Breakout 2 a

- For justification: what are fundamental advantages and disadvantages at smaller reactor size?
- What are the technical opportunities?
- Jacobs company: MMR design. What is market?
    - Private money from investors, market is huge
    - New use case for nuclear at micro size.
    - Size is unlikely bigger than 10 MWe per unit. Suggestion.
    - Ranges vary. Above 10 MWe, not as appealing because people want two reactors at site for redundancy.
    - Not necessarily grid-connected.
    - Market drivers: cost/unit energy good for these markets? Cost/kW is not important. Care more about LCOE.
    - Can't start on grid with product like this.
    - Small towns in Canada/Alaska, industrial facilities, mining, O&G
    - Campus where combination of facilities that need grid independence.
    - Need 10 MW for off-grid first market?
    - Lots of market, different reactors work better between 1 and 10 MW
    - Some reactors are required for process heat only. Focus on remote locations for electricity production.
    - What is tolerance for price?
        - Price up to 2$/kWh
        - Maine 30c/kWh
        - Lower price opens opportunities
        - What is the value of having own generation on site?
        - Program: new use cases will open up as technology is developed
        - Redundancy is important in some cases. Redundancy is everything!
        - Benefit at small size: have multiple units.
    - Can a nuclear unit be that small and still be cost-competitive?
        - Have to look at the cost of transporting fuel.
        - Highrises are using microturbines. If have large facility that needs redundancy and backup, I MW is a good size.
        - Would only be able to compete in huge market outside of city centers. (off-grid, no natural gas or cheap coal available)
    - Advantages specifically of small size
        - Low or no EPZ
        - Some countries want energy independence
            - Can use extra heat for desal or other applications
        - Easier autonomous control at small size? Control remotely.
    - MMRs can't compete for grid-tied base load. Everything but that!
    - What is size of potential market?
        - 200 GW generation worldwide (conservative estimate, geographical limitations)
        - Market is 10 and less. 2 MWe is most likely, depending on application.
        - Sandia studies: sweet spot is 6 MW

- What if use existing site and bunch units together? Can we have multipurpose application?
    - Cost will dictate this.
    - Larger units have higher efficiency, less units, less manpower
    - Microturbines have troubles. Break down. Can have turbine experts in one spot, but not distributed.
- Should we have turbine inside or outside?
- MMRs would open utilities to using nuclear.
- Should combine heat and power?
    - Do either electric or cogen. Don't need to separate all thermal or all electric.
- Need to match customer needs to technology!
- If just making heat, is there a lower limit to reactor size?
    - Yes, possible to make compact reactor. But to do that, need highly enriched fuel.
    - Gets more expensive at smaller scale.
        - Have enrichment limit at small size.
        -
- How is size connected to lifetime of reactor?
    - Small fast reactor for 30 years is achievable
    - Small cores have low burnup. Meet limit of steel or material.
    - Concerns with Plutonium production because of proliferation concerns.
- Range of lifecycle?
    - Anything less than 5 years is too frequent
    - Will probably want to do full core extraction
- What is the sweet-spot?
    - Depends on market and technology. No singular solution.
- Coolant temperature should be discussed
    - More important than size.
    - Heat needs are not much above 200 C → use heat on back end of condenser
- Highly-nonlinear safety at lower sizes
    - Consequences at smaller EPZ would be same as at larger EPZ
    - Not about EPZ, more about the source term and what can be maintained
        - Should aim for smaller source term
        - These are not much bigger than research reactors at universities. They don't have EPZs!
        - At site boundary: there is an allowable dose.
        - 10s of meters.
        - Balance of things around the reactor not impacting the reactor.
        - Not going to get dose if operating normally
- Common reactor approaches
    - Sensors
        - Different core instrumentation, change what want to detect
        - Technologies may not be commercially available like
            - Gamma, neutrons, temperature profiles

- Challenges with sensors at temperatures and hard. T up to 700 C depending on core design.

- Reliable, long-life, maintenance free
  - High-speed rotating machinery
  - 750 C heat source, can push to 60% efficiency
  - (Previously, couldn't get there)
  - No off-the-shelf
  - SCO2 good medium relative to He, but a lot of study needed
  - Magnetic
    - Heat exchanger + recuperator
  - Maintenance free turbo-alternator at 750 C
    - Also applicable to other heat sources
    - Lots of incremental current activity
    - Materials developed.
    - Permanent magnets, alternative materials
    - High turbine efficiencies, 60% with SCO2
    - 100 units, 1$/W
    - Smaller 500, 0.5c/W
    - Cost benefit to move to 10 MW machine
    - Material limitations are at 1000 C, 750 C materials available.
    - New materials need 25 years to test.
    - Need system development and integration from beginning.
    - 25 bar P
  - Power conversion side
    - Innovative power conversion. Thermoelectrics or otherwise?
    - Some machines operating for 15 years in aircrafts with lots of startup and shutdown
    - Ramping can take a big toll on power conversion unit
    - Big area for development!
    - Consider nuclear battery
      - Direct conversion from neutrons to electronics?
      - Less efficiency drops? No moving parts?
      - PARC: Navy considered solid-state nuclear reactor?
      - No one has worked out details of alternate power conversion technologies.
      - There are a small number of niche applications where this would be useful.
    - Autonomous operation problem
      - Lots of things to do
      - What is a reasonable depth of autonomy? How define autonomy?
        - People monitoring from remote application
        - Model after what FAA does. Human factors. Air traffic control

