Day 10: Inviting Disaster Ch 3

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Inviting_Disaster_Ch3

WHEN FLAGSHIP PROJECTS RUN OUT OF TIME

All of us can hope we never experience the waking nightmare that Roger Boisjoly lived through on January 28, 1986. At a teleconference the night before, regarding the launch of the space shuttle *Challenger*, Boisjoly had done all a loyal engineer could do to persuade his company, Morton Thiokol, to persuade NASA not to launch the shuttle during the bitter cold temperatures predicted for the next day at Kennedy Space Center.

At the start of the 8:45 P.M. EST teleconference between offices in Utah, Florida, and Alabama, things looked good for Boisjoly and several others at Thiokol who wanted NASA to hold off on the launch until warmer weather. Solid rocket manager Allan J. McDonald warned NASA managers that as company representative he would not sign the launch recommendation. He advised NASA not to proceed until the weather warmed enough to bring the boosters up to 53°F. Otherwise the rubber "O-ring" seals connecting the booster segments might leak, let gas burn through the steel casing, and cause a catastrophic failure.

NASA representatives replied over the telecon link that the leaking-seal problem was a known quantity and under control, and they added that there was no conclusive link between cold O-rings and leaks, anyway. After all, one of the worst gas leaks had happened when a booster was very warm. NASA engineers felt Thiokol's proposed lower limit of 53°F was not supported by any evidence and was inconsistent with the lower temperatures that Thiokol had already accepted during previous wintertime launch attempts. Booster manager Larry Mulloy wrapped up this point of view by demanding over the telecon line, "My God, Thiokol, when do you want us to launch—next April?"

After a thirty-minute break, Thiokol's engineer managers reported back that they would withdraw their objections. Since McDonald wouldn't put his name on the recommendation, booster-program vice president Joe Kilminster signed a form instead and faxed it to NASA. Boisjoly opened his journal that night and jotted down his feelings of anger and worry. At work the next morning, Boisjoly stopped by his boss's office to say that he hoped for a safe flight but also wished the seal on a joint would leak just enough to prove beyond all doubt that a serious problem existed. After Boisjoly left and was walking down the hall, ignition-systems manager Bob Ebeling asked him to step inside a conference room and watch the launch on the big TV. Boisjoly said no, but Ebeling insisted. Boisjoly worked his way to an open spot in the front of the room, sitting on the floor with his back against Ebeling's legs. Sixty seconds into the flight, Ebeling said a prayer of thanks for a safe flight. The *Challenger* broke up thirteen seconds later, painting puffy white streamers across the sky and throwing the room at the Wasatch Division headquarters into a dazed disbelief.

Boisjoly spent the rest of the day in his office, not even able to speak when people stopped by to ask how he was doing. He was not surprised the next day when a fellow employee told him that a videotape during launch showed a flame leak through a joint in the booster case, just before the disaster.

According to Diane Vaughan's *Challenger Launch Decision*, the definitive book on the subject, NASA and Morton Thiokol messed up because they conditioned themselves to rationalize and then tolerate a growing problem for the sake of bureaucratic goals. Never bringing the problem directly to the astronauts for their input, never taking the danger seriously enough to stop the program for a proper fix, NASA tried to contain the O-ring crisis by fiddling with small things such as insulating putty and the O-ring testing procedure, not even willing to delay the final launch to wait for warmer weather unless Thiokol came up with something more compelling than its technical judgment. It was the "normalization of deviance," according to Vaughan.

"There is only one driving reason that a potentially dangerous system would be allowed to fly," wrote chief astronaut John W. Young after the disaster: "launch schedule pressure."

DREAMING GREAT DREAMS

The British hydrogen-filled dirigible *R.101* and the space shuttle *Challenger* were both megaprojects born out of great national aspirations. The same high-flying promises it took to get them started forced them to keep going forward, despite specific, written warnings of danger by key technical people. In neither case, as in so many other predisaster intervals, did those well-intentioned, urgent memos make a shred of difference. The grim history of memos goes back at least to 1788, when engineer Thomas Telford warned the elders in charge of the grand, four-hundred-year-old St. Chad Church at Shrewsbury, England, that the masonry and timbers supporting the bell tower were fatally weak. Apparently expecting to hear instead that modest repairs would do, they declined Telford's warnings. The church collapsed early in the morning of July 9, a few weeks later.

To those in charge at NASA, caught between deadlines and the problem of never-enough money, the fact that a booster hadn't burned through so far was proof of safety. Understandably, the public's reaction afterward upon hearing of the warnings was anger and disgust. Apparently they didn't agree much with the ancient philosopher Cassius Longinus, who wrote: "In great attempts, it is glorious even to fail." Citizens wanted to know: Were those working on the project crazy, or just lazy? The answer is neither. The people behind the failures were the same ones behind the successes. They were the best and brightest of the aerospace world, and they had been working themselves to rank exhaustion. Their work hours were horrendously long, their commitment absolute. So how could it happen? Doesn't earnest effort count for something?

Each disaster shows in its own way how projects have a way of plowing forward despite bright red flags of danger. With the *R.101*, we'll see the driving personality of airship booster Christopher Birdwood Thomson. Sometimes such a man drives a project to great heights, sometimes to immolation. But he was accountable; Lord Thomson died aboard the *R.101*, along with forty-seven others. And the *Challenger* shows us how easy it is to pass over little glitches when there are so many bigger things going wrong and there is no time to stop and sort them all out.

The wreck of the airship *R.101* was so much a rehearsal for what happened with the *Challenger*, fifty-six years later, that we will see their stories in parallel.

THE BIG SHIP

Begin with the *R.101*, which at 770 feet long was the world's biggest airship when it crashed. Mrs. Shane Leslie got a good look at the aircraft on its way into history that night. She had been eating dinner at her cottage near Hitchin, England, when she heard the servants yelling. She looked outside to see a "ghastly red and green" light shining across the grounds. She joined the staff out on the grass. A giant dirigible, diesels roaring, was coming straight at her house. In the glow of its navigation lights she jumped over a fence as the servants ran in another direction, all of them convinced the house would be demolished in a fiery wreck. But the airship cleared the trees and the rooftop, too, and

by such a tiny margin that Mrs. Leslie could look through the windows and see people in the dining room. She said later that "horror descended on us all" as they watched the taillights dwindle. It was a compelling sign that the airship was so heavy it was running at the ragged edge of its capabilities.

