Advanced Silicone Materials for Effective Battery Thermal Management and Prevention of Thermal Propagation

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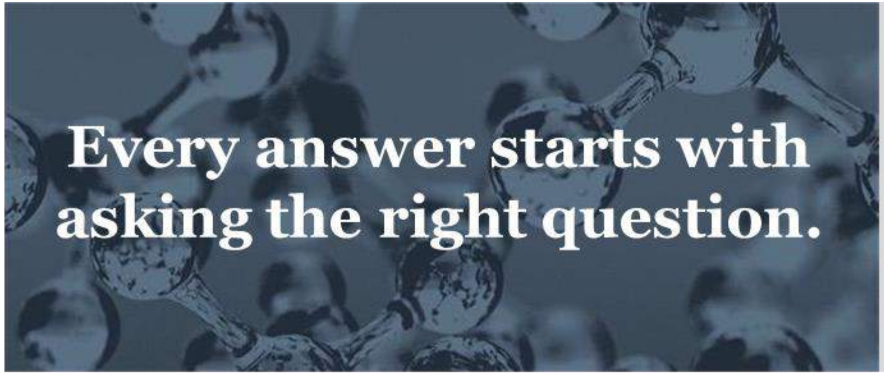
November, 2023

This is DOW



At Dow, these questions and the pursuit of solutions for the world's toughest challenges inspire us to collaborate and use our materials science expertise to create innovative solutions that transform our world and deliver a sustainable future.

2022 NET SALES	EMPLOYEES	MANUFACTURING SITES	GLOBAL REACH
$57B	**~37,800**	**104 sites**	**31 countries** in which Dow manufactures products

BROAD PORTFOLIO OF ENGINEERED MATERIALS FOR TRANSPORTATION

SAFE, DURABLE AND EVOLVING OPTIONS TO MOVE MOBILITY FORWARD

- Adhesives and Sealants
- Conformal Coatings and Encapsulants
- Acoustic solutions (PU, Acrylic, POE)
- Electrically and Thermally Conductive materials
- Foam technology (PU, Silicone, POE)
- Elastomers (POE, EPDM, Silicone)
- Polymer modifiers and Compatibilizers
- Composites
- Moldable Optics
- Synthetic leather and haptic materials

E-Mobility

- Silicone adhesives, gels, coating, foams, elastomers, thermal and EMI materials and 3D printing

Connectivity

- Silicone adhesives, gels, coatings, thermal and EMI materials

Autonomous

- Silicone adhesives, gels, coatings, moldable optics, thermal and EMI materials

Safety

- Airbag silicone coating and bonding
- Moldable optics for headlamps
- Tires solutions

Lightweight

- Silicone adhesives, elastomers and foams

Comfort

- Silicone leather
- Moldable optics light guides

Advance *safety, durability and visibility*

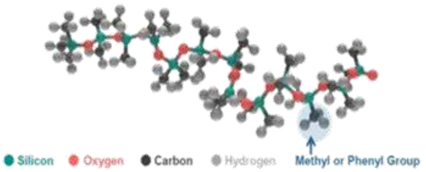
Enable *evolving technologies*

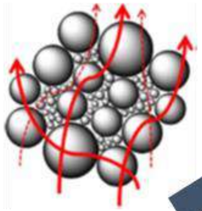
Enable *sustainable performance*

DOW®

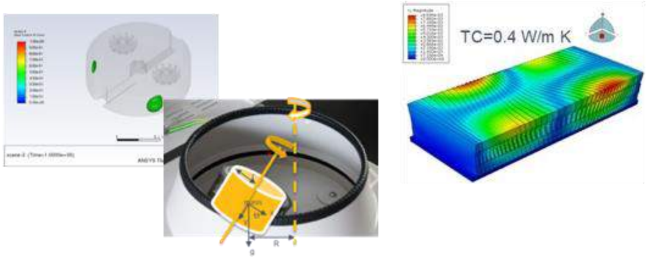
Dow contribution - Accelerated innovation

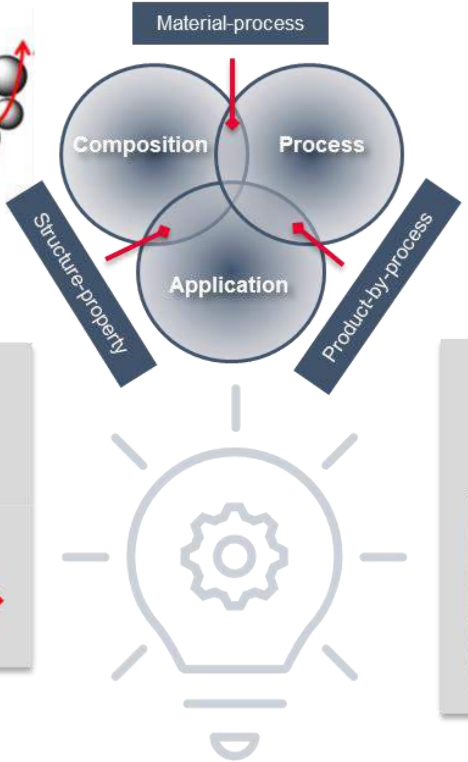
- **Foundational research** – Building and leveraging competency and understanding in conductive composite formulation science



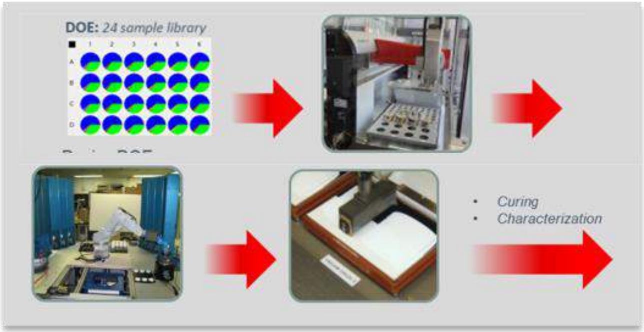


- **Modeling** – Enable faster scale up and understanding of filler dispersion in products and thermal performance in application



