Overview of X-Energy's 200 MWth Xe-100 Reactor

National Academy of Sciences

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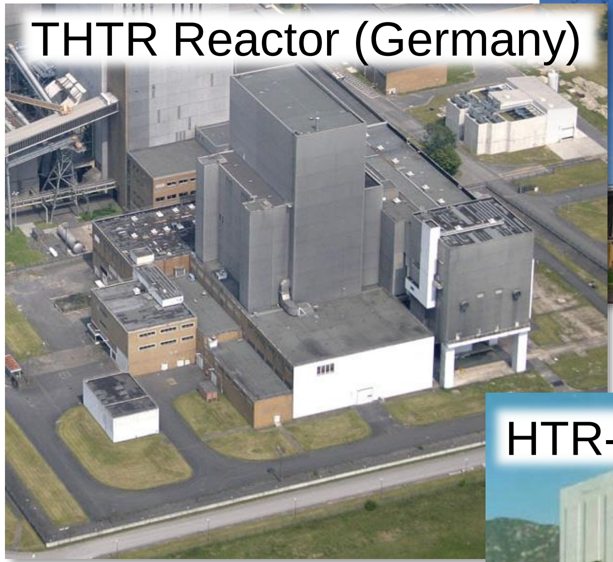
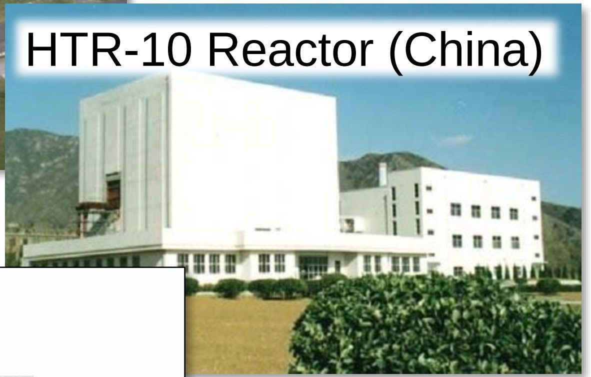
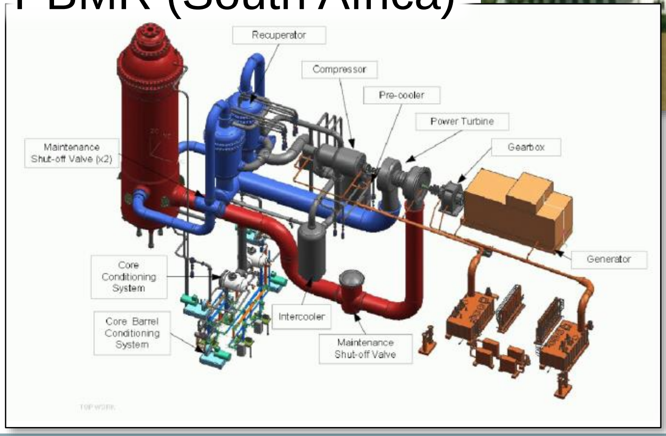
Advanced Reactor Design

Xe-100 Technology

- The HTGR is the most mature GEN IV advanced reactor technology, both in terms of Reactor and Fuel
- X-energy did not start from scratch – We benefit from a rich history of design development, testing and operation of Pebble Bed Reactors across the globe
- R&D requirements were identified in 2015 and were fully funded through to July 2021 by DOE ARC program (currently 80% complete)
- The Xe-100 design is a cutting-edge design evolution that can be deployed in the next 5-6 years while providing a cost competitive, low risk, carbon free, versatile energy source

