INNOVATIVE *with*

THE MAGAZINE WITH THE IDEAS OF THE FUTURE #02

SPOTLIGHT

ELIUM® RESIN: A BREAKTHROUGH INNOVATION IN COMPOSITE MATERIALS

Easy to use, performance, improved productivity and recyclability… Elium® resin is a breakthrough innovation.

ARKEMA
INNOVATIVE CHEMISTRY

CONTENTS

GLOSSARY: find explanations of some of the technical terms used in our articles (underlined) at the back of the magazine.

ELIUM® *by Arkema*

A two-minute explanation of new composite resin recycling

YouTube

dito

Elium® resin! Find out about this major innovation by Arkema's R&D, in our second issue of Innovative with. Our customers and our partners in industry and academia have plenty to say about the advances promised by this new thermoplastic resin—proven productivity gains, the solidity and durability of the composite parts obtained, but most of all the long-awaited prospect of recycling. This technological breakthrough is of particular interest for composite materials as it uses the same production tools as those used for thermosetting resins, which still dominate the composite sector.

Read about the Elium® revolution in wind turbine blades, construction and civil engineering with concrete reinforcements, in transportation with hydrogen tanks, and in sailing with a new generation of yachts. Elium® really has broken new ground in composite materials. While the challenges of the circular economy are driving considerable research efforts in all industrial sectors, we are proud to tell you about the performance and promises of this new material, which represents the future of composites which are, at last recyclable.

WE HOPE YOU ENJOY IT!

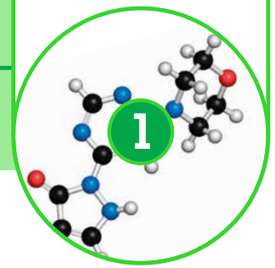
DENIS BORTZMEYER

Head of R&D Partnerships

ELIUM®: LEARN MORE ABOUT THIS *resin of the future*

Arkema, the specialty materials specialist, is forever seeking further innovation in response to economic and environmental challenges. Elium® is one such innovation. A resin with unique properties, allowing the products and systems that use it to be recycled, and offering comparable performance to traditional resins. Learn about its potential in six stages.

ACRYLIC MONOMERS

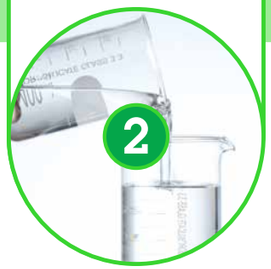


START

FORMULATION

ELIUM® RESIN

Liquid, very fluid, reactive and thermoplastic; non-toxic



POLYMERIZATION

Polymerization with an initiator (organic peroxide) or photoinitiator, at room temperature or higher

THERMOPLASTIC COMPOSITE MATERIALS

Elium® resin + natural fibers—glass, carbon etc. Uses the same processes as for thermoset resin composites (epoxy, vinyl ester, etc.)

Reuse of Elium® resin

Recycled composites

INDUSTRIES USING ELIUM® RESIN THERMOPLASTIC COMPOSITE MATERIALS

Wind power, construction and civil engineering, light and heavy road transportation, rail transport, sailing, sports and leisure, aviation

B2B APPLICATIONS

Wind turbine blades/hydrogen tanks for transportation ships, trucks, utility vehicles, freight trains, composite concrete reinforcements

5

CONSUMER APPLICATIONS

Hydrogen tanks for cars/ yachts/tennis rackets, skis, shoe soles, golf clubs, hockey sticks

CHEMICAL

reuse of the pure Elium® resin with the same original properties

MECHANICAL

reuse in recycled composite materials

GLOSSARY SEE PAGE 37

ELIUM® RESIN: A BREAKTHROUGH INNOVATION IN *composite materials*

Guillaume Clédat

MEET..

GUILLAUME CLÉDAT, Elium® resin Business Development Director

With its Elium® thermoplastic resin, Arkema offers a unique solution for manufacturing composite parts using the same methods as those used for thermoset resin parts, but with the major advantages of recyclability, more energy efficient production and thermosetting possibilities. This could benefit a number of sectors, such as wind power, automotive, construction and sailing.

Why did you develop Elium® resin?

Guillaume Clédat – We wanted to make thermoplastic composite materials more accessible for our customers and easier to use. And that's what Elium® resin does. It's easy to use as it is liquid like other resins, which are currently very widely used, but with the advantage of being able to polymerize at room temperature and harden more quickly. This is a real technological breakthrough compared to epoxy thermoset resins, for example , which need processes that are often more costly and energy intensive as they need to be heated to harden.

What applications are you aiming for?

G.C. – There is a wide range of uses, owing to Elium® resin's intrinsic qualities. It can be used to make a number of composite materials—with fiberglass, carbon, natural fibers—even with a very high rate of fiber. Arkema is a world market leader in specialty materials and this dominance means that we can target a number of industrial uses with Elium®.

What industries are you targeting with Elium®?

G.C. – The advantages of this resin primarily concern wind power, construction and civil engineering, transportation and hydrogen storage, as well as sailing. Elium® is used in wind turbine blades, composite reinforcement bars for concrete (rebars) in the civil engineering sector, in hydrogen tanks and in sailboat hulls (see next double page).

Ease of use, high performance, improved productivity and recyclability… Elium® resin is a breakthrough innovation.

ELIUM®, AN INNOVATION THAT HAS BEEN MAKING WAVES IN THE WORLD OF COMPOSITE MATERIALS SINCE ITS LAUNCH

2012
First patent applications for Elium® resin formulations.

2014
Start of production at the Arkema plant in Mollet del Vallès (Spain), the United States, South Korea and China

2016
Launch of the Arkema 3 Mini 6.50 boat, the hull and bridge of which are made from Elium® resin, and first competition

2017
Arkema wins a JEC Asia Innovation Award for the use of Elium® resins in wind power

2019
Arkema wins a JEC Asia Innovation Award for the use of Elium® resins for manufacturing bendable concrete reinforcements.

2020
Launch of the ZEBRA (Zero wastE Blade ReseArch) project

Each industry has its reasons for using Elium®, but our main customers report three main benefits, in addition to the ease of use for a thermoplastic composite material: performance, improved productivity in using the resin and recyclability.

What stage of development are you at?

G.C. – We started production in 2014 in three continents (Europe, North America and Asia). Our customers are now starting to incorporate it into their products. These include LM Wind Power's wind turbine blades, start-up Northern Light's sailboats and, very soon, Sireg's hydrogen tanks and composite reinforcement bars. Elium® sales are increasing sharply in all these markets and Arkema has trebled its annual sales since 2016.

Reasons to be proud of this invention?

G.C. – Our teams are extremely proud in more than one regard. Obviously for the reasons stated above, and because of the feedstocks selected for the formulation of Elium® resin. It contains no cobalt salts, typically used as catalysts to initiate the radical polymerization of the resins, but often classified as carcinogenic in Europe (CMR substances –), or styrene, which is toxic to reproduction and also classified as hazardous to human health.

How is Arkema establishing itself in this market?

G.C. – We face two challenges: maintaining a high rate of production, driven by brisk demand, while also ensuring uniform quality. So we are developing a global supply chain, setting up our production plants on three continents. But the main thing is to work with our customers and partners on creating a composites production industry that includes the new Elium® resin. We want to give them the broadest overview of the product for their applications. For Arkema, this is one more reason to be proud.

In addition to customers, which partners are involved in the venture?