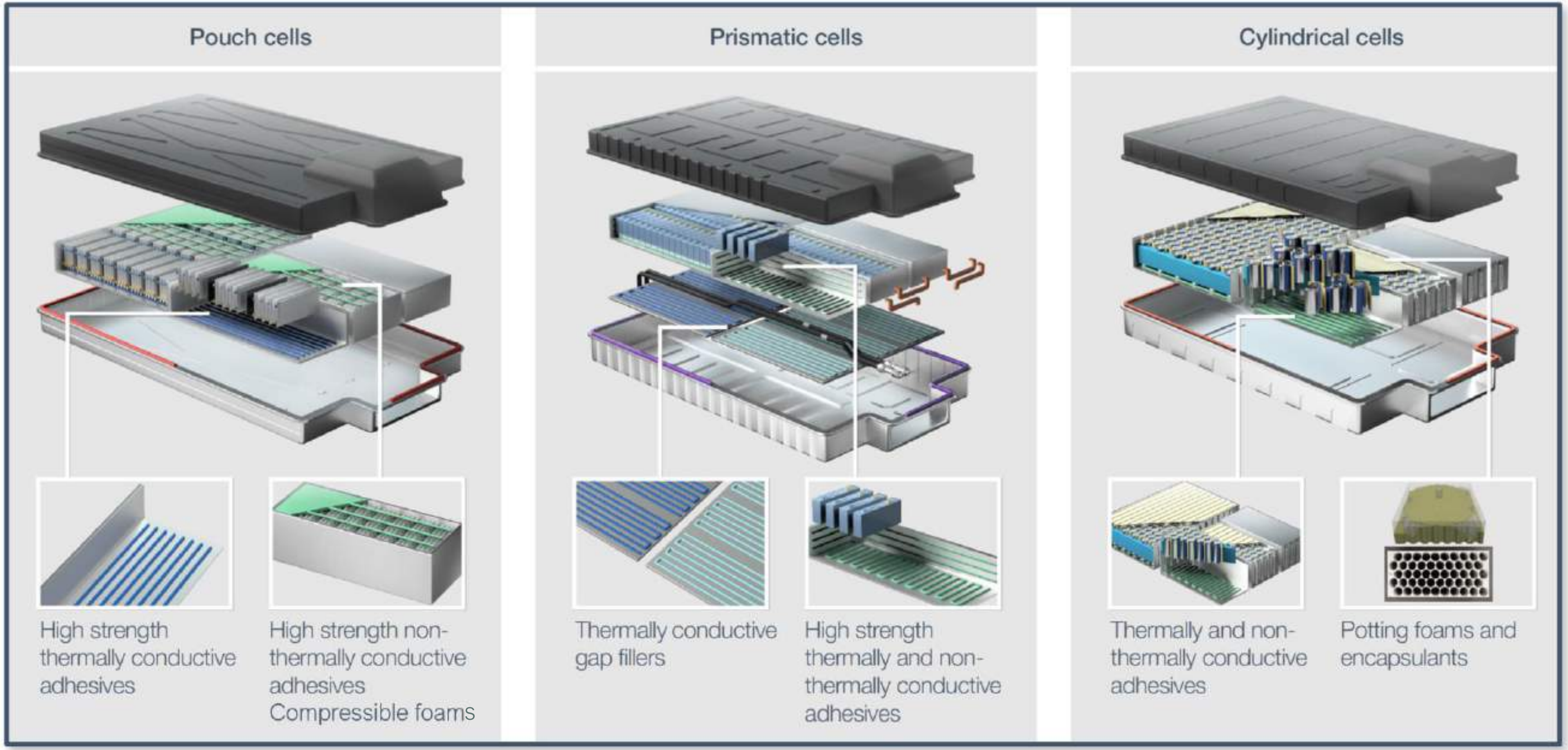


- **High-throughput screening** – Accelerate and improve workflow for formulation and process

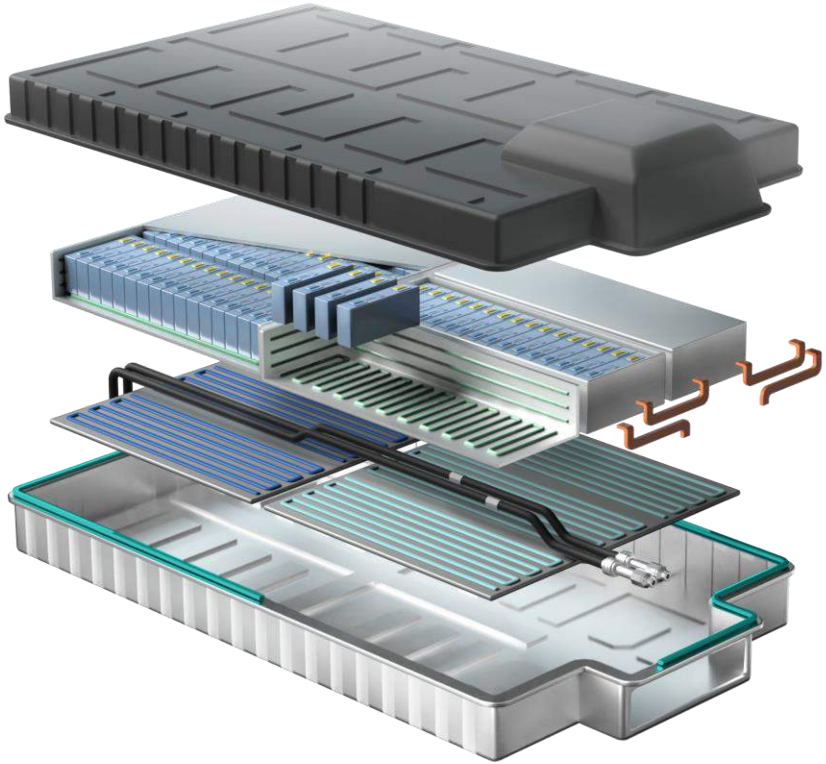


- **Application Science** – Enable easy adoption of materials and fundamental test capability to support customers

BATTERIES REQUIRE THERMAL MANAGEMENT AND FIRE PROTECTION



Effective thermal management : gap fillers

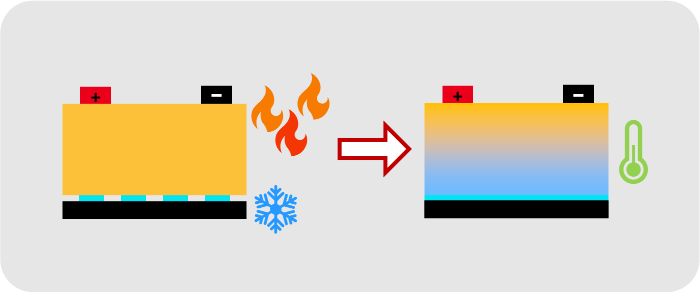


THERMALLY CONDUCTIVE GAP FILLERS

Goal:
Keep electronic device from **overheating**

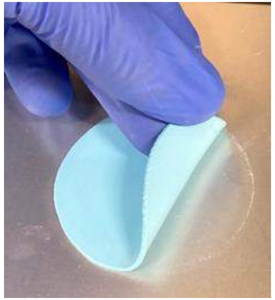
Challenge:
Surface roughness leads to **air gaps** which limit the heat flow towards the heat sink

Solution:
Apply a **thermally conductive gap filler** at the interface



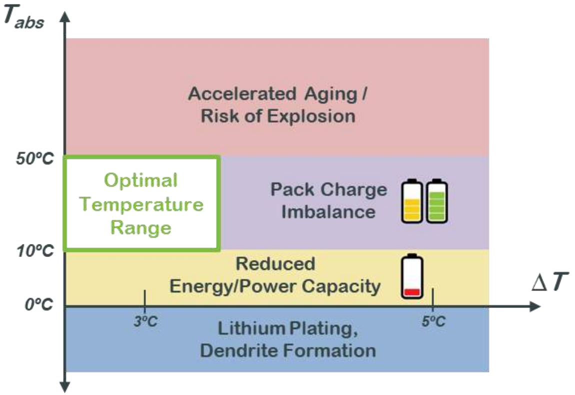
Gap filler:
Highly-loaded blend of conductive filler particles in polymer fluid

- Dispensed as liquid, stays in place
- Squeezed to achieve thin bondline
- Cures after assembly
- Soft elastomer after cure
- Tacky surface ensures good contact and low stresses



GAP FILLERS FOR EV BATTERY PACK

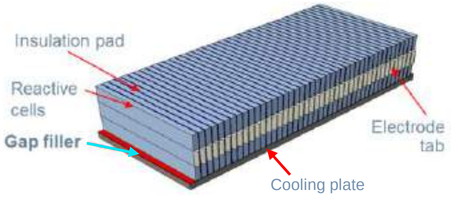
- Sophisticated **thermal management** of batteries is key to meeting the main challenges in **vehicle electrification**:
  - Driving range
  - Battery lifetime
  - Safety

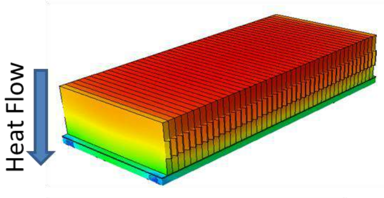


Adapted from: Scott Dudley, SAE International, Thermal Management Systems Symposium (2017)

- Gap fillers are a **crucial assembly component** within battery packs at the interface with cooling plate

