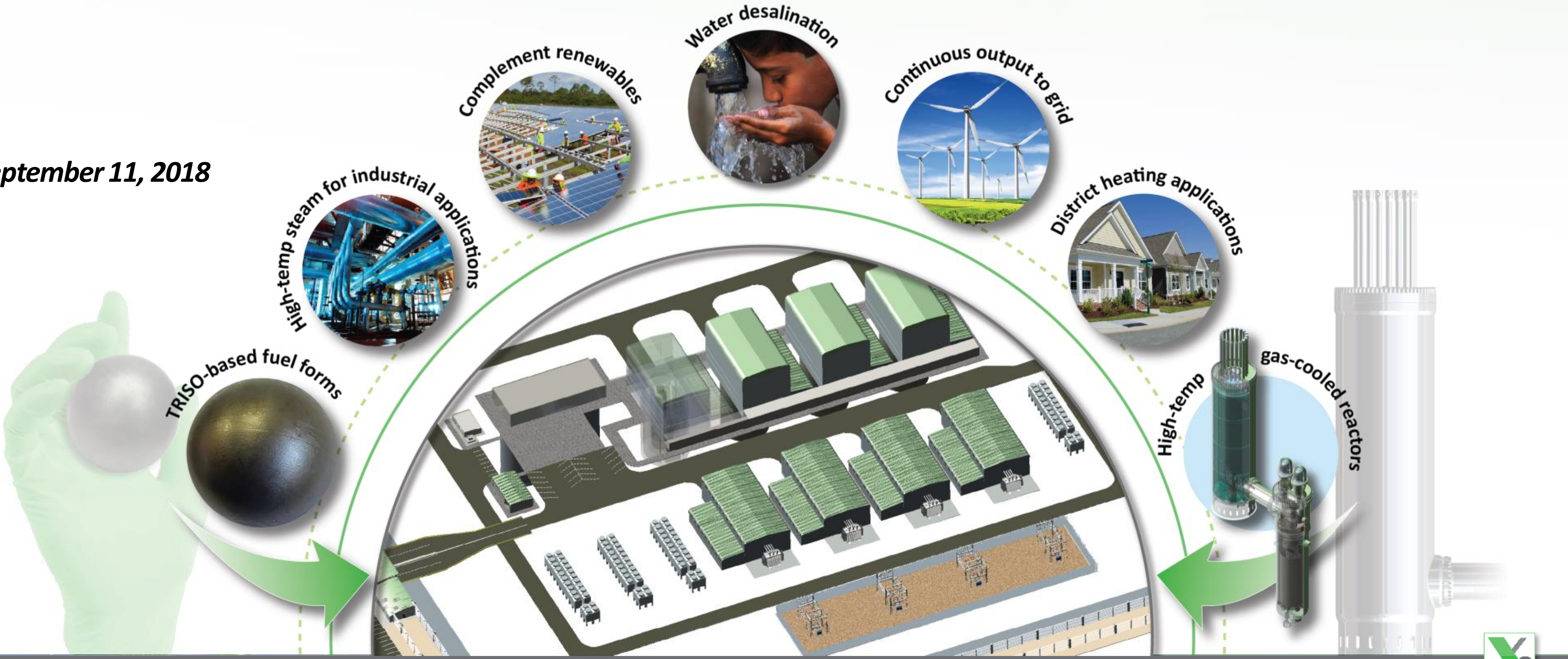
X-energy Xe-100 Reactor Initial NRC Meeting

September 11, 2018



X-energy: Who We Are

Harlan Bowers

REIMAGINING NUCLEAR ENERGY

"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

LICENSING

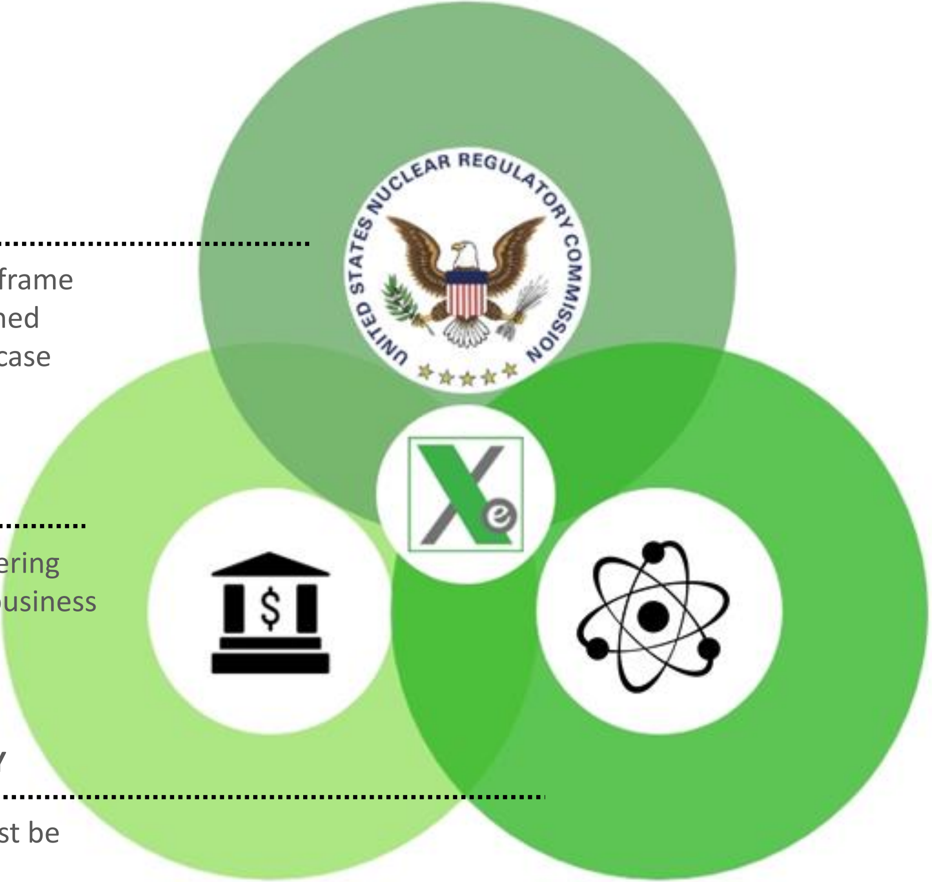
Licensing timeframe should be aligned with business case

ECONOMICS

Technology offering must support business case

TECHNOLOGY

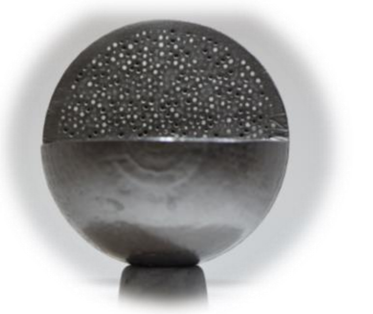
Technology must be licensable



X-energy Mission Statement

- To be the world's leader in development of **High Temperature Gas Cooled Reactors** and the **Fuel** to supply to those reactors:
  - Establish the organization needed to achieve our development goals;
  - Maintain an effective Safety and Quality culture throughout the organization;
  - Foster trust-based relationships with customers and government agencies;
  - Create win-win relationships with industry partners and suppliers; and
  - Implement robust and accurate project management to ensure efficient, cost-effective performance.

- To ***Change the World*** through innovative and implementable energy solutions - for domestic and international customers; for all communities; in a safe, secure, long-term, and economically viable way.



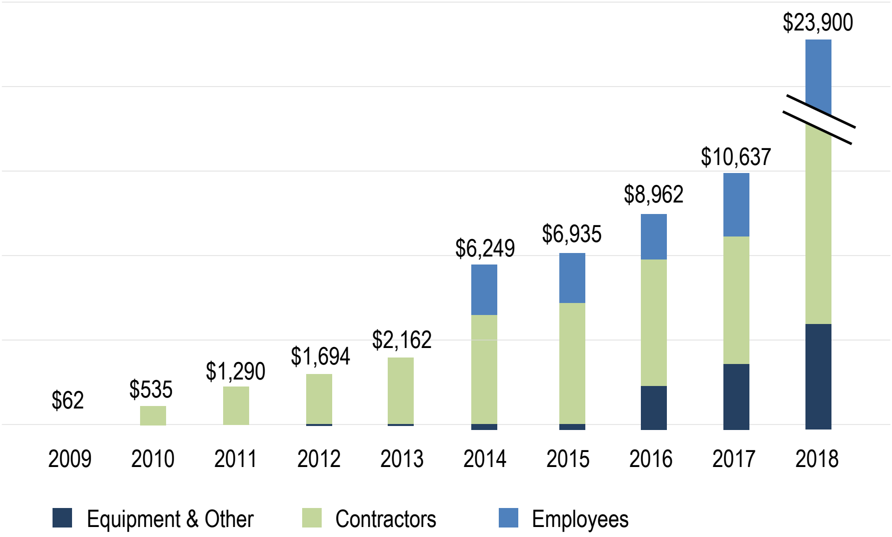
X-energy Strategy

- **Reactor**—to differentiate X-energy by:
  - Serving niche markets where long-term nuclear co-generation (electricity and process heat) energy has an advantage
  - Advance our reactor designs by winning and successfully executing multiple DOE and other U.S. Agency funding opportunities
- **Fuel**—to be a competitive provider of high-quality TRISO-based UCO fuel form, supplying X-energy and other advanced reactors
- **Licensing**—To pursue nuclear power plant and fuel fabrication facility licenses in the U.S. through the Nuclear Regulatory Commission

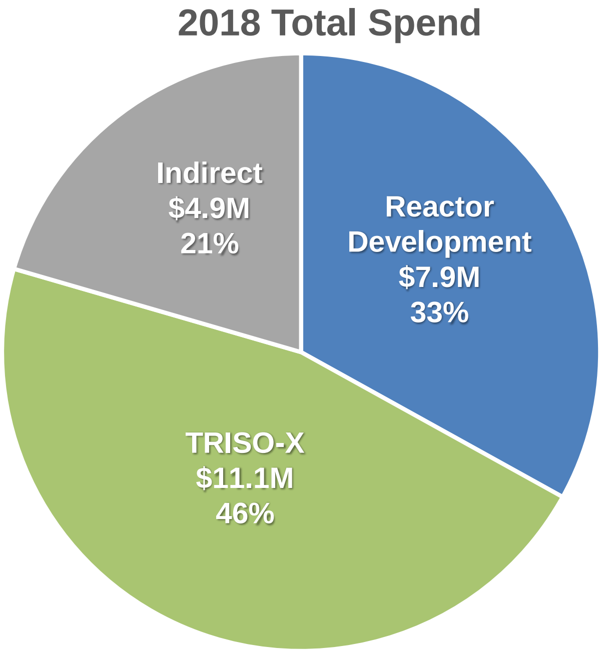
ISCE

Company Profile

- X-energy formed in 2009
- 2018 Expenditure Forecast: ~**$24M**
- Full Time Equivalents: **65 people**
- X-energy Strategic Partners including: Centrus Energy, TI, MPR Associates, Burns & McDonnell, Aerotherm, Southern Nuclear Development, multiple national labs



