# Microreactor designs that make economic sense


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Member of the U.S. National Academy of Engineering


MIT

MITei
MIT Energy Initiative

NSE
Nuclear Science and Engineering
science : systems : society

# ABOUT THE SPEAKER

**Jacopo Buongiorno** is the Battelle Energy Alliance Professor in Nuclear Engineering at the Massachusetts Institute of Technology (MIT), the Director of Science and Technology of the MIT Nuclear Reactor Laboratory, and a member of the US National Academy of Engineering. He teaches a variety of undergraduate and graduate courses in thermo-fluids engineering and nuclear reactor engineering. Jacopo has published over 100 journal articles in the areas of reactor safety and design, two-phase flow and heat transfer, and nanofluid technology. For his research work and his teaching at MIT he won several awards, among which an ANS Presidential Citation (2022), the ANS Outstanding Teacher Award (2019), the MIT MacVicar Faculty Fellowship (2014), the ANS Landis Young Member Engineering Achievement Award (2011), the ASME Heat Transfer Best Paper Award (2008), and the ANS Mark Mills Award (2001). Jacopo is the Director of the Center for Advanced Nuclear Energy Systems (CANES). In 2016-2018 he led the MIT study on the Future of Nuclear Energy in a Carbon-Constrained World. Jacopo is a consultant for the nuclear industry in the area of reactor thermal-hydraulics and safety, and a member of the Advisory council of the Institute of Nuclear Power Operations (INPO). He is also a Fellow of the American Nuclear Society (including service on its Special Committee on Fukushima in 2011-2012), a Fellow of the NUclear Reactor Thermal Hydraulics (NURETH) conference, a member of the American Society of Mechanical Engineers, past member of the Naval Studies Board (2017-2019), past member of the Secretary of Energy Advisory Board (SEAB) Space Working Group, past member of the Accrediting Board of the National Academy of Nuclear Training (2011-2025), and a participant in the Defense Science Study Group (2014-2015).

## HOW WE CHOOSE REACTOR DESIGNS

- I want to improve nuclear safety UN-NECESSARY, UNLESS IT SIMPLIFIES DESIGN AND OPERATION
- I want to “burn waste” THERE IS NO BUSINESS MODEL
- Innovation drives commercial success NOT UNDERSTANDING THE NUCLEAR INNOVATION CYCLE
- Everyone else thinks it’s a good idea FASHION
- I worked on this concept in my Ph.D. thesis KNOWLEDGE BIAS/PERSONAL PRIDE

## HOW SHOULD WE CHOOSE REACTOR DESIGNS?

- …
- …
- …
- …

# INTRODUCTION TO MICROREACTORS

# CLASSES OF NUCLEAR REACTORS

Electric output
NOAK Construction cost
NOAK Construction duration
Vendors

*Large Reactors*

~1000-1600 $MW_e$
~$3-10B
5-10 yrs

Westinghouse, KHNP, Rosatom, CNNC, CGN, EDF, GEH

*Small Modular Reactors (SMRs)*

~70-300 $MW_e$
~$1-3B
3-5 yrs

GEH, Westinghouse, Rolls Royce, EDF, Holtec, Nuscale, X-energy, Kairos, Terrapower, KHNP

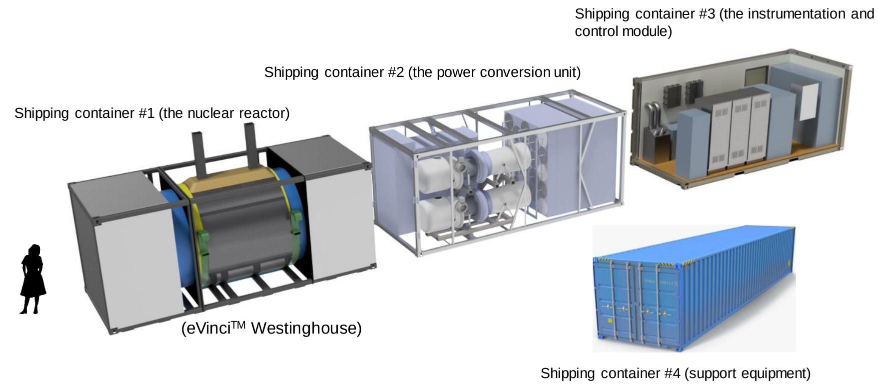
*Microreactors (Nuclear Batteries)*

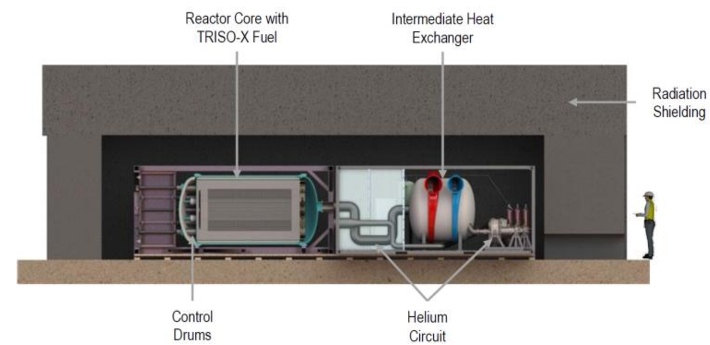
~1-20 $MW_e$
<$0.2B
<1 yr

Westinghouse, BWXT, X-energy, Oklo, Radiant Nuclear, Aalo, Valar, Antares

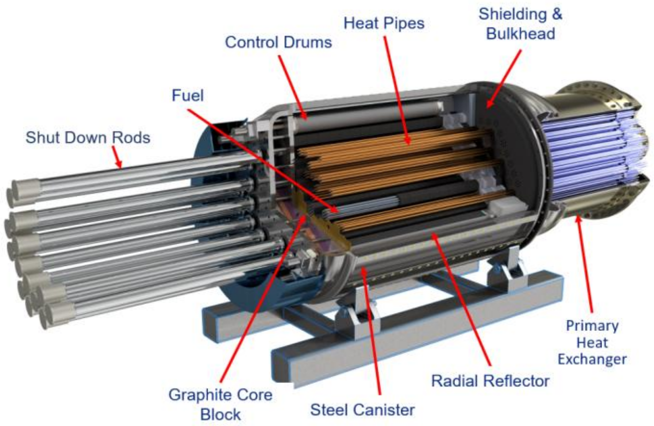
# MICROREACTOR DESIRABLE FEATURES

- Mass fabricated
- Transportable
- Co-located with end user
- Plug-and-play startup
- Semi-autonomous operation
- Combined heat and power
- Dry cooling
- Offsite refueling
- Passive safety
- Small investment and shorter schedule




# MICROREACTOR EXAMPLES



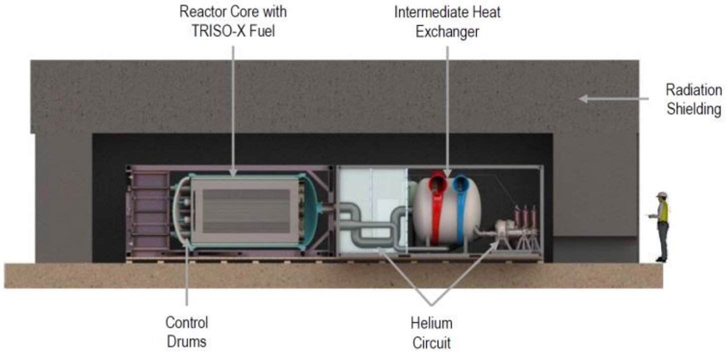

[ Westinghouse's eVinci ]
5 MWe

[ Core Power ]
10 MWe

[ Radiant ]
1 MWe

[ NASA and LANL's Kilopower ]
<100 kWe

[ INL's MARVEL ]
<100 kWe




[ X-energy's XENITH]
7 MWe

# MICROREACTOR EXAMPLES (not exhaustive)

Nuclear battery (transportable, plug-and-play microreactors) designs being developed

| Name | Company (Country) | Spectrum/moderator | Coolant | Fuel | Power |
|---|---|---|---|---|---|
| Pele | BWXT (US) | Thermal / graphite | Helium | HALEU TRISO | 3-5 MWe |
| eVinci | Westinghouse (US) | Thermal / graphite | Na in heat pipes | HALEU TRISO | 5 MWe |
| XENITH | X-energy (US) | Thermal / graphite | Helium | HALEU TRISO | 7 MWe |
| Kaleidos | Radiant Nuclear (US) | Thermal / graphite | Helium | HALEU TRISO | 1 MWe |
| Aalo-1 | Aalo (US) | Thermal / graphite | Na | LEU $UO_2$ | 10 MWe |
| n/a | MHI (Japan) | Epithermal / graphite | $CO_2$ in heat pipes | HALEU Carbide | <500 kWe |
| ARC | Alpha Tech Research Corp (US) | Thermal / Yttrium hydride | Fluoride salt | LEU (dissolved) | 12 MWe |
| HOLOS | HolosGen (US) | Thermal / graphite | Helium (or $CO_2$) | HALEU TRISO | <13 MWe |
| NuGen Engine | NuGen (US) | Thermal / proprietary composite | Helium | HALEU TRISO | 1-3 MWe |
| ODIN | Nano Nuclear (US) | Thermal | Low-pressure coolant | HALEU | 1 MWe |
| Phoenix | Black Mesa Advanced Fission (US) | Thermal / graphite | Potassium in heat pipes | HALEU $UZrH_{1.6}$ | 200 kWt, 40-50 kWe |
| Antares R1 | Antares (US) | Thermal / graphite | Na in heat pipes | HALEU TRISO | 300 kWe |
| Rolls-Royce | | | | HALEU TRISO? | <10 MWe |
| SMR-13 | JFA | Thermal / $H_2O$ | $H_2O$ | LEU+ $UO_2$ | 20 MWe |
| MN-1 | MobileNuclear Energy | Thermal | He | HALEU UC pellets | 1 MWt, 350 kWe |
| Hadron Energy | Halo MMR | Thermal / $H_2O$ | $H_2O$ | LEU $UO_2$ | 10 MWe |
| SOLO | Terra Innovatum (Italy) | Thermal / Composite solid (patent pending) | He (350°C) | LEU $UO_2$ with Zry | 1-20 MWe |
| PWR-20 | Last Energy (US) | Thermal / $H_2O$ | $H_2O$ | LEU $UO_2$ | 20 MWe |

