

THE THREAD THAT CHANGED THE WORLD

*How Carbon Fibre Was Invented, Nearly Sank
Rolls-Royce, and Quietly Wove Itself Into Everything:
The Science That Changed the World — Presents*

By

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TABLE OF CONTENTS

Introduction — The Black Thread	4
Part One — The Discovery	7
The Accident at Parma	8
The Newspaper in Osaka	13
The Farnborough Process	18
Part Two — The Fall and the Rise	23
The Chicken and the Jet Engine	24
Japan Takes the Thread	29
The Price of Strength	33
Part Three — Making the Thread	37
Inside the Furnace	38
The Rivals	42
Part Four — The Material Escapes the Lab	46
Racing Certainty	47
Weighing Nothing	51
Wind and Water	54
Wings of Black	57
Reaching for Orbit	61
The Invisible Everywhere	64
Part Five — The Fence Comes Down	68
From Secret to Commodity	69
The Watched Thread	74
The Problem of Forever	77

INTRODUCTION — THE BLACK THREAD

Somewhere near you, right now, there is almost certainly a piece of it. In the frame of a bicycle or the shell of a laptop; in the wing of the aircraft you last flew on, the blade of the wind turbine turning on the hill, the fishing rod in the shed, the running blade on a sprinter, the hull of a boat, the barrel of a telescope, the casing of a rocket climbing out of the atmosphere. It is black, and it is woven, and it is stronger for its weight than almost anything humans have ever made. Most people could not tell you where it came from, who invented it, or that it very nearly destroyed one of the proudest engineering companies in the world before it made anyone rich.

This is the story of carbon fibre — a single thread, and how it wove itself into everything.

It is a strange and human story, and it does not run in a straight line.

It begins by accident, in three different countries at almost the same time, in the hands of inventors who mostly did not know of one another. It passes through a national humiliation so severe that a government had to step in and nationalise a company to stop it collapsing. It is nearly abandoned as too expensive and too temperamental to ever be worth the trouble. And then, slowly, over decades of patient and unglamorous work — much of it in Japan, far from where it was invented — it becomes first the secret weapon of aerospace and motor racing, then the boast of expensive bicycles, and at last so ordinary that you can buy it by the roll.

There is a particular reason to tell this story now, and it is the reason this book exists at all. For most of carbon fibre's life, the ways of making it were owned. The processes were patented, the know-how was guarded, and for decades the material was, in a real sense, private property — a thing you needed a licence, and a fortune, to make. But a patent does not last forever. It is a bargain with time: twenty years of monopoly in exchange for telling the world exactly how the thing is done, and then the monopoly ends and the knowledge belongs to everyone. One by one, the founding patents of carbon fibre have expired. The secret has become common property. And a material that was once an aerospace exotic, restricted and expensive and watched over by governments, has become — quietly, and almost without anyone noticing — a commodity of the ordinary world.

That arc, from guarded secret to everyday commodity, is the deep shape of this book, as it is the shape of every technology in the end. But carbon fibre wears the arc more vividly than most, because it happened fast, and because the stakes along the way were so high: a bankrupt company, a nationalised industry, a race won, an aircraft reimagined, and now a growing mountain of the stuff that no one is quite sure how to dispose of.

A note on what this book is. It is a history written for the curious, not a textbook. Where I have had to choose between precision and readability, I have chosen readability, and the specialist will find simplifications they could quarrel with. The people and dates and companies are drawn from the public record as I understand it; the patents named are real and can be read by anyone. But the point of the book is not the footnotes. The point is the thread — where it came from, what it cost, and how it came to be everywhere.

Let us follow it back to the beginning, to a laboratory in Ohio, and a scientist who found something he was not looking for.

PART ONE — THE DISCOVERY

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CHAPTER 1

THE ACCIDENT AT PARMA

Almost every great material has a founding accident, a moment when someone looking for one thing found another and had the wit to notice. Carbon fibre has at least three such moments, in three countries, within a few years of one another — but the first, and the one that proved a thing was even possible, happened in 1958 in a laboratory at the Union Carbide research centre in Parma, Ohio, in the hands of a young scientist named Roger Bacon.

Bacon was not trying to invent a wonder material. He was trying to make a careful and rather obscure measurement. His subject was graphite — the soft, grey, familiar form of carbon that makes the "lead" in a pencil — and specifically the conditions of temperature and pressure at which it passes between its solid, liquid, and gaseous states, the so-called triple point. It is the kind of patient, exacting work on which science quietly depends, the sort of experiment that

fills a career and changes nothing. To make his measurements, Bacon was vaporising carbon in an electric arc at ferocious temperatures and pressures, and then examining what condensed inside the apparatus as it cooled.

And what he found, growing in the residue, were whiskers.

THE WHISKERS IN THE RESIDUE

They were slender almost beyond belief — some as long as an inch, but no thicker than a fraction of a hair, perhaps a tenth of its diameter. Under examination they proved to be something remarkable: filaments of nearly perfect graphite, in which the carbon atoms were arranged in long, clean, orderly sheets running the length of the whisker, with scarcely a flaw to interrupt them. And because they were so nearly perfect, they had properties that ordinary graphite does not. They were, for their weight, extraordinarily strong and extraordinarily stiff — closer to the theoretical strength that the carbon-carbon bond promises than anything anyone had managed to make before.

To understand why a scientist would stop and stare at a few carbon whiskers, you have to understand what engineers spend their lives wanting, and why carbon is so tantalising a candidate to give it to them. The eternal dream of the engineer is strength and stiffness without weight. A material that is strong but heavy — steel — will

hold up a bridge, but it will not fly well, and everything you build from it must fight its own mass. A material that is light but weak is good for very little. The prize, always, is something both strong and light, and nature is stingy with that combination.

Carbon, in principle, ought to be able to deliver it. The bond between two carbon atoms is among the strongest in all of chemistry, and carbon is a light element, low on the periodic table. Arrange carbon atoms into long, orderly chains and sheets, all pulling in the same direction, and you should get a material of almost miraculous strength for its weight. The maddening problem, for the better part of a century, was that no one could make bulk carbon behave that way. Graphite in the lump is soft and crumbly for a precise reason: its strong atomic sheets are only weakly held to one another, so they slide apart easily — which is exactly what makes graphite useful as a pencil and a lubricant, and useless as a structural material. The strength was there, locked at the level of the atoms, but it could not be got out.

Bacon's whiskers were the first time anyone had got it out. Here, at last, was carbon arranged so that its atomic strength ran the length of a fibre — a thread of nearly perfect graphite, all its bonds pulling one way, strong out of all proportion to its almost nothing weight. It was, in the truest sense, a proof of concept: a demonstration that the dream material could exist, that carbon could be coaxed into a form that harnessed its hidden strength. It was a genuine revelation.

It was also, for the moment, almost completely useless.

A REVELATION YOU COULD NOT USE

The trouble with the whiskers was everything about how they were made. They grew one at a time, in tiny quantities, in the residue of an experiment run at extreme temperature and pressure, at a cost per useful gram that beggared belief. They proved that high-strength carbon fibre was possible in principle; they offered not the faintest suggestion of how to make it in the lengths, quantities, and prices that engineering requires. You cannot build an aircraft, or a fishing rod, or so much as a tennis racket, out of inch-long whiskers grown by the milligram in a laboratory furnace. The gap between "this can exist" and "this can be manufactured" is where most wonderful ideas go to die, and for a while it looked as though carbon fibre might die there too.

Union Carbide did not give up on it. The company would go on to pursue carbon fibre in earnest, but by a different and more practical route: taking rayon — the same regenerated-cellulose material used to make textiles — and carbonising it, heating the rayon fibre until almost everything but its carbon had been driven off. This at least started from a real, spinnable, mass-produced fibre. But the early rayon-based carbon fibre was a disappointment against the promise of the whiskers: the process was inefficient, wasteful, and the resulting fibre retained only a modest fraction of carbon and only a

modest fraction of the strength Bacon's perfect filaments had shown was theoretically there. Union Carbide would later commercialise improved carbon fibres, and Bacon's own name would stay attached to the field he had opened — years afterward he would be granted a patent, US 3,716,331, for a process for making carbon fibres of high stiffness, and he would in time be honoured as one of the founding figures of the entire material.

But the accident at Parma, for all its importance, had only proved that the destination existed. It had not found the road. The whiskers said carbon fibre is possible; they did not say here is how to make it cheaply, by the mile, from something you can buy by the tonne. That crucial second insight — the one that turned a laboratory marvel into the seed of a global industry — was taking shape at the same time on the other side of the world, in the mind of a Japanese scientist who, the story goes, was set on the path by an article in a newspaper.

