The Future of Graphene Commercialization

The Graphene Council

Research, Development and Application

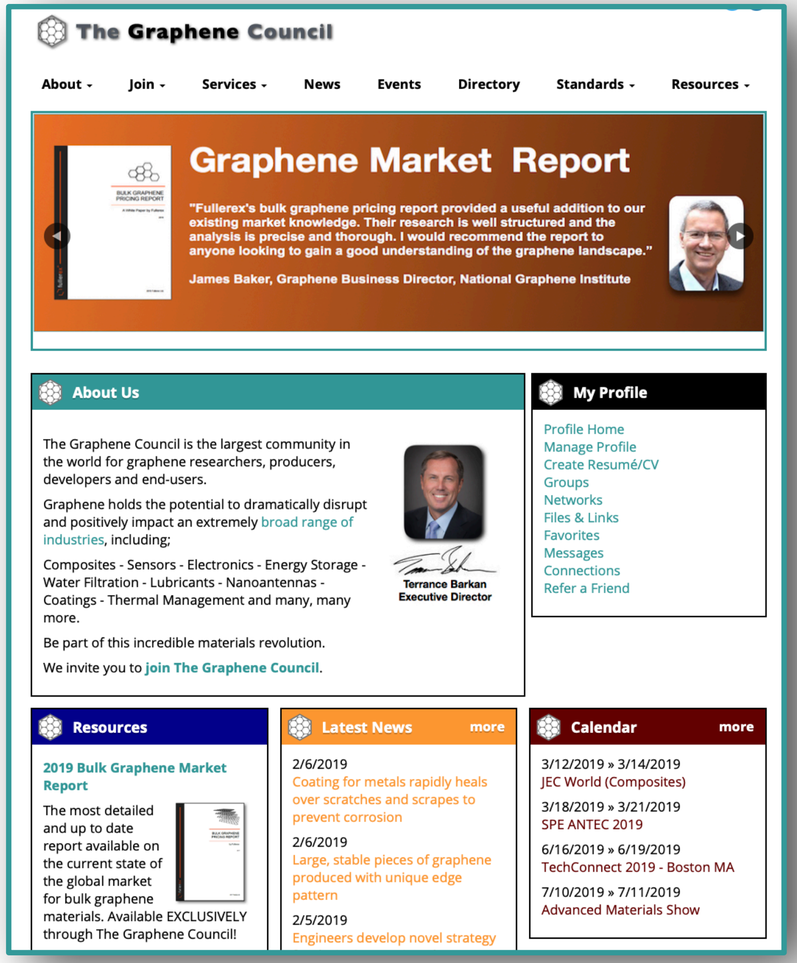
This presentation will;

- **Describe the type and characteristics of the most common forms of graphene used in commercial applications today.**
- **Identify markets where graphene is being used in industrial applications and actual products.**
- **Discuss what is necessary going forward for successful graphene commercialization.**

The Graphene Council

The Graphene Council:

- The largest community in the world for graphene researchers, developers, producers and other stakeholders.
- Formal members of the ISO/ANSI/IEC Graphene Standards development working groups.
- Produces original information, market research, content and reports on the state of the graphene industry.
- Facilitating commercialization through education and networking.
- Provides professional advisory services to producers, users and application developers.

