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ANALYSIS OF AN ENGINEEERING DESIGN: THE SPACE SHUTTLE CHALLENGER

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SUMMARY

From the many prescriptive methods and guidelines for engineering design it is possible to develop some simple and effective ways of assessing the quality of a design during the course of the design process. This paper describes one approach being developed, illustrated by aspects of the Solid Rocket Booster design for the Space Shuttle.

INTRODUCTION

It is difficult to assess the quality of the design work being produced during an engineering design project, before any hardware has been made or tested. Opinion based on prior experience is a start but a more objective approach built into the engineering design process itself would be more helpful. This requires some kind of breakdown of the engineering design process, and a structured way of analyzing the design work as it proceeds. The technique suggested here involves no more than asking a specific set of questions at the end of each phase of the engineering design process, based on some recommended procedures and guidelines for each phase. It can provide a revealing and coherent assessment of a design. The paper is intended to help stimulate discussion, not to describe the details of the proposed technique.

THE ENGINEERING DESIGN IN CONTEXT

When analyzing an engineering design it helps to have a model or map which shows the context within which the design process took place, and breaks it down into fairly distinct phases (1). It is necessary to distinguish between the overall project effort and that part of it regarded as the 'engineering design process', and to be able to visualize the project at different 'levels of resolution' (2). For the purposes of this paper the design process will be set in context and broken down as follows:

- o Within an external environment are markets;
- o Within a specific market are competing companies;
- o Within each company are engineering projects;
- o Within each project the design process takes place.

The design process associated with any particular project up to the test and develop stage is considered to pass through four main phases:

(i) *Task Clarification*
Through task clarification activities, the problem is defined.
Output is a design specification.

(ii) *Conceptual Design*
Through conceptual design activities many solutions are generated, selected and evaluated. Output is a concept.

(iii) *Embodiment Design*
Through embodiment design activities the chosen concept is developed.
Output is a definitive layout.

(iv) *Detail Design*
Through detail design activities every component is completely specified.
Output is production information.

THE SPACE SHUTTLE CHALLENGER

On January 28, 1986 the Space Shuttle Challenger exploded with the loss of all crew. A Presidential Commission compiled detailed evidence on the accident, and concluded in its report (3) that a principal cause was the failure of an O-ring seal in the aft field joint of the right-hand solid rocket booster (Figure 1). Two solid rocket boosters are attached to the main engine fuel tank, providing additional thrust for take-off during the first two minutes of flight. Essentially they are thin-walled, large diameter pressure vessels, assembled from cylindrical sections recovered from previous flights. An annular volume inside the vessel is filled with solid rocket propellant which burns from the central core hole outwards towards the shell. The shell therefore has to withstand a high pressure at steadily increasing temperature. The solid rocket booster sections are joined by means of a tang and clevis arrangement, with O-rings to seal the joint and 177 steel pins around its circumference to hold it together (Figure 2). The aft field joint failed during the Challenger flight, affecting the external mounting strut nearby and causing the catastrophic failure of the complete vehicle. Other factors such as wind shear, icy ground conditions and inadequate communications during the project were considered complementary causes of the disaster situation. To illustrate this particular design analysis approach, the failure of the aft field joint and seal arrangement will be considered in terms of guidelines for each phase of the engineering design process.

TASK CLARIFICATION

GUIDELINES:

- Define the problem in words or symbols
- Compile a design specification with input from all people involved
- Label all specification items with name of contributor
- List all changes and additions with date and name of contributor
- Obtain formal approval for document.

QUESTIONS:

1. Was the design problem clearly defined?
2. Was there an agreed specification?
3. Was the specification circulated to all those involved in the project?

EVIDENCE IN CASE OF SPACE SHUTTLE SOLID ROCKET BOOSTER:

1. Overall problem defined O.K.
2. Detail design specification developed
3. Management not involved with detailed specification.