CHAPTER 2

THE NEWSPAPER IN OSAKA

The second beginning of carbon fibre happened in Japan, and its genius lay in starting not from something exotic but from something utterly ordinary: an everyday acrylic textile fibre, the humble stuff of jumpers and cheap clothing.

The scientist was Akio Shindo, working at a Japanese government research institute at the end of the 1950s. The year was 1959 — almost precisely the moment Roger Bacon was examining his whiskers in Ohio, though neither man knew of the other's work. As the story has come down to us, Shindo's interest was sparked by a newspaper article describing early American experiments with carbon materials. Whether a single article truly lit the fuse or merely joined a train of thought already moving hardly matters; what matters is that Shindo, working independently on the far side of the planet, asked a different and far more fruitful question than anyone

had asked before. Not "how do we grow perfect carbon whiskers?" — a beautiful dead end for anyone dreaming of mass production — but something humbler and vastly more useful: "what cheap, abundant, everyday material could we start from, and bake down into carbon fibre in quantity?"

THE GENIUS OF STARTING WITH ACRYLIC

His answer was a synthetic polymer with a forbidding name, polyacrylonitrile, mercifully shortened by everyone since to PAN. It was already manufactured in enormous quantities as a common textile fibre — the acrylic in a thousand ordinary garments. And it had a hidden virtue that Shindo saw and others had missed. The molecules of PAN are built around a backbone of carbon atoms already strung together in a long, continuous chain. If you could contrive to burn away everything else — the hydrogen, the nitrogen, all the other atoms hung off that backbone — while keeping the carbon chain itself intact and aligned, you would be left with a fibre of almost pure carbon that had inherited the long, thin, oriented shape of the textile fibre you began with.

That was the whole of the insight, and it was enough to found an industry. Shindo filed a patent on it in September 1959: the use of PAN as the precursor — the starting material — for making carbon fibre. Take an ordinary acrylic thread; heat it carefully, in controlled stages, in the absence of oxygen so that it chars rather than bursts

into flame; and it transforms, molecule by molecule, into a thread of carbon. Because you began with a fibre that was already long, thin, and internally aligned, you ended with a carbon fibre that was too — and Shindo's early PAN-based fibres were markedly better than the weak rayon efforts, richer in carbon and stronger, made from a starting material you could buy cheaply and by the tonne.

This was the conceptual key that unlocked everything after. To this day, the overwhelming majority of the world's carbon fibre — the fibre in the aircraft, the turbines, the cars, the bicycles — is made from PAN, by a direct descendant of the route Shindo pointed toward: spin an acrylic precursor fibre, stretch it, oxidise it gently, and then carbonise it at high temperature until only the aligned carbon skeleton remains. Sixty years of relentless refinement have improved every step almost beyond recognition, driving the strength up and the flaws down. But the founding idea — begin with a common polymer fibre and cook it down to its carbon bones — belongs to Shindo.

THE PRECURSOR IS THE PRIZE

There is a lesson buried in this that runs through the whole history of the material, and it is worth naming plainly at the outset, because it explains a great deal of what follows. In carbon fibre, the precursor is very nearly everything. The strength, stiffness, and consistency of the finished thread are set, more than by any later flourish, by the

quality of the humble textile fibre you start with and the exquisite care with which you convert it. A single microscopic flaw introduced during spinning or oxidation becomes a point of weakness in the finished fibre, a place where it will break under load. To make good carbon fibre is, above all, to make an almost perfect precursor and then to cook it almost perfectly.

That is not glamorous knowledge. It is the accumulated, painstaking, often tacit understanding of how to spin the acrylic just so, how to hold it under exactly the right tension while it oxidises, how to raise the temperature through exactly the right stages in exactly the right atmosphere — knowledge won over decades of trial and failure, lodged in the furnaces and the hands and the habits of a company rather than in any single document. And it is precisely because this mastery is so deep and so hard to copy that a mere handful of companies would come, in time, to make most of the world's carbon fibre, and to hold that position for half a century even after the founding patents had expired. We will return to that paradox; it is one of the most interesting things about the material.

Shindo had found the door and shown that it opened onto a real, manufacturable material. But like Bacon before him, he had not walked through it to an industry. Turning the PAN insight into a fibre strong and stiff enough to tempt the makers of aircraft — and into a process that a nation's champion companies would license and build upon — would take a third team, in a third country, at one of the

great temples of aviation. And it would take, very shortly after, a disaster.

CHAPTER 3

THE FARNBOROUGH PROCESS

The third beginning of carbon fibre took place in England, at the Royal Aircraft Establishment in Farnborough — the government research centre where much of the nation's aeronautical science was done, a place woven deep into the history of British flight. It was here, in the early 1960s, that carbon fibre was turned from a promising material into one that an aircraft engineer might seriously want to hold in his hand.

The names most associated with the breakthrough are those of William Watt, Leslie Phillips, and William Johnson. Working with the PAN precursor whose promise Shindo had identified, they cracked the problem that stood between a merely interesting carbon fibre and a genuinely useful one: how to process the precursor so that the finished thread was not only carbon, but carbon of high strength and high stiffness together — the specific combination that aviation

craved. And the crux of their answer lay, as so often with this material, in the fine detail of the cooking.

TENSION, AND THE ORDERING OF THE ATOMS

Their key discovery was the importance of tension. If the PAN fibre was held stretched — kept under tension — during the early stages of heating, its long molecular chains were prevented from relaxing, curling, and tangling as they otherwise would. Held taut, the chains stayed aligned along the length of the fibre, and so the carbon structure that formed as the other atoms burned away inherited that alignment: orderly, oriented, its strong atomic sheets running the way you wanted the strength to run. Tension during oxidation, careful staging of the temperature, control of the surrounding atmosphere — these were the elements of what became known as the Farnborough process, and together they produced a British carbon fibre of a quality that made the aviation world sit up.

It is a recurring truth of this material, and worth pausing on, that its secrets are secrets of process rather than of substance. There is nothing exotic about the ingredients — an acrylic fibre and heat. The magic is entirely in the how: the tension, the timing, the temperatures, the atmosphere. This is why the knowledge was so valuable and so guardable, and why, decades later, the recipe could be public and the mastery still scarce. The Farnborough team had not discovered a new substance. They had discovered how to persuade a

common one to arrange itself into something extraordinary.

BRITAIN'S BRIEF LEAD

For a moment — and it was only a moment — Britain led the world in this strategic new material. The process was owned, on the nation's behalf, by the National Research Development Corporation, a government body whose particular job was to take publicly funded inventions and turn them into commercial licences for British industry. The NRDC licensed the Farnborough process to a small group of national champions: Rolls-Royce, the great aero-engine maker; Courtaulds, the textile firm that understood how to spin fibres; and Morganite, a maker of carbon and graphite products. A home-grown breakthrough in a strategic material, protected by patents, handed to the nation's best companies, arriving at the exact moment the aerospace industry was hungry for anything that could make aircraft lighter — it was, on paper, as bright a prospect as British industrial science had produced in years.

It is worth dwelling on just how irresistible the promise looked to an aircraft engineer, because that promise is what led directly to catastrophe. Everything about flight is a war against weight. Every kilogram removed from an aircraft is fuel saved, or payload gained, or range extended; and because structures must be built to carry their own mass, weight saved in one place cascades into weight saved everywhere. A material that offered the strength and stiffness of

metal at a fraction of the weight was, to an aviation designer, very close to magic. And Rolls-Royce, then locked in the enormous gamble of designing a new engine to power a coming generation of wide-bodied airliners, saw in carbon fibre the answer to one of that engine's central problems.

THE SEDUCTION OF THE STRONG, LIGHT THREAD

That engine was the RB211, and the temptation carbon fibre offered it was specific and enormous. At the very front of a large jet engine sits the fan: a wheel of big, curved blades that pulls in the vast river of air the engine needs to breathe. Those blades are heavy, and because they spin at tremendous speed, their weight punishes the design twice over — once as weight in itself, and again in the massive, heavy structure required to contain that spinning mass and to survive a blade coming loose. Lighten the fan blades, and you save weight not only in the blades but in the disc that holds them, the casing that surrounds them, the shafts and bearings that carry them, in a cascade running the length of the engine. Carbon fibre — strong, stiff, astonishingly light — seemed the perfect material for the most weight-critical component in the whole machine. Rolls-Royce designed the RB211's great fan blades to be made of it, in a proprietary form they named Hyfil, and staked a crucial part of a critically important engine on the new British wonder-thread.

