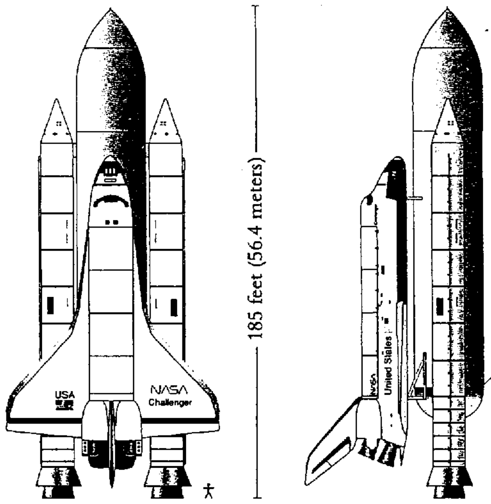
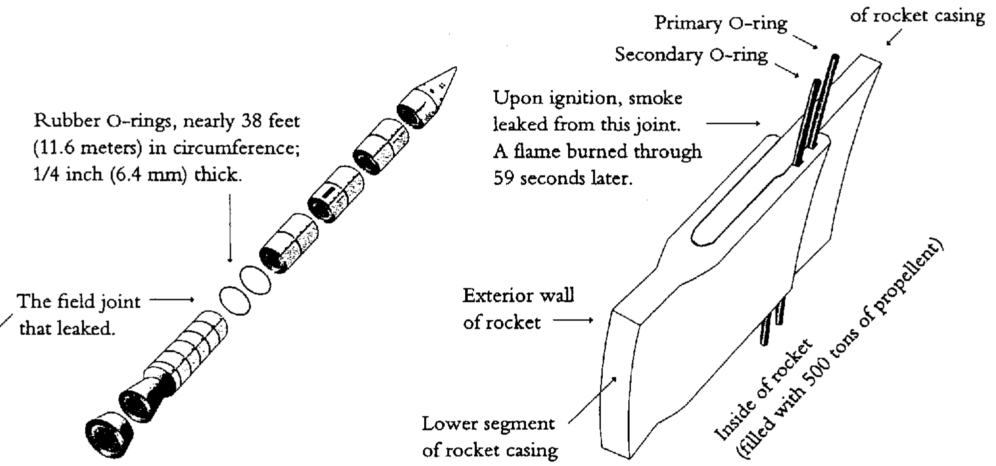
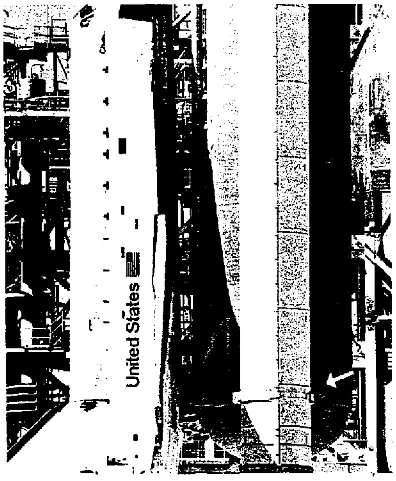
From Tufte, Edward. *Visual Explanations: Images and Quantities, Evidence and Narrative*. Cheshire, CT: Graphics P, 1997.

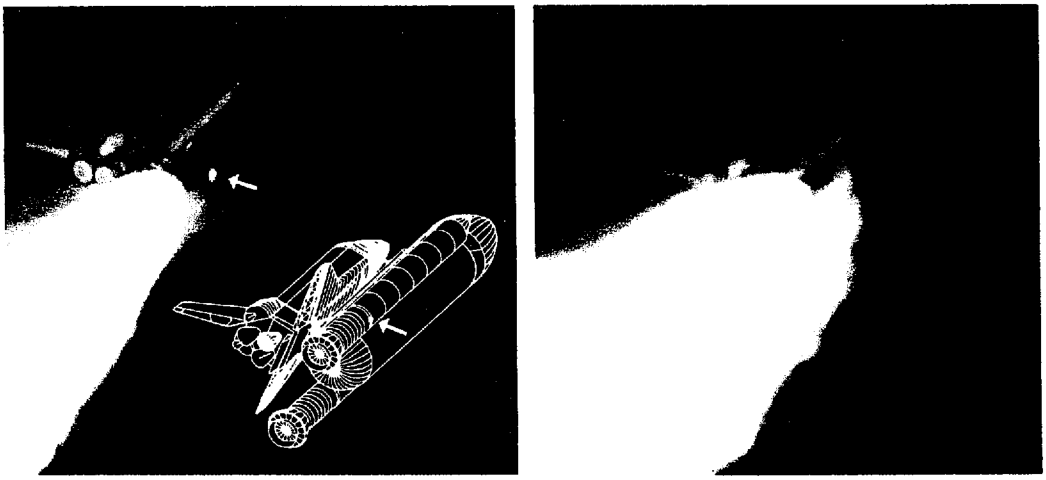




The shuttle consists of an *orbiter* (which carries the crew and has powerful engines in the back), a large liquid-fuel *tank* for the orbiter engines, and 2 solid-fuel *booster rockets* mounted on the sides of the central tank. Segments of the booster rockets are shipped to the launch site, where they are assembled to make the solid-fuel rockets. Where these segments mate, each joint is sealed by two rubber O-rings as shown above. In the case of the Challenger accident, one of these joints leaked, and a torch-like flame burned through the side of the booster rocket.

