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A Siemens Business

2018 NETL CO_2 Capture Technology Project Review Meeting
Pittsburgh, PA August 13 – 17, 2018

Advanced CO_2 Compression with Supersonic Technology (FE0026727)

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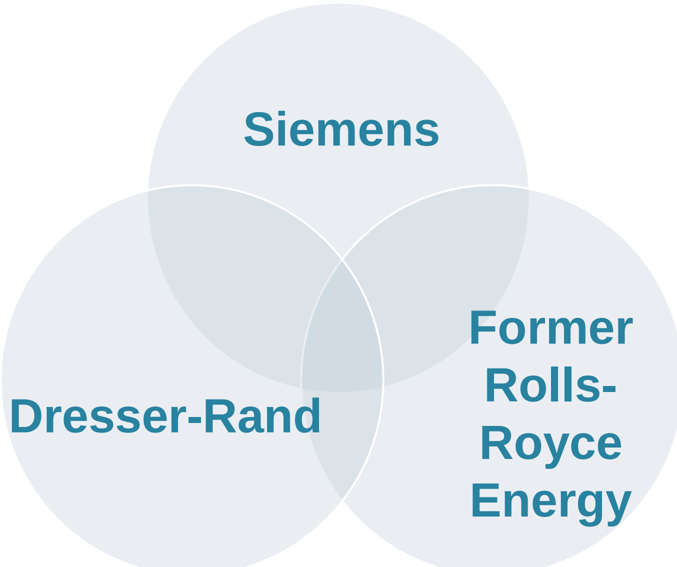
The Dresser-Rand business

Well positioned to compete and bring value to our clients



Taking advantage of low market activity to improve overall competitiveness

- Synergies from acquisition
- Operational excellence
- Technology, innovation & digitalization

Well positioned to compete in the current challenging market conditions

- Expanded technology and product portfolio
- Solutions based on full complement of Siemens portfolio
- Most extensive service network & largest installed base
- Enhanced client relationships & agreements

The Dresser-Rand business at a glance

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Revenue

Major source of O&G revenues for Siemens

Locations around the globe

14

Employees

5100

Services now part of Siemens Power Generation Services Distributed Generation and Oil & Gas

History of Innovation and Technology Leadership

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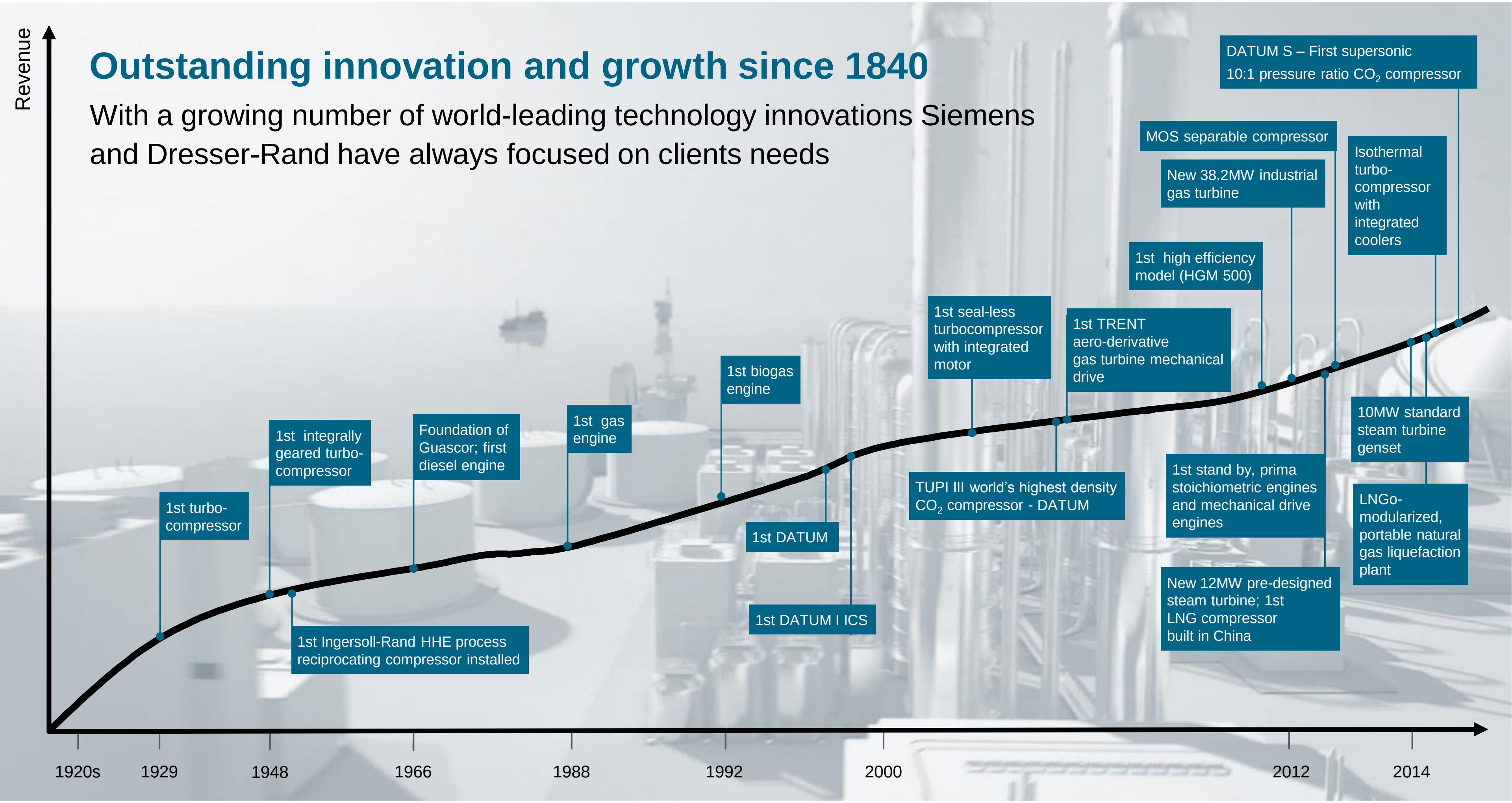
Outstanding innovation and growth since 1840

With a growing number of world-leading technology innovations Siemens and Dresser-Rand have always focused on clients needs



Sales, in logarithmic scale

Partnership with U.S. DOE

In 2008, The U.S. Department of Energy partnered with Ramgen Power Systems and the Dresser-Rand business by co-funding the adaption of flight-based supersonic compression to carbon capture and sequestration (CCS) applications requiring “100:1” total CO_2 compression ratios.

