TECHNICAL CHALLENGES FOR HYDROGEN COMPRESSORS

Rainer Kurz

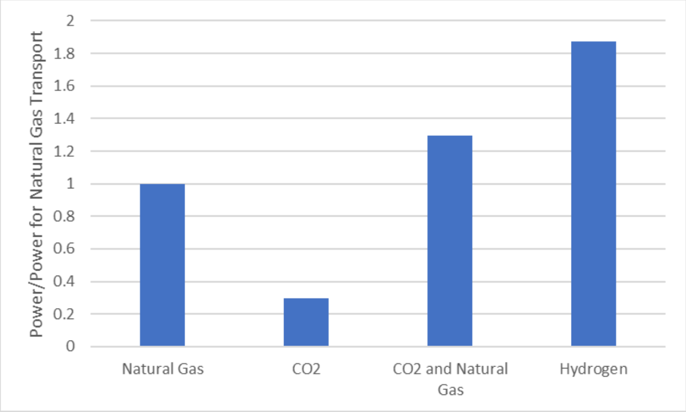
RKSBenergy LLC/San Diego State University

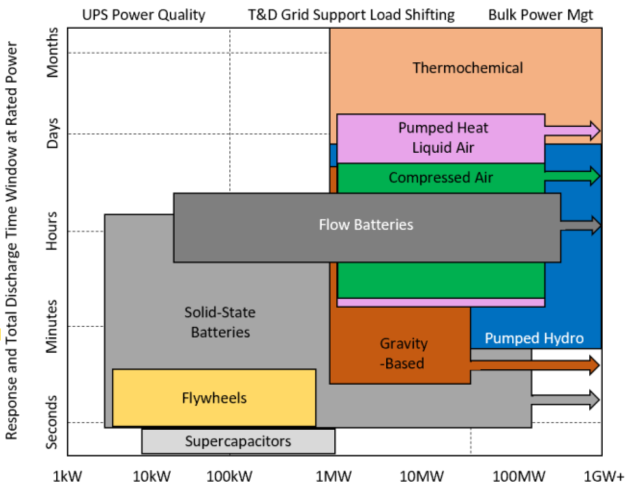
SDSU
College of Engineering
Aerospace Engineering

energy

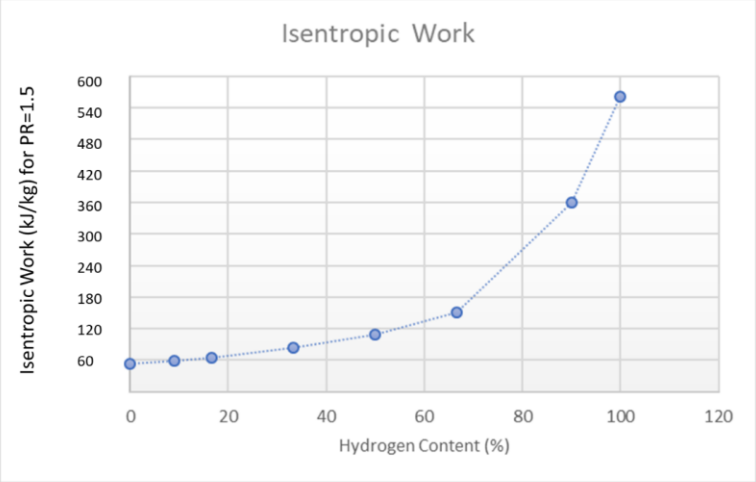
Introduction

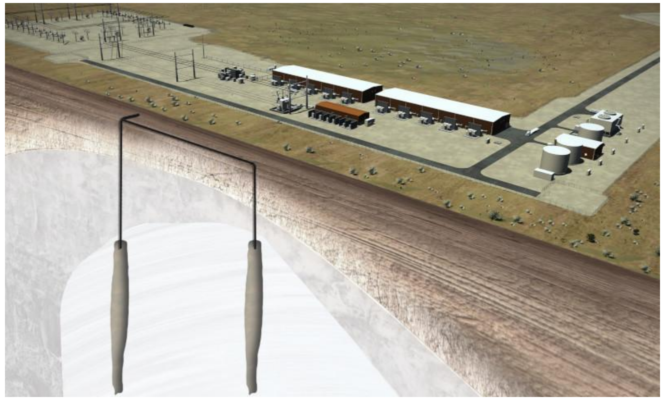
- Energy Storage
- Transportation cost
- Properties
- Compression Work





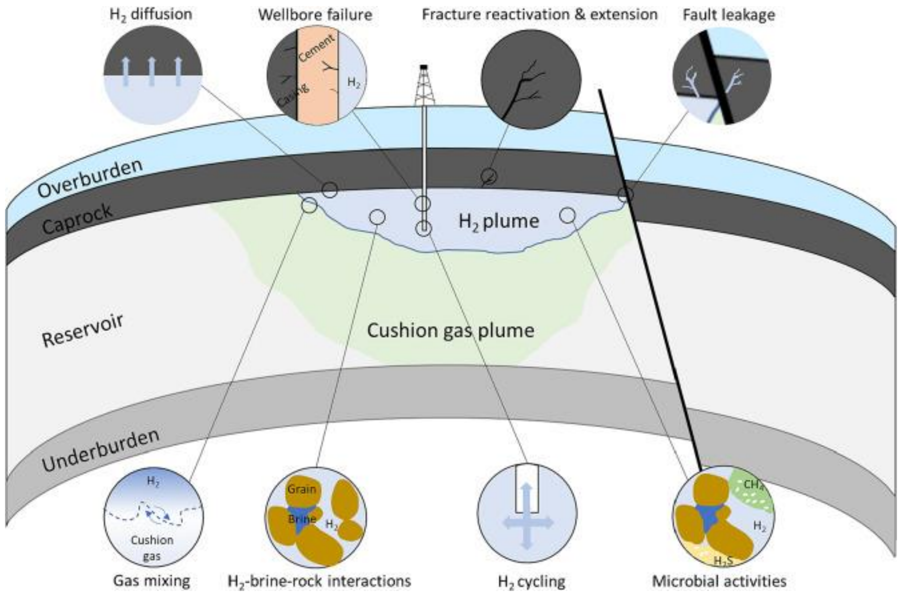
	Hydrogen	Natural gas	CO_2
Heat capacity (kJ/kgK)	14.3	2.3	0.839
Ideal specific heat ratio	1.41	1.32	1.28
Speed of sound (m/s)	1320	450	280