G.C. – We are working with academics, institutional partners and research centers to create a complete ecosystem centered around Elium® resin. They are helping us to establish it in specific markets. In wind power, for example, with the National Energy Lab in the United States, and in France as part of the ZEBRA (Zero wastE Blade ReseArch) project, coordinated by the Jules Verne research institute to develop zero waste wind turbine blades. All play a necessary role in establishing this new segment. ■

With its partner Team Lalou, Arkema built the first boat hull in Elium® resin in 2015

400%

increase in Elium® resin sales between 2019 and 2020

FOUR MAIN MARKETS, ONE GLOBAL AMBITION

Wind power

PRODUCTS CONCERNED: wind turbine blades.

ADVANTAGES OF ELIUM®:
- delivers improved productivity and lower costs during manufacturing compared to thermoset resins: quicker and more energy efficient production;
- Ensures that blades are recyclable, delivering similar performances to thermoset resins, or even stronger performance in terms of damage resistance.

STAGE OF DEVELOPMENT: test phase; ZEBRA (Zero wastE Blade ReseArch) project, production to begin in 2022.

CUSTOMERS: wind turbine blade manufacturers, composites manufacturers; energy companies; recycling companies.

GROWTH: Installed wind power capacity of 60.4 GW worldwide in 2019, representing a 19% increase in facilities relative to 2018 (out of total capacity of 651 GW). Additional 355 GW planned between now and 2024.

Source: Global Wind Report 2019

Concrete reinforcements

PRODUCTS CONCERNED: composite concrete reinforcement bars or FRP rebars .

ADVANTAGES OF ELIUM®:
- improved productivity, flexibility and responsiveness compared to epoxy thermoset composite reinforcements;
- Elium® reinforcements can be bent when hot and cut at just the right time on site, compared to thermoset composite reinforcements which have to be calibrated and and bent in the factory six or seven weeks in advance, and therefore risk becoming obsolete;
- limited losses and recyclability.

CUSTOMERS: reinforcement manufacturers, construction and civil engineering companies.

GROWTH: The worldwide composite reinforcements market was worth €480 million in 2015 and grew by 8.5% a year between 2016 and 2024. Total revenues will be €1.02 billion in 2024.

Source : Global Market Insights.

Sailing

PRODUCTS CONCERNED: sailboat hulls and decks.

ADVANTAGES OF ELIUM®:
- improved productivity (more energy efficient production) in building the boat;
- durability of the composite material made using Elium®;
- recyclability.

STAGE OF DEVELOPMENT: first models to be brought to market in mid-2021.

CUSTOMERS: composites manufacturers, boat builders, equipment suppliers.

GROWTH: The leisure sailing market is valued at €33.3 billion in 2020, and €44.7 billion in 2027. Growth of 4.1% between 2020 and 2027.

Source: Grand View Search

Hydrogen storage

PRODUCTS CONCERNED: composite hydrogen tanks for vehicles.

ADVANTAGES OF ELIUM®:
- Improved productivity for manufacturing hydrogen tanks;
- Same safety and performance standards as tanks made from epoxy thermoset resins;
- Recyclability.

STAGE OF DEVELOPMENT: test phase, to be launched on the market in 2024.

CUSTOMERS: equipment suppliers, engine manufacturers, energy companies.

GROWTH:
- in 2020, engine manufacturers had 75 hydrogen car prototypes; 6,000 composite hydrogen tanks produced for passenger cars.
- Worldwide target for 2030: production of 6 million hydrogen tanks per year. Potential demand for 10 to 15 million cars and 500,000 trucks.
- Target for France in 2030: 342,000 tons of low-carbon hydrogen for 300,000 light vehicles, 5,000 heavy vehicles, 250 trains, 1,000 boats.

Sources: Hydrogen Council; FW Engineering in JEC Composites Magazine – Sept 2018; French Multiannual Energy Program (PPE).

ELIUM® RESIN:
A GLOBAL INDUSTRIAL FOOTPRINT FROM THE OUTSET

Elium® resin composites

RECYCLING OPTIONS

Elium® resin allows thermoplastic composite materials to be recycled. Two recycling processes—mechanical and chemical—are currently being tested. Jean-François Devaux, expert research engineer at Arkema, and Clément Callens, BU Manager Industry of the Future & Thermoplastic Processes at CETIM Grand Est, explain.

Jean-François Devaux,
Senior Research Scientist, Arkema

Clément Callens
BU Manager Industry of the Future Cetim Grand Est

Composite materials have seen growth of 4% a year since 2016, with a ramp-up in thermoplastic composites compared to thermoset composites. But more still needs to be done to manage their end of life. Although a number of factors come into play, the thermoset nature of the resins used to make these materials makes them very hard to recycle. As a result, most end-of-life composites and production waste go to landfill, because there are no technically or financially viable recycling options, or to cement works for use as solid recovered fuels.

THE ELIUM® REVOLUTION

In a market that is monopolized by thermoset composites, Elium® resin represents an unprecedented innovation. It combines the advantages of a thermoset material with the recyclability of a thermoplastic material. Its potential is huge, particularly as 38,000 tons of composite waste is generated in France each year, out of total production of 380,000 tons. But although thermoplastic composite materials are profitable to use, the lack of recycling options may constitute an obstacle to their being used on a mass scale. That is why Arkema, alongside its industrial and academic partners, is working on developing recycling in a number of different projects and by creating two different but complementary processes.

MECHANICAL RECYCLING

This is the first realistic industrial solution for recycling thermoplastic composite materials, particularly those made from Elium® resin. To develop it, Arkema is collaborating in the REVEL project with the Grand Est Technical Center for Mechanical Industries (CETIM) and the M2P Technological Research Institute. According to Clément Callens, BU Manager Industry of the Future & Thermoplastic Processes at CETIM, "the aim is to position the recycling process for composite materials in the light of future applications, and therefore forthcoming industrial projects. To do this, we are evaluating the recyclability by thermomechanical means of production waste or end-of-life parts made from Elium® resin-based composites." Parts are crushed and heated and then the material obtained is turned into panels with high mechanical resistance. These recycled composites, which include fibers and resin, can be used in construction and civil engineering, transport, the production of industrial equipment—sectors that are looking for solutions to reduce weight, improve mechanical performance and simplify design. "This solution has the advantage of being adoptable by recycling companies using standard processes, on a small and medium scale, using less energy than complex chemical processes," explains Clément Callens.

> "This solution has the advantage of being adoptable by recycling companies using standard processes."

CHEMICAL RECYCLING

This is the second method for recycling Elium® resin composites. The process consists of crushing the composite and heating it to around 400 degrees in order to turn the solid resin into a gaseous monomer. "It can be recovered, purified and formulated into a resin that can be used in applications with the same level of performance as the virgin resin," states Jean-François Devaux, expert research engineer at Arkema. "Chemical recycling also allows operators to take larger volumes, and badly damaged or end-of-life composites do not pose an obstacle to recovering the resin. This means that we can ensure circularity with a material that can be reused for multiple applications." Recovered carbon or glass fibers can also be recycled, but for applications other than the original use.

GROUP EFFORT

In order to put these two recycling methods on a viable industrial footing, Arkema is working closely with its partners. The "REVEL" mechanical recycling project is at an advanced stage, with the development by CETIM Grand Est of its Thermosaïc® technological solution for recycling Elium® resin-based composites. Meanwhile, there have been several large-scale collaborations in chemical recycling, such as the MMAtwo project on the recycling of PMMA and, soon, Elium® composites (see inset), as well as the ZEBRA* program, which focuses on wind turbine blades (see next double page).

