Clean • Safe • Secure • Affordable

X-energy XENITH™ Analytical Methods

Public Presentation to the NRC – May 1, 2024

Non-Proprietary | Unclassified

Agenda

Section	Presenter
Introduction to X-energy and XENITH	Dr. Brad Rearden, *Senior Director, Microreactor Programs*
Regulatory approach to XENITH and Analytical Methods	Michael Dudek, *Manager, Licensing*
Overview of Quality, Design Process and Tool Suite	Dr. Dov Rhodes, *Lead, Technical Integration*
Tools and early-stage V&V - neutronics	Dr. Steve Wilson, *Manager, Nuclear Engineering*
Tools and early-stage V&V – reactor dynamics / thermal / structural	Dr. Adam Oler, *Manager, Reactor Dynamics and Multiphysics*

Introduction to X-energy and XENITH

Dr. Brad Rearden
Senior Director, Microreactor Programs

Changing the World

Dr. Kam Ghaffarian,
Founder and
Executive Chairman

"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 is a globally recognized technology visionary across energy, space and information technology.

Stinger Ghaffarian Technologies

- Created and grew Stinger Ghaffarian Technologies (SGT), Inc. to $650 million in annual revenue and 2,400 employees. SGT was ranked as the U.S. National Aeronautics and Space Administration's second largest engineering services company prior to being acquired by KBRwyle, subsidiary of KBR, Inc.

X energy

- Founded X-energy in 2009 to address innovation in critical energy solutions. In 2016 X-energy was awarded ~$60M from DOE to focus on an advanced nuclear reactor and TRISO fuel. In 2020 X-energy awarded the Advanced Reactor Demonstration Program for a value of $2.4 billion

Intuitive Machines

- 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, with the first commercial lunar landing achieved on February 22, 2024

Axiom Space

- Founded Axiom Space in 2017 to develop the first commercial space station. Axiom-1 launched in 2022. Axiom-3 launched Jan 18 – Feb 9, 2024

X-Energy at-a-Glance

Founded in 2009 *14 years of investment and development*	**Rockville, MD Headquarters** *Rooted in the nuclear community with proximity to the DOE and Nuclear Regulatory Commission ("NRC")*
50+ Years of R&D *Built upon years of R&D in high temperature gas reactors*	**~400+ Employees** *Leading Gen IV nuclear development and licensing team(1)*
$1.2bn Federal Funding *Selected for DOE's Advanced Reactor Demonstration Program(2)*	**~$610mm Investment** *Capital invested to date with ~$150 million of committed capital(3)*

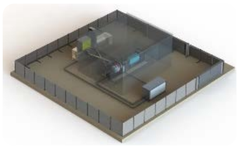
X-energy's Advanced Nuclear Technology

Our High Performing Reactor: Xe-100

- Gen-IV High-Temperature Gas-cooled Reactors (HTGR) have advantages in sustainability, economics, reliability, safety, and versatility in application
- Each reactor will be engineered to operate as a single 80 MWe unit and is optimized as a four-unit plant delivering 320 MWe

Our Clean and Safe Fuel: TRISO-X

- Our reactors will use tri-structural isotropic (TRISO) particle fuel, developed and improved over 60 years
- TRISO is designed not to melt and can withstand extreme temperatures that are well beyond the threshold of current nuclear fuels
- We manufacture our own proprietary version (TRISO-X) to ensure supply and quality control



Other Strategic R&D Initiatives

- We are developing advanced microreactor concepts for nuclear power and propulsion for potential military, space, and commercial applications

1) *As of December 2023*
2) *Awarded in December 2020*
3) *As of December 2023, includes $240mm of government funding, $103mm invested capital of Series C-2 financing, including a $30mm investment from Ares management, and $80mm capital commitment, including $50mm from Ares Management and approximately $30mm from Kam Ghaffarian*

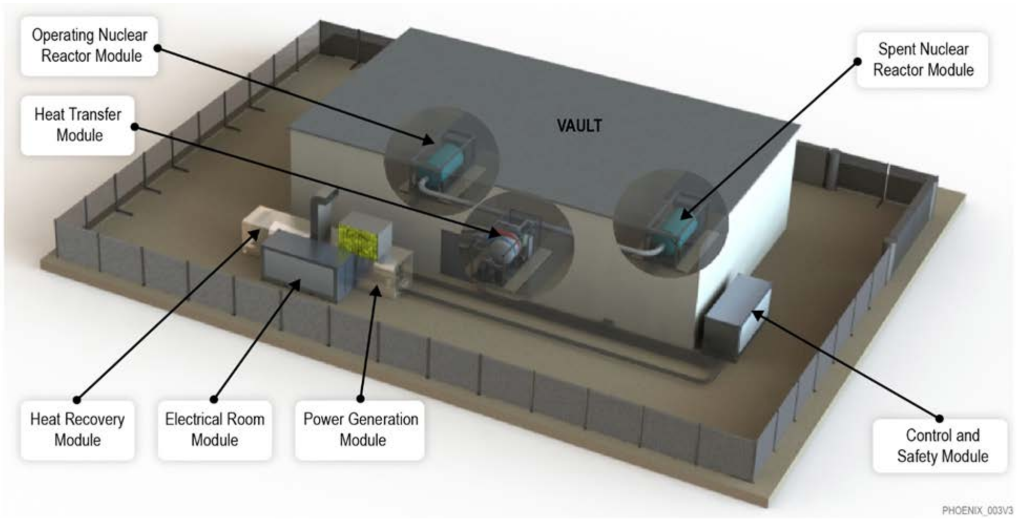
X-Energy and Project Pele

- Through the Strategic Capabilities Office’s Project Pele, the Department of Defense invested $45M in X-energy and our partners to develop the final design, perform prototype testing, and establish a supply chain capable of deploying our solution on a 2-year schedule.
- X-energy contributed another $20M as internal investment in initial conceptual design development, additional design fidelity, and engineering test unit demonstrations.
- Our final design was evaluated by military personnel as well as dozens of globally recognized subject matter experts across a broad range of disciplines, providing significant added value in ensuring the microreactor plant provided needed performance and is safe, resilient, and realizable on an accelerated schedule.
- Pele Prototype Project: Phase II contract modification signed September 11, 2023, for an additional $17.5M in DOD support for a higher power and more economically competitive design and engagement with the NRC in the regulatory process. Note that this program remains CUI.
- "Due to their extraordinary energy density, nuclear reactors have the potential to serve multiple critical functions for meeting resiliency needs in contested logistical environments," said Dr. Jeff Waksman, Project Pele program manager. "By developing two unique designs, we will provide the Services with a broad range of options as they consider potential uses of nuclear power for both Installation and Operational energy applications in the near future."

X-Energy Next-Generation Integrated Transportable High-Temperature (XENITH™) Microreactor Plant – Point Design

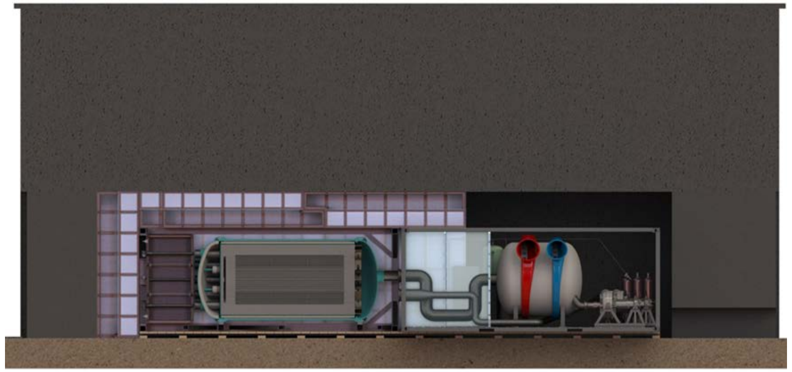
Design Philosophy

- Next generation of HTGR with novel features that enable high performance in a small, factory assembled, road transportable package
- Exploits mature technologies to accelerate deployment and licensing schedules
- Patents in progress for novel design elements
- Commercialization pathways supported by DOE Office of Nuclear Energy award for Market-Driven Optimization of XENITH



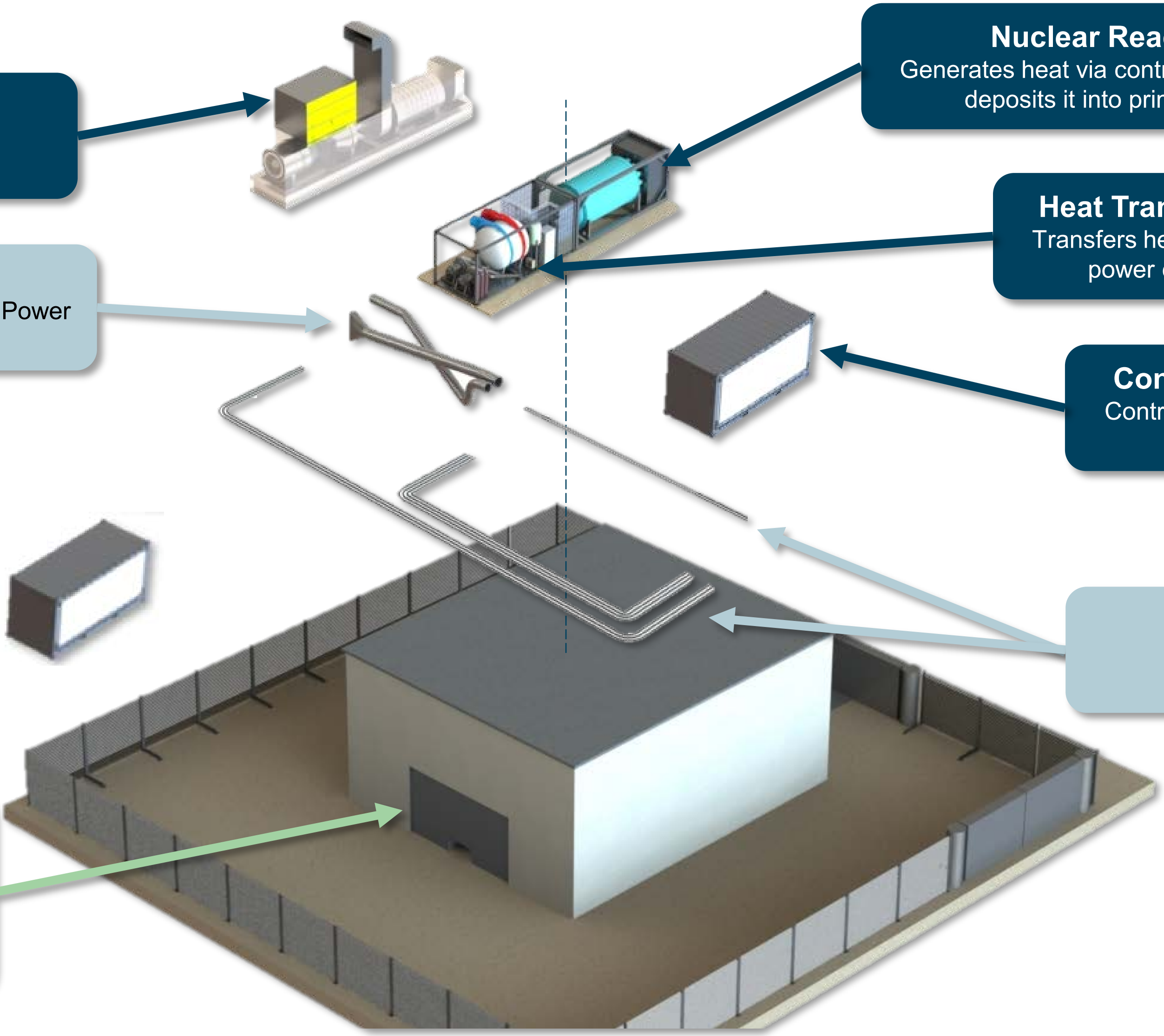
Attributes

- Targeting 3–10 MW net electricity output with optional waste heat recovery for process heat, desalination, hydrogen generation
- Modular design supports:
  - Factory assembly and testing
  - Transportability (to remote locations)
  - Alternate power conversion systems and upgrades
  - Reactor replacement
- Stand-alone operation or backbone of a microgrid
- Configurable radiation shielding enables collocation of site operations personnel and no residual radioactive material left at the site



