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The Facts in the Columbia Accident:
*Lessons about Limitations on Data and Models*

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The Columbia Accident

• Background -- setting the environment in which work was conducted and decisions made
• Specifics of the (structural) design -- requirements and resulting realities
• Physical cause of the loss -- the reality and details of the puzzle and the consistent scenario
• Issues of impact -- the cause of the damage and reasons for declaration of “safe”

How did this all happen…….
Shuttle Conceptual Development

• post-Apollo -- NASA has view of combined, integral program with Shuttle, Space Station, and space exploration
• Nixon rejected plans and cuts NASA’s budget
• 1970 -- NASA turns to justifying Shuttle on economic basis
• OMB forces NASA to keep development and operating costs low
• $5.5B ceiling imposed by OMB
• Cost ceiling resulted in tradeoffs to be made for savings in short term but resulting in vehicle with higher operational costs and greater risks
Thoughts on the Process Results
(from CAIB)

• “…the Shuttle emerged from a series of political compromises that produced unreasonable expectations - even myths- about its performance.”

• “The commitments made during the policy process drove a design aimed at satisfying conflicting requirements.”

• “It is the Board’s view that, in retrospect, the increased complexity of a Shuttle designed to be all things to all people created inherently greater risks than if more realistic technical goals had been set at the start.”
(Pertinent) Design Requirements -- Reentry and Temperature

• Withstand superheated air temperatures upon reentry due to aerothermodynamic heating in braking from orbital velocity of 17,500 mph to landing velocity of 220 mph

• Maximum temperature of 10,000°F in flow behind intersection of two shock waves at leading edge (around Panel 9)

• Boundary layer around Shuttle shields body from extreme temperatures

• Resulting temperature requirements dependent upon location on vehicle
  – nose and wing leading edge: 2800-3000°F
  – other portions of wing and fuselage: 700-1200-2300°F
  – top of fuselage: ice forms!
Resulting Design of TPS (Thermal Protection System)

3 major reusable components

• Leading edge and nose cap (2800-3000°F) -- RCC (Reinforced Carbon-Carbon) panels: layers of special graphite cloth molded and pyrolized at high temperature to desired shape

• Wing and Fuselage (1200-2300°F) -- Reusable tiles: 90% air and 10% silica resulting in VERY low heat transfer capability (conductivity and absorption)

• Fuselage areas with moderate heating (700-1200°F) -- blankets: low in heat transfer capability
Further Design Requirements for Wing Leading Edge

OVERALL: Provide aerodynamic load bearing, structural, and thermal control capability for area exceeding 2300°F

- Fly 100 missions
- Maintain aluminum wing structure at less than 350°F (covered with insulation to protect from radiation of RCC)
- Withstand kinetic energy impact of 0.006 foot-pounds
- Factor of safety of 1.4 (withstand 1.4 times load ever expected in operation)
Further Details of RCC Used in Wing Leading Edge

• Basic RCC production
  – individual layers (plies) of graphite-impregnated rayon fabric
  – further impregnated with phenolic resin
  – layered one ply at a time in unique mold for each part
  – packed in calcined coke and fired in oven to convert to carbon
    (three cycles with vacuum to make more dense)
  – outer layers (0.02-0.04 in) converted to silicon carbide in chamber
    with argon at 3000°F and pores filled with sealant
• Operational temperature range of -250°F to 3000°F
• Low thermal expansion coefficient to minimize thermal shock and thermoelastic stresses
• 22 RCC panels on each wing leading edge attached via stainless steel attachments and Inconel clevises; resulting gaps sealed
(Pertinent) Design Requirements -- Ascent and External Tank (ET)

- Accommodate 143,351 gallons of liquid oxygen (-297°F) and 385,265 gallons of liquid hydrogen (-423°F)
- Insulate tank so that
  - super-cold propellants do not boil
  - ice does not form on outside of tank while sitting on launch pad
  - structure is protected from aerodynamic heating during ascent
- Not reused
- Serve as main structural component during assembly, launch, and ascent
Resulting Design of External Tank Thermal Protection System

**OVERALL:** Must conform to and protect geometric details due to connecting hardware and other fittings

- Thermal protection provided by two materials
  - dense composite ablators for dissipating heat
  - low density closed-cell foam (3 types) for high insulation efficiency
- Foam applied via spray-on directly to aluminum substrate
- Bonding between foam and substrate dependent upon
  - surface preparation (primer used)
  - application method (and person performing work)
- Foam applied in multiple layers in some areas -- requires bonding enhancer
- Foam manually shaved down to one inch in some areas -- particularly near structural details
Impact requirement details

from: Shuttle’s “Flight and Ground System Specification-Book 1, Requirements”

