Operational Reactor Safety

22.091/22.903

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Professor of the Practice

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Lecture 23:
Current Regulatory Issues

Present Situation

- *It doesn’t get any better than this for nuclear energy!*
  - *Very Good Nuclear Regulatory Commission*
  - *Combined Construction Permit and Operating License*
  - *Early site permits supported by DOE*
  - *Concern about Global Climate Change*
  - *Rising and highly volatile natural gas and oil prices*
  - *Great rhetoric from the President and Congress about need for nuclear energy for environment, security and stability*
  - *Strong Pro-nuclear congressional legislation in the Energy Policy Act of 2005.*

Congress

- Passed Energy Policy Act of 2005
  - Nuclear energy provisions
    - Production tax credit - $ 200/kw – for first movers
    - Loan guarantees
    - Insurance protection of up to $ 500 million for regulatory delays for first 2 plants.
  - Effort to stimulate orders for new plants
- Department of Energy working to develop advanced reactor designs as part of Generation IV reactors - 2030

Present New Market Offerings

- AP-1000 (Westinghouse)
  - 1,000 Mwe – PWR
- ESBWR (General Electric)
  - 1390 Mwe - BWR
- EPR (Framatome – ANP)
  - 1,600 Mwe – PWR
- APWR – (Mitsubisi)_
  - 1,700 Mwe – PWR

Certified Designs

- AP-600 (Westinghouse)
- ABWR – 1250 Mwe (General Electric)
- System 80^{+} - 1300 Mwe (Westinghouse/CE)

Trends

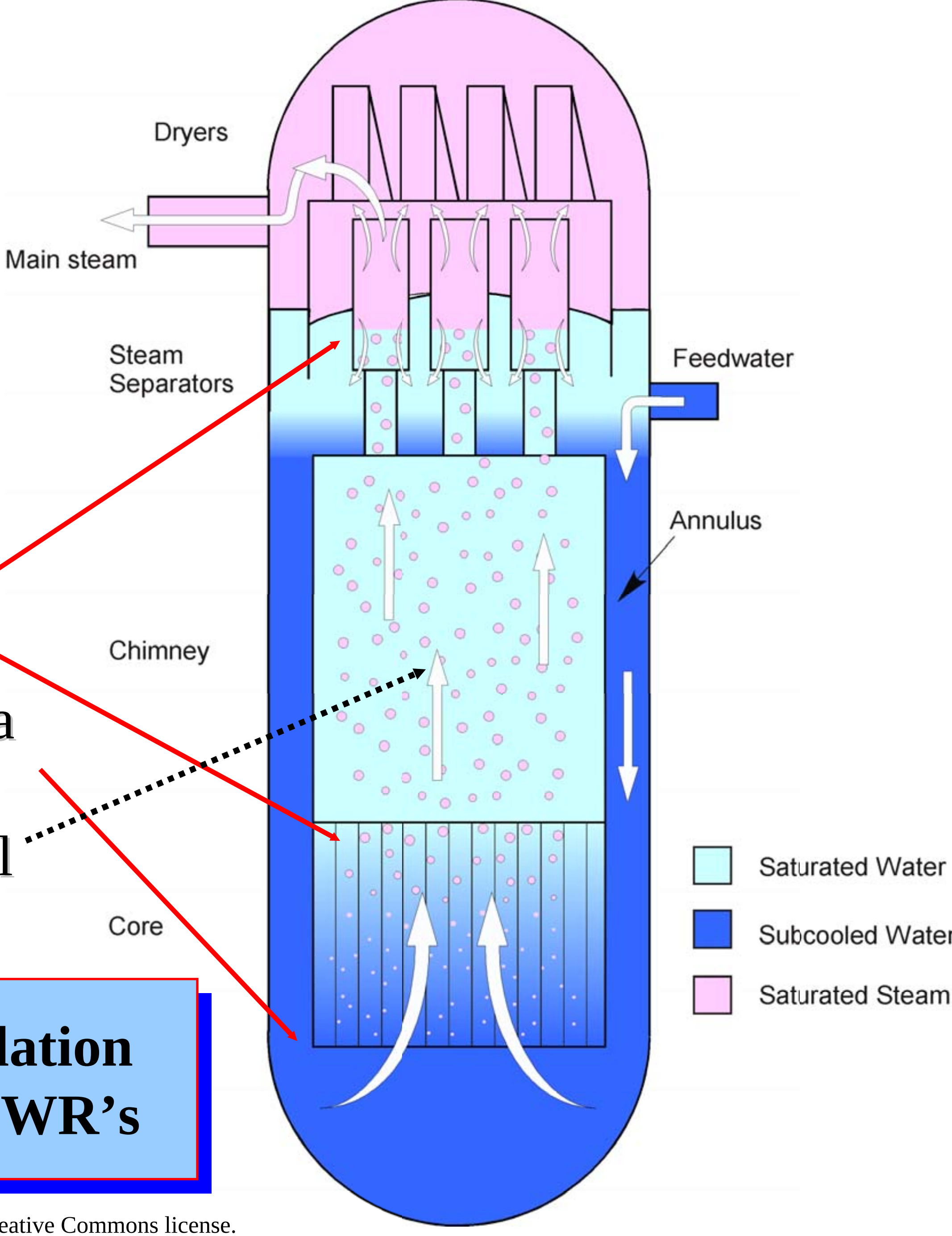
- More passive safety features
- Less dependency on active safety systems
- Lower core damage frequencies – 10^{-6}
- More back up safety systems – more trains
- Some core catchers
- Larger plants to lower capital cost $/kw
- Simplification in design
- Terrorist resistant features
- Construction time reduced but still long 4 years

ESBWR Design Features

- Natural circulation Boiling Water Reactor
- Passive Safety Systems
- Key Improvements:
  - Simplification
    - Reduction in systems and equipment
    - Reduction in operator challenges
    - Reduction in core damage frequency
    - Reduction in cost/MWe

Enhanced Natural Circulation Compared to Standard BWR's

- Reduced flow restrictions
  - improved separators
  - shorter core
  - increase downcomer area
- Higher driving head
  - chimney and taller vessel

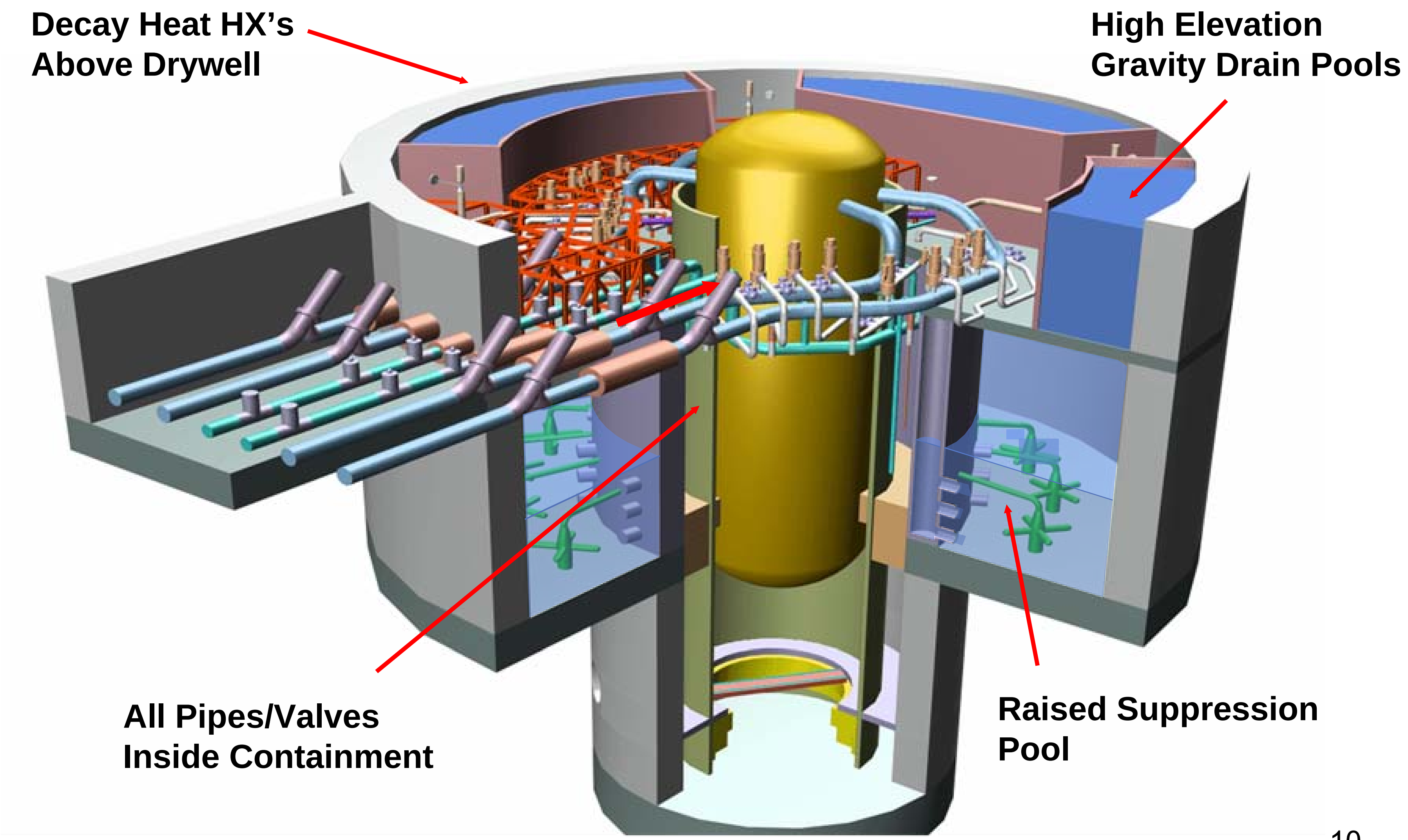


Differences relative to ABWR

ABWR	ESBWR
Recirculation System + support systems	Eliminated (Natural Circulation)
HPCF (High Pressure Core Flooder) (2 each)	Combined all ECCS into one Gravity Driven Cooling System (4 divisions)
LPFL (Low Pressure Core Flooder) (3 each)	
RCIC (Isolation/Hi-Pressure small break makeup)	Replaced with IC heat exchangers (isolation) and CRD makeup (small break makeup)
Residual Heat Removal (3 each) (shutdown cooling & containment cooling)	Non-safety shutdown cooling, combined with cleanup system; Passive Containment Cooling
Standby Liquid Control System–2 pumps	Replaced SLCS pumps with accumulators
Reactor Building Service Water (Safety Grade) And Plant Service Water (Safety Grade)	Made non-safety grade – optimized for Outage duration
Safety Grade Diesel Generators (3 each)	Eliminated – only 2 non-safety grade diesels