Customizable shielding contains the radiation

XENITH Point Design Functional Modularity



Power Generation Module (PGM)
Uses an industrial gas turbine to convert hot air into electricity

Air Pipe System (APS)
Delivers hot air from the HTM to the Power Generation Module

Electrical Room Module (ERM)
Conditions generator output and distributes to plant systems and external loads

Heat Recovery Module (HRM)
Uses turbine exhaust to boost cycle efficiency and heat water for district heating

Nuclear Island Building
Provide radiation shielding for components, operators, maintenance technicians, and general public
- Physically protect and restrict access to NRM and HTM

Nuclear Reactor Module (NRM)
Generates heat via controlled nuclear chain reaction and deposits it into primary working fluid (helium)

Heat Transfer Module (HTM)
Transfers heat from the reactor to the power conversion fluid (air)

Control & Safety Module (CSM)
Controls and protects the power plant and interfaces with plant operators

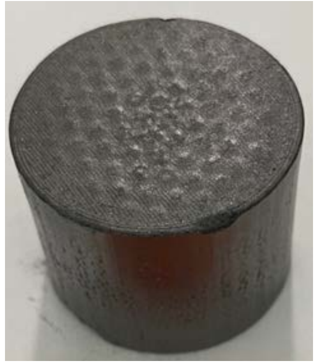
Inter-Module Cabling
Transfers data and power between plant systems

Plant Module

Inter-Module Connection

On-Site Structure

Engineering Test Unit Prototype Testing to Advance TRL



TRISO Fuel Compact

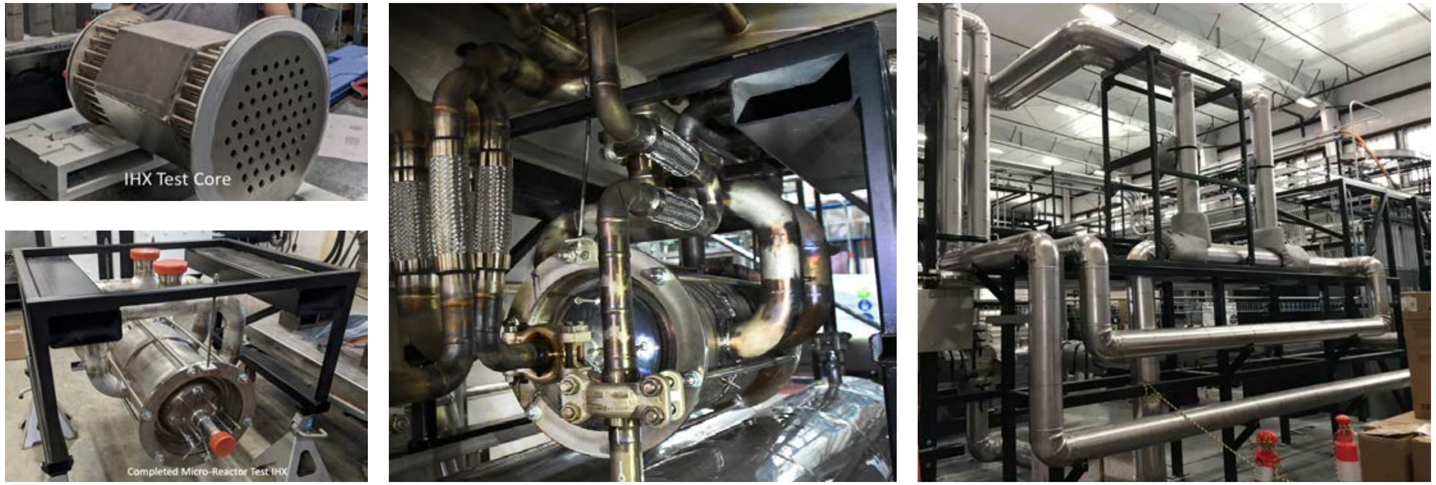
Manufactured at TRISO-X fuel facility for physical testing

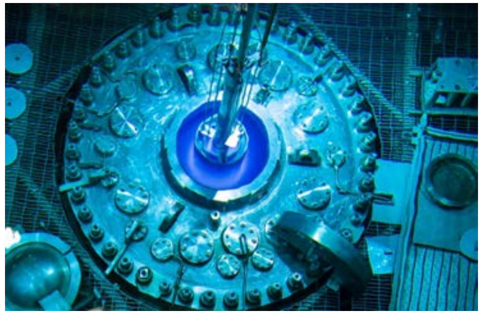
Helium Pressure Vessel

Large component integration testing at prototypic conditions

Helium Flow Loop

Helium-to-air heat exchanger testing at prototypic conditions





Irradiation Testing

Multiple proprietary irradiation test campaigns to prove the performance of materials in reactor environments

Meeting Objectives

Purpose:

- Summarize the scope of the upcoming *XENITH Topical Report on Analytical Methods* scheduled for submittal in June, 2024, including:
  - Overview of the processes for design, analysis, verification and validation (V&V)
  - Introduction to engineering software suite, and tool selection background
  - Early-stage V&V results (non-proprietary work)

Outcome:

- Receive feedback on the topical report scope and presented content

Process:

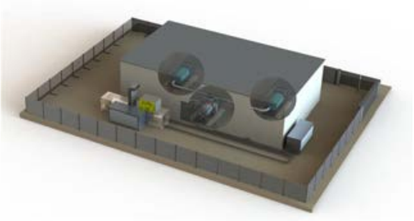
- Leverage feedback from this meeting as well as Rev. 1 of the topical report to improve our analytical methods and V&V processes; gain confidence in our engineering tools and models

Regulatory Approach to XENITH and Analytical Methods

Michael Dudek
Manager, Licensing

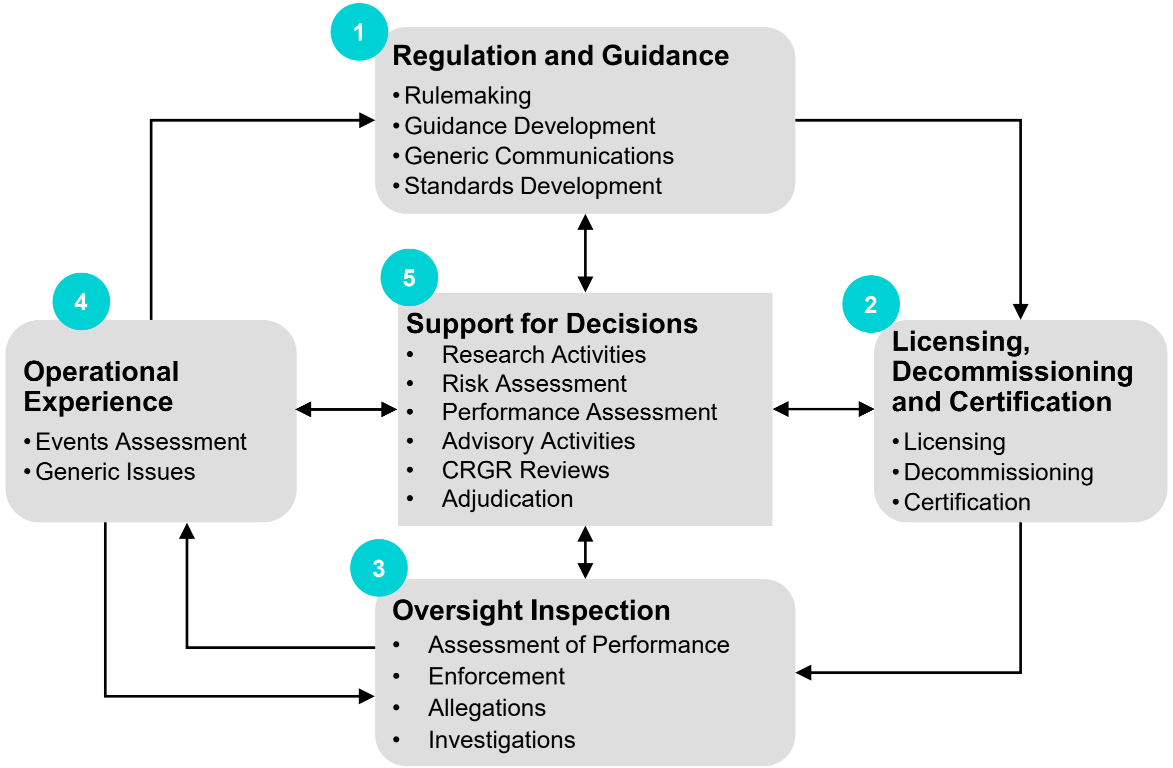
XENITH Licensing Strategy

- XENITH is docketed with the U.S. Nuclear Regulatory Commission (Project #99902118)
- Licensing the XENITH Design:
  - Safety (Design)
  - Security and Emergency Preparedness
  - Environmental
- Manufacturing the modules via NQA-1 processes where required
- Evaluating SECY-24-0008, "Micro-Reactor Licensing and Deployment Considerations: Fuel Loading and Operational Testing at a Factory“:
  - Fuel Loading at the Factory
  - Operational Testing at the Factory
  - Transportation of the Site
- Decommissioning or Refurbishment
- Post-Operation Transportation



Note: Details of the licensing plan are CUI

Regulatory Basis for V&V and Analytical Methods



The goal of XENITH's V&V Plan is to identify software verification and validation activities that, once completed, provide reasonable assurance that the chosen codes will perform their intended functions exhibiting a quality commensurate with the importance of the design's safety systems

- XENITH team has utilized Regulatory Guide 1.168, "Verification, Validation, Reviews, and Audits for Digital Computer Software Used in Safety Systems of Nuclear Power Plants," Revision 2, July 2013
- X-energy's Topical Report on Analytical Methods does describe XENITH's V&V Plan that is consistent with the applicable requirements are defined by the Institute of Electrical and Electronics Engineers (IEEE) Std. 1012-2004, "IEEE Standard for Software Verification and Validation" (Rev. 4); and IEEE Std. 1028-2008, "IEEE Standard for Software Reviews and Audits" (Rev. 5) as endorsed by Regulatory Guide 1.168
- XENITH team recognizes that the use of industry consensus standards, such as IEEE, is part of an overall approach to meeting the requirements of 10 CFR Part 50/52 when developing safety system for nuclear power plants
- XENITH's V&V Plan is also consistent with NUREG/CR-6101, "Software Reliability and Safety in Nuclear Reactor Protection Systems" (July 1993); and Draft Regulatory Guide DG-1120, "Transient and Accident Analysis Methods" (December 2002)
- High level design & analysis lifecycle guided by NASA Systems Engineering Handbook (Rev. 2, 2017)

Overview of Quality, Design Process, and Tool Suite

Dr. Dov Rhodes
Lead, Technical Integration

Alignment of R&D Design Stages with NQA-1 R&D Guidance

- X-energy R&D design control developed to apply appropriate rigor to facilitate rapid design prototyping of advanced nuclear systems
- We apply NQA-1 4.2.1 to align research maturity, technology readiness level (TRL), and X-energy design stage

<table>
<tr><th>NQA-1 Subpart 4.2.1 Guidance</th><th colspan="2">DOE/DOD Technology Readiness Level</th><th>X-energy R&D Design Phase</th></tr>
<tr><td rowspan="2">Basic Research</td><td>Basic Technology/ Research</td><td>TRL 1</td><td>Pre-Conceptual</td></tr>
<tr><td rowspan="3">Research to Prove Feasibility</td><td>TRL 2</td><td rowspan="3">Conceptual</td></tr>
<tr><td rowspan="4">Applied Research</td><td rowspan="2">TRL 3</td></tr>
<tr></tr>
<tr><td rowspan="5">Technology Demonstration</td><td rowspan="2">TRL4</td><td rowspan="4">Preliminary</td></tr>
<tr></tr>
<tr><td rowspan="4">Developmental Work</td><td>TRL5</td></tr>
<tr><td rowspan="2">TRL 6</td></tr>
<tr><td rowspan="2">Detailed/Final</td></tr>
<tr><td rowspan="2">System Commissioning</td><td>TRL 7</td></tr>
<tr><td rowspan="2">NQA-1 (i.e., outside Subpart 4.2.1 and into a graded application of NQA-1)</td><td>TRL 8</td><td>Production</td></tr>
<tr><td>System Operations</td><td>TRL 9</td><td>Operation</td></tr>
</table>

Leveraging X-energy’s Well-Established Quality Assurance System

X-e QAPD
(Quality Assurance Program Description)

X-energy quality vision, organization, and high-level requirements
- Calls out NQA-1 (2015), 10 CFR 50, 10 CFR 50 Appendix B, 10 CFR 52, 10 CFR 71
- *Reviewed and approved by NRC*

X-e QAM
(Quality Assurance Manual)

Implementation of QAPD quality program and requirements
- e.g. subsections from each requirement of NQA-1 Part I

R&D DQP
(Division Quality Plan)

R&D vision, organization, and high-level requirements
- Additions or exceptions to QAM
- Graded Approach to QA;
  - Based on *NQA-1 4.2.1 guidance for R&D*
- Underlying Quality Assurance Procedures (QAPs)

PQP
(Program Quality Plan)

XENITH design and development
- Address additions or exceptions to DQP
- e.g. organization, roles, information security, procurement…

Analytical Methods Tied to Design Lifecycle

Product development plan divided into Design Stages with well defined business, regulatory, technical and analytical objectives.

