AREVA Gen-IV SMR Technology Design & Development

Steam Cycle High Temperature Gas-cooled Reactor (SC-HTGR)

Farshid Shahrokhi

2014 IFNEC Meeting, Romania

AREVA

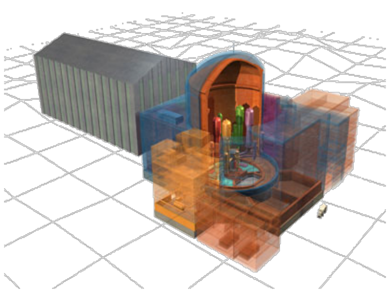
Topics

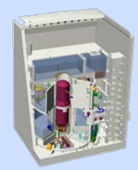
- AREVA Reactor Products
- AREVA High Temperature Reactor
  - Fuel form
  - Reactor design
  - Power plant design
  - R&D activities
- HTR Safety Case
  - Passive safety features
  - Licensing initiatives
- Development and Deployment Strategy
  - Market perspective
  - Development history
  - Development status and future plans

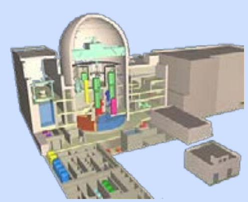
AREVA

AREVA Has a Full Reactor Range
Evolutionary and Innovative Reactor Designs

OFFERED	COMPLETING DESIGN	Generation IV
1600+ MWe PWR	1200+ MWe BWR	Fast Breeders
EPR	1000+ MWe PWR	High Temperature
	ATMEA	Smaller Unit Size
High-output Projects	Medium Size projects	Future Market Needs



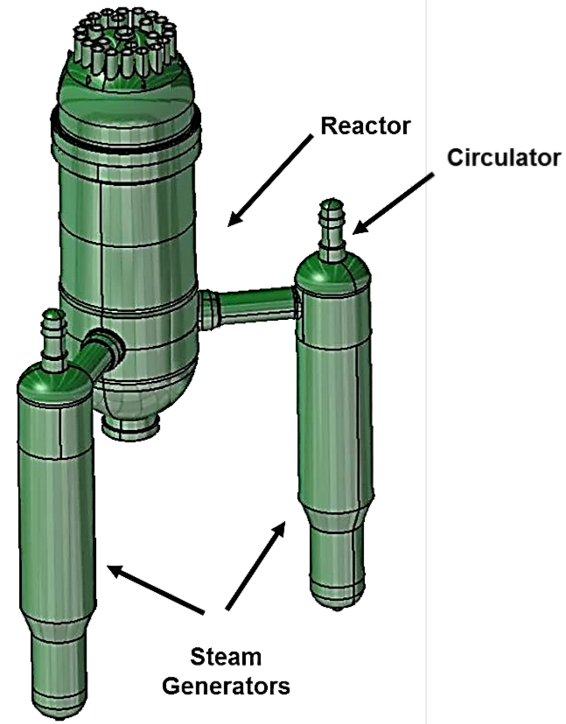




AREVA

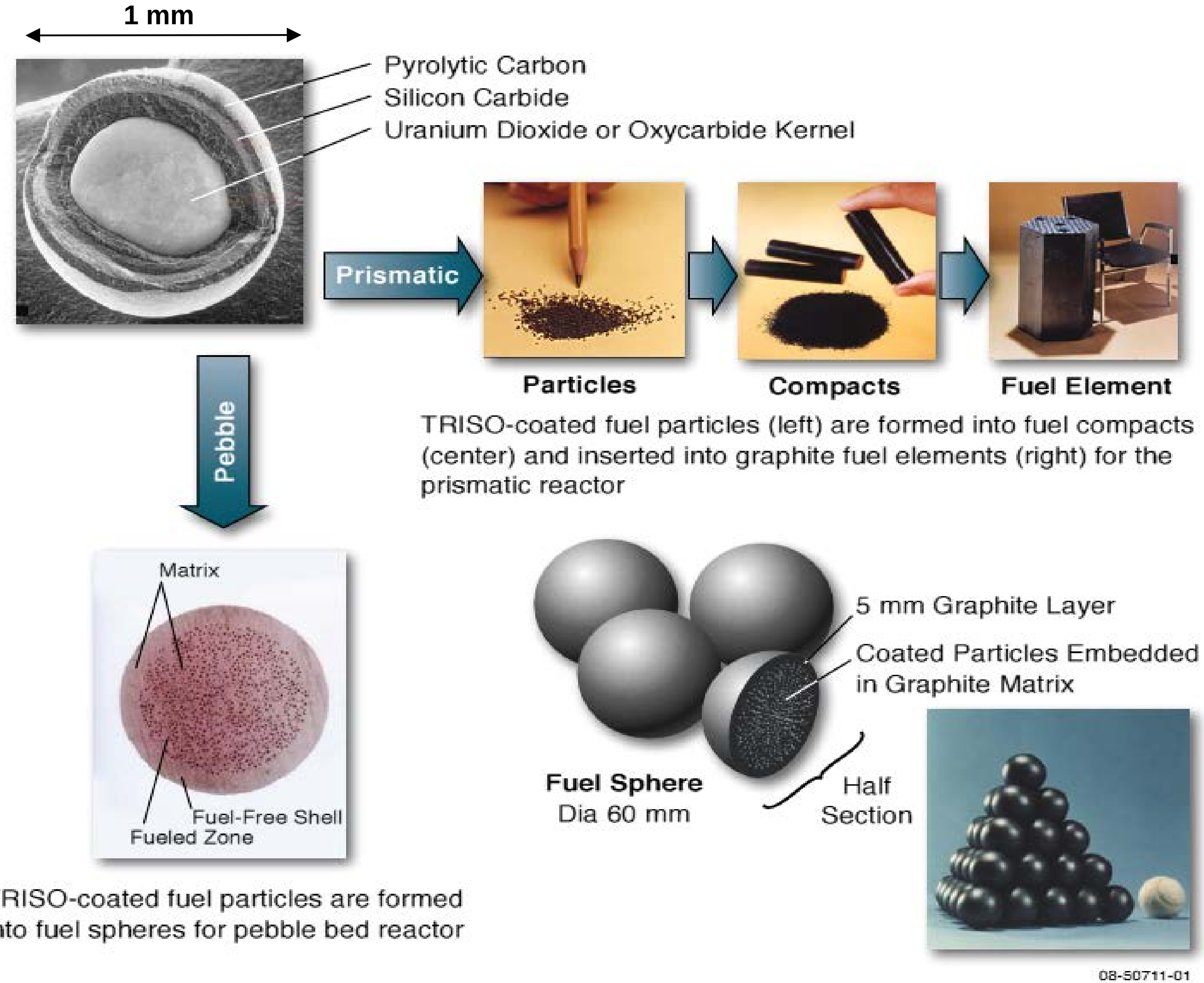
AREVA High Temperature Reactor Steam Cycle-HTGR

- **HTGR technology is well established**
  - **Helium-cooled**
  - **Graphite-moderated**
  - **Coated particle fuel**
- **Modular design and construction**
- **HTGR can meet many needs**
  - **High efficiency electricity for smaller markets**
  - **High temperature process steam**
  - **Cogeneration of process heat and electricity**
- **HTGR has inherent safety characteristics that allow "close-in" siting with energy users**