It was an audacious bet on a material barely out of the laboratory —

a bet that the strength which had so impressed everyone would hold up under the brutal realities of the front of a running jet engine. And it was about to go catastrophically, nationally, ruinously wrong. Not because carbon fibre was a bad idea; the entire remainder of this book is the story of how right the idea turned out to be. It went wrong because the idea was still a young one, its behaviour under sudden violent impact not yet understood or mastered — and because a fan blade at the front of an airliner's engine must survive a particular ordeal that the laboratory had not adequately reckoned with. To understand what happened next, and why it broke one of the proudest names in British engineering, we have to talk about birds.

PART TWO — THE FALL AND THE RISE

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CHAPTER 4

THE CHICKEN AND THE JET ENGINE

A jet engine, over its working life, will swallow birds. This is not a rare misfortune but a statistical certainty: fly enough aircraft through the sky where birds live, and sooner or later a bird will be drawn into an engine's intake at hundreds of miles an hour. The engine cannot always keep running through it — but it must, at the very least, fail safely, without the fan bursting apart and flinging blades like shrapnel through the wing or the fuselage. And so, before any new engine is allowed to carry passengers, its makers must prove that it can survive a bird strike. The test is exactly as brutal and as literal as it sounds: bird-sized masses — for many years, actual chickens — are fired into the running engine at flight speed to see what the fan does when something soft and heavy hits it at full song.

In the spring of 1970, Rolls-Royce fired a chicken into the RB211's beautiful new carbon-fibre fan. And the fan did the one thing it must

never do.

THE BLADES THAT SHATTERED

The Hyfil blades had, until that moment, been a triumph. They had passed test after test. They were gloriously light, exactly as strong as the engineers had measured them to be, and they performed beautifully under the steady, predictable loads of ordinary running — the huge but smooth forces of a fan spinning at speed. Everything about them, under the conditions the designers had focused on, worked. But carbon fibre carries a weakness that its very strength can hide, and the bird-strike test found it with a single blow.

The weakness is this. Carbon fibre is prodigiously strong when it is pulled steadily along the grain, along the direction of its fibres — that is what it is for. But it can be brittle, and poor at absorbing a sudden, sharp, concentrated impact delivered across the grain. A material can be far stronger than steel in tension and yet shatter like glass when something strikes it hard sideways. And a chicken hitting a fan blade at flight speed is precisely, catastrophically, such a strike: a soft, dense, several-pound mass slamming into a thin spinning blade edge-on, a sudden violent transverse blow of exactly the kind carbon fibre was least ready to take.

The blades shattered. Where a titanium blade would have dented, bent, and deformed — absorbing the blow by giving way and staying

more or less in one piece — the carbon-fibre blades broke apart. It was a comprehensive failure of exactly the kind that certification testing exists to catch, and it was ruinous for the programme, because there was no easy fix. The whole point of the carbon fan had been to save weight, and the only proven alternative that could pass the test was titanium — heavier, far more expensive, and, worst of all, arriving now, late, into a programme that had no room for any of those things. Rolls-Royce was forced to tear out the centrepiece of its engine and redesign it in metal.

THE WEIGHT THAT SANK A COMPANY

It is difficult to overstate what that failure set in motion, because the RB211 was not some side experiment that could be quietly written off. It was the engine on which Rolls-Royce had staked its entire future — chosen to power the Lockheed L-1011 TriStar, a major new American wide-bodied airliner, in a vast fixed-price contract that had seemed a coup when it was signed. The company had committed to delivering a specified engine, at a specified weight and price, by a specified date. The collapse of the carbon-fibre fan blew a hole straight through all three. The titanium redesign added weight the engine could not afford to carry, cost money the company did not have to spend, and consumed time in a programme that was already straining every resource Rolls-Royce possessed.

The costs spiralled past the point of survival. In February 1971,

Rolls-Royce — one of the most prestigious names in all of British engineering, maker of aero engines and of the finest motorcars in the world, a byword for national excellence — was forced into receivership. It was a genuine national shock, the kind of event that makes front pages and shakes governments. And the British government, unwilling to let a strategic aircraft-engine maker collapse and drag its international contracts and its workforce down with it, did something remarkable: it stepped in and nationalised the aero-engine business, taking Rolls-Royce into public ownership to keep it alive and to see the RB211 through to completion. The engine, in the end, was finished. It went on to become a great and long-lived success, powering aircraft for decades and spawning a family of engines that helped restore the company's fortunes. But that triumph came only after the company that built it had been broken and rescued by the state.

THE LESSON WRITTEN IN CARBON

There is no more vivid cautionary tale in the whole history of this material, and it is important to be precise about what it does and does not teach — because it is easy to draw the wrong lesson from it.

It does not teach that carbon fibre was a mistake. The entire rest of this book is the story of how completely right the underlying idea turned out to be, of carbon fibre going on to remake aviation and much else besides. The blades failed not because the material was

bad but because it was young: its behaviour under sudden impact was not yet understood, the design and manufacturing knowledge to make an impact-tolerant carbon component did not yet exist, and Rolls-Royce reached for it too far and too fast, placing it at the one point in the entire engine — the fan face, first to meet any bird — where the single weakness it still had was the single weakness that mattered most.

That is the real lesson, and it recurs throughout the history of technology: a material or an idea can be genuinely revolutionary and still be dangerous to bet the company on before it is ready. The pioneers who reach for a technology first are so often its casualties. Rolls-Royce bet on the thread before the world was ready for it, and the thread nearly destroyed it. The companies that would eventually grow rich on carbon fibre would mostly be others — arriving later, having watched and learned from this very failure, and having done the patient decade of work that turns a temperamental laboratory promise into a dependable industrial material. And a great deal of that patient work was, by now, happening not in Britain at all, but on the other side of the world.

CHAPTER 5

JAPAN TAKES THE THREAD

Here the centre of gravity of our story shifts, and shifts for good, from West to East. Carbon fibre had been born, in its three near-simultaneous beginnings, in America, Japan, and Britain. But the country that would come to make most of the world's supply, and to hold the commanding heights of the industry for the next half-century, was Japan — and, above all others, one company: Toray.

THE LONG PATIENCE OF TORAY

Toray Industries was, at its heart, a textile company — a maker of synthetic fibres — and that turned out to be exactly the right kind of company to master carbon fibre, for a reason that goes to the nature of the material. Carbon fibre is, at bottom, a textile problem wearing an aerospace disguise. It begins its life as a spun polymer fibre, and,

as we have seen, almost everything about the quality of the finished carbon thread is determined by the quality and consistency of that precursor fibre and the care of its conversion. A firm that had spent decades learning the deep, unglamorous art of making acrylic thread perfectly, reliably, at industrial scale, was far better placed than almost anyone to learn to make the precursor for carbon fibre perfectly — and then to master the furnaces that turned it into carbon.

In 1970 — the very year the Hyfil blades were shattering in Britain — Toray moved to acquire the practical rights to the PAN-based process pioneered by Shindo and developed in Japan, and set about industrialising it in deadly earnest. In 1971 the company launched a commercial carbon fibre it called T300, with a strength and consistency that opened real engineering possibilities and that would, in various improved forms, remain a workhorse of the industry for decades. And then Toray did the thing that actually wins in materials, the thing that is easy to describe and extraordinarily hard to do: it kept going, patiently, unglamorously, for decades. It refined the precursor and refined it again. It refined the oxidation, the carbonisation, the furnaces, the handling, the sizing, every step of a long and finicky process, year upon year, driving the strength higher and the flaws lower and the consistency tighter, building a depth of manufacturing know-how that competitors found almost impossible to match.

WHY A FEW FIRMS CAME TO OWN THE WORLD'S SUPPLY

The result is one of the more striking and less appreciated facts about this most modern of materials: its supply is concentrated in remarkably few hands. Toray grew to become the largest carbon-fibre maker on earth, commanding something like a third of global capacity, and together with a small number of other producers — several of them also Japanese — a mere handful of companies came to make the great majority of the world's carbon fibre. This is not an accident of commerce or a quirk of markets. It is a direct consequence of the material's deepest nature.

The knowledge required to make excellent carbon fibre reliably, at scale, and cheaply is deep, tacit, and accumulated only over decades. It is not the kind of knowledge that can be written down in full and handed over; much of it lives in the calibration of specific furnaces, in the accumulated instinct of experienced engineers, in ten thousand small solved problems that never appear in any patent. This is the crucial thing, and it complicates the neat story of patents and expiry that runs through this whole series. A patent can be read, and, once expired, freely used by anyone. But there is a vast distance between knowing that carbon fibre is made by carbonising PAN under tension and being able to actually make world-class carbon fibre. It is the distance between owning a recipe and running a great restaurant. Even as the founding patents lapsed and the basic method became public knowledge, the tacit mastery stayed concentrated in the firms

that had spent fifty years acquiring it — which is precisely why, to this day, the most demanding customers in the world still buy most of their carbon fibre from that same short list of companies.

