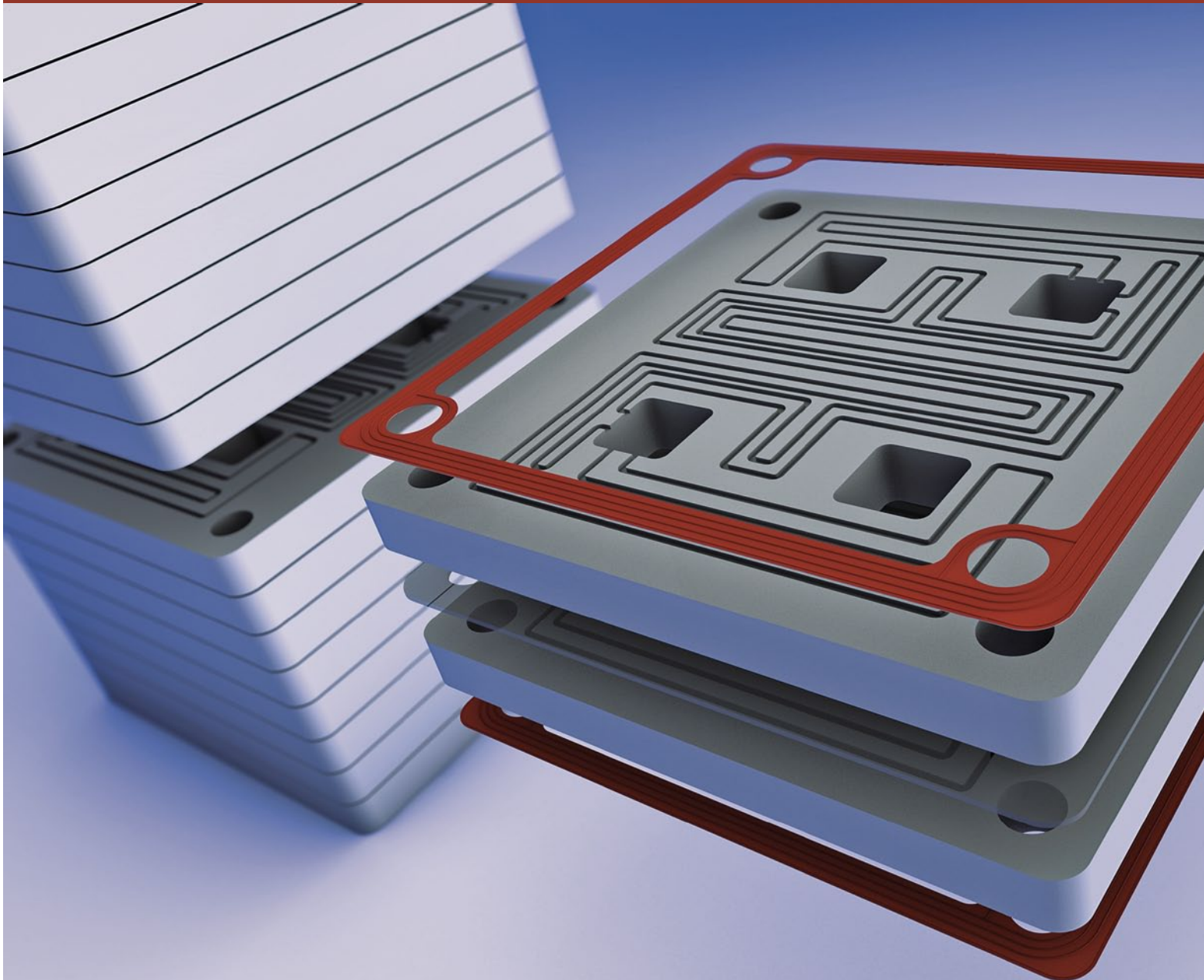


LEM SEALING TECHNOLOGY FOR FUEL CELLS

The patented Liquid Elastomer Molding (LEM) technology from Federal-Mogul makes it possible to manufacture extremely flat, light seals that are simultaneously pressure and media resistant. LEM seals offer significant, design-based advantages for sealing fuel cells. Benefits are, amongst others, efficient sealing capability, minimal seal compressed thickness, and serviceability of the stack.



