WHITE PAPER

Enabling the Liquid Hydrogen Economy Through Integrated Sealing Innovation

Author:
Janette Danella
Product Manager • Sealing Systems Platform Management

Market Opportunity

After a period of intense market hype, the clean hydrogen economy is transitioning to a more realistic and sustained growth phase. Governments and private industries continue to invest in hydrogen production, distribution infrastructure, aerospace propulsion, heavy transportation, and long-duration energy storage. Liquid hydrogen is particularly attractive where high energy density and efficient transportation are required, positioning it as a key technology for next-generation mobility and energy systems.

As hydrogen infrastructure expands, the drive for reliability, efficiency, and safety are paramount, highlighting that components once considered standard required upgrading and are critical to enabling the entire system. Components, such as seals, once considered standard industrial hardware are becoming critical system enablers. Reliable sealing directly influences equipment uptime, maintenance intervals, operational safety, and total lifecycle cost.

This evolution creates an opportunity for sealing technology providers to move beyond supplying components and become engineering partners capable of solving increasingly complex system challenges.

"As the liquid hydrogen market scales up, developing high-integrity sealing solutions capable of maintaining reliable performance under extreme cryogenic conditions will be critical to commercial success."

— **Philippe Allienne,** Business Development Manager Clean Energies

Why Liquid Hydrogen Demands a New Engineering Approach

Liquid hydrogen presents one of the most demanding sealing environments encountered in modern engineering. Unlike conventional industrial applications, successful sealing requires simultaneously balancing extreme cryogenic temperatures, hydrogen compatibility, mechanical loading, and hardware design.

At cryogenic temperatures, conventional elastomeric seals lose flexibility as they approach or pass their glass transition temperature (T_g). Reduced elasticity limits the seal's ability to maintain contact pressure, while thermal contraction changes seal geometry and hardware dimensions. These effects can reduce sealing force and create potential leakage paths.

Hydrogen introduces additional complexity. As the smallest molecule in nature, hydrogen readily diffuses through many materials and can exploit microscopic leakage paths that would remain sealed under other process gases. Material selection must therefore consider both cryogenic mechanical performance and long-term hydrogen compatibility.

Hardware characteristics further influence sealing performance. Surface finish, gland geometry, dimensional tolerances, and contact stress all affect the ability of a seal to maintain leak-tight performance. Existing standards for gaseous hydrogen applications frequently recommend extremely smooth sealing surfaces—often Ra 4 microinches or better—to minimize leakage pathways. While effective, these surface requirements substantially increase machining cost and manufacturing complexity.

Rather than optimizing only the sealing material, future hydrogen applications must be engineered as complete sealing systems where materials, hardware, and seal geometry work together to achieve robust performance.

Current Challenges with Existing Sealing Technologies

Today's hydrogen applications utilize several established sealing technologies, each offering distinct advantages and limitations.

- **Traditional elastomer O-rings** provide simplicity and cost advantages but are generally unsuitable for sustained liquid hydrogen service due to reduced elasticity at cryogenic temperatures.
- **PTFE-based and spring-energized seals** offer improved chemical compatibility and cryogenic performance compared with traditional elastomeric seals. PTFE-based materials provide low-temperature capability and chemical resistance but may present challenges related to creep and limited resilience. Spring-energized designs address some of these limitations by incorporating a metallic spring to maintain sealing force as temperatures and operating conditions change. Successful implementation requires careful optimization of material selection, spring loading, seal geometry, and mating hardware.
- **Metal seals** provide exceptional leak-tight performance and remain an important solution for critical static joints. However, they often require exceptionally smooth hardware finishes, precise machining, and robust hardware capable of maintaining consistent sealing stresses. These requirements can dramatically increase manufacturing complexity and overall cost while limiting flexibility in applications where thermal contraction, hardware variation, or dynamic motion must be accommodated.

No single sealing technology represents a universal solution. Instead, a successful application depends on understanding the interaction between material behavior, seal geometry, hardware design, and operating conditions.