The DOE identified two key objectives:

- Reduce cost
- Improve efficiency

Supersonic compressors offer the potential of lower capital costs, smaller footprints, competitive efficiencies, and waste heat energy recovery.

History and Testing Milestones

2008	Dresser-Rand and Ramgen Power Systems entered into an exclusive arrangement to further develop supersonic compression technology
2011	Construction of the world's first supersonic CO_2 compression test facility
2013	First HP compressor test phase concluded with successful demonstration of CO_2 shockwave compression
2014	Second HP CO_2 compressor test phase concluded; achieved 9:1 pressure ratio Dresser-Rand acquired assets of Ramgen Power Systems and established Seattle Technology Center in Bellevue, WA, USA
2015	Third HP CO_2 compressor test phase (DATUM S) concluded; achieved 11.5:1 pressure ratio
2016	Award signed (DE-FE-0026727)
2017	Design of LP CO_2 compressor completed and manufactured. Assembly began in fall 2017
2018	First LP CO_2 compressor test phase (DATUM S) concluded; achieved 12.0:1 pressure ratio

LP/HP 100:1 compressor train is sized at ~ 182 MWe , 90% capture 1.5 MTPA of CO_2

DATUM-S Compressor Program – DOE Partnership

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- Selection notification announced Aug 13, 2015: DE-FOA-0001190
- Award signed (DE-FE-0026727) March 16, 2016
- Program kick-off meeting held April 8, 2016
- Scope included:
  - Additional HP unit testing
  - Design / build / test the high flow coefficient LP stage to complete the 100:1 total pressure ratio demonstration
  - TEA including heat integration into Case B12B

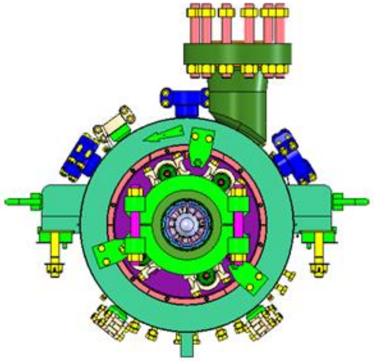
DOE partnership and support is critical to the success of this program.

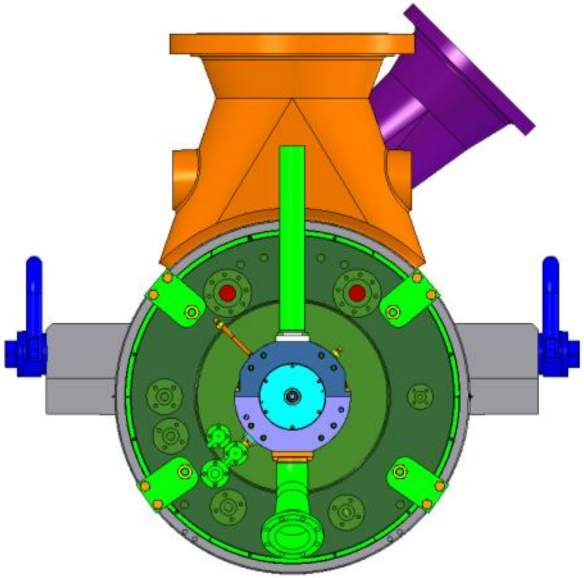
DATUM-S HP and LP Compressors

HP Compressor:

Commercial validation testing completed

10:1 PR / 220 psia suction pressure



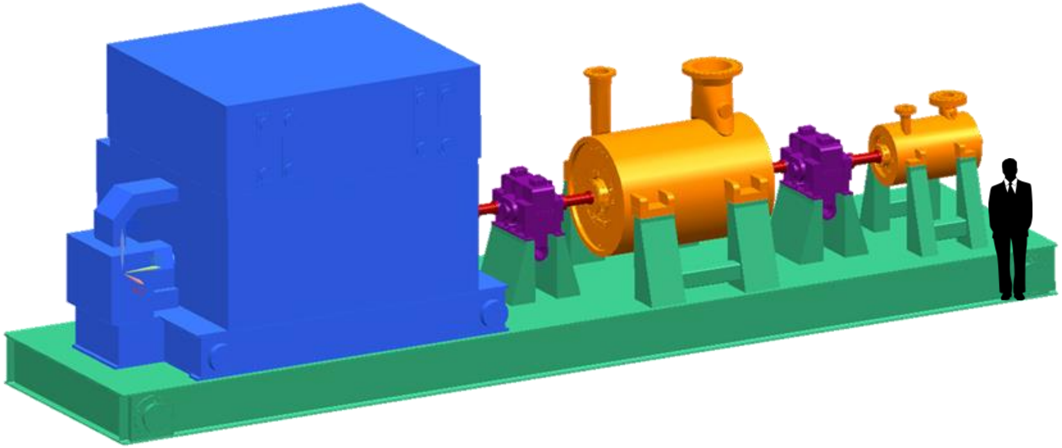


LP Compressor:

Commercial validation testing completed

10:1 PR

22 psia suction pressure



Integrated LP/HP Compressor Train

Single Driver

Minimum footprint

Minimum capital/installation cost

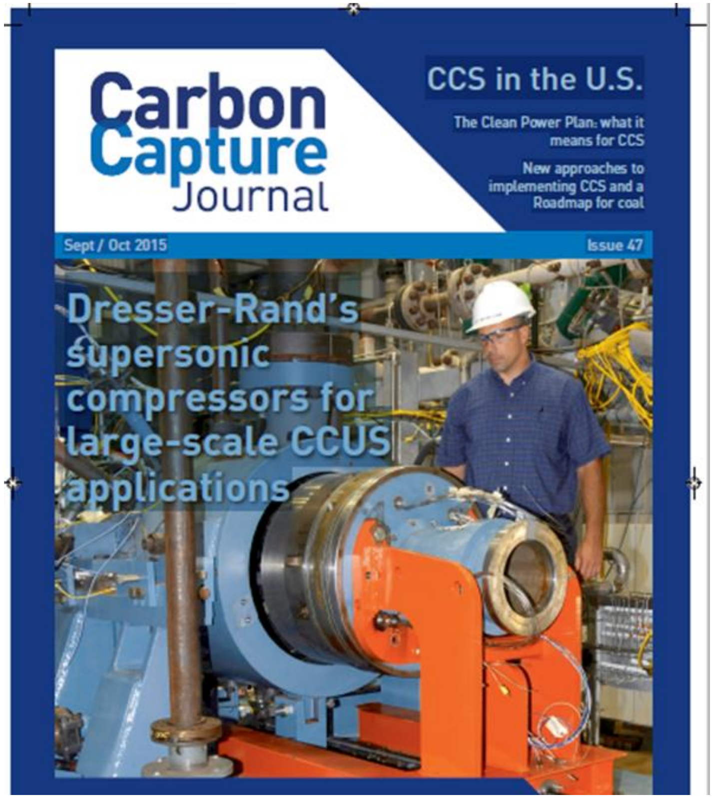
Waste heat energy recovery from both stages