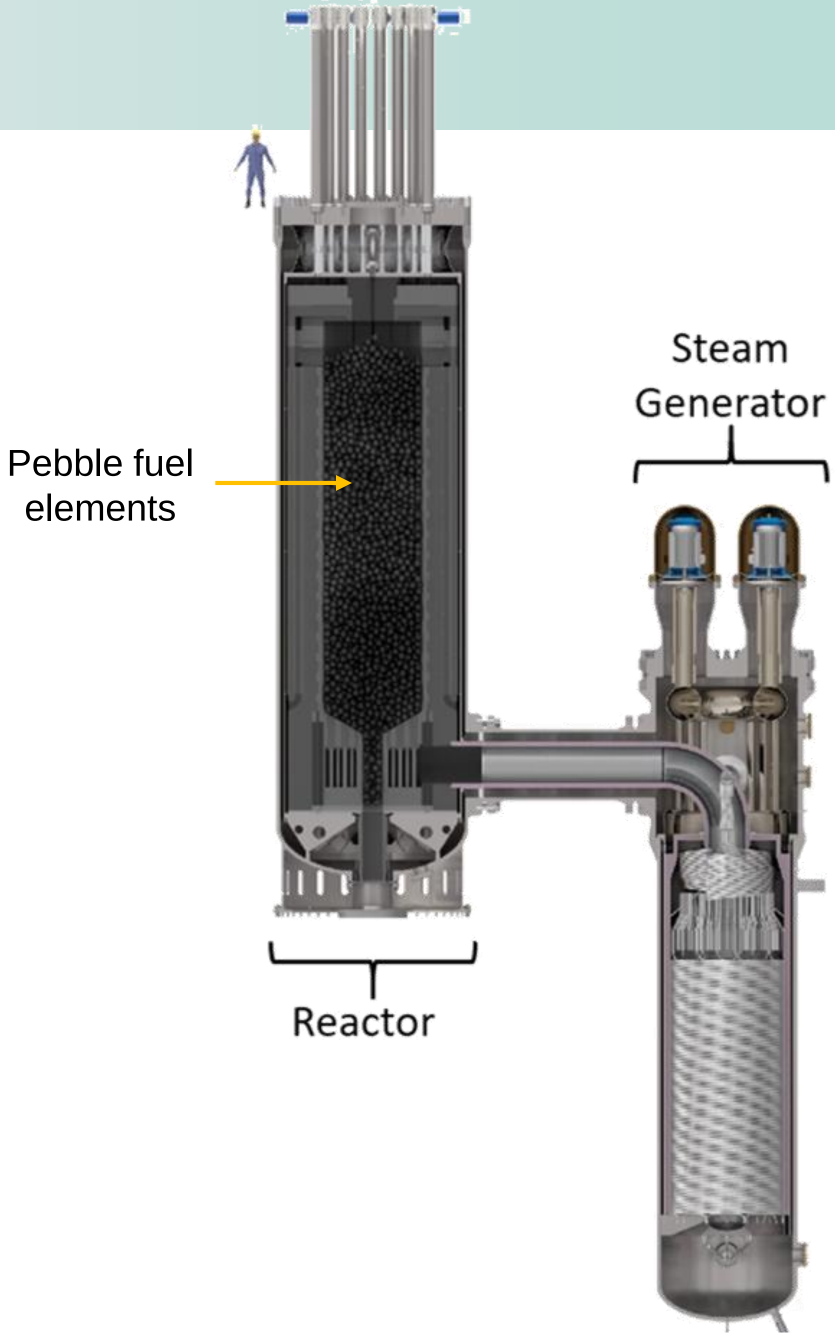






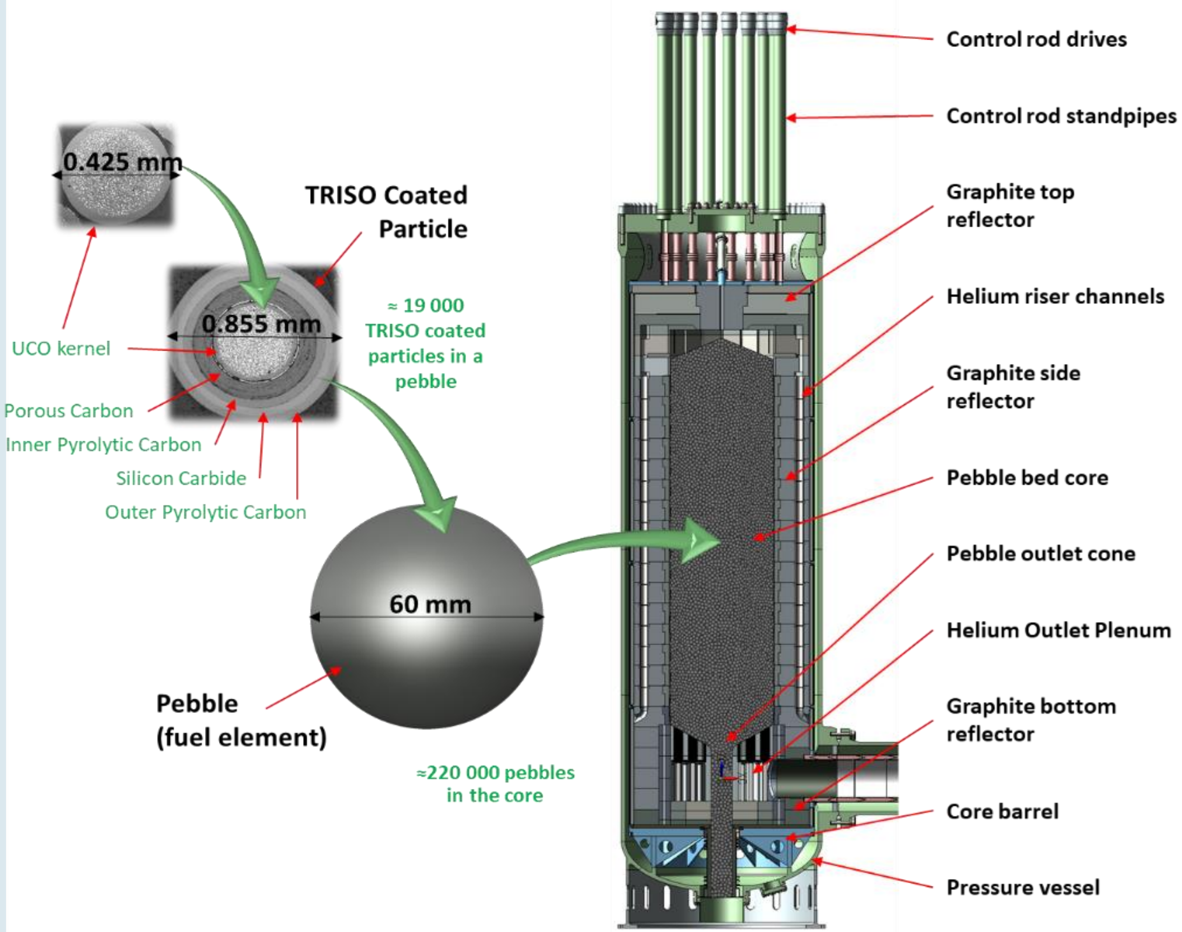
The Xe-100 Design Solution

- Proven High Temperature Pebble Bed Reactor – Derived from +50 years of design and development – Significantly reducing costs enabling competitive deployment
- Proven fuel technology (US DOE Advanced Gas Reactor irradiation program)
- Versatile Nuclear Steam Supply System (NSSS) deployable for electricity generation and/or process heat applications
- Conservative design not requiring new material development and or code cases (saving 15 – 20 years)
- Steam pressure and temperature designed to provide steam to multiple Commercially Off The Shelf Steam Turbine / Generator sets (typically those used in Combined Cycle Power Plants)



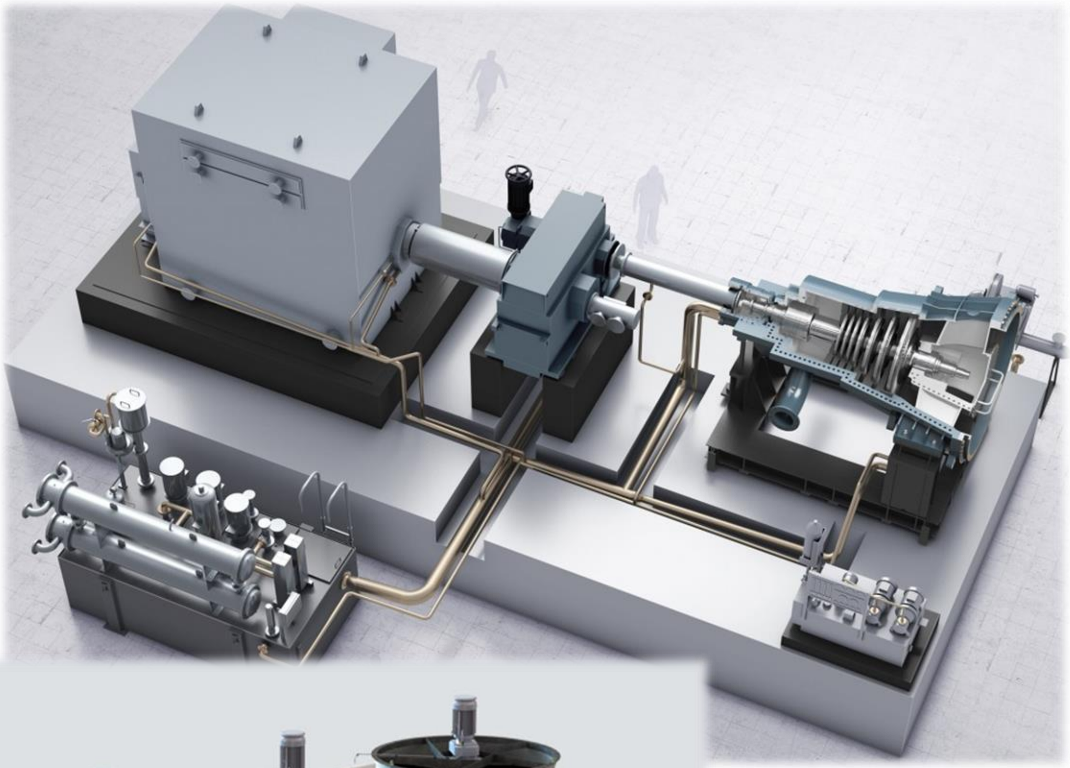
Basic Core Design Parameters

o	Maximum thermal power rating	200	MW
o	Effective core volume	41.56	m^3
o	Core average power density	4.81	MW/m^3
o	Effective core height	9.18	m
o	Pebble passes	6	times
o	Helium inlet / outlet temperature	260 / 750	°C
o	Helium flow rate (assume 9.6% bypass)	71.1	kg/s
o	Inlet pressure	6.0	MPa
o	Side reflector thickness	900	mm
o	Reactor core barrel thickness	35	mm
o	Reactor pressure vessel OD	4.78	m
o	Reactor pressure vessel thickness	95.0	mm
o	Reactor pressure vessel height	16.4	m
o	RCSS = RCS + RSS absorber rod banks	9 / 9	rods



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



Standard Technology Offering (4-Reactor Plant)

RB: Reactor Building
TB: Turbine Building
AB: Admin Building
HVY: High Voltage Yard
CR: Control Room
EB: Electrical Building
CT: Cooling Towers
HE-SFS: High Energy Spent Fuel Storage
ISFS: Intermediate Spent Fuel Storage
WS: Work Shop
CST: Condensate Storage Tanks
HeST: Helium storage
LW: Liquid waste
ST&IC: Stores and - Inventory Control
RW: Rad. Waste Building

Standard power plant consists of four independent Reactor Modules (Reactor and Steam Generator)

Each reactor module is connected to its own Steam Turbine/Generator

Single shared control room with only three operators

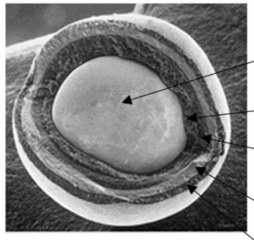
Resource Utilization

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



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

History

HTGR

1954	P Fortescue
1956	R Schulten

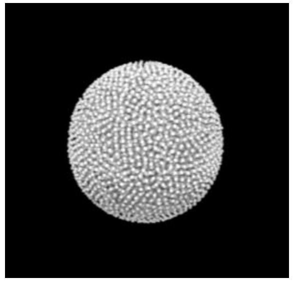
History of coated particles:

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	

Prototype pebble mold



Innovative visualization of particles in pebble

First fuel form pebbles produced at ORNL, Fall 2016

DOE's Dr. Rita Baranwal tours TRISO-X Pilot Lab

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

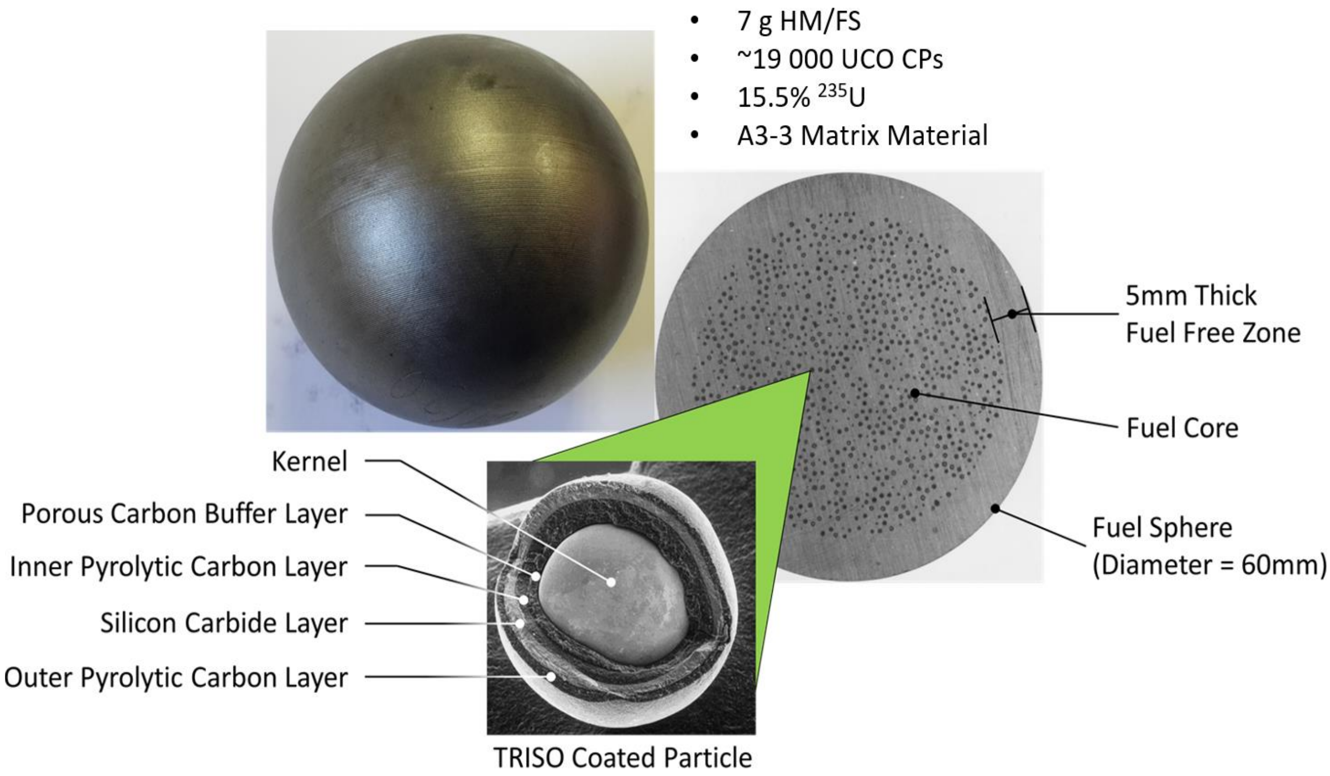
Pebble Fuel Design Data (Equilibrium Core)

- Fuel kernel:

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

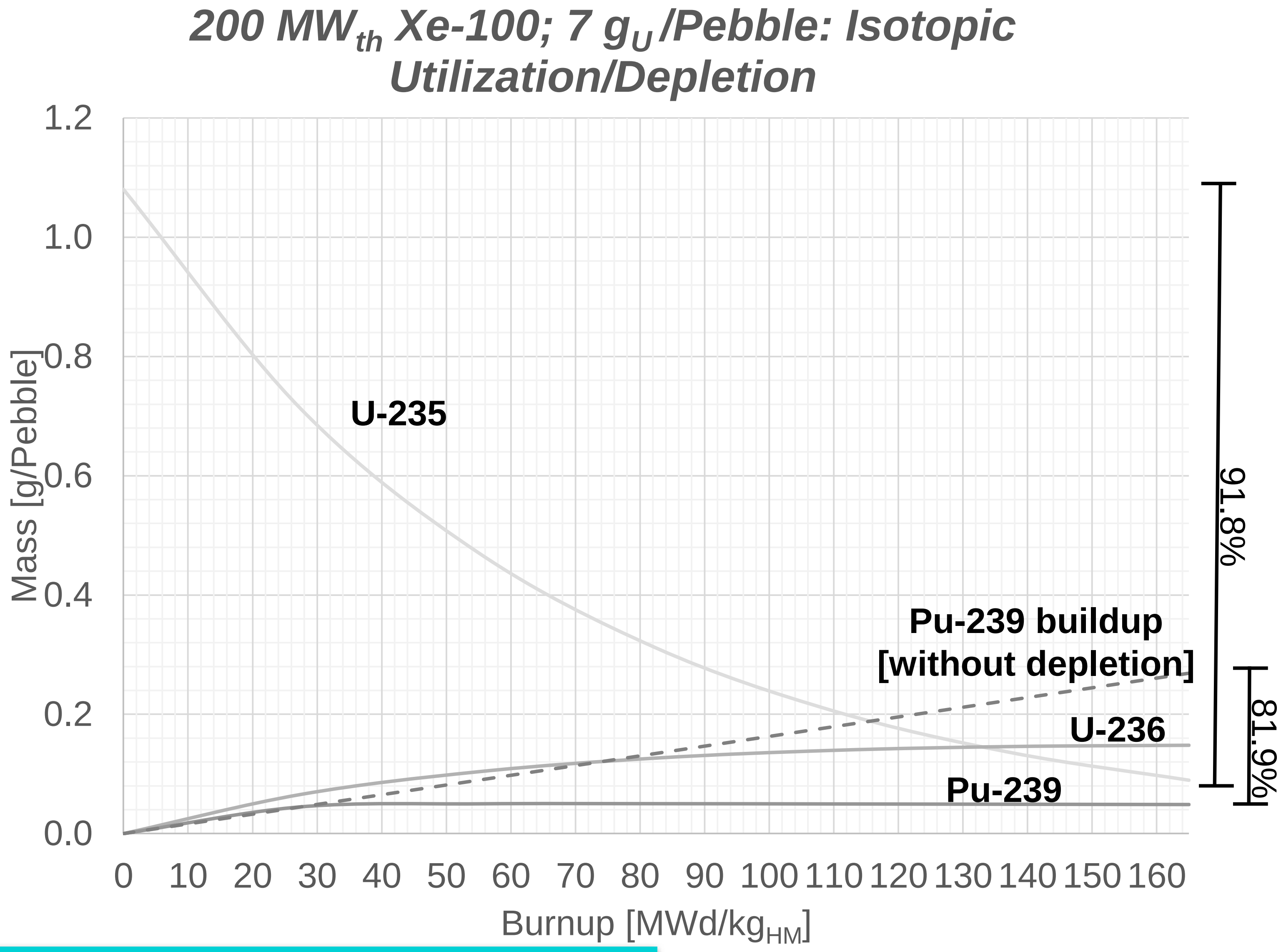
- Coatings:

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



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

Advanced Fuel Cycle

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
- Fast fission of the uranium-238 present in the fuel makes a minor contribution to power generation (0.5% of total power)
- This results in breeding due to neutron capture where various plutonium isotopes are formed
- In the Xe-100 about 82% of the bred plutonium is consumed in-situ – The bred plutonium is responsible for approximately 35% of total power in the equilibrium core

Nuclear Waste Management & Disposal

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High-Level Waste Comparison: Xe-100 *vs* typical PWR

Xe-100	
200 MWt	
40%	
80	MWe
168,500	MWd/t_U (Burnup)
7	g_U/Pebble
60	mm dia. pebble
1.13E-04	m^3/pebble
0.855	mm dia. TRISO
3.27E-10	m^3/TRISO
41.56	m^3 core vol
170	pebbles/day/reactor
92,836	pebbles/18 Mo./reactor
17 Eq Xe-100 reactors	
1.58E+06	pebbles/18 Mo./eq reactor
178	m^3 Pebbles/18 Mo.
241	*** m^3 Pebbles/18 Mo.**
18,857	TRISO/pebble
2.98E+10	TRISO/18 Mo./eq reactor
9.7	**m^3 TRISO/18 Mo.**
	* m^3 TRISO/18 Mo.
0.74	* Packing fraction

Xe-100 GEN IV

Safety guaranteed by Physics

- 4.81 MW/m^3
- 168,500 MWd/t_{HM}

Versus

Typical GEN III+ PWR

Safety guaranteed by Systems

- 109.7 MW/m^3
- 60,000 MWd/t_{HM}

AP1000	
3400	**MWt**
1200	MWe
60,000	MWd/t_U (Burnup)
10.2	m^3 Spent Fuel every 18 months
157	fuel 17x17 assemblies
214	mm assembly side dim.
4.267	m assembly active length
1.95E-01	m^3/assembly
10.2	**m^3 1/3 of core**