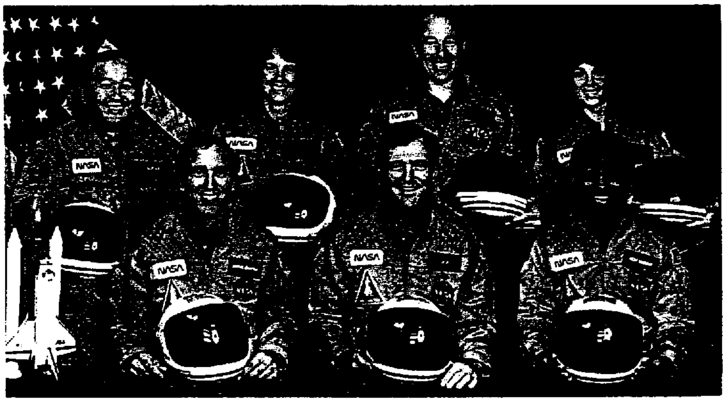


Less than 1 second after ignition, a puff of smoke appeared at the aft joint of the right booster, indicating that the O-rings burned through and failed to seal. At this point, all was lost.



On the launch pad, the leak lasted only about 2 seconds and then apparently was plugged by putty and insulation as the shuttle rose, flying through rather strong cross-winds. Then 58.788 seconds after ignition, when the Challenger was 6 miles up, a flicker of flame emerged from the leaky joint. Within seconds, the flame grew and engulfed the fuel tank (containing liquid hydrogen and liquid oxygen). That tank ruptured and exploded, destroying the shuttle.

As the shuttle exploded and broke up at approximately 73 seconds after launch, the two booster rockets crisscrossed and continued flying wildly. The right booster, identifiable by its failure plume, is now to the left of its non-defective counterpart.



The flight crew of Challenger 51-L. Front row, left to right: Michael J. Smith, pilot; Francis R. (Dick) Scobee, commander; Ronald E. McNair. Back row: Ellison S. Onizuka, S. Christa McAuliffe, Gregory B. Jarvis, Judith A. Resnik.

The Decision to Launch the Space Shuttle Challenger

ON January 28, 1986, the space shuttle Challenger exploded and seven astronauts died because two rubber O-rings leaked.[22] These rings had lost their resiliency because the shuttle was launched on a very cold day. Ambient temperatures were in the low 30s and the O-rings themselves were much colder, less than 20°F.

One day before the flight, the predicted temperature for the launch was 26° to 29°. Concerned that the rings would not seal at such a cold temperature, the engineers who designed the rocket opposed launching Challenger the next day. Their misgivings derived from several sources: a history of O-ring damage during previous cool-weather launches of the shuttle, the physics of resiliency (which declines exponentially with cooling), and experimental data.[23] Presented in 13 charts, this evidence was faxed to NASA, the government agency responsible for the flight. A high-level NASA official responded that he was "appalled" by the recommendation not to launch and indicated that the rocket-maker, Morton Thiokol, should reconsider, even though this was Thiokol's only no-launch recommendation in 12 years.[24] Other NASA officials pointed out serious weaknesses in the charts. Reassessing the situation after these skeptical responses, the Thiokol managers changed their minds and decided that they now favored launching the next day. They said the evidence presented by the engineers was inconclusive, that cool temperatures were not linked to O-ring problems.[25]

Thus the *exact cause* of the accident was intensely debated during the evening before the launch. That is, for hours, the rocket engineers and managers considered the question: *Will the rubber O-rings fail catastrophically tomorrow because of the cold weather?* These discussions concluded at midnight with the decision to go ahead. That morning, the Challenger blew up 73 seconds after its rockets were ignited.