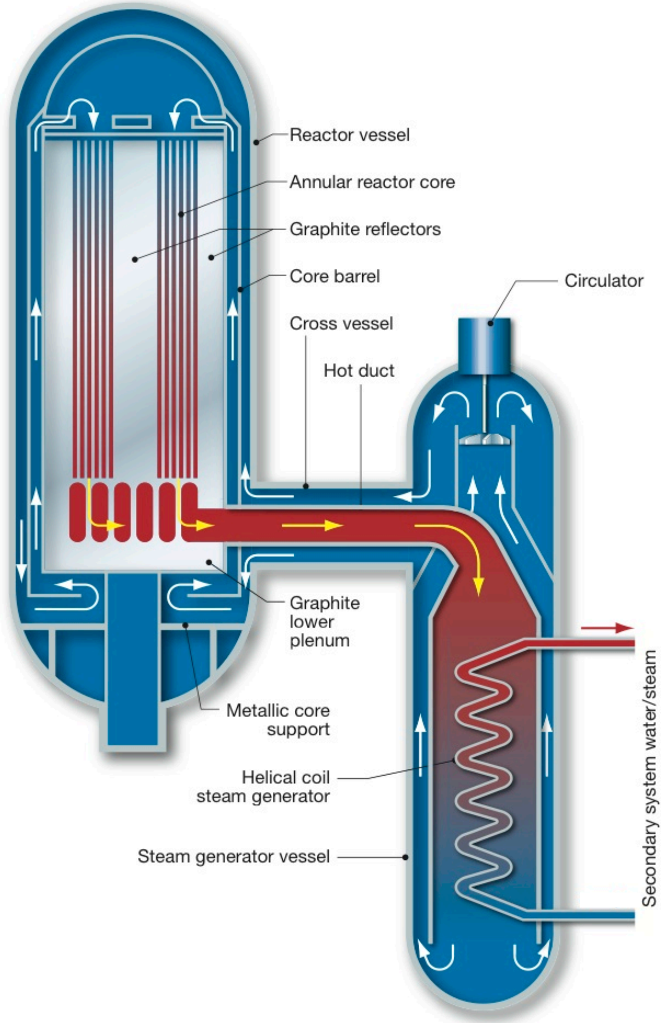
AREVA High Temperature Reactor Fuel Form

- Low Enriched U-235
- UO2 or UCO
- Ceramic coatings
  - Inner Buffer Layer
  - Inner Pyrolytic Carbon
  - Silicon Carbide
  - Outer Pyrolytic Carbon
- Fuel integrity is maintained during design basis and beyond design basis accidents
- Ceramic coated (TRISO) fuel particle retains virtually all fission products within the kernel and the coating layers during operating and accident conditions



AREVA High Temperature Reactor Key Features

- Targeting mainly process heat delivery
- Prismatic block annular core
- Helium cooled primary
- Steam cycle secondary
- Modular design
- Intrinsic safety characteristics
  - Passive decay heat removal
  - Large thermal inertia
  - Large negative temp/reactivity feedback
- Minimal reliance on active safety systems
- Sized to optimize steam production cost/passive safety
- Fully embedded reactor building
  - Partially embedded alternative possible



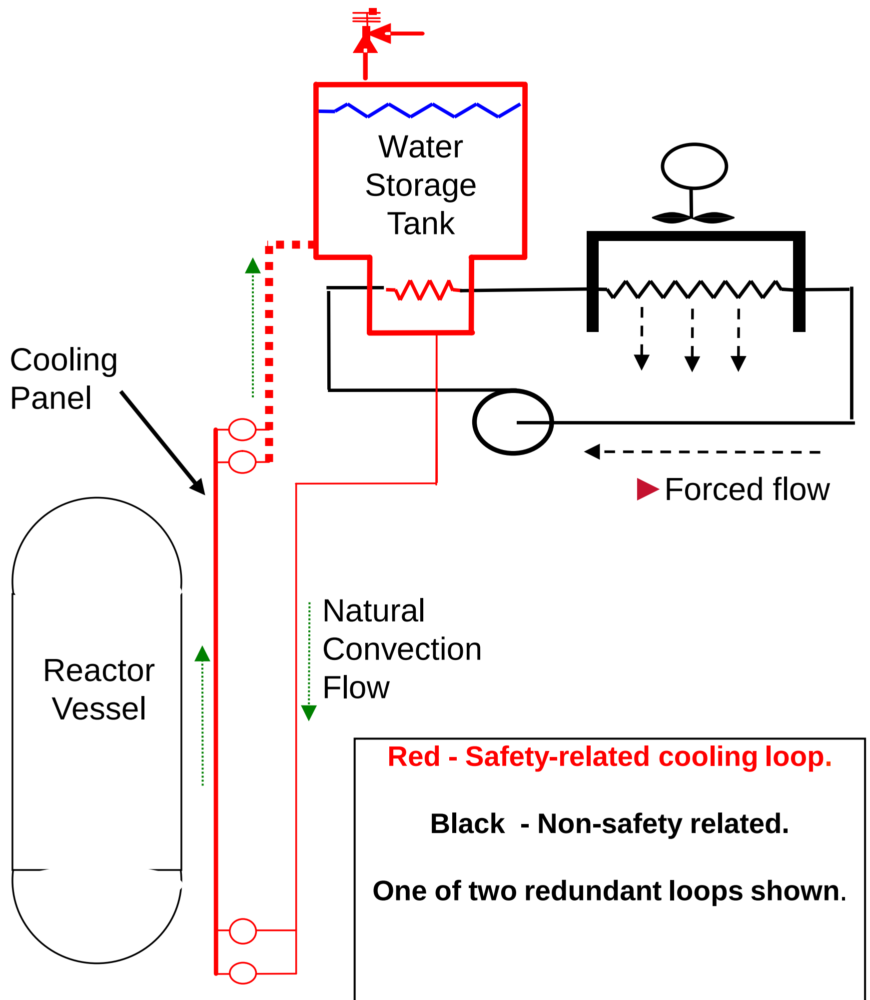
(1 of 2 steam generators shown)

AREVA

AREVA High Temperature Reactor

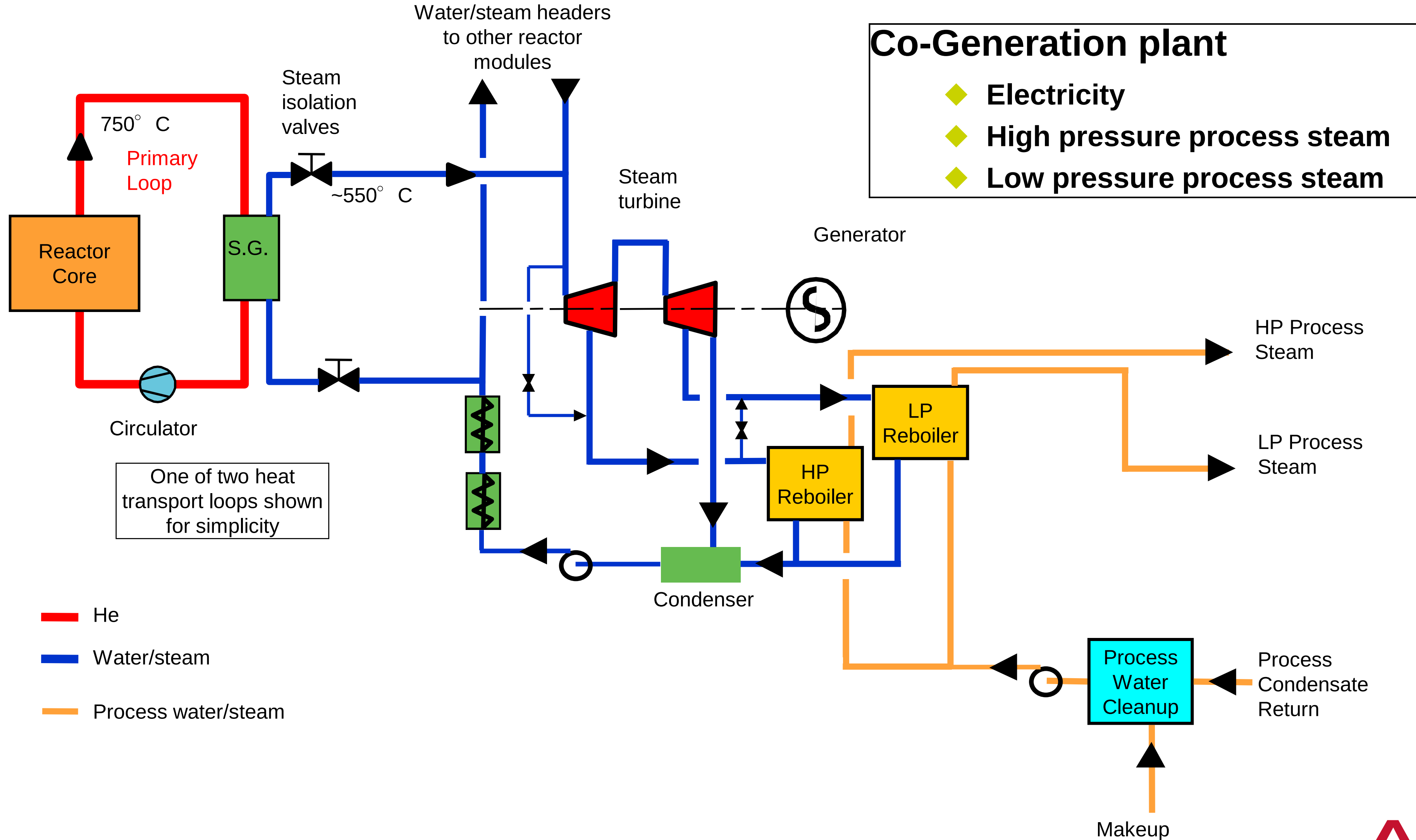
Cooling Systems -- Optimized for Reliability and Safety

