X-Energy’s Xe-100 Reactor Design Status

National Academy of Sciences

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Who are we?

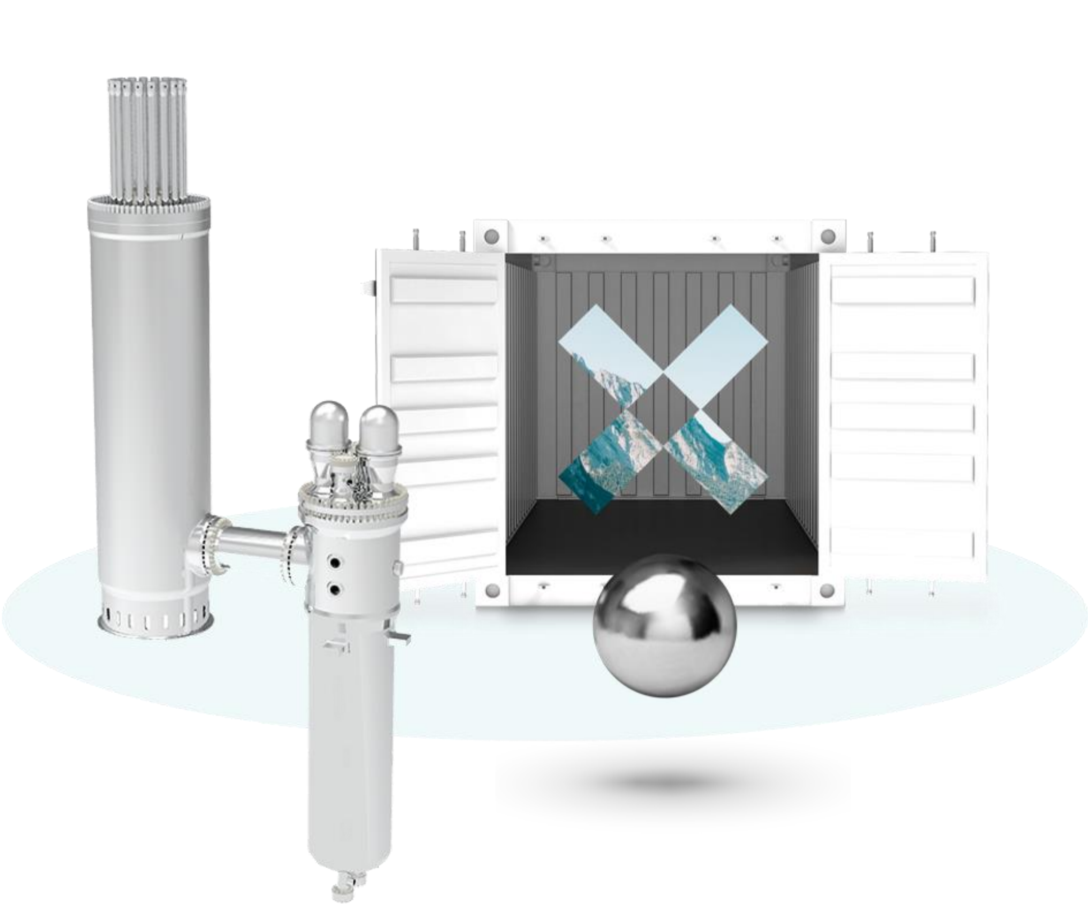
Two Challenges in Opposition

↑ Global Energy **Demand Up** 50% by 2050

↓ Need to drastically **Reduce Carbon** Emissions

X energy

We design & build reactors and the fuel that powers them



Reactor: Xe-100

We're focused on Gen-IV High-Temperature Gas-cooled Reactors (HTGR) as the technology of choice, with advantages in sustainability, economics, reliability and safety.

Reactor: Xe-Mobile

To address the need for ground, sea and air transportable small power production. We've developed reactor concepts with potential civilian government, remote community and critical infrastructure applications.

Fuel: TRISO-X

Our reactors use tri-structural isotropic (TRISO) particle fuel, developed and improved over 60 years. We manufacture our own proprietary version (TRISO-X) to ensure supply and quality control.

Space Applications

NASA, DOE, and DOD are exploring our technology and fuel for nuclear thermal propulsion and fission power for the lunar surface.

Leading the way with a Legacy of Success

Dr. Kam Ghaffarian
Founder & Executive Chairman

Space

Business Success

Founded and grew SGT to $650 mm in annual revenue and 2,400 employees. SGT was ranked as the U.S. National Aeronautics & Space Administration's second largest engineering services company.

Acquired by KBR in 2018 for ~$355 mm on an initial $25k investment

Moon 2021

Founded Intuitive Machines in 2016 to leverage NASA technologies for commercial space and terrestrial applications. Intuitive Machines won its first Commercial Lunar Lander Contract from NASA in 2018.

Landing on the Moon in 2022

ISS

Founded Axiom Space in 2017 to develop a commercial replacement to the ISS while making access to Low Earth Orbit global during the remainder of ISS' lifetime. Sole winner of NASA contract to commercialize International Space Station.

First commercial International Space Station

Energy

Nuclear Energy

Founded X-energy in 2009 with the goal of providing a SAFE, SECURE, CLEAN and AFFORDABLE energy source to consumers around the globe.

Xe's vision is to be the world's leading provider of highly innovative, 100% safe & environmentally friendly small-scale nuclear energy solutions for government, industry and private consumers.

Xe is commercializing & deploying a High Temperature Gas-cooled Reactor (HTGR) as well as manufacturing a proprietary version of TRISO fuel (TRISO-X) to ensure supply & quality control.

Unlocking Nuclear,
Disrupting the energy industry

Dr. Ghaffarian has invested over $85 mm in X-energy

Innovation & Investment

IBX is an innovation investment firm committed to advancing the state of humanity and human knowledge. We explore new frontiers in space, technology & energy to push human potential and make a positive impact in the world.

New frontiers in space, technology & energy

Philanthropy

Emerging Light Foundation

Emerging Light Foundation, which is dedicated to improving the condition of humankind through a variety of charitable endeavors was established to support, educate and inspire great purpose while helping transcend limitations all over the world.

Limitless Space Institute

Inspires and educates the next generation to travel beyond our solar system and to support future interstellar human space exploration.

Imagine. Believe. Execute.

Our traction, accomplishments & risk reduction to date

2009

Founded by Kam Ghaffarian

2010

Reactor science team in place, led by Dr. Eben Mulder & Dr. Martin Van Staden

2014

Completes market study, design choices, and finalizes design parameters for Xe-100

2015

Xe gets into the fuel business. Hires Dr. Pete Pappano, builds fuel team.

2016

Forms Customer Advisory Council

Achieves 50% conceptual design on Xe-100

Established pebble fuel manufacturing capability

2018

Begins regulatory engagement with NRC. Produces first pebble in pilot fuel facility

Canada passes a carbon tax

2019

Formally initiates commercialization track in Canada

2020

Selected by U.S. DOE for Advanced Reactor Demonstration Program

Selected by U.S. DOD for preliminary design of a mobile nuclear power plant

OPG advances engineering and design work with X-energy

Completes conceptual design; 50% of basic design complete

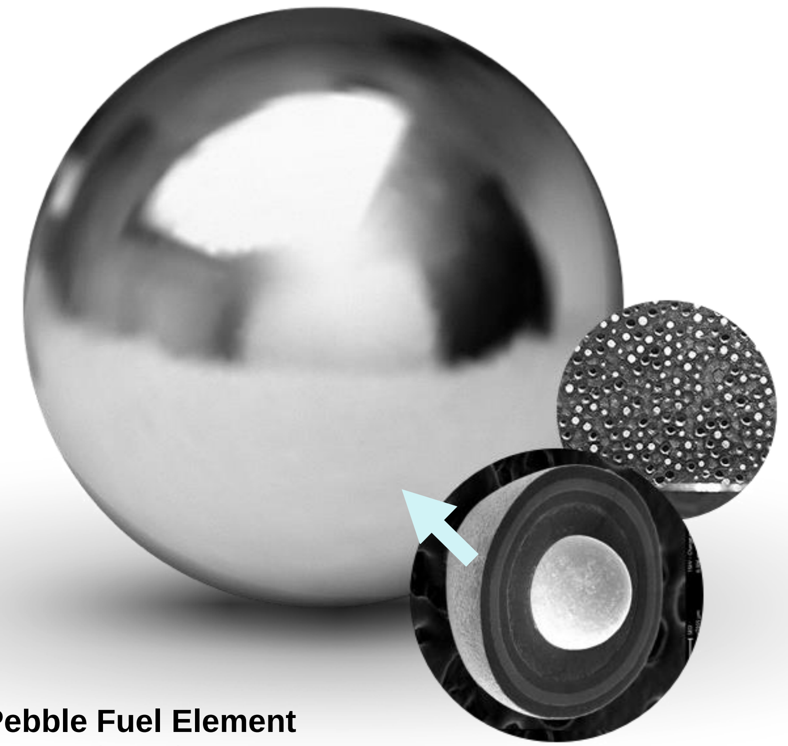
Launch Tri-Energy Partnership with Energy Northwest and Grant County Public Utility District to deploy first 4 reactors by 2027

X-energy is validated and best positioned in the U.S. and Canada

Program	Status and Award	Down-Selection
U.S. DOD Mobile Microreactor Program	• DOD will make final down-selection this year • Winner will deploy demonstration mobile microreactor initially at DOE site	X-energy, BWXT
OPG SMR Deployment	• OPG will make a final down-selection to a single winner this year • Winner will build reactor at Darlington site • Consortium of Canadian utilities has stated desire to build a *fleet*	X-energy, GE Hitachi, Terrestrial Energy
U.S. DOE Advanced Reactor Demonstration Program	• Final two winners selected • DOE cost contribution of $1.2 bn to X-energy project	X-energy, TerraPower

TRISO-Coated Fuel is the Key

Intrinsic Safety: Our Fuel



Pebble Fuel Element
(60mm)

TRISO-coated Fuel Particle
(≈1mm)

We manufacture our own proprietary TRISO encapsulated fuel (TRISO-X) to ensure supply & quality control.