Pre-Conceptual — Ideation and Business Case
- Synthesize market research into product ideas
- Convert customer demand into functional requirements
- Assess technical and business feasibility

Conceptual — Technology Selection
- Begin engagement with customers, regulators and stakeholders
- Compare solutions via simple analysis and evaluation criteria
- Select solution and product development plan

Preliminary — Optimization and Safety Assessment
- Iterate to meet detailed requirements
- Raise M/TRL through subscale subsystem testing
- Complete risk assessment, safety classification
- Submit design license application

Detailed — Completion and Validation
- Generate manufacturing drawings
- Finalize subsystem M/TRL maturation
- Perform subsystems confirmatory analysis
- Ongoing regulatory evaluation and operating license application

Final — Manufacturing and Preparation
- Finalize supply chain and MAI&T schedule
- Conduct integrated non-nuclear testing and validation
- Perform full systems confirmatory analysis
- Complete regulatory process

*Use lightweight methods;
spreadsheets, scripts, interpolations*

*Transition to high fidelity tools, develop models, &
execute early stage V&V*

*Complete & validate models,
begin confirmatory analysis*

*Finalize/release design drawings,
complete confirmatory analysis*

Implementing a State-of-the-Art Nuclear Engineering Tool Suite

X-energy adopts proven software, uniquely suited for design and analysis of next-generation HTGR technology

X-energy R&D Tool Suite

Neutronics & Shielding

SCALE
Reactor criticality, burnup, reactivity, composition, cross-sections, radiation and dose rates

MCNP
Power distribution, heat deposition, shielding, radiation damage

Reactor Dynamics

AGREE-Xe
HTGR spatial-temporal distribution of power and temperature, reactor kinetics

SERPENT
Cross-section generation for AGREE-Xe

Thermal Hydraulics

STAR-CCM+
CFD – temperature distribution, pressure, fluid flow, conjugate heat transfer

Mechanical & Structural

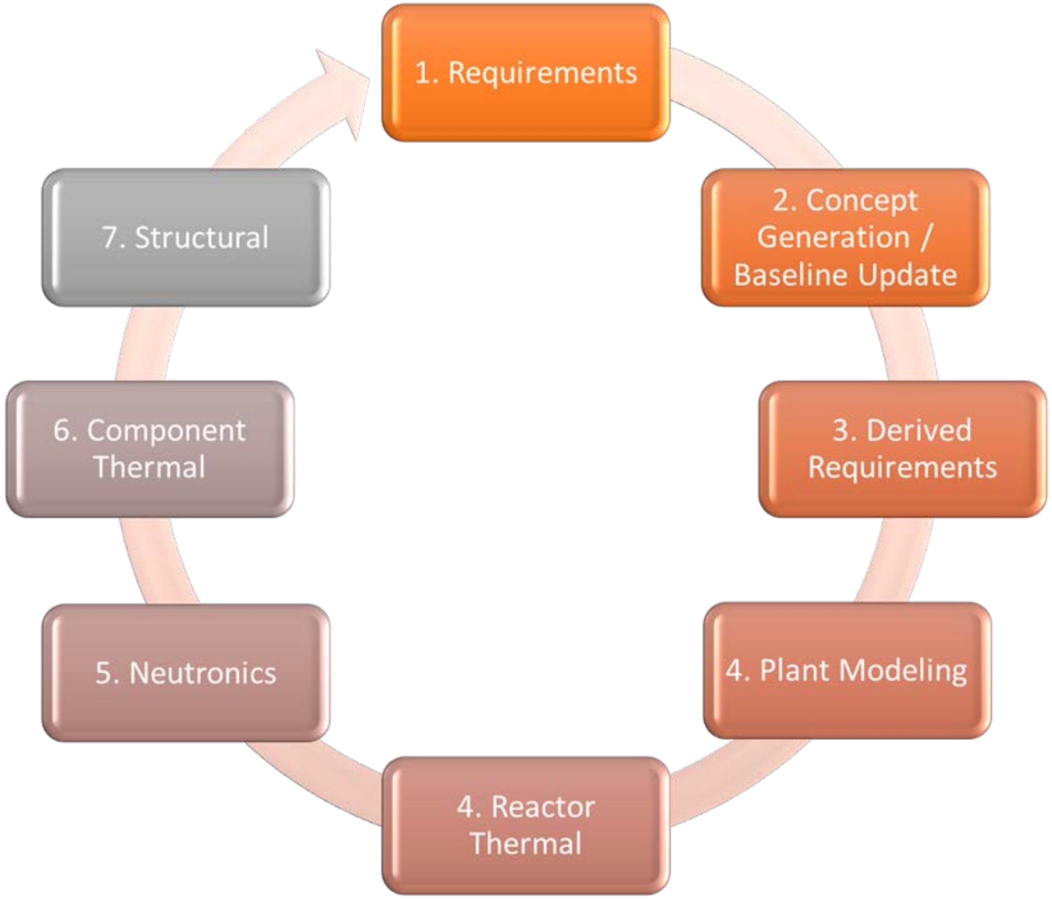
NX
3D CAD design

Ansys
FEA – stress, strain, deformation

Plant Performance

Flownex
Heat and mass balance, integrated reactor-plant dynamics and control

The XENITH team follows a regimented design cycle based on systems engineering best practices; requirements driven cycles result in a closed solution across disciplines.

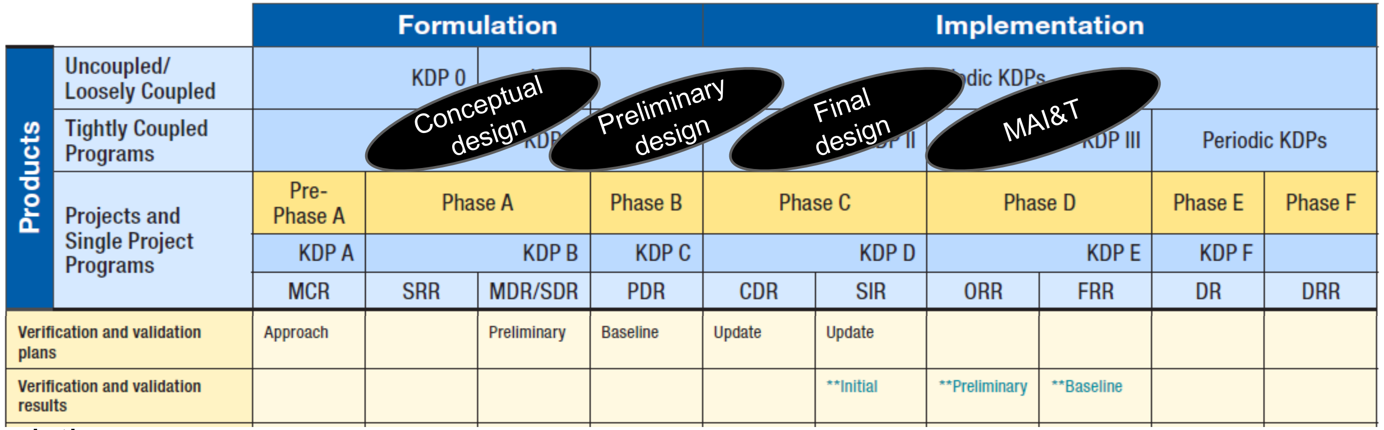


Verification and Validation Plan Spans Full Design Lifecycle

Verification: Does the program meet requirements?
- Is the computational method suitable for the problem
- Is it implemented correctly

Validation: Are the results accurate?
- Comparison of critical characteristics and phenomena against relevant experimental results, within intended parameter space?

We apply guidance of *NASA Systems Engineering Handbook* to plan V&V process over full development lifecycle



	Formulation				Implementation					
Uncoupled/ Loosely Coupled		KDP 0					dic KDPs			
Tightly Coupled Programs			KD			DP II		KDP III	Periodic KDPs	
Projects and Single Project Programs	Pre-Phase A	Phase A		Phase B	Phase C		Phase D		Phase E	Phase F
	KDP A		KDP B	KDP C		KDP D		KDP E	KDP F	
	MCR	SRR	MDR/SDR	PDR	CDR	SIR	ORR	FRR	DR	DRR
Verification and validation plans	Approach		Preliminary	Baseline	Update	Update				
Verification and validation results						**Initial	**Preliminary	**Baseline		

1. V&V approach planning (pre-conceptual design)
   - Identify needed design and analysis capabilities
   - Evaluate and select codes with suitable quality characteristics (e.g. NQA-1)
   - Begin formulating commercial grade dedication (CGD) plans to fill quality gaps.
2. Early-stage V&V (conceptual design):
   - Predict critical characteristics and estimate parameter space, to the extent possible with rough design.
   - Identify existing verification packages and validation data for each tool, aligned with predicted needs
   - Execute early-stage V&V calculations and identify any issues that arise.
   - Code-to-code comparison
3. Full V&V process (preliminary design):
   - Comprehensive phenomena identification (PIRT) and parameter space; nominal and off-nominal
   - Complete CGD
   - Formal software installation and V&V automation
   - Execute full set of code V&V
4. V&V update (final design)
   - Confirmatory analysis and model validation based on real data
   - V&V updates

V&V fidelity follows a phased process based on design maturity

Tools and Early-Stage V&V: Neutronics

Dr. Stephen Wilson
Manager, Nuclear Engineering

Selection of Radiation Transport and Depletion Analysis Tools

- There are many nuclear analysis codes built on the Monte Carlo, discrete ordinates, diffusion, method of characteristics, and other numerical approaches to solving a form of the linearized Boltzmann equation for neutral particle radiation transport.
- There are many codes built to solve some form of the radionuclide production/depletion/decay equations to produce isotopic inventories in the presence of a neutron flux field.
- Too many to easily list!
- Why use MCNP and SCALE?
  - Long history of application to many criticality safety, reactor physics, radiation shielding, and isotopic inventory problems similar to the systems we seek to analyze for this design project.
    - The details of many of these applications have been published in the open literature.
  - The broader nuclear engineering community has provided feedback to the development teams of these code systems for decades. This has resulted in extensive regression and verification test suites and many validation problems available in packages from RSICC or in the open literature (e.g. ICSBEP, SINBAD, et cetera).
  - Because of their age and pedigree, an ecosystem of support tools has grown up around these codes to extend their functionality.
    - For example, the ADVANTG tool to process MCNP inputs and automatically create Monte Carlo variance reduction parameters generated to converge a specific set of Monte Carlo tallies.
  - Likewise, many expert users of these codes are actively working in nuclear engineering within the national laboratory system, at private enterprises, and at the Nuclear Regulatory Commission.
- Physics fidelity, software quality, validation basis, supporting tools, regulator familiarity.

