Utilization of the Supercritical CO_2 Brayton Cycle with Sodium-Cooled Fast Reactors

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$S\text{-}CO_2$ Brayton Cycle Makes Good Sense for Advanced Nuclear Reactors

- **First applications envisioned for the $S\text{-}CO_2$ recompression closed Brayton cycle (Feher cycle) were power conversion for advanced nuclear power reactors**
- **Twelve years of experience at ANL working on $S\text{-}CO_2$ Brayton cycle development and code development and validation since 2002 continue to confirm initial notions about benefits**
  - $S\text{-}CO_2$ cycle is well matched to SFR – Cycle wants to operate with a CO_2 temperature rise in sodium-to-CO_2 heat exchangers of about 150 °C which is about equal to the sodium temperature rise through the core
  - Greater efficiency at SFR core outlet temperatures and above
  - Elimination of sodium-water reactions
  - Smaller balance-of-plant footprint reducing size of turbine generator building and portions of reactor building
  - Expected reduction in SFR $/kWe or LCOE
  - Enables load following to zero electrical grid demand and residual heat removal to initial decay heat levels

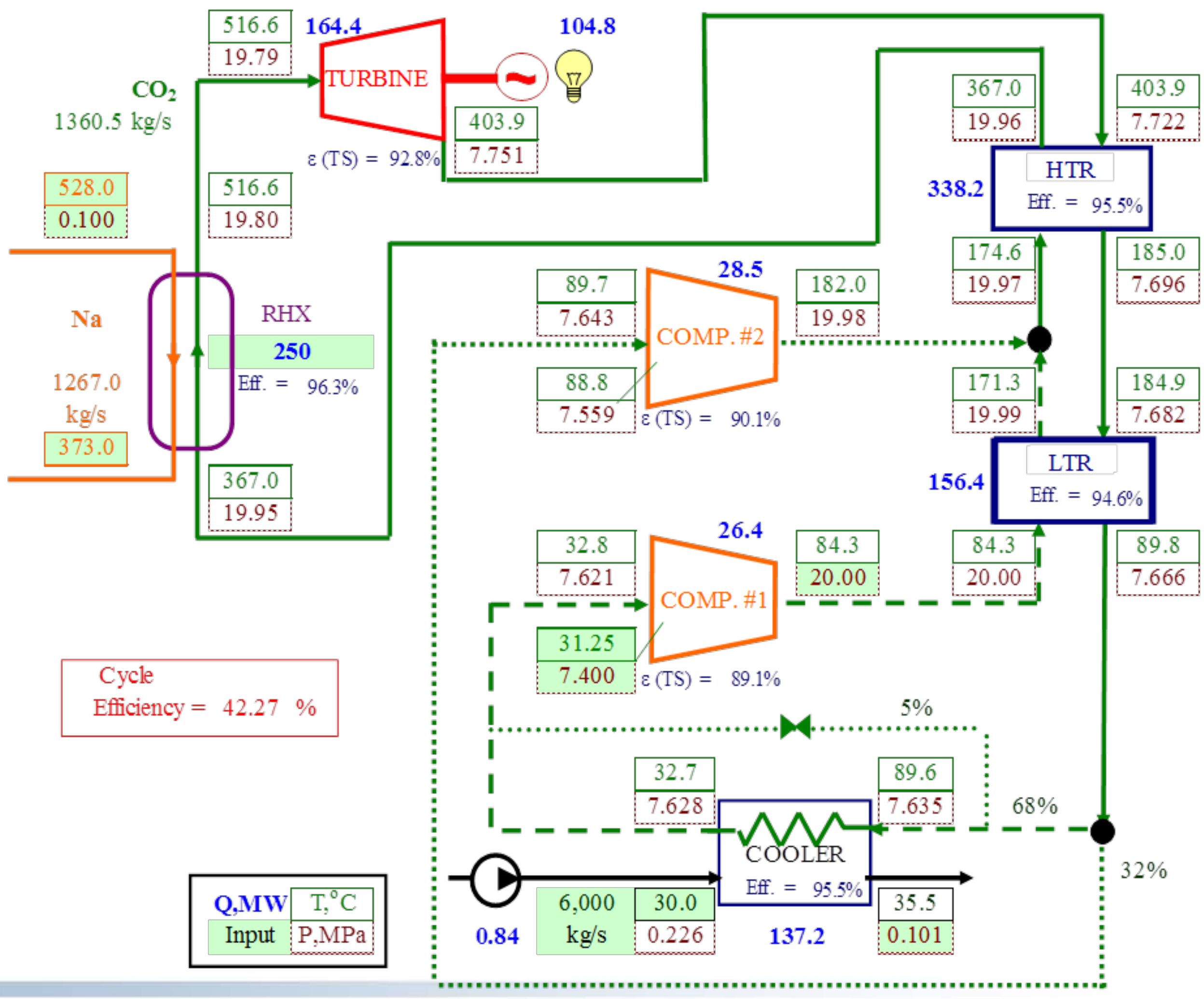
AFR-100 – Ideal Application for a S-CO_2 Brayton Cycle Power Converter

- **Advanced Fast Reactor (AFR) – 100**
  - 100 MWe-class (250 MWt) SFR Small Modular Reactor (SMR) under ongoing development at ANL to target emerging markets where a clean, secure, and stable source of electricity is required but a large-scale power plant cannot be accommodated
  - Incorporates options and innovative fast reactor technologies that have been investigated or are being developed under U.S. Department of Energy Nuclear Energy programs to achieve capital cost reductions, increase passive safety, and improve core performance
  - S-CO_2 Brayton cycle power conversion is one such innovation with superheated steam cycle as backup
- **Modeling incorporated into ANL Plant Dynamics Code used to optimize conceptual design of compact diffusion-bonded heat exchangers and turbomachinery as well as overall cycle conditions to minimize AFR-100 capital cost per unit output electrical power ($/kWe)**

Optimized S-CO_2 Brayton Cycle for the AFR - 100

- Gross cycle efficiency of 42.3 % (104.8 MWe)

ABR S-CO_2 CYCLE TEMPERATURES, PRESSURES, HEAT BALANCE, AND EFFICIENCIES



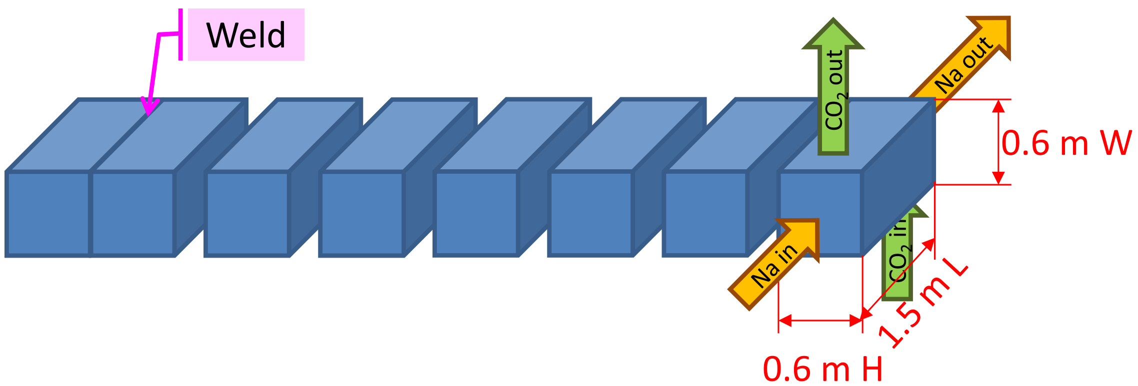
Optimized S-CO_2 Brayton Cycle Heat Exchangers

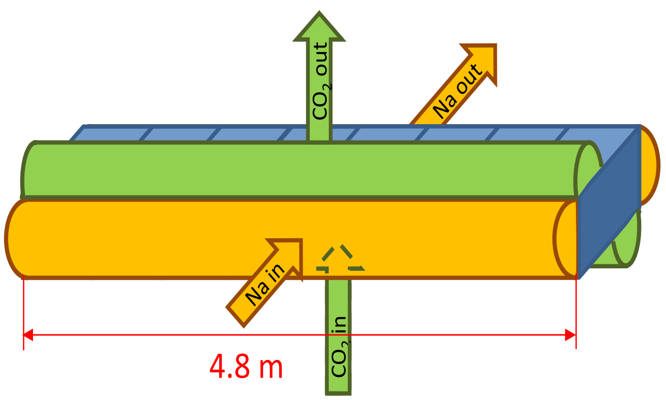
- Minimize nuclear power plant total $/kWe

