DRESSER-RAND

CO_2 Compression for Fossil Fuel-fired Power Plants

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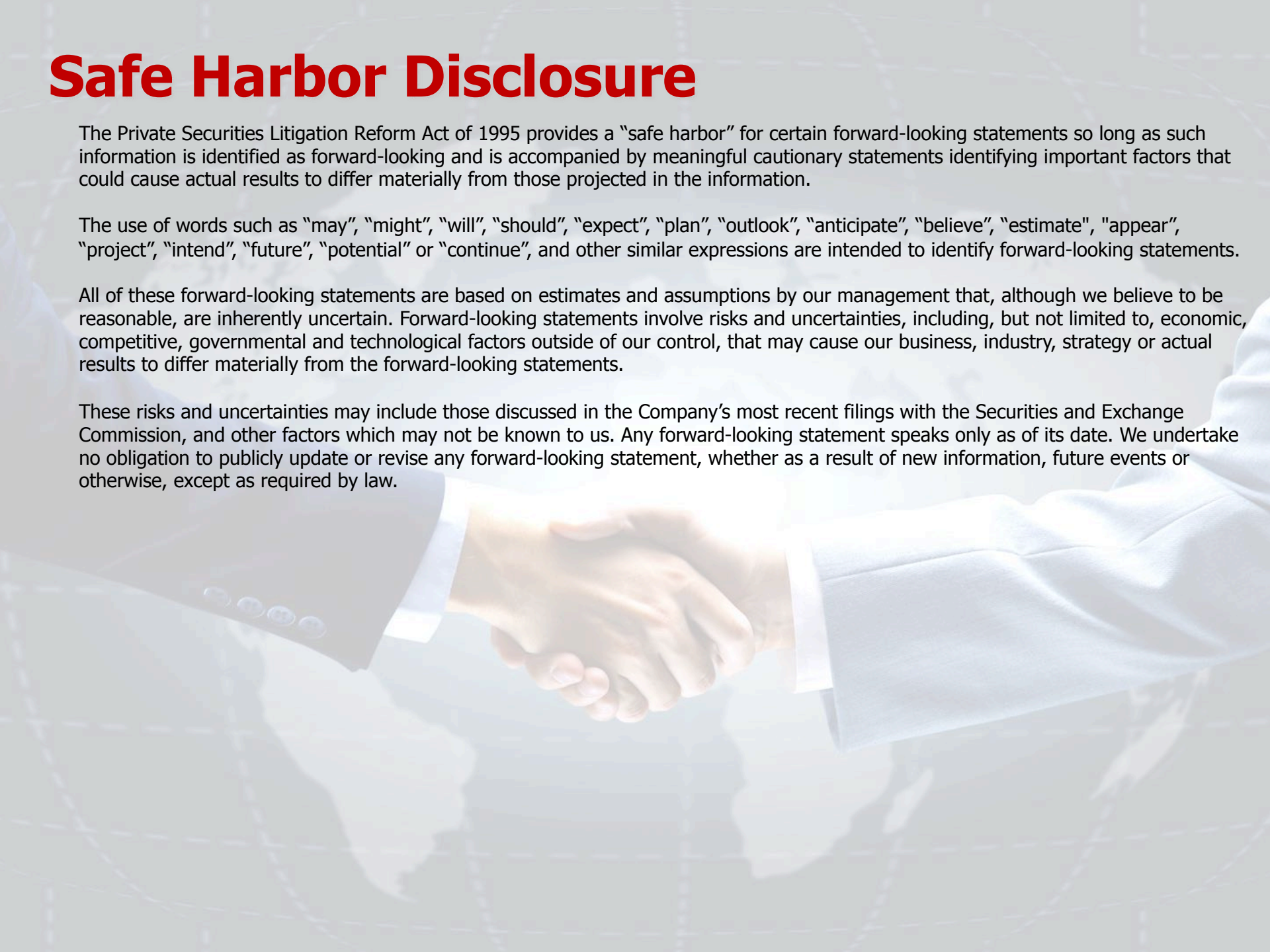
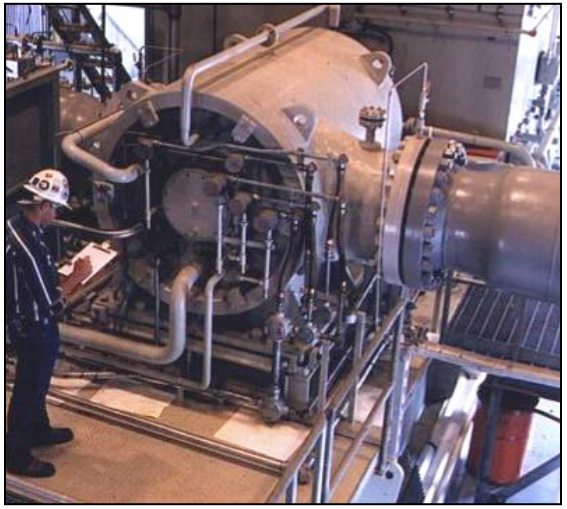