A brief history: Nineteenth-century experiments with teardrop and cigar-shaped airships showed that balloons rose well and could even motor around the sky, but they had no strength to carry big payloads. The Germans' solution was the dirigible: a line of gasbags held inside a rigid metal framework, with a smooth, streamlined skin covering the whole thing. The skeleton was a series of metal or wooden ribs regularly spaced along the length of the ship, held together by backbonelike girders running from stem to stern.

Although World War I proved that a hydrogen-filled gasbag had no place in aerial combat, airships did look well suited for long-haul routes and naval reconnaissance. From 1910 to 1914, Germany's five passenger zeppelins made two thousand trips with no crashes. Big airships could pack tons of cargo, and their flights were comfortable, even elegant, at speeds of up to seventy miles an hour. Early airplanes were rickety, a pain for passengers, and short of range and load. Airplane engines had to run on gasoline, which people of the era thought a frightful fuel.

After initial resistance from the Royal Air Force, boosters of British dirigibles put together enough support from the navy and governors of far-flung possessions like Australia and India for a major airship development program to bring the Empire closer. The plan began in 1923 with a proposal for five privately built airships, but after a change of government to the Conservative Party in 1924, the plan turned into a competition instead. It was a horse race of heroic proportions: private sector versus public sector, each building a single giant airship at least seven hundred feet long capable of flying to Australia, with fueling stops at mooring masts spotted around the commonwealth. Britain would manufacture and sell the winning design to other countries. Went the argument: a private company might skimp on safety, whereas the government enterprise could spend whatever it needed to advance the state of the art.

On one side was the Airship Guarantee Company, a subsidiary of

Vickers Limited, building a ship to be called the *R.100* or, more popularly, the "Capitalist Ship." On the other side was the Air Ministry itself, working out of the Royal Airship Works at Cardington, Bedfordshire, building a "Socialist Ship," the *R.101*.

Even before Neil Armstrong put his right foot down on the moon in July 1969, the Apollo program was shutting down. The budget cuts started in 1966 and chopped 140,000 jobs out of the aerospace industry within two years. And after the excitement of the first landing, public interest fell as steeply, with only a brief surge during *Apollo 13*'s crisis in space. Was it surprising that later landings drew yawns instead of viewers? America had promised to put a man on the moon before 1970. The first flight put two men there months before the deadline, with no apparent difficulty. America recovered so quickly from its moon fever that just a week after the *Apollo 11* landing, an opinion poll showed a solid majority of Americans believing that NASA was getting too much money.

At the time of the *Apollo 11*, a presidential panel headed by Vice President Spiro T. Agnew was finishing up work on a post-Apollo plan. The report came in September 1969: Given a reusable space shuttle and a space station, NASA could launch an atomic-powered Mars mission before 1986, maybe as soon as 1981. It would need a guaranteed budget of $8 to 10 billion per year. But one by one the big plums, such as the Mars Mission, dropped off as the Nixon administration and Congress turned their money to other matters. Then, in January 1972, with NASA's budget down to a third of the Apollo high point, President Richard Nixon agreed to develop a space shuttle: publicly because the craft would make space exploration easier and cheaper, privately because it would bring many jobs to important political territory. It would cut the cost of launching a pound of cargo into orbit by at least a factor of twenty. The shuttle should even turn a profit. Finally, NASA told the press, it could accomplish its goals absent any further major technological breakthroughs. Apollo had done most of the work.

The *R.101* was also capable of great things, on paper. The government promised in 1924 that in two years the great gasbag would be in the air, and soon afterward carrying one hundred passengers and fifty crew members on a steady time schedule. Cruising at sixty-five to seventy miles an hour, it would reach Egypt in three days or less, a full two weeks faster than any steamship. It would be a submarine spotter for the navy, a troop transporter for the army, and an aircraft carrier for the RAF. Drawings showed it carrying four airplanes inside a hangar, then dropping each plane as needed. "The versatility that is to be demanded of her borders on the magical," said an editorial in the *Evening Standard*.

The *R.101*'s chief designer was Royal Naval Air Service lieutenant colonel Vincent Richmond, an engineer of enormous energy and dedication. He had learned airship design from the Germans but had never designed an airship himself. Nevertheless, he went straight to work on the biggest airship in the world, mainly because there were so few airship designers. The 1921 crash of the British airship *R.38* had thinned the government ranks in this field. "One of the most fortunate of men," as Richmond called himself, he finally got his chance to join in world-class airship work. Richmond and his wife moved to a cottage outside Bedford so he could put in extra hours without interruption, working sometimes until dawn in his study.

The project made a lot of work for Richmond and his assistants because of the Air Ministry's determination that the *R.101* would be a test bed for breakthrough ideas. For example, the frame was made partially of low-tech steel and partially of aluminum alloy. Normally the ribs of dirigibles were like giant bicycle wheels—light, with spokelike wires for strength. The *R.101*'s designers had a different plan: each rib of the framework would be strong enough to support itself with no strengthening wires. This required much extra design work and extra metal to make sure the ribs would be stiff enough. The *R.101*'s creators followed the principle that when in doubt about a girder, make it stronger—and therefore heavier. It had a factor of safety of four, meaning that each girder was able to carry four times the expected stress.

As costs rose past the original estimate and the date of first flight stretched beyond 1927, questions from Parliament to the Air Ministry during debates grew ever more cynical. "When are you going to bring your two old horses out of the stall?" one member of the House of Commons demanded of the air minister.

PUSH THAT ENVELOPE

By 1972 NASA settled on the basic layout of the space shuttle: two solid rocket boosters to help with acceleration (the first time that solid rockets had been used for manned flight in this country) and rocket engines burning hydrogen and oxygen for the full eight-minute flight to orbit. Because the "orbiter" couldn't store enough fuel and oxidizer to run its engines, these liquids would be carried in a huge cylindrical container called the external tank and would flow across to the orbiter through big pipes. In flight, the two boosters would fall away first, splashing into the ocean under parachutes for recovery and reuse. The external tank would fall off later, on the way to orbit, burning and breaking up on the way down. After finishing its mission, the orbiter would return to Earth by using small self-contained rockets to start reentry, then land like a glider.

As development and tests began in the mid-1970s, two enormously difficult problems concerning the orbiter devoured most of the experts' attention. One was the revolutionary system of thirty-one thousand reusable, protective tiles that the orbiter—the manned and winged shuttle craft—needed on its belly and wing edges to survive the blowtorch heat of reentry.

