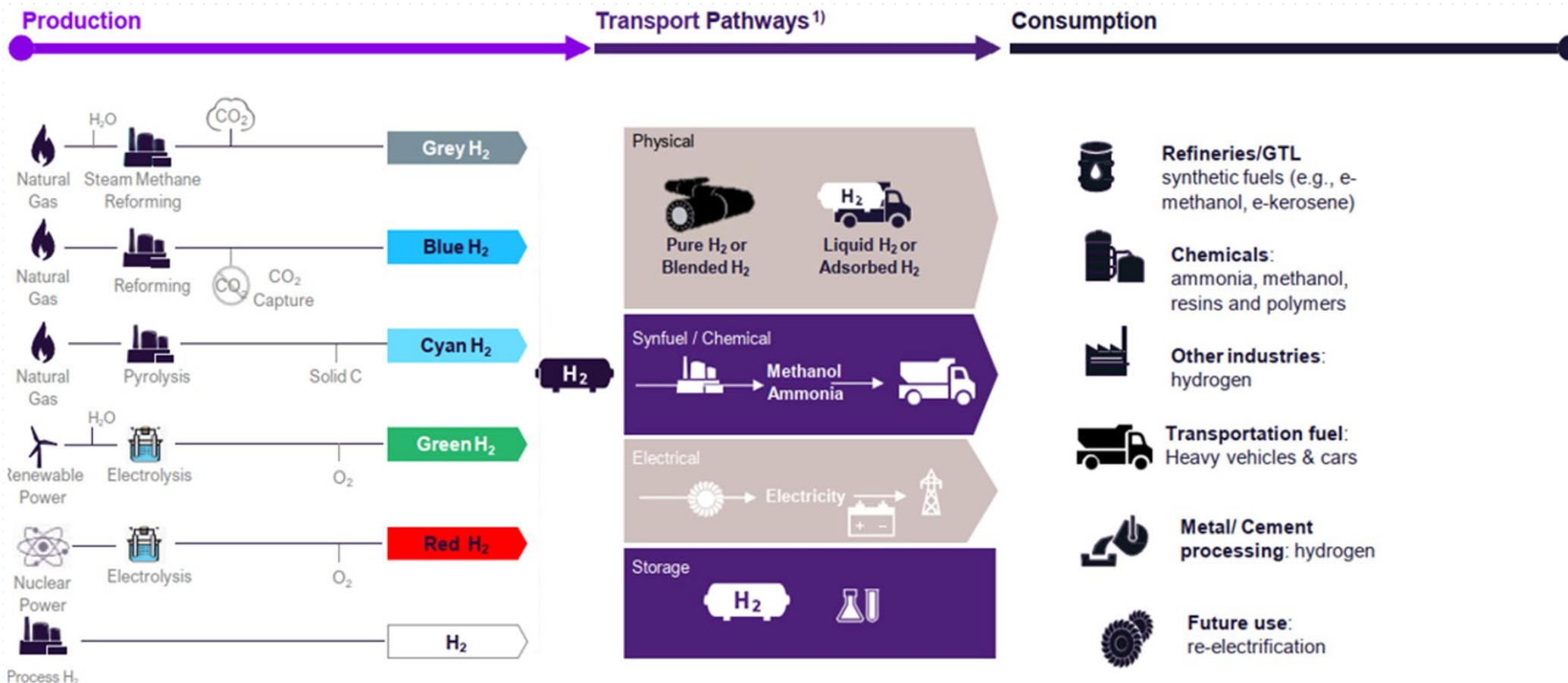


COMPRESSOR **TECH²** HYDROGEN **SUMMIT**

HOUSTON, TX APRIL 25, 2023

Steve Chaykosky
Joel Sanford
Valve Performance



¹⁾ Processes after H₂ production are independent of the production type, its always the same chemistry; maybe certificate trading; ²⁾ quantitative growth potential in a decarbonized environment; Abbreviation: CCS – Carbon Capture and Storage; SMR – Steam Methane Reforming; NG – Natural Gas

Some Sources of Hydrogen for Reciprocating Compression

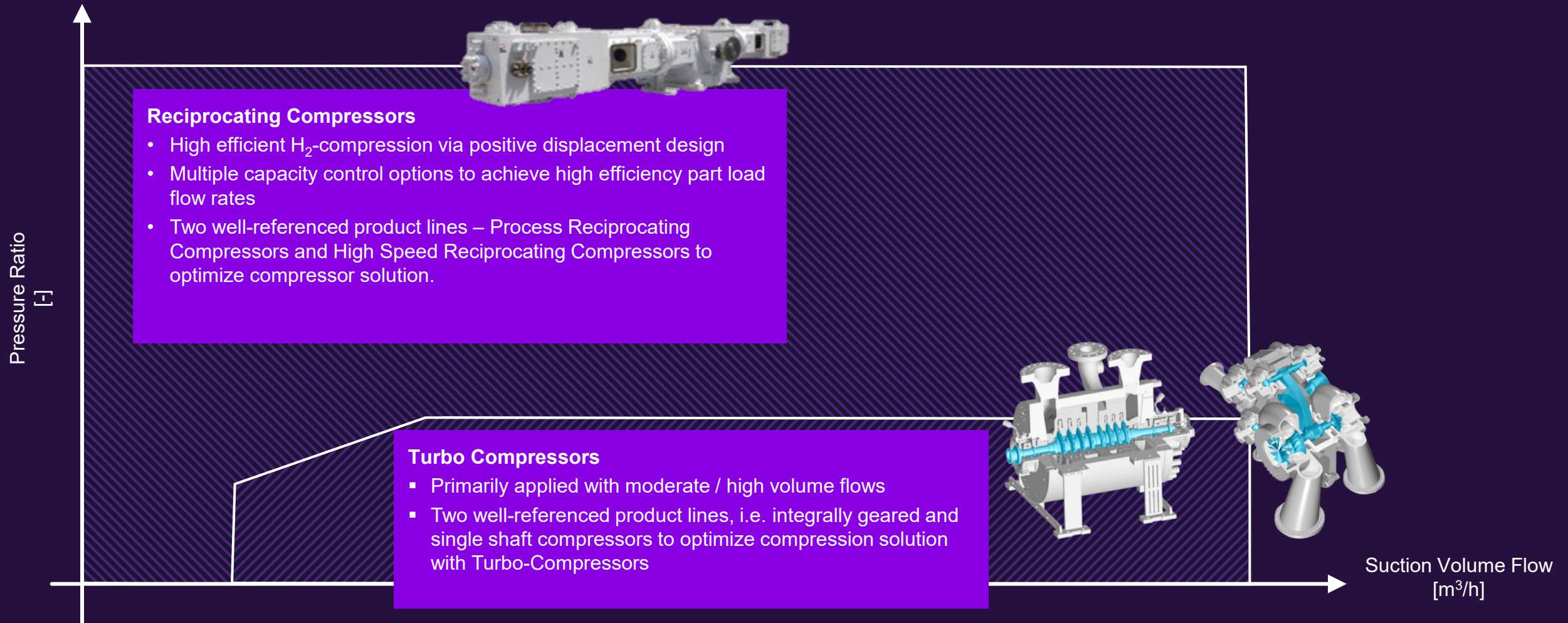
- Steam-methane reforming
- Autothermal reforming
- Partial Oxidation
- Electrolysis
 - ✓ Green H₂ if electricity is from renewable source: wind, solar, hydro