Heat Exchanger	Sodium-to-CO_2	CO_2-to-CO_2 High Temperature Recuperator	CO_2-to-CO_2 Low Temperature Recuperator	CO_2-to-Water Cooler
Heat Duty, MWt	250	338.2	156.4	137.2
Number of Diffusion-Bonded Blocks	96	48	48	72
Heat Duty per Block, MWt	2.60	7.05	3.26	1.91
Block Length/Width/Height, m	1.50/0.6/0.6	0.6/1.50/0.6	0.6/1.50/0.6	0.868/0.6/0.6
Channel Length for Heat Transfer Hot/Cold Side, m	1.500/1.732	0.439/0.439	0.439/0.537	0.748/0.715
Hot Side Channels	6 mm Wide by 4 mm High Rectilinear	1.3 mm Semicircular Diameter	1.3 mm Semicircular Diameter	2 mm Semicircular Diameter
Cold Side Channels	2 mm Semicircular Diameter	1.3 mm Semicircular Diameter	1.3 mm Semicircular Diameter	2 mm Semicircular Diameter
Hot Side Inlet/Outlet Temperature, °C	528.0/373.0	403.9/185.0	184.9/89.8	89.6/32.66
Cold Side Outlet/Inlet Temperature, °C	516.6/367.0	367.0/174.6	171.3/84.3	35.5/30.0
Hot Side Inlet/Outlet Pressure, MPa	0.100/0.100	7.722/7.696	7.682/7.666	7.635/7.628
Cold Side Outlet/Inlet Pressure, MPa	19.802/19.946	19.962/19.971	19.987/19.995	0.101/0.226
Hot/Cold Side Flowrate, kg/s	13.2/14.2	28.3/28.3	28.3/19.3	12.2/83.3
Block Mass, tonnes	1.701	2.653	2.653	1.586
Effectiveness, %	96.3	95.5	94.6	95.5

Welding Together and Manifolding of Compact Diffusion-Bonded Heat Exchanger Blocks

- Example of sodium-to-CO_2 heat exchanger units
- Reduces number of piping connections while maintaining transportable units





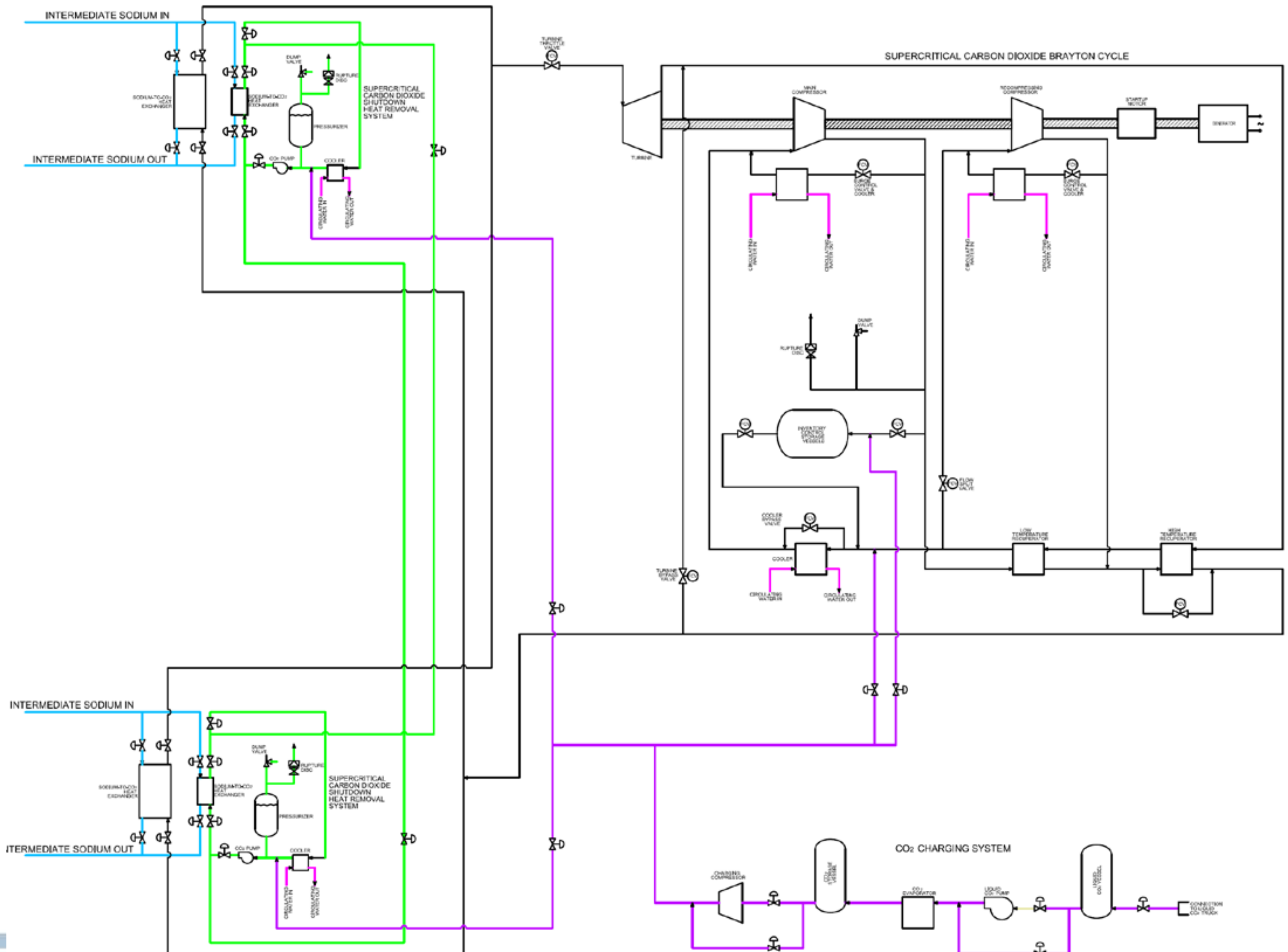
Optimized S-CO_2 Brayton Cycle Turbomachinery

- Minimize nuclear power plant total $/kWe

Turbomachine	Turbine	Main Compressor	Recompressing Compressor
Type	Axial	Centrifugal	Centrifugal
Power, MWt	164.4	26.41	28.53
Rotational Speed, rpm	3,600	3,600	3,600
Number of Stages	6	1	2
Axial Length without Casing, m	2.67	0.37	0.86
Diameter without Casing, m	0.89	1.90	2.03
Hub Radius Max/Min, cm	35.3/28.2	10.0/10.0	10.8/8.4
Blade Tip Radius Max/Min, cm	44.6/42.5		
Impeller Radius Max/Min, cm		56.9/56.9	63.2/58.7
Blade Height Max/Min, cm	16.4/7.2	8.7/1.4	11.1/1.2
Blade Chord Max/Min, cm	10.9/7.4		
Blade Length, Max/Min, cm		50.6/23.3	57.8/25.0
Inlet/Outlet Pressure, MPa	19.79/7.751	7.621/20.00	7.643/19.98
Inlet/Outlet Temperature, °C	516.6/403.9	32.79/84.3	89.66/182.0
Flowrate, kg/s	1360.5	952.2	435.4
Maximum Mach Number	0.38	0.47	0.50
Total-to-Static Efficiency, %	92.8	89.1	90.1