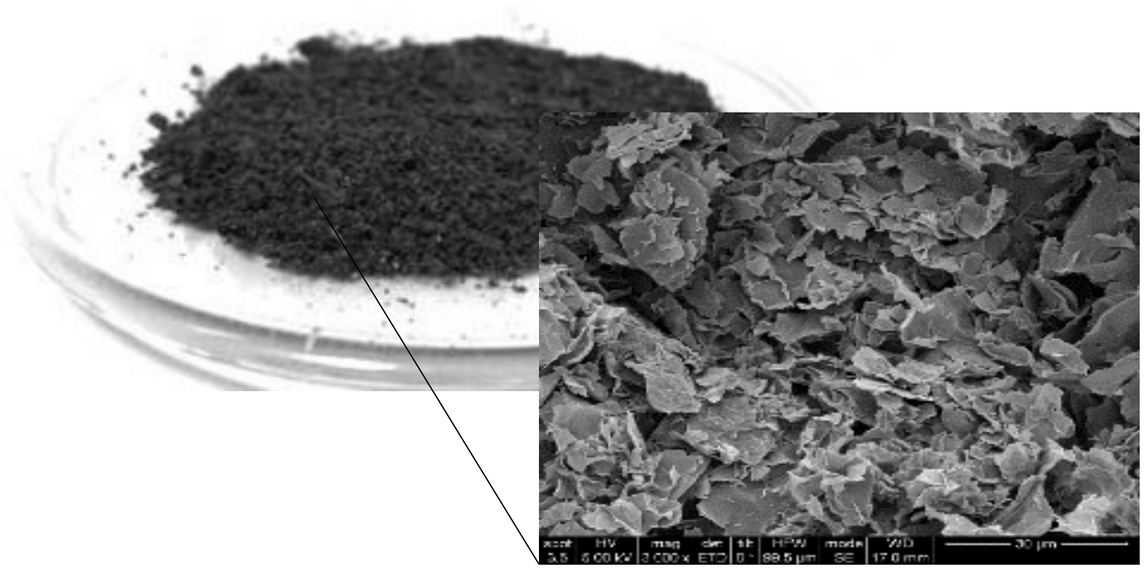


Forms of Graphene

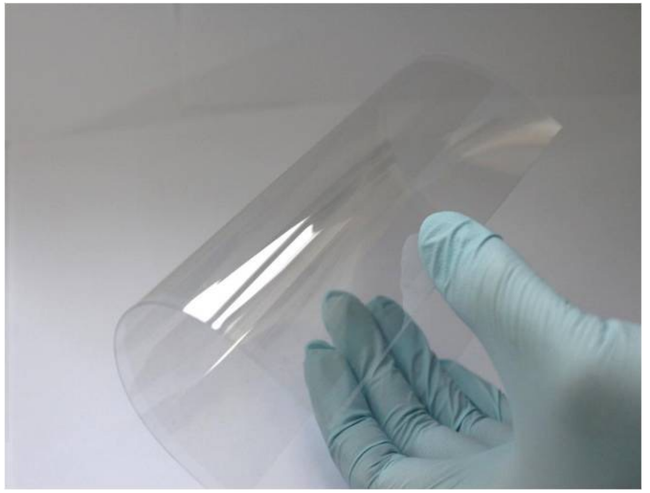
Commercially, Graphene is considered a family of related 2D Materials based on monolayers of Carbon

Forms of Graphene

- Graphene as a commercial product can be very broadly categorized into two material forms: **Bulk powder** or **continuous thin film**.



Dry flakes of Graphene Oxide *(image courtesy of Abalonyx AS)*



Forms of Graphene

A wide range of materials in the commercial market are currently referred to as “graphene”.

Number of Carbon Layers	Description
1	CVD, Mono-layer or “Pristine” Graphene
1 - 3	Very Few Layer Graphene (vFLG)
2 - 5	Few Layer Graphene (FLG)
2 - 10	Multi-Layer Graphene (MLG)
> 10	Exfoliated graphite or “Graphene nanoplatelets” (GNP)

Forms of Graphene

- **Besides the number of carbon layers, additional characteristics define the material.**
  - **Graphene Oxide (GO) - a compound of carbon, oxygen and hydrogen (typically approx. 65% carbon / 35% oxygen by weight).**
  - **Reduced Graphene Oxide (rGO) - Graphene Oxide in which removes much of the oxygen content resulting in approximately 95% carbon by weight.**
  - **Graphene Powder, Solution or Paste - Graphene material can be prepared in various physical forms including as a dry (usually black) powder, in solution (e.g. water or alcohol) or in a paste form (often as a dull reddish brown color).**
  - **Graphene Nano Platelets (GNPs) - GNPs typically have thickness of between 1 nm to 3 nm and lateral dimensions ranging from approximately 100 nm to 100 µm.**
  - **Functionalized Graphene - Chemical functionalization (adding specific elements to the surface of the graphene) is important in many applications.**

Forms of Graphene

Type	Carbon Layers	Properties/Applications	Typical commercial cost ($/KG)	Commercially available
Epitaxial CVD	1-2	Conductive/almost Transparent/ITO? High end electronics	Up to $500,000/m²	CVD systems- Scale up? Cost! ITO?
FLG	3-10	Conductor/flexible/very high surface area/Sensors	$100-2,000	Yes- consistency? Processibility?
MLG	11-20	Composites/Inks and coatings/ Lubricants/Printing	$50-1,500	Yes- variable product today!
GO	various	Insulator? Amorphous Hydrophillic-dispersions Defects and voids. Cement	$50-2,000	In Part- still evolving but growing
Graphite used in GNP production	50+	Lubricants/Refactories/brakes/ Engineering materials	$1-20	Established for 150 years Approx. 1m tonnes pa

