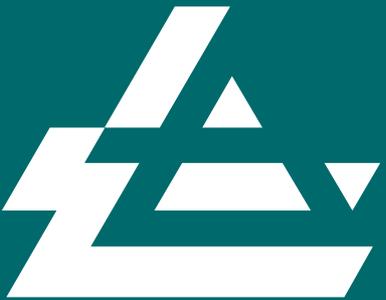


AIR
PRODUCTS



ITM Oxygen: Taking the Next Step

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Gasification Technologies 2009

Colorado Springs, CO

7 October 2009

Cryogenic Distillation is state-of-the-art for tonnage oxygen

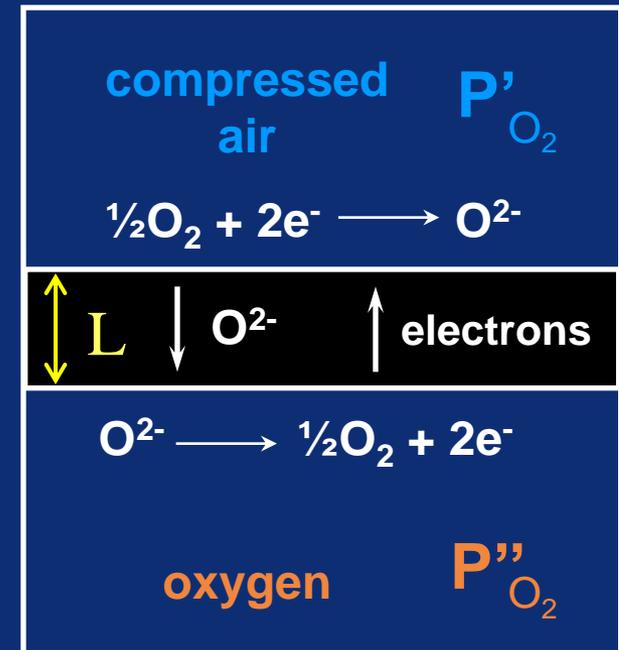


- Mature, reliable technology
- Energy intensive
- Requires 100's of equilibrium stages
- Represents ~15% of IGCC capital cost
- Consumes ~15% of IGCC gross power output