- U.S. DOE Contracts –
  - 2016 - Advanced Reactor Concepts: **$53M**
  - 2018 - Advanced Reactor Technology: **$10M**
  - Primary National Lab Support – ORNL, INL, ANL, SNL



X-energy Experienced-Based Leadership Team

Harlan Bowers

President

20 years of experience managing large (over $100M/yr) government task orders and performance-based contracts

Dr. Eben Mulder

SVP, Chief Nuclear Officer

30 years of experience in pebble bed design and architecture

Ralph Loretta

Chief Financial Officer

30 years of experience in energy generation & distribution financial management

Jeff Harper

VP for Business Development

30 years of experience in nuclear program management, business development, and strategy

Dr. Pete Pappano

VP for Fuel Production

15 years of experience in graphite & fuel fabrication

Dr. Martin van Staden

VP for Reactor Development

28 years of experience in power generation including nuclear and renewables

Carol Lane

Government Relations

30 years experience including service as U.S. Senate staff, service with the federal government, and industry

Clint Medlock

Southern Nuclear Consultant

27 years of nuclear energy experience and management

Partners Supporting Deployment

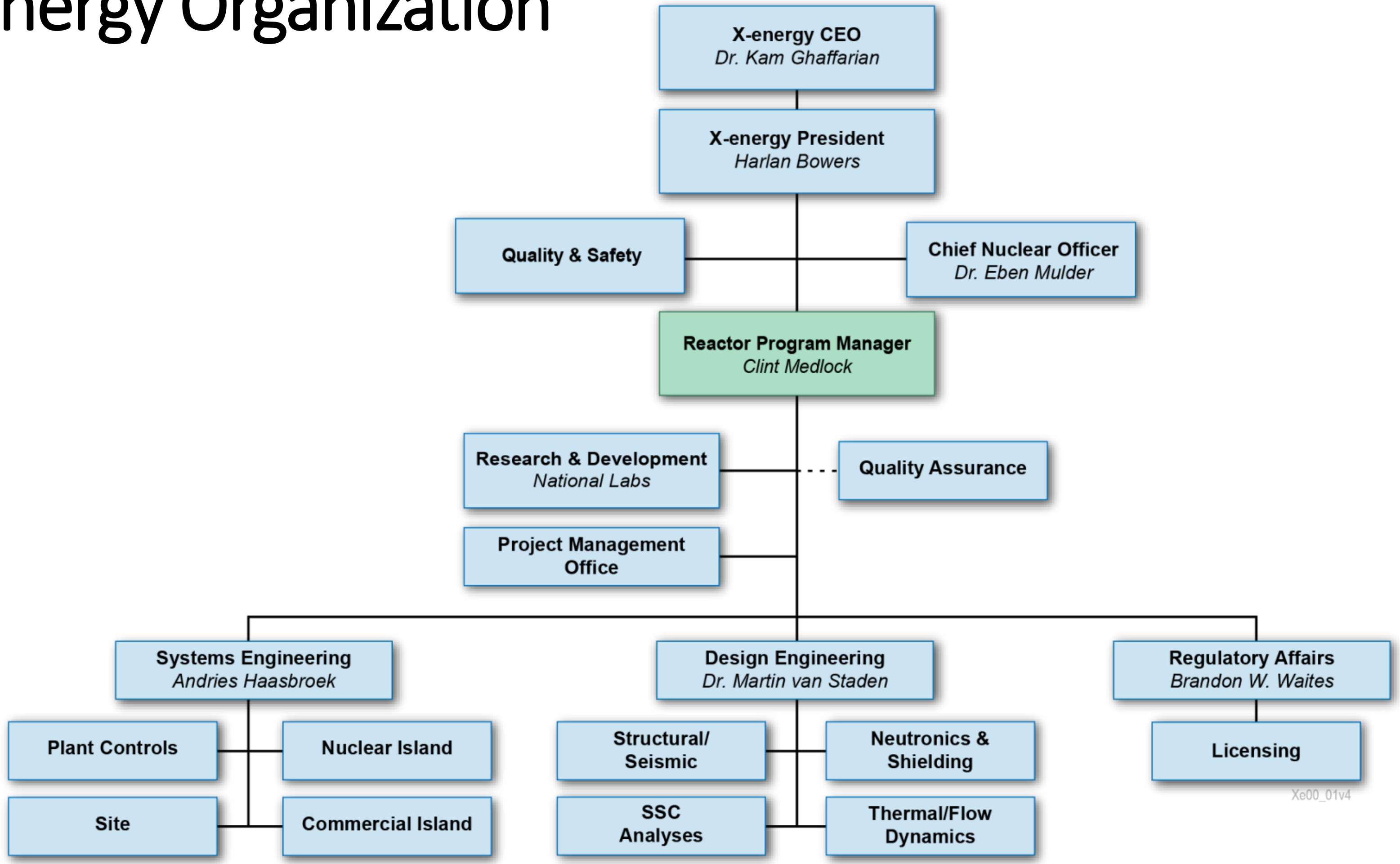
X-energy Strategic Partners

- INL Idaho National Laboratory
- Burns & McDonnell
- MPR
- Oak Ridge National Laboratory
- Centrus – Fueling the Future of Nuclear Power
- PSI
- Sandia National Laboratories
- SGL Group – The Carbon Company
- Excel Services Corporation
- Argonne National Laboratory
- Teledyne Brown Engineering – Everywhereyoulook™
- Sargent & Lundy
- BWXT – BWX Technologies, Inc.
- Southern Nuclear
- Technology Insights

X-energy Advisory Committee

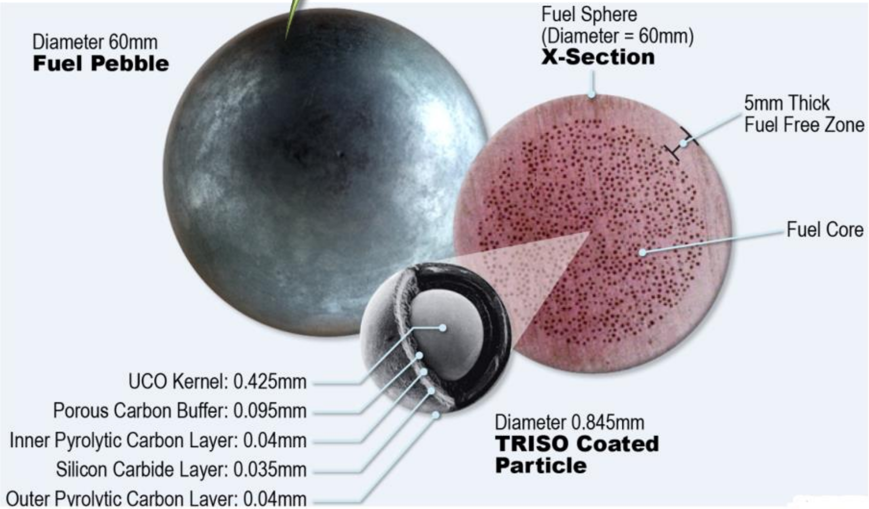
- Ontario Power Generation
- Southern Nuclear
- Exelon.
- Duke Energy®
- Dominion

X-energy Organization

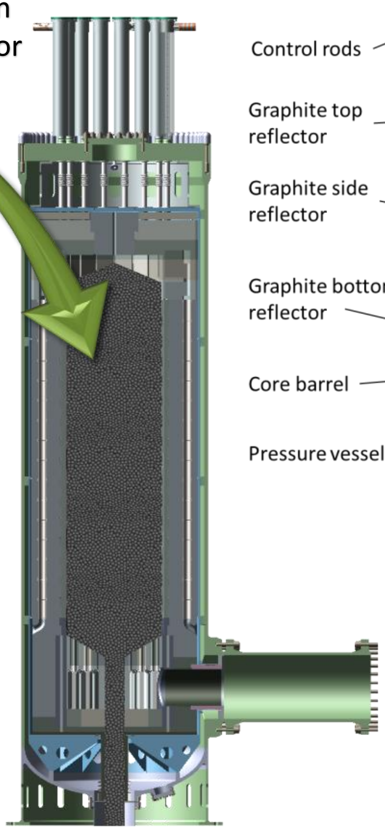


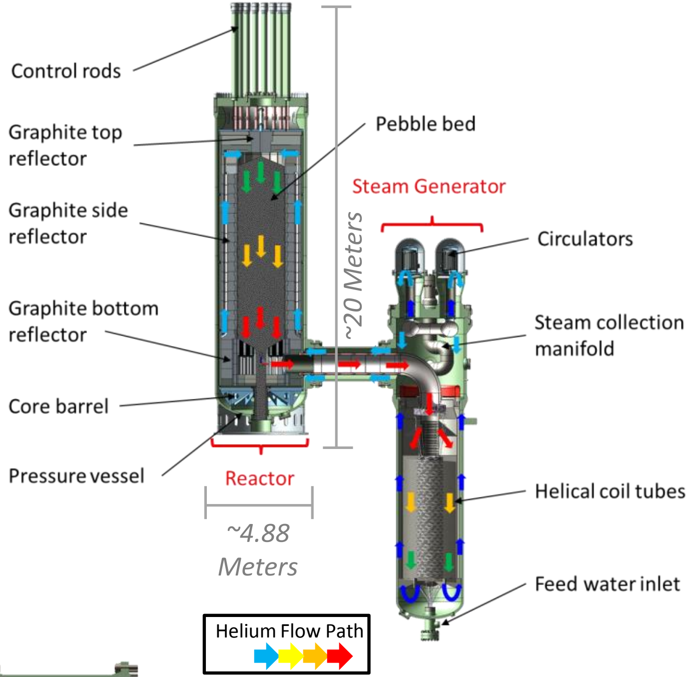
Overview – Pebble Bed High Temperature Gas-Cooled Reactor (HTGR)

