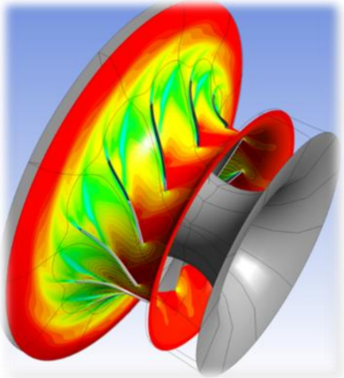
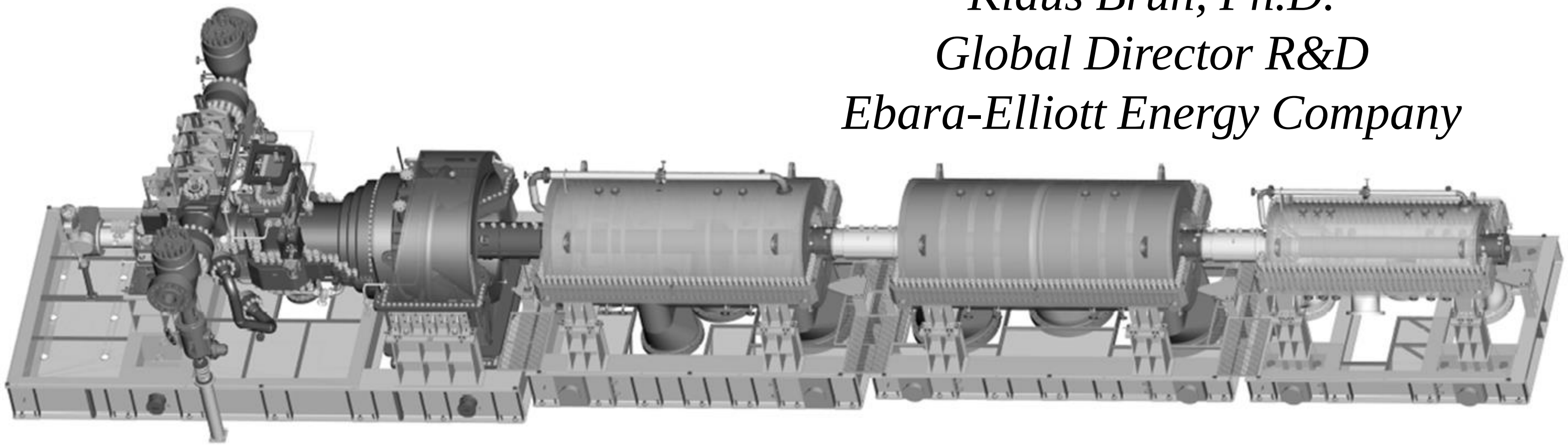


Technology Options for Hydrogen Compression

Klaus Brun, Ph.D.
Global Director R&D
Ebara-Elliott Energy Company



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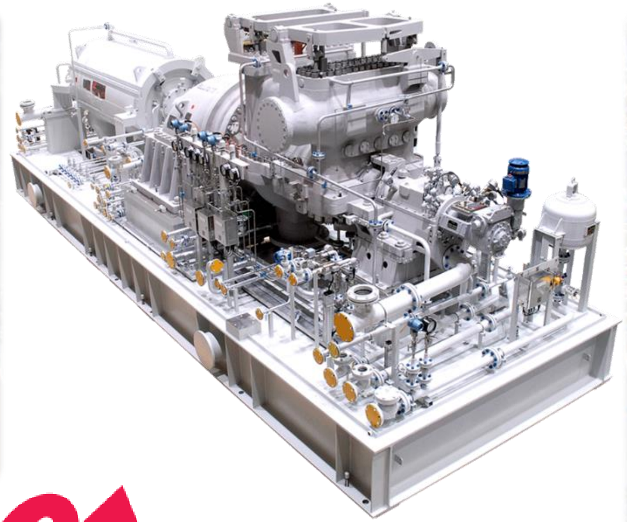