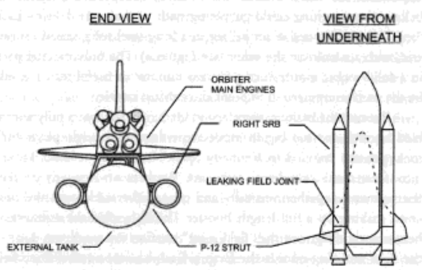
The other hurdle was the hydrogen-fueled space shuttle main engine (SSME). A shuttle needed three SSMEs, each of which would pack more power in less space than any rocket motor had ever been able to, along with tremendous durability to withstand reuse. The turbopumps on each main engine forced liquid hydrogen and oxygen into the system at a half ton per second. The pumps were about the size of a car's engine block, but each turned out sixty-three thousand horsepower, rotating at more than six hundred times a second. Engine tests began in 1975 and problems continued through 1979, with all major parts failing at one time or another. In 1977 alone, four engines went to pieces. Marshall Space Flight Center of Huntsville, Alabama, supervised development of both the main engines and the solid rocket boosters. The main engines didn't approach reliability until late 1979, less than two years before first flight.

If we think of Marshall as the stern parent and the shuttle's

propulsion components as offspring, the main engine was the brilliant but erratic child, hogging all the attention. That left the solid rocket booster in the role of the sturdy and dull brother. It was very hard, even impossible, for those outside the solid rocket booster program to believe that anything could go wrong with such simple devices. Each "solid" held 550 tons of propellant in a long steel tube, sealed on one end, with a nozzle on the other (see Figure 4). The only moving parts in a solid rocket motor during its two minutes of useful thrust would be the machinery needed to point the exhaust nozzle.

Because the manufacturer was in Utah, and because a fully assembled booster was too big to move across land in a single piece, each rocket motor traveled to Kennedy Space Center by railroad, broken into four main cylindrical segments. Workers at Kennedy stacked the segments together vertically and topped the stack with the nose cone, making up a full-length booster. Thiokol called the connection between each segment the "field joint" because the work was done in the field, meaning outside the factory. Each booster needed three field joints along the fuel-containing length. To visualize how a field joint works, imagine trying to string short pipes together into a high-pressure pipeline in such a way that you could disassemble and reassemble the whole pipeline every few months. You couldn't weld the pipes; you'd have to use some kind of mechanical joint with removable fasteners. One way to do this would be to provide the front end of each pipe with a slotted rim that the rear end of the next pipe could slide into. That's basically how the booster segments went together at Kennedy: pipes joined end to end, with each rim-and-slot junction held fast by 177 steel pins. For an ordinary pipeline this would have been fine, but not for the high-powered, hot-firing boosters. One challenge was that at each field joint a thin air gap remained between the solid fuel castings in each segment. Without some precautions, flame would fill this gap during a launch and attack the half-inch-thick steel of the booster's outer casing. To keep the flame at the core of the booster where it belonged, the field joints had heat-resistant putty to close off the gap between the fuel castings, and two rubber O-rings fitted into the rim-and-slot arrangement as a final seal.

FIGURE 4: SPACE SHUTTLE *CHALLENGER*



PROBABLE SEQUENCE

1. **Cold temperatures before launch reduce sealing ability of O-rings inside Solid Rocket Booster (SRB) field joints.**
2. **Exhaust gas leaks from aft field joint of right-hand SRB for first three seconds of flight, then stops.**
3. **Resuming at 58 seconds into flight, jet of flame weakens rear, P-12 strut between external tank and SRB.**
4. **Strut fails and tank ruptures as nose of SRB rotates into external tank.**
5. **Spacecraft breaks up, dumping fuel and throwing orbiter sideways into supersonic slipstream.**
6. **Crew compartment falls away with fragments.**

Adapted from NASA and President's Commission

"Solid rocket, solid technology" was the message of George Hardy, booster manager at Marshall Space Flight Center when he featured the solid rocket boosters at a press conference on October 14, 1980. NASA wanted "to maximize the state of experience on solid booster systems from the past and minimize pushing the state of the art," he said. Doing things this way kept costs down by limiting the test firings needed in Utah. NASA was scaling up the Titan 3 solid rocket motors, even sticking to the same vendors. Because the shuttle motors would be launching people, NASA would increase the margin of safety by adding one more O-ring to each field joint to prevent the leaking of hot exhaust gases, which could burn a hole through the steel case.

The press went baying after Morton Thiokol later, alleging that "inside baseball" was responsible for its booster contract with NASA. Some reports suggested that the company (which was the second-lowest bidder) was chosen because NASA administrator James Fletcher was from Utah and wanted to help old friends.

Whether or not this allegation was true—Fletcher denied it, and an investigation by the General Accounting Office didn't turn up proof of wrongdoing—it wouldn't be fair to conclude that the company was ill-prepared for the task. Thiokol had some of the oldest credentials in the big-booster business. Its motors were vital to some outstandingly successful missile programs during the 1950s and 1960s. Thiokol's founder, Kansas City chemist Joseph Patrick, invented the rubber compound that would make giant solid rocket motors practical. The adhesive even inspired the company name, which was concocted from the Greek words for *sulfur* and *glue,* two substances used by Patrick when he attempted to create a new type of antifreeze and instead stumbled onto a foul-smelling formula for artificial rubber.

A variation of that rubber was in high demand during World War II as a thick, resilient liner for fuel tanks on aircraft. It allowed tanks to withstand gunfire with minimal leakage. After the war, Thiokol president Joseph Crosby noticed that the California Institute of Technology's Jet Propulsion Laboratory was buying many buckets of the company's liquid rubber. He investigated and learned that the JPL found it to be an excellent binder for the oxidizer and fuel powders it was using for solid rocket motors. Thiokol decided to exploit this toehold in rocketry and in 1949 began manufacturing seventy-five-pound infantry support rockets at the Redstone Arsenal near Huntsville, Texas. This led to a military contract for the world's first big solid-fuel rocket, the Hermes, weighing five thousand pounds.

After Hermes, Thiokol won the bid to make the sixty-five-thousand-pound first stage for the new Minuteman 1 intercontinental ballistic missile (ICBM). Thiokol moved to a ten-thousand-acre spread in northern Utah and was in the game big time. At its production peak, Thiokol was building two Minuteman first-stage motors per day. Perhaps most relevant for the Shuttle contract, Thiokol worked with the air force in the 1960s to develop supersize solid rocket motors, one of 156 inches in diameter and another monster coded the "260," which would have been twenty-two feet across, intended for heavy lifts into orbit and so big that only barges or ships could have moved it. That idea never flew, but it gave the company the confidence to try for the shuttle booster contract, which it won in 1974.