THE immediate cause of the accident—an O-ring failure—was quickly obvious (see the photographs at left). But what are the general causes, the lessons of the accident? And what is the meaning of Challenger? Here we encounter diverse and divergent interpretations, as the facts of the accident are reworked into moral narratives.[26] These allegories regularly advance claims for the special relevance of a distinct analytic approach or school of thought: if only the engineers and managers had the skills of field X, the argument implies, this terrible thing would not have happened. Or, further, the insights of X identify the deep causes of the failure. Thus, in management schools, the accident serves as a case study for reflections about groupthink, technical decision-making in the face of political pressure, and bureaucratic failures to communicate. For the authors of engineering textbooks and for the physicist Richard Feynman, the Challenger accident simply confirmed what they already

[22] My sources are the five-volume *Report of the Presidential Commission on the Space Shuttle Challenger Accident* (Washington, DC, 1986) hereafter cited as *PCSSCA*; Committee on Science and Technology, House of Representatives, *Investigation of the Challenger Accident* (Washington, DC, 1986); Richard P. Feynman, "*What Do You Care What Other People Think?*" *Further Adventures of a Curious Character* (New York, 1988); Richard S. Lewis, *Challenger: The Final Voyage* (New York, 1988); Frederick Lighthall, "Launching the Space Shuttle Challenger: Disciplinary Deficiencies in the Analysis of Engineering Data," *IEEE Transactions on Engineering Management*, 38 (February 1991), pp. 63–74; and Diane Vaughan, *The Challenger Launch Decision: Risky Technology, Culture, and Deviance at NASA* (Chicago, 1996). The text accompanying the images at left is based on *PCSSCA*, volume 1, pp. 6–9, 19–32, 52, 60. Illustrations of shuttle at upper left by Weilin Wu and Edward Tufte.

[23] *PCSSCA*, volume 1, pp. 82–113.

[24] *PCSSCA*, volume 1, p. 107.

[25] *PCSSCA*, volume 1, p. 108.

[26] Various interpretations of the accident include *PCSSCA*, which argues several views; James L. Adams, *Flying Buttresses, Entropy, and O-Rings: The World of an Engineer* (Cambridge, Massachusetts, 1991); Michael McConnell, *Challenger: A Major Malfunction* (New York, 1987); Committee on Shuttle Criticality Review and Hazard Analysis Audit, *Post-Challenger Evaluation of Space Shuttle Risk Assessment and Management* (Washington, DC, 1988); Siddhartha R. Dalal, Edward B. Fowlkes, and Bruce Hoadley, "Risk Analysis of the Space Shuttle: Pre-Challenger Prediction of Failure," *Journal of the American Statistical Association*, 84 (December 1989), pp. 945–957; Claus Jensen, *No Downlink* (New York, 1996); and, cited above in note 22, the House Committee Report, the thorough account of Vaughan, Feynman's book, and Lighthall's insightful article.

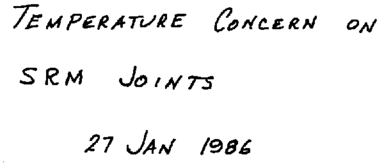
knew: awful consequences result when heroic engineers are ignored by villainous administrators. In the field of statistics, the accident is evoked to demonstrate the importance of risk assessment, data graphs, fitting models to data, and requiring students of engineering to attend classes in statistics. For sociologists, the accident is a symptom of structural history, bureaucracy, and conformity to organizational norms. Taken in small doses, the assorted interpretations of the launch decision are plausible and rarely mutually exclusive. But when *all* these accounts are considered together, the accident appears thoroughly overdetermined. It is hard to reconcile the sense of inevitable disaster embodied in the cumulated literature of post-accident hindsight with the experiences of the first 24 shuttle launches, which were distinctly successful.

REGARDLESS of the indirect cultural causes of the accident, there was a clear proximate cause: an inability to assess the link between cool temperature and O-ring damage on earlier flights. Such a pre-launch analysis would have revealed that this flight was at considerable risk.[27]

On the day before the launch of Challenger, the rocket engineers and managers needed a quick, smart *analysis* of evidence about the threat of cold to the O-rings, as well as an effective *presentation* of evidence in order to convince NASA officials not to launch. Engineers at Thiokol prepared 13 charts to make the case that the Challenger should *not* be launched the next day, given the forecast of very chilly weather.[28] Drawn up in a few hours, the charts were faxed to NASA and discussed in two long telephone conferences between Thiokol and NASA on the night before the launch. The charts were unconvincing; the arguments against the launch failed; the Challenger blew up.

These charts have weaknesses. First, the title-chart (at right, where "SRM" means Solid Rocket Motor), like the other displays, does not provide the *names* of the people who prepared the material. All too often, such documentation is absent from corporate and government reports. Public, named authorship indicates responsibility, both to the immediate audience and for the long-term record. Readers can follow up and communicate with a named source. Readers can also recall what they know about the author's reputation and credibility. And so even a title-chart, if it lacks appropriate documentation, might well provoke some doubts about the evidence to come.