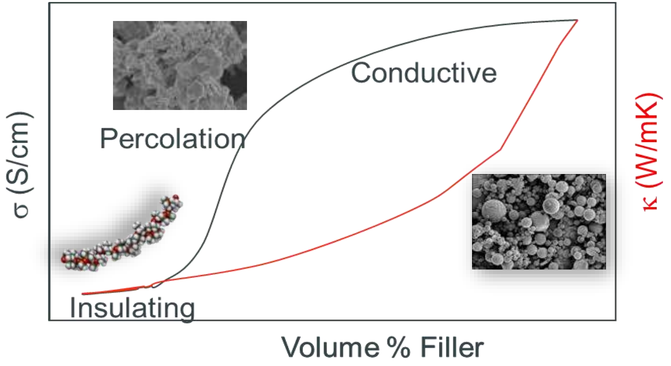
- **Performance requirements** include:
  - High flow rate
  - Tailored cure speed
  - Low post-cure hardness
  - High <u>thermal conductivity</u>
  - <u>Stability under accelerated aging</u>





GAP FILLER (GF) FORMULATION – BALANCING ACT

- GF are thermally conductive composites consisting of solid fillers, polymers and liquid materials engineered for dispensability, cure control and other specific properties



- Addition of fillers to matrix increases thermal conductivity by 3-40x polymer
- Common fillers:
  - Al_2O_3, ZnO, BN, ATH, Aluminum

Filler
- Thermally conductive (Al_2O_3, BN, SiO_2, ATH, Al)
  - Ceramic, metallic

Polymer
- Control of cross linking, modulus, mechanical performance
- Control of rheology
- Temperature stability

Treating agent
- Filler dispersion
- Rheology control and modification

Cure package
- Catalyst
- Inhibitor

Additives
- Adhesion promoters
- Stability additives
- Pigments

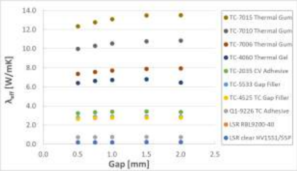
THERMALLY CONDUCTIVE GAP FILLER CRITERIA AND BALANCE

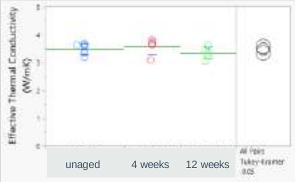
- **Low density**
- Low abrasion
- Flame retardant
- **Cost controlled**
- Stable supply chain
- **Low viscosity**
- **Matrix compatibility**
- EHS compliant
- Dielectric strength
- Stress relieving

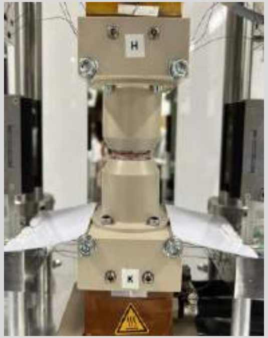
- **High thermal conductivity**
- Low thermal resistance
- Surface chemistry
- **Aging reliability**
- **Hardness stability**
- Dispensability
- Low VOC
- Reworkable
- Shelf-life stability

FIT THE BATTERY SPECIFICATION – BALANCING ACT

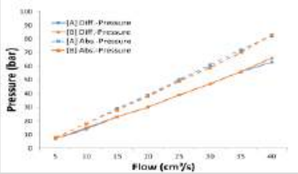
CONDUCTIVITY

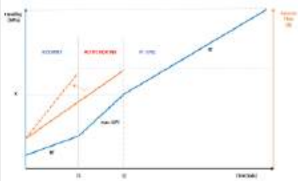




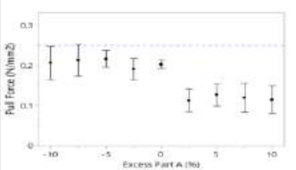


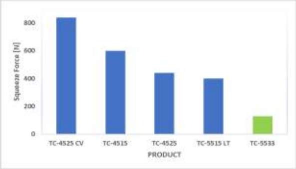
PROCESS/HANDLING

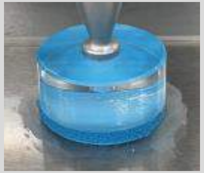


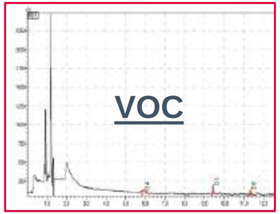


MECHANICAL PROPERTIES

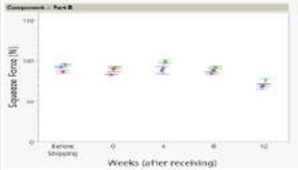


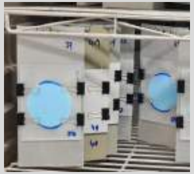


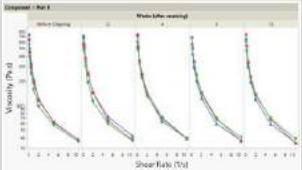




LONG-TERM STABILITY

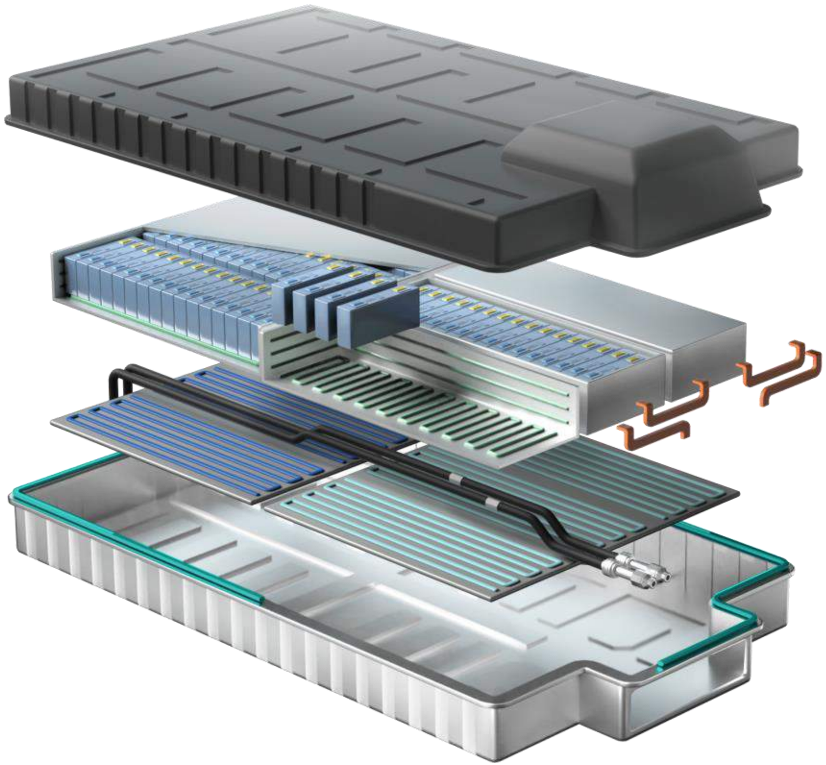






Top
Middle
Bottom

Mitigation of thermal runaway



Thermal runaway and propagation

- **Thermal runaway**:
  - Event within a battery cell
  - Excessive heat generated leading to individual cell failure
- **Thermal propagation**:
  - Heat transferred to adjacent cells
  - Chain reaction
  - Can lead to battery explosion

Short circuit

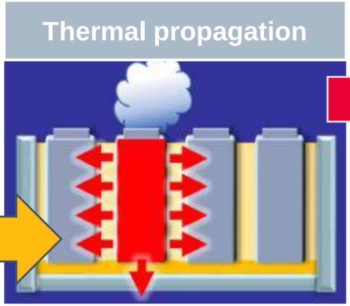
Overcharging/ discharging

Over temperature

Crash

Defects

Heat exotherm runaway



- **Prevention**
  - Inside the cell
  - Improvements in cell chemistry, structural design and battery management systems

- **Protection**
  - Materials between and around the cells/modules
  - Heat and flame protection
  - Prevent dielectric breakdown and short-circuit
  - Maintain structural integrity