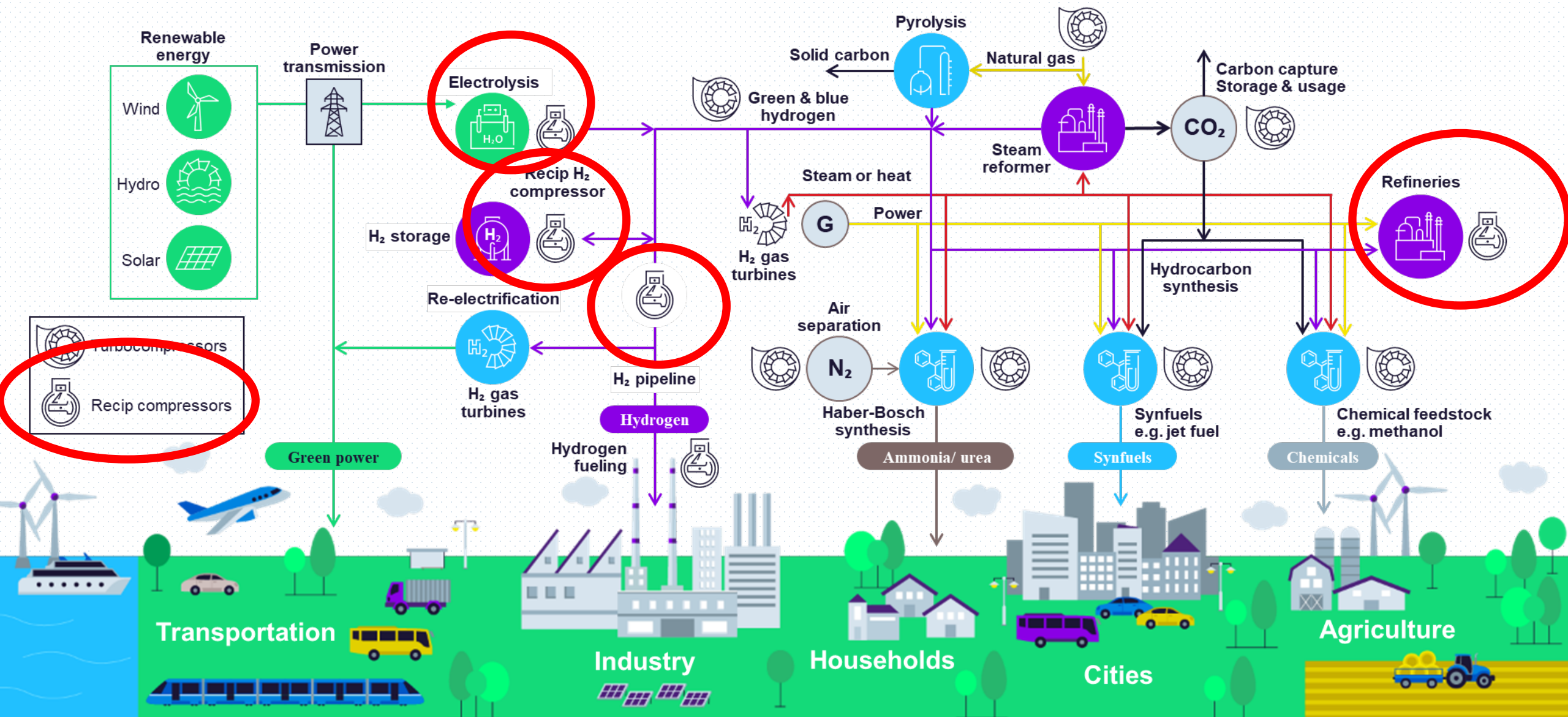
Why Use Recips in Hydrogen Service?

- Relatively low-cost and efficient compressor for low to moderate flow rates
- Easily handles higher discharge pressures
- Well-established metallurgy for pure H₂ and hydrogen-rich services
- Flow-control flexibility to match demand with minimal recirculation
 - ✓ Fixed-step flow control
 - Inlet valve unloaders
 - Clearance pocket unloaders (usually on outer head)
 - Stepless flow control
 - ✓ Infinite Step Control (ISC) finger unloader – controlled inlet valve leakage
 - Hydraulic Variable Volume Clearance Pocket (HVVCP) – automated control
 - Manually Variable Volume Clearance Pocket
- Variable Frequency Drive

Comprehensive product portfolio for Hydrogen Compression

Indicative areas for best economical trade-off for pure H₂ -compression





Reciprocating Compressors in Hydrogen Service

- Traditional oil refining processes
 - ✓ Hydrocracking: make-up and recycle gas
 - ✓ Hydrotreating: make-up and recycle gas
 - ✓ Flare gas and vent gas recovery: hydrogen & hydrocarbons, often sour gas
- Other energy sectors
 - ✓ Fuel for power gas turbines
 - ✓ Blend with pipeline natural gas
 - ✓ Underground storage
 - ✓ Fuel cells for transportation
- Renewable diesel
 - ✓ Hydrotreating

Compressor Performance – Efficiency & Reliability



- A compressor with a lower measured BHP / MMSCFD is more efficient
 - ✓ Brake Horsepower / Millions of Standard Cubic Feet per Day
 - ✓ Power Consumed / Compressor Flow Rate
- Compressor reliability & availability can be measured by the amount of uptime