The second chart (top right) goes directly to the immediate threat to the shuttle by showing the history of eroded O-rings on launches prior to the Challenger. This varying damage, some serious but none catastrophic, was found by examining the O-rings from rocket casings retrieved for re-use. Describing the historical distribution of the *effect* endangering the Challenger, the chart does not provide data about the possible *cause*, temperature. Another impediment to understanding is that the same rocket has three different names: a NASA number (61A LH),



TEMPERATURE CONCERN ON

SRM JOINTS

27 JAN 1986

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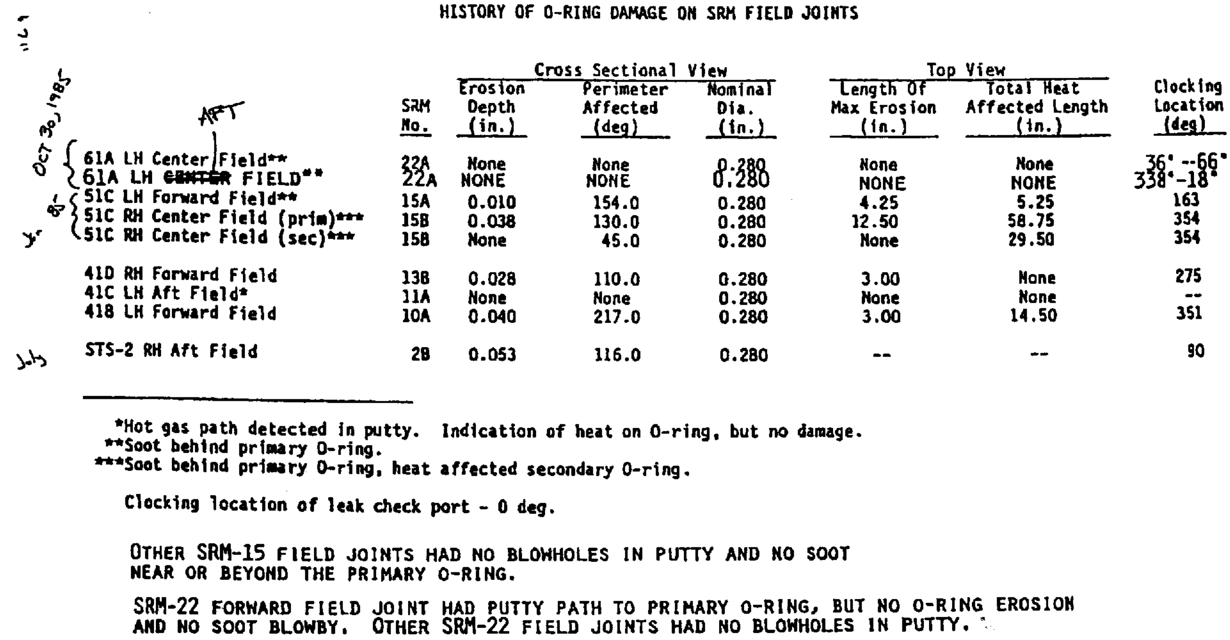
[27] The commission investigating the accident concluded: "A careful analysis of the flight history of O-ring performance would have revealed the correlation of O-ring damage and low temperature. Neither NASA nor Thiokol carried out such an analysis; consequently, they were unprepared to properly evaluate the risks of launching the 51-L [Challenger] mission in conditions more extreme than they had encountered before." *PCSSCA*, volume I, p. 148. Similarly, "the decision to launch STS 51-L was based on a faulty engineering analysis of the SRM field joint seal behavior," House Committee on Science and Technology, *Investigation of the Challenger Accident*, p. 10. Lighthall, "Launching the Space Shuttle," reaches a similar conclusion.

[28] The 13 charts appear in *PCSSCA*, volume IV, pp. 664–673; also in Vaughan, *Challenger Launch Decision*, pp. 293–299.



HISTORY OF O-RING DAMAGE ON SRM FIELD JOINTS

Oct 30, 1985

AFT

	SRM No.	Cross Sectional View: Erosion Depth (in.)	Cross Sectional View: Perimeter Affected (deg)	Cross Sectional View: Nominal Dia. (in.)	Top View: Length Of Max Erosion (in.)	Top View: Total Heat Affected Length (in.)	Clocking Location (deg)
61A LH Center Field**	22A	None	None	0.280	None	None	36° --66°
61A LH ~~CENTER~~ FIELD**	22A	NONE	NONE	0.280	NONE	NONE	338°-18°
51C LH Forward Field**	15A	0.010	154.0	0.280	4.25	5.25	163
51C RH Center Field (prim)***	15B	0.038	130.0	0.280	12.50	58.75	354
51C RH Center Field (sec)***	15B	None	45.0	0.280	None	29.50	354
41D RH Forward Field	13B	0.028	110.0	0.280	3.00	None	275
41C LH Aft Field*	11A	None	None	0.280	None	None	--
41B LH Forward Field	10A	0.040	217.0	0.280	3.00	14.50	351
STS-2 RH Aft Field	2B	0.053	116.0	0.280	--	--	90

*Hot gas path detected in putty. Indication of heat on O-ring, but no damage.
**Soot behind primary O-ring.
***Soot behind primary O-ring, heat affected secondary O-ring.