ANTICIPATING NEW COMPOSITE MATERIALS

With end-of-life Elium®-based composites coming onto the market in the next few decades, action is being taken now to prepare for this phase in order to be ready to receive these materials and make the most of them in terms of recycling or reuse. "While waiting for them to reach the end of their life, we can count on consumables made from Elium®-based composite materials arriving in 2024-2025, with production waste from the manufacturing of boats and wind turbine blades…" says Jean-François Devaux. "These account for 5-10% of composite materials made, and this waste contains significant volumes of Elium® resin, which we want to recover and reuse." Hence the importance of demonstrating the feasibility of recycling processes to specialist operators, as well as their financial viability.

* Zero wastE Blade ReseArch – MMATwo inset

ZOOM

SPOTLIGHT WHAT IS MMATWO?

MMAtwo is an ambitious project involving manufacturers and academics in creating a large PMMA recycling network. It is funded as part of the Horizon 2020 EU research and innovation plan and comprises thirteen partners from six different countries representing all stages of the PMMA value chain. Arkema is heavily involved in MMAtwo as a PMMA producer, and intends to go even further by coming up with a demonstration model for recycling Elium® resin-based composites. Scheduled for 2022.

Find out more about MMAtwo

ARKEMA TAKES UP

the challenge of recyclable wind turbine blades

At present, the blades of the 20,000 wind turbines—that's around 550,000 tons of composite materials—installed on average each year worldwide are made from epoxy resin/carbon or glass fiber-based thermoset composites. Their solidity and shock resistance make them materials of choice. The only disadvantage is a sizeable one: they cannot be recast and their end of life poses a serious environmental problem. In this fast-growing market, Elium® thermoplastic resin now makes it possible to manufacture blades from recyclable composites for the first time.

659 GW

worldwide wind power capacity in 2019

60.4 GW

new capacity in 2019 with the installation of new wind turbines, an increase of 19% on 2018. This is the second best result recorded, after 2015

1,000 GW

worldwide wind power capacity expected in 2024, a 54% increase in installations compared to 2019

15 and 20%

annual growth in the number of wind turbines worldwide

Source: Global Wind Energy Council.

Wind turbine blades: elium® supports THE CIRCULAR ECONOMY

A major user of wind turbines, ENGIE also sees itself as a playing a driving role in terms of their lifecycle. Vianney de Lavernée, Head of Strategy, CSR and Innovation at ENGIE France Renouvelables, tells us how the Group and its partners—including Arkema—are working to make them more durable and recyclable.

Vianney de Lavernée

"Elium® thermoplastic resin is the missing link in blade recyclability."

6 tons

of Elium® resin is used to make a wind turbine blade, or 18 tons for one wind turbine

recyclability target for wind turbine blades

100%

Total project budget for Zebra of

€18.5m

What is the link between ENGIE and Arkema in wind turbines?

Vianney de Lavernée – ENGIE and Arkema are both part of the wind power value chain in France. ENGIE operates onshore and offshore wind farms, and Arkema is involved upstream in producing the resin that is used with fibers to make wind turbine blades. From one end of the chain to the other, we are linked by targets for improving manufacturing processes and making them more environmentally friendly. This is why ENGIE and Arkema came together to launch the ZEBRA project in 2020.

What is the ZEBRA project?

V.d.L – ZEBRA stands for "Zero wastE Blade ReseArch". For this project, launched in September 2020, we pooled and mobilized members of the wind turbine production, operation and dismantling chain in order to demonstrate the recyclability of wind turbine blades using Elium® resin. As a major buyer of wind turbines in Europe and worldwide, ENGIE plays a driving role with regard to its suppliers, and Arkema offers a future-led solution that allows the blades to be fully recycled. Faced with this challenge, the other ZEBRA participants got involved, including fiber producer Owens Corning, blade manufacturer LM Wind Power, and SUEZ for recycling and materials eco-design. And, of course, our academic partners and researchers, the Jules Verne research institute and the CANOE platform.

What about current generations of blades?

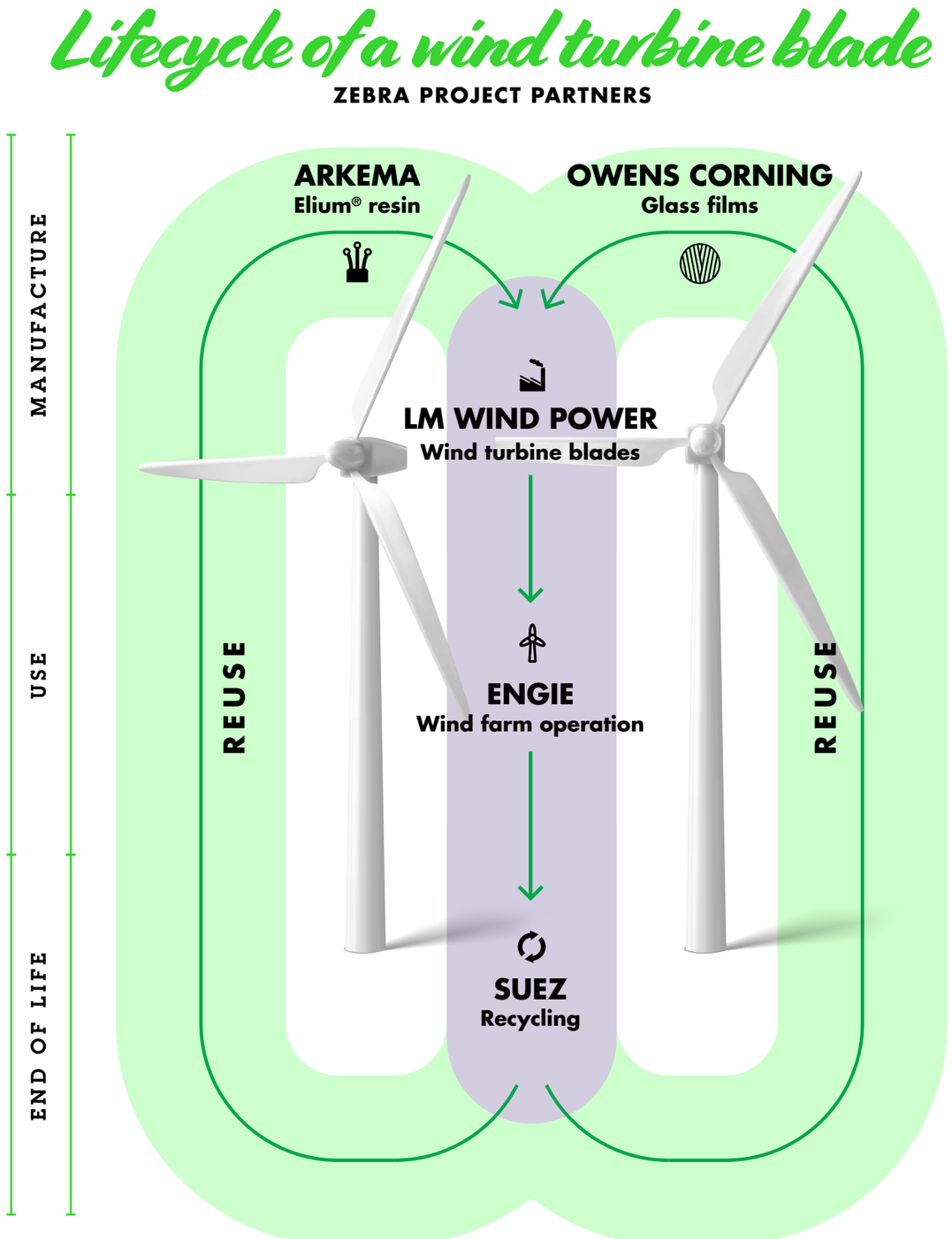
V.d.L – Blades from the generations produced up to now are made from thermoset resin, such as epoxy, and are not technically recyclable in a satisfactory way. The resin cannot be reused and the recovered fibers are not of optimum quality. The blades on their own make up just 4% of the wind turbine's weight, and the rest—the concrete base slab, steel poles, part of the nacelle—is recycled. But at ENGIE, we want to recycle more or less 100%. In 2019, we dismantled our first French wind farm dating back to 1991. With SUEZ and other partners, we managed to recycle 96% of the materials and we showed that you could recycle on an industrial level. But a solution still needs to be found for the blades, which are currently recovered in the form of solid recovered fuels.

