INDUSTRIES OF INDIA

THE NATURAL GAS PIPELINE

Steel, Pressure, Flow



KETINENI RAMARAO

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Reference numbers in square brackets refer to entries in the companion volume, The Natural Gas Pipeline: Source Companion.

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PART I
THE GAS

CHAPTER 1

A fire with no wood under it

For most of its history natural gas was something to look at rather than a fuel. It was hard to carry, store or sell, and the chapter that follows shows how that changed.

What came out of the ground in those places was mostly methane, the simplest hydrocarbon: one carbon atom with four hydrogen atoms attached. Pipeline gas is described by regulators and utilities as principally methane, with smaller amounts of ethane, propane, butane and other hydrocarbons, plus whatever contaminants the rock added, such as water, carbon dioxide, nitrogen and sulphur compounds[1,2]. The exact mix depends on the geology of the field it came from. That variation matters later in this book, because a pipeline is a piece of shared plumbing. Gas from many fields is poured into the same steel tube, and each pipeline publishes a quality specification, a set of limits that any gas must meet to be let in.

Natural gas has one deep disadvantage as a fuel: it is thin. Its volumetric energy density is almost a thousand times lower than that of crude oil[3]. That is the reason a pipeline exists at all.

The thinness problem

A barrel of oil holds the same energy as about 5,659 cubic feet of gas at room conditions[4]. Put another way, the energy contained in a given volume of natural gas is almost a thousand times lower than in the same volume of crude oil[3]. Oil can be poured into a barrel, a tanker or a railway tank. Gas at ordinary pressure must be moved in enormous volumes or squeezed hard, and every method of squeezing it, whether compression in a steel tube or cooling to a liquid, costs energy and money. Almost everything in this book follows from that one fact.

Where does the gas come from? In the ground, over very long periods, the remains of tiny organisms, buried in sediments, are cooked by heat and pressure. Given enough heat, the carbon-rich material breaks down into oil and then into lighter molecules, and finally into methane. Some methane is also made at lower

temperatures by microbes living on buried organic matter. The gas migrates upward through pores in the rock until it meets a seal, usually a layer of tight shale or salt, and collects beneath it. Early drillers were looking for those reservoirs, and in many places they found gas with oil, dissolved in it or floating above it. In the shale beds of western New York, where the first American commercial gas well was drilled, the gas came from an Upper Devonian black shale, the kind of rock that is the target of today's shale-gas plays[5].

The earliest use of gas that left a record is not European. In the salt country of Sichuan in south-west China, people dug brine wells from the Han dynasty onwards. A provincial chronicle office records that in 67 BCE twenty salt wells were dug at Linqiong and Pujiang, and that the Linqiong wells lay in a "fire-well trough"[6]. The reason for the name was practical. Brine has to be boiled to make salt, boiling needs fuel, and in places a deep well gave out gas as well as water. A well that gave both was a rare gift, because the same hole supplied the raw material and the heat. Over centuries the well-diggers refined their tools until they were drilling very deep holes by percussion, lifting the water with long bamboo tubes, and standing the whole apparatus under tall timber derricks. Those wooden towers, called tianche, appeared in the Han dynasty and grew with time, and the tallest known examples reach 110 metres[7].

Popular accounts add that the Sichuan salt-makers used bamboo as the first gas pipe. The idea is easy to picture. Bamboo is hollow, its internal diaphragms can be knocked out, and wrapped with varnished cloth the tube becomes a flexible, nearly gas-tight conduit. One popular history site describes exactly this and says the tubes carried gas from the well to the evaporating pans[8]. The provincial chronicle describes bamboo tubes for brine[6]. This book treats the bamboo gas line as a plausible and widely repeated account that rests on thinner evidence than the existence of the fire wells themselves. The firm fact is that people in the Sichuan basin were drilling deep wells, tapping gas, and using it as a fuel two thousand years ago. The fuller claim about bamboo pipelines awaits better sources.

The shape of the problem

The Sichuan salt works show the whole logic of the gas industry in miniature. Gas was valuable at the well because there was a use for it next to the well. Move the pans a few hundred metres and the gas would have to be carried, and carrying it took a pipe that did not leak, a flow that did not stop, and a fuel that burned only where it was meant to. People could build such a pipe from bamboo over short distances. Doing it over hundreds of kilometres for millions of customers took industrial steel, high-pressure compressors, welded joints that could be tested, instruments that could count the gas as it went by, and law that said who was allowed to own all of this.

That is the subject of this book. It is not a book about natural gas as a commodity. It is a book about the thing that carries it, the long steel tube, and everything that grew around that tube: the mills that roll the steel, the welders and the machines that replaced them, the corrosion that eats the pipe from outside and inside, the compressors that push the gas along, the storage fields that cushion it, the contracts that bind buyers to sellers, the rules that make pipelines carry other people's gas, and the explosions that taught the industry what it did not know.

It follows an order that mirrors the journey of the gas itself. First the gas and how people learned to use it. Then the pipe: how it is made, joined, protected and laid. Then the physics and machinery of pushing a compressible fluid across a continent. Then the great lines themselves, from the first long American trunk lines to the sea crossings of the Mediterranean and the Black Sea. Then law and price, which decide who may use a pipe and what the gas costs at the other end. Then failure: the ruptures, the leaks and the methane problem. And finally the people and firms who make this infrastructure, the things that depend on it, and the futures that engineers are trying to build on it.

A word about scale, to keep the figures in proportion. The Energy Institute counted global natural gas production at 4,124 billion cubic metres in 2024, and consumption at about 4,128 billion cubic metres, a record that grew 2.5 per cent over the year[9,10]. The United States, Russia, Iran and China together produced 53 per cent of that total[9]. Global Energy Monitor, which counts pipelines asset by

asset, tracks 4,158 gas transmission pipelines with a combined length of about 1.5 million kilometres[11]. Those figures describe only the large transmission lines. Underneath them lies a much larger mass of smaller gathering and distribution pipe, the last metres of the journey to the kitchen. In the United States alone, the national regulator reports about 300,000 miles of transmission pipeline and more than a million miles of distribution mains[12,13].

A pipeline is a strange kind of industry. It makes nothing and sells nothing, in the classical sense. It receives gas at one place and delivers a nearly identical amount at another, and all its value lies in the difference between the two places. Yet the same steel tube that sits unseen under a field is also one of the most politically charged objects in the world economy, and one of the most carefully engineered. The next two chapters tell how it began.

CHAPTER 2

Gas before gas: coal, lamps and the first gas mains

Before the industry could lay a single natural gas pipeline, it needed the idea that a town might buy gas at all. That idea did not come from natural gas. It came from coal.

In the seventeenth and eighteenth centuries several people in Britain showed that coal, heated without enough air to burn it, gave off a gas that burned with a bright flame. The Scottish engineer William Murdoch was the first to put the discovery to practical use. In 1792 he lit his house in Cornwall with coal gas. His employers, the Birmingham steam-engine makers Boulton and Watt, then built small gasworks for large customers, and the first of these was installed at a cotton mill in Manchester in 1806[14]. The reason is easy to see from the mill owner's side. A cotton mill ran long hours and was full of lint, and a candle was a fire risk. A flame fed through a pipe from a gasworks gave a steady light where it was wanted and did not need to be trimmed.

The decisive step was to supply a whole street. In 1807 gas lighting reached London, where it was cheaper and brighter than oil lamps, though the Museum of London notes that gas lamps carried a risk of explosion[15]. A century later this was ordinary city infrastructure. The transition was driven by economics and by a change in what people expected of the night. A lit street was safer to walk and a lit shop could stay open, so the gas lamp fed a new kind of public life.

The gas for those lamps was manufactured. A gasworks heated coal in closed retorts, drove off the gas, cleaned it, stored it in a large floating holder called a gasometer, and fed it into a network of cast-iron mains under the street. The coal left behind became coke, which could be sold as fuel, and the tar that came out with the gas became the raw material for a chemical industry of its own, producing the first synthetic dyes. In the United States the same technology crossed the Atlantic and spread through the cities in the nineteenth century, introduced as a European method for making gas from coal and other organic fuels[16].

Three things about this early gas industry shaped everything that came after.

First, it created the customer. By the time natural gas arrived in quantity there were already mains in the street, burners in the kitchen, cooks who trusted a pipe, and utility companies with franchises to serve a city. When natural gas finally reached a market, it did not have to invent demand. It had to displace a more expensive manufactured product that people already used.

Second, it created the habit of regulation. A gas company was a monopoly in its streets. It dug up the road, supplied a good that could kill, and charged each household for it. Cities granted franchises and set rules. The long argument over who should be allowed to charge what for gas, which runs through this book from the nineteenth-century municipal franchise to the twentieth-century federal pipeline regulator, started here.

Third, it taught the industry about danger. Gas leaks, and Los Angeles tested odorants after explosions that followed its 1927 switch to natural gas[17]. That experience shaped a rule that pipelines still follow, which the book reaches in Chapter 11.

A century of two gases

For most of the nineteenth century the two kinds of gas coexisted. In places with abundant coal, manufactured gas was good enough. In places that happened to sit on a natural gas field, people used the natural product, usually near the well. The map of early gas use is therefore a map of geology and of local convenience, and it rarely crossed a regional boundary. A town two hundred kilometres from a gas field could not use it, because there was no way to move it that far.

The conversion of the old mains came later and is a story in itself. Britain's gas industry changed from town gas to North Sea natural gas between 1967 and 1977. That conversion involved the adaptation of over forty million appliances and more than thirteen million customers[18]. It required a national programme of visits to every home. The British gas system had begun by importing liquefied natural gas by ship in 1959, and large finds off the Yorkshire coast in 1965 turned the national plan from importing to producing[19]. The point for this chapter is what the scale of

the conversion reveals. A century of coal gas had left behind a network of pipes, a set of burners, a population of trained fitters and a customer relationship that could carry a new fuel across a whole country.

This is the pattern that repeats through the history of the pipeline. A new infrastructure rarely arrives on bare ground. It borrows the rights-of-way, customers and legal habits of the one before it. The early gas companies did not know they were building a market for a fuel they had not yet found. But when natural gas pipelines became feasible, the market was waiting, and the pipelines could be financed on the strength of customers who already existed.

The coal-gas era also left a physical scar. Every manufactured gas plant produced coal tar and other waste, and many were closed and forgotten. The sites of former gasworks remain, in cities across Europe and America, often contaminated industrial land. They are a reminder that an industry is not finished when it stops selling a product. The record of the gas industry includes what it left in the ground as well as what it took out.

What turned a curiosity into an industry was a well in a small town in western New York.

CHAPTER 3

A washtub, a lead pipe and a wrought-iron line to Pittsburgh

The standard story of American natural gas begins in Fredonia, a village in Chautauqua County in the far west of New York State. The standard date is 1821. The US Energy Information Administration's history timeline and the National Energy Technology Laboratory both say that in 1821 William Hart dug the first successful well intended to produce natural gas, a shallow bore of 27 feet beside a creek that had been seeping gas, and that Fredonia's gas light company grew out of it[20].

The date has a problem, and the problem is a good example of how origin stories get made. A careful reading of the evidence by the petroleum geologists' association finds that the first documentation of a well being drilled at Fredonia is a newspaper notice in the Fredonia Censor dated 31 August 1825. A report in the same paper on 30 November 1825 declared the gas lights a success. The 1821 date, the account says, is "erroneous"[21]. By August 1825, two stores, a grocery, two shops and a mill in the village were lit by gas from the well[21].

So the first commercial natural gas well in the United States was drilled, on the best documentary evidence, around 1825, by a gunsmith who wanted a bigger flow from a seep. It was not a deep hole. Hart bored through shale to a modest depth and found the gas that was leaking naturally from the same rock, and the success was that it flowed more strongly. The gas came from an Upper Devonian black shale, the kind of rock that is the target of today's shale-gas plays[5].

The first pipes

What Hart did with the gas is as instructive as the well itself. He did not use a metal pipe, because he had none. The earliest conduits were wooden pump-logs, hollowed tree trunks with tar-laden cloth over the joints, laid for short distances. They leaked, because wood is permeable, and they were soon replaced with lead and tin piping[21]. The first commercial gasometer, a container for storing the gas,

was a vessel hung over a water-filled vat cut into solid rock, fed by about 25 feet of lead pipe. A first-person account says Hart's early gasometer was improvised from his wife Mary's washtub[21]. Observers noticed one more thing: the lit gas gave off no unpleasant smell[21].

The lesson of the washtub is that the three problems of the gas industry were present at Fredonia in the first year. Collection: a hole in the ground. Containment: a pipe that did not leak. Storage: a gasometer to even out the flow. The scale was a few shops. Everything else in the industry's history is the same three problems at larger scale.