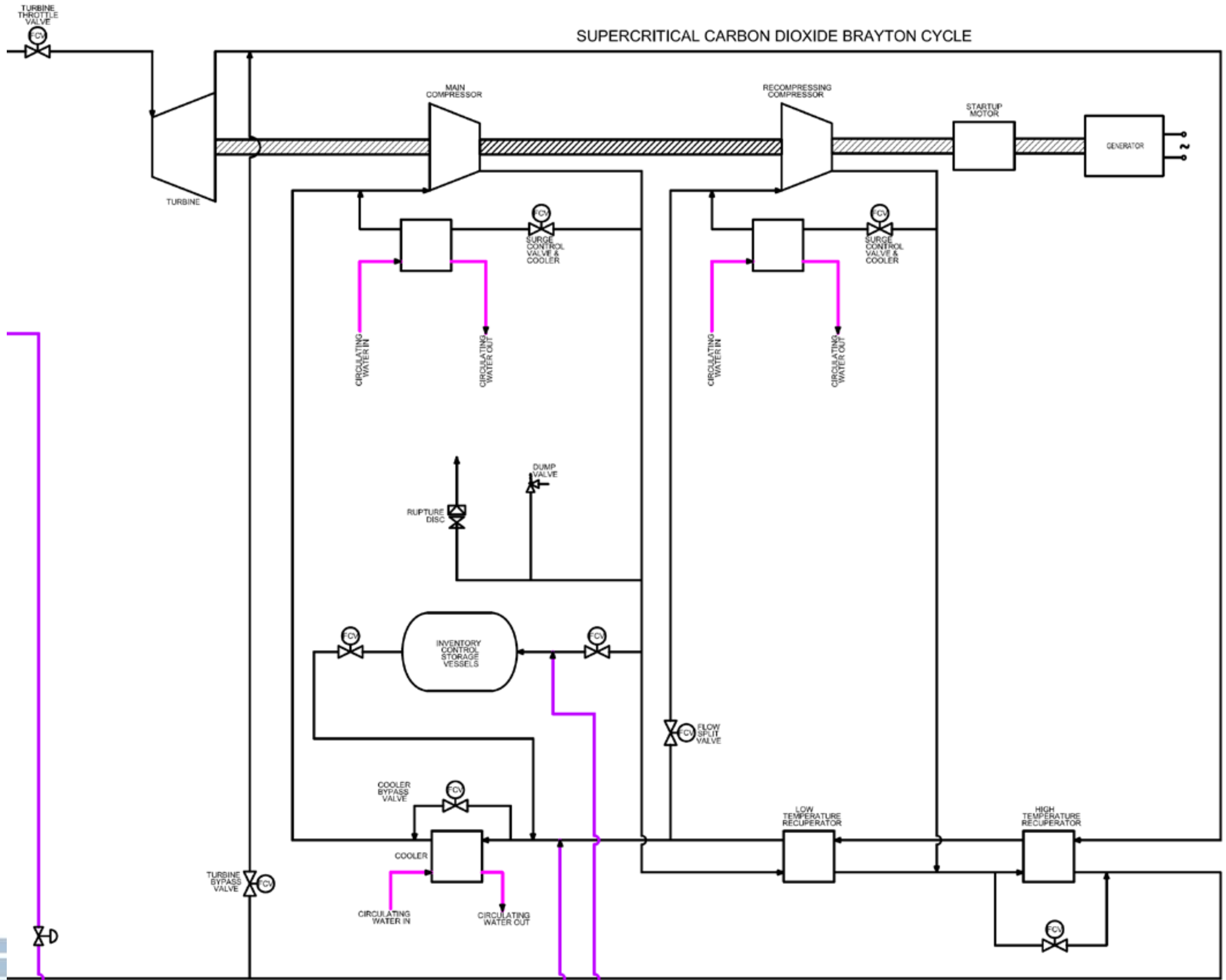
Flow Diagram for AFR-100 S-CO_2 Brayton Cycle

- **Includes power converter, normal shutdown heat removal systems, and CO_2 charging system**



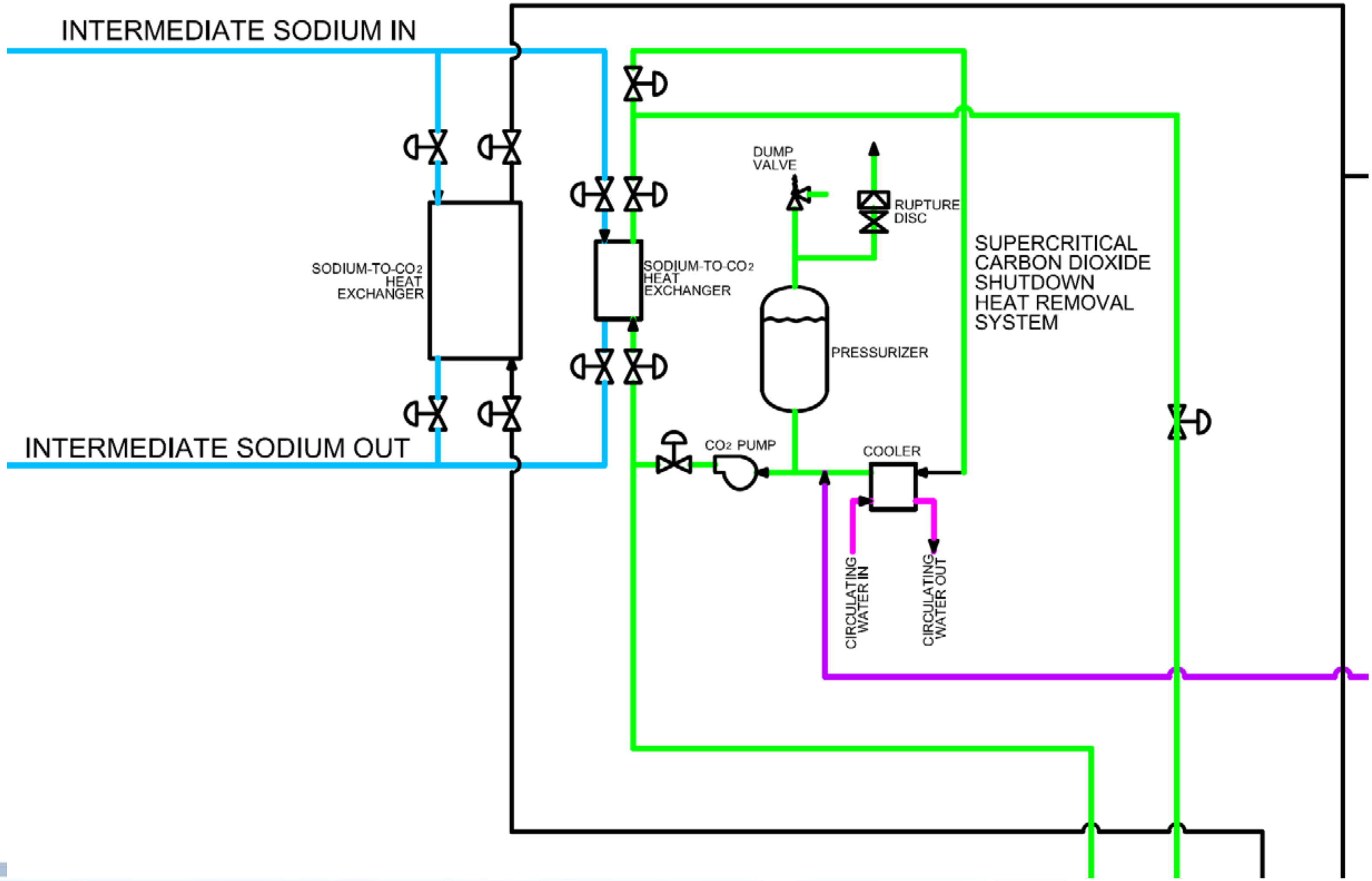
Flow Diagram for S-CO_2 Brayton Cycle Power Converter

- **Single shaft layout**



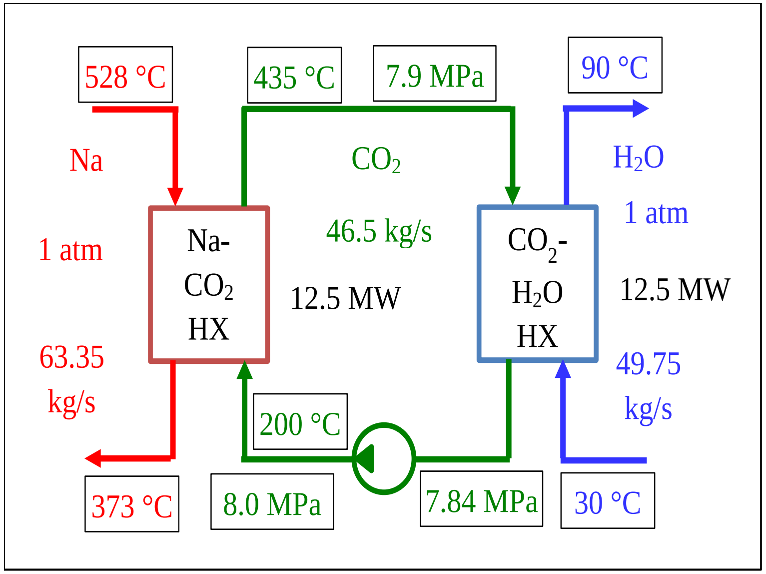
Flow Diagram for Normal Shutdown Heat Removal System for One Intermediate Sodium Loop