100:1 overall PR

DATUM-S Compressor Benefits

When compared to traditional subsonic compression solutions

- Smaller footprint, less equipment, less piping, fewer coolers
- Higher compression ratios
- Reduced need for gas intercooling
- Discharge temperatures exceeding 550°F (290°C)
- Waste heat recovery enables unmatched overall system efficiency



Improved availability, integration of waste heat and smaller footprint all underscore the merits of employing the DATUM-S compressor for the lowest total cost of ownership.

Waste Heat Integration

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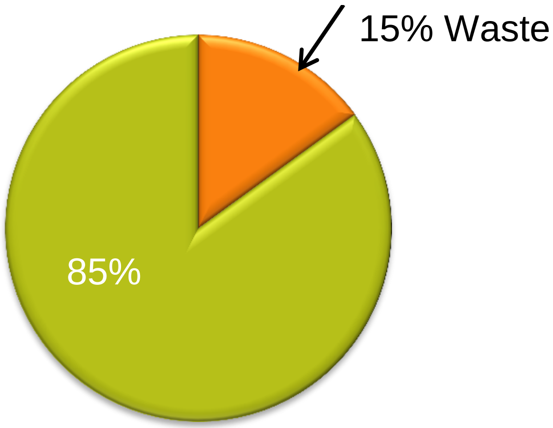

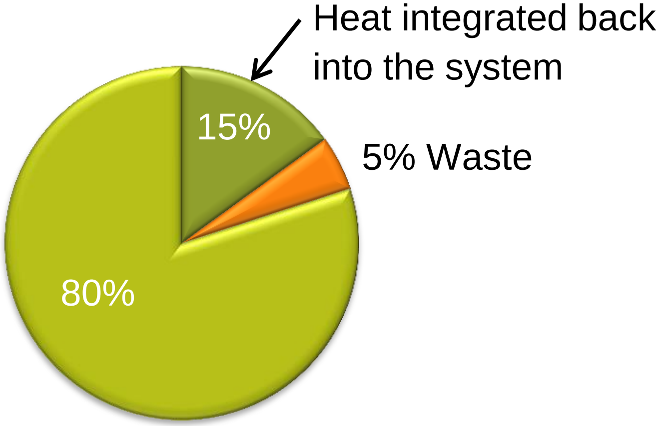

In a traditional system that is 85% efficient, 15% of the total energy input is lost and manifests itself mostly as low-grade heat.

In a DATUM-S compression system that is 80% efficient, 20% of the total energy input manifests itself as mid-grade heat.

If 75% of the mid-grade heat can be put to work, waste energy stream is reduced to 5%.

Multiple Opportunities for Waste Heat Integration

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- Regenerate sorbent / amine – Transfer heat from the compressed CO_2 and reduce steam diversion from the power cycle
- Sorbent drying – Utilize waste heat to dry sorbent after steam regeneration
- Amine reboiler – Utilize waste heat in the amine reboiler
- Boiler feed water heater – Utilize waste heat to heat boiler feed water and reduce steam diversion from power cycle

Schedule Summary (Fiscal Years Shown)

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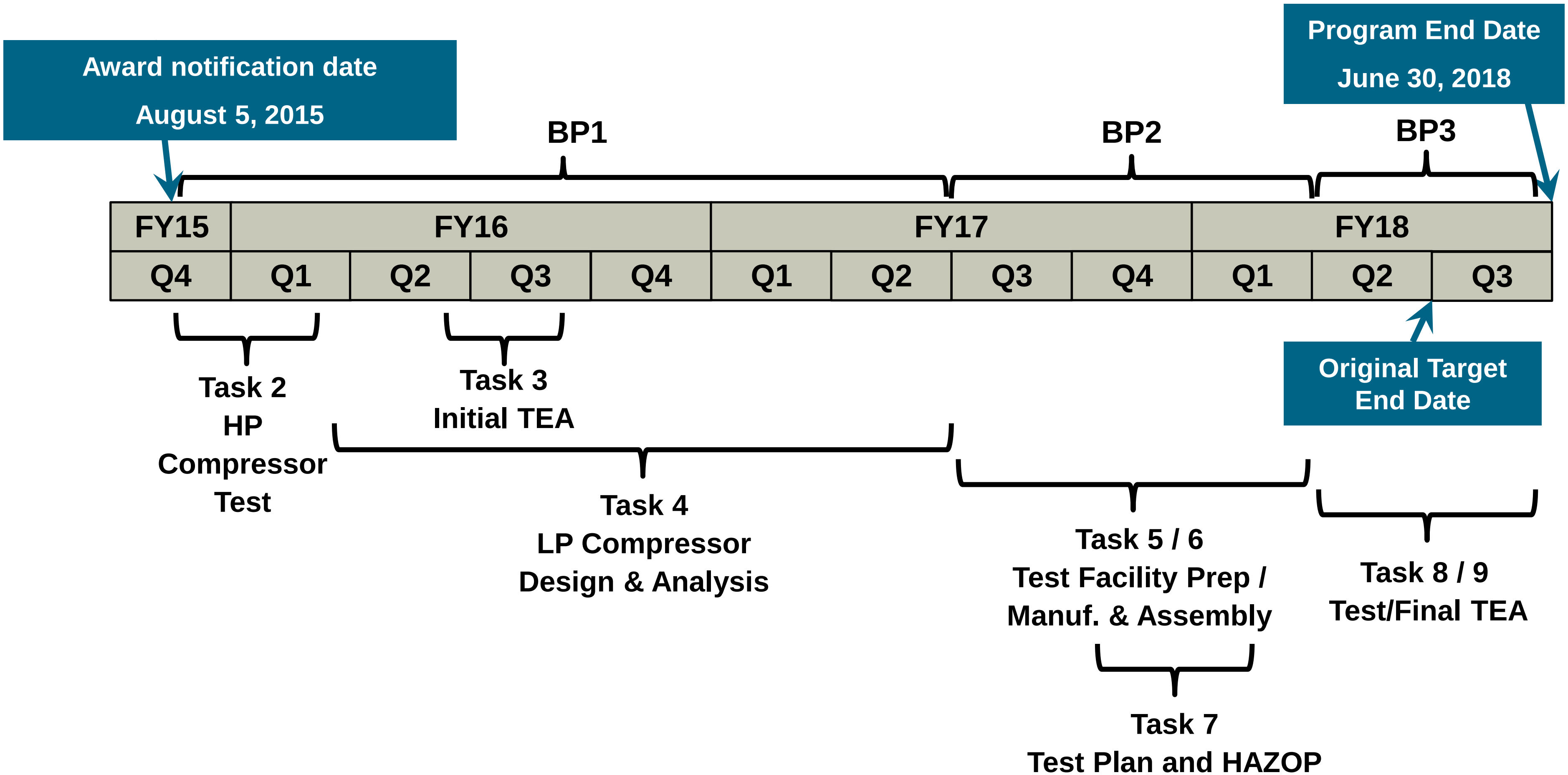

