GEN IV International Forum℠

OVERVIEW OF FHR TECHNOLOGY

Per F. Peterson
University of California, Berkeley

April 27, 2017

NEA Nuclear Energy Agency
cea
Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens
NATIONAL NUCLEAR LABORATORY
Argonne NATIONAL LABORATORY
INL Idaho National Laboratory
Berkeley UNIVERSITY OF CALIFORNIA
NPS PRAESTANTIA PER SCIENTIAM

Meet the presenter

Per F. Peterson holds the William and Jean McCallum Floyd Chair in the Department of Nuclear Engineering at the University of California, Berkeley. He performs research related to high-temperature fission energy systems, as well as studying topics related to the safety and security of nuclear materials and waste management. He participated in the development of the Generation IV Roadmap in 2002 as a member of the Evaluation Methodology Group, and co-chairs its Proliferation Resistance and Physical Protection Working Group. His research in the 1990's contributed to the development of the passive safety systems used in the GE ESBWR and Westinghouse AP-1000 reactor designs. Currently his research group focuses on heat transfer, fluid mechanics, and regulation and licensing for advanced reactors, including fluoride-salt cooled, high temperature reactors (FHRs).

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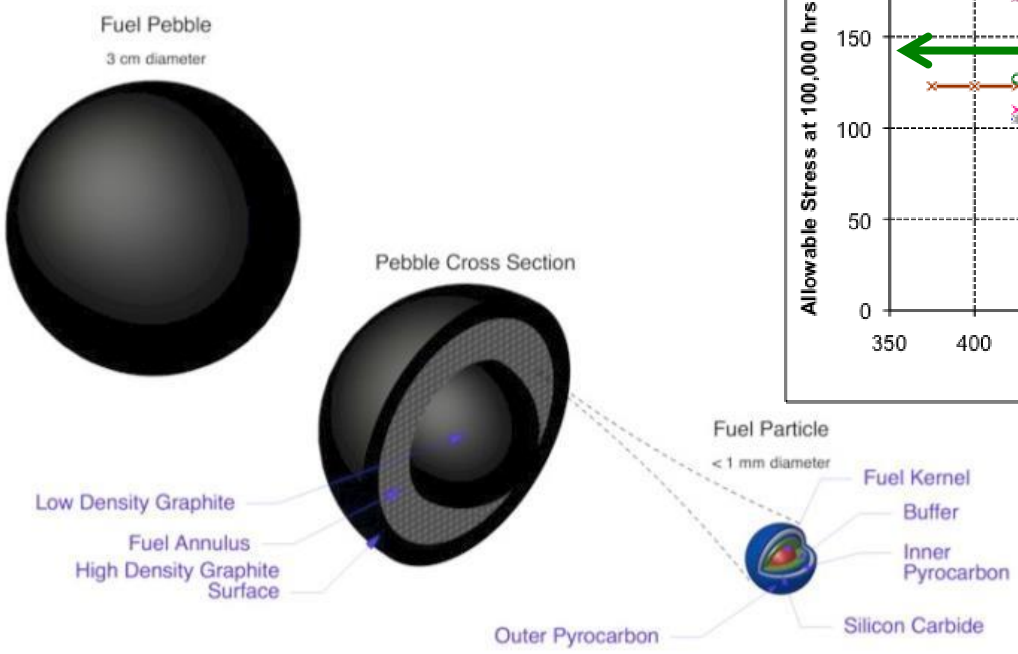
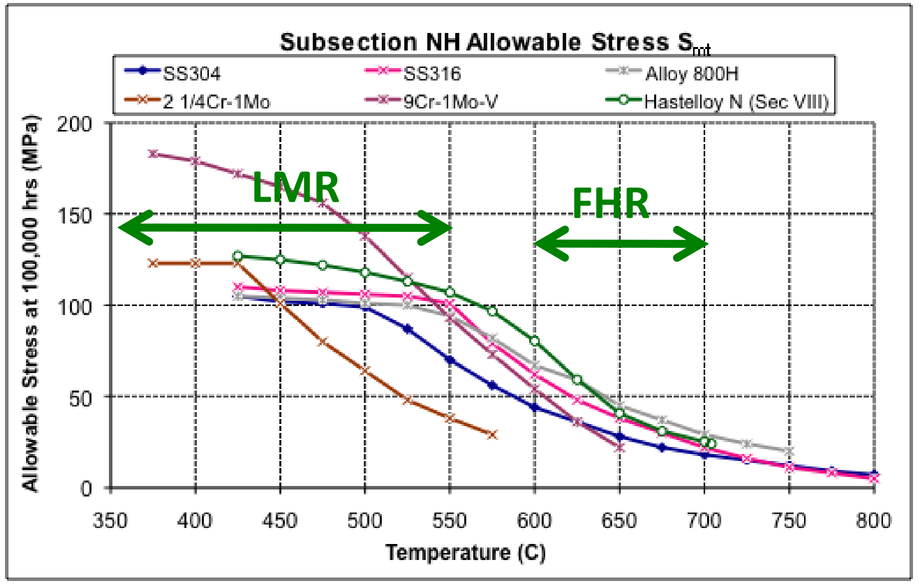
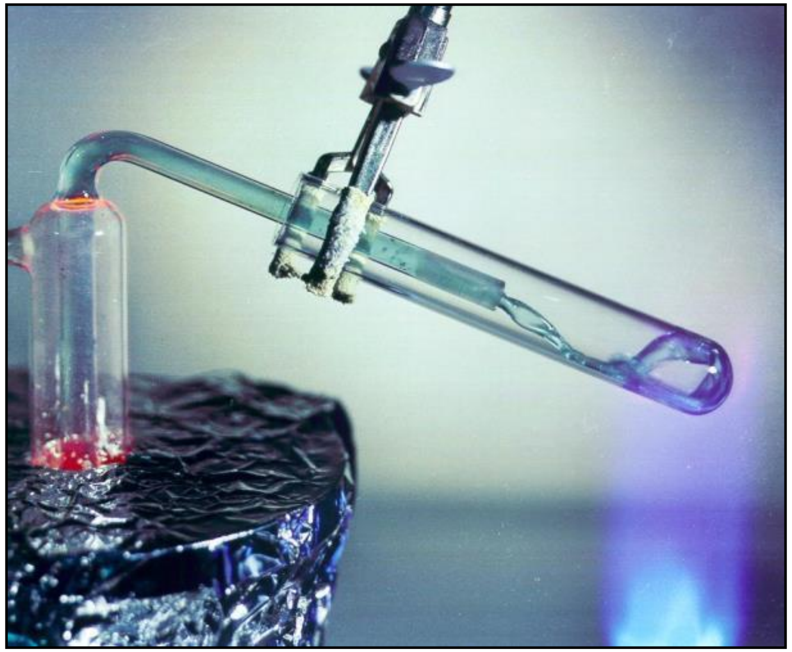
Fluoride salt cooled high-temperature reactors (FHRs) combine three earlier technologies

Coated particle fuel



Nickel-based structural materials





Liquid fluoride salt coolants

The idea of a fluoride-salt cooled, high temperature reactor dates to 2002

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FISSION REACTORS

KEYWORDS: *molten salt, high-temperature reactor, hydrogen production*

MOLTEN-SALT–COOLED ADVANCED HIGH-TEMPERATURE REACTOR FOR PRODUCTION OF HYDROGEN AND ELECTRICITY

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Accepted for Publication May 29, 2003

The molten-salt–cooled Advanced High-Temperature Reactor (AHTR) is a new reactor concept designed to provide very high-temperature (750 to 1000°C) heat to enable efficient low-cost thermochemical production of hydrogen (H_2) or production of electricity. This paper provides an initial description and technical analysis of its key features. The proposed AHTR uses coated-particle the boiling points for molten fluoride salts are near ~1400°C, the reactor can operate at very high temperatures and atmospheric pressure. For thermochemical H_2 production, the heat is delivered at the required near-constant high temperature and low pressure. For electricity production, a multireheat helium Brayton (gas-turbine) cycle, with efficiencies >50%, is used. The

FHRs leverage experience and technology from multiple sources

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- Passive Advanced Light Water Reactors
  - Established licensing methodology for passive safety
  - Integral Effects Test (IET) experiments, CSAU/PIRT
- Sodium Fast Reactors
  - Design and structural materials for low pressure, high temperature
  - Inert cover gas systems; thermal insulation and control, DRACS/RVACS
- High Temperature Gas Reactors
  - TRISO fuel / functional containment
  - Graphite and ceramic-fiber composite structural materials
- Molten Salt Reactors
  - Fluoride salt chemistry control and thermophysical properties
- Natural Gas Combined Cycle Plants (some types of FHRs)
  - Current dominant technology for new U.S. power conversion; adaptable to FHRs

FHRs have unique safety characteristics for accidents resulting in long-term off-site land use restrictions from Cs-137

	FHRs	LWRs
Low Cs-137 inventory	~30 g/MWe	~105 g/MWe
High thermal margin to fuel damage	T_{damage} > 1800°C	T_{damage} ~ 830 – 1250°C
High solubility of cesium in coolant	CsF has high solubility	Cs forms volatile compounds
Intrinsic low pressure	High coolant boiling temperature and chemical stability	High vapor pressure at accident temperatures

R&D has developed an improved foundation for understanding FHRs

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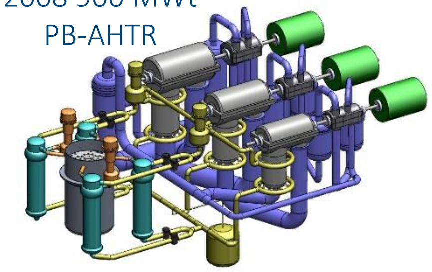
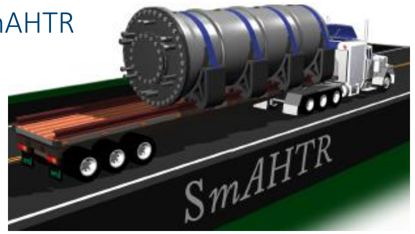
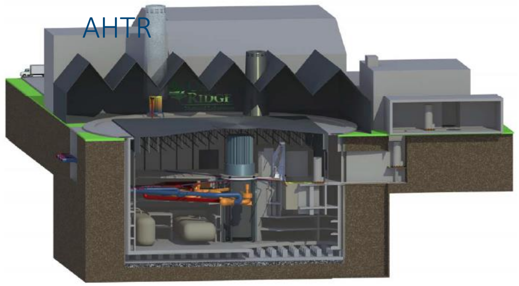
2008 900 MWt PB-AHTR



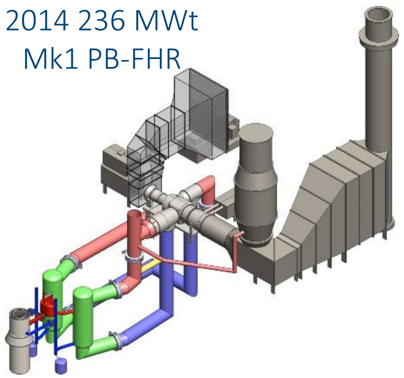
2010 125 MWt SmAHTR



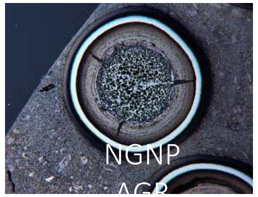
2012 3600 MWt ORNL AHTR

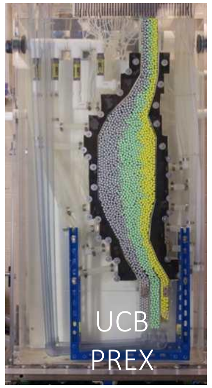


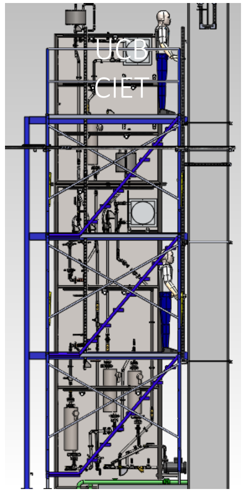
2014 236 MWt Mk1 PB-FHR



Multiple FHR Conceptual Design Studies







Experiments and Simulation


FHR

Preliminary FHR Subsystems Definition, Functional Requirement Definition, and LBE Identification White Paper
UCBTH-12-001

Preliminary Fluoride-Salt-Cooled, High-Temperature Reactor (FHR) Subsystems Definition, Functional Requirement Definition, and Licensing Basis Event (LBE) Identification White Paper

March 2012
Revision 3

Integrated Research Project Workshop 1
Department of Nuclear Engineering
University of California, Berkeley

Panel Members
Todd Allen (University of Wisconsin, Madison)
Syd Ball (Oak Ridge National Laboratory)
Edward Blandford (Stanford University)
Tom Downar (University of Michigan)
George Flanagan (Oak Ridge National Laboratory)
Charles Forsberg (Massachusetts Institute of Technology)
Ehud Greenspan (University of California, Berkeley)
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Regis Matzie (*ret.* Westinghouse Electric Company)
John McGaha (*ret.* Entergy)
Dan Mears (Technology Insights)
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Nicolas Zweibaum
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This research is being performed using funding received from the U.S. Department of Energy Office of Nuclear Energy's Nuclear Energy University Programs.

Expert Workshops and White Papers

Studies for FHR fuels and materials are encouraging

- INL testing of NGNP TRISO fuel shows excellent fission product retention up to 1800°C

http://www.world-nuclear-news.org/ENF-Triso_fuel_triumphs_at_extreme_temperatures-2609137.html

- **UW static corrosion tests show low corrosion rates for 316 SS and Alloy N in flibe at 700° C (1000 hr)**

USDOE-Funded Integrated Research Projects have advanced the understanding of FHR technology

UC Berkeley FHR research focuses on thermal hydraulics, neutronics, safety and licensing

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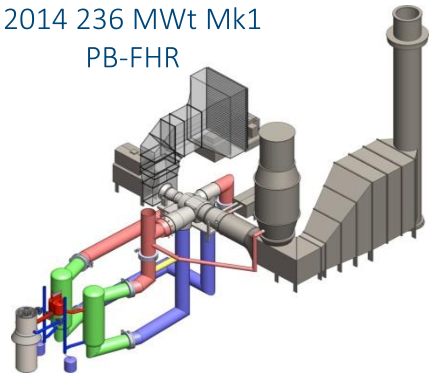
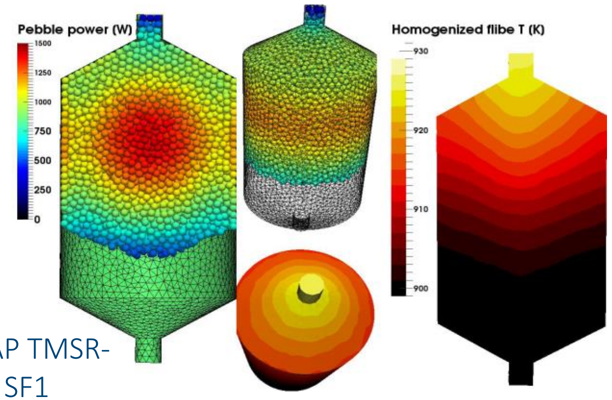
2014 236 MWt Mk1 PB-FHR



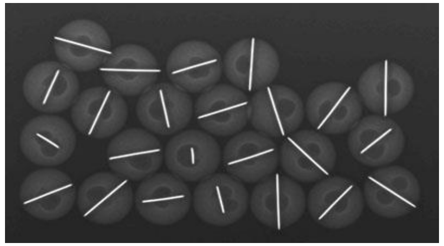
Conceptual Design Studies



SINAP TMSR-SF1

Coupled neutronics and thermal hydraulics

Separate and integral effect tests



X-PREX Pebble Bed Tomography

FHR

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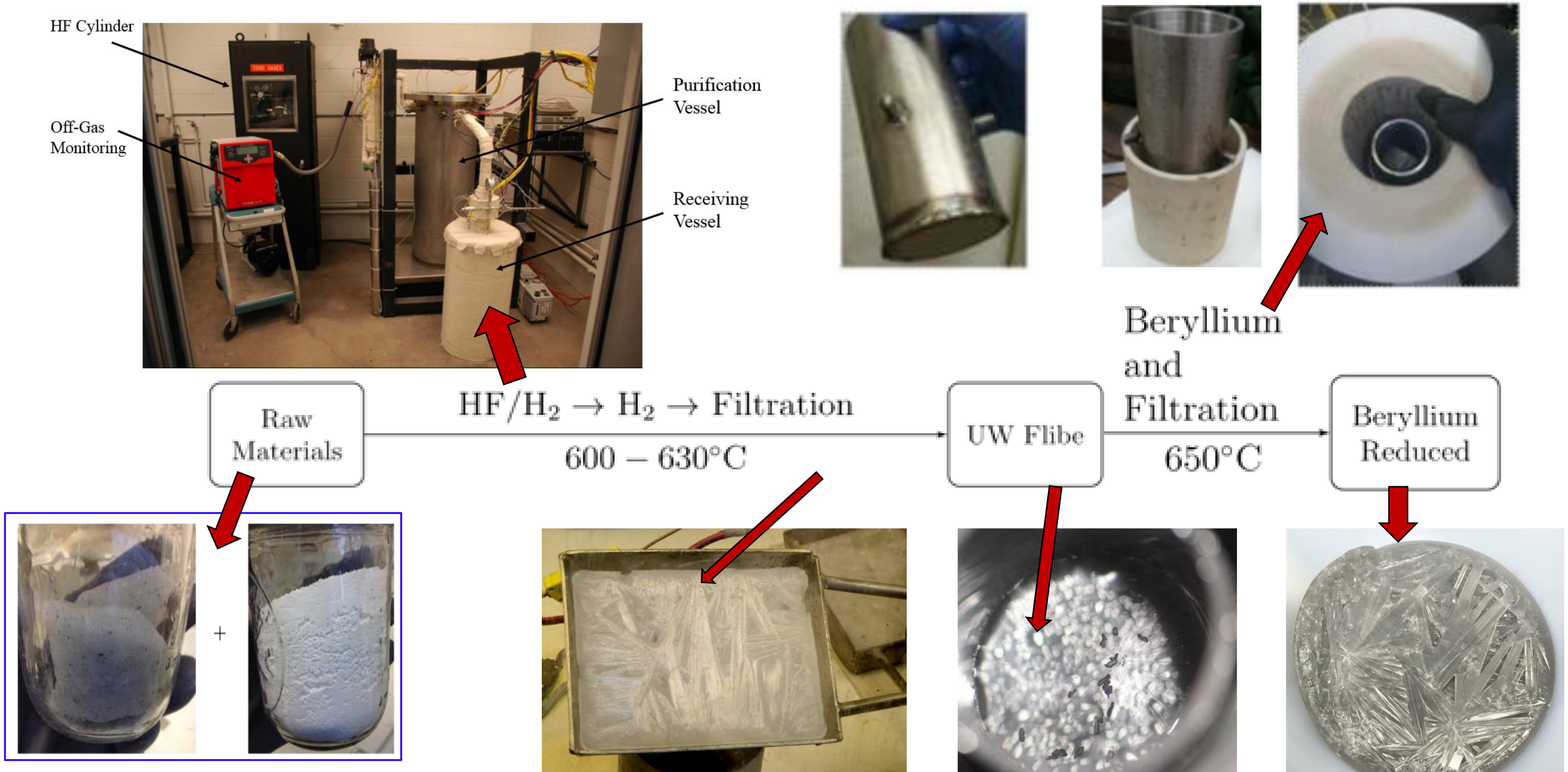
This research is being performed using funding received from the U.S. Department of Energy Office of Nuclear Energy's Nuclear Energy University Programs.