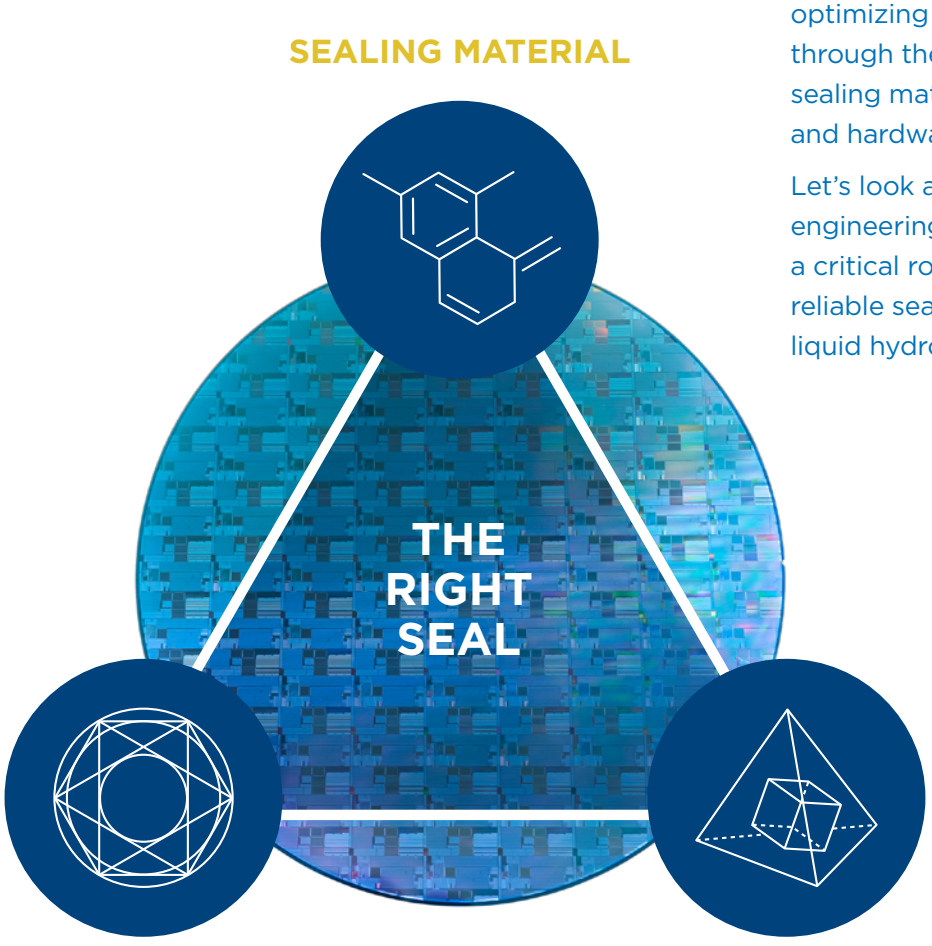
The Right Seal: An Integrated Engineering Approach

Successful liquid hydrogen sealing is not achieved via sealing material substitution alone. At Greene Tweed, we recognize that sealing performance results from the interaction of three critical engineering elements: material, seal design, and hardware geometry. Each element influences the others, and optimizing only one rarely produces the most reliable solution.

As hydrogen applications push engineering systems into increasingly demanding operating environments, this integrated approach becomes even more important. Extreme cryogenic temperatures, hydrogen permeation, thermal contraction, and demanding leak-rate requirements require engineers to consider the sealing system as a whole rather than as individual components.

The Right Seal:
Greene Tweed's integrated engineering approach to optimizing sealing performance through the interaction of sealing material, seal design, and hardware geometry.

Let's look at how each engineering element plays a critical role in developing reliable sealing solutions for liquid hydrogen applications.



Engineering Element 1:
High-Performance Materials

Materials engineering establishes the foundation for sealing performance, but developing the right material system extends far beyond selecting a single polymer. Liquid hydrogen applications require engineered materials that maintain mechanical integrity at temperatures approaching -253°C, resist hydrogen permeation, accommodate thermal contraction, and maintain sealing performance throughout repeated thermal and pressure cycles.

At Greene Tweed, we approach materials engineering from a systems perspective. Rather than optimizing a single material, we evaluate how multiple engineered materials interact to achieve the desired sealing performance.