Program executed in 34 months (vs 31 month initial plan)

Unrestricted

Olean: Dedicated High Pressure CO_2 Test Facility

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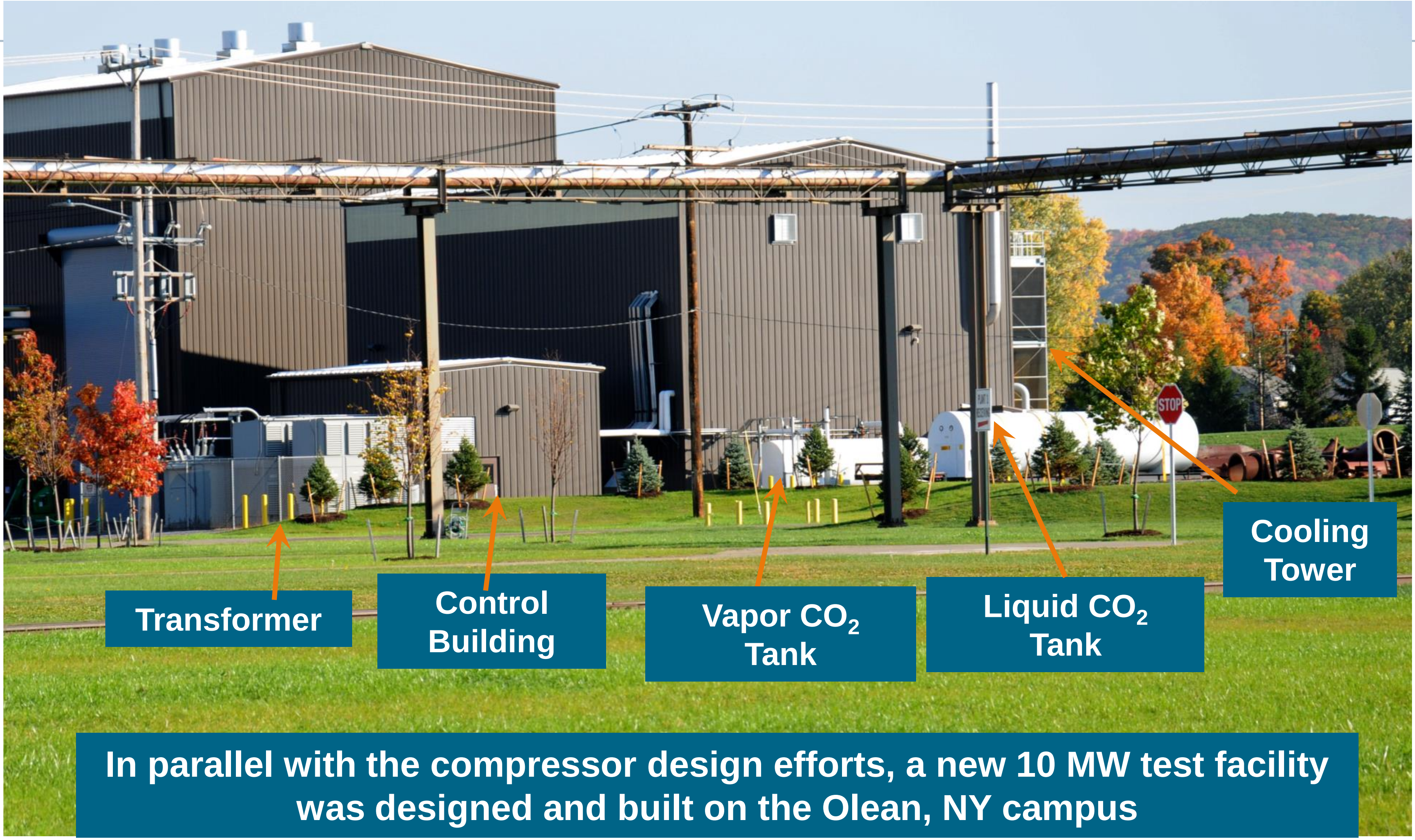

In parallel with the compressor design efforts, a new 10 MW test facility was designed and built on the Olean, NY campus

10MW HP CO_2 Compressor on Test Stand

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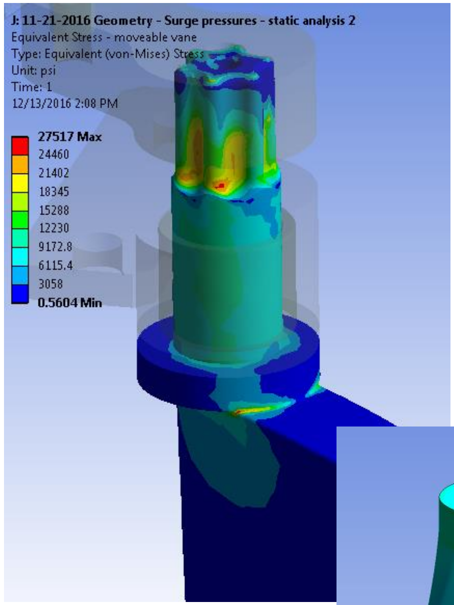
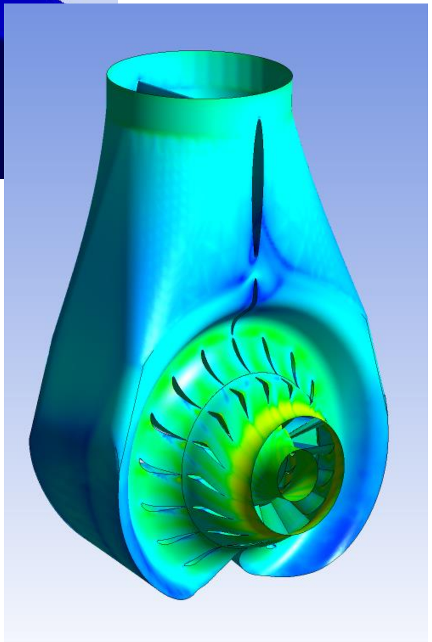
- 10MW electric drive
- Closed loop CO_2
- P1 = 210 psia
- P2 = 2,100 psia