Natural gas then spent most of a century as a local fuel. A gas well supplied the town nearest it, usually for lighting, and when the well failed the town went back to coal gas or oil. The oil boom that began in Pennsylvania in 1859 produced large volumes of gas alongside the oil, and most of it was burned off at the wellhead, flared into the night sky because there was no way to use it. A historian of petroleum records that natural gas piping to a town began in 1872, when gas from the Newton well was carried five miles to Titusville, Pennsylvania, which was then an oil capital[22].

Pittsburgh and the man with the stopcock

The first large city to take natural gas was Pittsburgh. In 1883 the Penn Fuel Gas Company began supplying it from a well some twenty miles away, through a wrought-iron pipe of 5 and 5/8 inches in diameter. The line used a telescoping joint, a coupling that let the pipe sections slide together and made it possible to assemble longer, tighter lines that were easier to screw together[23].

The most vivid figure in the Pittsburgh story is George Westinghouse. Known for the railway air brake and for the alternating-current power system, Westinghouse also had a gas business that few people now remember. In 1883 he began to drill for gas at his own house, a property called Solitude in Pittsburgh's Point Breeze district. The conventional view was that natural gas was dangerous, because it escaped from every crevice and occasionally caused violent explosions. On 29 May 1884 the drillers found much more gas than anyone expected. Westinghouse

devised a stopcock that brought the roaring jet under control. Within weeks he obtained a major patent for a "System for Conveying and Utilizing Gas Under Pressure" and by the end of the summer he had formed the Philadelphia Company. In 1884 and 1885 he produced twenty-eight inventions for the gas business, including better ways to dig wells and a meter to measure how much gas a customer used[24].

That list matters more than the man. A meter, a regulator, a safety valve, a better drill: each is a device that turns a dangerous flow into a controlled commodity. A gas industry is, among other things, a collection of devices for making an unstable substance behave. Westinghouse understood early that the business was not in the gas but in the control of it, and that control came from engineering of pressure.

Longer and leakier

By the late nineteenth century the pattern was clear: gas could be found in places that had few customers, and cities had customers but no gas. The way to link them was a long pipe. In 1891 one of the first lengthy lines was built, 120 miles from gas wells in central Indiana to Chicago. The US Energy Information Administration's timeline adds a blunt comment: the early pipeline was not very efficient at transporting natural gas[20].

The reason was the pipe. A nineteenth-century line was made of short lengths of cast or wrought iron, connected by threaded or collared joints. Every joint was a place for gas to escape, and the pressure that could safely be used was low. An industry narrative from the Magnolia pipeline in Texas puts it plainly: long-distance high-pressure gas lines were impractical in the early years because of leaks and because the industry could not make enough line pipe of suitable quality[25]. Compressors, machines that raise the pressure of the gas, became more common after about 1910, and began to be used to control the pressure within gas pipelines[23].

The Indiana-to-Chicago line shows a feature of the business that has not changed. A pipeline links a supplier in one place to a buyer in another, and the supplier and buyer are not the same company. In the 1890s the supplier was a field of wells that

would run out. A pipeline built on a field that fails is a stranded asset, a long steel tube with nothing in it. That is a risk the industry has priced into its contracts ever since, and the next generation of pipelines could be financed only because the contracts and the regulators learned how to share it.

The real step change had to wait for steel. A pipe that could carry high-pressure gas for a thousand kilometres had to be strong, uniform and joined without leaks. That needed new ways of making tube, and the story of the tube, from a pair of brothers in a German file factory, is where the next part of the book begins.

PART II
THE PIPE

CHAPTER 4

Making the tube

A transmission pipeline is two things at once: a very long, very thin pressure vessel and a continuous manufactured object. Understanding why it is built the way it is requires looking at how the tube itself is made, because the manufacturing method sets the limits on diameter, strength and cost.

Seamless: the Mannesmann brothers

The first great idea in tube-making came from a family file factory in Remscheid, in what is now Germany. Reinhard and Max Mannesmann filed a patent application in 1885 for a process of rolling seamless steel tubes, and the patent was granted in 1886[26]. Until then, tubes with thick walls were made by bending a flat plate or strip into a cylinder and joining the edge, which left a seam, the weakest place in the pipe. Or they were drawn and forged in laborious steps. The Mannesmann method made a hollow directly from a solid round billet of steel. The billet is heated to between 1,200 and 1,300 degrees Celsius and pushed between two angled rolls that spin it and draw it over a pointed mandrel, so the metal flows outward and a hole opens down the centre. In the early 1890s Max Mannesmann added the pilger rolling process, which rolls the thick hollow into a thinner-walled tube of great length[26].

Seamless tube has no weld along its length, which is a real advantage for strength and for confidence. Its limit is size. Standards cover both routes: API 5L and ISO 3183 describe seamless and welded steel pipe for pipeline systems[27]. In practice, piercing a solid billet becomes impractical at large diameters, so the usual division is that small and medium pipe can be seamless, and the large pipe that carries the big volumes is welded.

Welded: plate to pipe

A large-diameter pipe starts as a flat steel plate. The plate is milled square at its edges, curved into shape, and welded along its length. The most common route for pipe of transmission size is the longitudinally welded process, in which the plate is progressively bent, first at the edges and then across, in a giant press that forms a U and then an O, before it is closed and welded by submerged arc welding on the inside and outside of the seam. The pipe is then expanded cold inside a die by a hydraulic mandrel, so that it holds its shape to a tight tolerance and any residual stress is evened out. A manufacturer based in Mülheim an der Ruhr describes one such facility for longitudinally welded large-diameter pipe, with a capacity of up to 1.4 million tonnes, or around 2,000 kilometres of pipe, a year. The company, Europipe, was formed in 1991 by the merger of the large-diameter pipe activities of Dillinger Hüttenwerke, GTS Industries and Mannesmannröhren-Werke[28]. The plant's output of 2,000 kilometres of pipe is about the length of one very long pipeline each year.

A second route uses a coil of strip steel wound in a spiral, welded as it forms. Spiral-weld pipe made from coil that has been controlled-rolled in a steel mill, then welded by the double submerged arc process, is one documented route to high-strength line pipe[29].

Whichever route, the quality of the steel plate behind the pipe matters as much as the pipe-making itself. A pipeline plate needs to be strong, but it also needs to be tough, meaning able to absorb energy without cracking, and weldable in the field without special treatment[29]. Those three requirements pull in different directions, and the history of line-pipe steel is largely the history of getting all three at once.

Grades: what X70 means

Pipeline steel is classified by an American Petroleum Institute specification, API 5L, in grades named for the minimum yield strength. A grade named X70 is a steel with a specified minimum yield strength of 70,000 pounds per square inch. Higher grades are stronger: a grade X80 pipe has a yield strength window of 555 to 705

megapascals in the product specification level used for demanding service, made from low-carbon microalloyed steel designed for weldability[27].

Strength lets the engineer use thinner walls, and thinner walls mean fewer tonnes of steel per kilometre, which is the main cost of the pipe. The jump to higher-strength grades came not from adding more carbon, which makes steel brittle and hard to weld, but from the opposite approach: take carbon out and add tiny amounts of alloying elements such as niobium, vanadium and titanium, and control the temperature of rolling so that the steel is made of very fine grains. Fine grains give both strength and toughness. The supplier page describes the result as a low-carbon microalloyed design[27].

The grade has to be chosen with the weld in mind. A joint-industry project funded by the pipeline industry's trade association was set up because of several failures at girth welds in pipelines built from X70 pipe and welded under procedures qualified to the industry's standard[30]. High-strength steel is a bargain only if the people welding it in a muddy trench can reproduce the properties of the factory.

The arithmetic of wall thickness

How thick should a pipe wall be? The answer starts with a formula that goes back to the nineteenth century, the Barlow formula for a thin-walled cylinder. The hoop stress in a pipe wall is proportional to the pressure and the diameter and inversely proportional to the wall thickness. Re-arranged to give the permitted pressure, P equals two times the stress times the thickness divided by the diameter. US federal regulation writes this into law for gas pipelines. The design pressure is P = (2St/D) x F x E x T, where S is the yield strength, t the nominal wall thickness, D the outside diameter, F a design factor, E a longitudinal joint factor and T a temperature derating factor[31]. For a pipeline in the least populated areas, a Class 1 location, the design factor is 0.72. Other classes, where more people live along the line, take lower factors[32].

A worked example makes the numbers concrete. Take a 36-inch pipe in a grade with 70,000 psi specified minimum yield strength, with a wall 0.5 inch thick, in a Class 1 location, with the joint and temperature factors at 1.0. Then 2 x 70,000 x

0.5 / 36 gives 1,944 psi, and multiplying by 0.72 gives a design pressure of 1,400 psi. That is about 96.5 bar, or roughly ninety-six times atmospheric pressure. The example uses the regulatory formula[31] and the 0.72 factor for Class 1[32] and the meaning of the X70 name; real projects add further checks for fracture, fatigue, installation loads and corrosion allowance.

Notice the factor 0.72. It means the pipe is designed so that the hoop stress at the maximum permitted pressure is no more than 72 per cent of the steel's specified minimum yield. The remaining margin is for everything the formula does not capture: imperfections, dents, corrosion, the unexpected load from a landslide. As the line passes through more populated country, the factor drops, to 0.60, 0.50 and 0.40 for Class 2, 3 and 4 locations, so the same pipe would run at a lower pressure, or a thicker pipe would be needed to run at the same one. Even in Class 1 country the rule requires 0.60 or less at some road and railway crossings and on bridges, and 0.50 or less for pipe in compressor, regulating and measuring stations[32].

Why it adds up to millions of tonnes

A 36-inch line with a half-inch wall weighs on the order of 280 kilograms per metre of steel (the cross-section of the wall times the density of steel, about 7,850 kilograms per cubic metre), which is roughly 280 tonnes per kilometre. A line of 1,000 kilometres therefore contains about 280,000 tonnes of pipe steel, before the coatings and the valves. The historical record bears out the scale. The Soviet export pipeline from Urengoy to Uzhgorod, 2,765 miles long, was described in 1983 as comprising 2.7 million tonnes of pipe[33]. The Transcontinental line built from Texas to New York used more than 540,000 tons of steel for 1,832 miles[34].

That is why the steel mills and the pipelines grew up together. Chapter 23 returns to the mills that make the pipe.

CHAPTER 5

Joining the pipe

A thousand kilometres of pipe built from twelve-metre lengths has more than eighty thousand joints, by simple arithmetic. Each joint is a chance for the line to fail, which is why the history of pipeline construction is the history of how joints are made and checked.

Threads, collars and the leaking era

The pipes of the nineteenth century were joined by screwing them into collars or sliding them together in telescoping couplings. Pittsburgh's first big gas line in 1883 used a telescoping coupling that made longer lines easier to assemble[23]. But a threaded joint is a weak joint. Cutting a thread removes metal from the thickest part of the wall exactly where the stress is concentrated, and the joint depends on a seal of packing or paste. The industry's own account from a Texas pipeline marker describes the early long-distance high-pressure lines as impractical because of leaks and because of difficulty in making enough line pipe of suitable quality[25]. A line that leaked could not hold pressure, and a line that could not hold pressure could not carry gas far.

Welding arrives

Fusion welding changed this. The same industry narrative traces a shift in the pipelining trade from mechanical joints to welded ones, comparing it with the move from riveted to welded tanks. The effect on gas was larger still, because gas leaks through any imperfection. A welded joint is a continuous piece of steel, with no packing to dry out and no thread to loosen.

One of the first lines to show what the new methods could do was the Texas-Chicago pipeline. On 5 August 1931 its final link was laid. It stretched more than 900 miles, crossed 18 rivers and was served by ten mainline compressor stations, and the company's own history calls it the longest natural gas pipeline in the world at the time. The original line was 24 inches in diameter. Engineers used

aerial photography and mosaic maps to help choose a route shaped by topography, soil conditions, river crossings, timberland and other factors that affected construction cost. Later it was called Amarillo No. 1, and parallel lines called Amarillo No. 2, 3 and 4 were added in the decades that followed[35]. The company is today known as Natural Gas Pipeline Company of America, and it carries gas from the Texas Panhandle and the Permian Basin to the Chicago area.

The Texas-Chicago story makes a point about economics. The company's own history describes the line as connecting growing gas supplies in Texas with one of the nation's largest population centres[35]. A pipeline joins a supply and a market, and it exists only when both are large enough to justify the steel between them.

The girth weld

The joint between two lengths of pipe is called a girth weld. It is made in the field, on a right-of-way, in whatever weather there is, by welders who work in crews along the line. The standard that governs how girth welds are made, qualified and inspected for pipelines is API 1104, first published in 1953 by the American Petroleum Institute[36]. Before a crew may weld a single joint, the contractor must qualify a welding procedure, proving by destructive test that welds made to the procedure meet the strength and ductility requirements. Each welder is then tested. Each production weld is inspected, commonly by radiography, which passes X-rays or gamma rays through the weld onto film, or by ultrasonic testing, which sends sound pulses through the steel and listens for echoes from flaws.

