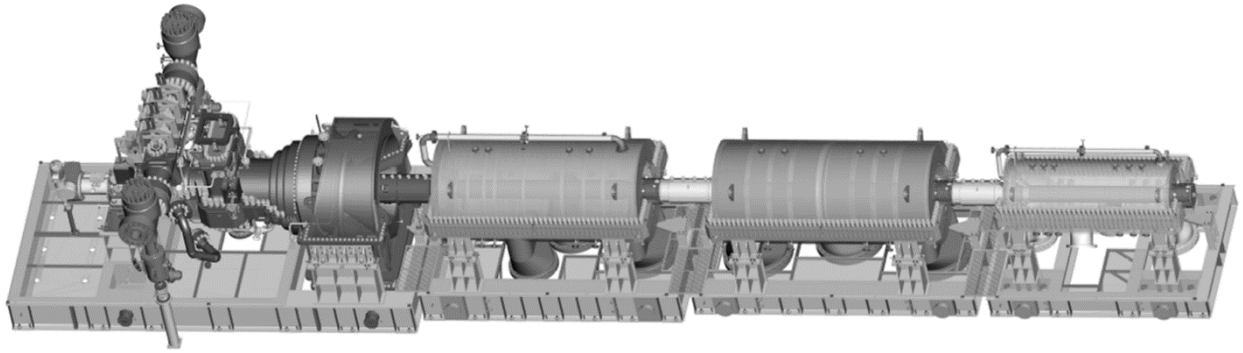

# Technology Options for Hydrogen Compression

Klaus Brun, Ph.D.

Elliott Group

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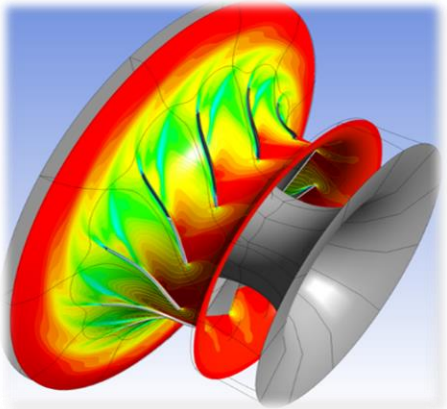

# Carbon-Free or Decarbonized Energy Pathways

- Green (wind/solar/hydro) and nuclear electricity direct
  - Centralized or distributed
  - Requires storage or peakers for load following
- Green and nuclear (red) hydrogen (electrolysis and pipeline transport)
- Fossil fuel (blue) Hydrogen (mostly from natural gas)
  - produced at fossil production site
  - produced at end-use site (pre-combustion carbon capture)
- Fossil plant post combustion (flue gas) carbon capture
- Fossil fueled oxy cycle plants

Requires Carbon Capture

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# Hydrogen Compression

Elliott Centrifugal Compressor Train

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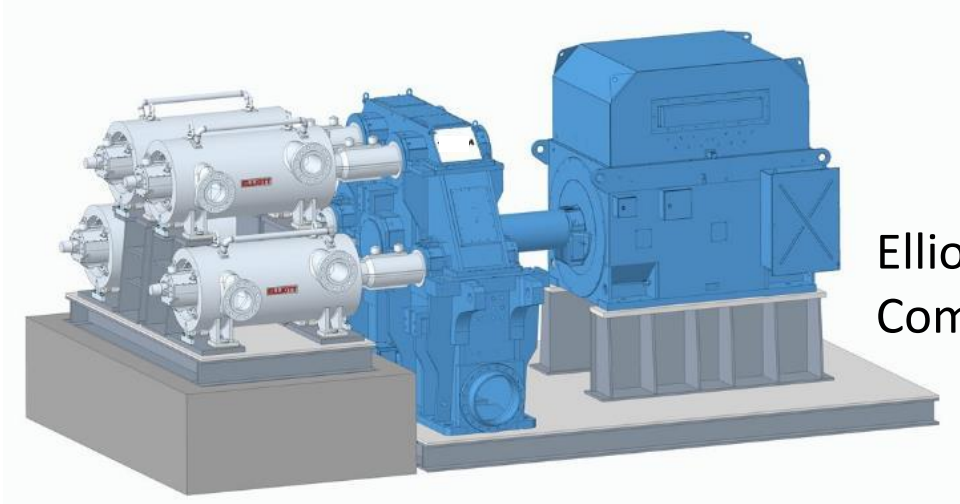
# Pure Hydrogen Compression