Mitigation of thermal propagation

Battery encapsulation

Thermal barrier sheets

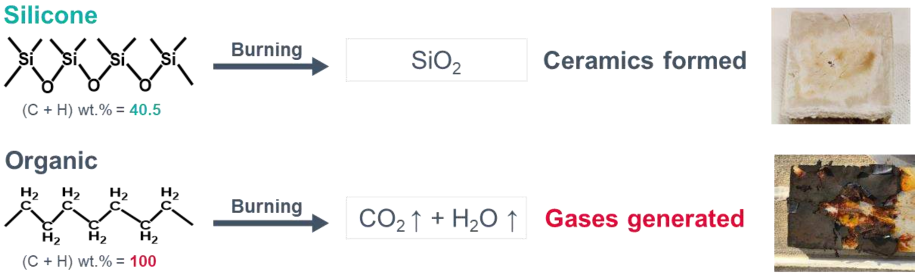
EV Gaskets/seals

Electrical protection

Fire/blast coatings

WHY SILICONES FOR BATTERY FIRE PROTECTION

- **Excellent thermal stability:**
  - From -60 to 250°C, and ceramification at >300°C
- **Flexible properties for normal use:**
  - Tailored compressibility, low density, water resistance, and excellent dielectric strength

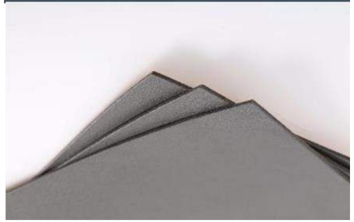


- Protection for all battery types – cylindrical, prismatic and pouch
- Materials can be coated, molded/overmolded, calendared, extruded and more
- Fast curing, lightweight, insulating, compressible & flame resistant

SILASTIC™ Liquid Silicone Rubber (LSR)

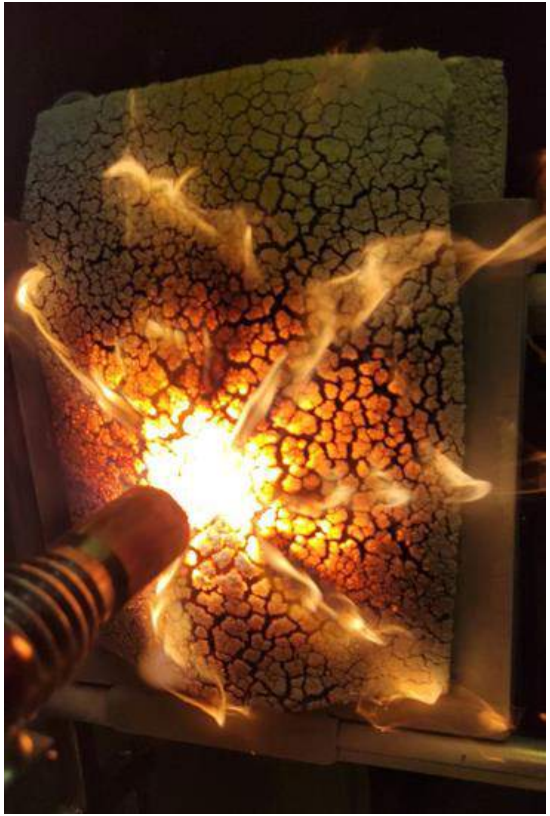
SILASTIC™ High Consistency Rubber (HCR)

DOWSIL™ LSR Foams



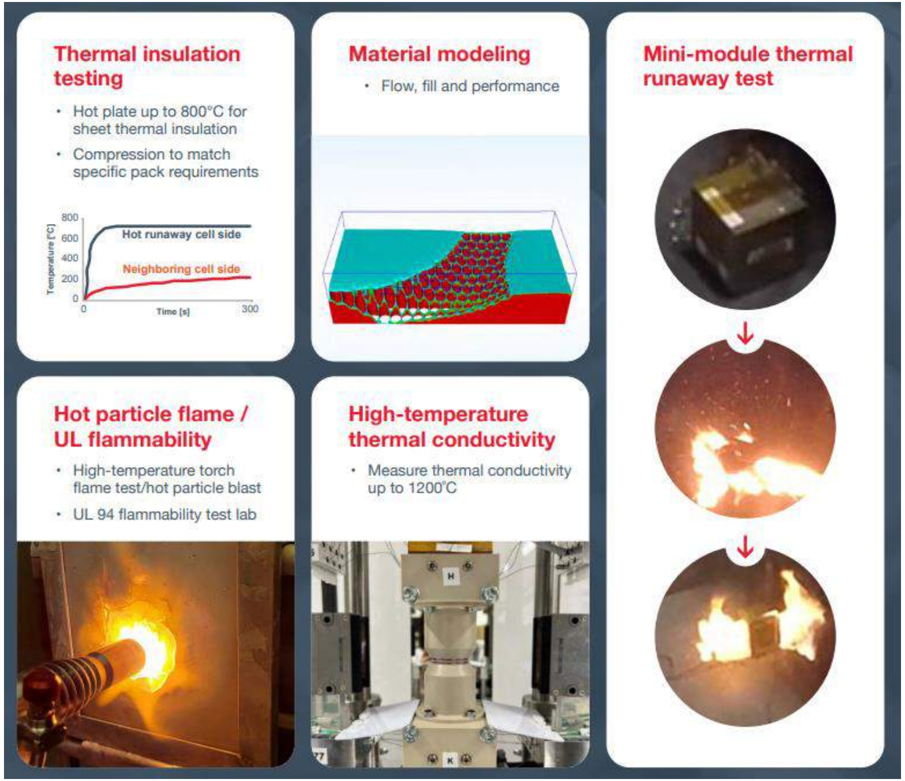
Inherent benefits of silicones

- Easy application (dispensing) for battery cell encapsulation and protection
- Negligible heat generation during cure
- Elastomeric nature, providing low stress (damping) or tuned compressibility
- Excellent property consistency over a wide temperature range
- High thermal stability
- Reliability over many charge/discharge cycles
- Low flammability and ceramification response (rather than combustion) when exposed to extreme temperatures.
- Tunable properties – viscosities, working times, and cured material properties – to meet requirements of specific battery design

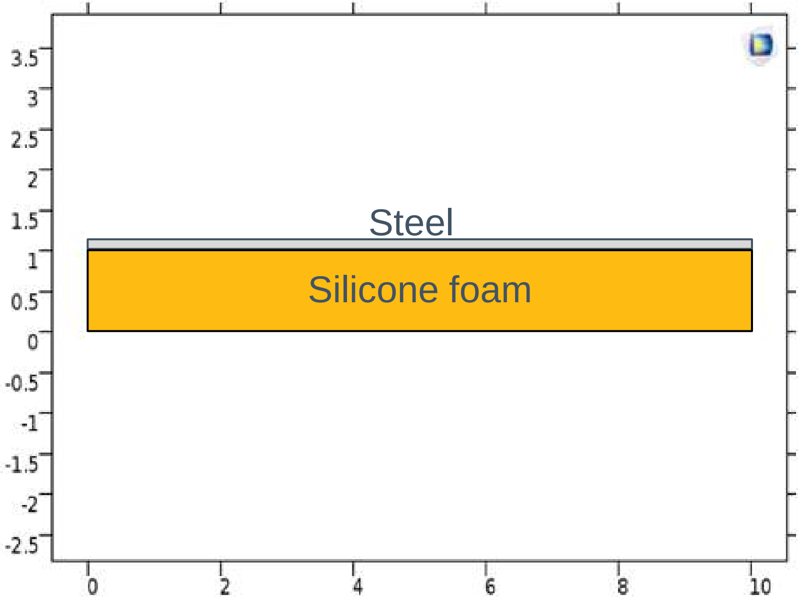


Global application test capabilities

- Selecting the right product for the specific application is crucial.
- Broad set of material-, simulation-, and application-based testing to select the right material:
  - Material modeling
  - Thermal insulation testing
  - Torch and flammability tests
  - Thermal conductivity testing
  - Minimodule thermal runaway testing



