

ITM Oxygen: The New Oxygen Supply for the New IGCC Market

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Ion Transport Membranes Will Significantly Impact Our Environment and Other National Interests Including Energy Security

ITM Oxygen

- **Power Generation Through Coal Gasification (IGCC)**
- **Hydrogen from Coal**
- **Oxygen Enrichment of Coal Combustion**

ITM Syngas/H₂

- **Hydrogen from Natural Gas**
- **Production of Environmentally Superior Transportation Fuels**

ITM SEOS

- **Military Oxygen Supply**
- **Controlled Environments**
- **Commercial Introduction Now**



FutureGen is One of Many Examples

Three Disruptive Technologies With Broad Applications

ITM SEOS

ITM Oxygen

ITM Syngas

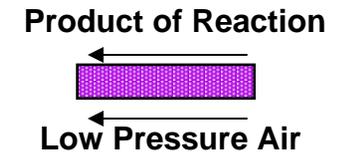
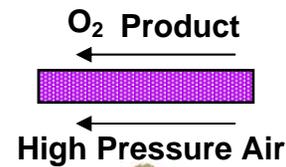
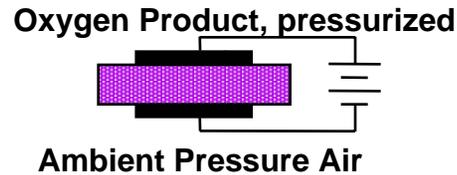
Our Driver

Pt. of use O₂/High Purity
25-60+% Cost Reduction

30+% Capital Reduction
35+% Power Reduction

30+% Capital Reduction

Fundamentals



Planar Membrane Design Status



3 liter/min



0.5 T/D



1 KSCFD Syngas

Current Level of Prototypes



5 liter/min



5 T/D



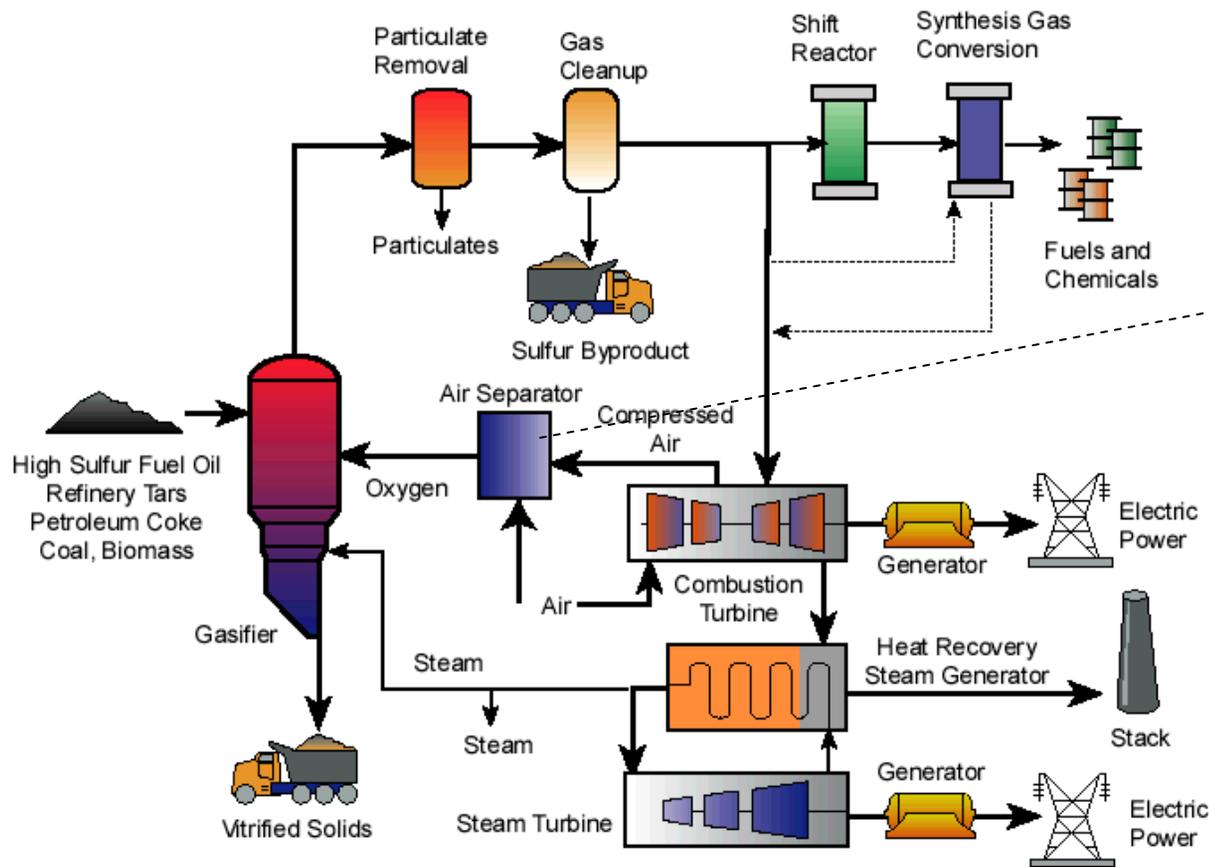
24 KSCFD Throughput

AIR PRODUCTS

Air Products' ITM Program

- **Ion Transport Membranes (ITM)**
 - **Extremely selective and very fast transport for oxygen**
 - **Non-porous ceramic membranes**
 - **Multi-component metallic oxides**
 - **Operate at high temperature, typically greater than 700°C**
 - **Material formulation is complex and dependent upon application**
 - **Crystalline structure incorporates oxygen ion vacancies**
- **Started R&D in 1988**
 - **Biggest and longest single R&D program**
- **Currently ~60 US Patents and equivalents in other countries**
 - **Materials and catalysts**
 - **Membrane and module structures**
 - **Process cycles**
 - **Applications and integrations**

Cryogenic Oxygen Supply is a Central Element in Gasification Processes



(from www.gasification.org)