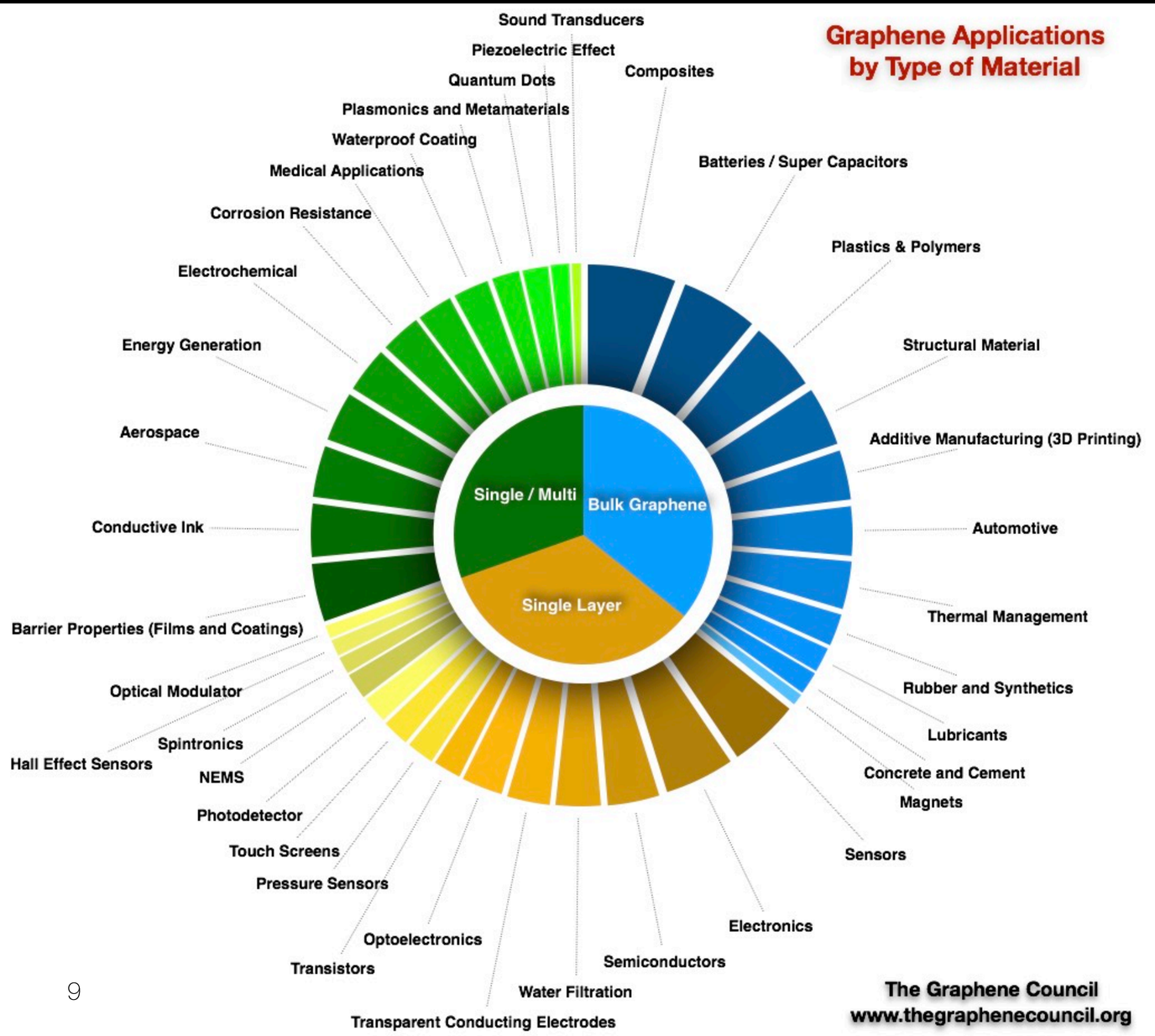
Forms of Graphene and the Concept of “Quality”

There is widespread confusion about the definition of “Quality Graphene”.

- **Material that is not suitable for one application may be ideal for another.**
- **Graphene “defects” may actually enhance the efficacy of the material for a particular application.**
- **There is no such thing as a reference material for graphene at this time.**
- **Because load factors can be quite low, the price of the material is not the most significant factor when selecting source material.**
- **The primary factor is in selecting a trusted and competent supplier of the material that understands your application areas.**

The Market for Graphene Materials

- More than 40 major vertical markets for graphene depending on the type of material and applications.
- Largest markets include Composites, Batteries, Plastics, Sensors, Coatings, Thermal Management and Conductive Inks.
- Major industries include automotive, aerospace, sporting goods, defense, construction.



The Market for Graphene Materials

- **Volume sold in 2018 estimated at approx. 600 tonnes (bulk graphene) for a total value of approx. $65 million.**
- **Production capacity estimated at 6,000 tonnes p.a. or 10 X the current market demand.**
- **More than 250 companies claim to produce graphene on a commercial basis (excluding many 100's of companies in China).**
- **Total market forecast is $300 million in 2027 based on consensus of available market reports.**

Data Source: Fullerex Ltd.

The Potential Market for Graphene Materials

Examples of Global Market Potential:

- **Marine Coatings consume 1,000,000 tonnes of product annually. If graphene is added at a load factor of just .5% by weight it would require 5,000 tonnes of graphene, nearly all of the current production capacity for just this one narrow application.**

- **Polymers for mechanical applications are produced at an annual capacity of approximately 250,000,000 tonnes. If graphene is added at a load factor of just 1% by weight, it would require 2,500,000 tonnes of graphene materials.**

Application Case Study:

Automotive

XGPU **Foams**

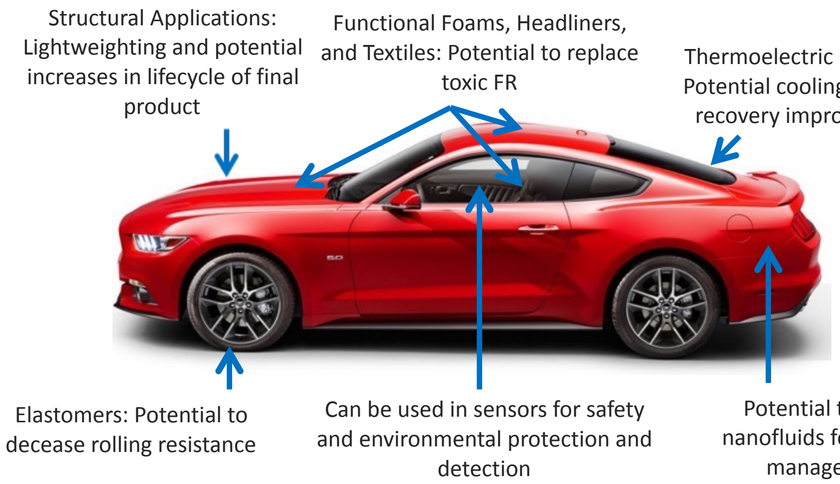
Multiple performance improvements in PU foam application, enabled by the addition of xGnP®

xGSciences™ + Ford Go Further

Graphene-Enhanced PU Foams

- **Improved compression strength by 20%**
- **Improved NVH (noise & vibration) by 17%**
- **Improved heat deflection temperature by 30%**

Parts in Production



Application Case Study:

Sporting Goods

xGnP® + Elastomers

Performance enhancements via graphene-enabled innovation

Graphene-Enhanced Golf Balls

More Speed Off the Tee ⬣ Spin Forgiveness ⬣ Increased Spin Control

- Graphene-infused Dual SoftFast Core maximizes compression energy while minimizing driver-spin and promoting high launch for long distance
- Softer golf balls compress easier on off center hits for distance all over the face

"We've innovated at every layer, starting with our groundbreaking new Graphene Dual SoftFast Core. The result is an extremely fast and soft-feeling ball that promotes high-launch and low spin off the tee for long distance, and incredible shot-stopping spin around the green."

– Dr. Alan Hocknell, SVP, R&D, Callaway Golf

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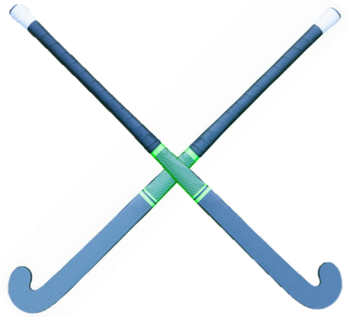
Commercialized Applications

Graphene Enhanced Formulations



Hockey Sticks

xGnP®

- **Extra Power**
- **Extra Feel**
- **Playability**
- Increased strength
- Greater durability

Batteries

xGnP®

- **Longer Life**
- **Better Charge Acceptance**
- **Improved Low Temp Performance**
- Longer lasting
- Improved electrical connectivity
- Faster recharging

LED Packaging

XGTIM®

- **Lower Thermal Resistance**
- **Easier application**
- Less material
- High thermal output