        - Simple fact that operators are far from reactor is different
      - Need fundamental architecture for control strategy. This will dictate how reactors are distributed. Same problems with SMRs
      - Design integration.
      - Human becomes decoupled from system.
      - How many people needed for reactors when there is a large number of reactors
      - Sandia demonstrated for NASA an autonomous reactor.
      - Cyber component
      - Smart things can be done with sensors to maintain cybersecurity!
      - How do we get away from frequent maintenance cycles?!
      - Modeling tools to do economics? Yes.
    - If already have inherent safety, cybersecurity is more about reliability
    - Have to convince the public you have control of your system!
    - Open-ended FOA for creative solutions?
      - Sensors not necessarily expensive, materials maybe
  - Tribology of seals
    - Impact of SCO_2 on wear
    - Especially at smaller scales, small turbomachinery
    - Temperature issues
    - Also issue with water.
  - Resilience (part of autonomous design?)
  - Rapid materials development
    - Protocol to get materials faster
  - Materials and fuels in a rapid way
    - Designed on a computer to application faster
    - Take from 30 to 5 years
  - Critical needs for sensors?
    - Lifetime, stability
    - Radiation stability specifically
    - Temperature
    - Solid cores → use ultrasonics to view cores
    - Non-contact probes : distance and movement of parts, need at 750 C because that is how you control turbine
- ARPA-E program
  - Development of a concept:
    - Development roadmap for MMR
    - What would be done with 30 M to make change
  - Integrated design concept that meet criteria:

        - Fill gaps of current DOE programs
        - DOE does not have program focused on MMR
        - Multiple applications
    - Targeted cross-cutting areas. Cover gaps to fill in
        - 5-8 M to simulate turboalternator
        - High stress advanced reactor sensors
            - Could do all 30 M on sensors
            - Valuable for many fields in broader advanced reactors
            - Part of work can go to regulator: white papers, topological reports
            - Cybersecurity
            - Smart sensors
        - Autonomous controls
            - Cybersecurity
        - Materials
            - Prove that materials characterization can be accelerated
        - Turboalternator concepts, power conversion units
    - Important to keep out of a specific reactor concept!
        - Don't want to exclude technologies because there can be learnings from different reactor types
    - What can we do with 30 M
        - Sensors and controls would be manageable
        - 5-8 M for smallscale prototype of turboalternator, experimental simulation
        - Long term: these technologies would help current nuclear, SMR, large-scale, others!
            - Naturally, things will start smaller, and this would help open that
    - What is biggest/most enabling
        - Autonomy! (sensors and controls integrated)
            - Bell: small reactors for lifetime of ship. Don't need cybersecurity because of design. Technology and approach is maybe already there.
                - Operator is at reactor
                - Lower temperatures
                - In sea and not back yard
        - Are materials/sensors/controls already covered by current DOE programs?
            - Design centers that have a technology problem. They can push their own technology solution as long as they show the advantage to other reactors and concepts.
            - Can't make full reactor and test for 30 M
            - ½ million, can give a reactor design
        - Hard to take multiple ideas and stitch them together
    - If concept is chosen, then may narrow things too much
        - Want to incentivize innovation
        - Want to focus on supporting the industry
        - How can we in industry accelerate timeframe? Need program to help manage that?

        - Don't have a paper competition
- Whatever technology is picked, NRC has to be integrated. Cannot have hands-off approach with NRC
    - They request money to look into areas more
    - NRC does not charge for generic issues, take advantage of this
    - Goes to Office of Research
    - Generic issues
        - Things seen across multiple units
        - Or seen across reactor designs
    - Different issues can be targeted to different agencies/entities
    - If ARPA-E is talking about commercialization, must engage NRC!!!
        - At least a plan to approach it
    - Remove ambiguity of regulation. Use T2M activities to explore NRC options
    - Need more industrial engineering
        - Need something that says how do we do it?
        - Manufacture in factories, transport, logistics
        - Regulators can help guide designs to take into account these factors
- Want to get some issues out of the way in an effort to move forward
- Does 10 c/kWh go with a 6 MWe size?
    - Yes.
    - Assuming autonomous, assembly line, etc.
    - Is 20 c/kWh good enough? Yes. 30 is also good enough.
- Don't need to be cheap. In certain markets can still make a large impact if more expensive.