• **3.2.1.2.14 Debris Prevention:** The Space Shuttle System, including the ground systems, shall be designed to preclude the shedding of ice and/or other debris from the Shuttle elements during prelaunch and flight operations that would jeopardize the flight crew, vehicle, mission success, or would adversely impact turnaround operations

• **3.2.1.1.17 External Tank Debris Limits:** No debris shall emanate from the critical zone of the External Tank on the launch pad or during ascent except for such material which may result from normal thermal protection system recession due to ascent heating

    *TPS able to withstand impact with kinetic energy of 0.006 foot-pounds*
Further evolution of impact issues for RCC panels

- Risk of micrometeoroid or debris damage to RCC panels evaluated several times
- Hypervelocity and low-velocity tests done with different projectiles
- Resulted in addition of 0.03-0.06 in thick layer of Nextel-440 fabric
- Analysis of design change shows Shuttle can survive re-entry with 1/4” diameter hole in lower surfaces of RCC panels 8-10 (hottest) or 1” diameter hole in others

Further considerations result in panel refurbishment after 18 or 36 missions
Physical cause of loss of Columbia --
Overview *(113th Program flight; 28th Columbia flight)*

- One large piece (and two smaller pieces) of foam separated from External Tank left bipod (-Y) ramp area at 81.7 seconds after launch
- Large foam piece is 21-27” long and 12-18” wide, tumbling at minimum of 18/second, and with relative velocity of 625-840 feet per second upon striking Shuttle at 81.9 seconds after launch *(weight ~ 1.7 pounds)*
- Foam piece struck Columbia on underside of left wing around RCC panels 5 through 9
- Resulted in breach/hole of 6-10” at point of impact
- During re-entry, superheated air penetrated through breach and progressively melted aluminum structure of left wing until aerodynamic forces caused loss of control, failure of wing, and break-up of vehicle
Evidence of cause -- the post event puzzle (*the impact event*)

- Post-launch photographic analysis showed foam piece, velocity, angle, etc. (*also seen in Day 2 of Mission*)
- CFD (Computational Fluid Dynamics) analysis shows path of piece results in impact with RCC Panel 8 (*NOTE: near highest heating point during re-entry*)
- Impact analysis and testing (also used to correlate analysis) showed creation of breach in RCC Panel 8 on order of 6”x11” to 7”x12”
- Later review of radar tracking showed object that drifted away from Columbia on Day 2 (analysis indicates consistent with size of damage to RCC Panel 8)
Evidence of cause -- the post event puzzle *(the re-entry)*

- Sensors on Shuttle show abnormal rise in temperatures and strains and loss of sensors *(recordings recovered from “Box”, but not telemetered to ground; also observed on ascent)*
- CFD (Computational Fluid Dynamics) analysis with 6-10” breach in lower portion of RCC Panel 8 shows results consistent with sensor readings
  - hot gas penetration began in cavity in wing leading edge
  - followed by plume of superheated air that penetrated aluminum spar
  - progressed to wheel well and continued destruction of wing structure
- Timing of damage and structure destruction consistent with abnormal roll and yaw forces recorded
Evidence of cause -- the post event puzzle (*the re-entry model*)

(Appendix F.2, Fig 34, p. 42)
Evidence of cause -- the post event puzzle (*the recovered pieces*)

- Many fewer pieces of left wing than right wing (*consistent with extensive destruction as ingested air may have been as hot as 8000°F*)
- Location of piece recovery consistent with analyzed initial damage
- “Knife edging” of damaged panels, ablation of panels, and deposited metal from melting upstream consistent with analysis

(Appendix F.2, Fig 34, p. 42)
Impact requirements unofficially “loosened” over years

- Photographic evidence of foam shedding exists for 65 of the 79 missions for which imagery is available (80%)
- Of 34 missions with no imagery, 8 where foam loss is not seen, and 6 where imagery is inconclusive, foam loss can be inferred from number of divots on Shuttle lower surface
- Foam loss at left bipod (-Y) ramp confirmed in 10% (7 of 72) cases where imagery is available of total of 113
- 1990 study by NASA personnel using probabilistic analysis and considering linked events leading to critical sub-system burn-through indicated 1 in 1000 probability of loosing Shuttle -- *No immediate action taken*
Recall the specific impact criterion…..