X-energy R&D Tool Suite

X-energy R&D Tool Suite

Neutronics & Shielding

- **SCALE** – Reactor criticality, burnup, reactivity, composition, cross-sections, radiation and dose rates
- **MCNP** – Power distribution, heat deposition, shielding, radiation damage

Reactor Dynamics

- **AGREE-Xe** – HTGR spatial-temporal distribution of power and temperature, reactor kinetics
- **SERPENT** – Cross-section generation for AGREE-Xe

Thermal Hydraulics

- **STAR-CCM+** – CFD – temperature distribution, pressure, fluid flow, conjugate heat transfer

Mechanical & Structural

- **NX** – 3D CAD design
- **Ansys** – FEA – stress, strain, deformation

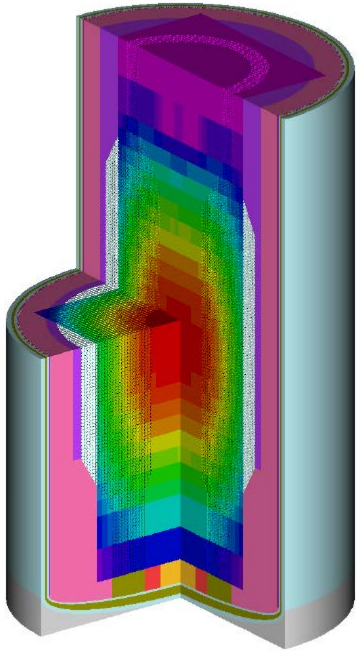
Plant Performance

- **Flownex** – Heat and mass balance, integrated reactor-plant dynamics and control

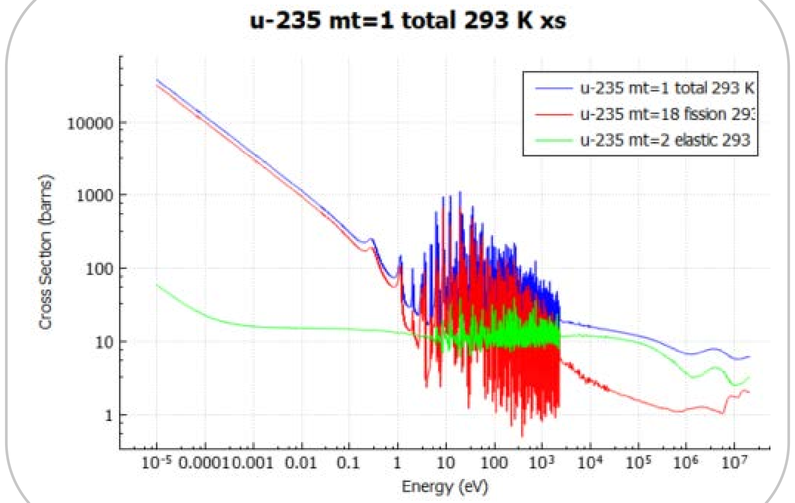
Non-Proprietary | Unclassified

SCALE – Introduction

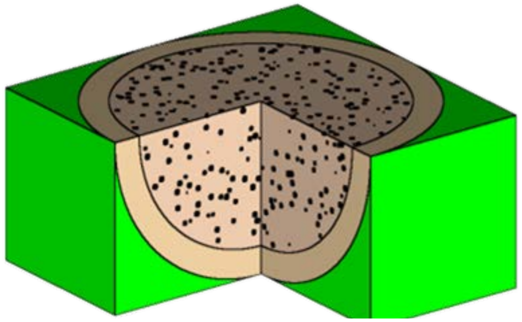
- SCALE is a system of modeling and simulation tools used for the analysis of nuclear systems
- Maintained by Oak Ridge National Laboratory under contract with the NRC, DOE and NNSA
- Collection of separate modules for doing specific analysis:
  - Primary and secondary neutron/gamma tracking
  - Multigroup and continuous energy cross section data
  - 1D/2D/3D Monte Carlo and Discrete Ordinates solvers
  - Depletion/decay/activation modules
- GUI for input creation and post processing



Fulcrum visualization of 3D cut of a TRISO model (left) and flux overlayed on 3D geometry (above), ORNL/TM-SCALE-6.3.1



Continuous energy cross section visualization in Fulcrum



SCALE Model of TRISO Pebble with Random Particle Distribution

SCALE – Selection

- SCALE contains many modules, but not all will be verified and validated by X-energy
- Key modules include:
  - ORIGEN – Activation, decay and depletion solver
  - KENO – Steady state Monte Carlo solver for neutron flux and keff
  - TRITON – Reactor and material depletion, coupling KENO and ORIGEN
  - TSUNAMI – Model sensitivity and bias estimation
- MAVRIC, a fixed source Monte Carlo solver with coupled weight window variance reduction, is not used as a primary analysis tool for shielding due to limitations in parallel execution and will not be validated by X-energy
  - Subcontractors may use MAVRIC and will be responsible for its validation

	Feature	SCALE
Features	**3D Monte Carlo Simulation, High Fidelity Modelling for Reactor Analysis**	Yes
	Material Depletion/Decay	Yes (TRITON and ORIGEN)
	Variance Reduction	Yes, weight window generation with MAVRIC, and next collision estimators
	Multithreading Support	Limited to KENO and specific submodules
	Cross Section Generation at Temperature	Yes, preprocessing with AMPX, and on the fly doppler broadening
Quality	**NQA-1**	No
	CGD	Under Development Internally
	Open/Closed source	Closed
	Licensing	RSICC
	NRC familiarity	Yes

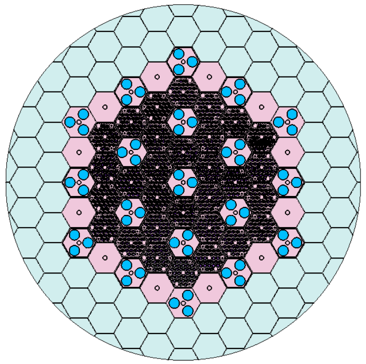
SCALE – Early-Stage V&V

Verification & Validation Process and Status

- Identified key phenomena and critical characteristics:
  - Related to steady state and depletion reactor analysis, focusing on use of KENO, TRITON and ORIGEN
- Established production version and hardware requirements
- Completed and document installation verification tests
- Identified ranges of interest/acceptance criteria for critical characteristics
- Collected validation data:
  - KENO – Ilas G., et al., "Validation of SCALE for High Temperature Gas-Cooled Reactor Analysis", ORNL/TM-2011/161, 2012
  - ORIGEN/TRITON – Radulescu, G, et al., "SCALE 5.1 predictions of PWR spent nuclear fuel isotopic compositions", ORNL/TM-2010/44, 2010
- Completed validation exercises on verified software:
  - KENO – HTTR, CNPS, VHTRC
  - TRITON/ORIGEN – Gösgen (ARIANE program), Takahama Unit 3

Summary of SCALE Critical Characteristics

	Acceptance Criteria (95% Conf.)	SCALE Module
k_{eff}	2%	KENO
Decay Heat	15%	ORIGEN
Fuel Burnup	12%	TRITON
Fission Product Inventory	Varies by Isotope	TRITON, ORIGEN
Activity	1.50%	ORIGEN
Neutron Activation	20%	KENO

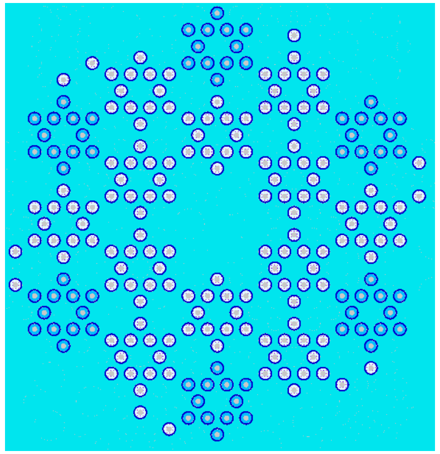


HTTR Keno Model, ORNL/TM-2011/161

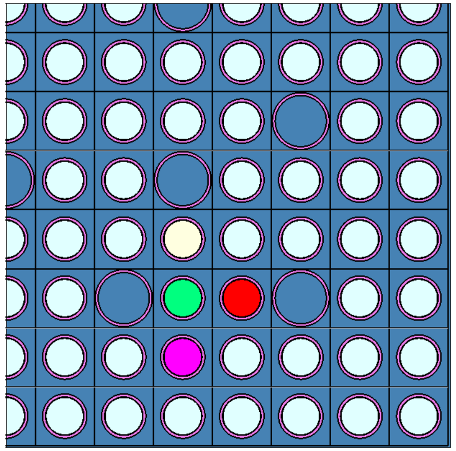
SCALE – Early-Stage V&V (continued)

- **Verification Test**
  - Some modules failed the verification sample test, general they are related to MG library generation and sensitivity analysis
  - These include:
    - BONAMI and BONAMIST: 1D/2D MG cross section generation for T-NEWT
    - 1D/2D TSUNAMI and 3D TSUNAMI using KENO-5: MG Sensitivity analysis
- **KENO**
  - Validation cases (HTTR, CNPS, VHTRC) documented and results compared well to benchmark values for keff
- **ORIGEN/TRITON**
  - Validation ongoing, initial results show good agreement with PWR benchmarks (Gösgen, Takahama)

More examples may be added as the reactor design progresses



VHTRC KENO Model



Gösgen Triton Model, ORNL-TM-2010/44

X-energy R&D Tool Suite

X-energy R&D Tool Suite

Neutronics & Shielding · Thermal Hydraulics · Mechanical & Structural · Plant Performance · Reactor Dynamics

SCALE
Reactor criticality, burnup, reactivity, composition, cross-sections, radiation and dose rates

MCNP
Power distribution, heat deposition, shielding, radiation damage

AGREE-Xe
HTGR spatial-temporal distribution of power and temperature, reactor kinetics

SERPENT
Cross-section generation for AGREE-Xe

STAR-CCM+
CFD – temperature distribution, pressure, fluid flow, conjugate heat transfer

