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Detailed Bottom-up Assessment of Microreactor Potential Cost Competitiveness

2024 Microreactor Program Winter Review

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Overview of Presentation

1. **Background**
   - Motivation
   - Approach
2. **Neutronics**
   - Core parametric consideration
   - Optimization for economic performance
3. **Cost Estimation**
   - Leveraging MARVEL cost data
   - Scaling costs for MARVEL-20 variant
4. **I&C Automation**
   - Quantifying cost-benefit of autonomous steady-state ops

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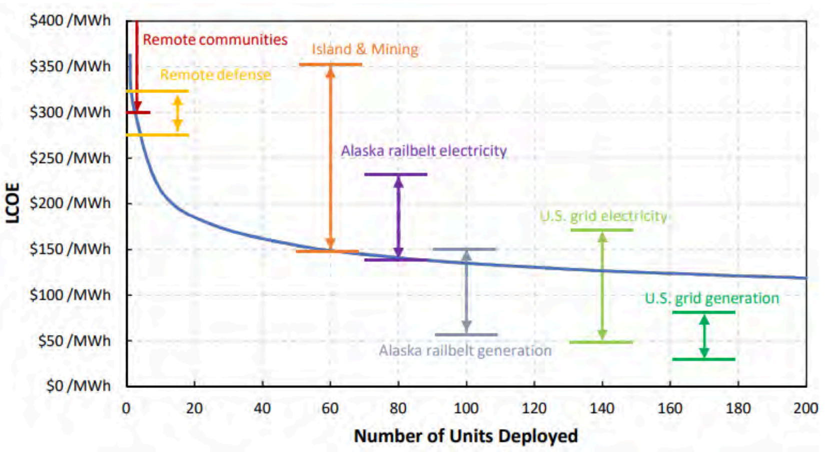
Background

- Motivation
  - Rising interest in the small/microreactors that can be deployed at a fraction of the cost and time (compared to the GW-scale reactors)
  - Economic competitiveness tied to mass production which is tied to demand → circular paradigm → need to unblock with techneconomic analysis
  - Need for detailed bottom-up assessment of microreactors costs for evaluating the competitiveness for several markets
- Opportunity
  - MARVEL cost data: only microreactor cost dataset available for detailed design, primary coolant system and fuel fabrication
  - Even through MARVEL is not built to be cost-competitive, MARVEL costs can still serve as a starting point for developing a microreactor cost model
- Scope
  - Develop alternate configurations of a microreactors using MARVEL as a starting point to derive a bottom-up cost estimate that is more representative of commercial concepts
  - Long-term: leverage cost data to consider other design parameters (e.g., TRISO fuel, HTGR)

Driving Question:

Can microreactors compete beyond niche markets?

(Shropshire, 2021)