The U.S. DOE describes TRISO fuel as "the most robust nuclear fuel on Earth," it retains waste and fission products within the fuel during ALL conditions **and cannot melt**, even during worst-case scenario accidents.

Why is this important?

- Because TRISO-X Fuel is the containment vessel we do not rely on traditional expensive, gigantic concrete & steel structures for the reactor, which must be built, maintained, and decommissioned.
- TRISO-coated has been tested up to 1800ºC, proving that it cannot melt, even without active cooling.
- TRISO-coated particles retain 99.999% of fission products.
- TRISO-coated fuel has been demonstrated over 40+ years in prototype and full-scale reactors. **This is a proven safety approach.**
- The low reactor power density and self-regulating core design (i.e., if cooling stops, the core shuts down), ensures the reactor is always 'walk-away safe.'

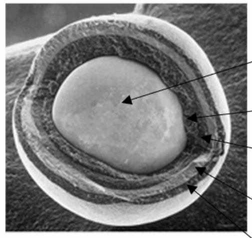
Physics, not mechanical systems, ensures 100% of safety.

TRISO-X Fuel Production

TRISO Coated Particle Fuel is the Key to Safety

- Each TRISO particle forms a miniature containment vessel that retains radionuclides at the source for full spectrum of off-nominal events
- Demonstrated ability to withstand extremely high temperatures for extended periods (1800 °C for 300+ hours) without fuel failure
- High level of maturity due to >$250M investment by DOE in design and qualification and characterization of the TRISO fuel
- World's only active TRISO fuel fabrication facility.

TRISO Coated Particle



History

HTGR

1954	P Fortescue
1956	R Schulten

History of coated particles:

1957	R A U Huddle
1959	W Goeddel
1961	J Oxley, Battelle fluidised bed coating

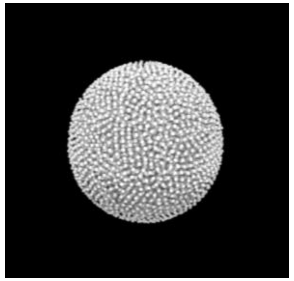
Manufacturing

United States	China
United Kingdom	South Africa
Germany	South Korea
Russia	Japan
France	

FUNCTIONS: TRISO COATED PARTICLE

- **Fuel Kernel – ρ=10.4 g/cm^3; D=0.350 mm**
  - Fission energy source
  - Retain short-lived radionuclides
- **Buffer layer (porous carbon) – ρ=1.05 g/cm^3; T=0.100 mm**
  - Void volume for fission gases
  - Accommodates fuel kernel swelling
  - Protect PyC and SiC layers from fission product recoil
- **Inner Pyrocarbon (iPyC) – ρ=1.85 g/cm^3; T=0.040 mm**
  - Diffusion barrier to fission products
  - Provide mechanical substrate for SiC deposition
  - Prevent Cl_2 from reaching kernel during SiC deposition
- **Silicon Carbide (SiC) – ρ=3.2 g/cm^3; T=0.035 mm**
  - Primary fission product barrier in all anticipated plant conditions
  - Load-bearing layer for TRISO particle
- **Outer Pyrocarbon (oPyC) – ρ=1.85 g/cm^3; T=0.040 mm**
  - Provide compressive stress on SiC during irradiation
  - Provide bonding layer with matrix graphite
  - Provide fission product barrier

Prototype pebble mold



Innovative visualization of particles in pebble

First fuel form pebbles produced at ORNL, Fall 2016

Former DOE Assistant Secretary Dr. Rita Baranwal tours TRISO-X Pilot Lab

Fuel is an integral part of the HTGR safety basis and economics

Pebble Fuel Design Data (Equilibrium Core)

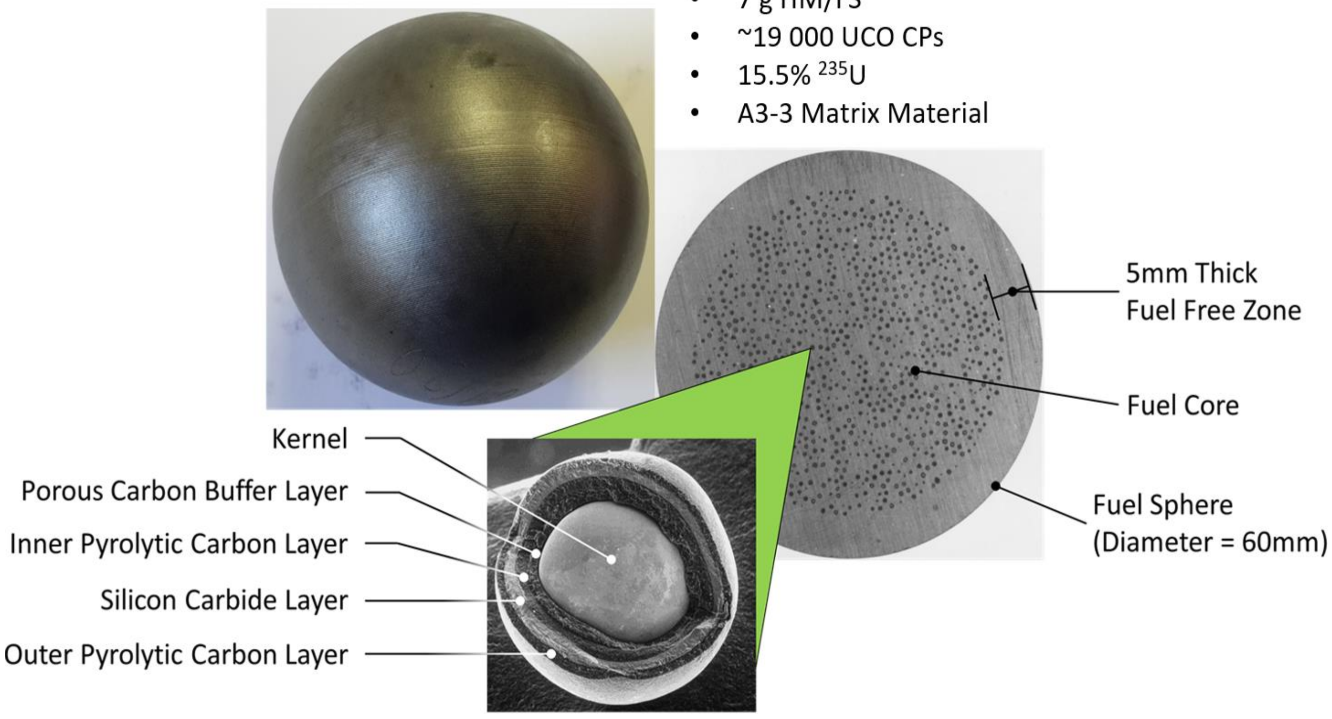
- Fuel kernel:

Composition	UCO	
U-235 enrichment	15.5	%
Diameter	0.425	mm
Density	10.4	g/cm^3

- Coatings:

	(mm)	(g/cm^3)
Buffer layer	0.100	≤1.05
Inner dense PyC layer	0.040	1.9
SiC layer	0.035	≥3.20
Outer dense PyC layer	0.040	1.9