Compressor Valve Types

Concentric Ring Valve



Ported Plate Valve



Poppet Valve



Magnum™ Valve

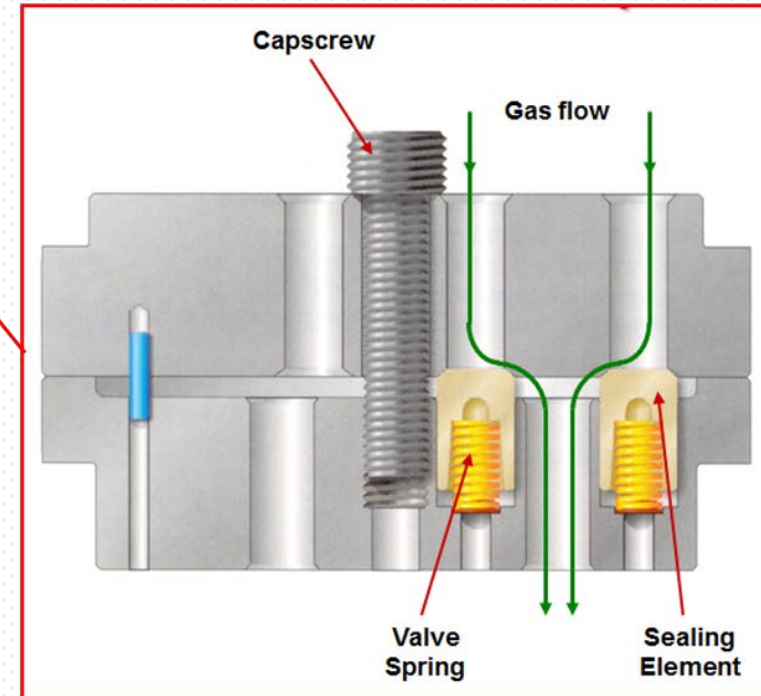
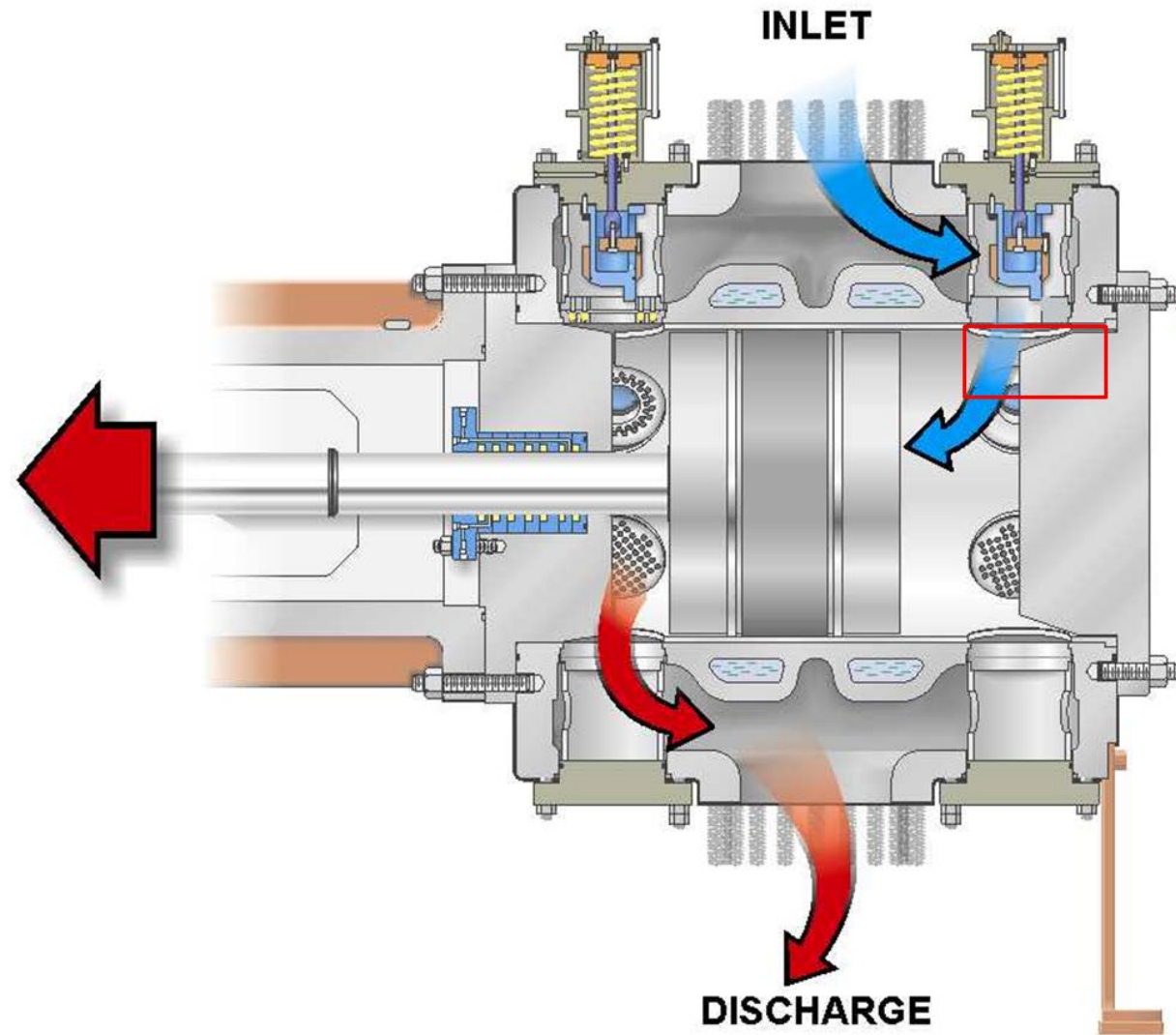