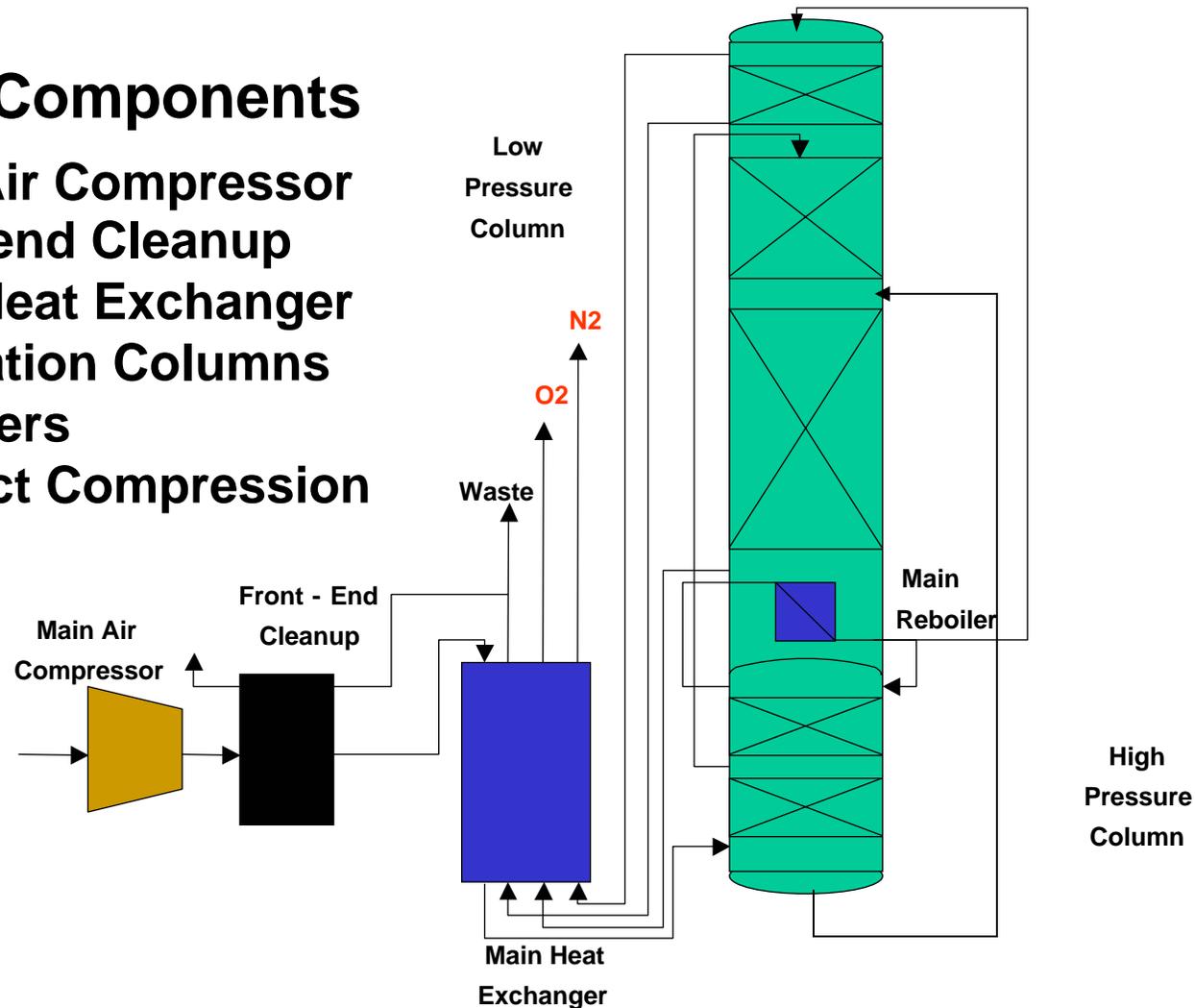


- **Mature, reliable technology**
- **Energy intensive**
- **Requires 100's of equilibrium stages**
- **Represents ~15% of an IGCC's capital cost**

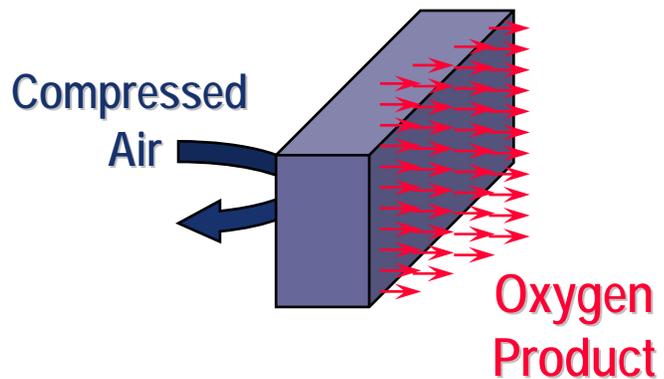
A Typical Air Separation Plant

Major Components

- Main Air Compressor
- Front-end Cleanup
- Main Heat Exchanger
- Distillation Columns
- Reboilers
- Product Compression



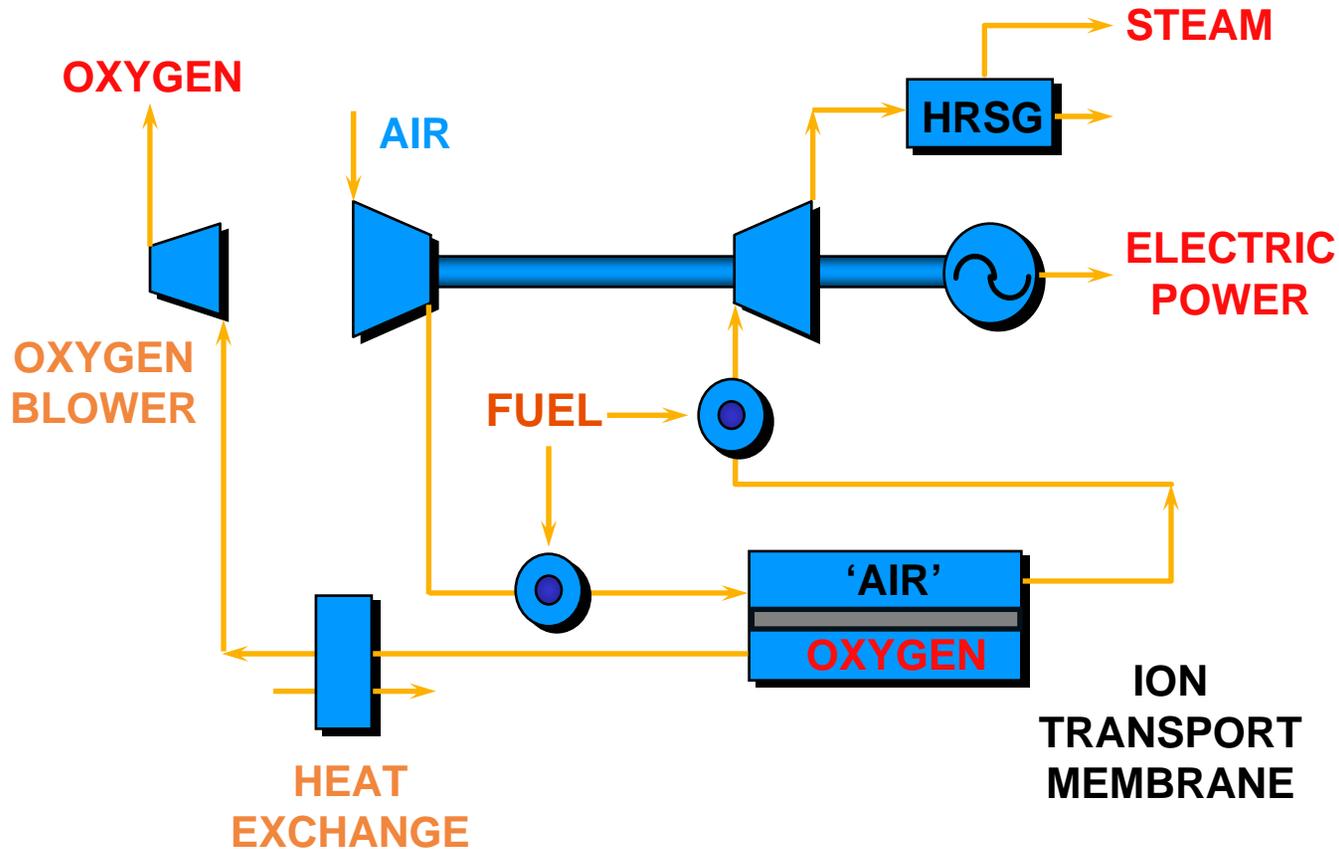
Ceramic Membranes: Revolutionary Technology for Tonnage Oxygen Supply



0.5 TPD module
(commercial-scale)

- Single-stage air separation leads to **compact** designs
- **Low pressure drop** on the high-pressure side
- **High-temperature** process has better **synergy with power generation systems**