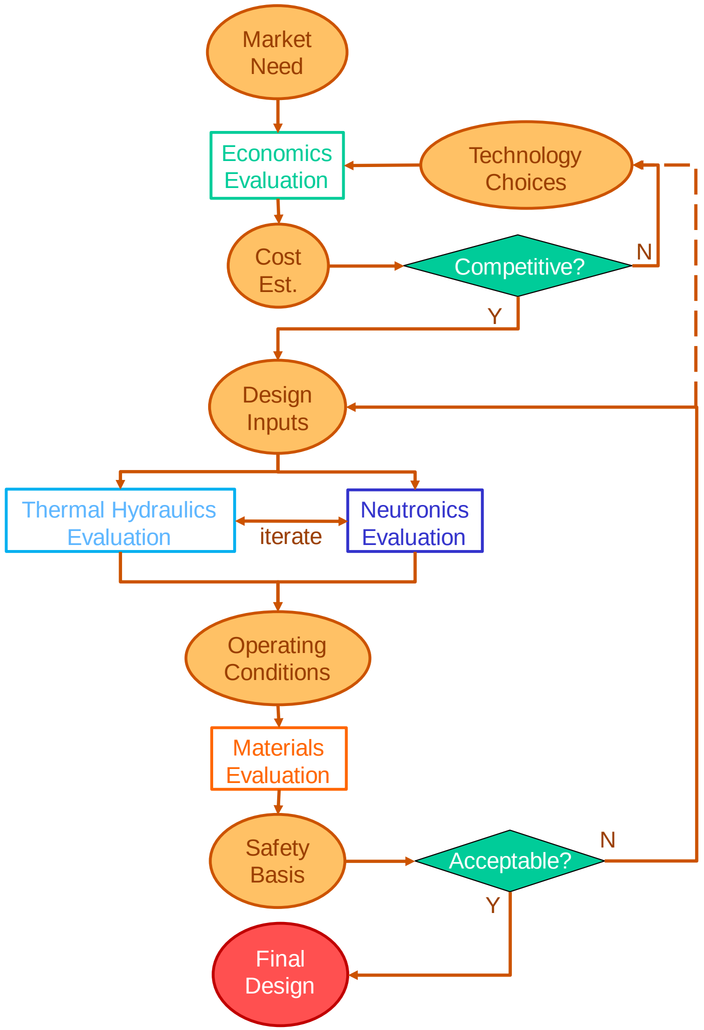
(Abou-Jaoude, 2021)

(Abou-Jaoude, 2021)

Approach

- Follow 'economics-by-design' approach from SA&I
  - Will not be able to fully optimize design within current scope
  - Can put economics as guiding principle for analysis
- Ultimate target is:
  - Capital cost (excluding fuel) **<$5,000/kW** *(Buongiorno, Jacopo, et al. Energies (2021))*
- Mass production cost reductions previously assessed in: https://doi.org/10.1080/00295450.2023.2206779