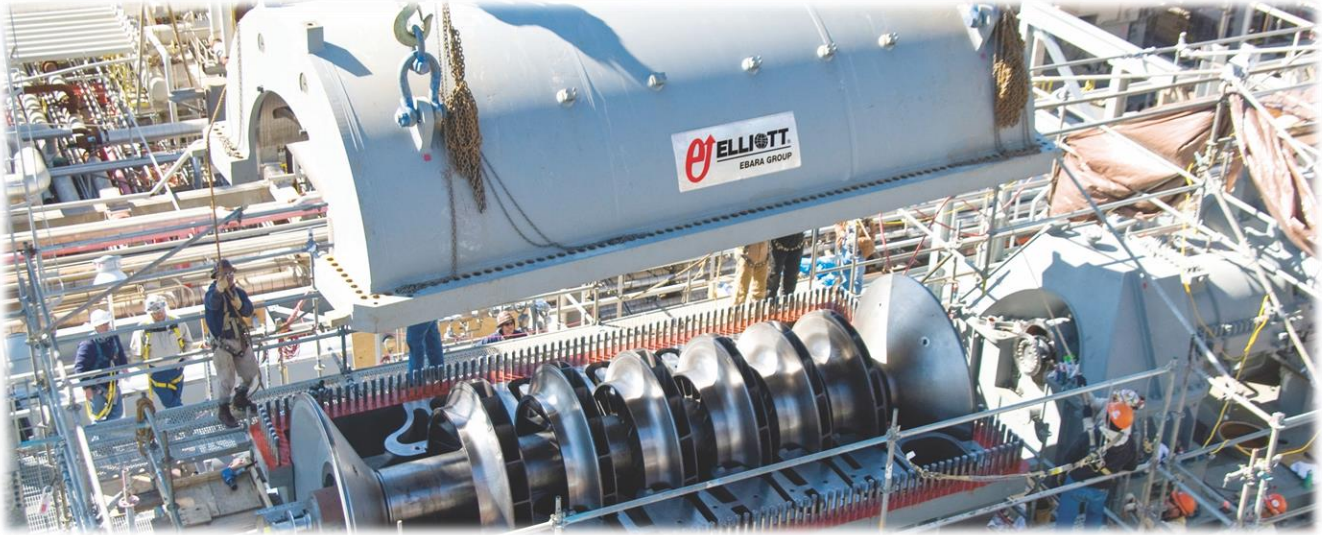

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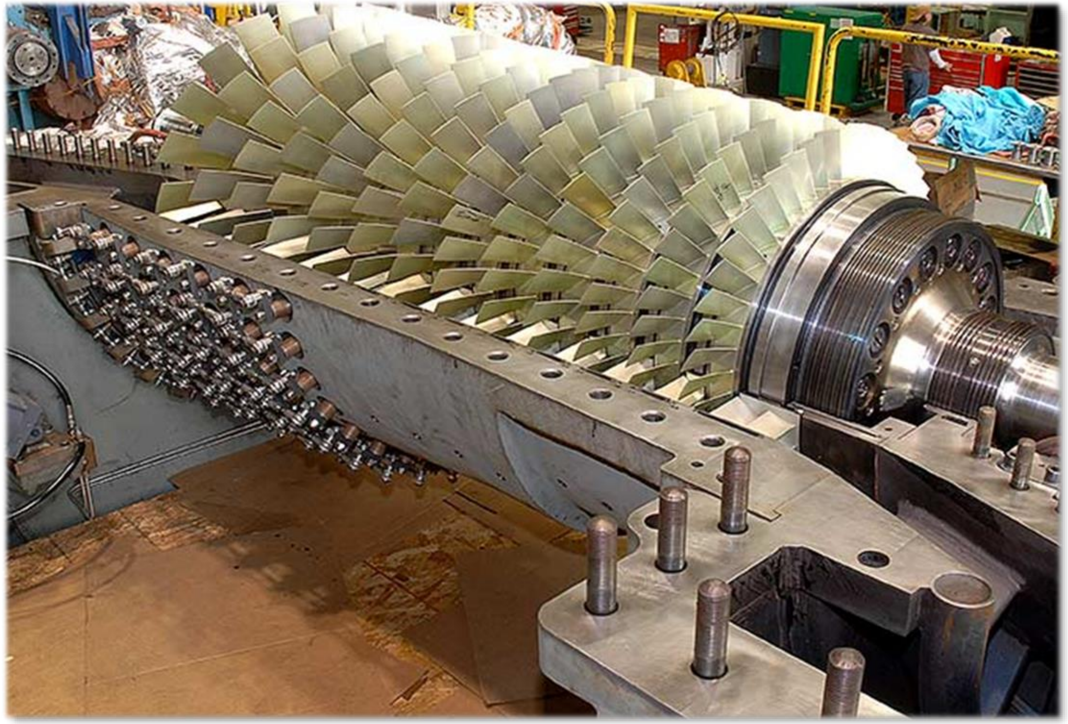
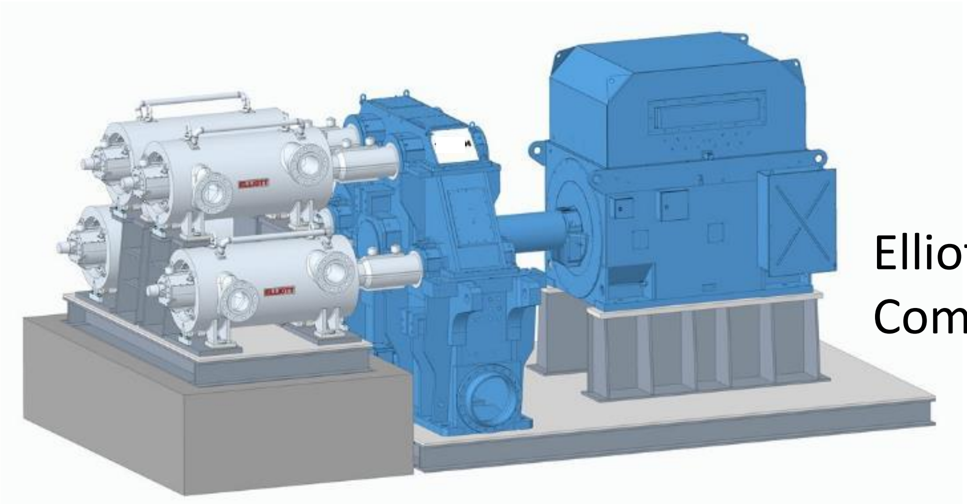


Pure Hydrogen Compression

<u>Compression Applications</u>:

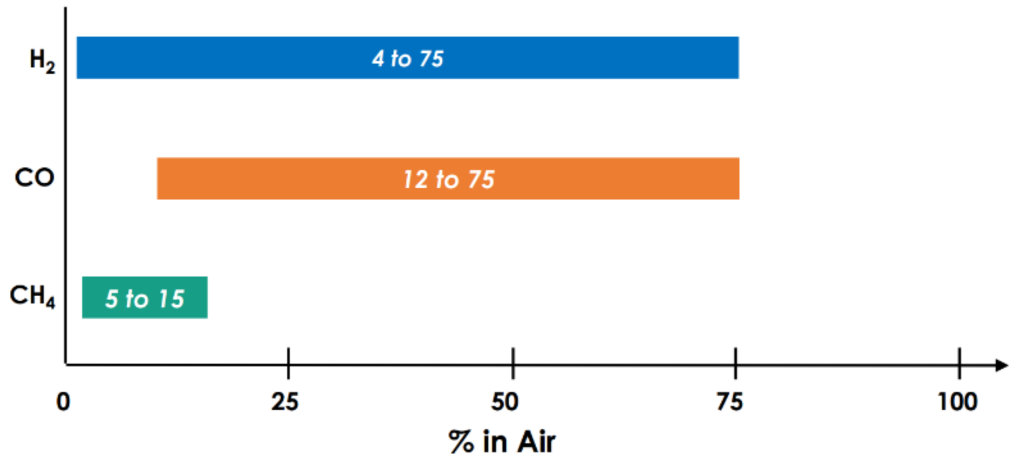
• Pipeline recompression (1400 psi)	PR 1.2-1.4
• Head station (Electrolyzer, steam reformer, gasifier to pipeline pressure or liquids plant)	PR 2.2-6.0
• Fuel supply to power plant	
a) Gas turbine combustor pressure from reformer (500+psi)	PR 1.5-3.0
b) Storage tank pressure (7000 to 14000 psi)	PR 10+



Elliott Flex-Op™ Compressor

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

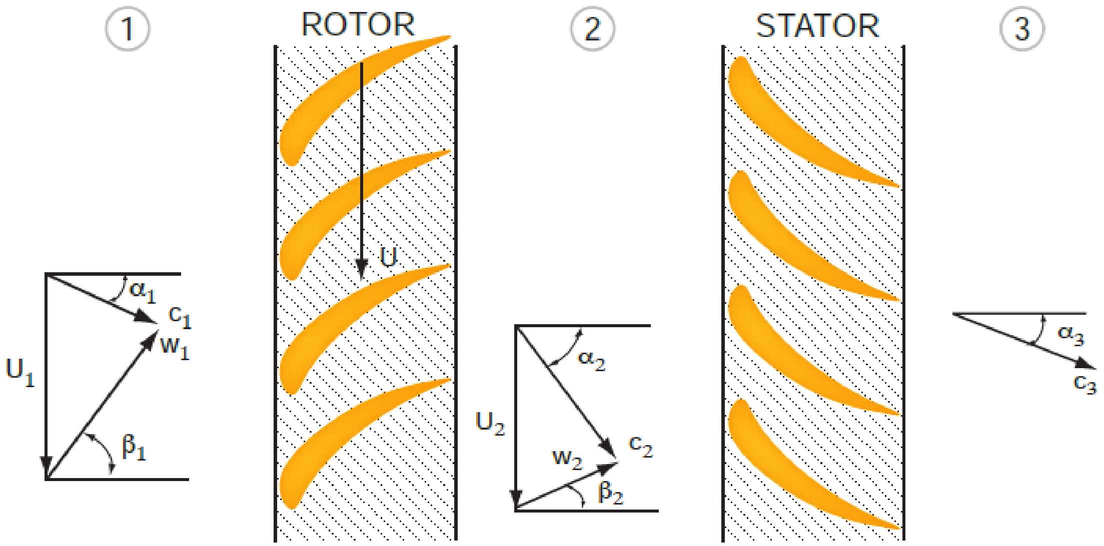
	Natural Gas	Hydrogen
Mol. Wt.	16.8	2.0
Density (lbm/ft^3)	3.4	0.34
Sound Speed (ft/s)	1375	4480
J-T Coeff. (°F/psi)	0.05	-0.004
Lower Heating Value (Btu/lbm)	21013	51598

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



Head and efficiency is not significantly affected.