Outline

- Brief Overview of the Power Penalty
- Review of Compression Technology Research
  - Multi-stage centrifugal
  - Intercooled centrifugal (liquid cooled diaphragm)
  - Shockwave – high ratio compression
- Conclusions



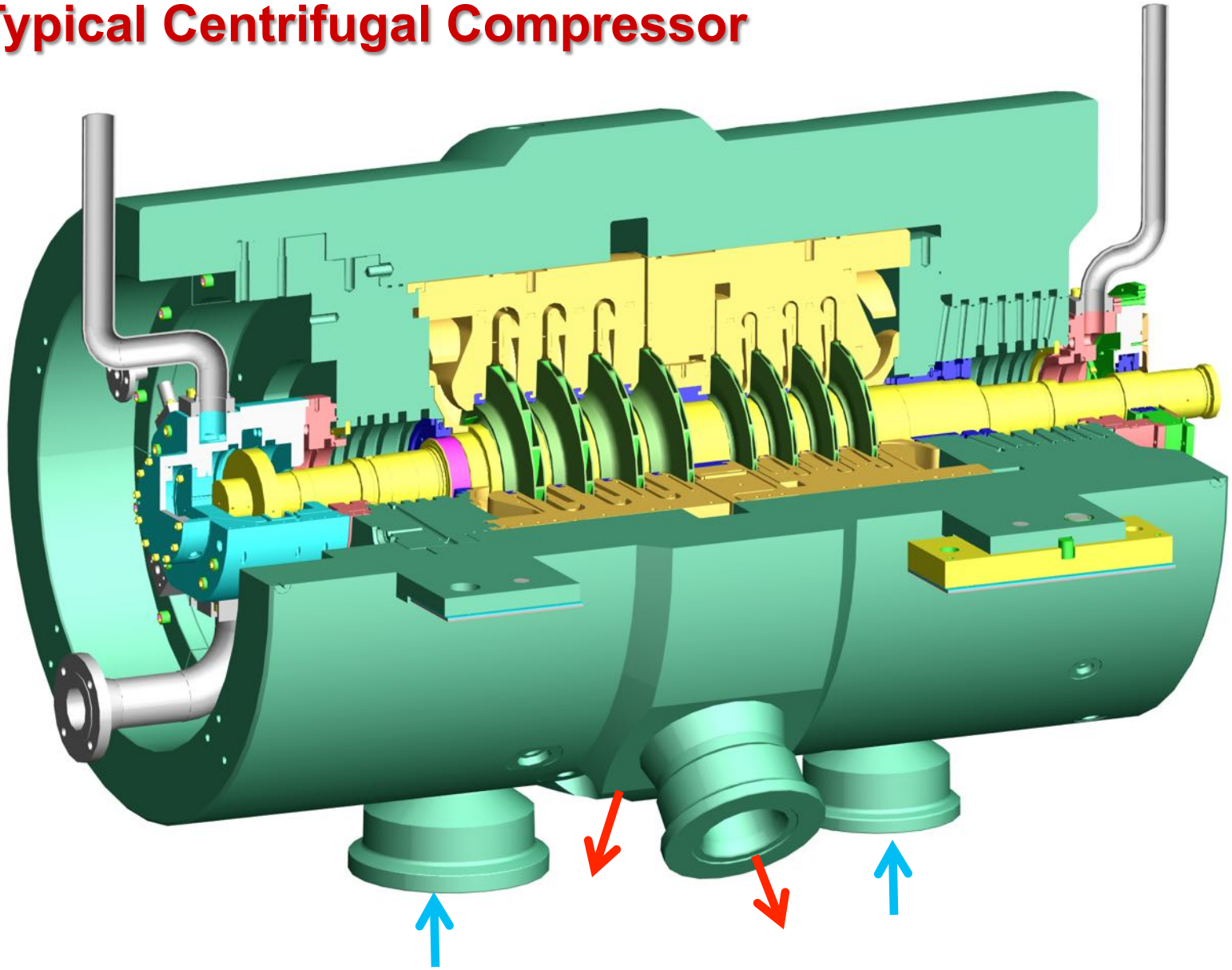
CO_2 Compression

- Compression is an integral part of any CO_2 capture system.
- Separation systems deliver CO_2 near 1 Bara and compression is required to increase pressure and reduce volume, making transport more practical.
  - Pipelines typically require ~ 2215 PSIA (153 Bara).
  - Injection pressures vary. (50 Bar – 600 Bar)
  - Given the high flow volumes, centrifugal compressors are generally employed instead of positive displacement screw or reciprocating compressors.
    - Small pilots (1-30 MW) would utilize positive displacement compressors
- Coal-based electric generating plants that are fitted with CO_2 capture systems have a compression penalty.
  - This penalty can range from 8–12% depending on the CO_2 exhaust state (temperature, pressure and purity) of the carbon dioxide prior to compression.
- With 90% capture typical compression flow rates are:
  - 1,000,000 lbm/hr (454,000 Kg/hr) of CO_2 for a 550 MW PC unit
  - 700,000 lbm/hr of (318,000 Kg/hr) of CO_2 for a 400 MW PC unit

CO_2 Compression Experience