2 Major Differences – Natural Circulation and Passive Safety

Passive Safety Systems Within Containment Envelope



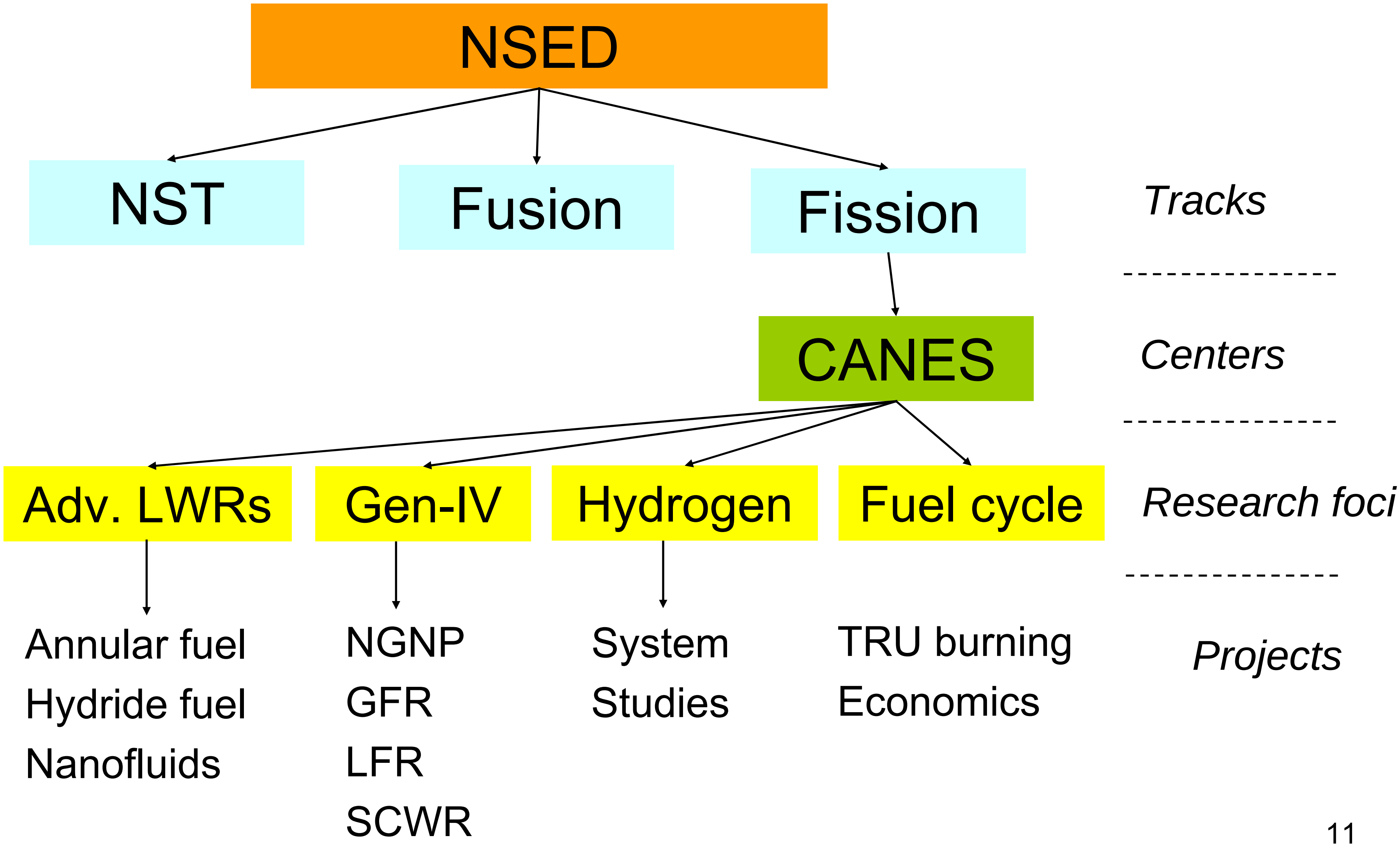
Decay Heat HX's Above Drywell

High Elevation Gravity Drain Pools

All Pipes/Valves Inside Containment

Raised Suppression Pool

Fission Research at MIT Nuclear Science and Engineering



NSED

NST

Fusion

Fission

Tracks

CANES

Centers

Adv. LWRs

Gen-IV

Hydrogen

Fuel cycle

Research foci

Annular fuel
Hydride fuel
Nanofluids

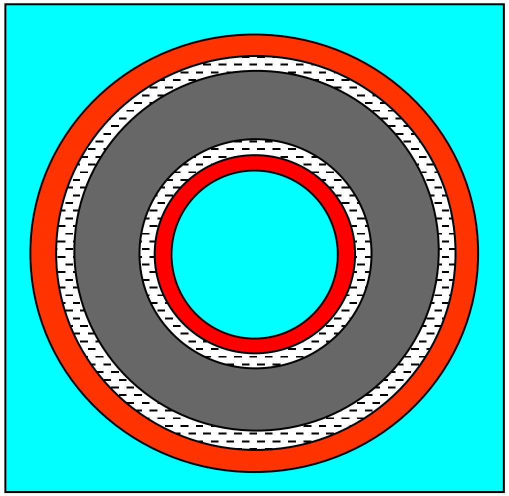
NGNP
GFR
LFR
SCWR

System
Studies

TRU burning
Economics

Projects

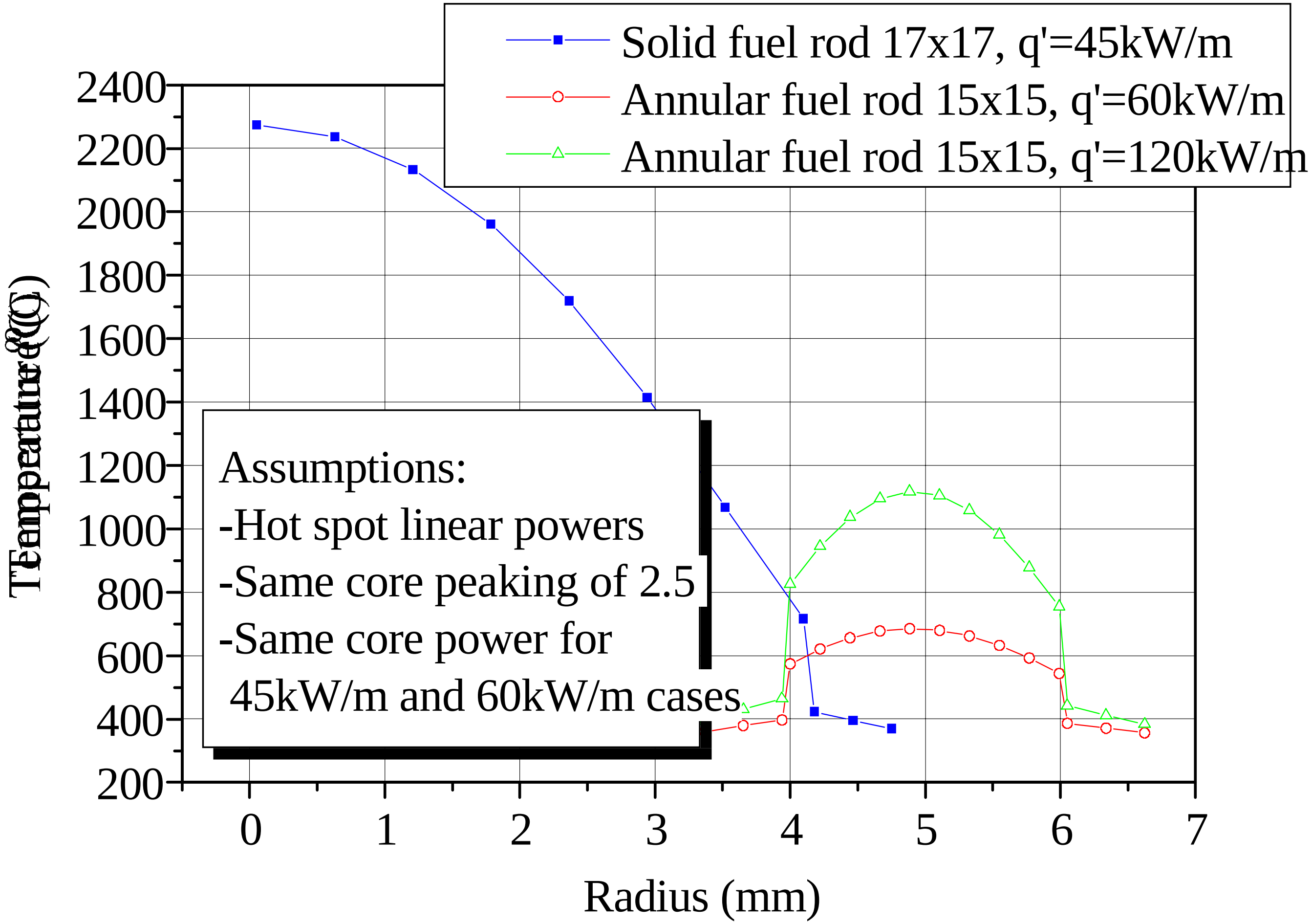
Annular Fuel for High Power Density PWRs



- Large project lead by MIT (Westinghouse, Gamma Eng. , Framatome ANP, AECL)
- Operates at low peak temperatures (1000°C lower than solid fuel)
- Fuel allows increase of power density by 50% keeping same TH margins
- Allows achievement of burnup of 90MWd/kgHM
- Appreciably increase of rate of return (economically attractive)

Thermal Hydraulic Performance: Fuel Temperature

- **Very low operating peak fuel temperature**

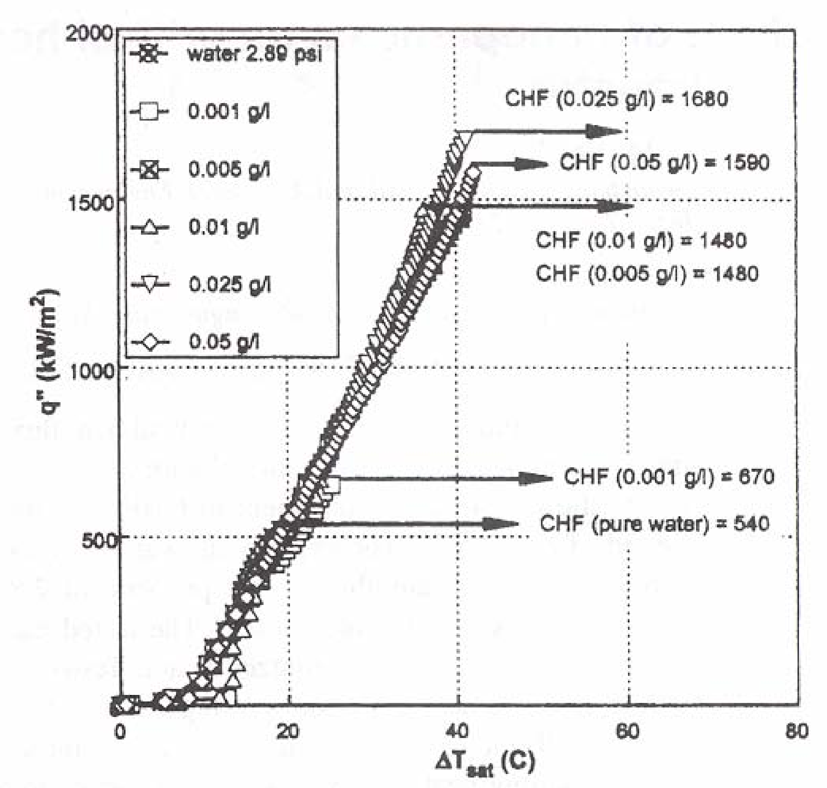


Assumptions:
-Hot spot linear powers
-Same core peaking of 2.5
-Same core power for
45kW/m and 60kW/m cases

Nanofluids Project

- *Nano… what? A **nanofluid** is an 'engineered' colloid = base fluid (water, organic liquid, gas) + nanoparticles*
- *Nanoparticle size: 1-100 nm*
- *Nanoparticle materials: Al_2O_3, ZrO_2, SiO_2, CuO, Cu, Au, C*
- *Critical heat flux increases*

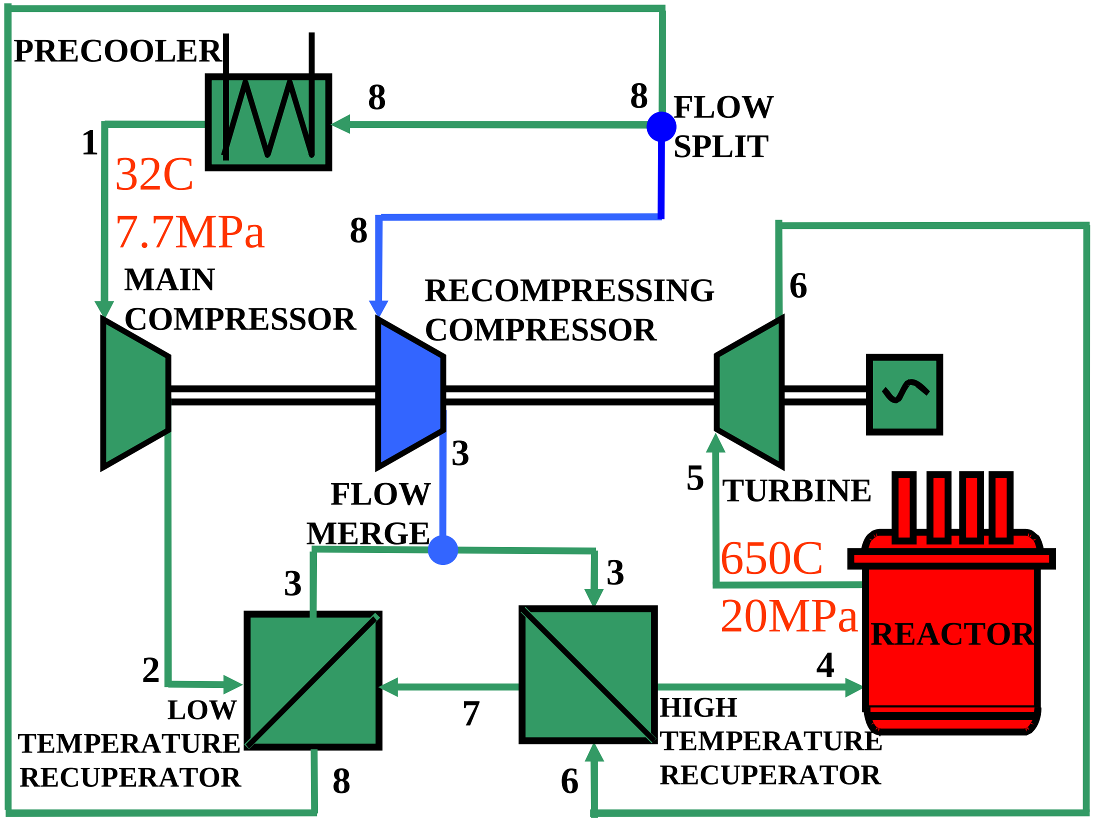
Makes nanofluids appealing for nuclear. Possibility of significant power density increase. But large gaps in database and understanding of the enhancement mechanisms exist.

