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Advanced CO_2 Compression with Supersonic Technology

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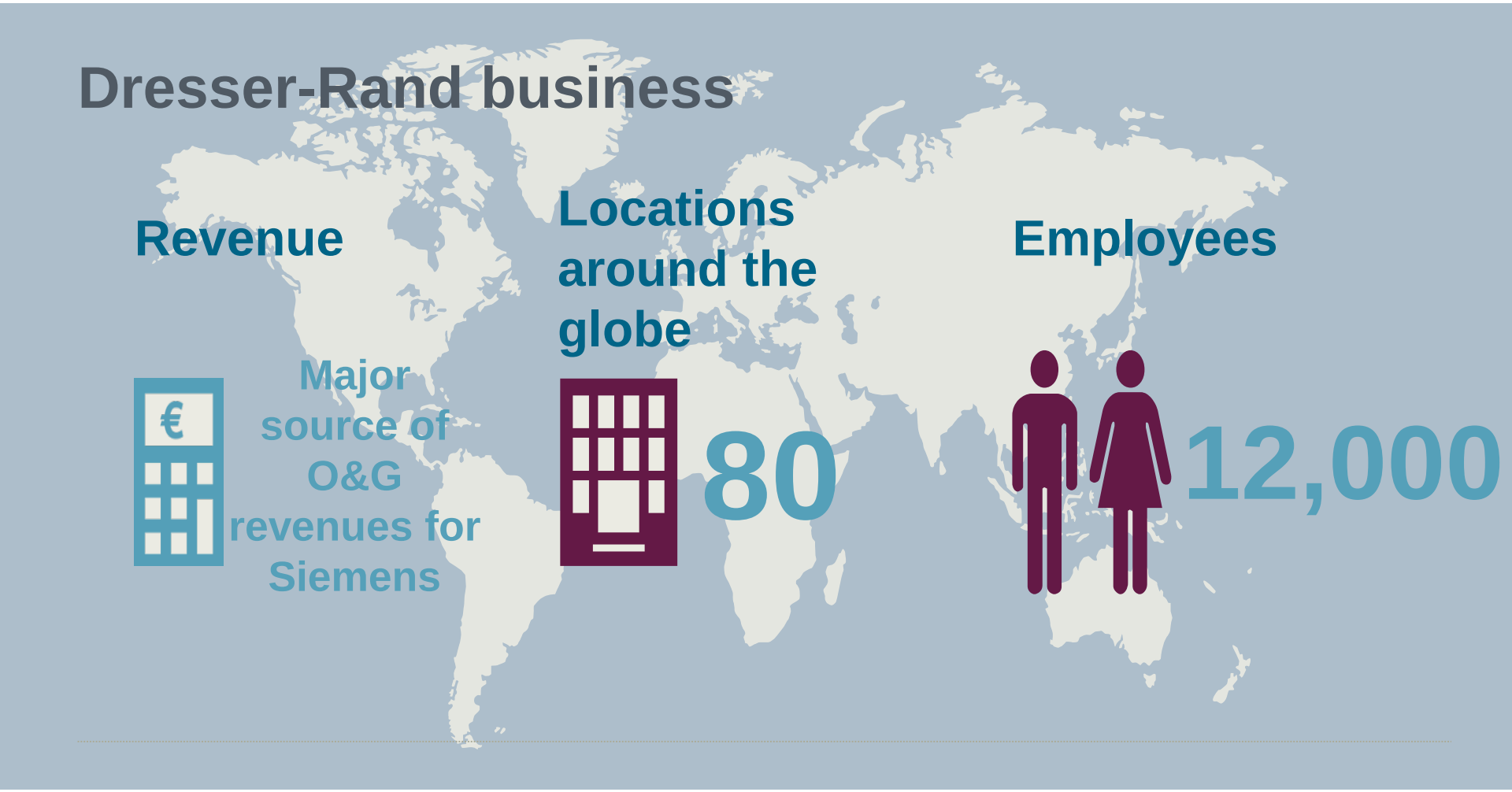
The Dresser-Rand Business at a Glance