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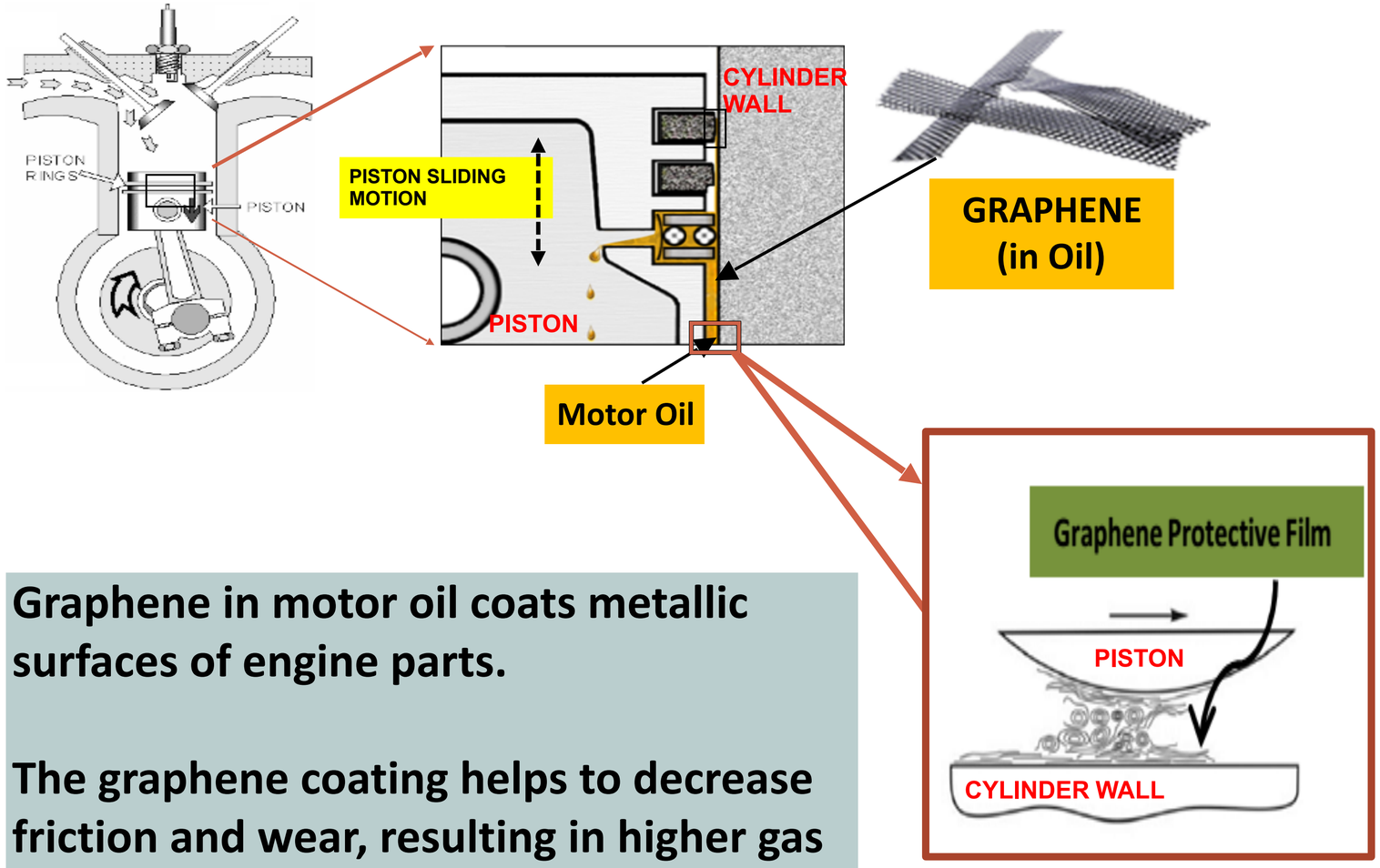
Benefits of Graphene Based Engine Oil Nanofluids

Stable Dispersion in Motor Oil

Right: 0.025 gram of graphene in 1L of conventional oil 10W-30. Remains uniformly dispersed for over 12 months without precipitation or separation.

Left: Conventional base oil 10W-30 without NTherma Graphene.



Graphene in motor oil coats metallic surfaces of engine parts.

The graphene coating helps to decrease friction and wear, resulting in higher gas mileage and longer engine life.

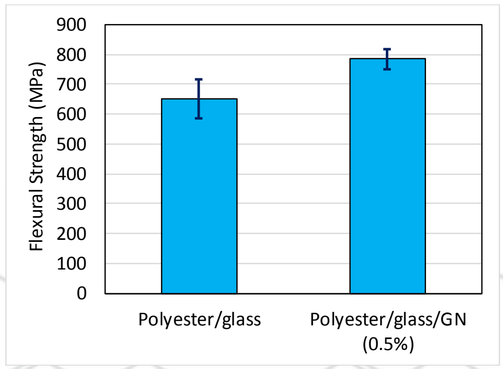
NTherma Corporation

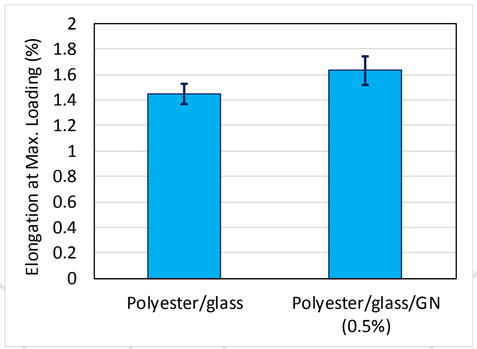
Graphene Pultrusion: Case Study

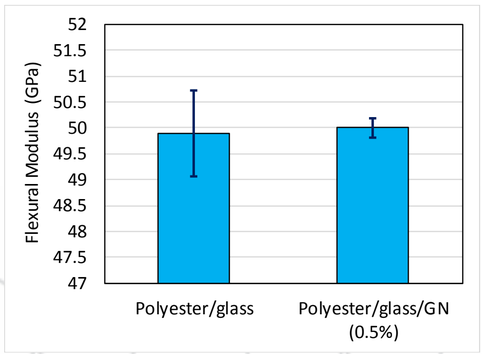
Improvements: >20% in flexural strength and >12% in the elongation only by addition of **0.5% graphene** to polyester/glass rods.