Organize Expert Workshops and White Papers

University of Wisconsin - Production, Purification, and Reduction of flibe (Li_2BeF_4)

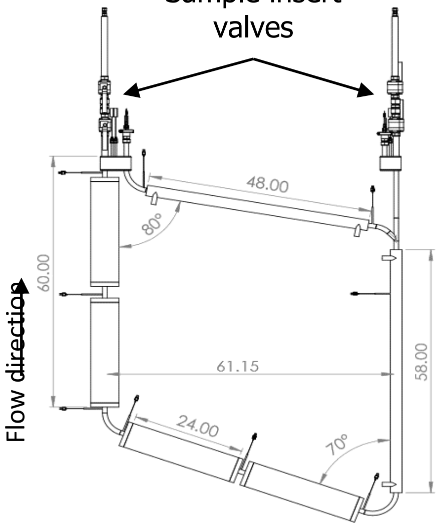


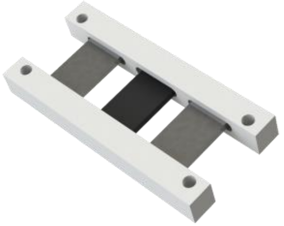
As-received BeF_2 **As-received LiF**

Melted FLiBe Salt

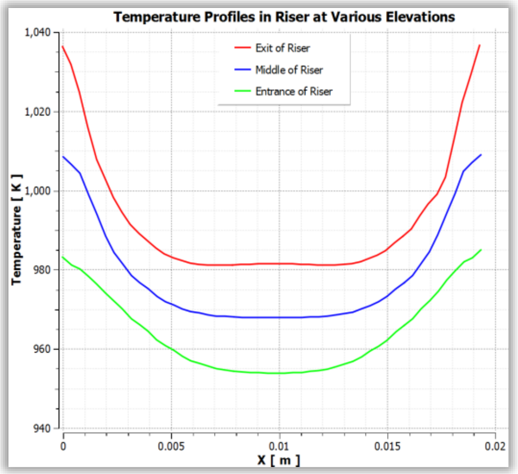
UW Natural Circulation Molten flibe Salt Flow Loop

Enable Measuring Corrosion Under a Wider Set of Conditions





Flow-loop schematic and sample holder



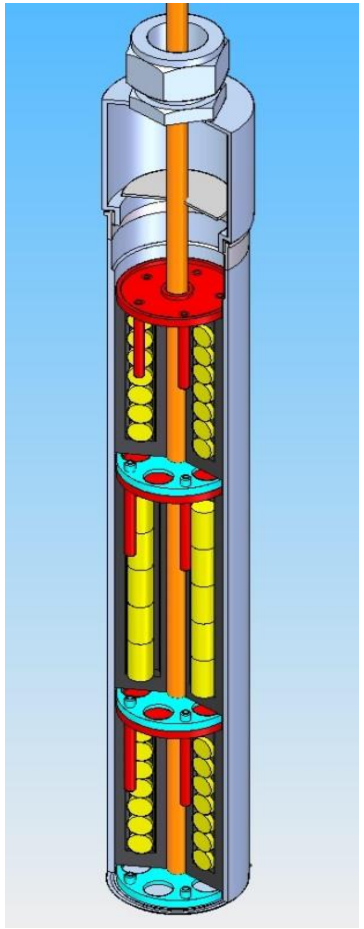
CFD predictions of temperature profiles at the bottom, middle, and top of the heated riser

IR image during heater testing - inside of the loop is at 700°C

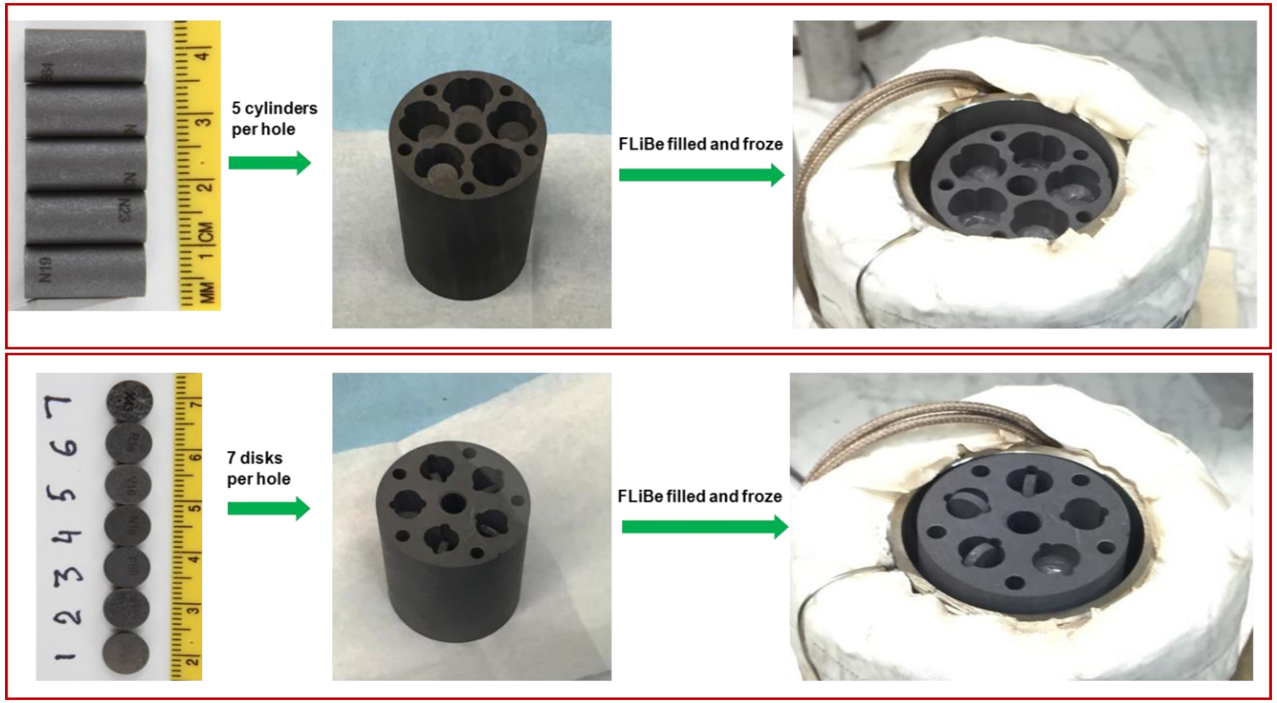
- **Thermal hydraulics**
  - **Flow velocities**
  - **Temperature profiles**
  - **Beryllium transport rates**
  - **Characteristics of the natural circulation**
  - **Heat transfer characteristics**
- **Mass Transport**
  - **Beryllium redox agent transport throughout system**
  - **Corrosion products transport**
- **Corrosion**
  - **Stainless Steel, SiC/SiC, Alloy 800H etc.**
  - **Flow-assisted corrosion**
  - **Dissolution in hot leg and plating on cold leg**

In-Reactor Materials Testing for FHRs

3rd FHR Irradiation in MITR (Fall 2016)



- 1000 hours at 700°C in enriched flibe
- Graphite and C/C specimens
  (previously irradiated SiC, 316SS, Hastelloy-N, TRISO)



Separate Effects Test (SET) and Integral Effects Test (IET) for FHRs, using simulant fluids

The similitude of convective heat transfer in oil and molten salts was discovered in 2005

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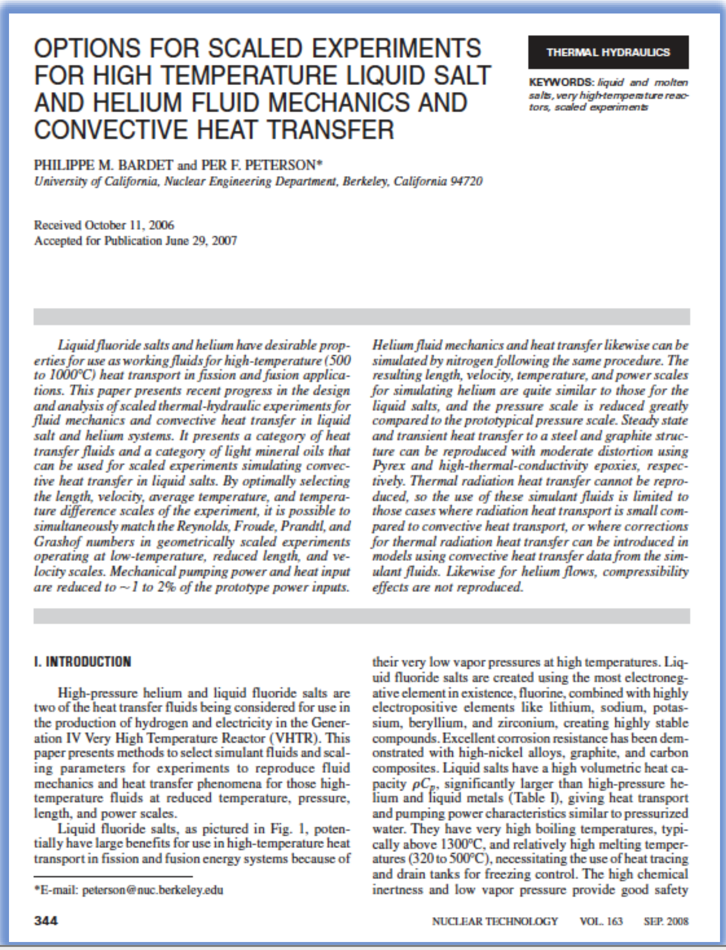
- By appropriate selection of length, velocity, average temperature, and temperature difference scales, it is possible to simultaneously match Reynolds, Froude, Prandtl, and Grashof numbers.
- Mechanical pumping power and heat input reduced to 1 to 2% of prototype power inputs.
- Steady state and transient heat transfer to steel and graphite structures can be reproduced using Pyrex and high-thermal-conductivity epoxies, respectively



OPTIONS FOR SCALED EXPERIMENTS FOR HIGH TEMPERATURE LIQUID SALT AND HELIUM FLUID MECHANICS AND CONVECTIVE HEAT TRANSFER

THERMAL HYDRAULICS

KEYWORDS: *liquid and molten salts, very high-temperature reactors, scaled experiments*

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Received October 11, 2006
Accepted for Publication June 29, 2007

Liquid fluoride salts and helium have desirable properties for use as working fluids for high-temperature (500 to 1000°C) heat transport in fission and fusion applications. This paper presents recent progress in the design and analysis of scaled thermal-hydraulic experiments for fluid mechanics and convective heat transfer in liquid salt and helium systems. It presents a category of heat transfer fluids and a category of light mineral oils that can be used for scaled experiments simulating convective heat transfer in liquid salts. By optimally selecting the length, velocity, average temperature, and temperature difference scales of the experiment, it is possible to simultaneously match the Reynolds, Froude, Prandtl, and Grashof numbers in geometrically scaled experiments operating at low-temperature, reduced length, and velocity scales. Mechanical pumping power and heat input are reduced to ~1 to 2% of the prototype power inputs. Helium fluid mechanics and heat transfer likewise can be simulated by nitrogen following the same procedure. The resulting length, velocity, temperature, and power scales for simulating helium are quite similar to those for the liquid salts, and the pressure scale is reduced greatly compared to the prototypical pressure scale. Steady state and transient heat transfer to a steel and graphite structure can be reproduced with moderate distortion using Pyrex and high-thermal-conductivity epoxies, respectively. Thermal radiation heat transfer cannot be reproduced, so the use of these simulant fluids is limited to those cases where radiation heat transport is small compared to convective heat transport, or where corrections for thermal radiation heat transfer can be introduced in models using convective heat transfer data from the simulant fluids. Likewise for helium flows, compressibility effects are not reproduced.

I. INTRODUCTION

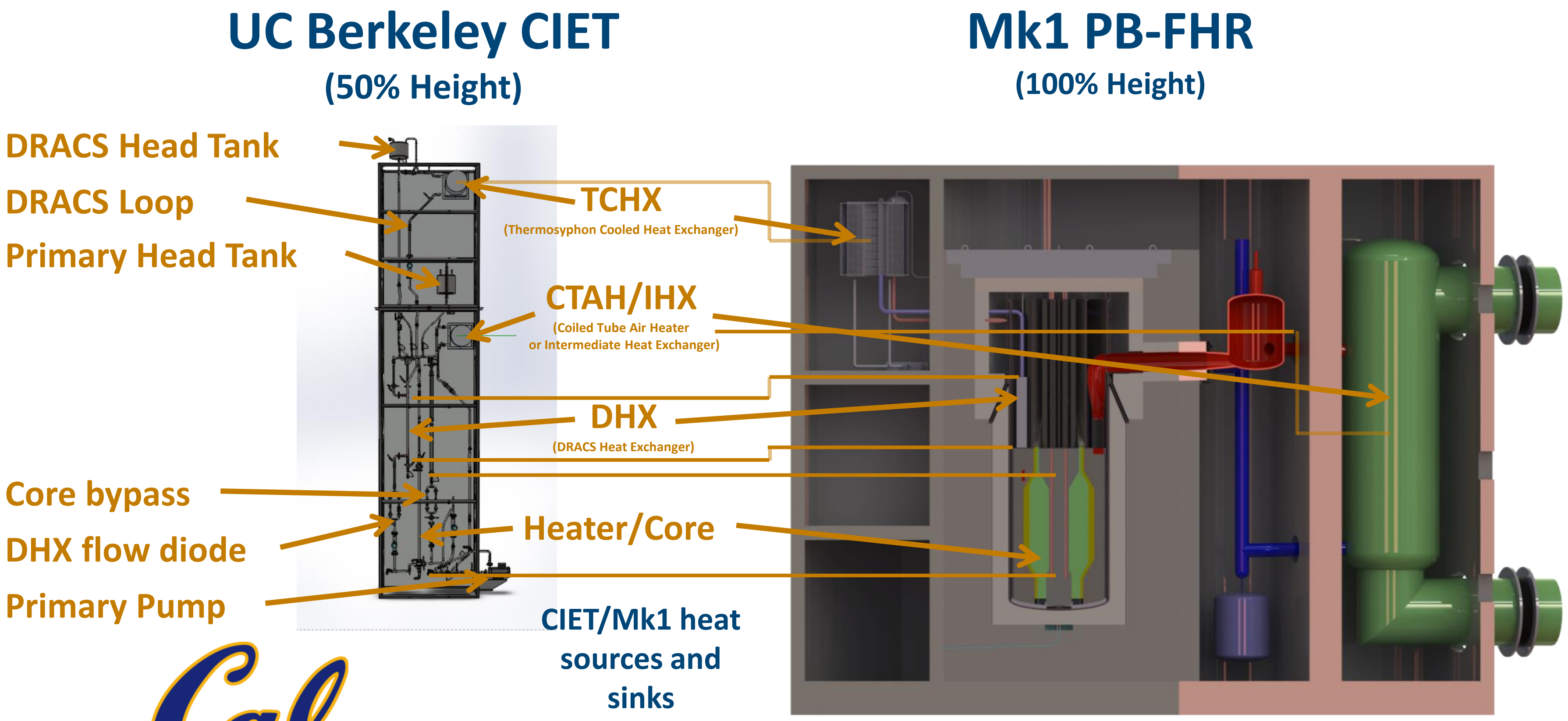
High-pressure helium and liquid fluoride salts are two of the heat transfer fluids being considered for use in the production of hydrogen and electricity in the Generation IV Very High Temperature Reactor (VHTR). This paper presents methods to select simulant fluids and scaling parameters for experiments to reproduce fluid mechanics and heat transfer phenomena for those high-temperature fluids at reduced temperature, pressure, length, and power scales.