- Utilizes S-CO_2 at about 8 MPa



AFR-100 Normal Shutdown Heat Removal System

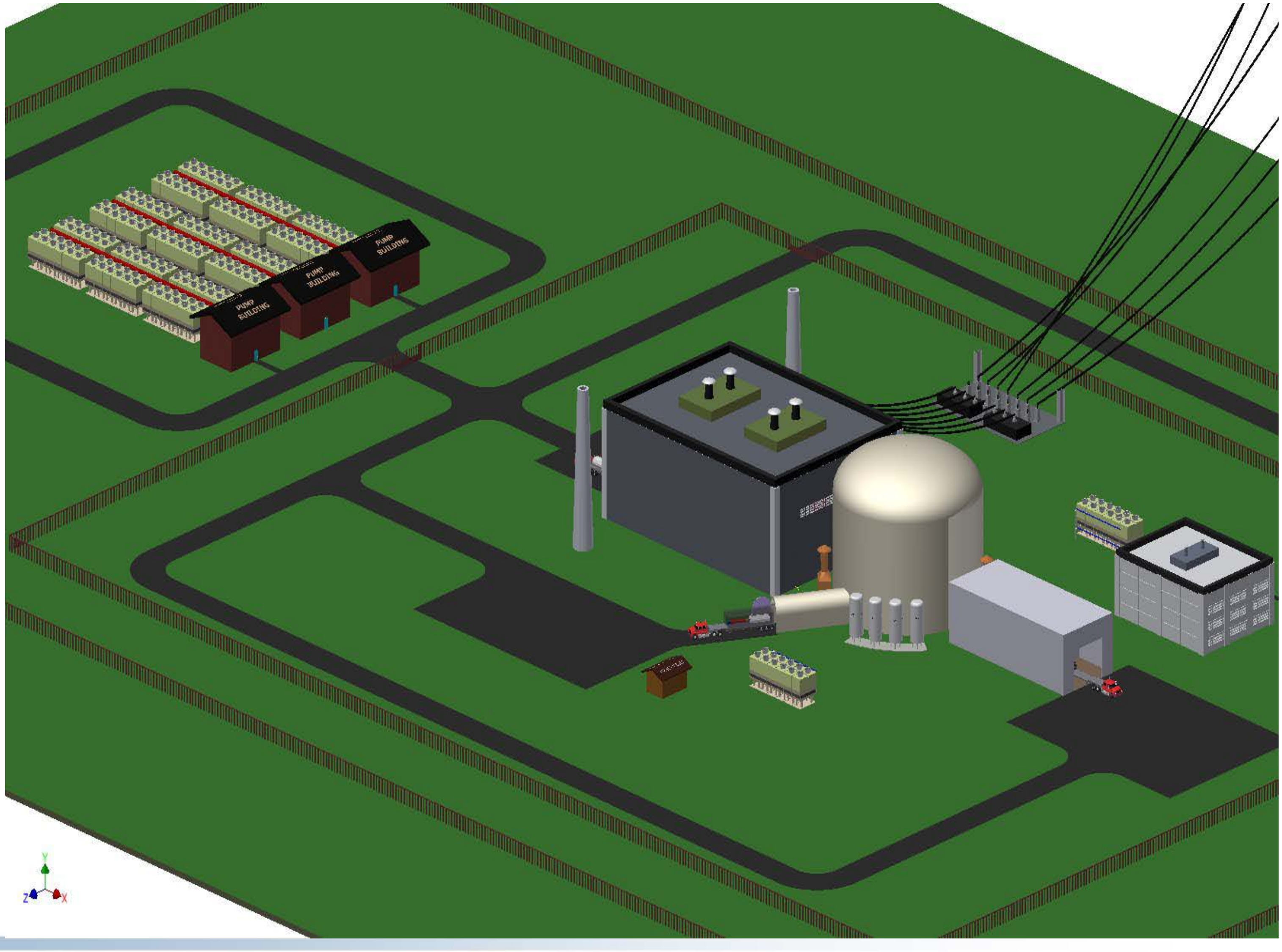
- Cools the reactor when it is shut down and the S-CO_2 Brayton cycle is also shut down or otherwise unavailable due to the need for maintenance or repair



Heat Exchanger	Sodium-to-CO_2	CO_2-to-Water Cooler
Heat Duty, MWt	12.5	12.5
Number of Diffusion-Bonded Blocks	1	1
Heat Duty per Block, MWt	12.5	12.5
Block Length/Width/Height, m	0.4/1.14/0.6	0.35/0.537/0.6
Hot Side Channels	6 mm Wide by 4 mm High Rectilinear	2 mm Semicircular Diameter
Cold Side Channels	2 mm Semicircular Diameter	2 mm Semicircular Diameter
Hot Side Inlet/Outlet Temperature, °C	528.0/373.0	435.3/200.0
Cold Side Outlet/Inlet Temperature, °C	435.3/200.0	90.0/30.0
Hot/Cold Side Flowrate, kg/s	63.4/46.5	46.5/49.8
Hot/Cold Side Pressure Drop, kPa	0.04/98.6	58.4/11.5

