X-energy and the Xe-100

DC ANS April Meeting

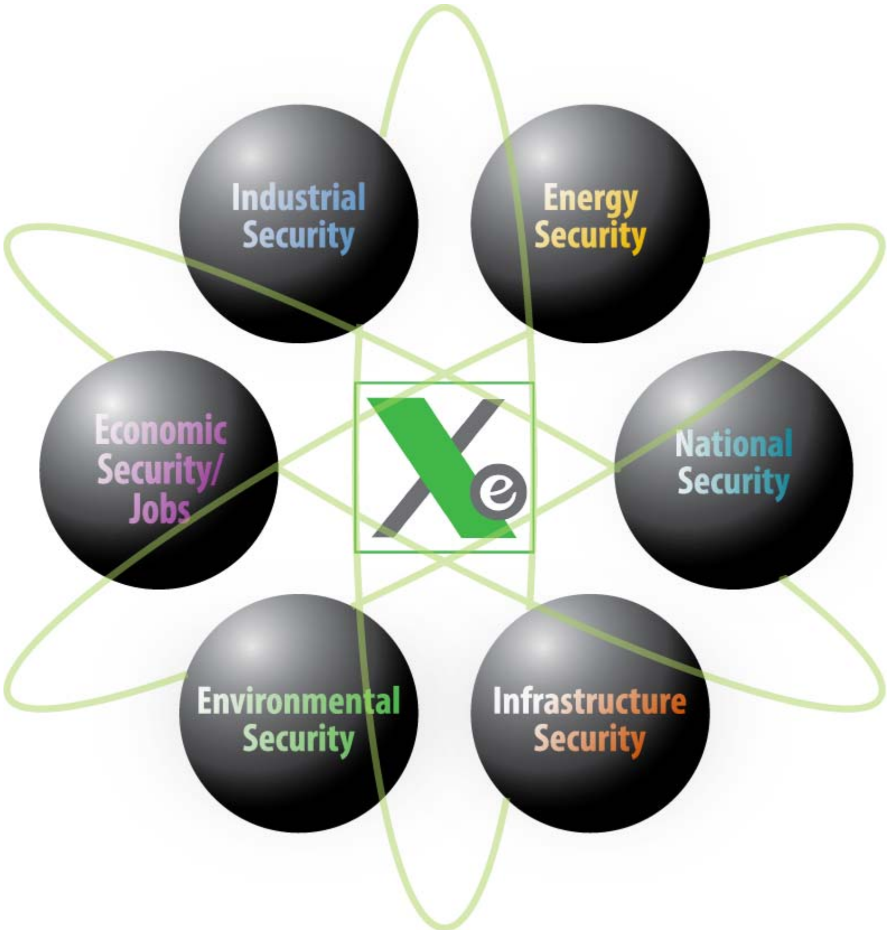
April 5, 2017

About X-energy

Harlan Bowers

Xe-100: Providing a Secure Future

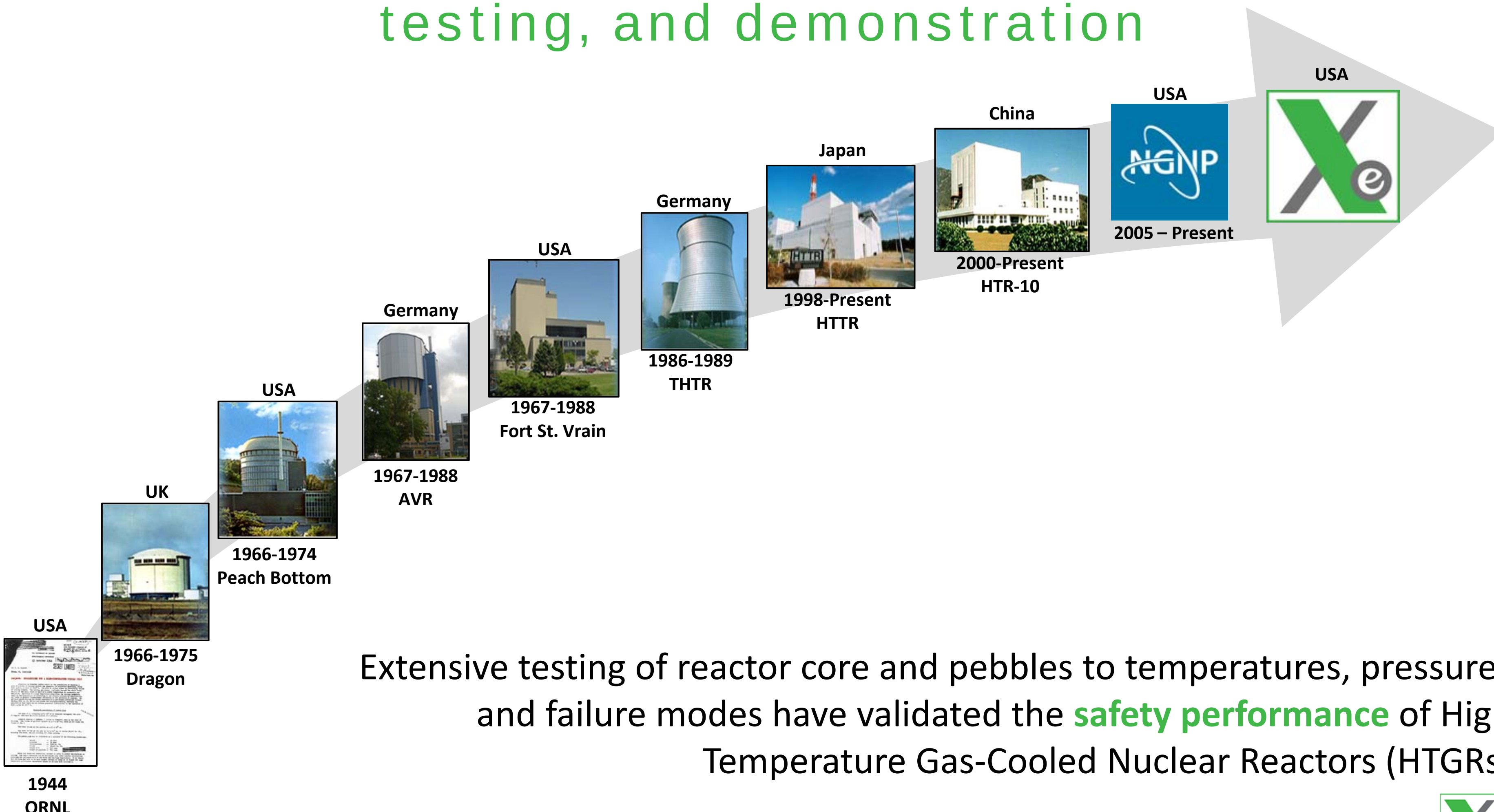
X-energy is developing an innovative nuclear power plant design solution, the Xe-100 and U.S.-made, proliferation-resistant fuel, which provides security sustainability for the global energy and process heat markets



> *"I am convinced that advanced reactors will become the backbone of our energy mix as we move through this century and develop clean carbon-free energy. President Kennedy once said that we are in a space race and my work with NASA reflects the progress he had hoped for.*
>
> *Today, I believe we are in an energy race. Providing clean energy across the world is my vision for X-energy and I believe that clean, safe, reliable nuclear energy is necessary to making this possible."*
>
> Dr. Kam Ghaffarian, Founder and Chief Executive Officer, X-energy