  - 1x to 10x → 70% cost drop in factory costs
  - 10x to 100x → 50% cost drop in factory cost
- Task breakdown in this scope:
  - Conduct neutronics analysis to evaluate alternate configurations
  - Simple thermal hydraulics verifications
  - Source term evaluation
  - Cost estimation (leveraging MARVEL data)
  - Iterate

Economics-by-Design



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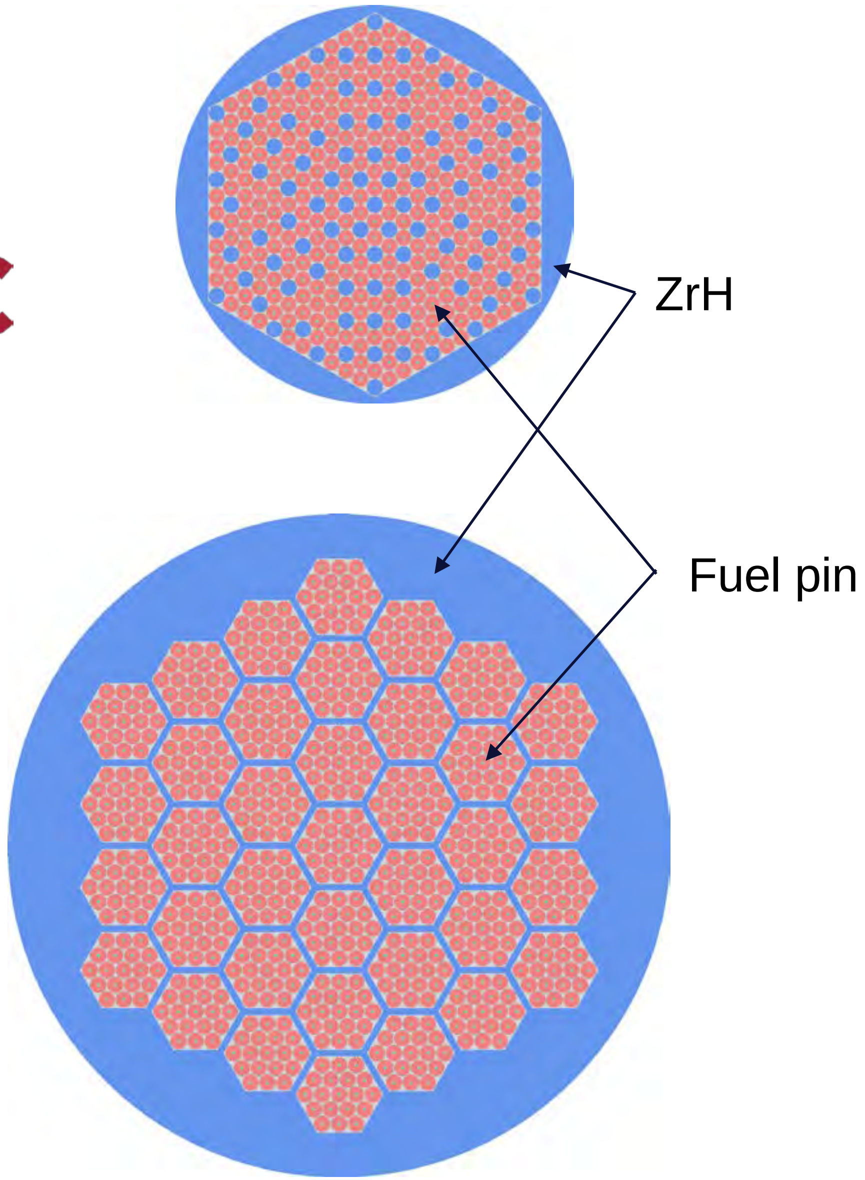
Core neutronics: Approach