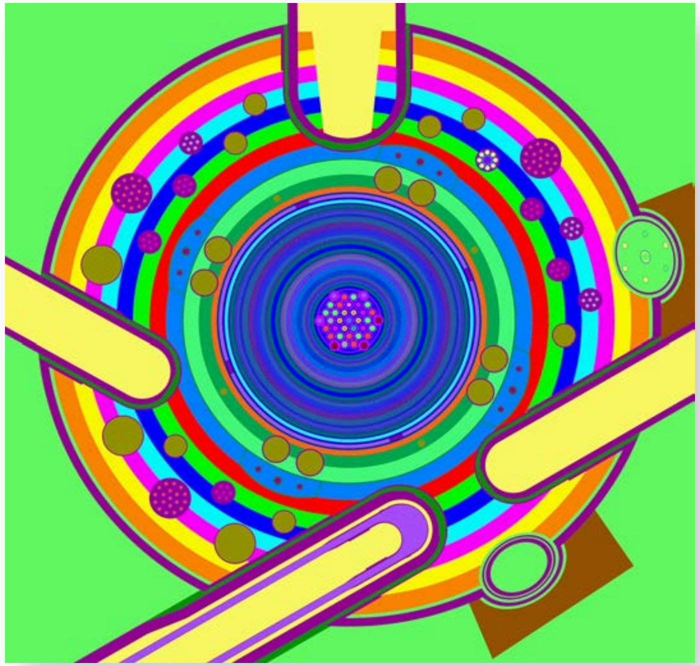
NX
3D CAD design

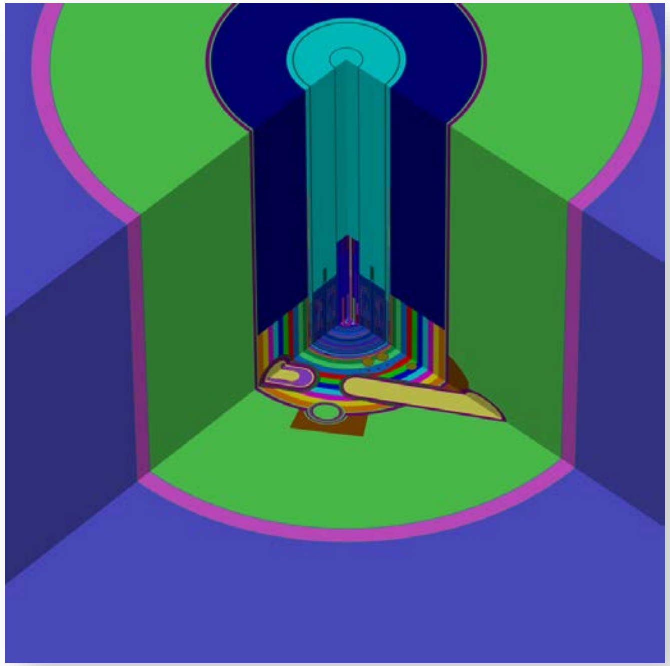
Ansys
FEA – stress, strain, deformation

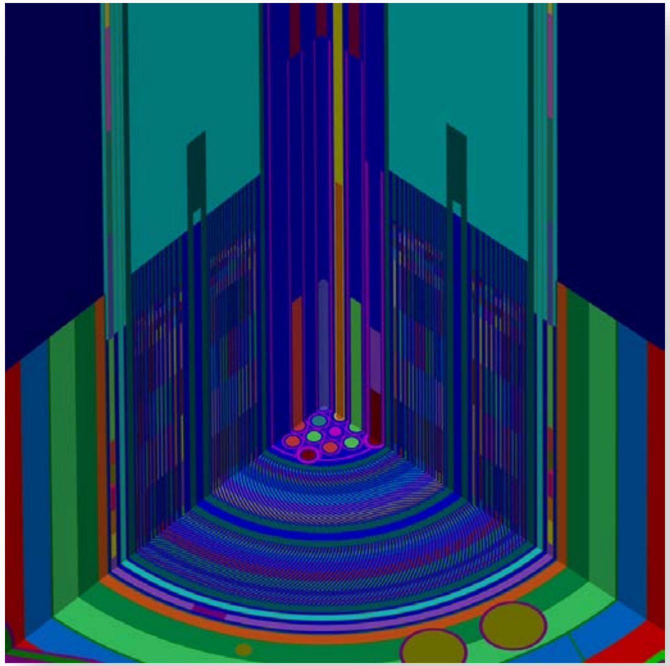
Flownex
Heat and mass balance, integrated reactor-plant dynamics and control

MCNP Code Usage

- The Monte Carlo N-Particle code can be used for general-purpose transport of several particles, including neutrons and photons
- The transport of these particles is through a three-dimensional representation of materials defined in a constructive solid geometry, bounded by first- and second-order user-defined surfaces
- Shown: visualizations of detailed MCNP models of the High Flux Isotope Reactor (HFIR) at Oak Ridge







MCNP Features and Selection

- MCNP (Monte Carlo N-Particle) is a radiation transport code that is used in a variety of areas:
  - Commonly used as a criticality safety, reactor physics and shielding analysis tool
- Developed by Los Alamos National Laboratory and distributed by RSICC at Oak Ridge National Laboratory
- While it can be used for a wide range of reactor analyses, for XENITH MCNP is used in two main areas:
  - Neutron and gamma heating for in-core and nearby ex-core structures (eigenvalue calculations)
  - Neutron and gamma radiation shielding for radiation workers and the general public (fixed source calculations)
- Multi-particle shielding and energy deposition calculations can be performed using the SCALE MAVRIC, a module in the SCALE package, but may be executed more efficiently using MCNP's parallelism
- MCNP 5.1.60 was chosen over more recent releases of MCNP for speed and compatibility of use with ADVANTG

	Feature	MCNP
Features	3D Monte Carlo Simulation, High Fidelity Modelling for Reactor and Shielding Analysis	Yes
	Material Depletion/Decay	No
	Variance Reduction	Yes, weight window generation with ADVANTG, next collision estimators
	Multithreading Support	Yes
	Cross Section Generation at Temperature	Yes, preprocessing with NJOY, no on the fly capability
Quality	NQA-1	No
	CGD	Under Development Internally
	Open/Closed source	Closed
	Licensing	RSICC
	NRC familiarity	Yes

MCNP Early-Stage V&V

Verification

- Regression tests distributed with installation; no variation in output files from generated compared to developers.

Validation

- MCNP: Photon Benchmark Problems - suite of benchmark problems developed in 1991 for photon benchmarking
- MCNP: Neutron Benchmark Problems: Suite of benchmark problems developed in 1991 for neutron benchmarking
- HTTR: High temperature gas reactor with similar power level and features to Xenith design
- VHTRC: High temperature gas reactor with multiple steady state temperature benchmarks.
- TOPAZ: Benchmark to show control system modeling

Benchmark	Phenomena	Status
Point Gamma Ray Source	Photon transport in shielding and core materials	Complete
Gamma Ray Skyshine	Skyshine from gammas	Complete
Cobalt-60 Air-Over-Ground	Photon interaction with ground materials	Complete
LLNL Pulsed Spheres	Fast neutron transport through shielding and core materials	Complete
Fusion Shielding	Fast neutron transport through shielding materials	Complete
Critical Assemblies (Reflected Systems)	Moderated neutron transport and multiplication in fuel, water, and graphite	Complete
HTTR	Moderated neutron transport and multiplication in reactor with similar power, size, temperature, and materials to Xenith	Complete
VHTRC	Response to reactor material temperature changes	Complete
TOPAZ	Control drums	Complete

Tools and Early-Stage V&V
– Reactor Dynamics / Thermal-Hydraulics / Structural Mechanical

Dr. Adam Oler
Manager, Nuclear Engineering, Reactor Dynamics and Multiphysics

X-energy R&D Tool Suite

SCALE
Reactor criticality, burnup, reactivity, composition, cross-sections, radiation and dose rates

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Power distribution, heat deposition, shielding, radiation damage

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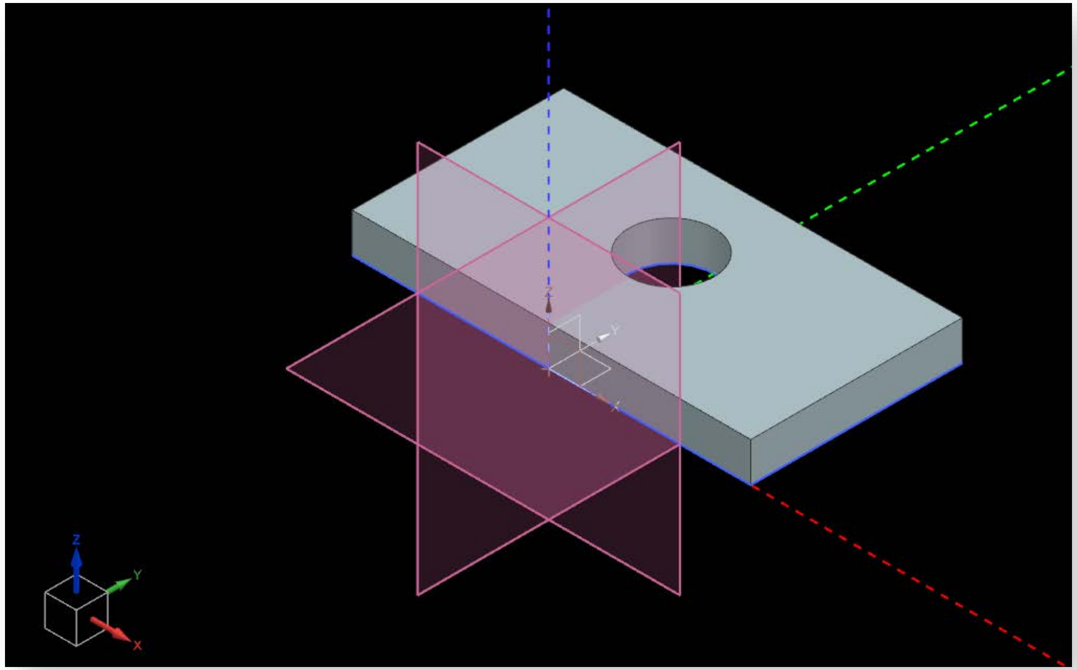
Siemens NX: 3D Computer Aided Design (CAD)

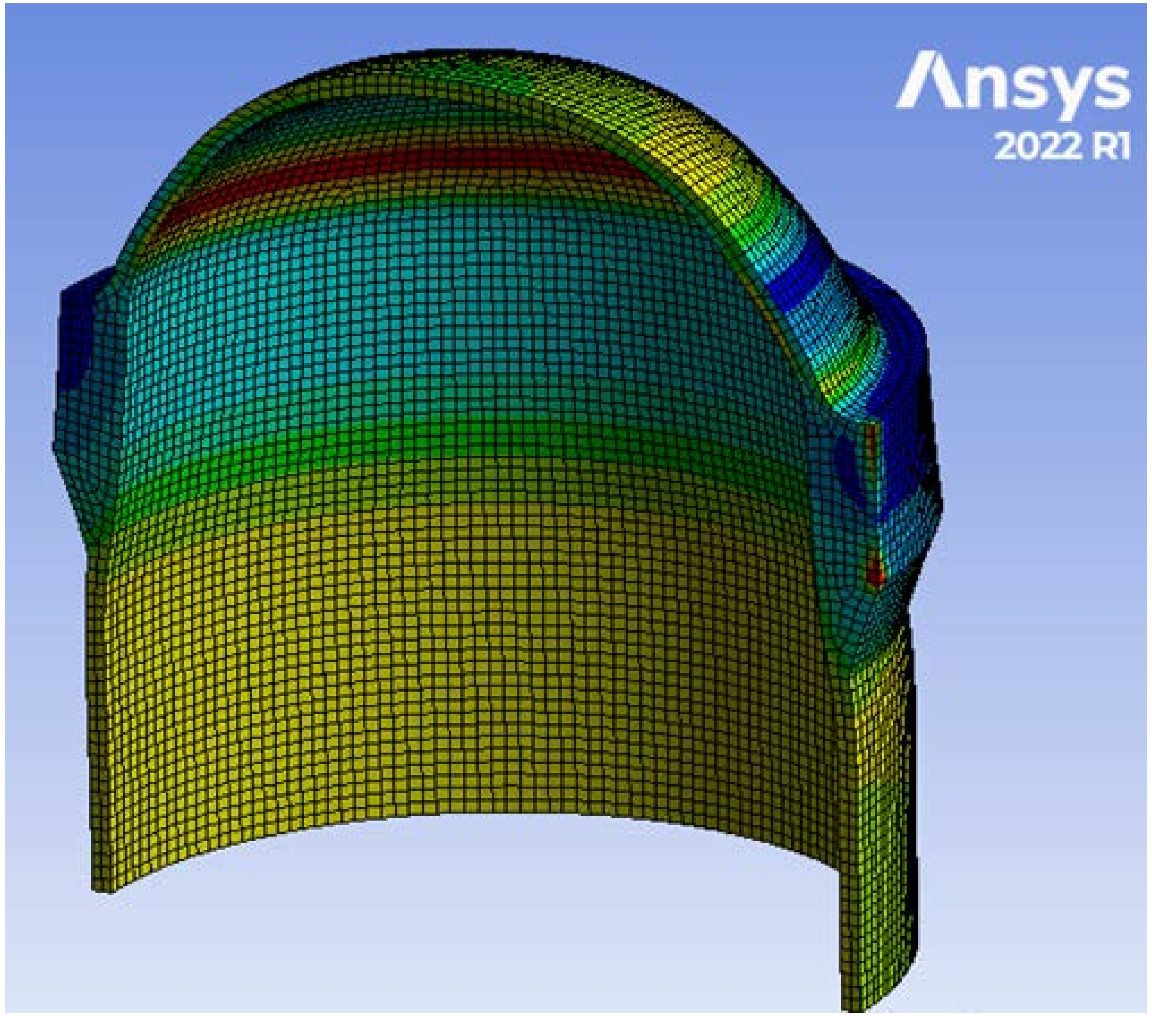
- General purpose industry standard computer-aided modeling program
- Core functionality:
  - Parametric solid modeling (feature-based and direct modeling)
  - Freeform surface modelling
  - Reverse engineering
  - Styling and computer-aided industrial design
  - Knowledge reuse, including knowledge-based engineering
  - Sheet metal design
  - Assembly modelling and digital mockup
  - Routing for electrical wiring and mechanical piping
- NX solid models considered the design "truth"
- **Structural analysis models (e.g., ANSYS) start from NX solid models**



