By proper use of the DFMEA tool, many design weaknesses can be identified and eliminated up front, before start of production.
Potential Failure Mode
5 Why Analysis of Causes

Potential Effect of Failure – and related SEV
Potential Cause(s) or Mechanisms(s) of Failure from 5 Why Analysis – and related OCC
Current Controls Detection / Prevention – and related DET
RPN

Recommended Action
Responsible & Completion Date
Action Results – Action Taken, new RPN
<table>
<thead>
<tr>
<th>Part #</th>
<th>Part Description of Component</th>
<th>Potential Failure Mode</th>
<th>Why 1</th>
<th>Why 2</th>
<th>Why 3</th>
<th>Why 4</th>
<th>Why 5</th>
<th>Potential Effect of Failure</th>
<th>Potential Cause(s) of Failure</th>
<th>OCC</th>
<th>O C C</th>
<th>Current Control Action</th>
<th>R P</th>
<th>Recommended Action</th>
<th>S E</th>
<th>G O</th>
<th>O C C</th>
<th>R P</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Motor</td>
<td>Motor won’t run</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Machine Down</td>
<td>Labyrinth penetrated</td>
<td>7</td>
<td>5</td>
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<td>10</td>
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<td>Rear clamp air seal failure</td>
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<td>Low or lost air pressure</td>
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<td>Seals penetrated</td>
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<td></td>
<td>Pressure transients</td>
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<td></td>
<td></td>
<td>Purge air contains water</td>
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<td></td>
<td></td>
<td>Condensation from chilled water</td>
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<td>Coolant getting past biomass interfering check valves</td>
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<td></td>
<td>Missing coolant tube in biomass</td>
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<td></td>
<td>Purge air contaminated</td>
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<td></td>
<td>Degradation from fast warm rise time</td>
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<td></td>
<td></td>
<td>Mechanical shock/vibration</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td>Other motor assembly problems</td>
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</tr>
</tbody>
</table>

**Potential Failure Mode and Effects Analysis (Design FMEA)**

**Device Code:**

**Supplier/Plant:**

**Customer Quality Approval:**
<table>
<thead>
<tr>
<th>Potential Failure Mode</th>
<th>Five Why Analysis of Causes</th>
<th>Plant Code</th>
<th>Supplier / Plant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Motor won't run</td>
<td>Motor shorted, phase to phase, or phase to ground, moisture ingress, labyrinth penetrated, gap too large, parts out of tolerance</td>
<td>7</td>
<td>4 3</td>
</tr>
<tr>
<td></td>
<td>Machine Down.</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>rear unclamp air seal failure, low or lost air pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thermal cycling, vacuum, seals penetrated, bad parts or assembly, pressure transients, poor cooling system design</td>
<td>7</td>
<td>4 3</td>
</tr>
<tr>
<td></td>
<td>purge air contains water, air dryer not working, condensation from chilled water, cooling water temp too low</td>
<td>7</td>
<td>4 4</td>
</tr>
<tr>
<td></td>
<td>Coolant getting past drawbar, interdrilling check valves, poor check valve design</td>
<td>7</td>
<td>5 2</td>
</tr>
<tr>
<td></td>
<td>Missing coolant tube in toolholder</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insulation breakdown</td>
<td>degradation from coolant attack, seals penetrated, purge air contaminated</td>
<td>7</td>
<td>5 2</td>
</tr>
<tr>
<td></td>
<td>insulation degradation from fast volt. rise, system mismatch</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>insulation degradation from fast volt. rise, system mismatch</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Proper matching of components - extra filter</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>
FMEA is a deliberate and thoughtful method for focusing on “expected quality” that

1) Identifies possible faults (failure modes) in a system (including their causes – ask the 5 Whys)
2) Evaluates the effects of the fault on the operational status of the system
3) Determines the risk priority of the failure (based on severity, probability of occurrence, and probability of detecting and avoiding the failure)
4) Recommends corrective actions for high risk items
5) Implements corrective actions until risk is reduced
6) Documents the design process and allows for efficient review and communication with respect to system safety

Product functions as intended and meets all of the customer’s implicit expectations.
### 1) Failure Modes: *What can go wrong?*

Analyze operating conditions, environmental conditions, - all potential **failure modes**.