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POTENTIAL OF LEM SEALINGS

New drive systems like the fuel cell and traditional ones like the combustion engine are in some respects faced with the same challenges: Both should evince the highest possible energy density. For that reason, they demand compact aggregates with low weight and high efficiency. Lightweight construction plays a major role. However, with increased energy density comes increased stress on the individual components through pressure and temperature, which can make lightweight construction a challenge.

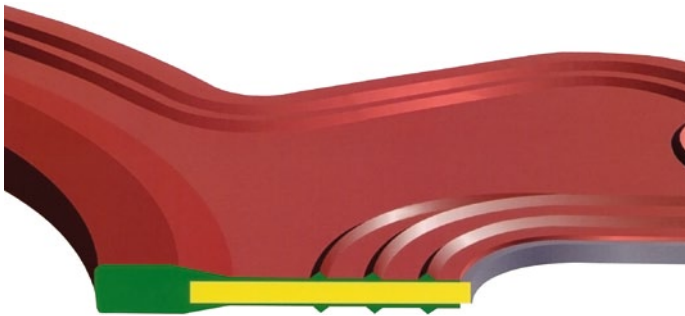
For that reason, Federal Mogul has been using LEM seals for sealing oil filters, oil coolers, oil pans, valve hoods, water pumps and vacuum pumps for a good ten years now. The construction and operational characteristics of these seals have made them into an economical solution to the problem.

With a compressed thickness in the range of just 0.3 mm and their low weight LEM seals make a very low sealing clearance possible, while the sealing joint simultaneously promotes high rigidity. For all that, LEM seals achieve a tight seal with high media resistance at low clamping force. To seal fuel cells today, solutions are often chosen that are based on liquid systems, such as wet-built sealing materials (Formed-in-Place-Gaskets, FIPG). A severe disadvantage of FIPG is that it can be nearly impossible to take a stack apart, since the sealing material, as a rule, is tightly affixed to the sealed component. In contrast, LEM seals are ready-to-install components. A stack with LEM seals can therefore be opened again if this proves necessary for maintenance or repairs with the seal being easily exchangeable.

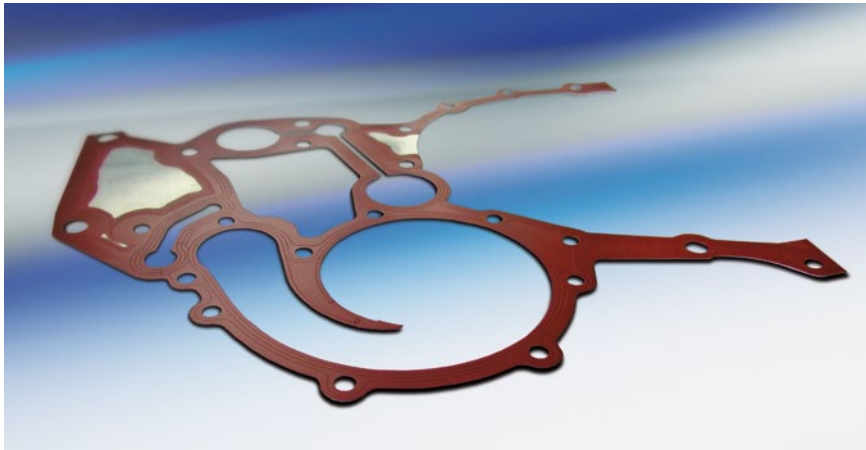
CONSTRUCTION AND DESIGN OPTIONS

The core of a LEM seal is formed by a solid substrate with a height of around 0.2 mm. After a suitable surface pre-treatment, a pattern of liquid silicone is placed on the substrate using a procedure related to screen printing. In a press mold with 3D-geometry, this network of silicone is distributed in a defined pattern on the substrate surface under pressure and heat. This allows the elastomer to cross-link within a few seconds, thanks to a special cross-linking system, which makes for short cycle times. A final stamping process for the seal contour provides clean, precise edges on all sides. During the press forming of the silicone, two functional, supplemental sealing elements are created: On the one hand the process creates a flat silicone layer with a height of 50 µm to 100 µm, which later provides the micro-seal. On the other hand, one to three line sealing elements with a defined cross section are created around every media channel in the vulcanizing form, assuring pressure-resistant sealing, ①. The geometry of these line sealing elements can be aligned three-dimensionally to a maximum linear pressure to the flange. Depending on the application, the height of the sealing element can be between 0.05 mm and 0.4 mm.

