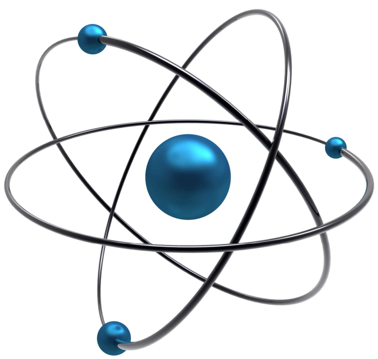
Making Sense of the Many Reactor Possibilities “Back to the Future – Part 2.5”



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A presentation for the American Nuclear Society

Northeastern Section Meeting

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Overview

- Introduction
- Historical View – Context & Legacy Reactor Observations
- Why this talk or What has changed?
- Clarification on Terminology
- Putting Reactors into Perspective
- Potential Game Changers
- How Do We Move Forward?
- Separating the Signal from the Noise
- Conclusion
- Q&A

Introduction

James Michael O’Connell

USNA Class of 1976

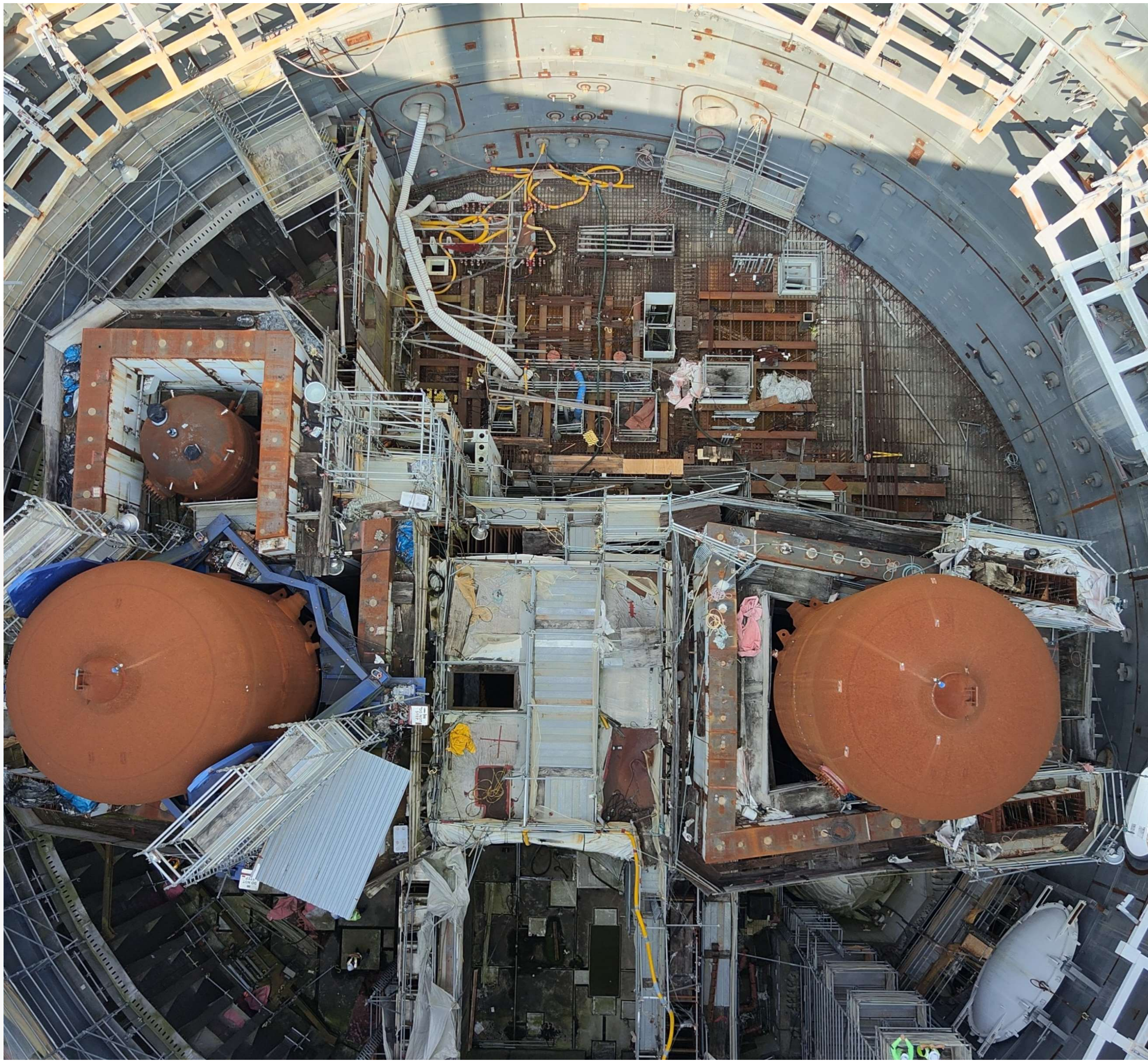
Navy Nuclear Program 77 – 83

GE BWR SRO 83 – 88

A/E/Consulting 89 – 01

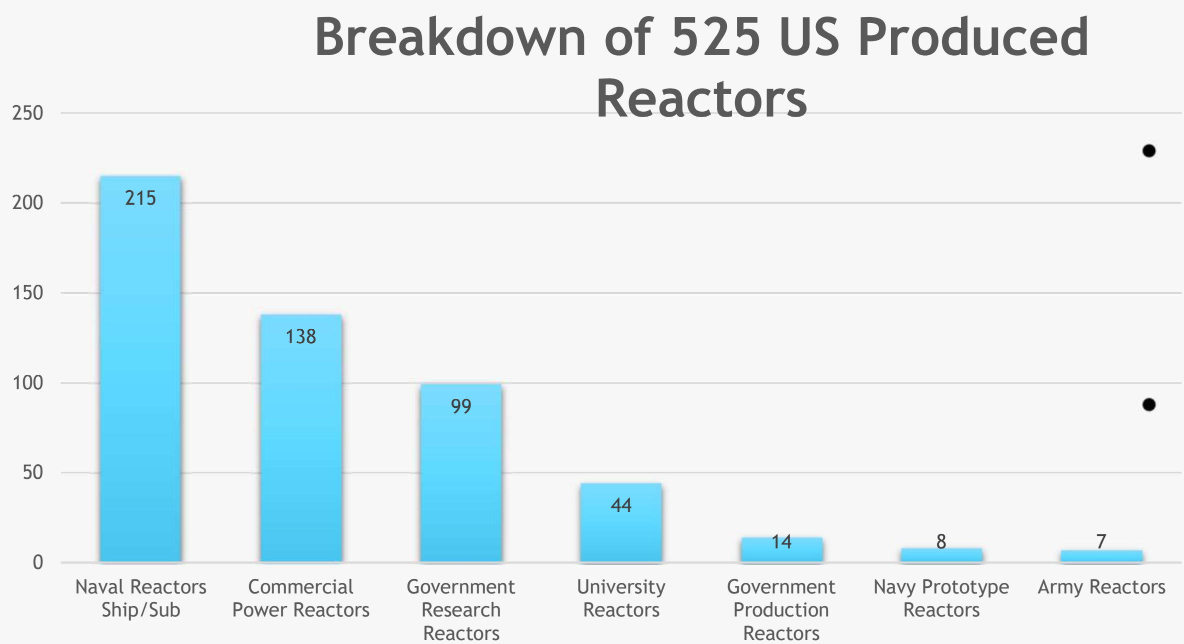
EPC 01 – 17

Decom 18 – 24



Current VC Summer 2 Containment

Historical View - Context



- Over 525 reactors have been built and run in the US – we know they work and the nuclear physics aspects are well understood.
- So, what are the questions?
  - Affordability
  - Predictability of construction
  - Scalability
  - High temperature materials
- Why the earlier emphasis on PWRs and BWRs?
  - Technology developments drive by US Navy paved a certain path
  - US utility grid sought out larger units led by W and GE
  - Cost/KWe drops with larger units

Legacy Reactor Observations

- Existing grid market place has strong preference for GW scale machines:
  - Generate lots of VARs when needed
  - Lowest $/KWe for O&M due to scale
  - Fleet operational excellence
- What will it take to become a significant player?
- What is sufficiently disruptive to change the game?