- **Main heat transport system**
  - **Established helical coil steam generator technology**
  - **Electric motor circulator with magnetic bearings**
- **Shutdown cooling system**
  - **Active system**
  - **Maximizes plant availability**
    - Maintenance
    - Rapid accident recovery for improved availability
- **Reactor cavity cooling system**
  - **Safety related heat removal system**
  - **Passive cooling of vessel and surrounding cavity (operates continuously – safety-related)**
  - **Active cooling of water storage tank during normal operation (non-safety)**



AREVA High Temperature Reactor

Single Reactor Module Design Supports Many Applications



Co-Generation plant

- Electricity
- High pressure process steam
- Low pressure process steam

AREVA

High Temperature Reactor R&D in USA
Sponsored by DOE

- **Advanced Gas Reactor (AGR) fuel research program**
  - DOE sponsored R&D program began in 2004
  - Purpose: TRISO Fuel Characterization and Qualification
  - Currently at phase 4 (AGR-3/4) of an 8 phase program
  - Irradiation and characterization work performed at DOE Laboratories
  - UCO fuel manufactured by B&W
  - UO2 fuel manufactured by AREVA and South African PBMR Pty
- **Codes and Methods Development**
- **Advanced Graphite Characterization (AGC)**
  - Nuclear grade graphite R&D
  - Design tools and ASME standards development
  - Irradiation at INL ATR reactor
  - A variety of Nuclear grade graphite
- **University programs**
  - Oregon State University, University of Wisconsin, Texas A&M and others
  - Air/Water ingress studies
  - RCCS performance studies

AREVA

HTGR is Intrinsically Safe
Walk Away Safe

- Multiple layers of protection
- No catastrophic failure scenarios
- Chemically compatible reactor materials
- Self-limiting reactor
- No operator or control action required to safely shut down
- No active post-accident cooling required

AREVA

USA Licensing Initiative

- **Early Days**
  - GA Peach Bottom 1 and Fort St Vrain
- **In the 1990's**
  - DOE MHTGR pre-application licensing
  - Draft SER NUREG -1338
- **In early 2000's**
  - Exelon / PBMR Pre-application Licensing
- **Mid- 2000's**
  - PBMR Pre-application design certification
  - NUREG 1860 – Technology Neutral Licensing
- **Late 2000's to present - DOE Generic HTR Pre-application Activities**
  - NGNP Licensing strategy (a report to congress 2009)
  - One week Technology Training
  - Eight Licensing Issue White Papers
  - ACRS Interactions (2013)
  - NRC Assessment Report (1^{st} draft August 2013)
  - NRC Assessment Report Final - ????

SC-HTGR from the SMR Market Perspective

- Modular reactor size offers significant market advantages
  - Incremental capacity addition
  - Serial production
  - Shared resources
  - Match capacity to facility energy needs
- Serves a variety of markets
  - Repowering of existing fossil-fired generating plants
  - Chemical processing facilities
  - Distributed steam production for Oil Sands and other distributed applications
- SC-HTGR characteristics offer unique advantages
  - Safety characteristics allow placement at existing fossil and industrial sites (with built up surroundings)
  - Low investment risk profile (for reactor plant and for close-in siting generating and industrial facilities)
  - Benign safety characteristics and long response times a good match for developing countries with limited nuclear experience and developing grids
- Modular SC-HTGR economic drivers
  - High thermal efficiency (very high compared to other nuclear options)
  - Unnecessary safety systems and emergency diesel generators eliminated
  - Serial modular construction
  - Good Uranium utilization (and reduced heavy metal waste stream)

AREVA

HTGR Development and Deployment
NGNP Industry Alliance, LLC

Mission - Promote the development and commercialization of High Temperature Gas-cooled Reactor (HTGR) technology

DOW

SGL GROUP
THE CARBON COMPANY

ConocoPhillips

US ULTRA SAFE NUCLEAR

Entergy

AREVA

Westinghouse

PTAC

TECHNOLOGY INSIGHTS

TOYO TANSO
Inspiration for Innovation

Wyoming

GRAFTech International

MERSEN

Advanced Research Center

SRS
COMMUNITY REUSE ORGANIZATION
two states, one future

Manufacturing Excellence Consulting, Inc.

HTGR Development and Deployment Strategy

- **The NGNP Alliance**
  - **Support and encourages US-DOE to <u>complete</u> the TRISO fuel, radionuclides transport and graphite R&D**
  - **Support our University based test facilities e.g. OSU and UW**
- **We have prepared a comprehensive Business Plan**
  - **Developed the cost bases of the reference design (done)** ✓
    - Design cost
    - Licensing cost
    - 1st plant deployment cost estimate
    - Supply chain development
    - NOAK cost targets
  - **Developed the project resource needs and engineering schedule (done)** ✓
- **We have started the implementation phase of the Business Plan**
  - **Creating investor value packages offering IP ownership / transfer opportunities and off-ramps**
  - **Execute project capitalization plan – In progress**

AREVA

Summary

- **To date the NGNP Industry Alliance members have invested over $200M**
- **The NGNP Alliance is seeking private, public or sovereign investment to continue the HTGR design and development**
- **Internationally, the NGNP Alliance**
  - **is collaborating with Korean Nuclear Hydrogen Alliance (see http://energy.korea.com/archives/49866);**
  - **has endorsed work on the High Temperature Test Reactor (a prismatic block HTGR) in Japan for JAEA, and**
  - **is working with the Nuclear Cogeneration Industrial Initiative (NC2I) European Alliance (see http://www.nc2i.eu/) to form an agreement that is mutually beneficial to our mission of commercializing HTGR**