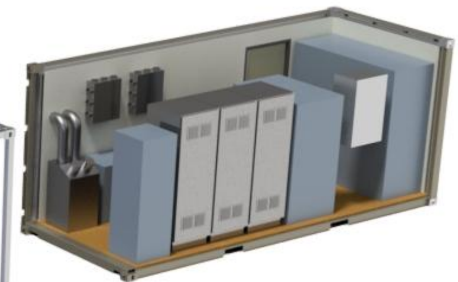
# MICROREACTOR EXAMPLES

| | eVinci | XENITH | BANR |
|---|---|---|---|
| Vendor | Westinghouse | X-energy | BWXT |
| Electric power [MW] | 5 | 6.6 | 15 |
| Thermal power [MW] | 15 | 20 | 50 |
| Thermal efficiency [%] | 33.3 | 33.0 | 30.0 |
| Power conversion cycle | Open-air Brayton | Open-air Brayton | Closed Rankine |
| Fuel form | TRISO particles | TRISO particles | TRISO particles |
| Initial $^{235}U$ enrichment [wt%] | 19.75 | 19.75 | 19.75 |
| Refueling period [years] | >8 | >10 | >5 |
| Moderator/Reflector | Graphite | Graphite | Graphite |
| Coolant | Sodium in heat pipes | Circulating helium gas | Circulating helium gas |
| Core outlet temp. [°C] | >750 | Up to 750 | 650 |
| Coolant pressure [MPa] | <0.1 (in heat pipes)<br><0.2 (helium fill gas in reactor canister) | 6.0 | 2.8 |

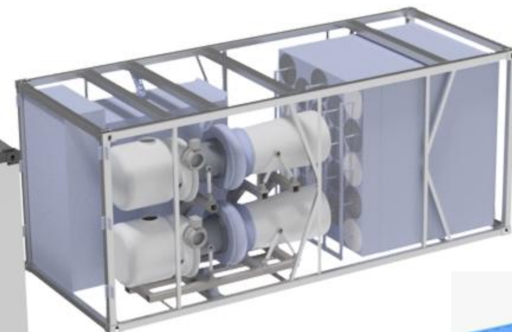
# TRANSPORTABILITY

Entire plant delivered in four truckload size containers (40’ x 14’ x 14’)

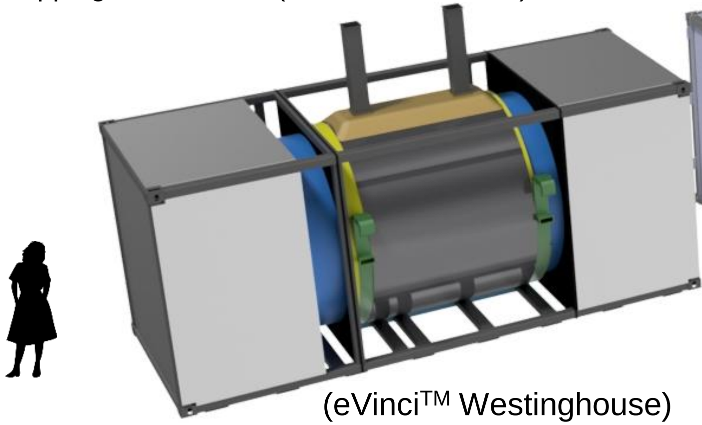
Shipping container #3 (the instrumentation and control module)



Shipping container #2 (the power conversion unit)



Shipping container #1 (the nuclear reactor)



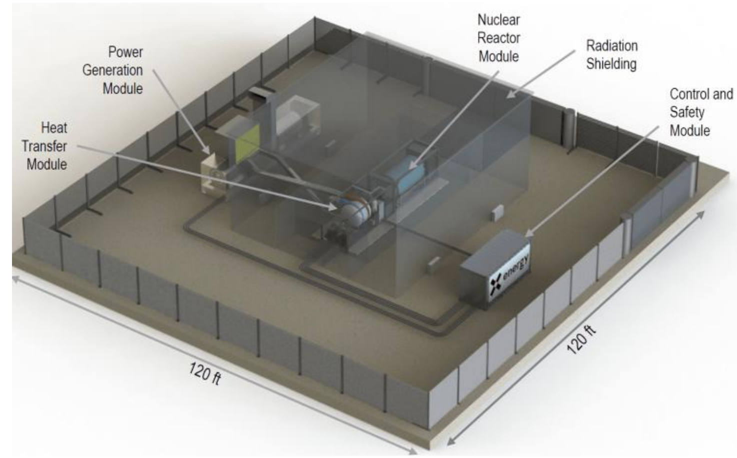
(eVinci[TM] Westinghouse)

Shipping container #4 (support equipment)

- Weights and sizes allow for deployment in remote areas (truck/rail/barge)
- Minimizes decommissioning and effort to return site to green field

# MICROREACTOR SITE LAYOUT

[ Westinghouse’s eVinci ]

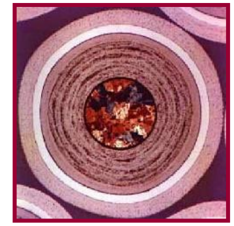


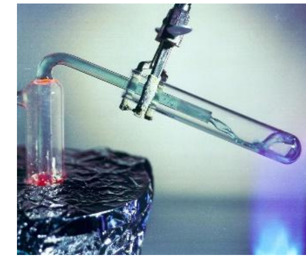

[ X-energy’s XENITH ]

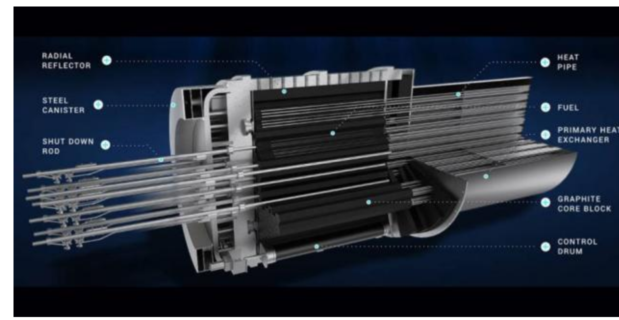
[ BWXT’s BANR ]

Layouts include (i) enclosure bay providing radiation shielding and missile protection, and (ii) security perimeter

# MICROREACTORS HAVE VERY ATTRACTIVE SAFETY FEATURES








## Inherent features

- Coolant does not boil off
- Ceramic fuel fully retains radioactivity at up to very high temperatures
- High thermal capacity prevents sudden temperature escalation
- Passive cooling requires no external intervention to cope with accidents

- Accidents like TMI, Chernobyl and Fukushima are eliminated by design
- Emergency planning zone is limited to site boundary (no evacuation needed)
- Testing at full scale becomes economically possible (NASA-LANL's KRUSTY example)

# THE PROBLEM WITH MICROREACTORS

## POTENTIALLY CRIPPLING UNCERTAINTIES

- Dis-economies of scale

- Fuel availability and cost

- Regulations for:

  - transportation to/from site
  - refueling facility
  - autonomous operation
  - urban licensing
  - security (including cybersecurity) and safeguards

- Business models for commercialization in domestic and international markets

# SIZE MATTERS

$$\text{LCOE}\left[\frac{\$}{\text{MWh}}\right] = \frac{\text{ICC}\cdot(\text{A/P,i,N})+\text{DC}\cdot(\text{A/F,i,N})}{W_e\cdot\text{CF}\cdot 8760} + \frac{\text{Fixed O\&M}}{W_e\cdot\text{CF}\cdot 8760} + \frac{\text{Variable O\&M}}{W_e\cdot\text{CF}\cdot 8760} + \frac{\text{FC}}{24\cdot\eta\cdot\text{BU}}$$

LCOE = levelized cost of electricity;
$W_e$ = electric output;
ICC = initial construction cost;
DC = decommissioning cost;
CF = capacity factor;
N = lifetime;
O&M = operations & maintenance;
FC = fuel cost;
$\eta$ = thermal efficiency;
BU = fuel burnup;
$(A/P, i, N)$ and $(A/F, i, N)$ = capital recovery factors;
i = discount rate

The effect of $W_e$ (~100x less than large LWRs) at the denominator of the LCOE equation is very challenging to overcome *even with* aggressive design simplification, factory fabrication, learning and automation.