Why This Talk or What Has Changed?

- Inability of GW scale projects to deliver on time and on budget
- New use cases driven by DoD demand for resilience
- Significant demand for clean electricity for data centers/AI processing cycles
- Willingness to pay premiums for clean nuclear reliability

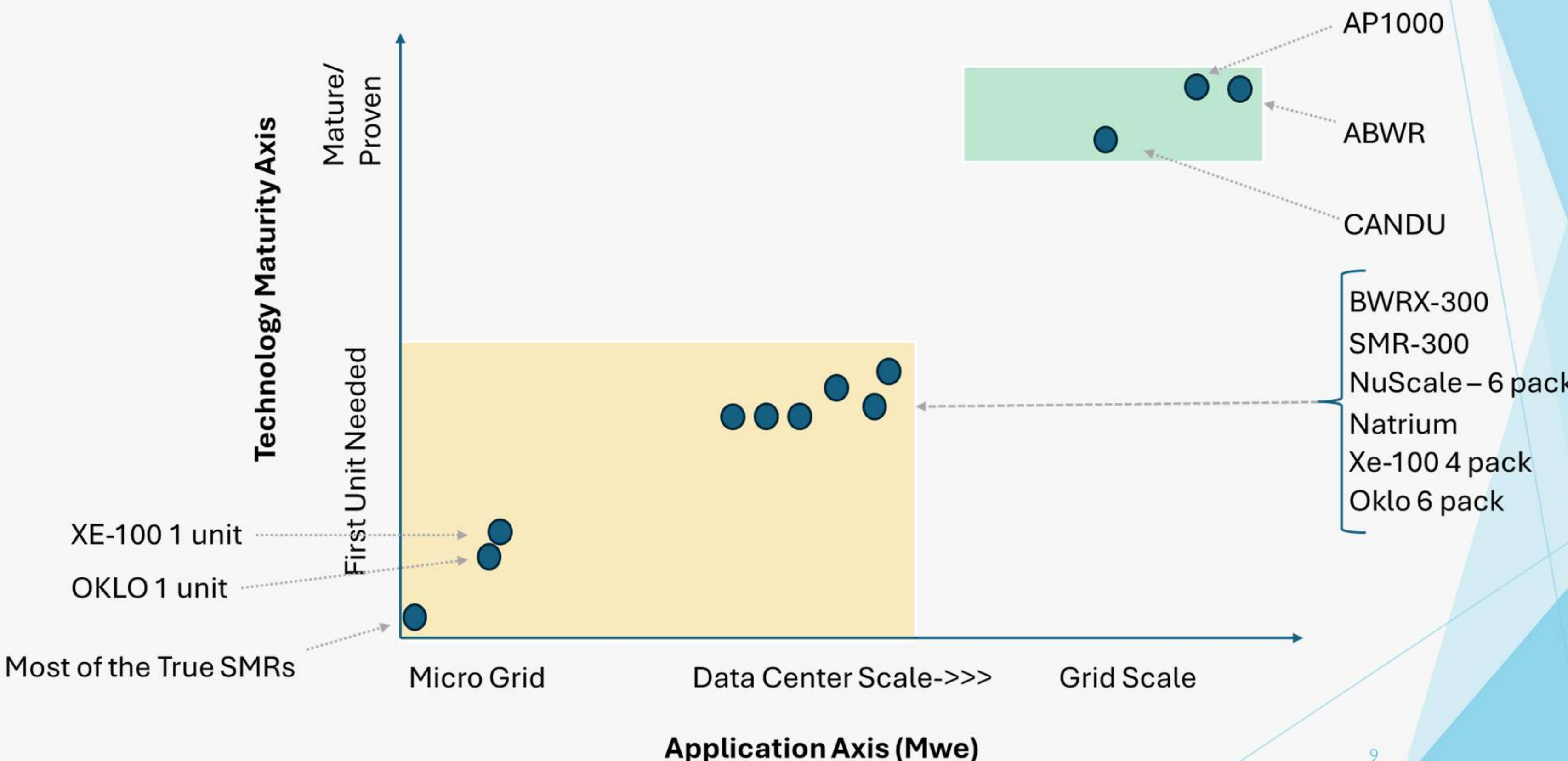
Proliferation of potential reactor designs across a range of plant outputs, temperatures and application