Compression Applications:

- Pipeline Recompression (1400 psi) — PR 1.2-1.4
- Head Station (Electrolyzer or Steam reformer to Pipeline Pressure or Liquids Plant) — PR 2.2-6.0
- Fuel Supply to Power Plant
  a) Gas Turbine Combustor Pressure from reformer (500+psi) — PR 1.5-3.0
  b) Storage Tank Pressure (7000 to 14000 psi) — PR 10+



Elliott Flex-Op™ Compressor

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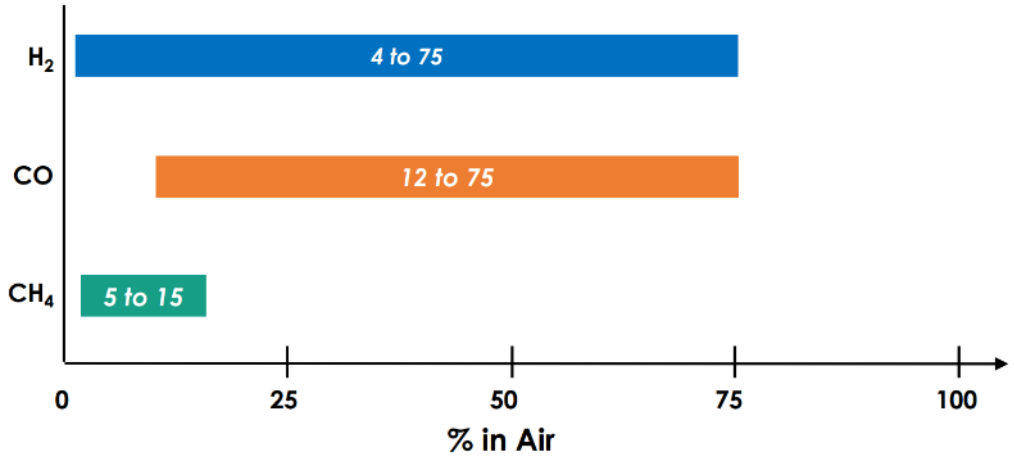
# Hydrogen versus Natural Gas

- Light Gas (MW=2): low density, high speed of sound, high leakage
  - Many effects to piping & compression systems
- Wide flammability range, negative J-T coefficient at pipeline conditions
  - Affects safety




Source: Dennis, R., 2020, "Hydrogen Storage: A brief overview of hydrogen storage options," TMCES Workshop, NETL, Pittsburgh

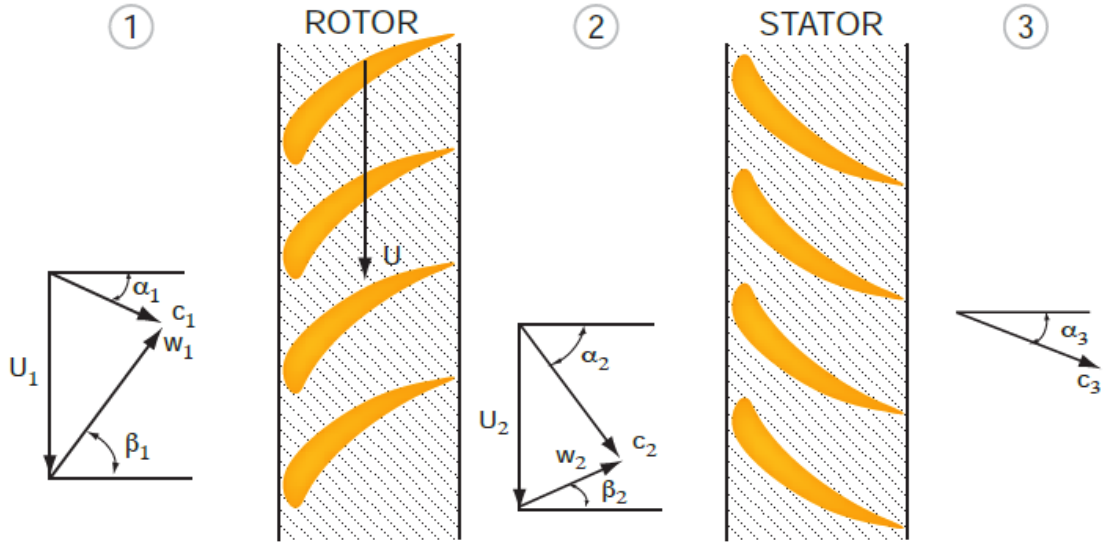
| | Natural Gas | Hydrogen |
|---|---|---|
| Mol. Wt. | 16.8 | 2.0 |
| Density ($lbm/ft^3$) | 3.4 | 0.34 |
| Sound Speed (ft/s) | 1375 | 4480 |
| J-T Coeff. (°F/psi) | 0.05 | -0.004 |
| Lower Heating Value (Btu/lbm) | 21013 | 51598 |