The classic technique is the stovepipe weld, a manual weld in which the welder works downhill around the pipe, using cellulosic electrodes and forming a root pass, a hot pass, filler passes and a cap[37].

From the 1960s, as pipelines moved offshore, the cost of lay-barges and the limits of weather windows created a push for faster, more repeatable welding, and the industry moved toward semi-automatic and then fully mechanised systems. A trade review of automated pipeline welding notes this demand arising once pipeline installation moved offshore in the 1960s, because lay-barge time was so expensive[38]. Several commercial automatic welding systems followed, marketed

by companies including CRC Automatic Welding, H. C. Price, Diametrics and the Belgian firm Arcos with its Orbimatic system[39]. In a mechanised spread, a welding head rides on a band around the pipe and uses a continuous wire, controlled by a computer, while an internal welding machine inside the pipe makes the root pass from within.

What a bad weld costs

A weld can fail in ways that cannot be seen from outside. A 2010 rupture in San Bruno, California, which killed eight people, traced to a defective seam weld in a pipe section that had been installed in 1956 during a relocation. The National Transportation Safety Board found that the pipe section was substandard and poorly welded, with a visible seam flaw that grew to critical size over decades. A contributing factor was an exemption that let old pipelines escape the requirement to be pressure-tested[40]. The chapter on failure, further on, returns to this.

For now the lesson is about time. The San Bruno line, whose rupture Chapter 21 describes, had been in service since 1956 when it failed in 2010[41]. Joints are a promise made to people who will live beside the pipe decades later. Pipe is tested before it is put into service, and hydrostatic testing is one of the construction phases PHMSA lists[42].

Hydrostatic test

The final proof of a new pipeline is the hydrostatic test. The completed section is filled with water, closed at both ends and pressurised above its operating pressure, then held while the pressure is monitored. If any defect is weak enough to fail at the test pressure, it fails in water, not in gas. Water is nearly incompressible, so the stored energy in a failing test is small compared with a rupture of the same pipe full of gas. The test is not only a check on welds but a check on the pipe itself, because a flaw that is going to break will usually do so during the test. The San Bruno finding about exemptions from pressure testing shows why it matters: old lines that were never tested to a known margin carried flaws that no one had proved safe[40]. A pipeline that passes the test is dewatered, dried, swept with a cleaning pig, and filled with gas. Only then does it begin to earn its keep.

CHAPTER 6

The enemy outside and inside: corrosion, coatings and current

A buried steel pipe is exposed to soil and water, and corrosion is an electrochemical reaction in which metal atoms go into solution as ions, a loss of metal that is commonly recognised as rust[43]. PHMSA describes it as a time-dependent threat that grows if left unmitigated, and counts about 18 per cent of pipeline incidents from 1998 to 2017 as caused by corrosion[44]. Much of what a pipeline operator does is aimed at stopping it.

Two defences

The defence is in two layers. The first is a coating. The earliest pipelines were buried without external coatings, then received tape wraps and coal tars; these were prone to disbonding, which lets water reach the steel[45]. Today coatings are applied by the pipe manufacturer, and fusion bonded epoxy is the most widely used. The girth welds are coated in the field when pipe sections are joined[45].

Coatings alone were found not to give complete protection: they disbond, and equipment and rocks in the backfill can damage them[45]. So the second defence is cathodic protection, used together with coatings.

Cathodic protection: Davy to Kuhn

The principle of cathodic protection goes back more than two hundred years to the English chemist Sir Humphry Davy. The Royal Navy had sheathed the wooden hulls of its ships in copper to protect them against marine growth and shipworm, and the copper was corroding. Davy showed that attaching a more reactive metal, such as zinc or iron, to the copper protected it, because the reactive metal corroded in its place[46]. The same idea works for a buried pipe. Connect the steel to a piece of a more reactive metal, a sacrificial anode of magnesium or zinc, or force a small direct current onto the pipe from a rectifier through a buried ground bed, and the

entire pipe surface becomes the cathode of the cell. Corrosion happens at the anode, not on the pipe.

Applying this to pipelines took a practical standard: how much protection is enough? The answer that the industry still uses came from the field work of Robert J. Kuhn, who worked on pipelines at New Orleans Public Service and stated in a 1933 paper a potential criterion for stopping corrosion. The criterion that came to be used that the pipe's potential relative to a copper-sulphate reference electrode should be at least minus 0.850 volt, though engineers have debated its scientific backing[47]. Today a pipeline's potential is measured at test points along the line, and the operator adjusts rectifier output to keep the whole line below that threshold. It is a rare case of an industry-wide rule that comes from the measurements of one engineer in one city's gas system.

The surprise of stress corrosion cracking

Coatings and cathodic protection address general corrosion. They did not prepare the industry for one of the most unsettling discoveries in pipeline history. In 1965, a gas transmission pipeline ruptured near Natchitoches, Louisiana. The investigation identified a form of failure that was previously unknown for buried pipelines, stress corrosion cracking, or SCC, in which fine cracks form in colonies on the outer surface of the pipe, perpendicular to the direction of the highest stress. Industry reviews describe the Natchitoches rupture as the first known case of SCC on a buried pipeline, and say multiple agencies and organisations examined the failure in depth[48]. The cracks can grow slowly for years, then link up into a long crack that runs. Two forms have since been recognised, with different environments, but both occur as colonies of parallel cracks that grow in depth and length, according to a US pipeline-safety technical review[49].

The Natchitoches rupture is a lesson in the limits of knowledge. The industry had a coating, a cathodic protection standard, a design formula and a welding code. It still did not know that a combination of stress, a particular soil chemistry and a disbonded coating could crack steel. Since then, operators have used inspection tools, to be described in Chapter 11, to look specifically for such cracks.

Corrosion from the inside

Inside the pipe, the gas is supposed to be dry and clean. When it is not, the inside of the pipe can corrode even though the outside is perfect. On 19 August 2000, a 30-inch natural gas transmission pipeline operated by El Paso Natural Gas Company ruptured next to the Pecos River near Carlsbad, New Mexico. The gas ignited and burned for 55 minutes. Twelve people camping beneath a concrete-decked steel bridge that carried the pipeline across the river were killed. The National Transportation Safety Board determined that the probable cause was a significant reduction in pipe wall thickness due to severe internal corrosion, and found that the company's corrosion control programme had failed to prevent, detect or control internal corrosion. Ineffective federal inspections of the company contributed[50]. A news summary of the report records the finding that the corrosion was likely caused by the combination of microbes and other factors inside the line[51].

Carlsbad shows why gas quality specifications, the limits on water and corrosive gases that a pipeline puts in its tariff, are more than a commercial convenience. They keep the inside of the pipe dry. The industry also uses chemical inhibitors, regular cleaning with pigs, and sampling of the liquids and solids that pigs push out to learn what is happening inside.

A pipe is alive

A reader who has followed the chapter will see that a pipeline is not a finished object. It is a system that is monitored and maintained for as long as it operates. Coatings deteriorate. Rectifiers fail, or are shorted by a neighbour's buried metal. A new power line along the same corridor can induce alternating current on the pipe. A field that was dry becomes wet. A farmer's drainage tile changes the soil around a section. The operators of old pipelines therefore keep a record of every inspection and every repair, because that history is the best predictor of where the next problem is. Before the next chapter moves to the way a pipeline is laid across the land and under the sea, one comparison is worth holding. Good coating and cathodic protection together have allowed steel pipelines to operate for many decades. Transco, described in Chapter 12, entered service in 1950 and is still in

service. They are old not because steel lasts forever but because people have kept paying attention to them.

CHAPTER 7

Laying the line: trench, river and sea

A pipeline right-of-way looks, to a passer-by, like a strip of cleared land with a row of markers. During construction it is a moving factory. A line of specialised crews and heavy machines advance along the route in a fixed order, in sections called spreads[42,52]. First the corridor is surveyed and cleared and the topsoil is stripped and stored. The pipe is trucked in and strung along the route, end to end. A bending machine shapes individual lengths to follow the ground. Welders join the lengths into a long string, the joints are inspected and coated, and a ditching machine digs a trench just ahead of a line of side-boom tractors that lift the string and lower it in. The trench is backfilled, the topsoil replaced, and the spread moves on. A long line is built in several such sections and the work is organised as a moving assembly line.

The cost figures are large and volatile. Oil & Gas Journal's 2023 survey of US land pipeline construction, built from annual reports that FERC-regulated pipeline companies file, put the average at a record $10.7 million a mile, up by more than two million dollars from the year before, because sharply higher miscellaneous costs outweighed falling material costs[53]. Global Energy Monitor reports about 69,700 kilometres of gas transmission pipeline under construction worldwide, at an estimated cost of US$193.9 billion, with Asia accounting for 82 per cent of it[54]. Dividing the two figures gives roughly US$2.8 million a kilometre, a crude world average that is not comparable with the US survey figure, which covers a different set of projects.

Under the river: directional drilling

Rivers, roads, railways and wetlands are crossed in different ways. For a narrow stream a trench can be dug across the bed. For a major river or an environmentally sensitive crossing, the modern answer is horizontal directional drilling. A drilling rig on one bank bores a small pilot hole in a long arc beneath the river, steering the bit with a downhole survey tool. The hole is then enlarged in stages with reamers,

and the pre-welded pipe string, laid out on the far bank, is pulled back through the hole[55].

The method traces back to a single job. In 1971 Martin Cherrington, who owned a utility drilling business in California, was asked by Pacific Gas and Electric to find a less costly and less disruptive way to install a four-inch gas line under a river. The crossing he made is regarded as the start of directional drilling for pipelines. It grew into a trenchless industry[56]. The advantage is that the river bed and banks are never opened. The limits are geology and length: loose gravels and fractured rock cause trouble, and a crossing is only as good as the hole.

Into the sea

Offshore, a different set of methods applies. A pipeline is laid from a vessel that welds the pipe on board and lowers it to the sea floor along a curved path. In the shallower method, called S-lay, the pipe leaves the stern over a long ramp and bends in an S-shape between the ramp and the sea bed. In deep water J-lay is used, with the pipe leaving the vessel at a steep angle, and some pipe is laid from a reel[57].

Three examples show how far the offshore art has gone. In the late 1970s the Trans-Mediterranean gas pipeline crossed the Strait of Sicily between Tunisia and Sicily in water as deep as about 600 metres, a world record for deepwater pipelaying at that time[58]. Sources do not agree on the depth: a 1979 trade report quoted about 2,300 feet, roughly 700 metres, so the figure is approximate. A trade journal from March 1979 recorded a 237 million dollar contract awarded to Saipem to lay three 20-inch pipelines from Cap Bon in Tunisia to Mazara del Vallo in Sicily[59]. The project showed that large-diameter gas lines could be built across a deep sea, not just across shallow shelves.

The second example is Langeled, which carries Norwegian gas from the Ormen Lange field to Easington on the English coast. It is 1,166 kilometres long, has a diameter of 42 to 44 inches, and a maximum capacity of 25.5 billion cubic metres a year[60]. Before the completion of Nord Stream it was the longest subsea pipeline in the world.

The third is TurkStream, two parallel lines across the Black Sea from the Russian coast near Anapa to the Turkish coast, more than 930 kilometres per string offshore[61]. The pipe is 81 centimetres in diameter and was laid at depths that exceed two kilometres, with a maximum of 2,200 metres, according to the project's fact sheet[62]. The vessel that laid it, Allseas's Pioneering Spirit, laid 1,860 kilometres of pipe in the Black Sea for the two lines, according to a news report on the completion of offshore construction[63]. The ship traces back to the vessel Solitaire, which Allseas launched in 1998 and which has been setting records for installation speed and depth since[64]. Gas supplies via TurkStream began in January 2020[61].

Tuning wall thickness to pressure

One offshore detail carries a general lesson. The Nord Stream pipeline from Russia to Germany, built across the Baltic Sea, uses 1,220-millimetre pipe in three sections with different wall thicknesses. Because the gas pressure falls as the gas travels, the pipe in the later sections can be thinner. The design pressure steps down from 220 bar at the start, at Portovaya on the Russian coast, to 200 bar and then 177.5 bar over three sections of reducing wall thickness[65,66]. Gazprom says the outlet pressure at the German landfall was 106 bar and that before Nord Stream no one in the world had built a gas pipeline able to carry gas over 1,224 kilometres without intermediate compressor stations[66]. That claim is from the operator's site. Even so, the design principle is clear. A pipe designed for a fixed pressure all along its length would carry steel that the later sections do not need. Offshore, where steel is expensive and each tonne must be lifted from a ship, the saving is large. On land, the largest single variable is not steel but the right-of-way, meaning the legal permission to build. Chapter 20 deals with that.