HP and LP unit is sized at ~ 182 MWe , 90% capture 1.5 MTPA of CO_2

DATUM-S LP CO_2 Compressor Design

- LP CO_2 compressor design evolved through the following process
  - System requirements
  - Conceptual design
  - Preliminary design
  - Final design
  - Production readiness and release
- Design decisions were based on extensive analysis of system components
  - Aero : 1D meanline, 3D CFD and flow path optimization
  - Mechanical : structural, modal, thermal and rotor dynamic





Rigorous design process executed to ensure compressor satisfies requirements

DATUM-S Optimization on OLCF's Titan Supercomputer

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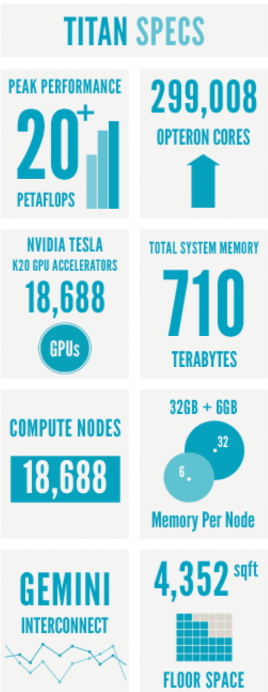

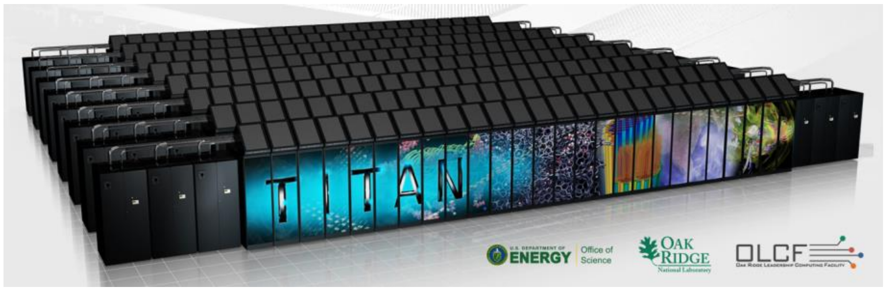

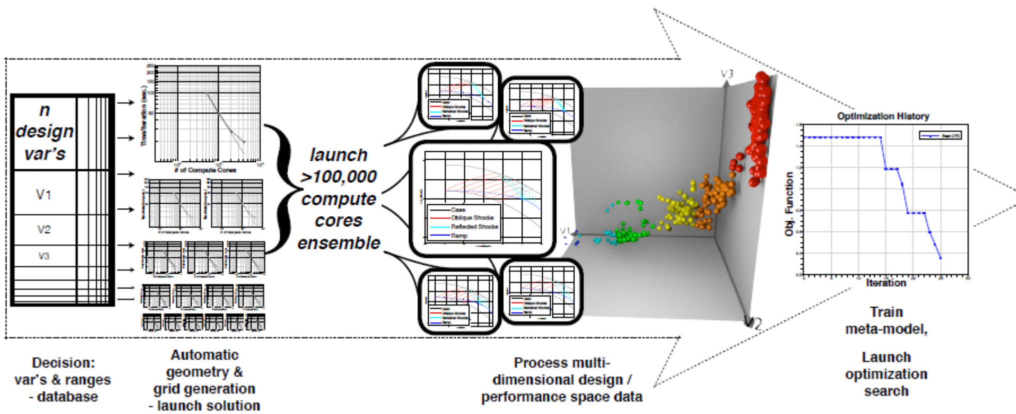

- Intelligently driven optimization is used to maximize compressor performance
- Database generation requires 17,000 simulations, 34 hrs on 128,000 cores
- Each optimization cycle requires evaluation of 600 simulations, 2 hrs on 76,800 cores

- **Access to the DOE OLCF Titan supercomputer has been invaluable to optimize DATUM-S aerodynamic designs**
- **DATUM-S development greatly accelerated by the ORNL Supercomputers**

LP CO_2 Assembly Tooling

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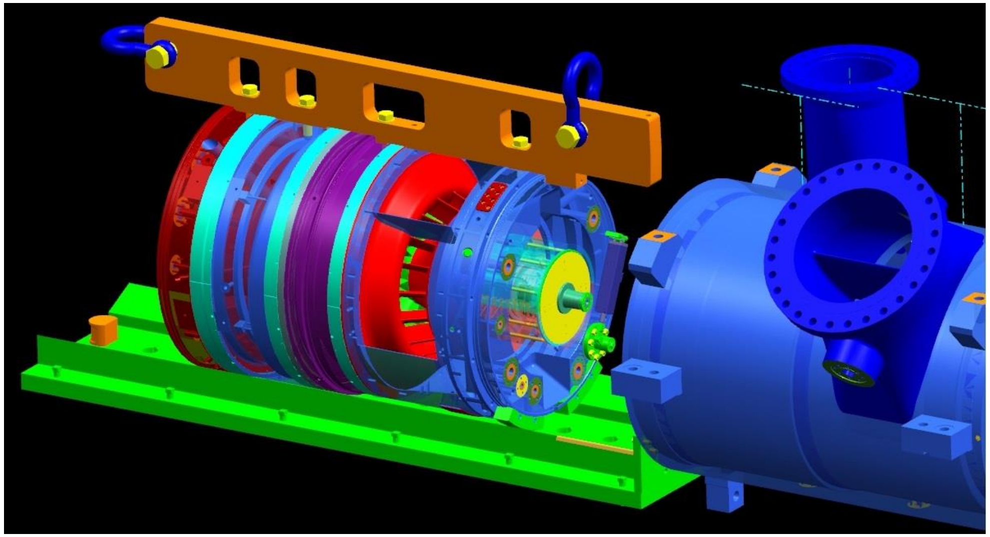