Ion Transport Membranes (ITMs) produce high-purity oxygen at high flux

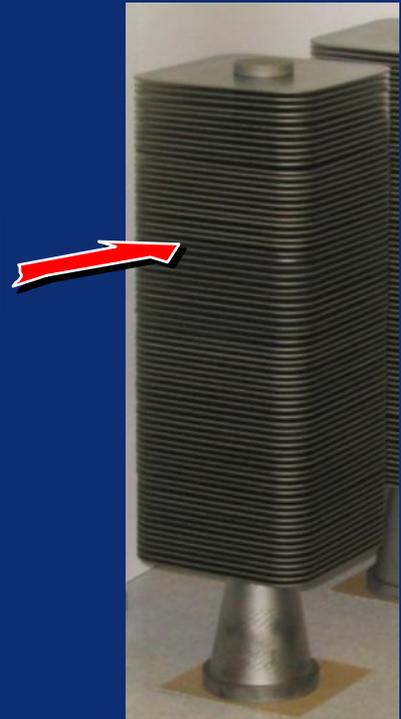
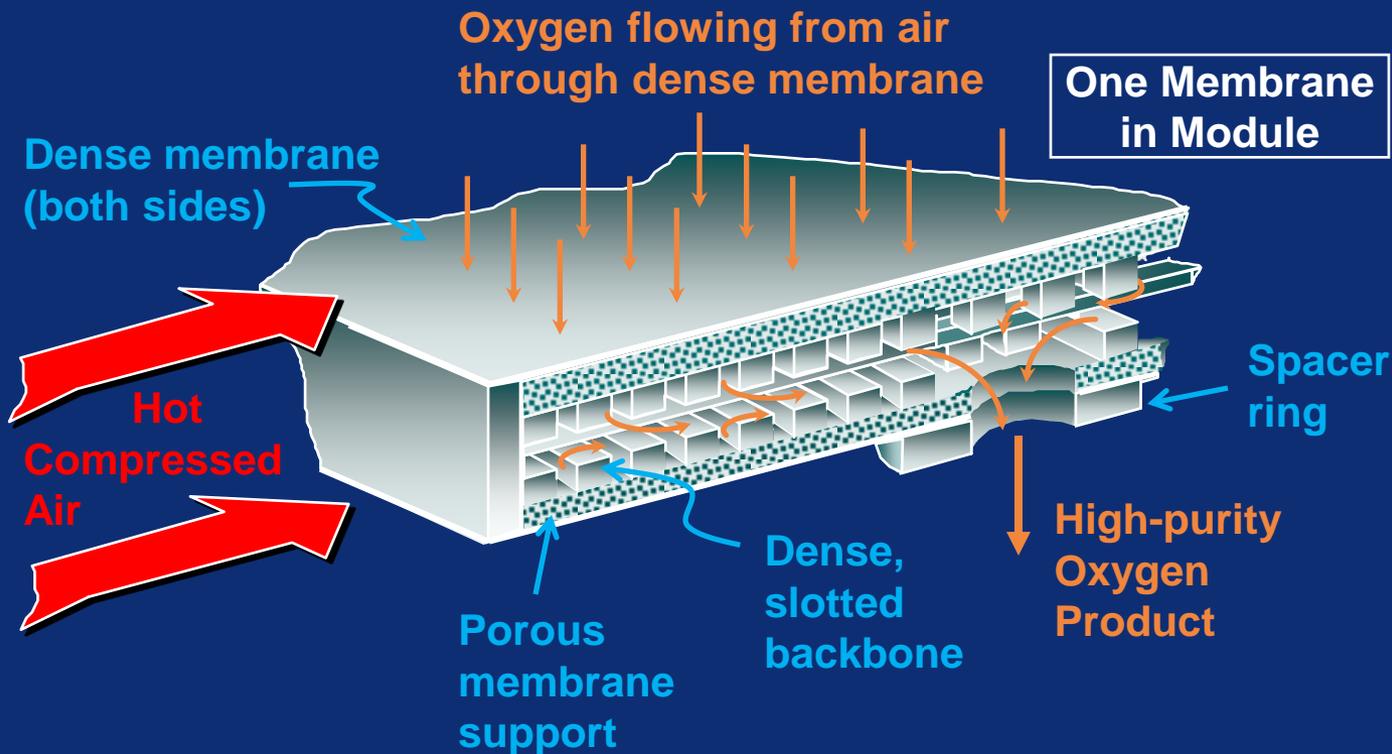
- Mixed-conducting ceramic membranes (non-porous)
- Typically operate at 800-900 °C
- 100% selective for O₂