- Dresser-Rand has more than 400 units in carbon dioxide service, totaling more than 900,000 HP (671 MW)
  - ~ 100 centrifugal compressors
  - ~ 300 reciprocating compressors
  - ~ 250 units are in CO2 injection service
- Centrifugal
  - First shipped in 1948
  - Max discharge pressure;
    - More than 8000 psia (552 bara) - delivery 2011
  - Max inlet flow greater than 48,000 acfm (82,000 m3/hr)
  - Total installed power > 400,000 HP (>300MW)

Typical Centrifugal Compressor



Multi-stage Centrifugal Compression

- DATUM® product is available in 15 different sizes
  - Mole Weights from 2-100
  - Discharge pressures ranging up to 15,000 psig (1,000 bar)
  - Flow rates from 5,400 cfm (9,200 m3/h) to 700,000 cfm (1,200,000 m3/h)
  - Shaft power ratings to more than 120,000 HP (90 MW)
  - It is believed that D-R currently holds the record for the highest gas density compressor ever produced with a discharge pressure of 550 bar (8,000 psi) with CO_2.
- Research continues to focus of developing new aerodynamic stages capable of higher efficiency over a broad operating flow map and higher head, enabling smaller, higher speed equipment.
  - CO_2 has a relatively low speed of sound and traditionally this class of equipment has been designed to operate sub-sonically, limiting impeller inlet relative Mach number to less than 1.