Innovating on a Proven Foundation

The Xe-100 is a revolutionary design for a nuclear reactor that builds on over 70 years of research, testing, and demonstration



Extensive testing of reactor core and pebbles to temperatures, pressures and failure modes have validated the **safety performance** of High Temperature Gas-Cooled Nuclear Reactors (HTGRs)

Reimagining Nuclear Energy

X-energy is reimagining nuclear's role in solving tomorrow's energy challenges

- Founded in 2009 out of Dr. Ghaffarian's desire to address the world's most serious energy challenges and make a lasting contribution to clean energy technology in the U.S. and around the world
- Leverages expertise from SGT, Inc. (www.sgt-inc.com) – 2nd largest engineering services contractor to NASA, and another prominent company founded & managed by Dr. Ghaffarian. He is also leading several other high-technology companies (www.axiomspace.com and www.intuitivemachines.com)
- Funding of ~$32M committed through 2017 to the company
- Nucleonics team, led by Chief Nuclear Officer Dr. Eben Mulder, leverages experience from TRISO-based reactors around the world, including experience at AVR & THTR (Germany)

Dr. Kam Ghaffarian
Founder/CEO

"I began X-energy because the world needs energy solutions that are clean, safe, secure, and affordable. With so much at stake, we cannot continue down the same path."

-Dr. Kam Ghaffarian, Founder & CEO

U.S. Department of Energy Endorsement

DOE Cooperative Agreement

X-energy began activities July 1, 2016 on a 5-year, $53M cooperative agreement with the U.S. Department of Energy focused on:

- Furthering the Xe-100 reactor design
- Establishing pebble fuel manufacturing capability
- NRC engagement

Milestones Completed to Date

- Mechanistic source term development roadmap
- Structural graphite selection criteria summary
- Pebble matrix graphite analysis summary

First fuel form pebbles produced at ORNL, Fall 2016

Prototype mold and first pebble

X-energy Leveraging a Proven Team

5-year, $53M cost-share Cooperative Agreement

National Labs receive 40%

Idaho National Laboratory
Idaho Falls, ID

Oregon State University
College of Engineering
Nuclear Science & Engineering
Corvallis, OR

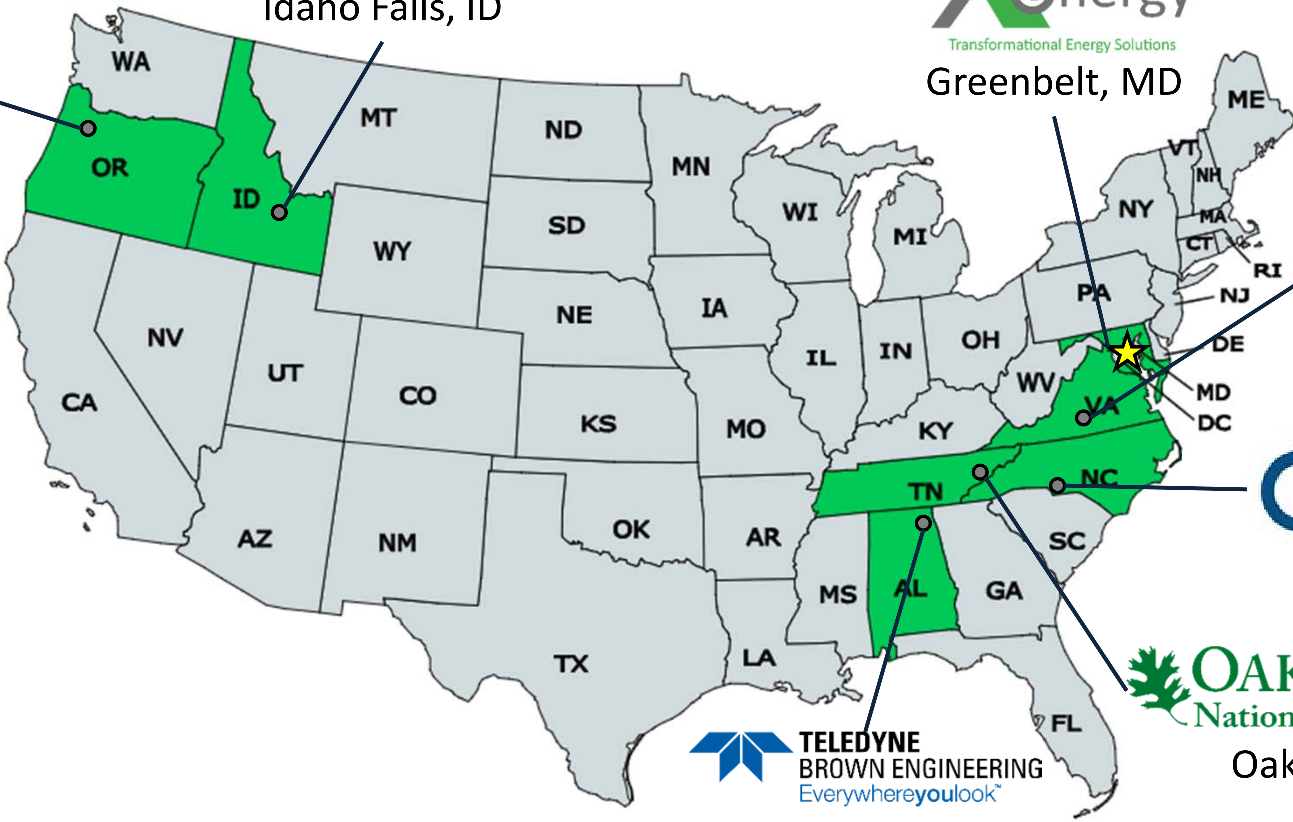
X energy
Transformational Energy Solutions
Greenbelt, MD

BWXT
BWX Technologies, Inc.
Lynchburg, VA

SGL GROUP
THE CARBON COMPANY
Charlotte, NC

Oak Ridge
National Laboratory
Oak Ridge, TN

TELEDYNE
BROWN ENGINEERING
Everywhereyoulook™
Huntsville, AL



Potential Customers

X-energy has identified three market segments with requirements that are aligned with the Xe-100's unique benefits:

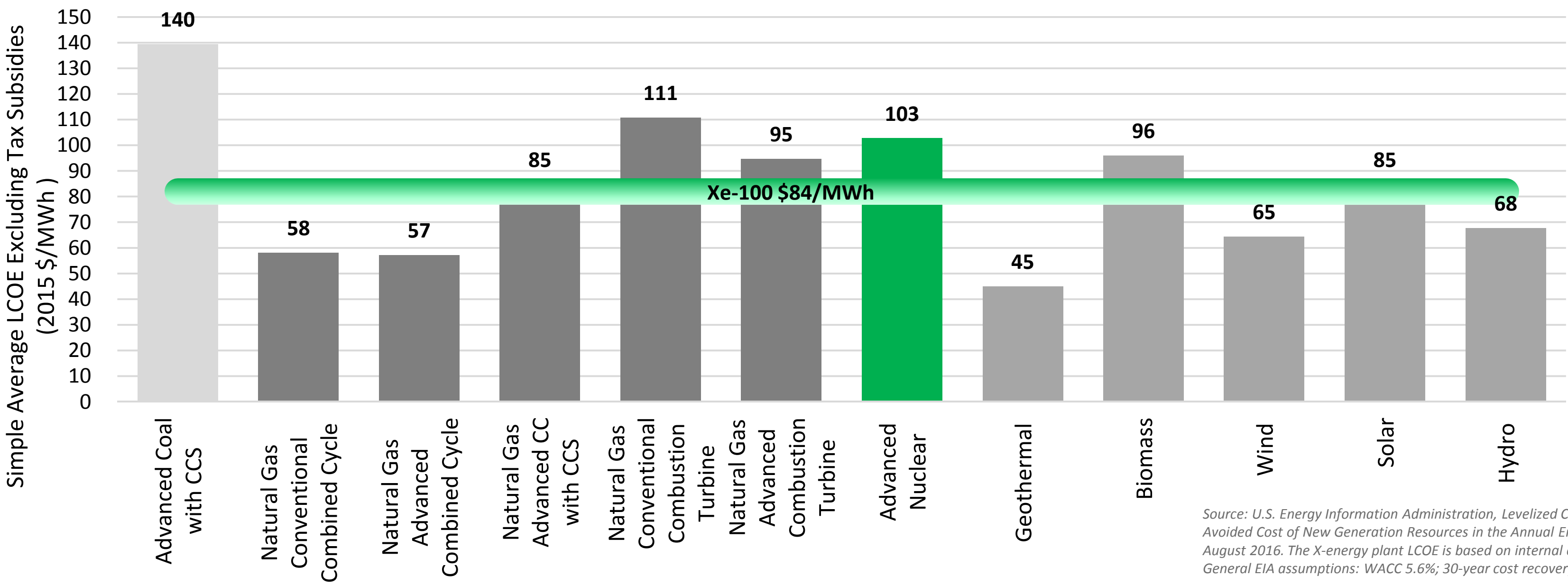
Compact, ultra-safe generation capacity that will replace retiring coal-fired power plants in line with federal mandates

Nuclear power that can support high-temperature industrial and commercial applications for the first time

On-base, grid-dependent power source that achieves resilience and energy security while supporting federal emissions reduction goals

X-energy Strategy

- **Be first to market**
  - Leverage U.S. government (i.e., DOE funding for advanced reactor development), Canadian government and strategic partners to bring Xe-100 to the market by 2030
- **Leverage existing knowledge**
  - License existing HTGR technology where possible (subsystems, components, fuel)
  - Leverage past lessons learned (South Africa/Germany)
- **Simple Product design**
  - Technically simple to design and operate
  - Lowest possible plant/operational cost
- **LCOE competitive with alternative fuel sources**
  - Natural gas combustion turbines
  - Advanced nuclear
  - Coal
- **Obtain NRC "Gold Standard" for safety**



Source: U.S. Energy Information Administration, Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2016, August 2016. The X-energy plant LCOE is based on internal estimates. General EIA assumptions: WACC 5.6%; 30-year cost recovery period.

Partners Towards Deployment

DOE ARC Teammates

INL – Idaho National Laboratory

Oak Ridge National Laboratory

BWXT – BWX Technologies, Inc.

SGL Group – The Carbon Company

Teledyne Brown Engineering – Everywhereyoulook

OSU – Oregon State University – College of Engineering – Nuclear Science & Engineering

X-energy Industrial Partners

Burns McDonnell

Southern Nuclear

SGL Group – The Carbon Company

X-energy Advisory Committee

Ontario Power Generation

SCANA – Power For Living

Southern Nuclear

Exelon

Duke Energy

Dominion

The Xe-100: A Nuclear Sustainable Solution

Dr. Eben Mulder

Contents

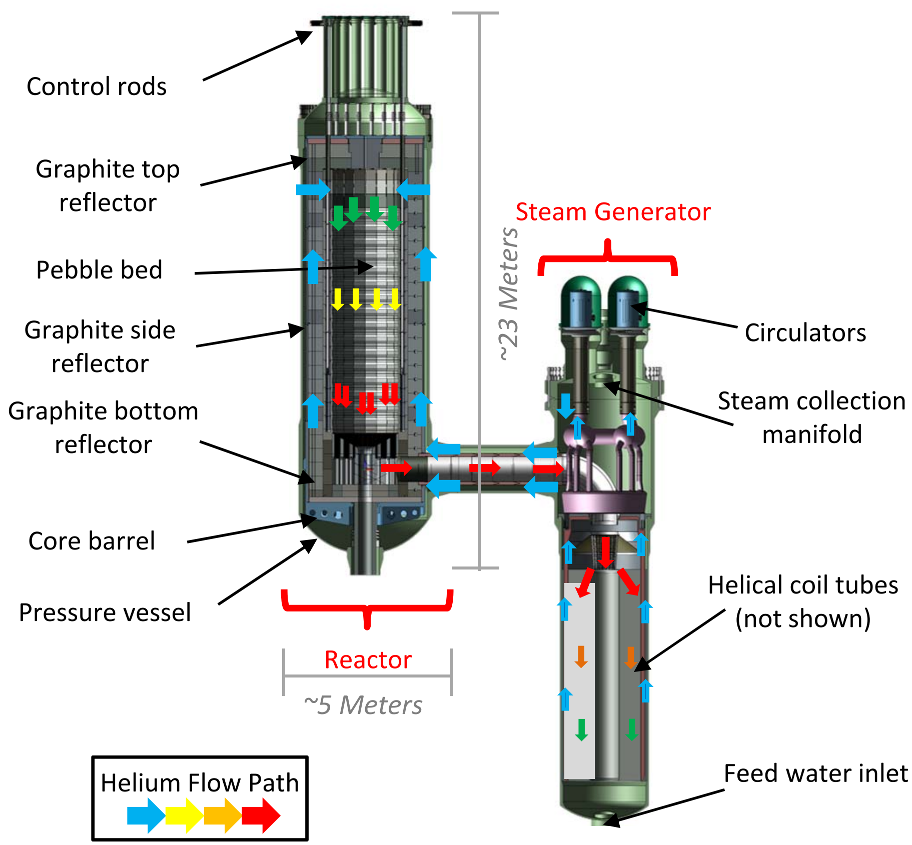
Definition of Sustainability

- One of the most often-cited definitions of sustainability is the one created by the Brundtland Commission, led by the former Norwegian Prime Minister Gro Harlem Brundtland. … ***development that "meets the needs of the present without compromising the ability of future generations to meet their own needs.“***

- Sustainability relates to the ***continuity of economic, social, institutional, and environmental aspects of human society, as well as the non-human environment.***

- Sustainability is therefore - ***exploiting natural resources without destroying the ecological balance of an area***

The Xe-100 Reactor



Xe-100 Reactor Specifications			
Thermal Output	**Steam Temperature**	**Steam Pressure**	**Electric Output**
200MW	565^{o}C	16.5MPa	~76MW

