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2017 NETL CO_2 Capture Technology Project Review Meeting
Pittsburgh, PA August 21 – 25, 2017

Advanced CO_2 Compression with Supersonic Technology (FE0026727)

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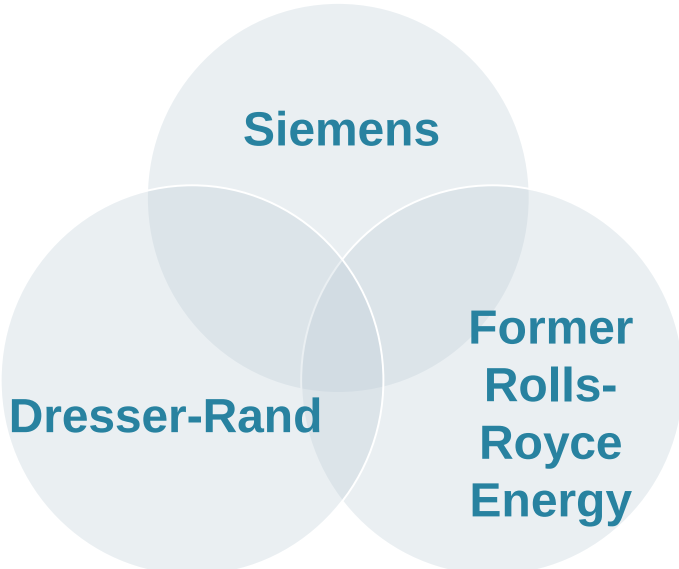
The Dresser-Rand business
Well positioned to compete and bring value to our clients



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

15

Employees

6,300

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

History of Innovation and Technology Leadership

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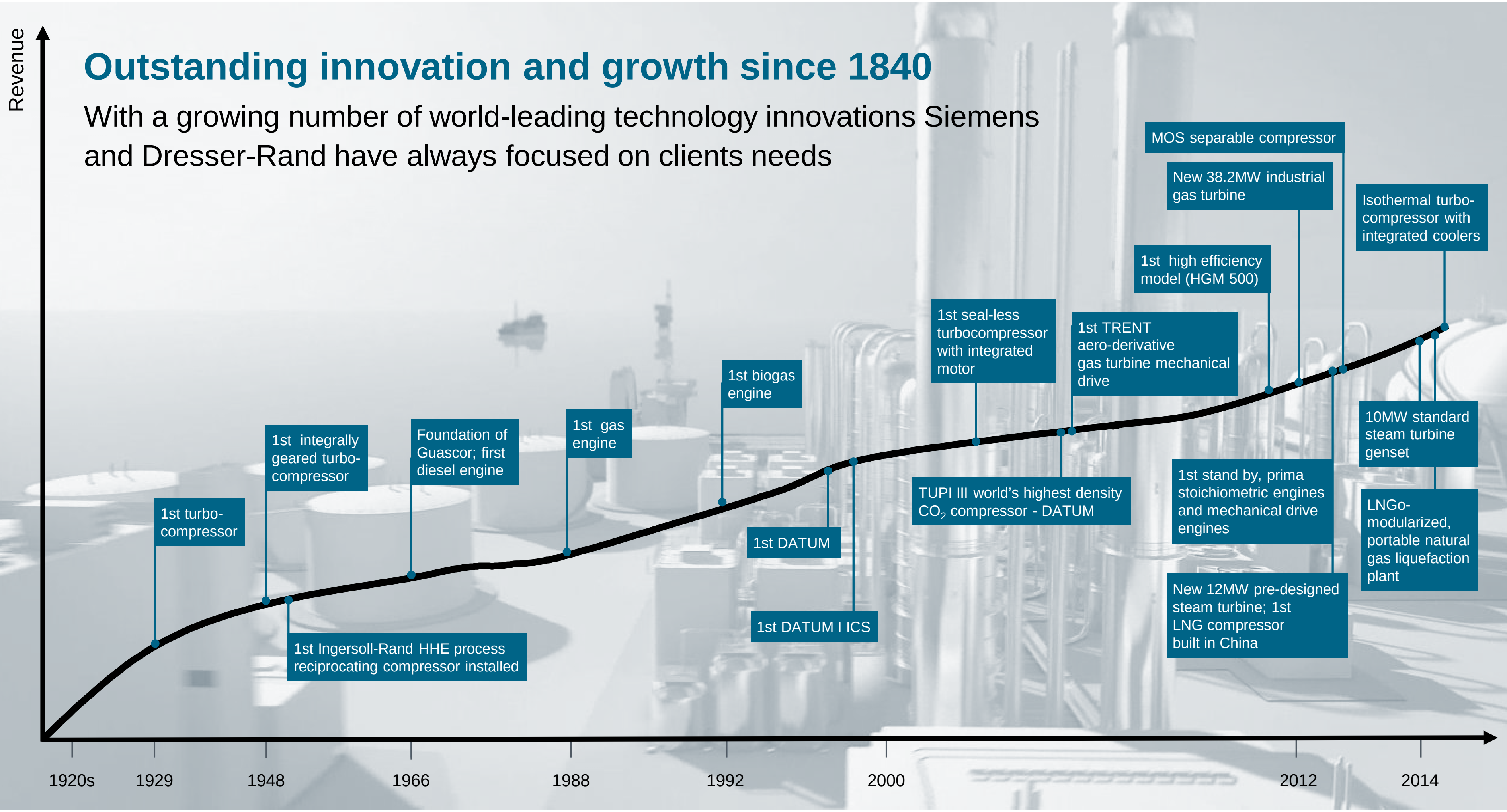
Outstanding innovation and growth since 1840