~18,000 Uranium Oxycarbide TRISO particles in a pebble



~220,000 pebbles in the reactor core



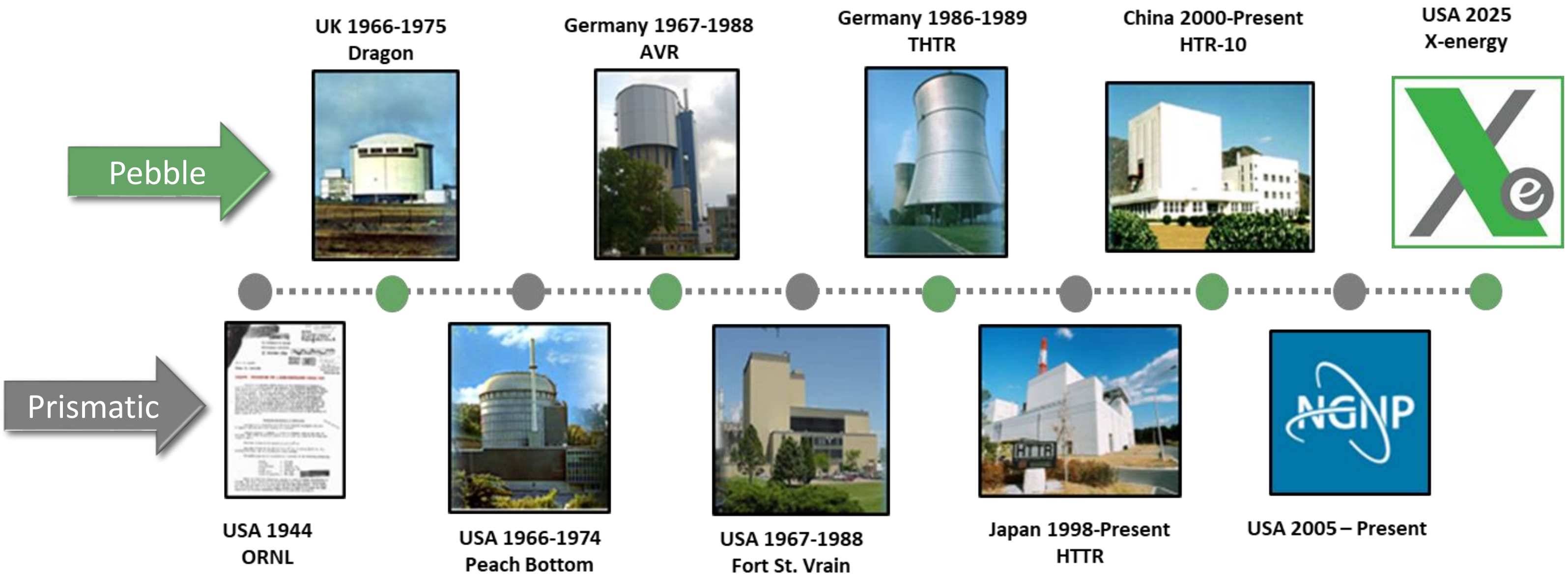


X-energy: Technology Overview

Dr. Martin van Staden

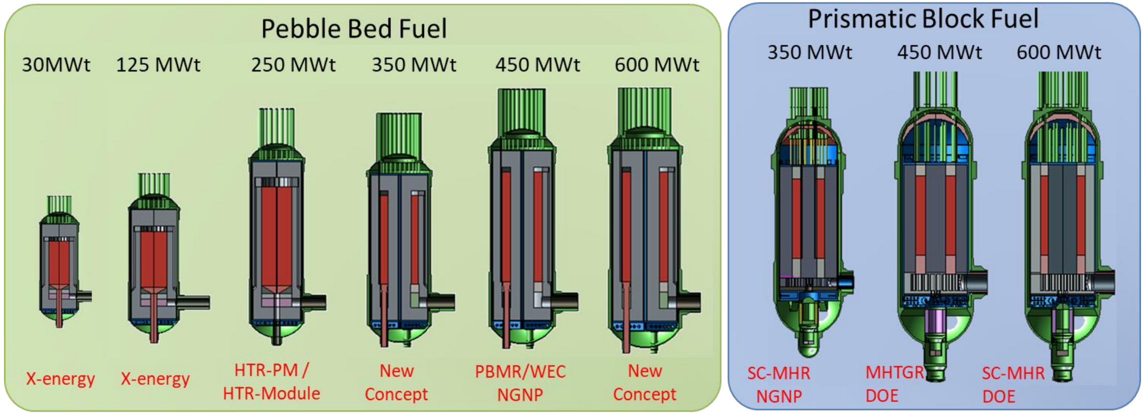
Reason for Selection of HTGR

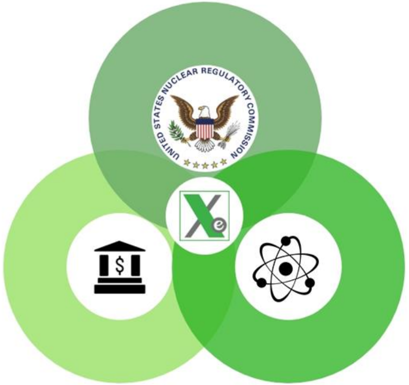
- Reasons for selection of HTGR as a technology:
  - Proven safety with more than 30 years of test and operational history
  - Potential deployment timeline within 2025-2030 timeframe
  - Technology demonstration and licensability
  - Significant U.S. DOE investment in NGNP through development and testing of UCO TRISO based fuel



Licensing / Technology / Economics

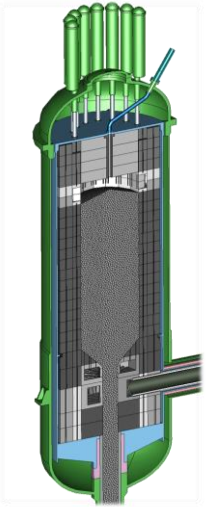
- Three Pillars for deployment success:
  – Licensing
  – Technology readiness
  – Competitive offering (Economic)
- X-energy performed a one-year trade study to determine the following parameters:
  – Fuel form – pebble vs. prismatic
  – Optimum reactor size
- In this study the following designs were reviewed:
  – Pebble bed ranging from 30 MWt to 600 MWt
  – Prismatic designs between 350 MWt and 600 MWt
- The study showed a 200 MWt pebble bed reactor with online refueling could provide a burnup of 160,000 MWd/tHM giving it an advantage over the prismatic designs that have an 18-20 month fuel cycle





The Xevolution

30–48 MWt

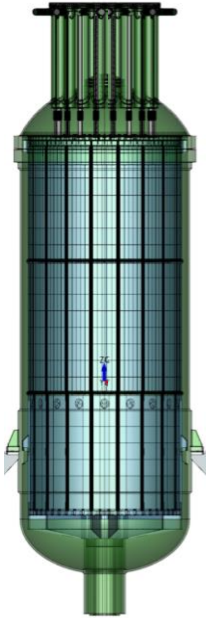


ST-OTTO
(ThUO)

100 MWt

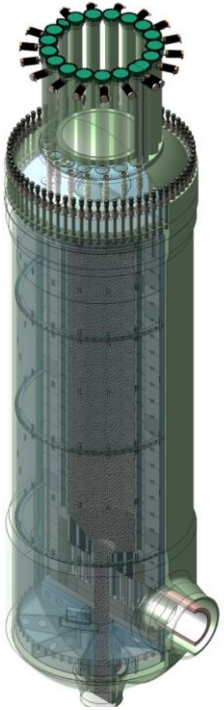
OTTO
(UO2)

125 MWt



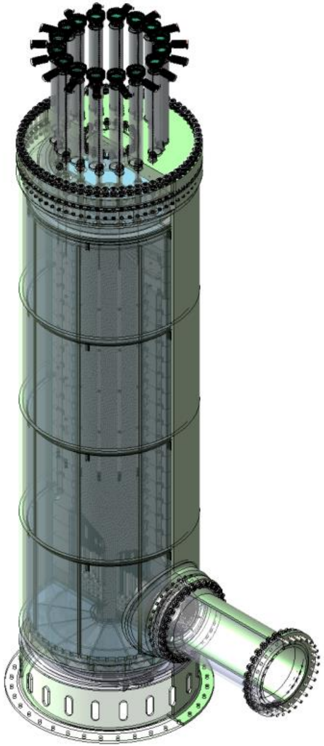
OTTO
(UCO)

Pre-conceptual Design
200 MWt



Multi-pass
(UCO)

Conceptual Design
200 MWt



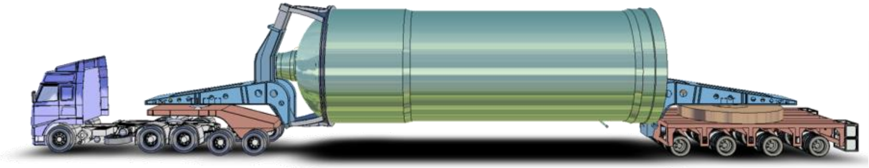
Multi-pass
(UCO)

Licensing / Technology / Economics

Reactor Development

X-energy is currently completing conceptual design of its Xe-100 reactor:

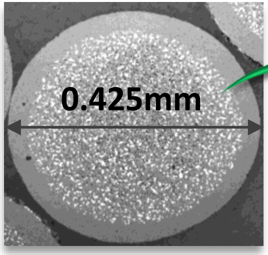
- Use of well proven UCO TRISO based fuel
- Proven intrinsic safety
- Operated without the need for a water source
- Load-following to 40% power within 15 minutes
- Continuous online fueling with passive on-site spent fuel storage
- Requires less time to construct (2.5 to 4 years)
- Factory assembled road transportable components/systems
- Deployable for electricity generation, process heat or co-generation



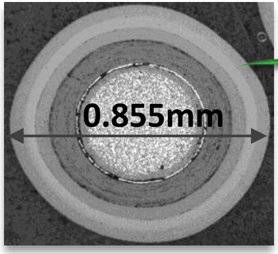
Xe-100 Plant Output

Thermal Output	Electric Output	Steam Pressure	Steam Temperature
200MWth	~75MWe	16.5MPa	565ºC