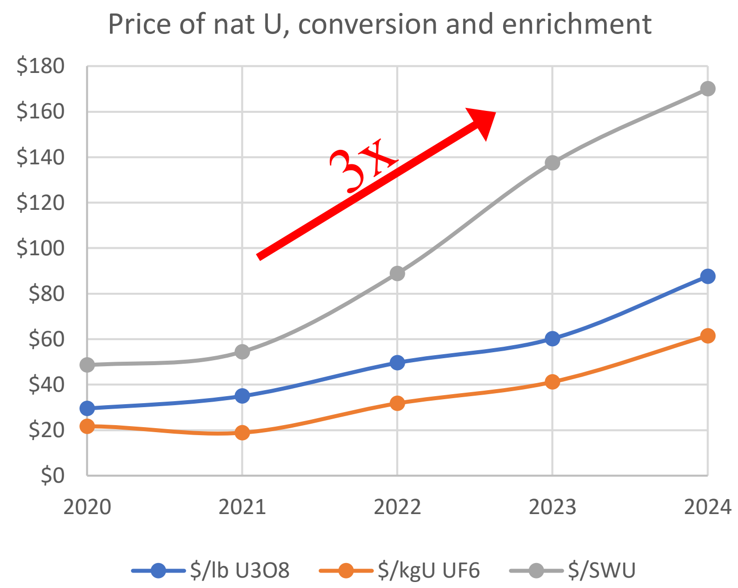
# WE ALSO HAVE A FUEL PROBLEM NOW

**Good old days (1960-2020)**

- All power reactors used the same LEU $UO_2$ pellet fuel
- Demand was more or less stable
- Cheap LEU came from enrichment facilities in the U.S., Europe and Russia, and
- Weapon HEU down-blending (Megatons to Megawatts)

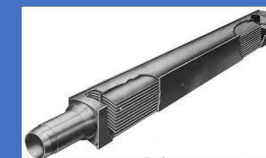
**The ugly new reality (2020-present)**

- Advanced reactors often require HALEU
- Vendors like expensive fuel forms (TRISO, metallic, hydride)
- Imbalance between projected demand and capacity for enrichment, conversion and fabrication is pushing up fuel costs
- Phasing Russia out of U.S. and European markets exacerbates the trend




Data courtesy of J. Hinze, $U_xC$, Oct 2024

# THE NEW FUEL LANDSCAPE

| Properties | $UO_2$ pellets  | TRISO particles  | U-10Zr rods  | UZrH plates  |
|---|---|---|---|---|
| *U Density (g/cm$^3$)* | 9.67 | 0.53 | 14.37 | 3.7 |
| *Melting Point (°C)* | 2800 | 2400 | 1380 | >1135 |
| *Thermal Conductivity (W/m-K)* | 3.6 | 10 | 28 | 18 |
| *Specific Heat (J/kg-K)* | 247 | 1200 | 130 | 295 |
| *Typical Enrichment (%wt)* | LEU | HALEU | HALEU (in fast reactors) | HALEU |
| *Typical Burnup (% FIMA)* | >5 | >10 | >10 | >2 |
| *FG release* | >1000°C | None up to 1600°C | ~80% at 5% FIMA | >400°C |
| *Fabrication Cost (\$/kg$_U$)* | <300 | >10,000 | >10,000 | >25,000 |

# THE NEW FUEL LANDSCAPE (2)

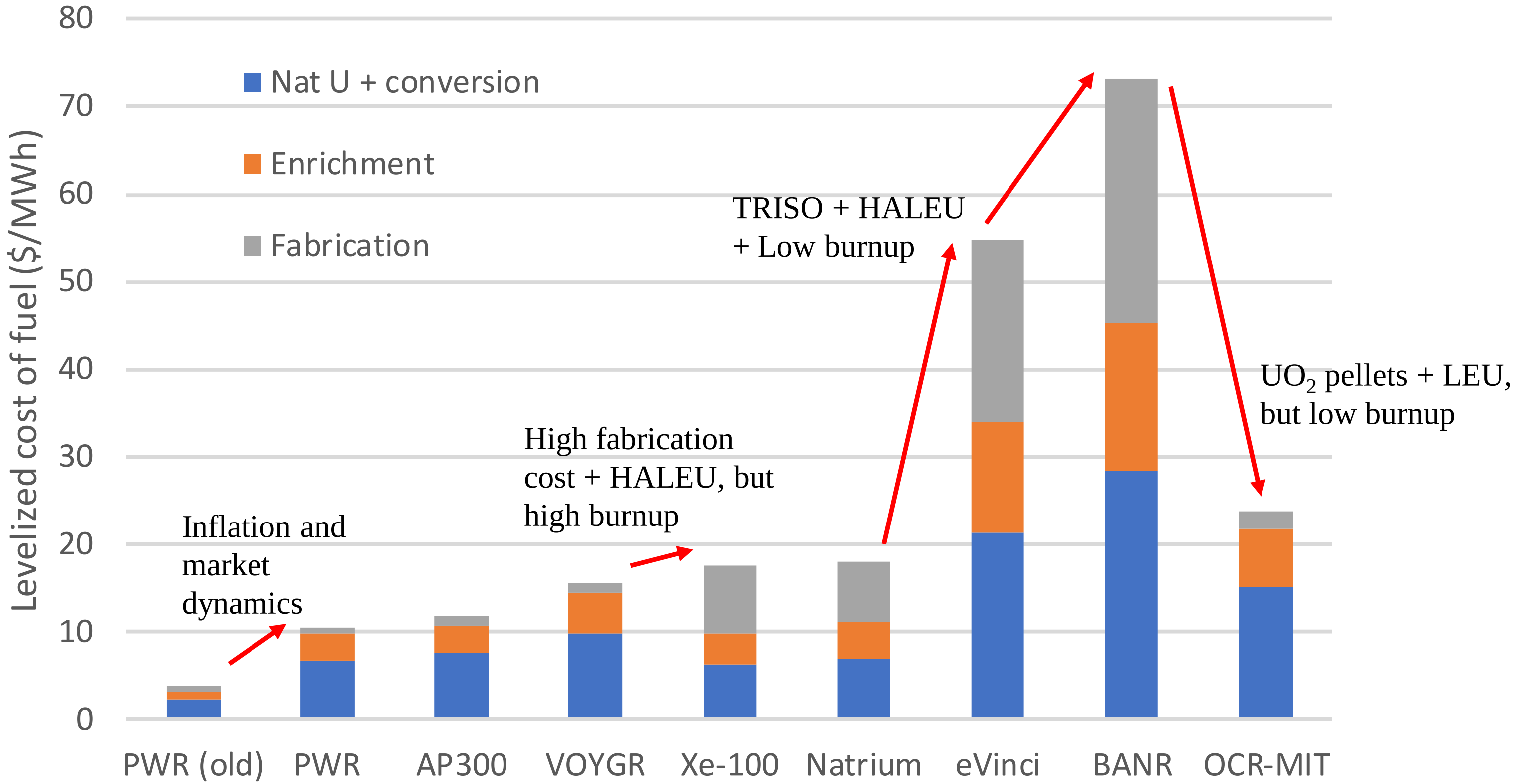
| Reactor technology | Vendor | Fuel form | U.S. fuel supply chain | Enrichment | Fuel available at scale now? |
|---|---|---|---|---|---|
| AP300 | WEC | $UO_2$ pellets | Mature | LEU | Yes |
| BWRX-300 | GEH | $UO_2$ pellets | Mature | LEU | Yes |
| VOYGR | Nuscale | $UO_2$ pellets | Mature | LEU | Yes |
| Pele | BWXT | TRISO | Pre-commercial | HALEU* | Small batch production |
| BANR | BWXT | TRISO | Pre-commercial | HALEU | No |
| eVinci | WEC | TRISO | Pre-commercial | HALEU* | No |
| Xe-100 | X-energy | TRISO | Pre-commercial | HALEU | No |
| Hermes | Kairos | TRISO | Pre-commercial | HALEU* | No |
| Natrium | Terrapower | Metallic | Non-existent | HALEU | No |
| Aurora | Oklo | Metallic | Non-existent | HALEU** | No |
| Aalo-1 | Aalo | Hydride | Established in Europe for TRIGAs | HALEU | Yes |

* From down-blended HEU

** From EBR-II spent fuel

# THE LEVELIZED COST OF FUEL FOR MICROREACTORS IS VERY HIGH

(Carrying charges not included)




| Reactor | PWR (old) | PWR | AP300 | VOYGR | Xe-100 | Natrium | eVinci | BANR | OCR-MIT |
|---|---|---|---|---|---|---|---|---|---|
| Fuel form | $UO_2$ pellets | $UO_2$ pellets | $UO_2$ pellets | $UO_2$ pellets | TRISO | U-10Zr | TRISO | TRISO | $UO_2$ pellets |
| Thermal efficiency (%) | 33 | 33 | 33 | 31.3 | 40.0 | 41.1 | 33.3 | 30 | 33.3 |
| Enrichment (%) | 4.5 | 4.5 | 3.8 | 5 | 15.5 | 16.5 | 20 | 20 | 4.0 |
| Burnup (MWd/kgU) | 50 | 50 | 37 | 40 | 160 | 146 | 72 | 60 | 19.2 |
| Yellow cake price ($/lb) | 30 | 82 | 82 | 82 | 82 | 82 | 82 | 82 | 82 |
| Conversion cost ($/kgU) | 22 | 73 | 73 | 73 | 73 | 73 | 73 | 73 | 73 |
| Enrichment cost ($/SWU) | 49 | 176 | 176 | 176 | 176 | 176 | 176 | 176 | 176 |
| Fuel fabrication cost ($/kgU) | 250 | 300 | 300 | 300 | 12000 | 10000 | 12000 | 12000 | 300 |

# MIT STUDY ON $UO_2$ FUELED MICROREACTORS

**Considered 6 + 1 reactor types (all thermal):**

1. Heat-pipes with solid moderator
2. Sodium with solid moderator
3. Lead-bismuth with solid moderator
4. Helium with solid moderator
5. Molten-salt with solid moderator
6. Organic fluid with water moderator
7. Water coolant and moderator (reference)