Liquid fluoride salts, as pictured in Fig. 1, potentially have large benefits for use in high-temperature heat transport in fission and fusion energy systems because of their very low vapor pressures at high temperatures. Liquid fluoride salts are created using the most electronegative element in existence, fluorine, combined with highly electropositive elements like lithium, sodium, potassium, beryllium, and zirconium, creating highly stable compounds. Excellent corrosion resistance has been demonstrated with high-nickel alloys, graphite, and carbon composites. Liquid salts have a high volumetric heat capacity ρC_p, significantly larger than high-pressure helium and liquid metals (Table I), giving heat transport and pumping power characteristics similar to pressurized water. They have very high boiling temperatures, typically above 1300°C, and relatively high melting temperatures (320 to 500°C), necessitating the use of heat tracing and drain tanks for freezing control. The high chemical inertness and low vapor pressure provide good safety

*E-mail: peterson@nuc.berkeley.edu

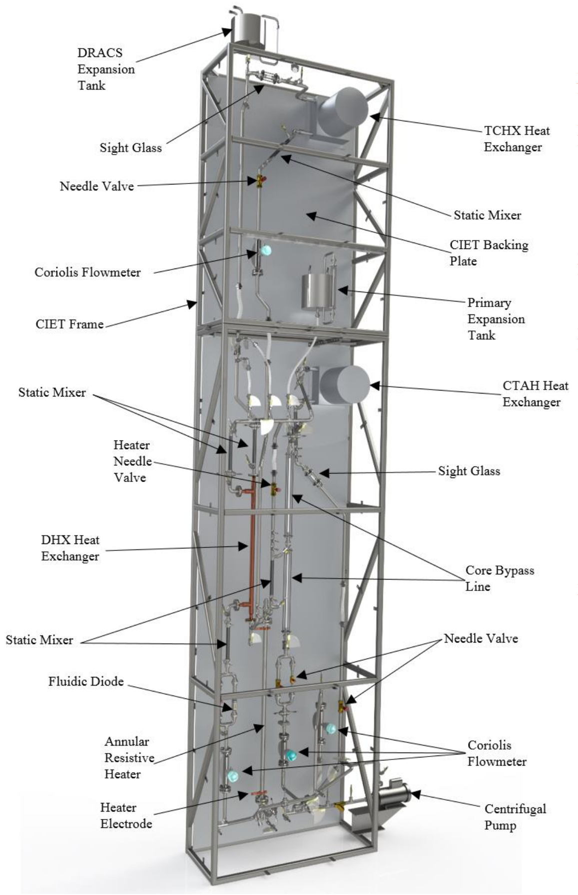
New experiments to verify similitude for key FHR/MSR phenomena will be valuable

The UCB Compact Integral Effects Test (CIET) facility scaling matches the Mk1 reactor design

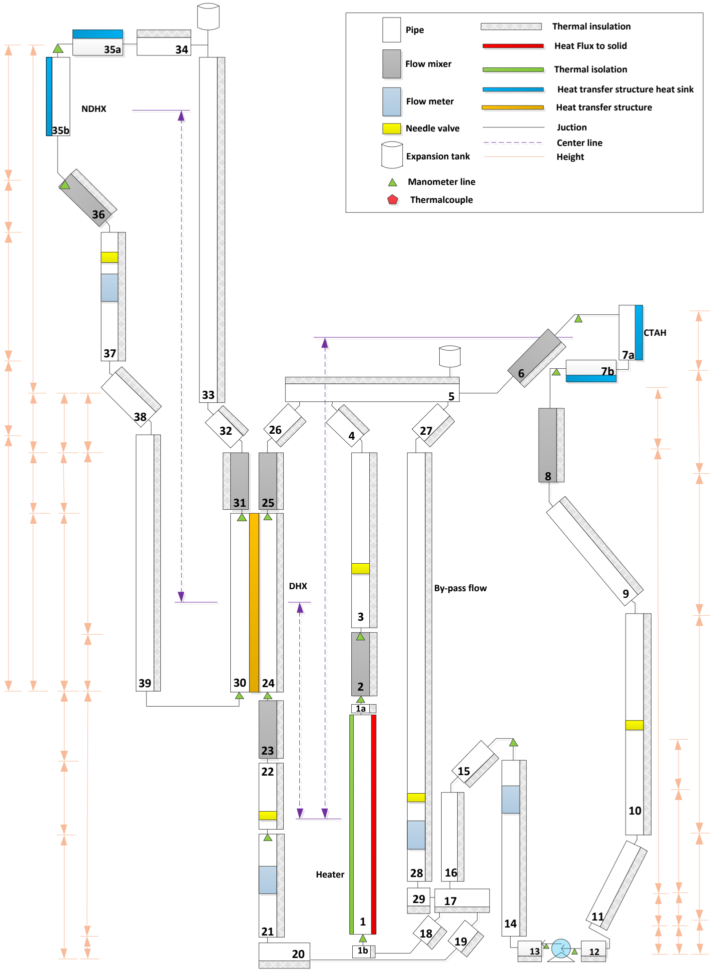


CIET can validate FHR transient models

CIET In Operation

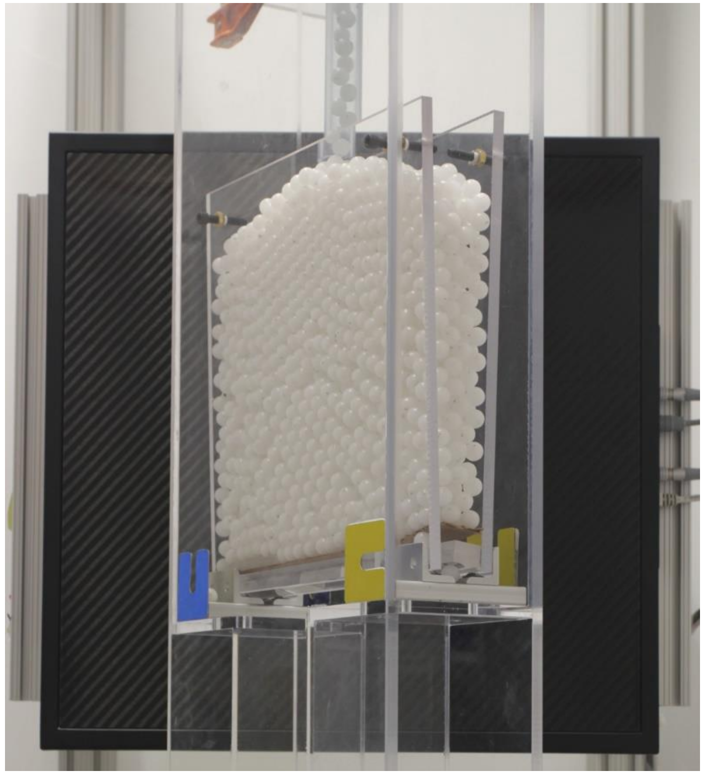


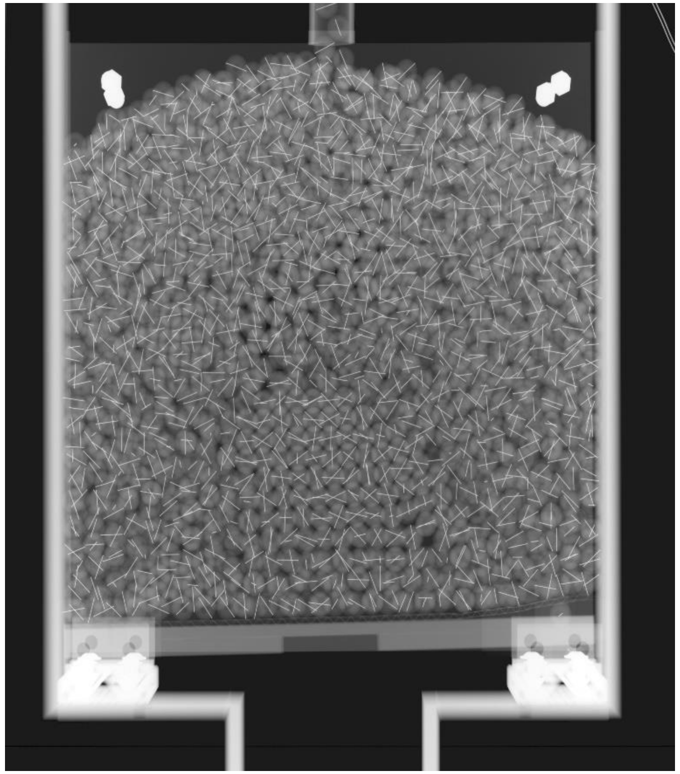
CIET Front View



RELAP Nodalization for CIET/FHR simulation

X-PREX experiments have enabled 3-D tomography of pebble translation and rotation



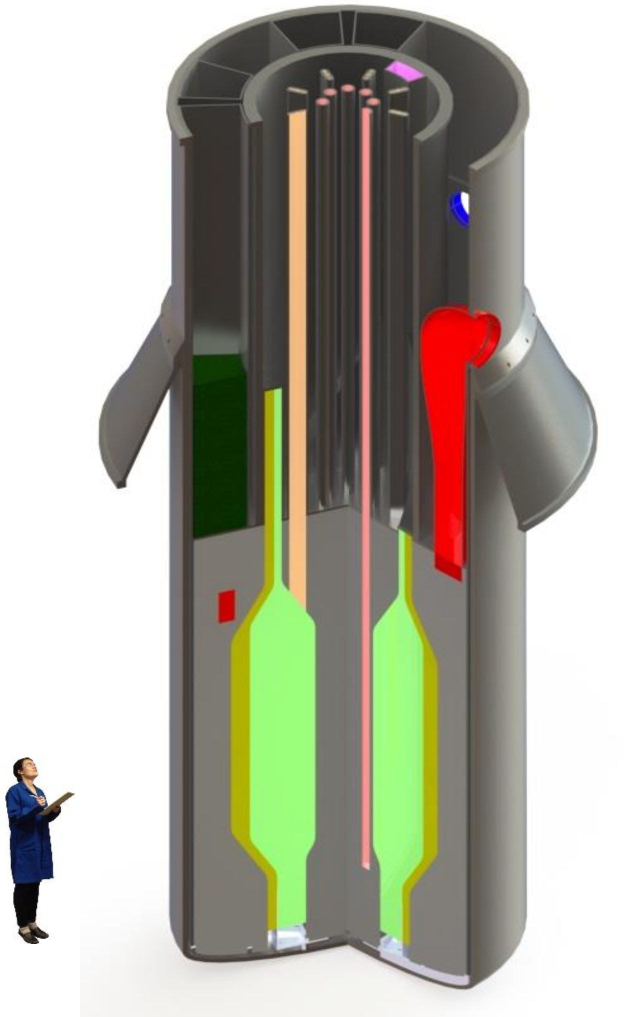


Mk1 PB-FHR Reference Design Overview

An example for FHR Design

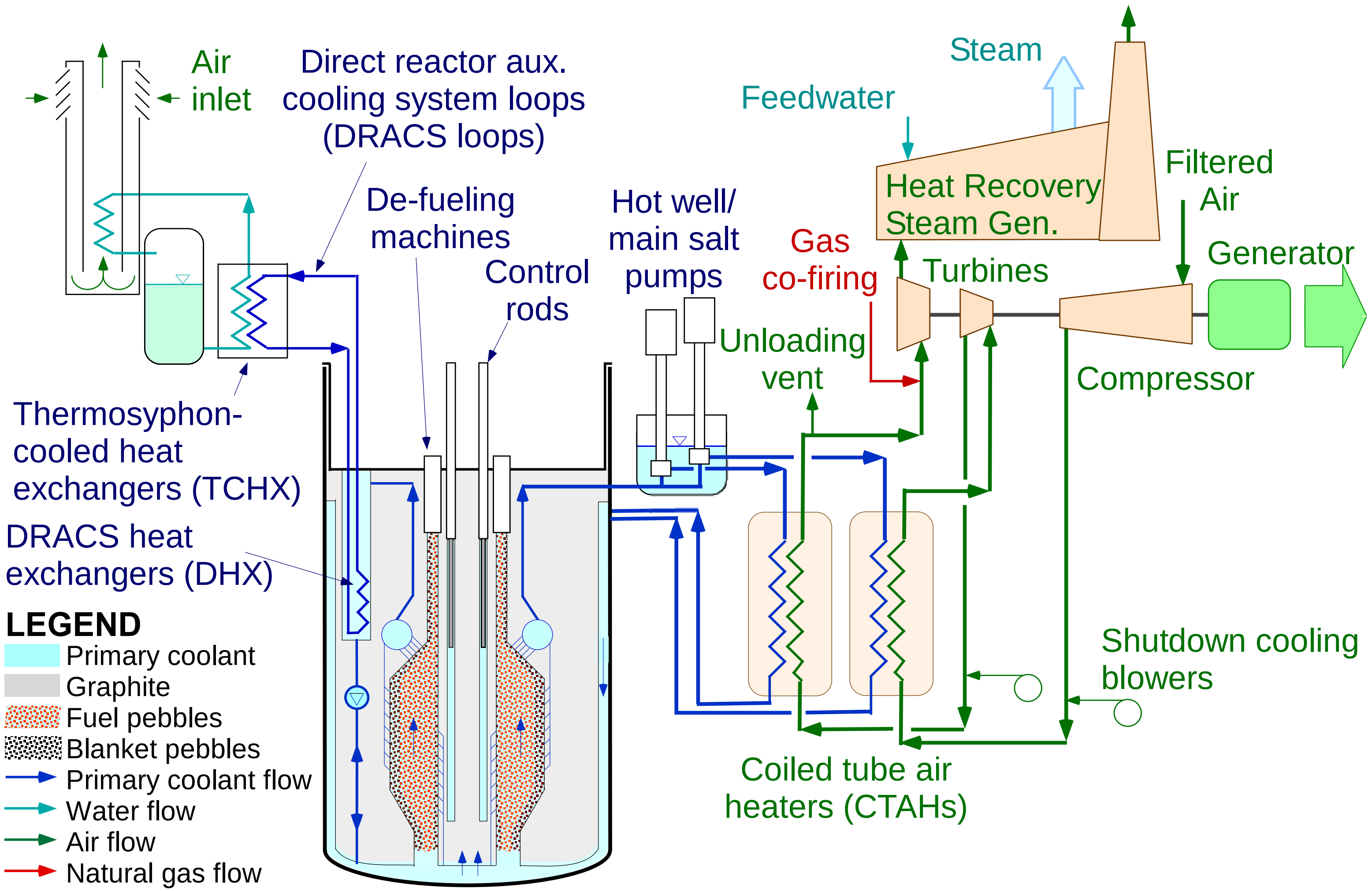
Nominal Mk1 PB-FHR Design Parameters

- Annular pebble bed core with center reflector
  - Core inlet/outlet temperatures 600° C/700° C
  - Control elements in channels in center reflector
  - Shutdown elements cruciform blades insert into pebble bed
- Reactor vessel 3.5-m OD, 12.0-m high
  - Vessel power density 3 x higher than S-PRISM & PBMR
- Power level: 236 MWth, 100 MWe (base load), 242 MWe (peak w/ gas co-fire)
- Power conversion: GE 7FB gas turbine w/ 3-pressure HRSG
- Air heaters: Two 3.5-m OD, 10.0-m high CTAHs, direct heating
- Tritium control and recovery
  - Recovery: Absorption in fuel and blanket pebbles
  - Control: Kanthal coating on air side of CTAHs