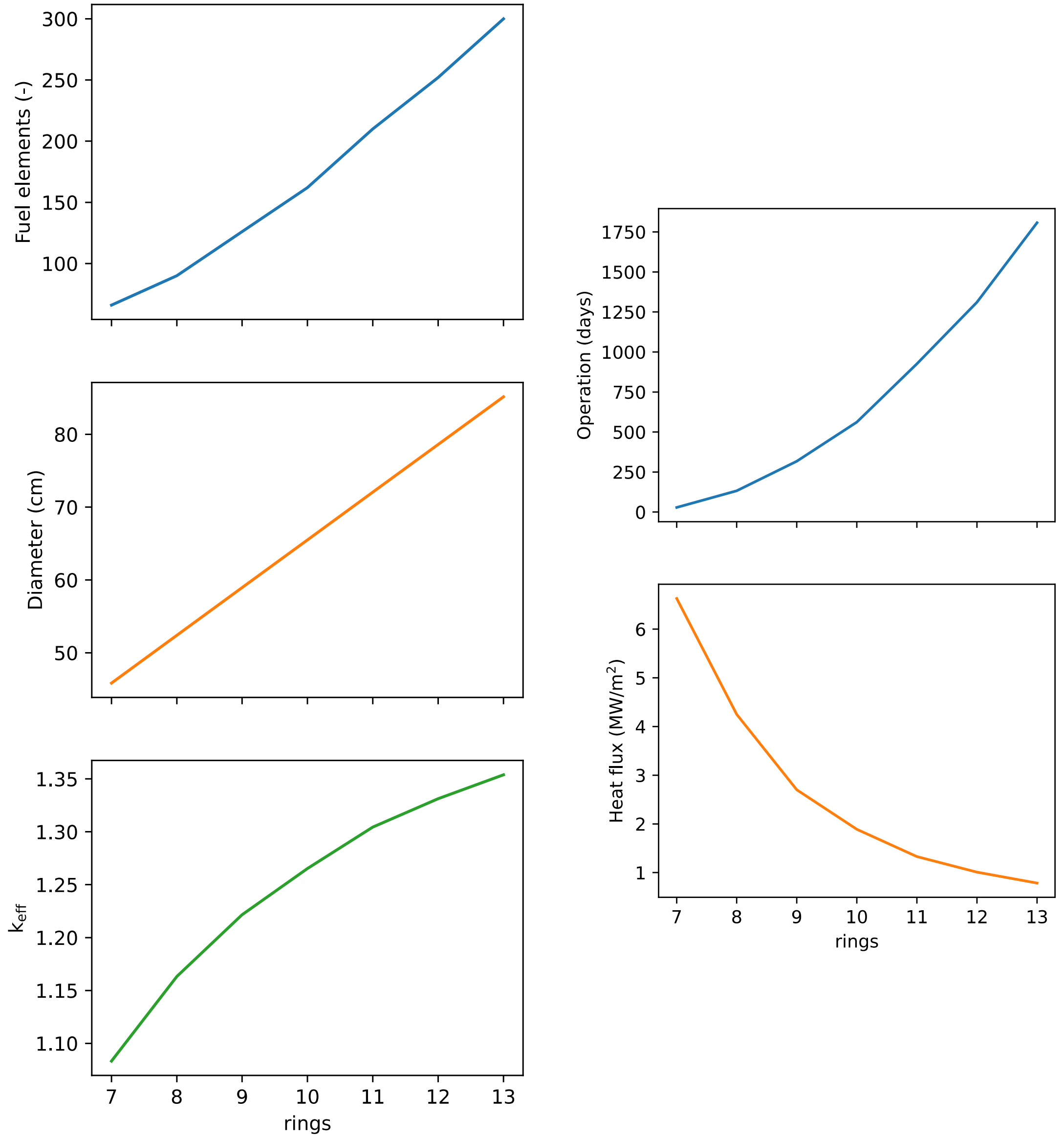
- Studies using OpenMC:
  - Monte-Carlo method
  - Scriptable API makes it highly parametrizable
  - 2D-model for simplified analysis
- “MARVEL-like” core as starting point
- Parametric study to find condition of viability
  - E.g., criticality and heat flux
  - Kept at 20 MW_{th}
  - Should operate for 2+ years full-time
- Two design variants considered:
  - Expanded MARVEL core
  - MARVEL core as a repeated assembly (bottom)