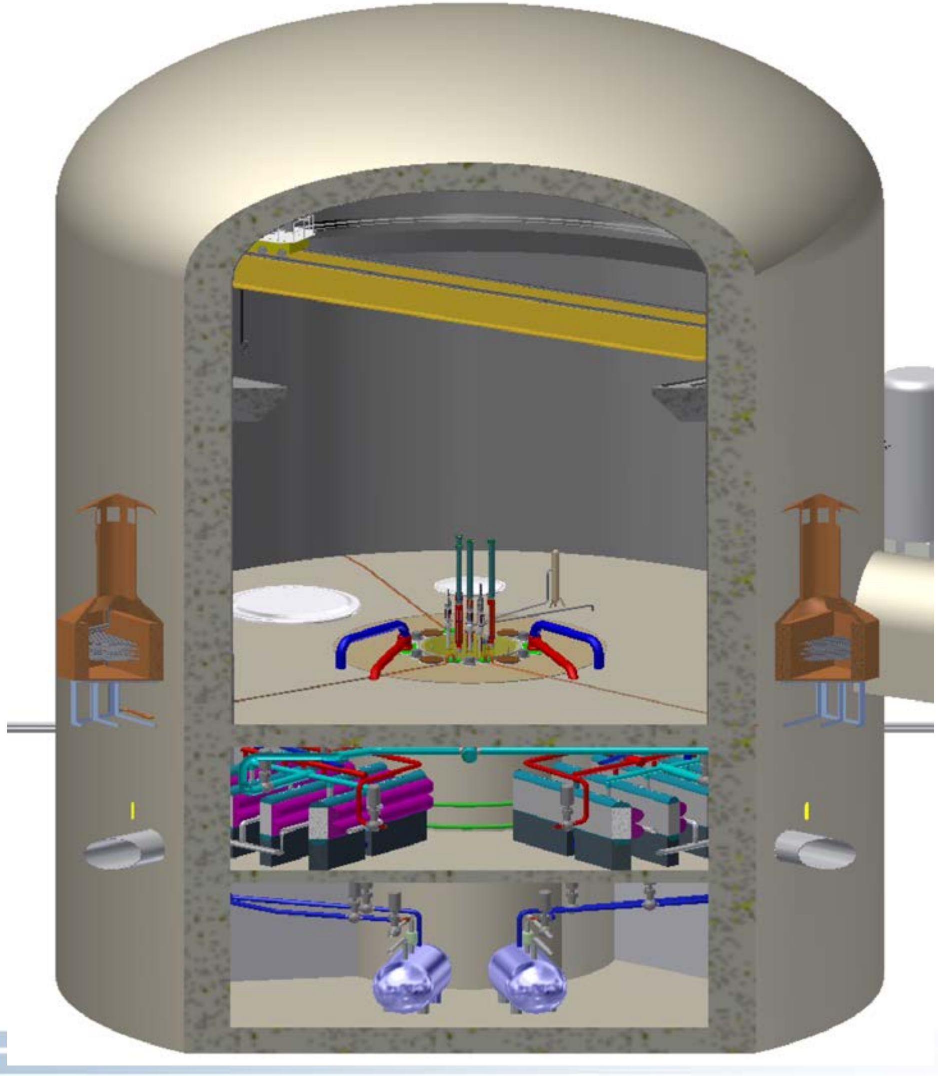
AFR-100 Nuclear Power Plant

- **Utilizes modular cooling towers**

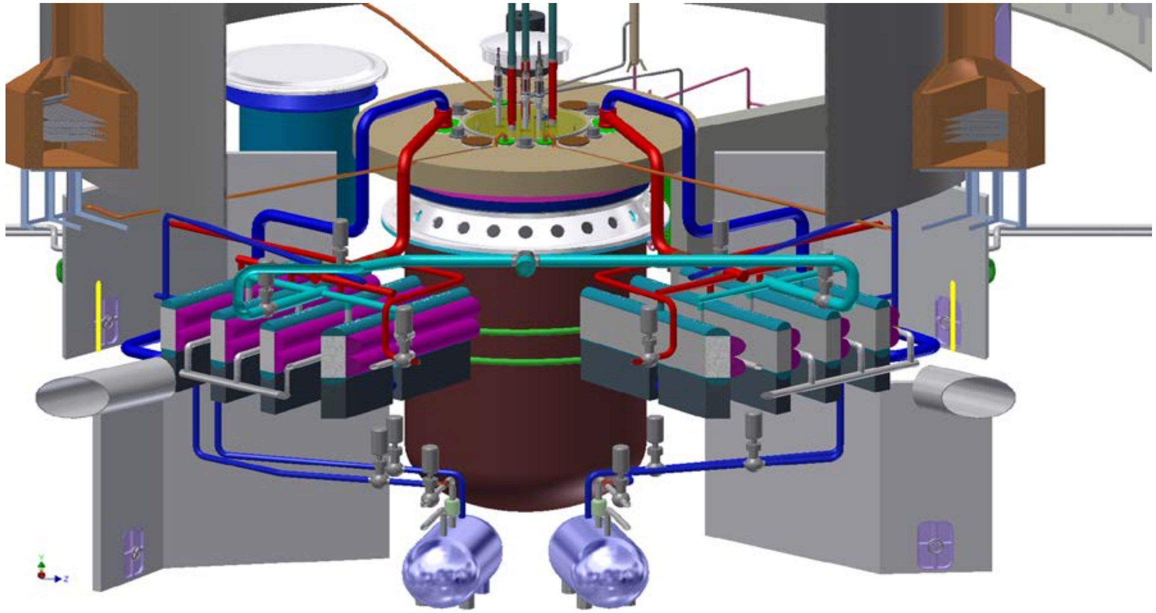


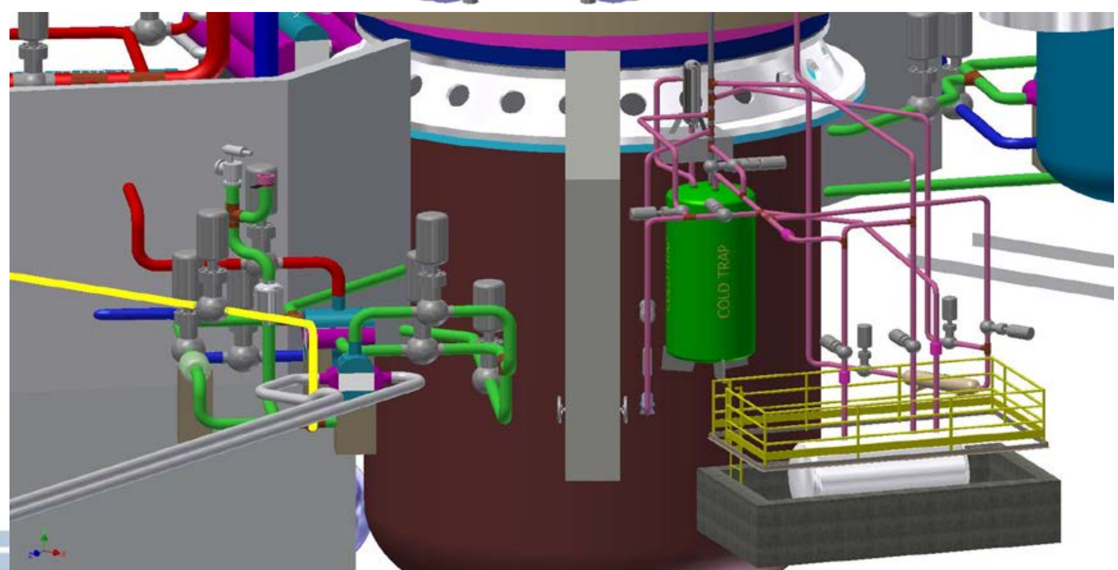
AFR-100 Reactor Building

- Sodium-to-CO_2 HXs are located inside of reactor building but outside of the containment portion



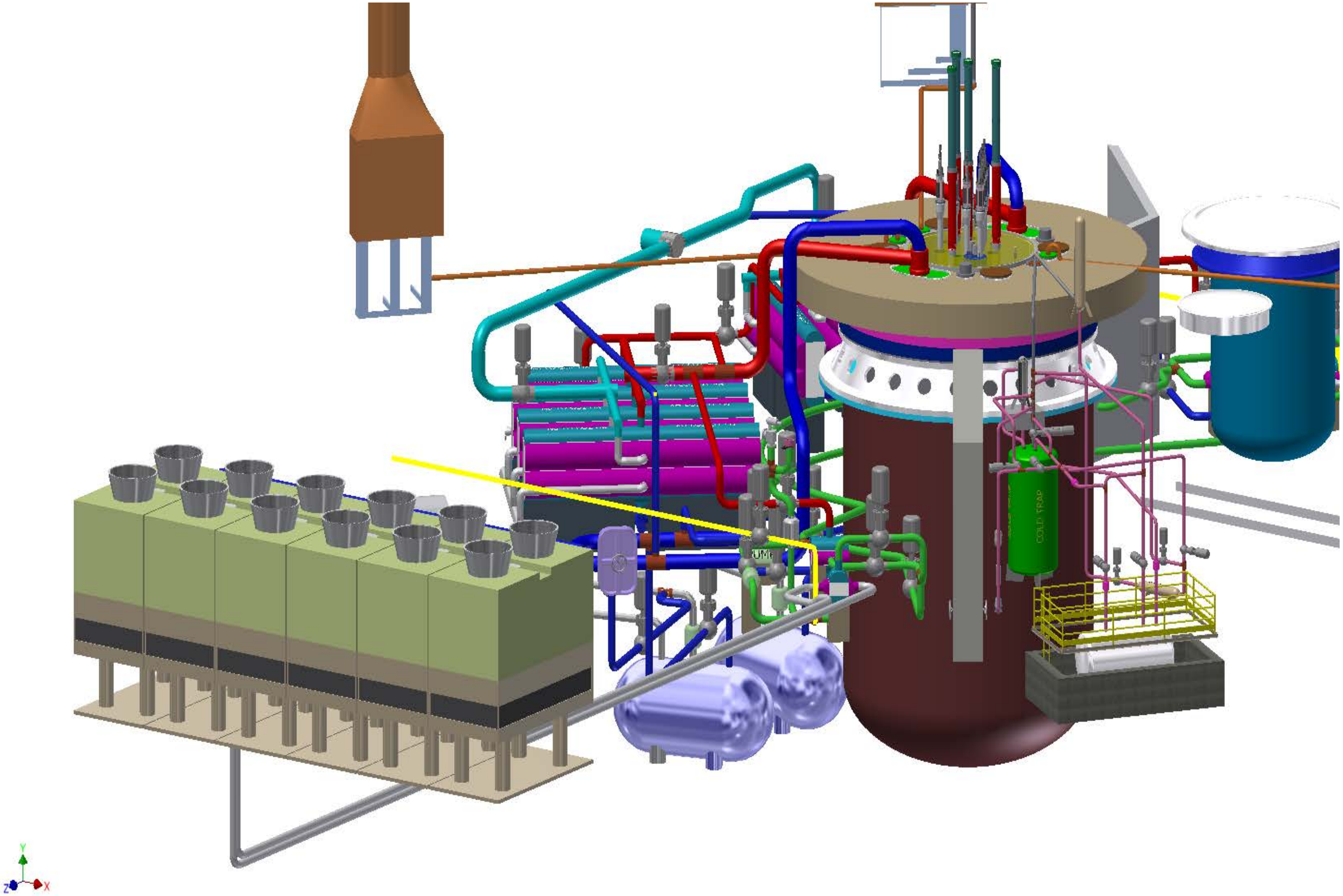
Sodium-to-CO_2 HXs and Normal Shutdown Heat Removal System