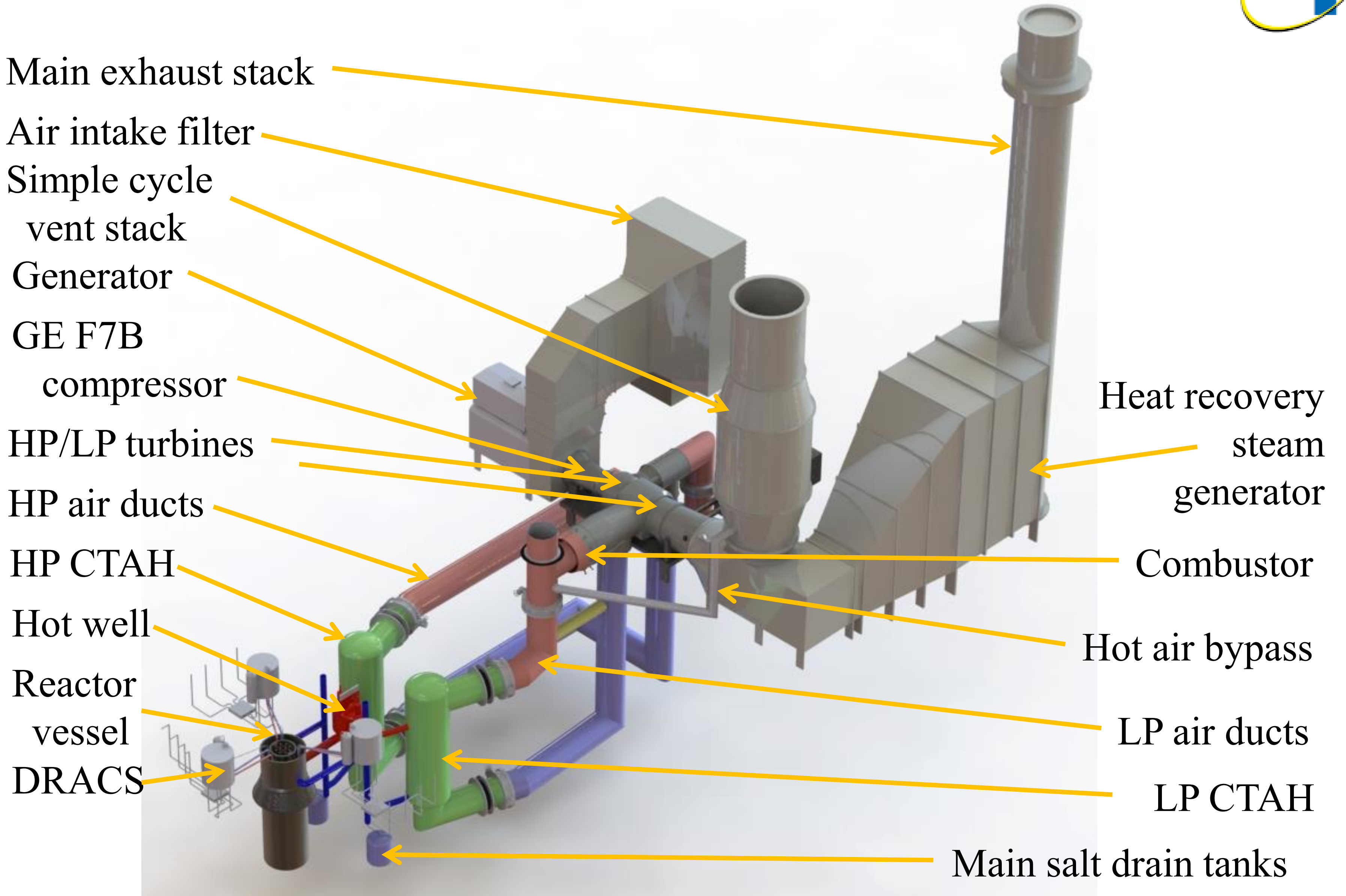


PB-FHR cross section

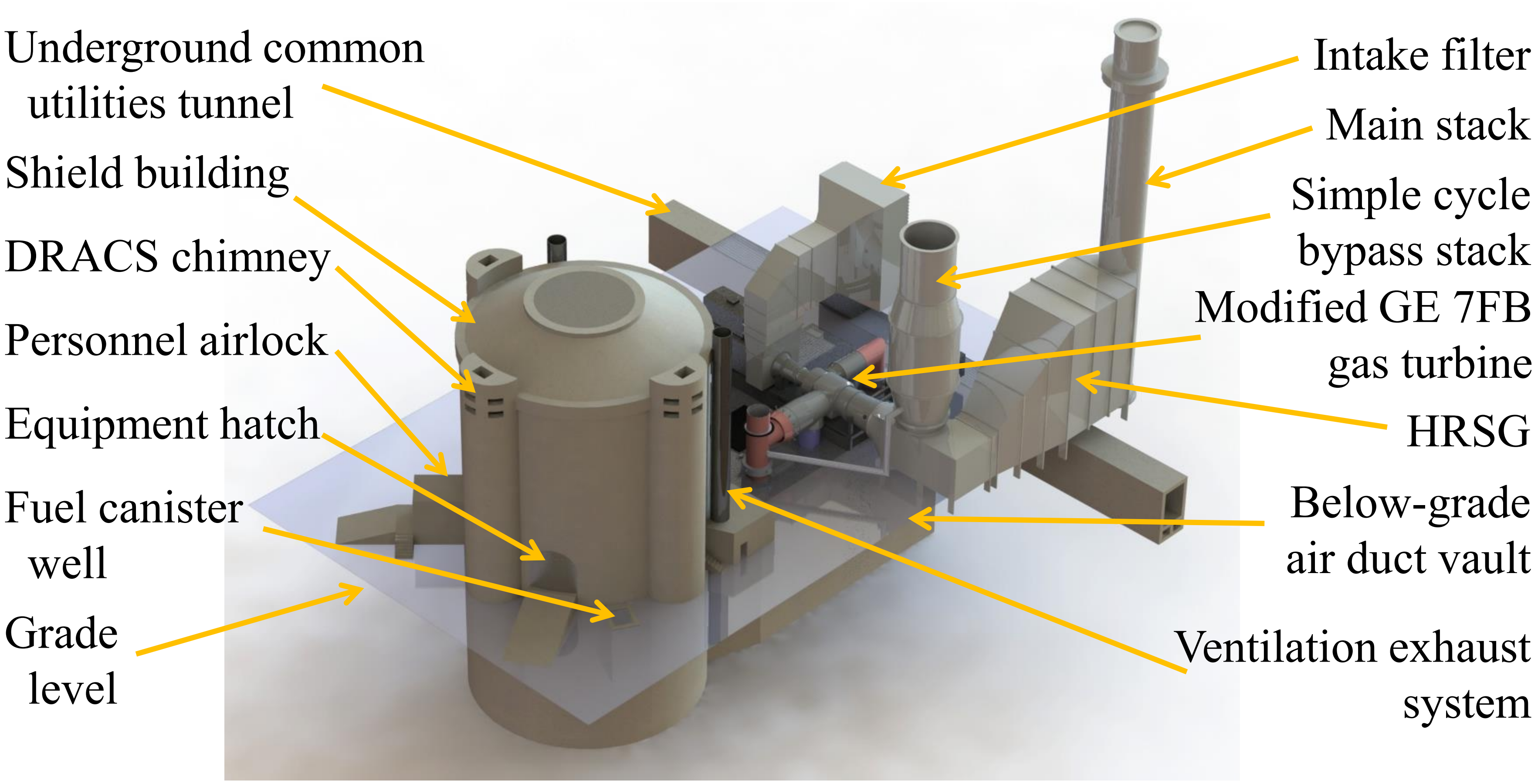
Mk1 PB-FHR flow schematic



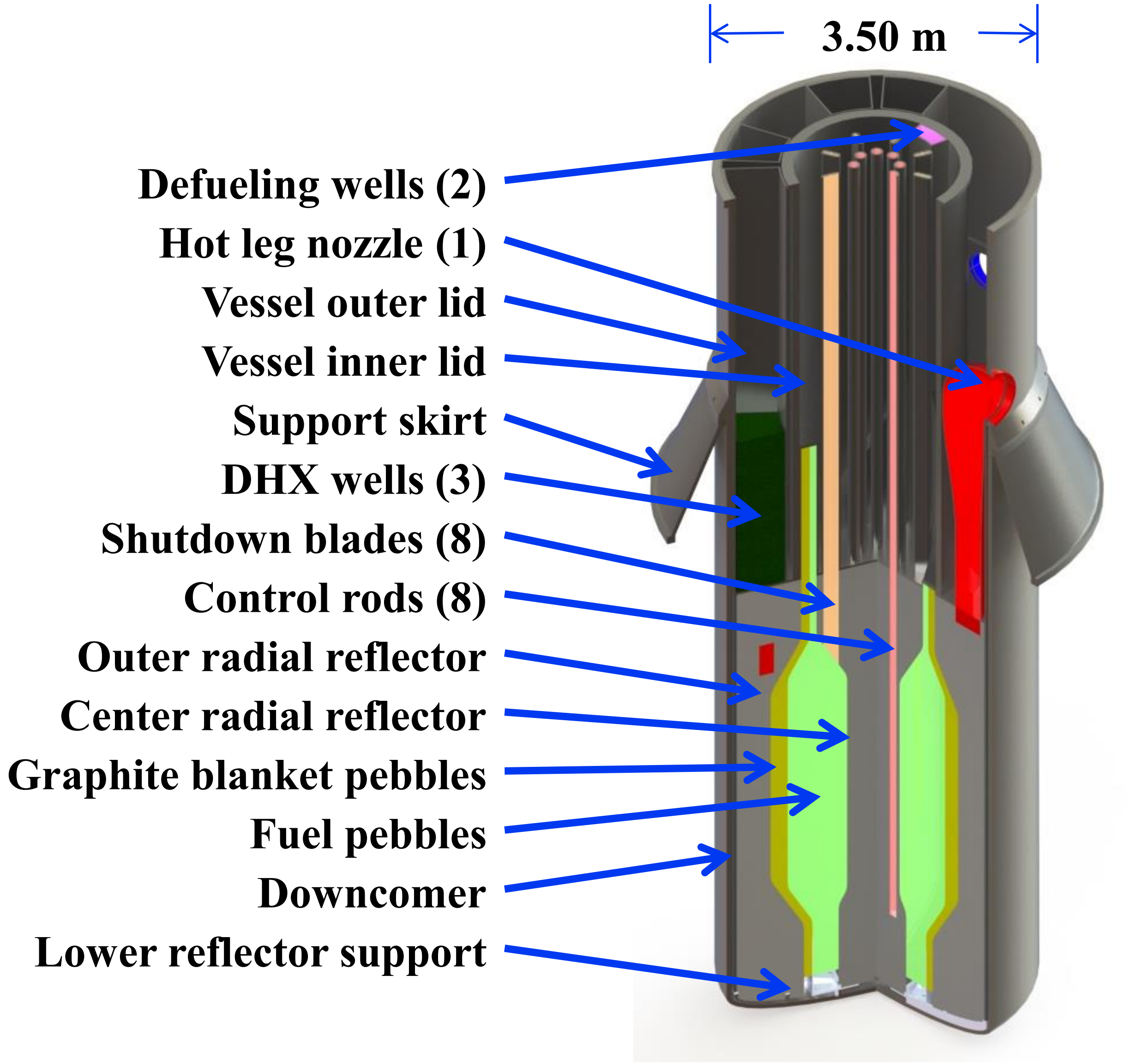
Mk1 NACC physical arrangement



The Mk1 structures are designed for modular construction



Mk1 Reactor Cross Section



Modular Construction for Small Modular Reactors: Concepts for reduced construction costs for multi-module reactor sites

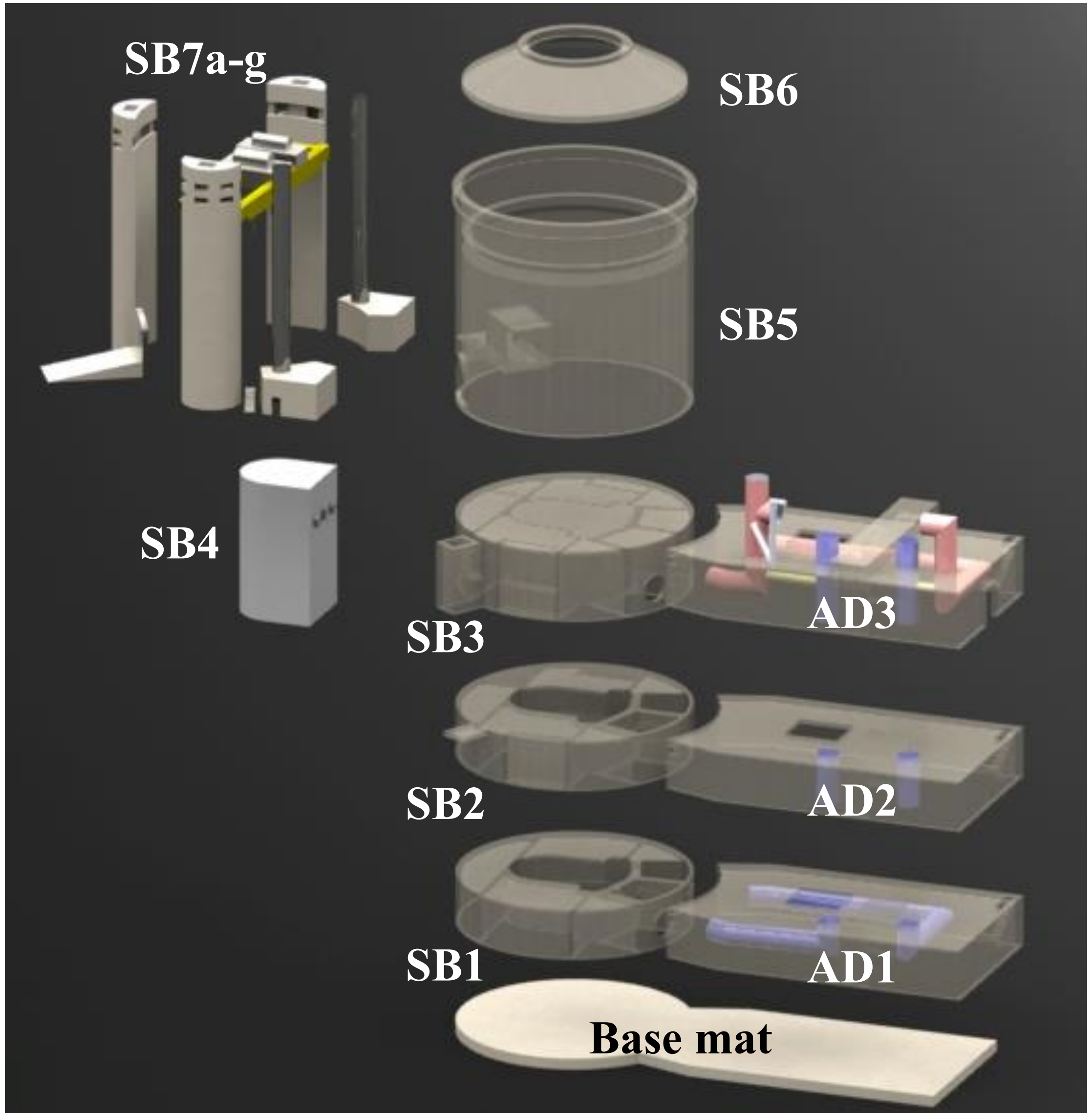
The Mk1 uses steel-plate composite modular construction