CONCEPTUAL DESIGN I - GENERATION OF ALTERNATIVE CONCEPTS

GUIDELINES:

- Abstract the problem
- Formulate the overall function
- Break down into sub-functions
- Draw up a system flow diagram (function structure)
- Generate ideas and concepts using selected creative methods
- Determine different solution principles for each sub-function
- Combine solution principles to generate complete solutions.

QUESTIONS:

1. Was the problem abstracted?
2. Was it broken into sub-functions?
3. Were a number of concepts produced?
4. Were a variety of working principles considered?
5. Were the principles suitably combined?

EVIDENCE IN CASE OF SPACE SHUTTLE SOLID ROCKET BOOSTER:

1. No apparent abstraction of problem: concept taken from Titan rocket.
2. Sub-functions used were taken from Titan rocket. Stayed within previous experience of successfully using O-rings.
3. Little evidence of alternative concepts.
4. No evidence of a systematic search for alternative principles.
5. In Titan rockets O-ring did not take brunt of combustion pressure and tangs were shorter so did not bend so much - a different application.

CONCEPTUAL DESIGN II - SELECTION AND EVALUATION

GUIDELINES:

- Select suitable combinations of solution principles
- Firm up into complete conceptual designs (concept variants)
- Evaluate concepts against technical criteria
- Evaluate concepts against economic criteria
- Search for weak spots
- Select final concept(s)
- Compile cost estimates
- Present final concept(s) for approval.

QUESTIONS:

1. Were the concept variants firmed up?
2. Were the concept variants evaluated: (a) against technical criteria?
   (b) against economic criteria?
3. Was the final concept checked for weak spots?
4. Were cost estimates developed?
5. Was the final concept presented for formal approval?

EVIDENCE IN CASE OF SPACE SHUTTLE SOLID ROCKET BOOSTER:

1. Choice was merely between use of 2 bore seals or 1 bore + 1 face seal.
2. Preliminary hydrostatic tests to 100 bar accepted after discussion. Analysis of cost factors found in favour of the selected contractor.
3. Weak spots were found:
   - Clevis rotated away from tang (Figure 3).
   - O-ring seal material had to be cut to length and bonded on site.
4. Yes, but there was 'cost growth' and schedule slippage.
5. Yes, but differences of opinion existed over concept approval.

EMBODIMENT DESIGN I - OVERALL LAYOUT

GUIDELINES:

- Simplicity
- Clarity
- Safety

QUESTIONS:

1. Is the design simple?
2. Is there clarity of function?
3. Is there clarity of form?
4. Is it safe
   - safe-life design?
   - fail-safe design?
   - redundancy built in?
   - protection built in?
   - warnings provided?

5. Primary Checks: Function O.K.?
Economics O.K.?
Safety O.K.?
Ergonomics O.K.?

Secondary Checks: Production O.K.?
Quality O.K.?
Assembly O.K.?
Transport O.K.?
Operation O.K.?
Maintenance O.K.?
Costs O.K.?
Schedule O.K.?

EVIDENCE IN CASE OF SPACE SHUTTLE SOLID ROCKET BOOSTER:

1. Joint has complex loadings, geometry, sealing and thermal conditions.
2. Load paths for forces not clear and operation of seals not clear.
3. Confusion over tolerances and joint gap.
4. O-rings operating outside recommended conditions: not safe-life.
   Failure of primary O-ring allows hot gases access to secondary O-ring: not fail-safe.
   Joint redesignated Criticality 1: no redundancy.
   No safety protection from gas channelling.
   No safety protection for strut connecting rocket to external tank.
   No safety warning of seal/joint failure.
5. Seal failure likely; inadequate protection; difficult to assemble.