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

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

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

Pure Hydrogen Compression – Increased Speed

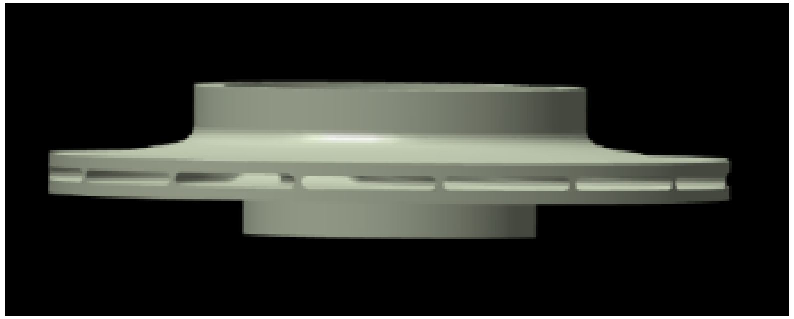
- Conventional Compressor (<u>1200 fps</u> tip speed impellers)
  - Electrolyzer to pipeline PR=2.5 40 impellers (4-5 cases)
  - Pipeline recompression PR=1.3 8 impellers (1-2 cases)
  - CGT fuel gas compression PR=2.0 30 impellers (3-4 cases)
- High Speed Compressor (<u>2400 fps</u> tip speed impellers)
  - 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

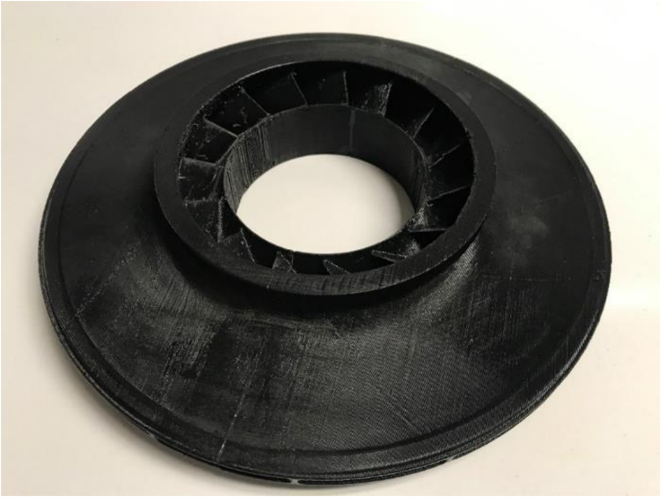
Advanced Impeller Materials for Hydrogen Service

- 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



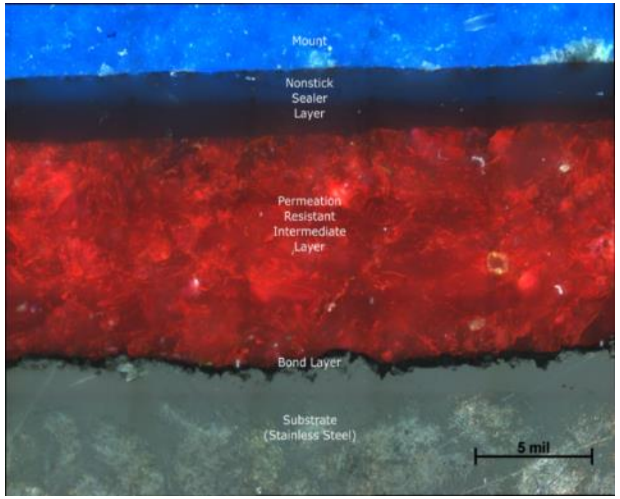
Continuously wound carbon fiber in
epoxy matrix through additive process

Hydrogen Coatings

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

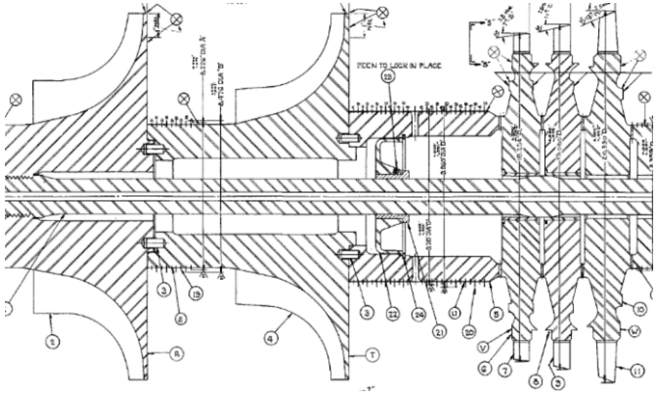
…but all coatings will eventually be worn away, spalled, or dis-bonded.

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



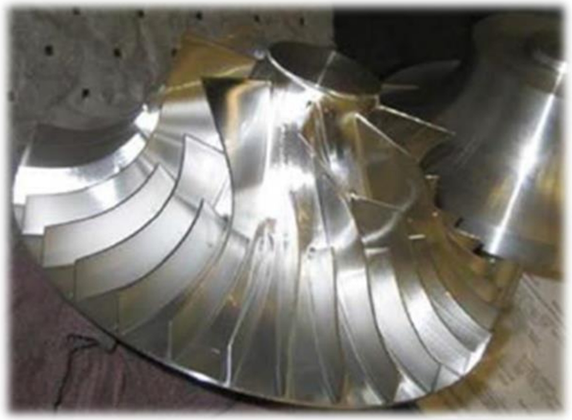
Advanced Impeller Designs for Higher Tip Speeds Wheels

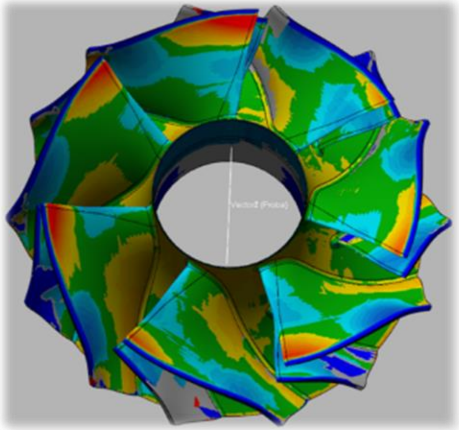
- Allow for higher impeller spin speeds (higher head) by reducing stress
- Use additive manufacturing for structural optimization