Why Hydrogen and Why Compression

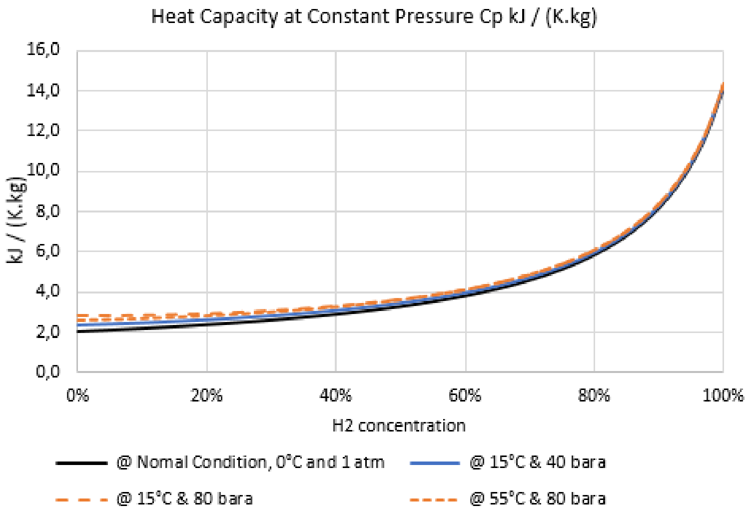
- Compression from Electrolyzer to Pipeline Pressure
- Pipeline Boost Compression
- Storage Compression
- Compression for industrial use

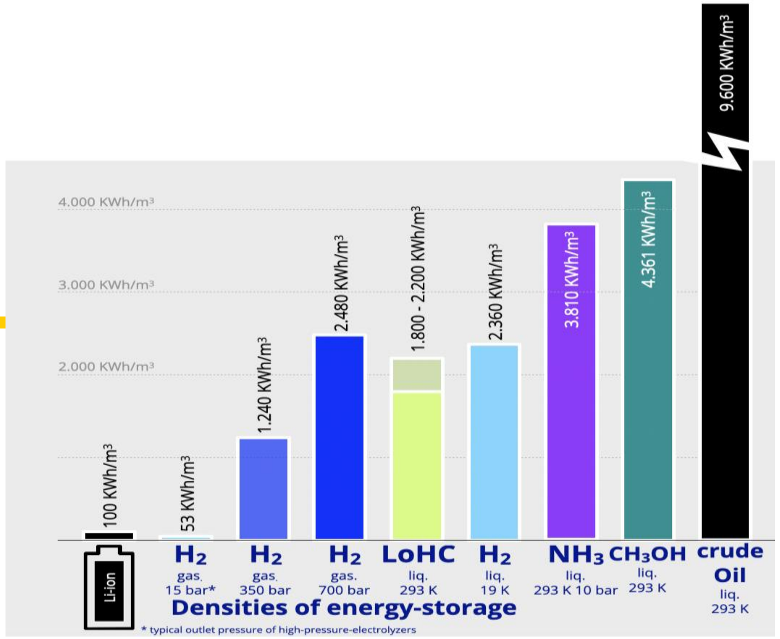


What's so special about Hydrogen Compression?

- Light Gas
- Low Energy Content per Volume
- High Heat Capacity
- High Work input needed for Given Pressure ratio

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





Energy density (by volume) of various energy sources

Pressure Ratio and Head – Compression Formula

To keep the same pressure ratio, Head Hact term must increase in proportion to the high cp value

$$\frac{P_2}{P_1} = \left[1 + H_{act} * \frac{n}{c_p * T_1}\right]^{\frac{\gamma}{\gamma-1}} = \left[1 + \frac{\omega * (r_2 c_2 - r_1 c_1)}{c_p * T_1}\right]^{\frac{\gamma}{\gamma-1}}$$

Can achieve the higher head required with either:

1) More speed, N, ω
2) Larger diameter, D
3) More stages of compression

	Hydrogen	Natural Gas	CO2
Heat Capacity (cp, kJ/kgK)	14.3	2.3	0.839
Ratio of Heat Capacities (γ)	1.4	1.3	1.3

Source: Brun K., Kurz R., Allison, T. "Pipeline Compression for the Hydrogen Economy", DOE Seminar 2021