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 manufacturing underway. Assembly to begin fall 2017 with testing in early 2018

LP/HP 100:1 compressor train is sized at ~ 200 MWe , 90% capture 1.5 MTPA of CO_2

DATUM-S Compressor Program – DOE Partnership

- 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 includes:
  - Additional HP unit testing
  - Design / build / test the high flow LP stage to complete the 100:1 total pressure ratio demonstration
  - LP unit demonstration for early 2018

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

DATUM-S HP and LP Compressors

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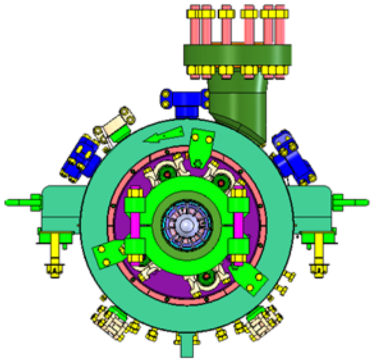
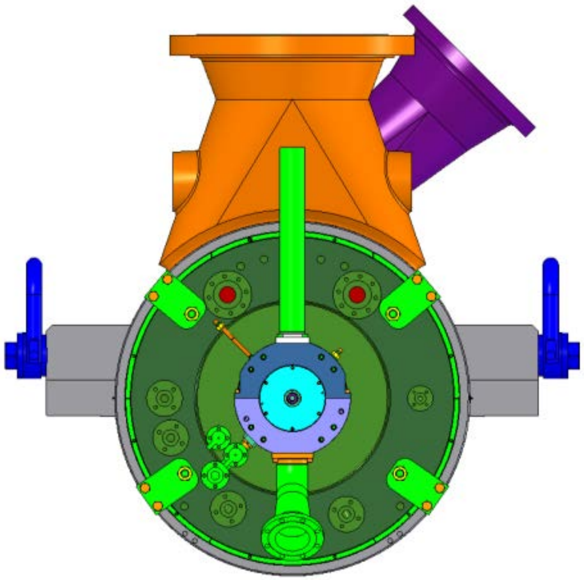
HP Compressor:

Commercial validation testing completed

10:1 PR / 220 psia suction pressure



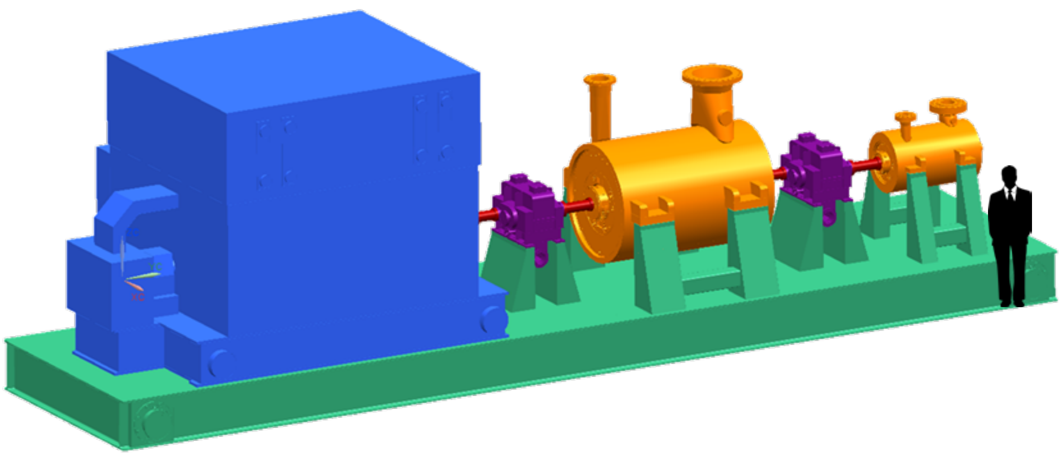


LP Compressor:

In Manufacturing Phase

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

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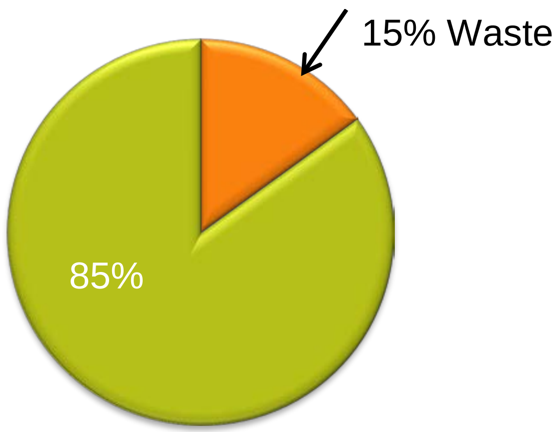
DATUM-S Compressor Benefits

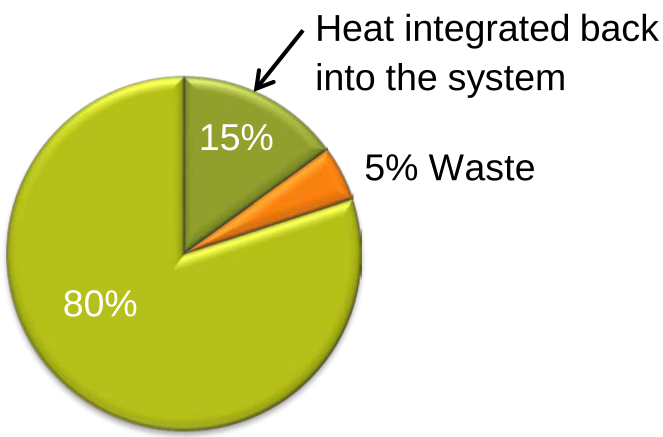
When compared to traditional subsonic compression solutions