Role of TRISO Fuel in Reactor Safety

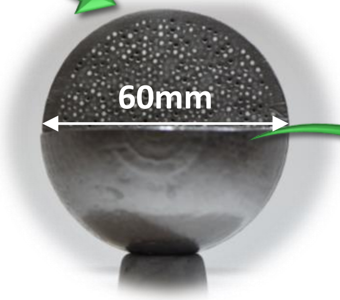


Optimized UCO kernel

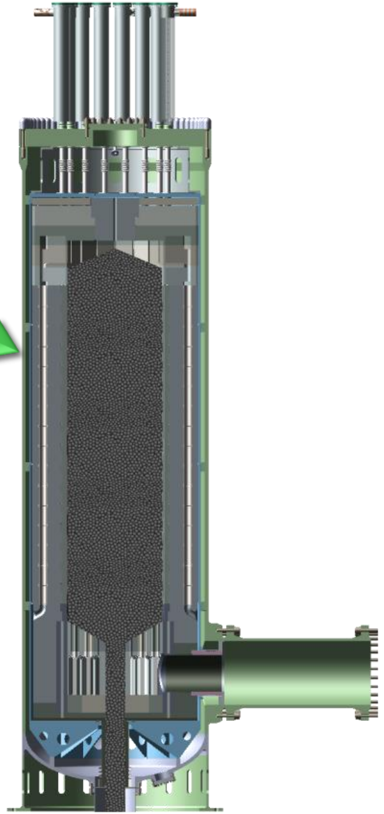


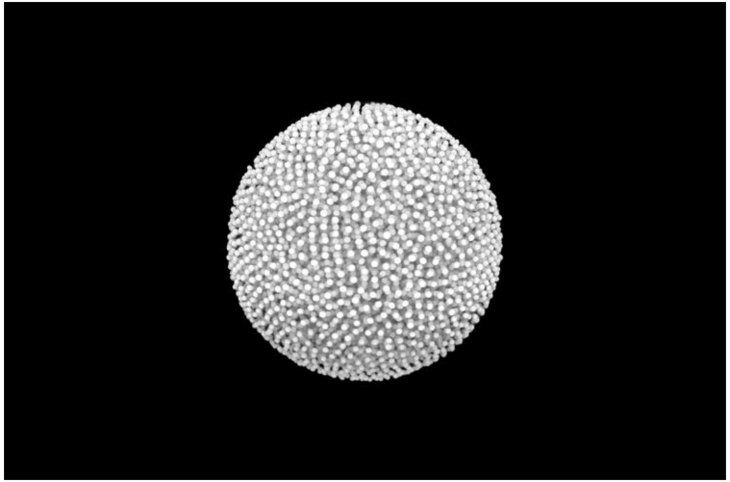
TRISO coating in modern CVD furnace

~18,000 TRISO coated particles in a pebble



~220,000 pebbles in the core

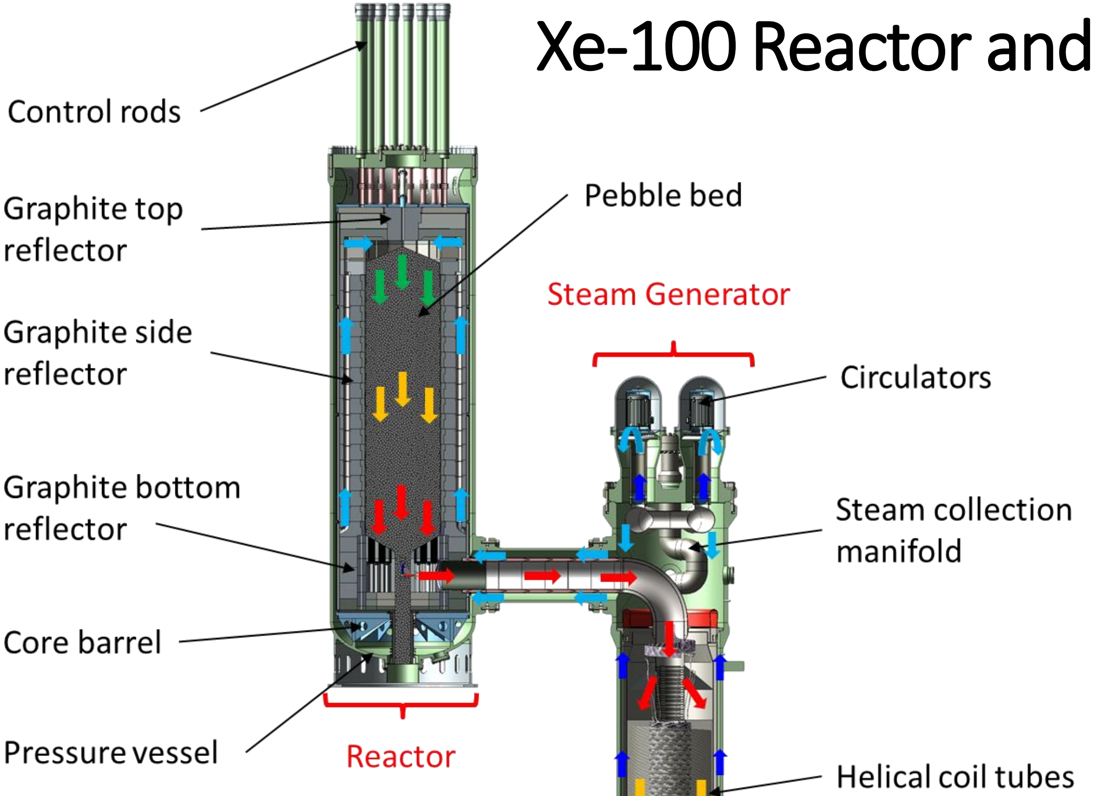




Innovative visualization of particles in pebble

Fuel is an integral part of the reactor safety basis and economics, therefore X-energy is developing in-house fuel manufacturing capability building on what was done through the DOE NGNP program.

Xe-100 Reactor and Steam Generator Detail



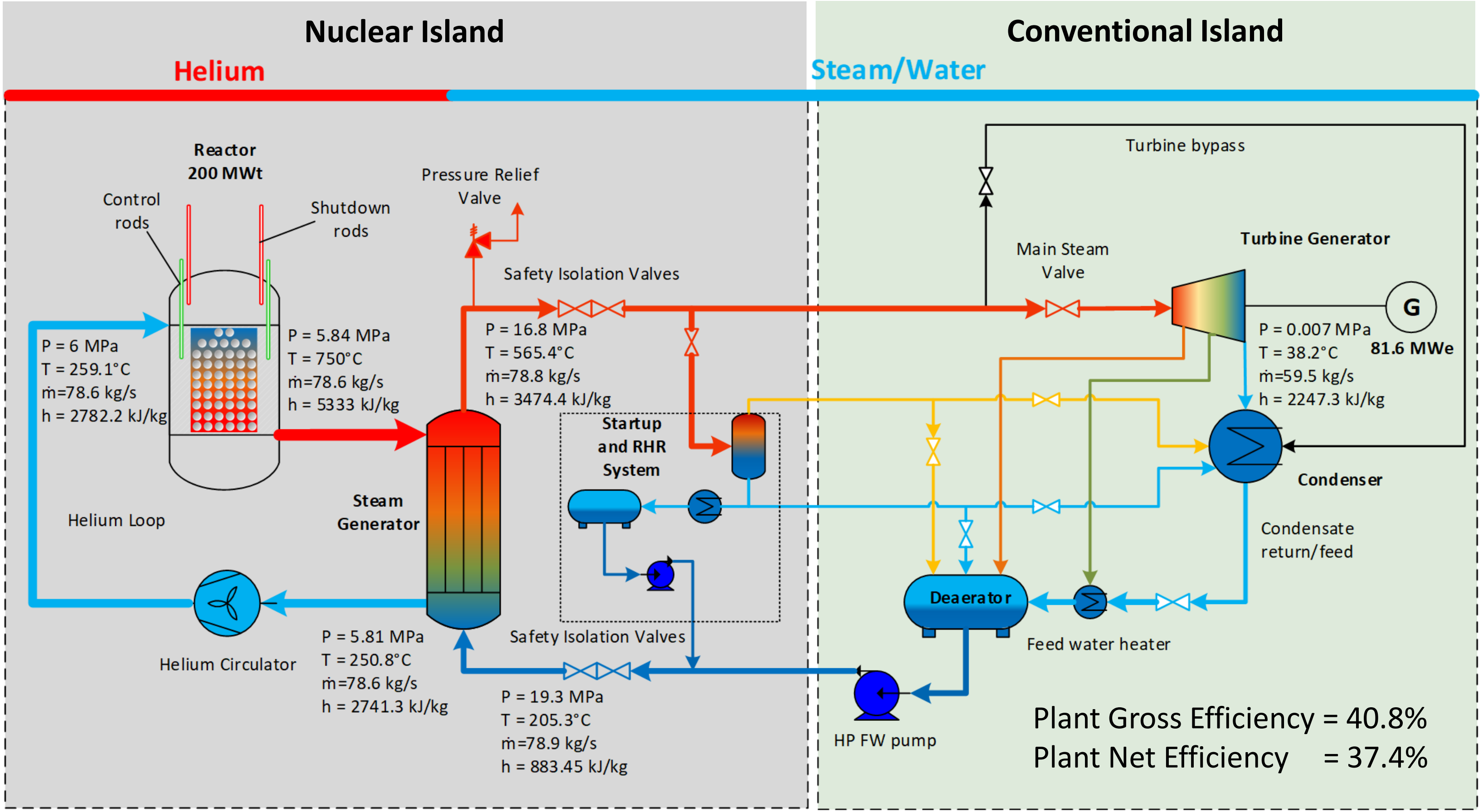
Key Technical Specifications:

- 200MWt Pebble Bed Reactor
- Rankine Cycle for power conversion – 75MWe
- Helical coil steam generator
- Steam at 565°C / 16.5MPa
- Multi pass fuel cycle (average 6 passes)

Reactor Pressure Vessel Material	
Component	**Material**
Bottom Head, Manway Shell, Crossover vessel	SA-508, Grade 3, Class 1
Vessel Flange, Top Head CRDM Housings	SA-508, Grade 3, Class 2
Top Head Fasteners	SB-637, Alloy 718
Center Manway Fasteners Bottom Manway Fasteners	SA-540, B24, Class 1
Note: *All material selections within existing ASME code requirements, no code cases needed*	

Reactor Graphite Reflector Material
IAW ASME Section III, Division 5
Irradiation program at ORNL underway

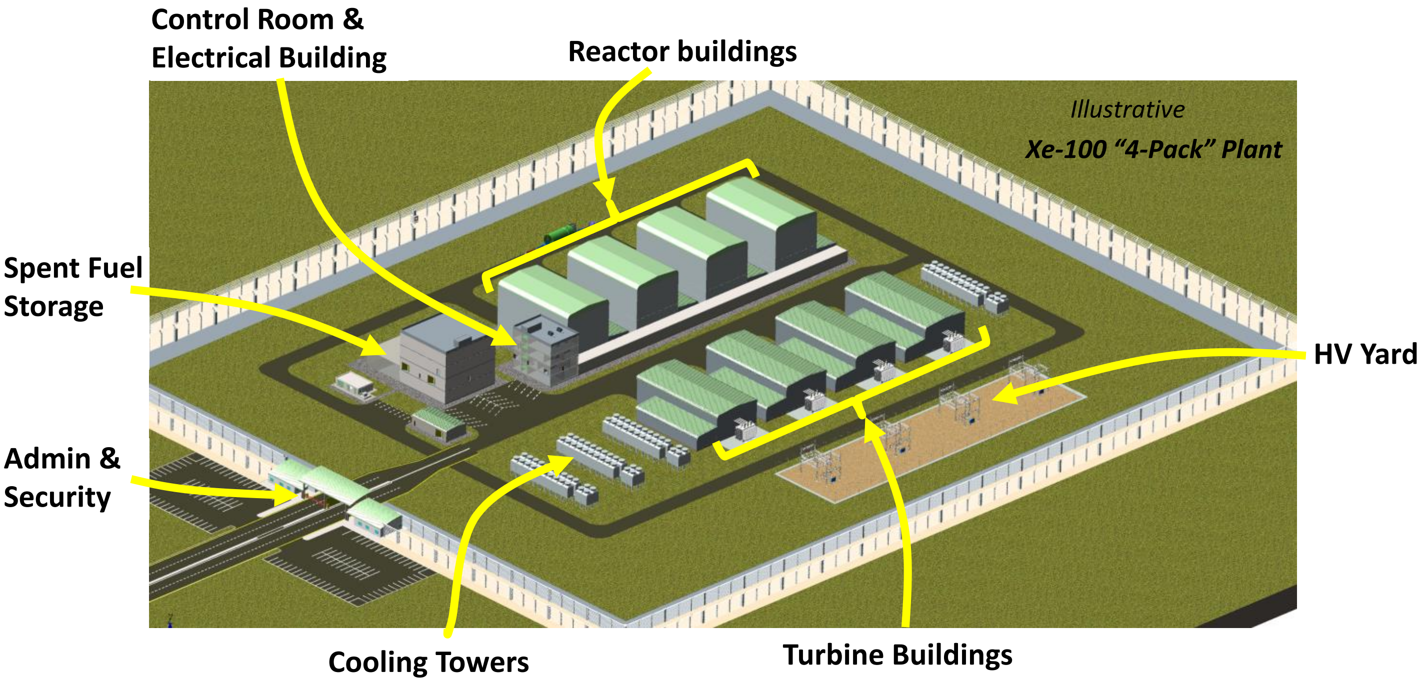
Xe-100 Energy Balance Process Flow Diagram