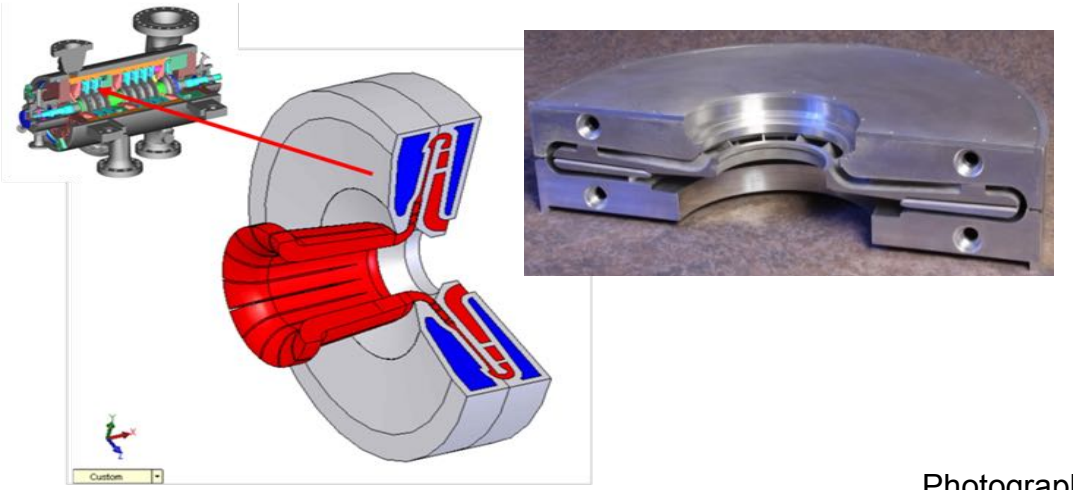
Example: North Sea CO_2 Injection Compressor

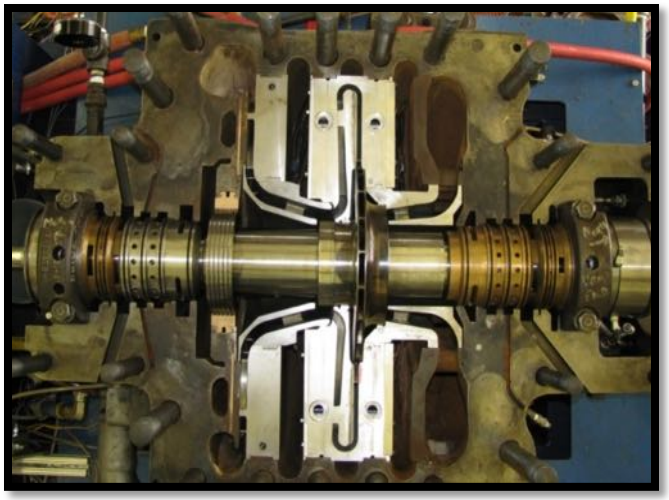
- First CO_2 re-injection project for the purpose of mitigating greenhouse emissions
- As of Jan 2015, 15.2 million tonnes CO_2 injected in 20 years.

- Objective: reduce the CO_2 content in methane from 9% to 2.5% (sale specification)
- Capture the CO_2 from an amine plant
- CO_2 storage in an aquifer
- Start-up: Aug 1996
- Injection: ~ 0.75 mill tonne CO_2/yr
- Availability: 98-99%

Liquid Cooled Diaphragms – Internal to Centrifugal

- DOE, SwRI and Dresser–Rand: Successfully completed DOE grant award DE-FC26-05NT42650
- Internal heat exchangers were developed and placed inside a multi-stage compressor casing
  - Integrated into the aerodynamic flow path
- The red flow path is the CO_2 gas path and blue region represents a cooling medium
- This approach eliminates the need for the CO_2 to exit the casing, travel through piping to a external cooler, then re-enter through another nozzle leading to the next stage.
- The internal heat exchanger results in no pressure drop and fits within the same envelope of the standard internal diaphragm (Moore, et al., 2007).