THE MATERIAL COMES OF AGE

Under Toray and its peers, through the 1970s and into the 1980s, carbon fibre grew up. It became stronger, more consistent, more predictable, and — slowly, haltingly — more available and less absurdly expensive. It was still, in this period, largely the preserve of aerospace and defence, still costly, still specialised. But it was now a real industrial material, made in genuine quantity by companies that thoroughly understood what they were doing, rather than a temperamental laboratory promise that might shatter a chicken test and take a national champion down with it. The scars of the RB211 were healing, and the knowledge that had been missing in 1970 was steadily being won.

The stage was set for the material to begin escaping the narrow, rarefied world of aerospace and finding its way, application by application, into the wider one. But there was still one great barrier holding it back from that wider world, and it was not technical. It was the price.

CHAPTER 6

THE PRICE OF STRENGTH

Before we follow carbon fibre out into the world, we have to reckon with the thing that kept it confined for so long: the cost. For most of its early life, carbon fibre was extravagantly, almost comically expensive — a material quoted not in the pounds-per-tonne of ordinary industrial stuff but at figures that placed it, weight for weight, in the neighbourhood of precious metals. In its early days the price ran to hundreds of dollars a pound. At those numbers, the question facing any engineer was never simply "is carbon fibre better than the metal?" — it almost always was — but the far harder "is it so much better that it is worth paying many, many times the cost of the metal it would replace?"

For most purposes, for a long time, the honest answer was no.

WHERE COST DOES NOT MATTER

But there are particular corners of human activity where the ordinary arithmetic of cost is suspended — where a pound of weight removed is worth almost any price — and it was in those corners that carbon fibre first made its home and earned its keep. The most important, by far, was aerospace, and especially the military and space programmes within it, where the value of lightness is so extreme, and the customer so often a government spending for strategic advantage rather than for profit, that a fantastically expensive material can still be the entirely rational choice. On a fighter aircraft, a spy satellite, a missile, a rocket, a pound of weight saved can be worth a truly enormous sum — in performance, in range, in payload, in the difference between a mission that is possible and one that is not. And so, for its first two decades, carbon fibre lived very largely in that rarefied realm: state-sponsored, defence-driven, aerospace-bound, and priced entirely beyond the reach of ordinary life.

This is why, to almost everyone alive through the 1960s and 1970s, carbon fibre simply did not exist as part of the world they could touch. It was real, and it was already quietly transforming what was possible at the frontier of flight — but it was locked behind a price that kept it out of daily life as completely as if it had been a state secret. In this it followed a pattern as old as technology itself, in which the most powerful new capabilities begin their lives affordable only to militaries, governments, and monopolies, and reach ordinary people only much later, if at all.

THE LONG ROAD DOWN

The history of carbon fibre from this point onward can be read, in one light, as a long and halting journey down the price curve — the slow descent from hundreds of dollars a pound toward something an ordinary manufacturer, and eventually an ordinary consumer, could actually afford. And each stage of that descent unlocked a new tier of possible uses, like a rising tide reaching new ground. Too expensive for anything but a satellite or a fighter; then cheap enough for a racing car, where a fortune buys a fraction of a second and lives are on the line; then cheap enough for an elite bicycle bought by a wealthy enthusiast; then for a premium component in an ordinary car; then, at last, for a camera tripod, a fishing rod, a phone case, a chair. Every single step down the price curve was also a step outward into a wider world, and the chapters that follow are, in a sense, the story of that descent told through the objects it reached.

What drove the price down was, in the first instance, exactly the patient manufacturing improvement of Toray and its peers — the decades of grinding refinement that squeezed cost out of the process a little at a time. But there was a second engine of the descent, one that would only engage fully at the very end of our story, and it is the engine this whole series is really about: the expiry of the patents, the escape of the guarded know-how into the public domain, and the entry of new producers who could at last make the material without paying anyone for the privilege of knowing how. The price of

strength, in other words, was destined to fall — and as it fell, the thread would finally be free to weave itself into everything. But before we follow it out into the world it would conquer, it is worth pausing to understand the thread itself: how this black filament is actually made, and what rivals it had to beat to earn its place.

**PART THREE — MAKING THE
THREAD**

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CHAPTER 7

INSIDE THE FURNACE

We have talked a great deal about carbon fibre being made, and about the mastery of making it, without ever quite watching it happen. It is worth pausing here, before we follow the thread out into the world it conquered, to stand in the factory and see the black filament actually being born — because the process is at once astonishingly simple in its ingredients and astonishingly demanding in its execution, and understanding it explains almost everything else about the material: why it costs what it costs, why so few can make the best of it, and why a strong, light thread is, at bottom, a triumph of controlled heat.

WHITE IN, BLACK OUT

The thing that arrives at the start of the line does not look like the future of aerospace. It is a creamy-white ribbon of ordinary-looking

synthetic fibre — the PAN precursor, thousands of individual filaments gathered side by side into a flat band called a tow, wound onto great spools like industrial cotton. This white ribbon is the raw material, and, as we have seen, its quality quietly determines the quality of everything that follows. Then it begins its journey through the furnaces, and it is a journey of transformation as complete as any in industry: what goes in white and soft and ordinary comes out black and stiff and extraordinary.

The first stage is oxidation, sometimes called stabilisation. The white tow is drawn slowly through long ovens filled with hot air, at a few hundred degrees — hot, but not yet the true fire to come. And crucially, all the while, it is held under tension, kept stretched, exactly as the Farnborough team discovered was essential, so that its long molecular chains cannot relax and tangle but stay combed out along the length of the fibre. In these ovens the precursor slowly changes chemically and turns black, becoming infusible — no longer able to melt — so that it can survive the far greater heat ahead. It emerges from oxidation dark and stable, transformed but not yet carbon.

Then comes the fire proper. The blackened tow passes into the carbonisation furnaces, where the temperature climbs to a thousand degrees and beyond, and where — this is vital — there is no oxygen at all. The furnaces are filled with an inert gas, usually nitrogen, so that the fibre does not burn but instead chars, driving off almost

every atom that is not carbon: the hydrogen, the nitrogen, the rest, all cooked away as gas, leaving behind the aligned carbon skeleton and little else. The fibre shrinks and darkens and densifies, and what emerges is carbon fibre — a thread that is now the better part of pure carbon, its atoms locked in the oriented sheets that give it its strength. For the very stiffest grades, the fibre goes hotter still, into graphitisation furnaces at extreme temperatures that perfect the ordering of the carbon further, buying more stiffness at more cost.

THE FINISHING, AND THE PRICE OF HEAT

Two more quiet steps matter. The raw carbon fibre, straight from the furnace, is chemically standoffish — resin does not stick to it well — and carbon fibre is almost never used alone; it is used embedded in a resin to make a composite. So the fibre is given a gentle surface treatment to make the resin grip it, and then coated with a thin protective "size" that keeps the delicate filaments from fraying and abrading as they are handled. Only then is the finished thread wound onto its final spools, ready to be woven into cloth, laid into moulds, or wound onto shapes.

Look at the whole line and you will notice what is not in it: no exotic elements, no precious ingredients, no rare earths. The inputs are an acrylic fibre and enormous quantities of carefully controlled heat. That is the deep truth of carbon fibre, and it explains two things at once. It explains the cost, because running fibre slowly through

hundreds of metres of precisely regulated ovens, at high temperature, under exact tension, in a controlled atmosphere, hour after hour, is enormously energy-hungry and enormously capital-hungry — the furnaces are the expense, not the material. And it explains a small, sharp irony we will meet again at the end of this book: that a material celebrated for making aircraft and turbines more efficient is itself born of a great deal of energy, cooked into being in furnaces that run day and night. The magic of the thread is not in what it is made of. It is in the fire, and the patience, and the control.

CHAPTER 8

THE RIVALS

It is tempting, having followed carbon fibre from an accident to an industry, to imagine it as the lone hero of a story about strong, light materials. It is not. Carbon fibre is one member of a whole family of advanced fibres that arrived to challenge metal in the second half of the twentieth century, and it did not defeat its rivals so much as find its own particular corner of the world and rule there. To understand what carbon fibre is, it helps to understand what it beat — and, just as often, what it works alongside.