<table>
<thead>
<tr>
<th>Failure Modes associated with equipment and energy (adapted from Dhillon)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structural systems</strong></td>
</tr>
<tr>
<td><strong>Kinematic systems</strong></td>
</tr>
<tr>
<td><strong>Thermodynamic systems</strong></td>
</tr>
<tr>
<td><strong>Fluid flow equipment</strong></td>
</tr>
<tr>
<td><strong>Electrical equipment</strong></td>
</tr>
<tr>
<td><strong>Material properties</strong></td>
</tr>
<tr>
<td><strong>Environmental effects</strong></td>
</tr>
</tbody>
</table>
Cause of Failures [adapted from Dieter, Engineering]
(Note that most of these causes can be avoided!)

1. Design deficiencies
   • Failed to consider effects of notches & stress concentrations
   • Inadequate knowledge of service loads and environment
   • Incorrect use of finite element analysis for complex parts
   • Relying on analysis results without adequate experimental validation

2. Material selection deficiencies
   • Inadequate material data / use of inappropriate data
   • Cost emphasized over quality
3. Manufacturing defects that remain in the final part

4. Inadequate maintenance, inspection, and repair

5. Overload and other “abuses” in service

6. Effect **of** Operating environment
   - Unexpected conditions, beyond those allowed for in the design
   - Deterioration of material properties due to prolonged exposure to the environment

7. Effect **on** environment / society
<table>
<thead>
<tr>
<th>List of Example Failure Modes</th>
<th>[Ref: Product Design, Otto &amp; Wood]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corrosion</td>
<td>Ingress</td>
</tr>
<tr>
<td>Fracture</td>
<td>Vibrations</td>
</tr>
<tr>
<td>Material Yield</td>
<td>Whirl</td>
</tr>
<tr>
<td>Electrical Short</td>
<td>Sagging</td>
</tr>
<tr>
<td>Open Circuit</td>
<td>Cracking</td>
</tr>
<tr>
<td>Buckling</td>
<td>Stall</td>
</tr>
<tr>
<td>Resonance</td>
<td>Creep</td>
</tr>
<tr>
<td>Fatigue</td>
<td>Thermal expansion</td>
</tr>
<tr>
<td>Deflections or deformations</td>
<td>Oxidation</td>
</tr>
<tr>
<td>Seizure</td>
<td>UV deterioration</td>
</tr>
<tr>
<td>Burning</td>
<td>Acoustic noise</td>
</tr>
<tr>
<td>Misalignment</td>
<td>Scratching and hardness</td>
</tr>
<tr>
<td>Stripping</td>
<td>Unstable</td>
</tr>
<tr>
<td>Wear</td>
<td>Loose fittings</td>
</tr>
<tr>
<td>Binding</td>
<td>Unbalanced</td>
</tr>
<tr>
<td>Overshooting (Control)</td>
<td>Embrittlement</td>
</tr>
<tr>
<td>Ringing</td>
<td>Loosening</td>
</tr>
<tr>
<td>Loose</td>
<td>Scoring</td>
</tr>
<tr>
<td>Leaking</td>
<td>Radiation damage</td>
</tr>
</tbody>
</table>

OU ME Sr. Design, Dr. Kremer, 9
2) Failure Effects

What are the effects of part failure on component performance, on system performance…?

Start with a **top-down**, system-level focus to lay out the overall design configuration

- **System** (automobile)
- **Subsystem** (propulsion system)
- **Component** (manual transmission)
- **Subassembly** (1-2 gear selector system)
- **Part** (selector rod, gear selector ring, gear selector, synchronizer, …)

Use a **bottom-up** approach focused on potential failure modes (from part level on up) to modify/justify/certify the design on the part level, component level, etc.

Bottom up questions: How can the part fail?…
How does the part failure affect the subassembly?…
3) Risk Priority

By measuring the relative importance of a given failure state, FMEA helps to establish priorities for product development.

The systematic FMEA process results in a Risk Priority Number (RPN) for each failure mode,

\[ RPN = (SEV) \times (OCC) \times (DET) \]

SEV = Potential Severity
OCC = Likelihood of Occurrence
DET = Probability of Detecting and avoiding

Starting with failure modes with the highest RPN, Possible actions are developed, evaluated/selected based on their estimated effect on RPN, and implemented.
Estimate the severity of failure (SEV)
Think Reliability (will it work) and safety (could someone get hurt)

- 1 = Still works, no performance impact, no danger
- 2-4 = Still works, poor performance,
- 5 = Limited function and/or some danger
- 6-9 = severely limited function, almost useless
- 10 = Inoperable and/or serious danger
Estimate the Probability of Occurrence (OCC)
Think Risk & Factor of Safety