Vogtle Unit 3 shield building wall panels, May 2014

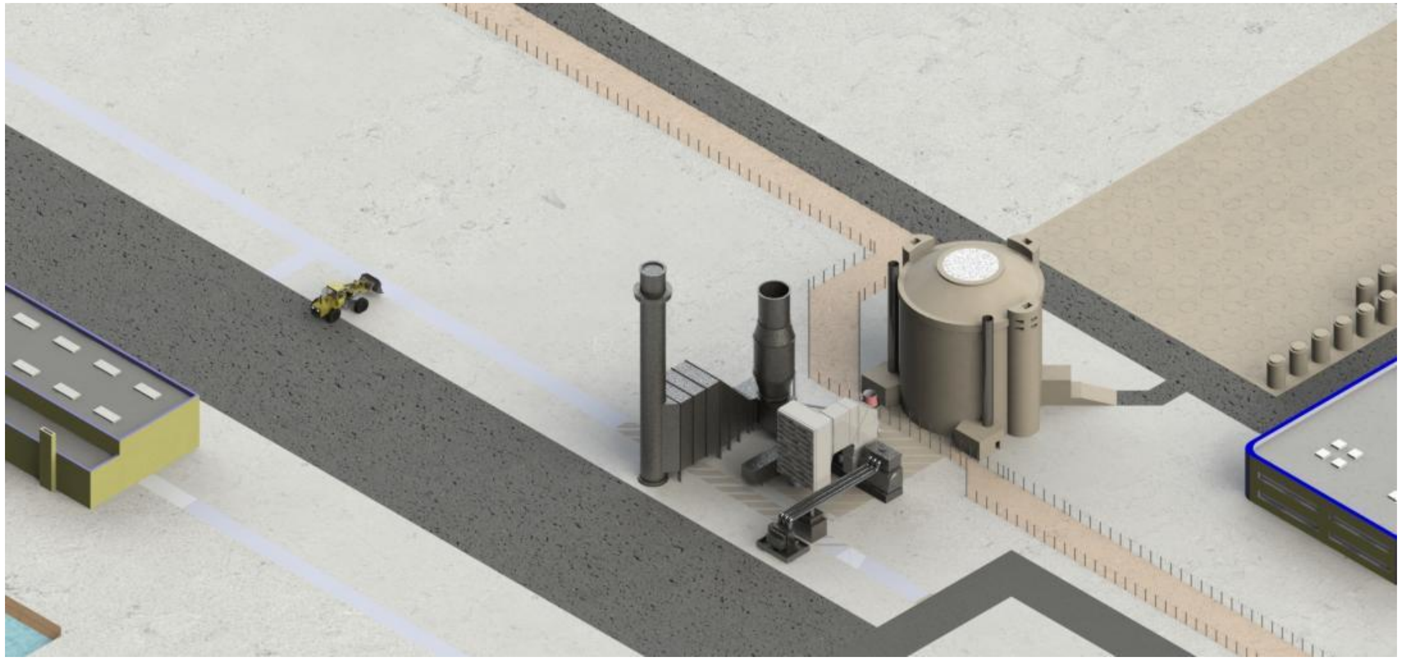
Summer Unit 2 CA20 Transported from MAB

CA20 being set in place by heavy crane

The Mk1 design uses 10 primary structural modules

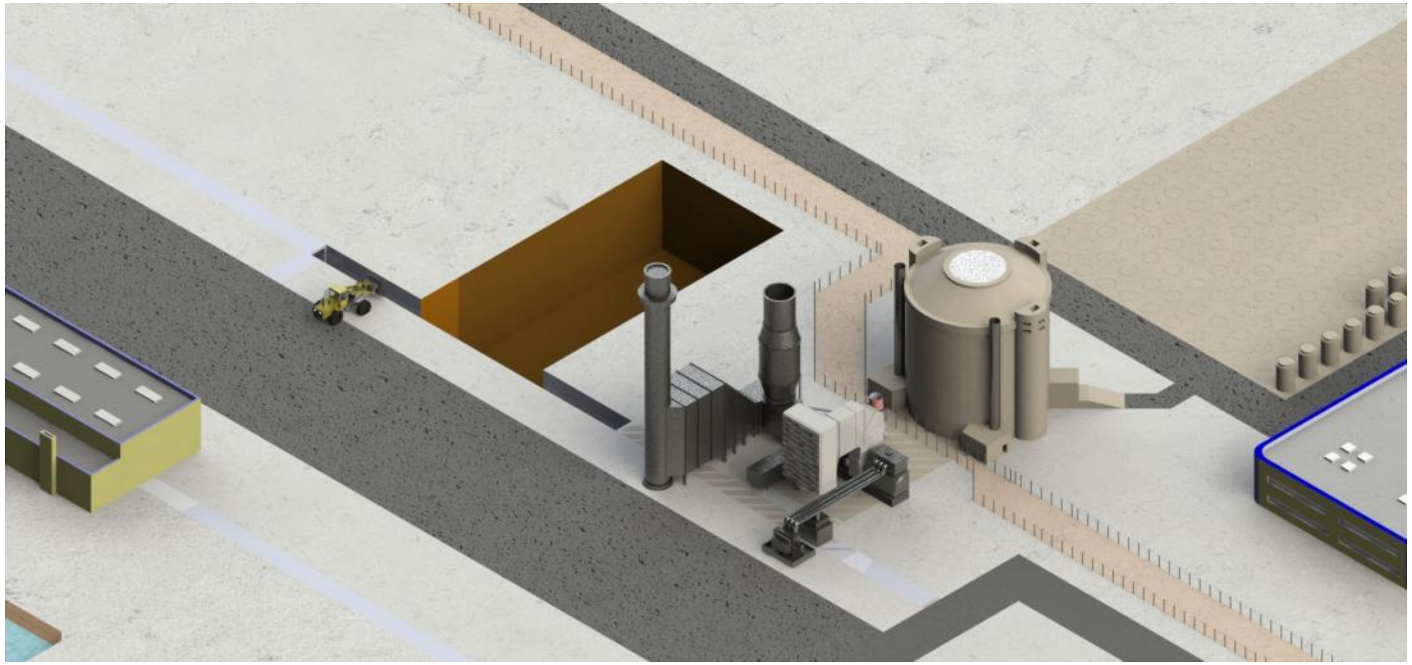


Mk1 Construction Story-Board (1)



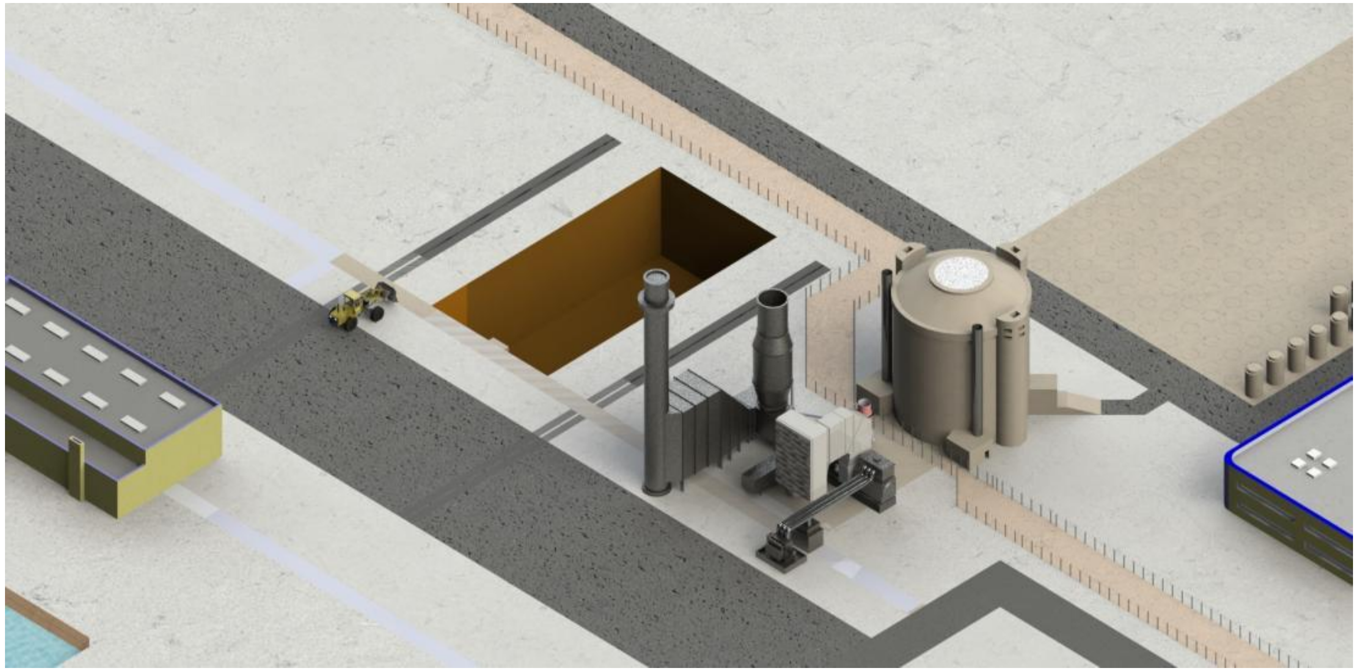
Construction occurs adjacent to an existing Mk1 module, outside a temporary protected area fence

Mk1 Construction Story-Board (2)



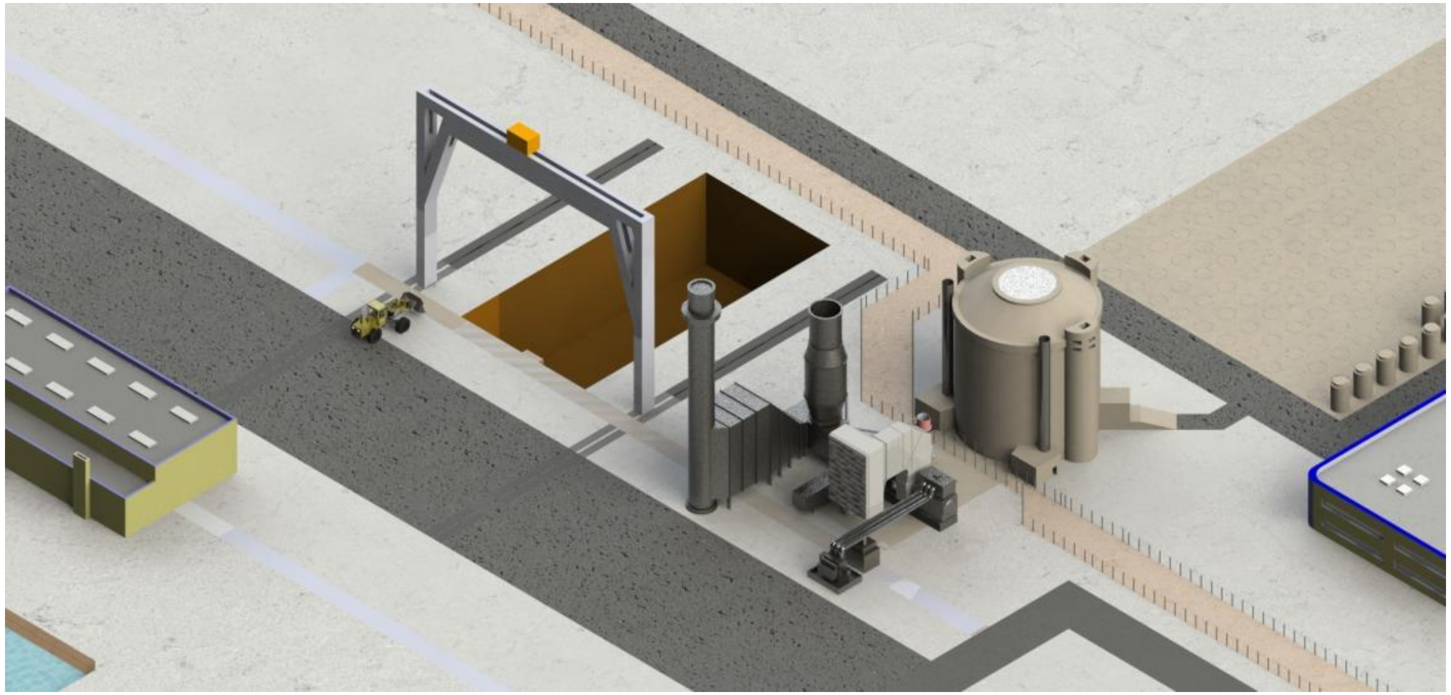
Excavation for the new Mk1 module

Mk1 Construction Story-Board (3)



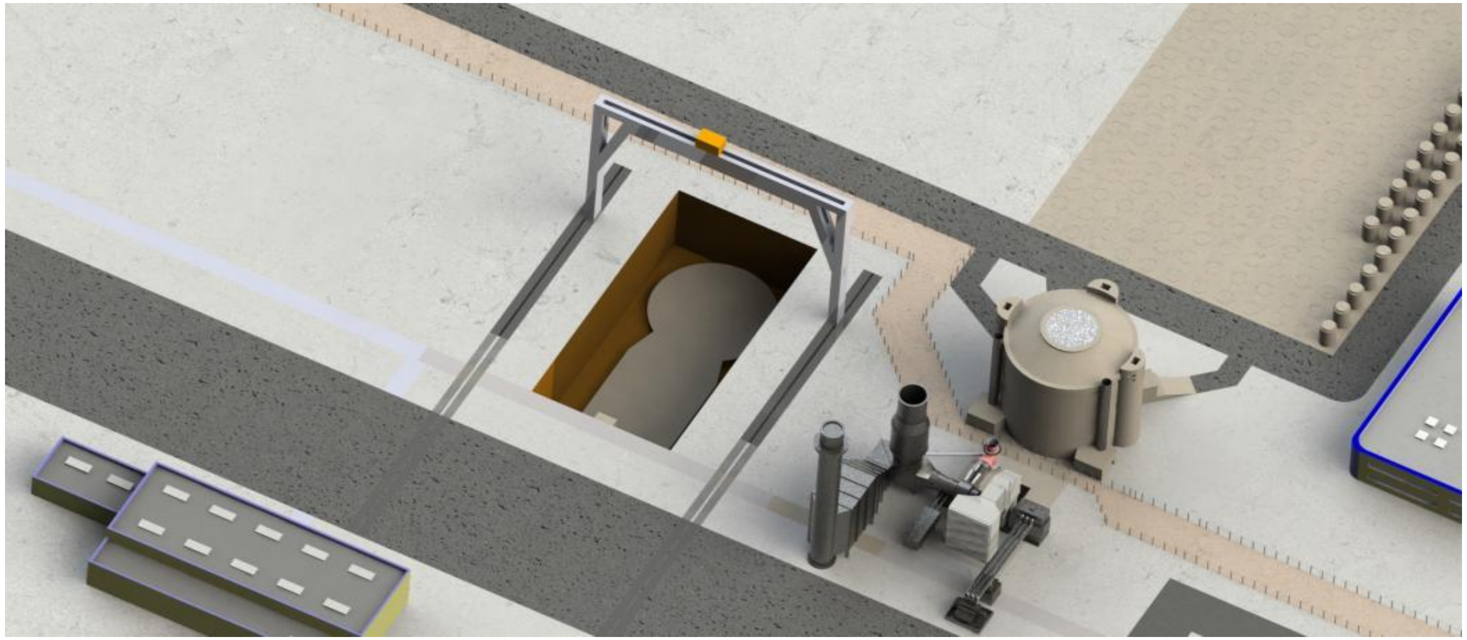
Construction of the common tunnel section, for plant utilities

Mk1 Construction Story-Board (4)



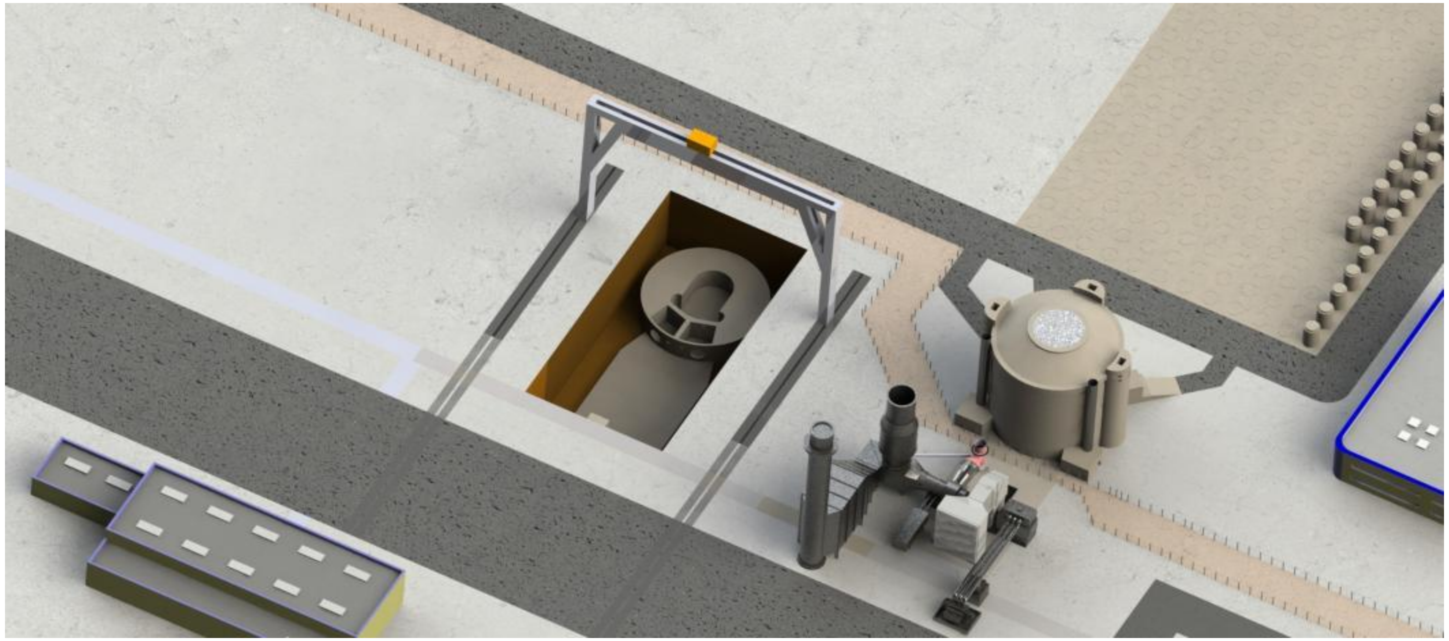
Construction lift tower

Mk1 Construction Story-Board (6)