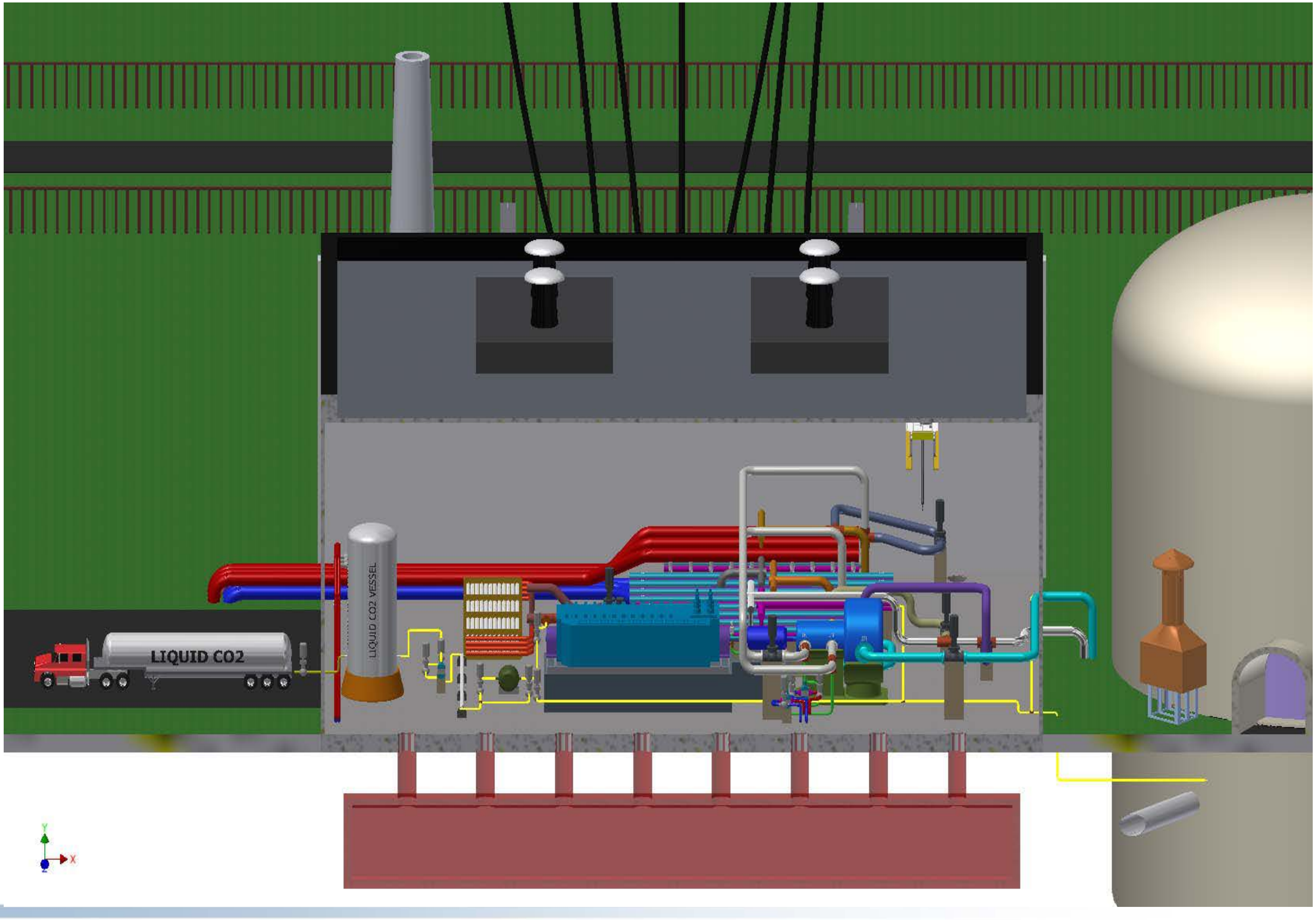
Normal Shutdown Heat Removal System

- **For one intermediate sodium loop**



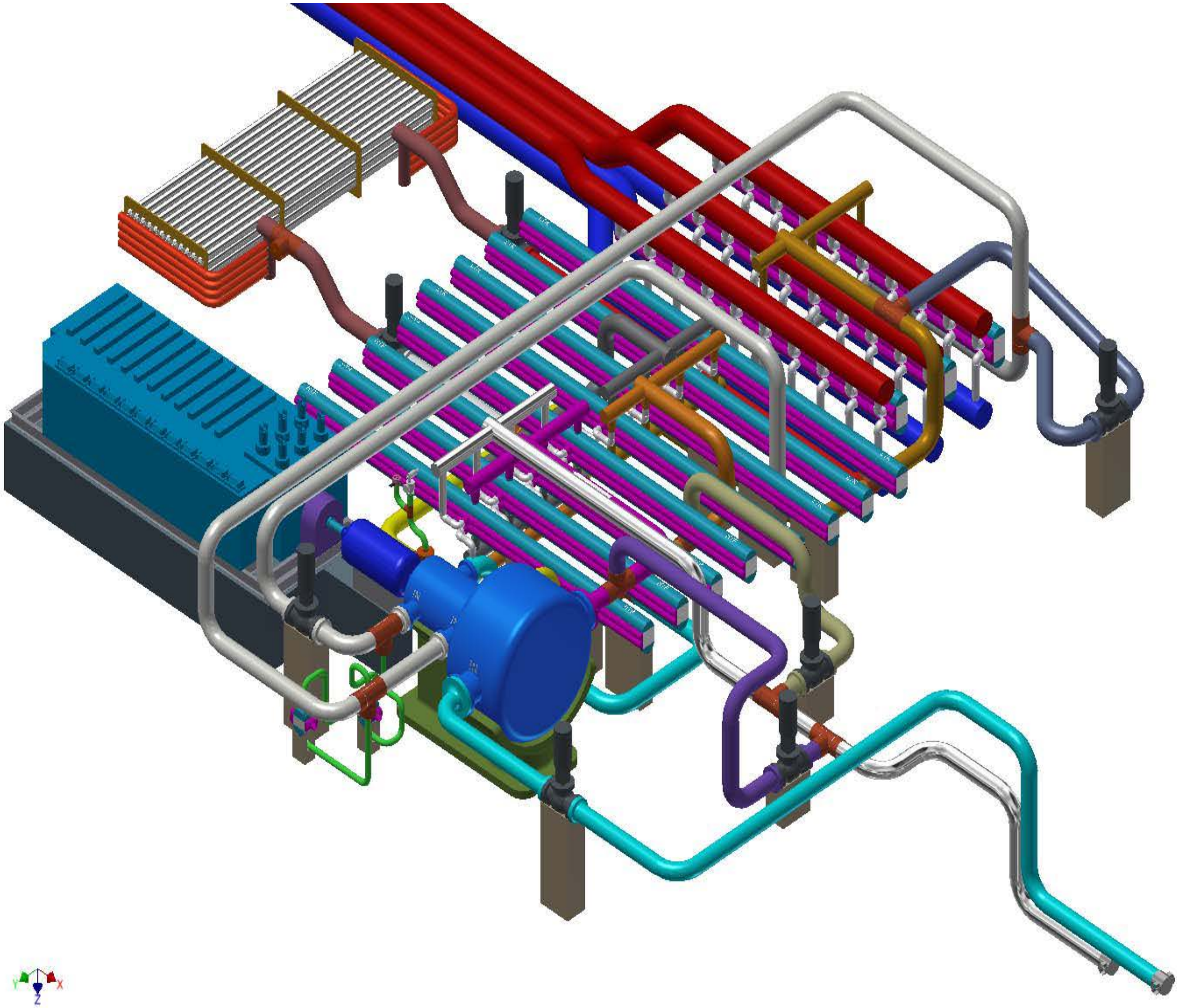
Turbine Generator Building

- 53 m (173 ft) long by 39 m (127 ft) wide by 16 m (53 ft) high



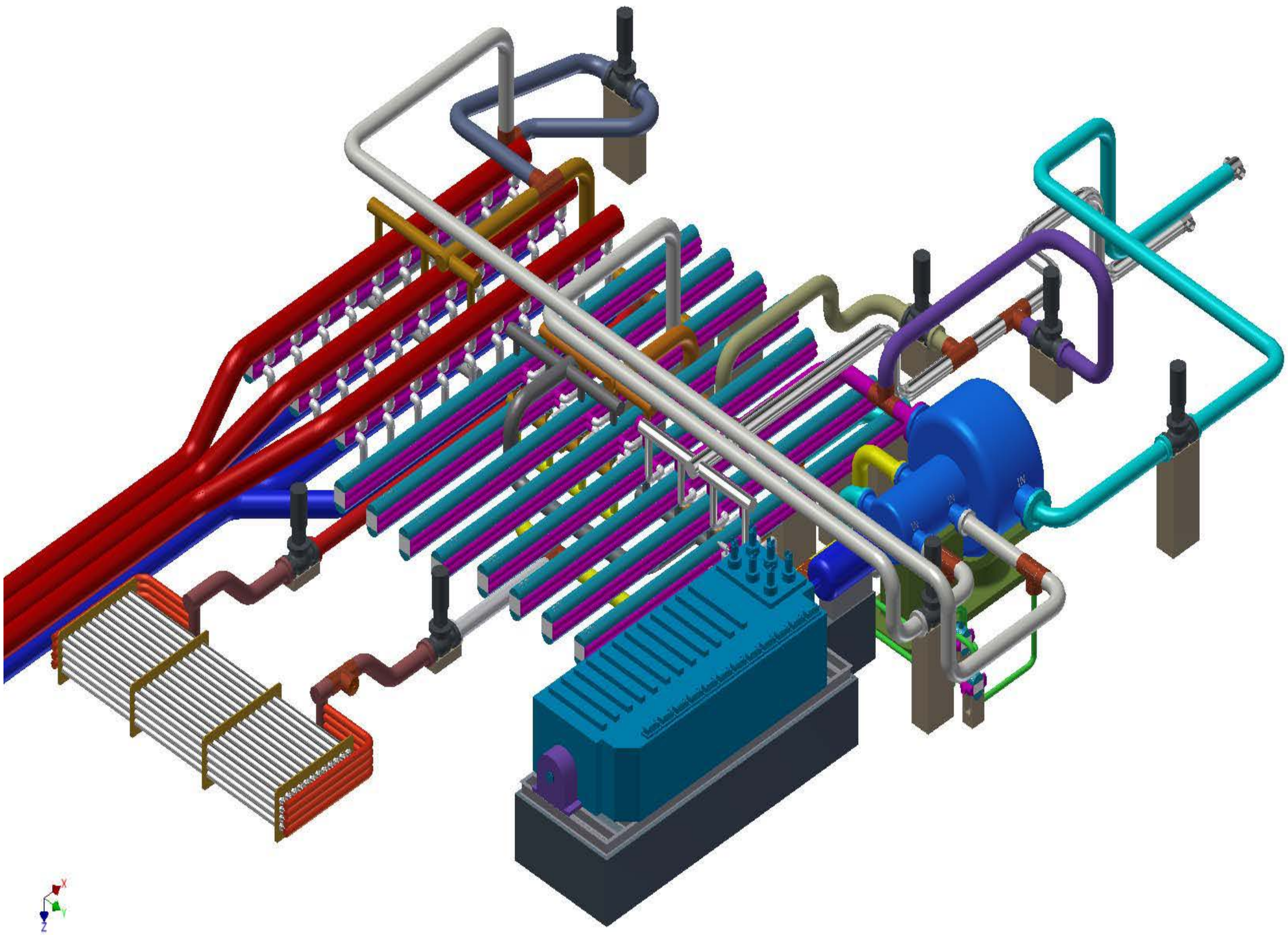
$S\text{-}CO_2$ Brayton Cycle Power Converter