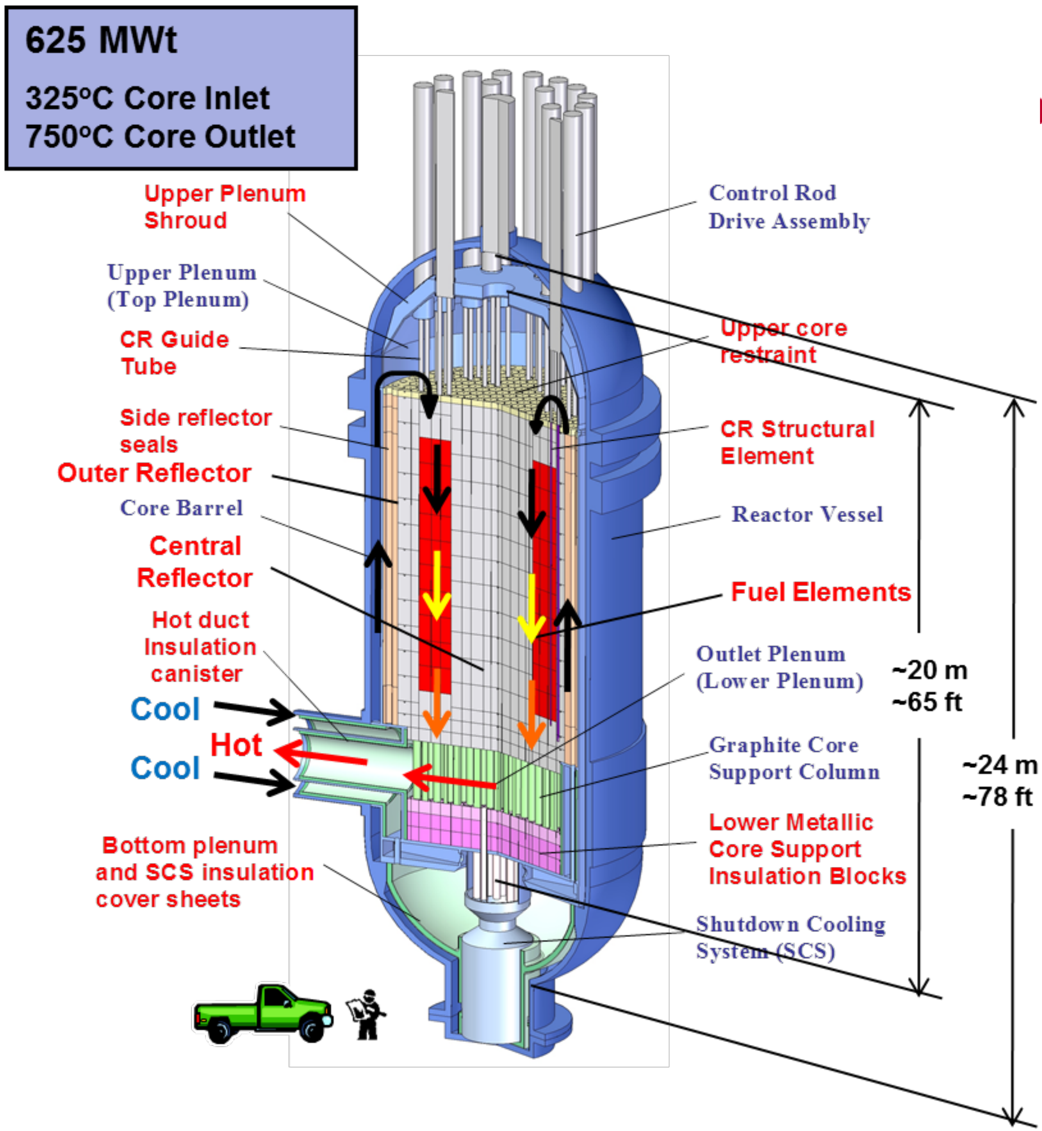
AREVA

Thank you

Questions?

Backup Slides

HTR Safety Case



- **Passive safety features**
  - **Negative temperature coefficient reduces reactivity as temperature rises**
  - **Helium coolant**
    - **Non-moderating**
    - **Gaseous phase during all conditions**
    - **Radioactively & chemically inert**
      - **- (can be carrier gas)**
  - **Ceramic coated-particle fuel**
    - **Maintains structural integrity during LOCA**
    - **Contains fission products during normal operation**
  - **Low power density (5.8-6.6 w/cc)**
    - **Maintain acceptable temperatures during normal operation and accidents**
  - **Annular graphite core with high heat capacity**
    - **Limits fuel temperature during LOCA (1600° C)**
    - **High temperature structural stability**
    - **High thermal inertia - long temperature rise time for LOCA**
  - **Cool reactor vessel & metallic internals with core inlet gas**

Nominal Operating Parameters

Fuel type	TRISO particle
Core geometry	102 column annular 10 block high
Reactor power	625 MWt
Reactor outlet temperature	750°C
Reactor inlet temperature	325°C
Primary coolant pressure	6 MPa
Vessel Material	SA 508/533
Number of loops	2
Steam generator power	315 MWt (each)
Main circulator power	4 MWe (each)
Main steam temperature	566°C
Main steam pressure	16.7 MPa

RS-HTGR Plant Design
–very small version for remote sites

RS-HTR Parameters	
Reactor type	Helium-cooled graphite-moderated
Fuel type	TRISO coated particle fuel
Reactor power level	54 MWt
Reactor inlet temperature	325°C
Reactor outlet temperature	750°C
Primary pressure	1.5 MPa
Core configuration	annular prismatic block core 36 columns 8 blocks high
Main steam temperature	566°C
Maximum electric output	20 MWe
Load following capability	Customer dependent
Refueling interval (at maximum power)	5-8 years

AGR 1, 2, 5/6, and 7 Testing Programs

Capsule	Test Description	Test Objective/Expected Results
AGR-1	Shakedown Test/Early Fuel Performance Demonstration Test Contents included compacts made from UCO fuel particles coated in 2-inch laboratory scale coater at ORNL. A baseline fuel particle composite and three variant fuel particle composites were tested. The variants included two particle composites coated using different IPyC coating conditions and one particle composite coated using different SiC coating conditions.	Gain experience with multi-cell capsule design, fabrication, and operation to reduce chances of capsule or cell failures in subsequent capsules. Obtain early data on irradiated fuel performance and support development of a fundamental understanding of the relationship between fuel fabrication process and fuel product properties and irradiation performance. Provide irradiated UCO fuel for accident simulation testing (i.e. heating tests).
AGR-2	Fuel Performance Demonstration Fuel Contents to include compacts containing UCO particles made in large coater and UO_2 particles made by B&W, AREVA, and PBMR in different size coaters. AGR-2 will have 6 independently monitored and controlled capsules in a test train design essentially the same as demonstrated in AGR-1. One capsule of UCO fuel will be operated with a maximum time-averaged temperature of about 1400˚C as a performance margin test of the fuel.	Provide irradiation performance data for UCO and UO_2 fuel variants and irradiated fuel samples for PIE and post-irradiation heating test to broaden options and increase prospects for meeting fuel performance requirements and to support development of a fundamental understanding of the relationship between fuel fabrication process and fuel product properties and irradiation performance. Also, establish irradiation performance margin for UCO fuel.
AGR-5/6	Fuel Qualification Fuel specimens made by fuel vendor using process conditions and product parameters, based on best performance from successful AGR-1 and AGR-2 experience, using AGR program process development results and AGR-1, AGR-2 data. Variations in cell irradiation temperatures per test specification. .	Provide irradiation performance data for the reference fuel and irradiated fuel samples for PIE and post-irradiation heating tests in sufficient quantity to demonstrate compliance with statistical performance requirements under normal operation and accident conditions.
AGR-7	Fuel Performance Model Validation Contents to include same fuel type as used in AGR-5/6. The irradiation would test fuel beyond its operating envelope so that some measurable level of fuel failure would occur (i.e., margin test).	Provide fuel performance data and irradiated fuel samples for PIE and post-irradiation heating test and PIE in sufficient quantity to validate the fuel performance codes and models and to demonstrate capability of fuel to withstand conditions beyond AGR-5 and -6 in support of plant design and licensing.

AREVA

NGNP/AGR 3/4 and AGR 8 Program Plan
Fission Product Transport

- **AGR-3/4**
  - Designed to fail (DTF) fuel particles
  - Concentric ring design to provide 1-D geometry to facilitate derivation of effective diffusivities in fuel matrix and graphite
  - Data on fission gas release from failed particles, fission metal diffusion in kernels, fission gas and metal diffusion in coatings, and fission product retentiveness of graphite matrix under normal and accident (post irradiation heatup) conditions
- **AGR-8**
  - DTF fuel particles
  - Piggyback design for different irradiation temperatures
  - Temperature cycling (TBD)
  - Temperature, fluence, burnup conditions enveloping NGNP

AREVA

TRISO Fuel Integrity

- Core contains 10-20 billion coated fuel particles, each engineered to retain fission products during normal operation and accidents
- Fuel particles retain fission products well above anticipated accident temperatures
- Fuel failure does not occur suddenly when a particular temperature limit is reached (i.e., no melting or LWR limits).
- Fuel particle performance is determined by time at temperature and burnup. Even at extreme accident temperatures, failure would take 100's of hours.
- Overall fuel performance is determined by the collective behavior of the particles (so we talk in terms of failure fractions or release fractions, not discrete particle failures which would not have any meaningful effect)
- In simplistic terms, we commonly speak of three main failure fractions – initial or as-manufactured failure fraction, incremental failure during operation, and incremental failure during accidents
- All three of these failure fractions are very small. This leads to the very low doses that result from HTGR operation and accidents. This is also the reason we can have a very small EPZ, etc.
- For rapid, extensive fuel failure to occur, fuel temperatures several hundreds of degrees C higher than the highest conceivable accident temperatures would have to occur. And these high temperatures would have to occur not just at the peak hotspot of the core, but throughout the whole core.
- Current qualification testing has heated particles hundreds of degrees higher than predicted peak accident temperatures with no failures.