What are the advantages of using Elium®?

V.d.L – Elium® thermoplastic resin is the missing link in blade recyclability, owing to its ability to be recycled by means of depolymerization or dissolution. This is what ZEBRA sets out to prove, while also demonstrating a similar performance to thermoset resin blades. Recyclability is therefore a central aim, but each of the project's partners needs to confirm the applicability of industrial use of this new resin.

>>

Lifecycle of a wind turbine blade



... When did you first decide to recycle blades?

Four years ago, we set up a dedicated entity at ENGIE for the development and operation of renewable energies in France. From this starting point, we received a number of questions from residents, local elected representatives and government bodies about what happens to wind turbines when they come to the end of their life. To respond to this, we launched a holistic approach with the aim of creating an economically and environmentally suitable system for dismantling wind turbines. This required the involvement of the various trades concerned—materials specialists, manufacturers, crane drivers, operators and recycling companies.

> "Elium® has the potential to allow 100% of a wind turbine to be recycled."
>
> **Vianney de Lavernée**

This resulted in ZEBRA. What are the next stages of the project?

V.d.L. – It did in a way, as other avenues were explored in terms of recycling wind turbines with thermoset composite blades. ZEBRA, meanwhile, is the result of two major stages: the development of Elium® in 2014, and a major effort early on to involve partners representing the wind power value chain. The project officially began in September 2020 and we have given ourselves three and a half years to demonstrate the feasibility of blade recycling.

What does this strategic shift in renewable energies mean for ENGIE?

V.d.L. – It is first and foremost the result of our strategic refocusing to step up the pace of energy transition towards a low-carbon economy. ENGIE is French market leader in renewable energies and No.1 in wind power, with 15% of installed capacity to date (2.6 GW). The Group also has global aims for renewable energies and plans to increase its installed capacity by 3 to 4 GW each year. This is a mature, competitive and demanding market, with high expectations for the incorporation of wind turbines into ecosystems, and for the quality of their lifecycle. That's why it's so important to work with our partners on these issues and to set up an effective system for dismantling installed wind farms, and ensure the sustainability of future wind farms thanks to innovations like Elium® and the right industrial facilities. ■

Duration of the Zebra project, from launch to completion in mid-2023:

42 months

Industrial partners and research centers:

7

In the United States, an industry transformed BY ELIUM® RESIN

Manufacture, use, end of life... the US wind power industry sees the arrival of Elium® resin as a truly disruptive innovation. This is the view of Derek Berry, engineer at the National Renewable Energy Laboratory (NREL) in Colorado and Director of the Wind Turbine Technology Area within the Institute for Advanced Composites Manufacturing Innovation (IACMI), two public organizations partnered by Arkema.

What does your collaboration with Arkema consist of?

Derek Berry – The reason why we are interested in Elium® resin is simple: at the National Renewable Energy Laboratory (NREL), a US Department of Energy laboratory, we were looking for a way to introduce recyclability into the composite materials used in wind turbines, especially the blades. For the last five years, we have been working closely with Arkema and industrial, institutional and academic partners to make this innovation happen. As part of the public-private partnership, the laboratory provides its research expertise, and evaluation and analysis equipment.

> "In addition to making wind turbine blades recyclable, Elium® resin has revolutionized how we produce them, more quickly and using less energy, as there is no need to heat the resin."
>
> **Derek Berry**

Derek Berry

How do you support your partners?

D.B. – We act on a number of levels: full-scale structural tests on small quantities of Elium® composites, such as 13-meter blades, in order to assess structural mechanical performance. Another important aspect of what we do is determining, by measuring all production and operating costs, the wind turbine's financial viability with Elium® composite blades compared to thermoset resin blades. Arkema conducts its own tests at the same time and we share our results. That gives us more credibility when offering this innovation to manufacturers and operators in the United States and worldwide.

Can you specify what Elium® resin offers?

D.B. – The initial promise is to make the part recyclable, which is a breakthrough innovation as recyclability is very hard to achieve with thermoset resin composites such as epoxy and polyester. But as brilliant as it may be, an innovation needs to be financially viable and easy to manufacture. Our tests have shown this to be the case: manufacturing blades from Elium® composite materials is similar to the process for manufacturing thermoset composites used for the last forty years. Because it's liquid, it is easy to use, but the possibility it offers of using heat-sealing also makes it very attractive to manufacturers. Heat-sealing replaces the bonding adhesive used for the blades made from thermoset composites, a costly process that makes the parts heavier, without sacrificing the wind turbine's performance.

How does this innovation support the wind power industry?

D.B. – The US wind power industry has grown steadily over the last twenty years and constitutes a financially viable and increasingly attractive energy source. Elium® resin helps to make wind power generation more competitive, effective and environmentally friendly with better management of end-of-life blades. This is essential for the United States, to support companies in the wind power value chain, such as General Electric, the parent company of blade manufacturer LM Wind Power. ■

RECYCLABLE AND COMPETITIVE ELIUM®

Resin hydrogen Tanks

Manufacturers of composite hydrogen tanks currently use thermoset resins. What is the advantage of using the new Elium® resin? Does it offer similar performance? Will the production process be improved, as well as the tank's duration and end of life? Which partners is Arkema working with to bring about this much awaited innovation in a fast-growing market?

6 million

hydrogen tanks will be produced worldwide in 2030

Estimated

342 000 T

of low-carbon hydrogen for France in 2030, with 300,000 light vehicles, 5,000 heavy vehicles, 250 trains, 1,000 boats

Sources: Hydrogen Council; FW Engineering in JEC Composites Magazine – Sept 2018; French Multiannual Energy Program (PPE).

Recyclable and competitive hydrogen tanks
MADE FROM ELIUM®

What does Elium® resin offer for composite hydrogen tanks? What stage of development are you at? Which companies are involved? Answers with Patrice Gaillard, Arkema's Scientific Director and President of CANOE.

"With Elium®, composite hydrogen tanks are stronger, recyclable and easier to produce." **Patrice Gaillard**

Patrice Gaillard

What are the development prospects of the composite hydrogen tank market?

