BWX Technologies, Inc.

BWXT's Advanced Nuclear Reactor (BANR)

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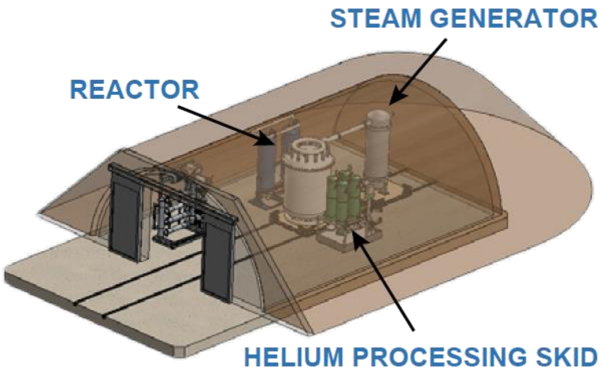
Basis for BWXT Advanced Nuclear Reactor (BANR)

- High TRL / MRL system developed using specific customer requirements for a remote industrial location
  - Result → unit cost too high to be economical
- Proposed targeted risk reduction activities as part of DOE's Advanced Reactor Demonstration Program (ARDP) to cut costs in half
- Risk reduction of lower TRL/MRL R&D and technologies that when consolidated into design enhance economics offering → BANR



Enablers of Risk Reduction:

- Qualification of U-dense fuel kernel (UN) within proven fuel architecture (TRISO)
- Core design leveraging computational engineering tools and optimized fuel system
- Advanced sensors enabling semi-autonomous control
- Manufacturing throughput and quality control enhanced through data science

BWXT Baseline Microreactor

Reactor Core:

50MWth; 5 year nominal lifetime before core skid replacement; thermal spectrum reactor

Fuel, Cladding, and Moderator:

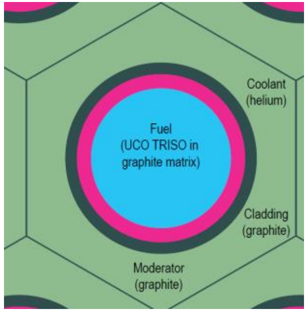
UCO TRISO in graphite matrix; graphite cladding; 19.75% enriched; graphite moderator block

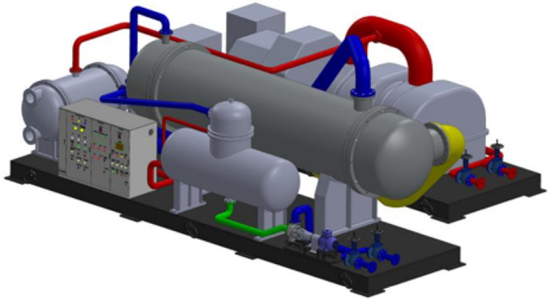
Coolant, Heat Transfer, Steam / Electrical Generator Systems:

Helium gas coolant; two configurations- power generation or co-generation; nominal Rankine Cycle of 33% efficiency for net 17 MWe

Control, decay heat removal, and inherent safety:

Coarse and fine reactivity control via mechanical means; passive heat removal; large heat capacity of UCO TRISO graphite matrix and moderator block couple with negative reactivity temperature coefficient for inherent, engineered safety





BWXT Baseline Microreactor Technical/Manufacturing Readiness Levels (TRL/MRL)

Reactor	TRL	MRL	Power Conversation and Process Heat	TRL	MRL
Fuel System	8	8	Steam Generator	7	7
Reactor Core	6	7	Helium Circulator	6	6
Reactor Vessel & internal structures	7	7	Piping	7	8
Reactor I&C	7	7	Heater, Reboiler, Water processing, & Balance of Plant I&C	7	8
Reactivity Control System	6	7	Turbine Generator and I&C	7	8
Passive Cooling	6	7	Control Room, I&C, support hardware	7	7
Reactor Supports & Skid	7	7			
Reactor Vault	7	8			
Helium Processing Skid	7	8			