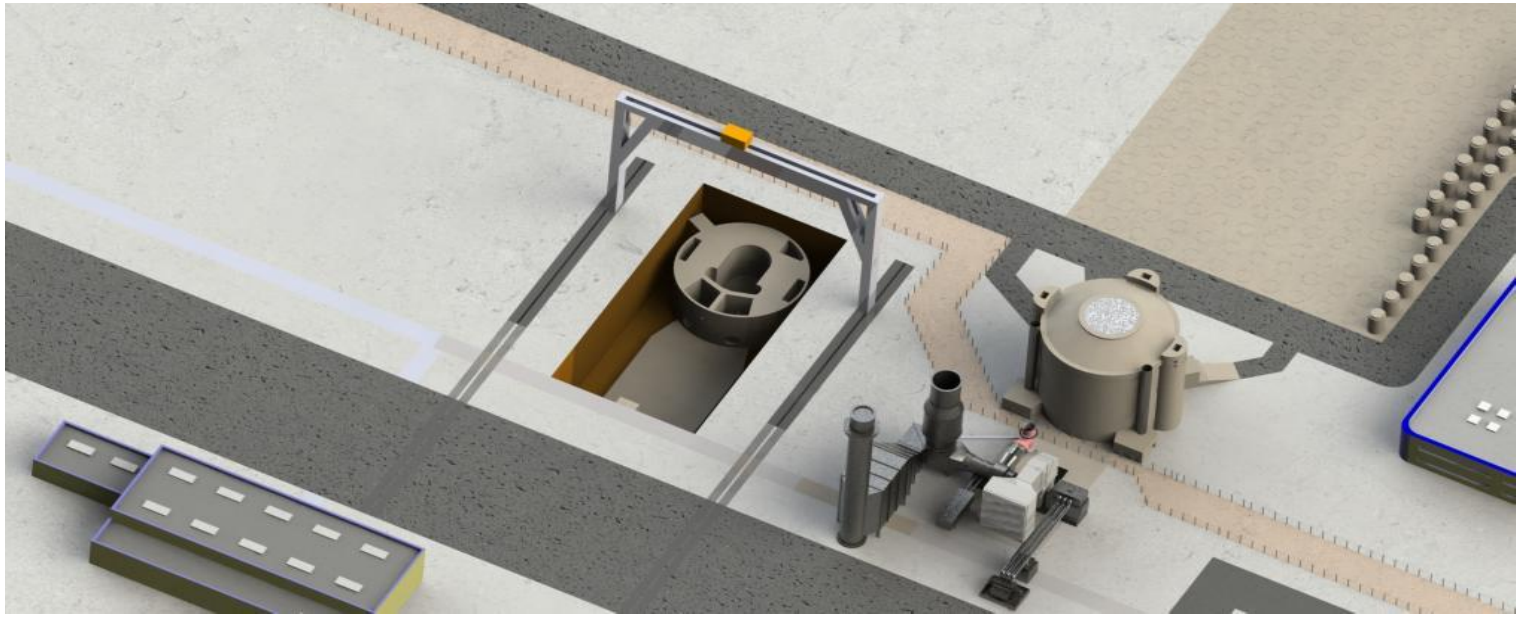
Pour base mat

Mk1 Construction Story-Board (7)



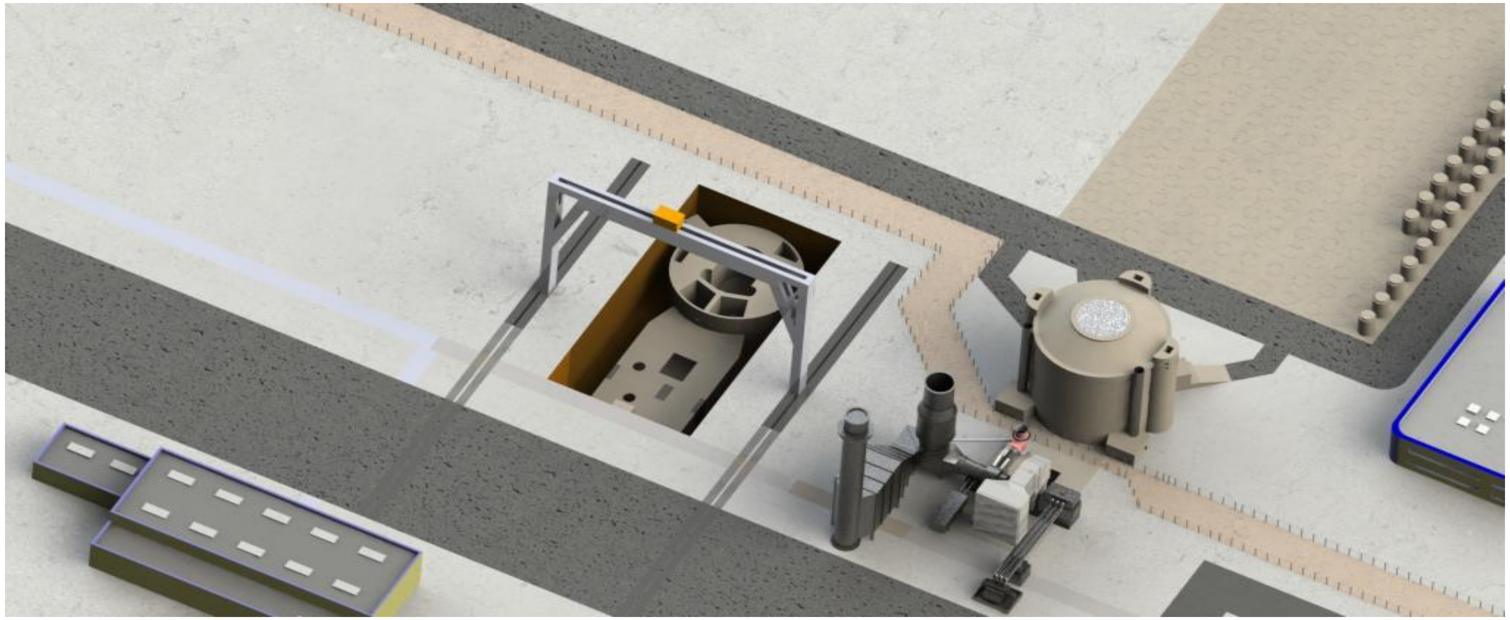
Install first-level module of Mk1 shield building

Mk1 Construction Story-Board (8)



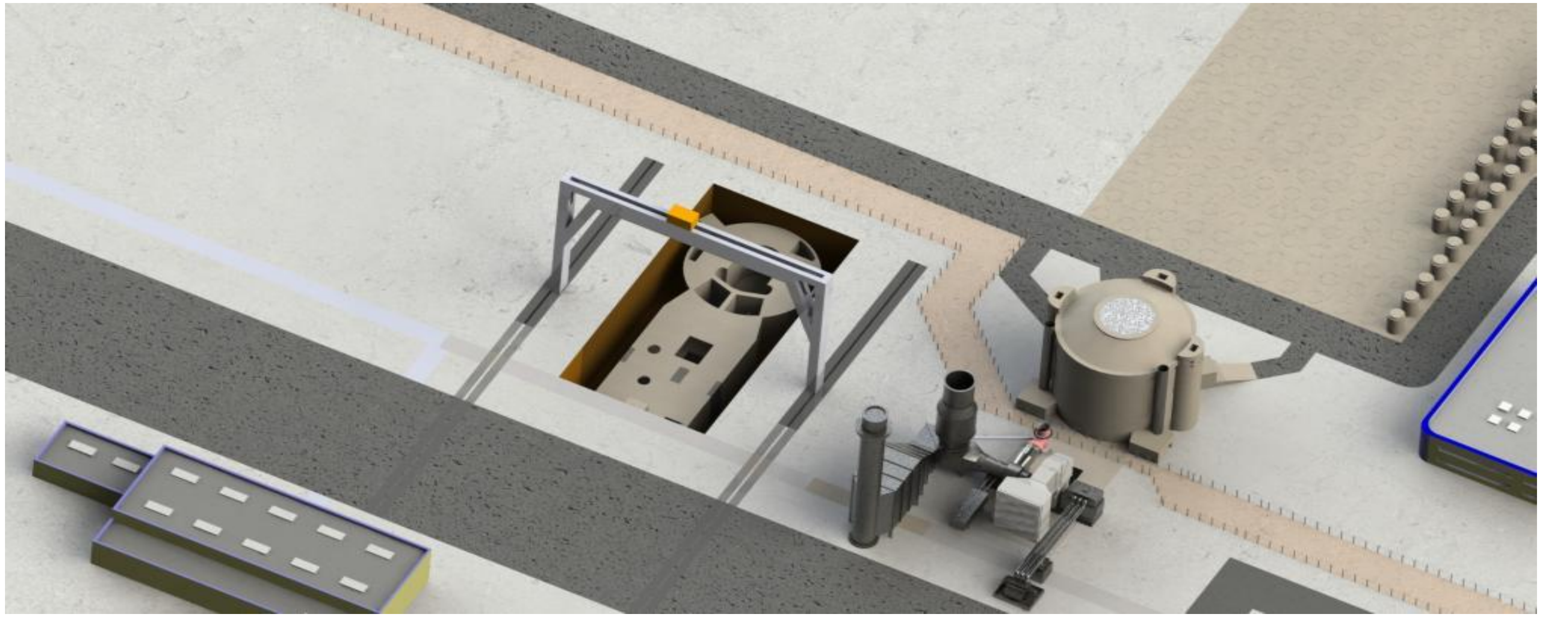
Install second-level module of Mk1 shield building

Mk1 Construction Story-Board (9)



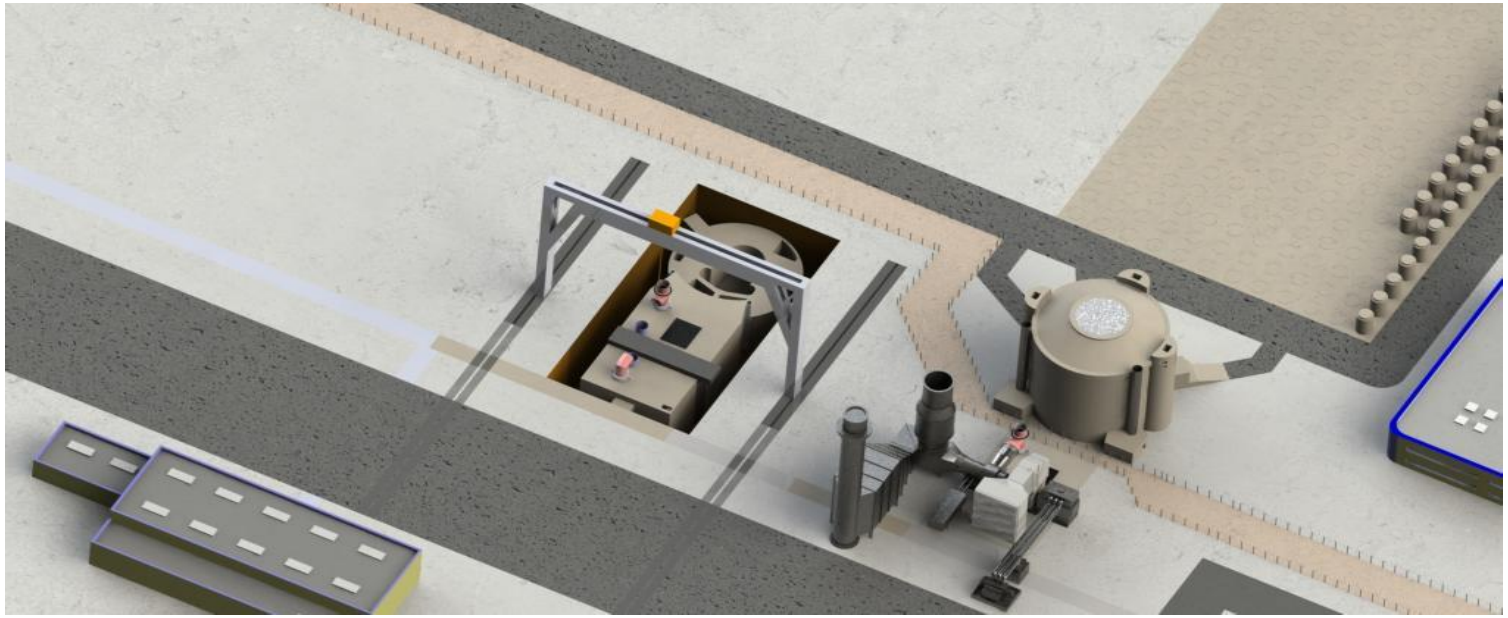
Install first-level module of Mk1 air-duct vault

Mk1 Construction Story-Board (10)



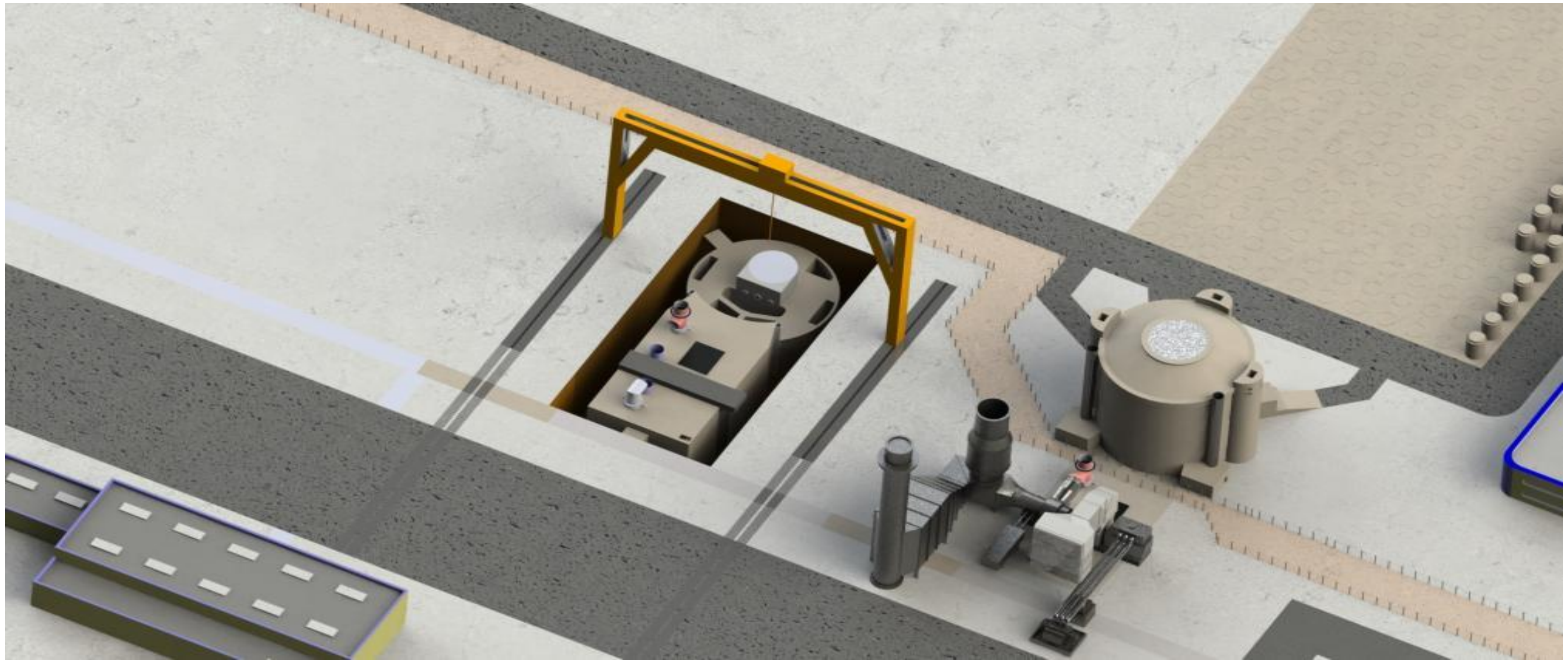
Install second-level module of Mk1 air-duct vault

Mk1 Construction Story-Board (11)



Install third-level module of Mk1 air-duct vault

Mk1 Construction Story-Board (12)



Install Mk1 reactor cavity module

Mk1 Construction Story-Board (13)

Install Mk1 CTAH and I.O. pipes

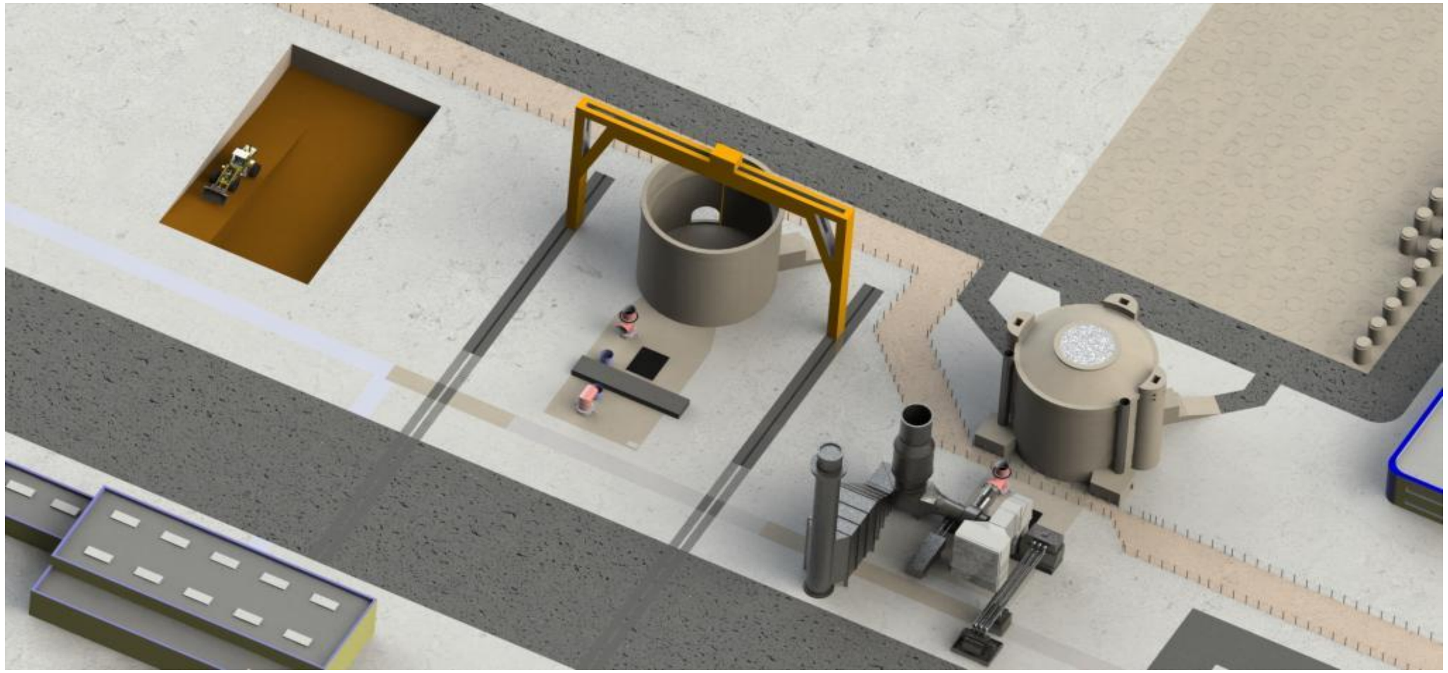
Mk1 Construction Story-Board (14)

Install third-level module of Mk1 shield building.