Tooling assemblies for bundle insertion into pressure case

10 MW LP CO_2 Test Configuration

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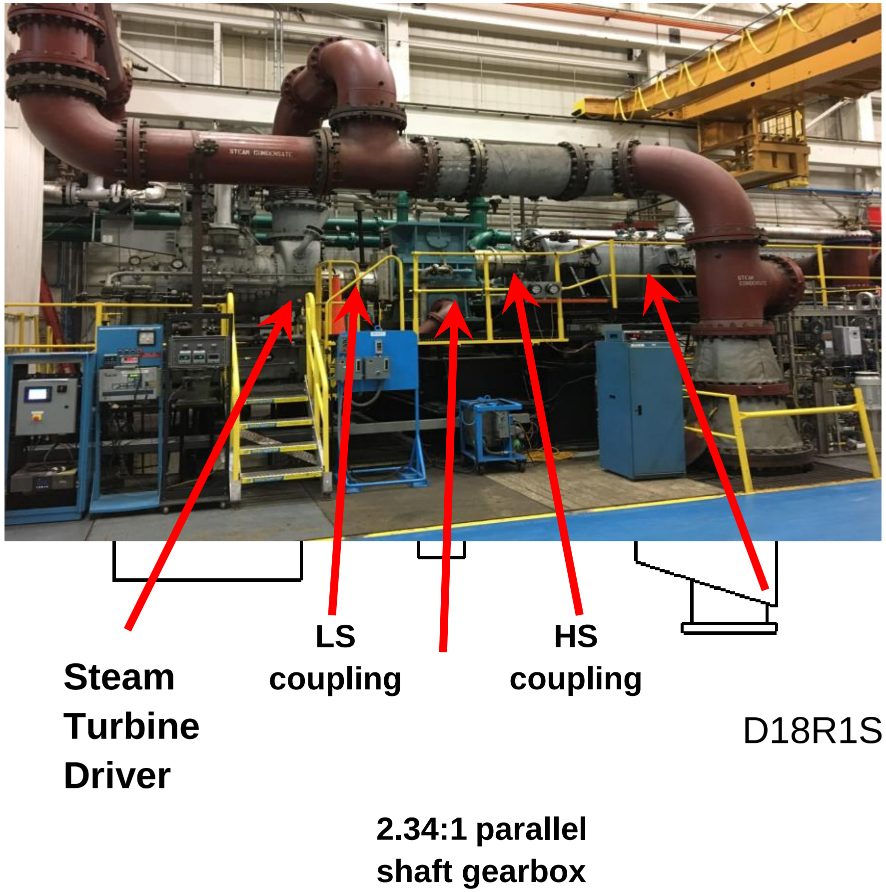
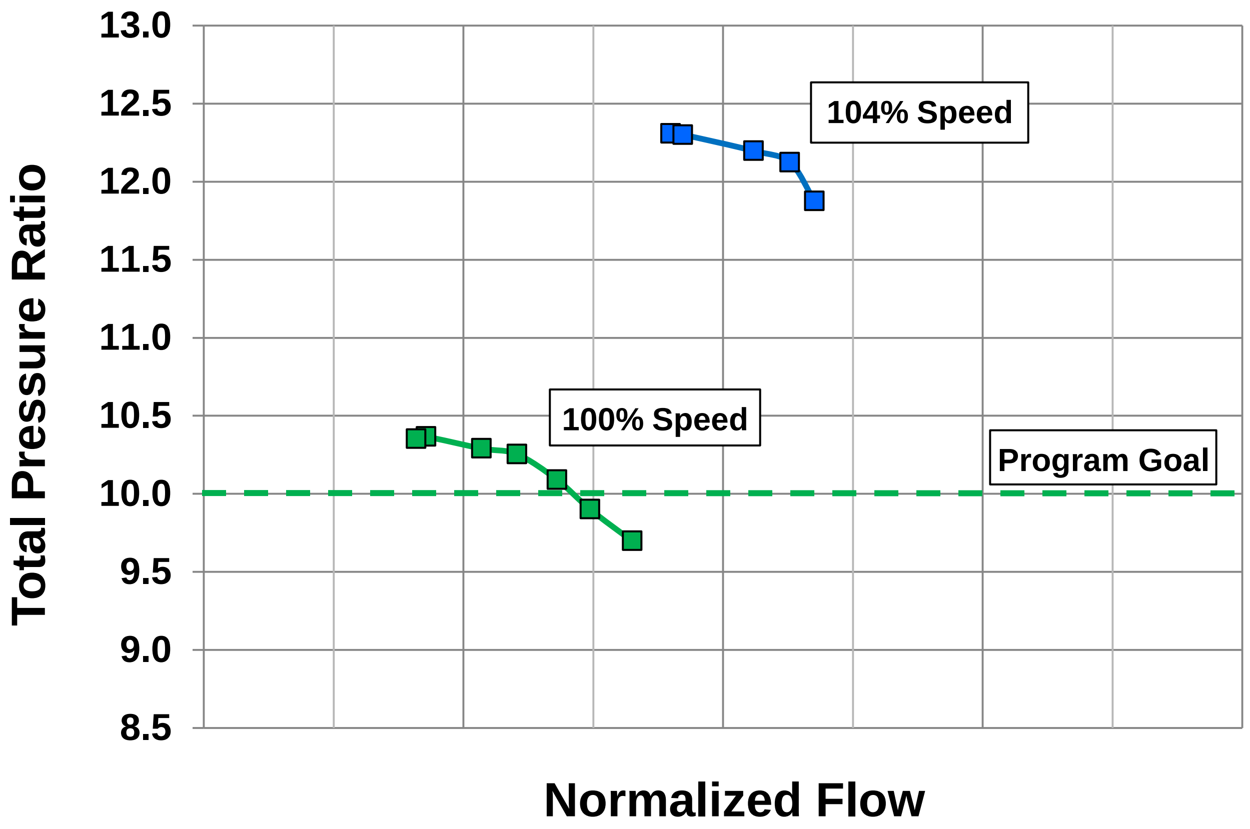
(Typical test arrangement shown for reference)