The fuel Thiokol used on the shuttle solid rocket boosters was almost exactly the same as on the Minuteman ICBM: aluminum powder and rubber binder, mixed with ammonium perchlorate to provide oxygen. This mixture is very stable if left cool and dry. The air force once tested a Minuteman motor after letting it sit in a silo for twenty-nine years. It burned fine.

NASA ordered seven test firings from Thiokol's test stand in Utah before the first launch in 1982. All tests included the effect called "joint rotation," which is the slight bulging of the steel cases upon ignition and which tends to ease open the seal at each field joint if not guarded against. One test even included a trial during cold weather, at an air temperature of 36°F.

One thing NASA did not ask Thiokol to do in the seven tests of an individual booster was reproduce the way the booster would writhe and bend under actual launch conditions. There were at least two dynamic forces that would be acting on the booster, and each worked in concert with low temperatures in January 1986 to bring about a failure. One force was the "twang," a bending of the whole shuttle stack after the main

engines lit but before the boosters came on. It caused the whole craft to bend backward about three feet, measured at the nose, and then rebound forward, like a flagpole sways in the wind. This was one force acting to pry open the field joints a small fraction of an inch.

The second force acting to pry the joints open (also not tested in Utah) was the stress accumulating at the struts attaching the boosters to the shuttle's big external fuel tank. Each booster had two lower struts, each mounted to a steel ring around the rocket's circumference. The lower strut numbered P-12 was just a foot from the hole that would appear in the *Challenger's* booster on the day of disaster.

Vincent Richmond and his assistants finished up the plans for the *R.101* in 1927. Steel girders started going up in the vast shed at Cardington that year. The giant dirigible was ready for the air in October 1929. The airship as it emerged from the shed was the biggest in the world, at 720 feet long, bigger than anything the Germans with their decades of zeppelin experience had attempted. Propulsion came from big wooden propellers on five "power cars" hanging from the belly by struts. The *R.101* was so streamlined that the space for crew and passengers lay almost entirely within the great skin.

In its operating style the *R.101* borrowed its traditions from both sea and air. The crew dressed in naval-type uniforms. The airship had rudders and an elevator like an airplane, but the commander in the control cab gave his orders to "coxswains." One coxswain operated the wheel that steered the ship up and down, another handled the wheel for left and right turns. If the pilot wanted to speed up or slow down he used a shiplike engine telegraph to dispatch his orders to engineers in each power car. During the day the navigator steered by compass and landmarks; at night he could go up a ladder to the top of the gasbag and navigate by the stars. But unlike an oceangoing vessel, this behemoth could not throw down an anchor in harbor or on shallow seas. The *R.101* couldn't refuel or even stop without a giant mooring mast or a giant shed to park in.

Visitors to the Royal Airship Works shed at Cardington came away awed by the size. Less obvious was how the ship was a strange blend of old and new, massive and delicate. Other airships used simple valves that let out excess pressure in the gasbags to keep the skin from bursting when they flew too high. The *R.101* used new, highly sensitive valves that had the problem of dumping gas every time the airship rolled from side to side.

The structure inside the skin was heavier than usual, all girders sized with an extra margin of strength. In this age before plastic film, the sixteen gasbags along the *R.101*'s length were made out of many thousands of cow intestines, cut into sections, lapped together, and varnished. The big bags, weighing half a ton each and confined in great steel-mesh nets, worked well enough, but only if kept free of moisture and if kept from rubbing against the metal girders.

Any big project must face one or more crises, and for the *R.101* the first came with its load tests in the hangar. The airship's weight proved appallingly high, and this massive error would feature prominently in the crash a year later. Originally planned to weigh ninety tons without hydrogen or fuel, the *R.101* came in a full twenty-three tons heavier than that.

The most glaring reason for the weight problem was its engines: seventeen tons of Beardmore diesels designed for powering locomotives. Parliament had directed the use of diesels, partially for political reasons and partially in the belief that the heavy diesel fuel was less prone to fire than gasoline. Diesels weighed twice as much per horsepower as gasoline engines and were so heavy that designers had to put extra steel into the dirigible frame to support them. Only later would it occur to the men at the Royal Airship Works that even with all this extra weight the *R.101* was still at risk of a gasoline fire, because each power car had to carry drums of gasoline for the small gasoline-powered engines that cranked the big diesels when starting them. The realization that the *R.101* was flying around with the worst of both worlds came too late to replace all the gasoline-powered starting engines.

Still the men were keenly aware of some risks. Those at the airship works knew that having so much flammable hydrogen around was a real danger. The Air Ministry banned airplanes from approaching within three miles of the ship. Once when the commander of the airship, Major G. H. Scott, saw a man standing under the airship take out a box of matches, he rushed over and knocked him down with a kick. All people going up the mooring mast had to surrender their matches and tobacco, and only one room in the airship was rated safe for smoking. In this room, chains held the ashtrays and lighters to the tables.

In lifting trials the *R.101* could hoist only thirty-five tons instead of the sixty tons planned. But it was enough for making local test flights around England, so with only minor changes the *R.101* began its trials in October and November 1929. On one of the trips it passed sedately over the royal palace at Sandringham, inspiring waves from the king and queen. The trials went smoothly enough, the ship taking to the air only on dry, windless days.

KICK THE TIRES AND LIGHT THE FIRES

On April 12, 1981, astronauts John Young and Robert Crippen took the space shuttle *Columbia* up for its first test flight. Close examination on orbit showed that sixteen of the black tiles on the topside were missing, having been pried loose by the shock of launch. But the critical tiles on the bottom of the shuttle stayed on, so the craft was spared having a hole burned through its aluminum skin upon reentry two days later. And the arrival at Edwards Air Force Base in California proved that the "flying brickyard" could indeed land safely despite having no engine power at the time and thus no second chance.

Successful flight or not, the Reagan administration cut $604 million from the space budget about this time. NASA knew that flying once a week was impossible for the time being. But it still promised routine access to space, and the schedule for the coming years showed a steady push in the pace. By 1984 it was clear from the numbers that things were not going as quickly as planned. That year, NASA had promised twelve launches but delivered five.