Combining Two Premium Brands

- **The strengths of the Siemens and Dresser-Rand brands are complementary**
- **Siemens,** Power and Gas Division, offers a broad spectrum of products and solutions for the environmentally compatible and resource-saving generation of electricity from fossil fuels and for the reliable transport of oil and natural gas
- **The Dresser-Rand business** is a leading supplier of high-speed rotating equipment solutions with the largest installed base in the industry
- No other competitor can offer our **global and financial strengths, combined with close client relationships and rotating equipment technology expertise** in oil and gas and environmental solutions

History of Innovation and Technology Leadership

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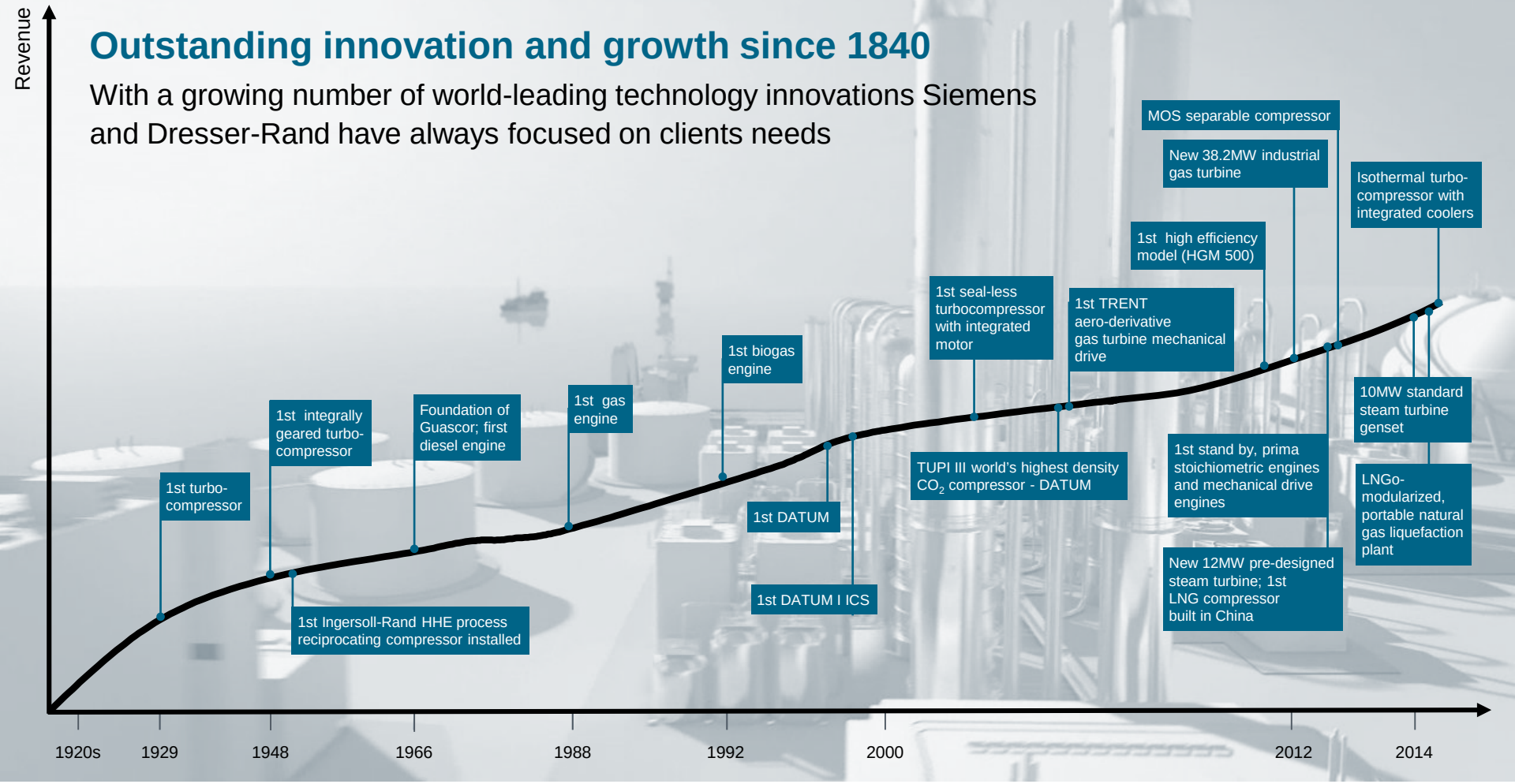
Outstanding innovation and growth since 1840