ASTM D790

	Flexural Strength (Mpa)	SD	Elongation at max Loading (%)	SD	Modulus (GPa)	SD
Polyester/glass	651.22	66.06	1.45	0.08	49.9	0.83
Polyester/glass/GN (0.5%)	784.24	34.96	1.63	0.11	50	0.19







polyester/glass

polyester/glass/GN (0.5 wt%)

Industrial Volume

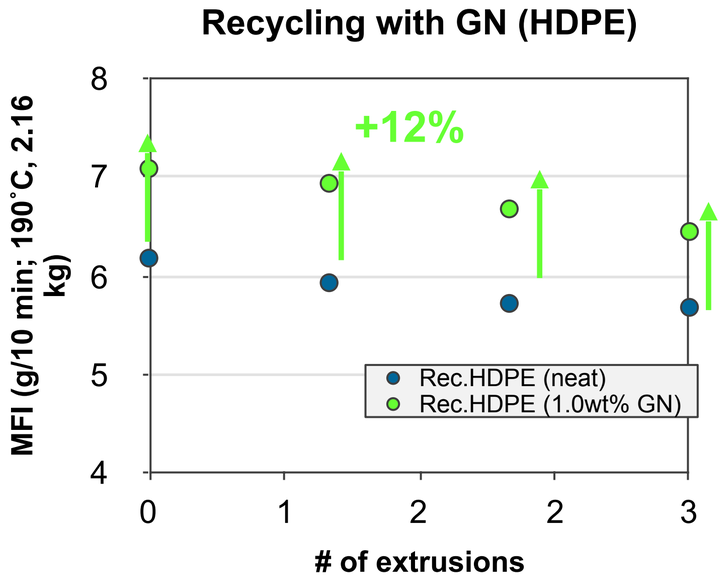
Proprietary Technology

Low-Cost

Recycled Materials: Processability

Melt Flow Index - MFI

- ✓ GrapheneBlack3X® acts as a processing aid increasing the MFI of the recycled polyethylene.
- ✓ At very low contents, there is an improvement of about 12% helping to control molecular weight and viscosity.
- ✓ GrapheneBlack3X® attenuates the decline of processability resulting from repeated processing cycles.



Industrial Volume

Proprietary Technology

Low-Cost

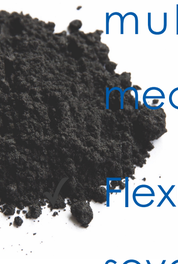
Processability

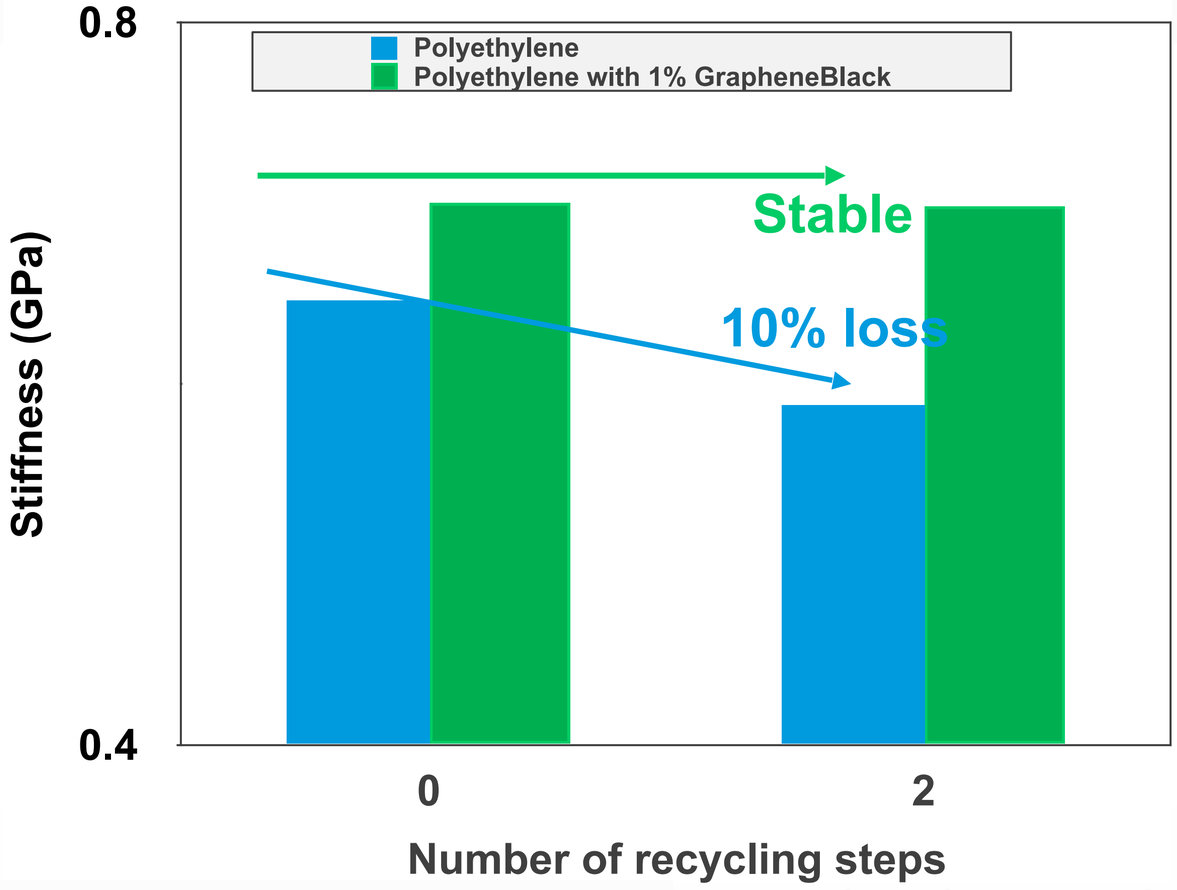
Extend Lifetime

Recycled Materials: Mechanical Performance

Flexural resistance

- ✓ GrapheneBlack3X® incorporation counterbalances the detrimental effect of multiple melt-processing cycles on the mechanical properties.
- ✓ Flexural performance remains unchanged after several successive processing cycles using 1wt% of GrapheneBlack3X® .