Clarification on Terminology

- Small Modular Reactors are neither small nor modular! Anything that gets past 5 Mwe has a number of support systems and supporting structures, thus while you may have a lot of factory-built modules, the plant as a whole is not a modular construction effort. Concrete and steel are not modules. If you are putting a reactor on the ground or in the ground, you need a foundation for example. Lots of rebar and concrete and all the plywood to form the structures!
- What do we mean by small? INEL has defined micro reactors as less than 30 MW electrical
- Cautionary Note: We nuclear professionals tend to get caught up by the technology of the technology, but that's not why these machines are purchased. Keep your eyes focused on who is paying or willing to pay.

Putting Reactors into Perspective

Maturity & Application



Listing or representation does not reflect all of the entrants

SMR and Large Reactor Comparisons

	Natural U	<5% Enrichment	>5% to < 20%
> 750 MWe	CANDU-6	EPR ABWR AP1000 Monark	
150 – 750 MWe		Rolls Royce SMR AP-300 BWRX-300 SMR-300 NuScale (6 pack)	General Atomics EM^2 TerraPower Natrium TerraPower MCR Xe-100 (four pack) Oklo Aurora (six pack)
30 - 150 MWe		NuScale – 1 unit MSR-100	ARC-100 Kairos XE-100 Oklo Aurora

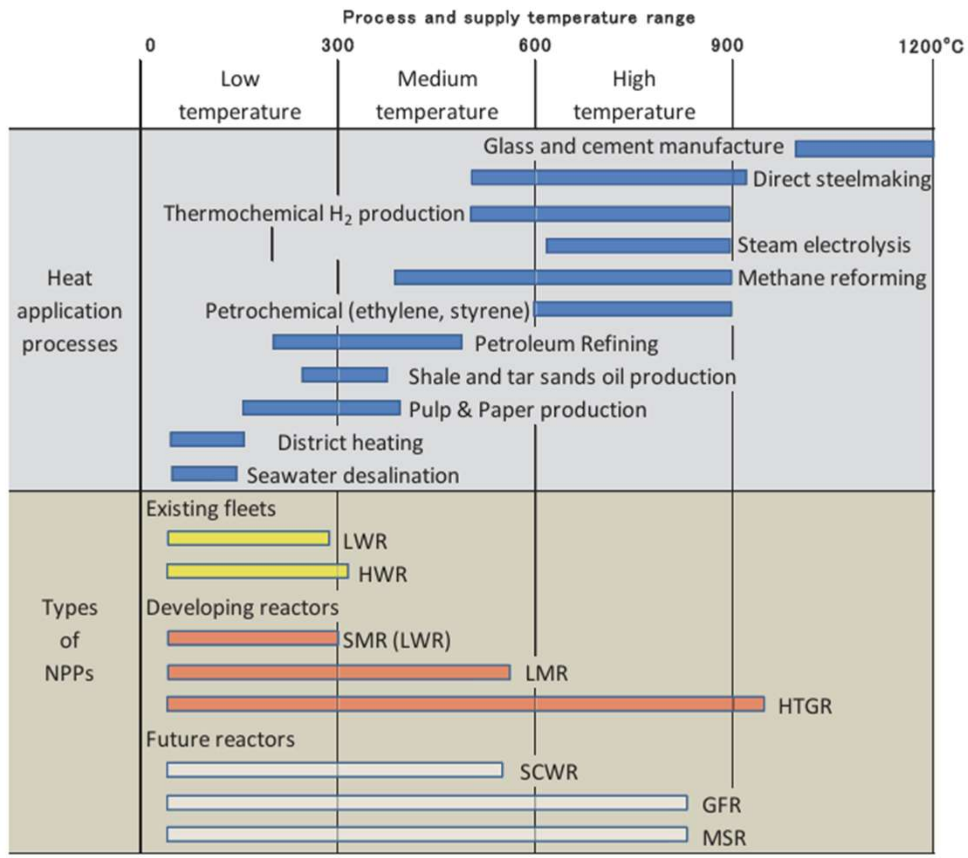
Listing or representation does not reflect all of the entrants