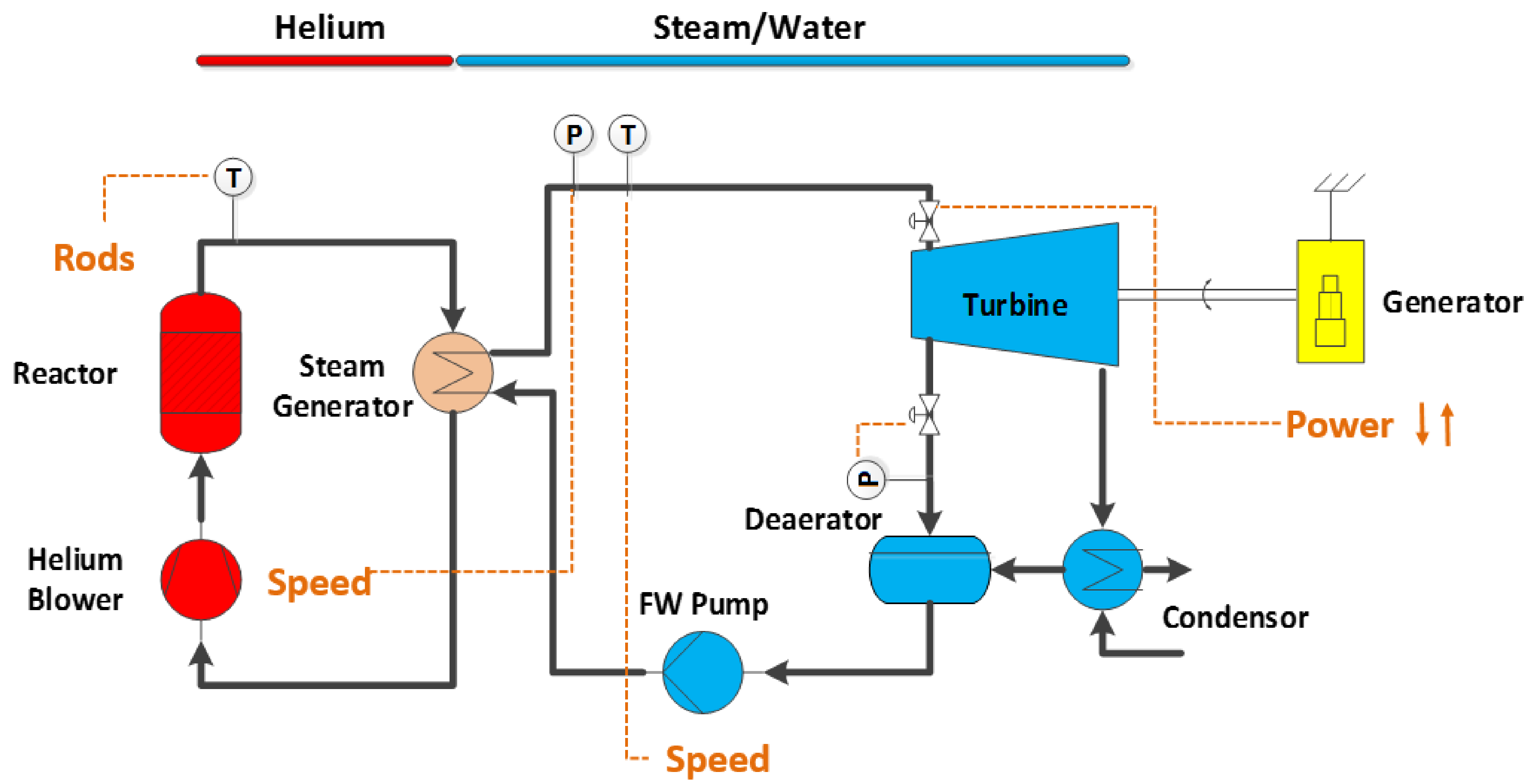
Technology

- The Xe-100 is a 200MWth/76MWe helium cooled power plant that features a 15.5% LEU fuel cycle
- Small size and modular construction result in relatively low cost – single reactor plant of <$1B, expandable to 8 reactors on plant site
- All components sized to maintain road transportability to reach remote locations and maximize siting flexibility

STATUS

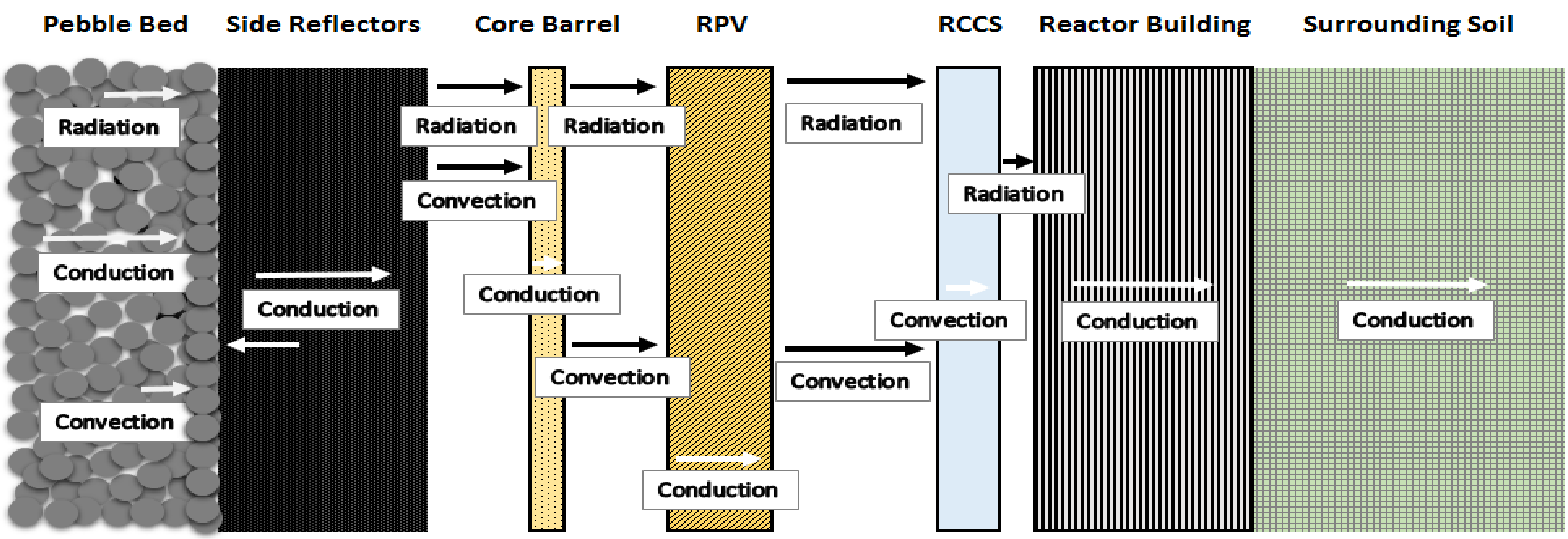
– Began Conceptual Design
– Conclude Concept Design by 2018