Data from NIST REFPROP at 70˚F, 1000 psi with "Gulf Coast Gas" mixture

# Design Challenges of Pure Hydrogen Compression

- Light gas compression
  - Low pressure ratio
  - Many stages (mechanical/rotordynamic) or high speed (high stress, novel materials)
  - Equation of state
- Sealing
  - Dynamic (seal leakage, scavenging)
  - Static (soft component hydrogen permeability and decompression bubbling)
- Materials and coatings
  - Hydrogen embrittlement (material loses ductility due to $H_2$ penetration)
  - Coating loss and disbonding
- Safety
  - Explosivity, wide flammability range, dispersion and impact radius, leak detection

# Light Gas Compression




**Efficiency is not significantly affected.**

**Head:** $$H = h_2 - h_1 = \frac{P}{W} = \omega \cdot (r_2 c_{u,2} - r_1 c_{u,1})$$

**Power:** $$P = \omega \cdot \Delta\tau = \omega \cdot W \cdot \Delta(r \cdot c_u) = \omega \cdot W \cdot (r_2 c_{u,2} - r_1 c_{u,1})$$

**P Ratio:** $$\frac{P_2}{P_1} = \left(1 + \frac{\eta}{c_p T_1} \cdot H\right)^{\frac{\gamma}{\gamma - 1}}$$

Specific Heat:
Natural gas – 2.3 kJ/kgK
Hydrogen – 14.3 kJ/kgK

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# Hydrogen Compression

- For the same geometry, speed, and number of stages for a hydrogen versus natural compressor, the hydrogen compressor produces similar head but significantly lower pressure ratio.
- To reach a desired pressure ratio, significantly more head is required and thus more power is required.
- To achieve desired higher head and higher pressure ratio, one can:
  - Increase the rotational speed
  - Increase the impeller diameter
  - Increase number of compression stages
- Material yield strength is limited to 120 ksi (827MPa) per API to avoid hydrogen embrittlement. This limits the impeller speed and diameter.

**Pure hydrogen compression requires either:**

- **Large number of compression stages**
- **High tip speed impellers**

# Pure Hydrogen Compression

- Conventional Compressor (1200 fps tip speed impellers)
  - Electrolyzer to Pipeline PR=2.5 40 impellers (4-5 cases)
  - Pipeline recompression PR=1.3 8 impellers (1-2 cases)
  - CGT Fuel Gas Compression PR=2.0 30 impellers (3-4 cases)
- High Speed Compressor (2400 fps tip speed impellers)
  - Electrolyzer to Pipeline PR=2.5 10 impellers (2 cases)
  - Pipeline recompression PR=1.3 2 impellers (1 case)
  - CGT Fuel Gas Compression PR=2.0 8 impellers (2 cases)