AREVA

Licensing Framework Interactions with NRC

White Paper	Submittal Date	NRC Public Meeting(s)
1. NGNP Defense-in-Depth Approach INL/EXT-09-17139	December 9, 2009	March 8, 2010
2. NGNP Fuel Qualification White Paper INL/EXT-10-18610	July 21, 2010	September 2, 2010 October 19, 2011 April 17, 2012 July 24, 2012 September 20, 2012 November 14, 2012
3. HTGR Mechanistic Source Terms White Paper INL/EXT-10-17997	July 21, 2010	September 2, 2010 October 19, 2011 April 17, 2012 July 24, 2012 September 20, 2012 November 14, 2012

AREVA

Licensing Framework Interactions with NRC – cont

White Paper	Submittal Date	NRC Public Meeting(s)
4. NGNP Licensing Basis Event Selection White Paper INL/EXT-10-19521	September 16, 2010	November 2, 2010 April 16, 2012 May 16, 2012 July 10, 2012 August 22, 2012 September 19, 2012 November 14, 2012
5. NGNP Structures, Systems, and Components Safety Classification White Paper INL/EXT-10-19509	September 21, 2010	November 2, 2010 July 10, 2012 September 6, 2012
6. Determining the Appropriate EPZ Size and Emergency Planning Attributes for an HTGR INL/MIS-10-19799	October 28, 2010	January 26, 2011 November 14, 2012

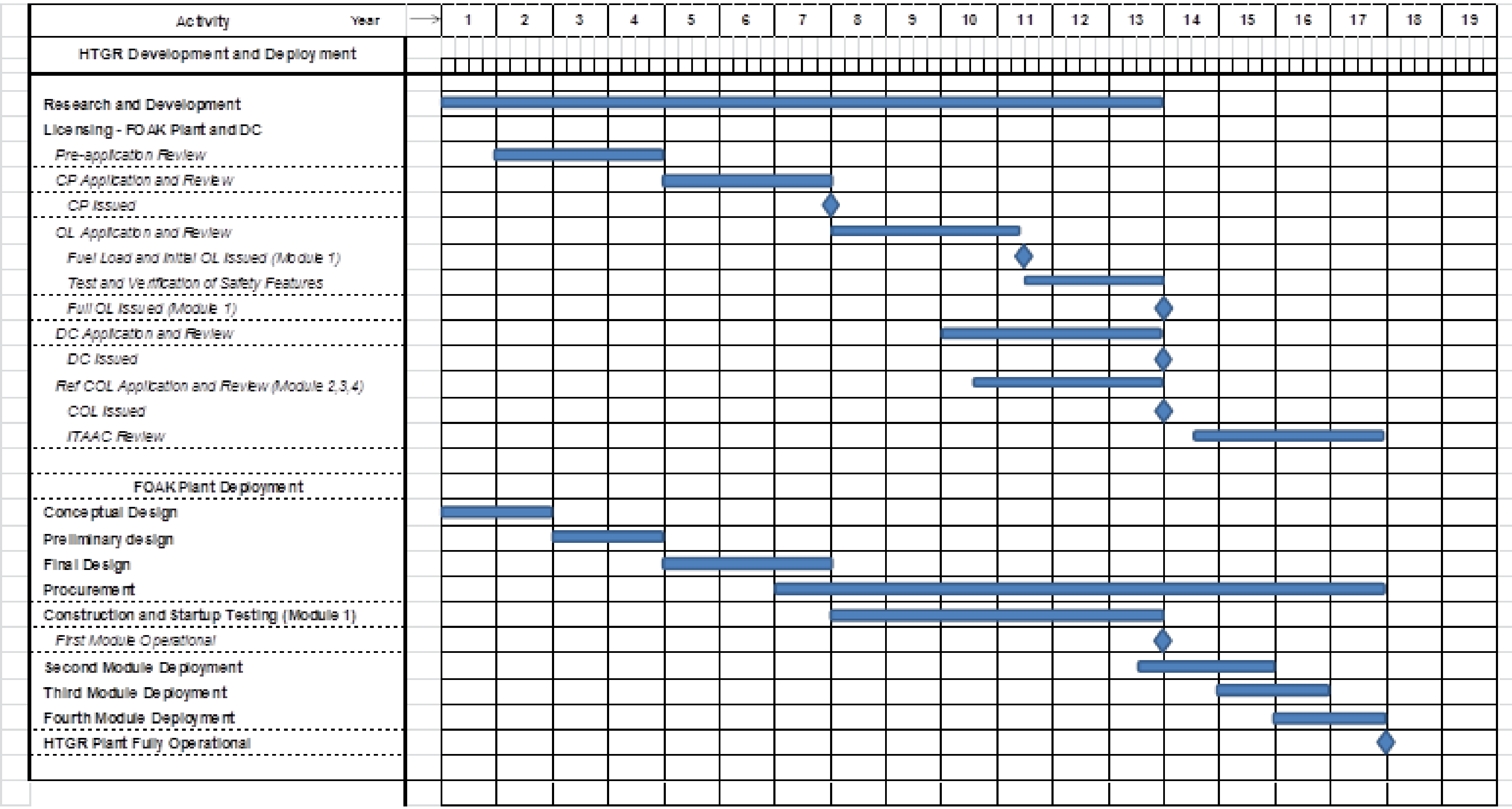
AREVA

Licensing Framework Interactions with NRC – cont

White Paper	Submittal Date	NRC Public Meeting(s)
7. NGNP Probabilistic Risk Assessment White Paper INL/EXT-11-21270	September 20, 2011	April 12, 2012 September 19, 2012
8. Modular HTGR Safety Basis and Approach INL/EXT-11-22708 (submitted for information only)	September 6, 2011	None