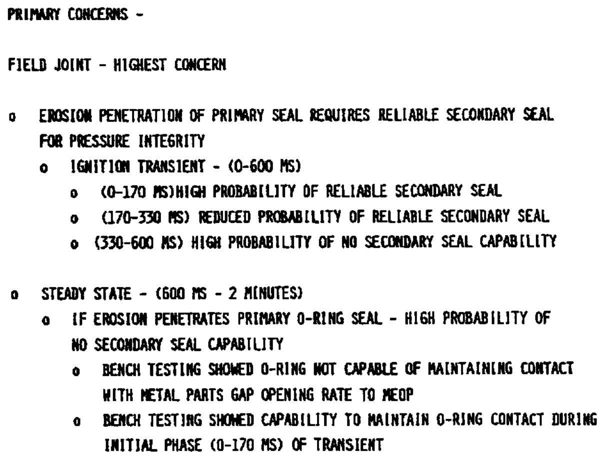
Clocking location of leak check port - 0 deg.

OTHER SRM-15 FIELD JOINTS HAD NO BLOWHOLES IN PUTTY AND NO SOOT NEAR OR BEYOND THE PRIMARY O-RING.

SRM-22 FORWARD FIELD JOINT HAD PUTTY PATH TO PRIMARY O-RING, BUT NO O-RING EROSION AND NO SOOT BLOWBY. OTHER SRM-22 FIELD JOINTS HAD NO BLOWHOLES IN PUTTY.

Thiokol's number (SRM no. 22A), and launch date (handwritten in the margin above). For O-ring damage, six types of description (erosion, soot, depth, location, extent, view) break the evidence up into stupefying fragments. An overall index summarizing the damage is needed. This chart quietly begins to define the scope of the analysis: a handful of previous flights that experienced O-ring problems.[29]

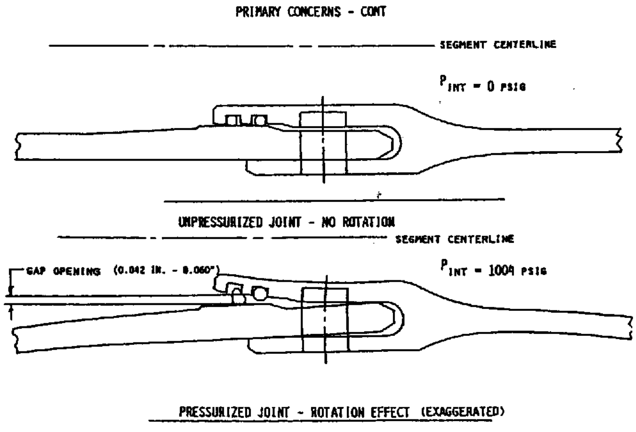
The next chart (below left) describes how erosion in the primary O-ring interacts with its back-up, the secondary O-ring. Then two drawings (below right) make an effective visual comparison to show how rotation of the field joint degrades the O-ring seal. This vital effect, however, is not linked to the potential cause; indeed, neither chart appraises the phenomena described in relation to temperature.



PRIMARY CONCERNS -

FIELD JOINT - HIGHEST CONCERN

- o EROSION PENETRATION OF PRIMARY SEAL REQUIRES RELIABLE SECONDARY SEAL FOR PRESSURE INTEGRITY
  - o IGNITION TRANSIENT - (0-600 MS)
    - o (0-170 MS)HIGH PROBABILITY OF RELIABLE SECONDARY SEAL
    - o (170-330 MS) REDUCED PROBABILITY OF RELIABLE SECONDARY SEAL
    - o (330-600 MS) HIGH PROBABILITY OF NO SECONDARY SEAL CAPABILITY
- o STEADY STATE - (600 MS - 2 MINUTES)
  - o IF EROSION PENETRATES PRIMARY O-RING SEAL - HIGH PROBABILITY OF NO SECONDARY SEAL CAPABILITY
    - o BENCH TESTING SHOWED O-RING NOT CAPABLE OF MAINTAINING CONTACT WITH METAL PARTS GAP OPENING RATE TO MEOP
    - o BENCH TESTING SHOWED CAPABILITY TO MAINTAIN O-RING CONTACT DURING INITIAL PHASE (0-170 MS) OF TRANSIENT