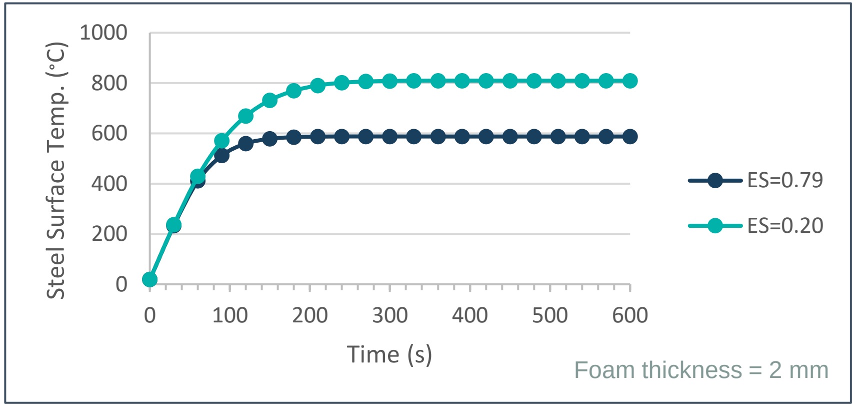
FEA MODELING, BASE PARAMETERS

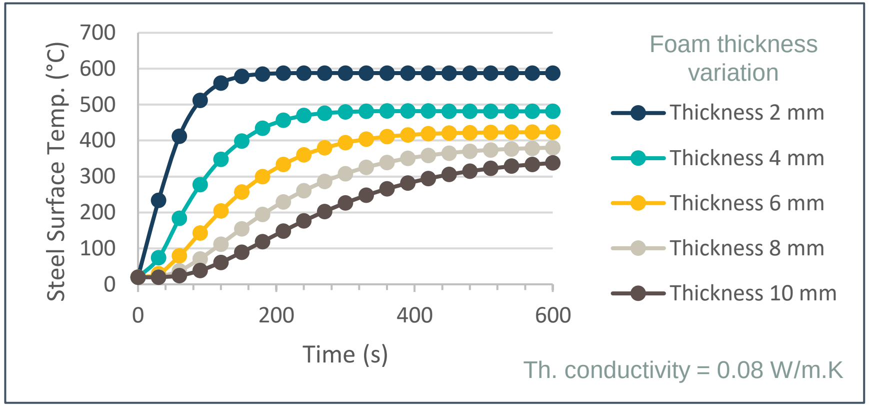


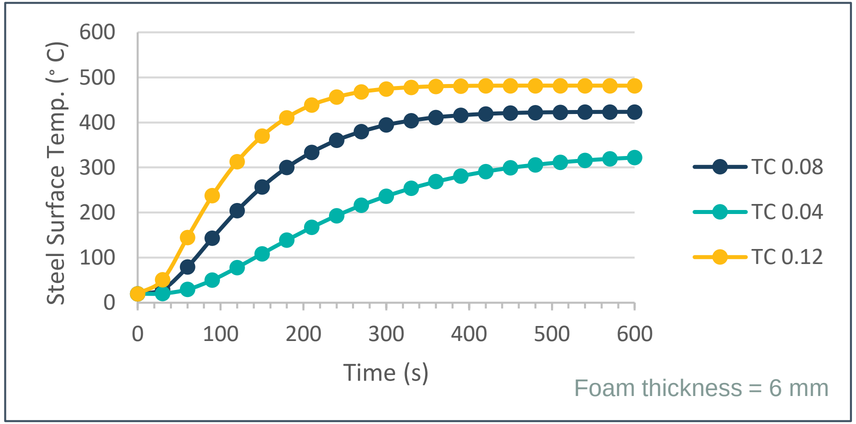
Material	Unit	Silicone	Steel
Thermal conductivity	W/m.K	0.08	44.5
Density	kg/m^3	400	7850
Heat capacity	J/kg·K	1500	475

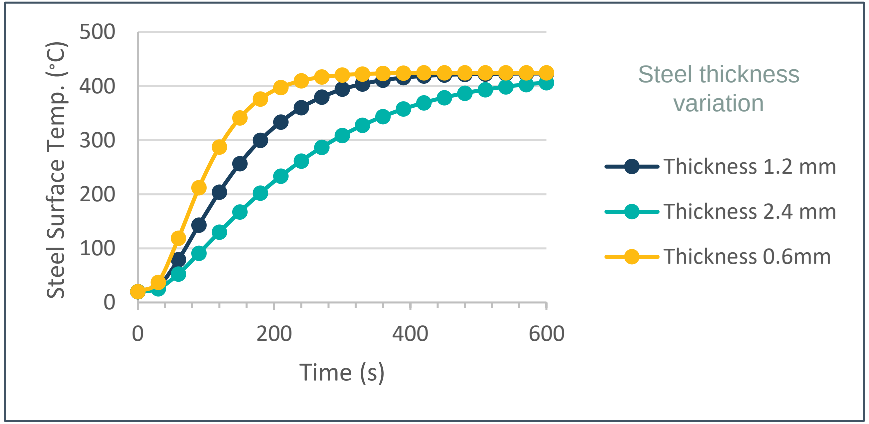
- **FEA model**
  - Si Foam bottom layer temp.: = 1200°C
  - Si Foam thickness: 2.0-10.0 mm
  - Steel thickness: 1.2 mm
  - Steel Emissivity:

FEA MODELING, RESULTS



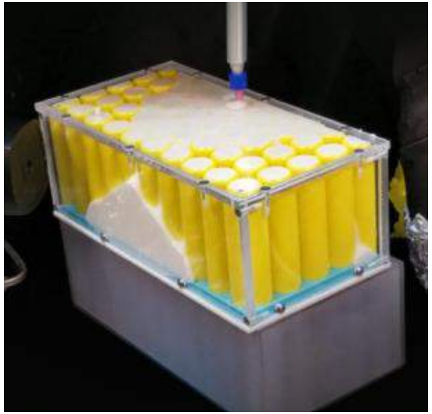


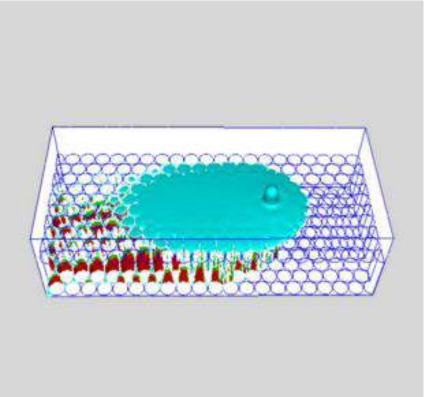




Cell encapsulation / Pottings

- Liquid dispensable silicones are excellent candidates for EV battery cell encapsulation
- Easy dispensing and filling into dense battery modules due to good flowability
- Room temperature curing while generating negligible heat – cell safety
- Final product form can be a gel, elastomer or foam encapsulant
- Good electrical isolation, mechanical protection, and stability during battery operation
- Modeling can assist with material selection and filling optimization
- The liquid precursors of gels and encapsulants are easily dispensed with standard two-part dispensing systems using a static mixer.
- For foams, static-dynamic, or dynamic mix heads are suggested for optimum foaming results





Cell encapsulation / potting – Material selection

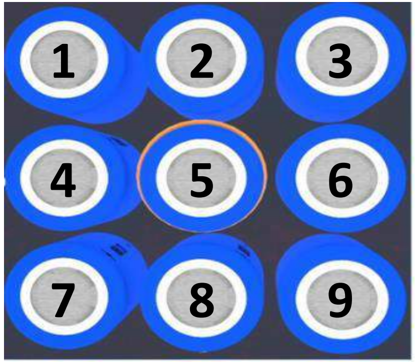
- Following products are recommended for cell potting/ encapsulation
- Different viscosities of encapsulants, gels, and foams are available for different applications
- Low viscosity gels and foams are excellent choices for potting cylindrical battery cells
- Higher viscosity foams are typically selected for potting pouch cells where flow must be tightly controlled
- These materials have been proven as effective mitigation materials in application and minimodule thermal runaway testing
- Adopted for applications in battery electric vehicles, e-scooters, e-bikes and energy storage systems