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

The U.S. Department of Energy partnered with 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

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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 compressor test phase concluded with successful demonstration of CO_2 shockwave compression

2014 Second 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 CO_2 compressor test phase (DATUM S) concluded; achieved 11.5:1 pressure ratio at maximum continuous operating speed (MCOS)

HP unit is sized at ~ 220 MWe , 90% capture 1.5 MTPA of CO2

DATUM-S Compressor Program – DOE Partnership

- Selection notification announced Aug 13, 2015: DE-FOA-0001190
- New 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 coefficient LP stage to complete the 100:1 total pressure ratio demonstration
  - LP unit demonstration planned for late 2017 and into early 2018

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

Development Testing History

DE-FE-0000493
"*Ramgen Supersonic Shock Wave Compression and Engine Technology*"

Program Complete March 31, 2015

50:50 cost share

DE-FE00-26727
"*Small and Large Scale Pilots for Reducing the Cost of CO_2 Capture and Compression*"

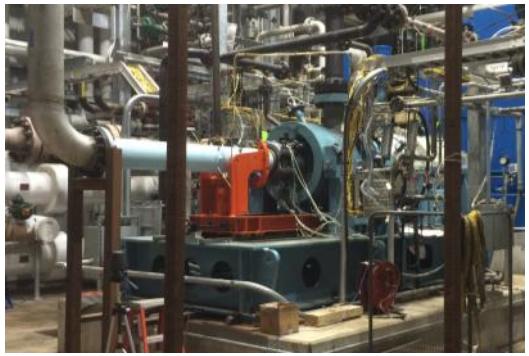
November 2015 – March 2018

50:50 cost share

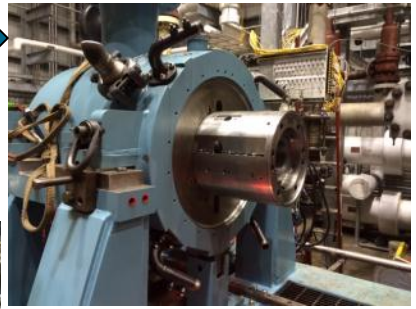
2013 | 2014 | 2015 | 2016 | 2017 | 2018

Build 1 – Gen2 Rampressor

Build 2 - Supercompressor



Build 3 – DATUM S



DATUM S Pilot Demonstration

DATUM-S Compressor Benefits

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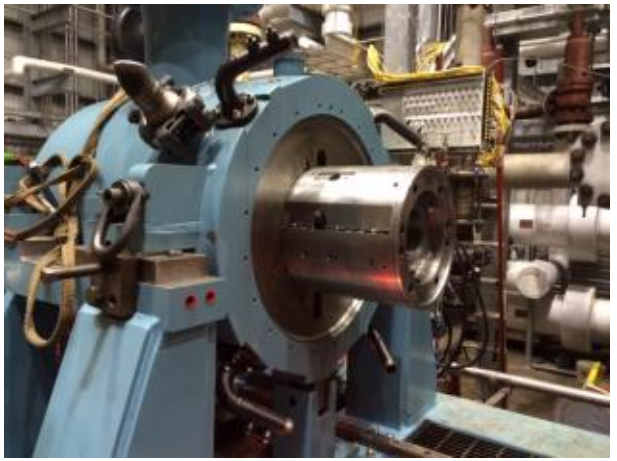
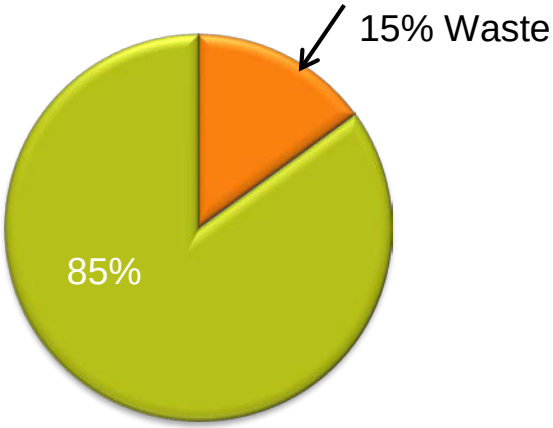
When compared to traditional subsonic compression solutions

