# Challenger calamity: Physicists turn sleuths in 'whatdunit'

Until last 28 January NASA symbolized the epitome of US science and technology. Born in 1958, a year after the Soviet Union took the lead in the race for space with its Sputniks during a period of intense Cold War rivalry, the agency was meant to be a new kind of Manhattan Project. It was intended to restore US pride in science and technology, which suffered humiliation of sorts when Navy Vanguard rockets blew up on liftoff in early tests. By 1969, however, NASA restored US confidence by sending men to the Moon and by repeating the exhilarating adventure virtually whenever it wanted. Indeed, for two generations of Americans the space program was one of the few memorable things that government seemed to get right.

Even so, when the time came for the shuttle in the 1970s, the public and its elected politicians seemed to have lost their interest in manned space ventures. The Challenger tragedy restored interest—for the wrong reason. It set off the most intensive inquiry of NASA ever made. Such an investigation went against the accepted wisdom within NASA, which made its own review of the 1967 Apollo fire, in which three astronauts died during a training exercise. The loss of Challenger and its crew of seven was more traumatic, in part because the fireball appeared on television replays for days. It shook the nation's confidence that the space program represents the can-do, thumbs-up, A-OK image that Americans, the spiritual heirs of Columbus, the Pilgrims and millions of others who came in search of a new world, have of themselves.

**Preventable.** It is clear from the report of the President's Commission on the Space Shuttle Challenger Accident that NASA is an incredibly troubled agency. The message of the report is that Challenger's destruction was preventable. The immediate cause of the catastrophe was traced to a mechanical failure in the lower joint of the right solid-fuel booster rocket, but the ultimate cause goes deeper—into the management structure and financial and political pressures that beset the agency.

Despite 17 years of unalloyed success since the first Moon landing, NASA accumulated many defects—among them a convoluted bureaucracy in which officials at the field centers tusseled for supremacy with leaders at agency headquarters and cost overruns. In addition, according to NASA testimony before Congress, the agency had been importuned to reduce shuttle costs and simultaneously increase the number of launches. Much of the pressure came from National Security Decision Directive 144, signed by President Reagan on 15 August 1984, ordering NASA to develop a "fully operational and cost-effective" shuttle program by 1 August 1988. Accordingly, the intent of the agency's National Space Strategy was to make over the four shuttles from primarily scientific research laboratories to a commercial cargo service that would pay its own way.

The reality of the shuttle program at the start of 1986 was in striking contrast to the dream of the early 1970s. Cost overruns and development delays have haunted the shuttle as persistently as any Pentagon weapons program. Originally priced at \$5 billion, the shuttle project escalated to more than \$20 billion and fell five years behind schedule. As part of the cost-cutting strategy, NASA put forward an ambitious timetable in an attempt to reduce the price of each launch. An early plan called for launching one shuttle per week—though by 1985 NASA officials retreated from that goal, projecting 15 flights for 1986 and 24 flights in 1989. Even such a curtailed schedule seemed improbable to the House Appropriations Committee and a panel of National Research Council. To make ends meet, NASA in recent years abandoned important projects, often of significance to space scientists, such as a mission to Halley's comet, to win the indulgence of Congressional budget-makers.

**Undercurrents.** NASA's budget limits and its conflicting goals appear as undercurrents in the Challenger commission's report, but the panel was charged by President Reagan's Executive Order 12645 to determine only what went wrong with the shuttle and to recommend what actions NASA should take to make sure it never happens again. The commission handed over its 256-page report at a little ceremony in the White House Rose Garden on 9 June, exactly 120 days from its start, in keeping with Reagan's directive. The occasion was not meant to be festive, considering the gravity of the commission's findings. Still, much as it sometimes hurts to know the truth, the rigor and realism of the report and its recommendations will go a long way to persuading NASA, Congress and the public that the errors exposed by the commission can be corrected.

With its inquiry the commission set a new standard for tenacity, thoroughness and timeliness by a Presidential panel. Its chairman, William P. Rogers, a former Attorney General under President Eisenhower and Secretary of State under President Nixon, has said when asked about the panel's work that he was motivated in part by a need to avoid the loose ends and controversy left by the Warren commission, which investigated the assassination of President Kennedy.

The Rogers commission had hurtled around the country on "red-eye" flights, eating fast food over conference tables, "kicking the tires"—as one member, Eugene Covert, an MIT aeronautical engineer, put it—at NASA centers and contractor facilities, "always asking questions, even some dumb ones, and too often getting astonishing answers." The 13-member commission and its staff of 43 full-timers and some 140 part-time specialists eventually interviewed more than 160 people, conducted 36 formal hearings, accumulated almost 12 000 pages of transcripts and gathered 6300 documents totaling around 122 000 pages.