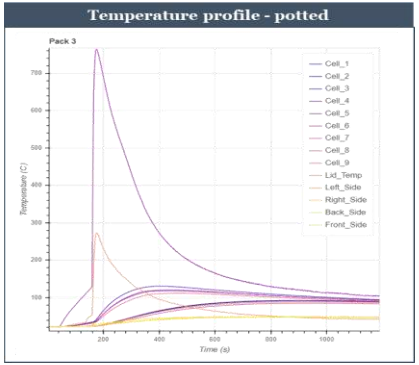
	Product	Viscosity [cP]		Working time [min.]	Cure time [min.]	Shore hardness	Dielectric strength [kV/mm]	UL 94 flame rating
		Part A	Part B					
FOAM	DOWSIL™ 3-8209 Silicone Foam	14,000	14,500	N/A	5	45 (OO)	5.9	V-0(1)**
FOAM	DOWSIL™ 3-8257 Silicone Foam	23,750	12,500	N/A	5	25 (OO)	5.0	V-0(1)**
FOAM	DOWSIL™ 3-8259 RF Silicone Foam	55,000	45,000	N/A	4	50 (OO)	7.7	V-0(1)**
FOAM	DOWSIL™ EF-6525 RTV Low Viscosity Silicone Foam	2,400	2,000	N/A	15	30 (OO)	6.8	V-0*
ENCAPSULANT	SYLGARD™ 170 Silicone Fast Cure Elastomer	3,400	1,300	4	12	42 (A)	14	V-0
ENCAPSULANT	SYLGARD™ 170 Silicone Elastomer	3,200	1,100	15	24 (hr)	47 (A)	18	V-0
GEL	DOWSIL™ 3-4150 Dielectric Gel	475	450	7	90	N/A	15	–
GEL	DOWSIL™ 3-4207 Dielectric Tough Gel	425	400	N/A	90	59 (OO)	-	V-1

* This is an internal test result base on the UL 94 test method. The material is not UL 94 certified. The material tested at 4 mm thick.
** Materials can achieve UL 94 V-0 in internal testing. Please contact Dow Technical Service for details.

LSRs and Foams for Battery Encapsulation

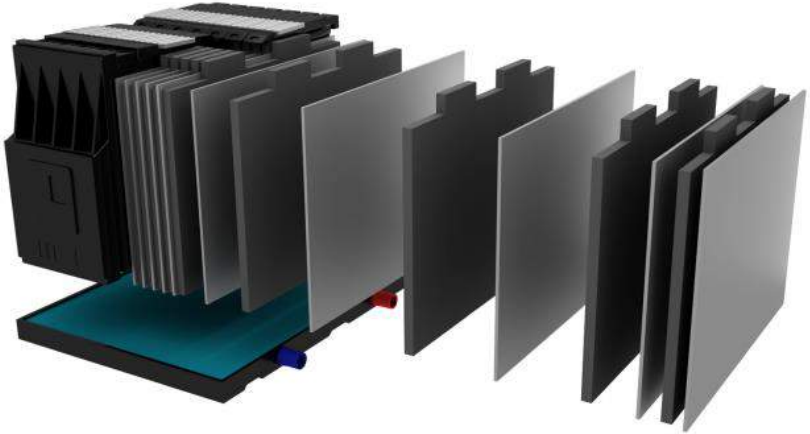
- **Ideal for liquid dispensed material**
  - Dispense / injection – end of assembly process
- **Material requirements**
  - Low viscosity to fill around cells
  - Longer working time (flow) and fast curing time (productivity)
- **Benefits**
  - Thermal insulation
  - Flame resistance / flammable gas barrier
  - Electrical isolation
  - Flexibility (shock / vibration damping)
  - Lightweighting





Thermal barrier / Compression pads

- Liquide silicone foam products can be converted into foam sheets
- These sheets can be easily placed or adhered between battery cells, battery modules or in other areas of the pack
- Silicone foams sheets are low-density materials that can function as a compression pad with low compression set (<10%)
- Excellent thermal insulation, enabling thermal propagation prevention mitigation in the event of a thermal runaway
- Inherent advantages of silicone foams:
  - Tailored compressibility (up to 80%)
  - Minimal hysteresis = rapid recovery
  - Fatigue resistance (>1000 cycles)
  - No material loss as powder

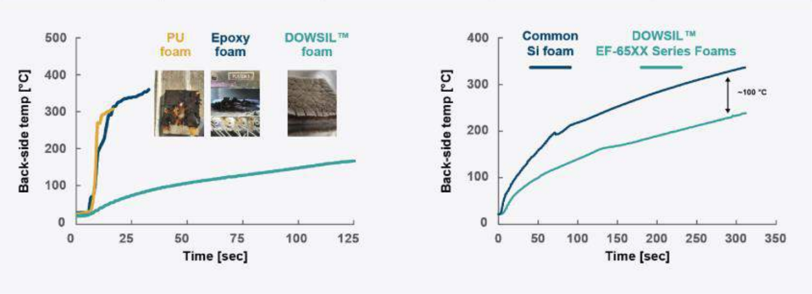


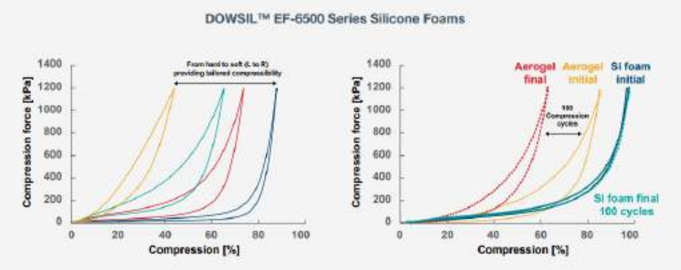
Thermal barrier / Compression pads – Material selection

Beside thermal stability over broad temperature range, silicone pads are designed to:

- Ceramify upon exposure to even higher temperatures or flame
- Maintain their structure, insulation performance and dielectric protection
- Offer tailored compressibility to meet design needs for pouch or prismatic cells
- Compared to high-end aerogel materials in a compression cycling test, benefits in hysteresis, fatigue resistance, and overall compressibility are realized

DOWSIL™ EF-6500 Series Silicone Foams				
Thermal stability	Thermal conductivity	Dielectric strength	High-temperature performance	Flammability
-40 to 250°C	<0.1 W/mK	>5 kV/mm	Ceramification	UL 94 V-0 possible



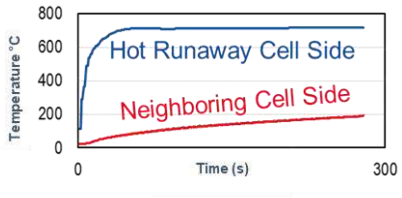


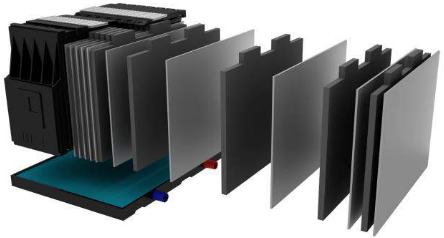
	Product	Viscosity [cP] Part A	Viscosity [cP] Part B	Snap time [sec.]	Density [kg/m3]	Recommended cure temperature	Durometer Shore [OO]
FOAM	DOWSIL™ 3-8235 Silicone Foam	77,000	91,000	200	208	RT to 100°C	35
FOAM	DOWSIL™ 3-8209 Silicone Foam	14,000	15,000	220	250	RT	45
FOAM	DOWSIL™ EF-6500 Series Silicone Foams – Tailored to meet your application needs with improved fire protection performance						
FOAM	DOWSIL™ EF-6555 Silicone Foam	28,000	31,000	300	240	60-120°C	38