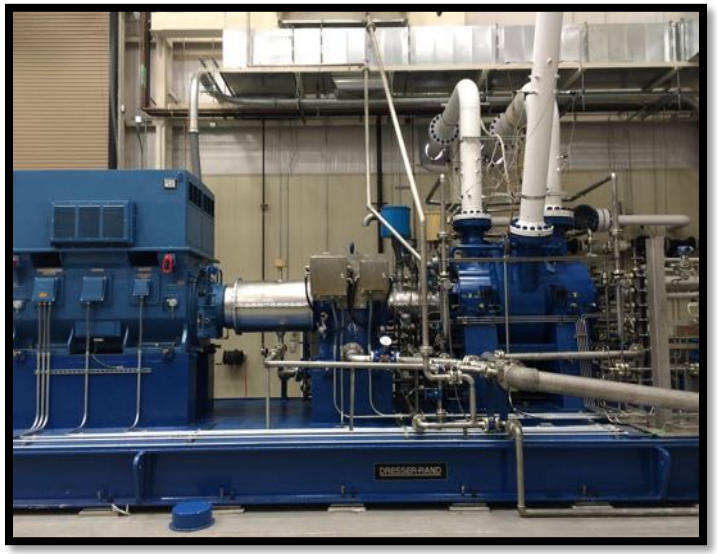
Photograph of Generation-1 Cooled Diaphragm Test Rig

- Reference; J. Moore, M. Nored and K. Brun, "Researchers Seek to Economically Compress Large Volumes of Carbon Dioxide," Pipeline and Gas Journal, 2007.

Liquid Cooled Diaphragms – Internal to Centrifugal

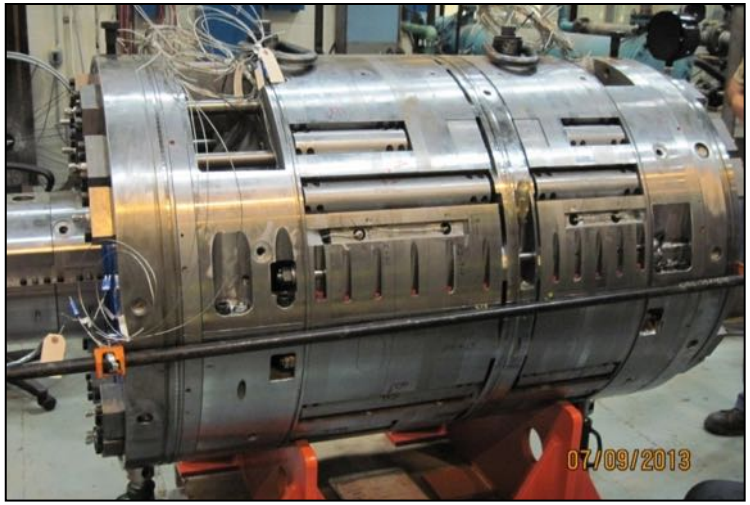
- Test results show cooled diaphragm can remove up to 55% of the heat of compression in each stage
- The technology led to the development of a pilot scale demonstration in a 3 MW, 6-stage back-to-back, 25:1 pressure ratio compressor in a CO_2 test loop constructed and operated at SwRI.

Dresser-Rand 6-stage CO_2 Compressor with Generation-2 Cooled Diaphragms



Liquid Cooled Diaphragms – Internal to Centrifugal

- The D-R compressor installed at SwRI is a D12R6B, 37 inch (0.93 M) case bore, 20 inch (0.5 M) diameter impellers
- Diaphragms were successfully developed with the same pressure recovery as a standard compressor flow path.
- The compressor was operated first without cooling and compared to identical operating conditions with cooling allowing for an apples-to-apples comparison.
- Cooled diaphragm technology reduces compressor power consumption by 3.0% (near surge) to 8.0% (near choke) when compared to adiabatic case with intercooling between the two sections.



Liquid Cooled Diaphragms – Internal to Centrifugal

- Generation 3 concepts envisaged.
  - Potential for up to 12+% savings with respect to the baseline conventional compressor

- Generation 3 endeavors to develop an advance heat exchanger design, which has the potential of reaching:
  - Similar power as an integrally geared compressor
  - More compact package
  - Improved reliability, to 99% availability

Ramgen – SuperCompressor™ – DATUM® S – History

- A by-product of a shock wave is compression and heat
  - Technology has been applied in supersonic jet engine inlet designs for decades
- In 2008, D-R invested in Ramgen's supersonic technology.
  - DOE Project DE-FE-0000493 - "Ramgen Supersonic Shock Wave Compression and Engine Technology"
- Late 2012 in Olean, NY, the team successfully tested a supersonic CO_2 compressor achieving a 9:1 pressure ratio in a single rotating disk.
  - Proof of concept – successful
- On Aug 8th, 2014, D-R announces the opening of the Seattle Technology Center along with the 11,000 Sq Ft testing lab.
  - Initial staffing is comprised of 19 engineers and support staff, all of whom are former Ramgen Power Systems employees.