Plant Gross Efficiency = 40.8%

Plant Net Efficiency = 37.4%

Xe-100 Reactor Four Module Plant Layout (300 MWe)

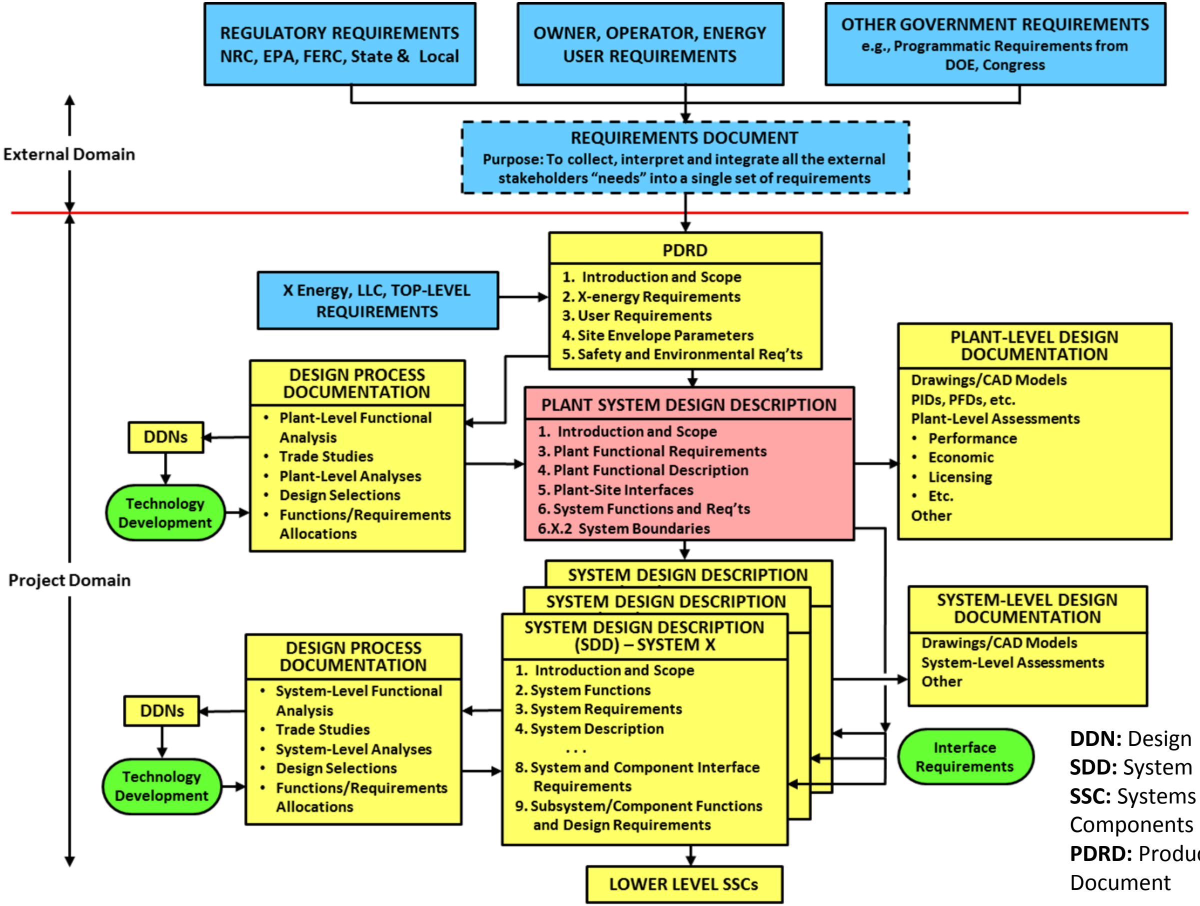


- **Scalable:** allows for sequential reactor build-out based on power demand
- **Small:** can be built on 13 acres of land and allows for grid independence
- **Safe:** small EPZ potential allows building close to existing infrastructure
- **Plant Life:** designed to achieve total life of at least 60 years

Technology Implementation

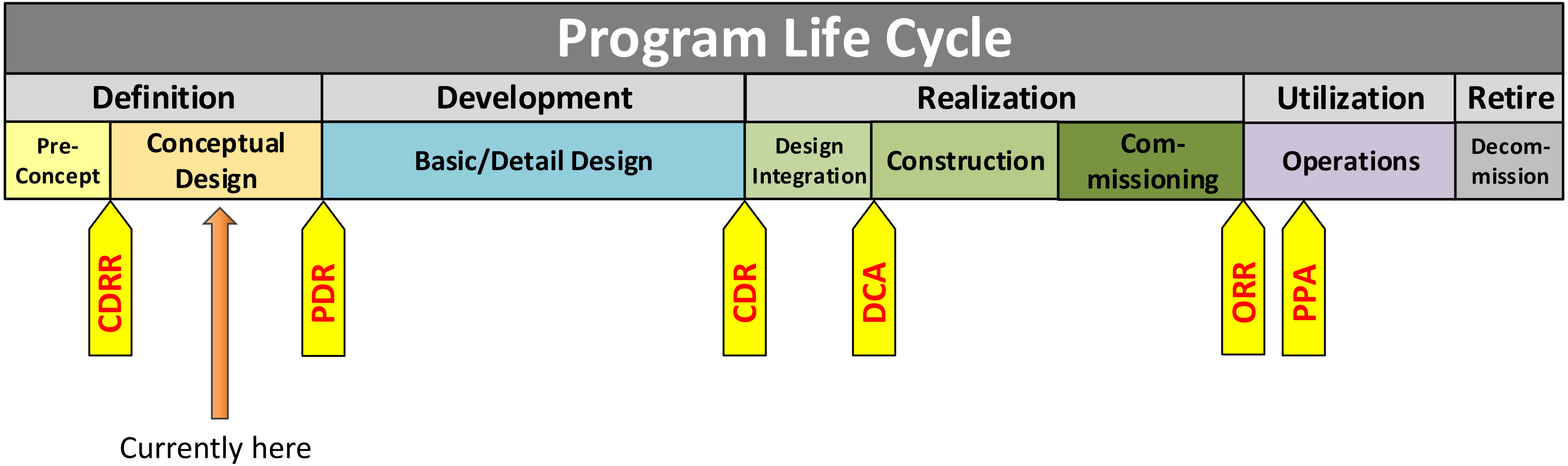
Dr. Martin van Staden

Requirements Definition and Flow-down



- X-energy is following a strict Systems Engineering approach for the design of the Xe-100 Plant
- All requirements are managed using a requirements management tool "Core" to track requirements flow down
- The Product Design Requirements Document (PDRD) interprets all requirements on a Plant Level and flows them down into the lower level systems

DDN: Design Data Need
SDD: System Design Description
SSC: Systems Structures & Components
PDRD: Product Design Requirements Document



CDRR: Concept Design Readiness Review

PDR: Preliminary Design Review

CDR: Critical Design Review

DCA: Design Completion Assessment

ORR: Operational Readiness Review

PPA: Plant Performance Assessment

System Engineering Process – Conceptual Design Phase

Each design phase is executed through a methodical process with certain deliverables and reviews after each sub-phase

Conceptual Design Sub-Phases:

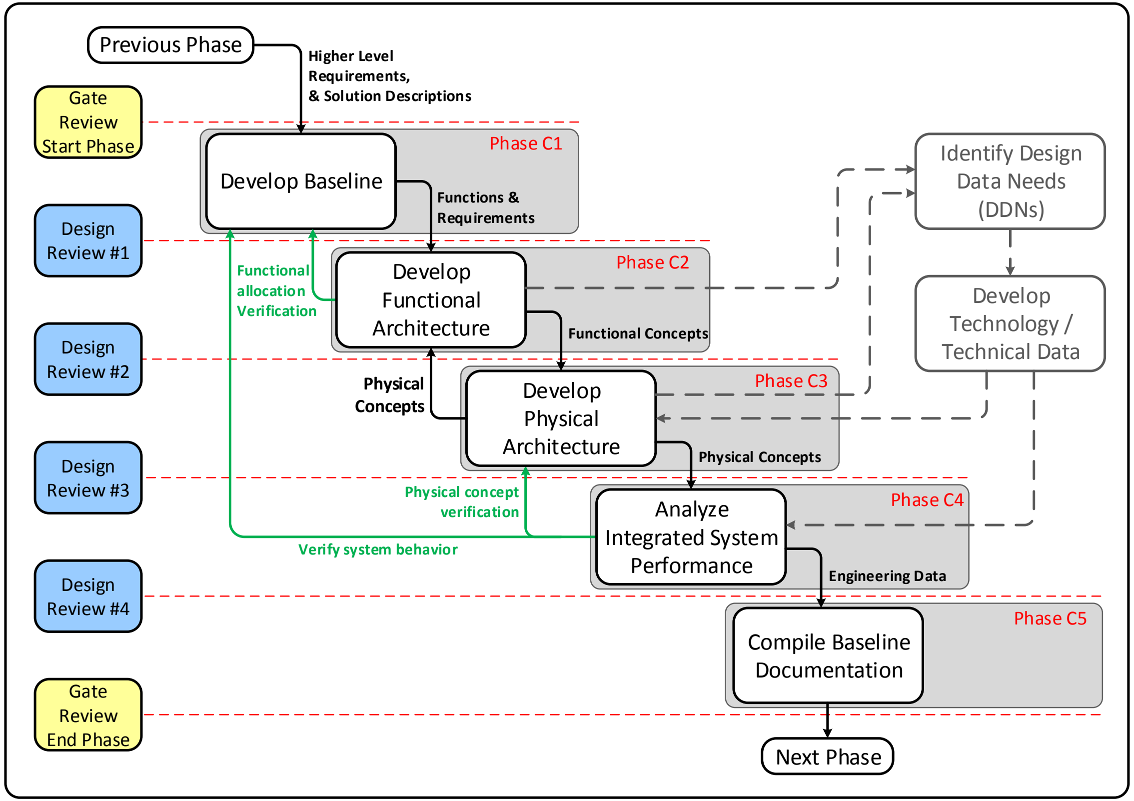
C1 - Design Basis:
Functions/requirements identified and allocated,