Patrice Gaillard – Promising! Public authorities in Europe and some elsewhere in the world are making green hydrogen—produced from renewable energies—one of their priorities for diversifying their energy production sources. The aim is to reduce greenhouse gas emissions and limit climate change, and this concerns the transportation sector in particular. Hydrogen vehicle production is set to take off. In 2030 in France, we expect to have 300,000 light vehicles, 5,000 heavy vehicles, 250 trains and 1,000 boats running on hydrogen. Worldwide, it is estimated that 10 to 15 million light vehicles could switch to hydrogen by 2030.

What types of tanks are currently on the market?

P.G. – The most widely used material is epoxy resin. This thermoset resin offers excellent mechanical resistance to contain hydrogen pressure and helps to reduce the weight of the tanks, which in previous generations were made from metal. We currently have a type 4 tank made from carbon fiber and epoxy resin wound around a liner. But epoxy—like all thermoset composites—also has its disadvantages, mainly its non-recyclability.

What does Elium® resin offer for tanks?

P.G. – Recyclability and improved productivity. Being able to recycle a tank is a big plus. Currently, used epoxy resin tanks that can't be recycled are taken to landfill or recovered as solid recovered fuels, primarily for heating cement works. Elium® resin doesn't damage the tank's carbon fibers during manufacture and use. During the recycling phase, through dissolution, both the resin and the carbon fibers are recovered, and they account for 77% of the tank price. So an Elium® resin tank offers real advantages: improved productivity during manufacture, recycling, as well as impressive solidity and durability.

Exactly how is the performance of an Elium® resin tank better than that of an epoxy tank?

P.G. – We absolutely can't compromise on performance, because of safety. Mixing Elium® resin with carbon ensures that the tank is as impermeable as one containing epoxy resin. The challenge is to ensure mechanical resistance to hydrogen pressure of 700 bar. We have even managed to produce Elium® tanks that are resistant to pressure of over 1,500 bar, which means that they can contain a larger quantity of hydrogen. Elium® resin also improves the tank's mechanical properties, and extends its working life. In theory, an Elium® composite hydrogen tank needs to last for thirty years.

What stage of development are you at?

P.G. – At the trial stage, with tanks due to come onto the market in 2024. Arkema's teams at the Lacq research center in southwest France are conducting these trials with the scientific association CANOE, which has expertise in the various composite manufacturing technologies, and industrial groups involved in tank wrapping. CANOE is specifically responsible for the formulation of Elium® resins and wrapping. This is a decisive stage: by using a wrapping robot for the filament winding of carbon fibers and Elium® resin around the liner, we will pave the way for upscaling the new generation of type 5 composite tanks.

ZOOM

CANOE IN BRIEF

An organization created in 2008 in Nouvelle Aquitaine, which in 2020 comprised 45 members (researchers, engineers, technicians, etc.) working on developing advanced materials and improving manufacturing procedures for finished and semi-finished products. Its clients include 114 SMEs and large groups. Its long-standing partners are the Nouvelle Aquitaine Region and Arkema. Its many collaborations with the academic world include the Institut Polytechnique de Bordeaux, the Jules Verne research institute in Nantes, and the University of Pau-Pays de l'Adour.

What form does Arkema's collaboration with CANOE take?

P.G. – Arkema is a founding partner of CANOE and also a customer. To attract other major partners, our link with France's leading chemicals company offers real possibilities in terms of technological development of cutting edge and innovative materials. We also offer our expertise to a number of companies to help them test their finished and semi-finished products. CANOE's independence is an asset, just like our presence in the local economic and academic fabric of the Nouvelle-Aquitaine region (see inset opposite).

Do you think that Elium® resin can transform the tank market?

P.G. – Absolutely. These tanks will be easier to produce and cheaper. Compared to epoxy resin, the manufacturing phase is reduced significantly, especially wrapping and post-heat treatment. This allows the manufacturer to reduce its capital expenditure and increase production rates. When the tank comes to the end of its life, the costly carbon fibers and the resin are recovered for other uses. Elium® is great news, because the EU is tightening regulations governing industrial waste taken to landfill and increasing recycling obligations. ■

* Sources: Hydrogen Council; FW Engineering in JEC Composites Magazine – Sept 2018; French Multiannual Energy Program (PPE).

Development of elium® tank manufacturing procedures: KEY PARTNERSHIPS

To optimize the technology for manufacturing Elium® resin-based composite hydrogen tanks, Arkema draws on the expertise of world-renowned universities in the field of composites. Two specialists give their stories.

"UV activation for dramatically improved productivity."

Jacques Lalevée

"Our expertise at the Mulhouse Materials Science Institute relates to the development of new photopolymerizable resins. In the course of manufacturing composite hydrogen tanks, when wrapping carbon fibers and Elium® resin around the liner, polymerization of the resin is activated under ultraviolet light, thanks to its photosensitive properties.

This photopolymerization reaction is more advantageous than conventional polymerization procedures because it delivers a material with excellent end qualities in a shorter time—a few seconds' exposure—and under gentle polymerization conditions, which means at room temperature and with no emissions of volatile organic compounds. This helps Arkema to improve the rate at which hydrogen tanks are produced by using this photoactivation.

Arkema is a major international name in our area of research, and that is why we have been collaborating closely and actively with them for many years in Elium® and other new photosensitive resins. This collaboration extends from an advisory role to active participation, as far as in-lab theses on the issues facing the company. The work we do directly with Arkema has led to the filing of a number of patent applications to make the most of these innovations." ■

PROFESSOR JACQUES LALEVÉE, University professor and head of the "Radical and Materials Chemistry" team at the Mulhouse Materials Science Institute. Université de Haute-Alsace, Mulhouse, France
RESEARCH AREA: photopolymerization

"I want to stress the word "unique", which is being used correctly for once, because what Elium® offers is completely new."

Professeur Sung Kyu Ha

Our collaboration is fruitful and essential as hydrogen will play a very important role in the future and its supply is set to become a huge market, driving the production of composite hydrogen tanks. And action needs to be taken now. The world should not miss this unique opportunity to make hydrogen an important part of a low-carbon and safe energy future. This paradigm shift can already be seen in South Korea, where it is supported by the government and major companies such as Hyundai, and awaited by the population to power their homes, factories and cars using green electricity. That is why Arkema and its partners—researchers, clients, tank manufacturers—need to do all they can not to miss out on this opportunity to develop a production chain of high-performance, recyclable, sustainable tanks.

Hydrogen gas is often considered environmentally friendly, contributing to zero CO_2 emissions. Ironically, however, hydrogen tanks are now made of non-recyclable thermoset epoxy-based materials that eventually generate waste from vehicles at the end of their life. Hanyang and Arkema are working together to develop recyclable hydrogen tanks and to replace non-recyclable materials in hydrogen vehicles with Elium® thermoplastic composites." ■

"The Hanyang Structures and Composites Laboratory has been working with Arkema since 2014 as part of the Elium® composites characterization basic research program. Our shared objectives include studying the long-term behavior of thermoplastic composites, especially those made from Elium® resin. In 2020, we set the Center of Excellence for Elium Composites, CEEC, in order to extend the fields of innovations using this innovative material.

Our work includes measuring and characterizing the mechanical properties of Elium®/carbon composite hydrogen tanks. To do this, we simulate and replicate the manufacturing and molding of containers for automotive production. Our added value for Arkema lies primarily in the advice we provide about tank design and use of hybrid fibers. It is by improving these two areas that Arkema will obtain the certification needed to use Elium® resin in tanks on the market.