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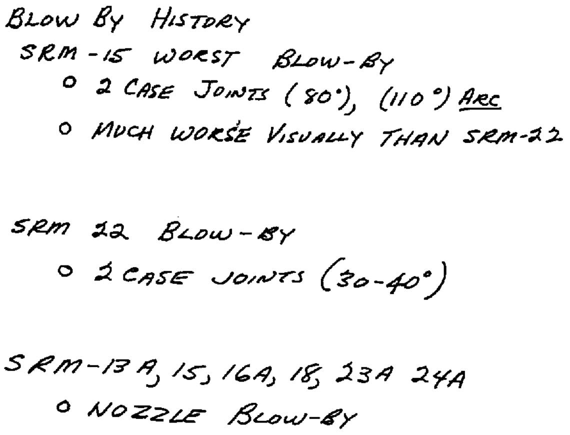
[29] This chart does not report an incident of field-joint erosion on STS 61-C, launched two weeks before the Challenger, data which appear to have been available prior to the Challenger prelaunch meeting (see *PCSSCA*, volume II, p. H-3). The damage chart is typewritten, indicating that it was prepared for an earlier presentation before being included in the final 13; handwritten charts were prepared the night before the Challenger was launched.



BLOW BY HISTORY

SRM-15 WORST BLOW-BY

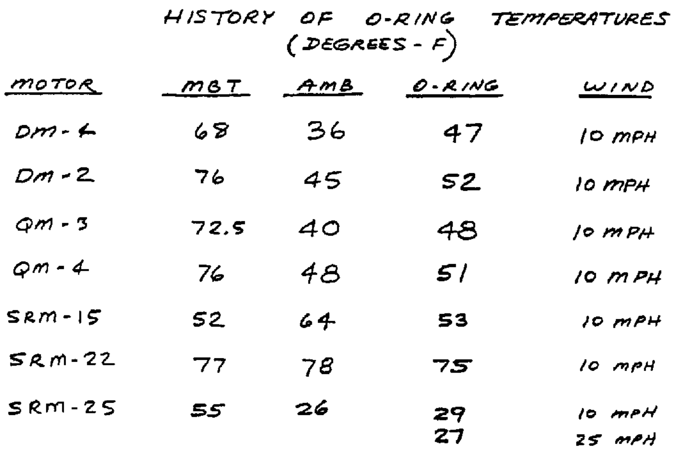
- o 2 CASE JOINTS (80°), (110°) ARC
- o MUCH WORSE VISUALLY THAN SRM-22

SRM 22 BLOW-BY

- o 2 CASE JOINTS (30-40°)

SRM-13A, 15, 16A, 18, 23A 24A

- o NOZZLE BLOW-BY



HISTORY OF O-RING TEMPERATURES (DEGREES - F)

MOTOR	MBT	AMB	O-RING	WIND
DM-4	68	36	47	10 MPH
DM-2	76	45	52	10 MPH
QM-3	72.5	40	48	10 MPH
QM-4	76	48	51	10 MPH
SRM-15	52	64	53	10 MPH
SRM-22	77	78	75	10 MPH
SRM-25	55	26	29 27	10 MPH 25 MPH

Two charts further narrowed the evidence. Above left, "Blow-By History" mentions the two previous launches, SRM 15 and SRM 22, in which soot (blow-by) was detected in the field joints upon post-launch examination. This information, however, was already reported in the more detailed damage table that followed the title chart.[30] The bottom two lines refer to *nozzle* blow-by, an issue not relevant to launching the Challenger in cold weather.[31]

Although not shown in the blow-by chart, temperature is part of the analysis: SRM 15 had substantial O-ring damage and also was the coldest launch to date (at 53° on January 24, 1985, almost one year before the Challenger). This argument by analogy, made by those opposed to launching the Challenger the next morning, is reasonable, relevant, and weak. With only one case as evidence, it is usually quite difficult to make a credible statement about cause and effect.

If one case isn't enough, why not look at two? And so the parade of anecdotes continued. By linking the blow-by chart (above left) to the temperature chart (above right), those who favored launching the Challenger spotted a weakness in the argument. While it was true that the blow-by on SRM 15 was on a cool day, the blow-by on SRM 22 was on a *warm* day at a temperature of 75° (temperature chart, second column from the right). One engineer said, "We had blow-by on the hottest motor [rocket] and on the coldest motor. [32] The superlative "-est" is an extreme characterization of these thin data, since the total number of launches under consideration here is exactly *two*.