Ansys Features and Selection

ASME NQA-1 COMPLIANT

- Generalized finite-element analysis software widely adopted across the nuclear, aerospace, and automotive industries. Used in approved reactor designs (NuScale, AP-1000)
- Advanced non-linear material capabilities including integration of custom user material subroutines
- Multiphysics integration with Fluent and CFX CFD
- ISO 9001 certified Quality Assurance program designed to be consistent with NQA-1 Subpart 2.7
- Documented automated software verification package
- Existing staff experience



Ansys Features and Selection

Selection Criteria for Structural Analysis Codes

	Selection Criteria	Abaqus	Ansys	Simcenter
Features	Geometry Modeling	3D Volume, Contact, Mass, and Spring Elements	3D Volume, Contact, Mass, and Spring Elements	3D Volume, Contact, Mass, and Spring Elements
	Material Modeling	Elastic, Anisotropic, Viscoelasticity, Temperature Dependent, Custom User	Elastic, Anisotropic, Viscoelasticity, Temperature Dependent, Custom User	Elastic, Anisotropic, Viscoelasticity, Temp. Dependent, Custom User
	Solvers	Implicit, Explicit	Implicit, Explicit	Implicit, Explicit
	User Interface	GUI, Python Scripting	Workbench GUI APDL, PyAnsys Scripting	GUI, Python Scripting
	CAD Integration	Catia, NX, ProEngineer, SolidWorks, Parasolid, STEP	Catia, Creo, NX, Inventor, SolidWorks, Solid Edge, STEP, Parasolid, AutoCAD	Femap, NX, Creo, Catia, Solid Edge
	CFD Solver Integration	Star-CCM+	CFX, Fluent	Star-CCM+
Quality	NQA-1 Subpart 2.7	Yes	Yes	Yes
	CGD	Under development	XE-100 Quality Plan	Not Planned
	V&V	Mature V&V package with software	Mature V&V package with software	Mature V&V package available
	NRC familiarity	Yes	Yes	Unknown

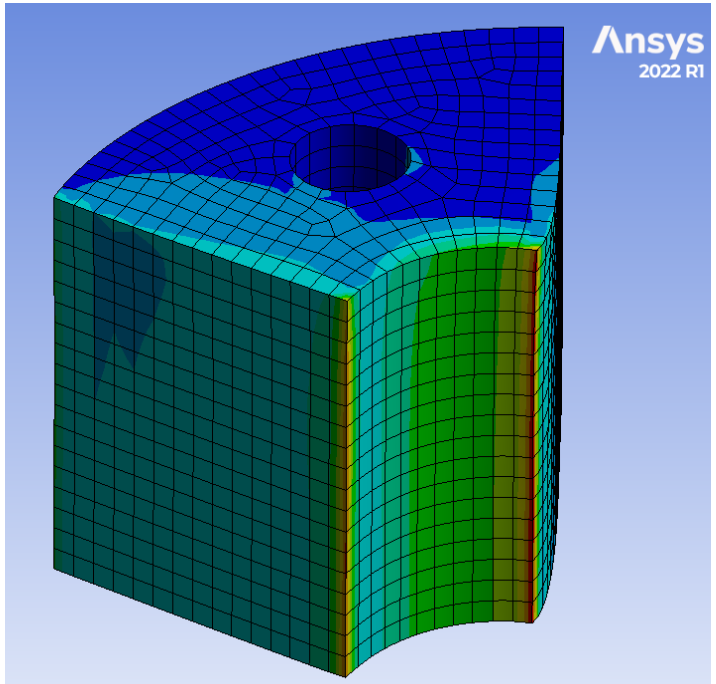
Ansys Early-Stage V&V

Verification

- QA services agreement procured
- Ansys Verification Test Package (VTP) documentation reviewed
- Automated VTP successfully run on test systems and results dispositioned

Irradiated Graphite Validation

- Phase 1 irradiated graphite model implemented in Ansys
- Graphite model results compared to ATR-2E creep literature data (Haag, 2005)



Phenomena and Critical Characteristics	Systems, Structures, and/or Components
Geometry Discretization	Reactor pressure vessel
	Reactor core/reflector
	Piping
Isotropic Material Models	Reactor pressure vessel
	Piping
	Support Structures
Anisotropic Material Models	Reactor core/reflector
Thermal Expansion • coefficient of thermal expansion • temperature loads	Reactor pressure vessel
	Reactor core/reflector
	Support Structures
	Piping
Thermal Creep	Reactor pressure vessel
	Reactor core/reflector
Irradiation Creep & Dimensional Change	Reactor core/reflector
Mechanical Loadings • pressure • force • displacement • Acceleration	Reactor pressure vessel
	Reactor core/reflector
	Piping
	Support Structures
Solvers • static • transient • modal • explicit	Reactor pressure vessel
	Reactor core/reflector
	Piping
	Support Structures

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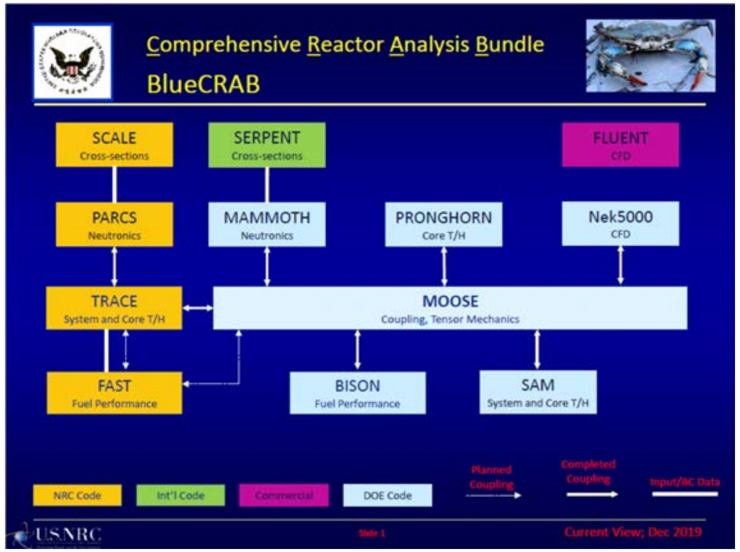
AGREE-XE Features and Selection

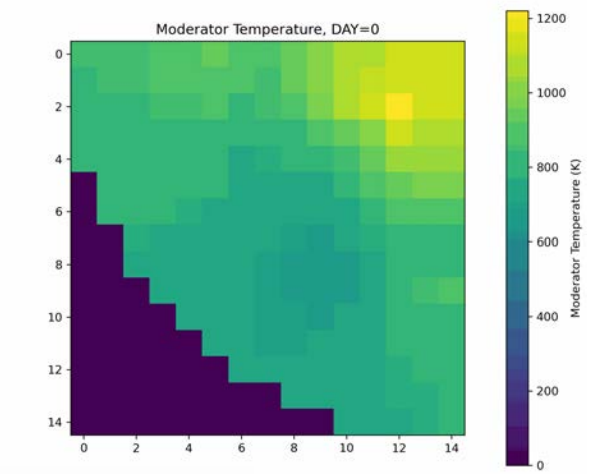
- AGREE-Xe is a neutronics and thermo-fluids code which solves the coupled neutronics and mass, momentum and energy equations in three-dimensions for steady state and time dependent safety analysis of the High Temperature Gas-Cooled reactor (HTGR)
- Chosen because of previous pedigree of AGREE which was developed at UM for the NRC for HTGR safety analysis beginning in 2009
- The derivative of AGREE named AGREE-Xe has over a decade of HTGR modeling experience and validation cases against operating reactors and heated experiments

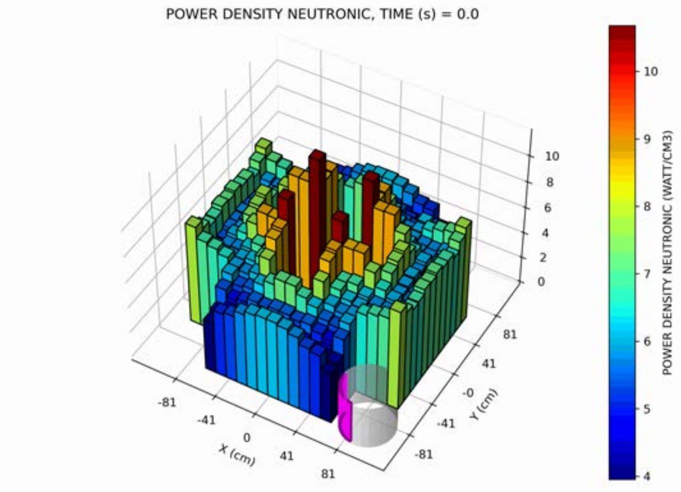


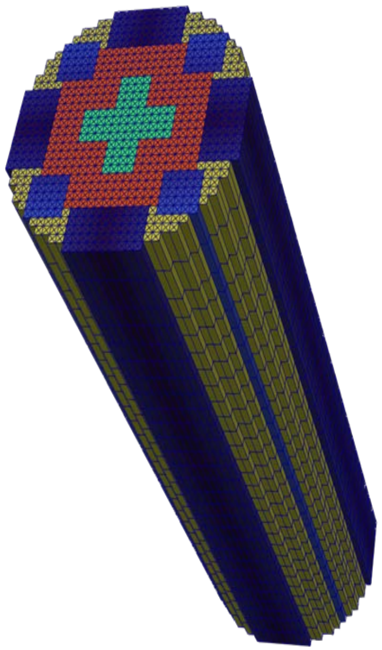
	Selection Criteria	AGREE-XE	BlueCRAB
Features	3D, Multi-group Neutronics	✓ YES	✓ YES
	Spatial and Point Kinetics	✓ YES	✓ YES
	Non-Orthogonal Geometry	✓ YES	✓ YES
	Monte Carlo Cross Sections	✓ YES	✓ YES
	Bypass and Cross flow modeling capability	✓ YES	✓ YES
	Macro/Meso/Micro Scale Heat Transfer	✓ YES	✓ YES
Quality	NQA-1	**In Progress**	NO
	CGD	**In Progress**	NO
	Closed source	✓ YES	✓ YES
	Licensing	✓ YES	NO
	NRC familiarity	✓ YES	Some

AGREE-XE Features and Selection

- AGREE has 3D modeling capabilities for visualizing user inputs and software outputs
- Transient modeling capabilities for displaying changes in reactor conditions as a function of time in 2D and 3D
- Outputs average and maximum temperatures for in-core reactor components:
  - Includes methodology for obtaining maximum TRISO temperatures in the fuel
- AGREE models reactivity and temperature feedback as a function of time accurately:
  - Control rod withdrawal and loss of forced coolant (LOFC) validation







Non-Proprietary | Unclassified

AGREE-XE Early V&V

Verification

- Verification suite from code developers created:
  - Performed unit and regression testing to ensure consistency across code updates

Validation

- High Temperature Engineering Test Reactor (HTTR):
  - Prismatic HTGR with experimental neutronics and thermal hydraulics data
  - Control rod withdrawal transient experiment validation
  - Loss of Forced Cooling Transient Experimental Validation
  - Criticality Steady State Neutronics Experimental Validation
- HTR-Proteus:
  - Fixed pebble arrangement HTGR core
  - Core 1 and 1A neutronics experimental validation
- MHTGR:
  - Computational Benchmark for neutronics and thermal hydraulics validation/verification
- HENDEL:
  - Heated experiment for thermal hydraulics validation of crossflow
- SNU:
  - Heated experiment for thermal hydraulics validation of crossflow and bypass flow

Critical Characteristics	HTTR	HTR-PROTEUS	MHTGR	HENDEL	STAR-CCM Validation
k-eff (± 1%) (steady-state)	x	x	x		
Delayed neutron fraction (βeff) (±5%)	x	x	x		
Temp. reactivity coefficients (±5%)	x		x		
Power peaking factor (±7%)			x		
Group scalar flux in each node (±5%)		x	x		
Control rod worth (10%)	x	x	x		
Fission Power (Steady State) (5%)	x		x		
Xenon reactivity (10%)	x		x		
Avg temperature in each node (±10%)	x		x	x	x
Pressure Drop / Bypass Flow (±10%)				x	x
Additional Critical Thermal-Fluid Flow Characteristics (TBD in PIRTs)				x	x