Industrial Volume

Proprietary Technology

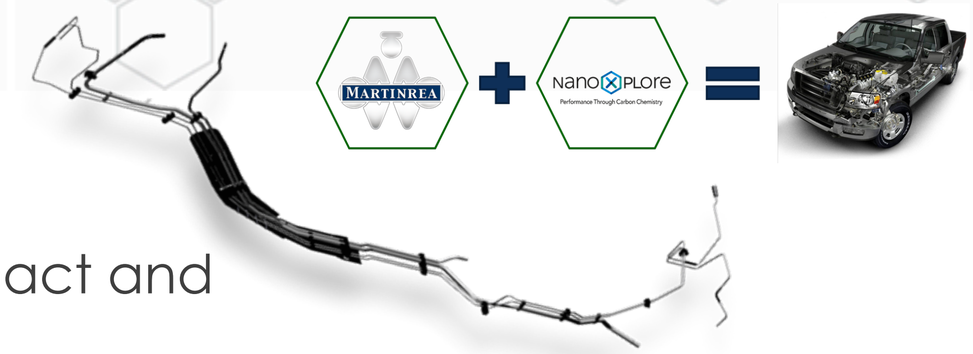
Low-Cost

Mechanical Properties

Graphene Enhanced Coatings

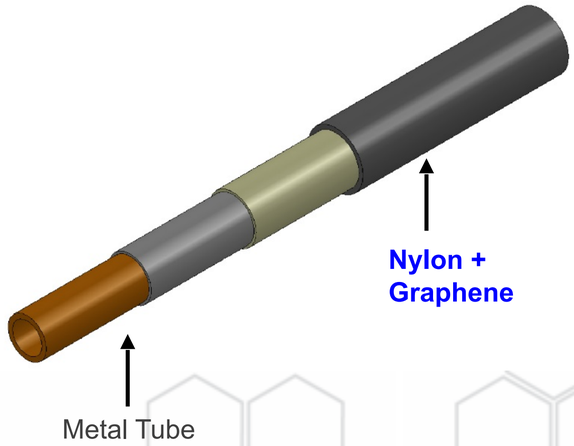
Abrasion Resistance:

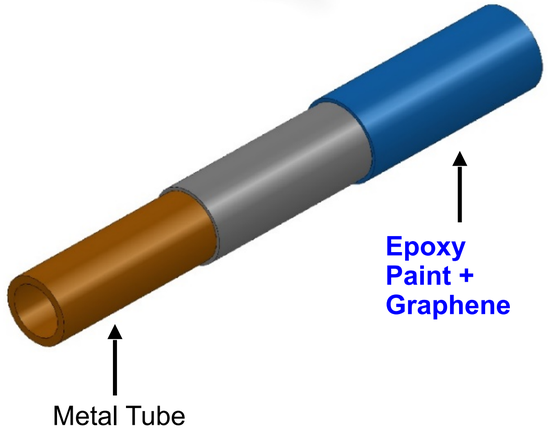
- Nylon / Graphene
- Epoxy / Graphene
- Improve robustness of coating to resist impact and abrasion conditions



Corrosion Protection:

- Improving the barrier to salt water solution penetration to base steel
- Prolonged component life





Industrial Volume

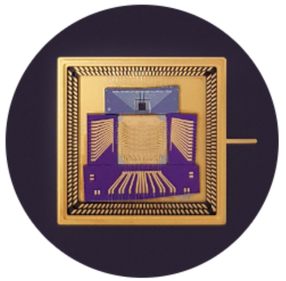
Proprietary Technology

Low-Cost

Grolltex Applications

Nano-sensing factories evaluating our material for ramps to begin 2020:

- SF based wearables sensor; patch to measure glucose in sweat
- Boston based mobile sensor; detect allergens in foods (gluten, peanut, etc.)
- Finland/UK (Nokia spin out); CMOS photosensor for imaging, spectroscopy, night vision
- G-FET device; automates drug and other ‘assays’, reduces time from months to hours



<u>Forecast</u>: Huge growth seen in nano/bio-sensing; wearables, DNA, new drug discovery, glucose monitoring, food allergens, etc.

Graphene and Textiles

Applications in Fibers and Textiles

- Printed electronics to create “smart fabrics”.
- Strengthening and light weighting ballistic materials (enhancing Kevlar).
- Thermal distribution (for cold or warm weather applications).
- Antibacterial properties.
- Improved strength and wear resistance.
- Flame retardation and resistance.
- Fibers may be coated or the fibers spun with graphene enhanced materials.
- Integrated capacitors / energy storage devices woven into the fabric.