Core neutronics optimization

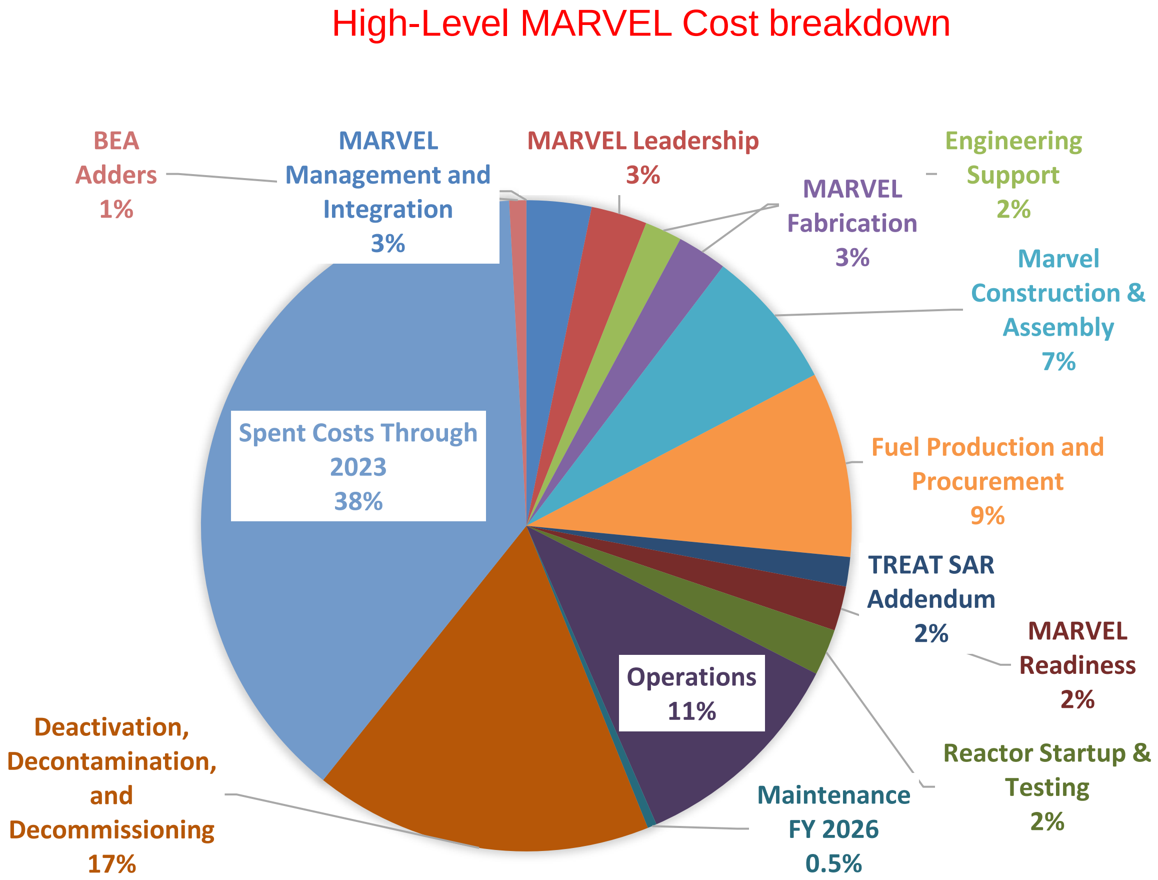
- Starting from the ‘expanded’ MARVEL design
- Original core critical from 6 rings
- Starting targets: shift power to 20 MWth but maintain size to within ISO container
- Increased number of fuel rings & add ZrH-only rods for increased moderation
- Suitable configurations:
  - 10-ring layout: ~2.5-year operations (min. requirement)
  - 12-ring: ~5-year operations
- Heat flux in line with typical SFR at 12 rings
- BU limit may be exceeded (higher operating temps may alleviate)

rings	Fuel elements	Height (cm)	2D keff	leakage	Op days for 20 MWth	Burnup (MWd/kgU)	Heat Flux (MW/m2)
12	300	85.15	1.354	0.097	1807	108.6	0.785
11	252	78.6	1.331	0.111	1311	101.6	1.010
10	210	72.05	1.304	0.130	912	92.4	1.330
9	162	65.5	1.265	0.153	562	81.3	1.890
8	126	58.95	1.222	0.182	317	65.4	2.700
7	90	52.4	1.163	0.217	133	43.4	4.250
6	66	45.84	1.083	0.266	29	14.6	6.630



Leveraging MARVEL costs

- Joint effort between MRP-SA&I
- Preliminary results: **72%** of MARVEL costs are mapped so far to the GN-COA (Generalized Nuclear Code of Account, joint INL-EPRI standard)
  - MARVEL cost estimate: 300+ items, 5 levels of detail
- All the costs included so far are capital costs. O&M costs to be included in the next step.
- MARVEL costs contains nonrecurring costs that need to be excluded for commercial-like reactor technoeconomics



Generating New Bottom Up Estimate

- New design : ***MARVEL-20*** (20MW$_{th}$ MARVEL)
  - Linear scaling, different variables for each subaccount
  - Example, several costs are normalized per unit mass of material considered
  - Re-build bottom-up cost for MARVEL-20 based on changed parameters
- Preliminary results, considering next:
  - Other scaling variables to be considered
  - Other Scaling methods
- Challenges
  - Some MARVEL cost items are vague, hard to interpret and map to the GN-COA