ITM Oxygen integrates well with power generation cycles

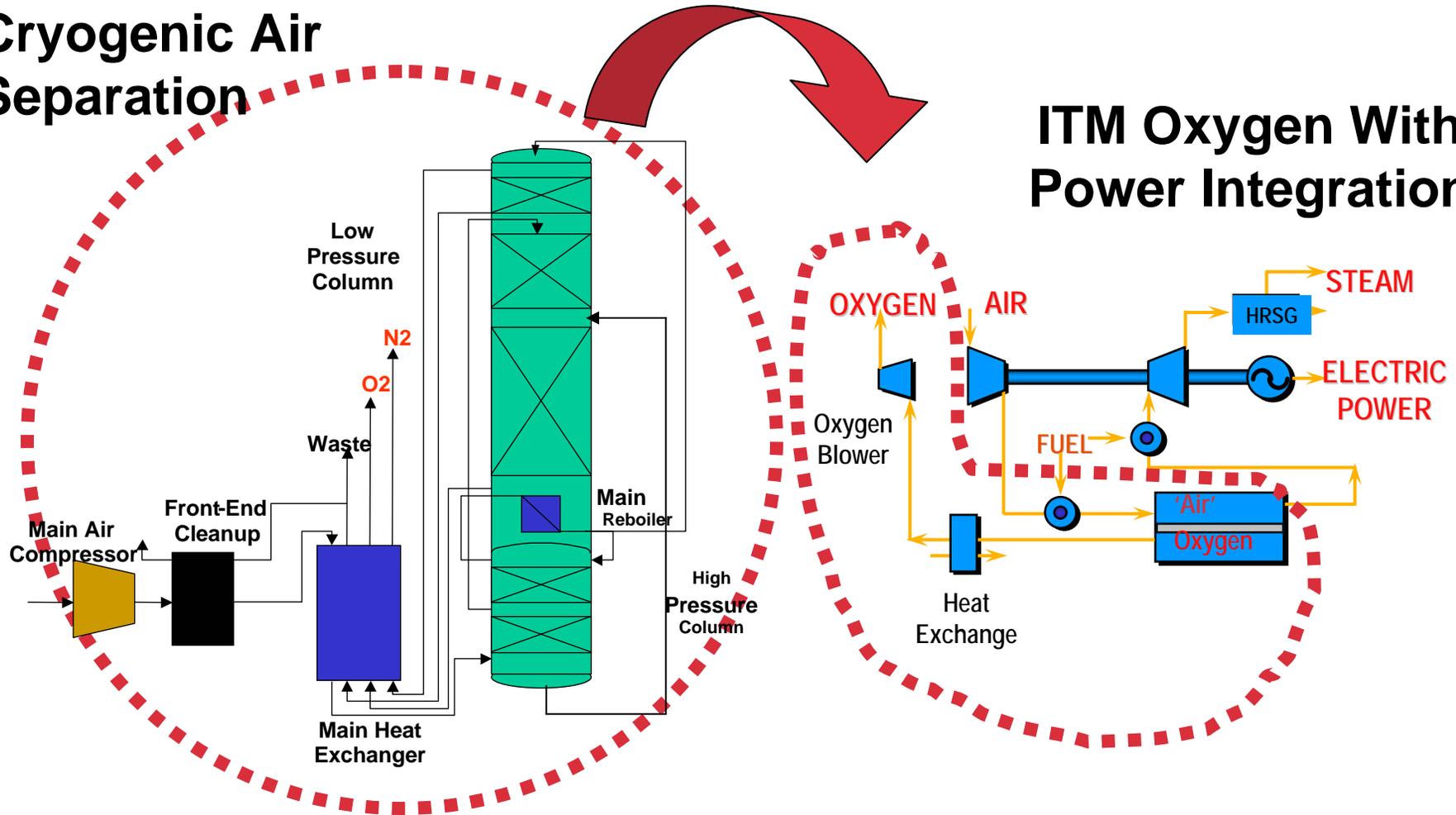


ITM Oxygen requires 35% less capital and 35-60% less energy

ITM Oxygen is Simpler and Requires Less Power

Cryogenic Air Separation

ITM Oxygen With Power Integration



- ➔ ITM O2 Has Much Simpler Flow Sheet and >35% Less Capital
- ➔ ITM O2 Has 35-60% Less Compression Energy Associated with Oxygen Separation

ITM Oxygen shows significant benefits for IGCC

- Integration with ITM Oxygen reduces specific capital cost by 7% and increases efficiency by 2%, with >35% capital and power savings in oxygen production

| | Cryo O2 | ITM O2 | Δ (%) |
|---|----------------|---------------|---------------|
| IGCC Net Efficiency (% HHV) | 39.5 | 40.4 | +2 |
| Oxygen Plant Power (kWh/ton O₂) | 235 | 147 | - 37 |
| Oxygen Plant Cost (\$/sTPD O₂) | 20,100 | 13,000 | - 35 |
| IGCC Specific Capital Cost (\$/kW) | 1094 | 1020 | - 7 |

- ITM Oxygen plant capacity 3,200 sTPD, 438 MW net power

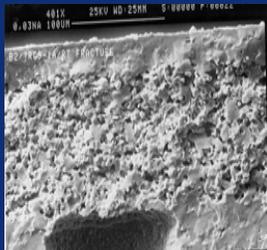
ITM Oxygen Program

- **Goal: Reduce Cost of Oxygen by One-Third**
- **DOE/Air Products R&D started 1999 (9 year, \$89 million)**
 - Phase 1: Technical Feasibility (0.1 TPD O₂)
 - Phase 2: Prototype (1-5 TPD O₂)
 - Phase 3: Pre-commercial Development (25+ TPD)
 - **Considering 150 TPD**
- **Development Team**