PROFESSOR SUNG KYU HA, Department of Mechanical Engineering, Director of the Hanyang Structures and Composites Laboratory. Hanyang University, Seoul, South Korea.
RESEARCH AREA: Innovative application of Composites: hydrogen tanks, wind turbines and energy storage systems.

CONSTRUCTION: ELIUM® WILL SPEED UP THE ROLLOUT

of composite concrete reinforcements

And what if using Elium® resin for concrete reinforcements was the turning point for civil engineering? In a market dominated by steel reinforcements, how does this new thermoplastic material make it easier to produce composite reinforcements and considerably improve their use on construction sites and their supply? Arkema and its partners are working with the building industry to teach it about the key advantages of Elium® composite reinforcements, which are rustproof but above all thermosettable. In other words, they can be bent directly on construction sites. This last feature—which thermoset composites do not have—is what makes all the difference!

8.5%
growth a year in composite reinforcements between 2016 and 2024

€1.02 billion
of expected total revenues for composite reinforcements in 2024 (vs. €480 million in 2015)

Source: Global Market Insights.

Thermoplastic reinforcements for concrete

THE ELIUM® REVOLUTION

Concrete reinforcements that can be bent at the last minute, and are ultra-tough and recyclable? This is the major innovation from thermoplastic reinforcement bar manufacturers in collaboration with Arkema. Explanations from Sonja Blanc, CEO of Italian technical building products manufacturer Sireg Geotech.

Why are you working with Arkema?

Sonja Blanc – Sireg Geotech has thirty years' experience in producing composite materials for the construction industry. We are a partner and a customer of Arkema and we are working together on creating the next generation of thermoplastic composite reinforcements for concrete, made from glass fibers and Elium® resin. This is a real challenge! Using these new rebars will help to ease the supply chain and provide improved mechanical performance and sustainability for buildings and structural works.

What are the market's development prospects?

S.B. – They're very promising. Currently, steel reinforcements make up most of the market. Thermoset composite rebars have so far been slow to emerge owing to a lack of standardization in their design and underdeveloped communication. But using Elium® resin changes things, and this innovation is ready to conquer the market. Within the next five to ten years, we expect fiber-strengthened composite rebars to make up 10% of the market. For us, growth of just 1% in the US market would be a considerable success, representing the delivery of 300 million meters of our fiberglass-strengthened composite reinforcements.

> "Elium® resin overcomes the production obstacles of thermoset resin reinforcements."
>
> **Sonja Blanc, Sireg Geotech CEO**

What does Elium® resin offer for thermoplastic composite reinforcements?

S.B. – Firstly, considerable improvement in productivity at the level of the supply chain. At present, the supply chain for thermoset resin reinforcements is not very responsive and not very flexible: rebars need to be supplied in the right shape and length from the manufacturer's plant to the construction site. This can take an average of six to seven weeks and deliveries are often over long distances. The consequences of this are regular losses over this period as the construction project evolves. By using Arkema's Elium® resin, Sireg has developed a heat bending machine and a procedure that can be carried out close to or even on the construction site. The result is considerably lower transportation costs, as the reinforcements are delivered straight and flat, and there are few or no losses, as they are bent on the construction site at the last minute to the desired length and shape. Sireg Geotech advises and supports bending centers and construction companies during this stage.

Is its performance similar to that of steel reinforcements?

S.B. – Absolutely, this is vital if we want to persuade the construction industry to take up this new technology, now that the obstacle of production complexity has been overcome. I would even go further in terms of performance, as composite reinforcements do not suffer from the wear and tear that the metal can experience. For structures such as bridges—or coastal structures more exposed to corrosion—this may prove valuable in terms of safety, durability and cost: a bridge with composite reinforcements can function without maintenance costs for 100 years. Lastly, to go back to production, we can envisage including seawater in the production process for concretes that use thermoplastic reinforcements without this posing a problem.

What about their recyclability?

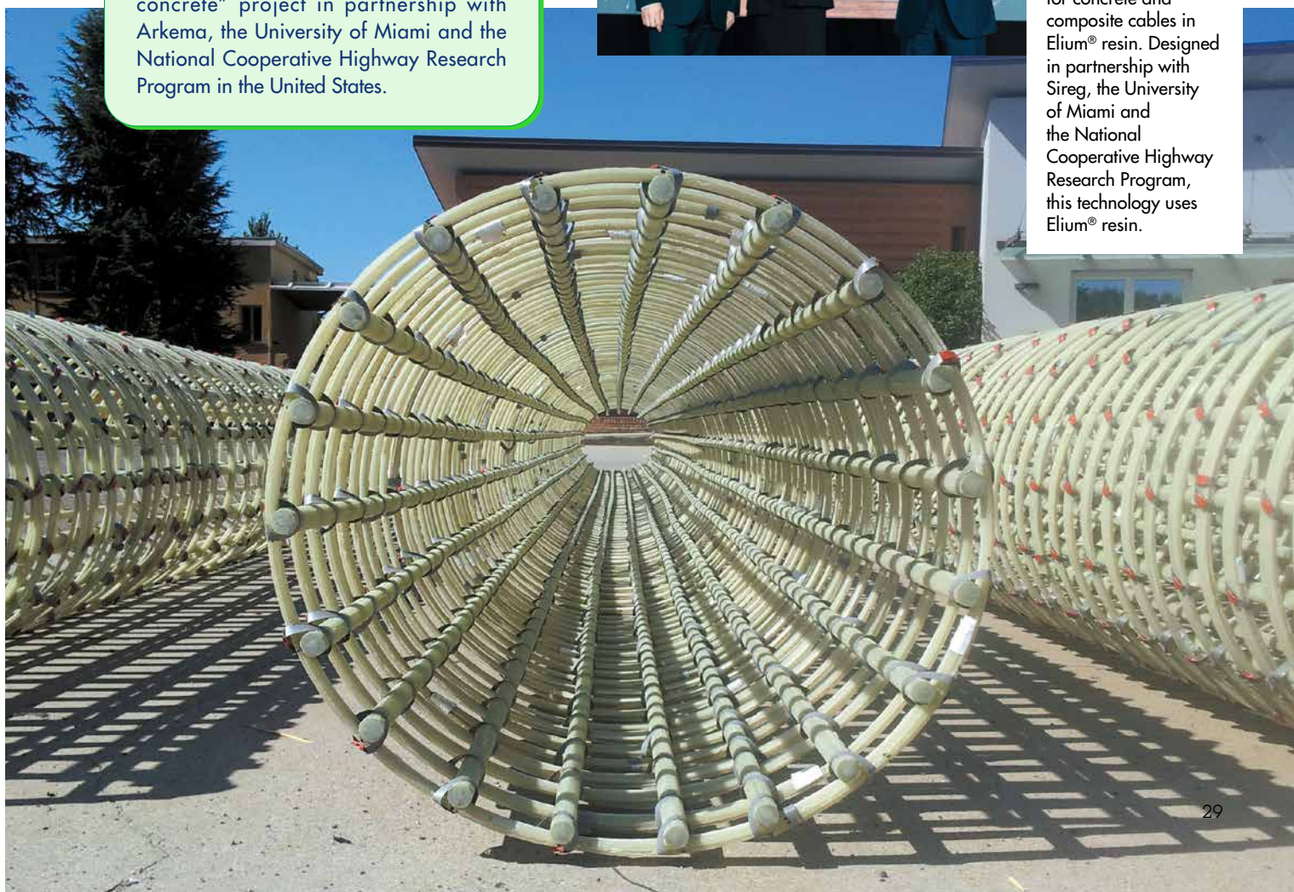
S.B. – With Elium® resin, we can claim zero-waste production. All production waste is crushed and reused for other applications. But the major contribution of this innovation is not recycling but limiting losses at the production stage thanks to the flexibility provided by shaping reinforcements closer to the construction site at the right moment.