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

NREC 2,100 fps 7075-T6 Aluminum impeller



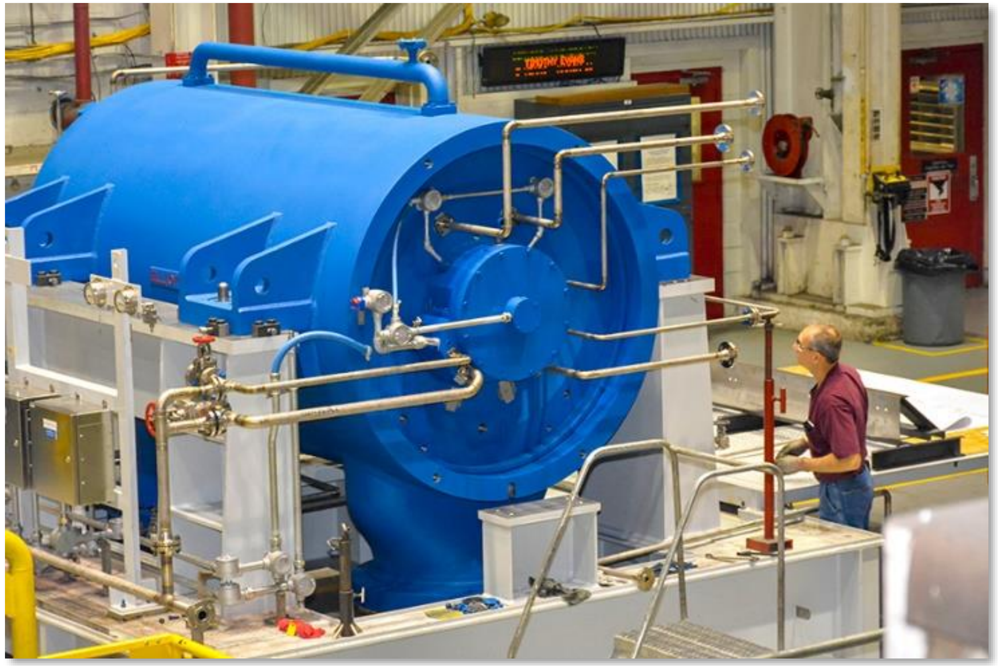


High Speed Mixed Flow Impellers

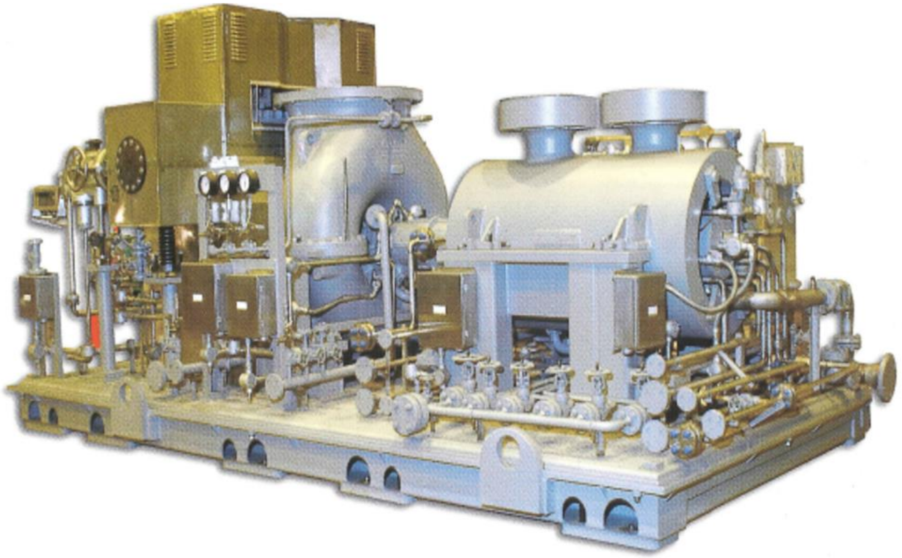
Elliott large diameter wheels

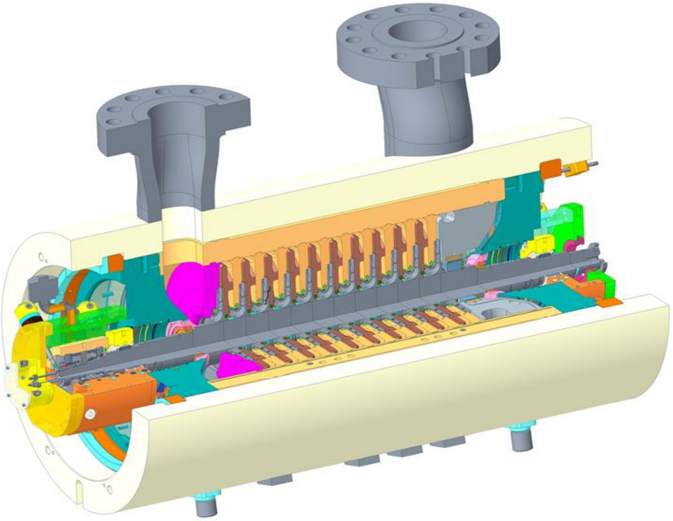
Design for High Head and Efficiency

Hydrogen Compression



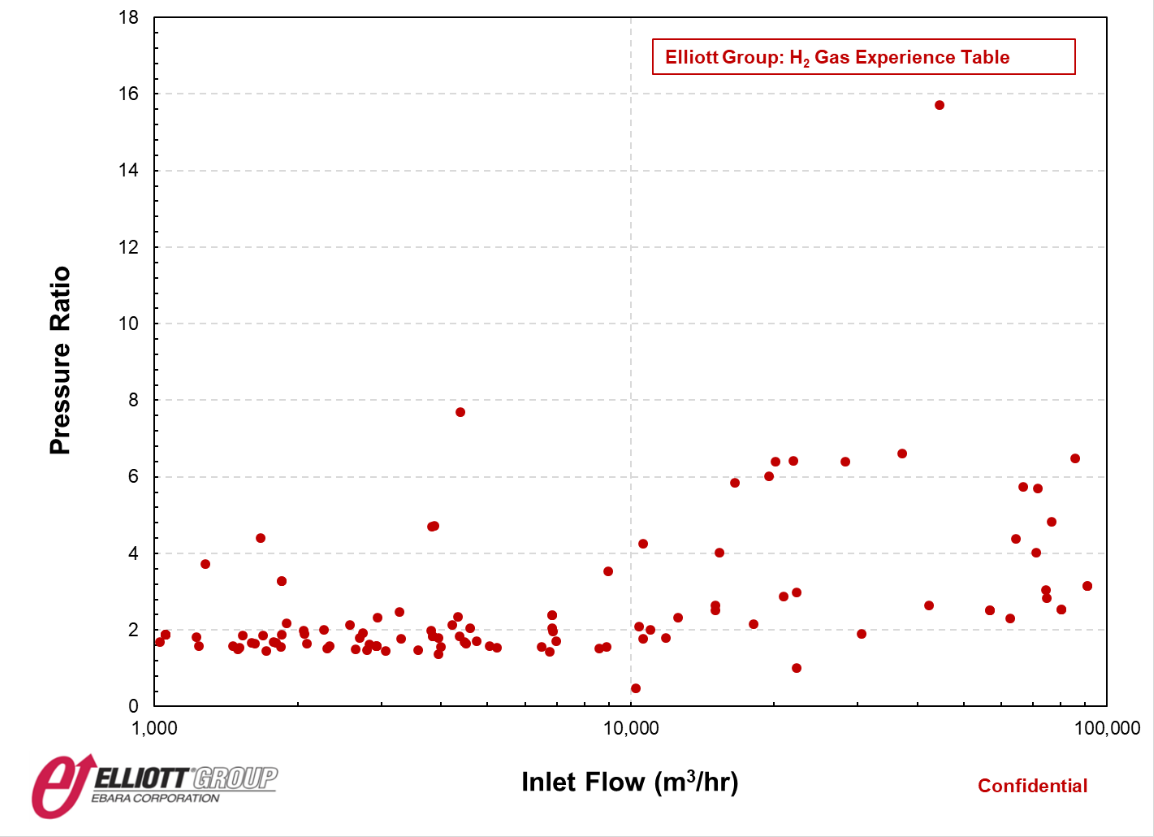
- Elliott has been building hydrogen compressors since 1955
- Over 100 hydrogen-rich compressor trains produced from 2001-2021
- Elliott has built compressors for a wide range of applications from pure hydrogen to hydrogen rich process applications