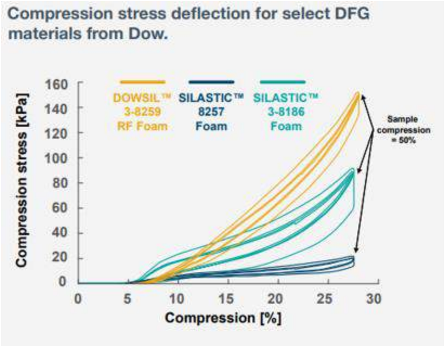
THERMAL BARRIERS FOR POUCH AND PRISMATIC CELLS : SILICONE FOAM

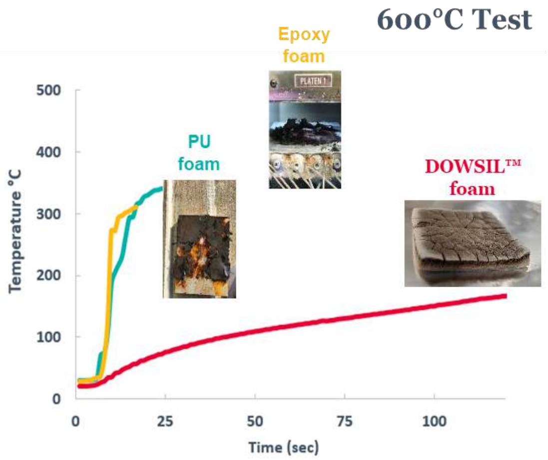
- **Ideal for pre-made pads and composites**
  - Prefabricated barrier added during pack assembly

- **DOWSIL™ foam sheet as thermal insulation pad**
  - Low thermal conductivity (<0.1 W/m.K)
  - Ceramifies upon exposure to heat/flame, low flammability >800°C
  - Low density (0.1-0.5 g/cm^3)
  - Tunable compressibility to match battery expansion/contraction





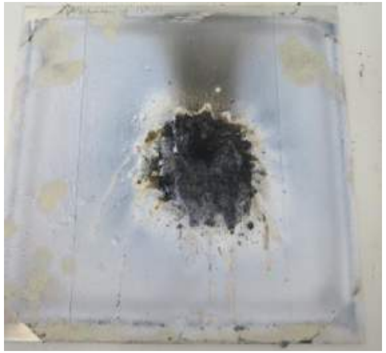




Fire / Particle-blast resistant coating

- Silicones based coating to protect the EV battery pack housing in case of thermal runaway
- Elastomeric silicone coating that undergoes ceramification once exposed to extreme temperatures
- DOWSIL™ FC-200X - reach out to learn more about this technology

External Lab "Rocket Test"		
Burn through	Backside temp (°C)	Rapid self-extinguish
No	<100	Yes



Thermal barrier at cover level : silicone coating (EXT testing)

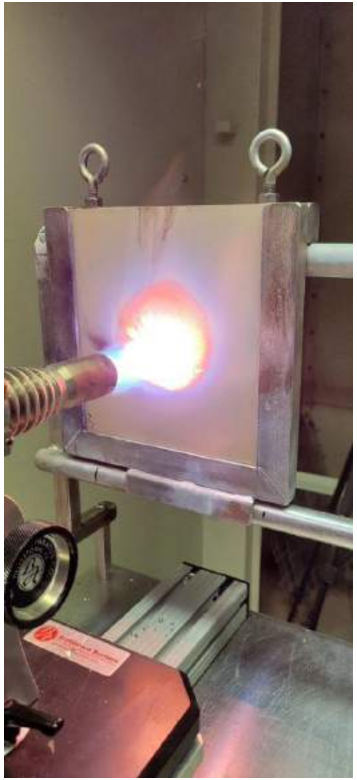
Pass – no burn through of substrate throughout duration of test, and no complete coating erosion exposing metal substrate

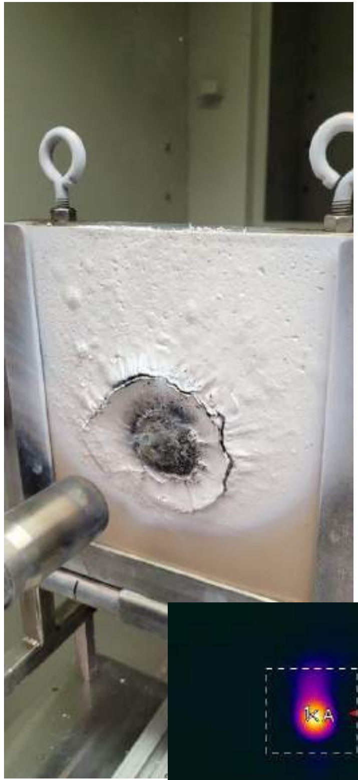
Fail – hole burned through the coating and substrate during exposure

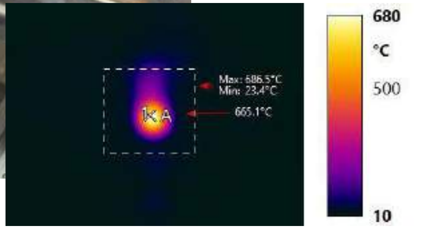
Pass

Fail

THERMAL BARRIER AT COVER LEVEL : SILICONE COATING (IN-HOUSE TESTING)







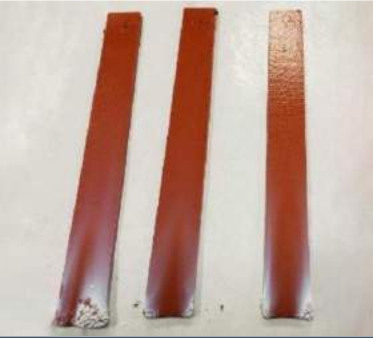
1000°C 30min

HCR materials for flame resistance and ceramification

- Silicones rubbers are remarkable versatile materials that can be produced in different formats for many applications within an electric vehicle. These materials can be formulated to meet specific performance and/or process requirements.
- With excellent dielectric properties coupled with resistance to extreme heat, cold, and aggressive fluids, SILASTIC™ HCR has shown to be an effective design solution in a wide range of electric vehicle powertrain applications.
- Applications for Silicone HCR within the EV battery:
  - Thermal and seal valve
  - Thermal barrier
  - Busbar coating
  - Hose protection
  - Connection cover

HCR materials for flame resistance and ceramification

- Flame-resistant and ceramifying HCR materials provide safety and peace-of-mind in the unlikely event of thermal runaway within a battery enclosure
- Flame resistant HCR:
  - Provide a barrier to flame and hot gasses
  - Maintain electrical and physical properties across wide temperature range and exposure durations
- Ceramifying HCR:
  - Provide a barrier to flame and ceramify during thermal event
  - Maintain physical properties across wide temperature range and exposure durations
- HCR materials can be applied by injection, transfer, compression molding, extrusion and calendaring



UL 94 flame bars, showing vertical burn orientation.

High-temperature torch exposure performed on HCR coated busbar test part.