**Sleuths.** When the commission began its investigation, some members doubted they would solve the mystery of the Challenger explosion. In the end, the commission cracked the case. What it found was that the principal suspects at the start of the inquiry, the gaskets,

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or O-rings, used as the ultimate seal between the four segments of the solid-fuel booster rockets, were the culprits. In fact, the report cites three distinct problems with the O-rings: Gas pressures within the rocket caused the outer steel casing to bulge, exerting rotational forces at the joints, which knocked the backup seal out of place so that only the primary seal could be counted on to withstand the combustion pressure; unexpected cold temperature caused the O-rings to lose their resiliency, so that they could not function as the joint rotated; and this anomaly caused the hot exhaust gas to erode the rubber O-rings, reducing their ability to retain a tight seal.

Perhaps the most damaging chapter of the commission's report deals with all these matters under the heading "An accident rooted in history." The chapter shows that the Challenger disaster could have been seen coming as far back as 1977, four years before the first flight of the Columbia shuttle. That year, after evaluating early laboratory tests showing a gap in the seals when the rocket joints were subjected to pressure, two engineers at NASA's Marshall Space Flight Center wrote a report urging a redesign. The problem was exactly the opposite of what the makers of the booster, Morton Thiokol Inc, assumed would happen. NASA rejected the judgment of its engineers. Over the years, the commission's report says, concern about the seals grew slowly, until 1985, when O-ring problems appeared regularly—in one instance with severe erosion in a launch at 53 °F. Upon testing the effects of temperature on the O-rings, Thiokol engineers found that resiliency was diminished at 75 °F and virtually nonexistent at 50 °F

**Experiment.** Even before the documents on seal temperatures came into the hands of the Rogers commission, one member, Richard P. Feynman of Caltech, during a lull in a televised hearing conducted a small experiment that brought the O-ring question to the attention of the panel, press and public. Squeezing a piece of O-ring in a C-clamp, Feynman dunked it in a glass of ice water for one minute. When he removed the clamp, the O-ring remained flat and only regained its original shape several seconds later. "I believe," he said at the time, "that has some significance for our problem."

Feynman's demonstration and irrepressible practice of holding impromptu interviews with news reporters, often in front of television cameras, annoyed some members of the commission—notably the chairman, Rogers, who was overheard once complaining to the vice-chairman, Neil Armstrong, the astronaut who first set foot on the Moon, that "Feynman is becoming a real pain." Feynman, whose class lectures and recent autobiography, *Surely You're Joking, Mr. Feynman* (Norton, 1985), attest to his flair for showmanship, also irked NASA officials.

To one commission member, Albert D. (Bud) Wheelon, executive vice-president of Hughes Aircraft Co and a member of the President's Foreign Intelligence Advisory Board, "Dick was the most probing panelist on the commission. Sure he's colorful, but he proved in his work on the commission that he's a terrific scientist."

**Contributions.** It happens that four of the 13 panelists are physicists: Feynman and Wheelon of course, Sally K. Ride, who holds a PhD from Stanford and is the only woman astronaut to have completed two shuttle missions, and Arthur B. C. Walker Jr of Stanford. Walker was Ride's thesis adviser when she earned her PhD for work on the effects of dust grains on the propagation of x rays in the interstellar medium. "Physicists seemed to have an advantage on the commission," Feynman told PHYSICS TODAY. "They muddle around in the physical laws, which are the basis for the technical issues we were dealing with. But I wouldn't isolate the physicists for making special contributions as physicists. I want to make it clear that individual physicists contributed in complementary ways to the work of the engineers and lawyers."

Thus, Ride provided insights into launch procedures from her experience as a shuttle astronaut; Wheelon offered his considerable knowledge of industrial management and space technology; Walker looked at materials and structures from the point of view of a physicist, thereby adding to the understanding of the engineers; and Feynman, says Walker, "was just Feynman: questioning everything brought up, accepting nothing as sacrosanct."

Walker, for his part, made 17 trips for the commission. Among his stops: Rocketdyne, another manufacturer of solid-fuel booster rockets, to examine design procedures and discuss flight incidents, and Parker Seal Co, makers of the rubber O-rings. He also went to Cape Canaveral to view Challenger's remains, dredged from the Atlantic.

Wheelon, who considers himself "a long way from my origins as a physicist from MIT," claims physicists "seem to be unique in giving good advice to the government. It has to do with their scientific upbringing and their peculiar way of seeing things. They are trained to be intellectually skeptical, to set forth hypotheses and test and retest these experimentally. Some people try to make things fit. Not good physicists. They are more willing to think in radical ways. That may be why they are often stellar performers on campus, but sometimes uncomfortable in corporate or government settings, where more conventional thinking is valued. Feynman attracted a lot of attention by challenging the commission with his personal report. He didn't detract from the formal report. The commission did the best job I've ever seen done by a review panel, and I've seen many. But Dick's view in his own language added a new dimension to the official report."