SONJA BLANC is Chief Executive Officer of SIREG GEOTECH. Since 2009, she has strengthened the Group's R&D and driven forward its international expansion. Sireg Geotech specializes in products in thermoplastic, thermosettable and composite materials for ground consolidation during tunnel excavation, for the reinforcement and restoration of infrastructures, and damaged historic buildings. Sustainability and taking account of environmental concerns are central to its strategy. Its R&D efforts have won a number of awards over the last few years, including the JEC Innovation Awards in Paris in 2019 in the "Constructions & Infrastructure" category for its "Bendable thermoplastic composite reinforcements for concrete" project in partnership with Arkema, the University of Miami and the National Cooperative Highway Research Program in the United States.

How are you working with Arkema to bring about this innovation?

S.B. – We are working together on a number of levels: in R&D, to identify the right Elium® resin formulation to give thermoplastic reinforcements the expected mechanical and durability properties; and during the manufacturing trial stage in order to perfect and improve this stage. Lastly, promotion and communication are a key aspect and the support of a worldwide composite materials expert such as Arkema is essential in convincing the civil engineering community of the relevance of this breakthrough innovation. ■

In 2019, at the JEC Innovation Awards, Arkema and SIREG were winners in the "Construction" category for the development of reinforcement bars for concrete and composite cables in Elium® resin. Designed in partnership with Sireg, the University of Miami and the National Cooperative Highway Research Program, this technology uses Elium® resin.



Composite reinforcements; between standardization and innovation: A COMBINED EFFORT

Elium® resin used in composite reinforcements has triggered a chain of innovations. In order to concretize and maximize this impact, Arkema is working closely with its university and industrial partners.

"By making it possible to bend composite reinforcements at distributors' or manufacturers' facilities, Elium® resin opens up decisive prospects for the industry."

Antonio Nanni

We are at the tipping point for rolling out fiber-reinforced polymer reinforcements for concrete. Construction professionals need a solution to the problem of corrosion in steel reinforcements. The composites industry has the opportunity to contribute its power of innovation and technological design. But to succeed, it needs to demonstrate the performance of these new types of reinforcements and show that their production can be scalable and competitive.

Using thermoplastic composite reinforcements as a viable alternative to steel reinforcements is an obvious choice in aggressive environments such coastal areas or when used with aggregates with high salt content and significant changes in temperature. Weather conditions can speed up the deterioration of concrete. But we need to be able to supply and manufacture this new generation of more resistant, effective and durable reinforcements efficiently for it to stand a chance of being adopted.

My role as a professional and independent researcher at the University of Miami is to help Arkema to identify the opportunities and constraints of these technologies, as well as testing, optimizing and validating its products, and contributing to the development of market standards. I am involved in the technical committees of a number of US and international organizations developing specifications for materials, test protocols, design guidelines and codes. Guidelines and specifications currently concern composite reinforcements using epoxy resin or vinyl ester, but we are thinking about including other materials such as Elium® resin, on the basis of their performance." ■

ANTONIO NANNI, Professor and Director of the Department of Civil, Architectural and Environmental Engineering, University of Miami, United States

RESEARCH AREA: construction materials (advanced composites and concrete), structural performance and industrial applications, including their inspection and renewal, with a focus on the sustainability of buildings and civil infrastructures

"I firmly believe that we have managed to present a concept that will overcome any remaining reservations: a technology comprising a bending procedure at a competitive cost and delivering high-performance thermoplastic composite reinforcements."

Ronald Müller

"From the outset, Arkema has demonstrated considerable interest in the technology developed by our high-tech start-up. In general, we focus on the production of semi-finished products for the construction sector, such as fiber-strengthened thermoplastic rods, tubes and strips. This includes fiberglass thermoplastic composite reinforcements, for which we are developing a bending technology. Our aim is to share our expertise to help companies that want to develop bendable reinforcements or make their reinforcements more flexible.

In this regard, Elium® resin opens up a number of possibilities: its mechanical properties are equivalent to those of epoxy resin, but it is unique in terms of additivation. Its highly fluid nature means that a variety of particles can be added and will be uniformly distributed in the finished product, the properties of which can be changed easily. It can be bent, welded, injected into a mold and melted, among other options. I think that all these advantages counterbalance a potentially higher cost than that of other thermoset resins.

I firmly believe that we have managed to present a concept that will overcome any remaining reservations: a technology comprising a bending procedure at a competitive cost and delivering high-performance thermoplastic composite reinforcements. Arkema is working with us on developing this concept, which we intend to present in July 2021." ■

RONALD MÜLLER, founding director of industrial equipment manufacturer Carbon Armors GmbH (Plochingen, Germany)

€33.3bn

Leisure sailing market in 2020

4.1%

annual growth between 2020 and 2027, with a market worth €44.7 billion in 2027

Source: Grand View Search

SAILING: RECYCLING *opens up new opportunities*

With a fleet of sailboats whose hulls and masts are not currently recyclable, the leisure sailing market is looking for ways to make boat building more responsible in response to increasing societal expectations. Elium® resin is a material that could revolutionize their production and end of life without any cost to performance. Arkema has been striving for years to deliver this innovation to sailboat manufacturers, thanks to the lessons learned on the trimaran it sponsors and which uses its materials.

Key dates

2007 – Creation of boatbuilder and ocean racing team Lalou Multi by Lalou Roucayrol

2013 – Start of sponsorship of the racing team by Arkema and technical partnership

2017 – Arkema 3 Mini 6.50 takes to the water

2020 – Arkema 4 Multi50 trimaran takes to the water

"Building a sailboat in recyclable thermoplastic composite is a world first."

Lalou Roucayrol

on track for recyclability with ELIUM® RESIN

Skipper Lalou Roucayrol and his Lalou Multi racing team have been involved in the Elium® resin story from the beginning. With the creation of the Arkema 3 prototype, a monohull whose hull and deck are entirely made from Elium® and the new Arkema 4 multi-50, a true floating laboratory that also draws on the strengths of this resin, he gives us his expert view of a material that could revolutionize sailing.

"Within the Lalou Multi team, we work with Arkema engineers from the Lacq research center. They help us to design, build and improve our racing boat models. Our collaboration goes beyond sponsoring the team, and it is a privilege as a professional skipper to be able to interact with the people who make the materials. It is within this framework that we have been trialing Elium® resin since production began in 2014. In the space of six years, we have clearly identified the very attractive prospects of using this material in sailing.

It all began with Arkema 3, a mini 6.50 built in 2016 with a view to being used in transatlantic racing. Apart from the mast and appendages like the keel, rudder and foils, the entire boat was made using Elium® resin, including the hull and the deck. This was the very first prototype sailboat made using this material, and the challenges were considerable: would the parts be as solid as the thermoset resin composites currently on the market? Would sailing performance be the same? This journey into the unknown was even more exciting given that Elium® resin promised something new compared to thermoset resins such as epoxy, polyester and vinyl ester, namely recyclability. Because when you think about the end of life of thermoset composite boats—they are non-recyclable and end up being crushed, taken to landfill or recovered in the form of solid recovered fuels.