PART III
PUSHING GAS

CHAPTER 8

Why gas is hard to push

Water in a pipe is easy to think about. In a liquid pipeline the average velocity stays constant along the line while the diameter does not change. In a gas pipeline compressibility and the changes in pressure and temperature make the average velocity vary along the pipe[67].

Density and pressure

At atmospheric pressure, methane is a very light gas. Raise the pressure to about 70 times atmospheric and the same mass occupies roughly one seventieth of the volume, a little more than that once real-gas behaviour is counted. That is why transmission pipelines run at high pressure: not to push the gas harder, but to make each cubic metre of pipe carry more gas. A pipe at 70 bar holds about seventy times as much gas as the same pipe at atmospheric pressure. The Nord Stream pipelines were designed with pressures of 220 bar at the start of the line[65]. The US design formula that sets the maximum pressure for a given wall thickness was shown in Chapter 4[32].

A real gas does not obey the simple ideal-gas law exactly, and the departure is described by a compressibility factor, usually written Z, a number that corrects the volume for the attraction and size of the molecules. At the pressures of a transmission line, Z for natural gas falls well below 1, so the pipe holds more gas than the ideal law predicts. Engineers read Z from charts or compute it from equations of state, and every serious calculation of how much gas sits in a pipe or how fast it flows includes it[68].

The Weymouth relationship

How much gas will a given pipe carry? The answer comes from the equations of steady gas flow in a pipe. Several forms exist. The simplest widely used one, named for Thomas R. Weymouth, who published it in a 1912 paper to the American Society of Mechanical Engineers[69], relates flow to the diameter, the

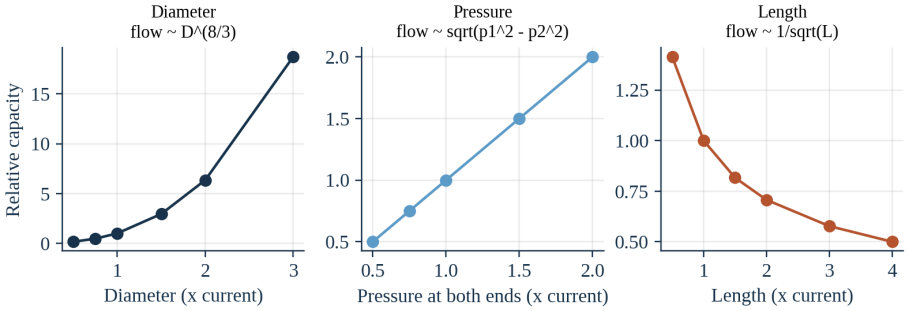
length, and the difference of the squares of the inlet and outlet pressures[70,71]. In words: flow rises with the diameter to the power of eight-thirds, rises with the square root of the difference between the squares of the two pressures, and falls with the square root of the length.

Those exponents explain the economics of pipelines better than any statement of principle.

First, diameter. Because in the Weymouth form flow rises with diameter to the power of eight-thirds[67,70], doubling the diameter multiplies the capacity by a little over six times. A pipe twice as wide uses only twice the steel for the same wall, and four times if the wall thickens in proportion, yet it carries six times as much. This is part of why trunk lines are large, such as Langeled's 42 to 44 inches[60].

Second, pressure. Because the driving term is the difference of squares, raising the pressure at both ends by a given factor raises the flow by about the same factor, for the same length. Double the pressure everywhere and the capacity doubles. That gives a second route to capacity, higher pressure, and it is limited by the steel and the regulation.

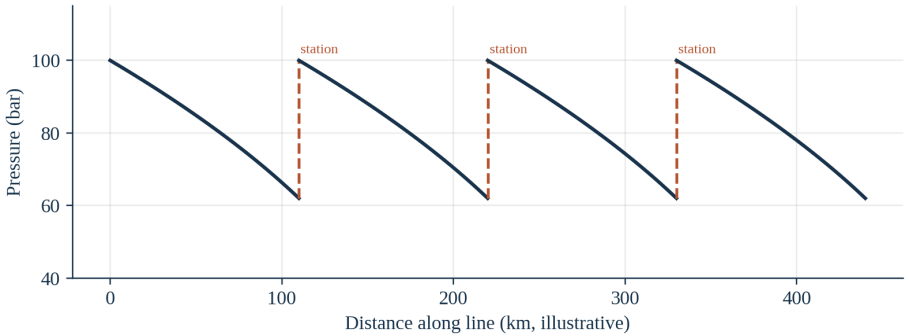
Third, length. Flow falls only as the square root of length. Doubling the length cuts the capacity by about 30 per cent, not by half. A pipeline can therefore be long and still carry a lot, provided the pressure is restored along the way.



Illustrative scaling from the Weymouth relationship: relative capacity of a pipe as diameter, pressure and length change, with all other factors held fixed. Computed for this book from the relationship cited in the text.

The sawtooth

As gas flows through a long pipe, friction against the wall drains pressure. The pressure falls slowly at first and then faster, because as the pressure falls the gas expands and speeds up[67]. The result is a curve. At some point the pressure has fallen too far, and a compressor must lift it again. A long pipeline therefore has a profile like a sawtooth: pressure falls along a stretch, jumps at a compressor station, falls again, jumps again.



Illustrative pressure profile along a pipeline with compressor stations, computed from the squared-pressure form of the flow relationship. The numbers are for explanation only and do not describe any real line.

Nord Stream was an exceptional case. It was designed with wall thickness that stepped down as the pressure dropped, and its operator reports a landfall pressure of 106 bar after 1,224 kilometres, with the whole line pumped by a single large compressor station at its start[66]. It could do so because the pipe was very large and the starting pressure very high. For a conventional onshore line, a pressure of about 70 to 100 bar and a station every few tens of kilometres are the norm, and the next chapter looks at the stations.

The gas is slow

One point is easy to miss. The speed of the gas in a pipeline is not the speed at which a change reaches the far end. CED's hydraulics text derives the gas velocity from the volume flow rate and the pipe diameter, and shows that the higher the

pressure, the lower the velocity[67]. Chapter 10 takes up what this means for linepack.

CHAPTER 9

The compressor station

A compressor station is the most visible part of a gas pipeline, a fenced plant of buildings, stacks and pipework beside the right-of-way. Its purpose is simple: take gas arriving at the pressure left after friction, raise it, and send it on.

The machines

The first compressors in the American gas industry were reciprocating machines, piston engines in which the same crankshaft drove a gas engine and a gas compressor. Compressors were being used more commonly in gas pipelines after about 1910 to control pressure[23]. The Texas-Chicago line of 1931 was served by ten mainline compressor stations along 900 miles[35]. A reciprocating compressor handles gas in pulses and needs heavy foundations, but it works well at the modest ratios and moderate flows of early lines.

As lines grew larger and flows increased, the industry shifted toward centrifugal compressors, which are essentially a stack of spinning impellers that fling gas outward and convert its speed to pressure. They deliver a smooth continuous flow and handle huge volumes. A centrifugal compressor needs a high-speed driver, and the usual partner was the gas turbine, derived from aircraft engines or designed for industrial duty, burning a little of the gas it moves to turn the compressor shaft. INGAA lists three prime movers: a turbine with a centrifugal compressor, a reciprocating engine with a reciprocating compressor, and an electric motor, which needs no air permit for fuel burning but needs a highly reliable power source nearby[72].

The manufacturers are concentrated. A turbomachinery market report credits GE Vernova and Baker Hughes, using gas turbines made by GE Aerospace, with about 85 per cent of the aeroderivative gas turbine market[73]. Aeroderivatives are only one class of turbine used in pipeline service, and other firms also supply industrial turbines and compressors; this book does not rank them. That market study is for the whole turbine business, not pipeline compressor drives alone.

What the gas pays

Moving gas costs gas. A compressor station burns a fraction of what it transports to power itself. The Journal of Petroleum Technology, in a paper on optimising fuel consumption, notes that compressor stations often consume 3 to 5 per cent of the gas they are transporting as fuel[74]. Across a long pipeline with many stations, the fuel burned along the way is a real cost and a real source of emissions, and shippers pay for it in a fuel charge in the tariff.

The trade-off between pipe and compression is the central design choice. A designer can make the pipe bigger and the stations fewer, or make the pipe smaller and the stations more frequent. A larger pipe costs more steel up front and burns less fuel for ever after. A smaller one saves capital and pays in fuel. The choice depends on the price of steel against the price of gas, on the length and on the expected flow.

The Siberian export line and the turbine argument

In the early 1980s the Soviet Union built the Urengoy-Pomary-Uzhgorod export pipeline, 2,765 miles long. A 1983 report in the Soviet pipeline-construction journal described it as comprising 2.7 million tonnes of pipe, 40 compressor stations exceeding 3 million kilowatts in total, more than 1,200 miles of weld joints and 794 water crossings, and said that planners had doubled the 1983 capital appropriation and adopted a construction pace 50 per cent faster than usual[33].

The project became a diplomatic dispute. In December 1981 the US State Department rescinded a permit granted to Caterpillar Tractor for the sale of 200 pipelayers, valued at 80 million dollars, to the Soviet Union for use on the Siberian gas pipeline[75]. The episode showed that a pipeline depends on specialised machines, pipelayers, turbines and compressors, many of which come from a short list of manufacturers, and that a pipeline built to move gas across a border can become a lever in international politics before a single cubic metre has flowed.

Station anatomy

A station contains more than compressors. Gas enters through scrubbers and filters that remove liquids and solids, passes through the compressor units, and is cooled in an aerial after-cooler, because compression generates heat that must be dissipated before the gas leaves the station[76]. Large valves let the operators route the gas through any unit, bypass the station, or isolate it. A relief and blowdown system lets the station vent gas safely in an emergency. A control room monitors every unit and reports to the pipeline's central control centre.

INGAA notes that reciprocating units let the volume be adjusted in small steps to follow demand[72].

CHAPTER 10

Linepack, storage and the winter problem

A gas pipeline is also a tank. A section of 36-inch pipe a hundred kilometres long, at 70 bar, holds a large volume of gas, many millions of cubic metres once the volume is measured at standard conditions. This stored gas is called linepack, and operators define it as the total volume of gas contained within the system[77]. Linepack matters because demand on a gas system does not match supply minute by minute. Households use gas in the morning and evening, power stations in the afternoon peak, and everyone uses more on a cold day. A pipeline can absorb a surplus or cover a shortfall for a few hours by letting its pressure rise or fall within its permitted range. That flexibility is free but limited, and for longer imbalances the system needs storage.

Underground storage

The standard answer is to store gas underground, close to the market, in geological formations that can hold it at pressure. There are three principal kinds, and the global survey of storage groups facilities in just these categories: depleted gas fields, aquifers and salt caverns, with smaller numbers in oil fields and rock caverns[78]. The same survey reports that working gas capacity worldwide reached a record 445 billion cubic metres at the end of 2024[78]. A depleted gas field is the cheapest: a reservoir that held gas for millions of years already has a seal and a set of wells, and re-injecting gas into it is natural. Aquifers are water-bearing formations with a suitable cap rock, and need more work. Salt caverns are made by dissolving a hole in a thick salt bed with fresh water, producing a vessel with smooth walls that can be filled and emptied quickly, which suits short-term balancing.

The pattern of use is seasonal. The US Department of Energy describes storage as historically a demand sink in summer, when demand is low, and a supply source in winter, when demand is high[79]. A storage facility is therefore a companion of the pipeline.

When a storage well fails

The risk of this arrangement was made visible in October 2015 when a well at the Aliso Canyon storage facility, outside Los Angeles, blew out. The leak ran from late October 2015 until it was sealed in February 2016. Aircraft measurements between 7 November 2015 and 13 February 2016 found atmospheric leak rates of up to 60 metric tons of methane per hour. At its peak the blowout effectively doubled the methane emission rate of the entire Los Angeles basin, and in total it released 97,100 metric tons of methane to the atmosphere[80]. The California Air Resources Board and the operator developed an agreement to mitigate the impact of the leak by 109,000 metric tons of methane-equivalent emissions[81].

Aliso Canyon is a reminder that storage is not passive. A reservoir kept at high pressure for decades, penetrated by dozens of old wells, depends on every well casing and valve being sound. After the blowout, regulators in several jurisdictions reviewed storage-well rules, and the episode became a reference point in the methane debate discussed in Chapter 22.

The shock of Uri

Winter is when the system is tested. In February 2021 a severe cold event, Winter Storm Uri, caused numerous outages, de-rates and failures to start at electric generating plants across the region. The Texas grid operator ordered 20,000 megawatts of rolling blackouts. The federal energy regulator's account of the joint report with the reliability corporation adds that natural gas fuel supply problems came from production declines, of which 43.3 per cent were caused by freezing temperatures and weather[82]. The episode exposed a dependency between the two systems: gas-fired power stations need gas deliveries, and the gas system needs working equipment and power. In a deep freeze, a failure on one side can reach the other.