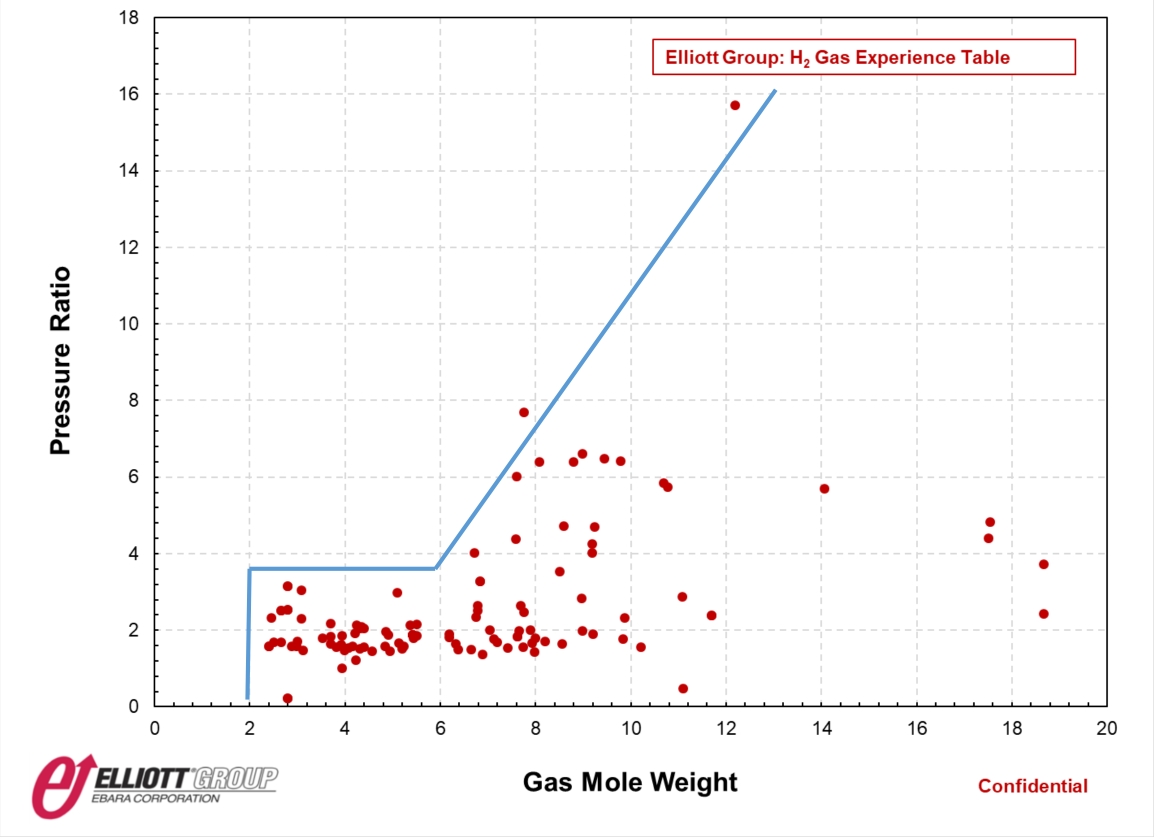




Compressors Designs in Hydrogen Environment

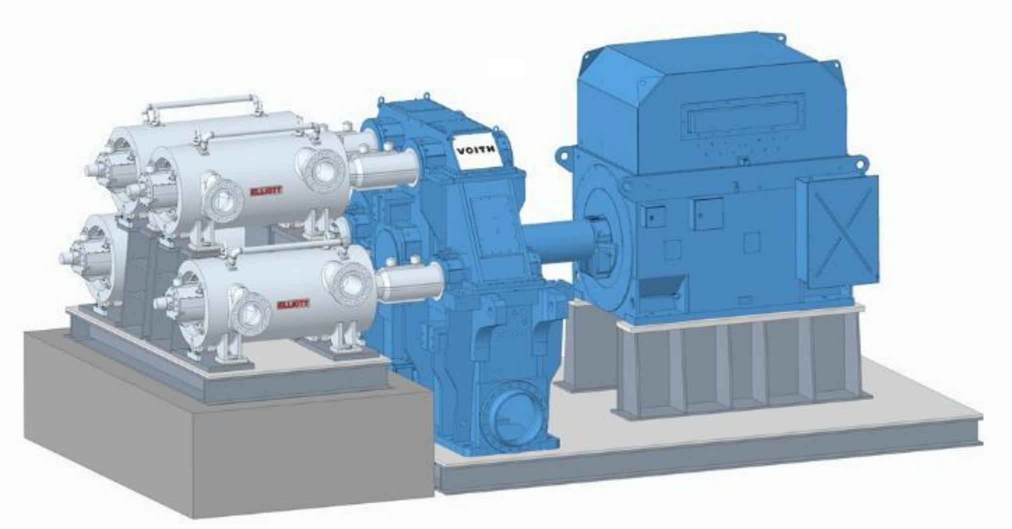
- Elliott is able to leverage a substantial experience base for H_2 compressors.
  - As previously mentioned high PR is difficult to achieve for high H2 concentrations
  - Plots below show a partial listing of Elliott compressor experience for high H2 concentrations