- 7 g HM/FS
- ~19 000 UCO CPs
- 15.5% ^{235}U
- A3-3 Matrix Material

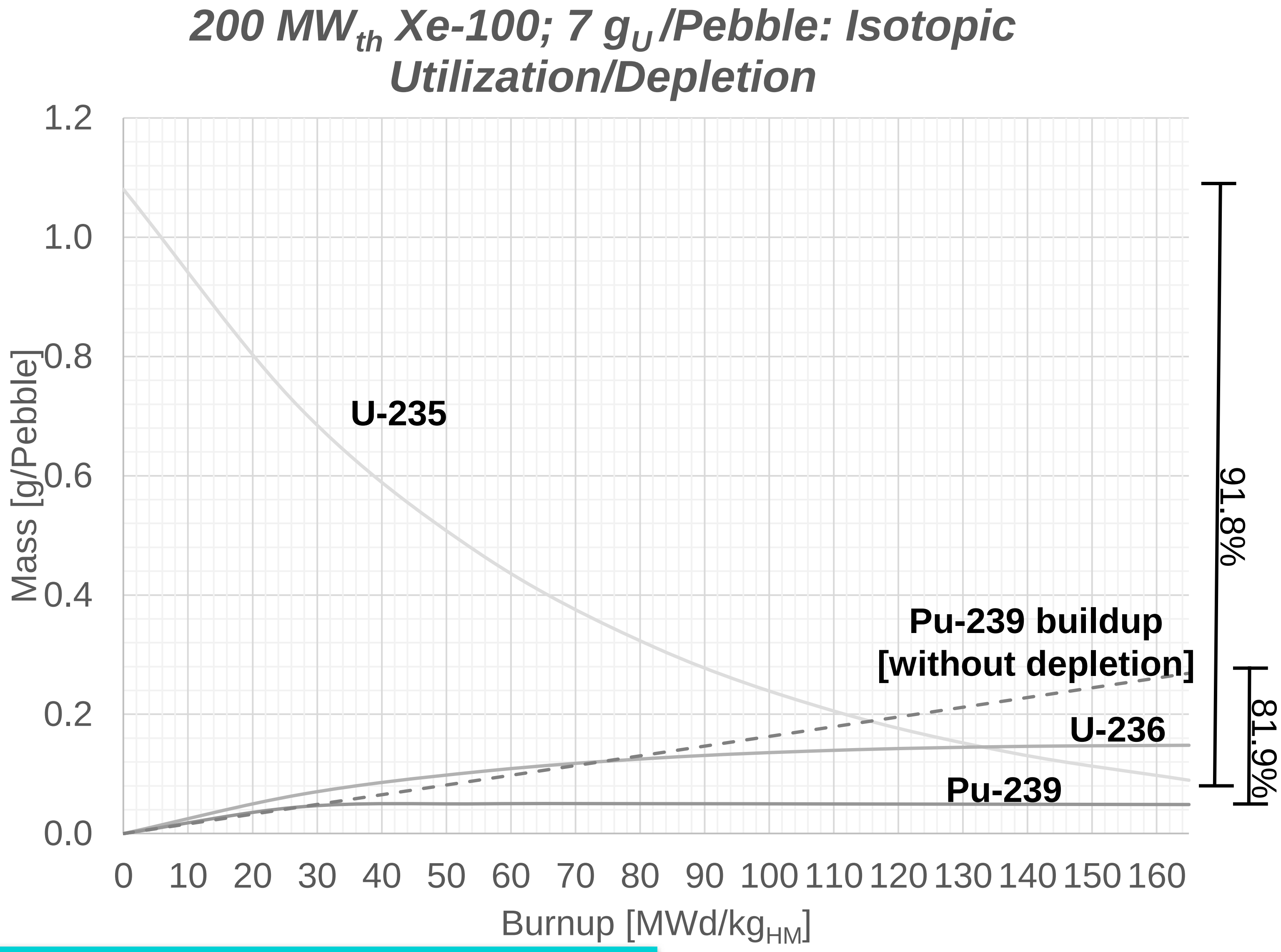


TRISO Coated Particle

Matryoshka dolls (nesting)

Highly In-Situ Utilization of both Fissile & Bred Fissile Materials

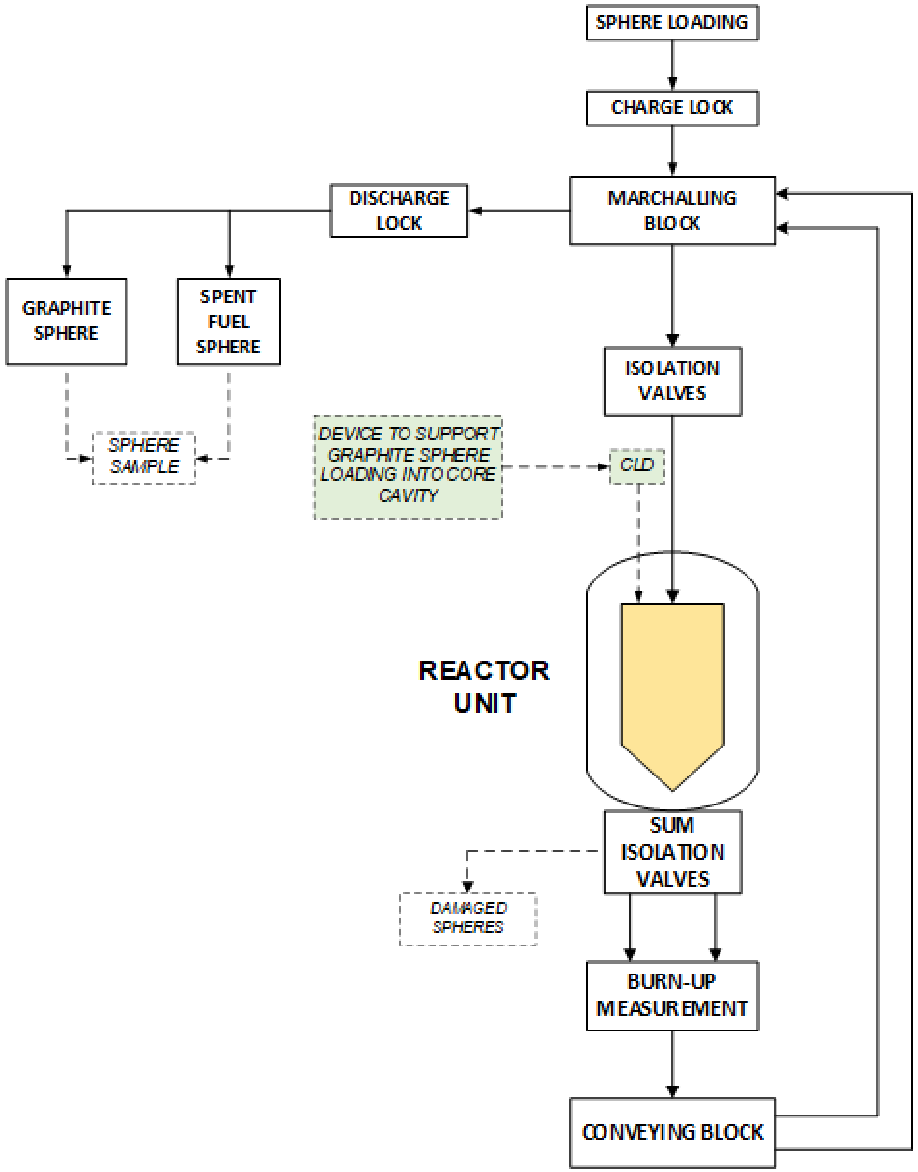
- The X-100 achieves exceptional utilization of both the fissile component of the fuel and the bred fissile material
  - The U-235 is depleted by 91.8%
  - An estimation is made of the in-situ utilization of the bred Pu-239 isotope of 81.9%



Xe-100 achieves high in-situ utilization of bred fissile materials

Fueling/Refueling – Burnup

- The Xe-100 with multi-pass recycling never has to be taken out of service for refueling.
- Pebbles that have not yet reached target burnup can be continuously reloaded and recycled during normal reactor operation.
- The fuel loading scheme is such that the pebbles remain in the reactor until they reach a target burnup of approximately 168,500 MWd/MgU.
- Pebbles with higher burnup are detected by the burnup measurement system (BUMS) and discharged from the internal pebble system and replaced with a fresh pebble.
- The pebble dwell period within the reactor core is approximately 1,320 equivalent fuel-power days.
- The pebble passes on average 6 times through the reactor during this period.

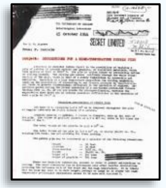


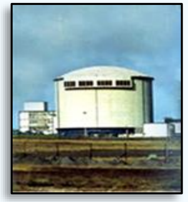
Xe-100

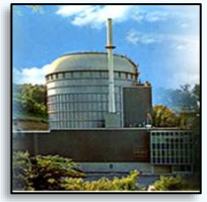
energy

We've taken HTGR technology to the next level

We are capitalizing on decades of learning & best practices in High Temperature Gas-cooled Reactor design.

USA

1944
ORNL

UK

1966-1975
Dragon

USA

1966-1974
Peach Bottom

Germany

1967-1988
AVR

USA

1967-1988
Fort St. Vrain

Germany

1986-1989
THTR

Japan

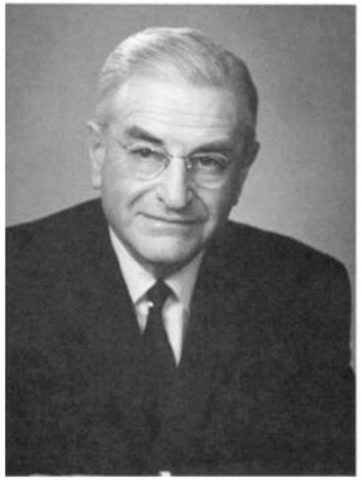

1998-Present
HTTR

China

2000-Present
HTR-10

USA
NGNP
2005 – Present

Fathers of The
Pebble Bed Technology


Farrington Daniels 1889 – 1972
Source: Robert A. Alberty, Nat. Academy of Sciences 1994


Rudolf Schulten 1920 – 1996
Source: Heinrich Bonnenberg 1968

>$700 million U.S. DOE investment, including development and testing of the safest fuel – UCO TRISO coated particles

Our optimized, meltdown-proof Xe-100 is the only Gen IV reactor deployable within 5 years.