Hydrogen Compression

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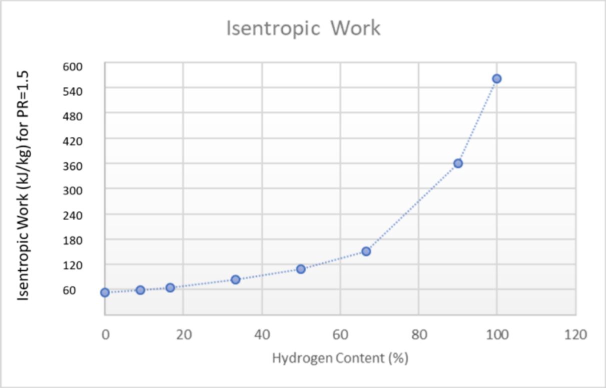
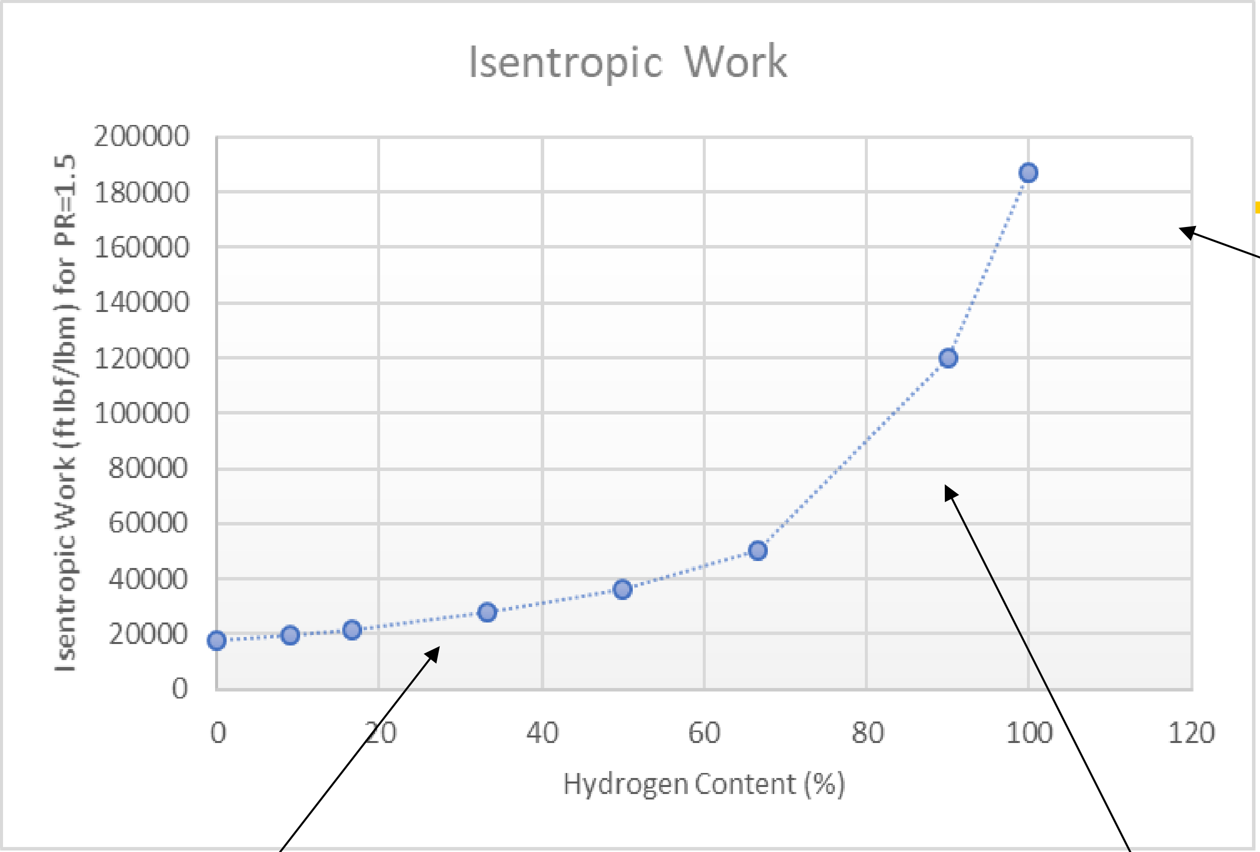
- High Heat Capacity
- High Speed of Sound
- High Volumetric Flow (low energy density)



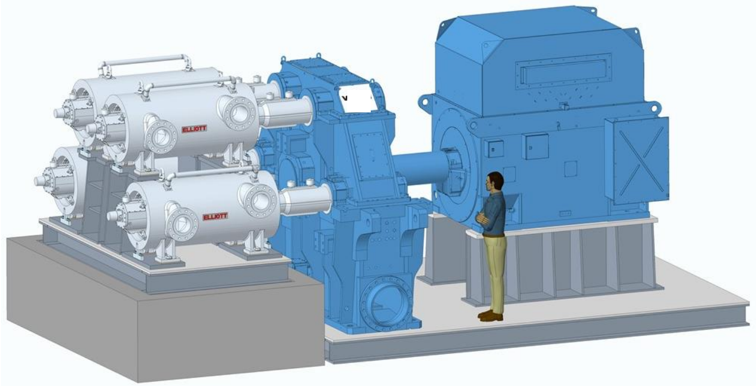
Hydrogen Mass Flow (t/d) [appr Electrolyzer Size-GW]		Hydrogen Volumetric Flow (m3/h)		
	288 K, 1 bara	288K, 20 bara	288K, 30 bara	288K, 100 bara
100 [0.21]	49,540	2,500	1,680	525
400 [0.83]	198,160	10,000	8,000	2100
1000 [2.08]	495,400	25,000	16,800	5250
2000 [4.17]	990,800	50,000	33,600	4200

As a reference, a centrifugal compressor with 24” flanges can handle about 45,000 m3/h, while a smaller machine, with, say 16” flanges flows about 17,000 m3/h. In other words, if the Hydrogen is available at 20 or 30 bar, even moderately sized centrifugal compressors can handle the flow in a single machine. As mentioned previously, to achieve similar pressure ratios for Hydrogen compression as required in natural gas, the power requirement for the same mass flow is drastically increased (by a factor of about 10).