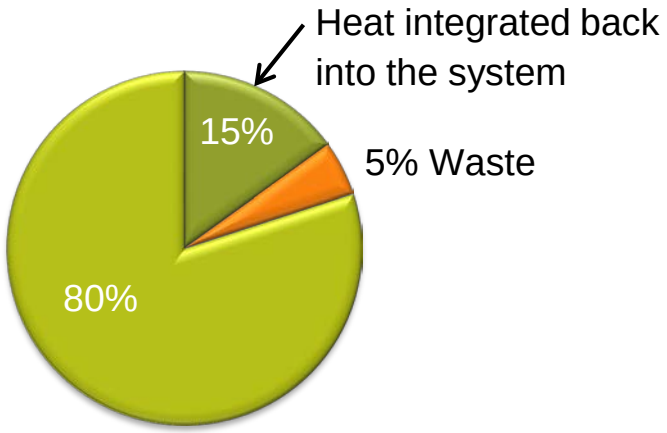
- Smaller footprint, less equipment, less piping, fewer coolers
- Higher compression ratios
- Reduced need for gas intercooling
- Discharge temperatures exceeding 550°F (290°C)
- Waste heat recovery enables unmatched overall system efficiency



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.

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

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

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

- 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.

Initial Techno-Economic Analysis Conclusions

- The TEA demonstrates a reduction in plant capital cost and decrease of COE can be obtained through DATUM-S CO_2 compression and heat integration
- Compressor heat integration also allows for a significant reduction in cooling water needed for compressor inter- and after-cooling compared to the water-cooled integrally-geared compressor in Case B12B
  - Allows subsequent reductions in the power, size, and cost of the make-up water system, circulating water pump, cooling tower, and cooling tower fans
- Further benefits are expected through system co-optimization and refinement

High-Pressure CO_2 Test Facility

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In parallel with the Gen1 design efforts, a new 10 MW, 2,200 PSI test facility was designed and built on the Olean, NY campus.