We are leveraging proven technology & billions of dollars of prior investment

Simple Design

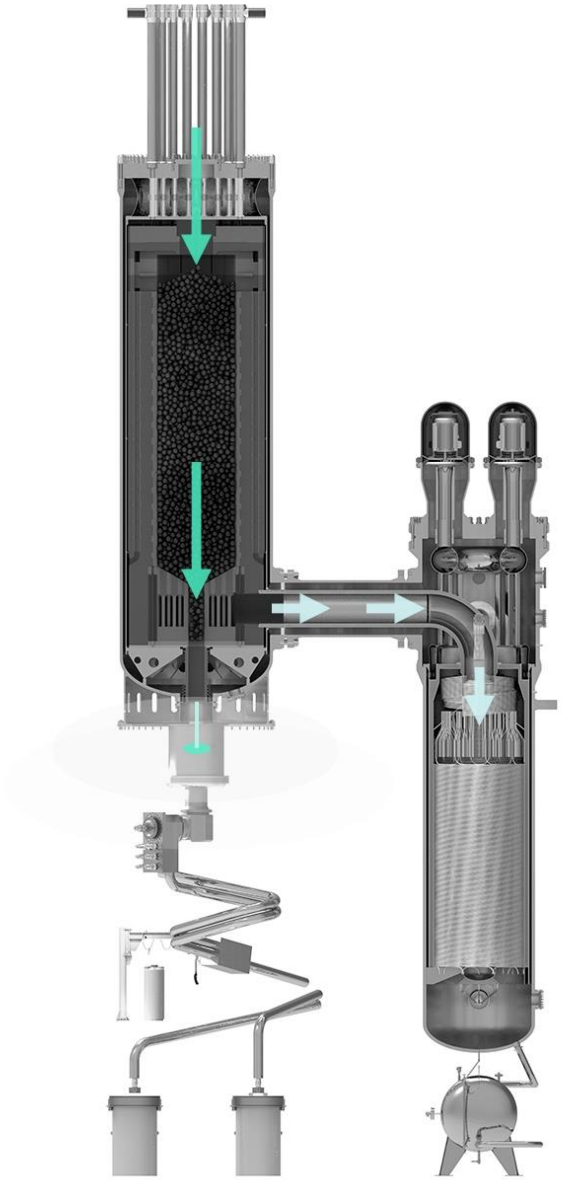
Relying on inherently safe designs allows for a drastic reduction of components.

Reduction of components enables predictability on costs & significant reduction of regulation barriers, as well as a much smaller physical plant footprint.

Why is this important?

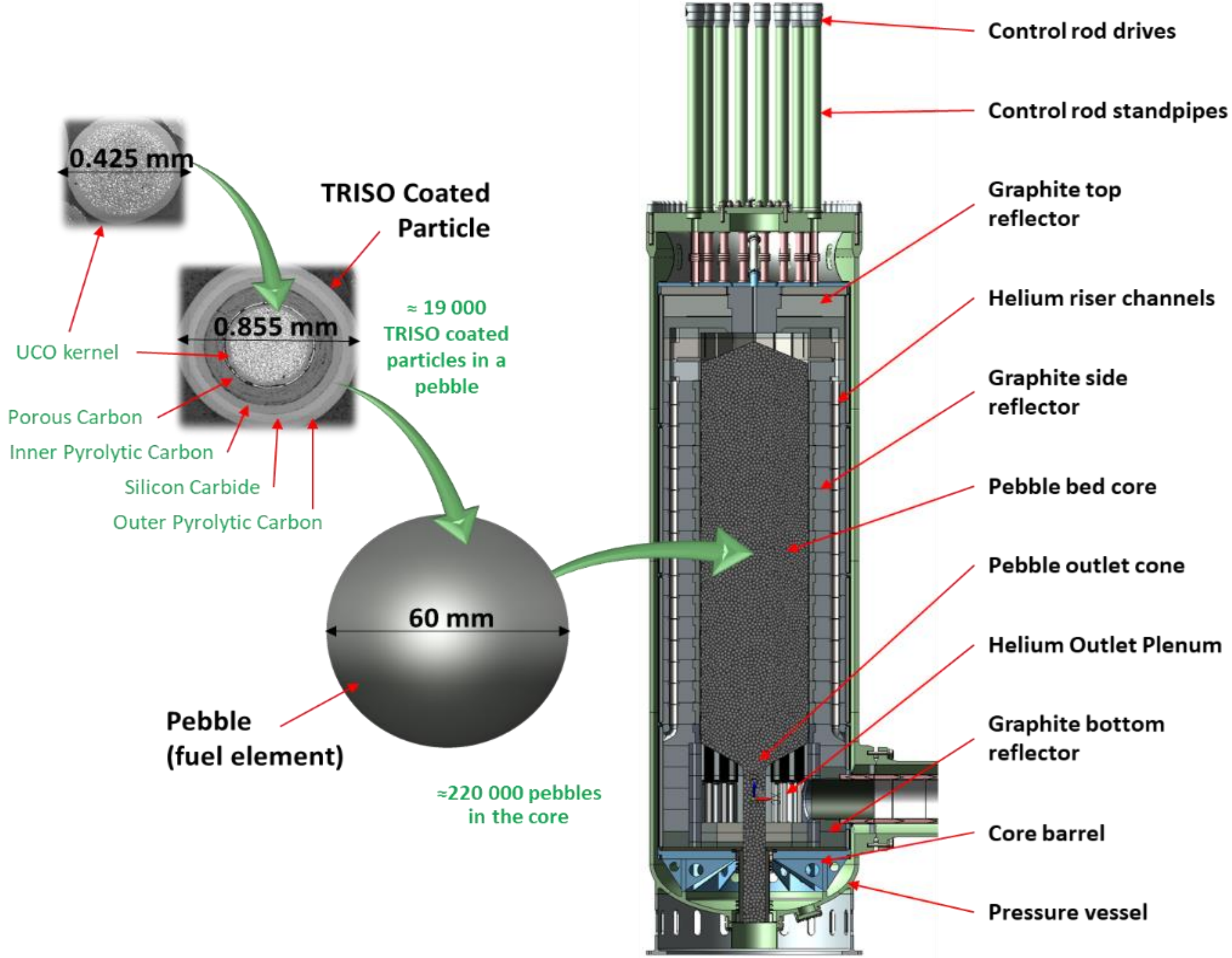
- Results in a Levelized Cost of Electricity well under $60/MWh-e and deployment in less than five years.
- 80 megawatt-electric modules optimized for the ‘sweet-spot’ size
- Standard 4-pack provides 320 MWe with load-following capabilities like a natural-gas plant
- High-quality outlet steam at 565ºC and 16.5 MPa in the standard design with higher temperatures attainable
- Deployment for **electricity or process heat**

1/10th the components of a traditional nuclear plant



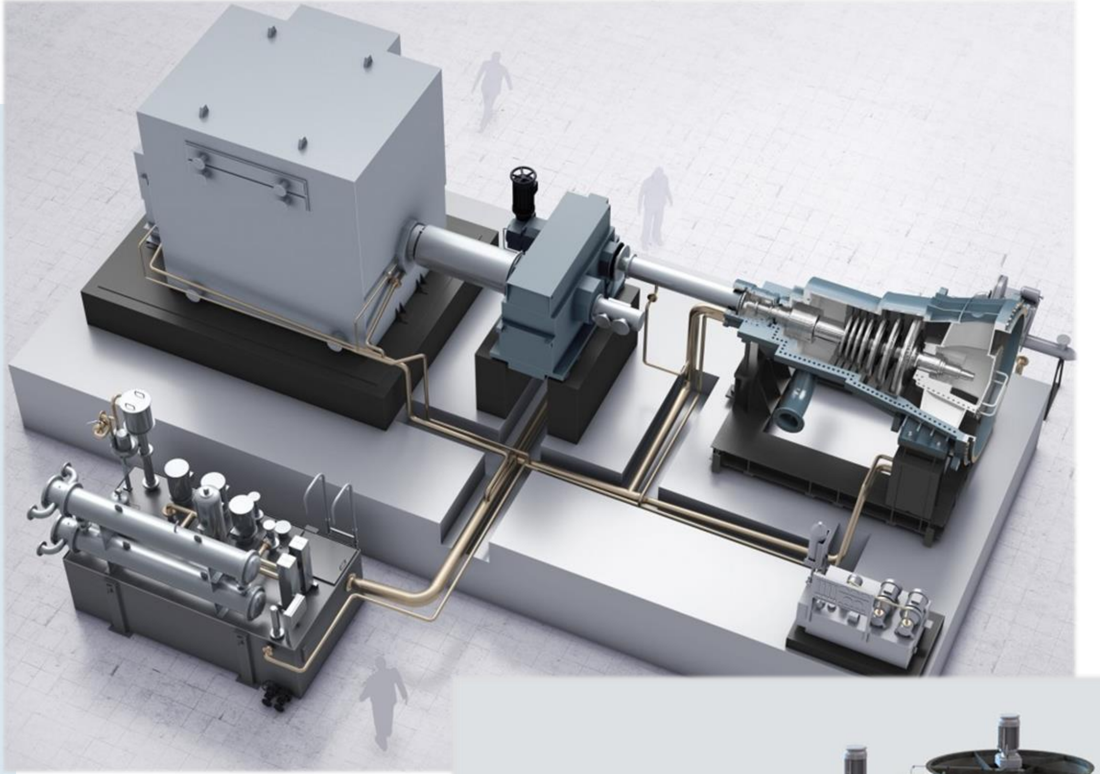
Xe-100 Reactor (80 MWe)