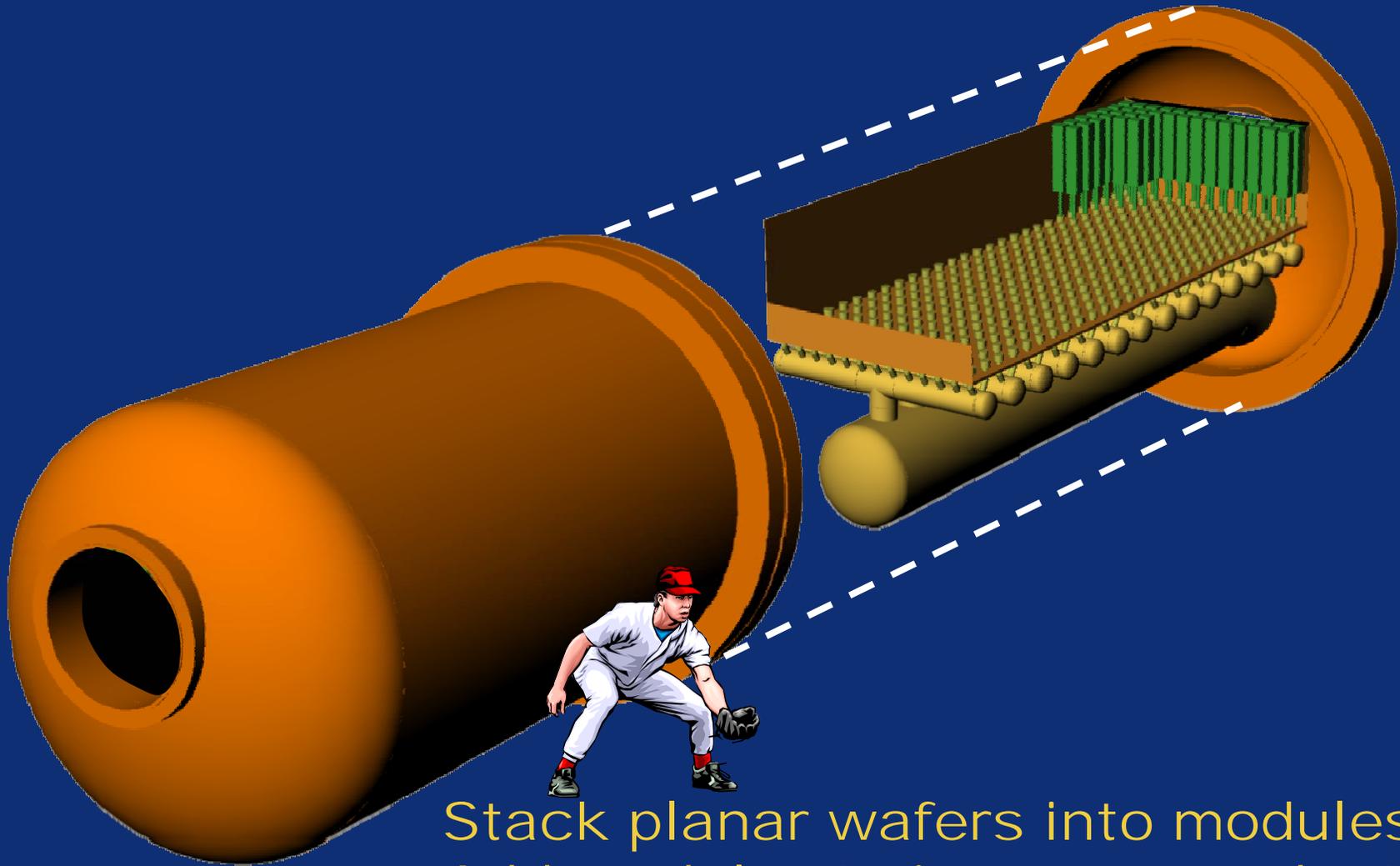


The Heart of ITM Oxygen Technology

Planar Membrane Wafer Stack



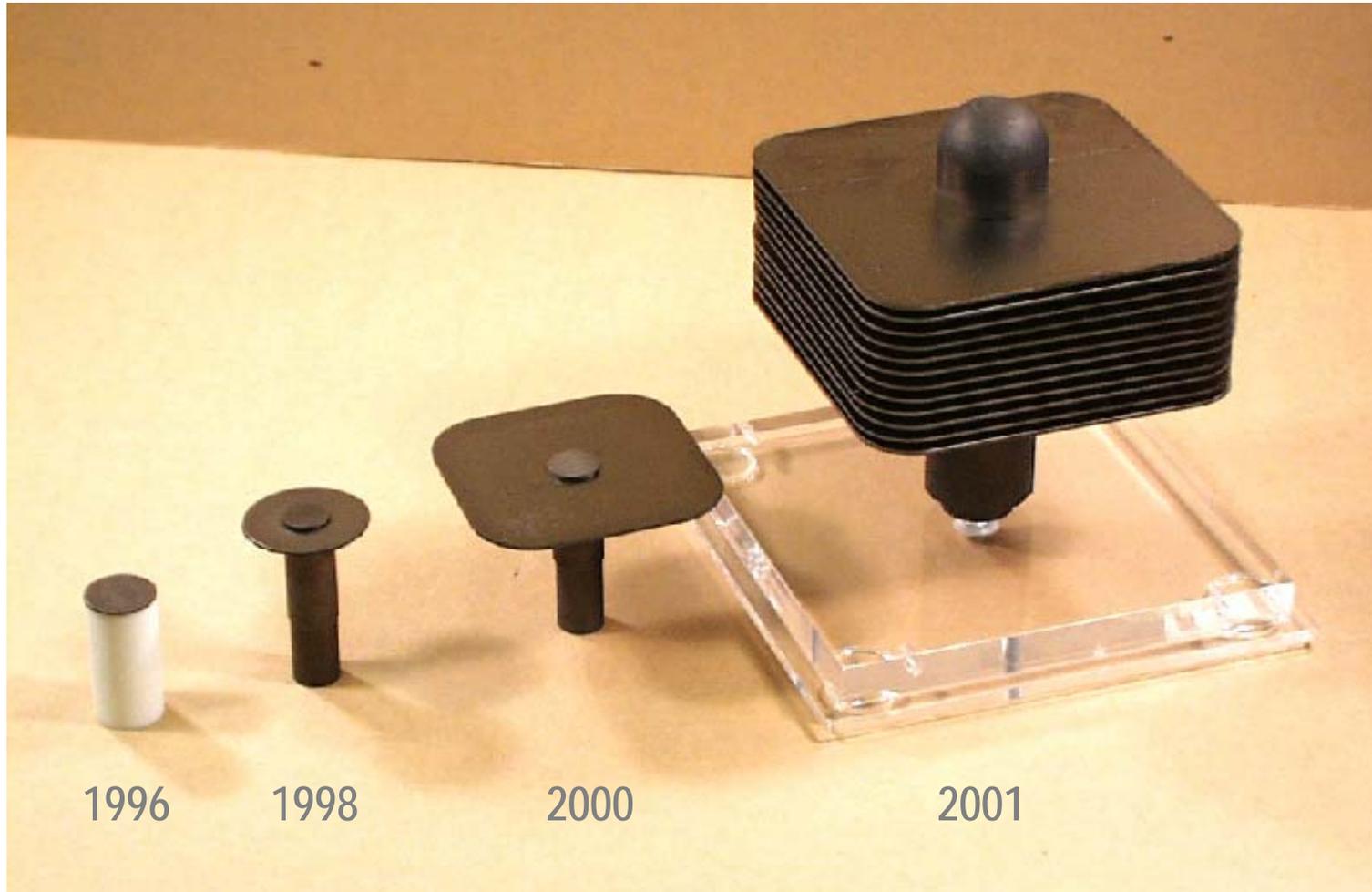
Commercial Vessel Concept



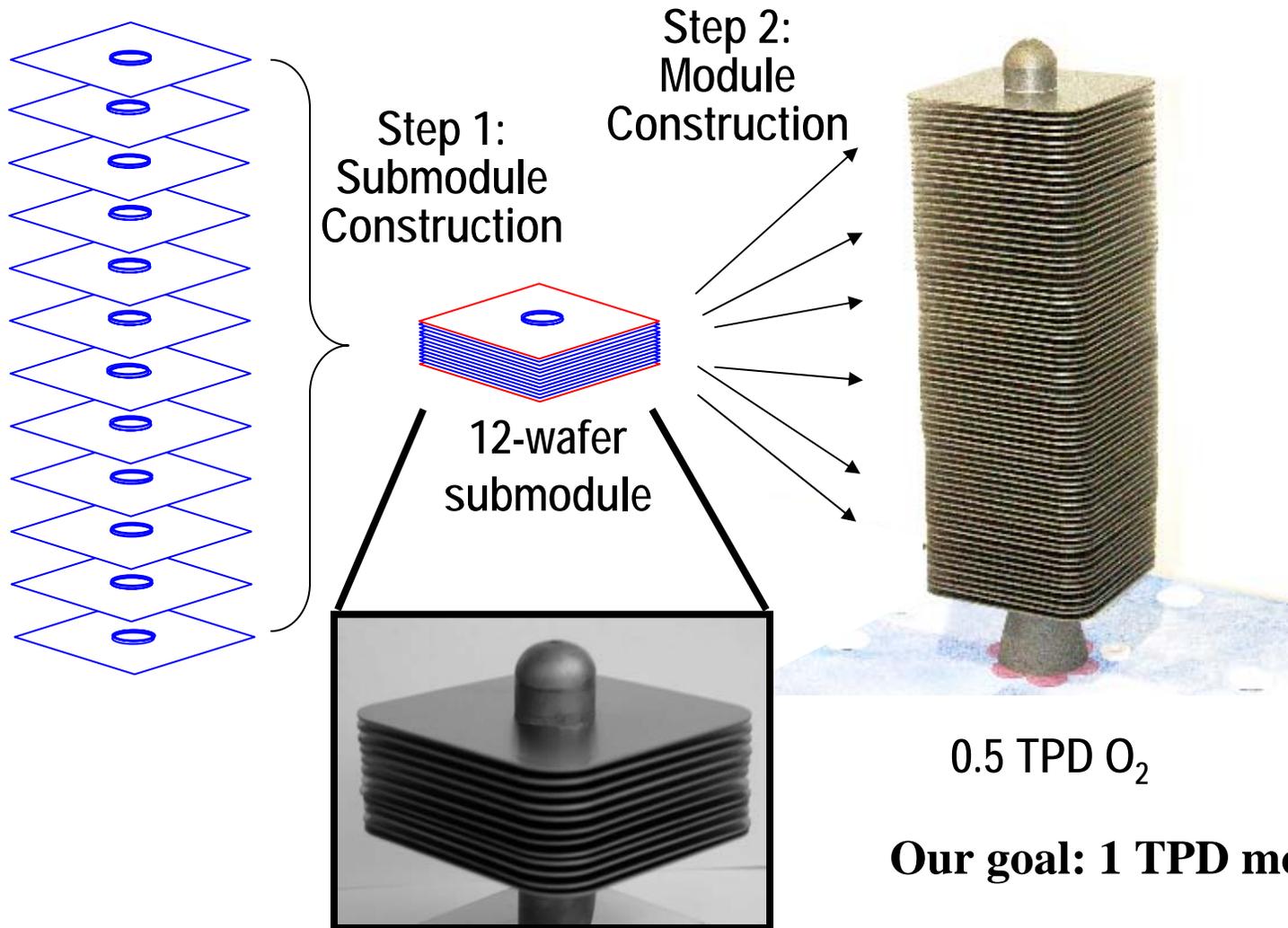
Stack planar wafers into modules,
Add modules to increase production

Ceramic Processing Development is a Major Component of This Program

Producing Commercial-size Wafers Since 2000



Commercial-scale ITM Oxygen Modules have been Fabricated



Developed ceramic processing steps and forward pathways using full-scale equipment