**Confrontation.** Feynman would have preferred a more critically outspoken report. Rogers, by contrast, wanted to avoid controversy and confrontation. According to Walker, Rogers worried that a combative report would not be effective, that NASA would close ranks and defend its practices. Feynman admits that he initially refused to sign the commission report because he opposed a draft statement that the panel "strongly recommends" continued support for NASA and the space program. The recommendation seemed innocuous enough, he said, but the members had not discussed the topic. Feynman agreed to sign after the proposed recommendation was "downgraded" to a "Concluding thought" and the wording changed. It now reads: "The commission urges that NASA continue to receive the support of the Administration and the nation. The agency constitutes a national resource that plays a critical role in space exploration and development. It also provides a symbol of national pride and technological leadership. The commission applauds NASA's spectacular achievements of the past and anticipates impressive achievements to come. The findings and recommendations presented in this report are intended to contribute to the future NASA successes that the nation both expects and requires as the 21st century approaches."

The day after the commission's report was released, Feynman held a news conference at Caltech to release 13 pages of "Personal observations on the reliability of the shuttle." He submitted his observations to the commission earlier in hope of influencing the wording of the report. Several members objected to its strong tone, but others prevailed on Rogers to publish Feynman's comments later as an appendix to the report. It is not a dissent, claims Feynman. It represents his own concluding thoughts in his own words, rather than in the more careful, measured prose of the formal report.

**Exaggeration.** In it Feynman is harshly critical of NASA managers for accepting the 24 flights previous to Challenger's last liftoff as a virtual guarantee that the 25th would also be successful. "It appears that there are enormous differences of opinion as to the probability of a failure with the loss





**Challenger explosion** 73 seconds after liftoff on 28 January led to an inquiry by a Presidential commission whose 13 members included four physicists—clockwise from top right, Richard Feynman, Arthur Walker, Sally Ride and Albert Wheelon.

of vehicle and human life," writes Feynman at the start of his paper. "The estimates range from roughly 1 in 100 to 1 in 100 000. The higher figure comes from working engineers and the very low figure from management.... Since 1 part in 100 000 would imply that one could put a shuttle up each day for 300 years expecting to lose only 1, we could more properly ask: 'What is the cause of management's fantastic faith in the machinery?' "

After examining several risk analyses of the shuttle and reusable rockets prepared for NASA and personally interviewing aerospace engineers at the Jet Propulsion Laboratory, Rocketdyne, Marshall Space Flight Center and elsewhere, Feynman concluded that "for whatever purpose, be it for internal or external consumption, the management of NASA exaggerates the reliability of its product—to the point of fantasy." During his news conference, he put it more bluntly: "As far as I could tell," said Feynman, "the engineering judgment, so called, consisted of making up numbers."

There was plenty of evidence of troubles with the booster-rocket seals, but records and testimony show that NASA ignored the warnings that something was wrong and, Feynman states, did not seek to understand the troubles. "The fact that this danger did not lead to a catastrophe before is no guarantee that it will not the next time, unless it is completely understood," he writes. "When playing Russian roulette the fact that the first shot got off safely is little comfort for the next."

**Models.** Feynman argues that mathematical models based on inconsistent and uncertain data, without physical understanding, are dangerous. His comments recall the famous remark about a research paper once made by Wolfgang Pauli: "It is not right. It is not even wrong." Indeed, NASA's confidence that nothing would go wrong with the seals because they worked before is dismissed by Feynman: "There is nothing much so wrong with this as believing the answer!"

In his independent examination of the shuttle's main engines, he questions assuming their reliability without "detailed understanding" of the flaws that had been detected in bearings, turbine blades, cooling pipes and other components. The main engines, he observes, were designed and developed "all at once with relatively little detailed preliminary study" of the materials or parts. This concern with NASA's "success-oriented" tactic of building the shuttle without testing each component separately along the way was expressed back in 1979 in two studies conducted by a National Research Council panel headed by Covert. In his paper, Feynman urges NASA to continue to test components, attempt to understand failures and discrepancies, and solve problems whenever they arise, as they have in sensors, actuators and rocket jets used for controlling and reorienting the shuttle in flight.

Feynman's observations conclude with an appeal to the commission: "Let us make recommendations to ensure that NASA officials deal in a world of reality in understanding technological weaknesses and imperfections well enough to be actively trying to eliminate them.... Only realistic flight schedules should be proposed, schedules that have a reasonable chance of being met. If in this way the government would not support them, then so be it. NASA owes it to the citizens from whom it asks support to be frank, honest and informative so that these citizens can make the wisest decisions for the use of their limited resources. For a successful technology, reality must take precedence over public relations, for nature cannot be fooled."

—Irwin Goodwin □