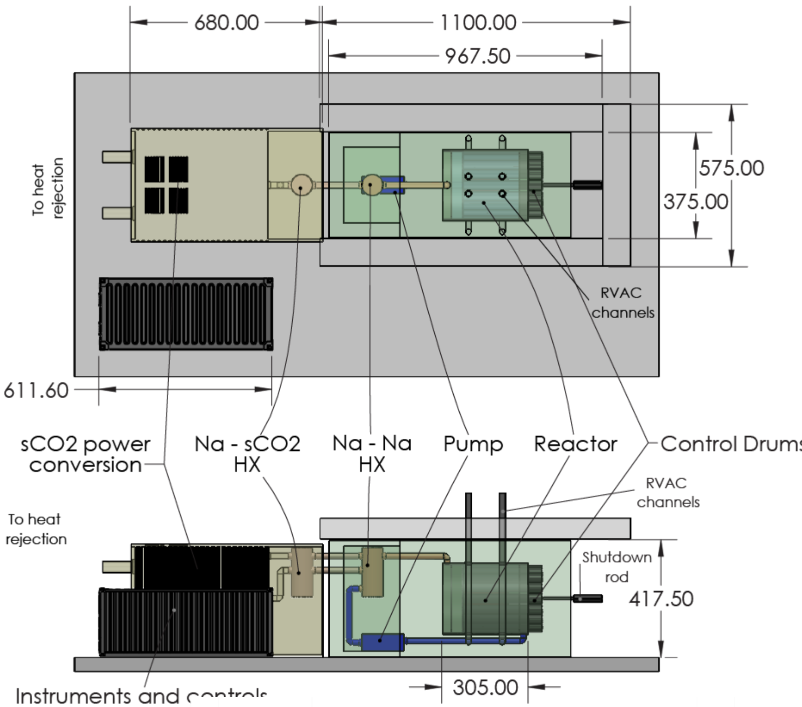
**Developed conceptual design for each reactor type with following requirements:**

- *Road Transportable:* Road containers (14’x14’x40’); core/reflector is 2.4 m OD.
- *Commercially Available Fuel:* $UO_2$ fuel pellets at 5% enrich.
- *Well-known Core Materials:* Zry and 316H (clad), FeCrAl (heat pipes), graphite (solid moderator).
- *Reasonably Long Irradiation Cycle:* No refueling for at least 3 years.
- *Passive Decay Heat Removal:* No AC power if both primary cooling fluid *and* the normal heat removal path through the BOP are lost.
- *Passive Reactivity Control:* Negative reactivity coefficient of power, two shut-down systems.
- *Commercial Off-the-Shelf I&C*: capable of a high-degree of automation.

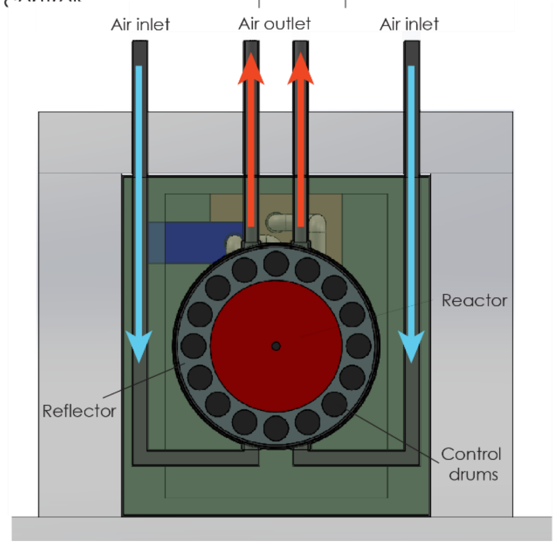
# MIT STUDY ON $UO_2$ FUELED MICROREACTORS (POINT DESIGNS)

| | Heat pipe cooled | Sodium cooled | Lead-bismuth cooled | HTGR | FLiBe cooled | Organic cooled | Water cooled |
|---|---|---|---|---|---|---|---|
| Thermal power (MW) | 5 | 15 | 15 | 15 | 11 | 15 | 15 |
| Core power density (kW/L) | 1.5 | 4.7 | 4.7 | 4.7 | 3.5 | 12 | 9.3 |
| BOP and thermal efficiency | $sCO_2$ Brayton, 32% | $sCO_2$ Brayton, 31% | $sCO_2$ Brayton, 31% | $sCO_2$ Brayton, 33% | $sCO_2$ Brayton, 36% | Organic (toluene) Rankine, 27% | Steam Rankine, 23% |
| Electric power (MW) | 1.60 | 4.65 | 4.65 | 4.95 | 3.96 | 4.05 | 3.45 |
| Core coolant | Na within heat pipes | Na | Pb-Bi | He | FLiBe (99.993% Li-7) | $C_{18}H_{14}$ | Water |
| Core inlet/outlet temperatures (°C) | 650 (isotherma system) | 358/510 | 358/510 | 380/565 | 550/600 | 285/304 | 285/320 |
| Coolant pressure | Sub-atmospheric | Atmospheric | Atmospheric | 6 MPa | Atmospheric | Atmospheric | 15 MPa |
| Volume of coolant in core ($m^3$) | 0.12 | 0.09 | 0.09 | 0.16 | 0.09 | 0.26 | 0.27 |
| Fuel enrichment | 4.7% | 4.8% | 4.7% | 5% | 3.1% | 3.2% | 3.4% |
| $UO_2$ mass (kg) | 1500 | 1770 | 1770 | 1770 | 1770 | 2000 | 2000 |
| Discharge burnup (MWd/kgU) | 3.7 | 9.5 | 9.5 | 9.5 | 7.0 | 8.4 | 8.4 |
| Cladding material | SS316 | SS316 | SS316 | SS316 | SS316 | Zry | Zry |
| Moderator/matrix material | Graphite | Graphite | Graphite | Graphite | Graphite | $H_2O$ | $H_2O$ |
| Reflector material | Graphite | Graphite | Graphite | Graphite | Graphite | $H_2O$ | $H_2O$ |
| Primary control mechanisms | Control Drums | Control Drums | Control Drums | Control Drums | Control Drums | Control rods | Control rods |
| Secondary control Mechanism | Central Contro Rod | Central Control Rod | Central Control Rod | Central Control Rod | Central Contro Rod | Borated Water Tank | Borated Water Tank |
| Decay heat removal | RVACS | RVACS | RVACS | RVACS | RVACS | Makeup Water Tank | Makeup Water Tank |

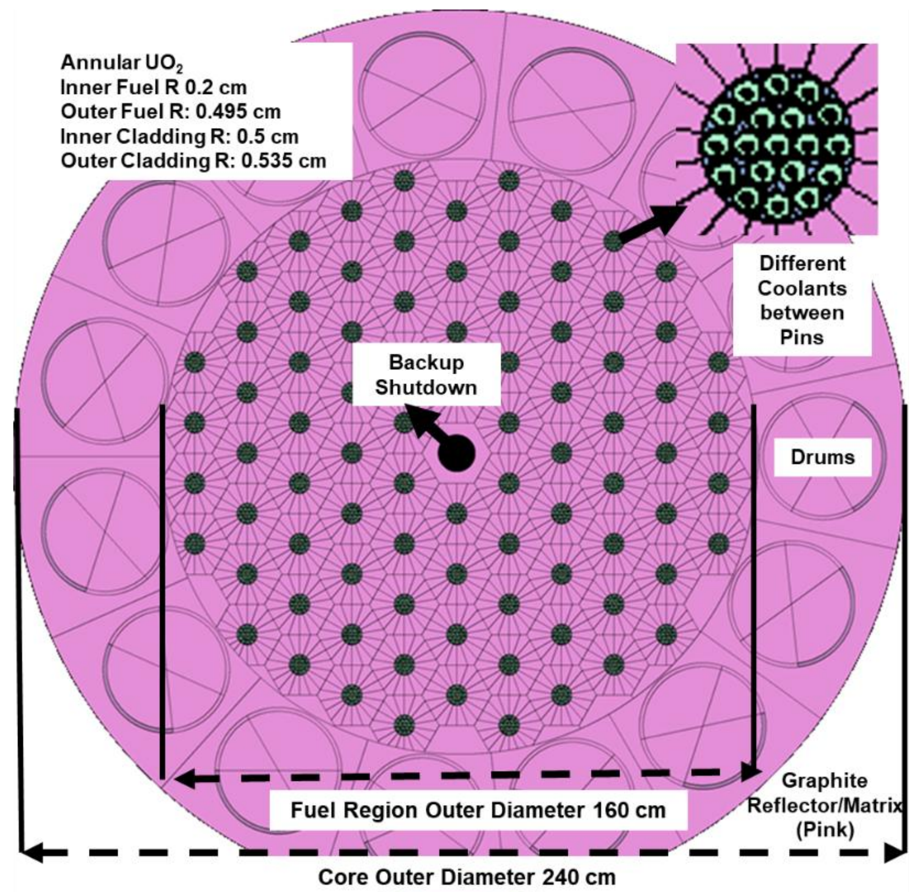
# $UO_2$-FUELED, Na-COOLED, GRAPHITE-MODERATED NUCLEAR BATTERY




layout (dimensions in cm)