Hydrogen-Natural Gas Blending

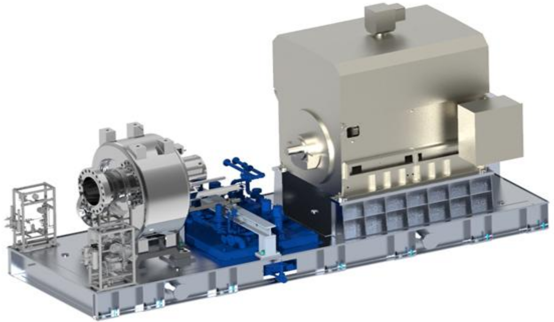


Multiple Compressor Bodies



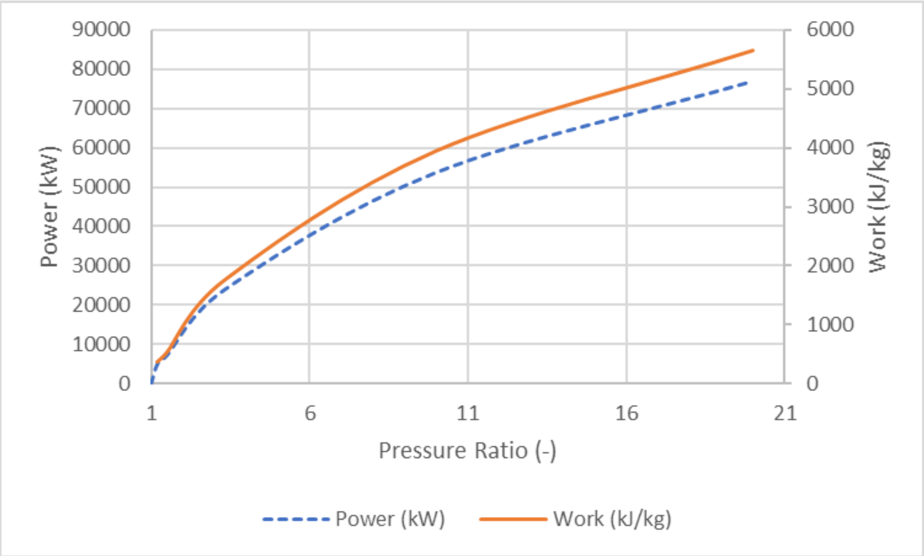
Conventional Pipeline Compressor

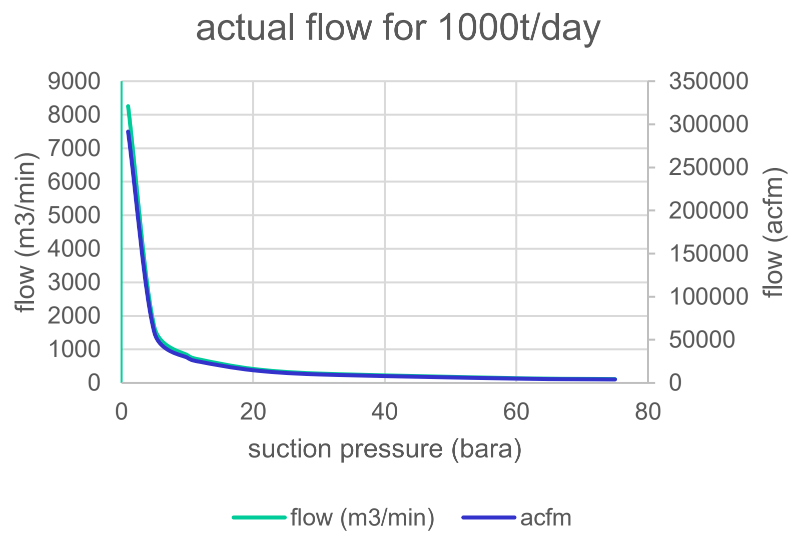
Single Body Process Compressor



Source: Kurz R., Allison, T., Brun, K. "Pipeline Compression for the Hydrogen Economy", DOE Seminar 2021