GLASS, THE HUMBLE WORKHORSE

The oldest and by far the most widespread of the reinforcing fibres is glass. Glass fibre — fibreglass — is made by drawing molten glass into fine filaments, and it has been reinforcing plastics since well before carbon fibre was practical. It is not as strong as carbon, and,

more importantly, it is nowhere near as stiff — a fibreglass structure flexes far more than a carbon one for the same weight. But glass fibre has an overwhelming advantage that has kept it dominant in sheer tonnage to this day: it is cheap. Extraordinarily cheaper than carbon. And so glass owns the vast middle ground where good-enough strength at low cost matters more than ultimate performance — boat hulls, storage tanks, building panels, wind-turbine blades in their bulk, the circuit boards inside every electronic device, the insulation in the walls. If carbon fibre is the exotic aristocrat of reinforcing fibres, glass is the workhorse that quietly does most of the actual work in the world.

KEVLAR, THE TOUGH ONE

The second great rival came from the DuPont laboratories, out of the work of the chemist Stephanie Kwolek, who in the 1960s discovered a family of remarkable polymers that could be spun into fibres of astonishing toughness. The most famous is Kevlar — an aramid fibre, light and phenomenally resistant to being pulled apart or struck. Kevlar is the fibre of bulletproof vests, of cut-resistant gloves, of high-strength ropes and cables, of protective gear of every kind, because its particular genius is in absorbing energy and resisting impact without shattering. But Kevlar has its own limits: it is superb in tension but comparatively weak in compression, and not as stiff as carbon. So it, too, found its niche — the niche of toughness and impact protection — rather than displacing carbon

from the niche of stiffness. There were other contenders as well, now mostly forgotten: boron fibre, stiffer even than early carbon but so hideously expensive and difficult that it faded from all but the most specialised uses.

WINNING A NICHE, NOT A WAR

Here is the real lesson of the rivals, and it is a lesson about how materials actually succeed. They almost never win outright. They win niches. Glass fibre won cheap-and-cheerful reinforcement, where cost rules. Kevlar won toughness and ballistic protection, where absorbing a blow is everything. And carbon fibre won the specific, precious niche of maximum stiffness and strength for the least possible weight, wherever a customer could afford to pay for it — structural performance at the frontier. Each fibre is, in its own domain, the right answer, and the others are wrong.

And more often than the tidy story admits, they do not compete at all but cooperate. Many real composite structures are hybrids — carbon fibre for stiffness where stiffness is wanted, glass for cheapness where performance can be relaxed, aramid for toughness where impact threatens — layered together in a single part, each fibre doing the job it does best. The world of advanced materials is less a battlefield with one victor than an ecosystem of specialists. Carbon fibre's triumph was never to vanquish the others. It was to become the undisputed champion of one supremely valuable quality —

lightness with strength and stiffness — and then, as its price fell, to carry that quality out of the laboratory and the aerospace hangar and into the wider world. And the first place the freed, understood thread truly went to prove itself in public was a racetrack.

**PART FOUR — THE MATERIAL
ESCAPES THE LAB**

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CHAPTER 9

RACING CERTAINTY

Motor racing is a business of small margins and large consequences. A tenth of a second a lap, compounded over a race and a season, decides championships; the failure of a few grams of material at two hundred miles an hour decides whether a driver walks back to the pits or is carried from the wreck. It is a world obsessed, above almost everything else, with weight — and, crucially, one where a great deal of money will very happily be spent to remove even a little of it. If ever there were a natural home for an outrageously expensive material that was stronger and lighter than anything else on earth, it was Formula One. And in 1981, carbon fibre and Formula One met in a way that changed both of them permanently.

THE CAR THAT WAS ONE BLACK TUB

The man who made it happen was John Barnard, a designer working

for the McLaren team, and his idea was genuinely radical for its time. Racing-car chassis were then built, as they had been for years, from aluminium — sheets folded, bonded, and riveted into a "tub," the central structure that held the driver, carried the engine and suspension loads, and formed the cockpit. Barnard proposed to throw that established approach away and build the central structure of the car — the monocoque, the survival cell wrapped around the driver — as a single moulded shell of carbon-fibre composite. Not carbon fibre used as a panel here and a bracket there, but carbon fibre as the very backbone and body of the car: one continuous, moulded, black tub.

It was, to many in the sport, a frightening proposition. Carbon fibre was still exotic and still shadowed, in some engineers' memories, by the brittleness that had shattered on a chicken-strike test only a decade before. And here was a man proposing to seat a driver inside the stuff and hurl him around a circuit at lethal speeds. The manufacturing was so new and so demanding that McLaren turned to the aerospace industry for help in actually making the shells — the expertise to mould such a complex, load-bearing carbon structure barely existed anywhere else. The car was the McLaren MP4/1, and it took to the track in 1981 as the first Formula One car built around a carbon-fibre composite monocoque. It won its first Grand Prix that same year, the British Grand Prix, in the hands of John Watson. But it was not a victory that made carbon fibre's case most powerfully. It was a crash.

PROVEN AT MONZA

Later in that 1981 season, at Monza — the fast, unforgiving Italian circuit — John Watson lost control of his MP4/1 at the Lesmo corners and went off at around 140 miles an hour. The accident was violent enough that the car was torn in two: the engine and gearbox were ripped clean away from the back of it. To the many sceptics who had warned about carbon fibre, this was the moment they had predicted — the moment the black tub would explode into a cloud of dust and take its driver with it.

It did not. The carbon-fibre monocoque, the survival cell around Watson, held together. As the engine and gearbox were torn off and the car destroyed around him, the cell that mattered stayed intact — and Watson climbed out and walked away from a 140-mile-an-hour crash that, in an older aluminium car, might well have killed or crippled him. The car looked like wreckage; the driver was unhurt.

Barnard would later put it with an engineer's satisfaction: the crash "disproved all the knockers." There had been, he recalled, plenty of people at the start who had said that a carbon-fibre monocoque, when it hit something, would simply go up "in a black cloud of dust." Monza proved the opposite. Properly designed, carbon fibre did not merely survive a crash — it protected its driver better than the metal it replaced, absorbing the enormous energy of the impact by breaking apart in a controlled, progressive way while keeping the

survival cell around the human being whole. The material once feared as treacherously brittle had just demonstrated, in the most public and dramatic arena imaginable, that in the right hands it was not only lighter and faster but genuinely, life-savingly safer.

That was the turning point for carbon fibre's reputation, and it is hard to overstate its importance. Within a few years, every serious Formula One car had a carbon-fibre monocoque, and the technology Barnard's team had pioneered became the foundation of modern racing-car safety — the carbon survival cell that has since saved a long roll-call of drivers from crashes that would once have been fatal. Motor racing had done two great things for the material at once. It had proven, before a watching world, that carbon fibre was superb and safe when used well, banishing the shadow of the RB211. And through the vast sums that racing spends chasing speed, it had begun to build up the industrial art of designing and manufacturing complex, high-performance carbon-fibre structures. The exotic aerospace thread had found a second home — a glamorous, fast, and highly visible one — and from there it began to spread.

CHAPTER 10

WEIGHING NOTHING

From the racetrack, carbon fibre began to seep out into the wider world of sport, and the path it took is the path by which many expensive technologies reach ordinary life: through the things that enthusiasts will pay a premium for. And few enthusiasts on earth will pay more, for less weight, than cyclists.

THE FEATHERWEIGHT MACHINE

A bicycle is, among other things, a machine for converting a human being's strictly limited power into forward motion, and every gram of the machine's own weight is a gram the rider must drag up every hill for the entire life of the bike. Serious cyclists have always been obsessive about lightness to the point of caricature — drilling holes in components to shave grams, paying extravagant sums for parts a fraction lighter than the ones they replace. Carbon fibre offered them

something close to a dream come true. Here was a frame material both lighter and, in skilled hands, stiffer than the steel and aluminium they were used to — and, better still, one that could be moulded into almost any shape and "tuned" in a way metal tubes never could: made to flex a little for comfort where flex was wanted, and to stay ruthlessly rigid where power was being put down, all within a single moulded frame.

As the price of the material came down and the techniques for moulding it into frames matured, carbon-fibre bicycles travelled the same road within their own small world that the MP4/1 had travelled in racing. First they were exotic rarities ridden by a few. Then they became the choice of the professional peloton, the fastest riders in the world. And then, as always happens, the aspirational amateurs followed, wanting to ride what the professionals rode, and carbon became the default material of the serious bicycle. For a great many people, a bicycle frame was the very first piece of carbon fibre they ever held in their own two hands — and lifting a good one for the first time produced a small, genuine astonishment, the strange sensation of holding a whole bicycle that seemed to weigh almost nothing at all.

THE DEMOCRATISATION BEGINS

The bicycle matters in this story out of all proportion to its size, because it marks a genuine threshold. Up to this point, carbon fibre

had been the near-exclusive preserve of institutions — air forces, space agencies, defence ministries, racing teams with budgets to match small nations. The bicycle was where it first became a true consumer product: a thing that an individual person could choose to save up for, buy, ride, admire, and show off to their friends. And with the bicycle came the beginnings of the material's peculiar mystique in popular culture — the sense of carbon fibre as the very marker of the high-tech, the premium, the cutting edge. The distinctive black weave, left visible and lacquered rather than painted over, became a thing people paid extra precisely so that others could see they had it.