- 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





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

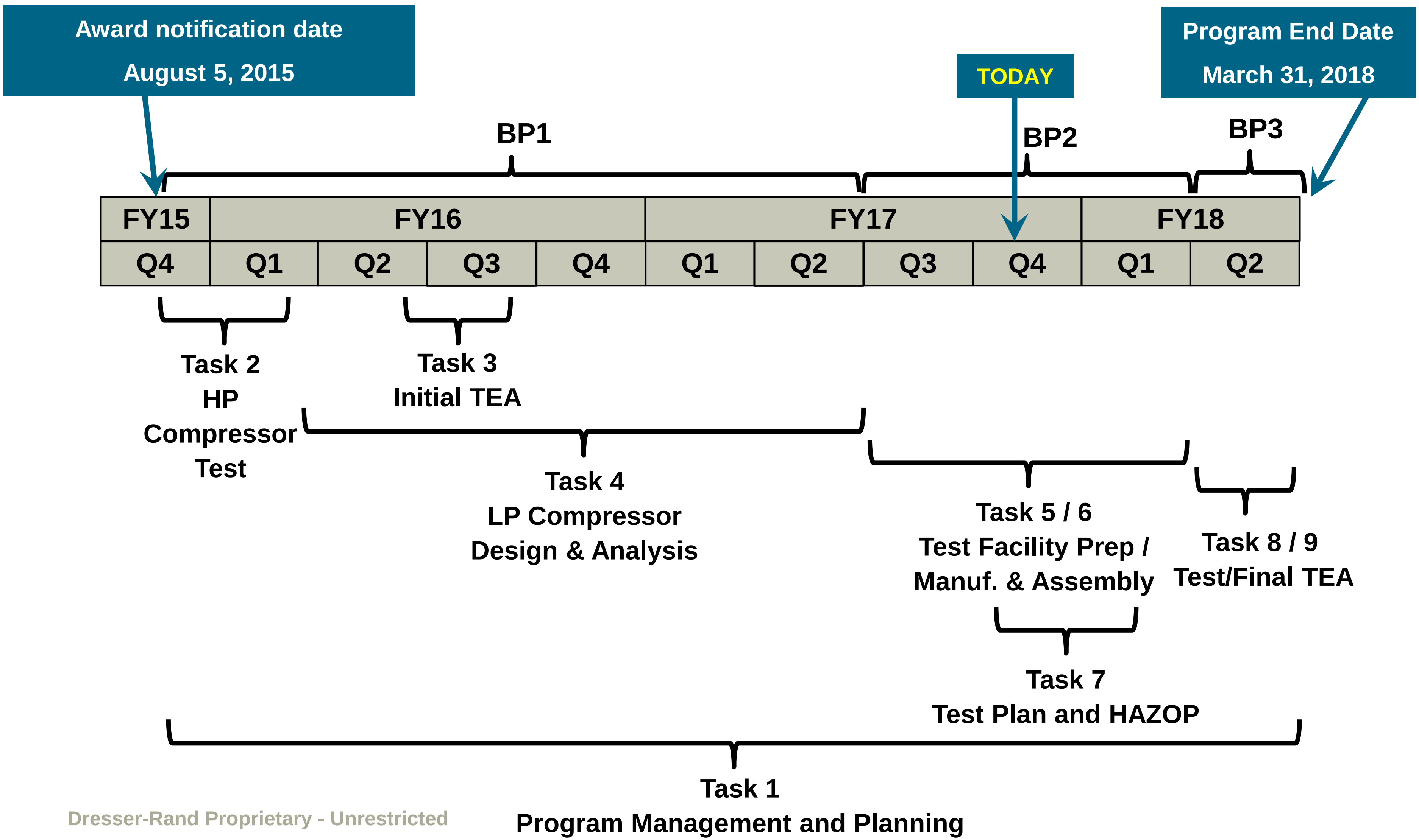
In a DATUM-S compression system that is 80% efficient, 20% of the total energy input manifests itself as mid-grade heat.

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

Multiple Opportunities for Waste Heat Integration

- 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)



Task/Sub-task Summary

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** Tasks completed or underway in green*

Task 1.0 – Project Management and Planning (BP1, BP2, BP3)

Task 2.0 – HP Compressor Test
Task 3.0 – Initial Detailed Techno-Economic Analysis
Task 4.0 – LP Compressor Design and Analysis
- Task 4.1 – Conceptual Design and Analysis
- Task 4.2 – Preliminary Design and Analysis
- Task 4.3 – Aerodynamic Optimization
- Task 4.4 – Final Design

Budget Period 1

Task 5.0 – Testing Facility Preparation
Task 6.0 – Manufacturing and Assembly
- Task 6.1 – Procurement and Fabrication
- Task 6.2 – Compressor Assembly and Instrumentation