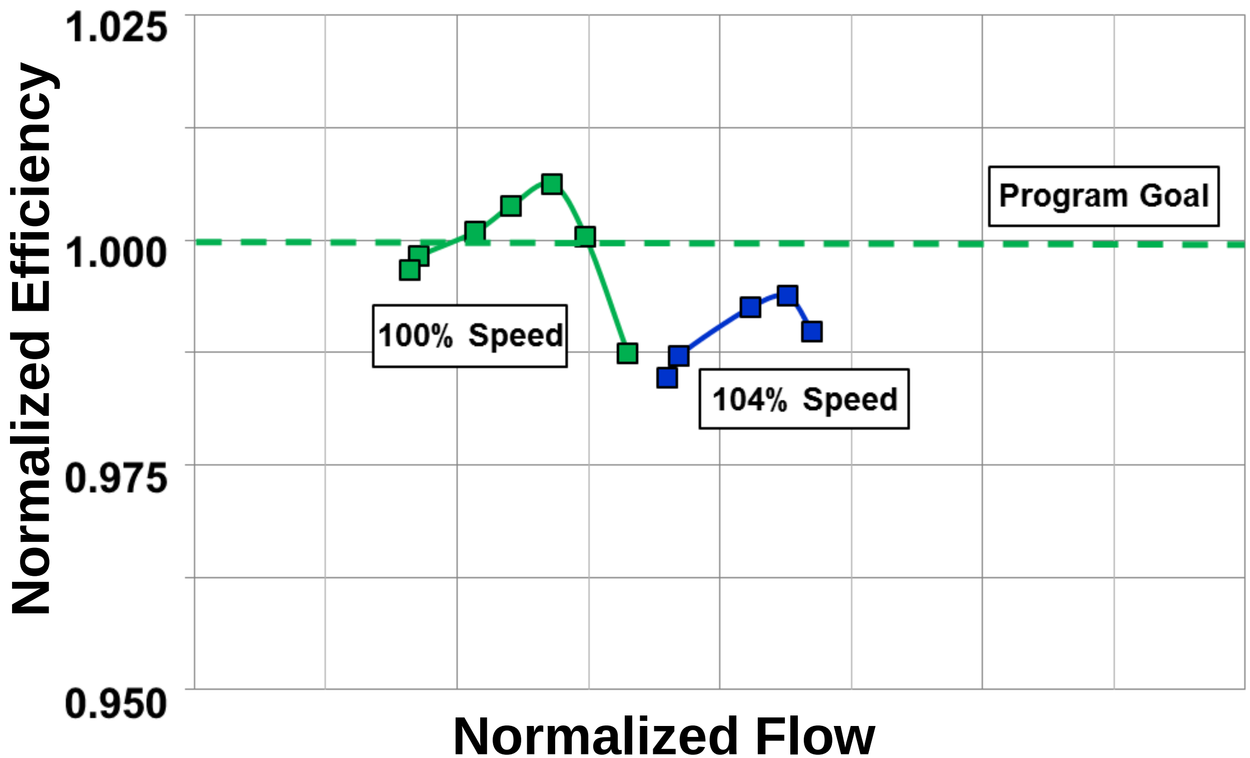
Selected test configuration leverages existing D-R production components to reduce overall program costs

Test Results: Pressure Ratio



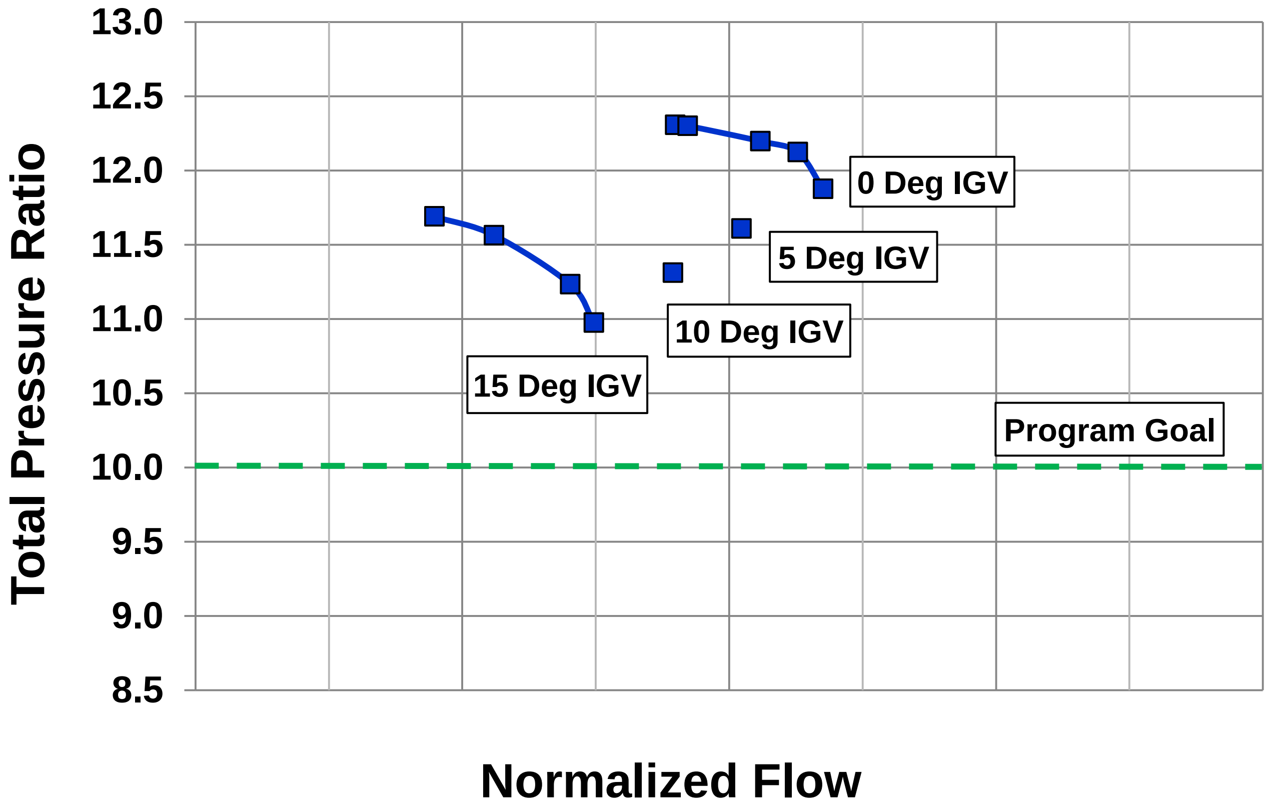
- Compressor achieved program performance target at design operating speed
- At 104% speed compressor achieved a pressure ratio in excess of 12:1
- Use of MIGVs significantly increases the compressor turndown capability
- Good agreement between CFD pre-test prediction and experimental data is observed

Test Results: Efficiency



- Compressor achieved program efficiency target at design operating speed
- At 104% speed a slight decrease in efficiency is observed
- Lessons learned from HP testing were incorporated in the design of the LP unit
- Good agreement between CFD pre-test prediction and experimental data is observed