CO_2 Supersonic Compressor

- 10:1 pressure ratio with single rotating disk on CO_2
  - Enables a 100:1 pressure ratio in a low-pressure (LP) and high-pressure (HP) case configuration
    - 22 PSIA (1.52Bara)=>2215 PSIA (153 Bara)
- Compression equipment
  - ~ 70% weight and size of traditional in-line centrifugal offering
  - ~ 50% weight and size of an integrally geared centrifugal offering
  - 30% aerodynamics turndown
- Integration of waste heat for amine regeneration or boiler feed water preheat

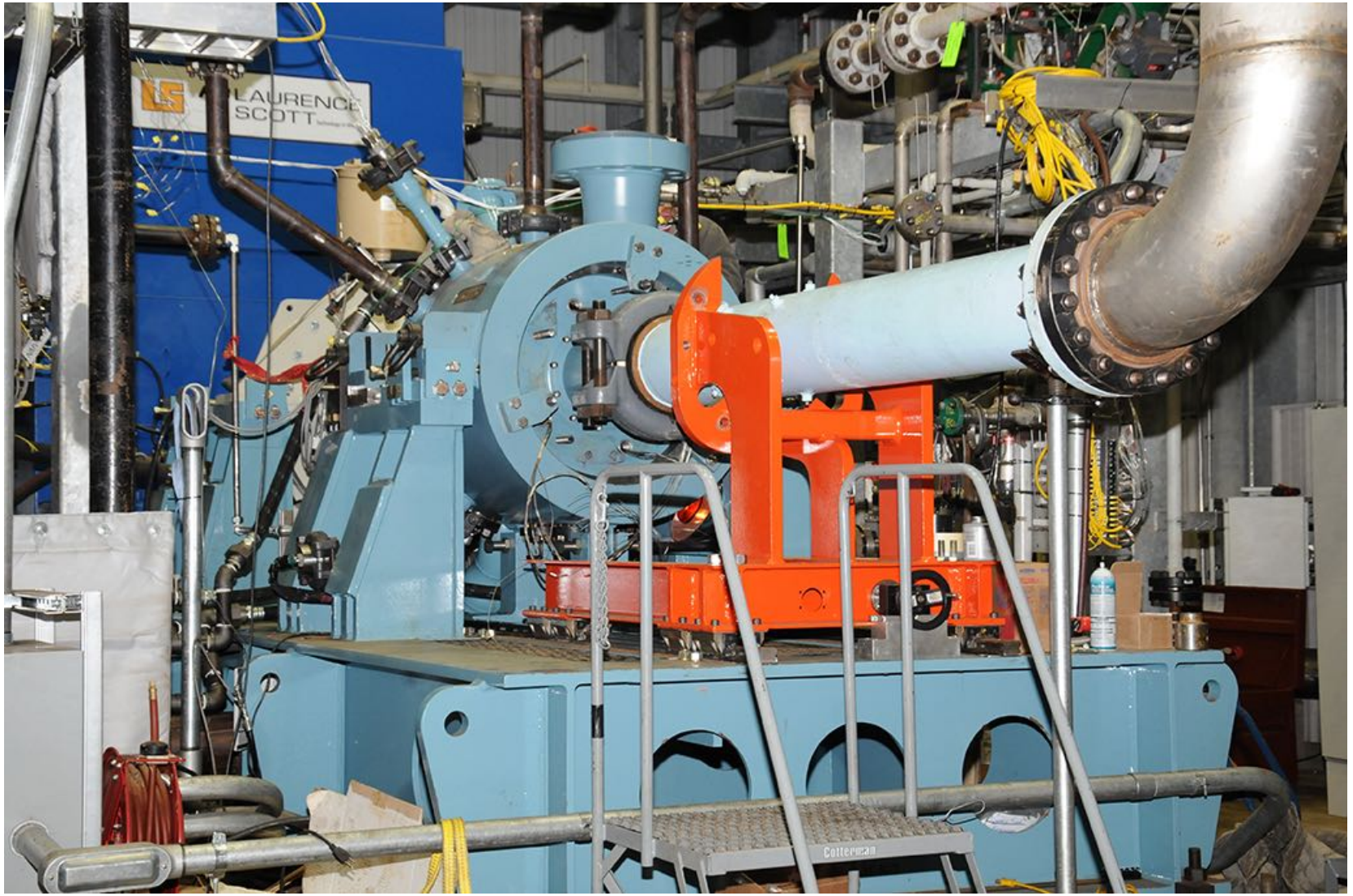
SuperCompressor™ – DATUM® S – Shock Wave Compression