24 Assembly Cask (Typ.)	
1.284	m Dia. inner cask
4.267	m Length inner cask
5.53	m^3 inner cask
11.1	**m^3 2 casks per outage**

AP1000 Alternative Correlation	
30.7	m^3 core volume
10.2	**1/3 core/18 Mo.**
6.82	m^3/yr

Xe-100 – Low Core Power Density; High Burnup
vs
AP1000 – High Core Power Density; Low Burnup

≈

HLW := 6.5 m^3 per year

Nuclear Security and Proliferation

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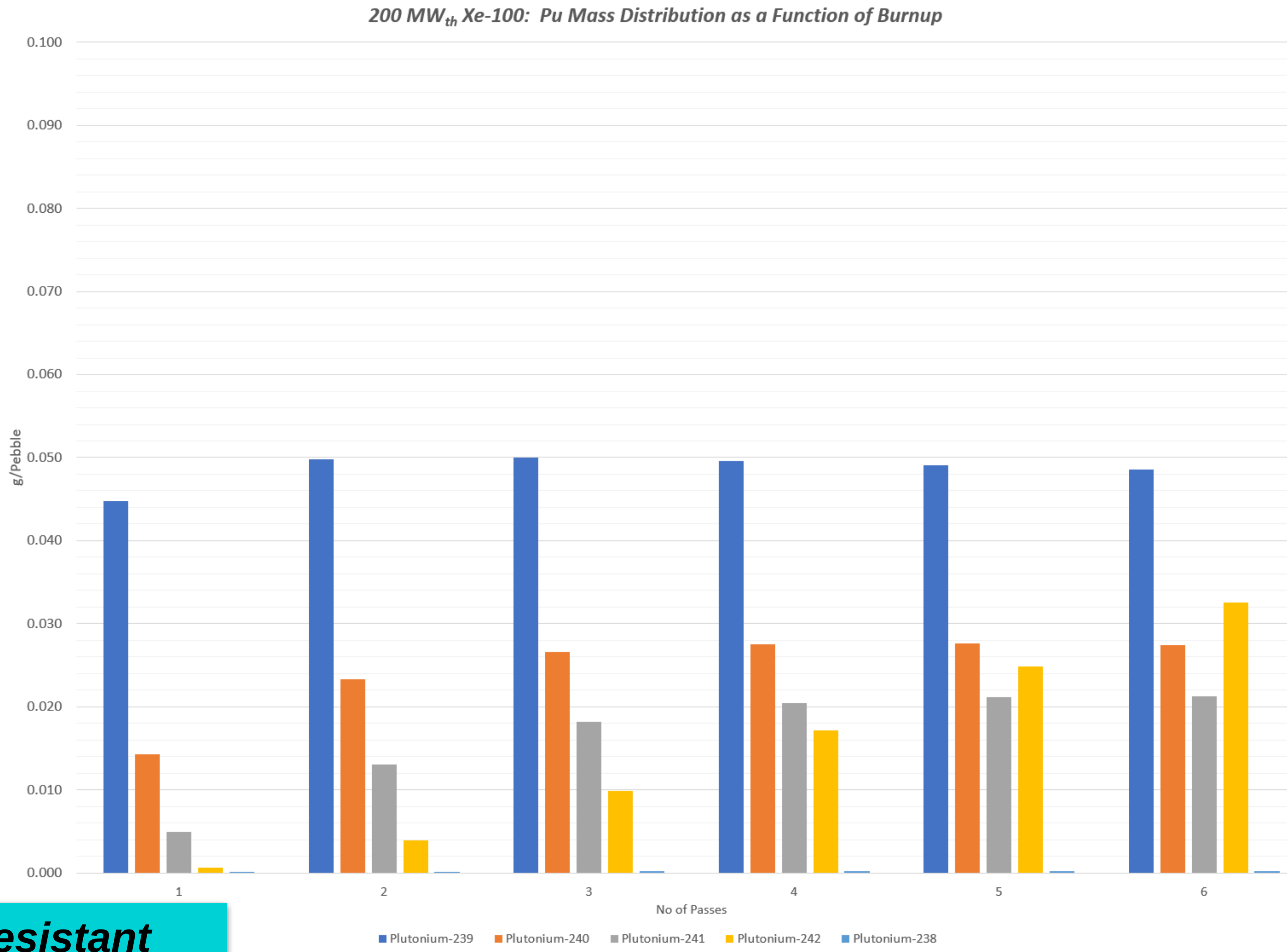
Xe-100: Highly Proliferation Resistant Solution

- **Odd isotopes are fissile and potentially weaponizable**
- **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**

- **TRISO particles very tough to crack mechanically**
- **Pu isotopes technically challenging to separate**