Magnum HammerHead™



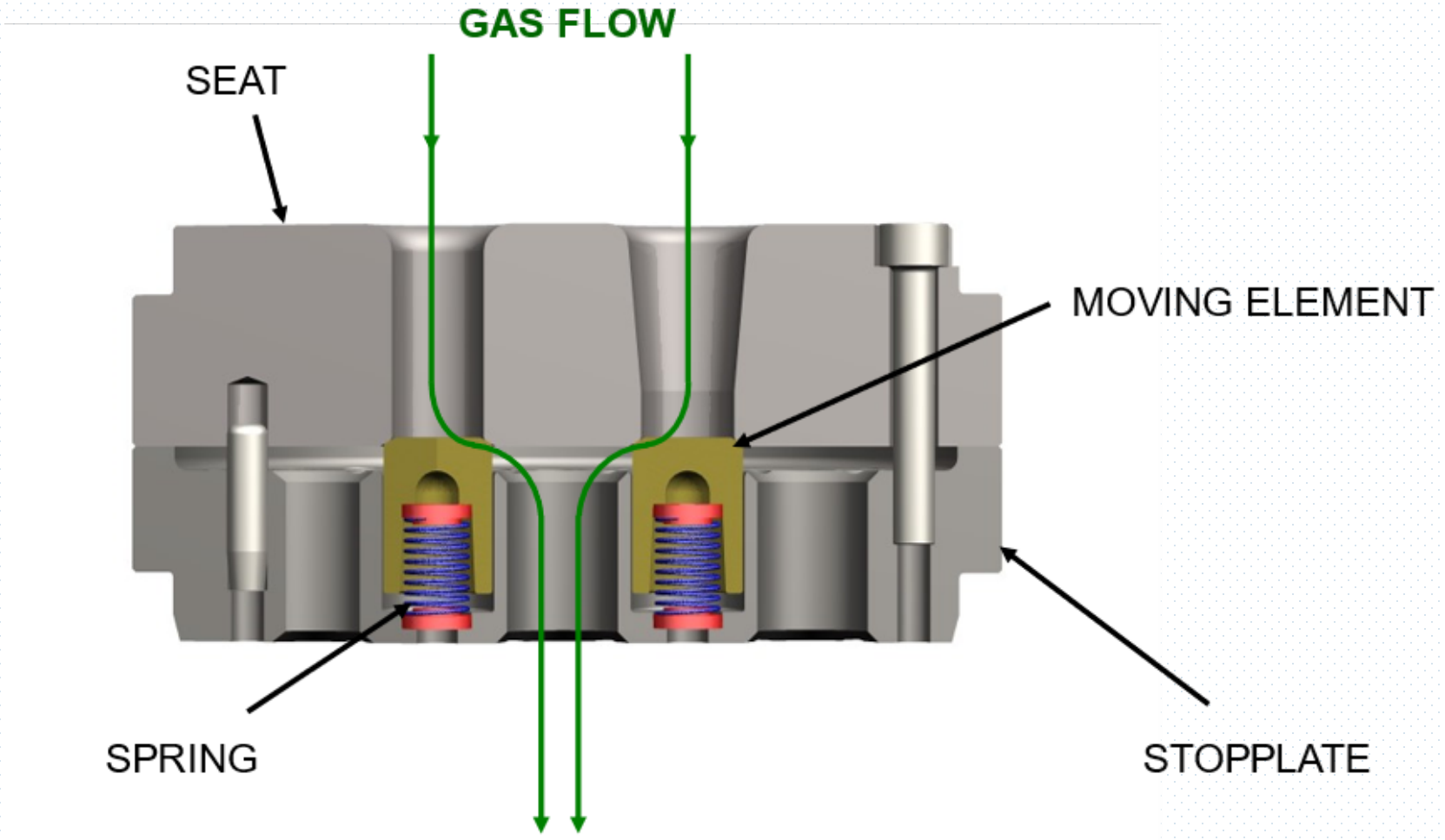
H2 Flow Path Through a Compressor Cylinder

- All of the H2 entering and leaving the cylinder must flow through the valves



Compressor Valve Efficiency

- Directly relates to compressor efficiency
 - ✓ Deliver required flow of H2 with minimal power consumption



Valve Efficiency

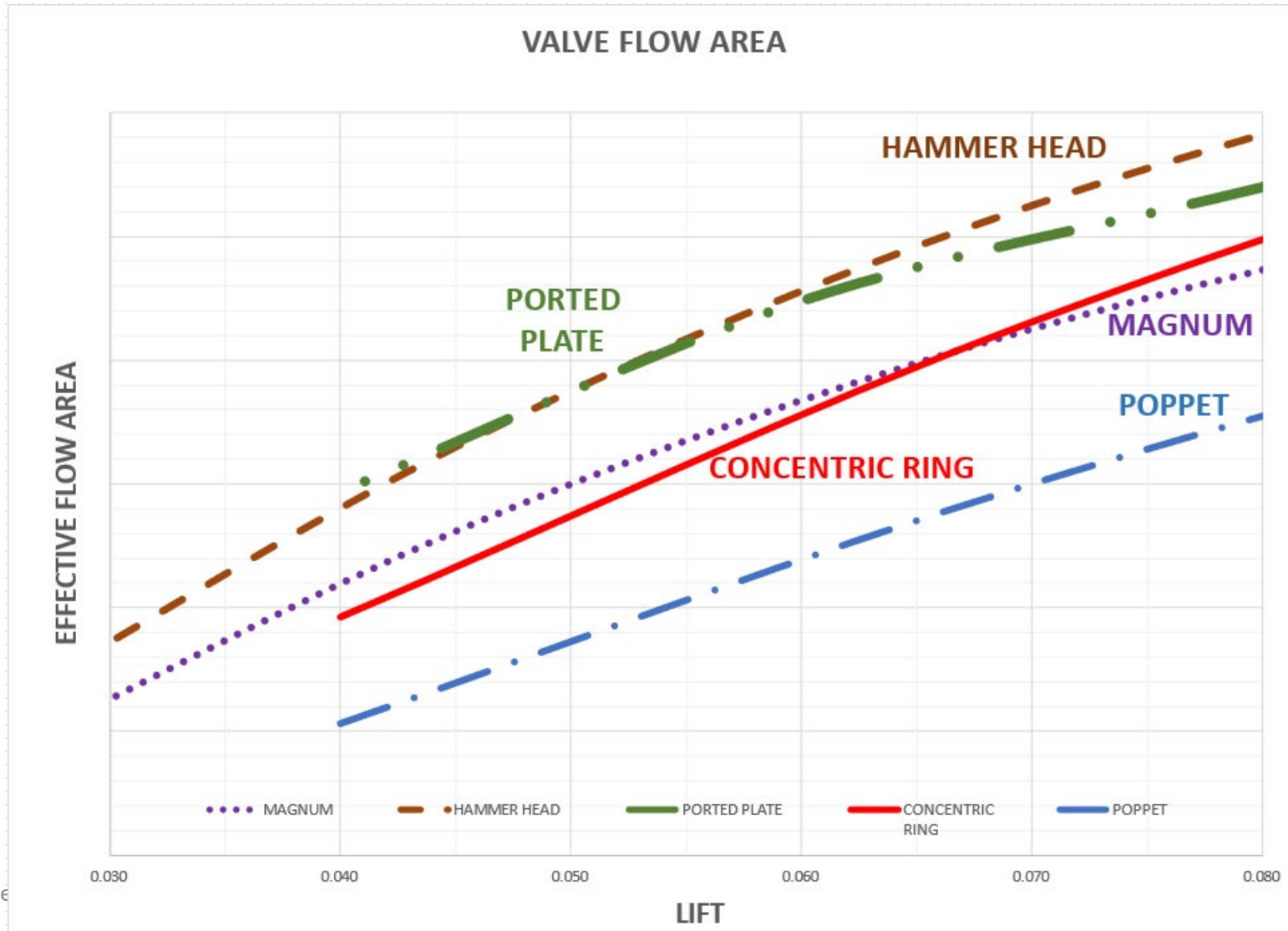
- A valve is an orifice
 - ✓ Valve flow area is defined by its geometry
 - High flow area and aerodynamic geometry minimize the valve pressure drop
 - Lower valve pressure drop minimizes power consumption of the motor or engine and therefore increases compressor efficiency
- A valve has volume in the inlet stopplate and discharge seat (valve clearance) that adds to the cylinder clearance volume
 - ✓ High valve clearance increases the cylinder clearance
 - Higher cylinder clearance reduces the compressor flow rate
 - High valve clearance therefore reduces compressor efficiency