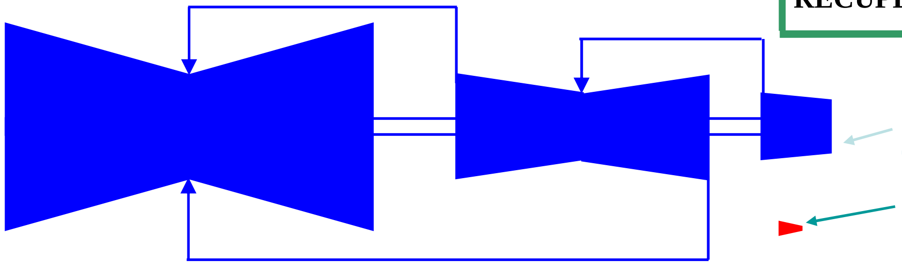


Supercritical CO2 cycle for Gen. IV reactors

- Achieves high efficiency at medium temperature
- Has ~25% lower cost than Rankine cycle
- CO2 abundant, cheap and does not leak as easily as helium
- Is extremely compact (300MWe turbine fits in home size refrigerator)
- Applicable to reactors with outlet temperature >500°C (most GenIV reactors)

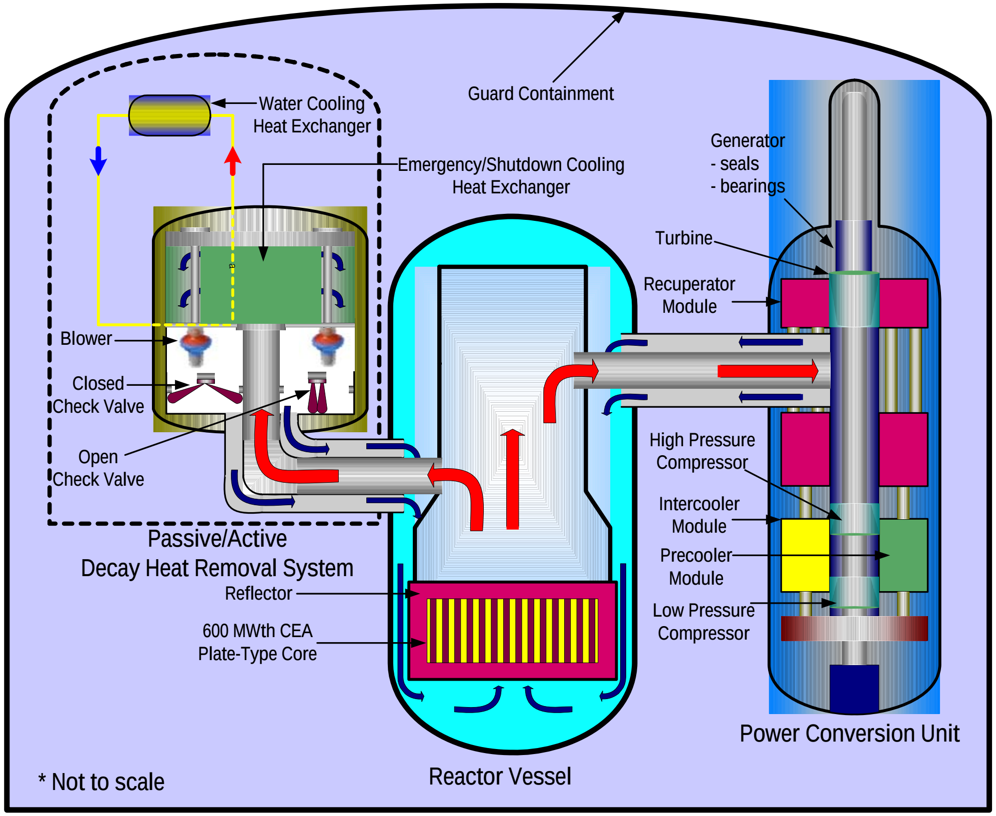
Thermal/net efficiency =51%/ 48%



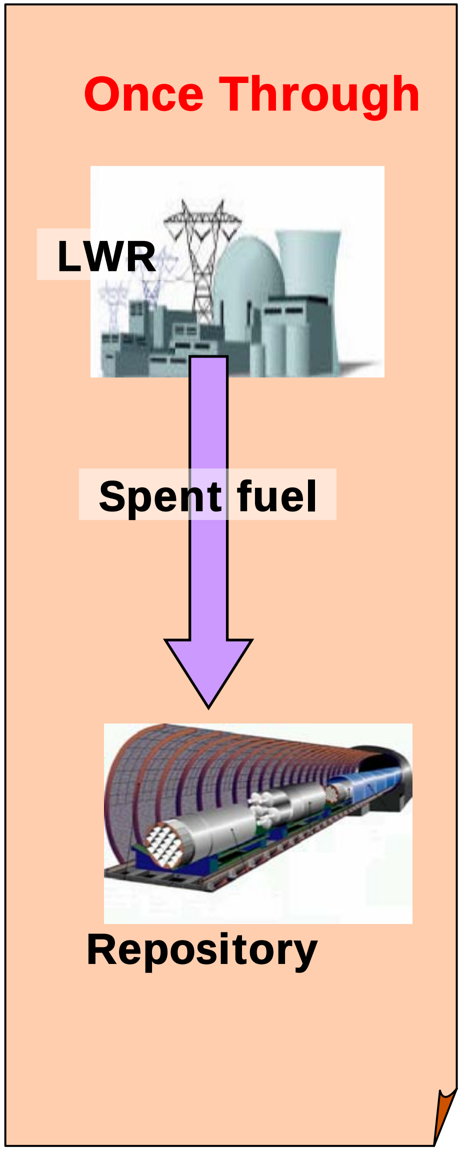


Gas Cooled Fast Reactor for Gen IV Service

- Strives to achieve Gen IV goals – sustainability, safety and economics
- Allows management of transuranics from LWR spent fuel
- Uses combination of active and passive decay heat removal systems (passive based on natural circulation at elevated pressure)
- Direct, highly efficient S-CO2 cycle
- Innovative tube-in-duct fuel assemblies with vibropack (U,TRU)O2 fuel
- Large power rating (1200MWe)
- Breed &Burn core, which does not require reprocessing possible



Fuel Cycle Options

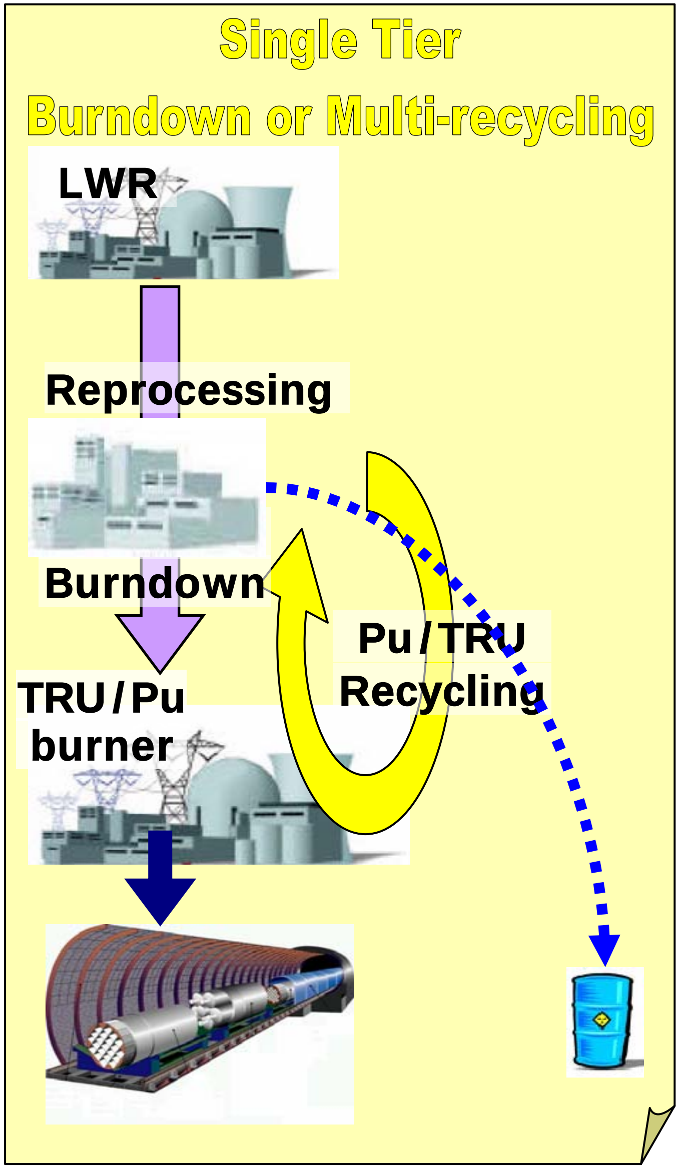


Once Through

LWR

Spent fuel

Repository



Single Tier

Burndown or Multi-recycling

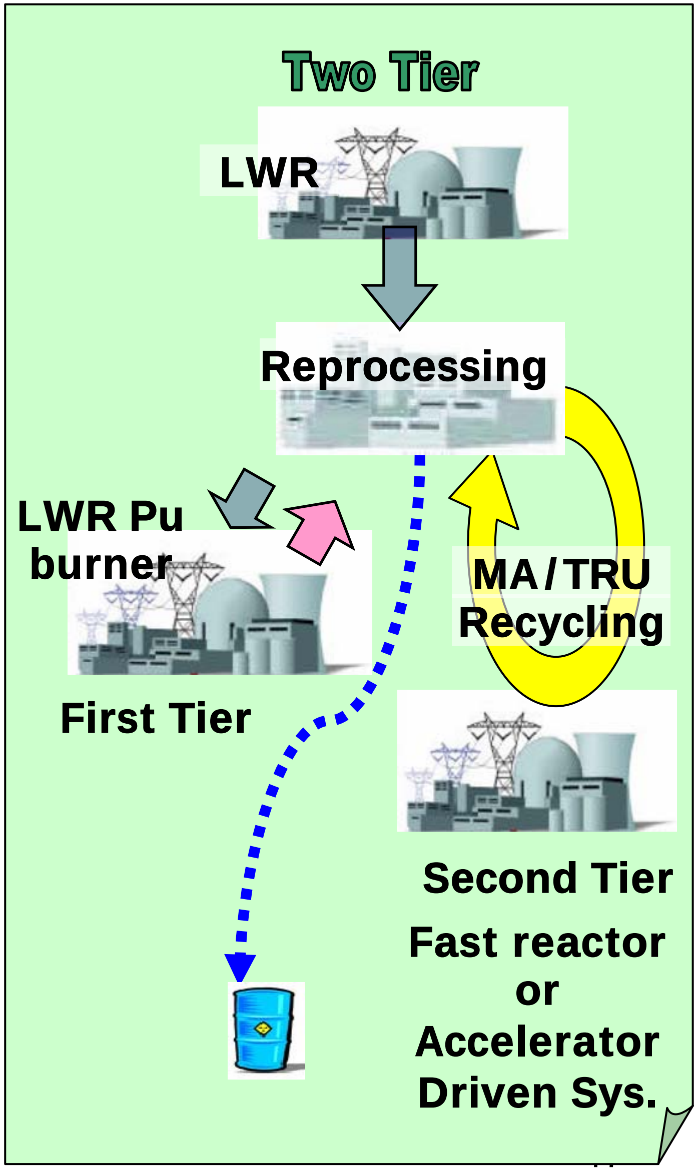
LWR

Reprocessing

Burndown

TRU / Pu burner

Pu / TRU Recycling



Two Tier

LWR

Reprocessing

LWR Pu burner

First Tier

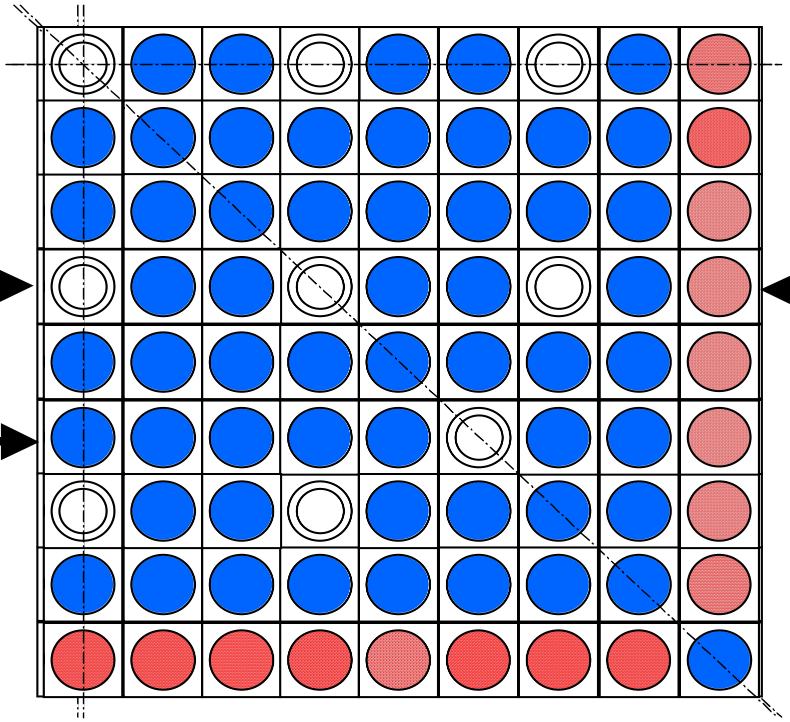
MA / TRU Recycling

Second Tier

Fast reactor or Accelerator Driven Sys.

