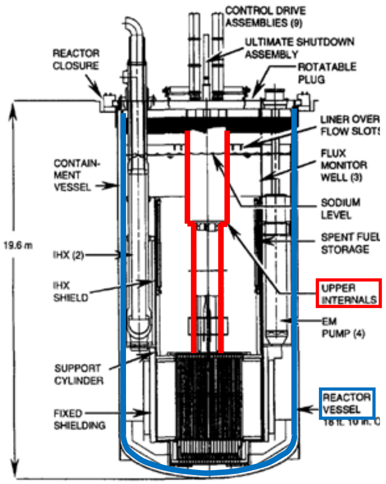
EPRI, DOE





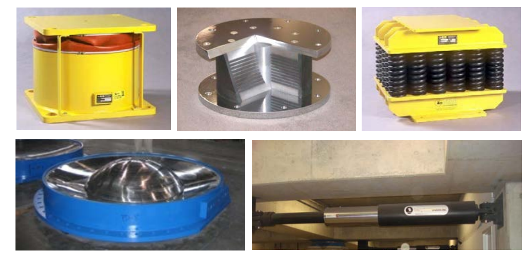


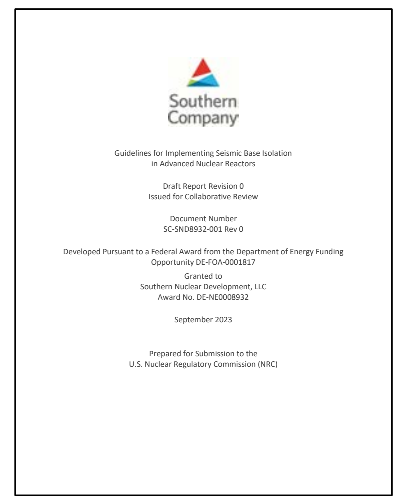
Seismic isolation and ARPA-E



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





Southern Company

Guidelines for Implementing Seismic Base Isolation
in Advanced Nuclear Reactors

Draft Report Revision 0
Issued for Collaborative Review

Document Number
SC-SND8932-001 Rev 0

Developed Pursuant to a Federal Award from the Department of Energy Funding Opportunity DE-FOA-0001817
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September 2023

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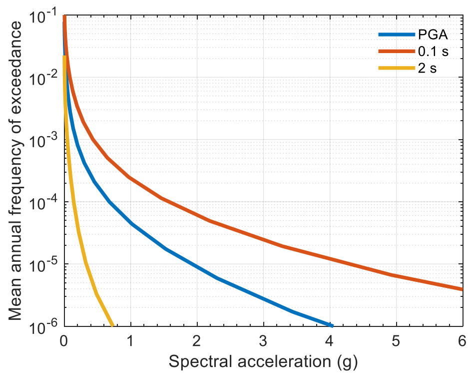
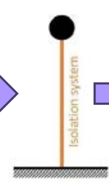
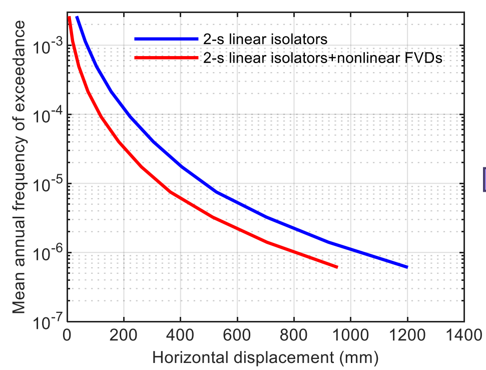
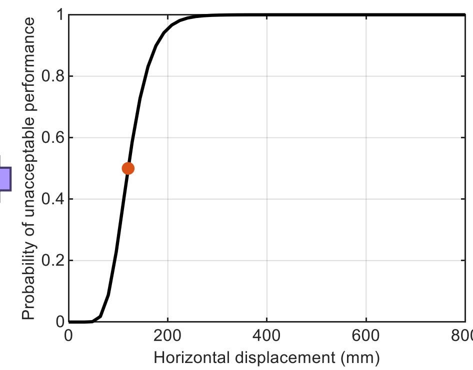
- Risk-based design of a seismic isolation system
- Seismic displacement demand curves
- Isolation-system fragility function
  - Increment F50 until target performance goal (TPG) achieved
    - Prototype testing