Challenges for USERS of Graphene Materials

Obstacles to adoption by potential users of graphene include;

- **Perception that graphene is prohibitively expensive (i.e. do not understand that the potential load factors can be very low, sub 1% or dramatically less, making price a minor issue).**
- **Lack of awareness regarding the particular types of graphene available and which are best suited for purpose.**
- **Hesitancy to introduce a new, unproven material to their production process or to change existing production processes (i.e. avoidance of risk).**
- **Lack of understanding of the significant potential benefits graphene can provide.**
- **Lack of awareness regarding reputable or reliable sources of graphene materials.**

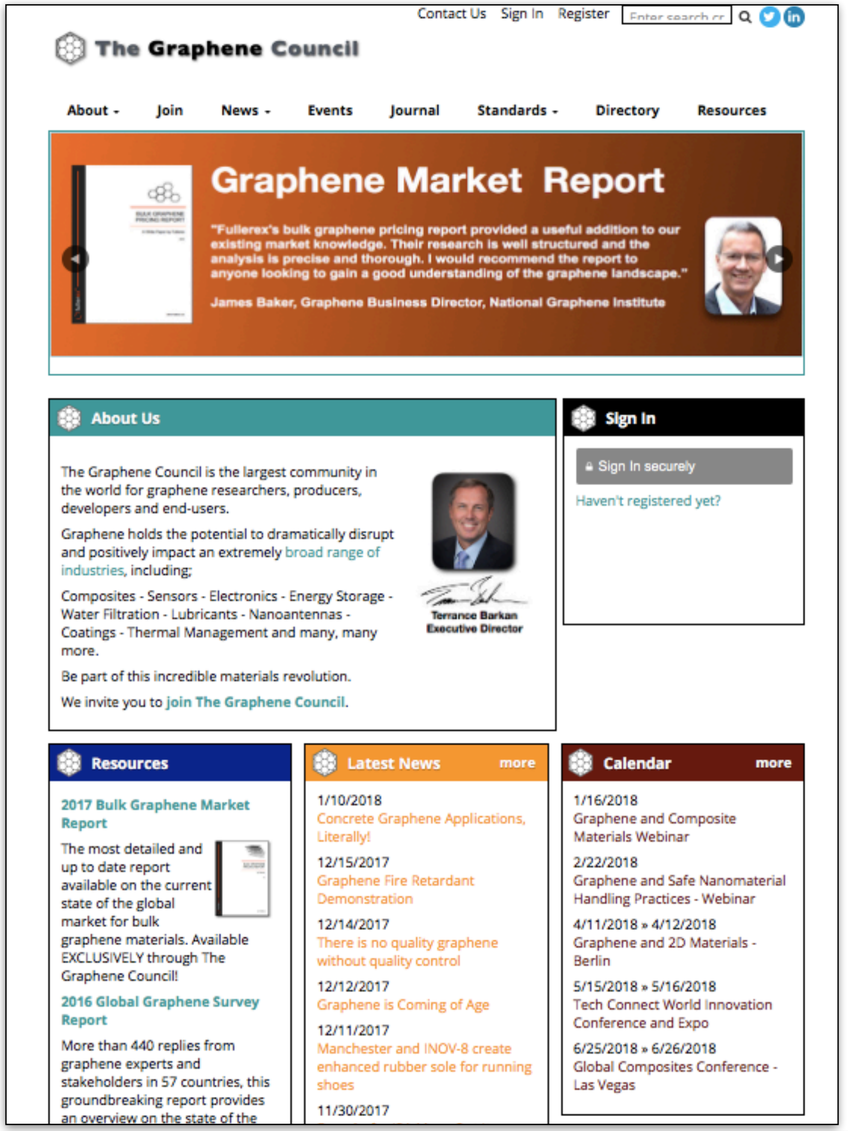
Challenges for PRODUCERS of Graphene Materials

Successful commercialization by producers of graphene requires;

- **Solid science regarding production methodology and the ability to tune or modify the graphene product to meet customer requirements (IP).**
- **Engineering capabilities to produce material at industrial scale with appropriate quality control as well as to maintain necessary health and safety protocols.**
- **Ability to work with clients to support the development of graphene enhanced applications (i.e. Development skills to be able to teach the client how to handle and use the graphene material correctly in their products / production processes).**
- **Investment in an adequately sized sales effort to uncover and stimulate demand.**
- **Lack of industry standards and certifications leads to confusion for buyers.**

Graphene News and Information

The Graphene Council

- Weekly graphene intelligence newsletter.
- Member of ISO/ANSI/IEC Graphene Standards working groups.
- Graphene Technology peer reviewed journal published by Springer Nature.
- Graphene Bulk Pricing and other market oriented reports.
- Verified Graphene Producer™ program.
- The most up to date source of information on graphene commercialization

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