Ceramic Processing Infrastructure

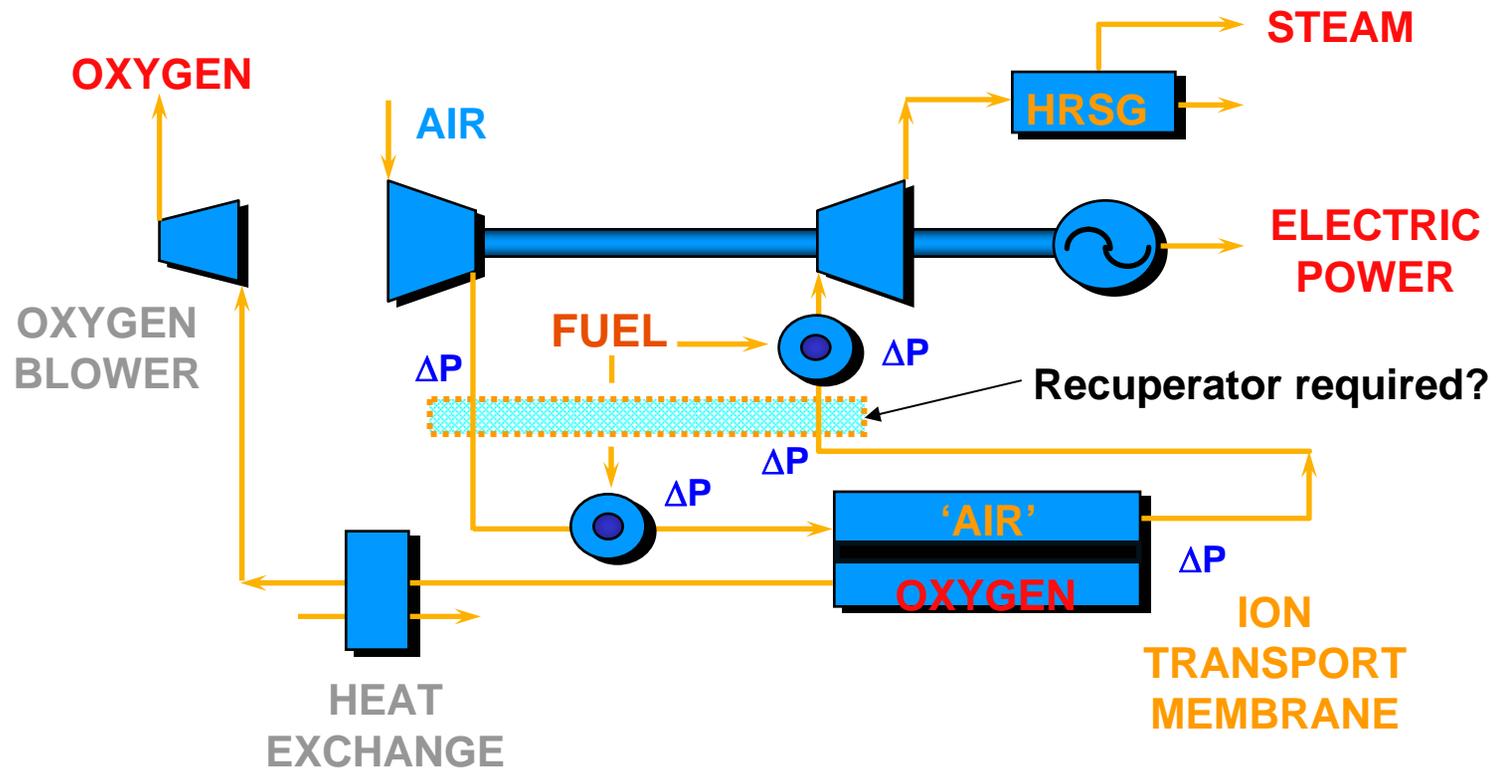


We Have Made Significant Progress

A Summary Of Major Milestones

- ✓ Developed a **stable**, high-flux material
- ✓ Devised a **planar** “wafer” architecture
- ✓ Demonstrated the **commercial flux target** under anticipated operating conditions
- ✓ Demonstrated **stable operation**
- ✓ Scaled-up and produced **commercial-size wafers** in large quantities
- ✓ Built **first commercial-scale ITM Oxygen modules**
- ✓ Re-confirmed the **economic benefits** of the technology
- **Confirm machinery integration pathway**
- **Test first commercial-scale ITM Oxygen modules**

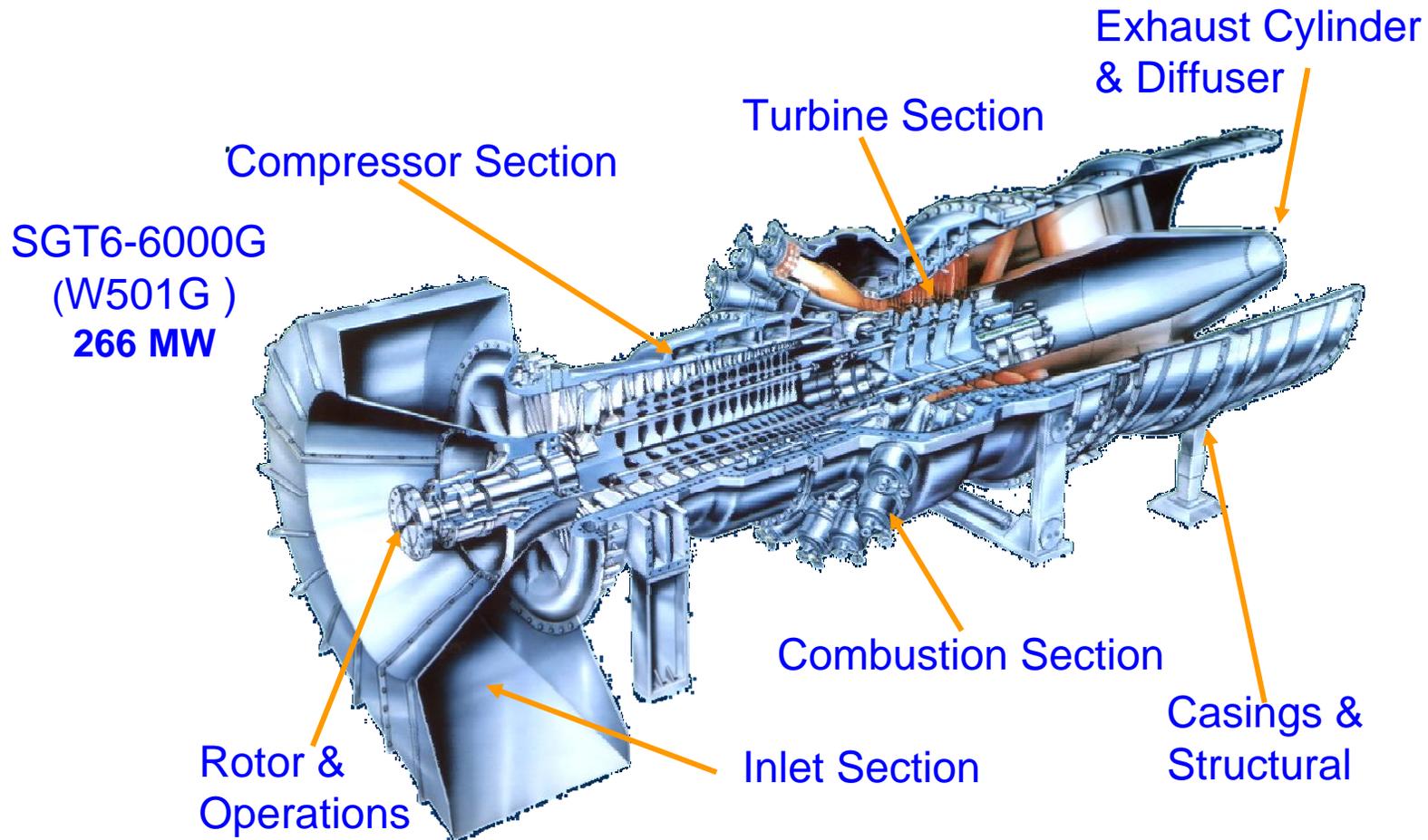
Gas Turbine Integration with ITM Oxygen



ITM Oxygen Needs:

- Significant air extraction (>50%)
- Re-insertion of non-permeate stream into turbine (pressure loss)
- Independent flow and temperature control of extracted air stream and non-permeate
- Good efficiency and capital cost advantage retained

Collaboration with Siemens



- Integration strategy: achieve air extraction/hot gas re-insertion without altering the existing compressor and turbine sections of the SGT6-6000G engine