Sizing

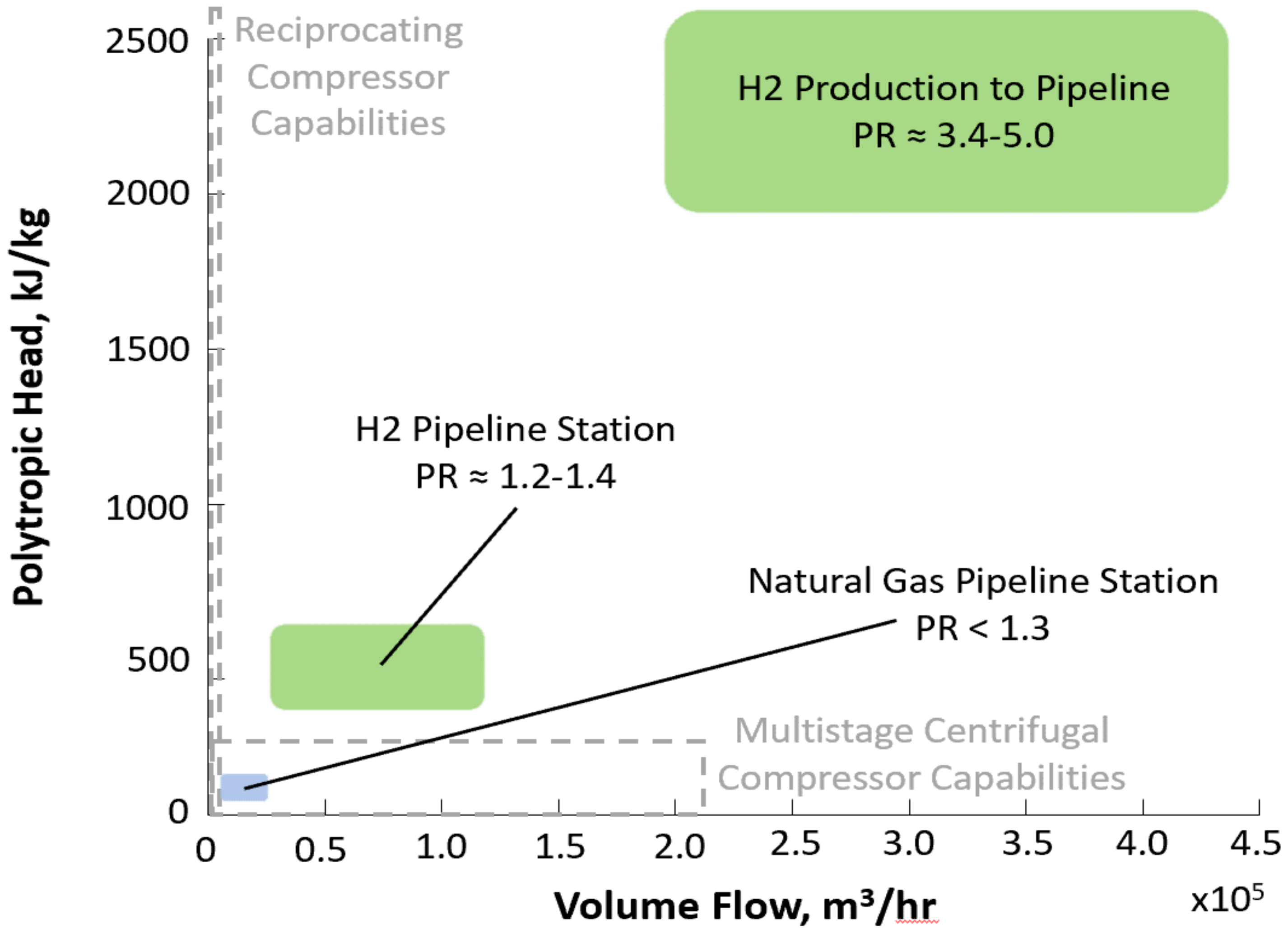




Compressor Power Demand (based on 85% isentropic compressor efficiency) and Compressor Work for 1000t/d of hydrogen. A conventional industrial compressor can produce about 250 to 300kJ/kg per casing, indicating a substantial gap in the capability of currently available compressors.

Actual Inlet flow for 1000t/d of hydrogen for different suction pressures (see also Table before)

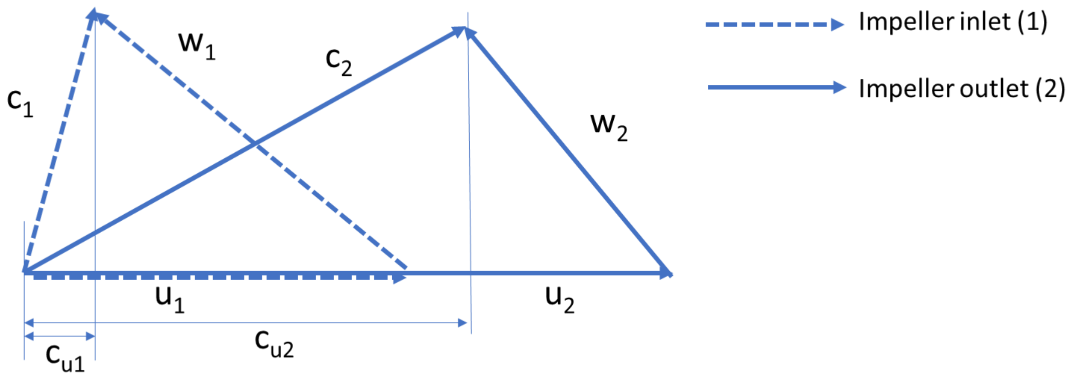
Flow vs Head for Hydrogen



Conceptual Methods for more Head

- increase the number of stages (this may require multiple compressor bodies)
  - -rotordynamics
  - -economics
- increase the tip velocity
  - -open faced
  - -aerodynamic shapes to minimize stress levels
  - -rotordynamics
  - -materials
- increase the head coefficient
  - -operating range and efficiency

Energy Transfer in Impellers/ Velocity Triangles



$$P = \dot{m} \cdot \Delta h = \dot{m} \cdot (u_2 c_{u2} - u_1 c_{u1})$$

- Work input is essentially dictated by the circumferential deflection of the gas in the impellers multiplied by the tip speed.
- Key to increase work seems to be an increase of tip velocity.
  - Increase in tip velocity for a given impeller increases the work capability by the square of tip velocity.
  - The increase of tip velocity, however is limited by structural strength, because increasing tip velocity increases the stress levels in the impeller, for geometric similarity, at about the square of tip speed.
  - On the positive side, the high speed of sound of hydrogen will likely not cause limits regarding Mach numbers in the impellers.
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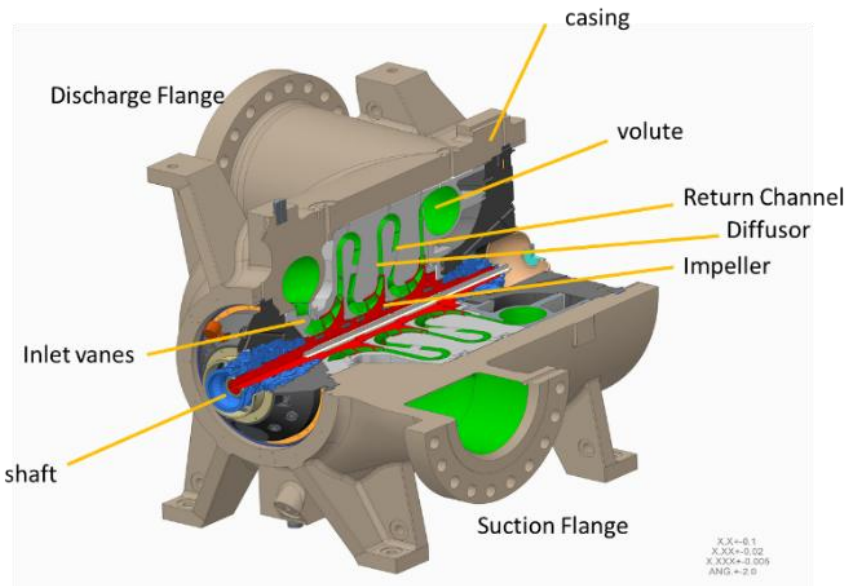
Compressor Aerodynamics and Options to Increase Head