- For the primary sealing interface, high-quality thermoplastics, like Avalon® PTFE and PcTFE-based materials provide the chemical resistance, low-temperature capability, and low-friction characteristics required for demanding cryogenic applications. Selected formulations, engineered with appropriate fillers, can be used to manage sealing performance, wear resistance, creep resistance, and manufacturability while maintaining reliable operation under liquid hydrogen conditions.
- Complementary to the PTFE and PcTFE elements, Arlon® PEEK materials serve as structural components within the sealing system. Their exceptional strength, dimensional stability, and cryogenic mechanical properties make them well suited for support rings, anti-extrusion elements, and force-balancing features that help maintain seal integrity under pressure and thermal cycling.
- Metallic energizers used in PTFE-jacketed seals provide the resilient loading required to maintain contact stress as temperatures fluctuate and materials contract. While many spring designs successfully translate from conventional sealing applications, alloy selection must be evaluated for hydrogen compatibility to ensure long-term mechanical performance in demanding environments. When paired with engineered sealing materials and structural support elements, properly selected metallic energizers become an integral part of a complete sealing system optimized for liquid hydrogen applications.

Greene Tweed engineers combine complementary materials and components to make a robust engineered sealing solution designed to address the specific challenges of liquid hydrogen applications. By leveraging the unique properties of each material, these assemblies can deliver improved sealing performance, structural support, and reliability under demanding cryogenic conditions. Material characterization—including hydrogen exposure testing, permeability evaluation, and cryogenic mechanical testing—provides the engineering data used to understand material behavior, establish design limits, and improve predictive engineering models.

Engineering Element 2:
Seal Design

Even the most advanced sealing material cannot compensate for an ineffective seal design. Seal geometry directly influences contact stress, deformation, load retention, and overall sealing performance under changing temperatures and pressures.

For liquid hydrogen applications, seal designs must accommodate thermal contraction, pressure variation, installation conditions, and application-specific loading while maintaining sufficient sealing force throughout the operating envelope. Selecting between O-rings, spring-energized seals, or other engineered sealing solutions requires understanding not only the operating environment but also the interaction between material behavior and mechanical design.

Finite Element Analysis (FEA) has become an essential engineering tool for evaluating seal deformation, contact pressure, and thermal effects before prototypes are manufactured. Predictive modeling enables engineers to evaluate multiple design iterations efficiently while identifying potential performance limitations early in the development process.

By integrating computational modeling with material characterization and application knowledge, seal design becomes a predictive engineering discipline rather than a trial-and-error process.

> " Ever put a puzzle piece in and then, 19 pieces later, realize that piece never actually belonged there? That's often what happens when a seal is designed around a standard solution rather than the actual demands of the application. By looking at geometry and material composition as interlocking pieces rather than separate design choices, we can find new ways to combine what we already have into a solution that performs better than any one piece could on its own. Sometimes the innovation is not inventing a completely new piece, but finding a better way to put the pieces we already have together."
>
> **— Allan Burleigh,** Applications & Design Engineer – Sealing Systems

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Engineering Element 3:

Hardware

Hardware is often overlooked during seal selection, yet it plays an equally important role in sealing performance. Surface finish, gland geometry, dimensional tolerances, and manufacturing variation directly influence contact pressure, sealing efficiency, and long-term reliability.

Current industry guidance for gaseous hydrogen sealing frequently recommends sealing surfaces approaching Ra 4 microinches (or better) to minimize potential leakage pathways. While these finishes improve sealing performance, they also increase machining complexity, manufacturing cost, and production lead times.

Greene Tweed considers hardware surface finish during seal selection and design, evaluating how sealing materials and geometries interact with the mating surface. By optimizing seal contact pressure, material properties, and geometry for specific hardware conditions, engineers can identify solutions that maintain reliable sealing performance while balancing manufacturing requirements and cost. This approach helps customers evaluate practical hardware specifications without unnecessarily increasing machining complexity.

Ultimately, successful hydrogen sealing requires treating hardware as an active component of the sealing system—not simply the surface against which the seal operates.