- Build 2, the path to a commercial product
  - Embodies patent-pending technology
  - Rig size 13,400 HP (10 MW) shaft power level
  - Mass flow 86 lbm/sec (40 Kg/Sec) (66 MMSCFD)
  - ~ 200 MW coal-fired plant
  - 220 psig suction, 2200 psig discharge pressure – HP stage
  - Program plan includes:
    - Design, fabrication, assembly and test
    - Test phase started March 2015
      - Pressure ratio of 9.7:1.0 achieved
    - Test phase expected conclusion August 2015
  - Follow-on compressor pilot demonstration program at a client site targeted for 2016

CO_2 Test Facility

- CO_2 and Inert Test Gas
  - 220 PSIG Inlet
  - 2200 PSIG Discharge
  - 3363 PSIG Discharge Design Rating
  - 1500 # ANSI, 5000 PSIG Helium and 1000 PSIG Nitrogen utility gas
- 10 MW VFD Driven Motor
- CO_2 Gas collection system
- Cooling Tower

Test Set-up



Benefits with Respect to Integrally Geared

- Smaller footprint, less equipment, less piping, less intercoolers
- Higher compression ratios:
  - 10:1 ratio in single rotating disk
- Discharge temperatures exceeding 550 F (290 C)
  - Benefits clients that can utilize waste heat for steam production or amine regeneration, etc.
- Waste heat recovery enables unmatched overall system efficiency.

Comparison for 100:1 Pressure Ratio

Supersonic	Traditional Centrifugal	IG Frame
– LP and HP smaller frame size	– LP and HP smaller frame Size	– Much larger frame size
– One rotating disk / case	– Multiple impellers	– Multiple impellers
– Potential for mid-grade waste heat (550F)	– Low grade waste heat (240F)	– Low grade waste heat (140F)
– 1 intercooler	– 3 intercoolers	– Up to 6 intercoolers

Summary DATUM® S

- In 2008, Dresser-Rand invested in Ramgen to support on-going CO_2 compressor technology development
  - Consistent with strategy to maintain leadership in CO_2 compression:
    - Team has leveraged the successes and lessons learned from our build 1 compressor development efforts and test results
    - CFD, validated via test, used to verify SuperCompressor™ performance
    - Client technology advisory council and VOC sessions underway.

- In 2015, Dresser-Rand expects to:
  - Conclude rig testing, enter scale up R&D program to further improved efficiency
  - Identify and engage technology collaboration partner

Summary

- The integrally geared (IG) compressor is the current benchmark for overall shaft power, but is very large and incorporates many coolers, bearings and seals:
  - Reduced reliability
- Inline centrifugal is more robust, more reliable but generally will consume slightly more power:
  - Will have a reduced footprint over IG
- Internally-cooled inline centrifugal test results show up to a 8% power savings over the same non-cooled inline centrifugal, but with slight increase of compressor costs due to manufacture of liquid-cooled diaphragms.
- DATUM® S – Supersonic compression solution:
  - High ratio results in slight increase of shaft horsepower over traditional centrifugal compressors
  - Delivers usable heat which when integrated in to system, will produce the lowest overall power for the compression service
  - Single rotating disk results in smaller footprint, reduced CapEx.
  - Size reduction of 33% percent compared to inline centrifugal.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