The CONFU Assembly Concept

Combined Non-Fertile and UO$_2$ Assembly



Guide Tubes

UO$_2$ Pins

4.2% Enrichment

Fertile Free Pins:

70 v/o – Spinel (MgAl$_2$O$_4$)

18 v/o – YSZ

12 v/o – (TRU) O$_2$

Total 13.2 kg of TRU/assembly

- *Multi-recycling of all transuranics (TRU) in fertile free pins leads to zero net TRU generation*
- *Preserves the cycle length, neutronic control and safety features of all uranium cores*

Courtesy of Shwageraus, E. Used with permission.

“Optimization of the LWR Nuclear Fuel Cycle for Minimum Waste Production” E. Shwageraus, M.S. Kazimi and P. Hejzlar, CANES, MIT (2003)

Risk Informed Design, Safety and Licensing

- Use PRA principles in design of CO2 gas reactor – avoid problems
- Technology neutral risk informed safety standards
- “License by test” regulatory approach for innovative reactors

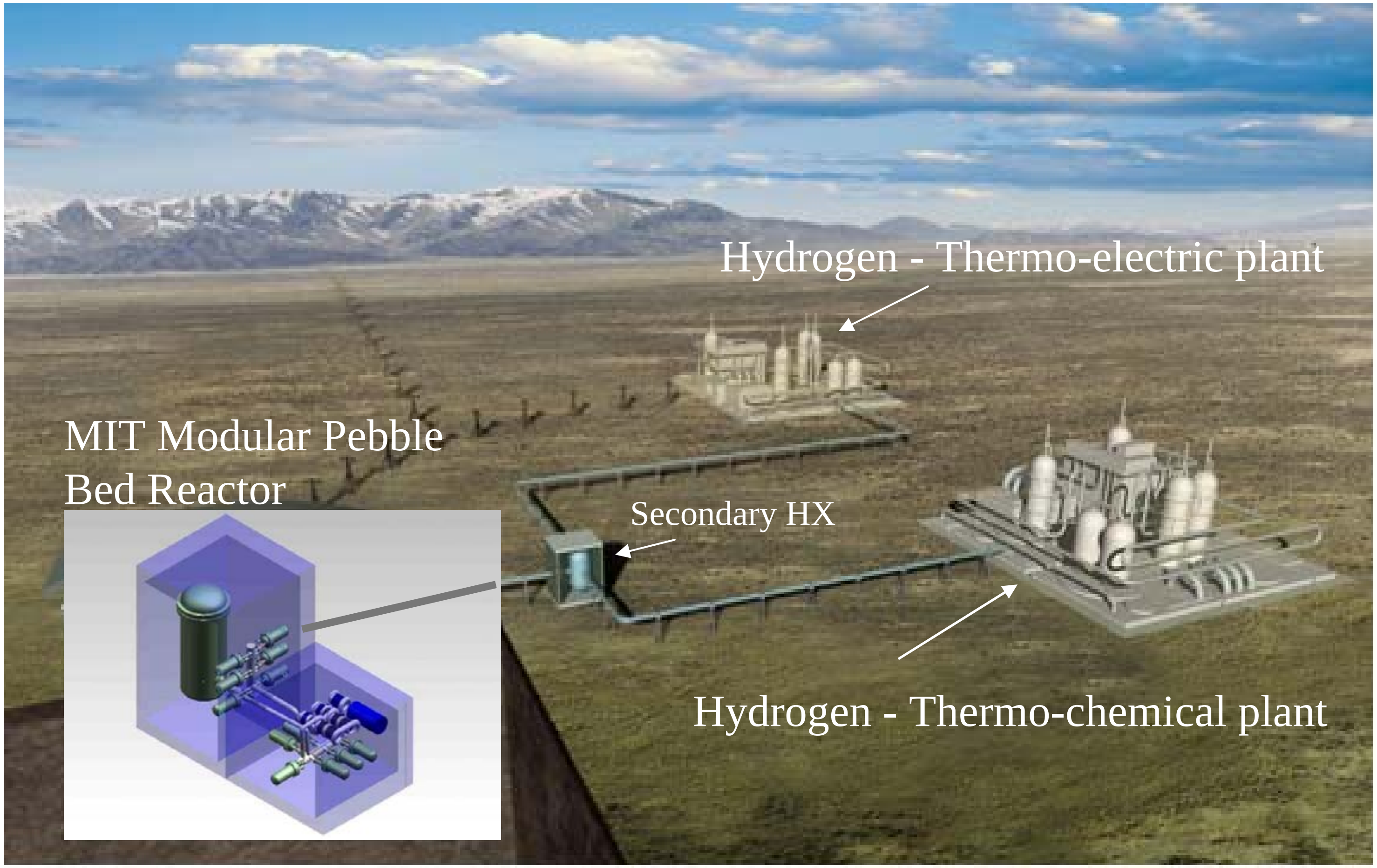
The “Next” Generation

- Next Generation Nuclear Plant (NGNP)
- Nuclear Hydrogen Production
- Pebble Bed Reactors – High Temperature Gas
- Risk Informed Design, Safety and Licensing

Next Generation Nuclear Plant

- High Temperature Gas
- Indirect Cycle
- Electric generation
- Hydrogen production
- Pebble bed reactor or block reactor?
- Built at the Idaho National Laboratory

Next Generation Nuclear Plant



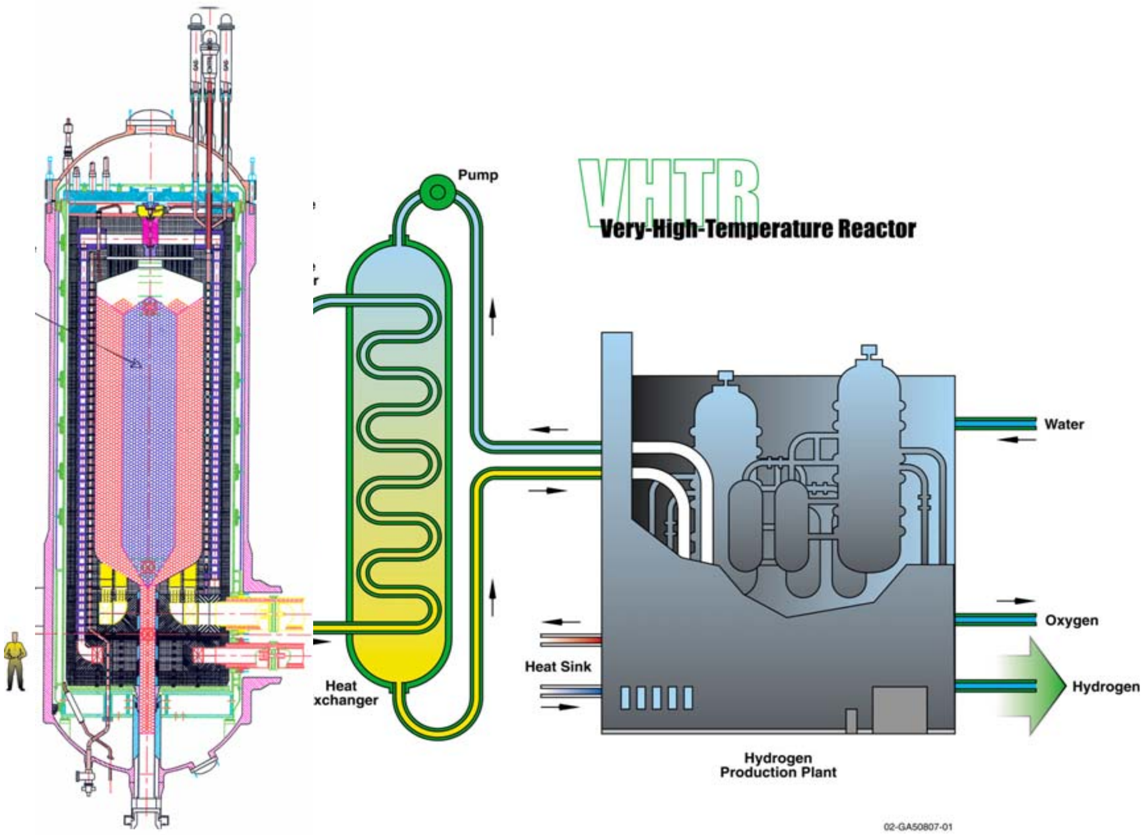
Very-High-Temperature Reactor (VHTR)

Characteristics

- ***Helium coolant***
- ***1000°C outlet temperature***
- ***Water-cracking cycle***

Benefits

- ***Hydrogen production***
- ***High degree of passive safety***
- ***High thermal efficiency***
- ***Process heat applications***



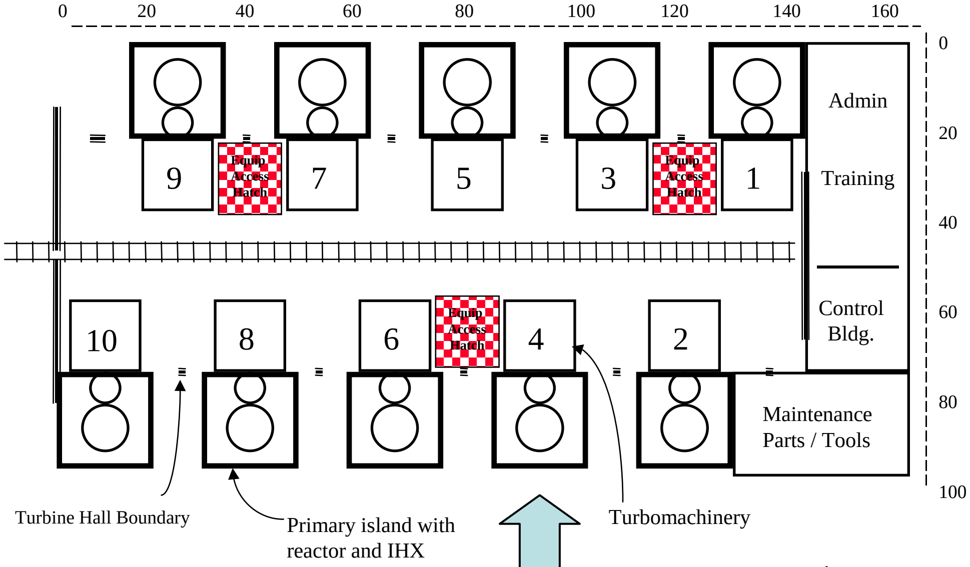
U.S. Product Team Leader: Dr. Finis Southworth (INEEL)

1150 MW Combined Heat and Power Station

VHTR Characteristics
- Temperatures > 900 C
- Indirect Cycle
- Core Options Available
- Waste Minimization

Ten-Unit VHTR Plant Layout (Top View)

(distances in meters)