#	**Scaling variables list (so far)**
1	Pit Volume
2	Concrete Volume
3	Mass of Vessels and Support Structures
4	Guard Vessel mass
5	Mass of Drum Poison
6	Mass of Rod Poison
7	Mass of BeO Reflector
8	Gamma shielding mass in guard vessel
9	Gamma shielding Mass in reactor
10	Neutron shielding Mass in guard vessel
11	Neutron shielding Mass in SCS
12	Mass of Pit Neutron Shielding
13	Mass of Primary Coolant Systems
14	Mass of coolant
15	# of the Nuclear IO sensors
16	# of the Non-nuclear IO
17	Number of fuel pins

Fuel Costs Considerations

- Cost per fuel elements decreases with increasing the number of elements.
  - In this work, the fabrication cost is calculated the purchase of > 600 fuel elements.
- MARVEL did no incur costs such as
  - Fuel Enrichment, conversion, mining
  - Cost associated with scope to be performed by TREAT.
  - Civil works
- 2017 Cost Basis report used to estimate mining, enrichment and conversion costs.
- UZrH fabrication cost is ***80,000*** 2023 USD/Kg compared to UO_2 **870** 2017 USD/Kg

Fuel Cycle Step	Historical Mean
Mining	$139.00/kg-NatU
Conversion	$13.00/kg-NatU
Enrichment	$125.00/SWU

SWU Calculation:

$$W_{SWU} = m_U \times V(x_U) + m_t \times V(x_t) - m_{NatU} \times V(x_{Nat})$$

With:

$$V(x) = (2x - 1)\ln\left(\frac{x}{1 - x}\right)$$

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Generating New Bottom Up Estimate

MAVEL 0 vs. MARVEL 20

Changes in design:

- 20 MW_{th} vs 0.085 MW_{th}
- Bigger core (R= 80cm)
- Different core configuration
- ZrH reflector instead of BeO
- Brayton Cycle vs. Sterling engine
- Other changes (next step)

Disclaimers:

- Preliminary estimates
- Not all MARVEL costs mapped
- Need to make assumption for non-incurred costs (e.g., site activities)
- Detailed (yet incomplete) estimated

$$\frac{MARVEL{-}20(\$/kW_e)}{MARVEL{-}0(\$/kW_e)}\ \%$$

ID	Title	%
10	**Capitalized Preconstruction Costs**	**0.2%**
13	Plant Licensing	0.2%
20	**Capitalized Direct Costs**	**0.8%**
21	Structures and Improvements	0.3%
211	Site Preparation/Yard Work	0.2%
212	Reactor Island Civil Structures	1.1%
22	Reactor System	1.3%
221.11	Reactor Support	0.6%
221.12	Outer Vessel Structure	1.6%
221.13	Inner Vessel Structure	1.6%
221.21	Reactivity Control System	0.4%
221.31	Reflector	1.1%
221.32	Shield	4.0%
222.12	Reactor Coolant System	1.6%
227	Reactor Instrumentation and Control (I&C)	2.2%
23	Energy Conversion System	189%
234	Feed Heating Systems	0.0%
25	Initial Fuel Inventory	0.4%
251	Initial Fuel Inventory Material	0.4%
251.2	First Core Conversion	0.8%
251.3	First Core Enrichment	0.6%
251.4	First Core Fuel Assembly Fabrication	0.2%
252	Initial Fuel Inventory Services	0.2%
252.3	Licensing Assistance	0.2%
27	Material Requiring Special Consideration	0.2%

ID	Title	%
30	**Capitalized Indirect Services Cost**	**0.04%**
33	Startup Costs	0.2%
34	**Shipping and Transportation Costs**	0.2%
341	Fuel Shipping and Transportation	0.2%
40	**Capitalized Training Costs**	**0.2%**
41	Staff Recruitment and Training	0.2%
50	**Capitalized Supplementary Costs**	**0.2%**
54	Decommissioning	0.2%
	Total Overnight Cost	**0.401%**
	Total Overnight Cost excluding the fuel	**0.406%**

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Mass Production Cost Reduction