Task 7.0 – Test Plan and HAZOP

Budget Period 2

Task 8.0 – Testing and Results Analysis
- Task 8.1 – Compressor Testing
- Task 8.2 – Test Results Analysis and Scaling Validation

Task 9.0 – Final Detailed Techno-Economic Analysis

Budget Period 3

Budget Update

	DOE Contribution	Total Project Spend
Invoiced to DOE through Mar 31, 2017	**$1,488,954**	**$2,977,908**
***Estimated* spend for Apr/May/Jun/Jul 2017**	**$321,234**	**$642,469**
***Estimated* total spend to date**	**$1,810,188**	**$3,620,377**
***Estimated* BP2 spend to date**	**$454,430**	**$908,861**
***Estimated* remaining BP2 spending**	**$1,520,747**	**$3,041,494**
Program Budget for reference only:		
BP1 (Mar 1, 2016 - Mar 31, 2017) Planned Spend:	$1,521,856	$3,043,713
BP2 (Apr 1, 2017 - Dec 31, 2017) Planned Spend:	$1,975,177	$3,950,355
BP3 (Jan 1, 2018 - Mar 31, 2018) Planned Spend:	$502,967	$1,005,932
Total Project Planned Spend:	$4,000,000	$8,000,000

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

- 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

- Final TEA will show the economic benefit of both cases, as well as results of co-optimizing dehydration level and DATUM-S pressure ratio splits

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

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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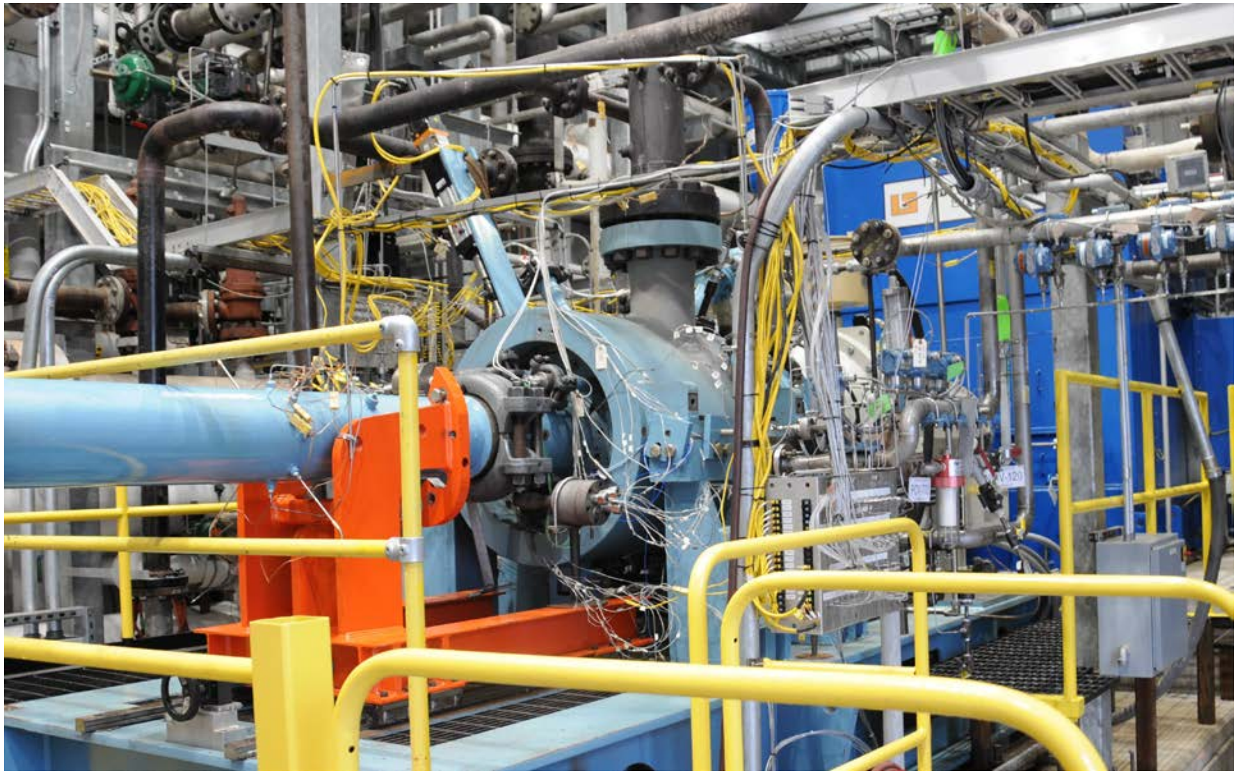