Micro Reactor Comparisons

	Helium	Molten Salt Liquid Metal	Water
> 5 < 30 MWe	BWXT – BANR Nanon - Kronos		Last Energy
> 1 – 5 MWe	X-Energy Zenith BWXT – Pele Nano – Loki Radiant - Kaleidos		
< 1 MWe	Nano – Zeus Antares		

Listing or representation does not reflect all of the entrants

Matrix of Reactors and Applications



Note: GFR — gas cooled fast reactor; HTGR — high temperature gas reactor; HWR — heavy water reactor; LMR — liquid metal reactor; LWR — light water reactor; MSR — molten salt reactor; NPP — nuclear power plant; SCWR — supercritical water reactor; SMR — small modular reactor.

Source IAEA- Technical Report
No. NP-T-4.1,
Opportunities for Cogeneration with Nuclear Energy

Potential Game Changers

- High Boiling Point Coolants
  - Greater thermal efficiency & resultant lower water requirements
  - Walk away safe does not need much additional equipment
- Fast Reactors
  - Better utilization of Uranium
  - Burn up potential for reducing long term waste
- Lack of Zircaloy Cladding
  - Avoids H2 generation potential
- Brayton Cycle
  - Eliminates need for large quantities of water

Proliferation of potential reactor designs across a range of plant outputs, temperatures and application

How Do We Move Forward?

Address the AP-1000 Lessons Learned

AP-1000 Accumulator

First Units

First two units at each site were twice to three times as expensive and took at least twice as long as predicted.

Subsequent Units

Subsequent units at multi-unit sites (PRC) showed schedule reductions of up to 50% and similar cost reductions. Even Vogtle Unit 4 was able to demonstrate lessons learned with its much quicker completion that Unit 3 due to Unit 3 being used to resolve all the engineering issues.

What have we really learned?

- Incomplete engineering means you don't know where the finish line really is and thus your understanding of total product delivery cost is at best a guess, at worst it is like playing Liars Dice.
- Backlogs will kill your project

Anticipate the Headwinds for New Reactors

- Licensing for Zero EPZs
- Price of admission – approx. $500M ea.
- HALEU /MOX production
- Fuel Fabrication – Triso and special forms
- Long Lead Forgings
- SMR or larger plant modular construction is more expensive for N<5
- First of a Kind Fabrication
- Skilled labor, i.e. electrician shortages led to quality issues on Vogtle

Prepare for New Builds

Rebuild the Supply Chain

limited number of large component manufacturers and limits on large forgings

Build nuclear construction management teams

New to rebuild the experienced PDs, PMs and supporting work forces to manage field operations. Welders in short supply everywhere, need hourly labor development programs to promote careers.

Figure Out How to Drive Field Work Efficiency

Construction productivity has been stale since the 1980’s and given risk aversion of most construction professionals adapting new technologies is more than just challenging.