HCR materials – Material selection

- SILASTIC™ HCR compound can be formulated for specific performance or processing requirements.
- HCRs are fully compounded with ready-to-use, heat-curable blends of HCR bases, fillers, modifiers, catalysts, and color pigments

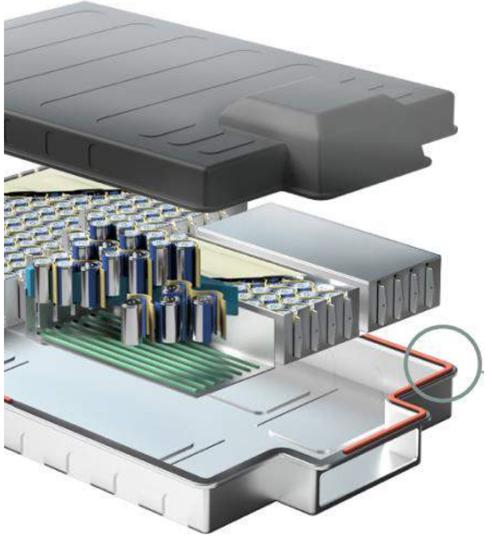
	FLAME RESISTANT		CERAMIFYING	
	SILASTIC™ HCM 50-1339 FR RED	SILASTIC™ HCC 67-1347 FR RED	SILASTIC™ HCC 65-1351 EV FR RED	SILASTIC™ HCx 67-1352 EV FR ORG
Specific gravity ASTM D792	1.18	1.26	1.71	1.4
Durometer [Shore A] ASTM D2249	49	67	65	71 / 67.5
Tensile strength [MPa] ASTM D412	7.7	10.6	2.7	7.7
Elongation [%] ASTM D412	439	511	235	455 / 493
Tear B [kN/m] ASTM D624	11.4	31.2		23 / 24

*Molding **Extrusion

EV gasketing and sealing

- DOWSIL™ silicone adhesives and sealants demonstrate high thermal stability and consistent properties over a wide temperature range
- Keep environmental elements such as moisture, salt and dirt out of the battery pack or various control units
- One/Two-part products that cures into adhesives, gasketing or sealing materials and include FIPG, CIPG LSRs, and DFGs

Technology	FIPG	DFG	CIPG
Seals by	Adhesion	Compression	Compression
Boundaries	No "service gasket"; Seal gap typically <2 mm	"Service gasket" Seal gap typically >2 mm	
Assembly method	Wet assembly (assembly **prior** to cure)	Dry assembly (assembly **after** cure)	
Recommended product group	One- and two-part RTV	Two-part RTV silicone foam	Two-part HTV (CIPG LSR)
Manual application	Yes	No	No
Application location	On assembly site	On assembly site or at tiered supplier	
Typical profile			

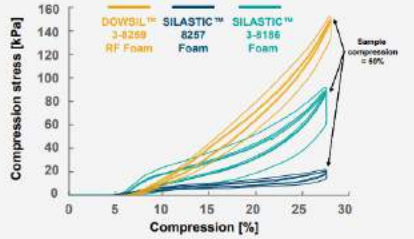


EV gasketing and sealing

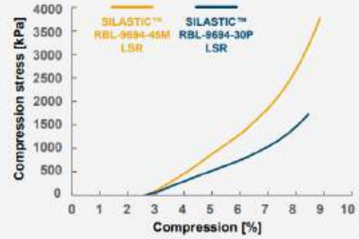
- CIPG and DFG materials are designed to form a serviceable compression gasket — as opposed to an adhesive seal, which may be a valuable design feature in your battery pack.
- Silicones offer a unique benefit in terms of their high thermal stability and potential to achieve UL certification for flammability
- DFGs / CIPGs from provide a range of compressibility with low compression set
- EV pack fire protection sealant in development, reach out to learn more about this product designed to maintain seal performance during a runaway event

Product	Thermal stability [C°]	Volume resistivity [Ω·m]	Dielectric strength [kV/mm]	High-temperature performance	Flammability
DOWSIL™ Standard Sealants and Adhesives (FIPG)	-40 to 250	$>10^{13}$	20-30	Ceramification	UL-50E, UL94 V0 Possible
DOWSIL™ EV Pack Fire Protection Sealant	-40 to 450	5.4×10^{14}	15	Ceramification and maintained structural integrity	UL-50E, UL94 V0 Possible
DOWSIL™ Dispensed Foam Gasket Materials (DFG)	-40 to 250	$>10^{14}$	3-6	Ceramification	UL-50E, UL94 V0 Possible
DOWSIL™ Cure-in-Place Gasket Materials (CIPG)	-40 to 250	$>10^{14}$	10-20	Ceramification	UL-50E, UL94 V0 Possible

Compression stress deflection for select DFG materials from Dow.



Compression stress deflection for select CIPG materials from Dow.



EV gasketing and sealing – Material selection

- DOWSIL™ silicone adhesives and sealants can be applied in a variety of ways according to specific battery configuration needs
- Wide range of products that can be dispensed manually or by appropriate automatic dispensing unit.
- From non-porous, liquid applied, cured-in-place gasket (CIPG) and formed-in-place gasket (FIPG) materials, to dispensed-foam gasket (DFG) formulations

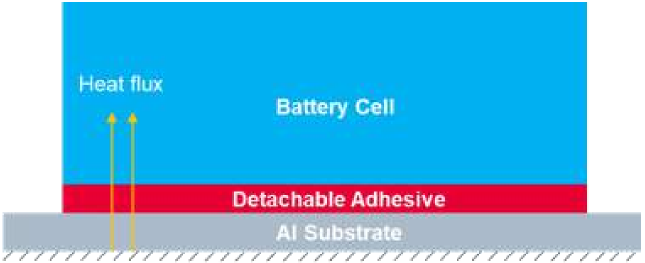
Product	Specific gravity	Viscosity $1s^{-1}$ [cP]		Tack-free time [min]	Durometer [Shore A]	Tensile strength [MPa]	Elongation [%]
		Part A	Part B				
DOWSIL™ 7091 Adhesive Sealant	1.4	1.3 mm (non-flowable)	N/A	28	32	2.5	680
DOWSIL™ 844 RTV Adhesive Sealant	1.35	1.3 mm (non-flowable)	N/A	15	37	2.2	400
DOWSIL™ 3-0115 Automotive Sealant	1.29	3 mm (non-flowable)	N/A	20-25	50	2.8	375
DOWSIL™ EA-3838 Fast Adhesive	1.34	350,000 to 450,000	550,000 to 700,000	5-8	40 (2:1)	>1.5 (2:1)	>250 (2:1)

Product	Specific gravity		Viscosity, $1s^{-1}$ [mPa s]		Snap time [minutes]	Cured density [g/cm3]	Durometer [Shore OO]
	Part A	Part B	Part A	Part B	1:1	1:1	1:1
DOWSIL™ 3-8259 RF Silicone Foam	1.1	0.99	65,000	62,000	2.5-3.7	0.30-0.36	50
SILASTIC™ 3-8186 Thixotropic Foam	1.12	1.22	135,000	125,000	3.5	0.23	40
DOWSIL™ 3-8257 Silicone Foam	1.06	1	20,000	12,000	2.5-5.0	0.11-0.16	25

Product	Cure conditions	Viscosity, $1s^{-1}$ [cP]		Specific gravity	Durometer [Shore A]	Tensile strength [MPa]	Elongation [%]	100% Modulus [MPa]	Developed for adhesion to	Compression set, non-post cure [%] 25%, 22 hrs. @ 177°C
		Part A	Part B							
SILASTIC™ RBL-9694-30P Liquid Silicone Rubber	5-10 mins @ 150°C	1,016,000	832,000	1.2	32	7.2	820	0.8	Plastics	31
SILASTIC™ RBL-9694-45M Liquid Silicone Rubber		889,000	827,500	1.2	45	7.25	600	1.45	Metals	29

CIRCULARITY / RECOVERY OF BATTERY CELLS COMPONENTS AT END-OF-LIFE

- **Battery life cycle**
  - Car industry under pressure about circularity
  - Battery cells recovery is critical
- **Cells encapsulated by silicone foams**
  - Acting as fire and moisture protection barrier or as explosion release valve (top)
  - Manually removable
- **Detachable adhesives for cells and module removal**
  - Dow's approach: thermal mapping of the cells exposed to heating (trigger)
  - Multiple initial prototype formulations achieving robust initial adhesion strength and providing potential "detachable" performances



WE LOOK FORWARD TO HEARING FROM YOU: CONTACT US

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