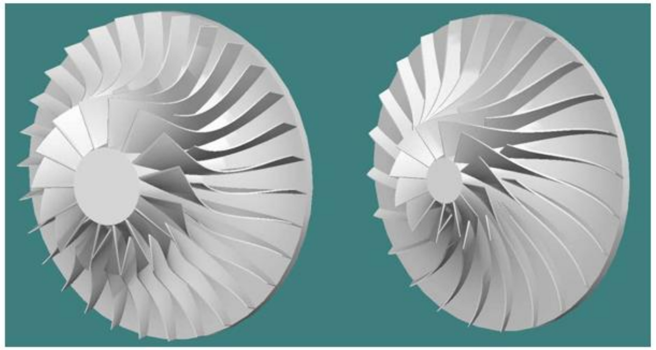
Shrouded Impellers

Max tip speed appr. 450 m/s



Centrifugal Compressor

Open Faced Impellers



Max. tip speed 600m/s, maybe more

Increased Tip Speed

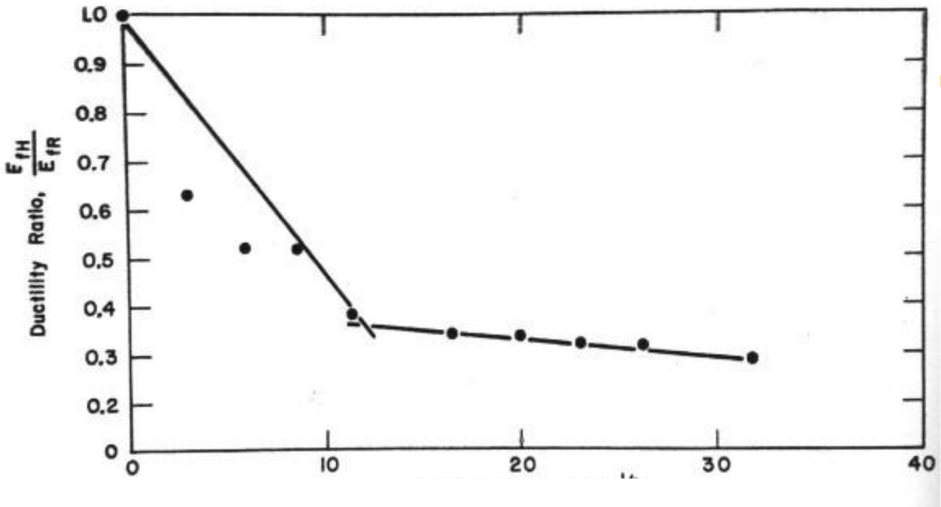
Stress Levels $\sigma = C\,\rho\,u_2^2$

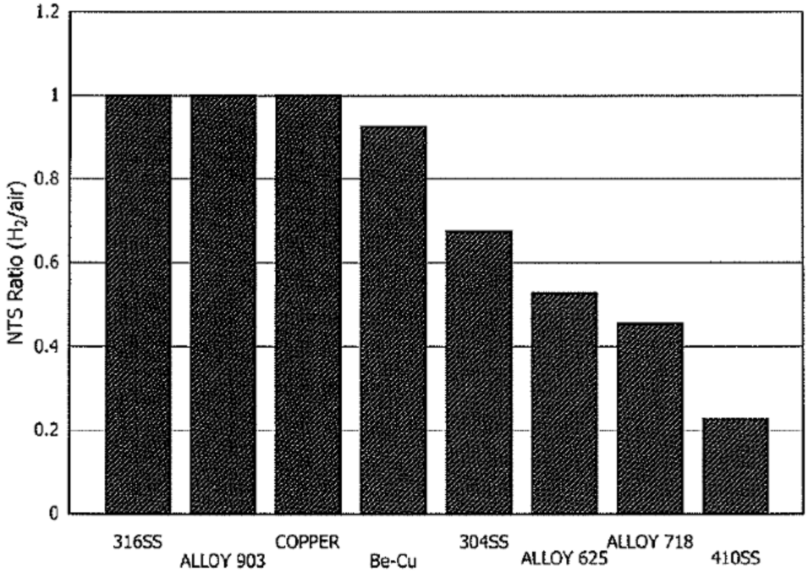
Rotor/shaft attachment: Hirth, Curvic or other tie bolt design; single piece rotor

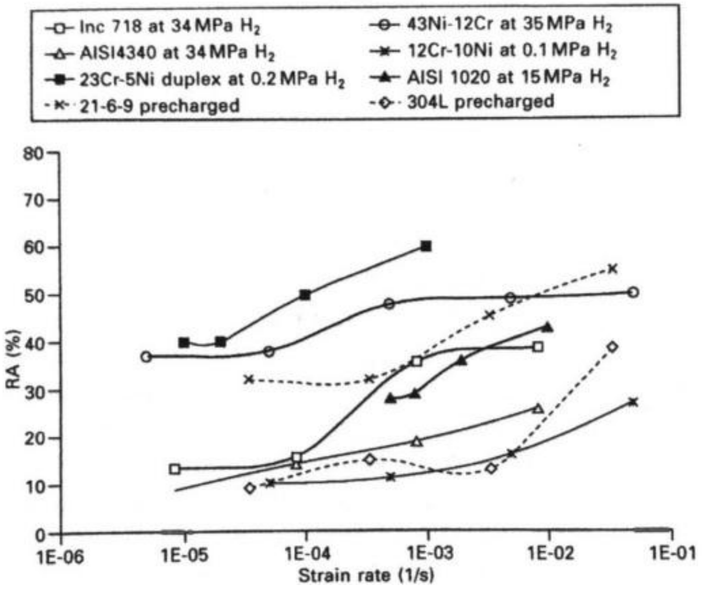
Shrouded (max u_2 appr. 450 m/s) vs Unshrouded (max u_2 appr. 600-700 m/s)