The lesson for pipelines is that the physical network is only part of the system. A pipeline can be sound and still deliver nothing because the wells that feed it have frozen or the electric motors that drive its compressors have lost power. Operators increasingly study gas and electricity as one coupled system. Storage also has a

strategic use. When a supplier is cut off, a buyer with full storage has time to find a substitute. Europe's experience after 2021 made this plain, and Chapter 15 returns to the European storage rules.

CHAPTER 11

Watching the pipe: meters, odour and pigs

An operator who cannot see a pipeline must infer its condition from measurements. The industry built a set of tools for this, and each one was made in response to something that went wrong.

Counting the gas

Every transfer of gas from one party to another is a sale, and a sale needs a count. Custody-transfer metering must be accurate to a fraction of one per cent, because small percentages on large flows are large sums. The traditional instrument is the orifice meter, a plate with a hole in it placed in the pipe. The pressure drop across the hole depends on the flow. In the last few decades multipath ultrasonic meters, which time sound pulses travelling with and against the flow along several paths across the pipe, have become standard for large flows. A manufacturer notes that they have been used in custody transfer and fiscal measurement applications for more than 35 years[83]. The meter is paired with a gas chromatograph that analyses the composition, because the energy content of the gas, not just its volume, is what is sold.

Teaching a smell to a gas

Natural gas is nearly odourless, which is a problem for a fuel that kills by explosion and asphyxiation. On 18 March 1937 the school in New London, in the East Texas oilfield, exploded just after the school day's end, killing about 298 of the roughly 500 students and 40 teachers in the building. The school's plumbers, with the school board's approval, had tapped a residue gas line of a nearby gasoline plant to save a monthly gas bill. The practice of using "green" or "wet" gas to save money was common. No one smelled a leak, because the gas had no odour[84].

The most important result of the disaster was a state law. House Bill 1017 of 1937 gave the Texas Railroad Commission authority to adopt rules on the odorisation of natural gas[85]. Other places had learned the same lesson in smaller ways. A history

of odorants records that after several explosions followed Los Angeles's switch to natural gas in 1927, the city's providers began testing odorants, and that other cities followed[17]. Today every distribution system adds an odorant, a sulphur compound with a strong smell, at a concentration that makes a leak noticeable well below the level at which it could burn. The smell of a gas stove is the memory of New London, built into the product.

Looking inside: the pig

Inspection from outside is of little use for a buried pipe. The industry sends instruments down the inside. Cleaning pigs reduce build-up of waxes and other contaminants, and smart pigs, or in-line inspection tools, travel through the pipe and record irregularities that may be corrosion, cracks, laminations or dents[86].

Instrumented pigs, often called smart pigs or in-line inspection tools, grew from the 1950s. A trade history notes that the earliest attempts to retrieve information from a pig came in 1959, when T. D. Williamson introduced a caliper tool for detecting dents, while Pan-American Petroleum developed a tool using magnetic flux leakage, and Shell Oil was developing a technique based on remote-field eddy currents. The same history says Tuboscope, which already made a tool to find defects in oil-well casing, was asked by clients to build a pipeline version[87]. Another account dates the first commercial smart pig to 1964, built by Tuboscope with magnetic flux leakage technology. It had six sensors and inspected only the bottom quarter of the pipe wall, recorded on reel-to-reel magnetic tape, and had no odometer wheels[88,89]. High-resolution tools followed in the 1970s[89].

A magnetic flux leakage tool induces magnetic flux into the pipe wall. Where there is metal loss, the flux leaks out of the wall in a saturated pipe, and sensors on the tool detect and measure it[86]. Ultrasonic tools measure wall thickness and metal loss, and transverse flux tools can detect axial defects such as stress corrosion cracking that conventional magnetic flux leakage and ultrasonic tools miss[86].

Control from a distance

All of this information flows to a control centre. PHMSA's control-room rules cover the controllers, control rooms and SCADA systems used to monitor and control pipeline operations remotely[90].

A sound system is not only instruments. It is the habit of reading them. The history of pipeline safety, told in Part VI, is in large part a history of organisations that collected good data and failed to act on it.

PART IV
THE GREAT LINES

CHAPTER 12

The American grid: from the Panhandle to the Marcellus

The United States built the first continental gas network, and it built it in three bursts: the late 1920s and 1930s, when welded steel made long lines possible; the late 1940s and 1950s, when war surplus and postwar demand multiplied them; and the 2000s onwards, when shale gas reversed the direction of the flows.



Selected milestones from Part IV: year of completion or entry into service, as given in the text. Positions along the line are schematic, not to scale.

The 1930s: Texas to Chicago

The first burst is the Texas-Chicago line of 1931, completed on 5 August, which Chapter 5 described: more than 900 miles, 24-inch pipe, ten compressor stations, described by its operator as the longest gas pipeline in the world at that date[35]. Its logic was the one the industry has followed ever since. A very large field, in this case the Texas Panhandle, was a long way from a very large market, the Chicago area. A pipe that linked the two earned its money from the difference in value between gas at the field and gas in the city.

The war and the Inch lines

The second burst began with a war. In 1942 German submarines were sinking tankers off the American coast, and the shipment of oil from Texas to the Northeast by sea was no longer safe. The federal government, with industry, built two petroleum pipelines from Texas to the East Coast, the Big Inch for crude oil and the Little Big Inch for refined products. Work began on the Big Inch on 3 August 1942. The second line ended at Linden, New Jersey, and was completed on 2 March 1944. The two lines cost 146 million dollars, financed entirely by the Reconstruction Finance Corporation, and carried over 350 million barrels of oil and products to the East Coast before the war in Europe ended, in May 1945, a record kept by the Texas State Historical Association[91].

They were oil lines, not gas lines. Their significance for this book is what happened after the war. The lines became the subject of a fight between the oil and gas industry, which wanted them converted to natural gas, and the railroad and coal industries, which opposed it. After auctions that failed and a lease to Tennessee Gas and Transmission for the winter of 1946-47, the lines were sold. The high bid, 143,127,000 dollars, came from a new corporation, Texas Eastern Transmission Corporation, and the purchase was final on 14 November 1947[91]. Texas Eastern converted the lines to natural gas[92], and today its system is the backbone of Enbridge's US gas transmission network[92].

One of the losing bidders went on to build something larger. A company organised in October 1948 as Transcontinental Gas Pipe Line Corporation set out to build

what would be the world's longest pipeline, 1,832 miles from Hidalgo County in Texas to New York City. Ground was broken in May 1949. More than 540,000 tons of steel were used, and 40 rivers were crossed[34]. A company history says its president, Claude Williams, had earlier pulled together investors to bid for the government's Inch lines, a bid that failed[93]. Transco entered service in 1950, and today carries about 16 per cent of the natural gas consumed in the United States, over a network of nearly 10,000 miles[94].

The line remains in service decades later, and Chapter 6 describes the coatings, cathodic protection and inspection that pipelines depend on for a long life.

What the grid looks like

In the 2025 annual reports to the national pipeline-safety regulator, operators reported 300,217 miles of natural gas transmission pipeline[12] and 1,394,662 miles of distribution mains[13], along with 113,143 miles of gathering lines[12]. Texas alone has 58,588 miles of gas pipeline, ahead of Louisiana with 18,900, Oklahoma with 18,539, Kansas with 15,386, Illinois with 11,900 and California with 11,770[23]. Those figures describe a network whose shape mirrors the geography of production: dense around the Gulf Coast and the Midcontinent, where the gas was.

The third burst: flows reverse

The shale revolution changed where the gas came from. The US Energy Information Administration describes Appalachia, meaning the Marcellus and Utica/Point Pleasant shales of Ohio, West Virginia and Pennsylvania, as the largest natural gas producing region in the United States in 2020[95]. Pipelines built to carry gas east from the Rockies felt the change. The Rockies Express pipeline, built to carry gas east, had by 2015 incrementally increased its westward capacity to 1.8 billion cubic feet a day[96].

That is an illustration of a basic property of pipelines: they are fixed, but the flows they carry are not. The steel in the ground can outlast the market it was built for, and the Big Inch lines, which changed from oil to gas, are the earlier example.

CHAPTER 13

A country built around a pipe: Canada

A pipeline can decide who owns a country's gas, and in Canada it nearly decided the government. Alberta had large gas reserves in the 1950s and a small local market. Ontario and Quebec had the market and no gas. The question was whether to build a line from one to the other, who would own it, and which route it would take.

The company

The company was incorporated by an Act of Parliament on 21 March 1951 under the name Trans-Canada Pipe Lines Limited. It was a subsidiary of Canadian Delhi, a company through which the Texas oilman Clint Murchison led natural gas exploration in western Canada[97]. A competing group proposed a route that would run through the United States. The plan favoured by the Canadian government was an all-Canadian route, which meant crossing the rock and muskeg of northern Ontario north of Lake Superior, some of the most difficult terrain a pipeline could take. The all-Canadian route was longer and costlier, and the private market would not finance it alone.

The Pipeline Debate

The Liberal Minister of Trade and Commerce, C. D. Howe, decided that a pipeline carrying Alberta gas to central Canada was a national necessity[98]. Between 8 May and 6 June 1956 the House of Commons fought one of the most famous confrontations in Canadian parliamentary history over a bill to give the company a federal loan for the northern Ontario section, the Pipeline Debate[98]. The debate was bitter largely over procedure: the government used closure to force the bill through. The pipeline became a symbol of the argument about American ownership of Canadian resources, and the government was defeated the following year. The federal government's help was arranged through a Crown corporation that built the northern Ontario section and leased it to the company.

The build

The construction was done at speed. In the first three years of construction, 1956 to 1958, workers installed 3,500 kilometres of pipe, stretching from the Alberta-Saskatchewan border to Toronto and Montreal[99]. The financing was split 50-50 between American and Canadian interests[99]. Gas service to Regina and Winnipeg began in 1957[99]. Alberta's own energy history describes the result as the first gas piped to eastern Canada over a single pipeline, longer than any other single length of pipeline in North America at that time[100].

The line that was not built, and the treaty that was

A later project shows how far the politics of a pipeline can go. In the 1970s several companies proposed pipelines to carry the gas of Alaska and northern Canada south. The Canadian National Energy Board held 214 days of hearings in 1975 to 1977. The agency's history records that the favoured route followed the Alaska Highway, developed by Foothills Pipe Lines in 1976, and that a treaty between Canada and the United States concerning transit pipelines was initialled on 28 January 1977 and ratified by the US Senate on 3 August 1977[101]. The treaty bound the two countries to let pipelines cross each other's territory without discrimination. A pipeline that crosses a border needs more than a permit. It needs a promise that both countries will keep the valve open.

What Canada shows

Three lessons carry beyond Canada. First, a pipeline is an instrument of national policy as much as a commercial project: governments decide routes, loans and ownership, because the pipe binds regions together. Second, the cost of crossing difficult ground, muskeg, rock and permafrost, is a driver of both the engineering and the politics. Third, once laid, the pipeline becomes the spine of a market. After 1958, Toronto and Montreal could burn Alberta gas, and an industry of distribution companies, appliance makers and industrial users grew on it.

CHAPTER 14

The Soviet Union and the long road west

The Soviet Union built the longest gas pipelines in the world and made gas a lever of foreign policy. The system began, as many systems did, with a local line.

From Elshanka to Moscow

In 1941 industrial gas reserves were found at Elshanka, 16 kilometres from Saratov, and a pipeline built in about six weeks took the gas to the Saratov power station, according to a Russian industry article[102]. In 1944 the State Defence Committee decided to build a line to Moscow. A Russian-language encyclopedia gives its length as 843 kilometres, with six compressor stations, a pipe 325 millimetres in diameter and a pressure of 5.5 megapascals, and its start of operation as 11 July 1946[103]. The same industry article calls it the first long-distance gas pipeline in the Soviet Union[102]. Both are Russian-language sources.

Brotherhood: exports begin

Exports to the west began in the 1960s. The operator of Ukraine's gas transmission system records that in 1967, after the Dolyna-Uzhhorod-Western Border pipeline, called Brotherhood, was commissioned, supplies of Ukrainian and Russian gas to Central and Western Europe began[104]. Naftogaz dates the first export, to Czechoslovakia, to 1967, and records that in 1978 the Soyuz pipeline was put into operation as the first transcontinental gas pipeline[105]. The first Western contract came in 1968. On 1 June 1968 the Soviet foreign-trade company Soyuznefteexport and the Austrian oil company OMV signed an agreement for gas supplies from the USSR to Austria[106]. The reasoning on both sides was practical: the USSR wanted hard currency and Austria wanted a second source of fuel, and the contract was the first of a long series.