Valve Lift – Relationship to Valve Efficiency

- Lift is the travel distance of the moving valve element (poppet, ring, plate)
- Higher Lift provides higher valve flow area, up to certain limit
 - ✓ Flow coefficients at various lifts are determined by laboratory flow tests
- Lower Lifts, in the range of 0.030” to 0.060” are applied in H2 compressors
 - ✓ Valve pressure drop is proportional to molecular weight of the gas
 - Low valve pressure drop in H2 service can therefore be achieved at Low Lift

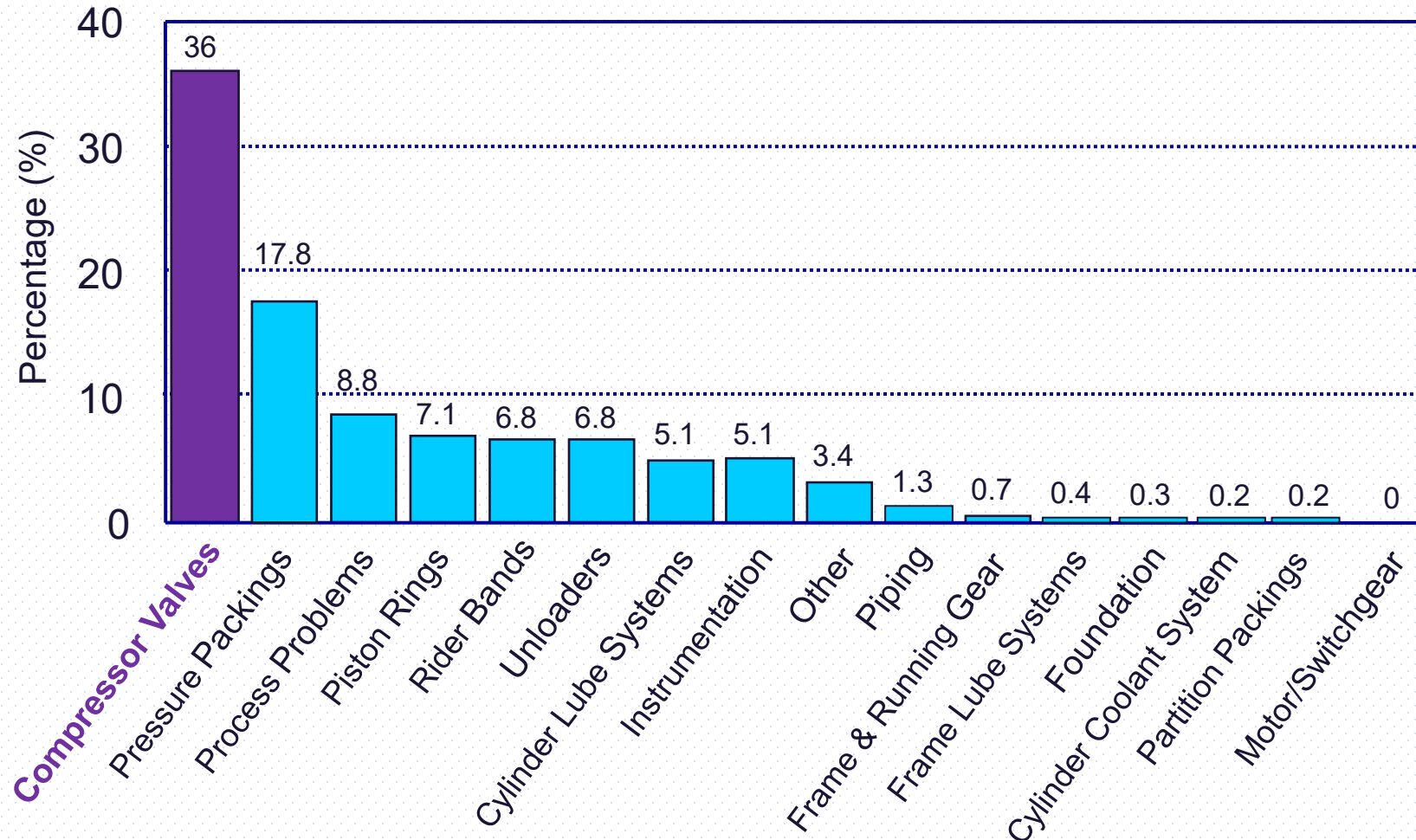
Valve Efficiency Optimization

- Provide high valve flow area with low clearance volume



Compressor Valve Reliability

- Valve reliability relates directly to compressor reliability



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Source: Hydrocarbon Processing, January 1996. "Increasing the Reliability of Reciprocating Compressors on Hydrogen Services", by Stephen Leonard, Dresser-Rand.