Basic Core Design Parameters



Conventional Island – Power Conversion

- 100% Commercial Off The Shelf steam turbine generator set – including condenser and all auxiliary systems
- High turbine thermal efficiency up to 42.3%
- Skid mounted turbine allowing fast swap out/replacement instead of in-situ refurbishment
- Condenser cooling can be done using wet or dry cooling modules
- Rankine cycle cooling uses off the shelf modular dry/wet or hybrid cooling towers



Xe-100 Flexibility

(1) Right size

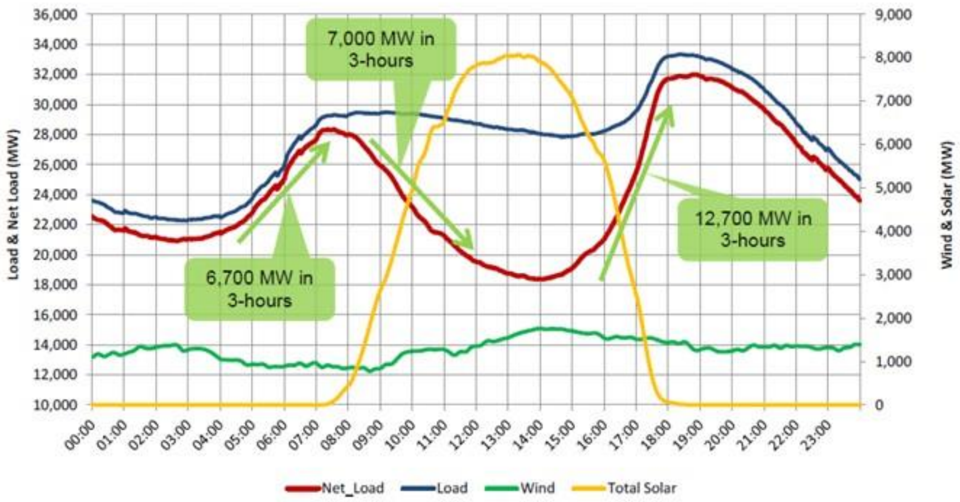
The reactor size of 200MWt (80MWe) has been designed to address the largest possible market providing a good fit for replacement of existing carbon-based heat sources such as coal and gas.

(2) Broad range of applications

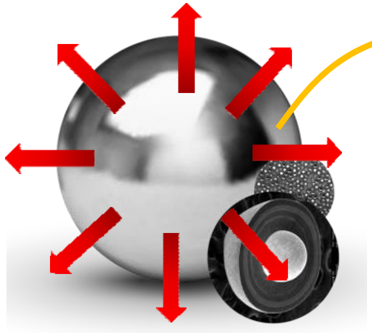
The nuclear island has been designed to be independent of the end use making our solution deployable for electricity and many other process heat applications, such as:

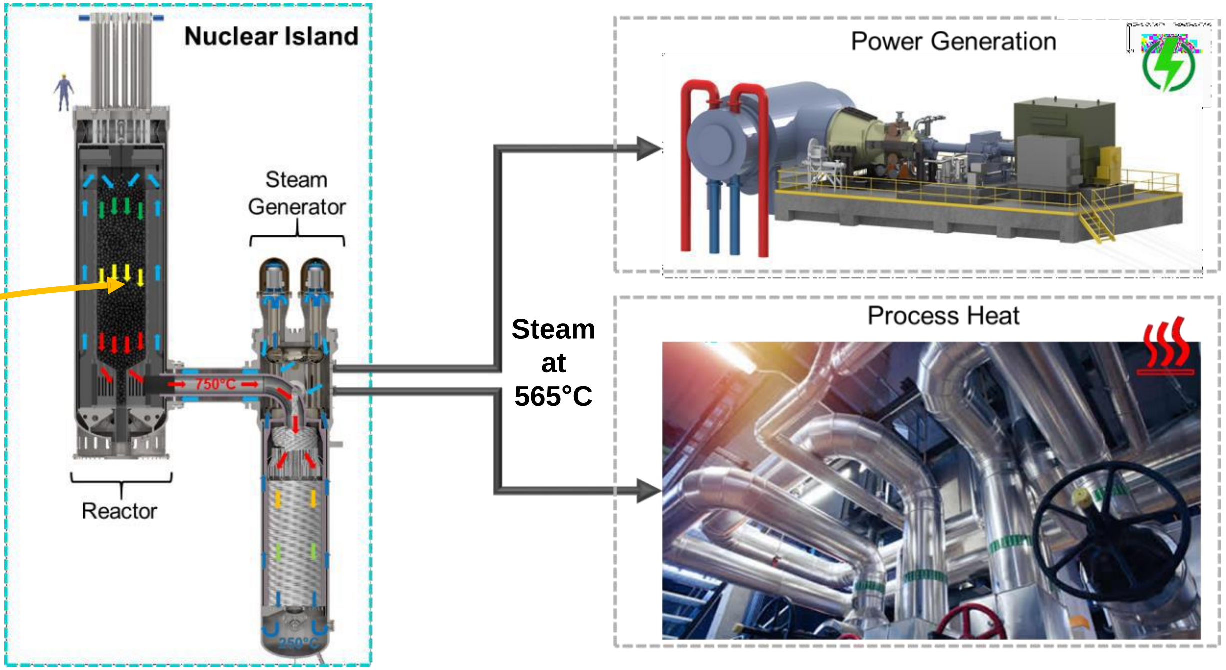
- Hydrogen production;
- Petrochemical processing;
- Desalination; and
- District heating.

The Xe-100 can do both simultaneously or switch between applications.



Heat is generated in the pebble fuel through fission and transferred to the steam generator using helium that cannot become radioactivate.





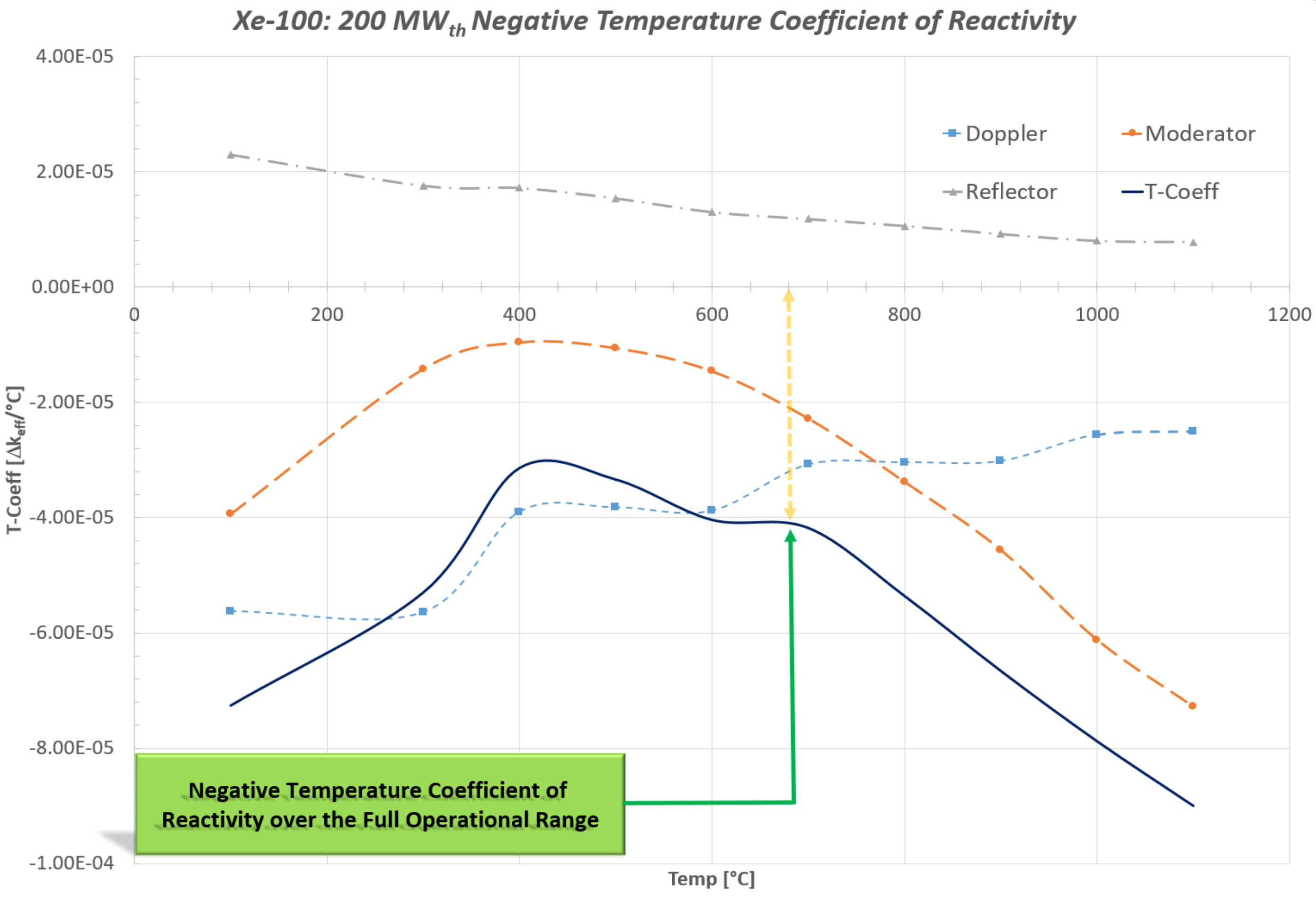
(3) Flexible power delivery

Designed to be capable of fast and efficient load following thus supporting the intermittency of solar and wind