Urengoy

The biggest project came in the early 1980s. The Urengoy-Pomary-Uzhgorod pipeline took gas from the giant Urengoy field in western Siberia 2,765 miles to the western border. A Soviet pipeline-construction journal called it the country's most important technical and economic goal for 1983, and described its scale: 2.7 million tonnes of pipe, 40 compressor stations over 3 million kilowatts, more than 1,200 miles of weld joints and 794 water crossings, with staged operation so that underground storage could be filled before winter[33].

The line arrived in a political storm. The Reagan administration sought to halt Western help for the project, including the Caterpillar pipelayers described in Chapter 9[75]. The European governments, whose firms were supplying equipment and who were to buy the gas, opposed the American measures. The line was finished anyway.

Yamal, the long road and the middle country

Russian gas reached Europe by several routes over the following decades, and the geography mattered. Much of it crossed Ukraine. A route through Belarus and Poland, the Yamal-Europe line, runs across four countries, Russia, Belarus, Poland and Germany, with a design capacity of 32.9 billion cubic metres a year, reached in 2006[107]. Routes under the sea, Nord Stream across the Baltic and TurkStream across the Black Sea, were built to bypass transit countries, a story told in Chapter 15.

The old Ukrainian transit route ended on 1 January 2025. The operator of Ukraine's system said that from 7 a.m. Kyiv time that day the system was operating without Russian gas transit[108]. After that, The Guardian reported, TurkStream was the only Russian gas route to Europe still in operation[109]. Russian pipeline supplies to Europe, according to TASS estimates based on Gazprom and ENTSOG data, rose by 14 per cent in 2024 to 32.1 billion cubic metres from about 28.15 billion in 2023[110]. The scale of the change since 2021 is considerable. In 2021, Russia supplied the European Union with 157 billion cubic metres, about half of its gas imports[111]. In 2024 the EU still imported 52 billion cubic metres of

Russian gas, 32 by pipeline and 20 as liquefied natural gas, about 19 per cent of its total gas imports, according to the European Commission[112].

What a unified system means

Inside Russia the system is one machine. Gazprom operates the Unified Gas Supply System, which delivered a record 395.8 billion cubic metres to the domestic market in 2024, according to the company's sustainability report[113]. The ranking site LNG Atlas, built from Global Energy Monitor data, lists Gazprom as the largest gas pipeline owner in the world, with 145,071 kilometres of attributed pipeline length, ahead of Kinder Morgan with 63,020 kilometres. It cautions that its numbers are a floor[114]. The reasons are partly geography and partly politics: a state with enormous reserves far from its cities and its customers builds a very long network under a single owner.

CHAPTER 15

Under the sea, and Europe's choices

Europe has little gas of its own beyond the North Sea, so it built a network of imports. The pipes came from four directions, and the sea was crossed more than once.

A field that fed a continent

In 1959 a very large gas field was found near Groningen in the north of the Netherlands, with production from 1963 and a peak year in 1976[115]. Its contracts allowed large daily and annual swings in the volume taken, and later export contracts from other suppliers could not easily replicate that flexibility[116]. The cost fell on the ground above. The Huizinge earthquake of 16 August 2012 put the damage to houses on the political agenda[117], and extraction at Groningen ended on 1 October 2023 after 60 years[118].

The first pipe across a sea

The first intercontinental gas pipeline system joined Algeria to Italy[119]. Built by 1983, the Trans-Mediterranean line runs through Tunisia, crosses the Strait of Sicily to Sicily, and had a capacity of 30.2 billion cubic metres a year[120]. Its length is given as about 2,500 km by one source; other sources give lower figures, and the book does not rely on a single number. The sea crossing was the hard part, with a depth that the sources record differently, which is why this book says only that it was several hundred metres deep.

Other crossings followed. Bacton in England to Zeebrugge in Belgium is the route of the Interconnector, operating since October 1998[121]. A direct subsea link, the Medgaz line, runs from Beni Saf in Algeria to Almeria in Spain; its operator gives its capacity as 10.16 bcm a year after a fourth compressor entered service at Beni Saf on 1 July 2022[122]. The Baltic Pipe, inaugurated at Goleniow in Poland on 27 September 2022, brought Norwegian gas to Poland through Denmark[123], and was fully operational in November 2022[124]. And the Trans Adriatic Pipeline, 878 km

through Greece, Albania, the Adriatic Sea and Italy, began commercial operations on 15 November 2020[125].

The longest of them

Langeled brought Norwegian gas from Nyhamna to Easington on the English coast, and Norwegian exports through it began on 1 October 2006[126]. Sources give its length as 1,164 km[127] and 1,173 km[128], the difference probably reflecting what is counted, and the second source calls it the world's longest subsea gas pipeline. It is made of 42 to 44 inch pipe and has a capacity of 25.5 bcm a year[127]. The Norwegian line is a reminder that Europe's pipes were not all about Russia: Norway became the supplier whose gas arrived by a route that crossed no third country.

Nord Stream

The most contested sea pipeline was Nord Stream, which took Russian gas under the Baltic directly to Germany. Its two strings run 1,224 km and could carry 55 bcm a year[129]. Construction began in April 2010, the first string came into service in November 2011 and the second in October 2012[129]; Reuters put the cost of the first project at 7.4 billion euros[130]. A second pair of lines, Nord Stream 2, cost about 9.5 billion euros[131]. Germany halted its certification on 22 February 2022, after Russia recognised two regions in eastern Ukraine[132]. On 26 September 2022 seismic networks detected two events near Bornholm, and pressure drops were reported on three of the four strings of Nord Stream 1 and 2[133]. Gazprom has said that the Nord Stream lines had no intermediate compressor stations, relying on compression at the shore; the claim is the company's own.

What the choices were

Europe's pipelines made a set of political choices solid. Russia's pipes, Norway's, Algeria's and the Caspian's each created a dependence, and each could be turned off or bypassed. In 2021 Russia supplied the EU with 157 bcm[111]. The Maghreb-Europe line, 1,400 km long and in service since 1996, carried more than

10 bcm a year via Morocco until Algeria ordered an end on 31 October 2021[134]. The pattern since has been to replace pipes with liquefied gas from tankers and with new interconnectors, a theme of Chapter 25.

Europe's answer: fill the tanks

The practical response to 2022 was storage. A regulation adopted on 27 June 2022 required member states to fill underground storage to at least 80 per cent of capacity before the winter of 2022/23 and to 90 per cent before later winters[135]. It treats stored gas as a strategic reserve, the idea of Chapter 10 turned into law.

CHAPTER 16

China and Asia: building a grid in twenty years

China was a late and fast builder. Its first big gas pipeline, the West-East line, was built in the early 2000s to carry gas from Xinjiang to Shanghai.

West-East

Construction of the first West-East Gas Pipeline began on 4 July 2002. The line is 3,843 km long, was connected in full on 1 October 2004, and carried 12 bcm a year at first, rising to 17 bcm by the end of the decade[136]. From it grew a national network, fed from three directions.

The second line

The second West-East line was far larger. It became fully operational on 30 December 2012: 8,704 km from Horgos on the Kazakh border in Xinjiang to Hong Kong, made of one trunk line and eight regional lines, crossing 15 provincial regions, at a cost of 142.2 billion yuan and a design capacity of 30 bcm a year[137]. The National Energy Administration's account adds that it has 87 stations and 321 valve chambers, and that its completion connected 20 built and under-construction pipelines into a network of nearly 40,000 km[138]. Xinhua describes it as carrying gas from Central Asia to Shanghai, Guangzhou and Hong Kong[137].

From the west and the south

From Central Asia the Turkmenistan-China pipeline, 1,830 km, opened Line A in December 2009 with 15 bcm a year, and Line B in October 2010 with 15 bcm[139]. From Myanmar, a 793 km line from the Bay of Bengal to Yunnan carries 12 bcm a year[140]. From the north, the Power of Siberia line, a 3,000 km pipeline, was launched in December 2019[141]. Gazprom gives its export capacity as 38 bcm a year, drawn from the Chayandinskoye and Kovyktinskoye fields[142]. A

memorandum on a second line, Power of Siberia 2, through Mongolia, was signed in 2025, with the price and timeframe unclear[143].

How big it became

China's national reporting counts long-distance gas pipelines at 124,000 km in 2023, up by more than 4,000 km in a year[144]. The China-Russia East Route, the line that carries Power of Siberia gas, was reported fully connected in December 2024, 5,111 km from Heihe to Shanghai through nine provinces after nearly ten years of construction[145]. In 2024, according to the Institute for Energy Research, China imported 43 per cent of its gas supply, 182.2 bcm, and over half of that, 105.6 bcm, arrived as liquefied natural gas[146]. The remainder, about 76.6 bcm by subtraction, came by pipeline, so the pipes from Central Asia, Myanmar and Russia sit next to a larger flow of tankers.

The reform

China's pipes were long owned mostly by the large state companies. In December 2019 it created a national pipeline company, PipeChina, to open access to the infrastructure[147]. The new firm was assembled from midstream assets including pipelines, LNG terminals and storage[148]. The reform reached the price as well as the ownership. In December 2023 the National Development and Reform Commission set tariffs for PipeChina's inter-provincial lines by region for the first time, in four zones: Northwest, Northeast, Central-East and Southwest. The number of tariff rates fell from 20 to 4, and the price of a movement is calculated from the zone's rate and the distance between the point where gas enters and the point where it leaves, and published[149]. A consultancy report on the change says most charges fell, that the Southwest zone has the highest tariff, and that new pipelines will follow the zone benchmark instead of a separate trial tariff in their first years[150]. The same report says the three state oil companies were still the main users of the service, though in the north and the eastern section of the West-East system other shippers had grown significant[150].

By its own description it now runs about 63,800 km of gas pipelines with a primary transport capacity of about 420 bcm a year, linking 25 domestic sources,

the import pipelines from Central Asia, Russia and Myanmar, 25 LNG terminals and 21 underground storage facilities[151].

Lines that stalled

Asia also shows pipelines that took years and sometimes were not built. The Hazira-Bijaipur-Jagdishpur line in India, 1,850 km, was installed in 1986 to 1989[152]. The Iran-Pakistan line was planned at 2,775 km, with construction beginning in 2011[153]. TAPI, from Turkmenistan through Afghanistan and Pakistan to India, has seen 14 km of pipe installed in Herat province in Afghanistan[154]. A pipeline needs a buyer, a seller and security of passage in every country on the way. When one is missing, steel sits in a yard.

CHAPTER 17

Other continents

The same logic, a field in one place, a market in another and a border in between, runs through the lines of the southern hemisphere and the Gulf of Guinea.

South America: Bolivia to Brazil

The Bolivia-Brazil pipeline, Gasbol, is 3,150 km long and has operated since July 1999[155]. It came after years of negotiation: Brazil and Bolivia signed a letter of intent on energy integration in November 1991 and a gas sales contract in February 1993, which could take effect only when financing was found[156]. Construction began in 1997[157]. Gasbol carried Bolivian gas to Sao Paulo and beyond, and it tied two economies together on a single supply route. Its 20-year supply contract later came up for renewal, and the talks were complicated by uncertainty over how much Brazilian pre-salt gas could be commercialised and by Bolivia's need to add reserves to keep supplying[158].

West Africa: a line under the sea

The West African Gas Pipeline is 678 km long. It starts at Itoki in Nigeria, joins the existing Escravos-Lagos system and runs offshore east to west to Takoradi in Ghana, with branches to Cotonou in Benin, Lome in Togo and Tema in Ghana. The main line is 20-inch pipe laid at an average water depth of 35 metres, in places 50 to 70 metres, and as close to the coast as 6.5 km[159]. Eighty-five per cent of its gas goes to power generation, and the foundation customers were the Takoradi power plant in Ghana and the electricity utilities of Benin and Togo[159]. The project was reviewed by the World Bank's Inspection Panel, whose 2008 investigation report led to a management action plan[160]. The line shows a pipeline used to build a regional electricity market rather than serve a single city.

North Africa: one gas, two routes

Two lines carry Algerian gas to Spain. The Maghreb-Europe line, 1,400 km long and in service since 1996, ran through Morocco and carried more than 10 bcm a year until Algeria ordered an end on 31 October 2021[134]. The Medgaz line, from Beni Saf in Algeria to Almeria in Spain, crosses the sea directly[122]. The same seller, the same buyer, two routes: one went through a third country and one did not, and only one was left running.

PART V
MONEY, LAW AND LAND

CHAPTER 18

Who may carry, and who may sell

A pipeline is a natural monopoly: it makes no sense to lay two pipes where one will do. Every gas country has had to decide what the owner of the only pipe may do with that power. The American answer took more than fifty years and went through a famous failure, and it is worth following in order because Europe, Russia and China each reacted to it.

The Natural Gas Act

Regulation began locally. In the nineteenth century gas was made from coal and delivered inside one city, and city governments, seeing a natural monopoly, regulated it[161]. When interstate pipelines like the 1931 Texas-Chicago line appeared, no state could regulate a pipe that crossed its neighbours. The Natural Gas Act of 1938 gave that job to the federal government. It regulated pipeline rates and the building of pipelines, but did not set the price producers received at the wellhead[161].