With its focus on blow-by rather than the more common erosion, the chart of blow-by history invited the rhetorically devastating—for those opposed to the launch—comparison of SRM 15 and SRM 22. In fact, as the blow-by chart suggests, the two flights profoundly differed: the 53° launch probably barely survived with significant *erosion* of the primary and secondary O-rings on both rockets as well as blow-by; whereas the 75° launch had no erosion and only blow-by.

[30] On the blow-by chart, the numbers 80°, 110°, 30°, and 40° refer to the *arc* covered by blow-by on the 360° of the field (called here the "case") joint.

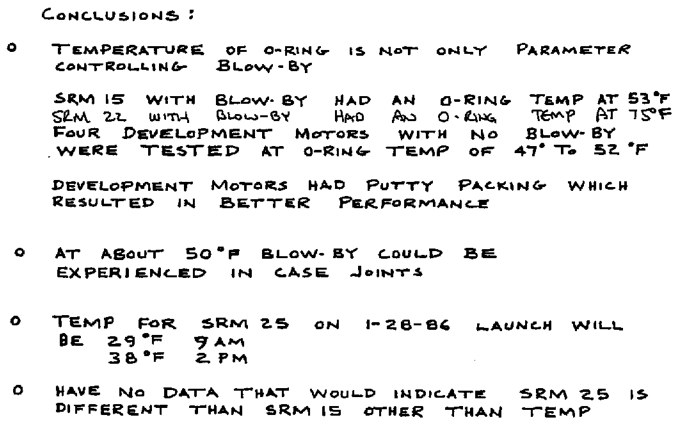
[31] Following the blow-by chart were four displays, omitted here, that showed experimental and subscale test data on the O-rings. See *PCSSCA*, volume IV, pp. 664–673.

[32] Quoted in Vaughan, *Challenger Launch Decision*, pp. 296–297.

These charts *defined the database for the decision:* blow-by (not erosion) and temperature for two launches, SRM 15 and SRM 22. Limited measure of effect, wrong number of cases. Left out were the other 22 previous shuttle flights and their temperature variation and O-ring performance. A careful look at such evidence would have made the dangers of a cold launch clear. Displays of evidence implicitly but powerfully define the scope of the relevant, as presented data are selected from a larger pool of material. Like magicians, chartmakers reveal what they choose to reveal. That selection of data—whether partisan, hurried, haphazard, uninformed, thoughtful, wise—can make all the difference, determining the scope of the evidence and thereby setting the analytic agenda that leads to a particular decision.

For example, the temperature chart reports data for two developmental rocket motors (DM), two qualifying motors (QM), two actual launches with blow-by, and the Challenger (SRM 25) forecast.[33] These data are shown again at right. What a strange collation: the first 4 rockets were test motors that never left the ground. Missing are 92% of the temperature data, for 5 of the launches with erosion and 17 launches without erosion.

Depicting bits and pieces of data on blow-by and erosion, along with some peculiarly chosen temperatures, these charts set the stage for the unconvincing conclusions shown in two charts below. The major recommendation, "O-ring temp must be ≥ 53°F at launch," which was rejected, rightly implies that the Challenger could not be safely launched the next morning at 29°. Drawing a line at 53°, however, is a crudely empirical result based on a sample of size one. That anecdote was certainly not an auspicious case, because the 53° launch itself had considerable erosion. As Richard Feynman later wrote, "The O-rings of the solid rocket boosters were not designed to erode. Erosion was a clue that something was wrong. Erosion was not something from which safety could be inferred."[34]



CONCLUSIONS :

- o TEMPERATURE OF O-RING IS NOT ONLY PARAMETER CONTROLLING BLOW-BY

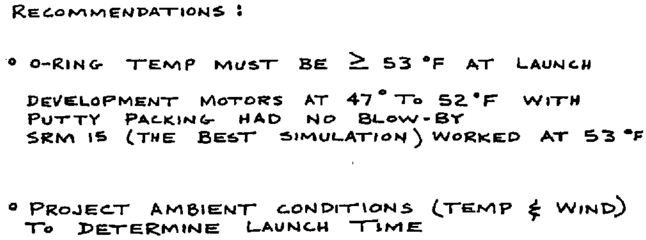
  SRM 15 WITH BLOW-BY HAD AN O-RING TEMP AT 53°F
  SRM 22 WITH BLOW-BY HAD AN O-RING TEMP AT 75°F
  FOUR DEVELOPMENT MOTORS WITH NO BLOW-BY WERE TESTED AT O-RING TEMP OF 47° TO 52°F

  DEVELOPMENT MOTORS HAD PUTTY PACKING WHICH RESULTED IN BETTER PERFORMANCE

- o AT ABOUT 50°F BLOW-BY COULD BE EXPERIENCED IN CASE JOINTS

- o TEMP FOR SRM 25 ON 1-28-86 LAUNCH WILL BE 29°F 9 AM
  38°F 2 PM

- o HAVE NO DATA THAT WOULD INDICATE SRM 25 IS DIFFERENT THAN SRM 15 OTHER THAN TEMP



RECOMMENDATIONS :