- 10MW electric drive
- Closed loop CO_2
- P1 = 210 psia
- P2 = 2,100 psia

HP unit is sized at ~ 220 MWe , 90% capture 1.5 MTPA of CO_2

DATUM-S Optimization on OLCF's Titan Supercomputer

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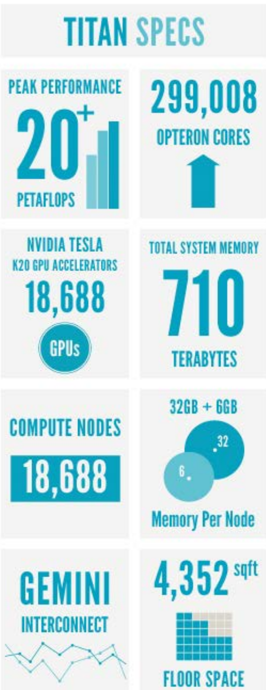
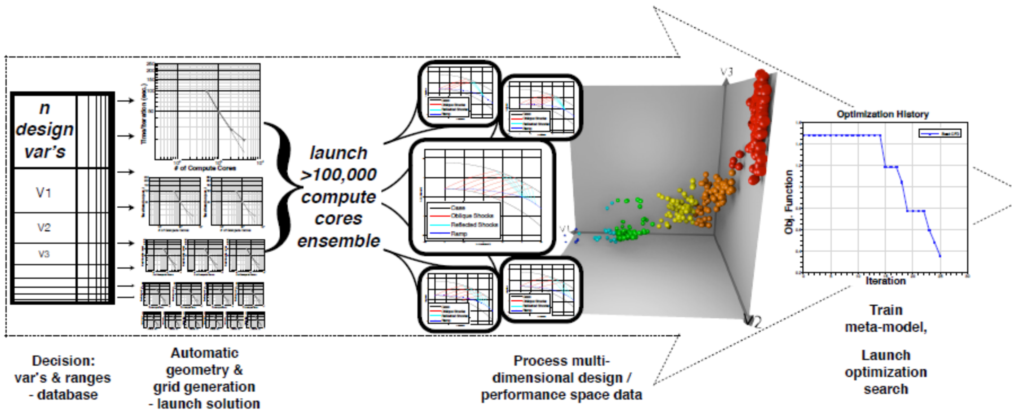
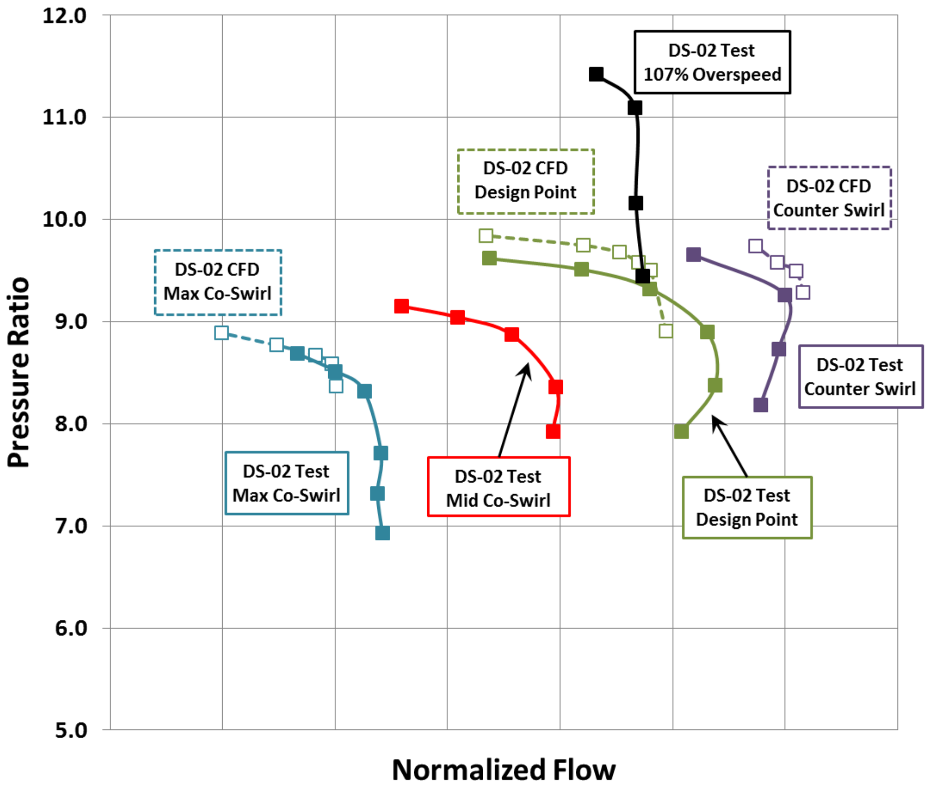