- O₂ flux $\propto \frac{1}{L} \ln \left(\frac{P'_{O_2}}{P''_{O_2}} \right)$



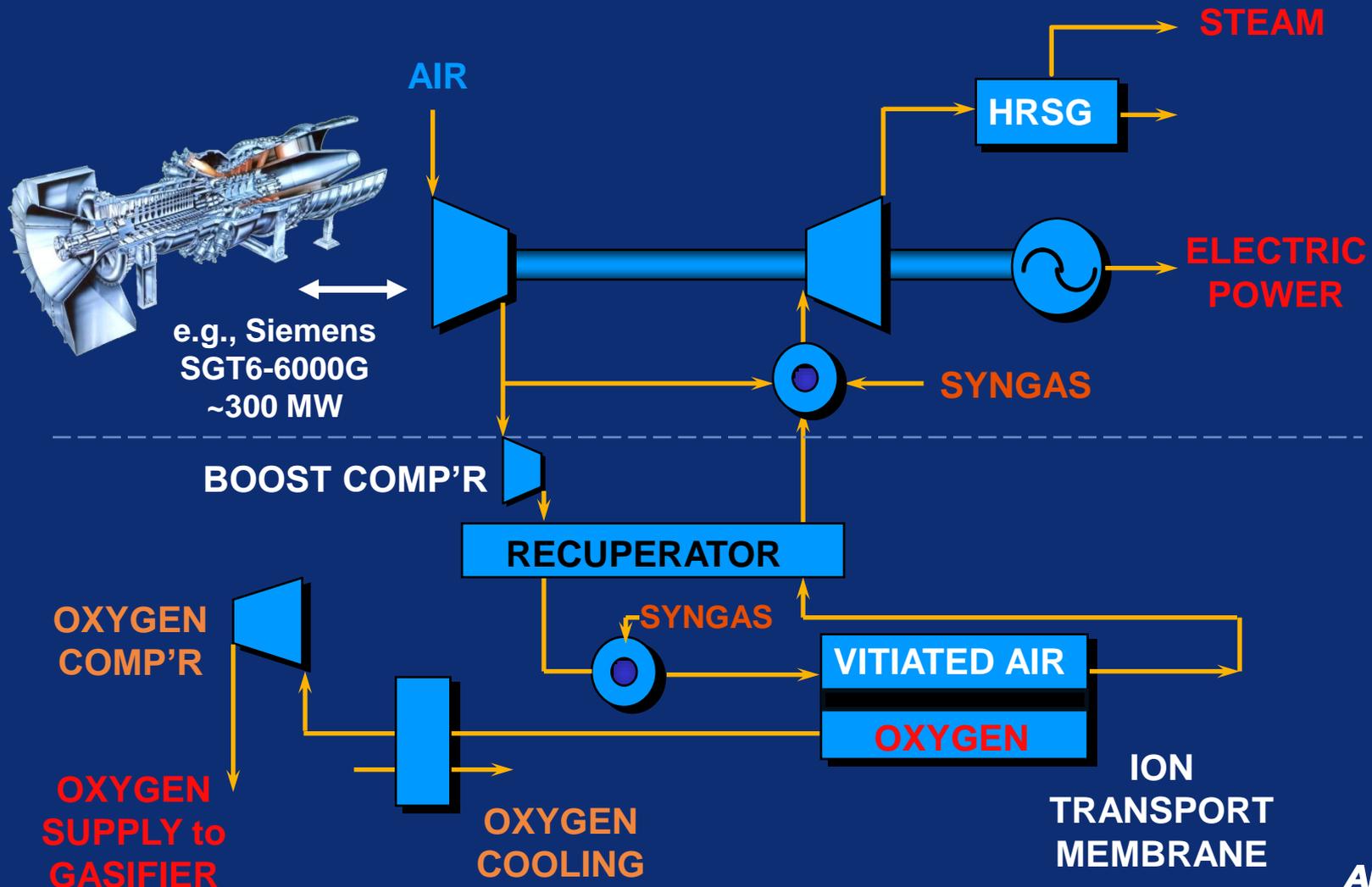
ITM Oxygen membranes are supported thin-film planar devices

- Very fast transport for oxygen, **very compact**
- **Low ΔP** on the air side



1/2-TPD module

ITM Oxygen integrates well with gas turbine power cycles



We are building commercial-scale ITM modules ...