Inherent Safety

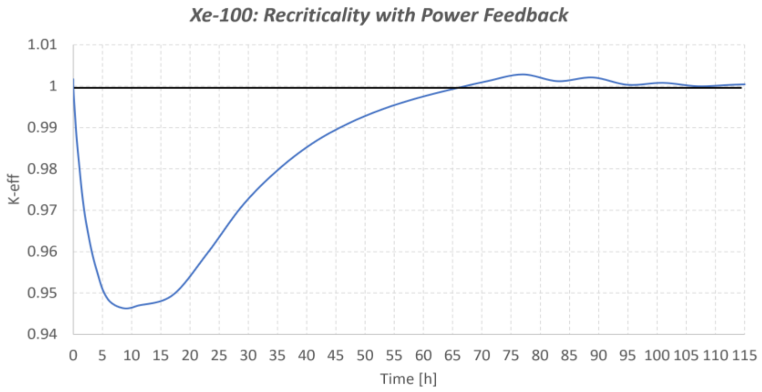
Reactivity Control and Shutdown System (RCSS)

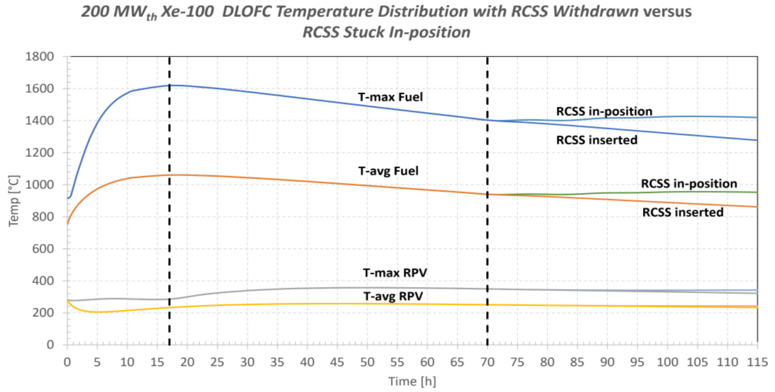
- The primary shutdown mechanism is the **strong negative temperature coefficient** over the entire operational range
- The reactivity control system (RCS) provides a second independent means to shut the reactor down
- The diversely actuated reserve shutdown system (RSS) comprises of 9 shutdown rods that are inserted into channels in the side reflector for shutting the reactor down
- As a Defense in Depth option defueling approximately 1.0m^3 of pebbles will shut the reactor down without the use of control rods

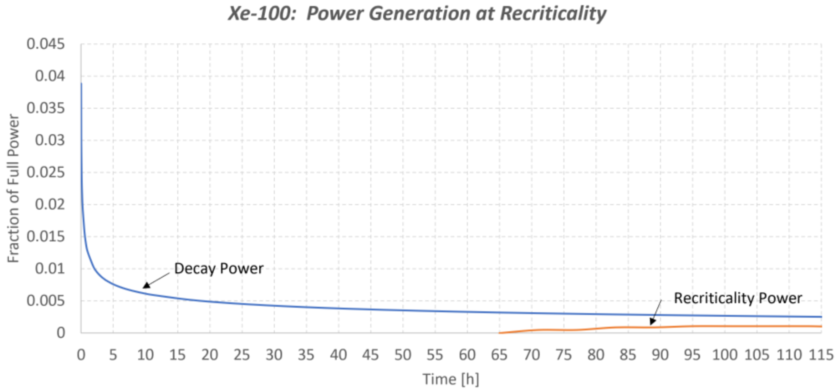


Xe-100 Design Base Event: DLOFC with and without RCSS Actu

- Assumptions:
  - At the onset of the DLOFC the pressure drops from 6.0MPa to 0.1MPa
  - All heat is locally deposited, i.e. no heat is carried away by the exiting helium
  - The reflectors are considered to have achieved EOL fluence, i.e. thermal conductivity will be at its worst
  - RCSS fails to insert
- Sequence of assumptions is followed by a best estimate analysis
- As the core starts heating up – The negative temperature coefficient will shut down the nuclear chain reaction
- The decay heat vs integrated power is depicted over time
- Fuel and RPV temperatures and xenon concentration vs reactivity simulation over time are depicted

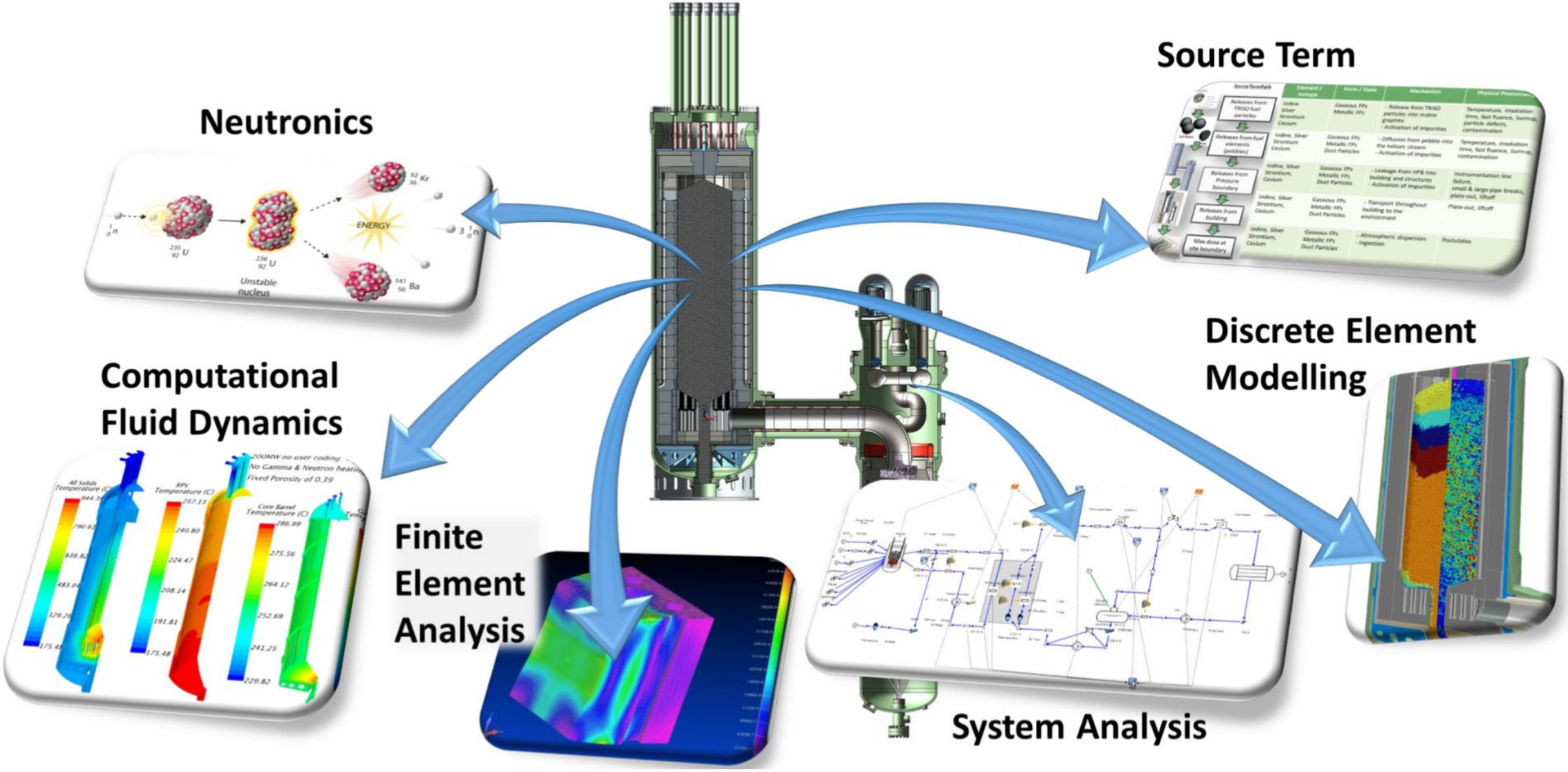






Our Recent Progress

Established modeling and simulation capabilities are applied for design and licensing



We have made incredible progress

Left: X-energy's TRISO-X production line at Oak Ridge National Laboratory

- Successful operation of the TRISO-X fuel production line for over XX years
- Submitted fuel topical report?
- On track for license submittal for commercial scale TRISO-X Fuel Fabrication Facility later this year.