High Speed Compressor Challenges:
- Materials
- Seals/Bearings
- Drivers

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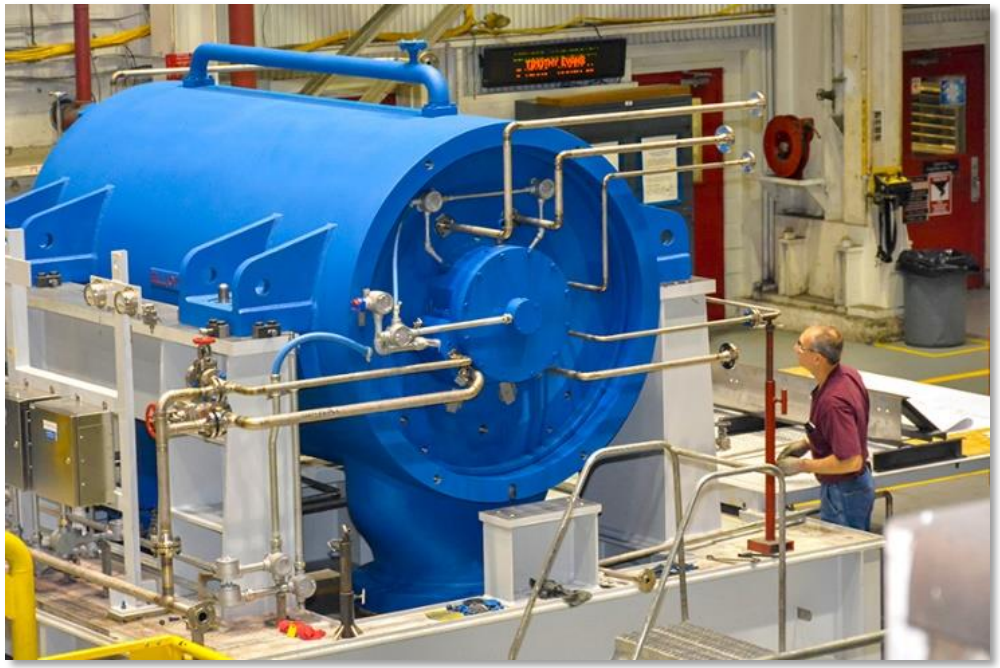
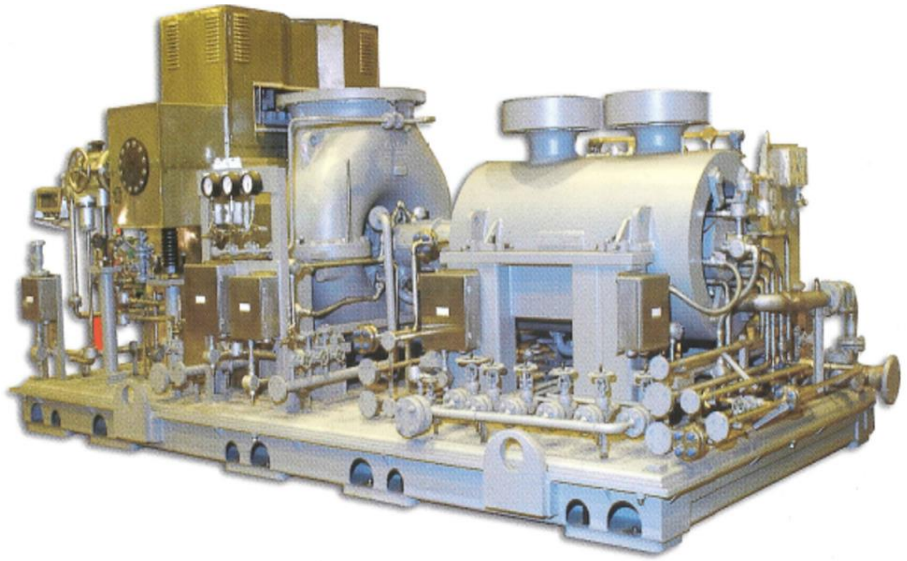
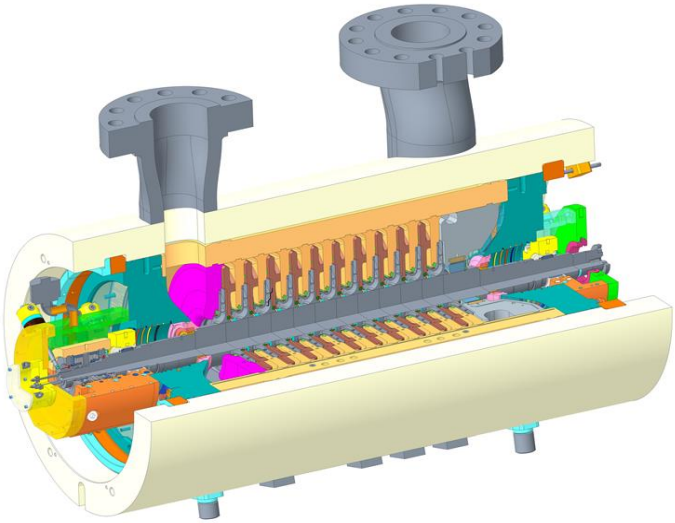
# Hydrogen Compression