With the patented process, there are other geometric liberties available for the arrangement of the sealing elements. Depending on requirements, the silicone can be partially applied to the substrate. The three-dimensional sealing elements can receive a variable height over the span between two screw points. With this topography, it is also possible to achieve even linear pressure on the sealing element with an upward bend on the flange between the points where bolting force is applied. Additionally, silicone



① Cross-section of seal with flat 50 µm silicone layer, three line sealing elements as well as an edge sealing element



② Example of a complex LEM seal for dividing several media from each other and sealing them against the environment

seals can be created on the seal's edges, in order to seal off T-joints and high pressure areas. An additional degree of freedom is found in the substrate material itself. Here one can in principle use a broad spectrum of materials.

MATERIAL PROPERTIES AND OPERATIONAL BEHAVIOUR

Using the patented manufacturing process, complex geometries can be generated on the substrate, sealing different media off from each other as well as from the environment, ②. Even in geometries with several media channels, the substrate provides a comparatively high seal rigidity. This does not just have advantages in operations, since, though LEM seals are relatively light components, the substrate affects a high dimensional stability and makes both assembly and operation as a whole easier. Likewise, thanks to the rigidity of the substrate in combination with the micro-geometry of the sealing elements, it is possible to create seals for flange widths of only 4 mm.

In machine-processed flange surfaces, the required roughness factor for the seal lies at an R_z of $\leq 25 \mu\text{m}$, under ideal conditions of up to $30 \mu\text{m}$. Cast surfaces may evince a standard R_z of up to $30 \mu\text{m}$. With that, LEM seals are no different from other seals with respect to the requirements on the component surface, and instead tend to be less demanding.

Due to the very flat seal geometry, the effective contact surface for the silicone sealant to the surrounding media is

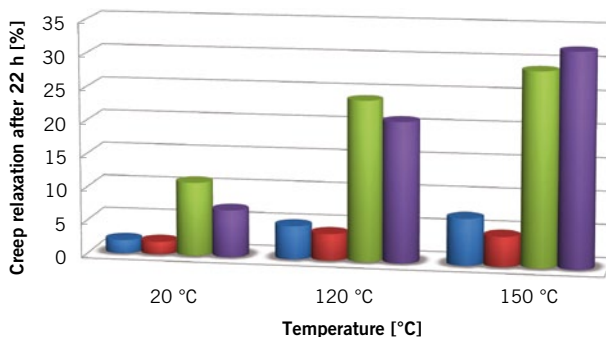
extremely small. For that reason, LEM seals have been validated and have proven themselves in use in automobiles for the media oil, coolant, air and water.

With respect to its potential use as a sealing technology for fuel cells, the small seal clearance is advantageous in reducing permeation in gaseous media. The latter is an advantage for use in fuel cells, because the cells must be protected from contamination even before application, while impermissibly high hydrogen out-gassing is unacceptable simply for safety reasons. LEM technology brings optimal properties for both of these requirements.

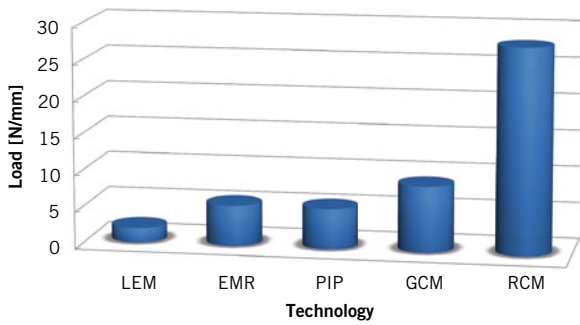
LEM seals cover a temperature range from $-40 \text{ }^\circ\text{C}$ to $180 \text{ }^\circ\text{C}$ and are suitable for use at a medium pressure of up to 30 bar. Compared to many other sealants, silicone has the unique property of retaining its sealing characteristics and flexibility to a great extent even at low temperatures. This also speaks for use in demanding mobile applications.