C2-Functional Definition:
System functional architecture defined,

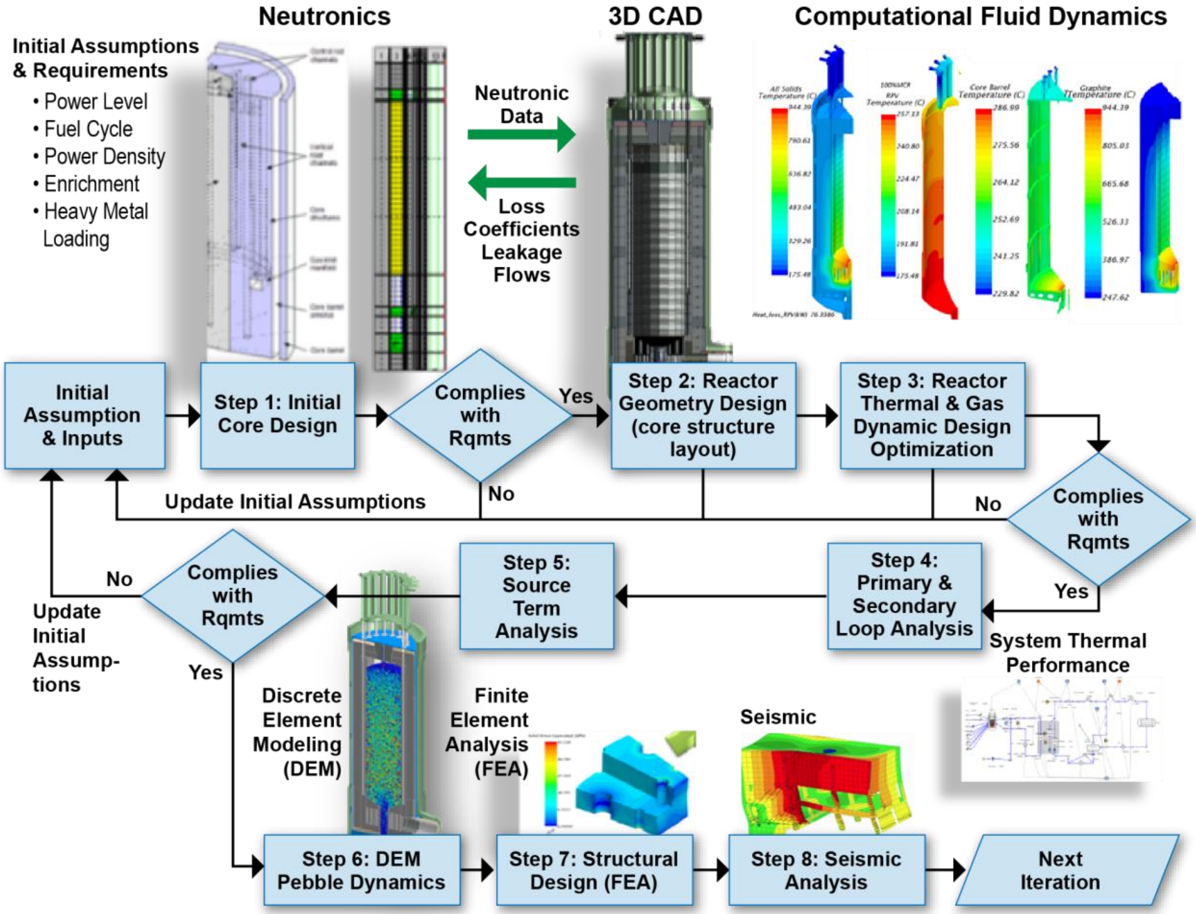
C3- Physical Definition:
System physical concept developed,

C4-Performance Evaluation:
System behavior demonstrated

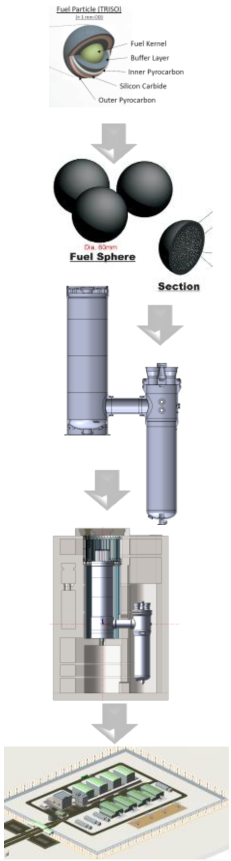
C5-Baseline Documentation:
System solution adequately described



Reactor Integrated Design Process



Radionuclide Source Term Calculation Path



Source Term Path

Releases from TRISO fuel particles

↓

Releases from fuel elements (pebbles)

↓

Releases from Pressure boundary

↓

Releases from building

↓

Max dose at site boundary

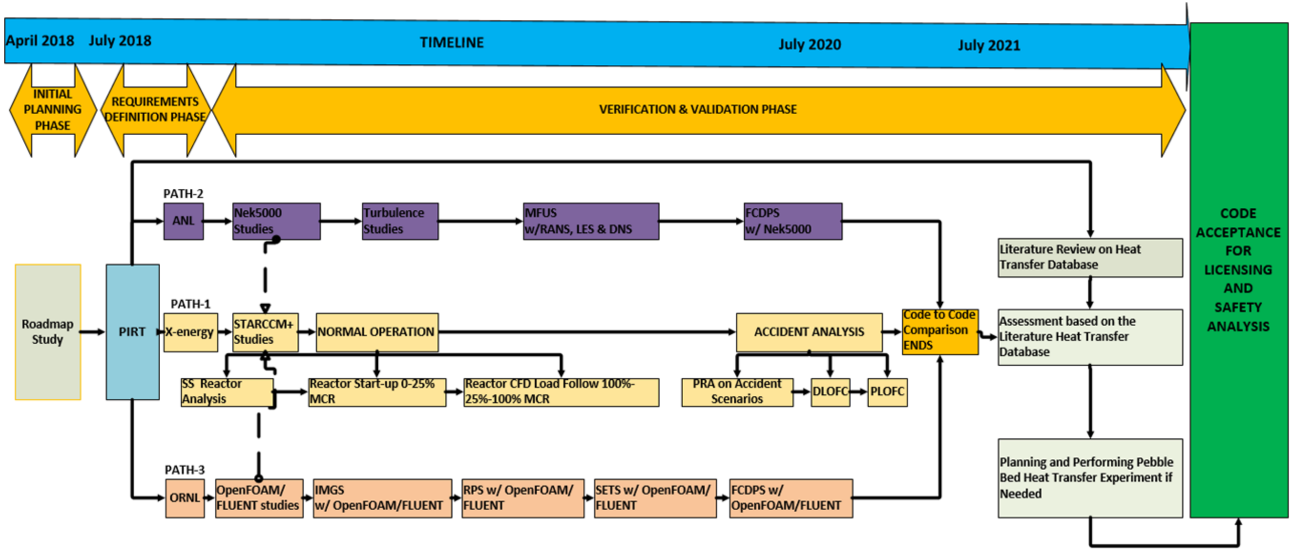
Element / Isotope	Form / State	Mechanism	Physical Phenomena	Methods / Software Codes
Iodine Silver Strontium Cesium …	Gaseous FPs Metallic FPs	- Release from TRISO particles into matrix graphite - Activation of impurities	Temperature, irradiation time, fast fluence, burnup, particle defects, contamination	VSOP, MGT SCALE, PARCS, ORIGEN FLOWNEX XS-Term STAR-CCM+
Iodine, Silver Strontium Cesium Graphite dust	Gaseous FPs Metallic FPs Dust Particles	- Diffusion from pebble into the helium stream - Activation of impurities	Temperature, irradiation time, fast fluence, burnup, contamination	VSOP, MGT SCALE, PARCS, ORIGEN, FLOWNEX XS-Term STAR-CCM+
Iodine, Silver Strontium, Cesium Graphite dust Metallic dust	Gaseous FPs Metallic FPs Dust Particles	- Leakage from HPB into building and structures - Activation of impurities	Instrumentation line failure, small & large pipe breaks, plate-out, liftoff	ORIGEN XS-Term STAR-CCM+ Flownex
Iodine, Silver Strontium, Cesium Graphite dust Metallic dust	Gaseous FPs Metallic FPs Dust Particles	- Transport throughout building to the environment	Plate-out, liftoff	XS-Term MELCOR STAR-CCM+
Iodine, Silver Strontium, Cesium Graphite dust Metallic dust	Gaseous FPs Metallic FPs Dust Particles	- Atmospheric dispersion - Ingestion	Postulates	XS-Term STAR-CCM+

Development of Analysis Tool Roadmaps

X-energy has developed a number of roadmap documents in conjunction with the DOE Labs and prominent universities:

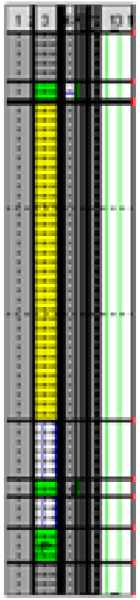
- Neutronics analysis tools roadmap
- CFD heat transfer analysis V&V Roadmap
- Mechanistic Source Term Roadmap
- Graphite Core Structures Design Roadmap

Example of Heat Transfer CFD V&V Roadmap

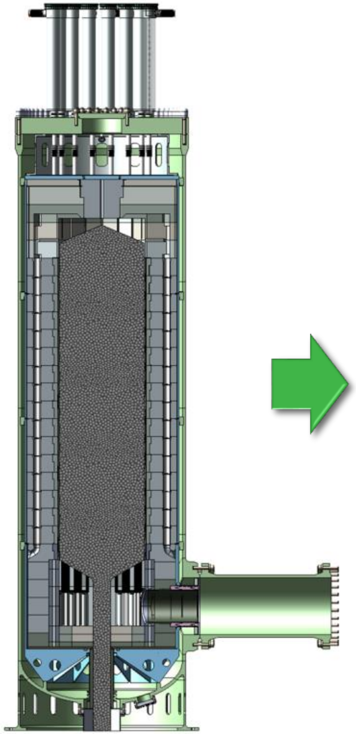


Reactor Design Analysis

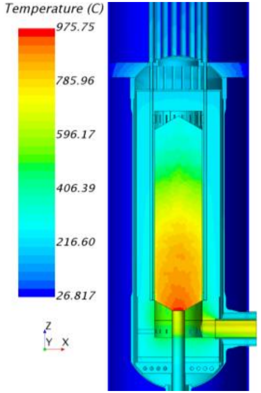
Neutronics stress analysis → 3D Geometry → Thermal flow → Static & thermal load



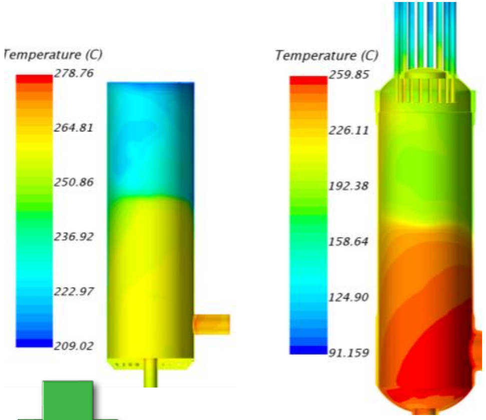
New core design (Neutronics)