Our many trials have proved conclusive. Arkema 3 has demonstrated equivalent mechanical performance to our epoxy models, the top end of thermoset resins. Elium® resin even offers a slight advantage: it is slightly more resilient to the impact of waves, chunks of wood, etc., and returns to its original shape without losing its mechanical qualities in terms of energy recovery. Once performance is established, the boat's end of life needs to be taken into consideration, and Elium® resin stands out as revolutionary for the sailing industry and even shipping vessels.

On the back of these encouraging results, we have designed and built Arkema 4, another trimaran prototype using Elium® resin. The aim was to show the market that

"Producing racing yachts responsibly without compromising over performance."

the technology was viable from A to Z, as well as the exceptional and unique recyclability of this resin. We made 30% of the parts from recycled Elium® resin. The arm molds, for example, were made from Elium®-based composite materials. They were cut and then crushed before the depolymerization and purification stages, which allowed the monomer to be recovered. This was used to formulate a new "recycled" Elium® resin with unchanged properties. The regenerated resin was introduced into the construction process to create new composite parts. This is the case for the cockpit, the deckhouse* and part of the front outrigger arm fairing, areas where resistance to impact are valuable, and which were made using recycled resin.

This world first was achieved in late 2020 and was a turning point. Use of this material in yachts is now taking off but it could also be used in commercial boats such as cargo boats, making them lighter with an aluminum hull and a superstructure** made from Elium® composite material. The outlook is therefore very encouraging for our industry, which will be able to begin sustainable production once it has got used to this new resin."

*All parts located above the hull (deck, gangway, helm etc.).
**Superstructure on the deck of a vessel corresponding to the cabin "roof".

ARKEMA 4 MULTI50: FROM DREAM TO REALITY!

Be the first to see the film of the genesis of the Arkema 4 Multi50 project: from dream to reality!

Elium® is in the running with
NORTHERN LIGHT

Using natural fibers and environmentally sustainable resins such as Elium®, Fabio Bignolini and Andrea Paduano, founders of Italian start-up Northern Light, hope to revolutionize the sailing sector with technological innovations allowing raw materials to be reused and waste to be reduced. Their dream is to solve one of the sector's biggest problems: composite boats abandoned when they reach the end of their life, stuck in shipyards, ports or in the countryside.

Which parts of your boats are made using Elium® resin?

Fabio Bignolini & Andrea Paduano – The hull, deck and the structures are made from natural fibers, recycled carbon and Elium® Resin. This helps to make our boats 90% recyclable. Currently, the traditional yacht and racing fleet is made from a non-recyclable mix of glass fiber and thermoset table resins.

Is recyclability your main advantage?

F.B. & A.P. – Absolutely! We are both young; we created our start-up Northern Light just over a year ago, and we are sensitive to the advantage of recyclability. Elium® resin, which has been an integral part of the entrepreneurial project since it was created, is the solution. Eco-design requires recyclability, sustainable materials and reduced energy consumption at the production stage.

What are the challenges relating to this innovation?

F.B. & A.P. – Clearly persuading our clients that our models deliver the same performance as the traditional models they know made from thermosettable resins. This means resistance, rigidity, etc. This is a huge challenge as we are the first to offer it on the market. That's why we want to test out one of our models in racing. If the trials are conclusive, professional skippers will validate and give credibility to our choice of options and materials, primarily Elium®.

What does Northern Light offer?

F.B. & A.P. – Two boats are soon to come out of our workshops: Ecoprimus, a small dinghy for children, and Ecoracer 769, our 9-meter sport yacht that will compete in regattas. The Ecoprimus will be on the water in May; the first prototypes are already out. We're all young but we have big ambitions. We plan to build other eco-designed models, such as a 10-meter yacht and a small foiler. Our sights are set on the mass yachting market.

"We are offering something new, basing the design of our boats on recyclability."

Fabio Bignolini and Andrea Paduano

Northern Light and Arkema: a sustainable partnership?

F.B. & A.P. – Yes, because of the importance of Elium® resin for our boats, but that's not all. Arkema is also helping us to design Elium® resin hull production molds, still with the same idea, and we are planning a partnership to develop new recyclable materials. Arkema is a source of inspiration as the company designed the very first prototype using Elium® resin, the Arkema 3 Mini 6.50, a demonstration model built four years ago with skipper Lalou Roucayrol's Lalou Multi shipyard.

*Foiler: monohull boat that uses the dynamic support of several foils (submerged wings or level, streamlined and submerged airfoils) as a replacement for or in addition to the Archimedean mode of the hull or hulls.

FABIO BIGNOLINI Head of operations at Northern Light, co-founder of the sailing team, winning yachtsman in the European and Italian ORC (Offshore Racing Congress) championships.

ANDREA PADUANO Technical director of Northern Light and yachtsman.

GLOSSARY

A

Additivation: Putting additives into a product.

C

CMR: substances that are Carcinogenic, Mutagenic and Toxic for human reproduction.

F

FRP (Fiberglass Reinforced Polymer) Rebar: A term used in construction to describe reinforcements used in concrete, made of plastic composite and glass fibers.

I

Initiator: chemical compound that initiates the polymerization reaction under the action of a catalyst, heat or UV emissions.

J

JEC World: the world's largest trade fair dedicated to composite materials and their applications. It is attended by all the big names in the industry involved in innovation, business and exchanging ideas, and awards are presented for innovations.

M

Monomer: molecule that, by means of successive linkages with identical or different molecules, creates a polymer structure.

P

Photopolymerizable: molecular transformation (polymerization, reticulation or depolymerization) under the action of light, often ultraviolet.

PMMA: PolyMethylMethAcrylate

Polymer: heavyweight molecule, generally organic or semi-organic (e.g. wood, collagen, starch, thermoplastic materials, elastomers, etc.).

PVDF : polyvinylidene fluoride resins and copolymers. These present a high level of stability and durability in extreme environments (high temperatures, abrasion, chemical aggression) and smoke and flame-retardant properties.

R

Reactive thermoplastic resin: based on polymerization of the caprolactam monomer, used to make polyamide 6. This is a complicated procedure requiring anaerobic conditions (no oxygen) and no humidity, for which polymerization is not robust.

S

Solid recovered fuels: materials made mainly from wood, paper, card and plastics from waste generated by economic activities. They are not recycled owing to the lack of dedicated facilities. They are taken to landfill or recovered in incineration or co-incineration plants to produce heat and/or electricity for industry, partially or fully substituting for fossil fuels.

SMC: Sheet Molding Compound is used for compression molding—often of large parts—where higher mechanical resistance is required. SMC is a mix of polyester resin, inert fillers, reinforcing fibers, catalysts, dyes and inhibitors, releasing and thickening agents. SMC can be used for molding complex shapes. First-rate mechanical properties, excellent surface aspect and a high level of electrical insulation make SMC the ideal material for Class A automotive body panels, high resistance electrical parts and various structural parts.

V

VOC: Volatile Organic Compounds are characterized by their high level of volatility and disperse easily into the atmosphere, workshops and offices, creating a direct and indirect impact on living beings and the environment. They include many substances that can be biogenic (natural) or manmade.

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