- In previous work, the factory fabrication and the mass production of microreactors were assessed
- MARVEL as use-case; assuming findings are applicable to MARVEL-20
- Main findings:
  - Shifting from stick-built to 10 units/year production can decrease costs by ~70%
  - Non-fuel CAPEX so far: 12,879$/kWe → ~3,863 $/kWe
  - Still within the bounds of the target by (Buongiorno 2021)

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Assessment of Factory Fabrication Considerations for Nuclear Microreactors

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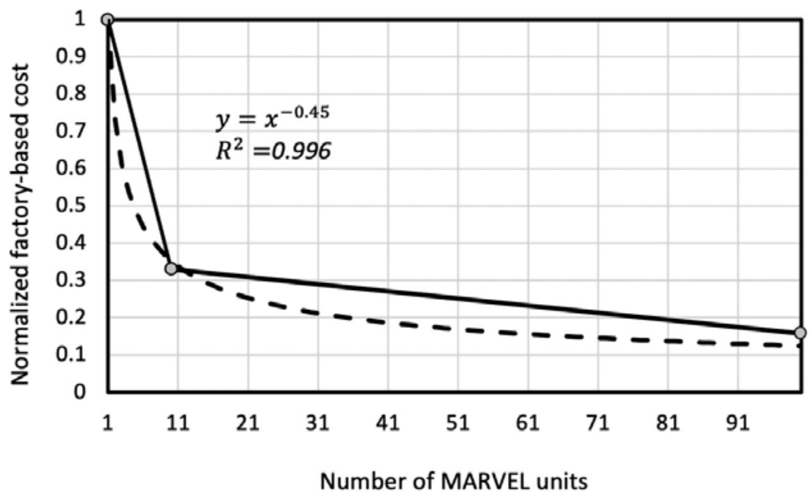

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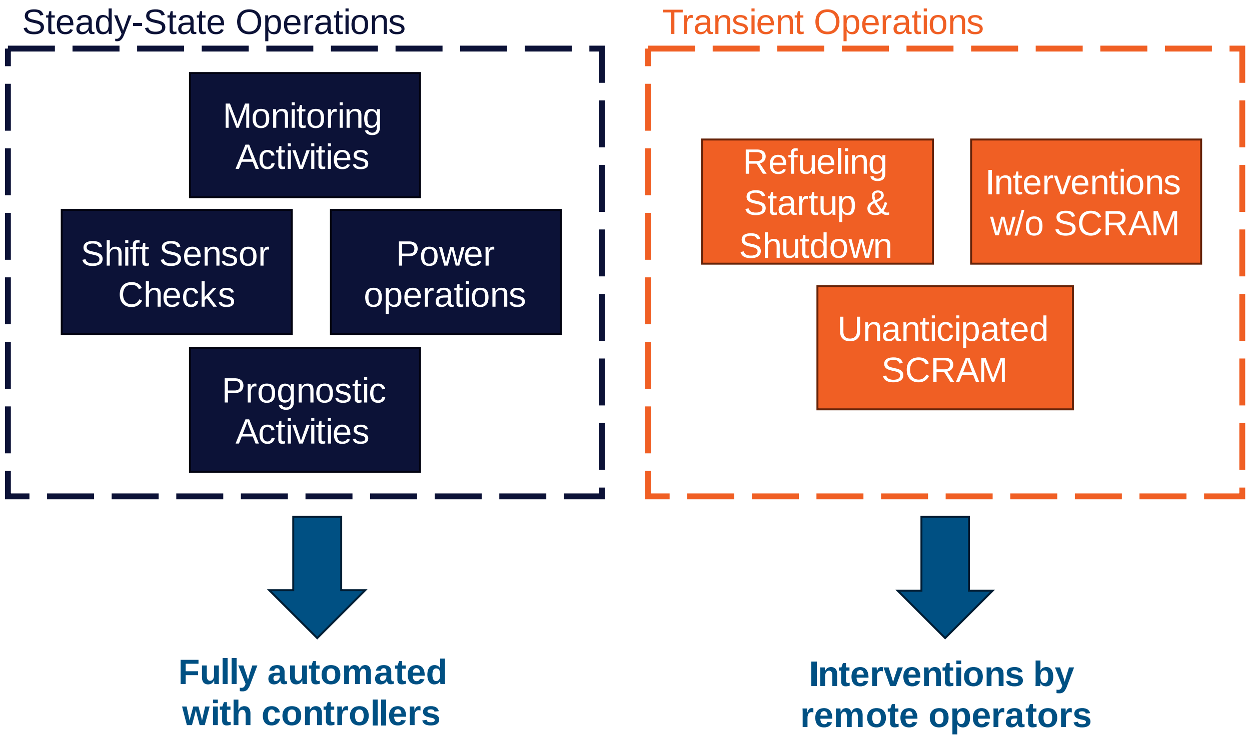
Framework for Automated Operation Assessment