- All-ceramic construction

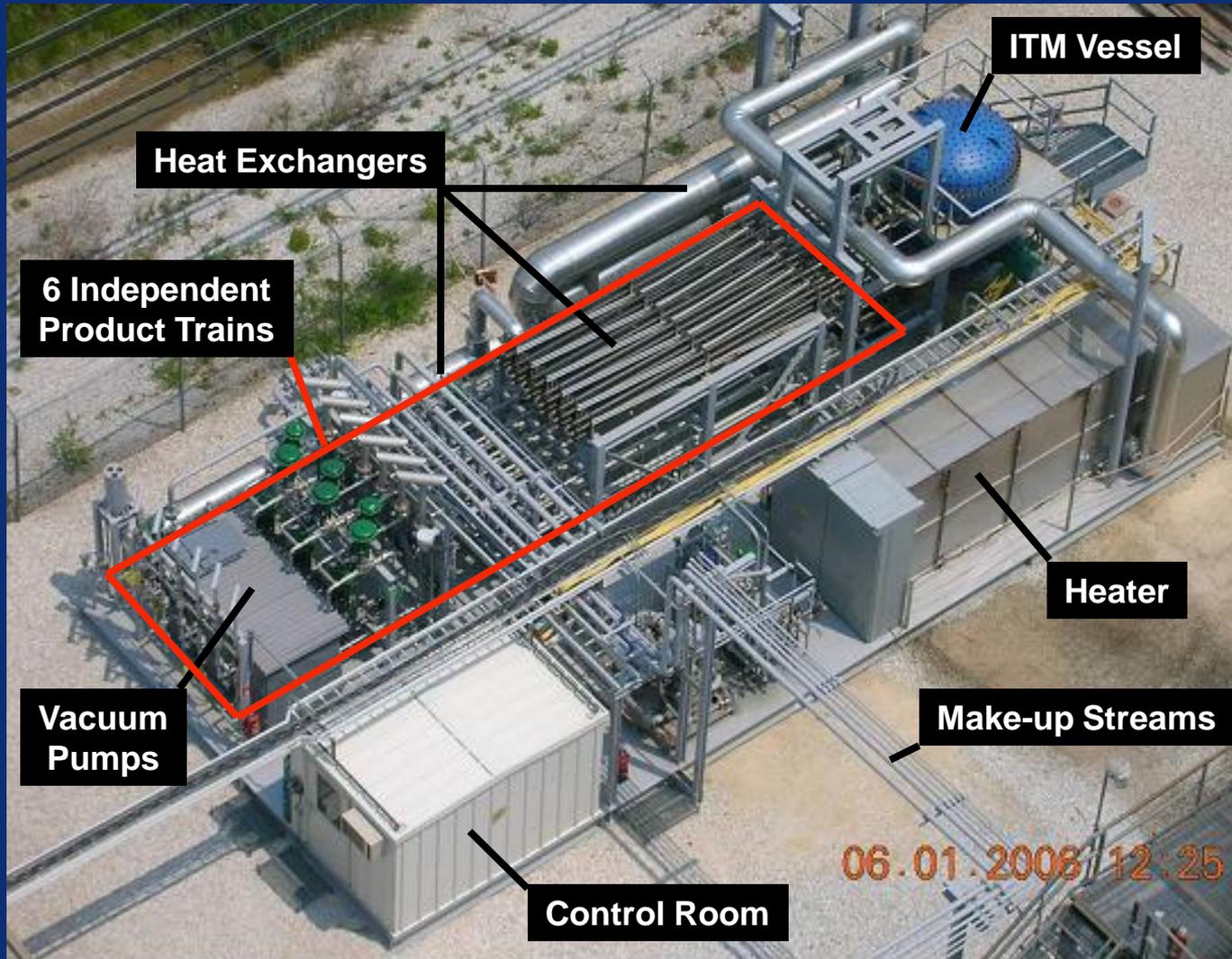
1/2-TPD Modules



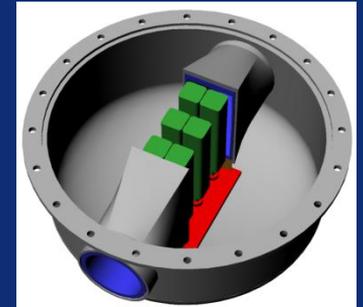
1-TPD Module



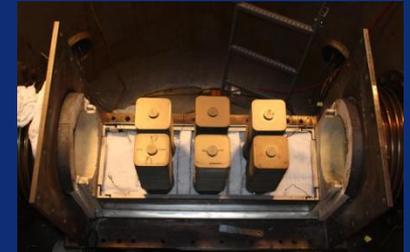
... and testing them in pilot plant



ITM Vessel Internals



6 Modules Installed



Flow Duct Installed



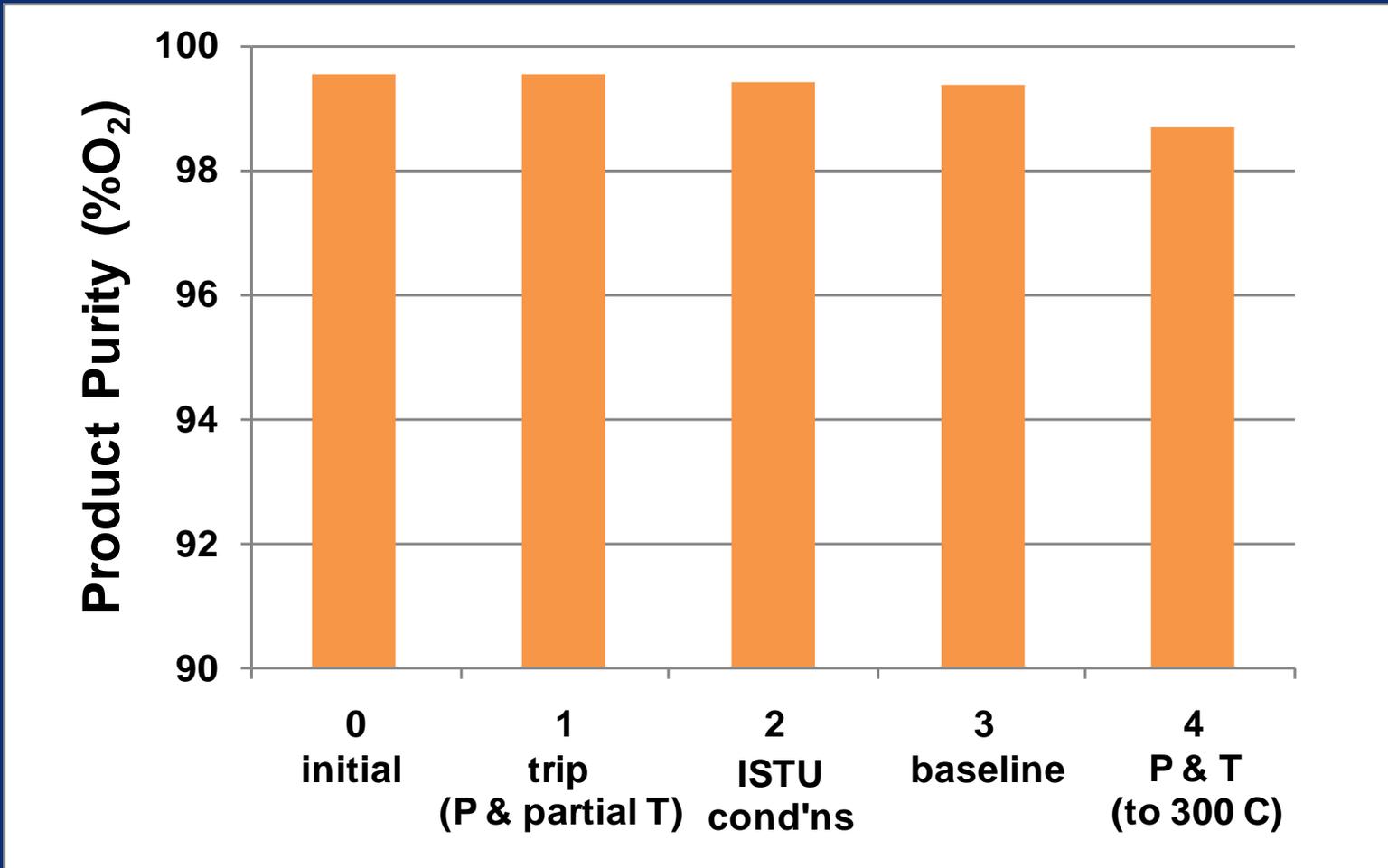
Pilot plant testing highly successful

- Over **600 days** cumulative operation in multiple runs with ½-TPD modules since 2006
- Demonstrated **>99% oxygen purity** from numerous commercial-scale modules and seals
- Oxygen **flux** consistently **met or exceeded expectations** and has remained **steady over multi-week tests**
- Completed retrofit of **advanced control system** to improve ceramic reliability during startup/shutdown cycles

ITM physical properties make thermal cycling challenging

- Large **CTE**
- **Chemical expansion** with changes in O₂ loading
- Ceramic - to - metal **seals** must accommodate expansion differences
- Metal components of seals must yield **elastically** to avoid overstressing the ceramic
- Stresses in the ceramic are managed by **controlling** thermal and oxygen **gradients using proprietary process control** methods

Our ability to cycle ITM modules continues to improve



Positive test results with multiple banks of modules

- Confirmed flux performance for all modules
 - **record high flux** measured for one module
- ΔP across three banks similar to predicted value
- Tested **multiple seal designs** simultaneously