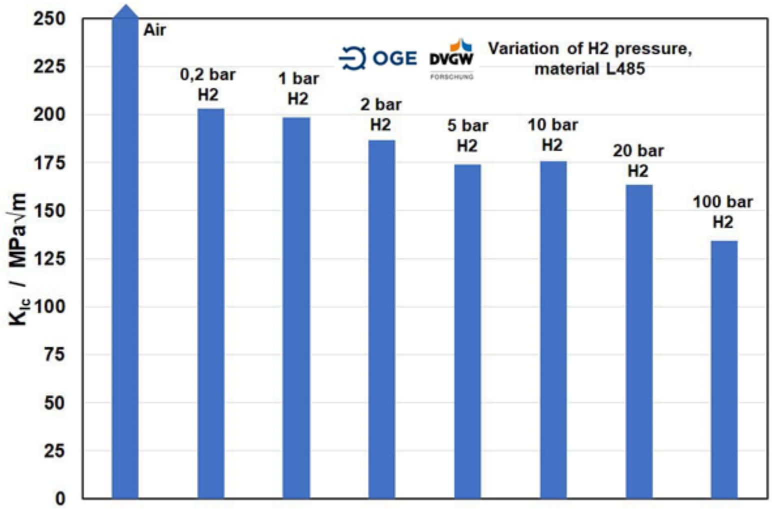
Materials (high strength to density ratio: Aluminum or Composites)

However: Hydrogen Embrittlement









Materials: Strenghth and Embrittlement

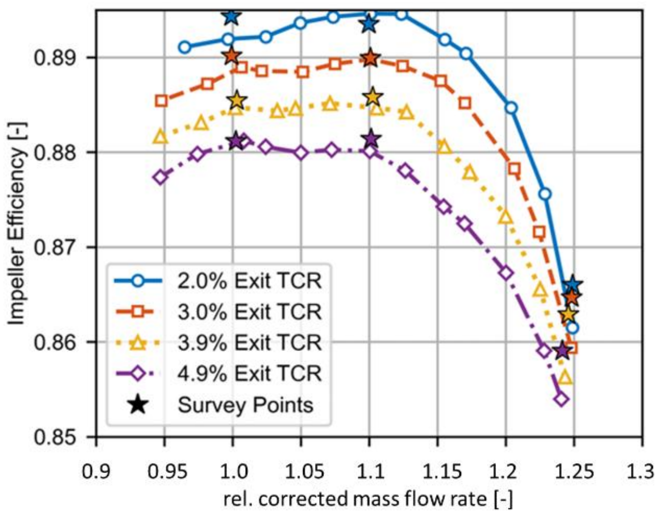
Alloy	AISI 4340 (Steel)	ASTM B247 Grade (Aluminum 7075-T6)	ASTM B381 Grade FS (Ti-6Al-4V)
Tensile (MPa)	965	469	896
Density (kg/m^3)	7833	2796	4429
Specific Strength (kN m/kg)	123	168	202
Breaking Length (km)	12.6	17.1	20.7

Specific Strength Comparison of Candidate Materials

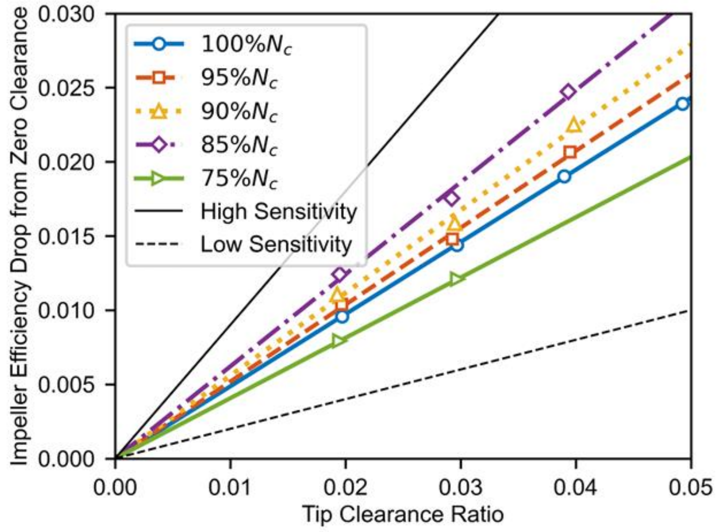
Material	Hydrogen Embrittlement Susceptibility (P_{He}/P_{H2})
Aluminum 7075-T6	Low (1.01)
Haynes 188 (Cobalt Base)	Low (1.00-1.16)
Beryllium Copper (copper base)	None (1.0)
Austenitic SS 304	Low-Moderate (1.11-1.84)
Austenitic SS 316	Low
Austenitic SS 310	Low
Ferritic SS 430	Low
Austenitic SS (age hardened) A 286	Low (1.02)
Ti-5Al-2.5Sn	Low (.96-1.08)
Duplex Fe-26Cr-6.5Ni	Low (1.09)
Ti-6Al-4V	1.06-1.35
Ti-6Al-6V-2Sn	1.09-1.84
Steel 0.18C	1.25-1.81
U-1.5Mo	1.32
Pt-25Ir	1.32-4.07
Zr-0.5Cu	1.41-1.69
Nickel	1.82-3.55
Ti-13V-11Cr-3Al	1.99
Haynes 25	2
Fe-38Ni-12.5Cr-5.4Mo-2.33Ti	2.53-3.29
H11,35NCD16,4340,300M, Maraging Steels	3.53
Hi-T tempered Martensite	1.42-2.19
Continuously rolled 230ksi 0.75% steel	1.57-1.63

Hydrogen Susceptibility of some materials, indicated by the burst pressure in Hydrogen relative to the burst pressure in a non-Hydrogen (ie. Helium) atmosphere.