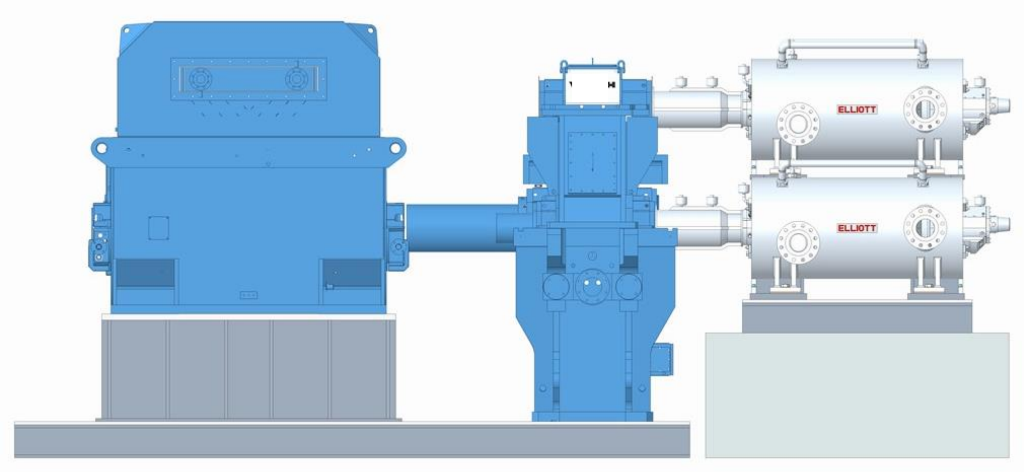




Flex-Op^{TM} Compressor Arrangement

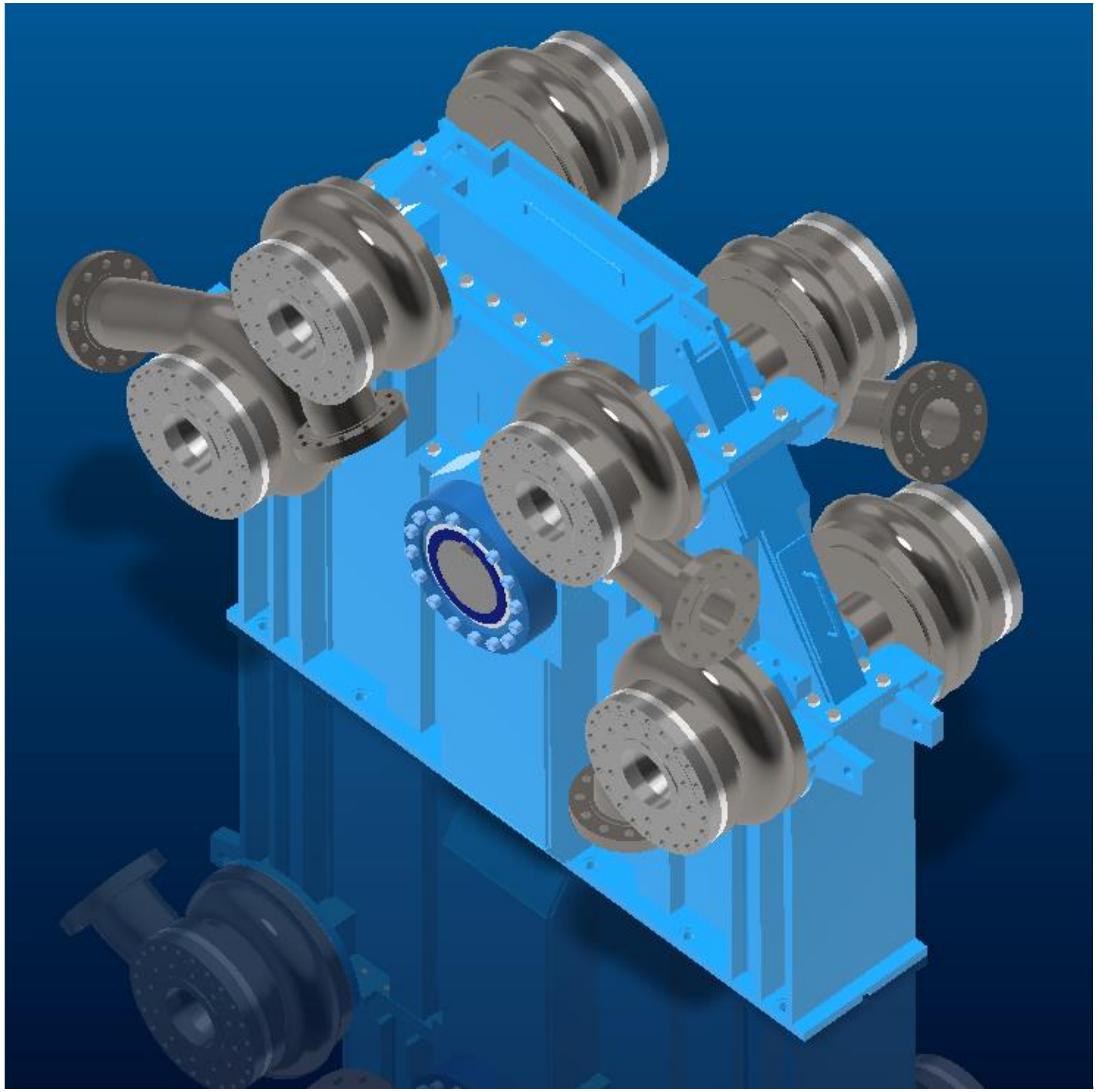
- 3-4 integral barrel arrangements with casing optimized speed
- High flow, high ratio, high efficiency
- Potential to engage/disengage individual compressors and switch between series and parallel operation
- Intercooled
- Multiple side streams/extractions
- Compact with ease of access for maintenance and repair
- Process gas free from oil contamination
- Up to 48 impellers