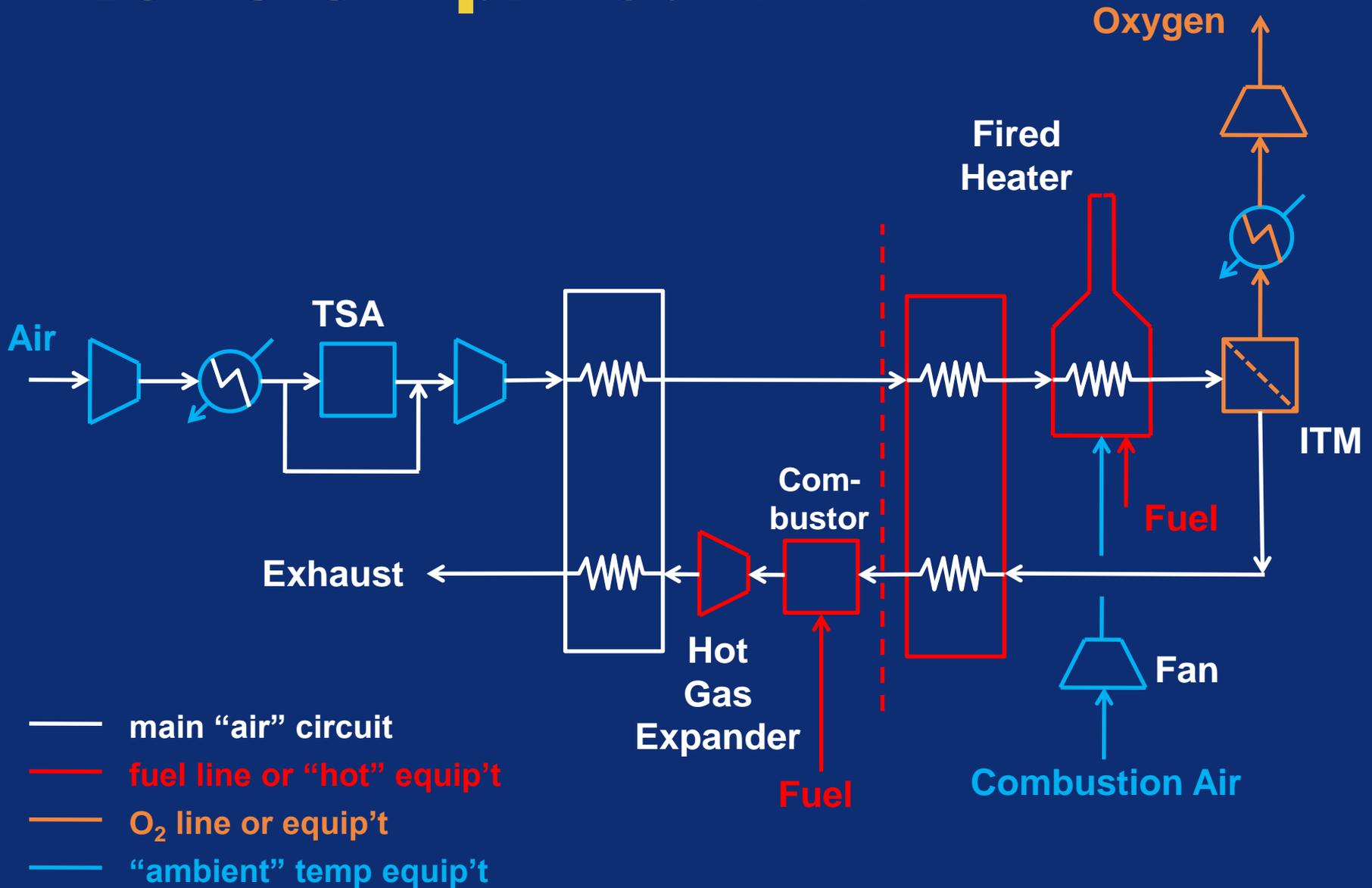
Future testing in pilot plant

- Test **1-TPD** modules
 - minor modifications to ITM vessel internals
 - ensure flow and temperature uniformity
- Continue **module reliability** testing
 - simulate process transients (temperature, pressure, composition) from turbomachinery integration
- Continue testing **prototype component designs** for next phase of scale-up

Next scale-up stage is the ISTU (Intermediate-Scale Test Unit)

- 150-TPD ITM Oxygen system **integrated with hot gas expander** to co-produce power
- Use commercial design concepts to allow scale-up to the next test platform
 - vessel and internals housing **large ITM module array**
 - process controls
 - contaminant mitigation
- Located at existing Air Products ASU site
 - infrastructure, logistics, op's support