That mystique would spread far beyond bicycles, into every product that wished to signal performance and quality. Fishing rods and tennis rackets, golf-club shafts and hockey sticks, skis and archery bows and violin bows, camera tripods and spectacle frames and watch cases, and eventually the interior trim of expensive cars and the shells of expensive gadgets. The visible carbon weave became a design language in its own right — a visual shorthand, instantly understood, for light, strong, expensive, advanced. But it began, for most ordinary people, with sport, and very often with a bicycle: the first affordable, ownable, liftable piece of the aerospace thread, light enough in the hand to make you laugh.

CHAPTER 11

WIND AND WATER

If Formula One taught carbon fibre to be safe and the bicycle taught it to be owned, it was the world of wind and water — of sailing and the sea — that pushed the material to some of its most spectacular extremes, and did so largely out of the public eye. Sailing, like motor racing, is a sport obsessed with weight and stiffness, and for many of the same reasons; and like motor racing, at its highest level it commands budgets vast enough to buy the very best the material can offer.

WEIGHT ALOFT

Consider first the mast of a racing sailboat. A mast is a long pole standing high above the deck, and weight up there, far from the boat's centre of gravity, is uniquely punishing — it makes the boat roll and pitch and want to tip, so that every kilogram saved aloft is

worth several saved low in the hull. A tall, light, stiff mast is therefore worth almost any price to a serious racing sailor, and carbon fibre delivers exactly that: a spar that stands high and stays stiff against the enormous pull of the sails, at a fraction of the weight of aluminium. Carbon masts, and then carbon hulls, and carbon booms and rigging, transformed competitive sailing as thoroughly as the black tub transformed Formula One.

THE BOATS THAT FLY

Nowhere was this pushed harder than in the America's Cup, the oldest and most lavishly funded trophy in sailing, where teams backed by great fortunes chase tiny advantages with something close to aerospace intensity. Cup boats became, in effect, carbon-fibre machines — their hulls, masts, and structures built from the black weave to be as light and stiff as human ingenuity and enormous money could make them. And then came the most dramatic step of all: foiling. Engineers realised that with structures stiff and strong and light enough, a sailboat could be lifted clear out of the water altogether, rising up on slender underwater wings — hydrofoils — to skim above the surface with the drag of the water almost gone, reaching speeds that would have seemed impossible a generation before. Those foils, thin and highly loaded and utterly unforgiving of failure, are carbon fibre through and through. The sight of a large sailing yacht flying above the sea on carbon foils is one of the purest spectacles the material has produced — a direct, visible consequence

of a thread strong and stiff enough to hold a boat in the air.

THE EVERYDAY WATER

And, as always, the exotic bled into the ordinary. The fishing rod, bending and springing without breaking, became a carbon-fibre product for the same reasons the mast did. So did oars and paddles and canoe hulls, kayak shafts and the masts of ordinary dinghies. The sea and the river, like the racetrack and the road, quietly filled with the black thread — most of it never seen, all of it doing the same simple, valuable job of being strong and stiff and weighing almost nothing.

CHAPTER 12

WINGS OF BLACK

While carbon fibre was making its glamorous, visible way through motor racing and sport, it was also — far more quietly, and in the end far more consequentially — coming home to the very industry that had first reached for it and been so badly burned: aviation. The lesson of the RB211 had been thoroughly learned. Carbon fibre would return to aircraft not as a reckless bet on an immature material at its single most vulnerable point, but as the mature, mastered, patiently understood foundation of an entirely new kind of flying machine.

THE COMPOSITE AIRLINER

For decades after Rolls-Royce's disaster, aircraft remained overwhelmingly made of aluminium, and carbon fibre crept back into them only gradually and cautiously — first in non-critical

fairings and panels, then in secondary structures, edging step by careful step toward the load-bearing heart of the aircraft as engineers' confidence and, above all, their manufacturing skill grew. Each success built the knowledge and the trust for the next. And then, in the 2000s, came the great leap. Boeing designed a new airliner, the 787 — the "Dreamliner" — with carbon-fibre composite not as a supporting player but as the primary structure of the aircraft: the wings, and the fuselage itself, the very body of the machine, built largely from the black weave rather than from metal. Around half of the 787, by weight, would be composite material, much of it carbon fibre. Airbus followed with its A350, built on the same conviction, with a composite fuselage of comparable extent — something on the order of half its weight in composites as well. For the first time, large passenger aircraft carrying hundreds of people across oceans would be, in their very bones and skin, carbon fibre.

The motivation was, at root, the same one that had tempted Rolls-Royce forty years earlier — weight, and everything that flows from it — but now realised safely and at vast scale. A lighter aircraft burns less fuel, and in commercial aviation fuel is the difference between profit and loss, and increasingly the difference between environmentally acceptable and unacceptable. But a carbon-fibre fuselage brought more than lightness. Because composite does not fatigue and corrode the way aluminium does, it allowed design choices that improved the experience of flying itself: a cabin that could be kept at higher humidity and lower altitude-equivalent

pressure without the metal-fatigue penalty that would impose on an aluminium tube, and larger windows in a structure strong enough to carry them. The whole shape of the modern, efficient, long-range airliner — how far it can fly, how little it can burn, how it feels to sit inside for fourteen hours — is bound up intimately with the properties of the material it is made from.

THE MANUFACTURING REVOLUTION

To build an entire airliner out of carbon fibre demanded solving manufacturing problems of enormous difficulty and expense. It meant learning to lay down and cure vast composite structures — whole wings, whole barrel sections of fuselage — reliably, repeatably, and safely, to the merciless standards that civil aviation rightly demands, where a hidden flaw is not a warranty claim but a catastrophe. This was carbon fibre not as a moulded racing tub or a bicycle frame, but as primary aerospace structure at industrial scale, produced by the thousand, and mastering it took years and fortunes and more than a few painful setbacks along the way. But it was mastered. And in being mastered, it hauled the entire global industry of carbon-fibre manufacturing up to a new level of scale and capability. The sheer, sustained demand from the composite airliners became one of the great engines of the material's production, helping to build the manufacturing capacity that would, in turn, help bring the price down for everyone else — the cyclists and the tripod-makers and all the rest.

The wings of black were, in the end, the full vindication of the original dream — the very dream that Rolls-Royce had reached for a generation too soon and been broken by. Aviation had always wanted a strong, light material with which to remake flight itself. Forty years after a fired chicken shattered the first attempt and sank a great company, aviation had that material at last, mastered and trusted, and it built its newest and most advanced aircraft out of it, from the spars of the wings to the skin of the fuselage.

CHAPTER 13

REACHING FOR ORBIT

If aviation is a war against weight, spaceflight is that war carried to its absolute extreme. To lift a single kilogram from the surface of the Earth into orbit costs a fortune in fuel and engineering — for much of the space age, a sum that made every gram genuinely precious. Nowhere in all of human activity is lightness worth more than on a rocket, and so nowhere was carbon fibre more welcome, more quickly, almost regardless of cost. The material born to lighten aircraft found in the rocket its most demanding and most grateful customer.

THE LIGHTEST POSSIBLE STRUCTURE

A rocket is, to a first approximation, a thin shell wrapped around an enormous quantity of fuel, and every kilogram of that shell is a kilogram of payload it cannot carry to orbit. Carbon-fibre composite,

offering structural strength and stiffness at the lowest possible weight, is close to an ideal material for it, and it found its way into rocket structures of every kind: the interstages that connect a rocket's segments, the fairings that shroud the payload at the nose, and — importantly — the pressure vessels that hold gases and propellants, wound from carbon fibre to contain great pressure in a shell of minimal mass. Satellites, too, came to lean on it heavily, and for an additional reason beyond mere weight: carbon-fibre structures can be made extraordinarily stable against changes in temperature, barely expanding or contracting as a spacecraft swings between the ferocious heat of sunlight and the deep cold of shadow. For a satellite carrying delicate instruments that must stay in precise alignment, a structure that holds its shape whatever the temperature is worth a very great deal.

THE REUSABLE AGE

In the modern era of spaceflight, as private companies have driven relentlessly to lower the cost of reaching orbit — above all by making rockets that can fly, land, and fly again — composites have become more central still. A reusable rocket must be light enough to be economical yet tough enough to survive not one flight but many, along with the stresses of landing, and carbon-fibre structures are part of how that balance is struck. There is even a specialised cousin of the material for the very hottest places: carbon-carbon, carbon fibre in a carbon matrix rather than a resin, which can withstand

blistering temperatures and turns up in rocket nozzles, the leading edges of spacecraft that must survive re-entry, and the brakes of high-performance aircraft, where ordinary materials would simply melt.