We have made incredible progress

Right: Xe-100 control room simulator in Rockville, MD

- NRC Engagement
- Licensing update
- Basic and detailed phases of plant design
- Engagement with Canadian Regulator
- O&M cost reduction (ARPA-E award) by:
    - Using digital twins for generating baseline operational data
    - Use EPRI guidelines to develop ‘Super Crews’ to perform O&M activities
    - Develop maintenance strategies to optimize fleet maintenance operations
    - Develop white papers and topical reports to support Regulatory approval

Advanced Reactor Demonstration Program – 2027

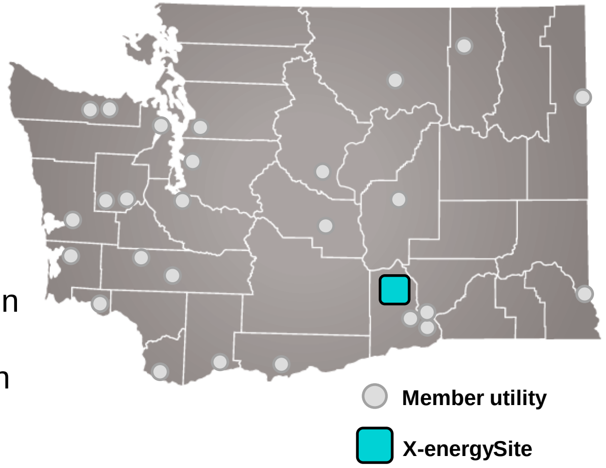
ARDP Details

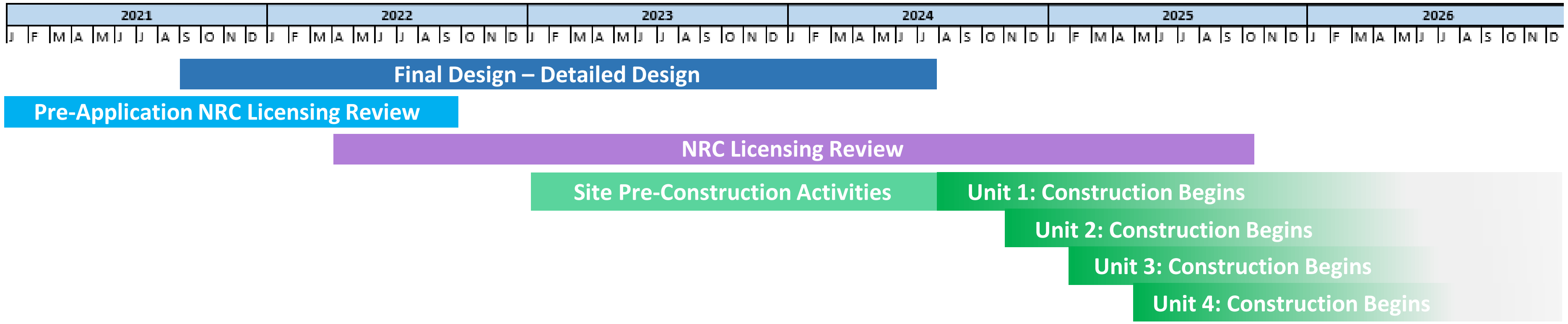
- In May 2020, the Department of Energy announced the Advanced Reactor Demonstration Program (ARDP)
- X-energy and TerraPower were selected as program winners in October 2020
- Program designed as a public-private partnership:
  - Government provides winning bids with 50% cost share for first-of-a-kind advanced nuclear plant
  - Plant must be commercial (*not* demonstration)
  - Plant must be ready for deployment by 2027
  - ✓ Government motive? Kick-start advanced nuclear industry
- X-energy partnered with Energy Northwest, a top-tier customer

Energy Northwest

ENERGY NORTHWEST

- Membership includes 28 public power utilities, including 23 of Washington state's 29 public utility districts.
- State law mandates zero carbon grid by 2045, with limited additional upside in Washington state for renewables.
- EN is a public agency with tax-advantaged capital access.





2027
4 Units Operating

TRi-Energy Partnership

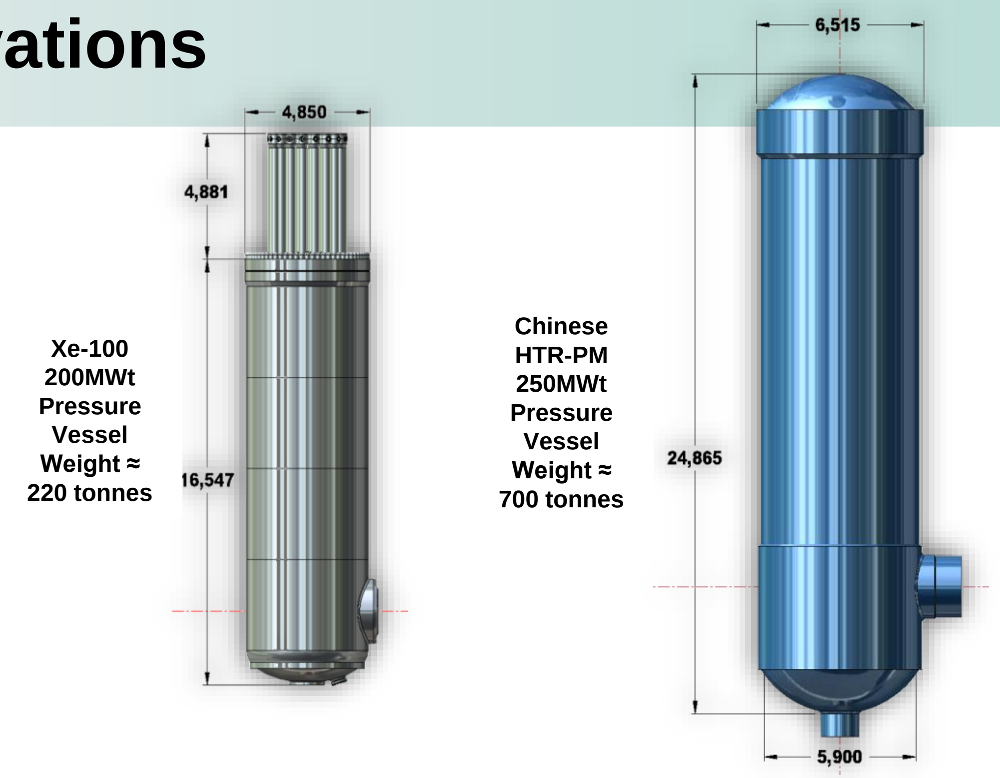
TRi-Energy Partnership Details
• On April 1, 2021, X-energy, Energy Northwest, and the Grant County Public Utility District signed a memorandum of understanding establishing the mutual partnership to support the development and commercial demonstration of the country's first advanced reactor. • The TRi-energy partnership provides the framework for the team's deployment of 4 Xe-100s under the DOE's ARDP. • The TRi-energy will also enable Energy Northwest and Grant County to meet the State of Washington's clean energy goals established under the Clean Energy Transformation Act to deliver 100% carbon-free electricity by 2045.

Competitive Advantage

energy

Xe-100 Advantage: Technical Innovations

- The main advantages for the Xe-100 lie in the UCO fuel which allows:
  - Thermodynamic optimization and therefore a higher core power density
  - Fuel burnup increase from 90,000 MWd/t_{HM} to about 168,500 MWd/t_{HM}
    - Increased fuel utilization of around 85% per t_{HM}
    - Proportional reduction in spent fuel volume
    - Reduction in cost of fresh and spent fuel management
  - Better fuel utilization impacts economics positively
- The smaller RPV has the following advantages:
  - Road and rail transportable
  - Lead times for large forgings reduced
  - Reduced construction costs due to smaller crane requirements
  - Overall plant cost reduction