Tests have also shown that LEM sealing elements provide an extraordinarily good dynamic recovery under variable pressure and under effects of high temperatures, ③. The good creep resistance means that the sealing properties are guaranteed for a long time. With respect to the partially high level of operating temperatures for fuel cells, the seal's persistent resilience after temperature exposure should certainly be viewed as an important factor.

Also advantageous is the ratio between the required tightening torque and the sealing action. Here, LEM seals achieve best values compared to other sealing technologies, since the sealing action is achieved at lower bolt forces and thus potentially produces less warping and lower flange material stress, ④.



③ Creep relaxation (ASTM F38): the silicone sealing elements of LEM seals demonstrate a very good recovery after compression



④ Load-to-seal testing: the ratio between the required linear loads and the effected seal (EMR = Edge Molded Rubber, PIP = pressed-in-place, GCM = graphite-coated metal, RCM = rubber-coated metal)

SUITABILITY OF LEM TECHNOLOGY FOR FUEL CELLS

Due to its comparably high power density, the low temperature fuel cells with proton exchange membrane (NT-PEM) (also referred to as a polymer-electrolyte membrane-fuel cells, Polymer Electrolyte Fuel Cell, PEFC) has special potential for development of automotive solutions. The individual cells, which are only around 2 mm thick, have a very complex symmetrical structure consisting of two bipolar plates as electrodes, two gas diffusor systems as well as a polymer membrane in the middle as a solid electrolyte for ion exchange.

The cell's entire system is sensitive to catalytic exhaust substances such as CO and sulfur compounds. At the same time, water is produced in the oxidation of the fuel. Along with the supply of clean fuel and clean air, a secure seal in each individual cell, protecting it from the environment and neighboring cells, is therefore decisive for the cell's lifespan. Since a single cell only provide up to around 1 V of current, up to 200 cells are connected in a stack in a row for instance. The high number of the

seal clearance makes the importance of suitable sealing technology clear.

HT-PEM fuel cells (High Temperature-Polyelectrolyte Membrane fuel cells) with an operating temperature of around 160 °C, which distinguish themselves in contrast to NT-PEM through using around 30 % less of necessary system components (for example, lower coolant use and no gas-humidification), have a somewhat lower power density. Technically they are however a possible area of application for LEM sealing technology, just as NT-PEM.

What speaks for the LEM technology is that it makes low seal clearance with a secure seal possible even at low tightening torque. The possible topography of the sealing elements is ideally suited for components with long paths between the tightening bolts that hold the stack together. With respect to the structure of the cells and the materials used in them, low tightening torques can possibly contribute to lower warping over all, or to reduced mechanical stress on the individual cells. On top of all this, the stack can be disassembled without being destroyed, if needed (serviceability).

The height of the resulting seal clearance in practice limits the selection of the type of seal that can be used for fuel cells, since the numerous seal clearances in a stack would add considerably to the over all building height. Depending on the technology with which it is being compared, a LEM seal can reduce the individual seal clearances by 50 % and more. In fuel cell stacks, that has an especially noticeable effect: If, for example, a stack of this kind consists of a number of cells ranging into the hundreds of cells connected in a row, the space savings through low-stacking seals can be significant.

SUMMARY AND OUTLOOK

For fuel cell technology, LEM technology opens up new possibilities, combining minimal seal clearance heights, a secure seal at minimal tightening torque and easy access to the stack, ⑤.

At the start of 2010, there were already more than 20 million LEM seals in automotive use, so that one can truly call this a comprehensively proven technology. Typically it solves sealing problems where other technologies fail.

PROPERTY	FIPG	LEM
SEAL CLEARANCE HEIGHT	+++	+++
RIGIDITY OF SEALING BOND	++	++
MEDIA COMPATABILITY	+++	+++
WEIGHT	+	+
TOPOGRAPHY	---	+++
PROCESS RELIABILITY	+/-	+++
CYCLE TIME	+	++
SUITABILITY FOR ASSEMBLY	+/-	+++
ACCESS/MAINTENANCE	---	+++

⑤ Comparison of the technical suitability of FIPG and LEM for sealing fuel cells