Serpent Features and Selection

- Serpent is a 3D, continuous energy Monte Carlo transport code
- Compatible with Monte Carlo Cross Section libraries such as ENDF/B VII.1
- Supports a wide range of geometries and options for generating cross sections to be passed to deterministic codes:
  - Triangular mesh and cartesian mesh options have strong compatibility with AGREE-Xe
- Chosen because of previous pedigree with AGREE-Xe for generating homogenized multi-group constants for deterministic spatial kinetics modeling

	Selection Criteria	Serpent	Shift
Features	3D Neutron Transport solving	✓ YES	✓ YES
	Cross Section Generation Support	✓ YES	✓ YES
	Custom User-defined geometries	✓ YES	NO
	Monte Carlo Cross Sections	✓ YES	✓ YES
Quality	NQA-1	NO	NO
	CGD	NO	NO
	Closed source	✓ YES	✓ YES
	Licensing	NO	NO
	NRC familiarity	NO	NO

Serpent Early-Stage V&V

Note: All Serpent and AGREE-Xe Results with ENDF/B-VII.1 Library

- Verification testing suite created and executed:
  - Focused on installation verification for cross-section generation
- Validation efforts modeled same reactors as AGREE-Xe for neutronics comparisons:
  - HTR Proteus
  - HTTR
  - MHTGR

HTR Proteus experimental benchmark comparison against MCNP, Serpent, and AGREE-Xe (4-group)

Case ENDF/B-VII.1	Core	Benchmark k_{eff}	MCNP6.1 k_{eff}	Diff (pcm)	SERPENT k_{eff}	Diff. (pcm)	AGREE 4G k_{eff}	Diff. (pcm)	Diff. (pcm) AGREE-SERPENT
4	1	1.0048	0.9989	-580	1.00067	-412	1.009334	453	865
5	1A	1.0034	0.9970	-640	0.998515	-488	1.007566	416	904
6	2	1.0029	0.9969	-600	0.998350	-454	1.010600	770	1224

HTR Proteus experimental benchmark comparison against MCNP, Serpent, and AGREE-Xe (8-group)

Case ENDF/B-VII.1	Core	Benchmark k_{eff}	MCNP6.1 k_{eff}	Diff (pcm)	SERPENT k_{eff}	Diff. (pcm)	AGREE 8G k_{eff}	Diff. (pcm)	Diff. (pcm) AGREE-SERPENT
4	1	1.0048	0.9989	-580	1.00067	-412	1.007335	253	664
5	1A	1.0034	0.9970	-640	0.998515	-488	1.005736	233	721
6	2	1.0029	0.9969	-600	0.998350	-454	1.008488	558	1024

X-energy R&D Tool Suite

X-energy R&D Tool Suite

Neutronics & Shielding

SCALE
Reactor criticality, burnup, reactivity, composition, cross-sections, radiation and dose rates

MCNP
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Star-CCM+: Computational Fluid Dynamics (CFD)

ASME NQA-1 COMPLIANT

- Built in CAD Modeling
- Computational Fluid Dynamics:
  - Pressure Drop
  - Design of flow paths
  - Pressure vessel cooling
- Conjugate Heat Transfer:
  - Insulation Sizing
  - 3D temperature distribution
    - Input to structural analysis
- Parametric Sensitivity Analysis
- Parametric Optimization
- Steady State and Transient Analysis

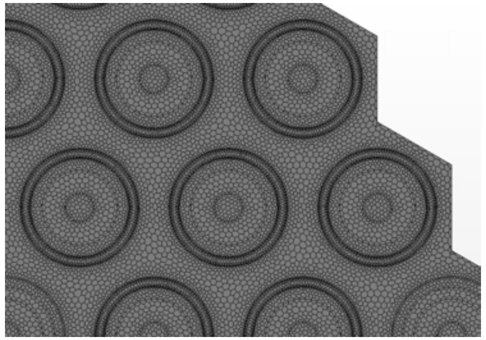

Figure: High resolution conformal conjugate heat transfer mesh

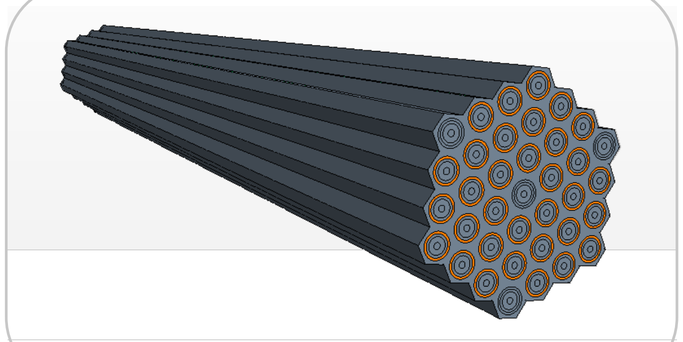

Figure: HTTR fuel block assembly (33-pin)

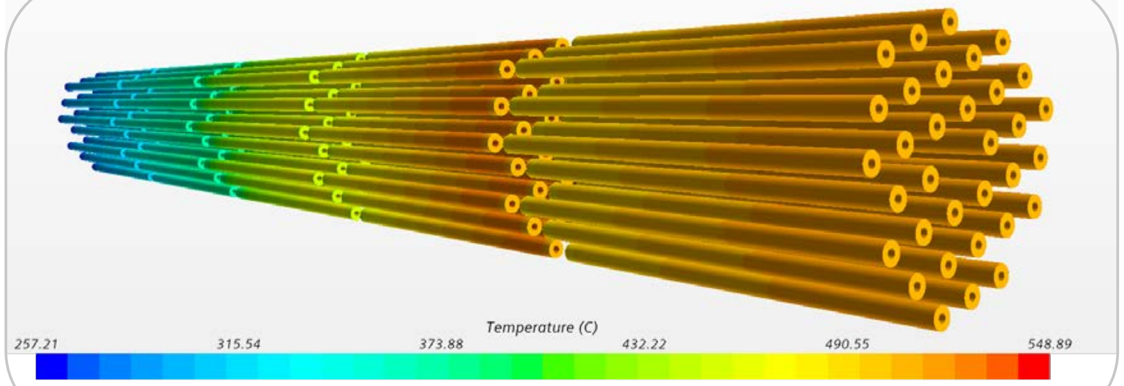

Figure: HTTR fuel temperatures at steady-state low power

Star-CCM+ Features and Selection

- Star-CCM+ is a computational fluid dynamics software using finite volume methods
- Star-CCM+ and ANSYS Fluent are the only commercially available, NQA-1 compliant CFD software packages
- Star-CCM+ has seen more popular usage in the nuclear industry than Fluent
- Contains built-in meshing capability
- Integrates well with CAD from SolidWorks and NX

Selection Criteria for Computational Fluid Dynamics

	Selection Criteria	Star-CCM+	ANSYS Fluent	OpenFOAM	Nek-5000 / RS
Features	**Finite Volume**	yes	yes	yes	no
	Finite Element	Solid models	no	no	yes
	User Support	yes	yes	no	no
	User Interface	Graphical	Graphical & text-based	Text-based	Text-based
Quality	**NQA-1**	yes	yes	no	no
	CGD	N/A	N/A	no	no
	Open/Closed source	proprietary	proprietary	open source	open source
	NRC familiarity	yes	yes	no	Some

Star-CCM+ Early Stage V&V

Verification & Validation Process

- Identified key phenomena and required verification cases from the verification package provided by Siemens for Star-CCM+
- As design is further developed, refining selection of phenomena to those relevant to the design and identify range of interest for validation exercises
- Further validation exercises will be selected and completed as the design matures

Phenomena and Critical Characteristics	Systems, Structures, and/or Components	Design Scenario
Constant temperature fluid flow • pressure drop	Helium piping	NOC/LOFC
	Air piping	NOC/LOFC
Forced Convection (*Ri* < 0.1) • temperature rise • pressure drop • heat transfer coefficient	Reactor core/reflector	NOC
	Inlet/outlet plenum	NOC
	Circulator cooling	NOC
	Reactor Pressure Vessel	NOC
	Control drum	NOC
Buoyance Driven Flow (*Ri* > 10) • temperature rise • pressure drop • heat transfer coefficient	Reactor core/reflector	LOFC
	Inlet/outlet plenum	LOFC
	Reactor Pressure Vessel	NOC/LOFC
	Control drums	LOFC
Mixed Convection (0.1 < *Ri* < 10) • temperature rise • pressure drop • heat transfer coefficient	Reactor core/reflector	NOC
	Reactor Pressure Vessel	NOC
Radiative Heat Transfer • Thermal resistance across gap	Reflector/drum gap	NOC/LOFC
	RPV to environment	NOC/LOFC
Conduction • Temperature gradient across core • Peak temperatures	Fuel blocks	NOC/LOFC

NOC: Normal operating conditions LOFC: Loss of forced coolant

X-energy R&D Tool Suite

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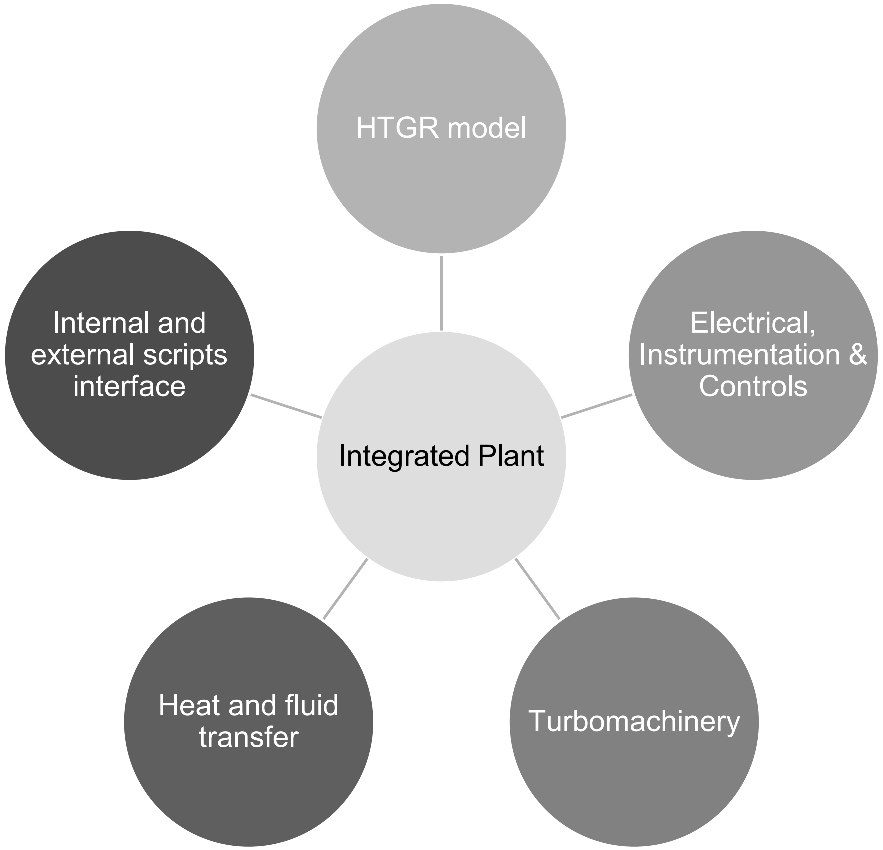
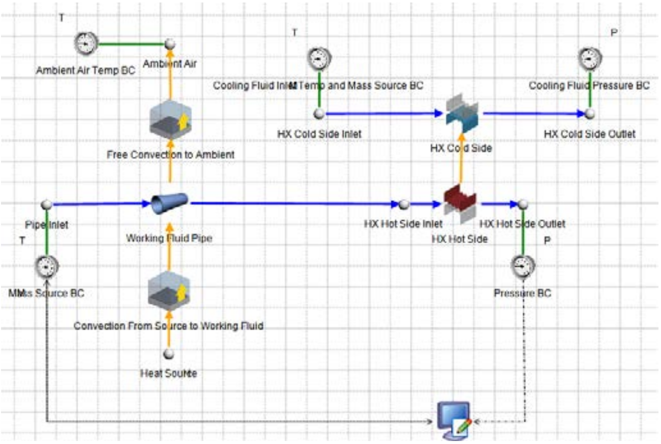
Flownex: Integrated Plant Modeling Tool for HTGRs