BANR Technical/Manufacturing Readiness Levels (TRL/MRL)

Reactor	TRL	MRL	Power Conversation and Process Heat	TRL	MRL
Fuel System (BANR scope)	4	4	Steam Generator	7	7
Reactor Core (BANR scope)	4	4	Helium Circulator	6	6
Reactor Vessel & internal structures	7	7	Piping	7	8
Reactor I&C (BANR scope)	4	5	Heater, Reboiler, Water processing, & Balance of Plant I&C	7	8
Reactivity Control System (BANR scope)	4	5	Turbine Generator and I&C	7	8
Passive Cooling (BANR scope)	4	4	Control Room, I&C, support hardware	7	7
Reactor Supports & Skid	7	7			
Reactor Vault	7	8			
Helium Processing Skid	7	8			

BANR as Risk Reduction Program

Image courtesy of ORNL

Important attributes of risk reduction program that will enhance economic offering:

- UN TRISO enabling higher power and/or longer core life
- Higher core outlet temperature may enable direct Brayton Cycle or Combined Cycle to increase efficiency (from 33% to 50%+)
- Incorporation of advance manufacturing technologies that will make cores faster and less expensive to build
- Incorporate in-core sensors to enable semi-autonomous operation and minimize staffing

Baseline advantages compared to current nuclear systems:

- Configurations for electricity, process heat, or both
- TRISO as accident tolerant and proliferation resistant fuel form
- Fuel form and passive cooling approach eliminates need for external power to perform safety functions and increases coping time during accident scenarios
- Modular, mobile, and factory constructed skids reduces construction time and costs
- Smaller emergency planning zone anticipated

Baseline advantages plus consolidation technology risk reduction efforts provide pathway to economically viable reactor system and fuel cycle

Conversion of Natural Uranium Oxide to UF_6

- Existing U.S. Supplier is Shut-Down
  - Only U.S. Converter (Honeywell - Converdyne) shut-down/mothballed since October 2017
    - Located in Metropolis, Illinois
  - Capacity is ~ 7,000 MTU / year
  - National Security needs about 2,000 MTU / year

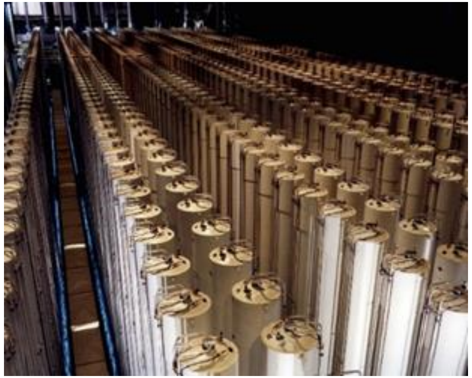
- BWXT is developing strategy and plans to create a new conversion capability (rightsized and modern) should Honeywell-Converdyne decide to permanently close their facility
  - Potentially co-locate with LEU and HA-LEU enrichment facility

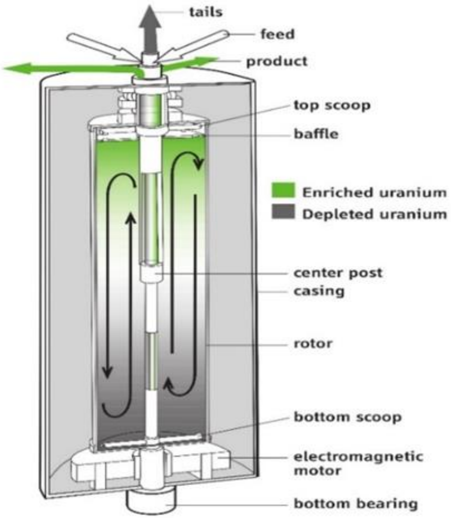
LEU & HA-LEU Enrichment

- BWXT is currently able to downblend HEU to HA-LEU during initial steps of fuel manufacturing process (e.g., TRISO and/or other ceramic/metallic coated fuels) for demonstration quantities