Compressor Valve Reliability Factors

- Materials of construction
 - ✓ Gas compatibility
 - ✓ Tensile and yield strength
 - ✓ Impact resistance
 - ✓ Corrosion resistance
- Moving element design
 - ✓ Lift
 - ✓ Surface contact configuration

Compressor Valve Materials for H2 Service

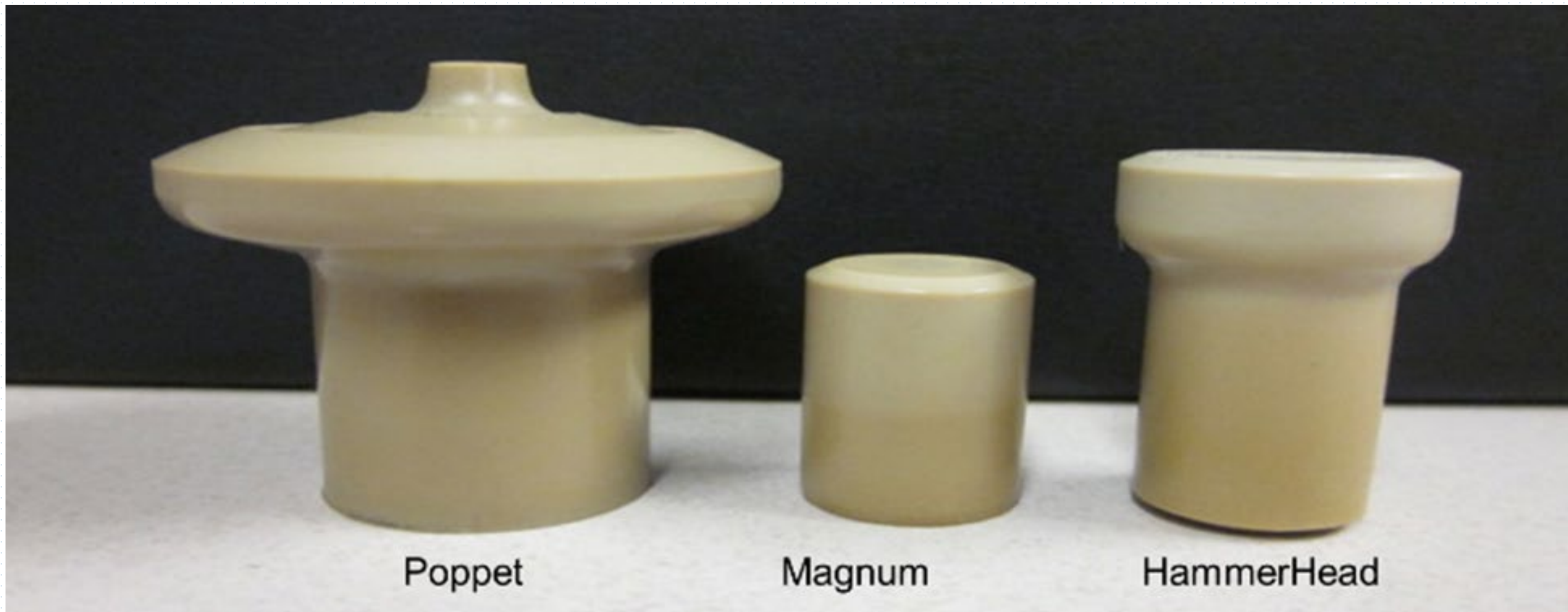
- Seat and Stopplate (valve bodies)
 - ✓ Nodular iron (ductile iron)
 - ✓ 17-4 PH stainless steel for H2 with sour gas (flare or vent gas)
- PEEK moving elements (PolyEtherEtherKetone)
 - ✓ High-strength thermoplastic
 - ✓ High impact resistance
- Springs
 - ✓ 17-7 PH stainless steel
 - ✓ Chrome-silicon alloy steel
 - ✓ Elgiloy[®] or Hastelloy[®] for sour gas
 - ✓ Many other wire materials

Moving Element Design

- Forces acting on the valve's moving elements
 - ✓ Differential pressure force (discharge pressure – inlet pressure in each H2 cylinder)
 - Pressure rating of moving element depends on geometry and material
 - Smaller, robust elements with low tensile (bending) stresses have higher ratings
 - ✓ Impact velocity force from valve opening and closing events
 - Lower lifts in H2 service minimize the impact velocities
 - Lower compressor speeds (300 to 600 rpm) in H2 services minimize impacts
 - Impact velocity increases as operating pressure increases
 - Since H2 valves have low lifts, impact velocities are low, even at higher pressures