• “The Space Shuttle System, including the ground systems, shall be designed to preclude the shedding of ice and/or other debris from the Shuttle elements during prelaunch and flight operations that would jeopardize the flight crew, vehicle, mission success, or would adversely impact turnaround operations”

• Thermal Protection System able to withstand impact with kinetic energy of 0.006 foot-pounds

(Almost no damage resistance)

(∼1 ounce dropped from 1 inch !!!)!!!!!!!
Impact knowledge and concern during Mission of Columbia

• Post-launch photographic analysis on Day 2 showed foam piece separation and impact
• Debris Assessment Team formed to address potential damage and effects
• Many emails, discussions, requests for imagery of shuttle occur during shuttle flight
• Engineers used “Crater” model to assess impact event
The “Crater” Model

• Empirical model (quite complex equation) developed during Apollo program to assess impact damage due to micrometeoroids
• Modified, using further data (ice and foam impactors), in early 80’s to predict depth that debris will penetrate TPS tile
• Originally correlated for impact pieces up to 1 cubic inch in volume and weight of 0.002 pounds
• Later data went to impact pieces up to 3 cubic inches in volume but same weight
• Provides conservative estimates when used in validated range
• Until Columbia, normally used to predict whether small debris (usually ice on External Tank) posed a threat during launch
The Final Results

- Engineers extrapolated beyond validated region of “Crater” (up to factor of 640 -- later determined to be 400)
- Conclusion of no “safety of flight issue” for impact of tile
- Less concern for impact of RCC panels due to experience
- Request for imagery of shuttle after impact discussed multiple times and eventually decided against

Loss of lives and vehicle
Questions???
Issues and Lessons

- (Mental) Models -- creation, realization, and the bounds
- Experimental Data -- reality or a model?
- Extrapolation -- the eternal evil
- Interpolation -- questions of fidelity

The limitations that are part of all we do
An Overall Outlook

Reality
  - observations
  - conceptions

Model(s)
  - language
  - mathematical tools

Manipulation/Analysis
  - communication

Decision/Action Plan
  - consideration/comparison
What is a Model?

- An outlook on / attempt to capture reality
- A filter through which reality is viewed and interpreted
- Limited by its assumptions
- Needed to be validated \(\text{self-consistent}\) and verified \(\text{consistent with reality}\)

\textit{Pertains to human behavior and the scientific world}
What is an Experiment / A Data Point / An Experience?

• A measurement of a set of quantities
• A *derivation* related to measured quantities via a (implicit or explicit) model
• A model in and of itself
• Pertinent only within its defined and *verified* regime
Models and Boundaries

- Verified regimes / previous experience(s) define pertinent realms of model
- Increased experience gives greater confidence in model *(probabilistic/statistical aspects)*
- Venturing outside boundaries of experience violates assumptions
- Model has internal boundaries of level of fidelity

*A model is *not* reality*
Some definitions.....

- **known-known** -- the item has been identified and its effects understood (with some statistical variation)
- **unknown-known** -- the item has been identified but its effects not understood or even clearly identified
- **unknown-unknown** -- the item (and associated effects) has not even been recognized as existing *(unk-unks)*

*Uncertainty (characterized via probability and statistics) lurks in all this*
Extrapolation -- issues and dangers

- Extrapolation is always based on a model (implicit or explicit)
- Density of data tends to decrease near model boundaries
- Potential (risk of) failure of model increases towards model boundaries
- Knowledge of behavior outside boundaries does not exist (or exists with much greater uncertainty)

The risk of encountering unknown-unknowns and known-unknowns increases
Interpolation -- issues and dangers here?

- Interpolation is always based on a model (explicit or implicit)
- The data/experience on which the model is based has a specific fidelity based upon measurement
- There is variation of and within the data and thus the model

*How fine can we interpolate?*
Some (bad) examples

• Liberty ships
• The Comet
• Weather forecasting
• $1 \text{ in } 10^9 \text{ (or more...)}$
Issues associated with sampling

- What does one actually measure?
- With what level of fidelity is measurement done?
- What model(s) are incorporated (implicitly and explicitly) into the data and its interpretation?
- How often (time) does one sample?
- How fine a grid (distance) does one use for sampling?

Coupled issues -- a systems problem
Principles and Rules

• Be aware of the difference between a model and reality
• Understand that all our perceptions of our universe are models / seen through models
• Know the model assumptions and limitations and stay/work within these
• Venture outside the model in exploration but be aware of the associated risks
• Know the internal limitations of data, experience, and model and do not break those internal bounds