Accelerating Innovation Through Integrated Validation

Developing the right seal extends far beyond selecting an engineered material or optimizing a seal geometry. True engineering confidence is achieved by validating that material behavior, analytical predictions, and physical seal performance align under representative operating conditions. At Greene Tweed, validation is an integral part of the engineering process that continuously informs material development, design optimization, and customer application support.

The process begins with material characterization. Hydrogen exposure testing performed on material coupons provides valuable insight into compatibility, dimensional stability, permeability, and changes in mechanical properties following hydrogen exposure. These data establish the engineering foundation for understanding how materials behave in hydrogen environments while providing critical inputs for predictive finite element analysis (FEA) models. By incorporating measured material behavior into simulation, engineering teams can more accurately predict seal deformation, contact stress, and performance across a range of operating conditions.



While analytical models are powerful design tools, they must ultimately be validated through representative physical testing.

Ultra-low Temperature Seal Validation Apparatus

To support the development of next-generation hydrogen sealing solutions, Greene Tweed has invested in an ultra-low temperature seal validation system capable of reproducing liquid hydrogen operating conditions. The test capability cools representative sealing hardware to temperatures of -253°C (or lower) while using helium as the test medium to evaluate sealing performance under controlled pressure conditions. Helium is used as a representative test gas because its small atomic size makes it useful for detecting potential leakage paths in sealing systems. While hydrogen exposure testing evaluates material compatibility, helium-based cryogenic testing provides complementary insights into the leakage performance of complete sealing assemblies. By combining ultra-low temperature exposure with pressure variation and thermal cycling, engineering teams can directly evaluate static seal leakage and observe how complete sealing systems perform under conditions representative of customer applications.

This capability bridges the gap between material characterization and real-world application performance. Material testing verifies how engineered materials respond to hydrogen exposure, while

cryogenic seal testing validates the interaction between the sealing material, hardware geometry, and seal design under representative operating conditions. Together, these complementary validation methods provide significantly greater confidence than either approach alone.

Rather than treating validation as a qualification exercise, Greene Tweed conducts testing throughout the product development lifecycle. Experimental data improves engineering models, predictive analysis guides design optimization, and physical validation confirms sealing performance while identifying opportunities for continued refinement. This iterative engineering methodology reduces development risk, shortens qualification timelines, and enables customers to deploy innovative sealing solutions with greater confidence.

Looking Ahead

The transition to a hydrogen economy is already underway, and the engineering challenges associated with liquid hydrogen cannot wait until infrastructure reaches full commercial scale.

Developing reliable hydrogen systems requires technologies that are proven, validated, and ready for deployment as investment accelerates. Success will depend not only on producing hydrogen, but on enabling every component of the value chain to operate safely, efficiently, and reliably.

For sealing technologies, this means moving beyond incremental product improvements and into integrated engineering solutions. Future systems will demand greater reliability, faster qualification, lower lifecycle costs, and shorter development timelines. Meeting these expectations will require close collaboration between material scientists, design engineers, equipment manufacturers, and end users throughout the development process.

At Greene Tweed, we believe the strategic opportunity lies not in waiting for the hydrogen economy to mature, but in helping enable it. Investments in advanced materials, predictive engineering, and application-specific validation capabilities are investments in the infrastructure that will support the next generation of hydrogen technologies. By partnering with customers early in the design process and validating sealing solutions under representative operating conditions, engineering teams can reduce technical risk, accelerate product qualification, and help bring innovative hydrogen systems to market faster.

Greene Tweed is already putting this integrated approach into practice, developing innovative sealing designs that are currently undergoing customer testing and evaluation. These patent-pending innovations reflect the potential of combining advanced materials, seal design, and application-specific engineering to address the demanding requirements of liquid hydrogen systems. As development and validation progress, these solutions could help establish new benchmarks for cryogenic sealing performance and reliability.

The organizations that will lead the hydrogen economy will be those that move beyond supplying individual components and instead serve as engineering partners—combining deep application knowledge, advanced materials expertise, and rigorous validation to solve complex system challenges. As hydrogen infrastructure continues to evolve, this collaborative approach will be essential to transforming promising technologies into reliable, commercial solutions.

Greene Tweed
1684 South Broad Street,
Lansdale, PA 19446 USA
Phone: (+1) (215) 256-9521

gtweed.com

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