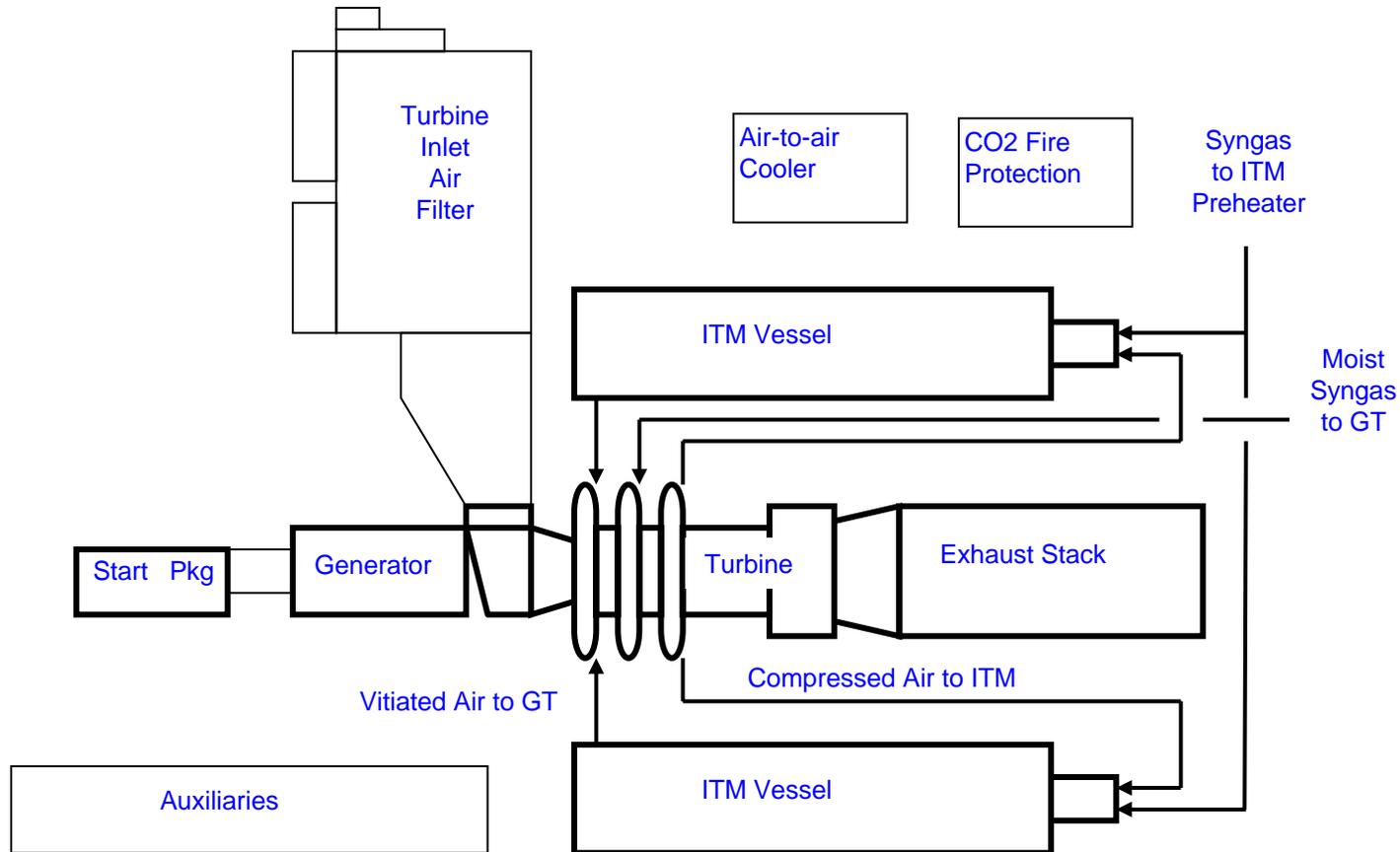
Siemens SGT6-6000G /ITM Oxygen Integration: Issues and Solutions

| Issue | Solution |
|--------------------------------------|---|
| Syngas vs. Natural Gas | Redesign of burner |
| Hot non-permeate return to combustor | New connections to burner Physical piping arrangement considered Materials selection Recuperation advantageous |
| NOx control | Steam injection |
| ≥ 50% Air Extraction | Achieved 55% air extraction without substantial changes to compression section. |

Siemens SGT6-6000G /ITM Oxygen Integration: Issues and Solutions, cont'd

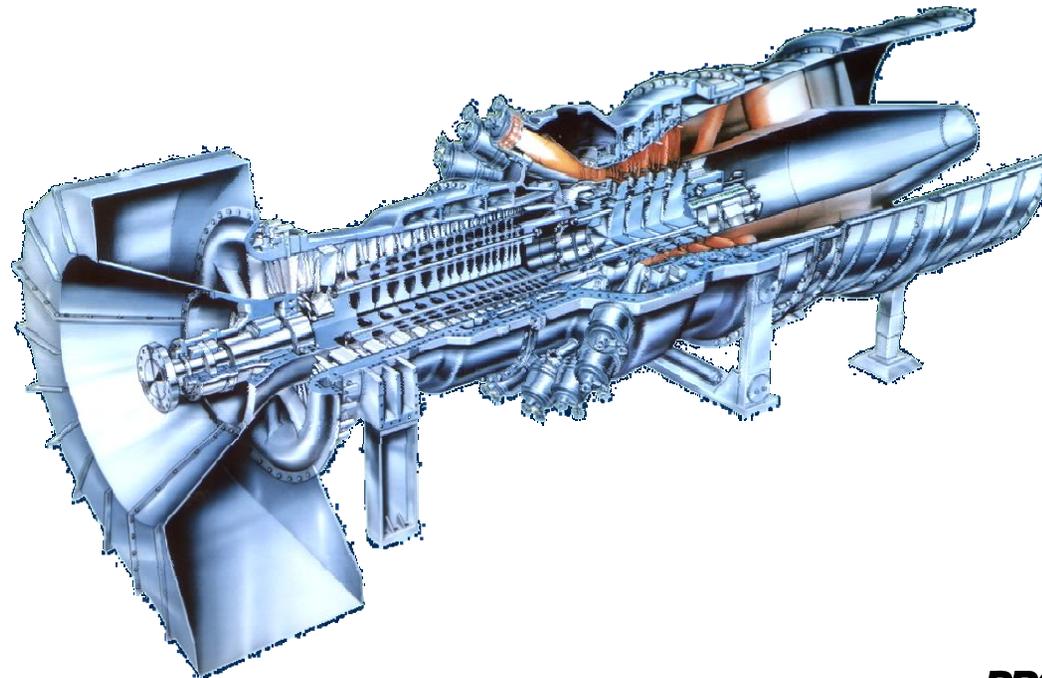
| Issue | Solution |
|---------------------|---|
| Pressure Drop | Effects of pressure drop can be mitigated by various process changes. |
| Hot gas manifolding | Maximize gas distribution uniformity. |
| System Operation | Control system adds complexity, but does not pose any insurmountable challenges |

SGT6-6000G/ITM Oxygen Layout



Siemens SGT6-6000G /ITM Oxygen Integration: Work in Progress

- ✓ Identify Major Obstacles and Solution Paths
- ✓ Develop Conceptual Designs
- Estimate Nth Unit Costs
- Estimate Development Requirements/Costs

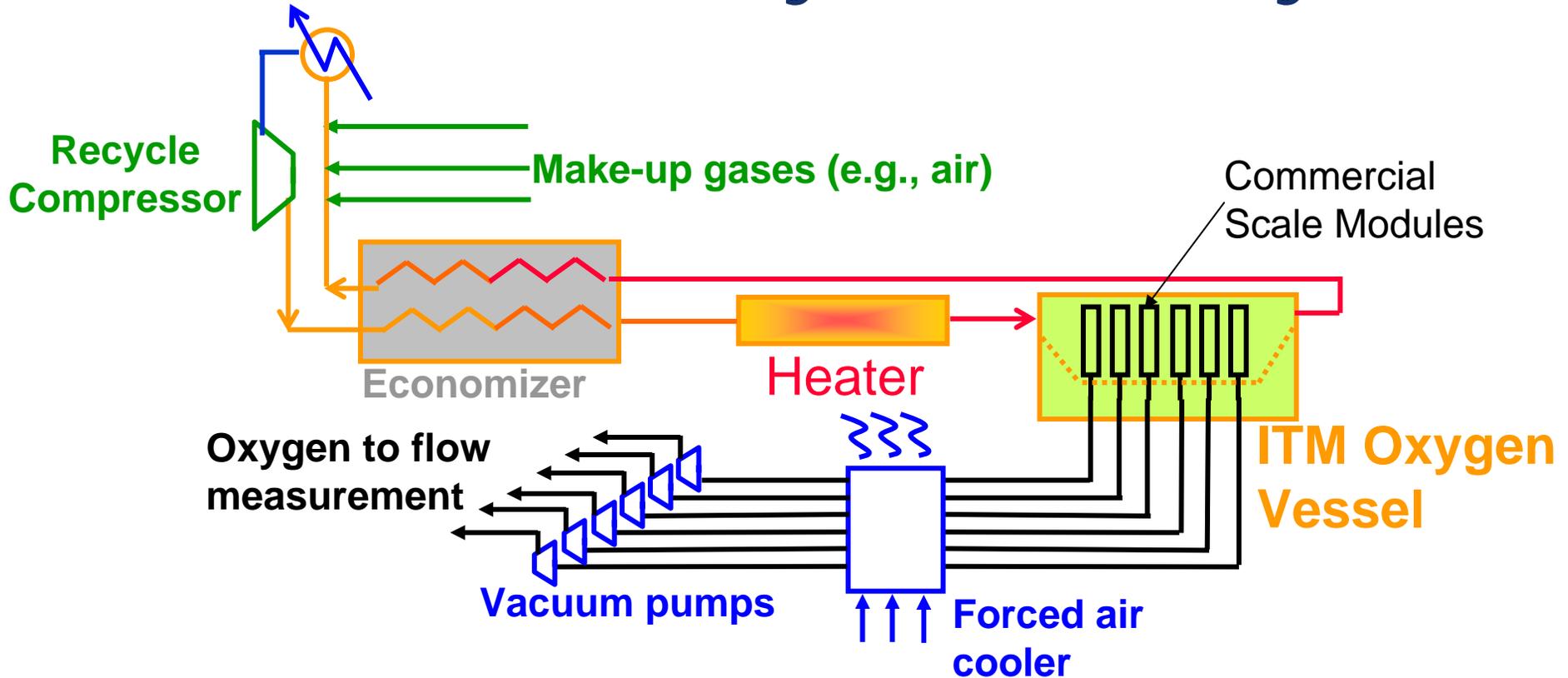


Phase 2 Concludes with Operation of a Subscale Engineering Prototype (SEP)