EMBODIMENT DESIGN II - DETAIL LAYOUT

GUIDELINES:

- Force transmission
- Division of tasks
- Self-help
- Stability
- Calculations
- Materials selection
- Use of standards and codes
- Use of bought-out parts
- Layouts & drawings

QUESTIONS:

1. How good are the force transmission paths - flowlines?
   - deformations?
   - secondary forces?
2. Is the division of tasks appropriate (separated, combined or divided)?
3. Is self-help used - self-reinforcing?
   - self-balancing?
   - self-protecting? What about self-damaging?
4. Is the design stable?
5. Are the calculations correct?
6. Are the materials well-chosen?
7. Are applicable standards and codes met?
8. Are bought-out parts appropriately used?
9. Are layouts and drawings properly done?

EVIDENCE IN CASE OF SPACE SHUTTLE BOOSTER ROCKET:

1. Force flowlines concentrate around pins - poor load distribution. Joint rotates considerably, affecting seal performance (Figure 3). Ice and putty create detrimental secondary forces.

2. Critical tasks of load-carrying and sealing are combined instead of being separated.
3. Self-reinforcing used but minor gas leaks create a self-damaging situation.
4. Design unstable:
    - Joint gap leads to seal leak
    - Joint rotation leads to bigger leak
    - Putty allows gas channelling
    - Gas channelling leads to burnt seals
    - Burnt seals lead to bigger leak
    - Bigger leak leads to high temperatures at joint
    - High temperatures lead to hole in casing
    - Hole in casing leads to strut failure
    - Strut failure leads to catastrophic failure.
5. Calculations on tang/clevis rotation incorrect, as shown by tests.
6. Material for O-rings a poor choice (narrow temperature range).
7. Leak test procedure questioned in 1980. Criticality of 1R (adequate redundancy) was changed to 1 (no redundancy) in 1982, to avoid issue.
8. O-rings being used outside manufacturer's recommendations.
9. Layouts and drawings O.K.

Note: Many alternative solutions were put forwardby the engineers: 43 possible concepts to fix the field joint problem and 20 for nozzle joints. The engineers wanted changes but management closed the issue.

DETAIL DESIGN: COMPONENTS AND ASSEMBLY

GUIDELINES:

- Shape-Material interaction
- Material-Manufacture interaction
- Manufacture-Shape interaction

QUESTIONS:

1. How good are the interactions between shape, material & manufacture?
2. What about strength, stiffness, fatigue, residual stresses, flaws, tolerances, surface finish etc.?
3. Is it easy to assemble the components?
4. Are the testing and commissioning procedures adequate?
5. Are the production documents in order?

EVIDENCE IN CASE OF SPACE SHUTTLE SOLID ROCKET BOOSTER:

1. Incompatible interactions between shape, material and manufacture.
2. Strength O.K. but not the stiffness: large diameter thin-walled tube. Cyclic loads from "twang" and wind shear. Tube sections to be reused after recovery from sea: not possible to stay within dimensional and geometric tolerances essential for adequate O-ring seal performance.
3. Very difficult to assemble - no guarantee on actual joint gap and O-ring likely to to twist on assembly (inducing residual stresses).
4. Leak test detrimental to seal's performance during flight and promotes channelling in joint putty - incorrect test procedure which pushes primary O-ring to the wrong side of its O-ring groove.
5. Documentation good but management understanding of it poor.

SUMMARY OF ANALYSIS

A summary of the checklist questions and assessment for the case of the Space Shuttle Solid Rocket Booster aft field joint and seal is given in Table 1. This analysis indicates serious weaknesses in the design of the particular field joint, based on guidelines suggested for high quality engineering design. The guidelines for Task Clarification were generally satisfied, but in Conceptual Design too few concept variants were produced for acceptability. In the Embodiment

Design phase safety aspects of the design were unacceptable, the division of tasks for the joint were poor, the use of self-help was poor and, above all, the resulting design was inherently unstable. Also the materials selection was questionable and important calculations were incorrect. In Detail Design there were stiffness and tolerance problems in the design which made assembly difficult, and the leak-testing procedure designed for the O-rings was faulty.