Electricity or Steam Production

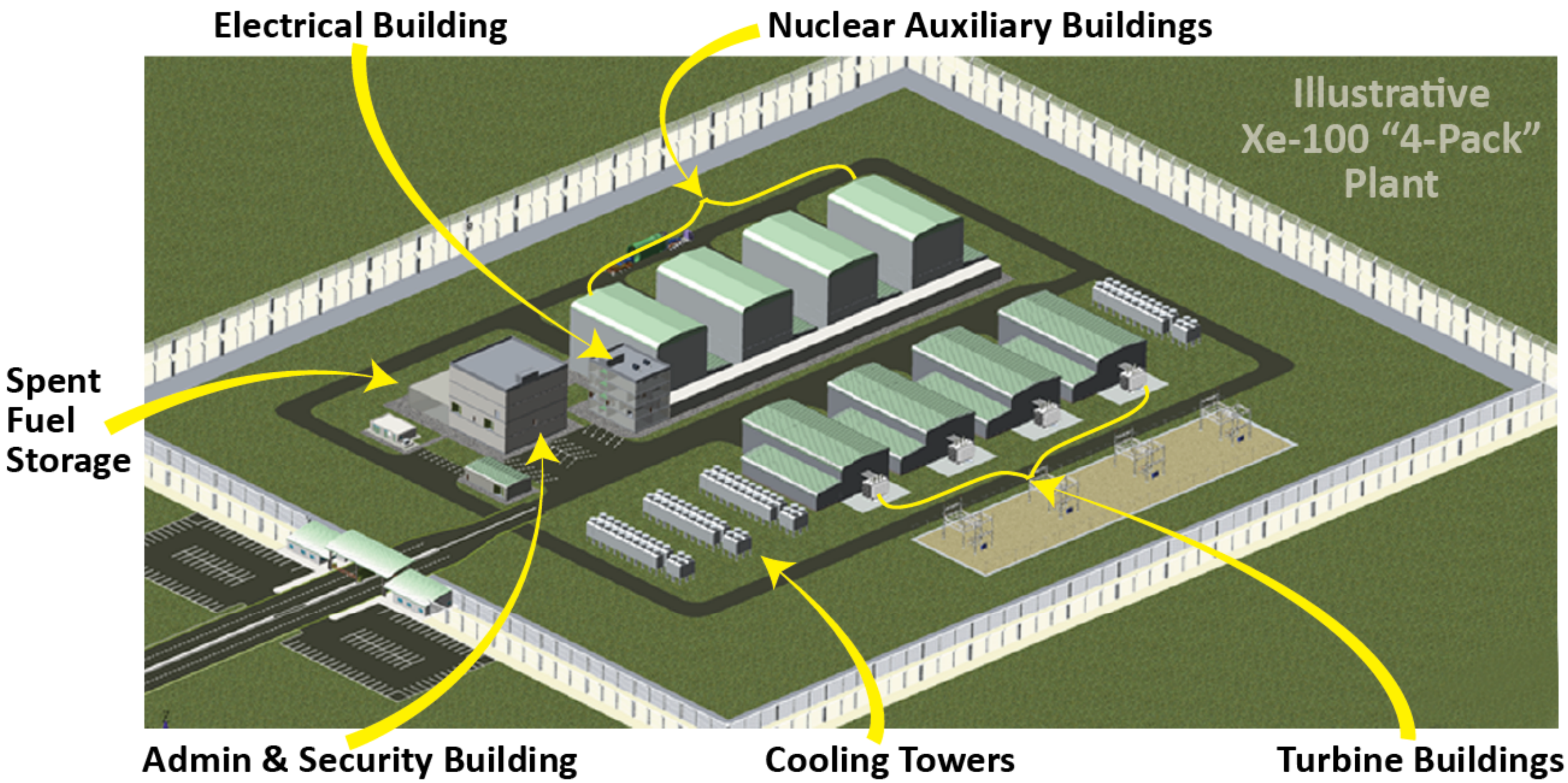


Passive Heat Removal

- During a loss of forced cooling, with or without helium pressure, heat from the core is passively removed via:
  - Conduction through the pebbles and side reflector
  - Convection and thermal radiation to the core barrel and Reactor Pressure Vessel (RPV) to the reactor cavity cooling system (RCCS)
  - Normal heat removal through RCCS by natural convection
  - Conduction through the concrete to the environment if the RCCS is not available



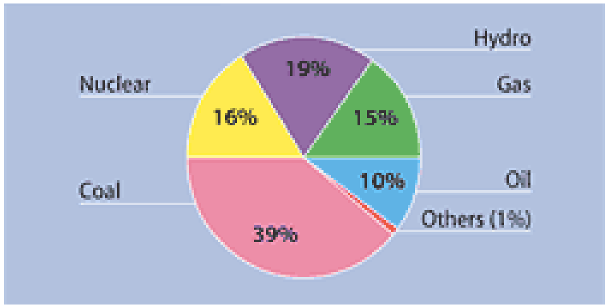
Xe-100 Plant Layout

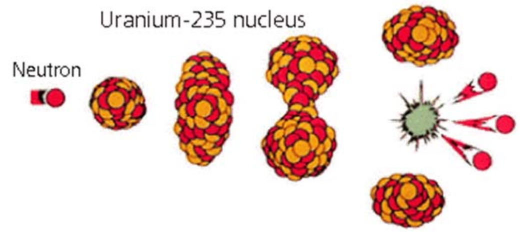


- **Secure:** underground reactor layout is possible
- **Scalable:** allows for build-out based on power demand
- **Small:** can be built on 10 acres of land and allows for grid independence
- **Safe:** smaller EPZ allows for building close to existing infrastructure

Layout is not to scale

Issue #1: Economics





U.S. average levelized costs (2013 $/MWh) for plants entering service in 2020[1]

Plant type	Capacity factor (%)	Levelized capital cost	Fixed O&M	Variable O&M (including fuel)	Transmission investment	Total system LCOE	Subsidy[2]	Total LCOE including Subsidy
Dispatchable Technologies								
Conventional Coal	85	60.4	4.2	29.4	1.2	95.1		
Advanced Coal	85	76.9	6.9	30.7	1.2	115.7		
Advanced Coal with CCS	85	97.3	9.8	36.1	1.2	144.4		
Natural Gas-fired								
ConventionalCombined Cycle	87	14.4	1.7	57.8	1.2	75.2		
Advanced Combined Cycle	87	15.9	2.0	53.6	1.2	72.6		
Advanced CC with CCS	87	30.1	4.2	64.7	1.2	100.2		
Conventional Combustion Turbine	30	40.7	2.8	94.6	3.5	141.5		
Advanced Combustion Turbine	30	27.8	2.7	79.6	3.5	113.5		
Advanced Nuclear	90	70.1	11.8	12.2	1.1	95.2		
Geothermal	92	34.1	12.3	0.0	1.4	47.8	-3.4	44.4
Biomass	83	47.1	14.5	37.6	1.2	100.5		

1. One fission produces about ***200 MeV*** *versus* One molecule of CO_2 formed releases about ***4.2 eV*** – i.e. almost ***50 million times smaller***
2. High efficiency – High temperatures in a ***Rankine cycle***
3. Inherent safety – Safety guaranteed by the Physics
4. Xe-100 can provide – Electricity; Heat; Hydrogen; Synthetic fuels
5. Distributed generation – Variable size; Continuous fueling; Low cooling water needs; ***Suitable for developing countries***
6. Mass production – Short construction lead times; Modular