NASA came under intense pressure to maintain a reliable launch schedule for its satellite customers. It proved impossible even with all four shuttles flying. Now it was clear what a tough bargain NASA had driven for itself. Before the shuttle, NASA had been able to set its own launch schedule to meet the man-moon-decade goal. Now its customers set the pace, or wanted to.

There were many reasons for the clash between promise and reality, but they came down to a machine that was immensely complex and resisted all attempts at making operations as routine as an airliner flight, which some Reagan administration officials felt was so close they had started discussions with airlines about commercializing the operations. It was far premature. Tiles needed close inspection after each flight, and engines and control systems kept showing distress. In its November 1983 flight (STS-9), the *Columbia* suffered a major electronics breakdown and a fire in an auxiliary power unit during its descent. The APU's hydrazine fuel exploded as the shuttle was parked. The mishap could have destroyed the spacecraft in flight if it had happened a little sooner.

A visit to any one of hundreds of shuttle suppliers would have shown the rank impossibility of a once-per-week schedule. The work was far too exacting. Consider Morton Thiokol's role in particular. Each pair of motors, called a flight set, accumulated hundreds of thousands of documents as it moved from Kennedy to two plants in Utah for final cleaning, filling, and curing of the propellant, and then for return to Kennedy for assembly with the rest of the parts to make a full booster. For example, each expended motor went to Utah with as much as nine tons of rubber insulation glued to the interior walls. All of that scorched and clinging scrap had to be cut and sandblasted off; then each section had to be scanned for defects by the biggest X-ray machine in the world.

The solid rocket boosters were simple but ominously powerful: powerful enough to do 71 percent of the heavy lifting for two minutes, pushing two thousand tons far past the speed of sound. NASA liked to tell the press that each booster turned out as much power as all the engines on seventeen 747 airliners at full thrust.

Greg Katnik, a technician at Kennedy Space Center who supervises the final inspection of the launch complex before each flight, once told me about the fury of the solid rocket boosters. He explained that remote-controlled cameras surround each shuttle before flight, aimed to photograph critical parts of the launch sequence in case of mishap. To protect them from the heat and blast, each camera has a steel cover weighing about eighty pounds. During the *Challenger's* launch in April 1984, the booster exhaust caught one of these camera covers. The force of the blast ripped the cover from its bolts. The cover passed under the *Challenger's* external tank, heading south, then crashed through a six-inch-thick concrete wall and kept going. Completely crumpled, it rolled to a stop four hundred feet away.

The *R.101* floated back into its hangar in late November 1929, sheltering there for the next six months. In December the Air Ministry agreed to major changes, though not to the extent of changing the five power plants from diesel to lightweight gasoline models.

The engineers of the Royal Airship Works thought up three ways to give the *R.101* more lifting power: lighten the ship by pulling out anything unnecessary, add enough length to fit another gasbag, and make room for more hydrogen in all the bags by letting out the wire harnesses holding in the gasbags. All the actions had side effects. Obviously, removing sections of inner structure or adding length might weaken the airship. Less obviously, expanding the gasbags increased the opportunities for the bags to chafe against the girders, which would open leaks. When workers removed the bags for inspection, they found that fifteen of the sixteen bags had pinhole leaks too numerous to count. The Royal Airship Works finished two of the changes by April 1929, but for the next three months political problems kept workers from beginning the long process of cutting the ship in half and lengthening it.

First the work had to wait so the *R.101* could appear at the annual RAF Air Display to be held in late June. This would help quell public impatience. Soon after the airship left the shed to get ready for the event, a 140-foot rip opened in the silver-painted canvas of the right-hand side. Another great hunk of the cover tore the next day. Riggers climbed up to inspect the damage and came down with the terrible news that the cover was rotting away all over the vast acreage of the dirigible. There wasn't time to replace the cover before the air show, so men with patches, thread, and needles climbed up to seal the rips as the ship floated at anchor at the mast. This quick fix allowed the *R.101* to get off as scheduled on June 27, 1930.

Ralph Booth, captain for the privately built rival airship *R.100*, rode along while the *R.101* prepared for its appearance at the air show the next day. He was alarmed to see the airship drop nine tons of water ballast during the day to maintain altitude, even though it had used up two tons of fuel along the way. It even had to dump fuel on one flight to stay aloft. This was the clearest possible sign that the airship had too little lift.

After the *R.101* reached 102 hours of flight test, only half the hours originally thought necessary before receiving its airworthiness certificate, the flying trials halted once more. England had just one big mooring mast, and the rival *R.100* needed that mast to prepare for its flight to Canada. The *R.101* went back into its shed. This enforced idleness would have been an excellent time to add the extra bay, but that was out of the question because Sir John Higgins, a high official of the Air Ministry, wanted to make sure that one of the two airships took off for Canada on schedule. If a serious problem arose with the *R.100* during preparations, the *R.101* would have to be ready to take her place. Thus, major repairs would have to wait.

It was at this point, July 1930, that a dispassionate observer could have seen the depth of the Air Ministry's impatience with the *R.101*'s progress. Regardless of any public assurances about the importance of safety, the working priority was flights first, safety second. The *R.101* was so short of lift that it needed lengthening; its gasbags were leaking twenty-two thousand cubic feet of hydrogen a day; and its outer envelope was failing in great rips in mild summer weather. Regardless, this airship was supposed to start across the Atlantic on short notice, as is, if the *R.100* faltered.

The situation greatly alarmed at least one man, F. McWade. McWade was the chief inspector at Cardington for the Aeronautical Inspection Directorate, and he held the authority to grant or deny the vital "Permit to Fly" and the airship's certificate of airworthiness. On July 3, McWade defied the rules by sending a confidential memo directly to the Air Ministry office in London, bypassing the usual chain of authority. McWade's memo explained that he had only renewed the airship's Permit to Fly for a few weeks, because urgent fixes were needed. He said that the gas leaks were very serious and the cloth

padding around the girders was not solving the problem. Furthermore it risked corrosion to the steel girders because the pads were attracting water. McWade wrote that it would be best for Cardington to pull out every bag, each weighing a half ton, for repairs. McWade ended by saying that under the circumstances he could not support extending the Permit to Fly past July 19.