- BWXT has developed a strategy to create an enduring capability that meets the DOE/NNSA long-term Domestic Uranium Enrichment requirements

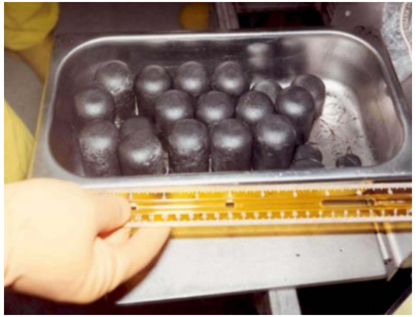
- BWXT has also developed a near-term strategy, plan and estimate to provide 3 MTU per year of HA-LEU that is free of peaceful use obligations
  - Will use U.S. developed gas centrifuge technology (DOE-ORNL is the design authority and maintains the IP)
  - Sited at BWXT owned facility in Erwin, Tennessee actively licensed for all enrichments (LEU, HA-LEU and HEU)
  - Will require U.S. sourced natural uranium feedstock as UF_6 in order to produce un-obligated HA-LEU
  - Approximately 5 to 6 years to construct, commission, and begin production





HA-LEU De-conversion

- No existing HA-LEU de-conversion capability exists in the U.S.
- BWXT has developed the strategy, plan and estimates to perform chemical de-conversion at the HA-LEU enrichment plant
  - Avoid shipping HA-LEU as UF_6
  - No currently licensed economical shipping containers for HA-LEUF_6
  - Would have to ship in very small HEU safe containers (5A/5B’s) for which there are none currently available
- Built concurrently with enrichment plant having an Initial capacity = 120% of HA-LEU enrichment plant annual capacity
- Low-Risk Technical Approach (tried and true chemical processes)
  - BWXT has demonstrated experience with chemical conversions of multiple forms of uranium

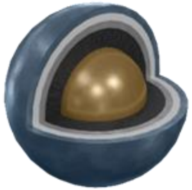


TRISO Fuel Manufacturing

- BWXT has re-started their TRISO facility and is establishing the capacity to manufacture hundreds of kilograms per year of TRISO fuel to meet DOD applications and NASA demonstration needs
  - Ability to downblend HEU to HA-LEU as part of initial process
  - Under contract to demonstrate full capability by end of 2021

- BWXT has developed the strategy to expand capacity to approximately one metric ton per year in existing facilities if the demand is required

- BWXT has recently commissioned at internal conceptual design activity to create a new TRISO manufacturing facility at one of our existing NRC licensed sites
  - 4 MTU / yr initial capacity (in 1 MTU / yr modules)
  - Expandable to 8 MTU / yr



TRISO Facility Multi-functionality

- Demonstrated Capability to Manufacture Coated Particle Fuels for a Wide-Variety of Demonstration Reactors and Applications
  - Kernel types include:
    - Uranium Oxide
    - Uranium Carbide
    - Uranium Alloys
    - Uranium Nitride
    - Uranium Oxi-Carbide
  - Coating types include:
    - Ceramic (e.g., SiC)
    - Graphitic
    - Refractory Metals
- Full Scale Scrap Recovery for Manufacturing Scrap (return enriched uranium to feedstock form)