Xe-100 VS HTR-PM

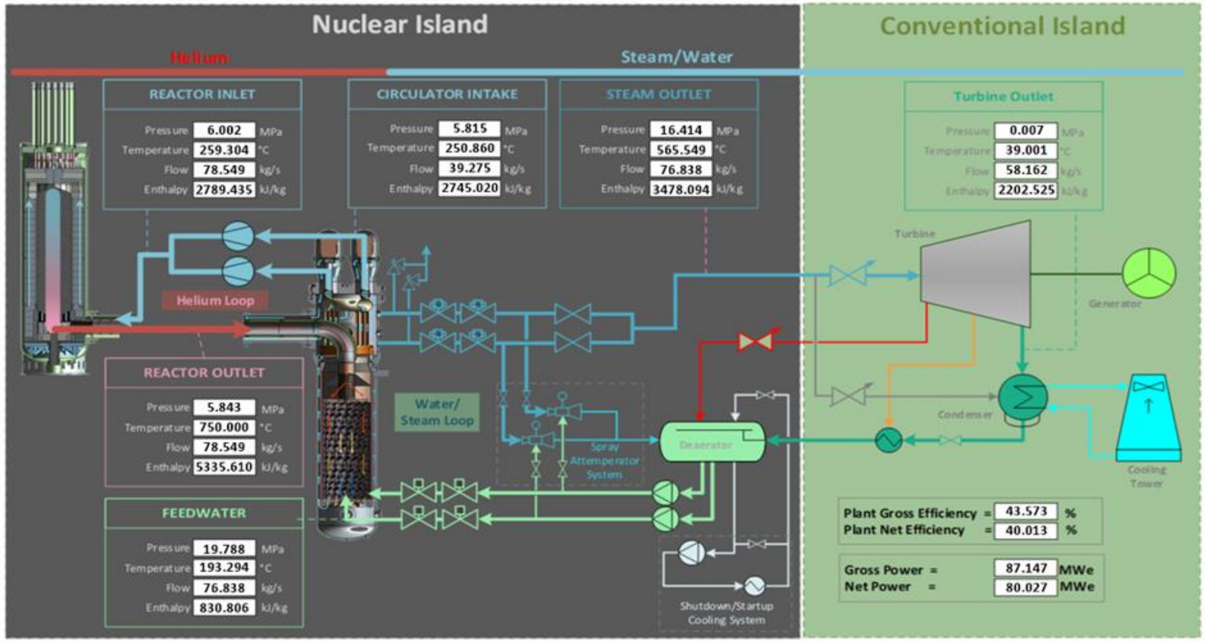
Innovative Control Approach

- X-energy has developed an Integrated Modular Automatic Control (IMAC) system that controls the plant using specific operation modules:
  - Startup module
  - Load following module
  - Shutdown module

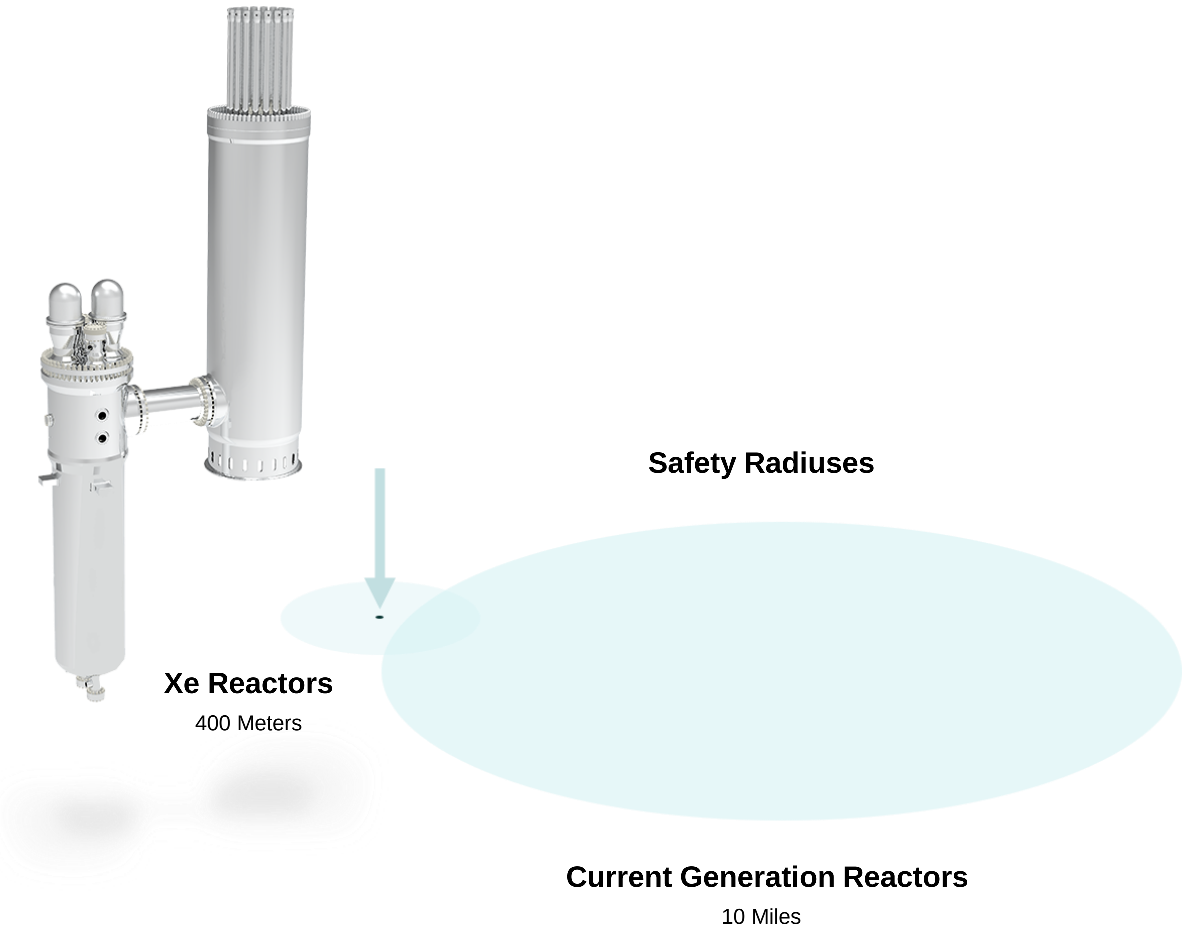
- IMAC enables the plant controller to ensure that all parameters are within the required limits before initiating the next step in the operational maneuver and therefore significantly reduces the workload on the operator and reduces the possibility of operator error

- The table below shows a typical operational table with key control variables for the load following module:

Controlled Variable	Set point	Manipulated Variable
Steam Generator Inlet Temperature	750°C	Control Rod Position
Main Steam Pressure	16.5 MPa	Helium Circulator Speed
Main Steam Temperature	565°C	HP Feed pump Speed
Electrical Load	40 – 100%	Turbine Throttle Valve Position



Smaller Footprint – Safety Case Dictates the Site Boundary



Xe-100 does not need additional systems to ensure safety. All safety functions are intrinsic to the design.

Current-generation reactors require 10 times as many safety systems as our Xe-100—operator action, water pumps, back-up electric power, etc.—to prevent a reactor from melting down in an emergency scenario.

Why is this important?

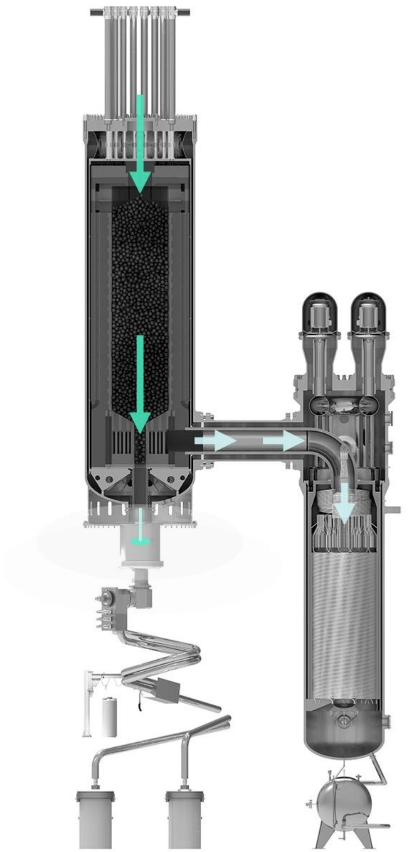
- Uncomplicated layout utilizing natural features to ensure safety means no need for complex safety systems, resulting in lower capital costs.
- Simple control system with only 4 variables allows for more automated operations & fewer personnel.
- Turbine generator can be air- or water-cooled—affording geographic siting flexibility.

Allows siting locations/applications unavailable to today's nuclear reactors.

We are ready for the market today

- X-energy has performed a bottom-up costing on nearly all systems and component of the Xe-100.
- Cost estimates are backed by quotes and industry estimates for >95% of the Xe-100 cost items.
- Focus is provided by multi-level Pareto analyses to help identify the most significant cost areas, as well as for systems and components.
- Full-scale requests for proposal were sent to top international manufacturers and suppliers for the identified systems.
- Overnight costs and LCOE for the Xe-100 have been estimated for FOAK and NOAK plants using both the:
    - Air-cooled condenser system; and
    - Wet-cooled condenser system.

Ready for market at a competitive cost



TRISO-X enables the Xe-100 to:

1. Be walk-away safe;
2. Have fewer components (eliminating high-cost traditional safety systems);
3. Increase predictability for costs and accelerate descent down the cost-curve toward NOAK;
4. Accelerate licensing for the first commercial Gen-IV advanced reactor to be deployed in the West;
5. Decrease the overall plant footprint;
6. Allow for truly modular deployment (capturing revenue from one unit while the second is deployed); and
7. Provide high quality steam to enable the decarbonization of industrial processes; and
8. Scale to meet the global market need for clean, reliable, and flexible nuclear power.

Why is this important?

We will deliver Gen-IV at a cost well below $60/MWh and in less than five years from order.

Conclusions

Opportunity

Never before has there been such a crossroads of need, opportunity & ability to disrupt the energy industry.

X-energy: a transformative approach to nuclear energy.


energy
empowering earth
Clean • Safe • Secure • Affordable