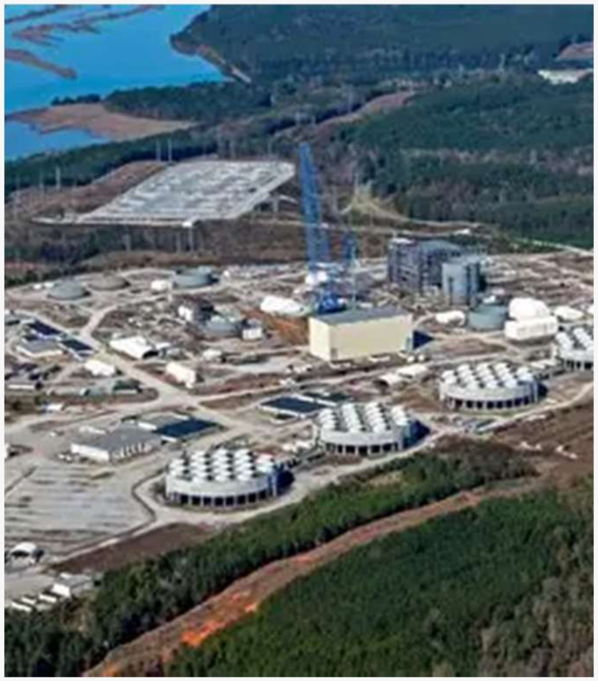
Risk Management Model Limits when GW scale is reached

Not enough fee on any of these new builds to offset overruns.

Better or innovative contracting models needed.

Indian Point Unit 1 late 50’s

A Path Forward



VC Summer 2 & 3 Site As Left

Gen III

VC Summer 2 & 3

A firm has been awarded the rights to finish the partially complete twin units using the vast amount of finished equipment already on site.

Palisades 2 & 3

Project by Holtec will result in two SMR-300 plants in 5 to 7 years which is basically a two loop PWR design (low risk).

Darlington & Clinch River BWRX-300

Twin projects launches around the GEH BWR technology at a site in Canada and TVA's site.

Gen IV

Terra Power Natrium Reactor

Project using sodium cooling is moving with construction underway at the Wyoming site.

Oklo @ INL

Pioneering first unit at DOE site with expedited approvals.