McWade's memo went first to the chief of his department. The chief knew he was supposed to pass the memo on to the secretary of the Air Ministry, but instead he contacted R. B. Colmore, director of airship development at the Royal Airship Works. It was Colmore's job to both promote the use of airships and oversee their safe flight. Asked for his comments, Colmore wrote back in a reassuring tone that padding around the girders was a good remedy and would be done soon. This was so soothing that McWade's boss never sent the warning letter onward and upward to London. Instead he wrote back to McWade saying he had better make sure the padding was well executed. McWade, his duty to warn completed, dropped the issue. The *R.101* got its flight permit extended when the time came.

Finally, more than three weeks after the *R.101* went into the hangar to pass the time, Cardington received permission to add the extra bay. In five weeks of nonstop work to meet the flight schedule for Lord Thomson's October meeting in India, riggers cut the airship in half, added 45 feet of length to make the total length 770 feet, and replaced the entire rotting skin.

By 1929, Christopher Birdwood Thomson was the driving force to complete the *R.101*. Holding the cabinet position of Secretary of State for Air, Lord Thomson was the sort of fellow that technical people have trouble dealing with, but who under the right circumstances could drive subordinates to extraordinary achievement. Thomson favored bold and prompt action, having first gotten attention as a young engineer lieutenant in South Africa when he cleared a blocked railway line promptly and decisively. That maneuver had impressed Lord Kitchener, who became Thomson's mentor. Thomson had served out the war, turning to diplomatic duties afterward. At every point in his life his boldness and verve had served him well.

Lord Thomson believed that airships would dominate air travel for at least the next two decades. The *R.101* would lead the way. In January 1930, during a debate in Parliament, Thomson said: "This is one of the most scientific experiments that man has ever attempted, and there is going to be no question of risk—while I am in charge—being run, or of any lives being sacrificed through lack of foresight."

Regardless of growing misgivings among his subordinates as fall approached, he held no fear for the safety of the "old bus," as he affectionately referred to the *R.101*. "It's as safe as a house," Thomson once told the press, "except for the millionth chance."

THAT STILL, SMALL VOICE

In 1977, four years before the shuttle's first flight, engineers at Marshall Space Flight Center had begun circulating memos about their worry that the field joints on the solid rocket boosters might not hold the high pressures of the first ignition, peaking at almost one thousand pounds per square inch. Each booster had three field joints, which were splices that connected the four segments of each booster upon assembly in Florida. But the engineers' concerns receded into the background during the first ten flights, since few missions showed signs that hot gas had gotten past the insulating putty and reached the first set of hard rubber O-rings that helped stop combustion gas from escaping through the field joints before it reached the exhaust nozzle. But in 1984 something changed for the worse, possibly a test procedure that used pressurized nitrogen gas to check on the field-joint seals. During more than half of the next fourteen shuttle missions, there were signs that hot gas was scorching the first of two O-rings. On some of these flights, gas even touched the second, outer O-ring, meaning the gas had almost reached the outside of the steel case.

The worst damage occurred during the January 1985 cold-weather launch of the *Discovery*, when five O-rings sustained heat damage. You may have seen the effect of cold weather on rubber. A garden hose left out in winter weather turns as stiff as a pipe regardless of whether it has water in it. During the post-accident investigation, physicist Richard Feynman would demonstrate the principle by dipping a segment of an O-ring into a glass of ice water.

In August 1985 top officials from Marshall flew to Utah to talk over the problem with Morton Thiokol management. Roger Boisjoly, a seal engineer with Thiokol, got the assignment to put together a "Seal Task Force" to come up with a quick solution.

After three months of work, the *R.101* emerged from the shed on October 1, 1930, leaving barely enough time for a departure on October 3. The men were close to frantic by Thomson's insistence on taking the airship to India and back in time to attend a conference in London on October 20. From Thomson's view, the Royal Airship Works had already spent two years more than expected to make the airship flightworthy, and now it was time to finish the job, regardless of the setbacks. He and his predecessor as Secretary of State for Air had fought for their higher expenses against stiff opposition in Parliament and had taken much abuse for the delays. The men got the message: the future of the airship business in England depended on getting Lord Thomson to India on time.

With the new gasbag slotted in and the ship lightened up, there was enough time for a single test flight. The *R.101* left its mast on October 1, returning seventeen hours later. Due to engine troubles, the crew did not attempt to see how the ship handled at full speed, and of course nobody knew how the *R.101* would behave in rough weather because none of the test flights had ever been run during a storm. Perhaps the crew could continue flight tests with passengers, on the way to India.

Simple human haste probably played a role in the sinking of the *Titanic*, according to metallurgist Dr. Tim Foecke of the National Institute of Standards and Technology. D. Colvilles & Company, the Scottish company that supplied the bars of wrought iron that went into the *Titanic*'s three million rivets, was under pressure at the time to complete other big projects, and they had too few skilled artisans to meet the demands. The iron went out the door with four times the normal percentage of slag inclusions, and there was no good quality control method to counter this problem at the time. This slag made the rivet heads more prone to shear off under the grazing collision that the *Titanic* suffered, opening the hull at plate seams. We know from undersea observations that the ship sustained neither giant rip nor gash; instead the size of all the openings, taken together, was about the square footage of a throw rug.

Thomson wanted to leave on October 3, a Friday, but Colmore persuaded him to delay to give the crew some rest because they had been working nonstop since the test flight. They agreed that the *R.101* would leave for the conference on October 4. In that way it would still arrive on time.

Told days before the flight by the director of Civil Aviation that the ship was not ready, Thomson shot back that anyone who was afraid didn't have to go. Proof of his confidence in the ship was the great pile of trunks and suitcases he brought along, estimated by the mast's elevator attendant as equivalent in weight to twenty-four people, though the flight crew's personal baggage was under strict control. The ship also carried rolls of carpet and extra provisions for a formal dinner planned in Egypt, along with extra diesel fuel so the airship wouldn't have to refuel during the party; the smell might spoil the food's aroma.

Likewise, predictions of bad weather for the departure made no impression on Thomson at all. On the cold and rainy night of October 4, 1930, the *R.101* unhooked from the mast at the airship works just as Thomson had wanted, bound southeast for its first stop, Ismailia, Egypt.

By January 28, 1986, after four days of weather holds and mechanical problems, the *Challenger's* crew was raring to go. The weather was clear, calm, and frigid after a cold front's passage. The seven-person crew climbed in just before 8:00 A.M. Among them was the winner of NASA's "Teacher in Space" competition, a public relations extravaganza that put thirty-seven-year-old Christa McAuliffe, a high school history teacher from Concord, New Hampshire, in the national spotlight. She was not the first amateur on a shuttle—Senator Jake Garn and Representative Bill Nelson had wangled joyrides before—but certainly she was the most prominent. Her students had come to the Cape to see the launch. She would be spending the mission keeping away from switches and giving live television talks on microgravity and life in space.