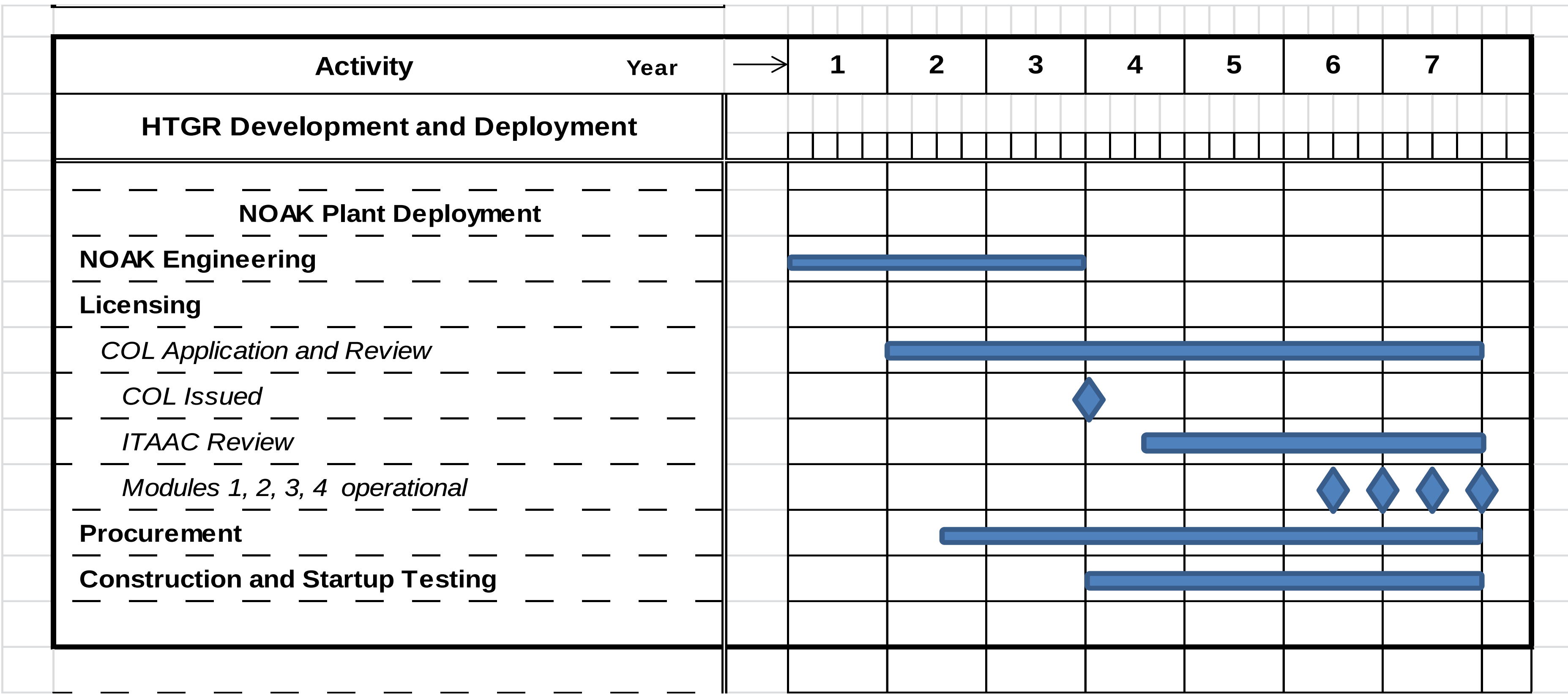
AREVA

Schedule for FOAK Plant

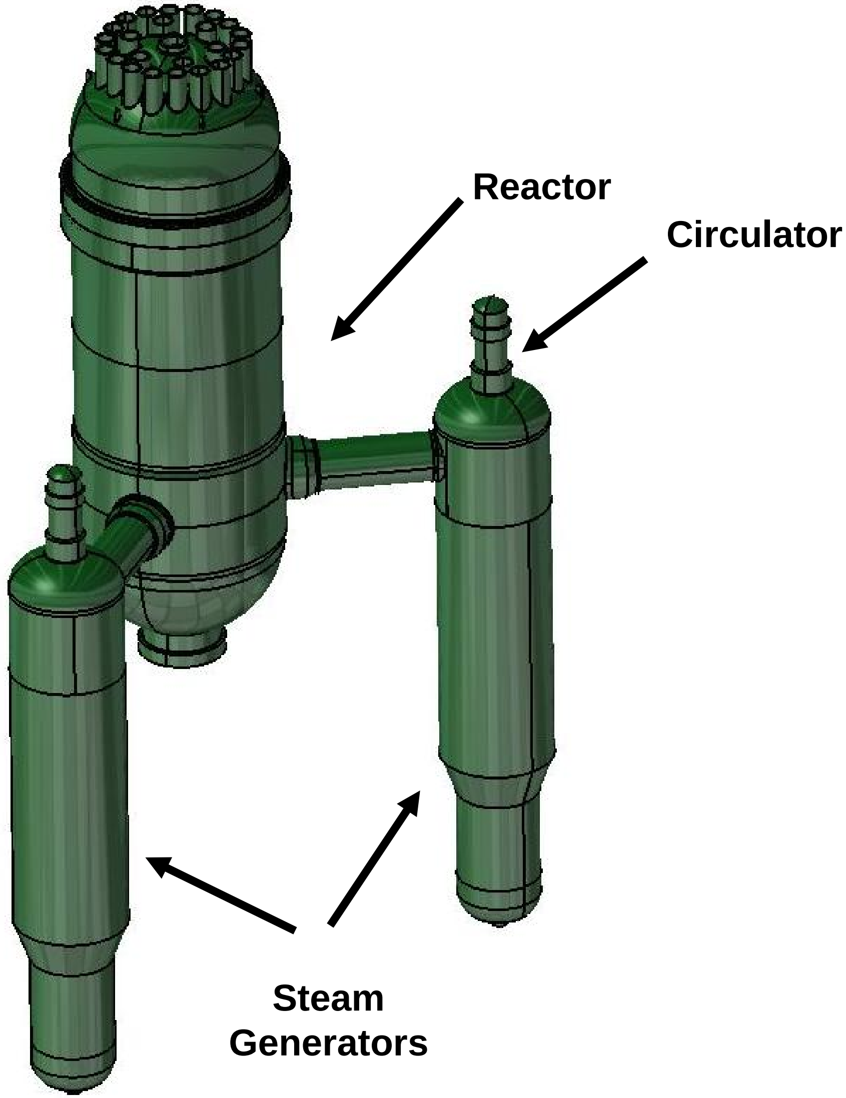


AREVA

Typical NOAK Plant Deployment

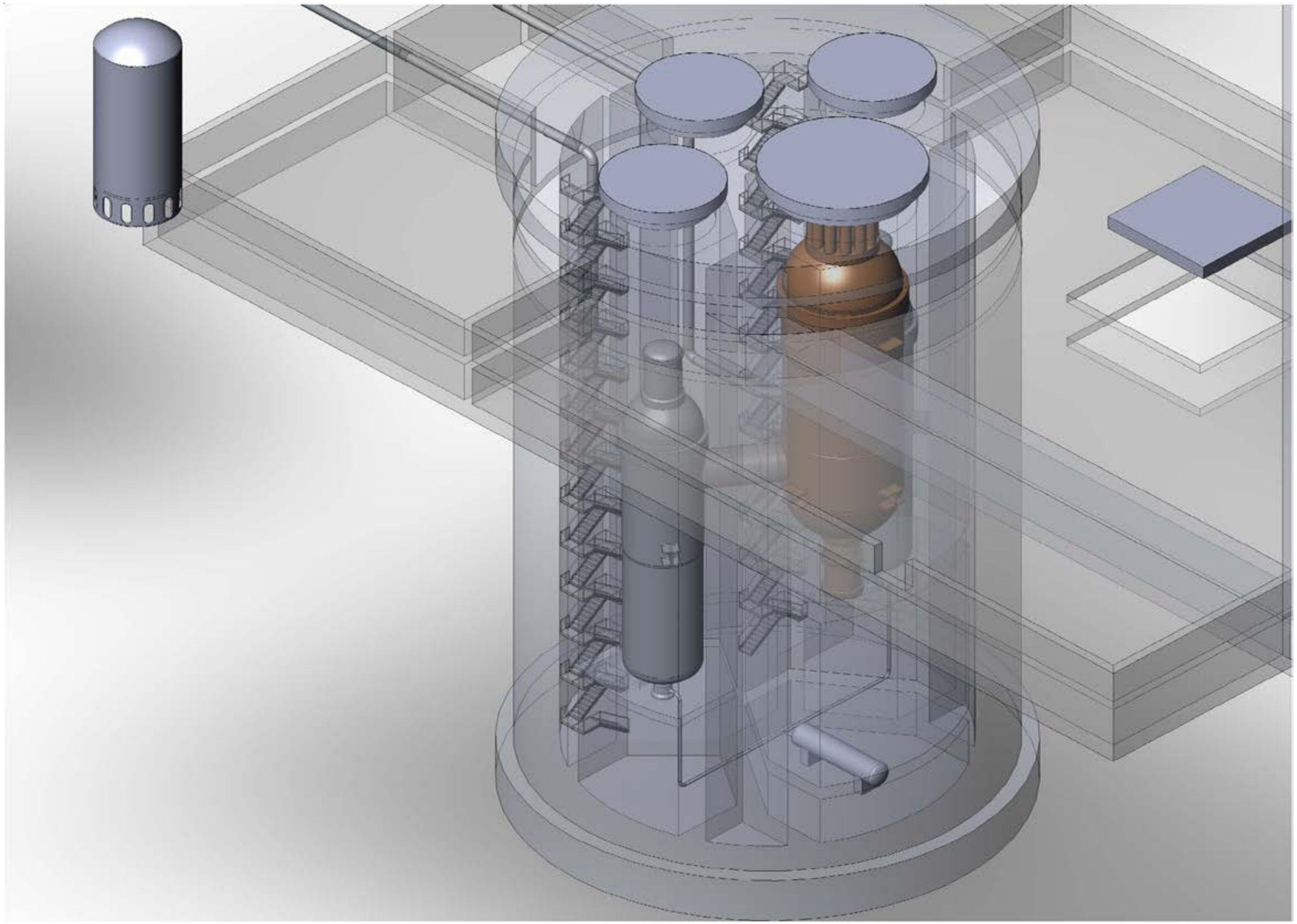


AREVA