The thread that began as an inch-long whisker in an Ohio furnace now helps carry human beings and their machines off the planet altogether, and — increasingly — helps bring the rockets home to be flown again. It is a long way from a pencil-lead measurement to the structure of a spacecraft, and carbon fibre travelled the whole of it in a single lifetime.

CHAPTER 14

THE INVISIBLE EVERYWHERE

By the turn of the twenty-first century and the decades that followed, carbon fibre had done the thing that only truly successful materials ever do: it had begun to disappear. Not vanish, but disappear in the deeper sense — becoming so widespread, so various, and so ordinary that people simply stopped noticing it, until it was everywhere and remarked upon nowhere. This chapter is a brief tour of that ubiquity, because the sheer, sprawling range of it is the surest possible measure of how far the thread had travelled from an inch-long whisker in an Ohio furnace.

THE TURNING BLADES

Consider, first, the wind turbine. The great blades of a modern wind turbine are among the largest single moving structures that human beings build — some of them longer than a football pitch — and

they face a punishing three-way engineering demand. They must be long, to sweep a greater circle and catch more wind and so generate more power. They must be light, or they will tear themselves apart under their own enormous weight as they swing around. And they must be stiff, or they will flex alarmingly in a gust and risk striking the very tower that holds them up. Long, light, and stiff, all at once: it is almost a definition of what carbon fibre is for. As turbines grew ever larger in the global drive for cheaper renewable electricity, carbon fibre found its way into their blades — particularly into the long spars that run their length — and the material born to make aircraft lighter became, quietly, a working part of the machinery of the energy transition.

BODIES AND BLADES

Consider, too, the human body remade. Carbon fibre became a defining material of advanced prosthetics — most visibly the curved running blades that allow amputee athletes to sprint, storing and returning the energy of each stride in a way no rigid limb ever could, so that the prosthetic gives something back to its wearer with every step. It became the stuff of lightweight wheelchairs that a person can lift with one hand, of orthotic braces, of medical and dental devices that must be strong and light and, increasingly, transparent to the X-rays and scanners that metal would block and confuse. A material conceived for engines and airframes found a second and quieter calling in giving individual human beings back their movement and

their independence.

THE EVERYDAY EXOTIC

And consider, finally, the long — almost comic — inventory of ordinary objects into which the once-priceless thread has now been woven. Camera tripods and drone frames; fishing rods and golf-club shafts; tennis rackets and hockey sticks and skis and archery bows; violin bows and loudspeaker cones; spectacle frames and watch cases; the trim of cars and the shells of laptops and phones; the hulls of boats and the masts of racing yachts; and the structures of the very rockets now climbing to orbit and, increasingly, flying themselves back to be flown again. In every one of these the same three properties are quietly at work — strength, stiffness, lightness — and in every one of them the material that was once locked behind a price only a government could pay now sits, unremarked, in the hands of ordinary consumers, most of whom have no idea quite what it is they are holding, or where it came from, or what it once cost.

This is exactly what it looks like when a material finishes escaping the laboratory: not a single triumphant application that everyone can name, but a thousand small ones that nobody bothers to, a quiet saturation of the whole manufactured world. The exotic has become the everyday. And it is worth being clear that this transformation — from the priceless, restricted aerospace secret of the 1960s to the commonplace consumer material of today — did not happen by

patient manufacturing improvement alone. It happened, in its final and decisive phase, for the reason this whole series exists to trace: because the fences came down.

PART FIVE — THE FENCE COMES DOWN

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CHAPTER 15

FROM SECRET TO COMMODITY

For nearly all of the story we have followed, carbon fibre has been, in a real and enforceable sense, owned. Not the element carbon, of course — no one owns that — but the ways of making the fibre: the precursor chemistry, the processing under tension, the furnace recipes, the countless hard-won refinements accumulated over decades. Much of that was protected by patents; much of what the patents did not cover was guarded jealously as trade secret, held tight inside a small handful of companies. To make carbon fibre, for a very long time, you needed either a licence or the deep, tacit, decades-in-the-winning mastery that only a few firms possessed. The material was, in effect, a fortress — with a moat of patents and a keep of secret know-how.

This chapter is about the walls of that fortress coming down.

THE TIMER RUNS OUT

A patent, as this whole series keeps insisting because it is the whole point, is a bargain struck with time. In exchange for publishing exactly how an invention works — laying it out in full, for anyone in the world to read — its owner receives twenty years of exclusive right to it. And then, on a specific and unremarkable morning, that right expires, and the invention passes into the public domain, free from that day forward for anyone at all to use. The founding patents of carbon fibre — Shindo's precursor insight, the Farnborough process, Bacon's high-modulus method, and the great wave of refinements that followed through the 1960s, 1970s, and into the 1980s — were, by their very nature, filed decades ago. And one by one, each on its own quiet morning, they have run out their twenty years and lapsed into the commons.

The consequence is quietly enormous. The basic science and much of the core process of making carbon fibre is now, simply, public knowledge that anyone is free to use — published, unpatented, there for the reading. The recipes that were once fortresses have had their gates thrown permanently open, their protection long expired. The barrier to entering the carbon-fibre business is no longer permission. No one needs a licence to make carbon fibre by the fundamental routes any more. The only remaining barrier is capability — the money and the accumulated skill to actually build the furnaces and run the difficult process well. And that, too, has spread.

THE COMMODITY ARRIVES

As global demand climbed and the fundamental patents expired, new producers entered the field — reaching well beyond the original Japanese and Western firms. A wave of new manufacturers, notably in China, built carbon-fibre capacity at very large scale, backed in some cases by national industrial strategy. More producers meant more supply and fiercer competition, and more competition meant falling prices. The long descent down the price curve, driven for decades by the patient manufacturing improvement of the incumbents, accelerated sharply as the material became something that more and more companies, in more and more countries, could simply make. Carbon fibre began, at last, to behave less like a guarded aerospace exotic and more like a commodity — a material you could order by the roll, in a range of grades and quantities to suit almost any purpose, at prices that would have seemed frankly impossible in the era of hundreds of dollars a pound.

This is the deepest theme of this book, and of the series it belongs to, made visible with unusual clarity in the life of a single material. A technology begins as a secret — guarded, expensive, available only to the powerful and the well-funded. It is fenced off by patents, so that its inventors can profit from their risk and their genius, and, in exchange for that protection, its inner workings are published for all the world to read. And then, inexorably, the fences come down: the patents run out their term, the guarded know-how spreads and leaks

and is independently rediscovered, new makers enter, and the price falls and falls. The secret becomes common property, and the exotic becomes ordinary, and the marvel that a generation earlier could belong only to a superpower's air force ends up in a child's kite or a commuter's bicycle. Carbon fibre has walked that entire road, from an inch-long whisker guarded in a corporate laboratory to a commodity that anyone with sufficient capital can now manufacture. The thread that was once a fortune is becoming, before our eyes and within a single lifetime, just another material.

WHAT STAYS BEHIND THE WALL

It would be too neat, and not quite honest, to say the fortress is entirely gone. The founding patents have indeed expired, and the basic method is genuinely free. But the deepest manufacturing mastery — the tacit, accumulated, furnace-by-furnace skill of making the very best fibre, the aerospace-grade thread, reliably and at the largest scale — still lives in a few firms, and it is not so easily copied, patent or no patent. The most demanding customers on earth, the makers of airliners and rockets and the finest racing machines, still buy overwhelmingly from the companies with fifty years of practice behind them. The commons has opened at the base of the mountain; a guarded summit remains.

That is, in truth, how a great many of these stories really end — not with the old leaders overthrown and their knowledge seized, but with

the floor beneath everyone raised. The basic material becomes cheap and available to all, democratised and commoditised, even as the genuine frontier stays hard and stays concentrated. The fence around the ordinary grades of carbon fibre has come down for good. The climb to the extraordinary grades is still a real climb, and only a few are near the top. Both things are true at once, and both matter.

CHAPTER 16

THE WATCHED THREAD

There is a fascinating counter-current to the story of the last chapter, and it complicates the simple picture of fences coming down. For even as commerce and expired patents have worked to free carbon fibre — to turn it into a commodity anyone can buy — governments have worked, quietly and deliberately, to keep a fence up around its highest grades. Carbon fibre is not only a wonder material. It is a strategic one, and a dangerous one, and the same properties that make it precious to an aircraft maker make it precious to people building things that nations would rather they did not.