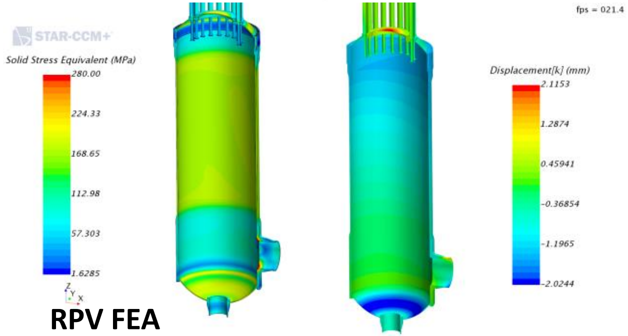


Detailed 3D CAD



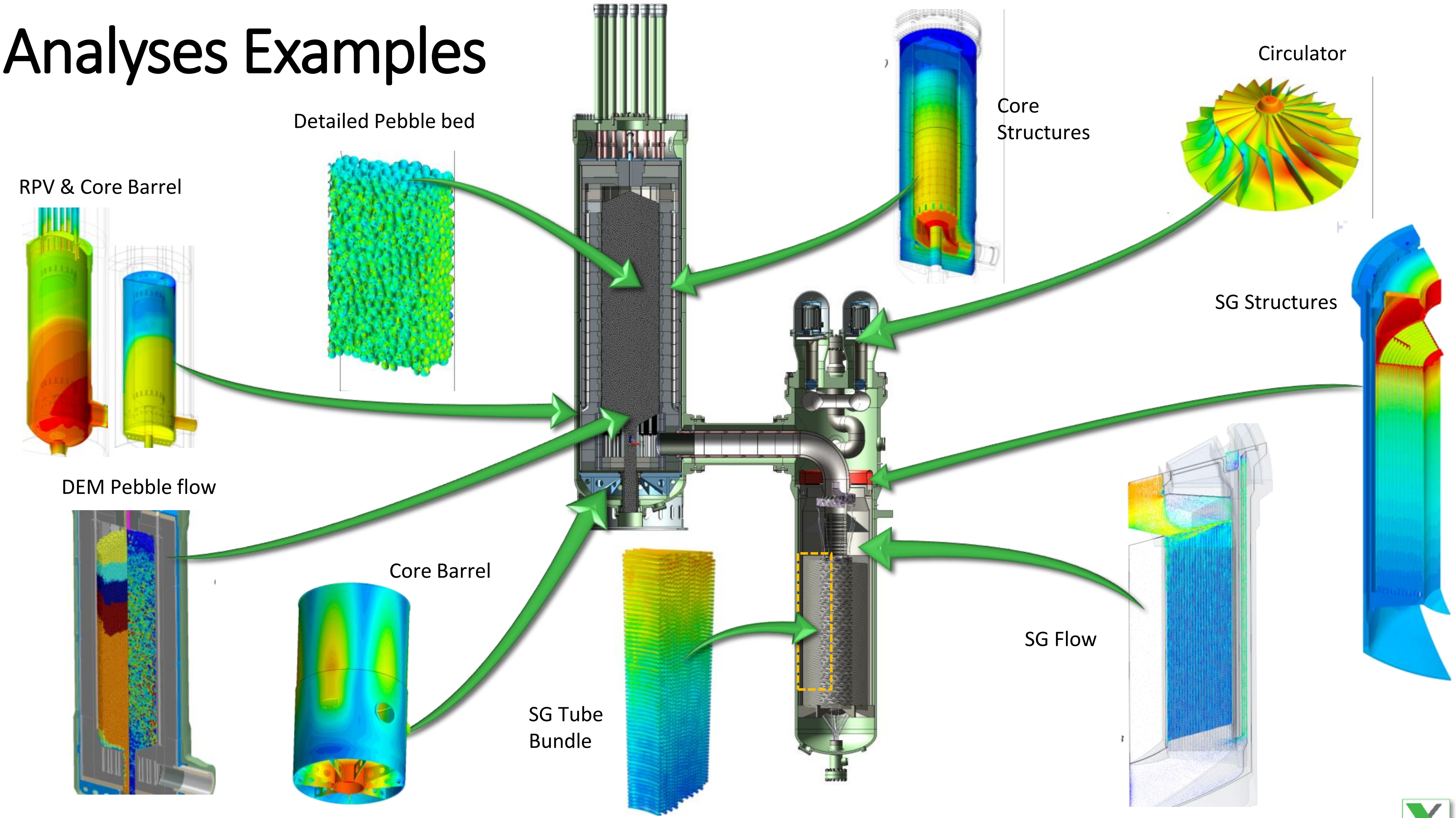
Detailed CFD





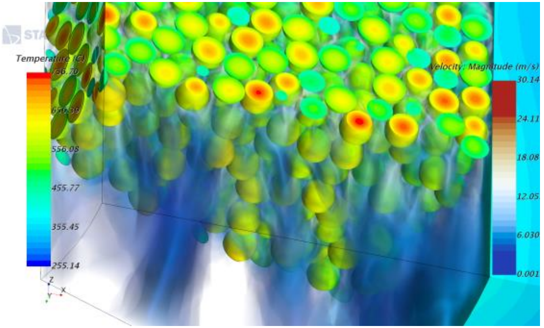
RPV FEA

Analyses Examples

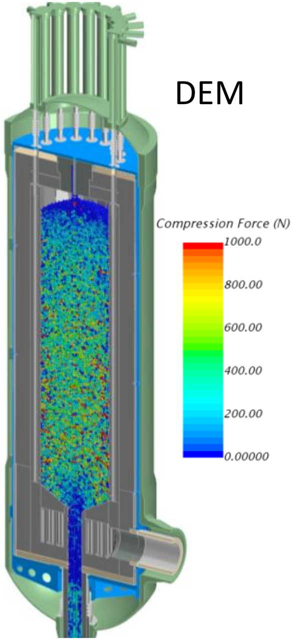


Verification and Validation

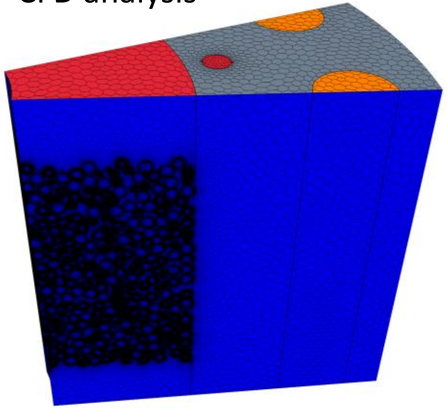
- Using models to perform verification and validation of simplified porous media models
- Directly export Discrete Element Model (DEM) results to mesh pebbles
- Heat is generated in the fuel core zone of the pebble, providing valuable insight into the pebble temperature distribution

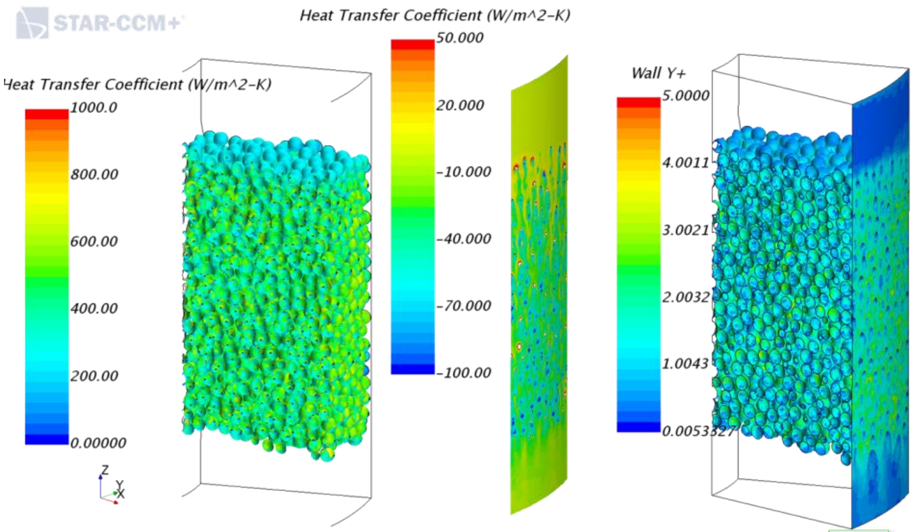


DEM



Detailed randomly packed physical geometry meshed for CFD analysis

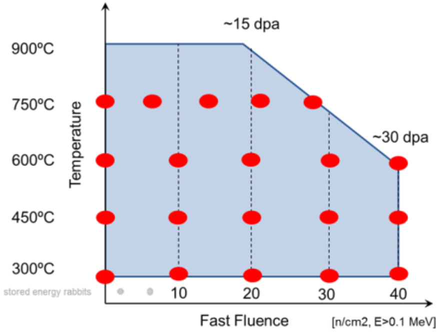




Graphite Modeling & Irradiation

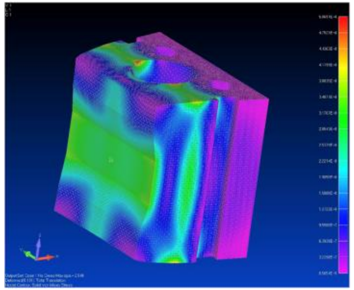
- Structural graphite performs the following important functions in a pebble bed reactor:
  - Defines the core geometry
  - Defines the helium flow path
  - Reflects neutrons
  - Provides heat removal path and heat capacitance during loss of forced flow events
- X-energy has developed in-house graphite lifetime analysis tools for prediction graphite lifetime using guidelines outlined in ASME Section III Division 5
- Graphite irradiation campaign is underway with SGL at Oak Ridge in HFIR
  - Temperature range is between 250°C and 750°C
  - Dose range up to 30 dpa