RVACS




core cross-section

# MIT STUDY ON $UO_2$ FUELED MICROREACTORS (NOAK COST RESULTS)

LCOF = levelized cost of fuel; COC = cost of coolant; CME = cost of major equipment; CSPTI = cost of site preparation, transportation and installation; CIC = cost of I&C; O&M = complexity of O&M

| Reactor Design | Figures of Merit | | | | | |
|---|---|---|---|---|---|---|
| | LCOF ($/MWh) | COC ($/kW) | CME ($/kW) | CSPTI ($/kW) | CIC ($/kW) | O&M (1-4) |
| Heat pipe cooled | 113 | 15 | 10,900 | 1,881 | 4,700 | 1 |
| Na-cooled | 46 | 15 | 4,700 | 632 | 1,600 | 3 |
| Lead-bismuth-cooled | 45 | 200 | 5,000 | 667 | 1,600 | 3 |
| HTGR | 46 | 0.4 | 4,700 | 626 | 1,500 | 2 |
| FLiBe-cooled | 34 | 3,700 | 6,300 | 742 | 1,900 | 4 |
| Organic-cooled | 39 | 640 | 4,500 | 726 | 1,900 | 2 |
| Water-cooled | 49 | 6 | 5,500 | 954 | 2,100 | 2 |

| Figure of Merit | Cost Item | Reactor Design | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Heat pipe cooled | Na-cooled | Lead-bismuth-cooled | HTGR | FLiBe-cooled | Organic-cooled | Water-cooled |
| CME | Permanent Support Equipment | 1,370 | 1,370 | 1,460 | 1,370 | 1,370 | 1,370 | 1,430 |
| | Reactor Equipment (Nth of a Kind) | 11,920 | 11,280 | 12,640 | 12,410 | 15,570 | 6,250 | 7,480 |
| | Secondary Heat Removal | 930 | 1,100 | 1,340 | 1,200 | 1,500 | 1,040 | 1,580 |
| | BOP Equipment | 3,230 | 7,990 | 7,990 | 8,300 | 6,640 | 9,700 | 8,480 |
| CSPTI | Site Work | 1,220 | 1,130 | 1,260 | 1,260 | 1,130 | 1,130 | 1,260 |
| | Transport | 780 | 790 | 820 | 820 | 790 | 790 | 830 |
| | Installation | 1,010 | 1,020 | 1,020 | 1,020 | 1,020 | 1,020 | 1,200 |

All figures in $k

# BASIS FOR COST ESTIMATES (NOAK)

**Permanent Support Equip.**

| Description | Qty. | 2022 Rate | Extension | Reference and Data Identifier | |
|---|---|---|---|---|---|
| Transformer | | $3,000 | $218,000 | A | FAC-8132 |
| Lightning Protection System | | | $4,100 | A | FAC-8134 |
| Reactor Cover (Steel Only) | 20 | $7.60 | $312,000 | D | 05 12 23.77 3070 |
| Emergency Power | 500 | | $340,000 | A | FAC-8112 |
| Misc Utilities | Allow | | $150,000 | Estimators Judgement | |
| Impact Absorbers (Reuse) | | | | | |
| Steel Shell | 2,500 | $17.25 | $43,000 | Expert Opinion, (note 1) | |
| Foam Allow | 420 | $752.40 | $302,000 | Supplier Budget Quote | |

**Summary Estimate Values $1,370,000 ... Permanent Support Equipment**

**NOAK Reactor Equipmenmt (Nth of a Kind)**

| Description | Qty. | 2022 Rate | Extension | Reference and Data Identifier | |
|---|---|---|---|---|---|
| Ext. Vessel | 7,500 | $33.00 | $247,500 | Expert Opinion, (note 1) | |
| Ext. Head Pgk | 1,500 | $49.50 | $74,250 | Expert Opinion, (note 1) | |
| Int. Vessel | 3,500 | $27.50 | $96,250 | Expert Opinion, (note 1) | |
| Int. Head Pkg | 5,000 | $44.00 | $220,000 | Expert Opinion, (note 1) | |
| Core Support | 3,500 | $71.50 | $250,250 | Expert Opinion, (note 1) | |
| Certification costs ASME | Lot | $110,000 | $110,000 | Allowance | |
| Piping / Misc | Lot | $137,500 | $137,500 | Allowance | |
| RVACS... SS shell/pipe loops | 42,371 | $23.38 | $990,400 | Expert Opinion, (note 1) | |
| Shielding Spts | 3,500 | $22.00 | $77,000 | Expert Opinion, (note 1) | |
| Shielding | 15,000 | $4.40 | $66,000 | Supplier Budget Quote | |
| | 1,408 | $182.60 | $257,100 | Supplier Budget Quote | |
| Saddles | 4,000 | $19.80 | $79,000 | Expert Opinion, (note 1) | |
| Support Module | 12,500 | $24.20 | $302,500 | Expert Opinion, (note 1) | |
| Reflector | 5.4 | $13,200.00 | $71,000 | Supplier Budget Quote | |
| | 7.2 | $35,166.08 | $254,000 | Recent Fab Estimates | |
| Insulation | 56 | $4,653.00 | $260,600 | NREL | Reference E |
| Electrical Pen. Assemblies | Lot | $82,500.00 | $82,500 | Allowance | |
| Control Drums | 2 | $1,352,000 | $2,704,000 | Recent Quote, NOAK | |
| Core Fab | Used for all reactor types due to similarity of core design and size. | | $5,000,000 | Complexity Allowance | |

**Summary Estimate Values $11,280,000... Reactor Equipment (NOAK)**

**Secondary Heat Removal**

| Description | Qty. | 2022 Rate | Extension | Reference and Data Identifier |
|---|---|---|---|---|
| Vessel | 15,000 | $17.25 | $258,750 | Expert Opinion |
| Support Module | 12,000 | $13.20 | $158,400 | Expert Opinion |
| Misc Heat Exchangers | 2 | $82,500 | $165,000 | Allowance commercial |
| Heat Exchanger Media | 1 | $375,000 | $375,000 | Allowance commercial |
| Salt Pump | 1 | $82,500 | $82,500 | Supplier Budget Quote |
| Valves, piping allowances | 1 | $57,500 | $57,500 | Allowance |

**Summary Estimate Values $1,100,000...Secondary Heat Removal**

(note 1: Expert opinion (B. Dunkin, VP Nuclear Products) based on industry knolwedge and firm fixed priced history for similar material supply)

| Reference | Source and Data Identifier |
|---|---|
| A | **DOD Facilities Pricing Guide ...** ufc_3_701_01_c6_Data_Tables_July_2020 Table 3 |
| B | **Direct Quote Redmond Heavy Haul...** worksheet and contact data provided. |
| C | **RS Means, 2016 Heavy Construction Cost Data...** Unit Values Escalated YOY * |
| D | **RS Means, 2016 Building Construction Cost Data...** Unit Values Escalated YOY * |
| E | **NREL Cost Study ...** Unit Values Escalated YOY * |
| F | **Solar Turbines, Div Catepillar...** Budget Quote Value Escalated YOY * |
| G | **McClure 2013, Home advisor 2020a** |

* Unit values escalated @ 2% YOY (Year over Year) except CY 2022. CY 2022 escalated @ 10% per US PPI Index note that Producer Price Index (PPI) would indicate higher than 10% escalation in 2022, but this estimator believes it to be an anomoly. 2% represents YOY escalation from 2016 data, then 10% for 2022 estimated based on date of initial quote.

# BASIS FOR COST ESTIMATES (NOAK)

**Site Work**

| Description | Qty. | 2022 Rate | Extension | Reference and Data Identifier | |
|---|---|---|---|---|---|
| Mobilize | | | $50,000 | Estimators Judgement | |
| Earth work | 935 Yd | | $26,000 | C | 31 23 16 6110 |
| Lot Preparation | 6000 sf | | $70,000 | G | |
| Vault | $/CY | 161 | $101,400 | C | 03 30 53 4500 |
| Vault | 41 CY | 65 | $23,000 | C | 03 30 53 5950 |
| Foundation | 35 | 78 | $264,000 | C | 03 30 53 0740 |
| Control Building | 300 | 300 | $174,000 | A | FAC 1457 |
| Securty Zone | 5,000 | 3,200 | $147,300 | A | FAC-8521 |
| Security Zone | 350 | 350 | $32,000 | A | FAC-8722 |
| Security Zone | 300 | 300 | $242,000 | A | FAC-1498 |

Summary Estimate Values $1,130,000... Site Work

**Transport**

| Description | Size | 2022 Rate | Extension | Reference and Data Identifier | |
|---|---|---|---|---|---|
| NB Reactor Module | 125,000 | 1000 miles | $33,500 | B | Redmond Heavy Haul |
| NB Power Conv. Module | 40,000 | 1000 miles | $29,600 | B | Redmond Heavy Haul |
| Reactor Vault Cover | 45,000 | 1000 miles | $13,250 | B | Redmond Heavy Haul |
| Misc 5 Loads Legal | 5 | $2,000 | $10,000 | B | Redmond Heavy Haul |
| Spent Fuel Shipments back | 3 | $200,000 | $600,000 | 3 spent fuel shipments | |
| Refueled units shipment | 3 | $33,545 | $100,635 | 3 refuel shipment | |

Summary Estimate Values $790,000... Shipment (1,000 Mi.)