- *Do additional capital costs for controller outweigh on-site staffing costs?*
- Frameworks for users to estimate cost reductions from automation
- Sensor-based approach:
  - Use # of sensors to determine number of FTEs needed per reactor
  - Use # of sensors to calculate controller hardware costs during steady state operations
  - Conduct differential analysis
- Automation:
  - Only for steady-state operations
  - Transient ops are assumed to require remote intervention



$$U = \sum_{i=1}^{N_s} f_{m,i}\,(t_{mp,i} + t_{m,i})$$

$$\Delta C = U_M P - [(N_s C_c \times CRF) + U_T P + C_w]$$

U	Utilization (% of time) for operation
U_M	Utilization (% of time) for fully manual operation
U_T	Utilization during transients for autonomous ops
$f_{m,i}$	Frequency of sensor i operation demand (Hz)
$t_{m,i}$	Duration of sensor i operation measurement
$t_{mp,i}$	Processing time of sensor i operation
N_s	Number of sensors
C_c	Controller cost per sensor ($)
C_w	Wireless transmission costs ($)
CRF	Capital Recovery Factor
P	Cost per FTE ($)

Automation Framework Usecase

- Inputs based on MITR (6 MWt) as a use case
- Framework levers (inputs & assumptions) can be parameterizable
- Cost savings from full automation **~90%**
- Remote intervention of staff during transient operations are **trivial**. Anticipating each staff can cater to ***19 reactors*** under current assumptions

Inputs	Values
Total # of sensors	249
# of power sensors	76
# actuators	55
# load following ops	2
Ramp rate (%P/mins)	20%

+

Assumptions	Values
# sensor checks per shift	2
% sensor checks for power ops	30%
# sensor monitoring per day	1
# of prognostics per week	1
Startup/shutdown ops duration	8h
Unanticipated SCRAMs	0.5/yr
Unanticipated interventions	24/yr
FTE Cost	$250k/yr
Controller cost per IO	$5k
I&C lifetime	10 yr
Assumed WACC	8%
Secure information transfer fee	$60k/yr

Results	Values
Fully manual staffing costs	$2.7M/yr
Levelized I&C costs	$233k/yr
Transient intervention costs	$13k/yr
% cost savings	**-89%**

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Next Steps

- TH considerations: simple analytical model to verify needs
- Develop source term model analysis to assess the number of barriers needed for a commercial system
- Complete MARVEL cost mapping & re-baseline all estimates to 2023 USD
- Make simplified design assumptions for components not included in MARVEL (e.g., sodium pumps, residual heat transfer system)
- Iterating between neutronics – costs – source term – TH, etc.
- Leverage I&C study to determine MARVEL-20 operational needs
- Considerations outside scope:
  - Fuel material limit considerations
  - Transient safety analysis and systems design
  - Detailed engineering optimization
- Broader Questions:
  - Are MARVEL costs baselined correctly with design parameters?
  - Are MARVEL fuel fabrication costs representative?

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Questions?

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