Graphite Irradiation test envelope



Graphite Structural Analysis

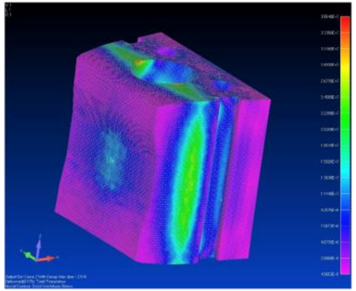
Without creep



Max dpa 2.5

Max Von Mises stress 54 MPa – above allowable – failure

With Creep

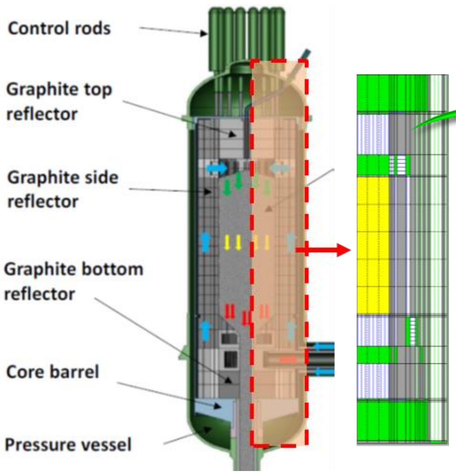


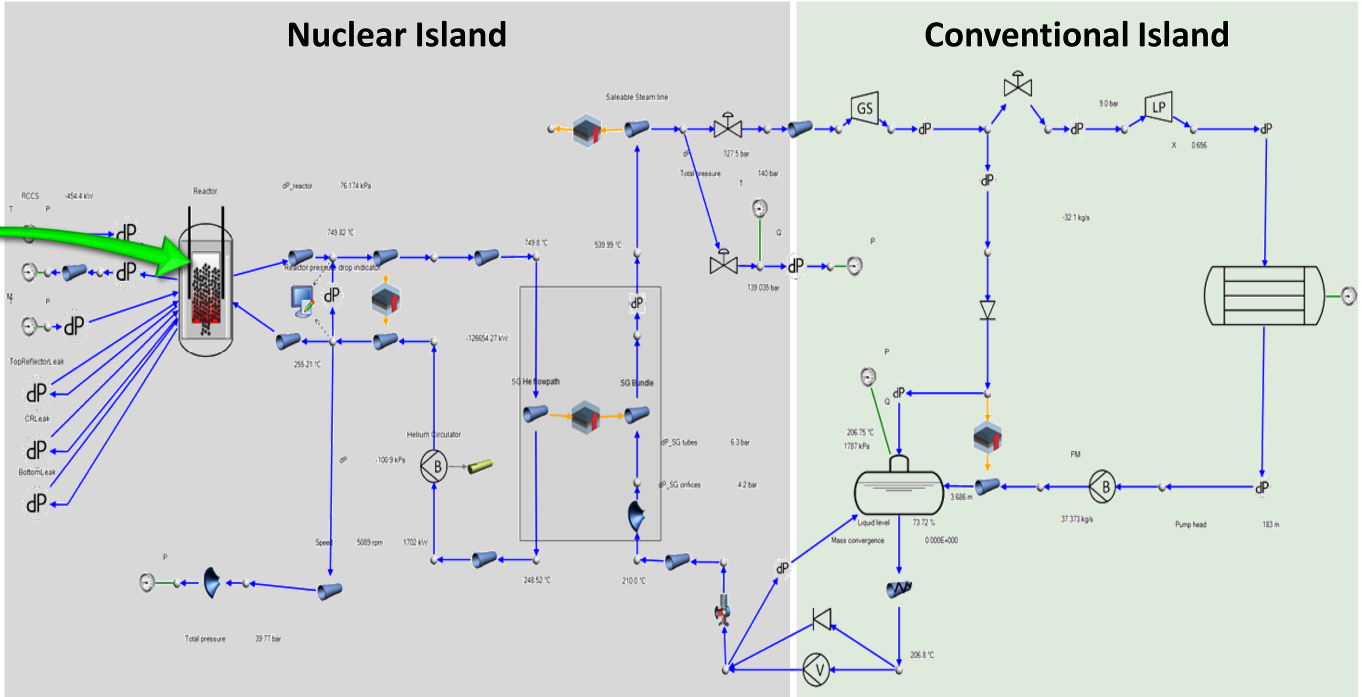
Max Von Mises stress 3.8 MPa POF 5.1E-4

Comprehensive Systems Analysis

- Comprehensive full system analysis using Flownex compressible transient flow code (NQA 1 compliant)
- Perform system transients and develop control philosophy

Detailed 2D Reactor sub-model





Program Status

Clint Medlock

X-energy Advanced Reactor Concepts Award

DOE COOPERATIVE AGREEMENT

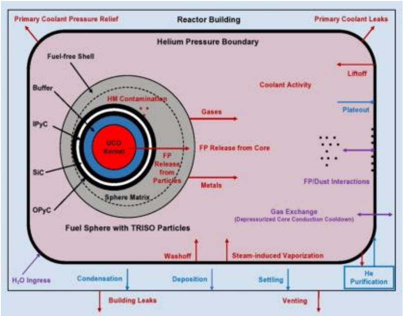
X-energy began activities July 1, 2016 on a 5-year, $53M cooperative agreement with the U.S. Department of Energy focused on:

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

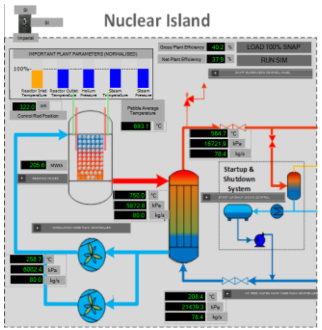
MAJOR ACCOMPLISHMENTS

- Developed structural graphite TRL and operating envelope
- Developed probabilistic risk assessment fault tree
- Completed three white papers on regulatory issues
- Developed unique mechanistic source term codes
- Implemented a plant level engineering analysis toolset software package
- Developed Porous media heat transfer model and performed initial V&V using detailed pebble CFD

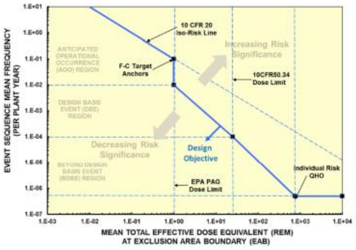
Source term code development



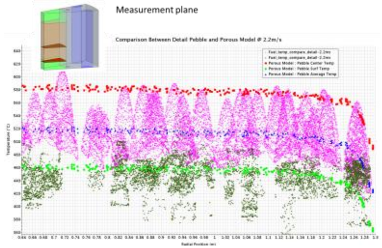
Plant level engineering analysis toolset



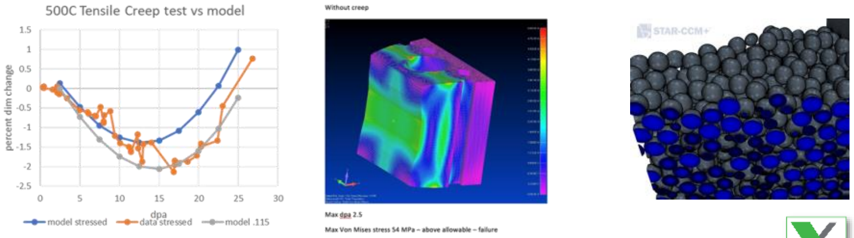
Probabilistic risk assessment



Porous media heat transfer model

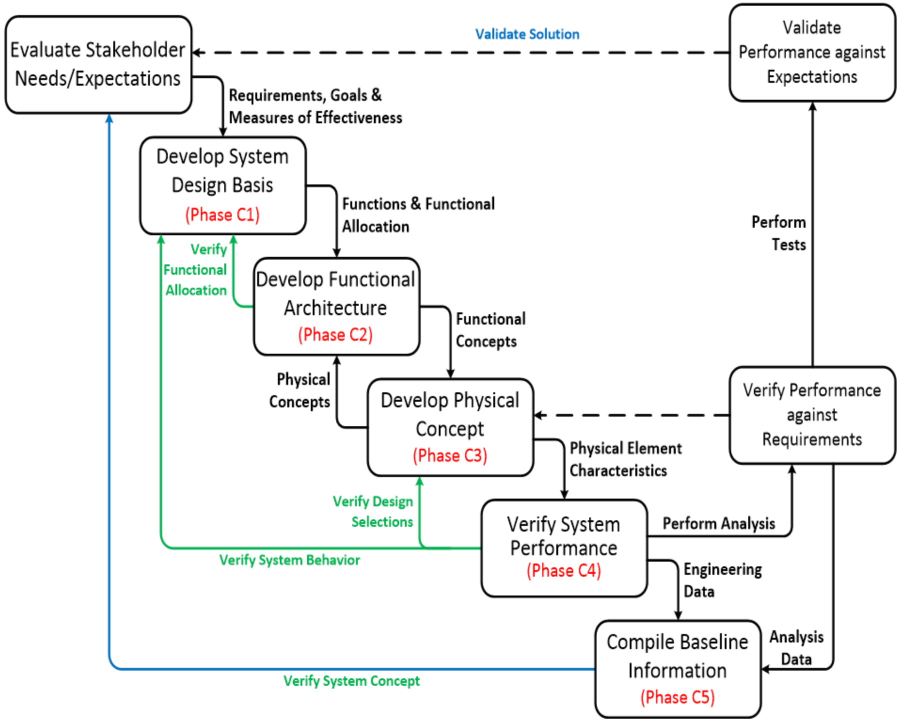


Graphite lifetime modelling



Program Status

System	CD Maturity	Current Phase (% CPLT)
Plant-Level Definition		
Plant System	C4	C2 (20%)
Distributed Control System	C4	C3 (90%)
Investment Protection System	C2	C1 (20%)
Plant Site	C2	Pre-Concept
Major Systems Definition (supporting Licensing Basis)		
Reactor System	C4	C3 (80%)
Steam Generator System	C4	C3 (75%)
Reactor Cavity Cooling System	C4	C3 (40%)
Fuel Handling System	C3	C3 (35%)
Spent Fuel Storage Facility	C3	C3 (10%)
Helium Circulator System	C2	C2 (100%)
Helium Services System	C2	C2 (100%)
Reactor Protection System	C4	C2 (0%)
Startup and Shutdown System	C3	Pre-Concept
Nuclear Island Civil Structures	C3	Pre-Concept
Auxiliary Systems Definition		
Nuclear Island HVAC System	C2	Pre-Concept
Nuclear Island Cooling Water System	C2	Pre-Concept
Nuclear Island Electrical System	C2	Pre-Concept
NI Fire Detection and Suppression System	C0	Pre-Concept
Plant Access and Security System	C1	Pre-Concept



Acronyms and Abbreviations

Acronyms and Abbreviations

-A-	
ANL	Argonne National Laboratory
-C-	
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
CRDM	Control Rod Drive Mechanism
CVD	Chemical Vapor Deposition
-D-	
DDN	Design Data Need
DEM	Discrete Element Modeling
DOE	Department of Energy
-E-	
EPZ	Emergency Planning Zone
-F-	
FEA	Finite Element Analysis
FP	Fission Products
-H-	
HFIR	High Flux Isotope Reactor
HM	Heavy Metal
HTGR	High-Temperature Gas-cooled Reactor
HV	High-voltage
-I-	
INL	Idaho National Laboratory
N-	
NGNP	Next Generation Nuclear Plant Alliance
NQA	National Quality Assurance
NRC	Nuclear Regulatory Commission
-O-	
ORNL	Oak Ridge National Laboratory
-**P-**	
PDRD	Product Design Requirements Document
RPV	Reactor Pressure Vessel
-S-	
SDD	Systems Design Description
SG	Steam Generator
SNL	Sandia National Laboratories
SSC	Systems Structures & Components
-T-	
TRISO	Tristructural ISOtropic
-U-	
UCO	Uranium oxide – carbide mixture
-V-	
V&V	Verification and Validation

X Energy, LLC
7701 Greenbelt Road, Suite 320
Greenbelt, MD 20770
Phone: 301.358.5600

www.x-energy.com
@xenergynuclear