Mk1 Construction Story-Board (15)

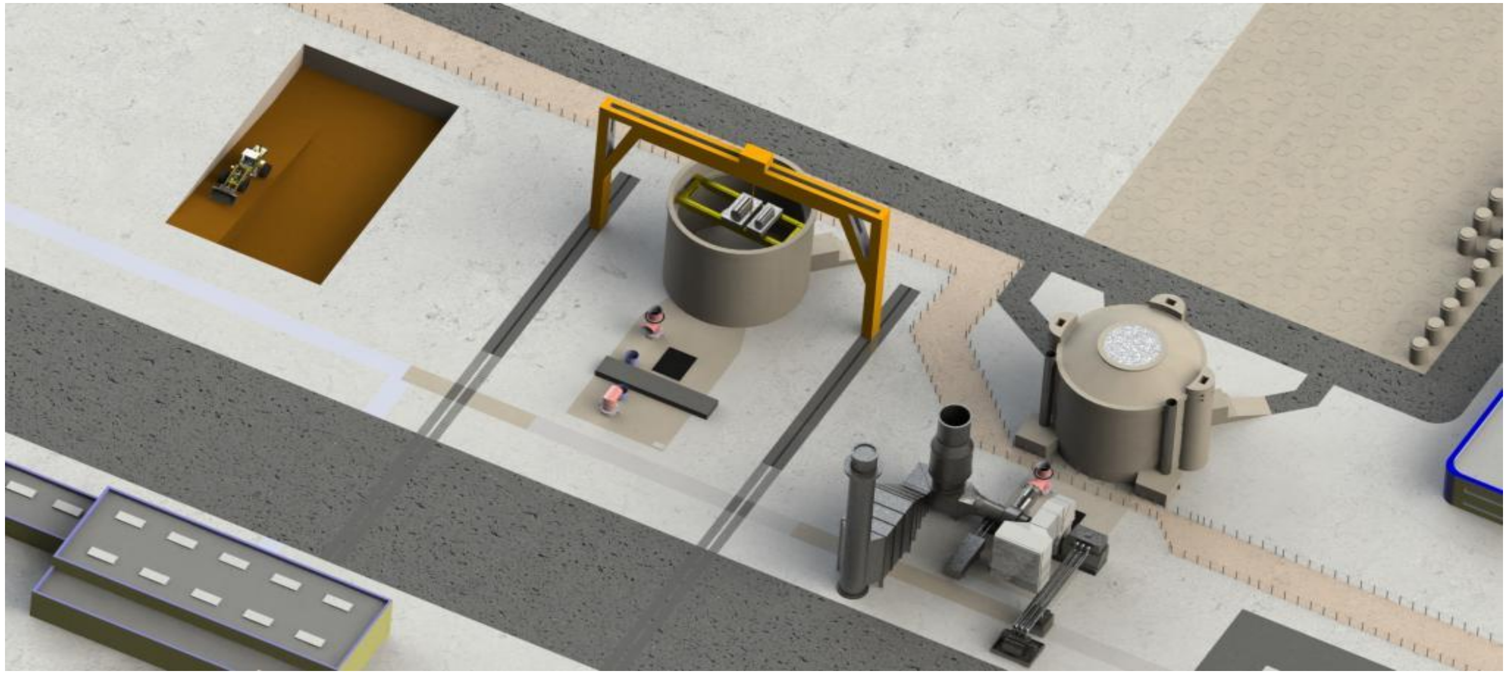
Back fill below-grade structures to grade level
Excavation for the next unit may begin

Mk1 Construction Story-Board (16)



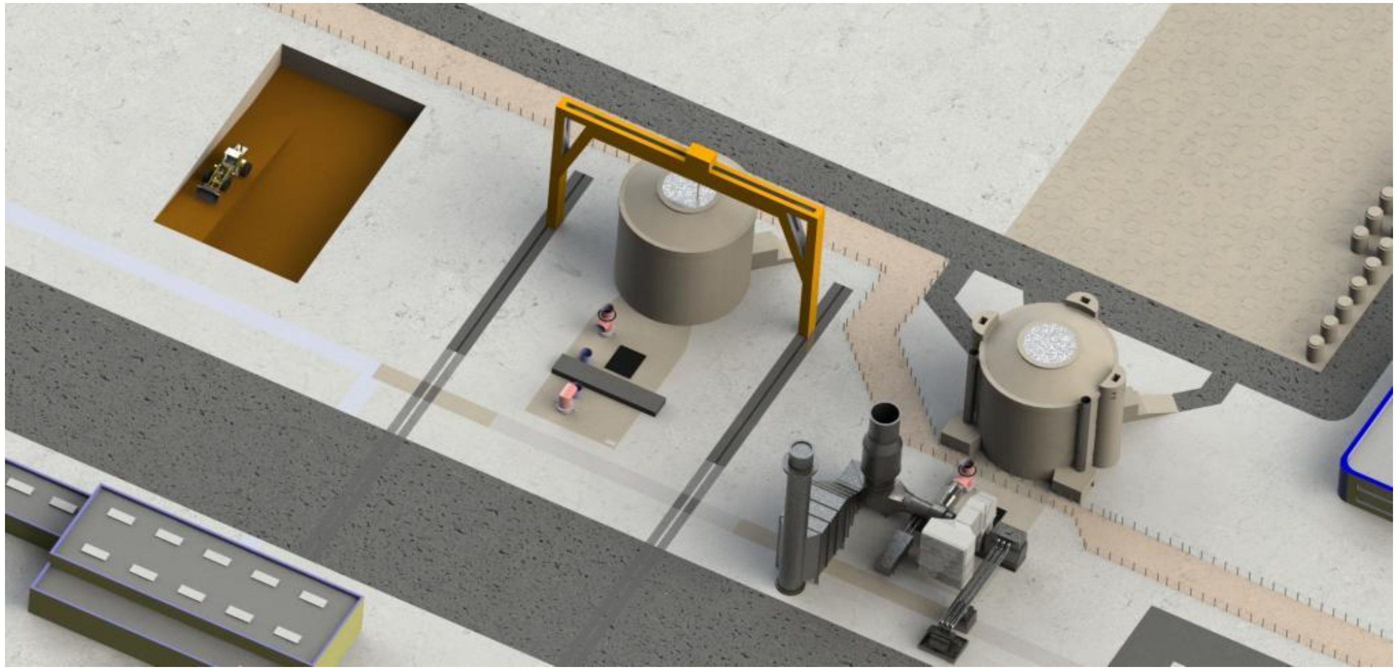
Install main shield building cylinder.

Mk1 Construction Story-Board (17)



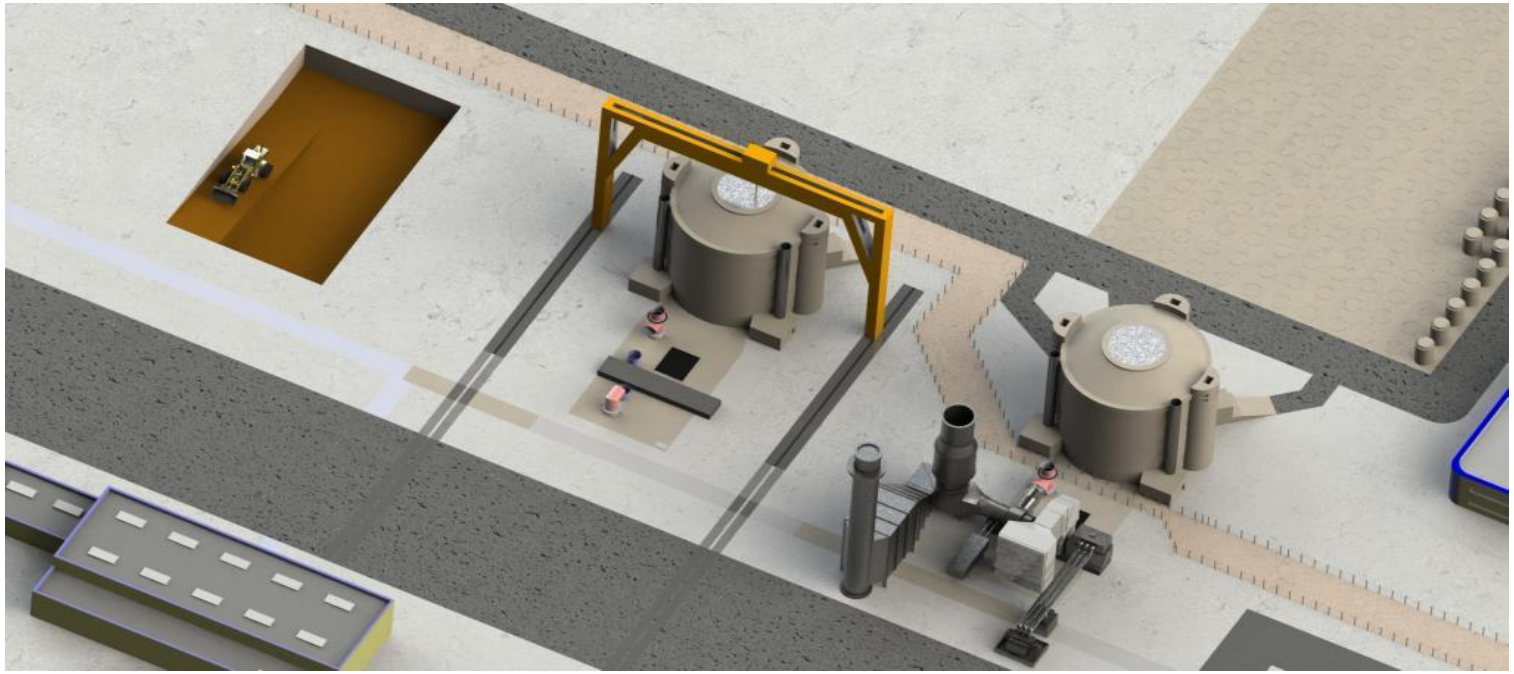
Install polar crane.

Mk1 Construction Story-Board (18)



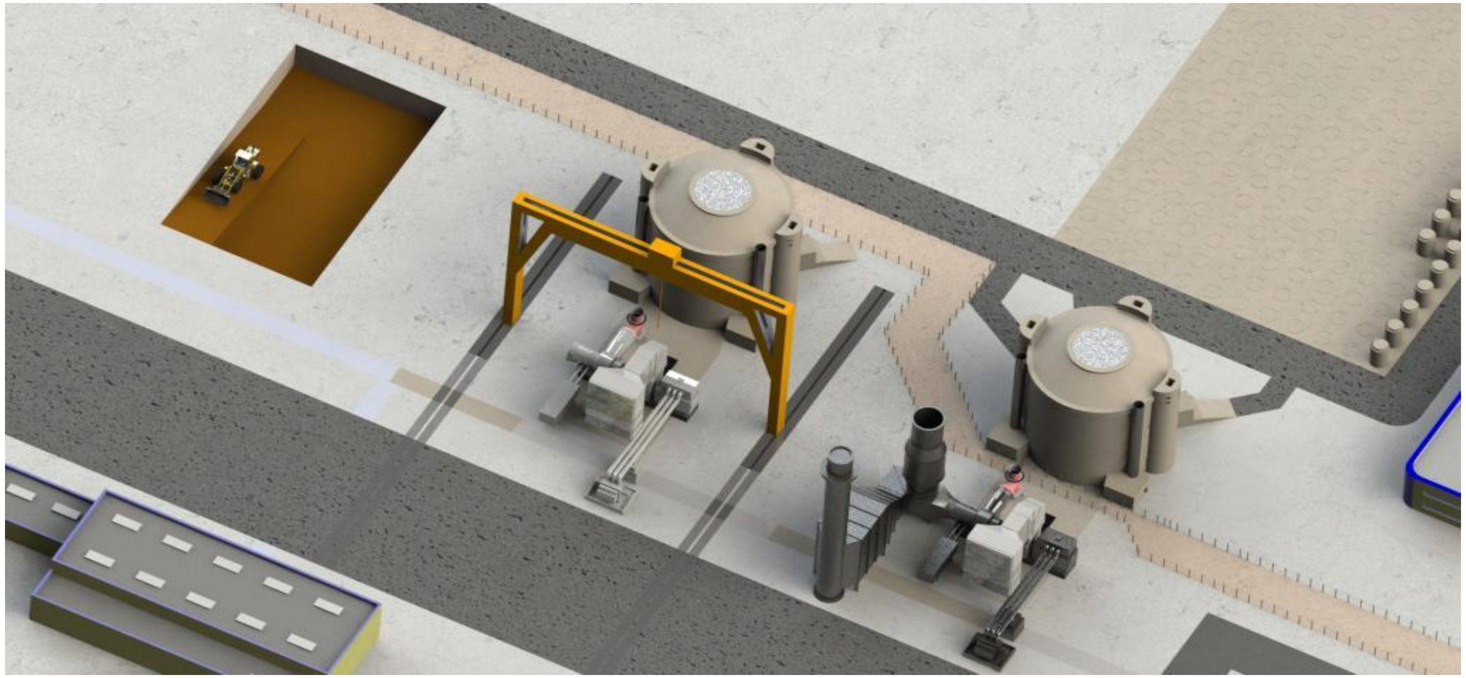
Install shield building roof.

Mk1 Construction Story-Board (19)



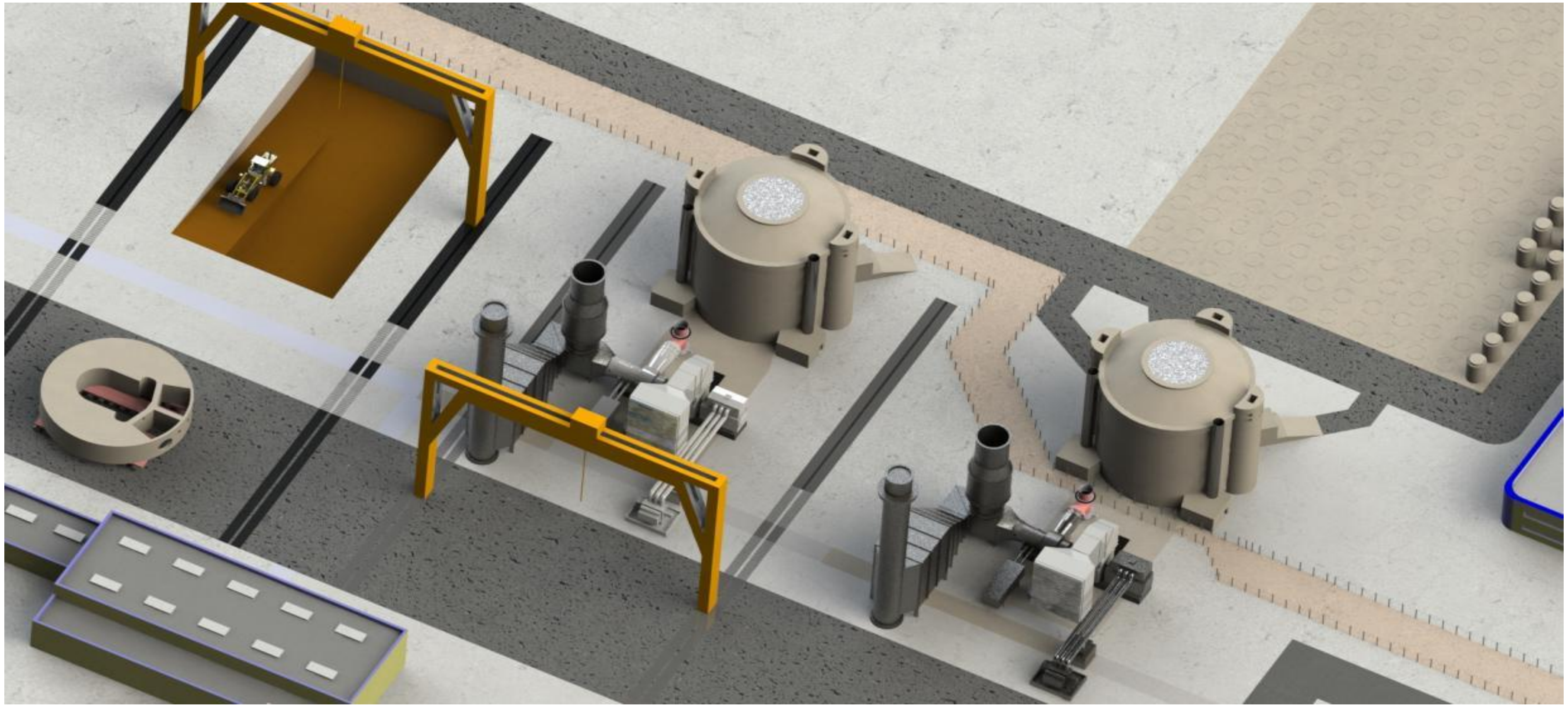
Install DRACS chimneys and ventilation filter and exhaust enclosures.