10MW HP CO_2 Compressor on Test Stand

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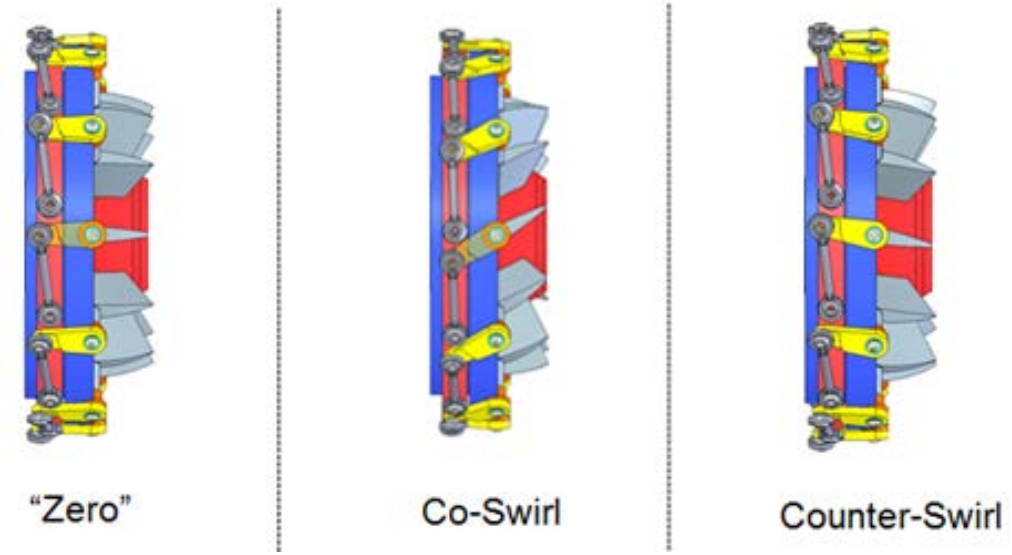
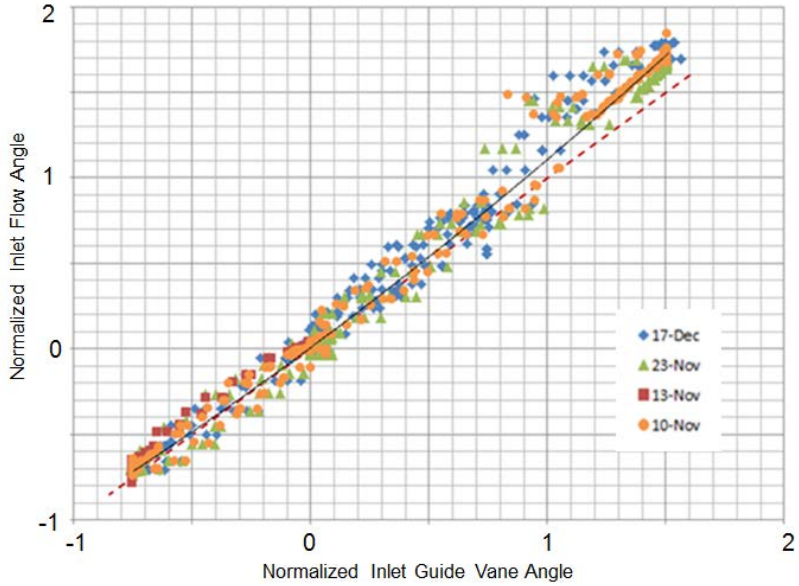
- 10MW electric drive
- Closed loop CO_2
- P1 = 210 psia
- P2 = 2,100 psia

HP unit is sized at ~ 220 MWe , 90% capture 1.5 MTPA of CO2.