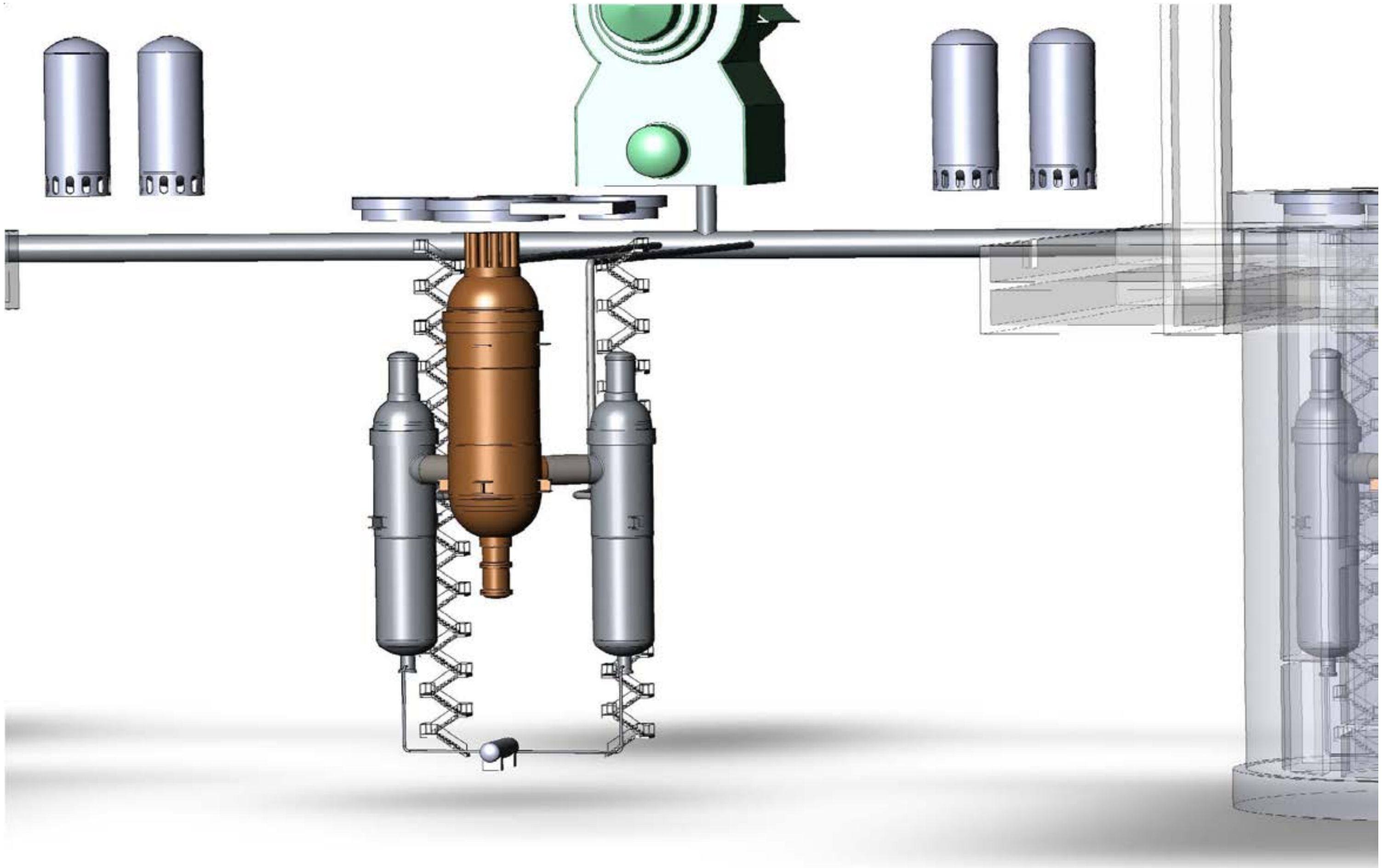


Reactor
Circulator
Steam
Generators

SC-HTGR Plant Design

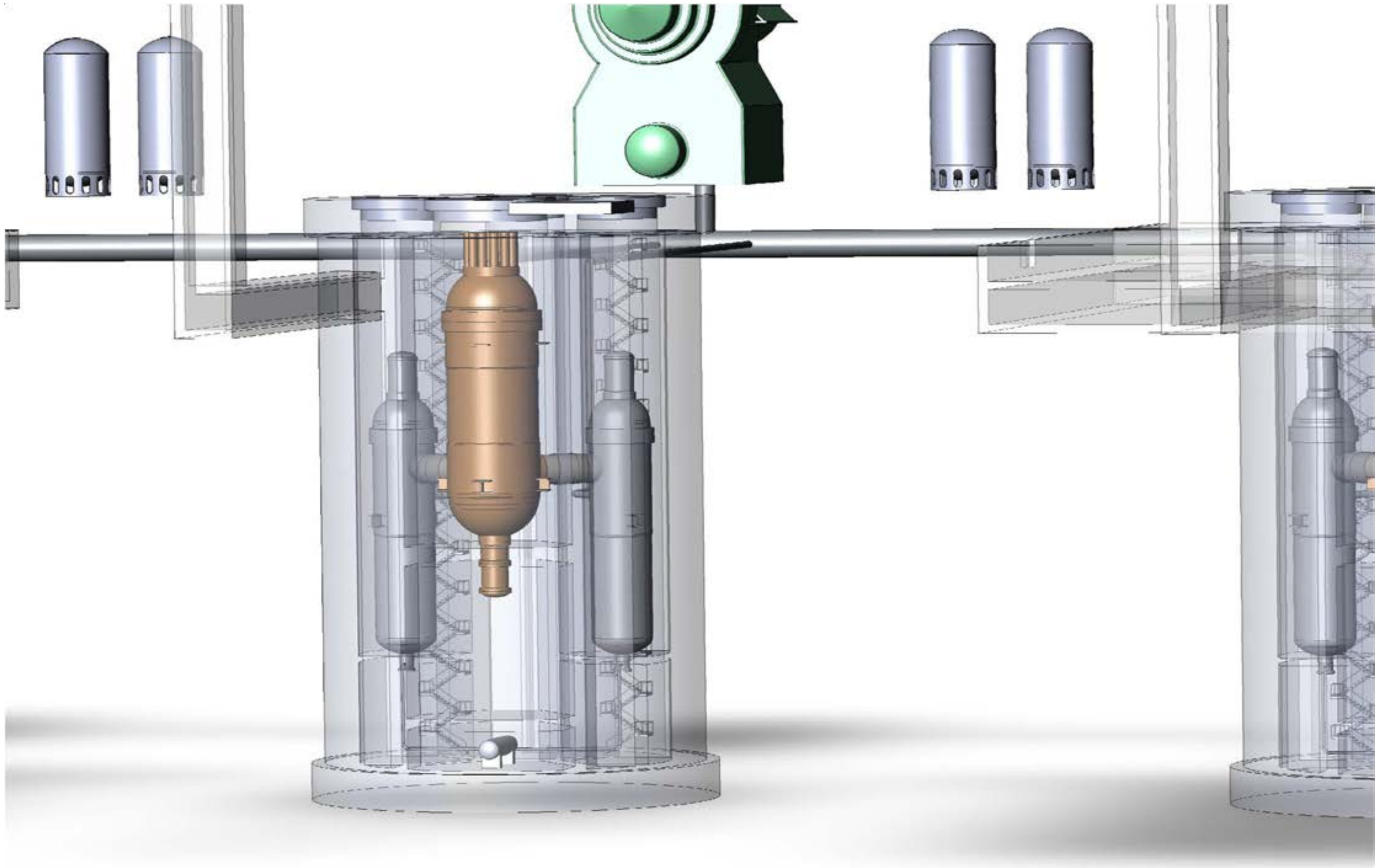


SC-HTGR Plant Design

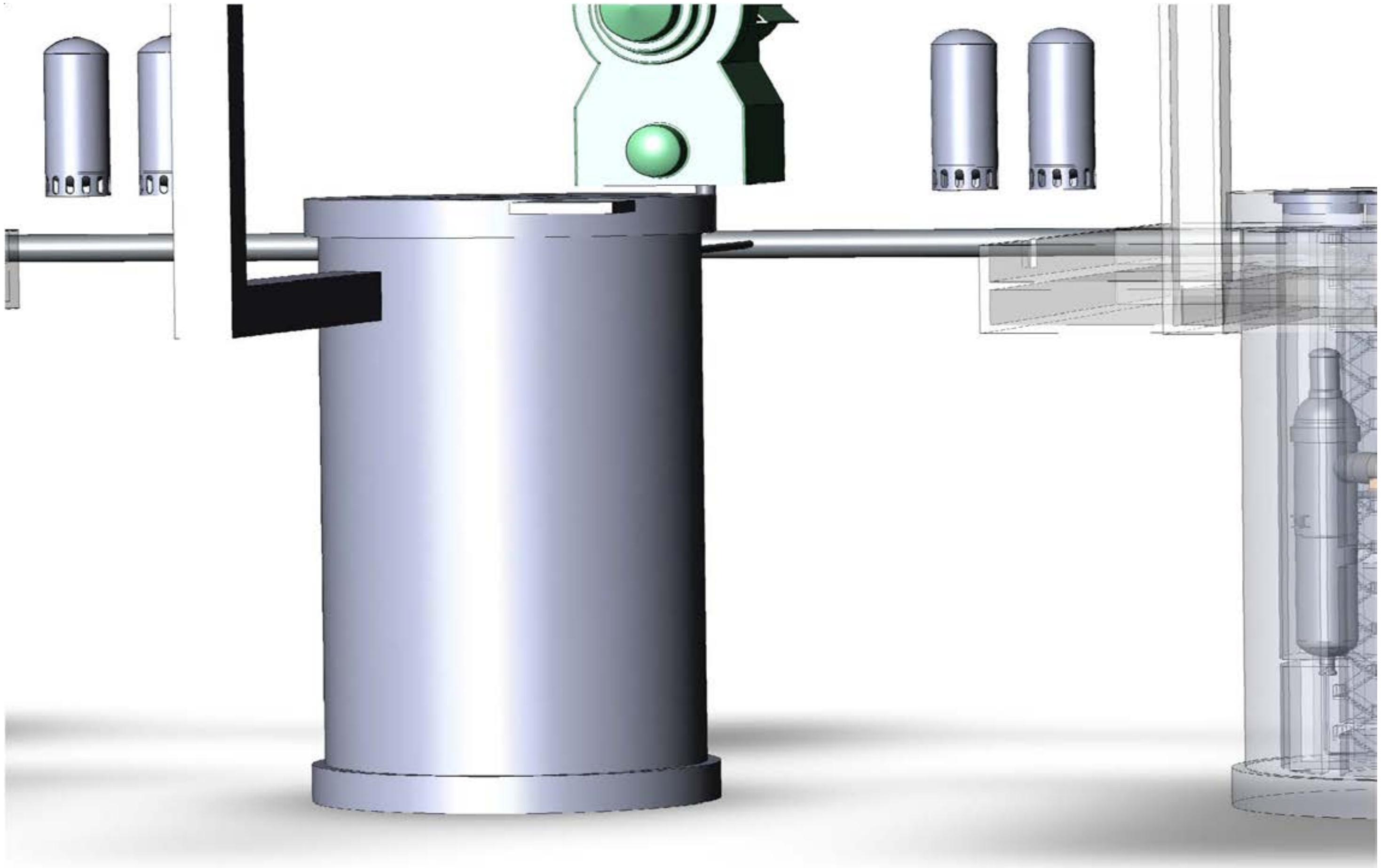