- Intelligently driven optimization is used to maximize compressor performance
- Database generation requires 17,000 simulations, 34 hrs on 128,000 cores
- Each optimization cycle requires evaluation of 600 simulations, 2 hrs on 76,800 cores

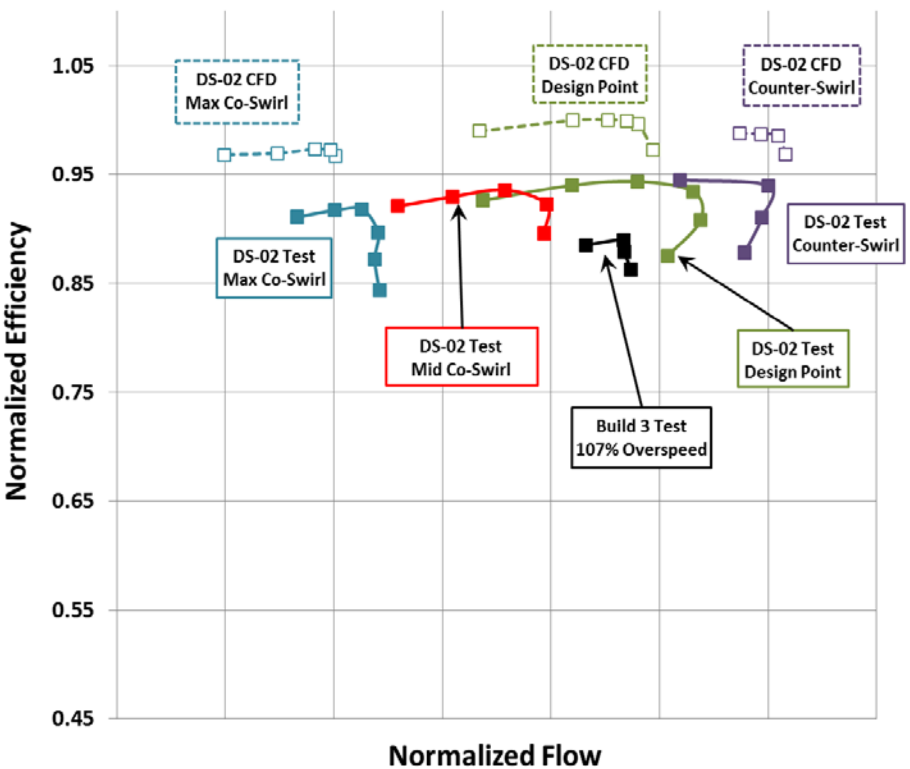
- Access to the DOE OLCF Titan supercomputer has been invaluable to optimize DATUM-S aerodynamic designs
- DATUM-S development greatly accelerated by the ORNL Supercomputers