**Installation**

| Description | Qty. | 2022 Rate | Extension | Reference and Data Identifier | |
|---|---|---|---|---|---|
| Mobilize | | | $60,000 | Estimators Judgement | |
| Crane costs | 150T | 2 | $23,950 | C | 01 54 33 2760 |
| Field logistics eqpt. | Lot allow | | $25,000 | Estimators Judgement | |
| Site trailer | Lot allow | | $25,000 | Estimators Judgement | |
| Labor Hi-Skilled | 200 | $/Hr. | $53,000 | Estimators Judgement | |
| RVACS | 480 | $/Hr. | $113,200 | Estimators Judgement | |
| Labor Lo-Skilled | 600 | $/Hr. | $106,750 | Estimators Judgement | |
| Labor Special | 300 | $/Hr. | $90,000 | Estimators Judgement | |
| Labor Mgt | 450 | $/Hr. | $191,000 | Estimators Judgement | |
| Eng. Start up | 600 | $/Hr. | $332,500 | Estimators Judgement | |

Summary Estimate Values $1,020,000... Installation

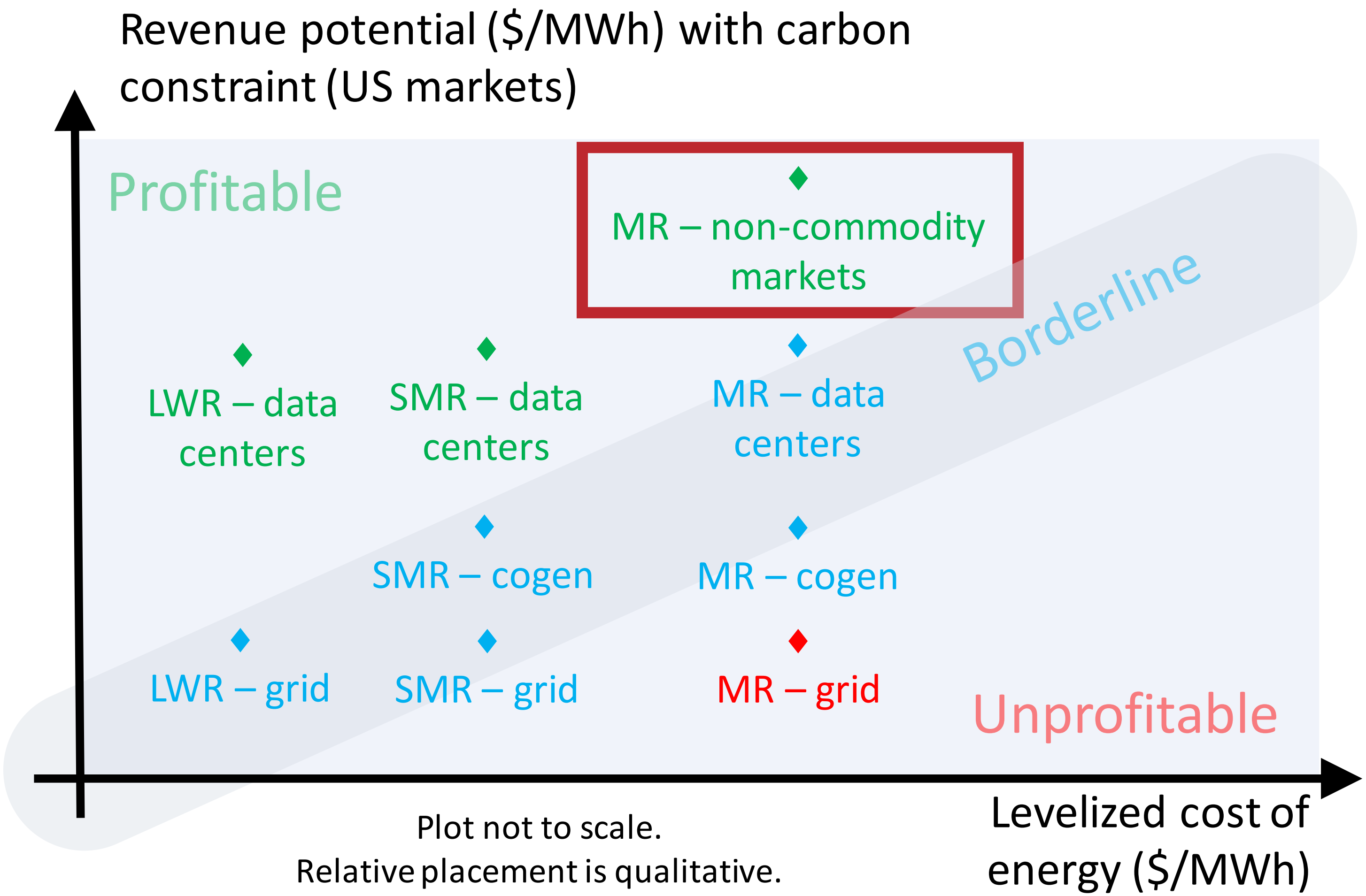
# THE MICROREACTOR DIS-ECONOMIES OF SCALE

$$LCOE\left[\frac{\$}{MWh}\right] = \frac{ICC\cdot(A/P,i,N)+DC\cdot(A/F,i,N)}{W_e\cdot CF\cdot 8760} + \frac{Fixed\ O\&M}{W_e\cdot CF\cdot 8760} + \frac{Variable\ O\&M}{W_e\cdot CF\cdot 8760} + \frac{FC}{24\cdot\eta\cdot BU}$$

LCOE = levelized cost of electricity; $W_e$ = electric output; ICC = initial construction cost;
DC = decommissioning cost; CF = capacity factor; N = lifetime; O&M = operations & maintenance;
FC = fuel cost; $\eta$ = thermal efficiency; BU = fuel burnup; $(A/P, i, N)$ and $(A/F, i, N)$ = capital recovery factors; i = discount rate

| Parameter | Large LWR (best in class) | $UO_2$-fueled Na-cooled microreactor (NOAK) |
|---|---|---|
| $W_e$ [MWe] | 1000-1400 | 4.65 |
| ICC/$W_e$ [$/MWe] | 3500-4500 | 7000 ☹ |
| CF [%] | 90-93 | 80 ☹ |
| N [years] | 60-80 | 30 ☹ |
| FTEs [people/reactor] | 500-750 | 10 |
| FTE/$W_e$ [people/MWe] | 0.50-0.65 | 1.0-2.0 ☹ |
| FC [$/$kg_U$] | 3600 | 3600 |
| BU [MWd/ $kg_U$] | 50 | 9.5 ☹ |
| $\eta$ [%] | 35 | 31 ☹ |
| LCOE [$/MWh] | ~60 | ~190 |

# THE PROFITABILITY MAP




(LWR = Large LWR; SMR = Small Modular Reactor; MR = Microreactor)

Higher LCOE does not necessarily mean unprofitable, but focus on right markets is essential.

# MARKETS FOR MICROREACTORS

## COMMERICAL SUCCESS CAN COME FROM

- A strong policy signal recognizing the non-emitting nature, economic impact, and contribution to energy security of nuclear *electricity*

**Happening in the U.S. now but will it last?**

AND/OR

- Capture of new markets in which nuclear products could sell at a premium

**Within reach with the right technology**


**SOLUTION**

- Dense and clean energy source (the Microreactor)
- Modular industrial systems
- Co-located and universally applicable
- Distributed, but not interconnected

# WHAT ARE MODULAR INDUSTRIAL SYSTEMS?

- Any process/production technologies that can be modularized and mobilized.
- Deploys in increments, *n*, *n*+1, *n*+2,… *n*+*m* over time.
- Plug-and-play (minimal civil work) matches revenue to debt quickly. Minimizes risk of under-utilization.

**Mega-datacenters vs. Containerized DCs**


$400M over 2 years vs. on-site DCs in 1 month
50 MW grid with diesel vs.10+1 microreactors

**Pharma facility vs. Containerized bioreactors**


$450M over 2-4 years vs. on-site pharma in 2 months
centralized grid vs. microreactor