- Elliott has been building hydrogen compressors since 1955
- Over 100 hydrogen-rich compressor trains produced from 2001-2021
- Elliott has built compressors for a wide range of application from pure hydrogen to hydrogen rich process applications

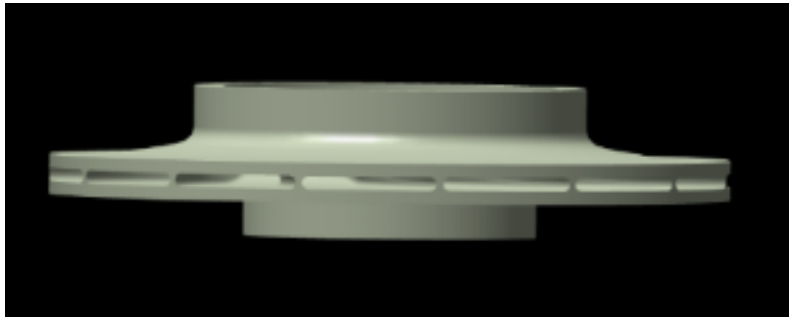






# Advanced Impeller Materials for Hydrogen Service

- Allow for higher impeller spin speeds with materials with higher strength-to-density ratio
  - Current standard is MS-212H (17-4 PH stainless steel/105 ksi minimum yield strength)
  - API 617 limits material to 120 ksi maximum yield strength
  - Titanium alloys are not ideal for hydrogen service



Advanced Ceramic Matrix Composites

Aluminum 6061 or Aluminum 7075

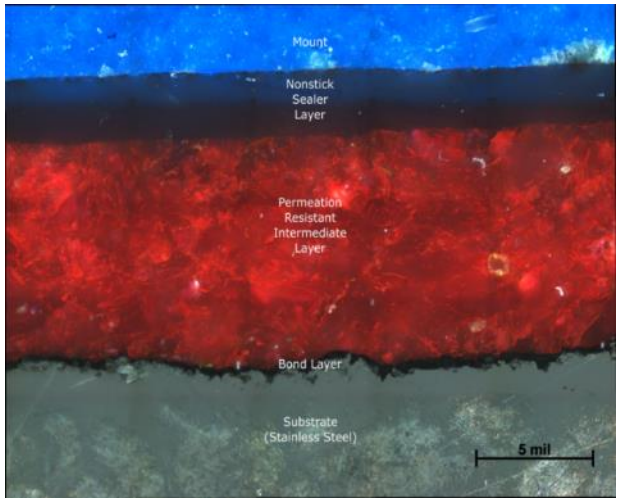
Continuously wound carbon fiber in epoxy matrix through additive process

# Hydrogen Coatings

- Prevent and limit hydrogen embrittlement
- Improve erosion and corrosion resistance
- Anti-fouling

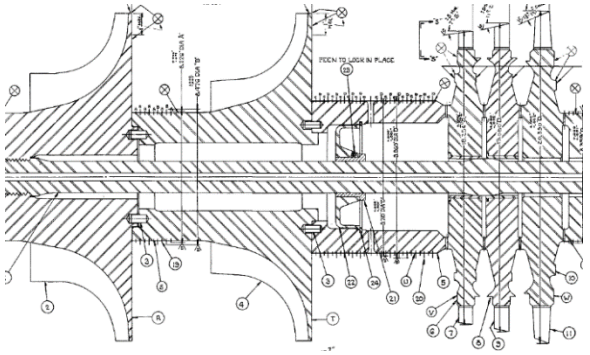
… but all coatings will eventually be worn away, spalled, or dis-bonded.