- o O-RING TEMP MUST BE ≥ 53°F AT LAUNCH

  DEVELOPMENT MOTORS AT 47° TO 52°F WITH PUTTY PACKING HAD NO BLOW-BY
  SRM 15 (THE BEST SIMULATION) WORKED AT 53°F

- o PROJECT AMBIENT CONDITIONS (TEMP & WIND) TO DETERMINE LAUNCH TIME

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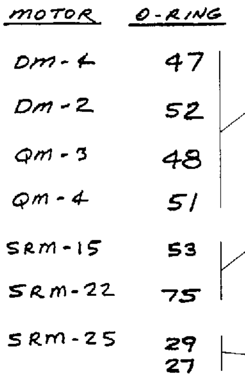
[33] The table of temperature data, shown in full at left, is described as a "History of O-ring Temperatures." It is a highly selective history, leaving out nearly all the actual flight experience of the shuttle:



MOTOR	O-RING
DM-4	47
DM-2	52
QM-3	48
QM-4	51
SRM-15	53
SRM-22	75
SRM-25	29 27

Test rockets ignited on fixed horizontal platforms in Utah.

The only 2 shuttle launches (of 24) for which temperatures were shown in the 13 Challenger charts.

Forecasted O-ring temperatures for the Challenger.

[34] Richard P. Feynman, "*What Do You Care What Other People Think?" Further Adventures of a Curious Character* (New York, 1988), p. 224; also in Feynman, "Appendix F: Personal Observations on the Reliability of the Shuttle," *PCSSCA*, volume II, p. F2. On the many problems with the proposed 53° temperature line, see Vaughan, *Challenger Launch Decision*, pp. 309–310.

The 13 charts failed to stop the launch. Yet, as it turned out, the chartmakers had reached the right conclusion. They had the correct theory and they were thinking causally, but they were not *displaying* causally. Unable to get a correlation between O-ring distress and temperature, those involved in the debate concluded that they didn't have enough data to quantify the effect of the cold.[35] The displayed data were very thin; no wonder NASA officials were so skeptical about the no-launch argument advanced by the 13 charts. For it was as if John Snow had ignored some areas with cholera and *all* the cholera-free areas and their water pumps as well. The flights without damage provide the statistical leverage necessary to understand the effects of temperature. *Numbers become evidence by being in relation to.*

This data matrix shows the complete history of temperature and O-ring condition for all previous launches. Entries are ordered by the possible cause, temperature, from coolest to warmest launch. Data in red were exhibited at some point in the 13 pre-launch charts; and the data shown in black were not included. I have calculated an overall O-ring damage score for each launch.[36] The table reveals the link between O-ring distress and cool weather, with a concentration of problems on cool days compared with warm days:

Flight	Date	Temperature °F	Erosion incidents	Blow-by incidents	Damage index	Comments
51-C	01.24.85	53°	3	2	11	Most erosion any flight; blow-by; back-up rings heated.
41-B	02.03.84	57°	1		4	Deep, extensive erosion.
61-C	01.12.86	58°	1		4	O-ring erosion on launch two weeks before Challenger.
41-C	04.06.84	63°	1		2	O-rings showed signs of heating, but no damage.
1	04.12.81	66°			0	Coolest (66°) launch without O-ring problems.
6	04.04.83	67°			0	
51-A	11.08.84	67°			0	
51-D	04.12.85	67°			0	
5	11.11.82	68°			0	
3	03.22.82	69°			0	
2	11.12.81	70°	1		4	Extent of erosion not fully known.
9	11.28.83	70°			0	
41-D	08.30.84	70°	1		4	
51-G	06.17.85	70°			0	
7	06.18.83	72°			0	
8	08.30.83	73°			0	
51-B	04.29.85	75°			0	
61-A	10.30.85	75°		2	4	No erosion. Soot found behind two primary O-rings.
51-I	08.27.85	76°			0	
61-B	11.26.85	76°			0	
41-G	10.05.84	78°			0	
51-J	10.03.85	79°			0	
4	06.27.82	80°			?	O-ring condition unknown; rocket casing lost at sea.
51-F	07.29.85	81°			0	

[35] *PCSSCA*, volume IV, pp. 290, 791.

[36] For each launch, the score on the damage index is the severity-weighted total number of incidents of O-ring erosion, heating, and blow-by. Data sources for the entire table: *PCSSCA*, volume II, pp. H1–H3, and volume IV, p. 664; and *Post-Challenger Evaluation of Space Shuttle Risk Assessment and Management*, pp. 135–136.