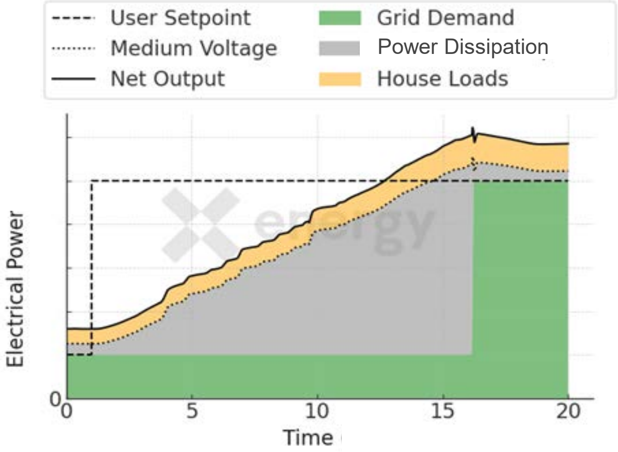
ASME NQA-1 COMPLIANT

FLOWNEX® SIMULATION ENVIRONMENT



Flexible ‘drag & drop’ user interface





Transient modeling of integrated plant behavior

Flownex: Integrated Nuclear Plant Modeling

- State-of-the-art reactor modeling suite was developed by South Africa's PBMR engineers – to fill a gap in HTGR simulation capabilities
- Integrated plant steady-state and transient performance:
  - Runs in approx. real time
  - Drag & drop user interface facilitates architecture exploration studies
  - Built-in distributed control system (DCS) modeling suite
  - Couples to other software through application programming interface (API)
  - Key part of our physics based Digital Twin

Integrated Nuclear Plant Modeling Tools

	Selection Criteria	Flownex	RELAP-5 3D (according to INL SME)
Features	Reactor modeling	**2D HTGR core geometry + point kinetics**	2D core commonly used. Coupled with NESTLE as 3D nodal or point kinetics. 3D thermal hydraulic modeling possible using 3D components.
	Power conversion modeling	1D network with built-in fluid/heat-transfer components and turbomachinery maps	1D network, limited pre-programed pump. Compressor and turbine components available.
	User interface	Flexible drag & drop for architecture studies	Card based decks, often created in notepad or Excel worksheet. Third-party software available (e.g., SNAP, 3KeyMaster).
	Control	Built-in DCS allows plant control test bed	Card based control variables, no visualization.
	External coupling	API for Python, MATLAB and Excel	Coupling available via PVM protocol.
Quality	NQA-1	**Yes**	NQA-1 level 3, developing software mode.
	CGD	**Passed X-energy audit for Xe-100**	Licensees need to perform it.
	V&V	Mature V&V package comes with software	Extensive benchmarking of software modeling. Test runs are included with install, but no automated V&V after install.
	Licensing	**NRC socialization started by Xe-100**	Developed for and used by US NRC for LWR applications. Code features for advanced reactor modeling developed for US DOE. Used as licensing tool by different advanced reactor companies.

Flownex: Early-Stage V&V

Verification & Validation

- Comprehensive NQA-1 compliant V&V suite provided by the software developer (MTECH)
  - Turbomachinery
  - Piping, valves, etc.
  - Reactor
  - Heat exchangers
- X-energy standard install and automated execution of V&V suite
- Successfully ran and passed all acceptance criteria
- Developed detailed validation plan to be pursued as the design matures.

Phenomena and Critical Characteristics	Systems, Structures, and/or Components
Conduction Convection	All HX equipment
	Reactor Components: Core, Reflectors, RPV
	Piping
Friction pressure drop	All HX equipment
	Reactor Components: Core, Reflector, RPV, etc.
	Piping
Isentropic Expansion and Compression	Air Compressor
	Air Turbine
Point Kinetics Heat Generation	Reactor Components: Core, Reflectors, RPV, Piping

X-energy R&D Tool Suite

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Validation of Transient Analysis with HTTR Control Rod Withdrawal Benchmark

- Simulate single control rod withdrawal in a fuel block:
  - Point Kinetics in a simplified geometry
- Code validation of AGREE-Xe and Flownex vs experimental data
- 0.00034 dk/k (34 pcm) reactivity insertion in 6.59 seconds:
  - Document reactor power during transient simulation
- Excellent agreement between Flownex/AGREE-Xe and measurements

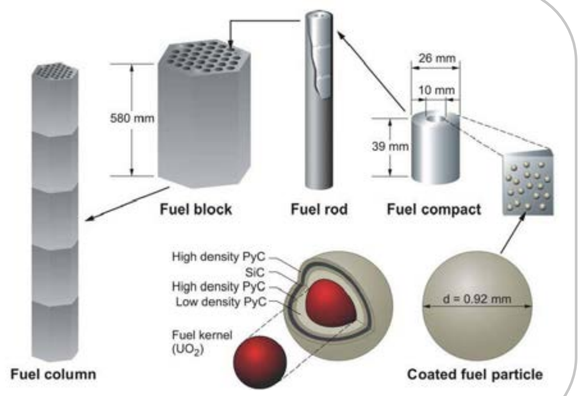

Figure: Fuel column composition for HTTR

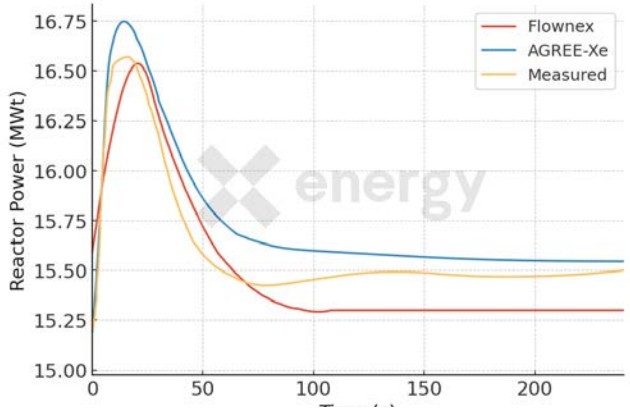

Figure: Overall HTTR reactivity change due to reactivity insertion and thermal feedback

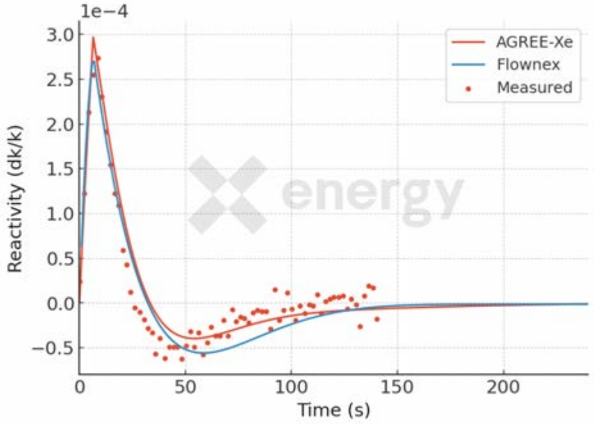

Figure: Reactor power during transient

X-energy toolkit allows for full system design and operation development.

Accurate Analysis Provides Insights Into Component Performance

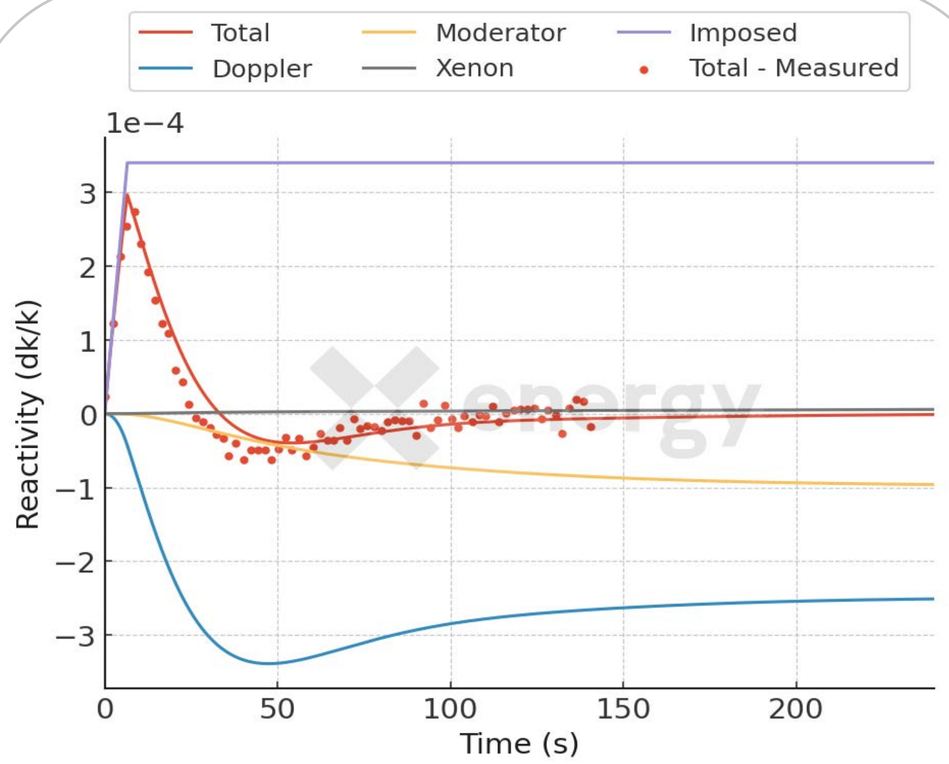

Figure: HTTR reactivity feedback experimental and simulated components

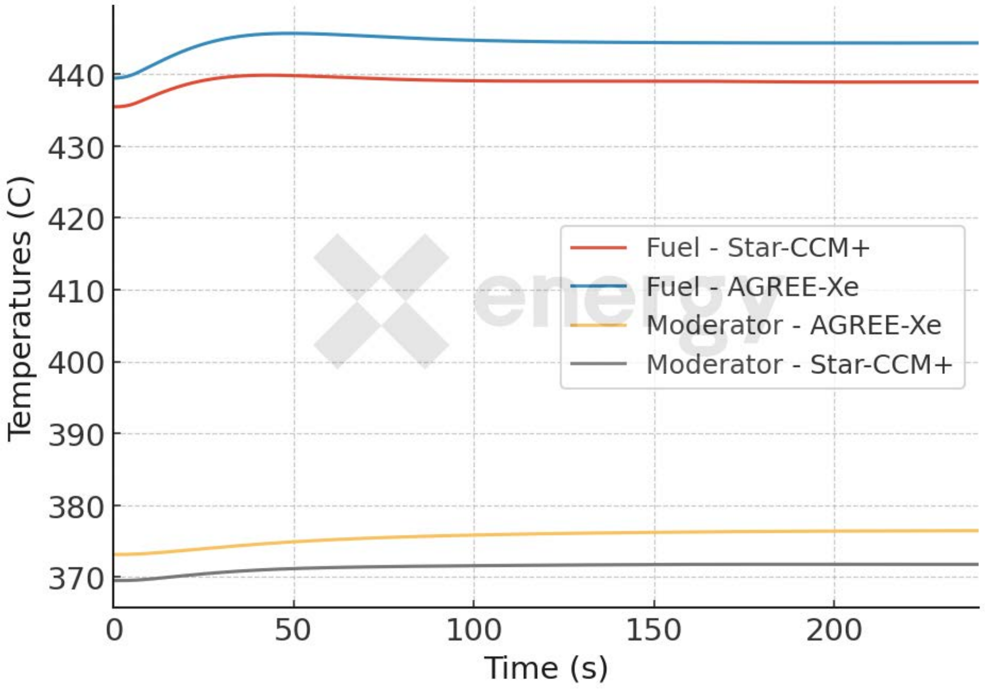

Figure: HTTR simulated temperatures for control rod withdrawal

X-energy toolkit allows for full system design and operation development.

Wrap Up

Dr. Dov Rhodes
Lead, Technical Integration

Summary

- Analytical methods – and expert engineering team – apply experience and lessons learned from Pele's Xe-1 as well as the ARDP Xe-100.
- XENITH development leverages a robust NQA-1 design and analysis process, paired with a state-of-the-art nuclear engineering tool suite.
- Early-stage V&V and quality assessment of engineering software provides confidence in fidelity of design and analysis process.
- This presentation outlines the scope and contents of the Analytical Methods Licensing Topical Report, to be submitted in June 2024.
  - Early feedback is welcome!