THE DUAL-USE PROBLEM

The trouble is that a material this good at being strong and light has uses that are anything but benign. The very same high-performance carbon fibre that stiffens an airliner's wing can form the casing of a

missile or the body of a military drone. It can be wound into the pressure vessels and motor cases of rockets — including the kind that carry warheads. And most sensitively of all, high-grade carbon fibre is prized for the rotors of gas centrifuges: the fast-spinning machines used to enrich uranium, which can produce fuel for a power station or material for a bomb depending only on how far the enrichment is pushed. A centrifuge rotor must spin at tremendous speed without flying apart, which is precisely the sort of task at which strong, light carbon fibre excels. This makes the material what the security world calls "dual-use" — equally at home in a peaceful product and in a weapon — and it places carbon fibre on a very short list of materials that governments watch with real anxiety.

THE FENCE THE STATE KEEPS UP

The result is that the best carbon fibre is not, in fact, freely available to just anyone, patents or no patents. High-performance grades are subject to export controls — restricted under international arrangements designed to slow the spread of missile and nuclear technology, monitored and licensed, their sale to certain countries and certain buyers forbidden or tightly policed. A nation seeking to build an advanced carbon-fibre industry from scratch may find that the best fibre, and the machines to make it, are simply not for sale to it at any price. This is why the development of indigenous carbon-fibre capability has been, for several nations, a matter of national strategy and considerable secrecy: if you cannot buy the best

thread, and cannot buy the machines to make it, you must painstakingly learn to make it yourself — reconstructing, in effect, the very mastery that the incumbents spent fifty years acquiring.

Here, then, is a striking irony to set against the theme of this whole book. The founding patents of carbon fibre have expired, and the commodity grades have become genuinely, globally available — the fence around the ordinary material has come down. And yet, at the very top, the state has built a new kind of fence, not of patents but of export controls and national-security law, to keep the best of the material out of the wrong hands. Carbon fibre is at once democratised and controlled: free at the base, watched at the summit. The commons opened for the common grades; for the extraordinary ones, a different and more anxious kind of gate swung shut. It is a reminder that patents are not the only fences humans build around knowledge — and that some fences are put up on purpose, and meant to stay.

CHAPTER 17

THE PROBLEM OF FOREVER

There is a sting in the tail of this story, and it grows sharper and more urgent with every year that passes. The very properties that make carbon fibre such a triumph — its strength, its stiffness, its stubborn, magnificent refusal to weaken, corrode, rot, or decay — become, at the end of a product's life, a genuine curse. We have spent more than sixty years learning to make ever more of a material that is designed, in effect, to last forever and to resist very nearly everything. And now, belatedly, we are beginning to face the question we never properly asked at the start: what on earth do we do with all of it when we no longer want it?

THE MATERIAL THAT WILL NOT DIE

Consider what carbon fibre is, from the unglamorous point of view of disposal. It does not rust. It does not rot. It does not biodegrade in

any useful timeframe. And the fibres themselves are, in almost every finished product, locked inside a hard, cured resin — usually a "thermoset," a plastic that has been irreversibly set by curing and cannot simply be melted back into a workable form the way a metal or a thermoplastic can. The result is a composite that is fiendishly, deliberately difficult to take apart. You cannot melt a carbon-fibre part down and recast it, because the resin does not melt back into anything useful and the fibres are woven and tangled all through it. A carbon-fibre component that has reached the end of its life is a lump of one of the most durable materials humanity has ever made, and every property we engineered into it is now working against us: it does not want to become anything else, and it does not want to go away.

For a long time this scarcely mattered, because there simply was not very much carbon fibre in the world, and most of what existed was still in use. But that is changing, and changing fast. The wind turbines whose long light blades we celebrated a chapter ago are now, in their first great generation, beginning to reach the end of their working lives in large numbers — and their enormous composite blades are proving genuinely, expensively hard to dispose of: too big to bury easily, too tough and too bonded to recycle cheaply. By some estimates, on the order of two hundred thousand tonnes of blade material will reach the end of its service life across roughly the decade and a half from 2020 — and much of it, for want of anything better, has been going to landfill or to the incinerator.

And the turbines are only the leading edge. The first generation of carbon-fibre airliners will one day be retired. The bicycles and rackets and car parts and boat hulls will wear out and break. The mountain of end-of-life carbon fibre is only beginning to grow, and we do not yet have a good, cheap, scalable, and clean way to deal with it.

THE UNFINISHED CHAPTER

There is real and genuinely promising work under way, and it deserves acknowledgement. Researchers are developing processes to recover the valuable fibres from old composites — heating them in the absence of oxygen to burn off the resin and free the fibre, a technique called pyrolysis; or dissolving the resin away chemically, called solvolysis; or grinding the composite down mechanically for reuse as a lower-grade filler. Each approach has promise and each has drawbacks, and a recovered fibre is generally not quite as good as a virgin one. There are efforts, too, further upstream: to design composites from the very start with their eventual disassembly in mind, using resins that can be un-set and taken apart, so that a material meant to last forever at least has a plan for what happens after forever ends. And there is a slowly spreading recognition — the beginning of wisdom in these matters — that a material this durable needs an end-of-life strategy designed in from the first, not bolted on in a panic decades later.

But it is unfinished work, all of it, and it is a real and growing problem, and it would be dishonest to end this book on a note of tidy, unqualified triumph. The thread that wove itself so brilliantly into everything has left us with a genuine question that we have not yet answered: what to do with a material that, by design, does not want to leave.

THE FAR SIDE OF THE THREAD

And yet the deeper story remains what it has been all along. A strange, strong, black thread, discovered by accident and insight in three countries at very nearly the same moment; bet on too soon and too boldly in a jet engine that shattered on a bird-strike test and dragged a national champion into receivership; nurtured for patient decades by careful hands, most of them Japanese, until it grew reliable and strong; proven safe in a 140-mile-an-hour crash at Monza and vindicated at last in the wings and skin of an airliner; and then, as its price fell and its patents lapsed and its once-guarded secret became common property, woven quietly into a thousand ordinary things. That arc — the long journey from guarded marvel to everyday commodity — is the arc of very nearly every technology that ever changed the world. Carbon fibre is simply one of the clearest and fastest examples of it we have, run through in a single human lifetime, vivid enough that we can see the whole shape of it at once.

We live now on the far side of the thread, inside a world it quietly holds up: lighter aircraft, taller turbines, faster and safer cars, and countless small objects made better by its presence. Most people will never know its name, or that it was once worth its weight in silver, or that it nearly sank Rolls-Royce, or that the recipes for making it — once among the most closely guarded secrets in all of materials science — now belong to everyone alive. But they do. The fences came down, as the fences always, eventually, do. The thread that changed the world is ours now, mountain of leftovers and all — and the last and hardest chapter of its story, the one about what we do with it when we are finally done, is still being written, by us, right now.

A NOTE ON SOURCES AND METHOD

This book is a work of popular history, written for the general reader from the public record. The central events and figures — Roger Bacon's discovery of graphite whiskers at Union Carbide in 1958; Akio Shindo's 1959 identification of polyacrylonitrile as a precursor for carbon fibre; the Farnborough process developed by Watt, Phillips, and Johnson and licensed through the National Research Development Corporation; the failure of the RB211's carbon-fibre Hyfil fan blades under bird-strike testing and the resulting receivership and nationalisation of Rolls-Royce in 1971; Toray's commercialisation of PAN-based fibre from 1971 and Japan's rise to dominance; John Barnard's McLaren MP4/1 of 1981 and John Watson's Monza crash that vindicated the carbon monocoque; the roughly half-composite structures of the Boeing 787 and Airbus A350; and the mounting end-of-life challenge of composite wind-turbine blades — are drawn from widely available published

accounts and are, to the best of the author's understanding, accurate in their essentials. Dates and figures have been kept deliberately round where the sources vary, and where I have simplified the science or compressed the chronology in the service of a readable story, I have tried hard not to distort it. The specialist and the historian will nonetheless find more detail, and the occasional correction, in the primary sources, and are warmly encouraged to seek them out.

The patents named in these pages are real and freely readable by anyone. Unlike the other books in this series, this one was not built by ranking a database of expired patents; a single material's story is told by its history, not by citation counts, and the patents here serve as landmarks along a narrative rather than as chapters in their own right.

The deeper argument, though, is exactly the one that runs through the whole series. A patent is not a wall but a gate with a timer set upon it. Everything held behind it is on its way, by design, to becoming ours. Carbon fibre is one long, vivid, high-stakes demonstration of that passage — a guarded secret that became a common commodity within a single lifetime — and this book has been an attempt to stand on the far side of the thread and watch the whole of it unwind.