Oil Refinery

Hydrogen Production

Desalinization Plant

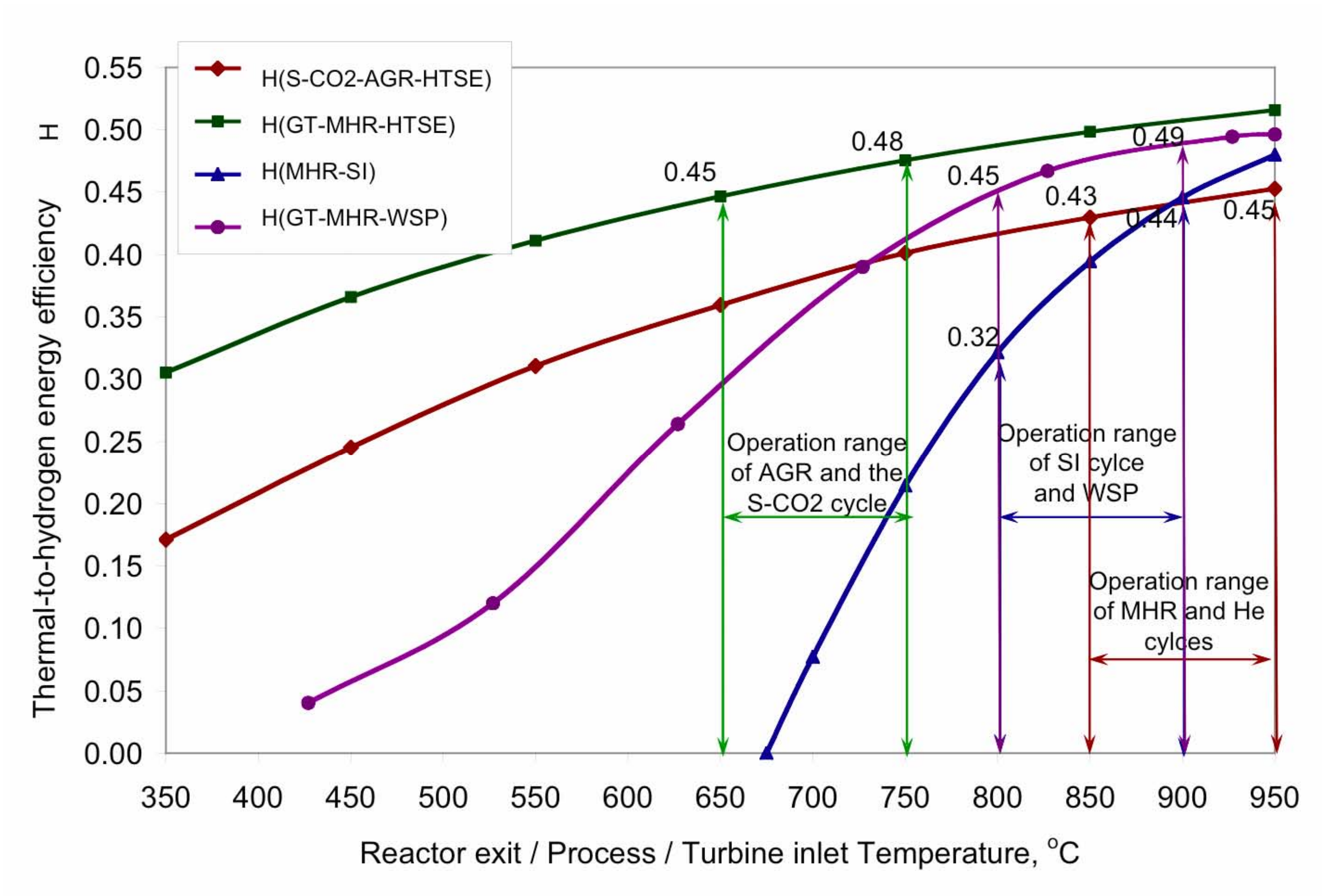
Overview of the efficiency of nuclear hydrogen production options

- The hydrogen production efficiency =
  LHV for gaseous product/thermal energy of fission reactors
- Deviation from ideal efficiency values can be due to:
  - heat losses
  - irreversibilities in the components
- Final comparison should take the same conditions into account

Approach	**Electrochemical**		**Thermochemical**	
Feature	**Water Electrolysis**	**High Temperature Steam Electrolysis**	**Steam-Methane Reforming**	**Thermochemical Water Splitting**
Required temperature, ^{o}C	< 100, at P_{atm}	>100, at P_{atm}	> 700	> 800 for S-I WSP > 700 for UT-3 > 600 for Cu-Cl
Efficiency of the process, %	65 – 80	65-95 (200>T>800 ^{0}C)	60-80 (T>700^{0}C)	> ~40, depending on TC cycle and temperature
Energy efficiency coupled to LWR, %	21-30	~30	Not Feasible	Not Feasible
Energy efficiency coupled to MHR, ALWR, ATHR, or S-AGR, %	21-40	35-45 (Depending on electrical cycle and temperature)	> 60 (T>700^{0}C)	>~ 40, depending on TC cycle and temperature

Hydrogen Production Energy Efficiency

Comparison of the thermal-to-hydrogen efficiency of the HTSE, SI and WSP related technologies as a function of temperature



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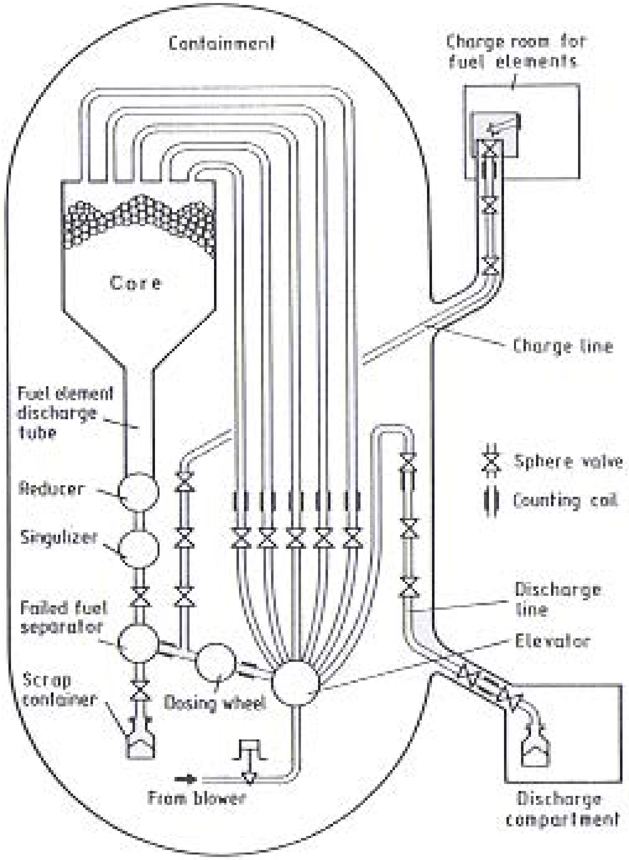
Pebble Bed Reactor Research

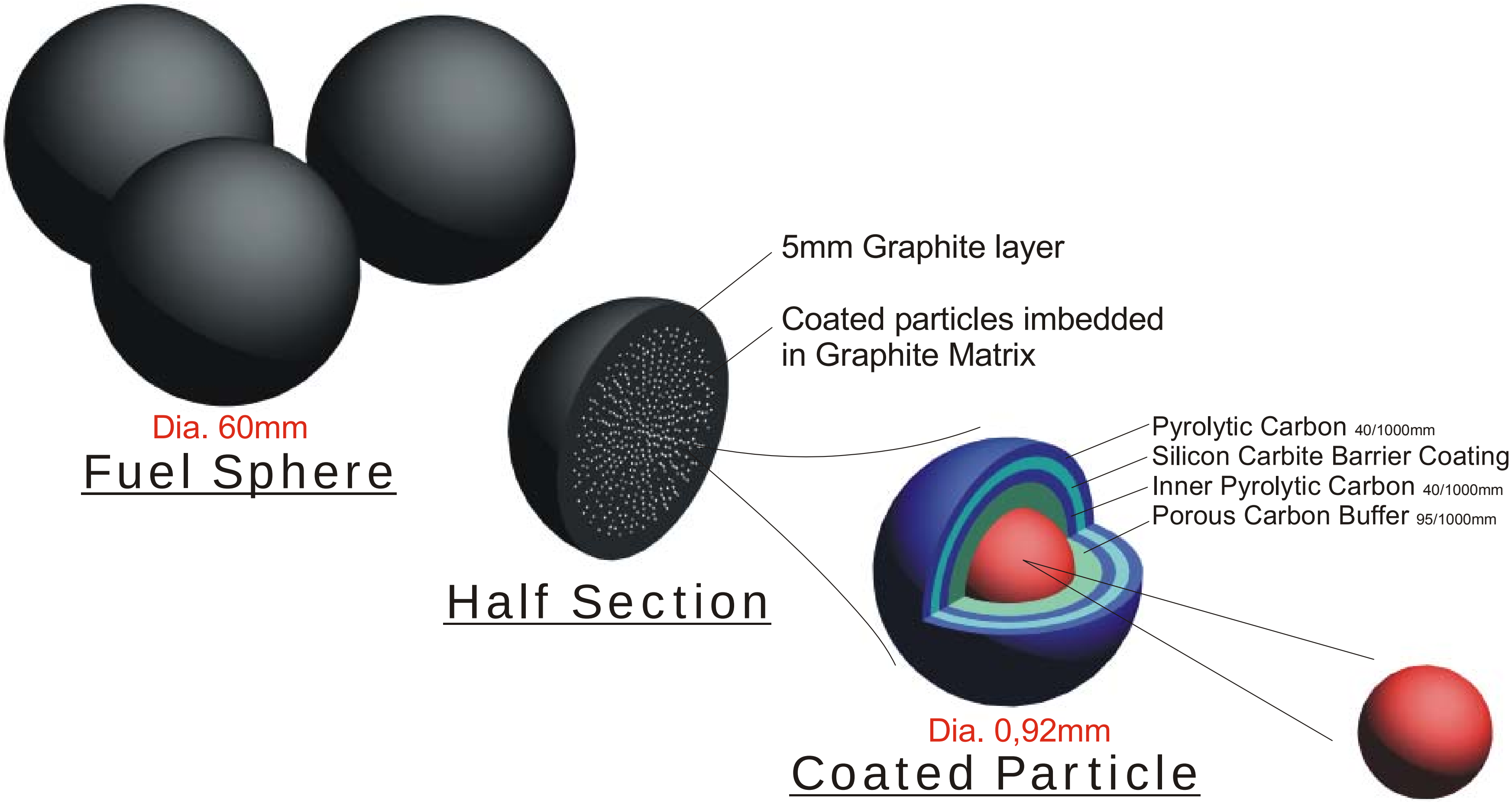
- Reactor physics modeling of core - MCNP
- Fuel performance model
- Safety analysis – LOCA and Air Ingress with CFD tools
- Pebble Flow modeling and experiments
- Balance of plant modularity – “lego style”
- Overall plant conceptual design
- Non-proliferation studies
- Waste disposal studies
- Intermediate Heat Exchanger design and testing

What is a Pebble Bed Reactor ?



- 360,000 pebbles in core
- about 3,000 pebbles handled by FHS each day
- about 350 discarded daily
- one pebble discharged every 30 seconds
- average pebble cycles through core 10 times
- Fuel handling most maintenance-intensive part of plant

FUEL ELEMENT DESIGN FOR PBMR



Dia. 60mm

Fuel Sphere

5mm Graphite layer

Coated particles imbedded
in Graphite Matrix

Half Section

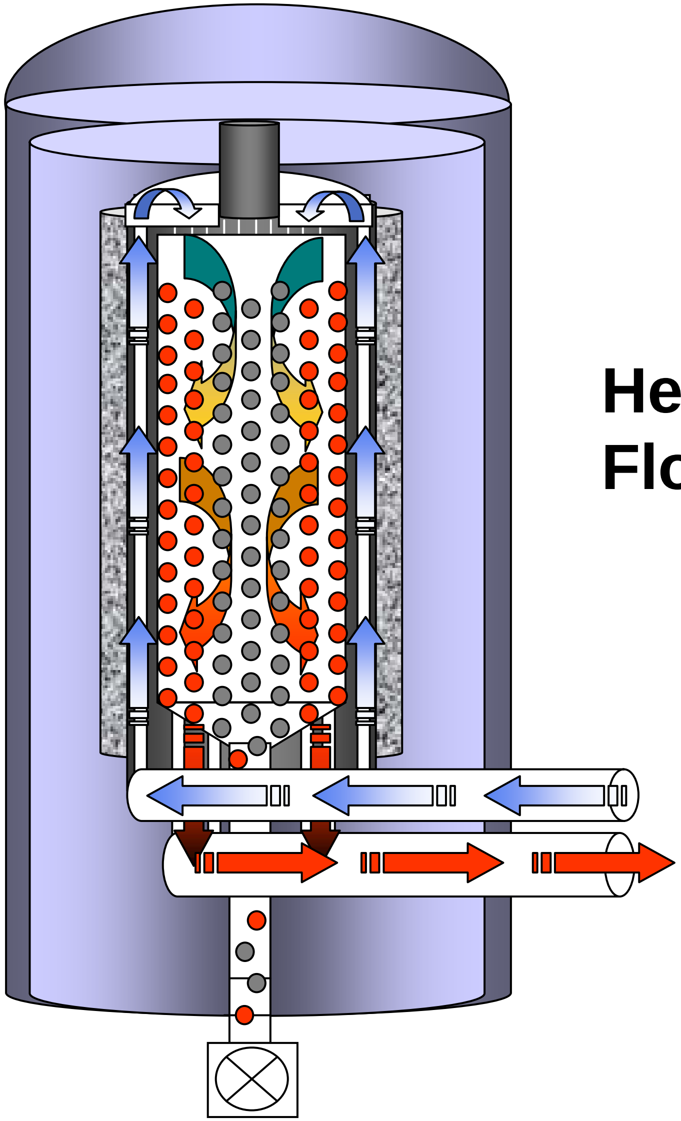
Pyrolytic Carbon 40/1000mm
Silicon Carbite Barrier Coating 35/1000
Inner Pyrolytic Carbon 40/1000mm
Porous Carbon Buffer 95/1000mm