Moving Element Design

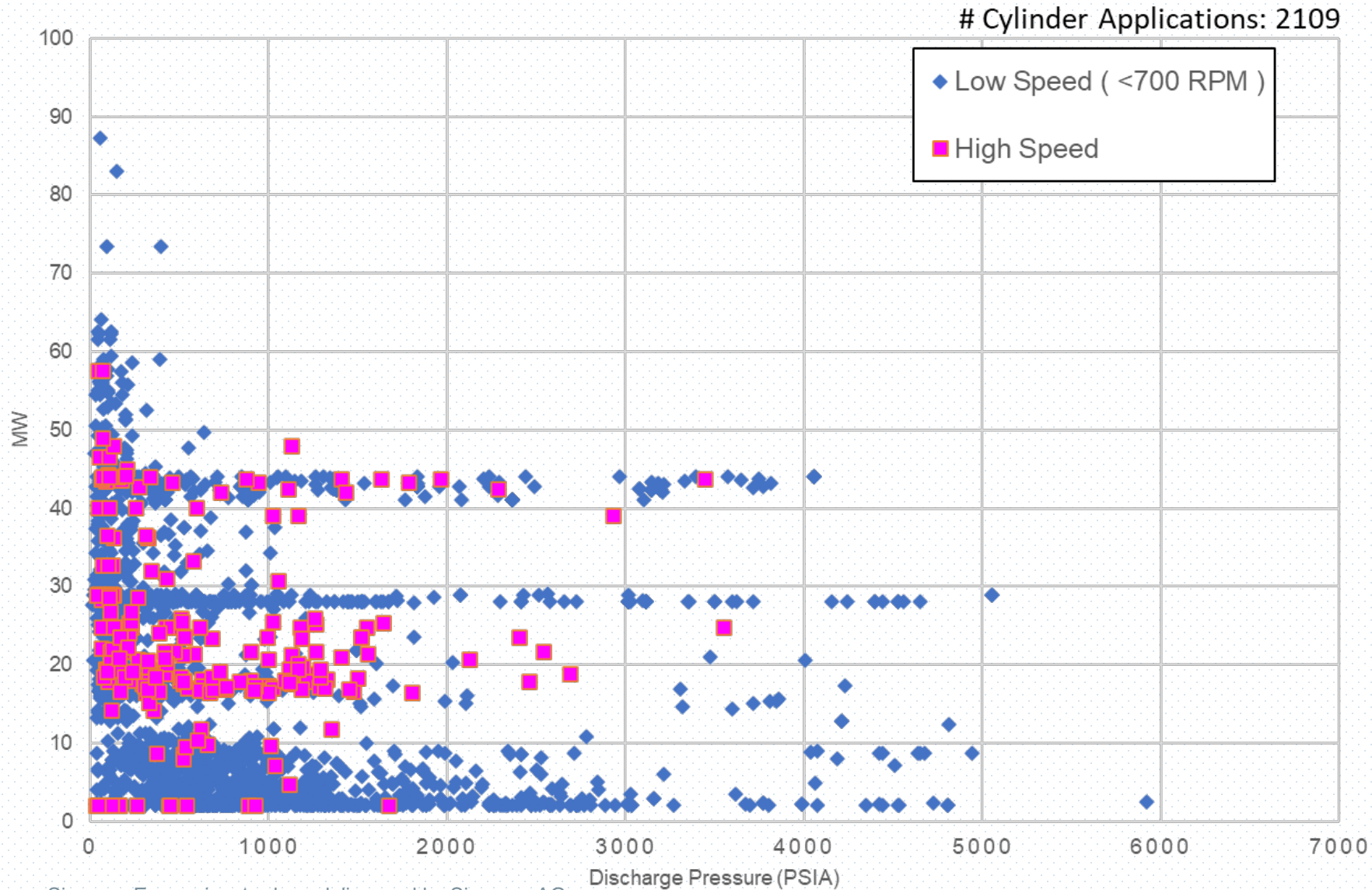
- Strength of moving element depends on material and geometry
 - ✓ Various types of PEEK elements are proven in H2 applications
- Configuration of surface contact area
 - ✓ Flat contact
 - Concentric rings with rectangular cross-sections open on an outer edge
 - High point loads on the edge are the typical fracture initiation point
 - Circular ported plates also have flat contact areas
 - Most ported plate failures also originate at the outer edge
 - ✓ Angled contact
 - Miniature poppet elements
 - Able to withstand very high impact velocities
 - Impact energy is better dispersed with optimized angled surface contact



Magnum™ Valves in H2 Applications

- First applied in 1997
- Withstands high differential pressures and discharge pressures
- Ideal combination of good flow area and low clearance
- PEEK moving element
 - ✓ Used in all stages of compression
 - Ease of inventory
- Low-stress spring design, even at solid height

Magnum Valve (Installations thru 6/29/21) Molecular Weight vs Discharge Pressure



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Case Study – Increased MTBF in a U.S. Refinery’s H2 Compressors



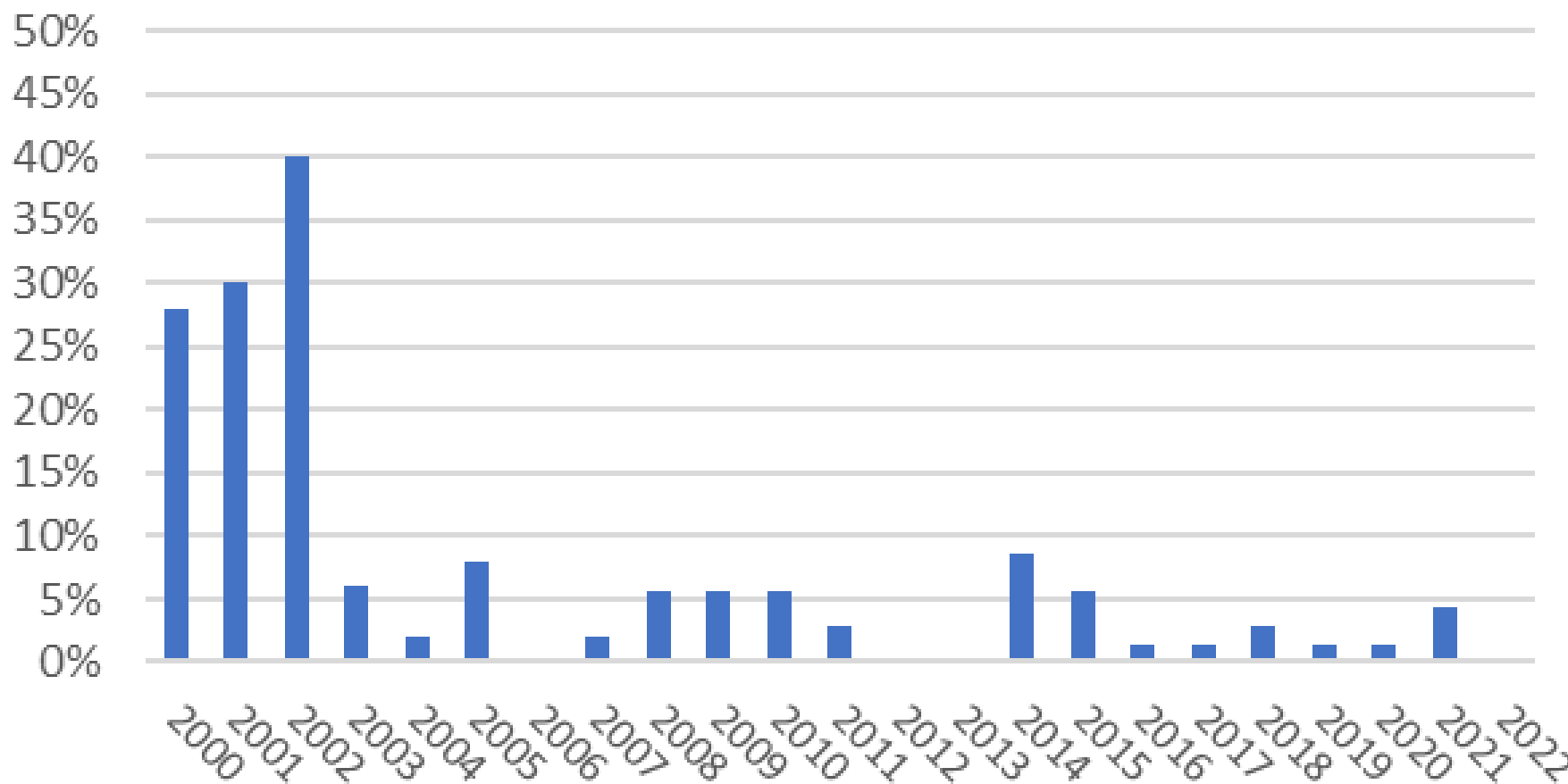
- Year 2000 to 2002
 - ✓ Fleet of 21 compressors with 50 cylinders in continuous operation
 - ✓ Valve MTBF was 10 months
 - ✓ Average of 16 valve failures/year
 - ✓ Crew of mechanics changed valves every 3-4 weeks
- Year 2003 to 2007
 - ✓ Same compressor fleet
 - ✓ Magnum™ valves introduced in 2003
 - ✓ Most cylinders outfitted with Magnum™ valves by 2007
 - ✓ Average of 2 valve failures/year