**Cannot be used to increase material yield strength limits for long term service applications.**



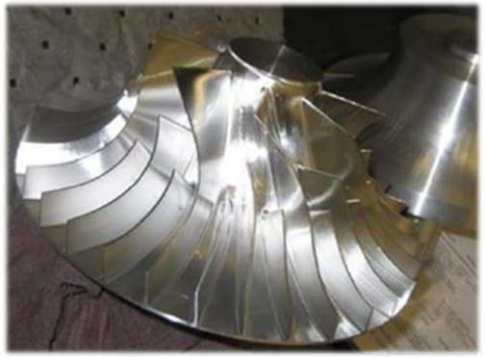

# Advanced Impeller Designs for Higher Tip Speeds Wheels

- Allow for higher impeller spin speeds (higher head) by reducing stress
- Use additive manufacturing for structural optimization



Elliott 39HT Nitric Acid Turbocompressor
1,124 fps - 1961

Concepts NREC 2,100 fps
7075-T6 Aluminum impeller

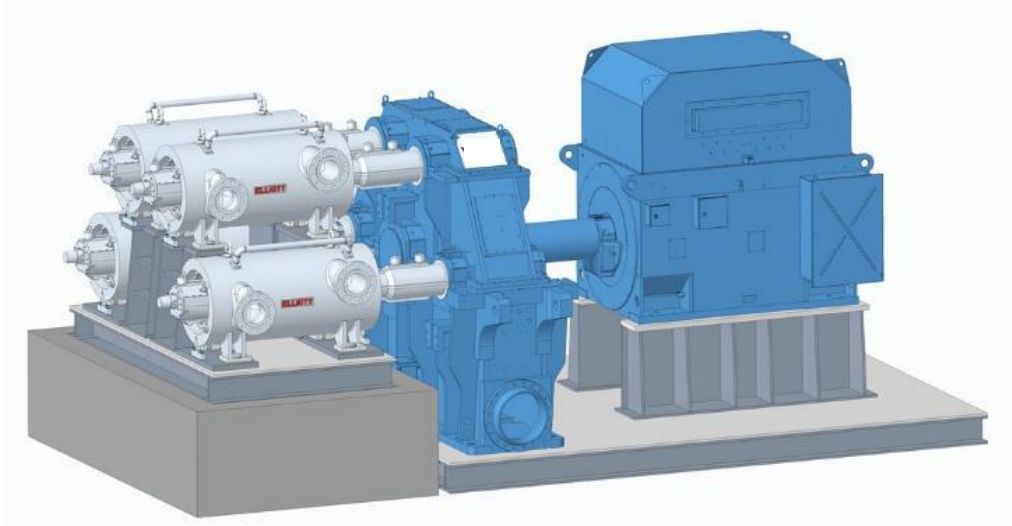


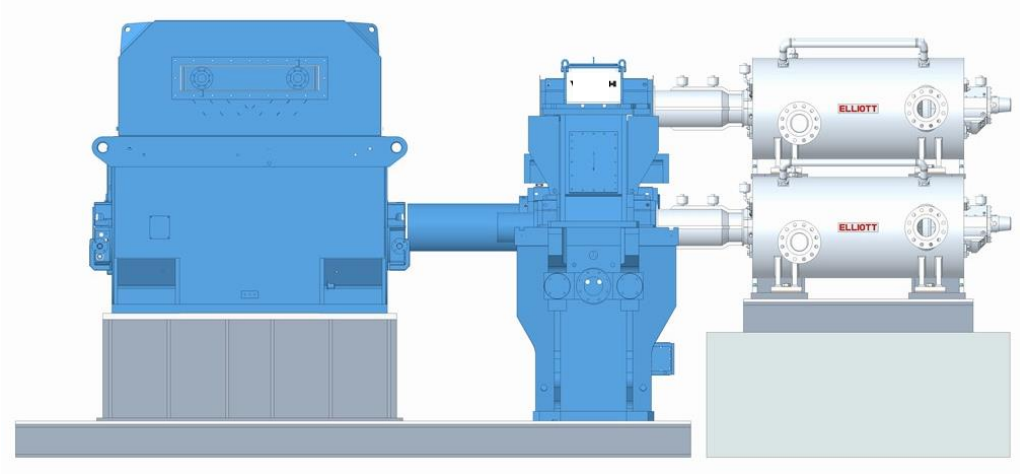
Baker Hughes HPRC – 2015

Elliott large diameter wheels

# Or a more conventional solution… Flex-Op™ Compressor Arrangement

- 3-4 integral barrel arrangements with casing optimized speed
- High flow, high ratio, high efficiency
- Potential to engage/disengage individual compressors and switch between series and parallel operation
- Intercooled
- Multiple side streams/extractions
- Compact with ease of access for maintenance and repair
- Process gas free from oil contamination