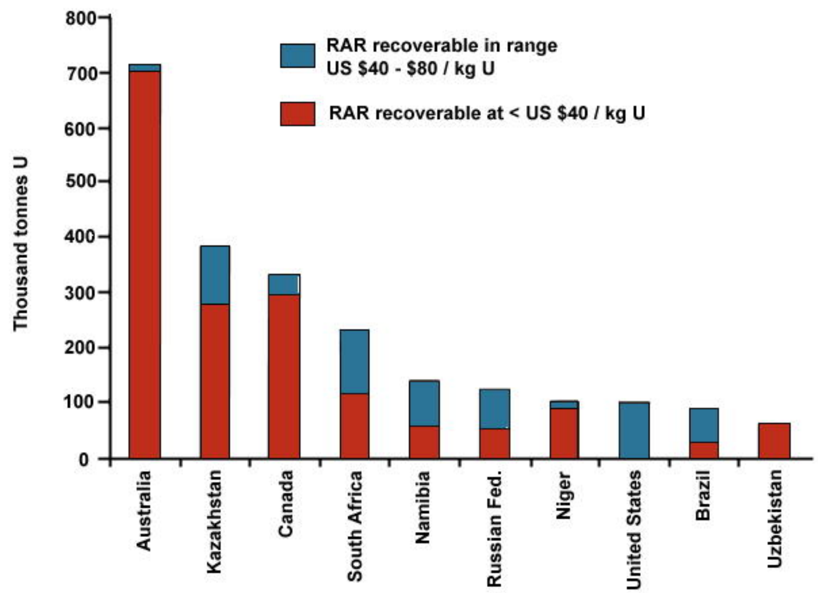
Issue #2: Security of U/Th supply

- Current usage is about 66,500 tU/a
- Considering 4.7 Mt worldwide – Supply for 70 years at the current rate
- As price and geological knowledge increase more sources would become economically viable – 10 Mt estimates supply 200 years
- Xe-100 can utilize a plutonium fuel cycle without change.
- A closed thorium cycle will dramatically save uranium. With a “fertile blanket” in a Prebreeder/Netbreeder design it is estimated that each ton of ore can yield 60 times more energy.

Note: Current supply rate is assumed! What if this premise changes!

Issue #2: Security of supply

High-grade ore - 2% U,	20,000 ppm U
Low-grade ore - 0.1% U,	1,000 ppm U
Granite	4 ppm U
Sedimentary rock	2 ppm U
Earth's continental crust (av)	2.8 ppm U
Seawater	0.003 ppm U

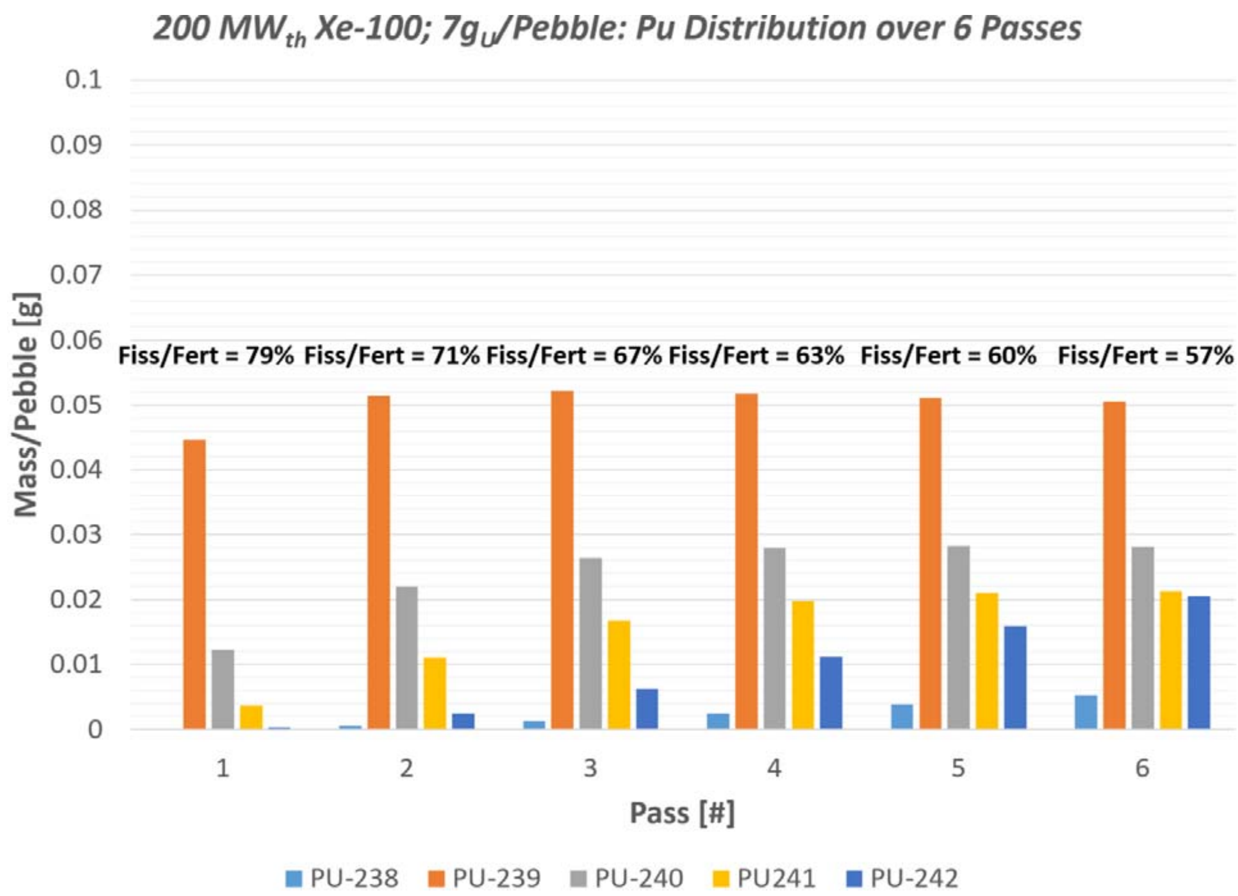


Issue #3: Proliferation Resistance

1. High burn-up – ***163,000 MWd/t$_{HM}$***
2. High ***in situ utilization*** of fissile plutonium produced
3. Xe-100 can be used as a plutonium dispositioning facility
4. ***Closed circuit*** fuel handling

Issue #3: Proliferation Resistance

- Odd isotopes are fissile and potentially weapons material
- Even isotopes are fertile and add proliferation resistance when included in discharge
- Xe-100 fuel cycle (Multi-pass) renders Pu isotopic mixture useless for nuclear proliferation