Case Study – Increased MTBF in a U.S. Refinery’s H2 Compressors



- Year 2008 to 2015
 - ✓ Fleet of 27 compressors with 70 cylinders in continuous operation
 - ✓ Average of 1 Magnum™ valve failure/year
- Year 2016 to 2022
 - ✓ Same fleet of 27 compressors with 70 cylinders in continuous operation
 - ✓ All cylinders in refinery outfitted with Magnum™ & HammerHead™ by 2016
 - Total of 500 valves in continuous operation
 - ✓ Valve MTBF was 60 months
 - Average of 1 valve failure/year

% Annual Valve Failures

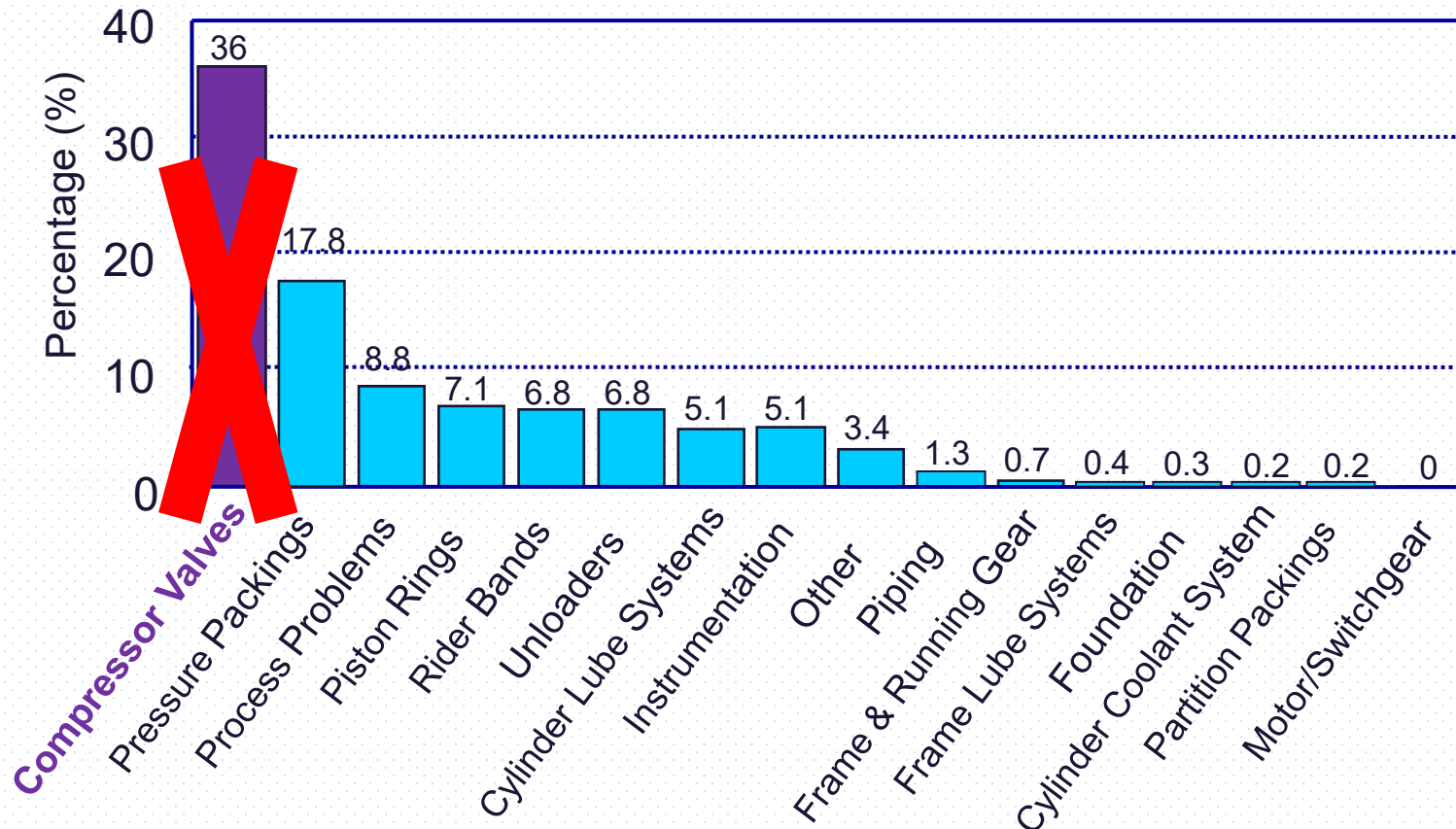


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Case Study – Increased MTBF in a U.S. Refinery’s Compressors



- Quote excerpt from rotating equipment engineer at refinery
 - ✓ *“Prior to this [valve conversion] effort we had significant numbers of unplanned “costly” shutdowns. Today we typically run turnaround to turnaround where we perform our overhauls on a preventive maintenance basis.”*



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Concluding Remarks

- Reciprocating compressors are critical equipment for delivering high-pressure H₂ in traditional refinery applications
- Reciprocating compressors are being applied in newer H₂ services
 - ✓ Electrolysis
 - ✓ H₂ liquefaction plants
 - ✓ H₂ storage caverns & pipelines
- Efficient compressor valves minimize power consumption
- Reliable compressor valves minimize downtime, which streamlines operations

Thank You !

Questions ?