The other six crew members, as diverse as America itself, had their own unique stories to tell. Pilot and copilot, Dick Scobee and Mike Smith, were both trained as test pilots. Flight engineer Judy Resnik had been the second American woman in space. Air Force lieutenant colonel Ellison Onizuka was the first Japanese American to head for space, and physicist Ron McNair was the second African American astronaut. Greg Jarvis, a payload specialist from Hughes Aircraft who was going along to study fluid flow in space, would have flown on the previous mission had he not been bumped by Representative Bill Nelson.

Packed into the *Challenger's* payload bay were a tracking satellite and a one-ton comet observatory called Spartan-Halley. What was most important for NASA was not this payload, but the one to follow: NASA needed to get this flight finished so it could prepare the *Challenger* to carry a space probe called the *Ulysses*. The *Ulysses* would be studying the north and south poles of the sun after getting a gravitational boost from a close flyby of Jupiter. The *Challenger* had to go up again on May 15 for the *Ulysses* to make the rendezvous, and NASA would need every available moment after the Teacher in Space flight to get things ready.

When the "ice team" made its last checks during a two-hour hold in the countdown, the temperature of the left booster was 33°F, and the right booster was fourteen degrees colder. But with all contractors signing their approval for launch, this otherwise alarming development became nothing more than a notation in the preflight logbook. The countdown resumed and ignition took place at 11:38 A.M. It began with the lighting of each of the three main liquid-fueled engines on the rear of the *Challenger*, then both solid rocket boosters. Lit by a barrel-size igniter at the top that threw a plume of fire down the central core, each solid rocket motor came to full power in one-quarter second, sending in the blink of an eye a plume of white smoke over a fence twelve hundred feet away. The boosters' twin columns of white fire visually overwhelmed the pale blue exhaust of the liquid-fueled engines, or "hood ornaments," as booster engineers called them.

The gas from the boosters entered the exhaust nozzles at 5,700°F and left at four thousand miles per hour. A booster was the ultimate cutting torch, so hot that a steel plate near the support posts needed replacement every three or four flights because so much metal boiled away. Unseen at the time, but noticed later on film, black smoke was puffing out of the right-hand booster, at the lowermost field joint. It's likely that the hole closed soon afterward, when aluminum slag from the burning fuel stopped it up, but then opened again as the shuttle's speed rose and aerodynamic stresses increased.

At fifty-eight seconds after booster ignition, ground-based telescopic cameras caught a glow from the right booster. This glow was from a jet of flame playing onto the tank and the area of the lower P-12 "sway strut" connecting the right-hand booster with the tank. The strut failed under the heat at seventy-two seconds and the booster pivoted around the upper struts, thus shattering the external tank like a giant egg. A fireball erupted as the *Challenger* orbiter broke free and tipped sideways at supersonic speed. Never designed for this kind of shock, the craft broke up. Some fragments flew as high as 122,000 feet before falling into the ocean. One of the bigger fragments was the crew compartment, where several of the crew members remained alive—until the cabin hit the water at more than two hundred miles per hour.

THE MISSING LINK

In that long and agonizing teleconference the night before, the erratic behavior of the O-ring seals consumed so much attention that the subject of exactly how a leaking booster might cause a disaster never came up. Boisjoly had been most concerned about a leak occurring in the first few seconds. Such a leak would have cut into the fuel tank, dumping fuel and blowing up not only the shuttle but the pad as well. But that's not what happened.

When interviewing an executive at Thiokol ten years after the disaster, I said that it was certainly bad luck that the leak of hot gas happened to point right at a strut connecting the external tank to the booster, clearly the worst possible place. By bad luck, I meant that if the gas leak had broken out at one of many other locations on the booster nothing disastrous might have happened. The booster with the burned-through hole in it never did

burst like a punctured balloon, after all, nor had the hole grown to be extremely large even after seventy-three seconds of flight. The booster had less than a minute left to burn, and its power was already dropping off, so it was close to squeaking by when the P-12 strut failed and made the whole structure go to pieces.

"It wasn't bad luck," the executive said. According to him, the strut was the link between the engineers' generalized worries about a leak through the field joints and the catastrophe that actually happened. The P-12 strut was a stress-concentration area. This is where the gas leak broke out, and it was the first time a gas leak had ever cut through the steel case. Cold acting on the O-ring rubber, a poor joint design, and stress concentration at the struts all combined to make enough of a hole to bring the *Challenger* down.

A few minutes past 2:00 A.M. the next morning, engine operator Joe Binks climbed down the ladder from the body of the *R.101* into his power car. It was time for him to relieve the other engineer on duty, Arthur Bell. Binks looked out the window to see a steep roof in the gloom and called out in alarm to Bell, saying he had seen a church, just a few yards off.

It was the roof of the rebuilt Beauvais Cathedral, a soaring Gothic structure that had been the site of one of the first recorded failures of high technology. It was here in 1284 that either two or three 158-foot-high choir vaults collapsed, for reasons unknown, twelve years after the construction of the cathedral had been completed.

Bell couldn't hear what Binks was saying over the diesel's roar, though, and by the time he understood, the *R.101* had glided past the obstacle without a collision. The airship pitched and heaved as it left Beauvais, heading for a low range of hills called the Bois des Coutumes. The airship calmed as it reached the shelter of the rising ground. The engine telegraph called for a "slow" setting on the engines, and Bell backed off on the throttle. It was in time to hear a cry from the chief coxswain, running along a catwalk to warn everyone he could: "We're down, lads!"

The nose of the *R.101* touched the ground at low speed, skidded, then bumped up again with the recoil. Then it fell back down again, the rest of the craft settling in. At least one of its gasbags had broken open, and a hydrogen fire started in the nose and swept back toward the tail. The front of the *R.101* lay draped across a stand of oak and hazelnut trees, with the rest of its length reaching back into a beet field. Among the wreckage were dozens of pith helmets, which had been taken along for use in the tropical climate.

Of the fifty-four men aboard, forty-eight died immediately or soon afterwards, including Sir Thomson. Among the dead was the boyish and excitable Sir Sefton Brancker, the director of Civil Aviation and one of the first innovators in British aviation. It was Brancker who had tried to persuade Thomson that the *R.101* wasn't ready.