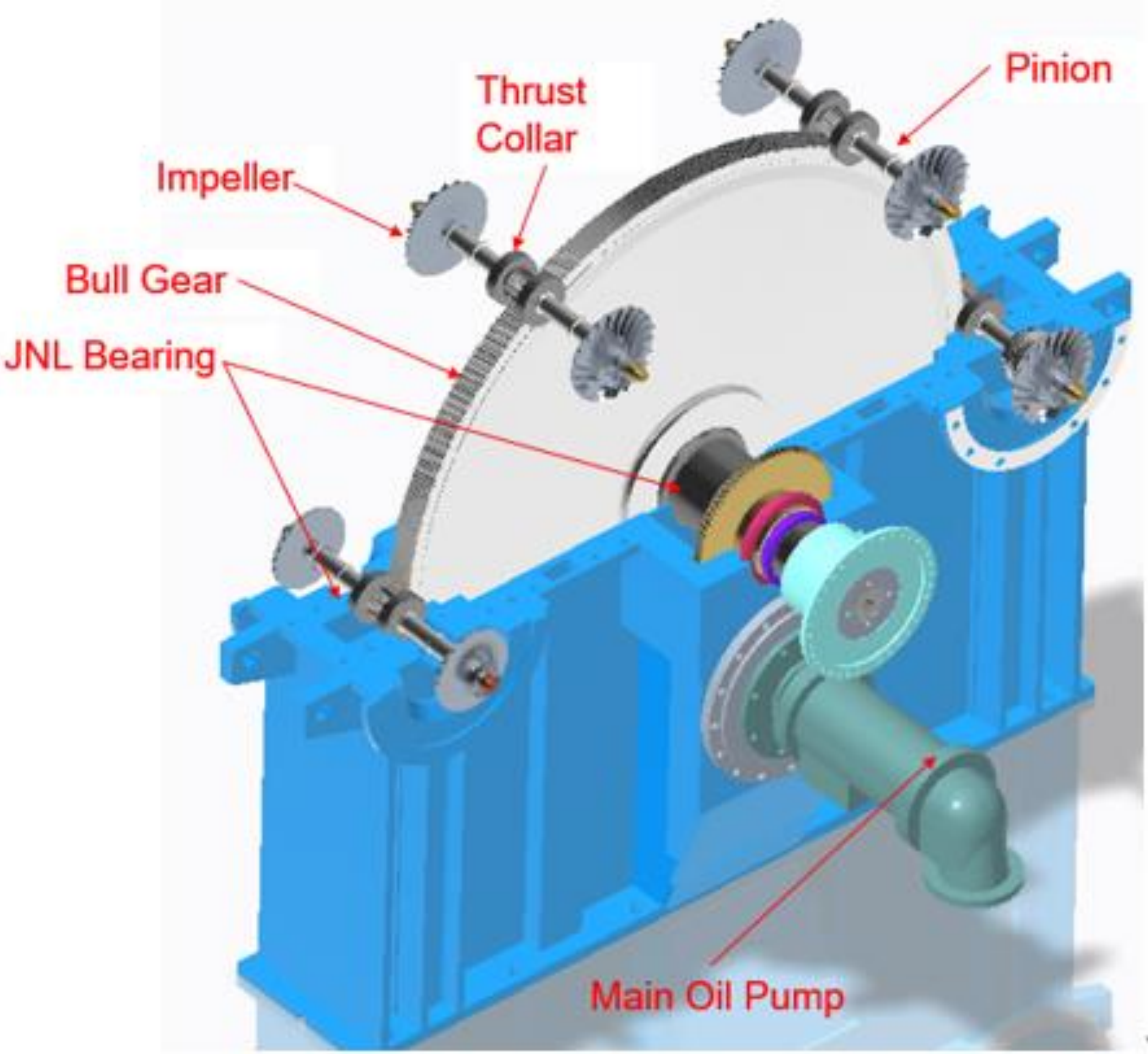




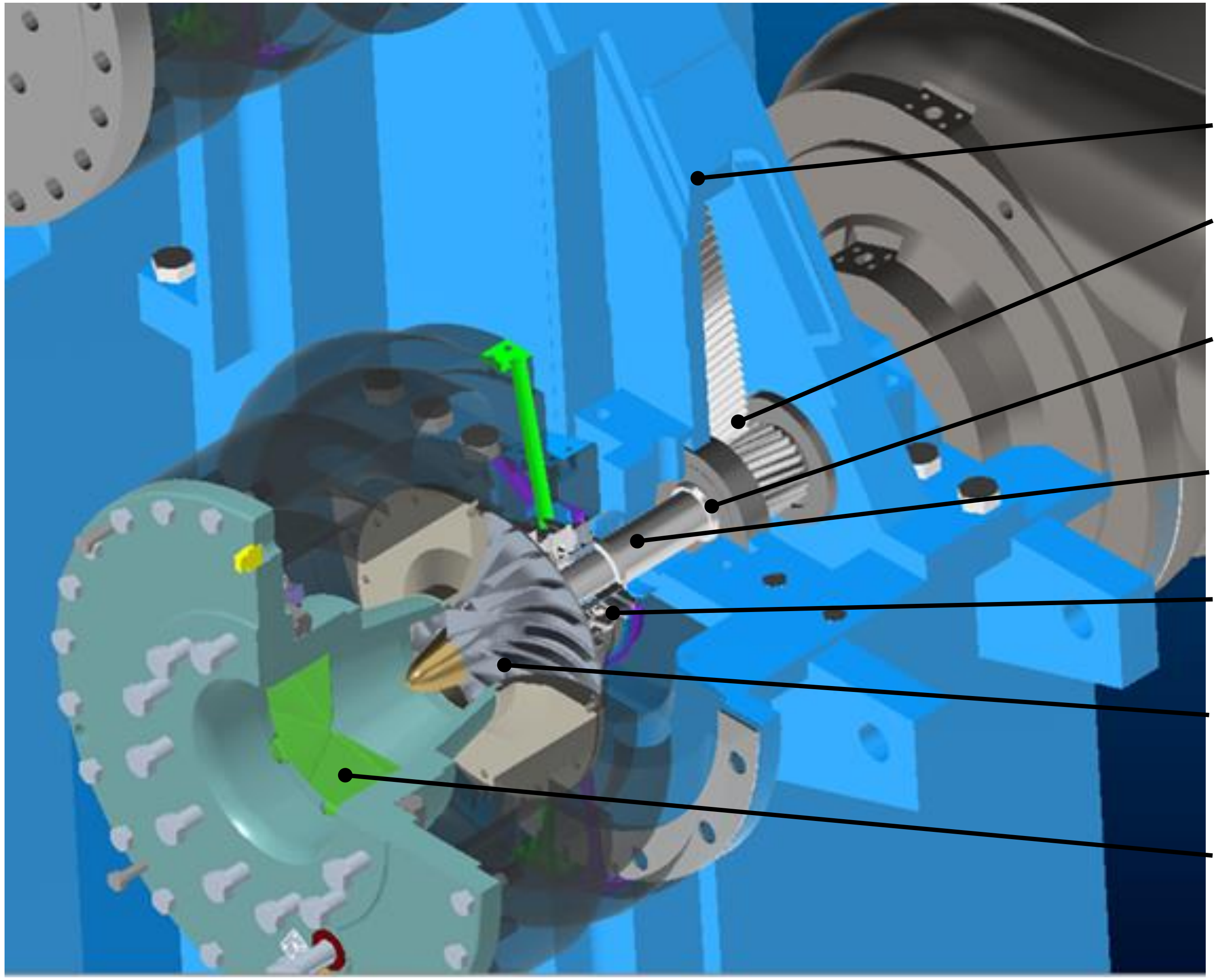
VFD Arrangement (with Voith gearbox)

High Speed Integrally Geared Compressor





Integrally Geared Hydrogen Compressor from Elliott Group



Up to 7 stages of inter-cooling to ensure high thermodynamic efficiency and maximum impeller structural integrity (not shown)

Fabricated gear casing in three different size frames

Up to four pinions and eight stages using single helical gears.

Optimized hydrodynamic thrust collars for minimal mechanical losses.

Tilting pad journal bearings for excellent lateral rotordynamic response and stability.

Proprietary seal design offers zero leakage and compact design for improved rotordynamics.

High strength aluminum alloy centrifugal impellers with hirth attachment for long life and easy maintenance.

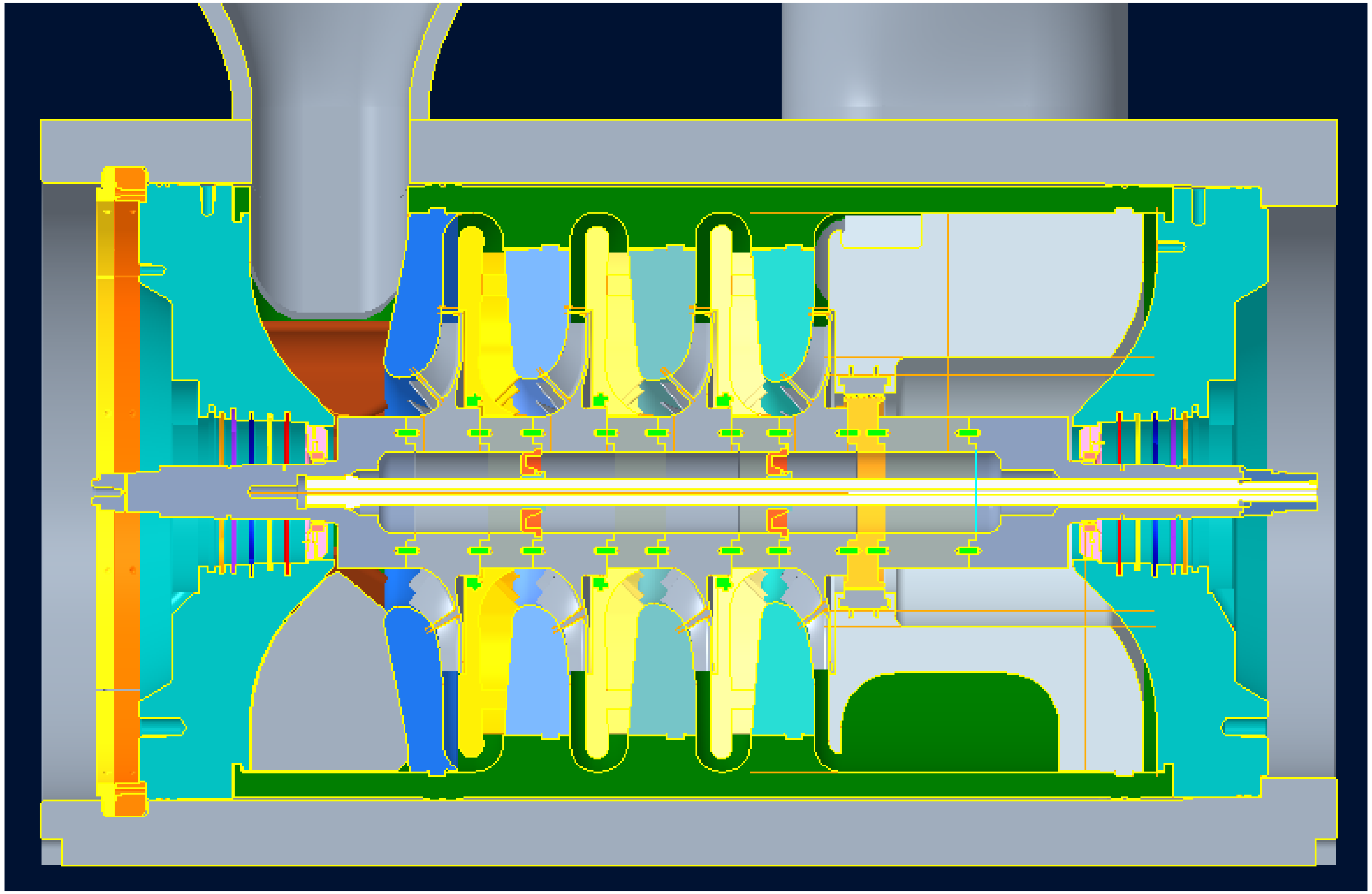
Variable geometry inlet guide vanes to control flow.