AREVA

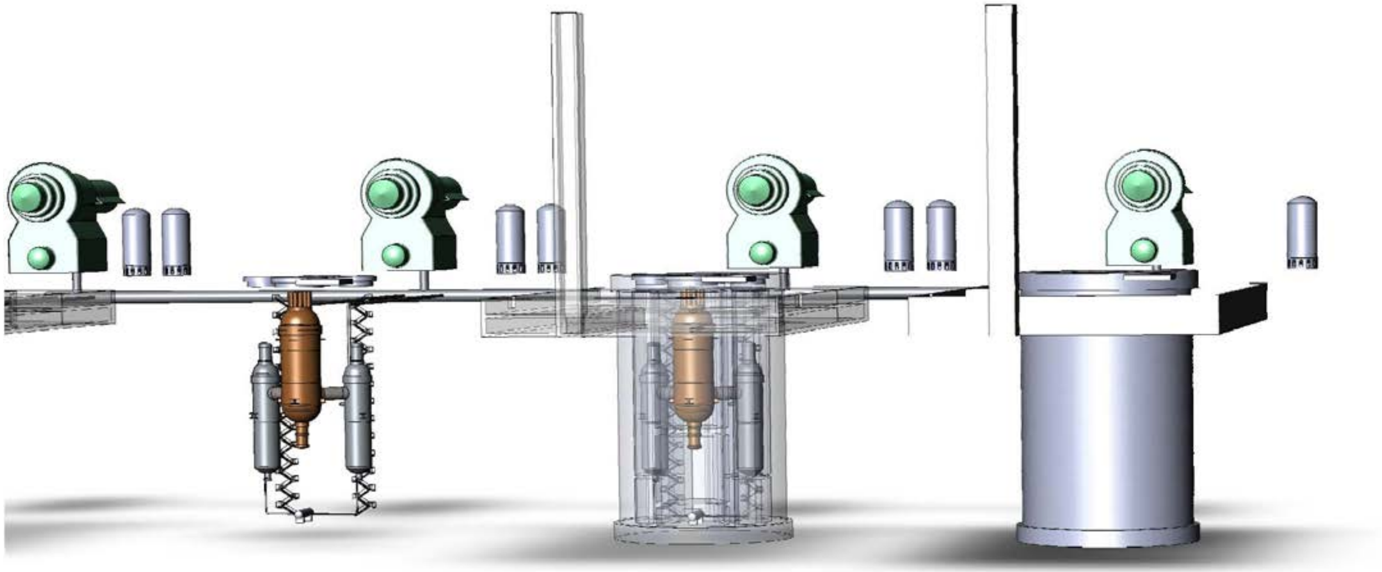
SC-HTGR Plant Design



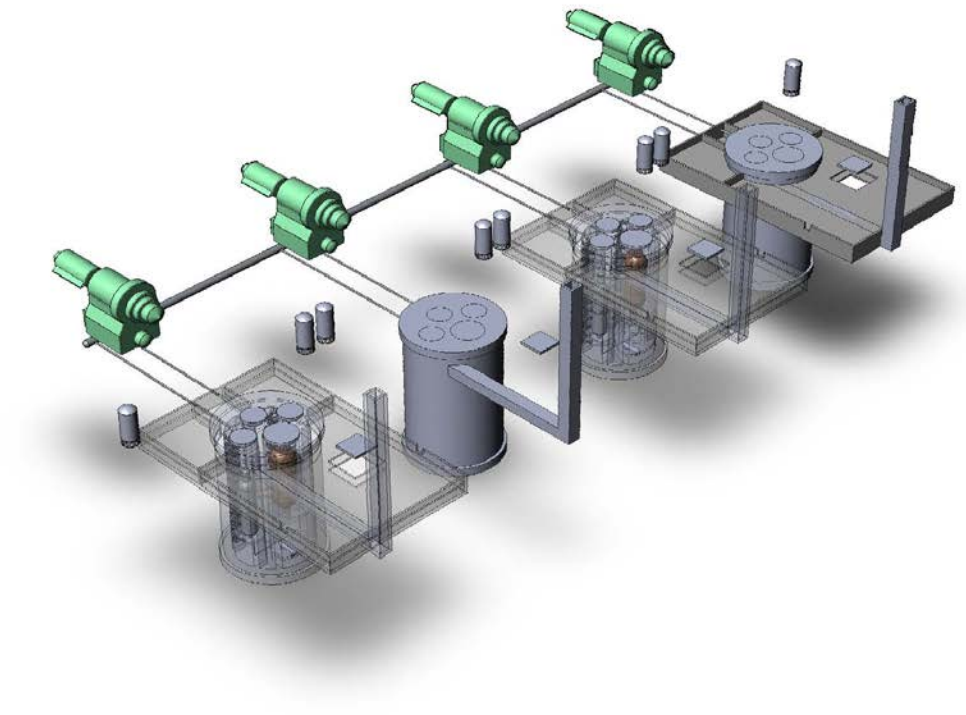
SC-HTGR Plant Design



SC-HTGR Plant Design



SC-HTGR Plant Design



SC-HTGR Plant Design