Dia. 0,92mm

Coated Particle

Dia.0,5mm
Uranium Dioxide
Fuel

Reactor Unit



Helium Flowpath

AVR: Jülich

15 MWe Research Reactor

HTR- 10 China
First Criticality Dec.1, 2000

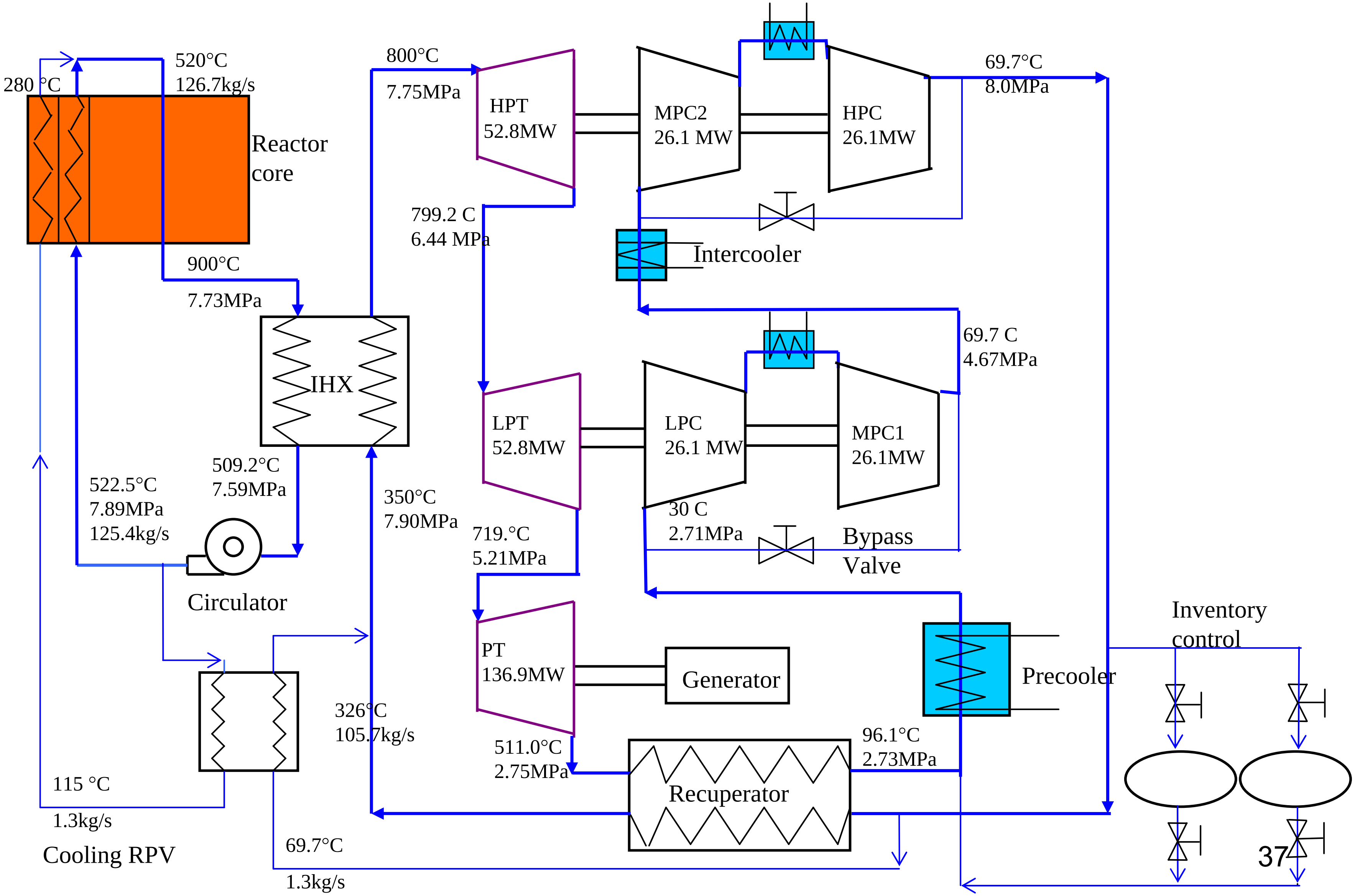
China - Rongcheng Site for 19 Pebble Bed Reactors for 3600 Mwe @ 190 Mwe each

Demonstration Plant

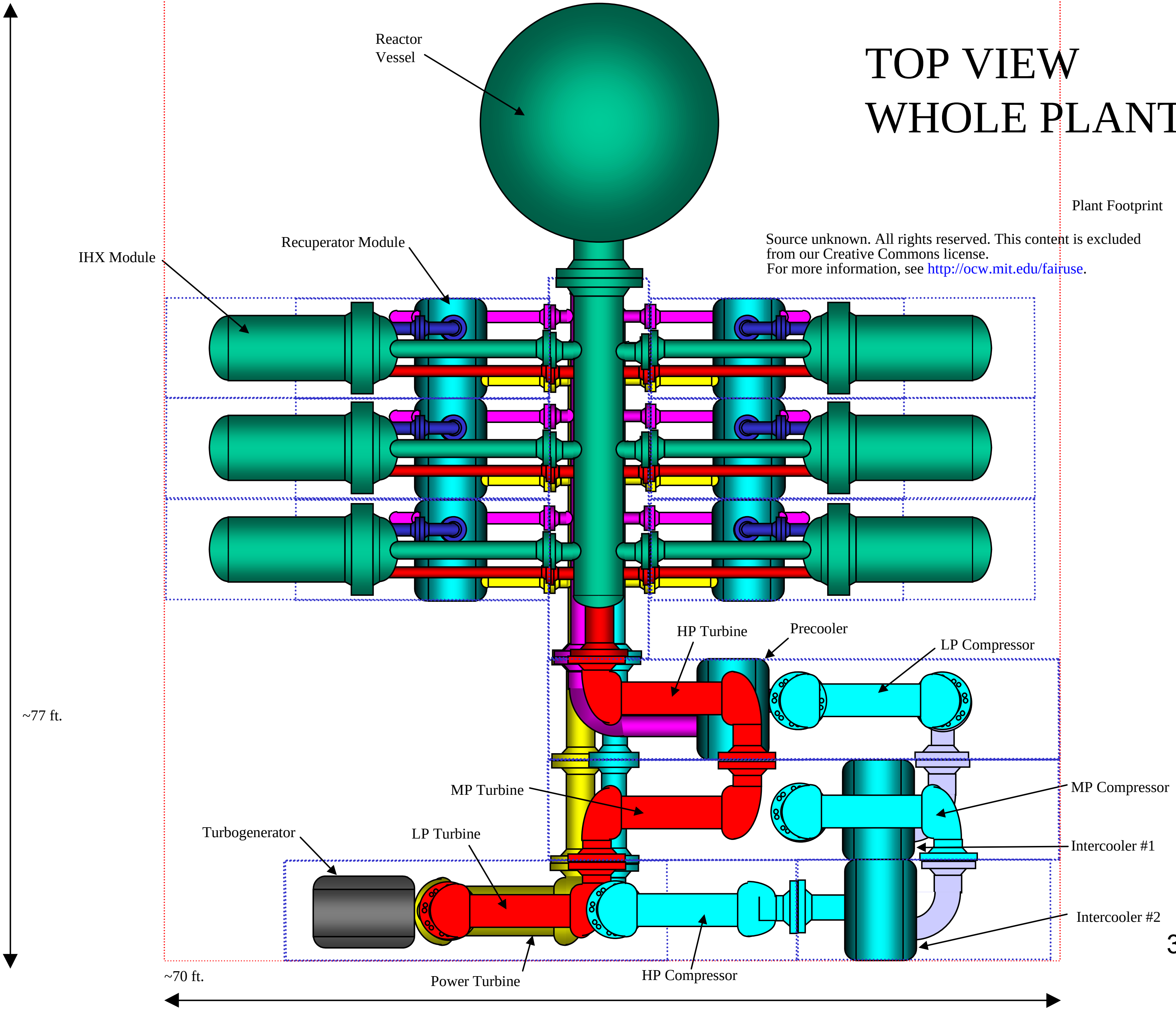
Features of MIT MPBR Design

Thermal Power	250 MW
Gross Electrical Power	132.5 MW
Net Electrical Power	120.3 MW
Plant Net Efficiency	48.1% (Not take into account cooling IHX and HPT. if considering, it is believed > 45%)
Helium Mass flowrate	126.7 kg/s
Core Outlet/Inlet T	900°C/520°C
Cycle pressure ratio	2.96
Power conversion unit	Three-shaft Arrangement

Current Design Schematic



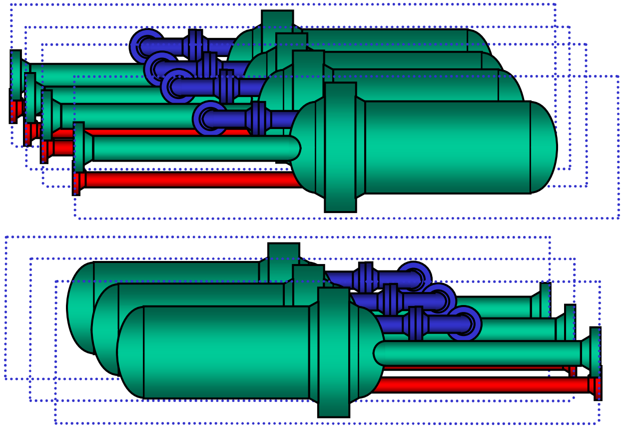
TOP VIEW
WHOLE PLANT



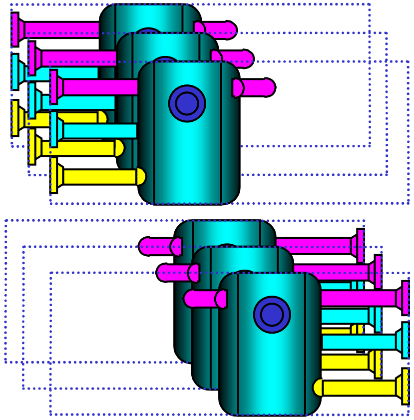
PLANT MODULE SHIPPING BREAKDOWN

Total Modules Needed For Plant Assembly (21): Nine 8x30 Modules, Five 8x40 Modules, Seven 8x20 Modules