Phillips and the shortage it made

In 1954 the Supreme Court decided Phillips Petroleum Co. v. Wisconsin. It held that producers selling gas into interstate pipelines were "natural gas companies" under the Act, and so were subject to federal oversight of their prices[161]. The Federal Power Commission set prices by the cost of service, which was workable for a handful of pipelines but not for thousands of producers. In 1959 it faced 1,265 applications for rate increases or reviews and could act on 240. In 1960 it switched to prices by region, but by 1970 it had fixed rates for only two of five areas, and in most areas prices were frozen near 1959 levels. In 1974 it set a national ceiling of 42 cents per thousand cubic feet[161].

The effect was the opposite of what was intended. Prices held below market value raised demand and cut the reward for finding new gas. The federal commission controlled only gas sold across state lines, so producers could sell for more inside

the producing state. In 1965 a third of proved reserves were committed to intrastate buyers; by 1975, almost half. In the winters of 1976 and 1977 schools and factories in the Midwest closed for lack of gas, while the producing states felt little shortage[161]. Congress answered with the Natural Gas Policy Act of 1978, and the long move to deregulation began. The first federal safety statute is separate, and had followed in 1968[162].

Unbundling

The central change was FERC Order 636, the Restructuring Rule, issued on 8 April 1992[163]. It required pipelines to separate their sales of gas from their transportation of it, and created unbundled services, including firm and "no-notice" transportation, storage, and a programme for releasing unused capacity to others[164]. Before it, a pipeline bought gas at the wellhead and resold it to the local utility; after it, the producer and the utility could deal directly and the pipeline sold a service, not a molecule. That change is what made the trading hubs of Chapter 19 possible.

The European contract

Europe had no such history of price controls but built a contract instead. Long-term supply contracts tied the gas price to the price of oil products and carried take-or-pay obligations, under which a buyer pays for a minimum volume whether or not it takes it[165]. The arrangement put volume risk on the buyer and price risk on the seller, and it let a producer borrow against a long, certain income to build a pipeline. From about the end of 2008, as hubs grew, a hybrid market appeared in which hub prices competed with oil indexation[165].

CHAPTER 19

Price, hubs and bottlenecks

Where several pipes meet, a price can be set. The place is called a hub. A hub price is a measure of scarcity at that place, and it is only as good as the pipes around it.

Henry Hub

Henry Hub is in Erath, Louisiana, a nexus of interstate and intrastate pipelines[166]. NYMEX natural gas futures began trading on 3 April 1990, with Henry Hub as the delivery point near Lafayette[167]. The order of events matters. Open access and unbundling in the late 1980s and early 1990s had let buyers and sellers deal directly. A futures contract needed a place where they could physically meet. A physical interchange where many lines joined served as one, and the price of US gas has since been quoted relative to this one place.

A winter in Boston

A price at one place can split from the national price when the pipes into that place are full. In New England the two big lines, Tennessee and Algonquin, carry about 3.5 Bcf/d into the region. That capacity is greater than average January consumption, but the peak days decide the stress on the system, and in the winter of 2013-14 LNG deliveries fell and the lines were congested[168]. The gap between a regional hub and Henry Hub is called basis, and the January 2014 forward basis for New England settled at $17.41 per million British thermal units[168]. At the Algonquin Citygate hub serving Boston the day-ahead price averaged $22.53 from 1 January to 18 February 2014, a record for the series that began in 2001, and the February bidweek price reached $33.79[169]. Gas was the same molecule as in Louisiana. What differed was the room in the pipe.

A hub with no ground

In Europe the hub is a point on paper. The Title Transfer Facility, set up by Gasunie in 2003, is a virtual transfer point inside the Dutch transport network, where a party can pass gas already in the system to another by nominating the volume, the period, the buyer and the seller. Its traded volume is now the largest in Europe, more than eighty times what the Netherlands consumes[170]. The daily spot price peaked in March 2022, stayed mostly below 100 euros per MWh in April and May, rose again from June, and set an all-time high of 316 euros on 26 August[171]. A price quoted in one small country could rise so high because the pipelines that had delivered Russian gas, described in Chapters 14 and 15, were no longer open.

Britain's equivalent is the National Balancing Point, a gas exchange rather than a place. When Norwegian gas began to flow through the Langeled pipeline on 1 October 2006, the seller was already selling it on the NBP[126]. Hubs matter to contracts as well as to traders. The International Energy Agency reports that the share of oil-indexation in Europe's import prices fell from above 90 per cent in 2005 to below 25 per cent in 2019, as buyers moved to hybrid and hub-indexed formulae[172].

Ships without a hub

Pipes need a hub because gas stays where the pipe puts it. LNG cargoes can change destination, and an Asian LNG benchmark, the Platts JKM, is an assessment rather than a point on a map. It reflects the spot value of cargoes delivered ex-ship to Japan, South Korea, China and Taiwan, assessed each day from reported trades, bids and offers, and it is referenced in spot deals and in short-, medium- and long-term contracts[173]. The industry body GIIGNL says that recently signed LNG contracts are priced against a variety of indices: oil, JKM, TTF, AECO and mixed baskets[174].

When the pipe is full

A hub price can also be negative. In West Texas gas production outran pipeline capacity, and the price at the Waha hub traded below zero on 42 per cent of trading days in 2024[175], meaning producers paid to have gas taken away. A producer could not burn the gas safely or store it cheaply, and no pipe could carry it out. Relief came with the Matterhorn Express, the first new large gas pipeline out of the Permian in years[176]. The owner describes it as an approximately 580-mile intrastate line designed for up to 2.5 billion cubic feet a day to the Katy area near Houston[177], and the federal energy statistics agency lists the same 2.5 Bcf/d capacity[178]. The same lesson applies in both continents. The steel decides the price: where there is spare pipe, prices converge, and where there is not, they split.

CHAPTER 20

Land, law and the right to cross

A gas pipeline crosses thousands of properties, and a single holdout could stop it. The legal tool that prevents this is eminent domain. Section 7(h) of the Natural Gas Act lets a company holding a certificate of public convenience and necessity from the federal regulator take the easements it needs from owners who refuse[179]. In 2021 the Supreme Court extended that to land in which a state holds an interest. In PennEast Pipeline Co. v. New Jersey it held, five to four, that the section authorises certificate holders to condemn all necessary rights-of-way, whether owned by private parties or by states[180,181].

The power makes pipelines possible, and it makes them contested. Two Appalachian lines show the range of outcomes.

Mountain Valley

The Mountain Valley Pipeline is about 303 miles long, carries up to 2 billion cubic feet a day, crosses the Appalachian Trail and ran years behind schedule[182]. It was first estimated at 3.5 billion dollars in 2018, and a regulatory filing put its cost at almost 10 billion[183]. In 2023 the dispute reached Congress. Section 324 of the Fiscal Responsibility Act of 2023, the law that suspended the debt ceiling, directed federal agencies to issue the necessary permits and limited the courts' jurisdiction over challenges[184]. Opponents, including climate and conservation groups and residents along the route, objected[185]. The operator says the line entered service on 14 June 2024[186].

Atlantic Coast

The Atlantic Coast Pipeline went the other way. Dominion and Duke cancelled it on 5 July 2020, with about 8 billion dollars of cost and uncertainty over permitting and litigation[187]. Its estimates had risen from 4.5 billion to 8 billion after legal challenges[188].

Constitution

The Constitution Pipeline shows a different gate. It was a 121-mile line through Pennsylvania and New York, about 98 miles of it in New York. Federal approval does not remove the state's role under the Clean Water Act: the New York Department of Environmental Conservation denied the water-quality certification in a letter of 22 April 2016, saying the company had not given enough information. In August 2017 the Second Circuit held that the denial was within the state's statutory authority and not arbitrary or capricious[189].

What the owner of the land keeps

For most landowners the experience is an easement, not a lawsuit. FERC's guide for landowners says the company negotiates the easement and the compensation with each owner. The construction right-of-way is generally 75 to 100 feet wide and the permanent one about 50 feet. The owner keeps title and pays the taxes, but trees whose roots could damage the pipe or its coating, and anything that blocks inspection from the air, are generally not allowed on the strip[190].

Whose land it is

In Canada the question can be who has the authority to agree. The Coastal GasLink pipeline, 670 km and costing $6 billion in CBC's account, had agreements with 20 First Nations band councils, including five of the six Wet'suwet'en band councils. The Wet'suwet'en hereditary chiefs said that the councils' authority under the Indian Act covered only their reserves, and that the chiefs held authority over the nation's traditional territory. An interim injunction ordered in December 2018 that the company be allowed access along a forest service road, and on 31 December 2019 a British Columbia judge granted a further injunction after finding that the company had the approvals it needed[191]. A permit settles the law. It does not always settle who regards the route as theirs to grant.

What the cases show

None of these cases is mainly about engineering. The steel, welding and coating of Part II are the same. The difference was time and consent. A pipeline's cost rises with every year of delay, and its customers' needs can change while it waits. A company with the power to condemn land still needs to win in court, in the permitting agencies and, as Mountain Valley shows, sometimes in the legislature.

PART VI
WHEN PIPES FAIL

CHAPTER 21

Ruptures

Pipelines are among the safer ways to move energy, measured per unit delivered, but a failure releases a great deal at once. Each of the accidents below changed a rule, and each tells a different story about what goes wrong: a crack no one had known could exist, a wall eaten from inside, a weld made badly and never tested, a pipe hit by a digger.

Natchitoches, 1965

Before dawn on 4 March 1965 a 24-inch natural gas line owned by Tennessee Gas Pipeline ruptured near Natchitoches, Louisiana, and killed 17 people[192]. The New York Times reported that nine of them were children[193]. The state's pipeline safety history says the accident is credited with helping bring about the Natural Gas Pipeline Safety Act of 1968[192]. Its technical lesson was as important. The failure began in a colony of cracks on the outside of the steel. It was the first recognised case of stress corrosion cracking on a buried pipeline[194], a failure mode that had been unknown before, which is why Chapter 6 treats it separately from ordinary corrosion.

Carlsbad, 2000

At 5:26 a.m. on 19 August 2000, a 30-inch El Paso Natural Gas line ruptured beside the Pecos River near Carlsbad, New Mexico. The gas burned for 55 minutes, and twelve people who were camping under the bridge that carried the pipe across the river were killed[195]. The safety board's finding was that the wall had been reduced by severe internal corrosion, and that the operator's corrosion control programme had failed to prevent, detect or control it[196]. The failure was inside the pipe, where wet, contaminated gas had gone on working on the steel for years, which is the reason pigs and gas-quality limits matter (Chapter 11).

San Bruno, 2010

On 9 September 2010, at about 6:11 in the evening, a 30-inch section of Pacific Gas and Electric's Line 132 ruptured at an intersection in San Bruno, California. The pipe section that failed was about 28 feet long and weighed about 3,000 pounds; it was found 100 feet from a crater roughly 72 feet by 26. PG&E estimated that 47.6 million standard cubic feet of gas was released. The fire destroyed 38 homes, damaged 70 and killed eight people[41].

The safety board's probable cause had two parts. The first was the quality control of a 1956 relocation project, which allowed a substandard, poorly welded pipe section with a visible seam weld flaw to be installed; the flaw grew over time to a critical size and the pipe ruptured when pressure rose during badly planned electrical work at a terminal. The second was an integrity management programme that failed to find and replace the section[41]. Two further findings concern the rules rather than the company: exemptions of existing pipelines from the requirement for pressure testing, which would likely have found the defect, and the absence of automatic or remote-control shutoff valves, together with a flawed emergency response, which made the fire last longer than it need have[41].

Ghislenghien, 2004

On 30 July 2004 a gas pipeline at Ghislenghien in Belgium, buried 1.10 m below the surface[197], exploded after being damaged by construction work[198]. It killed 24 people and injured 132[199]. Third-party damage is the most ordinary cause of pipeline failure: someone digs where they should not.

Ufa, 1989, and Cleveland, 1944

Two older disasters involved other forms of gas but sit in the same safety record. In June 1989 gas leaked from a pipeline near the Trans-Siberian railway close to Ufa, and the cloud exploded as two passenger trains passed. Official figures put the toll at 575 killed and 800 injured, and the blast was estimated at the equivalent of 10,000 tons of TNT[200]. On 20 October 1944 in Cleveland, a tank holding liquefied natural gas equivalent to 90 million cubic feet exploded and set off the

worst fire in the city's history[201]. A history of the event counts 131 killed[202]. It was an early warning about storing gas as a cryogenic liquid next to homes.