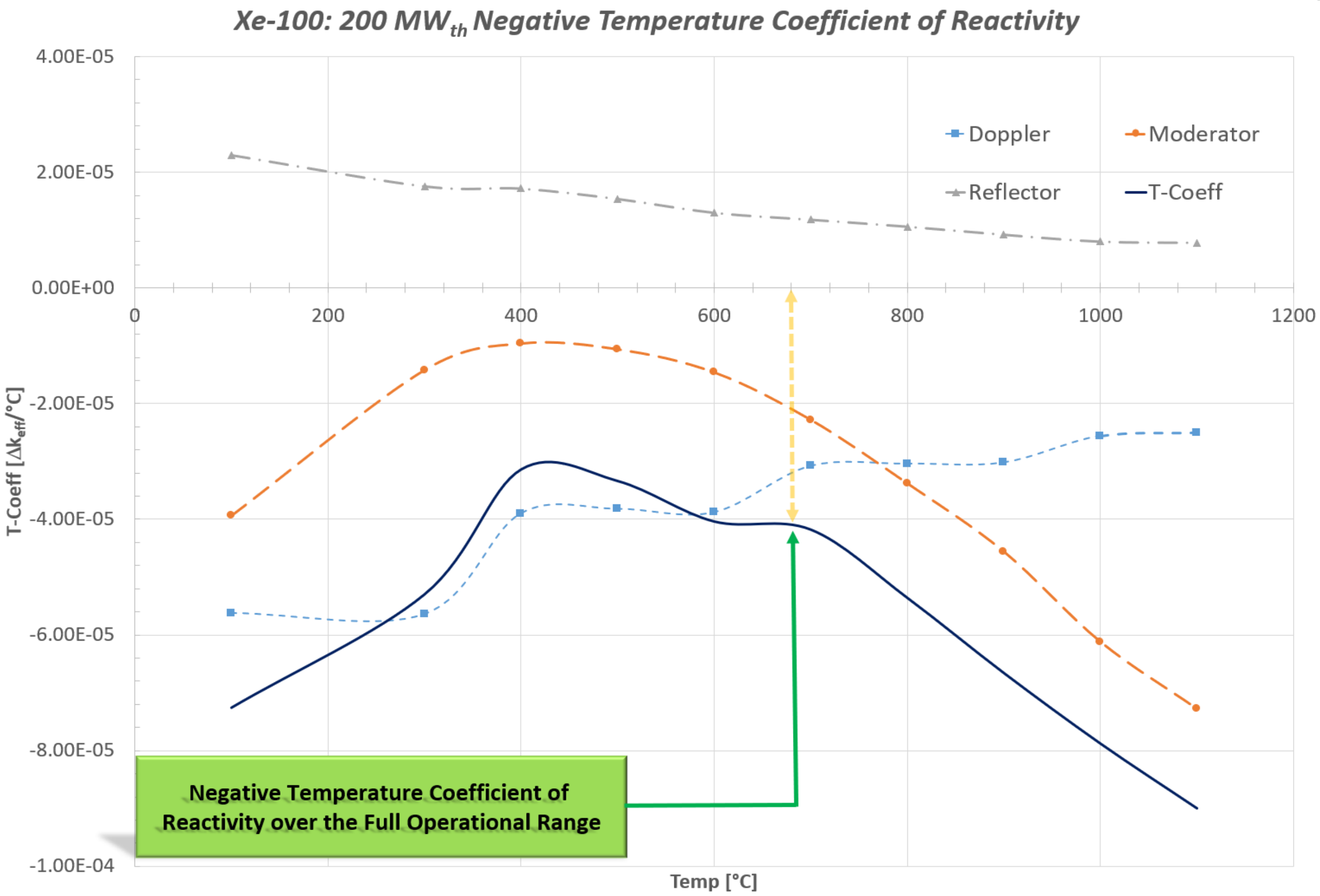


Xe-100 extremely Proliferation Resistant

Nuclear Safety

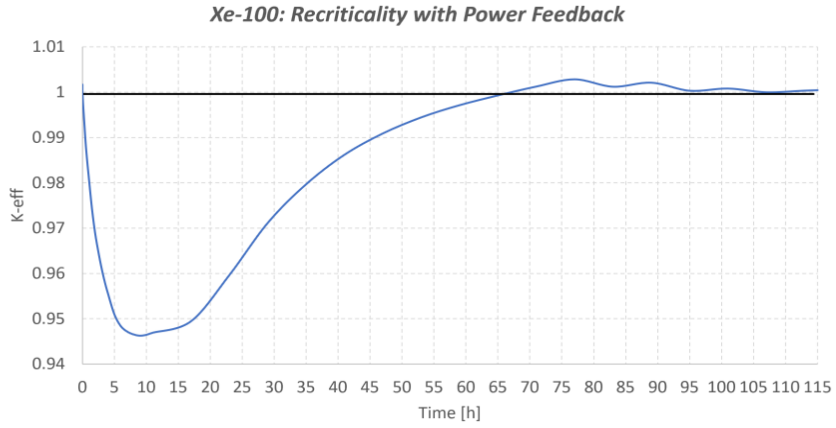
Reactivity Control and Shutdown System (RCSS)

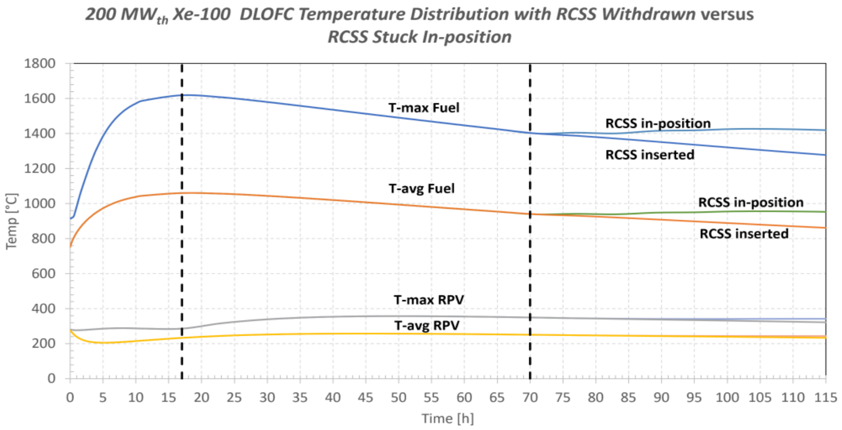
- The primary shutdown mechanism is the **strong negative temperature coefficient** over the entire operational range
- The reactivity control system (RCS) provides a second independent means to shut the reactor down
- The diversely actuated reserve shutdown system (RSS) comprises of 9 shutdown rods 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

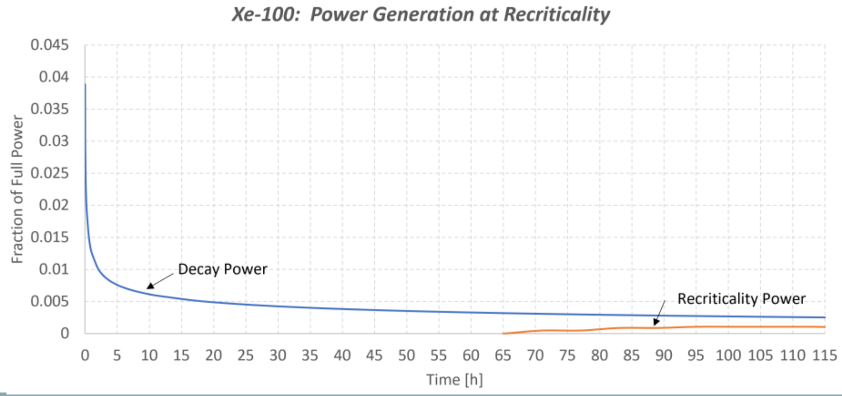


Xe-100 Design Base Event: DLOFC with and without RCSS Actuated

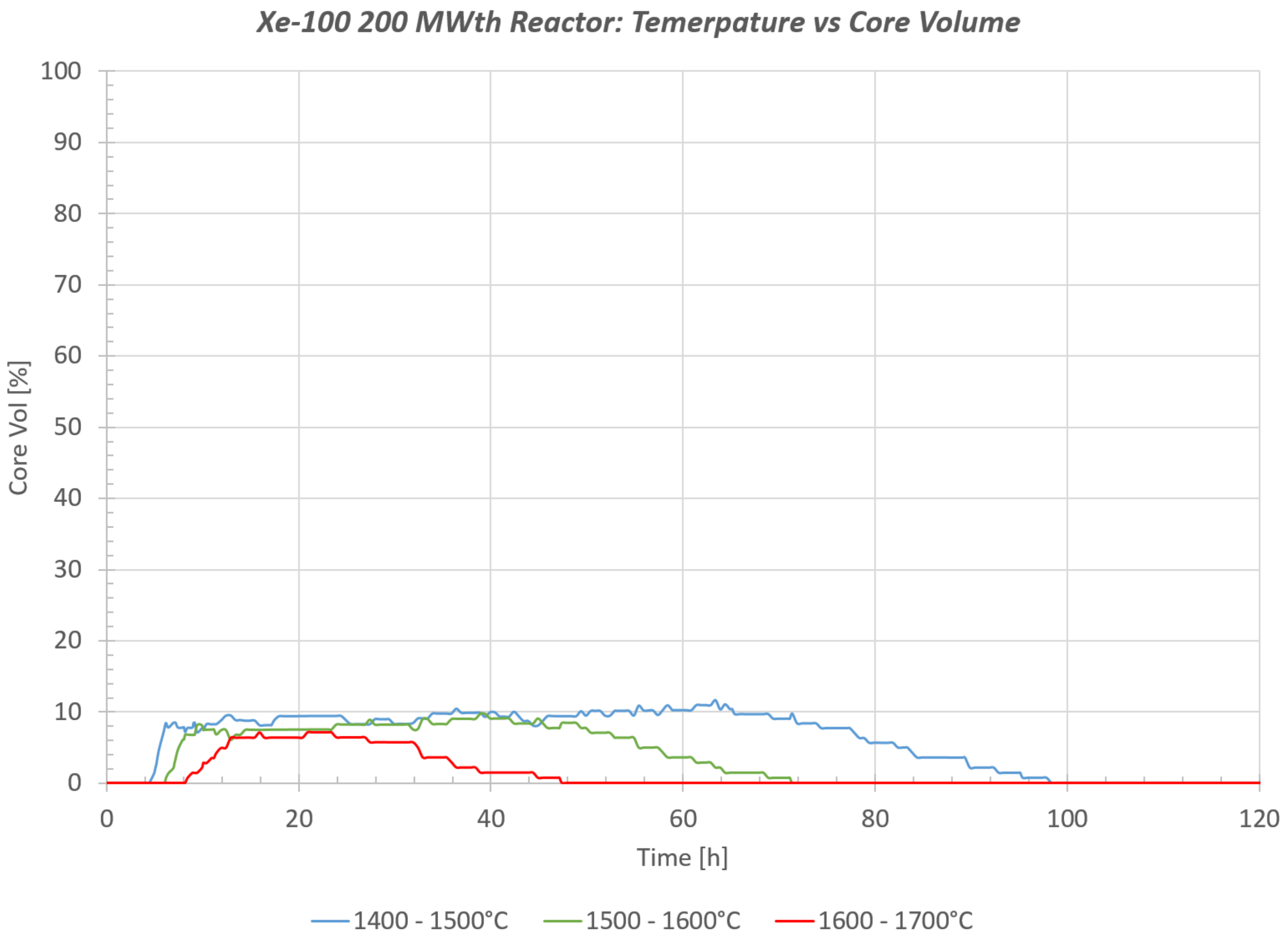
- Assumptions:
  - At the onset of the DLOFC the pressure drops from 6.0MPa to 0.1MPa
  - All heat is locally deposited, i.e. no heat is carried away by the exiting helium
  - The reflectors are considered to have achieved EOL fluence, i.e. thermal conductivity will be at its worst
  - RCSS fails to insert
- Sequence of assumptions is followed by a best estimate analysis
- As the core starts heating up – The negative temperature coefficient will shutdown 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