DATUM-S HP Performance Results: Pressure Ratio



- Testing demonstrated that the DATUM-S compressor can achieve a peak pressure ratio of 11.5:1
- Use of MIGVs increases the compressor turndown capability
- Good agreement between CFD (dashed lines) pre-test prediction and experimental data (solid lines) is observed

DATUM-S HP Performance Results: Efficiency



- Compressor testing demonstrated improved efficiencies compared to prior compressor designs
- Improved agreement between CFD pre-test prediction (dashed lines) and experimental data (solid lines) compared to earlier designs
- Lessons learned form HP testing are being incorporated in the design of the LP unit

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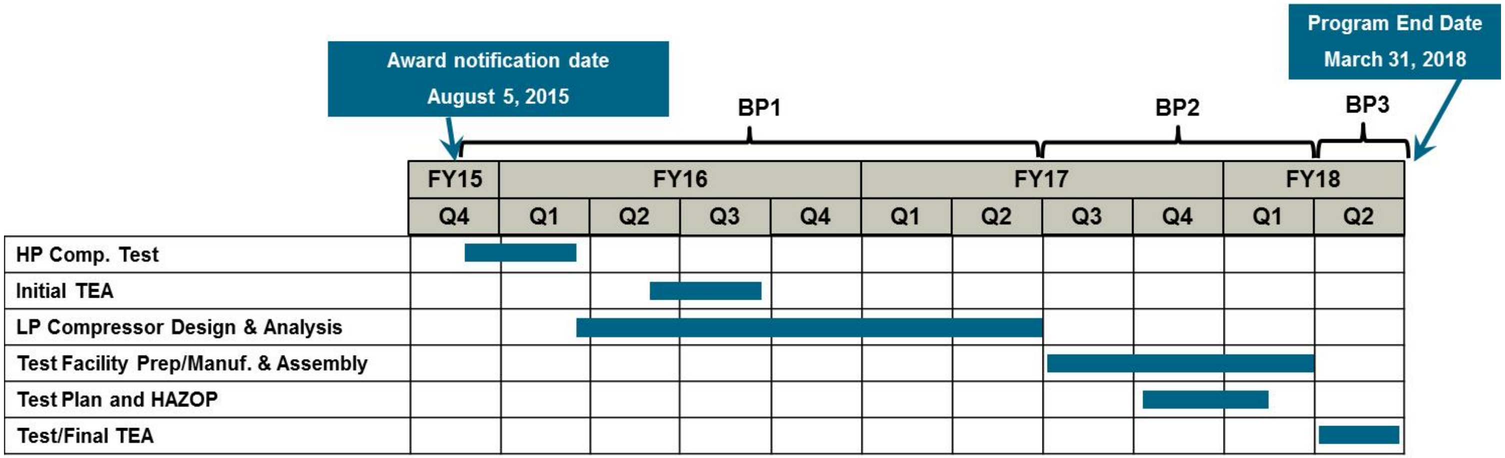
Program Summary



- Completed HP compressor testing and successfully demonstrated operation of a single stage 10:1 unit with discharge temperatures of 550 °F
- Completed initial techno-economic analysis for integration of waste heat showing benefit for Carbon Capture and Sequestration applications
- Completed LP DATUM-S compressor aerodynamic optimization efforts and final design; manufacturing in process, testing January 2018

Advanced CO_2 Compression with Supersonic Technology Program is on target to complete design, manufacturing, and testing of the LP compressor unit by March 31, 2018 within budget.

Summary

- Dresser-Rand business continues to develop and commercialize supersonic compression technology to reduce cost and improve efficiency of compression for CCS applications.
- An initial techno-economic analysis was performed which showed reduced plant capital cost and COE compared to the baseline case B12B from *Cost and Performance Baseline for Fossil Energy Plants, Volume 1a, Revision 3.* Further benefits are expected through system co-optimization and refinement.
- Development testing of the DATUM-S HP compressor demonstrated that the unit can achieve a pressure ratio of 11.5:1 at MCOS.
- Final design of the LP compressor complete; program is on schedule to meet target dates for start of testing and program completion.

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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