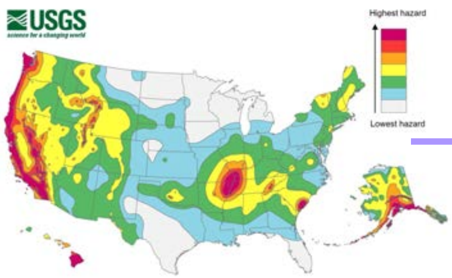


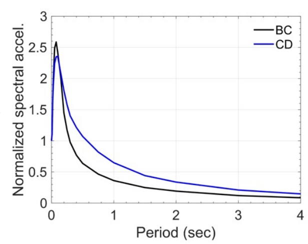




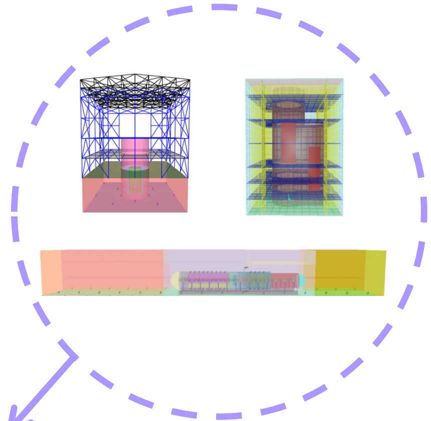
TPG

Standardization of design and licensing

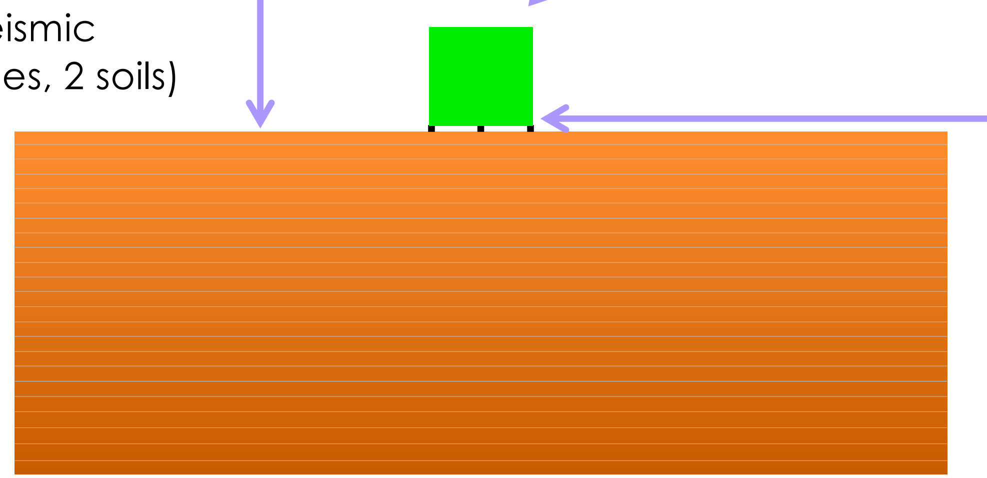


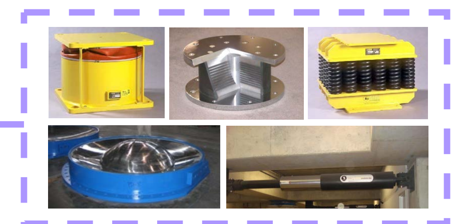


Pre-binned seismic hazard (6 zones, 2 soils)

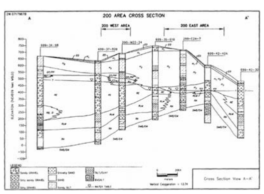


Licensed design spaces





Licensed isolation systems



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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Idaho National Laboratory: Chandrakanth Bolisetti, Justin Coleman

Electric Power Research Institute: John Richards, Hasan Chakas

Southern Company: Ben Carmichael, Brandon Chisholm, Jason Redd

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