Test Results: IGV Actuation at 104% Speed



- Compressor IGV actuation at constant speed provided an increase in compressor operating range while achieving a total pressure ratio in excess of the program goal
- Further compressor testing for larger IGV operating angles planned as part of Dresser-Rand internal R&D efforts

Tasks 3.0 - Initial Techno-Economic Analysis

- The Dresser-Rand business performed an initial Techno-Economic Analysis (TEA) to evaluate the benefit of integrating the DATUM-S compressor for a CCS application
- NETL Baseline Case B12B from *Cost and Performance Baseline for Fossil Energy Plants, Volume 1a, Revision 3* was used as a benchmark and baseline
- A thermodynamic tool was created to model the CO_2 compressors, heat exchangers, and changes to the plant steam cycle
- Compressor selection and staging were configured to provide the TEG dryer inlet pressure at 439 psia
- For the initial TEA, a hybrid approach that provides heat to both the amine reboiler and boiler feed water heater was selected
  - CO_2 is routed to amine reboiler and waste heat is recuperated to around 300 ^oF (149 ^oC)
  - Remaining heat energy is used in the feed water heater

Selected approach increases both plant net output power and efficiency, and reduces plant capital cost.

Task 3.0 - Initial Techno-Economic Analysis

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- Existing Case B12B dehydration pressure level constrained DATUM-S compressor ratios, but value of heat integration was still apparent
  - Displaced steam generated 15.8 MWe additional power, for a net gain of 3 MWe electricity (turbine - compressor power) from B12B Baseline
  - Plant CAPEX reduced $15M; COE reduced by $1.17/MWh
  - Circulating cooling water flow reduced by 21,000 gallons per hour

- Case B12B baseline CO_2 compressor underestimated actual power requirement
  - Commercial selection of comparable integrally-geared compressor indicated Case B12B compressor would consume 42.7 MW, a 7 MW increase from the baseline
  - Compared to updated selection, DATUM-S enables a net gain of 10 MWe (turbine - compressor) above the proposed / modified B12B baseline

Initial TEA showed strong benefit from DATUM-S with heat integration

Task 9.0 - Final Techno-Economic Analysis

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	Case B12B	Case B12B alternate	DATUM S w/ heat integration		
	Baseline	Lower IG comp. perf.	Case DR1	Delta to baseline	Delta to alternate
Gross Power, MWe	641.5	641.5	656.3	14.8	14.8
Aux Load, MWe	91.3	99.7	104.7	13.4	5.0
Net Power, MWe	550.2	541.8	551.6	1.4	9.8
HHV Net Plant Eff., %	32.5%	32.0%	32.6%	0.1%	0.6%
HHV Net Plant Heat Rate, Btu/kWh	10,508	10,672	10,482	-26	-190
COE w/o T&S, $/MWh	133.17	135.40	132.13	-1.04	-3.27
$\Delta COE/COE_{comp}$, %	—	—	—	-10%	-27%

Significant CAPEX and COE reduction achieved with DATUM-S and heat integration

Task 9.0 - Final Techno-Economic Analysis

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	Case B12B alternate	DATUM S w/ heat integration		DATUM S w/ improved heat integration	
	Lower IG comp. perf.	Case DR1	Delta to alternate	Case DR2	Delta to alternate
Gross Power, MWe	641.5	656.3	14.8	657.0	15.5
Aux Load, MWe	99.7	104.7	5.0	104.3	4.6
Net Power, MWe	541.8	551.6	9.8	552.7	10.9
HHV Net Plant Eff., %	32.0%	32.6%	0.6%	32.6%	0.6%
HHV Net Plant Heat Rate, Btu/kWh	10,672	10,482	-190	10,460	-212
COE w/o T&S, $/MWh	135.40	132.13	-3.27	131.95	-3.45
$\Delta COE/COE_{comp}$, %	—	—	-27%	—	-28%

Sensitivity study (closer HX approach, better utilization of heat) shows even larger benefit

Task 9.0 - Final Techno-Economic Analysis

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- For the final Techno-Economic Analysis, the plant architecture remained the same as for the initial TEA, with the heat of compression displacing steam used in the amine reboiler and boiler feedwater heaters.
- Case B12B dehydration pressure level was not altered (439 PSIA). This constrained DATUM-S compressor ratios as in the initial TEA.
  - Co-optimization of the TEG dehydration pressure and DATUM-S pressures represents an opportunity to further improve TEA results.
- Thermodynamic model was updated for the final TEA:
  - Excel model was replaced with one in Thermoflex
- Heat integration from the DATUM-S results in significant improvement
  - Displaced steam generated 14.8 MWe additional power, for a net gain of 1.4 MWe electricity from B12B Baseline
  - Plant CAPEX reduced $16M; COE reduced by $1.04/MWh
  - Circulating cooling water flow reduced by 21,500 gallons per hour
- Case B12B baseline CO_2 compressor underestimated actual power requirement
  - Commercial selection of comparable integrally-geared compressor indicated Case B12B compressor would consume 44.0 MW, an 8.3 MW increase from the baseline
  - Compared to updated selection, DATUM-S enables a net gain of almost 10 MWe above the proposed/modified B12B baseline

Final TEA shows strong benefit from DATUM-S with heat integration

Summary

- Completed HP and LP compressor testing
  - 11.5:1 pressure ratio in HP
  - 12.0:1 pressure ratio in LP
  - Discharge temperature is approximately ~550F
- Completed final TEA for integration of waste heat shows benefit for Carbon Capture and Sequestration applications
  - 28% reduction in COE for the cost of compression duty
  - 21,000 gallon reduction in cooling water
- Program was executed in 34 months compared to 31 month original schedule
- Program was executed within 1.6% of total initial budget, $8.13M vs $8.00M

Dresser-Rand business continues to develop and commercialize supersonic compression technology to reduce cost and improve efficiency of compression for CCS applications.

Acknowledgements

The Dresser-Rand business gratefully acknowledges DOE/NETL support for the continued development of supersonic compression technology under contracts DE-FE-0000493 and DE-FE00-26727. We would also like to acknowledge Mr. Robin Ames and Ms. Lynn Brickett for the support provided during the execution of this project, and Mr. Travis Shultz for providing information required for the techno-economic analysis.

The Dresser-Rand business also acknowledges the continued support by DOE Oak Ridge Leadership Computing Facility for providing, as part of the ALCC program, the Titan supercomputer time used for the aerodynamic optimization of the DATUM-S HP and LP compressors.

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