One of the survivors, Harry Leech, had been in the smoking room at the instant of the crash. The room had only two exits and both were blocked, so Leech smashed his way out through the fireproof wall. He jumped and landed in a tree. Binks and Bell waited in their power car, gaining a reprieve when a water ballast container broke above them and doused the structure. Then they jumped free, landing on the wet, soft ground of a hillside.

Disaster arose from a combination of elements, decided a court of inquiry: insufficient testing of new designs, setting out in bad weather without preparation, and loss of buoyancy at a critical moment. Said the 1931 report, "When it became important to avoid further postponement and the flight to India thus became urgent, there was a tendency to rely on limited experiment rather than tests under all conditions. . . . It is impossible to avoid the conclusion that *R.101* would not have started for India on the evening of October 4 if it had not been that reasons of public policy were considered as making it highly desirable for her to do so if she could. . . ."

Mourning was long and elaborate. A crowd estimated at one hundred thousand watched the coffins leave Beauvais by train. The funeral procession arrived at Boulogne, where a British destroyer accepted the transfer. In England a special train carried them into Victoria Station. The dead lay in state at Westminster Hall, leading up to a memorial service in St. Paul's Cathedral. Prime Minister Ramsay MacDonald said that the crew's "sacrifice has been added to that glorious list of Englishmen who,

on uncharted seas and unexplored lands, have gone into the unknown as pioneers and pathfinders, and have met death. . . ." During the procession from Westminster Hall to the railroad station, a half million people lined the streets. The ceremonies ended at a mass grave in Cardington.

Britain reacted by shutting down the entire dirigible program, even taking possession of the successful, privately built *R.100* and dicing it into scrap. NASA held a memorial service for the *Challenger's* crew at Kennedy. It was attended by President Reagan and ten thousand other people. The agency responded to the *Challenger* disaster by stopping all flights for almost three years and negotiating a settlement with Morton Thiokol that had the company surrendering $10 million of profits. Thiokol worked up what has since proved to be a very successful seal for the field joints. NASA buried every last fragment of the *Challenger* under tons of concrete, using two abandoned Minuteman 3 silos, just as the agency had buried the burned hulk of *Apollo 1's* capsule.

A QUESTION OF RISK

After the *Challenger* disaster there was some anger among old-line astronauts at NASA for including members of the public on the flights. Until further notice, they reasoned, space travel was only for professionals, who were willing and able to take the risk.

I can't buy that argument. In the case of the *Challenger*, the explosion broke up the ship before anyone could lift a finger, anyway, and too quickly to send a radio message. Even if the ship had seven right-stuff test pilots on board, strapped in every one of the available seats, it wouldn't have made a bit of difference that morning. And the idea that civilians need to be shielded from danger is preposterous; more than a hundred Americans die every day in car crashes. We tolerate this astonishing carnage year in and year out as the price of mobility. Even ordinary people like me, like you, like Christa McAuliffe, should have the privilege of taking personal risks for the greater good.

If Boisjoly, prisoner of bureaucracy that he was, had been allowed the proverbial single phone call, I wish he could have summoned Dick

Scobee, the *Challenger's* commander, to the telecon. Scobee would have heard that his flight the next day was going to be an off-the-chart experiment. The *Challenger's* solid rocket boosters would be operating well outside of their tested boundaries, going farther up a sketchy but suggestive trend line of gas leaks that were becoming so common that the engineers had been finding them on almost every other flight. The crew could have heard that the flight was shaded with an element of danger simply because every flight under cold conditions showed damage to the O-rings. It would have given Scobee a choice, and the chance to insist on more information from NASA and Morton Thiokol. Crew members could have decided for themselves whether to take the chance. Putting a tracking satellite in orbit, even preparing for the important launch of the *Ulysses*, was less than a top national priority.

Both airship and spacecraft were prisoners of the many promises made to get them built: promises of safety, low cost, on-time performance, and solid technology. In hindsight, the same drive and optimism that got the work under way would look tragically misguided. According to Gerald C. Meyers, former chairman of American Motors, business managers in general avoid making contingency plans for failure. That's the kind of tack taken by losers and negative thinkers; a manager sees his job as planning for product success and continual market growth instead.

So that means the rest of us have to think about such things on our own, particularly when approached to support cutting-edge projects. One of the reasons the Apollo program had political support as long as it did was that the original budget estimates were not set artificially low (in the traditional "lowball" ploy to get the work started, then increase the budget later). The shuttle, on the other hand, started with impossible promises of cheapness and efficiency and soon got jawboned between budget cutbacks and foreseeable technical problems. The orbiter's main engines were not "just like" the Saturn's engines; the solid rocket boosters had to perform in a different dynamic environment, and the heat-protection tiles for the orbiters were radically new. Once promised to fly as many as sixty times per year, the highest rate ever achieved by the space shuttle has been eight flights a year. The "space transportation system" achieved only three flights in 1999.

This would make it easy to say that NASA has the wrong stuff, but that's just what the press was saying about the string of delays just before the final launch of the *Challenger*, ridiculing the space agency for malfunctions. We're supposed to know better by now: space travel is inherently dangerous, and so when the manager of such a program says things are not working quite right and the schedule needs to include a safety break, that should be fine with the rest of us.

There are cases in our technological history of people who stopped a project cold to get things right. After workmen had finished putting a reactor into America's first nuclear submarine, the *Nautilus*, a small steam pipe burst during dockside trials. The head of the nuclear-navy project, Hyman G. Rickover, heard that the pipe had been fabricated from the wrong material and that as a result it had no more strength than a tube you'd see as part of a guardrail. Finding further that the shipbuilder's quality-control records couldn't establish whether any more of the wrong piping had found its way into the steam system, Rickover ordered that all steam lines of that diameter—that meant thousands of linear feet—be cut out and replaced with the right stuff. According to his assistant Ted Rockwell, Rickover made a general announcement that he wanted this remembered as red-letter day, a blow for quality control that would never be forgotten. Of course it was expensive, but it sent a very clear message throughout the navy and its contractors that this guy really did value safety over deadlines. Was a costly renovation like this embarrassing to the navy? To Rickover, that would have been a stupid question. What he called the "discipline of technology" demanded nothing less.

Making the time and budget for realistic qualification tests could have saved the *R.101* and the *Challenger*. The next chapter explores why a tough round of testing—so often shortchanged—helps close the door to disaster.