What the list teaches

Read together, the cases make four points. A failure mode can be unknown until it happens, as with stress corrosion cracking. Defects installed on the day of construction can wait half a century, as at San Bruno. Gas that is wetter or dirtier than the design allows will corrode a line from inside. And the people nearest to a rupture are rarely the ones who made the decision that caused it. The response of regulators in each case, a statute in 1968 and revised integrity rules after the later accidents, followed the harm.

CHAPTER 22

Methane: the leak in the product

Natural gas is mostly methane, and methane that escapes is a powerful greenhouse gas. Methane is responsible for around 30 per cent of the rise in global temperature since the Industrial Revolution[203]. A pipeline is, in a sense, a long container of the stuff, so any account of pipelines has to ask how much gets out.

The size of the pipeline's share

The IEA's Global Methane Tracker puts total human-caused methane emissions at about 610 million tonnes a year, of which the energy sector is responsible for 145 Mt in 2024. Oil is the source of about 45 Mt of that and natural gas nearly 35 Mt[204]. Within oil and gas, upstream operations, the wells and the equipment around them, account for nearly 85 per cent of methane emissions, and gas transportation and other downstream operations for the remaining 15 per cent. Most of the downstream share comes from gas transportation, whether by pipeline or as LNG and regasification[204]. The Agency revised downstream emissions upward in its 2025 edition, to around 13 Mt globally from 8 Mt a year earlier, using new data on operating pipelines, measurement studies and satellite analysis[204].

So the long-distance pipe is a smaller source than the field. That is not the same as a small source, and the numbers are still being revised.

Why a pipeline releases gas

Some emissions are deliberate. Operators vent gas to inspect or maintain a pipeline, or for safety reasons, for instance when a section has to be emptied before work. Some are unintended, from a faulty seal or a leaking valve[204]. A large event, such as the Aliso Canyon blowout described in Chapter 10, is a separate kind of emission: one failure of one well released 97,100 metric tons of methane[80].

Finding and fixing

The oil and gas industry's methane emissions could be cut by around 75 per cent with well-known measures: programmes to find and repair leaks, replacement of leaking or high-emitting equipment, and plugging leaky wells[204]. The most cost-effective cuts are at leaky facilities that already have access to gas markets, because the recovered gas can be sold[204]. In the United States, facilities must report methane from equipment leaks and vented emissions under the EPA's Subpart W[205]. Measurement is improving through satellites. MethaneSAT's first look found that emissions intensity varies by region, the age of infrastructure, operating practices and pipeline takeaway capacity[206]. The last point links this chapter to Chapter 19: takeaway capacity matters to emissions, though the source does not say how much.

PART VII
WHO BUILDS IT, AND WHAT DEPENDS ON IT

CHAPTER 23

Pipe mills, pipelayers and operators

An industry study has to separate three kinds of business that get lumped together as "the pipeline company". One makes the steel. One lays it. A third owns and runs the line. They are different firms with different risks, and a given pipeline often involves all three, plus a fourth party who pays to use it.

The mills

Large-diameter line pipe is made by a small number of mills that qualify for each project. The Nord Stream projects show the pattern. For the first line, the German mill EUROPIPE, a joint venture of Salzgitter and Dillinger, supplied 75 per cent of the pipe for the 1,200 km line, and the Russian mill OMK at Vyksa the rest[207]. For Nord Stream 2 about 2,500 km of pipe, roughly 2.2 million tonnes, was divided between Europipe at 40 per cent, OMK at 33 per cent and the Russian group Chelpipe[208]. The number matters because the mill chooses nothing about where the gas goes: it sells to whoever builds, and the order books follow the pipeline map.

The pipelayers

Offshore, the second business is the vessel. Allseas won the Nord Stream 2 pipelay contract for both lines in 2018 and 2019 and planned to use three vessels, Pioneering Spirit, Solitaire and Audacia[209]. Solitaire has been laying pipe since her launch in 1998[210], and she also built the 116 km of Nord Stream Line 2 in Russian waters[211]. The pipelay firm bears the risk of weather, schedule and welding quality, and has the specialised equipment, so it is a business of its own, not a department of the pipeline owner.

The owners and operators

The third business owns the line and decides who may use it. On land, the largest names in North America show the range. Kinder Morgan says that it owns an interest in or operates about 65,000 miles of natural gas pipelines and that they carry about 40 per cent of the gas produced in the United States[212], a statement by the company itself. Williams operates Transco, nearly 10,000 miles of pipe[94]. In Russia the owner is a single group, Gazprom, with the Unified Gas Supply System (Chapter 14).

In the European Union the rules separate ownership of the gas from ownership of the network, and a transmission system operator runs each national grid. Open Grid Europe in Germany runs a network of more than 12,000 km[213]. Ownership can be shared across borders. In December 2018 a consortium of Snam (60 per cent), Enagas (20 per cent) and Fluxys (20 per cent) bought 66 per cent of the Greek operator DESFA[214]. The effect is that a company whose home market is one country may hold the grid of another.

Four parties on one line

Take a single line. A mill sells the pipe. A contractor lays it. An owner finances it and holds the right of way. Shippers, who may be gas producers, traders or utilities, buy capacity and move their own gas. Only the shipper cares about the price of gas. The owner earns a fee for capacity whether or not gas is cheap. That separation, set by the rules of Chapter 18, explains why a pipeline can be a profitable business even when the gas it carries is not.

CHAPTER 24

Fertiliser, power and the winter

Few people buy gas for itself. They buy what it does: a warm room, an electric current, a bag of fertiliser. Following gas to those uses explains why a pipeline outage reaches so far.

Gas in the bag

About 70 per cent of ammonia is used to make fertilisers[215]. The Haber-Bosch process, about a century old, fixes nitrogen from the air using hydrogen at high temperature and pressure[216]. In most plants that hydrogen comes from natural gas, so gas is both the feedstock and the fuel. The 2022 European price shock showed what follows. The industry's trade body said in August 2022 that gas cost 8 to 10 times more in Europe than in the United States, and that most European fertiliser production had been curtailed or shut[217]. That is the association's own claim. A written question in the European Parliament quoted CRU Group estimates that about half of European ammonia production capacity and a third of nitrogen fertiliser capacity had closed[218]. A change in a pipeline map in the Baltic and Ukraine, in other words, was felt in the price of food inputs.

Gas in the wire

Gas-fired power stations are the other big user. The IEA found that industry and electricity generation together accounted for around 75 per cent of the growth in gas demand in 2024[219]. The wire and the pipe depend on each other, which Winter Storm Uri showed in February 2021 (Chapter 10): generating plants failed and gas production fell, and ERCOT ordered 20,000 MW of rolling blackouts[82].

Who burns it, by sector

In the United States in 2023 the electric power sector took about 40 per cent of the gas consumed (12.93 trillion cubic feet), industry 32 per cent (10.51), homes 14 per cent (4.48), commercial buildings 10 per cent (3.31) and transport 4 per cent

(1.27)[220]. Gas supplied about 43 per cent of US utility-scale electricity generation, and about 41 per cent of the energy used in homes[220]. Homes use it for space and water heating, cooking and clothes drying, and industry uses it both as fuel and as a feedstock, a raw material for products[220]. In the United States, then, the pipeline feeds a power grid before it feeds a kitchen.

Demand now

Demand is still growing, more slowly. Global gas demand rose 2.8 per cent in 2024 and below 1 per cent in 2025[221]. Whatever its growth rate, the demand is spread across millions of burners, boilers and reactors, and the pipelines of the previous chapters exist to feed them.

CHAPTER 25

The competition from the ship

A pipeline is fixed and a tanker is not. Liquefied natural gas can go anywhere there is a terminal at each end. The growth of that trade is the main change in how the world moves gas, and it works through pipelines at both ends.

Gas as a liquid

Liquefied natural gas, LNG, is natural gas cooled to about minus 260 degrees Fahrenheit, roughly minus 162 degrees Celsius, for shipping and storage. In that state its volume is about 600 times smaller than the gas in a pipeline. The liquefaction process was developed in the nineteenth century, and it makes it possible to move gas to places that pipelines do not reach[222]. The price of the shrinkage is energy: the US Energy Information Administration estimates that 7 to 15 per cent of the gas delivered to an export plant is burned to run the liquefaction equipment[222].

The pipe at both ends

At an import terminal the LNG is unloaded from the ship, held in cryogenic storage tanks and turned back into gas, and after regasification the gas travels on by pipeline[222]. EIA describes the export plants as consuming feed gas delivered to them by the gas system. Some US power plants make and store LNG on site, and use it when electricity demand is high or when pipeline capacity is short, a practice called peak shaving[222].

What the American case shows

The United States was a net exporter of LNG from 2016 through 2023. Its baseload export capacity rose from about 1 billion cubic feet a day in 2016 to about 11.44 billion at the end of 2023. In 2016 exports averaged 0.5 billion cubic feet a day to 17 countries; in 2023 they averaged 11.90 billion to 43 countries, and made up 57 per cent of total US natural gas exports[222]. The change followed the

shale growth described in Chapter 12: more gas in the pipes, and a new way to sell it that did not depend on a pipeline reaching the buyer.

The world trade

Global LNG trade grew by 2.4 per cent in 2024 to 411.24 million tonnes, connecting 22 exporting markets with 48 importing ones[223]. Europe's LNG imports fell by 21.22 million tonnes that year, to 100.07 million, partly because storage was high at the start of the year[223]. The IEA records that global LNG supply grew 2.5 per cent, or 13 bcm, in 2024, far below the average of 8 per cent a year in 2016 to 2020, because of project delays and feedgas problems in some older producing countries[224]. Total gas demand in 2024 was about 4,166 bcm, up 2.9 per cent[225]. Looking ahead, the IEA says the US and Qatar account for 70 per cent of the roughly 300 bcm a year of new liquefaction capacity expected to come online by 2030, based on the official timelines of projects that have reached a final investment decision or are under construction[221].

Ship and pipe together

The ship does not replace the pipe. Both the Waha story of Chapter 19 and the European response of Chapter 15 show the pair working together: the ship sets the price at the margin, and the pipe decides whether a particular place can reach it.

CHAPTER 26

The pipe tomorrow

A new proposal is to use the existing steel for hydrogen. It is a different gas, and the asset is the same long, buried, regulated steel tube that the rest of this book describes. The question is how much of that asset can change its cargo.

A map on paper

The European Hydrogen Backbone initiative, a group of gas network operators, set out a vision of a dedicated hydrogen pipeline network of 39,700 km by 2040, connecting 21 European countries. Its first report, in July 2020, described 23,000 km in ten countries. In the updated vision 69 per cent of the network is repurposed natural gas pipeline and 31 per cent is new pipe, needed to reach places with small gas grids but high expected hydrogen demand. The group estimated the investment at 43 to 81 billion euros, and a transport cost of 0.11 to 0.21 euros per kilogram of hydrogen over 1,000 km[226]. These are the operators' own plans and estimates, not a built network, and the group itself says the routes and timelines are not set in stone[226].

The size of the starting point matters. The US Department of Energy puts the American natural gas pipeline network at about three million miles, against a little over 1,600 miles of dedicated hydrogen pipeline[227].

The steel problem

Transmission pipelines are generally made of low-carbon, high-strength steel, and exposure to hydrogen while the steel is under mechanical load can cause hydrogen embrittlement, which is complicated and hard to detect[228]. Embrittlement of pipeline steels has been studied extensively, and the ASME B31.12 code recommends a maximum grade of X52[229]. That is lower than the grades of modern gas lines described in Chapter 4, so many of the strongest lines may be the hardest to convert.

Blending

A less drastic idea is to blend small amounts of hydrogen into the natural gas stream. The US HyBlend initiative, led by the National Renewable Energy Laboratory with more than 30 partners, studies materials compatibility[227]. Its technical summary says that blend limits depend on the design and condition of the pipeline materials, of the pipeline equipment such as compressor stations, and of the equipment that burns the gas, such as appliances and turbines. Limits vary greatly: recently announced demonstrations and deployments ranged from below 1 per cent to 30 per cent[227]. The HyBlend programme tests pipeline materials in varying hydrogen concentrations at pressures up to 100 bar[227]. NREL's own analysis of a blending network calculates the compressor power a station needs at different blend levels[228]. There is no single safe percentage that applies to every system.

A change of gas has happened before

The pipeline industry has changed the gas in its pipes once at national scale. Britain's main conversion from town gas to North Sea natural gas ran from 1967 to 1977 and involved some 13 million customers and 40 million appliances[18]. Chapter 2 tells that story. It required a visit to every home, because the burners had to change as well as the pipes. A hydrogen conversion would have the same shape: the pipe is only one part of a system that ends in a kitchen, a boiler or a furnace.

What the history suggests

The pipelines in this book changed hands, changed direction and changed cargo. The Big Inch carried oil and then gas. Rockies Express, built to carry gas east, increased its westward capacity as the Marcellus grew[96]. A pipe is a long-lived piece of steel whose use is decided by the market around it, and the likely future is one of more adaptation rather than a single replacement.