X-Energy @ Calhoon City

Four pack to support Dow Chemical

Separating the Signal from the Noise

Assessing New Developments

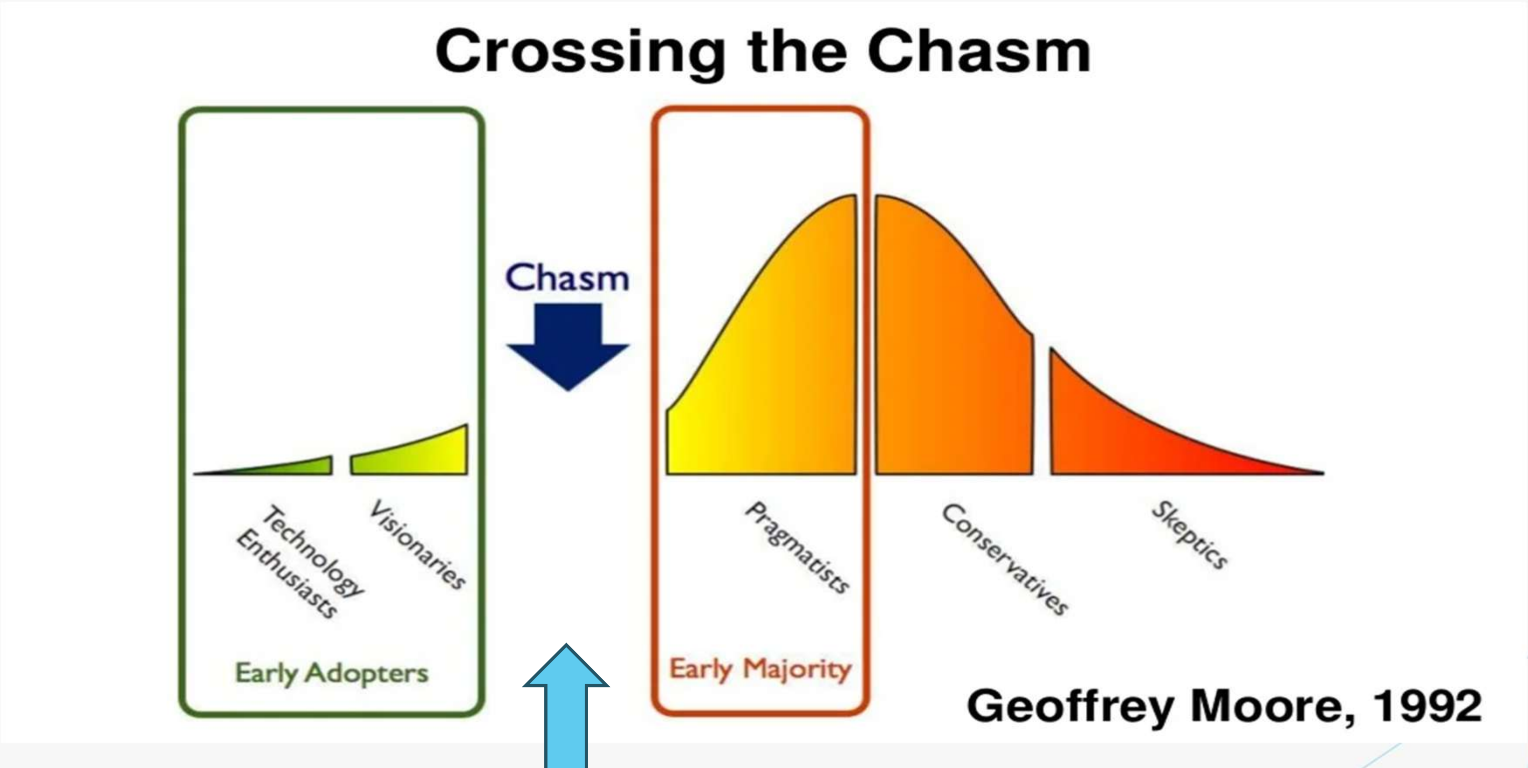
- Potential Customer Base – Use cases drive demand
- Scalability – will it scale or be a niche?
- Game Changer - Possesses Disruptive Economics?[1]
- Ability to Cross the Chasm aka Do They Have Enough Money to Cross the Finish Line?[2]

1. Professor Clayton Christensen, *The Innovator's Dilemma, 1997*
2. Geoffrey Moore, *Crossing the Chasm, 1992*

Are There Disruptive Technologies Coming in Nuclear?

- The late Clayton Christensen of the Harvard Business School observed that disruptive technologies generally don't come from current market leaders – prime example is a number of the Apple user interface innovations came from Xerox's Palo Alto development center
- So, which if any of the new entrants will become the next major technology?
  - Uniquely low-cost starting point? i.e. not a lot of legacy expenses
  - Able to exploit low-cost principles?
  - Able to live without an expensive containment or back up systems
  - Accident tolerance & minimal EPZ?

Getting from Concept to Product Delivery



About $500 M is the size of the chasm per reactor type

Handicapping Reactor Developers

- Do they have a contract?
- Are they using off the shelf fuel?
- What sort of game changer is being offered? i.e. will the juice be worth the squeeze?
- Are they disruptive? i.e. better economics due to lack of legacy boat anchors or overly complex designs bogged down by classic regulatory & utility engineering staffs?

Conclusion

This period of time is a lot like Silicon Valley in 1970’s and early 80’s – many potential vendors of personal computers. Not that many will succeed. Expect a lot of consolidation as potential winners try to cross the chasm. “Best technology does not always succeed”.

Q & A

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