Temperatures vs Core Volume in a DLOFC



Advantages or Attributes of the Xe-100

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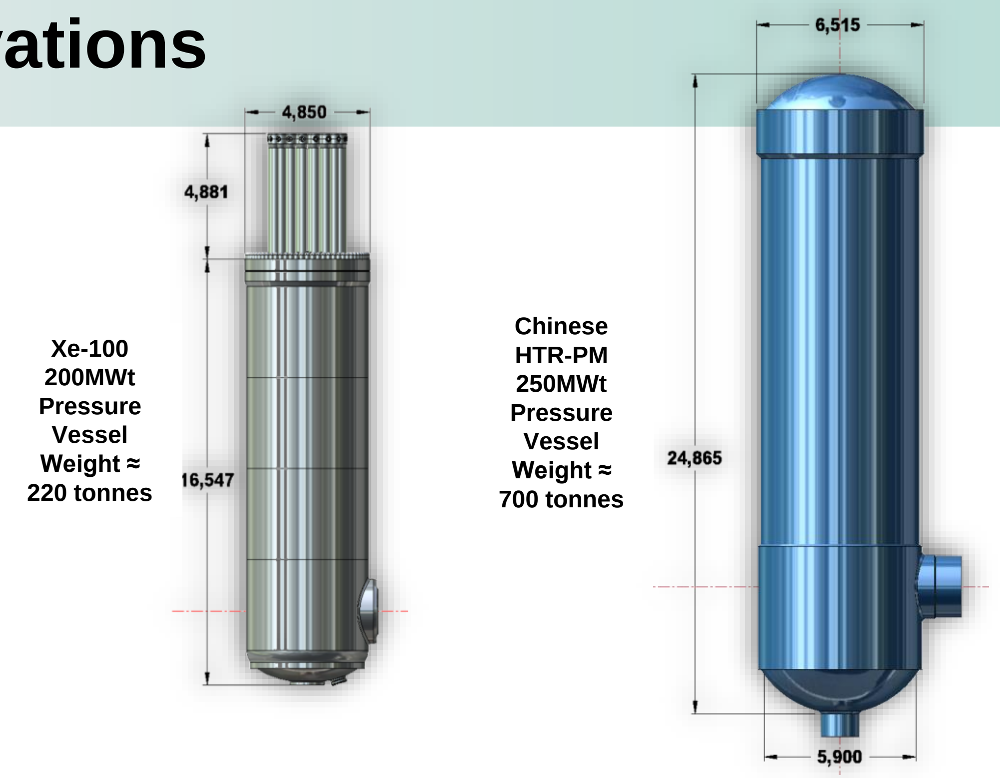
Fueling/Refueling in the Xe-100

- The Xe-100 with multi-pass cycling (6 passes) never has to be taken out of service for refueling
- Low excess reactivity guaranteed because of continuous fueling
- The pebble dwell period within the reactor core is approximately 1,320 equivalent fuel-power days
- Exceptionally high target burnup of approximately 168,500 MWd/MgU enabled via the use of UCO
- Fully wetted perimeter of pebbles and low core power density (0.9 kW/pebble); low temperatures are thus maintained in the fuel during its entire operational life; in turn this guarantees low radionuclide release rates during operation
- Fast fission of the uranium-238 present in the fuel makes a minor contribution to power generation (0.5% of total power) but results in Pu breeding due to neutron capture forming various Pu isotopes
- In the Xe-100 about 82% of the bred Pu is consumed in-situ – The bred Pu responsible for about 35% of total power in the equilibrium core

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 169,000 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
- The enrichment level of 15.5% is based on:
  - Balance between fission product buildup decay heat generation) and maximum fuel temperature achieved during a DLOFC (the design basis event (DBE));
  - Fit within the irradiation test envelope of the AGR program



Xe-100 VS HTR-PM

Xe-100 Advantage: Commercial Innovations

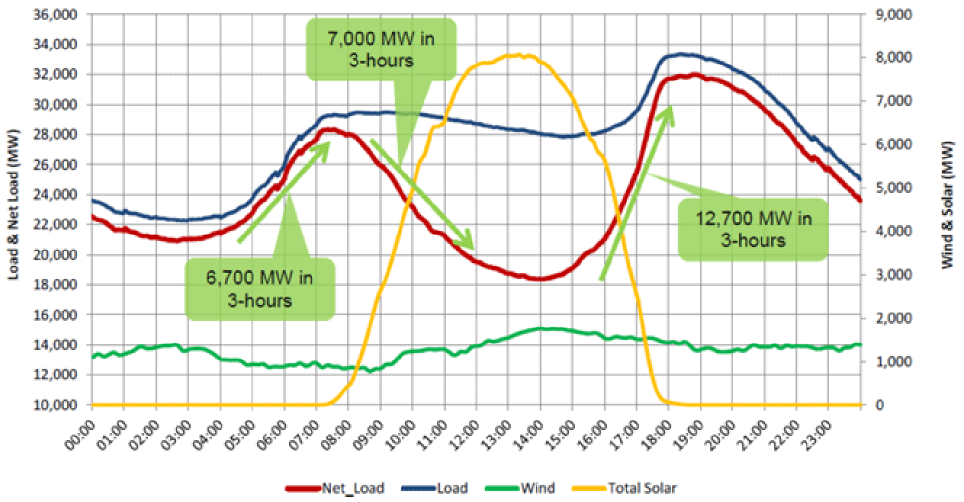
(1) Right size

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.

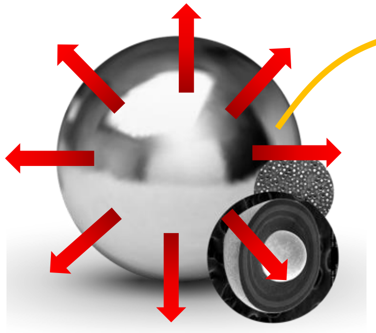
(2) Broad range of applications

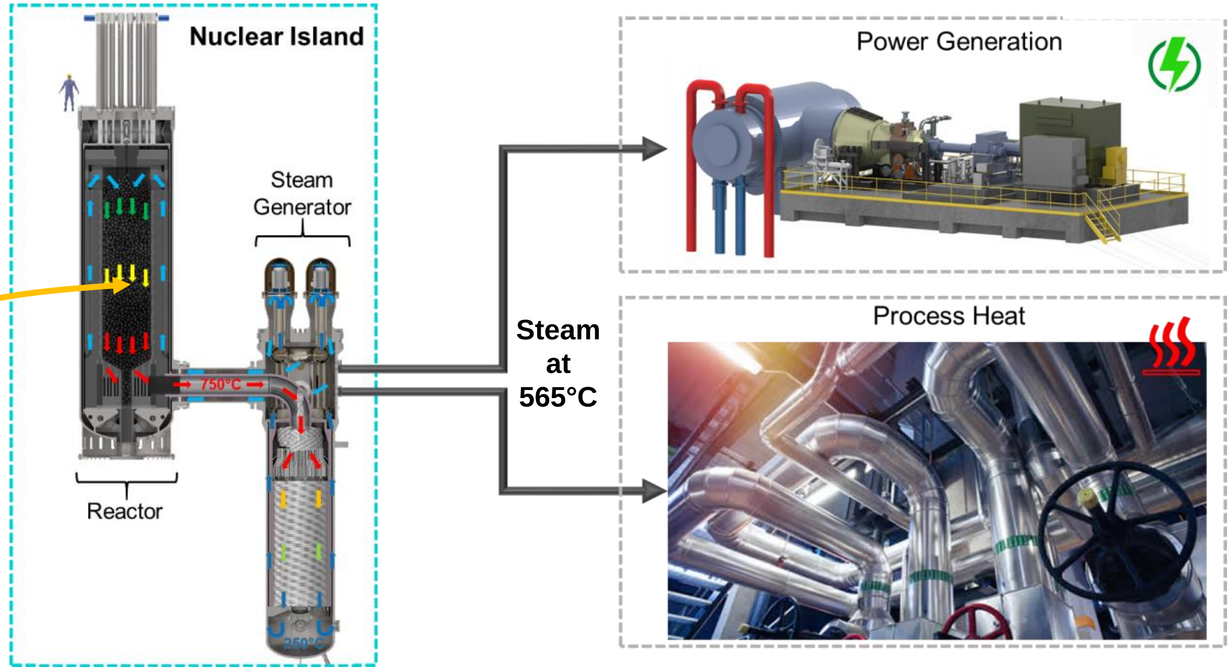
The nuclear island has been designed to be independent of the end use making our solution deployable for electricity and many other applications that require process heat to replace carbon-based fuels

- Hydrogen production
- Desalination
- Petrochemical industries
- District heating ….