ISTU simplified BFD



ISTU engineering status

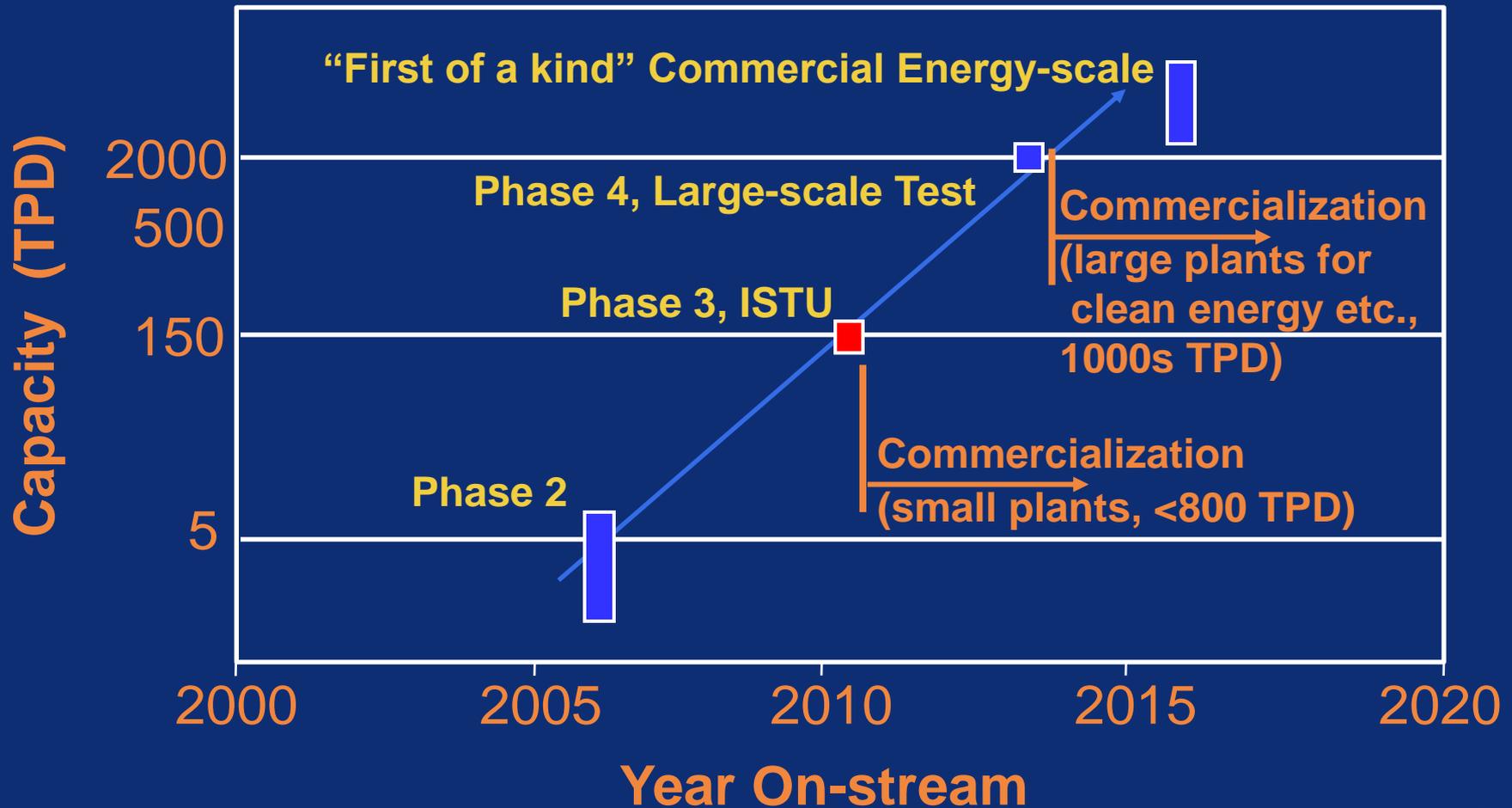
- Front-end engineering and design (FEED) nearing completion
- Project kickoff for long-lead items
- Operation and testing with ITM modules in 2011

We welcome EPRI to the team

- EPRI will execute tasks in process economics, plant operability, and power plant integration
- EPRI collaborative of 7 global power companies will advise on deployment in the power industry
 - additional utilities, coal producers, and related energy industry participants are welcome



ISTU development is critical to commercialize energy-scale ITM Oxygen



The future remains bright for ITM Oxygen

- **Commercial-scale ITM Oxygen modules** are being **built and tested** successfully
 - flux and purity targets verified
 - good thermal cycling demonstrated
 - performance with multiple banks of modules demonstrated
- ISTU project at **150-TPD** scale **well underway**
- **EPRI** and industry collaborative **on-board** to **advise on** power plant **deployment**
- **ITM Oxygen well positioned** to meet the needs of clean energy applications and **additional development supporters are welcome**

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