Issue #4: Emissions

1 pebble:
7g with 15.5 wt% enriched Uranium,
27.4 MWh

2.66 metric tons of coal

8.0 metric tons of CO_2

about 0.8 metric tons of ash

Ref: EIA https://www.eia.gov/tools/faqs/faq.cfm?id=667&t=2

Issue #4: Emissions Comparison

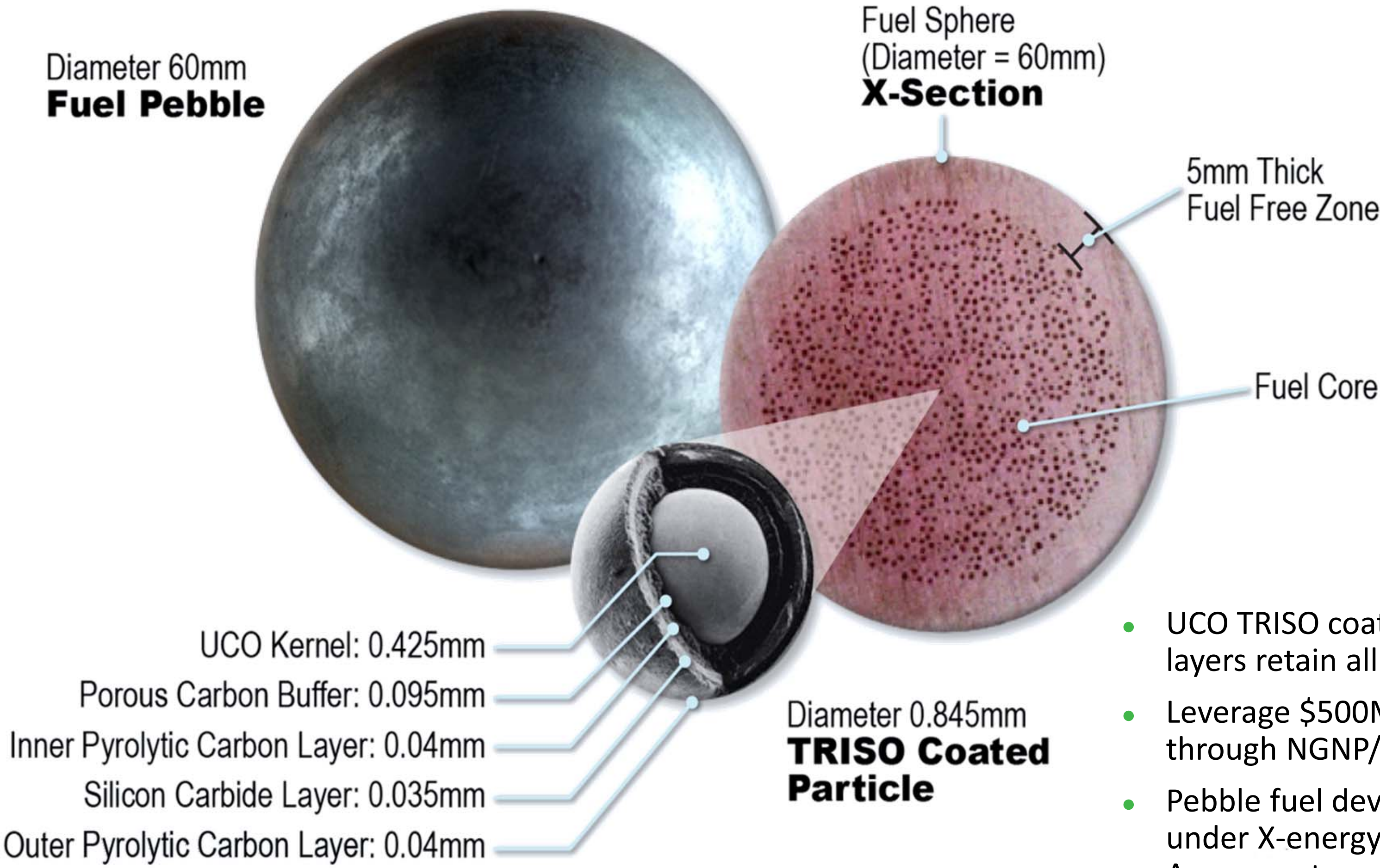
Typical 618 MW Coal-Fired Power Unit

- CO_2 = 9,125,000 tons per year
- SO_2 = 746,198 tons per year
- NO_2: 37,148 tons per year
- N_2O: 113 tons per year
- Ash = 1,155,833 tons per year

9 x Xe-100

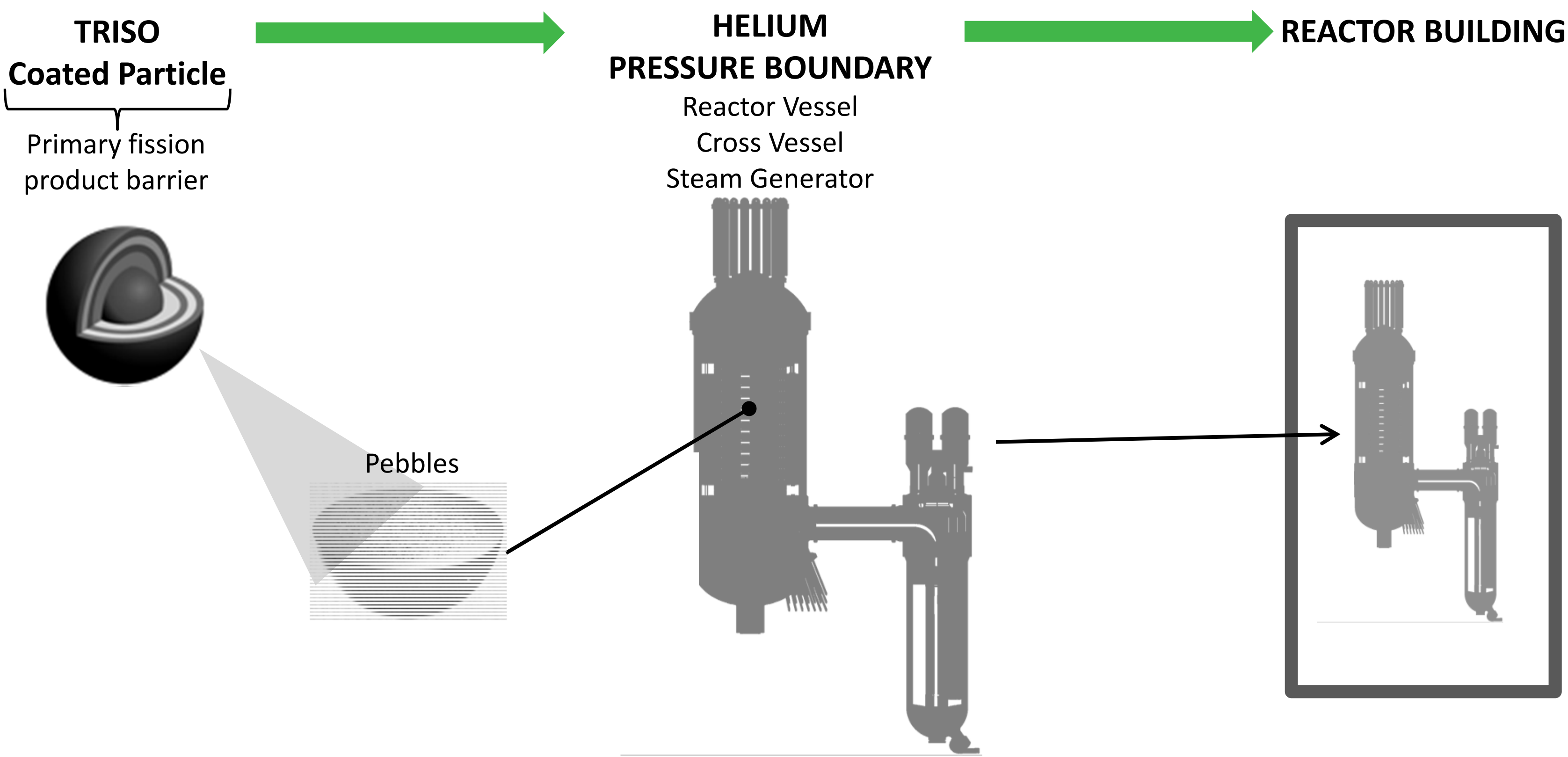
- CO_2 – None
- SO_X – None
- NO_X – None
- N_20 – None
- Ash – None
- 118 t of radio-active pebbles per year (11 t high level waste)