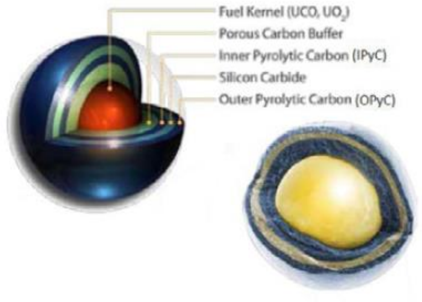
BANR Licensing

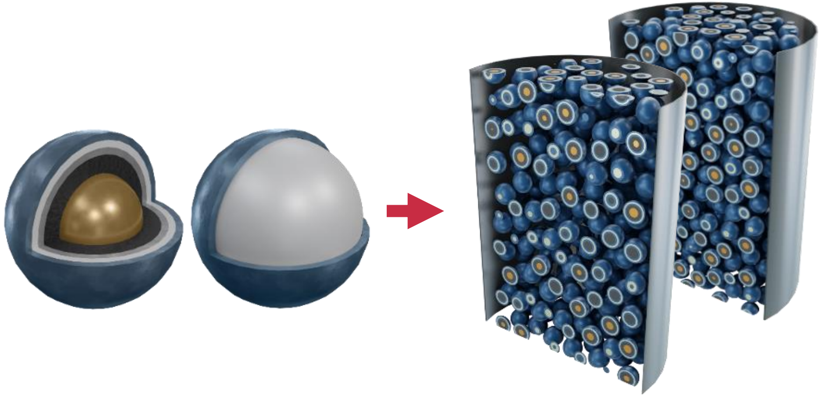
- Existing nuclear fuel cycle, sans HA-LEU enrichment capabilities, can accommodate most advanced reactor approaches and systems

- Existing waste management and facility decommissioning ecosystem can accommodate our system; future changes could benefit economics

- Licensing focus of our risk reduction efforts:
  - Regulatory engagement plan
  - Quality assurance plan
  - UN TRISO fuel performance technical report(s)
  - Advanced manufacturing and instrumentation technical report(s)

Nuclear Security and Non-Proliferation

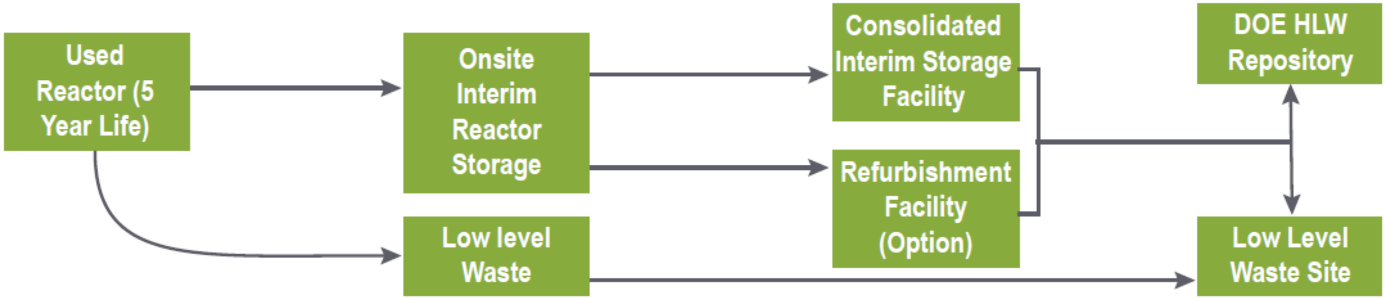




- Key proliferation resistance feature is fuel itself → 19.75% HA-LEU TRISO
- Obtaining significant quantities of U-235 or Pu requires extremely difficult processing steps of large quantities of graphite (baseline) or SiC (BANR) and encased coated particles
- Overall nuclear security posture benefits from being loaded with fuel at manufacturing facility and no on-site refueling