Fully packaged solutions: integrated lubrication system, integrated intercoolers, drive motor, and seal rack (not shown)

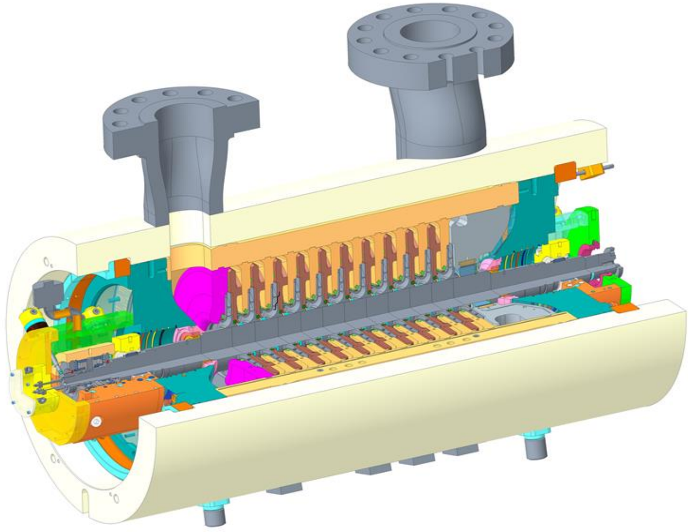
Inline – Hydrogen Compressor

Development Targets

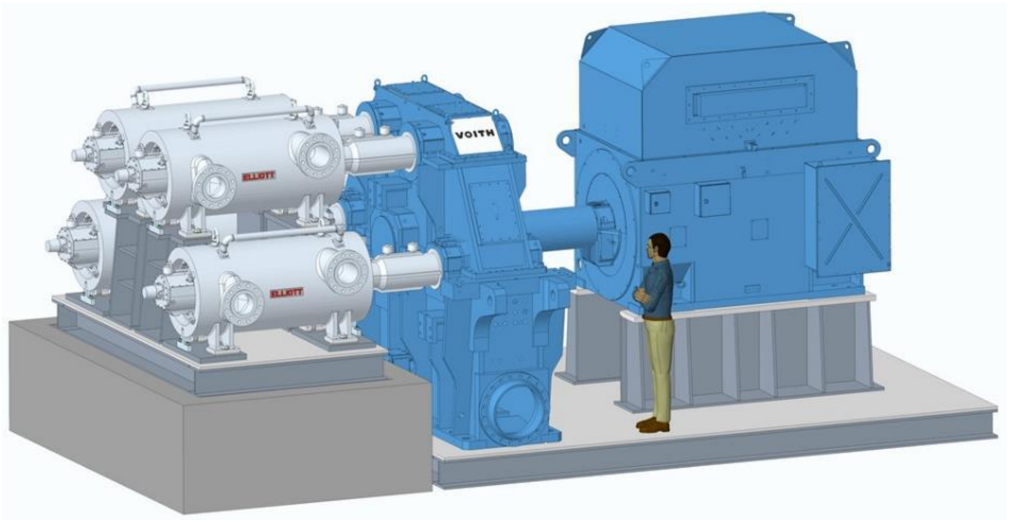
- 100% Hydrogen Service
- Pressure Ratio = 1.5 in a single casing
- Mass Flow=2,820 lbm/min (13,946 ICFM)
- Power = 24,000 HP
- Four High Speed Stages
- 38MB development size
- Can be scaled up or down
- 2-3 stage configuration possible for low PR applications
- EDGE style inlet
- Internal volute
- Stacked rotor design with a tie bolt



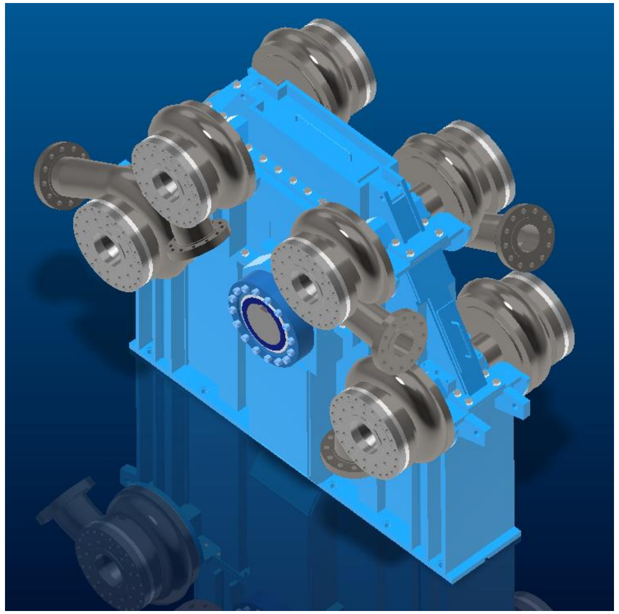
Hydrogen Compression Technology Options



Conventional High Speed
In-Line Centrifugal Compressors



Flex-Op Multi-Body
Centrifugal Compressors



Integrally Geared Conventional and
High Speed Centrifugal Compressors

__Pressure Ratio__: 1.2 1.4 1.6 1.8 2.0 2.4 2.6 3.0 3.2 3.4

__Application__:

Blower Pipeline Transport Pipeline Header Production Storage

Elliott-Ebara Turbomachines for Decarbonization of Energy Streams

- Centrifugal Compressors (API)
  - Barrel/Horizontal Splt
  - Inline/Back-To-Back
- Axial Compressors (API)
- Steam Turbines (API)
- Single Valve Steam Turbines
- Gas Expanders
- Cryo Pumps
- Cryo Single Phase and Multi Phase Expanders
- Custom Pumps (hydrocarbons, sCO2, ammonia, liquid hydrogen, etc.)

Elliott Centrifugal Compressor Train

ELLIOTT GROUP
EBARA CORPORATION

Thanks a lot! Questions?

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