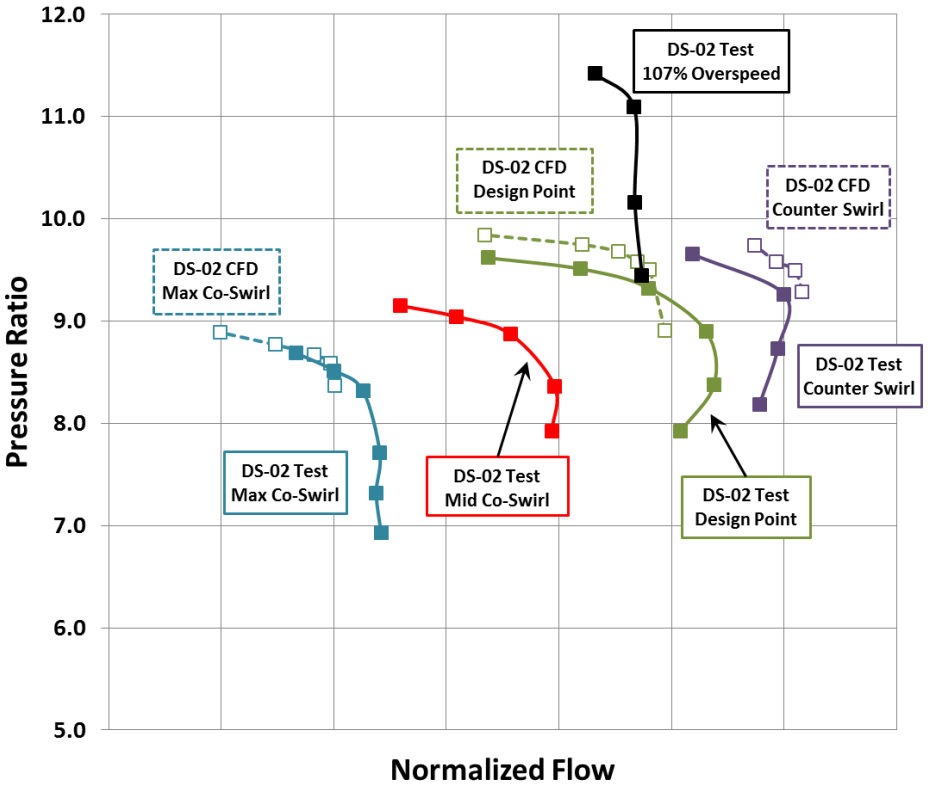
DATUM-S HP Compressor Testing





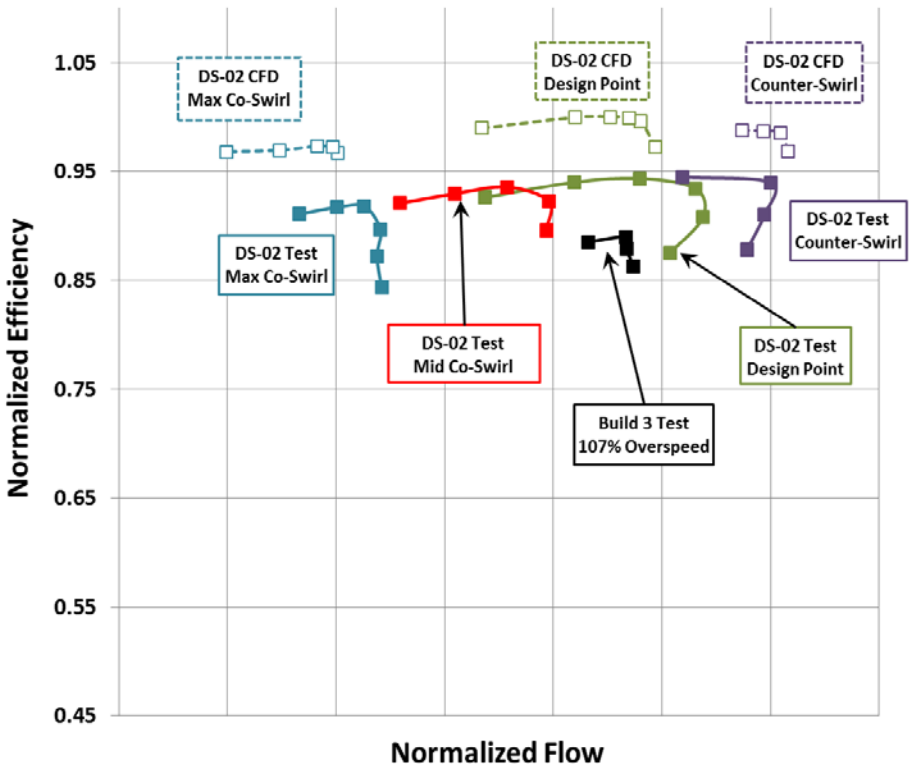
- In September 2015, Dresser-Rand began performance testing of the second iteration of the DATUM-S compressor design
- Moveable inlet guide vanes (MIGV) were incorporated to change the angle of the gas flow into the inducer providing better aerodynamic turndown for changes in CO_2 volume flow

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 significantly 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
- Small efficiency penalty is observed when the MIGVs are actuated
- 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