Fuel is the Key to Unsurpassed Safety



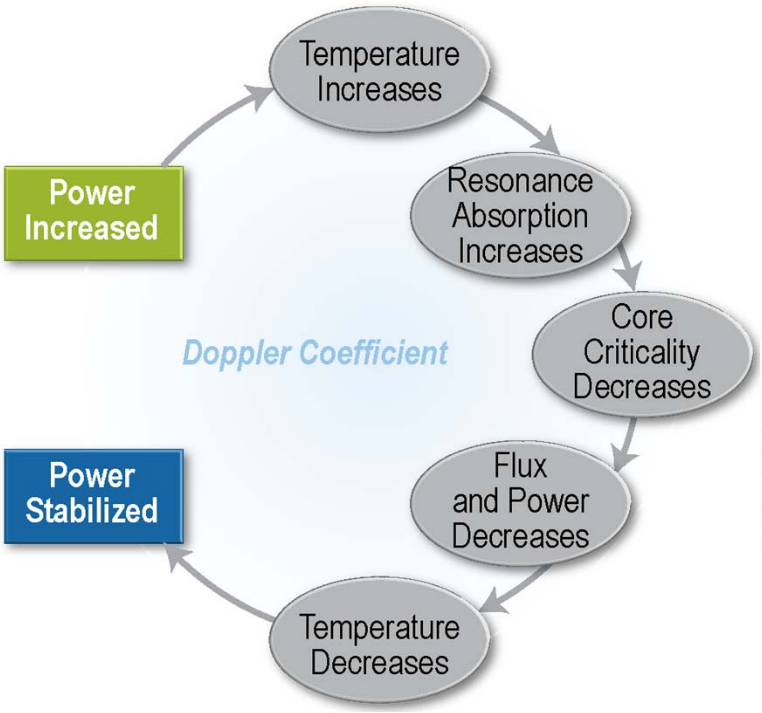
- UCO TRISO coated particles in carbon layers retain all fissile products
- Leverage $500M investment by DOE through NGNP/AGR programs
- Pebble fuel development is a key thrust under X-energy's DOE Cooperative Agreement
- Lab scale fabrication processes will lead to pilot scale production capacities

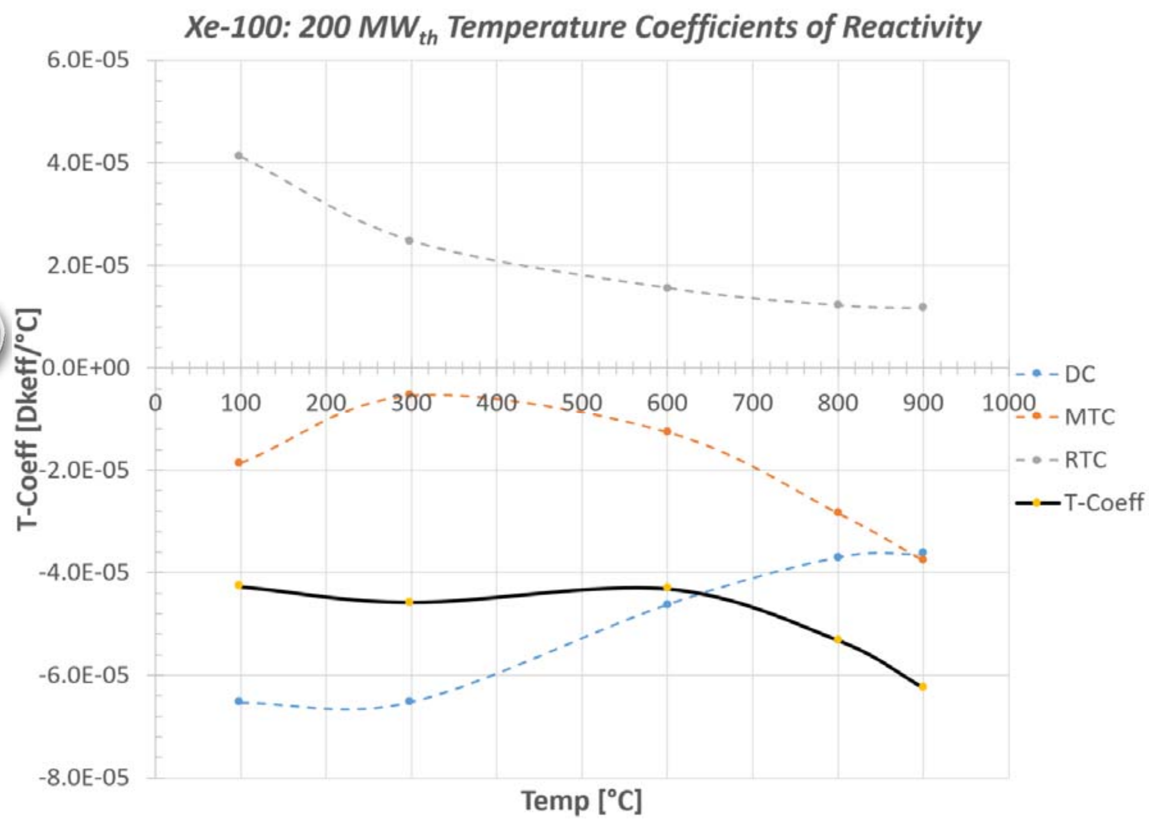
Issue #5: Concept of Functional Containment



Issue #5: Negative Temp. Coefficient

If the temperature increases, the nuclear chain reaction dies down due to overall negative temperature coefficient





Issue #6: Waste

1. Waste minimized due to ***high efficiency*** and ***distributed generation***
2. High Level Waste (HLW) is ***stored on-site*** for interim
3. HLW is fully contained, ***highly regulated***
4. HLW will ***not leach out*** in the biosphere – Pebble packaging
5. ***Actinide incineration*** in X-Energy motivated by:

The aim is to destroy LWR TRUs

- DOE-NE
- Reprocessing and burning in fast reactors

Goal: 10-100x reduction of Yucca Mtn. storage

Issue #6: Xe-100 HLW Position

Waste produced by an Xe-100 power plant:

- Generates 200 MW_{th} continually over 60 years with an availability > 95%
- Creates about 0.008 g of HLW per kWh
- Over its lifetime it would be producing about 9.99E10 kWh
- Thus 778 metric tons of HLW (radioactive pebbles) is produced during the lifetime of the plant

Handling of the HLW for the Xe-100:

- Each 7 g of HLW is packed in 196 g of a graphite package (the fuel sphere)
- The spent fuel spheres are stored in spent fuel storage casks on-site for the interim (more than the lifetime of the reactor)
- Then the spent fuel could:
  - Be left at subgrade, secure interim storage facilities for as long as need
  - Be transported to a licensed site for deep geological disposal in boreholes

Conclusions

- The case for ***nuclear sustainability*** has been proven:
  - Nuclear energy provides in ***¼ of the OECD current demand***
  - Proven, mature technology with more than ***12 000 reactor years*** of operation in the OECD
  - ***Safety*** is proven
  - R&D underway in many countries ***to enhance safety, proliferation resistance, to reduce uranium consumption and waste production, and to increase competitiveness of nuclear energy***, often via international collaborations

- Indicators for nuclear energy:
  - ***Safety***
  - ***Reliability***
  - ***Competitiveness***
  - ***Efficient use of natural resources***

Conclusions

- For the U.S. to maintain its ***technology leadership position*** it needs to focus on:
  - ***Training of nuclear professionals*** in both conventional and GEN IV type plant
  - Switch to ***mode-2 R&D*** in:
    - Developing and implementing calculation techniques and methodologies
    - Develop reactors "fit-for-purpose" based on pebble bed technology
    - Develop advanced fuel cycles – ***Pu/MA incineration***; Open/closed ***Th cycles***
    - Develop high-temperature ***materials***
    - ***Enhancement of fuel*** coatings for higher temperature applications

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