- Footprint = 32 m (106 ft) long by 33 m (109 ft) wide

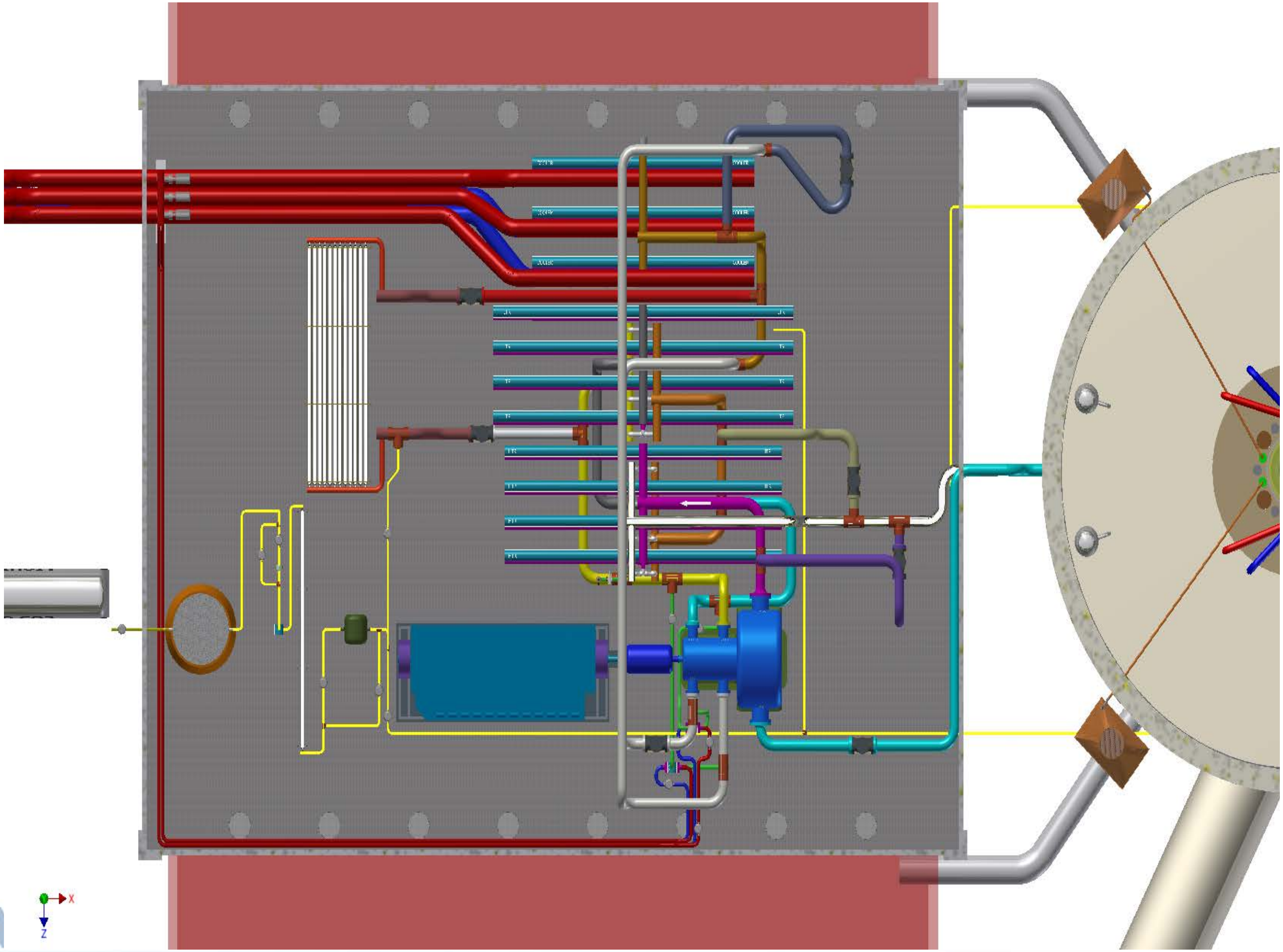


S-CO_2 Brayton Cycle Power Converter

- **Footprint = 32 m (106 ft) long by 33 m (109 ft) wide**

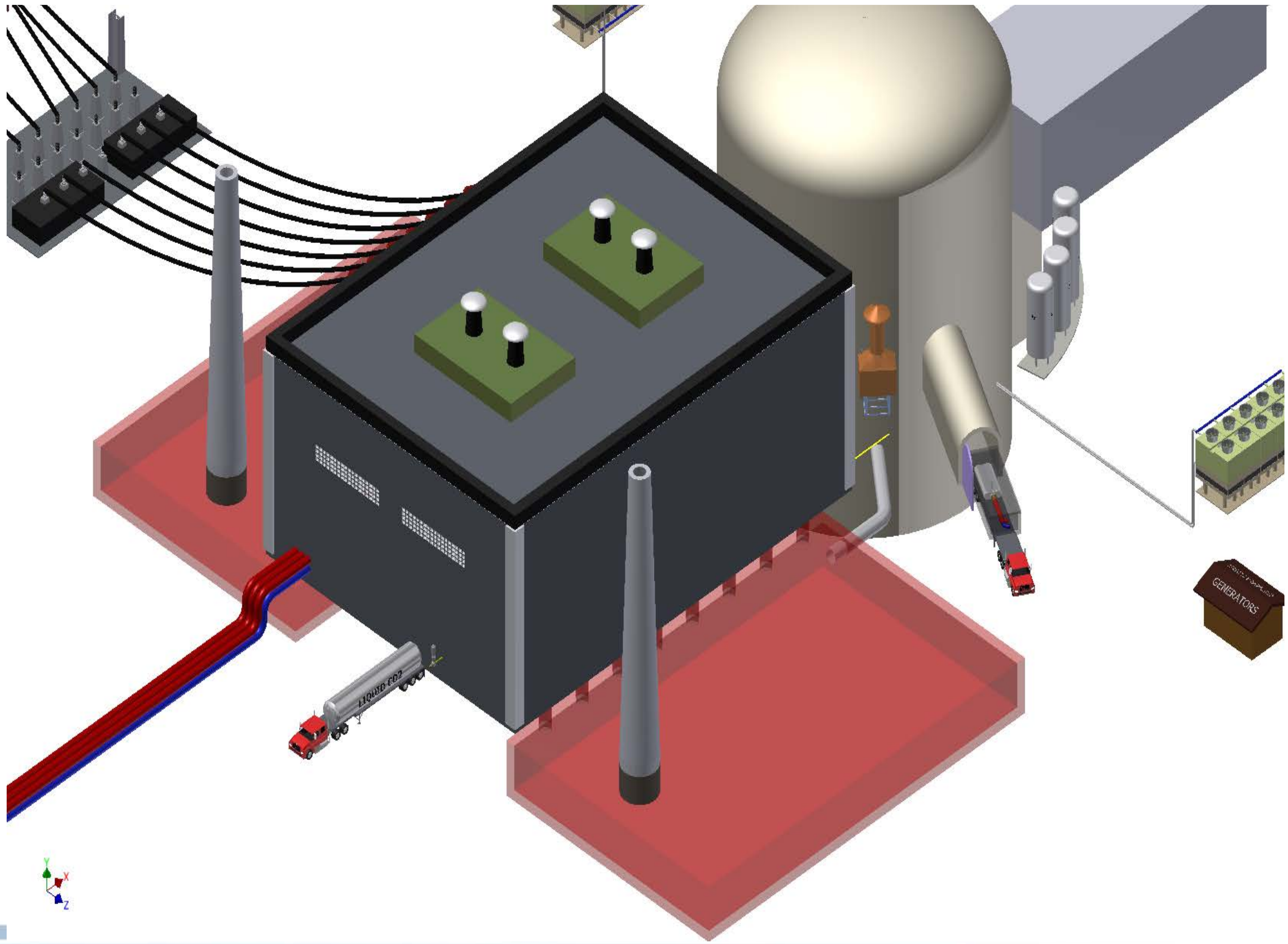


S-CO_2 Brayton Cycle Power Converter Plan View



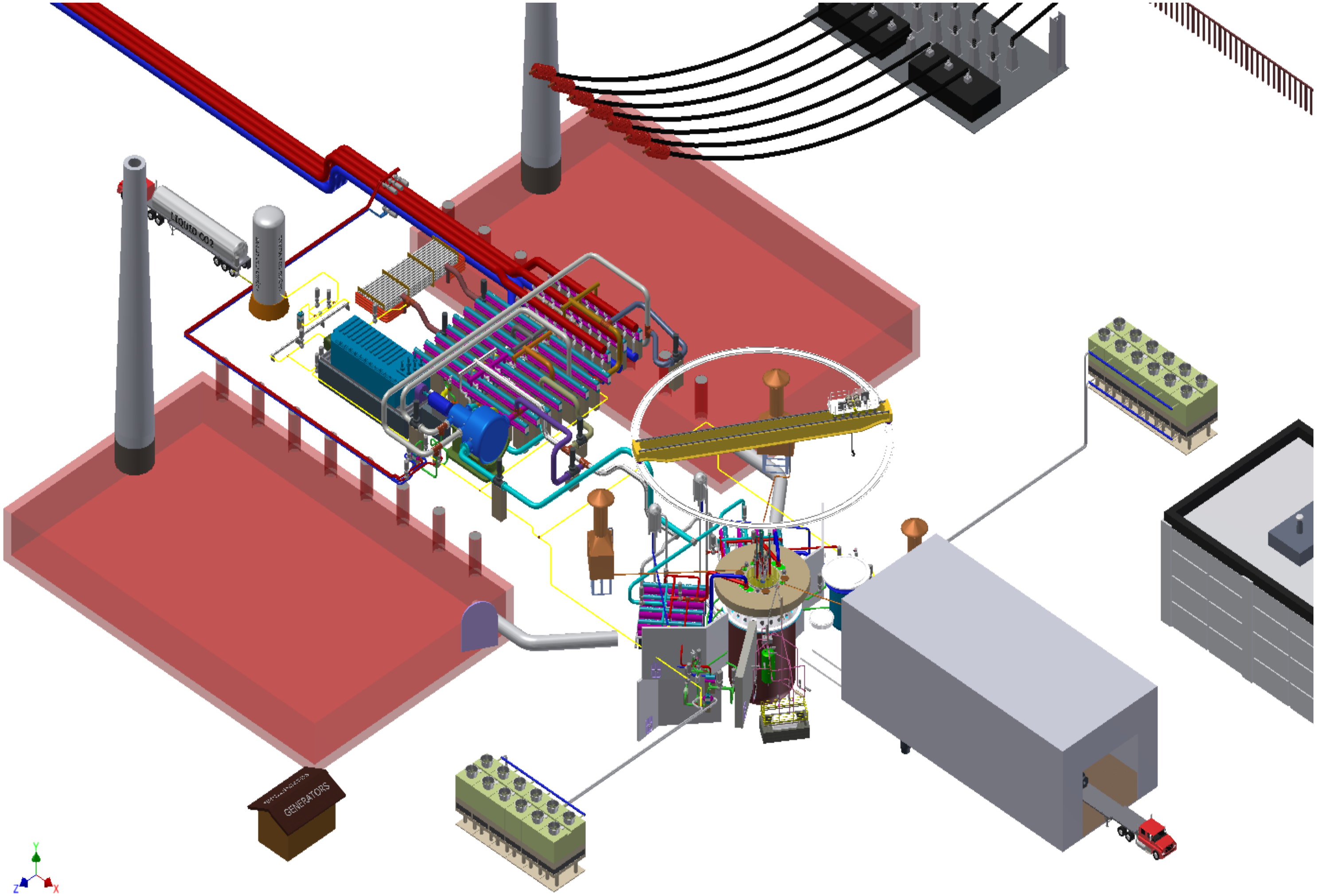
Below-Ground CO_2 Collection Volumes

- CO_2 is toxic and plant personnel must be protected against health hazards from spreading CO_2 cloud following release



Summary Overall View

- Following collection in below-ground volumes, CO_2 can be slowly released through stacks to mix with atmosphere



Summary

- **$S\text{-}CO_2$ Brayton cycle power conversion makes good sense for advanced nuclear power reactors**
- **Twelve years of experience at ANL working on $S\text{-}CO_2$ Brayton cycle development and code development and validation since 2002 continue to confirm initial notions about benefits**
  - $S\text{-}CO_2$ cycle is well matched to SFR – Cycle wants to operate with a CO_2 temperature rise in sodium-to-CO_2 heat exchangers of about 150 °C which is about equal to the sodium temperature rise through the core
  - Greater efficiency at SFR core outlet temperatures and above
  - Elimination of sodium-water reactions
  - Smaller balance-of-plant footprint reducing size of turbine generator building and portions of reactor building
  - Expected reduction in SFR $/kWe or LCOE
  - $S\text{-}CO_2$ Brayton cycle with automatic control strategy and active reactor control enables load following down to zero electrical grid load demand and can continue to be used for residual heat removal from reactor down to initial decay heat levels