Heat is generated in the pebble fuel through fission and transferred to the steam generator using helium that cannot be activated





(3) Flexible power delivery

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

Challenging Technical Issues for Commercialization

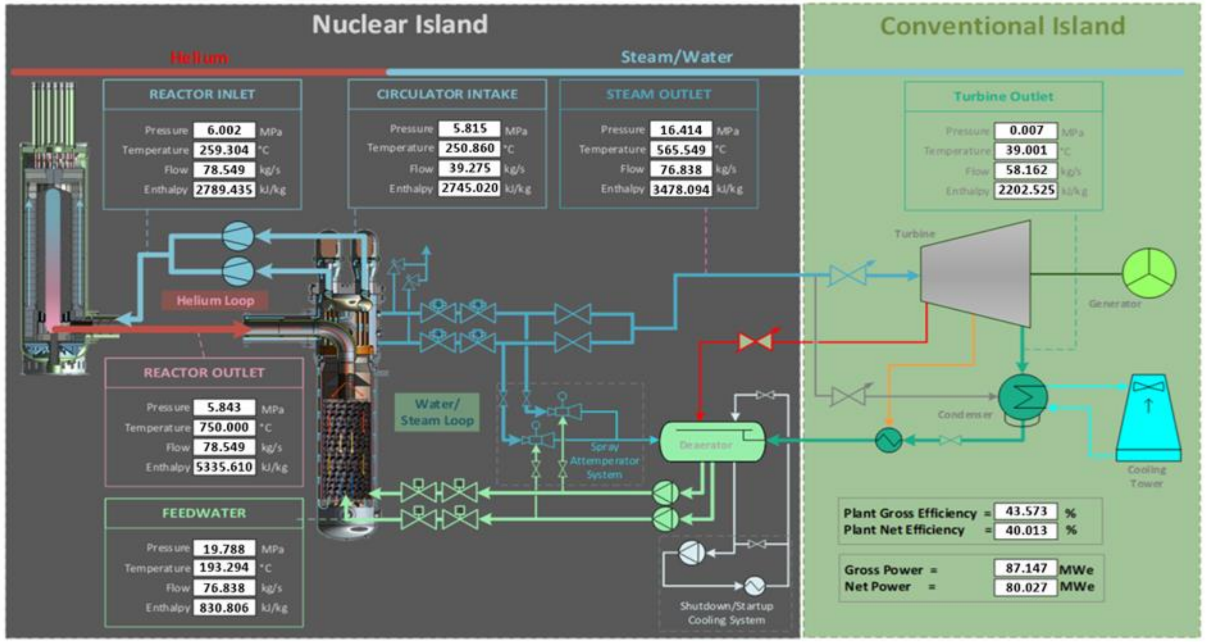
Innovative Control Approach

- 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

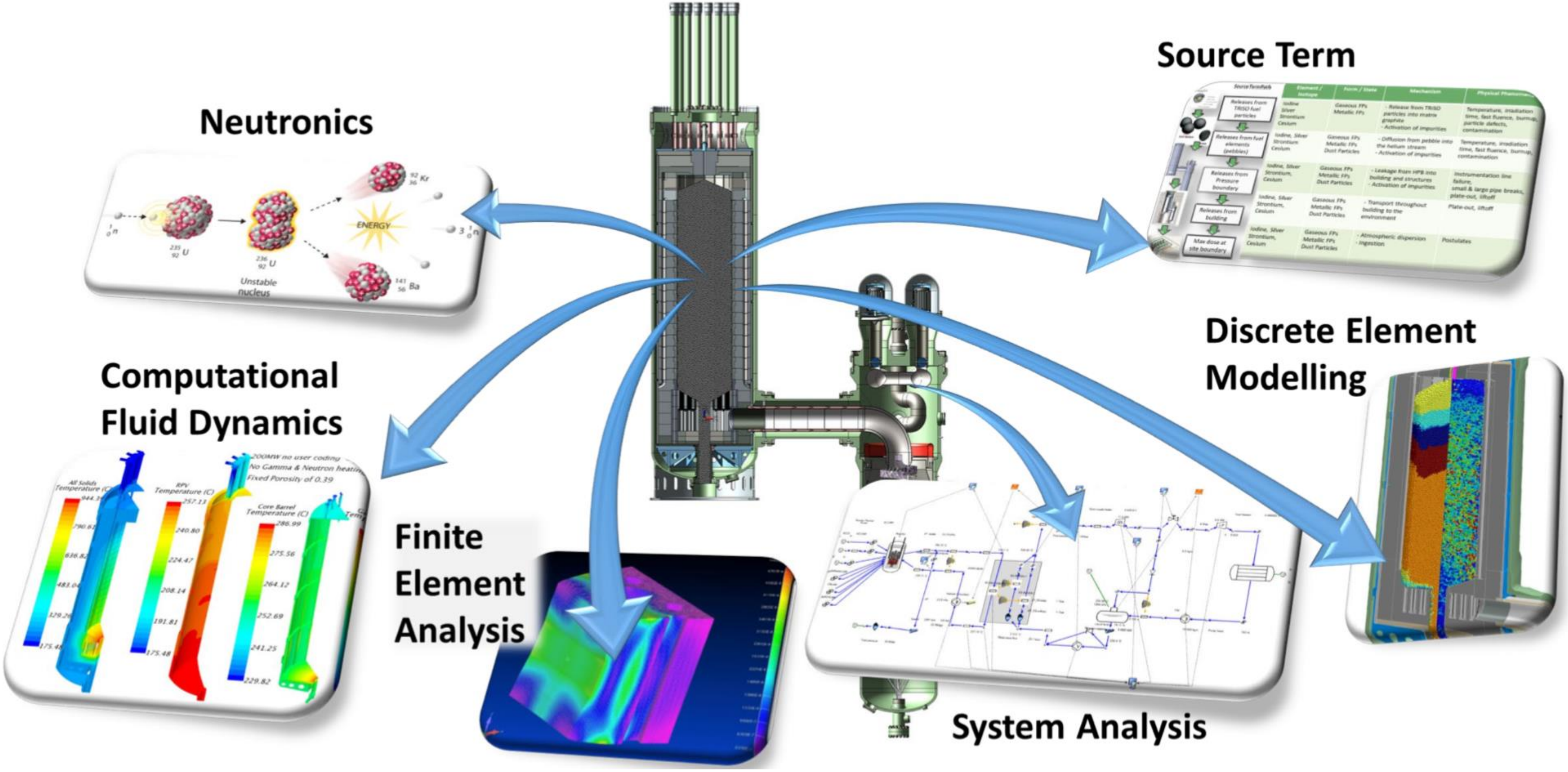


Mockup Plant Control Room - 4 x Reactor Modules

- ARPA-E award to prove reduction of the plant operations and maintenance (O&M) costs through:
  - The development and use of digital twins for generating baseline operational data
  - Development of EPRI guidelines to develop ‘Super Crews’ to perform O&M activities
  - Develop maintenance strategies to optimize fleet maintenance operations
  - Develop the white papers and topical reports to support Regulatory approval

Challenging Licensing Issues for Commercialization

Established modeling and simulation capabilities are applied for design and licensing