Broad Project Goals:

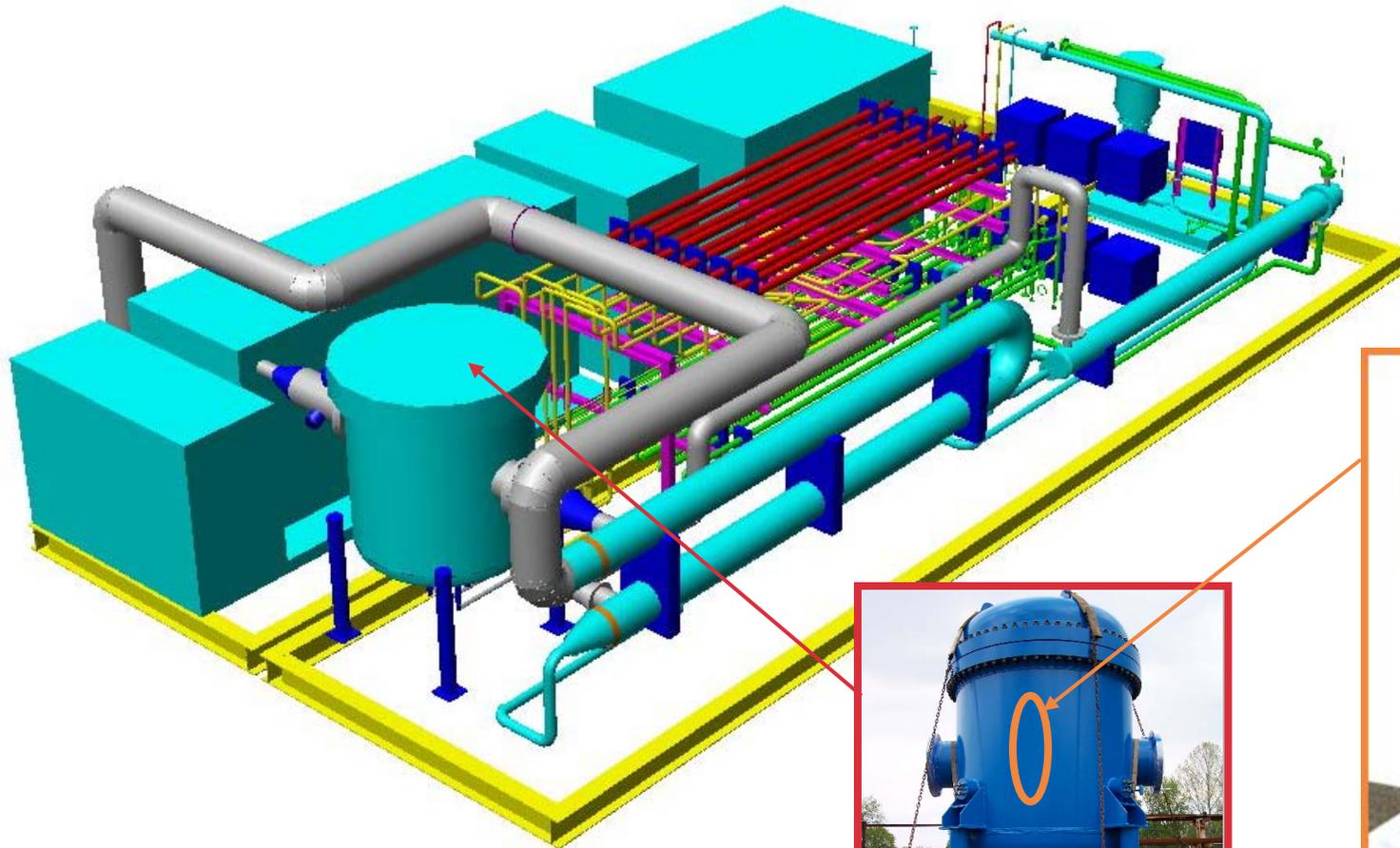
- **Test Commercial Scale Modules (up to 1 TPD oxygen each)**
- **Test concepts for vessel internal design**
- **Test process control strategy**

SEP Test Facility Process Cycle



- Recycle Loop minimizes compressed feed gas requirement
- Performance of individual modules monitored independently
- Fully instrumented for remote operation/monitoring