Mk1 Construction Story-Board (20)



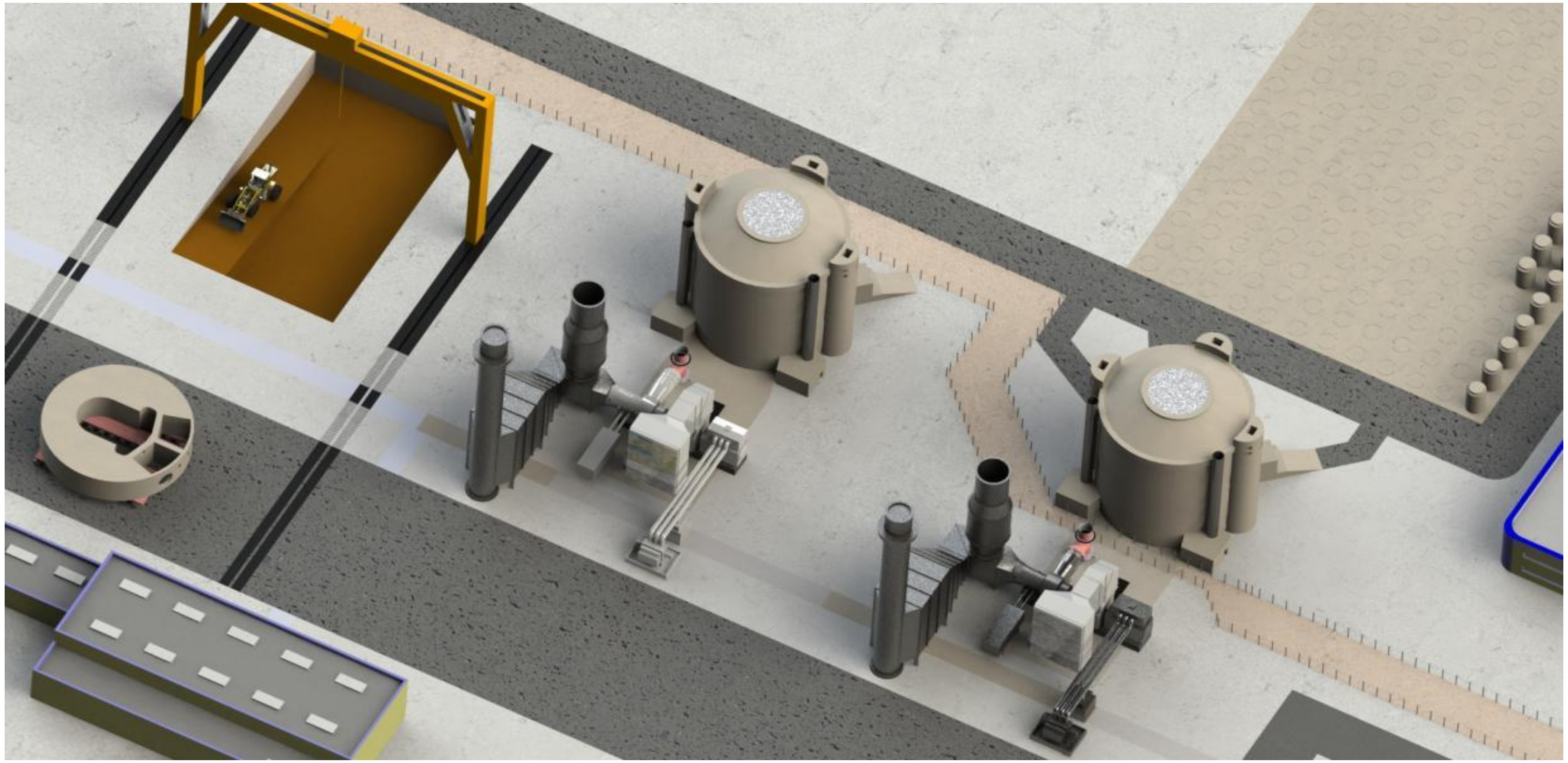
Install gas turbine, intake filter housing, generator and main transformer).

Mk1 Construction Story-Board (20)



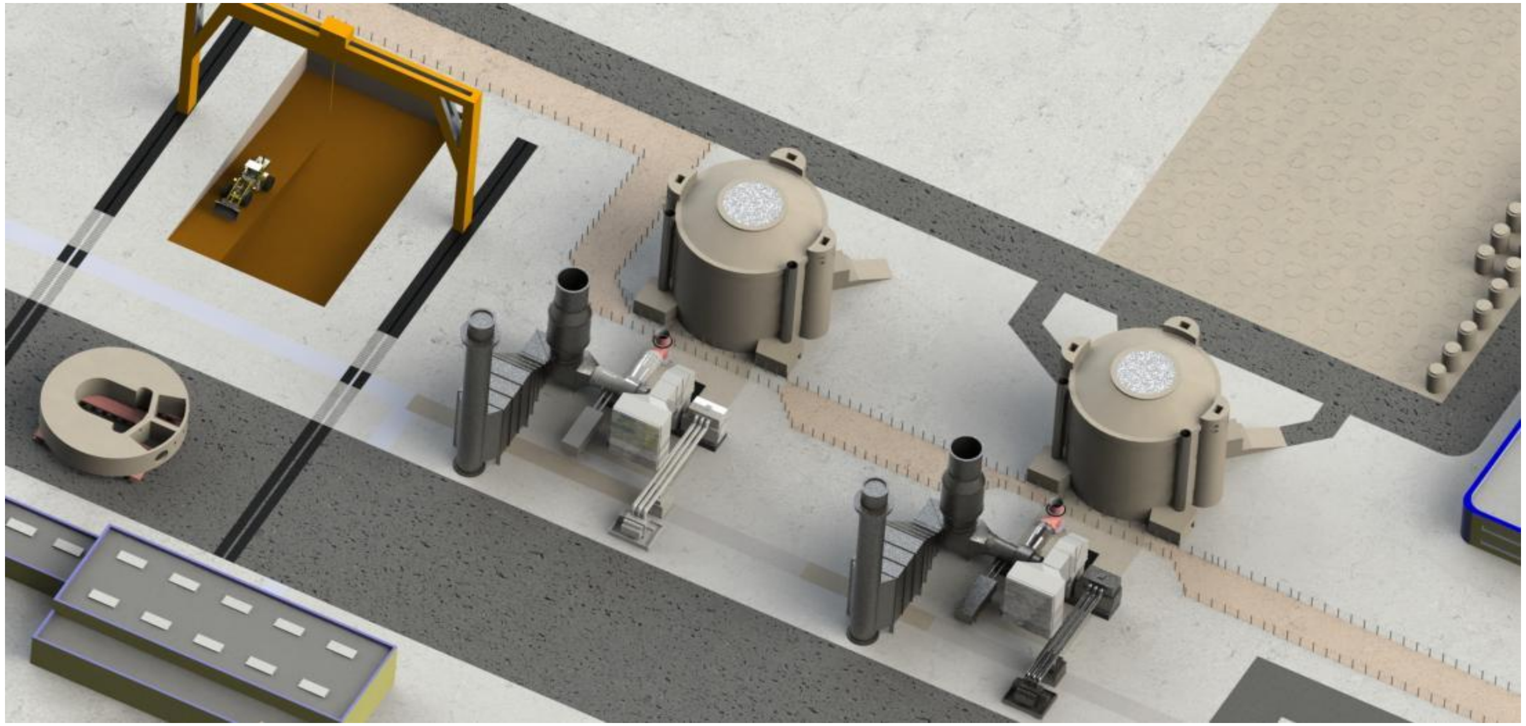
Install heat recover steam generator and stacks.

Mk1 Construction Story-Board (21)



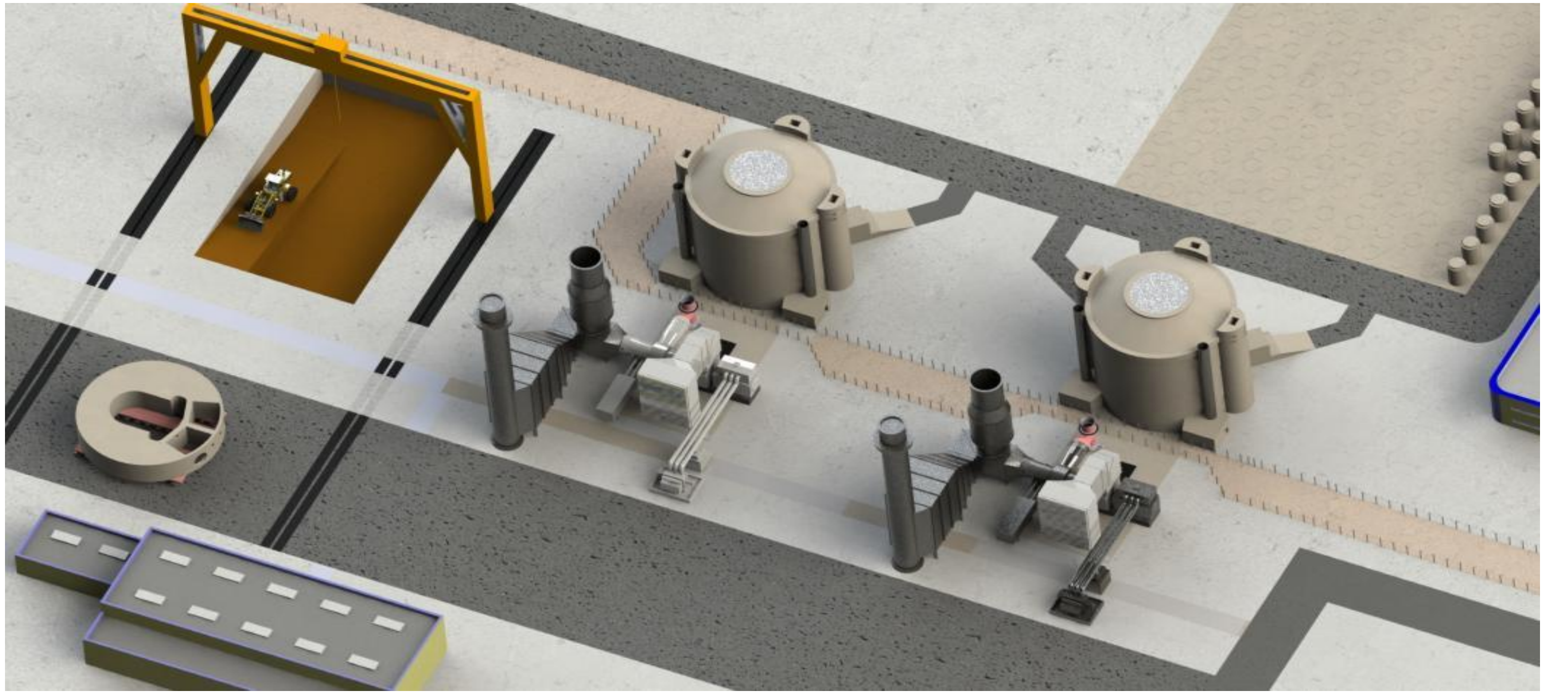
The crane and rails are removed.

Mk1 Construction Story-Board (22)



Install new protected area fence, and remove temporary protected area fence.

Mk1 Construction Story-Board (23)



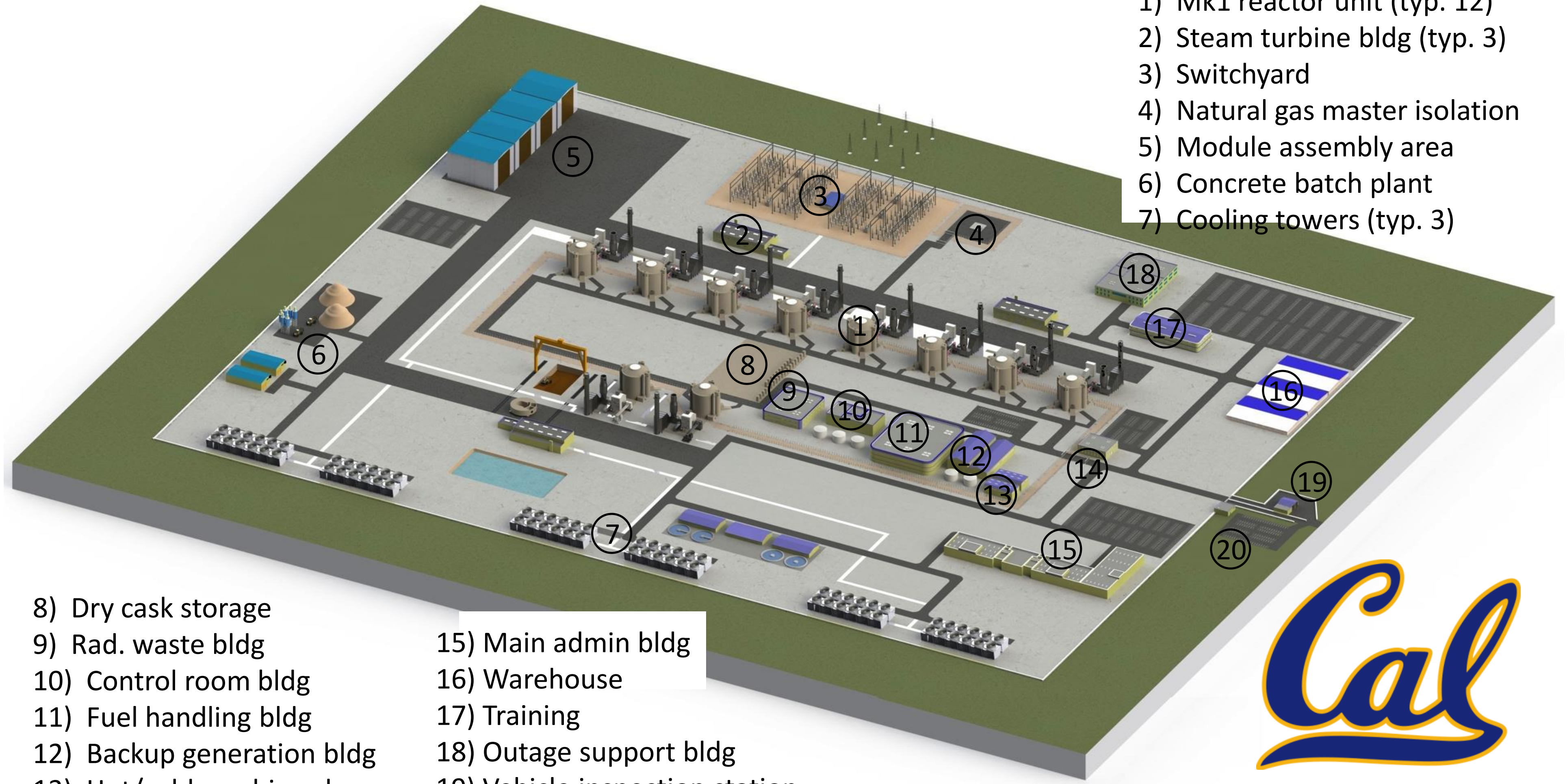
Construction on next unit continues

Notional 12-unit Mk1 PB-FHR nuclear station

1200 MWe base load; 2900 MWe peak

GEN IV International Forum[SM]

1) Mk1 reactor unit (typ. 12)
2) Steam turbine bldg (typ. 3)
3) Switchyard
4) Natural gas master isolation
5) Module assembly area
6) Concrete batch plant
7) Cooling towers (typ. 3)



8) Dry cask storage
9) Rad. waste bldg
10) Control room bldg
11) Fuel handling bldg
12) Backup generation bldg
13) Hot/cold machine shops
14) Protected area entrance

15) Main admin bldg
16) Warehouse
17) Training
18) Outage support bldg
19) Vehicle inspection station
20) Visitor parking

Cal

For more info: http:// fhr.nuc.berkeley.edu

UPCOMING WEBINARS

23 May 2017	Molten Salt Reactor	Dr. Elsa Merle, CEA, USA
12 June 2017	Lead Fast Reactor	Prof. Craig Smith, US Naval Graduate School, USA
18 July 2017	Thorium Fuel Cycle	Dr. Franco-Michel Sendis, NEA/OECD