CONCLUSIONS

The simple technique of asking a set of structured questions at the end of each phase of an engineering design project can help in highlighting the good and bad features of a design before any hardware is made, and in assessing design quality during each project phase. This paper has outlined the approach, using the design of the Space Shuttle Solid Rocket Booster as an illustrative example. It is crucial that managers involved with the engineering design process appreciate the importance of monitoring the quality of design work as it proceeds. In the Presidential Commission Report on the Space Shuttle Challenger are copies of many memoranda from design engineers working on the project warning management about weak spots in the solid rocket booster design and offering improved solutions. The warnings were taken too lightly and a multi-billion dollar project was lost in a matter of 70 seconds.

REFERENCES

1. Pahl, G. and W. Beitz. *Engineering Design* (K.M. Wallace, ed.). London: The Design Council, 1984.

2. Hales, Crispin. *Analysis of the Engineering Design Process in an Industrial Context.* Eastleigh, U.K.: Gants Hill Publications, 1987.

3. Presidential Commission. *Report of the Presidential Commission on the Space Shuttle Challenger Accident.* Washington, D.C., June 6th, 1986.

ACKNOWLEDGEMENTS

All evidence used in the example has been taken from the Report of the Presidential Commission on the Space Shuttle Accident (Reference 3). Acknowledgements are due to this Commission for their investigative work.

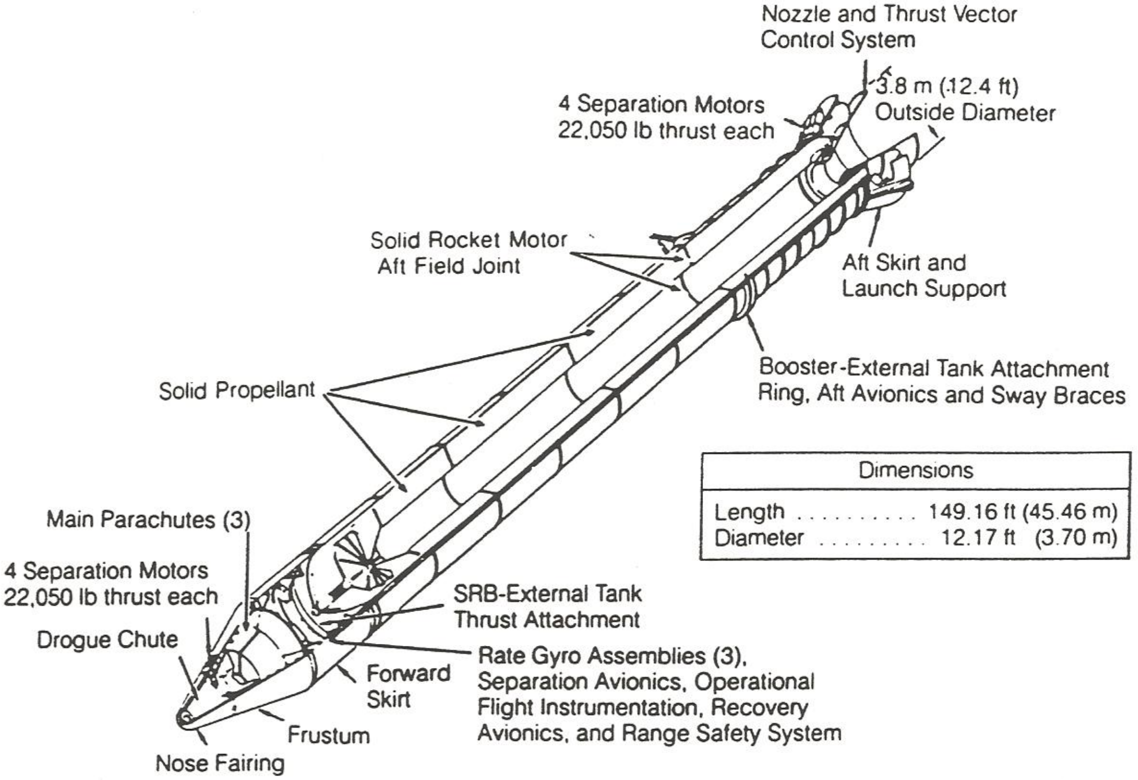

Figure 1 Cutaway view of the Solid Rocket Booster showing Solid Rocket Motor propellant and aft field joint. (Taken from Presidential Commission Report, Ref.3)