ITM Oxygen Prototype for 1-5 TPD Oxygen



0.5 TPD O₂

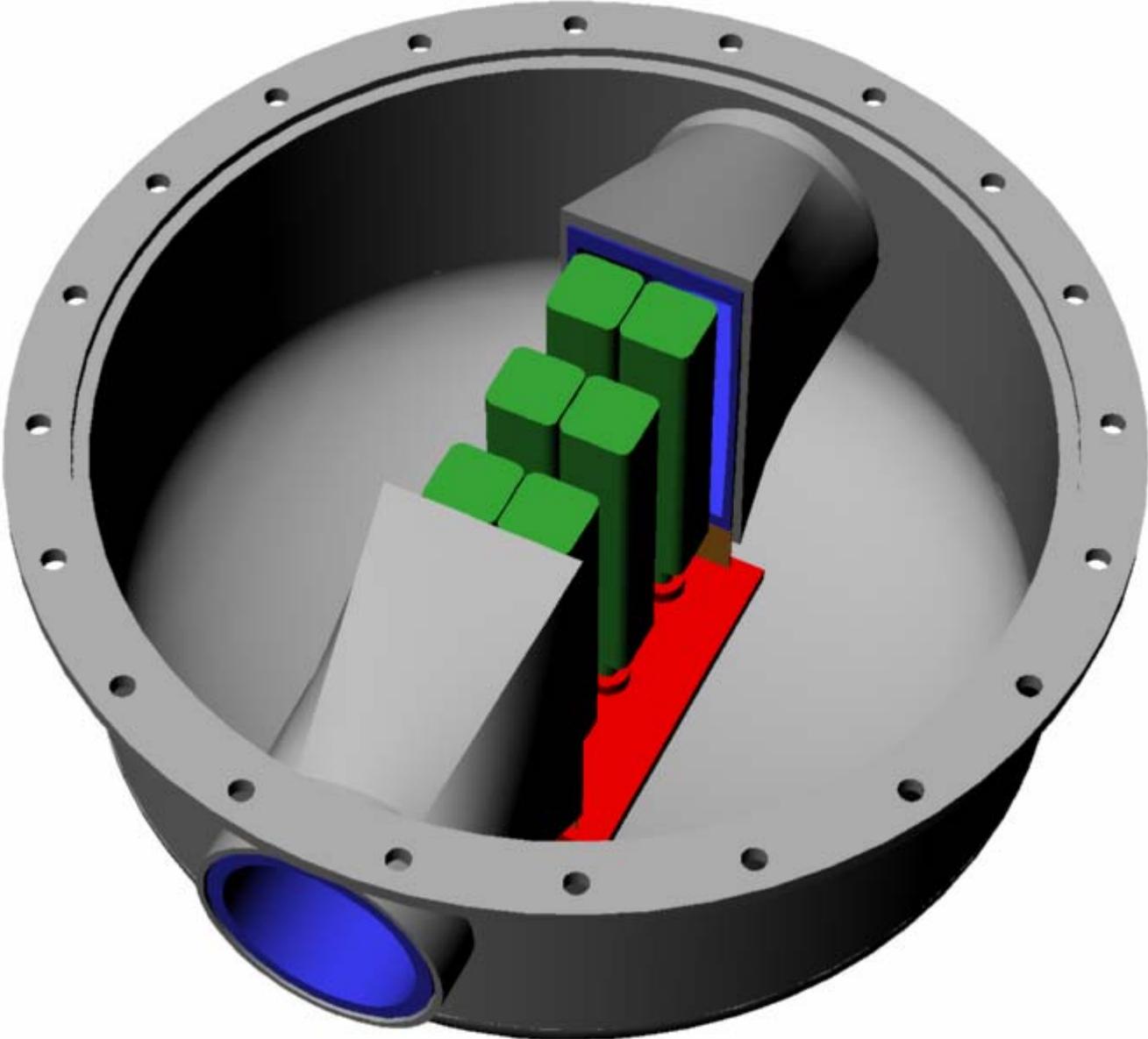


Commercial-scale Module

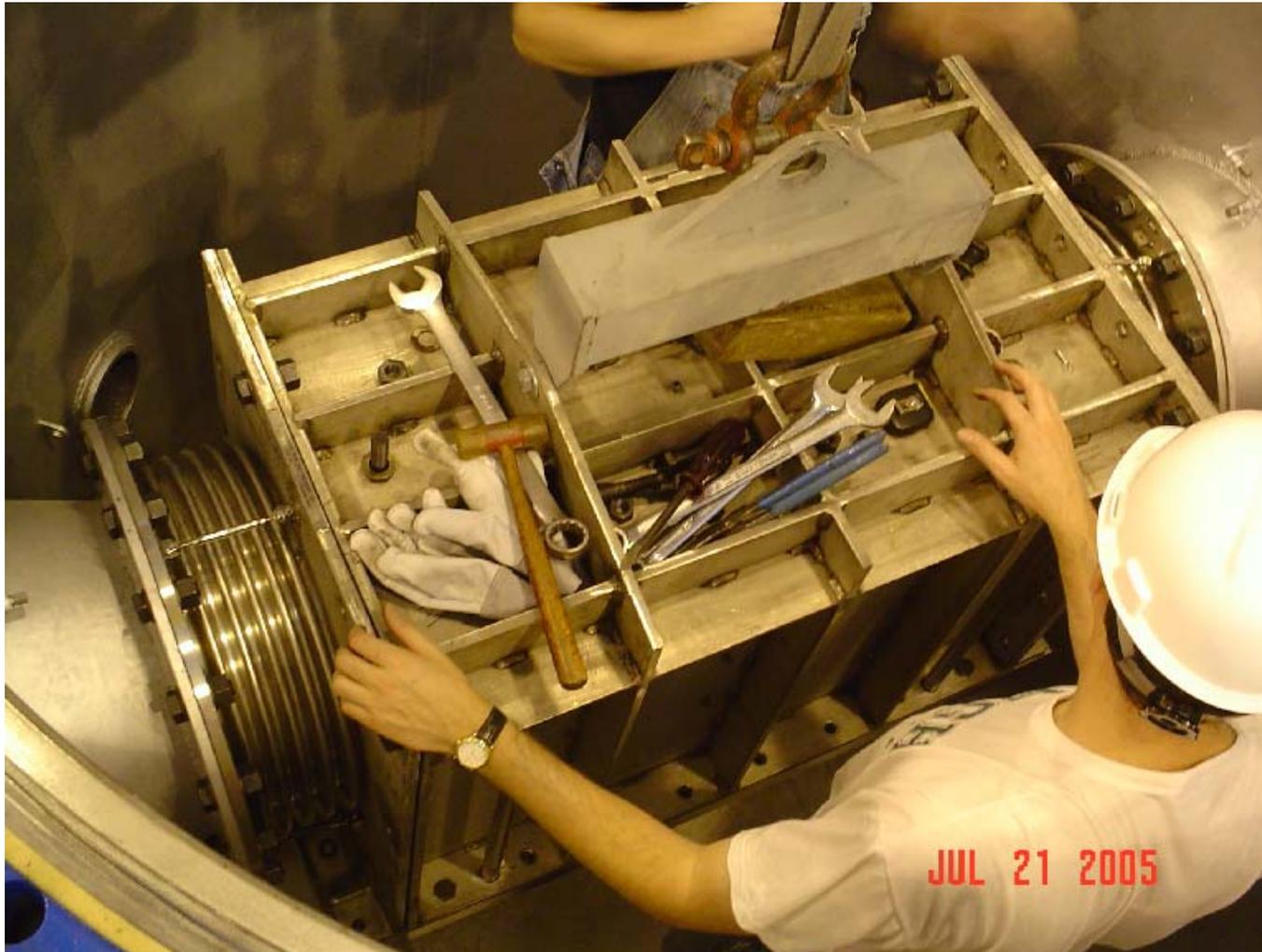


Currently in Start-up



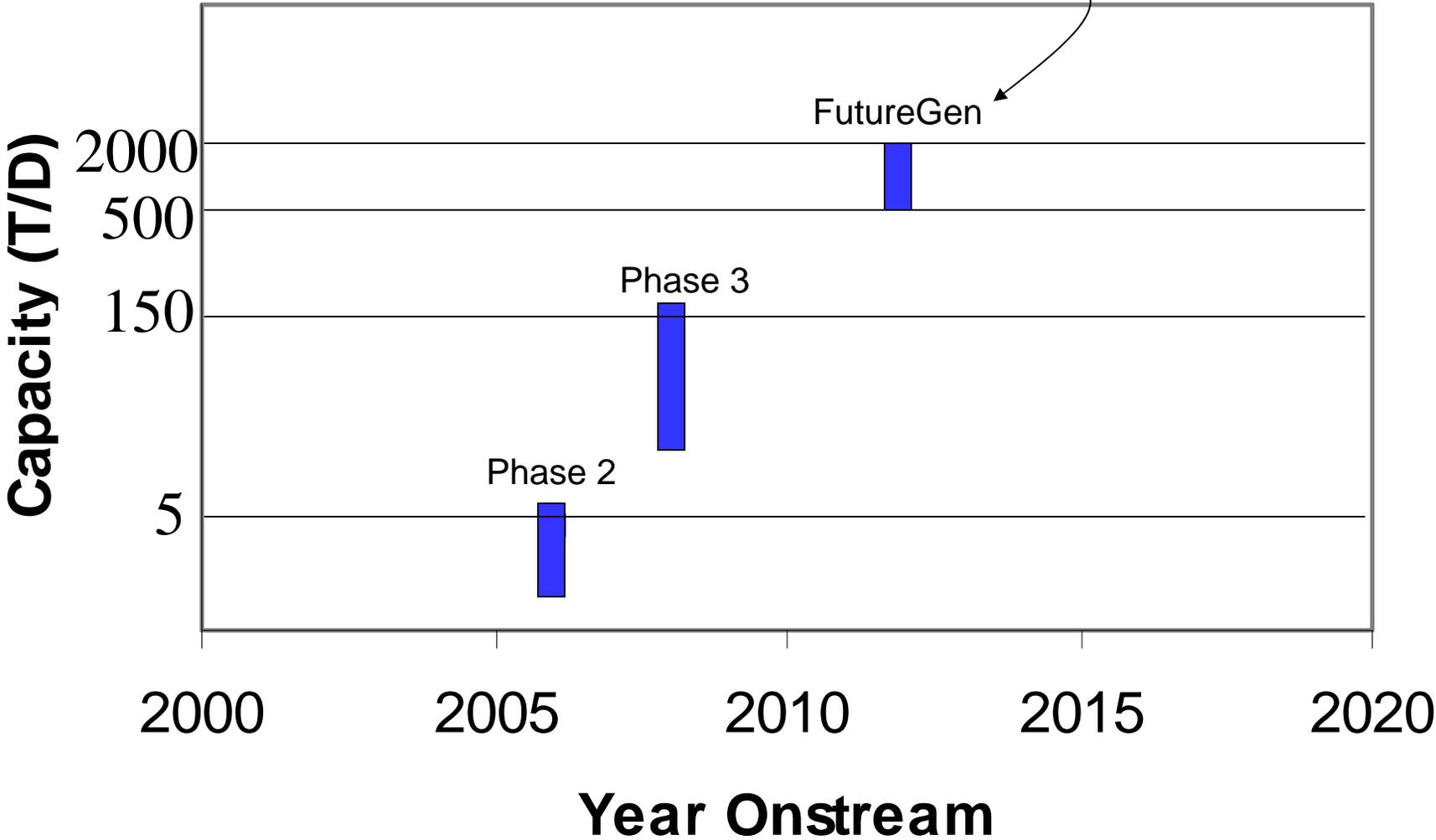


SEP Flow Duct Houses ITM Oxygen Modules with 3-6 TPD Capacity



ITM Oxygen Development Plan Being Developed With The DOE

Consistent with current DOE FutureGen timing of 2012



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