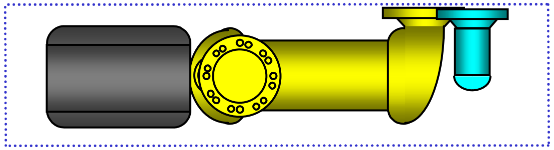
Six 8x30 IHX Modules



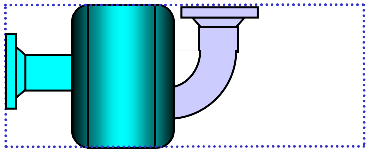
Six 8x20 Recuperator Modules



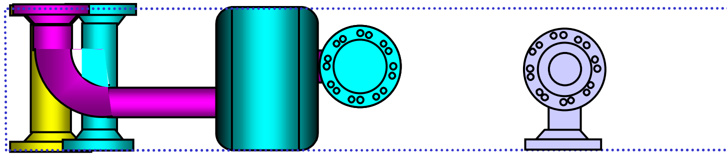
8x30 Power Turbine Module



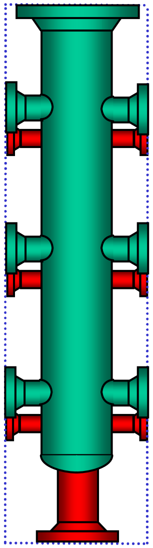
8x20 Intercooler #2 Module



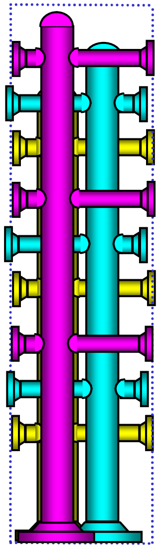
8x40 Piping and Precooler Module



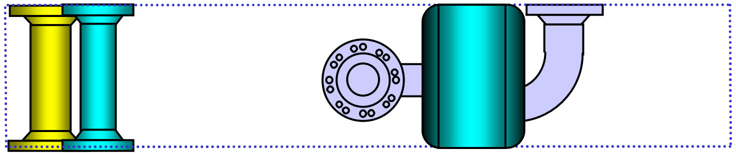
8x30 Upper Manifold Module



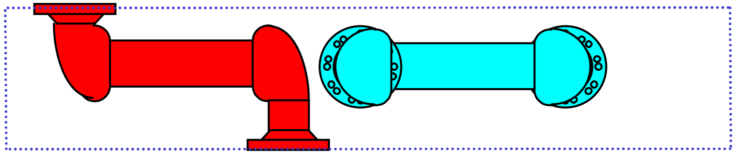
8x30 Lower Manifold Module



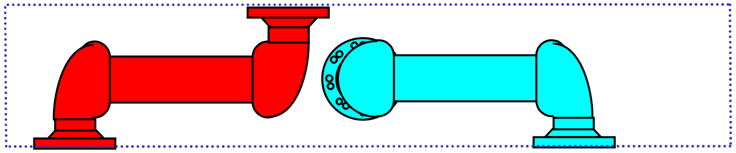
8x40 Piping & Intercooler #1 Module



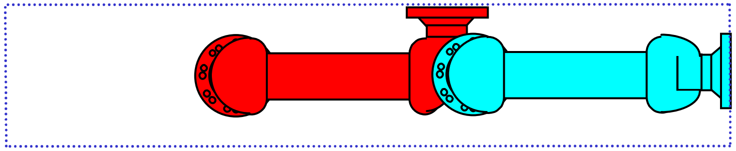
8x40 HP Turbine, LP Compressor Module



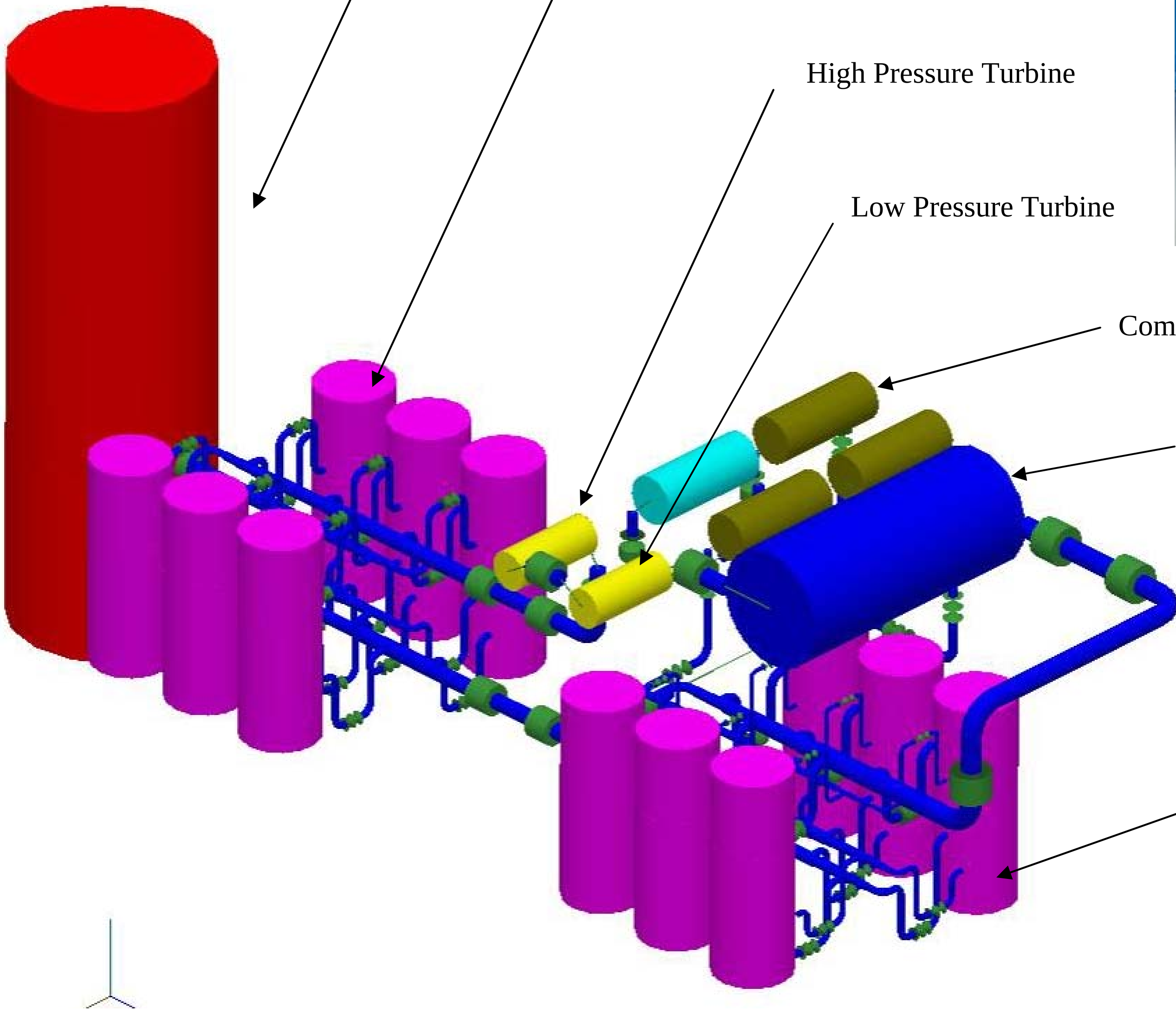
8x40 MP Turbine, MP Compressor Module



8x40 LP Turbine, HP Compressor Module



Present Layout



Reactor Vessel

IHX Vessel

High Pressure Turbine

Low Pressure Turbine

Compressor (4)

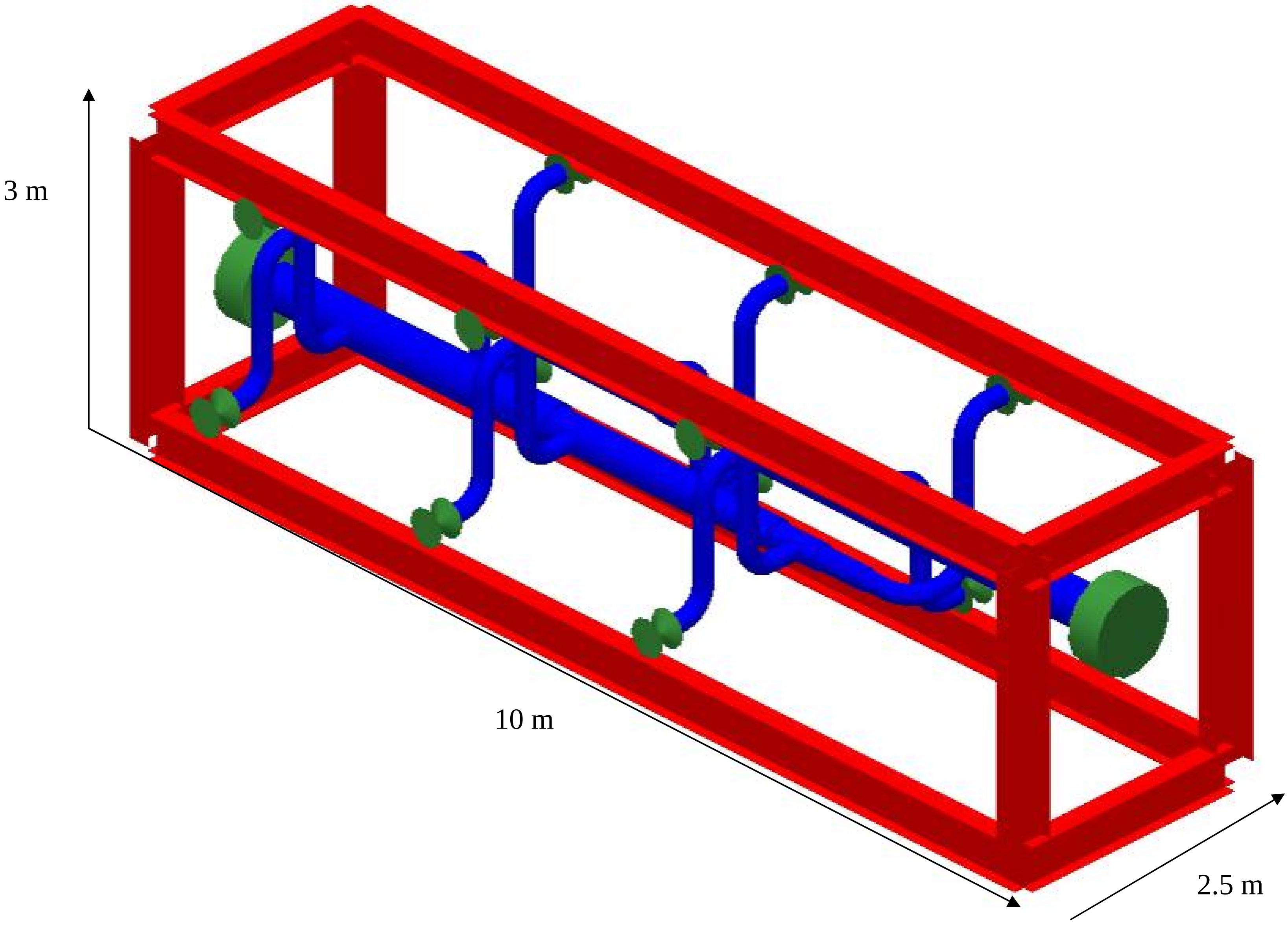
Power Turbine

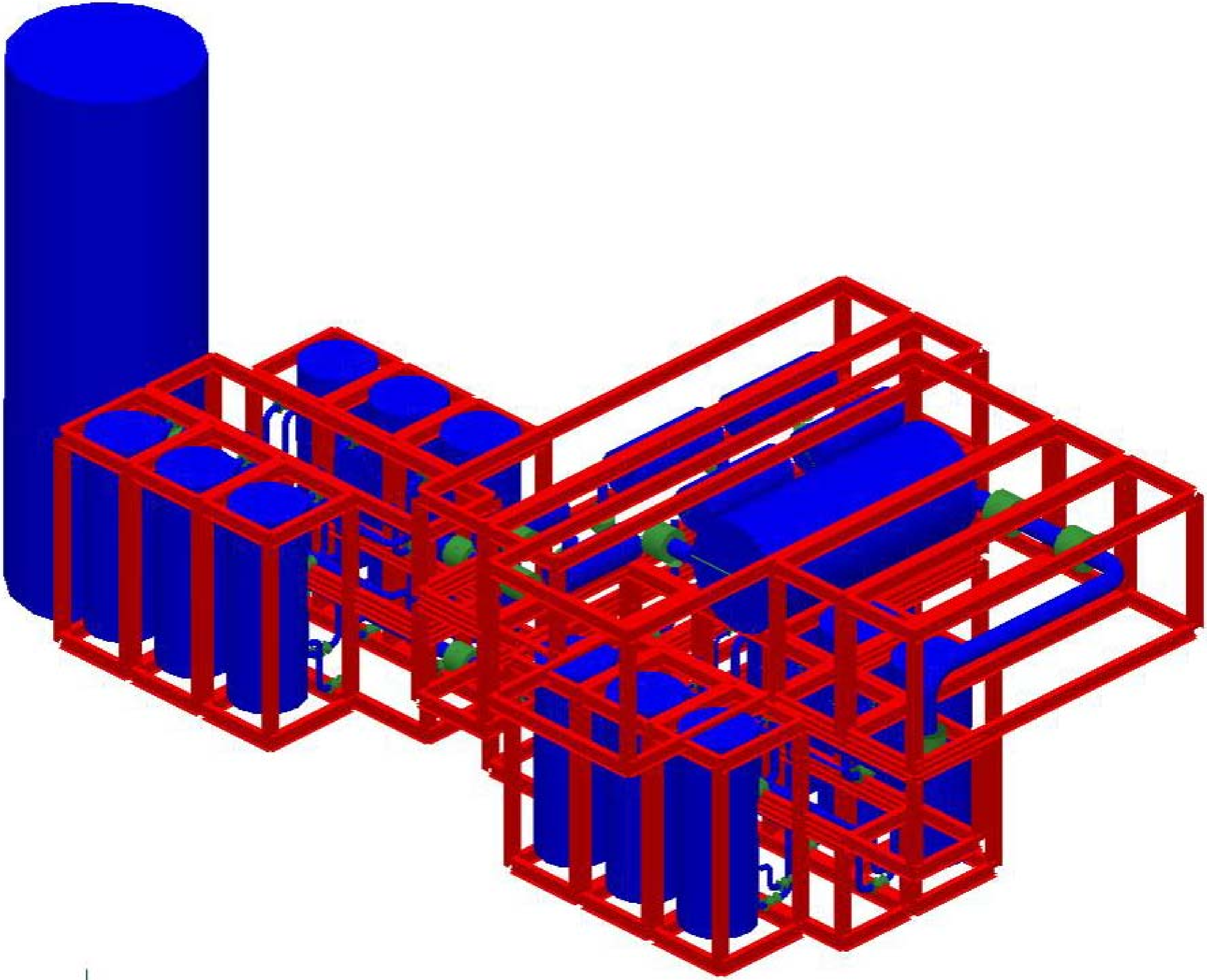
Recuperator Vessel

Space-Frame Concept

- Standardized Frame Size
- 2.4 x 2.6 x 3(n) Meter
- Standard Dry Cargo Container
- Attempt to Limit Module Mass to ~30t / 6m
  - ISO Limit for 6m Container
  - Stacking Load Limit ~190t
  - ISO Container Mass ~2200kg
  - Modified Design for Higher Capacity—~60t / 12m module
- Overweight Modules
  - Generator (150-200t)
  - Turbo-Compressor (45t)
  - Avoid Separating Shafts!
  - Heavy Lift Handling Required
  - Dual Module (12m / 60t)
- Stacking Load Limit Acceptable
  - Dual Module = ~380T
    - Turbo-generator Module <300t
- Design Frame for Cantilever Loads
  - Enables Modules to be Bridged
- Space Frames are the structural supports for the components.
- Only need to build open vault areas for space frame installation - RC & BOP vault
- Alignment Pins on Module Corners
  - High Accuracy Alignment
  - Enables Flanges to be Simply Bolted Together
- Standardized Umbilical Locations
  - Bus-Layout of Generic Utilities (data/control)