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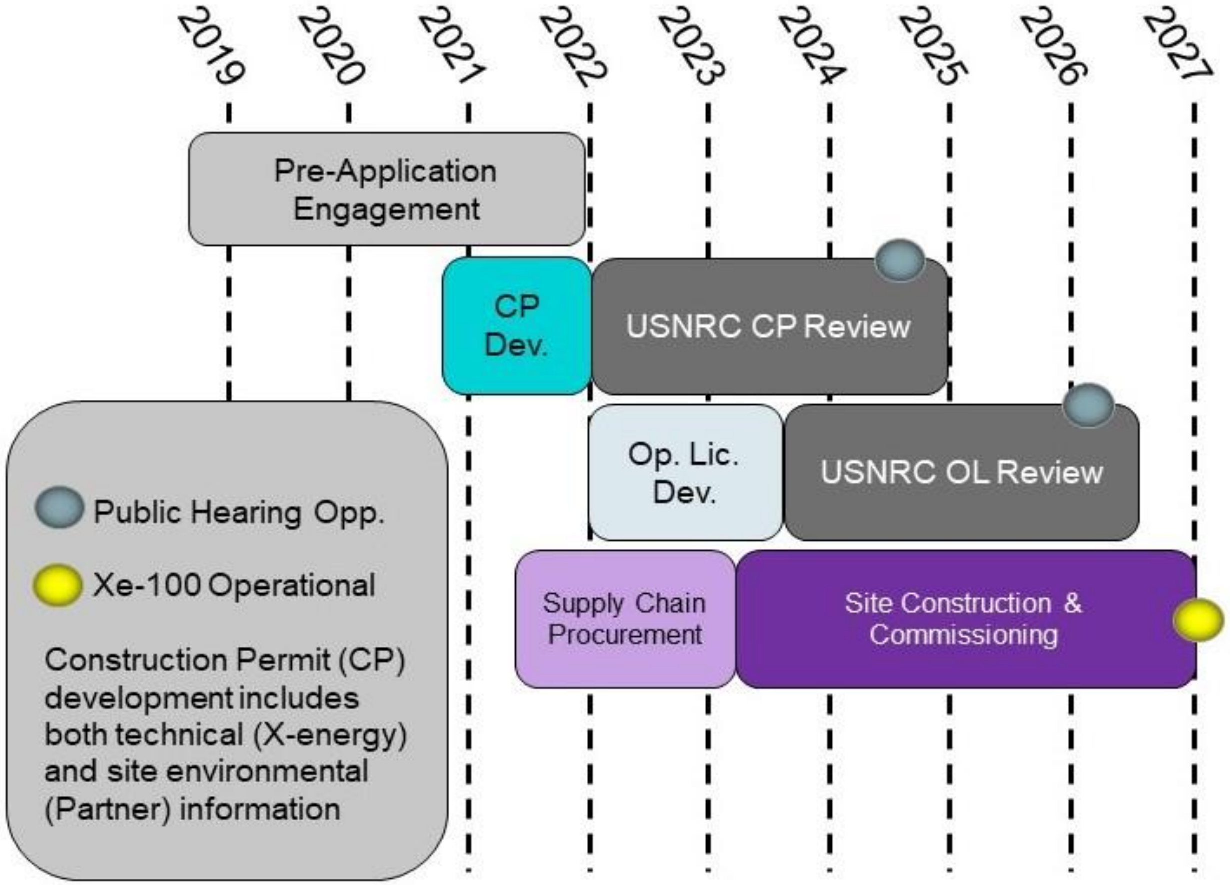
We are actively pursuing an aggressive licensing path in the U.S.

- The Xe-100's simple safety case and recent efforts by the USNRC to modernize existing regulations for advanced reactors improve the regulatory environment.
- U.S. regulatory review will most likely follow a 2-part activity (Construction Permit followed by Operating License) for a 1st-of-a-kind unit.
- Subsequent licensees gain review efficiencies through a standardized design process and generic environmental reports in the late 2020's.
- X-energy actively engaged in pre-application activities with the USNRC in 2020/21 to derisk regulatory processes.
- Target application in late 2021/early 2022 depending on the business cases.
- USNRC is adopting less deterministic, more risk-informed licensing posture favorable to X-energy.

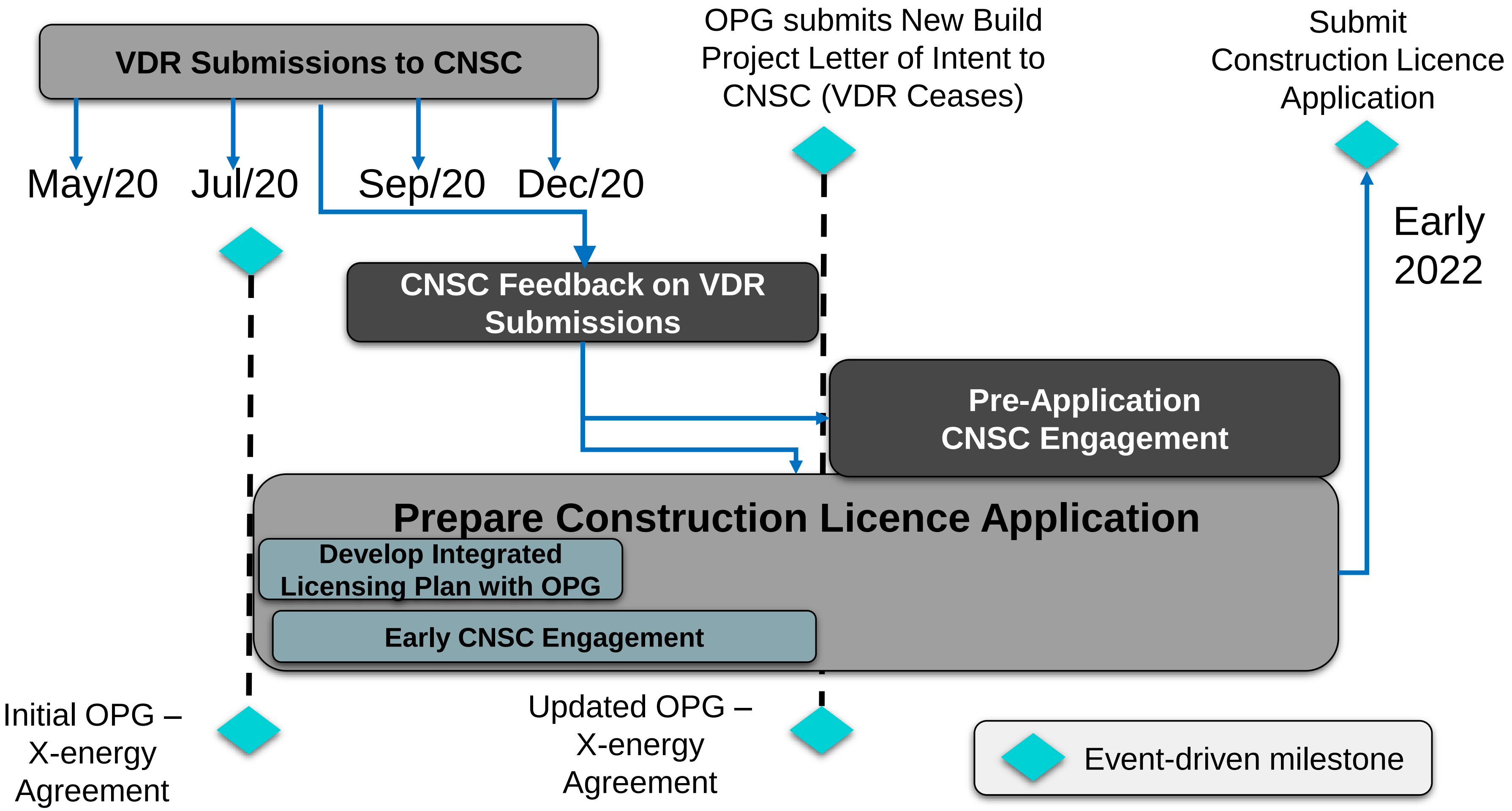
"The NRC is the Global Gold Standard [of Regulation]" Doug True, Chief Nuclear Officer, Nuclear Energy Institute



We are licensing the only Gen IV reactor in Ontario Power's timeline

- The CNSC licenses activities, not designs.
- The Xe-100 design will be ready to support a Construction Licence application in 2022.
- Schedule developed to support Ontario Power Generation (OPG) as prospective applicant.
- X-energy is proposing all Vendor Design Review (VDR) submissions in 2020. VDR aims to conclude there are "no fundamental barriers to licensing."
- CNSC feedback on VDR submissions in 2020/21 will be factored in and de-risk the Construction Licence application.

X-energy has partnered with the most experienced Safety & Licensing team in Canada



Construction and Operating Costs

Construction and Operational Costs

- X-energy has performed a bottom-up costing on as many systems and component of the Xe-100 plant as possible
- Cost estimates are backed by quotes and industry estimates for >95% of the Xe-100 cost items that are derived from the Systems Breakdown Structure
- 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:
  - Air-cooled condenser system
  - Wet-cooled condenser system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