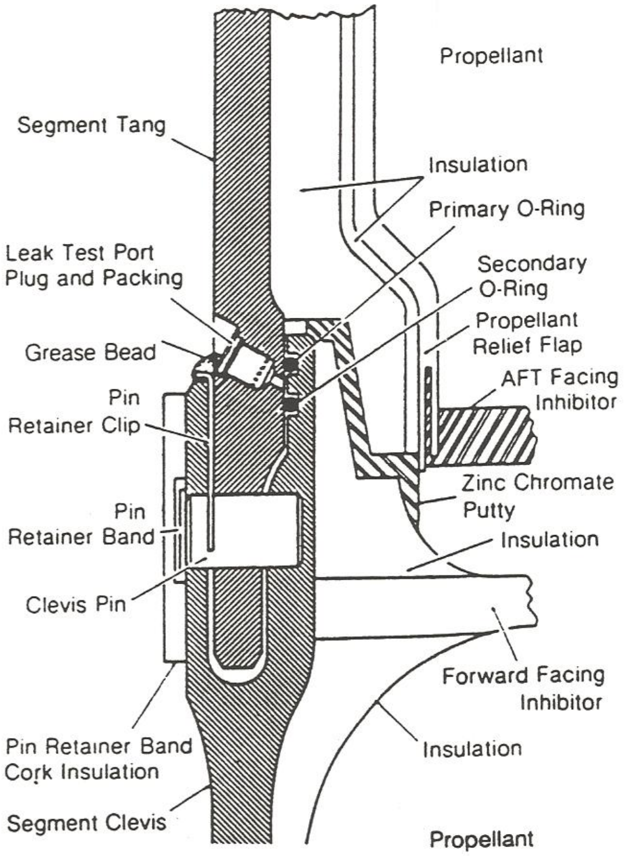

Figure 2 Solid Rocket Motor cross section shows positions of tang, clevis and O-rings. Putty lines the joint on the side towards the propellant. (Taken from Presidential Commission Report, Ref.3)

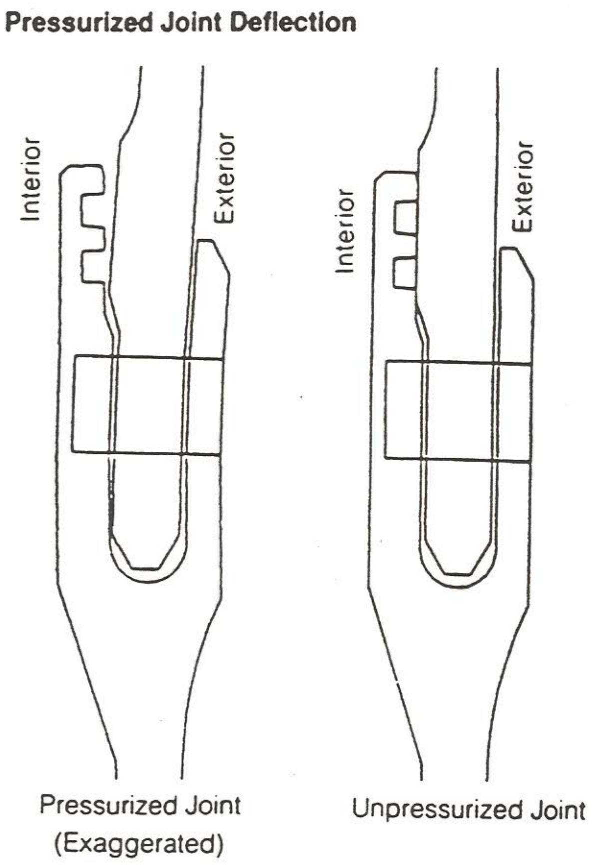

Figure 3 Drawings show how tang/clevis joint deflects (rotates) during pressurization to open gap at location of O-ring grooves. Inside of motor case and propellant are to left in sketches. (Taken from Presidential Commission Report, Ref.3)