VFD Arrangement (with Voith gearbox)

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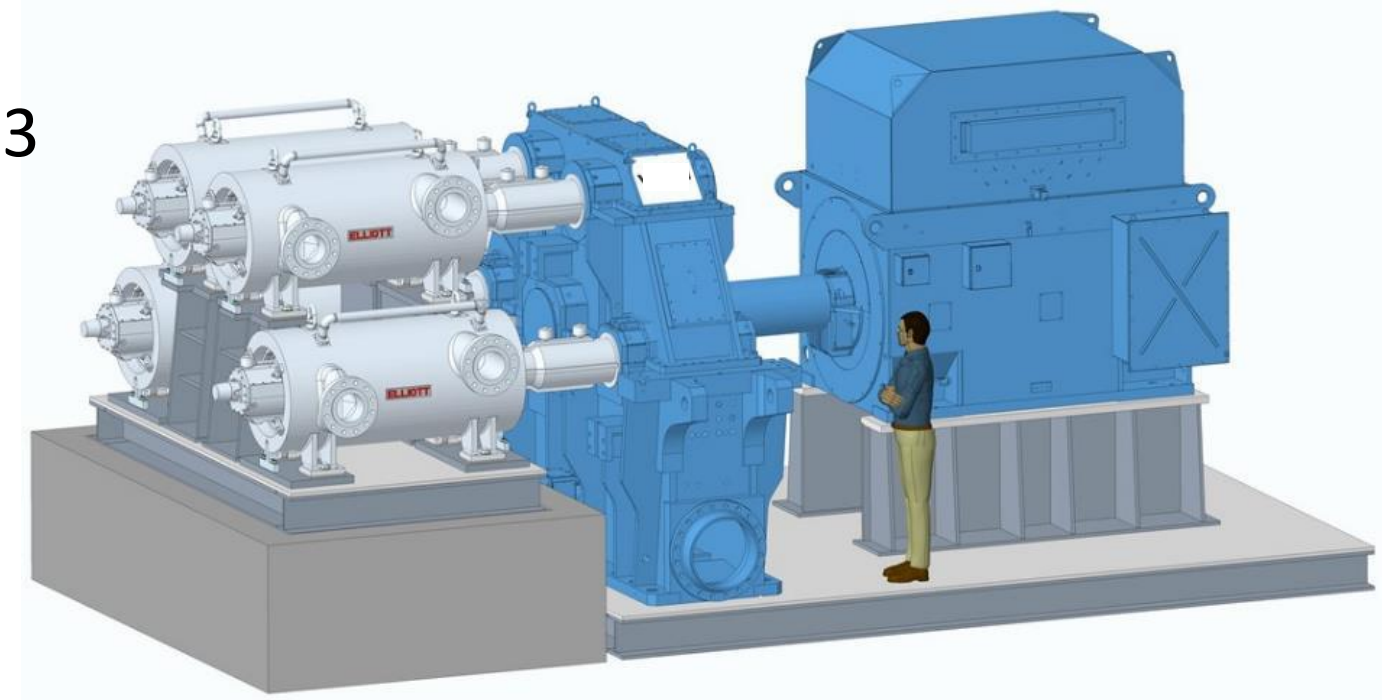
# Case Study: Hydrogen Pipeline Transport

- Speed: 15,000 RPM
- Power: 7500 HP
- 100% hydrogen
- Intercooler between Body 2 and 3
- Flow: 240,000 kg/day
- 4X 15MB9 Casings
- Pressures: 365 PSIG inlet to 1015 PSIG discharge
- 2.78 Pressure Ratio



**Demonstrated industrial design works for pipeline applications and is available now.**

# Thanks a lot! Questions?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