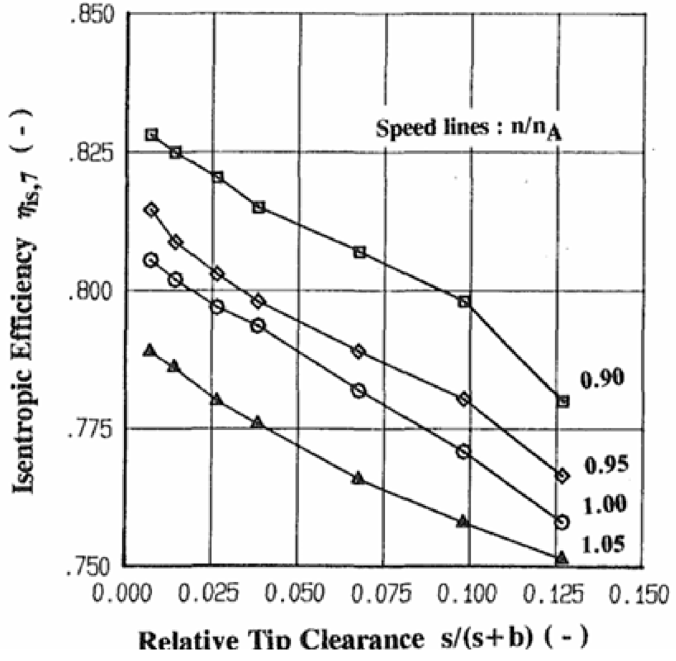
Open Faced Impellers: The Clearance Issue



Effect of tip clearance TCR on the HECC impeller efficiency map at 100% corrected speed. Survey points indicated with stars



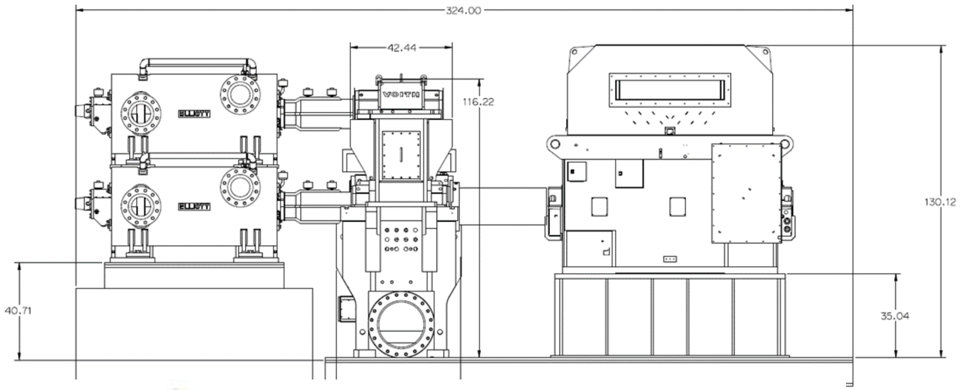
HECC impeller efficiency drop as function of tip clearance ratio (TCR) , with typical high-low range of sensitivity indicated

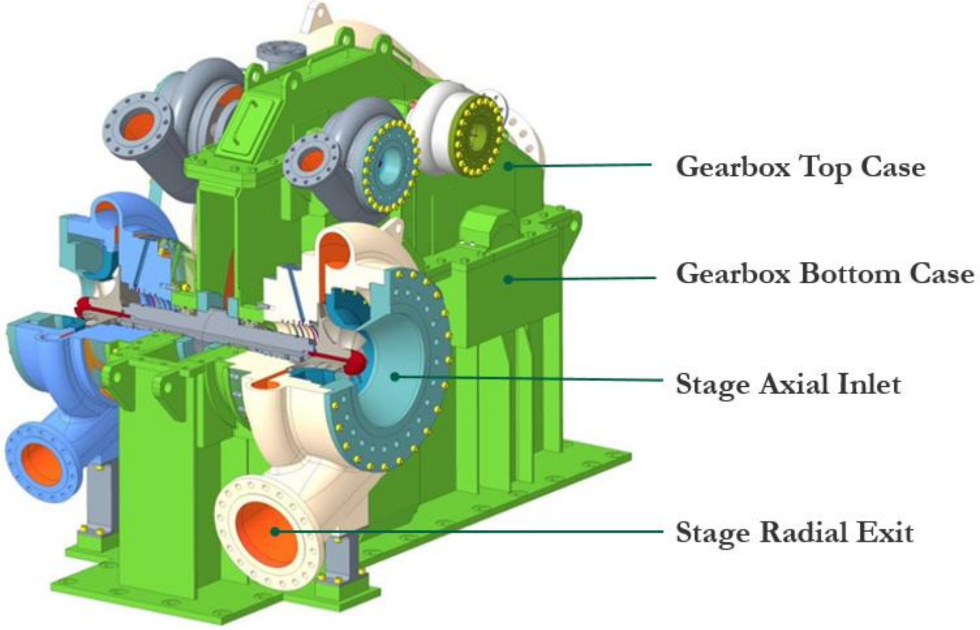


Change in isentropic efficiency with changes in tip clearance for an open faced impeller

Architectures

- Architectures for more impellers
- Integrally geared
    - Open Faced Impellers, possibly Aluminum
- In line:
    - Open Faced Impellers
    - 2 Stages open faced, rest Closed face
    - Materials (eg Composites)
- All: maximize Tip Speed





Summary

Pres sure Ratio	Conven-tional	30% increase head coefficient (radial ending blades)	Increase of tip speed from 350 m/s to 450 m/s	Increase of tip speed from 350 m/s to 640 m/s	Max two impellers at 640m/s per casing, rest 450 m/s
1.5	16 [2]	12 [2]	10 [2]	5[1]	8 [1]
3.3	53 [6]	41 [5]	32 [4]	16 [2]	26 [3]

- Number of Stages
- Tip Velocity
- Head Coefficient

Impact of tip speed and blade geometry on number of impellers (assuming 33 kJ/kg per impeller for a baseline natural gas design, and assuming a maximum of 9 impellers per casing). Number of casings in brackets; conservative estimate.

Conclusions

- The pathway to the successful use of centrifugal compressors in hydrogen compression leads through the capability to operate at **high tip velocities**, which in turn lead to high stress levels in the impellers.
- Higher tip velocity can be achieved by combinations of aerodynamic mechanical design (ie low stress, clearance control, high work coefficient), and materials.
  - Open faced impellers allow higher tip velocities than shrouded impellers, but may incur efficiency penalties due to clearance losses.
  - Integrally geared compressors, and has been used some in-line compressors.
  - In Line Compressors with multiple open faced impellers on a single shaft have been built.
  - Material choices, in particular the move to composite materials may allow to stay with shrouded impellers and traditional backsweep while still allowing for high tip speeds. These materials, however, have not been employed in commercial use yet.