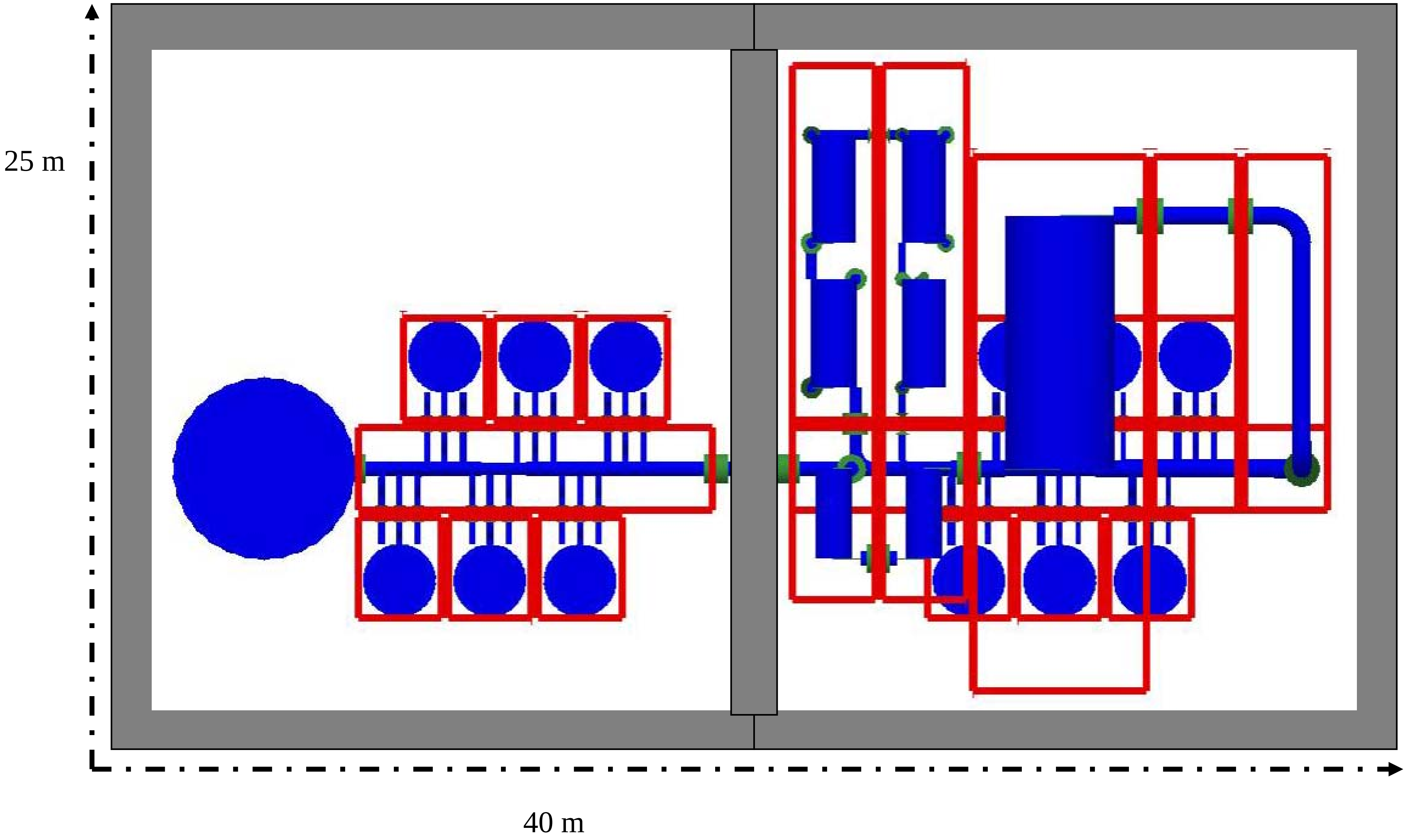
Upper IHX Manifold in Spaceframe



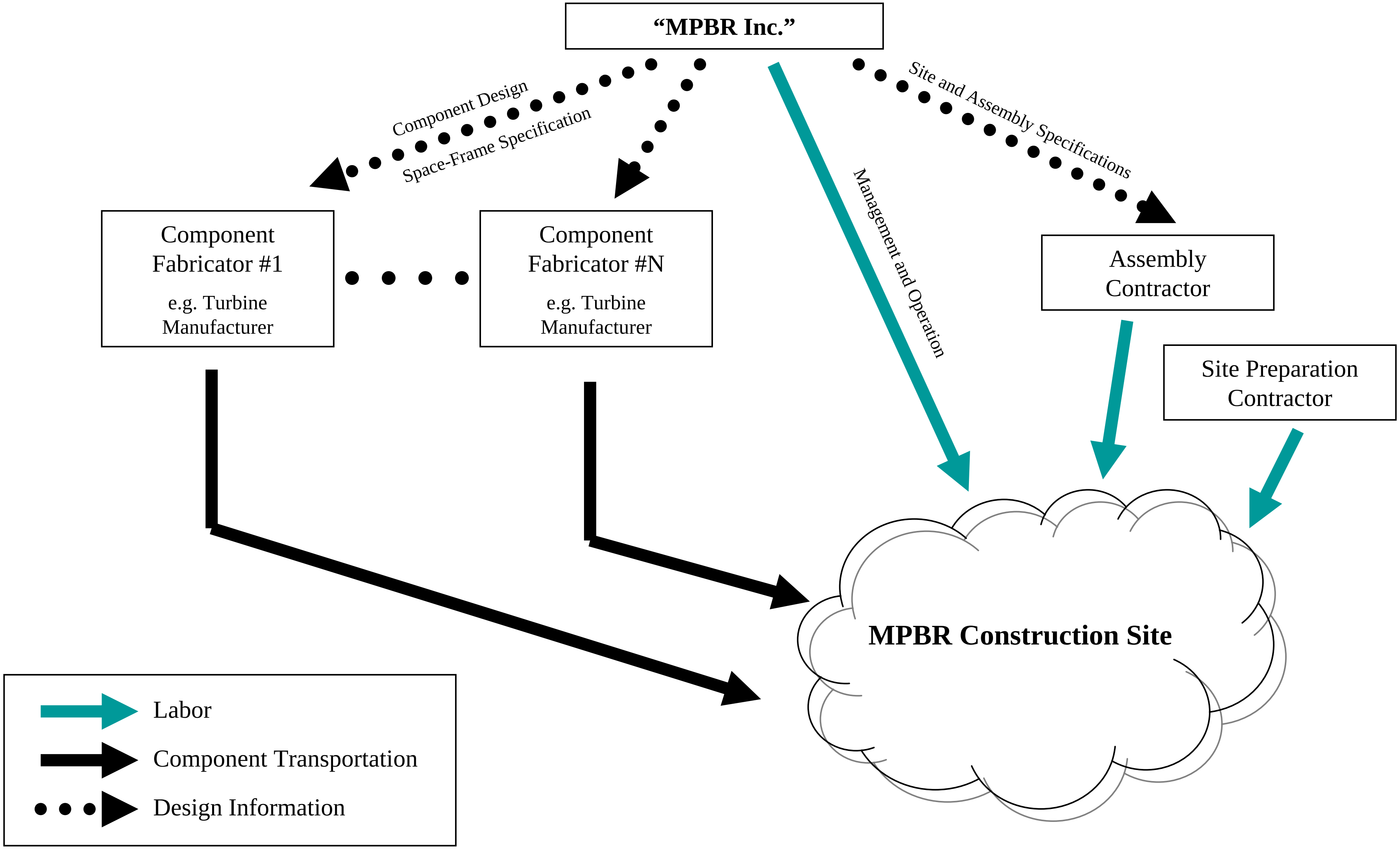


"Lego" Style Assembly in the Field

Overall Structure



Distributed Production Concept



"MPBR Inc."

Component Design

Space-Frame Specification

Site and Assembly Specifications

Management and Operation

Component Fabricator #1

e.g. Turbine Manufacturer

Component Fabricator #N

e.g. Turbine Manufacturer

Assembly Contractor

Site Preparation Contractor

MPBR Construction Site

Labor

Component Transportation

Design Information

Distributed Production Concept - Virtual Factory !

- Evolution of the "Reactor Factory" Concept
- There Is ***NO*** Factory
  - Off-load Manufacturing Capital Expense to Component Suppliers
    - Decrease follow-through capital expense by designing to minimize new tooling—near COTS
    - Major component fabricators become mid-level integrators—following design delivered from HQ
  - Reduces Transportation Costs
    - Component weight ≈ Module weight: Why Transport It Twice?
  - Enables Flexible Capitalization
    - Initial systems use components purchased on a one-off / low quantity basis
    - Once MPBR demand established, constant production + fabrication learning curve lower costs

- Site / Building Design Does Not Require Specialized Expertise
  - Enables Selection of Construction Contractors By Location / Cost
  - Simplified Fabrication Minimizes “MPBR Inc.” Workforce Required

- Simple Common Space-Frame Design
  - Can be Easily Manufactured By Each Individual Component Supplier
  - Or if necessary sub-contracted to generic structural fabricator

- Modern CAD/CAE Techniques Enable High First-Fit Probability—Virtual “Test-Fit”

Challenges

- Unless the cost of new plants can be substantially reduced, new orders will not be forthcoming.
- The novel truly modular way of building plants may be the right way to go – shorter construction times.
- Smaller units may be cheaper than larger units – economies of production may trump the economies of scale when financial risks are considered.
- The bottom line is cents/kwhr not $/kwe !!

Why Helium Gas? Why Now? Differences Between Water Reactors

- Higher Thermal Efficiencies Possible
- Helium inert gas
- Minimizes use of water in cycle - corrosion
- Single Phase coolant – fewer problems in accident
- Utilizes gas turbine technology
- Lower Power Density – no meltdown !
- Less Complicated Design (No Emergency Core Cooling Systems Needed)
- ***Lower cost electricity***

Generating Cost

PBMR vs. AP600, AP1000, CCGT and Coal

(Comparison at 11% IRR for Nuclear Options, 9% for Coal and CCGT[1])

(All in ¢/kWh)		AP1000 @			Coal[2]		CCGT @ Nat. Gas = [3]			
	AP600	3000Th	3400Th	PBMR	'Clean'	'Normal'	$3.00	$3.50	$4.00	$10.00
Fuel	0.5	0.5	0.5	0.48	0.6	0.6	2.1	2.45	2.8	7.0
O&M	0.8	0.52	0.46	0.23	0.8	0.6	0.25	0.25	0.25	0.25
Decommissioning	0.1	0.1	0.1	0.08	-	-	-	-	-	
Fuel Cycle	0.1	0.1	0.1	0.1	-	-	-	-	-	
Total Op Costs	1.5	1.22	1.16	0.89	1.4	1.2	2.35	2.70	3.05	7.25
Capital Recovery	3.4	2.5	2.1	2.2	2.0	1.5	1.0	1.0	1.0	1.0
Total	4.9	3.72	3.26	3.09	3.4	2.7	3.35	3.70	4.05	8.75

[1] All options exclude property taxes

[2] Preliminary best case coal options: "mine mouth" location with $20/ton coal, 90% capacity factor & 10,000 BTU/kWh heat rate

[3] Natural gas price in $/million Btu

Pebble Power Applications

- Electricity – Direct or Indirect Cycle
  - high temperature gas turbine
  - steam cycle using steam generators
- Process Heat
  - Hydrogen – high temperature thermo-chemical process
  - Desalinization – bottoming cycle
- Electricity and Process Heat
  - Oil Sands
  - Oil Shale
  - Hydrogen – High Temperature Steam Electrolysis
  - Oil Production and Refining
  - Coal – Gasification and Liquifaction
- Drivers for nuclear are CO2 and Economics

Syncrude Plant Site in Alberta

Image Courtesy of Syncrude

Summary

Main strategic research lines in fission:

1) *Improve LWR economics*

2) *Develop NGNP Plant with Hydrogen Production*

2) *Develop Gen-IV systems*

3) *Improve nuclear fuel cycle*

4) *Global Nuclear Energy Partnership*

Fast Neutron Reactors that "burn" waste and breed fuel – design course objective

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