TABLE 1 - DESIGN ASSESSMENT WORK SHEET

PROJECT: AFT FIELD JOINT	DESIGN ACCEPTABILITY		
TASK CLARIFICATION:	High	Marginal	Low
1. Design problem clearly defined?	▨	☐	☐
2. Agreed specification?	▨	☐	☐
3. Specification circulated?	☐	▨	☐
CONCEPTUAL DESIGN I - CONCEPT GENERATION			
1. Problem abstracted?	☐	☐	▨
2. Broken into sub-functions?	☐	▨	☐
3. Several concepts produced?	☐	☐	▨
4. Many working principles considered?	☐	▨	☐
5. Principles suitably combined?	☐	▨	☐
CONCEPTUAL DESIGN II - SELECTION AND EVALUATION:			
1. Concept variants firmed up?	▨	☐	☐
2. Concept variants evaluated: Technical?	☐	▨	☐
Economical?	▨	☐	☐
3. Concept weak spots found?	☐	☐	▨
4. Cost estimates developed?	▨	☐	☐
5. Concept formally presented for approval?	☐	▨	☐
EMBODIMENT DESIGN I - OVERALL LAYOUT			
1. Design simple?	☐	☐	▨
2. Design function clear?	☐	▨	☐
3. Design form clear?	☐	▨	☐
4. Safety: Safe-life design?	☐	▨	☐
Fail-safe design?	☐	☐	▨
Redundancy built in?	☐	▨	☐
Protection built in?	☐	☐	▨
Warnings provided?	☐	☐	▨
5. Primary Checks: Function O.K.?	☐	▨	☐
Economics O.K.?	☐	▨	☐
Safety O.K.?	☐	☐	▨
Ergonomics O.K.?	☐	▨	☐
6. Secondary Checks: Production O.K.?	☐	▨	☐
Quality Assurance O.K.?	▨	☐	☐
Assembly O.K.?	☐	☐	▨
Transport O.K.?	▨	☐	☐
Operation O.K.?	☐	☐	▨
Maintenance O.K.?	☐	▨	☐
Costs O.K.?	☐	▨	☐
Schedule O.K.?	☐	▨	☐
EMBODIMENT DESIGN II - DETAIL LAYOUT			
1. Force transmission paths: Flowlines O.K.?	☐	☐	▨
Deformation O.K.?	☐	☐	▨
Secondary forces a problem?	☐	▨	☐
2. Appropriate division of tasks?	☐	☐	▨
3. Self-help used: Self-reinforcing?	☐	▨	☐
Self-balancing?	▨	☐	☐
Self protecting?	☐	▨	☐
Self-damaging?	☐	☐	▨
4. Design stable?	☐	☐	▨
5. Calculation correct?	☐	☐	▨
6. Materials well-chosen?	☐	▨	☐
7. Applicable standards and codes met?	▨	☐	☐
8. Bought-out parts appropriately used?	☐	▨	☐
9. Layouts and drawings properly done?	▨	☐	☐
DETAIL DESIGN - COMPONENTS AND ASSEMBLY			
1. Shape, material and manufacture interactions O.K.?	☐	▨	☐
2. Strength, stiffness, fatigue, creep, O.K.?	☐	▨	☐
Residual stresses, flaws, etc, O.K.?	▨	☐	☐
Tolerances, surface finish, etc. O.K.?	☐	☐	▨
3. Easy to assemble components?	☐	☐	▨
4. Testing and commissioning procedures adequate?	☐	☐	▨
5. Production documents in order?	▨	☐	☐