**Land agriculture vs. Containerized hydroponics**

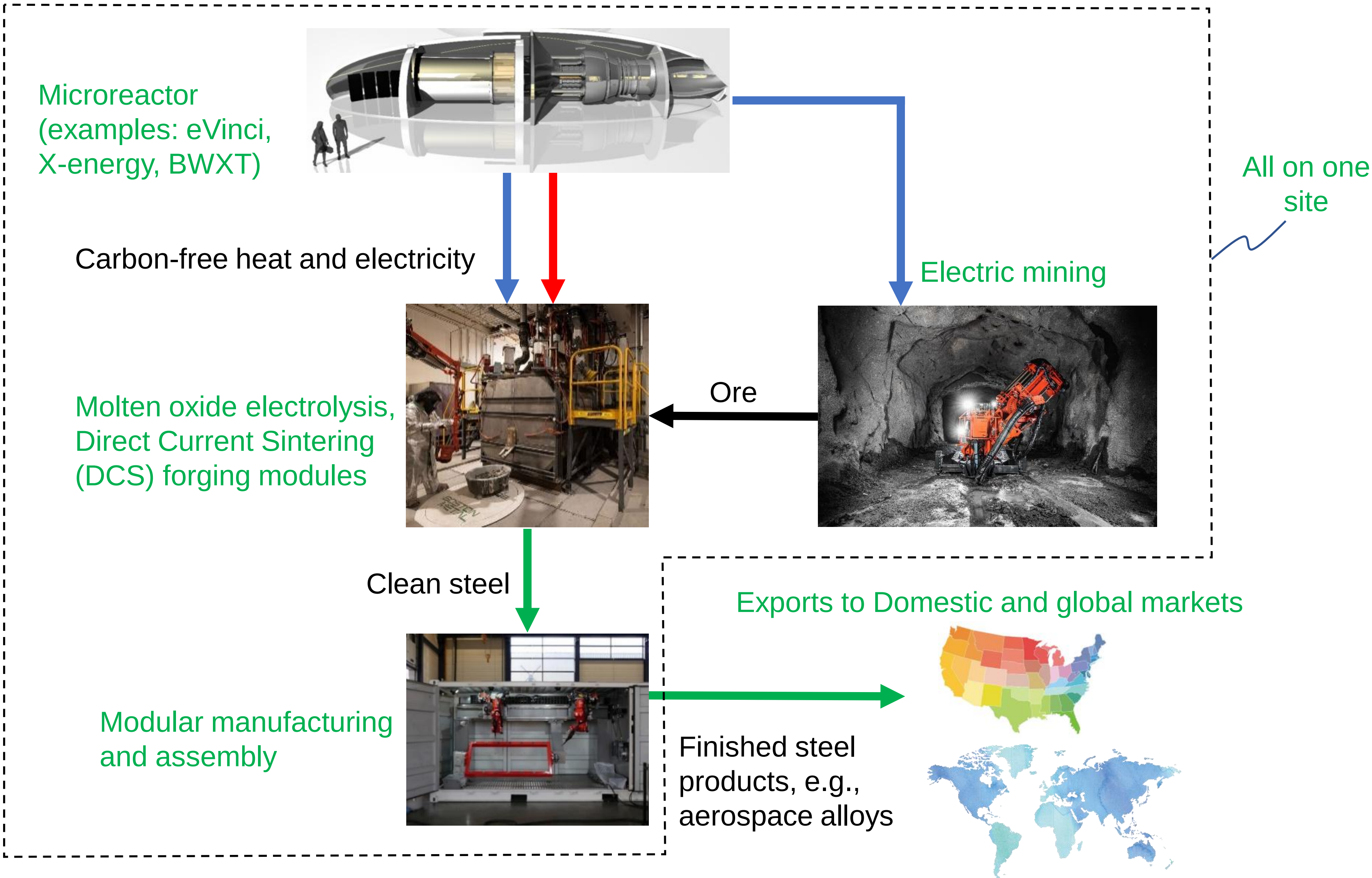

Needs land the size of North America vs. 10x yield for ¼ the water
diesel vs. microreactor

**$H_2$ facility vs. Containerized $H_2$**



$80M over 2 years vs. on-site $H_2$ in 1 month
20 MW centralized grid vs. 4 microreactors

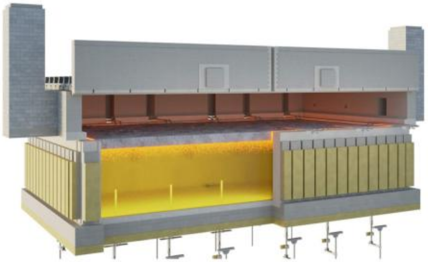
# MICROREACTORS COULD PENETRATE NON-COMMODITY MARKETS WHERE THEY CAN ENJOY A SIGNIFICANT COMPETITIVE ADVANTAGE




Systems features: (1) No grids or pipelines needed; (2) Shortened markup chains; (3) Allows for incremental provisioning; (4) Carbon-free products

# THE ECONOMIC POWER OF INCREMENTAL PROVISIONING AND HIGH VALUE-ADDED PRODUCTS

Boston Metal's molten oxide electrolysis module



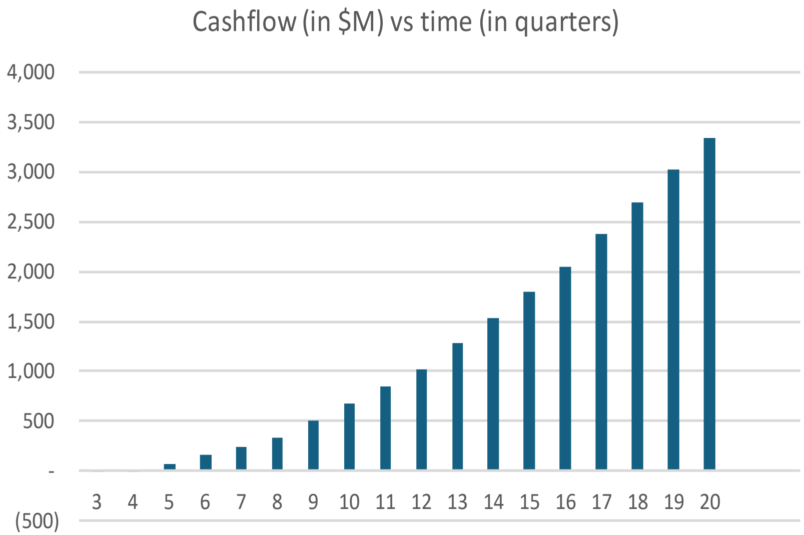
Horns Glass Industries' electric furnace


Freight Farms' containerized farming module

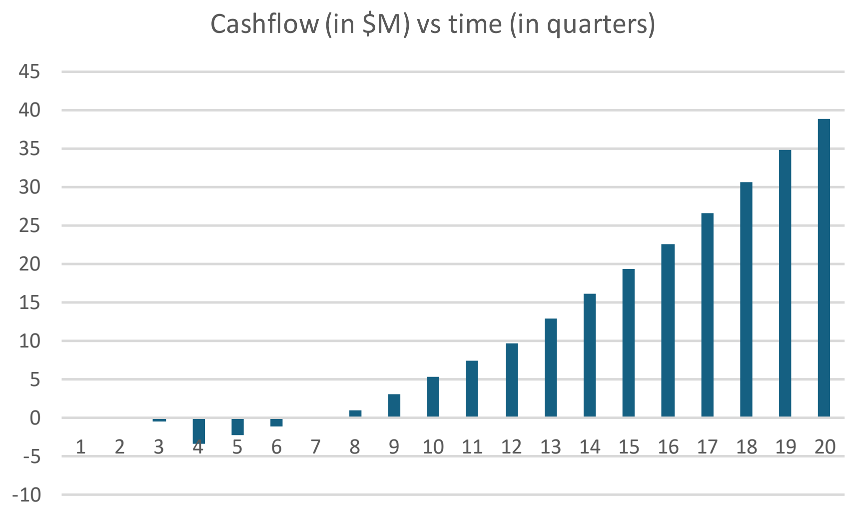
| Product assumptions | | | | |
|---|---|---|---|---|
| | **Steel Roof Cladding** | **Luxury Cast Glass** | **Candy Cap Mushrooms** | Notes |
| **Product price** | $22,366/ton or $8/sqft | $23,471/ton or $40/sqft | $352,740/ton or $10/oz | |
| **Equipment used in production line** | Advanced metallurgic production* + balance of equipment | Horn Glass Industries + Glass Service S.r.l. cast tile** | 50 Freight Farms hydroponic crates** | Representative suppliers |
| **Maximum annual yield per line** | 32,850 tons | 1,825 tons | 57 tons | |
| **Inventory utilization** | 70% | 70% | 70% | Net revenue of inventory / maximum revenue of inventory |
| **Cost of production equipment per line** | $4,825,000 | $1,900,000 | $6,344,000 | Excludes microreactor |
| **FTEs per production line** | 10 | 10 | 10 | $100k/yr direct salary |
| **Electric power required per line** | 15 MW | 4.4 MW | 1 MW | No credit for heat cogeneration |
| **Growth** | One line added per year | One line added per year | One line added per year | |
| **Microreactor assumptions** | | | | |
| **Microreactor refueling period** | 5 years | 5 years | 5 years | Conservative assumption |
| **Microreactor cost** | $30,000/kW | $30,000/kW | $30,000/kW | Includes fabrication and fuel, conservatively assumed to be incurred every 5 years. |
| **FTEs per reactor** | 5 | 5 | 5 | $100k/yr direct salary |
| **Financial assumptions** | | | | |
| **Cost of business** | 15% | 15% | 15% | General & administrative |
| **Cost of capital** | 14% | 14% | 14% | Assumes high project risk |

* cost estimates conservatively scaled from a mini-mill ** cost estimates from vendors' quotes

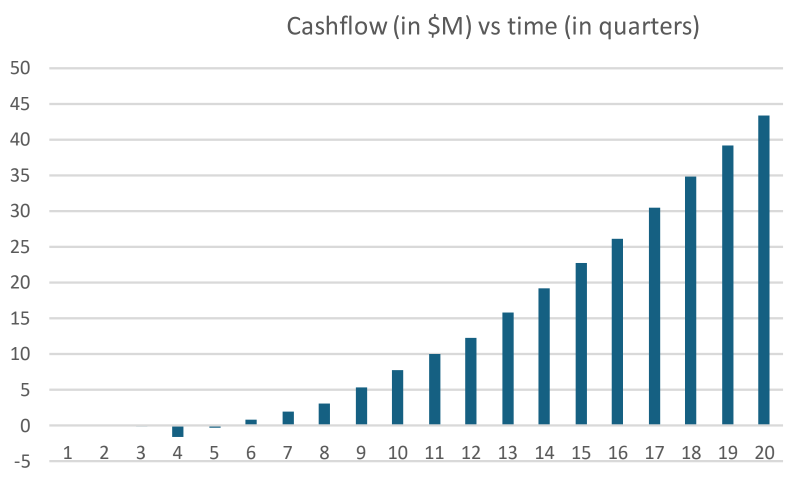
# THE ECONOMIC POWER OF INCREMENTAL PROVISIONING AND HIGH VALUE-ADDED PRODUCTS (2)




Microreactors and steel roof cladding




Microreactors and luxury cast glass




Microreactors and candy-cap mushroom

ROI (5-year cashflow / maximum negative cashflow):

- 198 (steel)
- 12 (glass)
- 28 (mushroom)

J. Buongiorno et al. “The Value of Versatile Nuclear Microreactors”, *SPE Technical Bulletin*, Vol. 1-2, pages 70-77, 2024