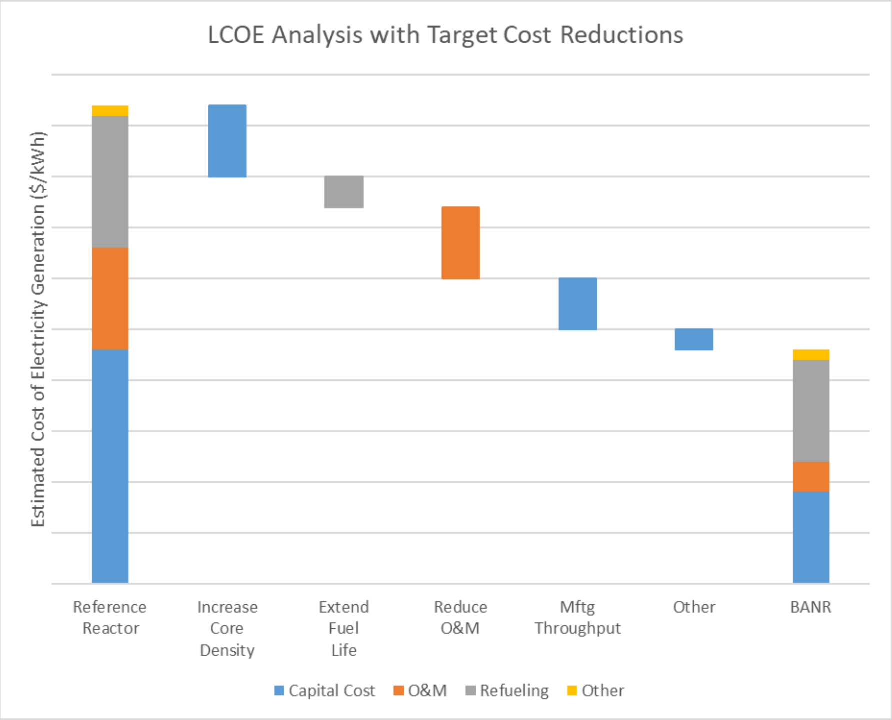
Nuclear Waste Management and Disposal

- End users (other than utilities) have expressed interest in:
  - System that minimizes waste generation on site and
  - Does not involve consolidate storage of spent reactor skids
- Reactor skid based system minimizes local waste generation volumes and allows for interim storage on site before removal
- Enables consolidated storage elsewhere or refurbishment facility for most expensive components and systems associated with reactor skid
- Difficult nature of processing TRISO fuel makes fuel and fuel system likely candidate for high level waste repository, not fuel cycle closing options



Construction and Operating Costs

- Primary capital cost drivers challenging the nuclear industry remain:
  - Core thermal performance per dollar
  - Achieving economies of scale in manufacturing
- BANR potential a model for industry wide challenges:
  - Design and fuel cycle options technically feasibly
  - Deploy reactors and fuel with predictable costs (cheaper) and schedules (faster) along with improvements in safety
- Targeted investment to streamline supply chains and bolster economic competitiveness of the U.S. nuclear industry and enable exportation of safe and secure nuclear reactors



Back-Up

Questionnaire to presentation reference

- **ADVANCED REACTOR DESIGN (All questions → slide 3)**

- **RESOURCE UTILIZATION**
- What will be the impact on the mining and use of uranium and thorium resources? (Not addressed; too early to determine)
- Describe fuel characteristics and in-reactor parameters that impact the overall efficiency of the consumption of fissile material. (See slide 3 and slide 6)
- In what sense is the proposed advanced reactor technology and fuel cycle sustainable? (See slide 15)

- **ADVANCED FUEL CYCLE (All questions with some not addressed as too early to determine → slides 7 – 11)**

- **NUCLEAR WASTE MANAGEMENT and DISPOSAL (All questions with some not addressed as too early to determine → slide 14)**

- **NUCLEAR SECURITY and PROLIFERATION RESISTANCE (See slide 13)**

- **NUCLEAR SAFETY (See slide 3)**

- **ADVANTAGES or ATTRIBUTES of your ADVANCED REACTOR DESIGN (See slide 6)**

- **CHALLENGING TECHNICAL ISSUES for COMMERCIALIZATION (See slides 4-6)**

- **CHALLENGING LICENSING ISSUES for COMMERCIALIZATION (See slide 12)**

- **CONSTRUCTION and OPERATING COSTS (See slide 15)**