DATUM-S Optimization on OLCF's Titan Supercomputer

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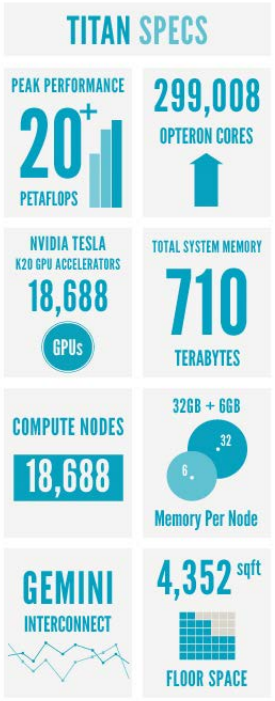
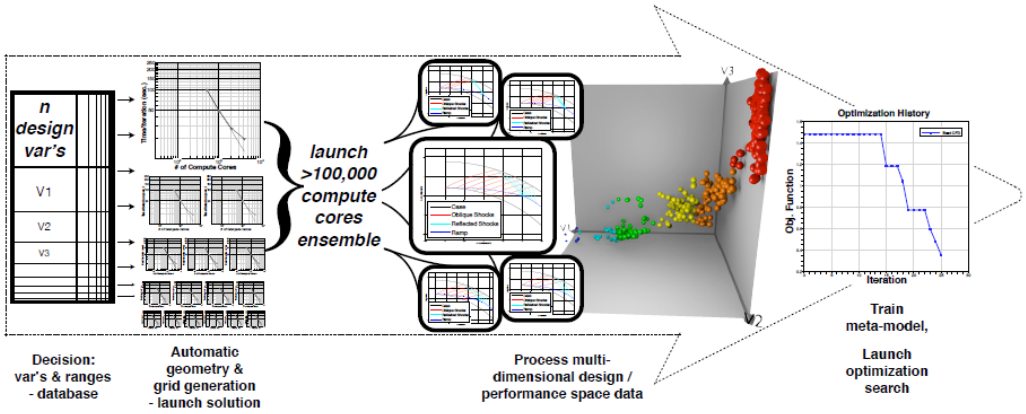
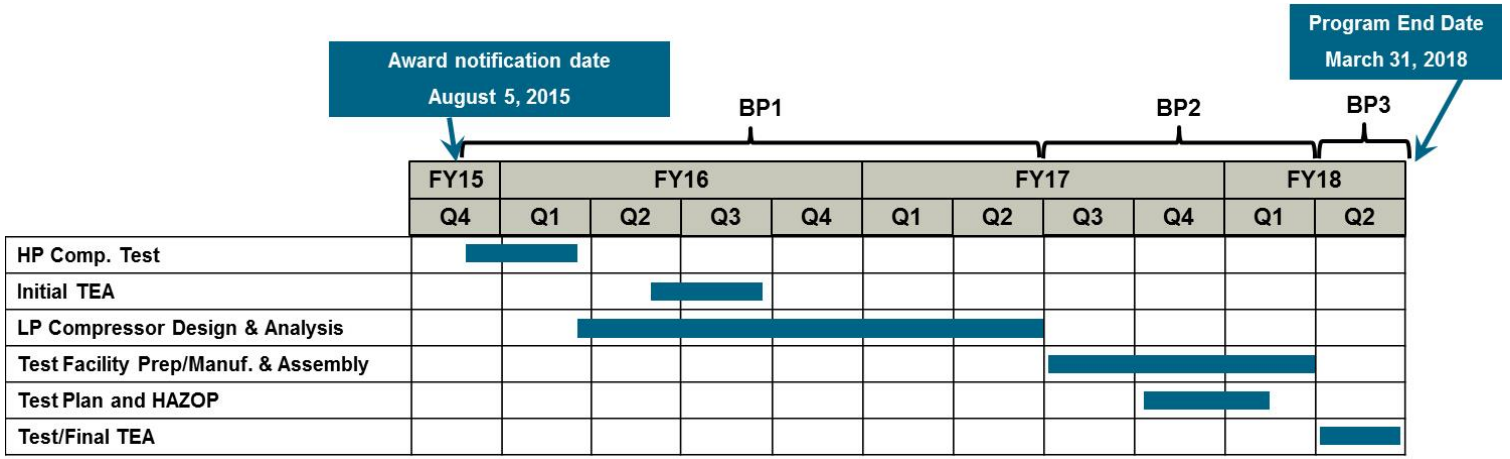




- Intelligently driven optimization is used to maximize compressor performance
- Database generation requires 17,000 simulations, 34 hrs on 128,000 cores
- Each optimization cycle requires evaluation of 600 simulations, 2 hrs on 76,800 cores

- 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

Program Status



- Completed HP compressor testing and successfully demonstrated operation of a single stage 10:1 unit with discharge temperatures of 550 ^{o}F
- Completed initial techno-economic analysis for integration of waste heat showing benefit for Carbon Capture and Sequestration applications
- Completed LP DATUM-S compressor conceptual design and analysis; preliminary compressor design and aerodynamic optimization efforts ongoing

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.
- Conceptual 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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