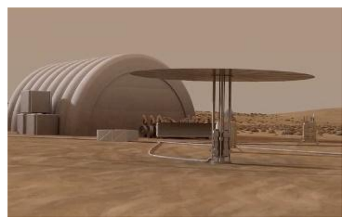
# THIS APPROACH COULD APPLY ACROSS EVERY SECTOR OF THE ECONOMY


military bases


microgrids (remote communities, islands)


mining sites


indoor farming

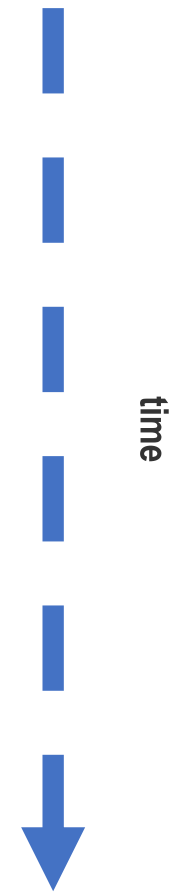

space installations


high-end metals, ceramics and glass


data centers


indoor aquaculture


portable pharma




Largest margin or early need determines relative order of deployment

# (CONTINUED)


district heating


flood protection


desalination

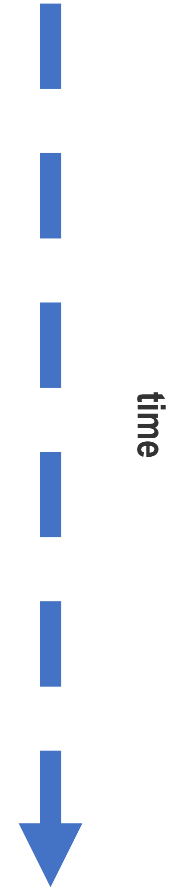

freight ship propulsion


e-vehicle charging stations


hydrogen electrolyzers


existing factories and chemical plants


biofuels




This goes way beyond the electric grid, which represents only ¼ of global GHG emissions

# ARE MICROREACTORS HAPPENING?

## NEW REACTOR PROJECTS IN NORTH AMERICA

(with completion date, as stated by vendors)

*Large LWRs*

- None ☹

*SMRs*

- BWRX-300 (GEH): 300 MWe, OPG Darlington, 2030
- Natrium (Terrapower-GEH): 840 MWt, former coal power plant site in Kemmerer (Wyoming), 2030
- Xe-100 (X-energy): 4x100 MWe units, Dow's site in Seadrift (Texas), 2030

*Microreactors prototypes*

- BWXT (Pele): <5 MWe, INL site, 2028 (DOE authorization)
- MARVEL: 20 kWe, INL site, 2027 (DOE authorization)
- eVinci (Westinghouse): 5 MWe, INL site, 2027 (DOE authorization)
- Kaleidos (Radiant Nuclear): 1 MWe, INL site, 2027
- Hermes (Kairos): 35 MWt, Oak Ridge, 2027 (NRC license)

*Others in the pipeline :*

- SMR-300, AP300, Terrestrial, ARC, Oklo, Nano, Xenith, Nuscale, Aalo*, Valar*, Antares* (* "4th-of-July" DOE Reactor Pilot Program)

## HOW WE CHOOSE REACTOR DESIGNS

- I want to improve nuclear safety
- I want to “burn waste”
- Innovation drives commercial success
- Everyone else thinks it’s a good idea
- I worked on this concept in my PhD thesis

## HOW WE *SHOULD* CHOOSE REACTOR DESIGNS

- Reactor features arise from comparison of multiple designs under a consistent set of assumptions, and are informed by market needs
- There is a credible cost estimate, not just a target, showing potential competitiveness in designated markets
- Supply chain is available for fuel and all alloys selected
- There is reasonable past operating experience with the design

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**Papers in Refereed Journals**

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- L. J. Fernandez de Losada, J. Buongiorno, A. Manera, “Assessment of the Lifecycle Cost of Nuclear-Grade Coolants for Advanced Reactors”, *Annals of Nuclear Energy*, submitted, 2024.
- G. Park, J. Buongiorno, K. Shirvan, “Bottom-Up Levelized Cost Estimation of Low-Enriched and Low-Pressure Nuclear Batteries”, *Nuc. Eng. Design*, 438, 113936, 2025.
- J. Buongiorno, F. Duarte, C. Ratti, “A new beginning for nuclear”, *Domus*, Nov 2024.
- S. Paul, N. Klimenko, F. Duarte, C. Crawford, C. Gorman, C. Ratti, J. Buongiorno, “When Cities Go Nuclear: Exploring the Applications of Nuclear Batteries Toward Energy Transformation”, *Urban Science,* 8, 2024. Urban Science, 8, 226, 2024. https://doi.org/10.3390/urbansci8040226
- J. Buongiorno, K. Shirvan, R. Freda, “The Value of Versatile Nuclear Microreactors”, *SPE Technical Bulletin*, Vol. 1-2, pages 70-77, 2024.
- *I. Naranjo De Candido, A. Al Rashdan, A. Abou Jaoude, J. Buongiorno, “Assessment of Technoeconomic Opportunities in Automation for Nuclear Microreactors”, *Nuc Sci Eng*, 2024. DOI: https://doi.org/10.1080/00295639.2024.2372511
- E. Gateau, N. Todreas, J. Buongiorno, “Consequence-based security for microreactors”, *Nuclear Engineering and Technology*, 56, 1108-115, 2024.
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- F. Antonello, J. Buongiorno, E. Zio, “Insights in the Safety Analysis of an Early Microreactor Design”, *Nuclear Engineering and Design*, Vol. 4, 112203, Apr 2023.
- F. Antonello, J. Buongiorno, E. Zio, “A Methodology to Perform Dynamic Risk Assessment Using System Theory and Modeling and Simulation”, *Reliability Engineering & System Safety*, 228, 108769, 2022.
- J. Buongiorno, B. Carmichael, B. Dunkin, J. Parsons, D. Smit, “Can Nuclear Batteries Be Economically Competitive in Large Markets?”, *Energies*, 14, 4385, 2021.
- J. Buongiorno, R. Freda, S. Aumeier, K. Chilton, “A Strategy to Unlock the Potential of Nuclear Energy for a New and Resilient Global Energy-Industrial Paradigm”, *The Bridge*, 51, 2, June 2021.

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**Papers in Conference Proceedings:**

- L. Lallemant, J. Buongiorno, S. Islam, "Conceptual design of a Fission Batteries Process (FIBAPRO) facility", *Proc. ICAPP 2024*, Las Vegas, June 9-12, 2024.
- E. Germonpré, J. Buongiorno, K. Shirvan, J. I. Lee, J. Parsons, R. Macdonald, "Factors for Competitive Decentralized Hydrogen Production with Nuclear Microreactors", *Proc. ICAPP 2024*, Las Vegas, June 9-12, 2024.
- B. Dunkin, J. Buongiorno, K. Shirvan, R. MacDonald, S. Cetiner, E. Saito, T. Conboy, C. Forsberg "Evaluation of Capital Costs for $UO_2$-fueled Microreactors", *Proc. ICAPP 2024*, Las Vegas, June 9-12, 2024.
- M. D. Chew, J. Buongiorno, "A Cybersecurity Framework For Nuclear Microreactors", *Proc. ICAPP 2024*, Las Vegas, June 9-12, 2024.
- N. Kallieros, G. Park, K. Shirvan, J. Buongiorno, "Safety analysis and design specifications of MIT's sodium graphite micro-reactor", *Proc. ICAPP 2024*, Las Vegas, June 9-12, 2024.
- F. Fakhry, J. Buongiorno, S. Rhyne, B. Cross, P. Roege, B. Landrey, "A Central Facility Concept for Nuclear Microreactor Maintenance and Fuel Cycle Management", *Proc. ICAPP 2023*, Gyeongju, South Korea, April 23-27, 2023.
- E. Gateau, N. Todreas, J. Buongiorno, "Consequence-based security for microreactors", *Proc. ICAPP 2023*, Gyeongju, South Korea, April 23-27, 2023.
- F. Antonello, J. Buongiorno, E. Zio, "A Methodology for the Dynamic Risk Assessment of Nuclear Batteries", *European Safety and Reliability Conference (ESREL)*, Dublin, Aug 28-Sep 1, 2022.
- J. Buongiorno, B. Carmichael, B. Dunkin, J. Parsons, D. Smit, "On the Economic Potential of Portable Micro-reactors", *Proc. ICAPP 2021*, Abu Dhabi, UAE, 16-20 October 2021.

**Reports and Book Chapters**

- E. Germonpre and J. Buongiorno, "Moving beyond high costs: a case study for hydrogen production with nuclear microreactors", Chapter 15, in *New Directions in Nuclear Energy*, 2024. (in press)
- S. B. Prasad, J. Buongiorno, "Levelized Cost of Fuel (LCOF) studies for microreactors using TRISO fuel in hydride and beryllium-based composite moderators in open and closed fuel cycles", CANES report MIT-NFC-135, Mar 2025.
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- L. Lallemant, J. Buongiorno, S. Islam, Design of a Fission Batteries Process (FIBAPRO) facility, CANES report MIT-198-ANP-TR, November 2023.
- M. Chew, J. Buongiorno, A Cybersecurity Framework for Nuclear Microreactors, CANES report MIT-197-ANP-TR, June 2023.
- J. Buongiorno, An Economic Evaluation of Micro-Reactors for the State of Washington, CANES report ANP-TR-190, Jan 2021.

MIT