• 1 = No chance, lots of operating experience, low uncertainty
• 2-4 = little chance, some operating experience and some testing to validate design, good information and low uncertainty
• 5-7 = some chance, no operating experience and minimal testing - design based on analysis, good information
• 8-9 = Good chance of occurrence sometime during life of product, Poor information about loads and operating conditions, wild guess at models, no testing
• 10 = 100% Chance of occurrence during life of product
Estimate the Probability of Detection and Avoidance of failure (DET)

Will there be a warning that allows the failure to be avoided?

• 1 = 100% chance to detect and avoid

• 2-9 = Some chance to detect and avoid (select # based on likelihood)

• 10 = no chance to detect and avoid
1. Anticipated Failure Modes
2. Effect of the Failure
3. Cause of the Failure
4. Frequency of Occurrence of the Failure
5. Severity of the Failure
6. Detection of the Failure
7. Calculate Risk Priority Number
8. Recommend Corrective Action
9. Approve and Implement Corrective Action
Cart Ramrod Failure Modes

- Failure of Safety System – Unit 91
- Uncontrolled Drive – Shenanigans
- Loss of power – Shenanigans
- Loss of steering – Shenanigans
- Failure of Structure – Large Farva
Anticipated Failure Mode

• “How could this part, system, or process fail?”
• Anticipate how the design could fail, but don’t make a judgment on the likelihood of failure.
• Could it break, deform, wear, corrode, bind, leak, short, open, etc.?

- Electrical Interlock failure due to short circuit, dirt, corrosion, improper use
Effect of the Failure

- Describing the effect of the failure in terms of customer reaction
- For example - would a shorted wire cause a fuel gauge to be inoperative, or would it only cause a dome light to remain on

- Electrical Interlock failure – would cause cart to become inoperable
Cause of Failure

• Analyzing what conditions can bring about the failure mode

• 5 Whys

For example:

• Why would interlock fail? – loose connections.

• Why would connections be loose? - Wire housing wears down.

• Why…
Severity of the Failure

• Rank the consequence of failure on scale from 1 to 10
  • 1 - a minor failure undetectable by user
    – a part that is out of specification but does not affect performance
  • 10 - a potential safety problem, or lack of conformance with specifications or government regulations
    – Lack of prior warning to failure raises severity

Electrical Interlock failure

➢ 9 – Failure without prior warning which causes major customer dissatisfaction due to an inoperable system
Frequency of Occurrence

- Estimate the probability that the given failure is going to occur on a scale from 1 to 10
- 1 - a low probability of occurrence (~10%)
- 10 - a near certainty of occurrence (~100%)

- Electrical Interlock failure
  - 2 – Low failure rate with similar parts having similar functions
Detection Ranking

- Probability that a potential failure will be detected and avoided before it occurs, on a scale from 1 to 10
  - 1 - an obvious problem that would quickly be detected
  - 10 - a problem that is impossible to detect and avoid
- Can change depending on any corrective action taken

9 – Connection would corrode over time and cause failure after an extended period of use
Calculate Risk Priority Number

• RPN for the Failure Mode = Severity * Frequency of Occurrence * Detection Ranking
• Purpose: to assess current risk (and to compare the effects of proposed changes by calculating hypothetical RPNs of different scenarios, to help decide what corrective action to take).

RPN = SEV*OCC*DET = 2*9*9 = 162
Recommend Corrective Action

- The basic purpose of FMEA is to highlight potential failure modes
- The team must provide sound, corrective actions to prevent the outlined failures
- Responsible parties and timing for completion should be included in all corrective actions

- Use of corrosion resistant materials in latching mechanism
- Ensure water proofing of all electrical components
  - Battery housing
  - Controller
  - Wiring
- Regular maintenance
  - Inspect wires for any wear
4) Corrective Actions

What can be done to eliminate or reduce the possibility of failure?

Table 13-4 Corrective actions for failure-experience matrix

<table>
<thead>
<tr>
<th>Design change to improve part</th>
<th>Changed vendor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct replacement</td>
<td>Added adhesive</td>
</tr>
<tr>
<td>Change of material</td>
<td>Improved quality control</td>
</tr>
<tr>
<td>Supplement part</td>
<td>Changed lubricant type</td>
</tr>
<tr>
<td>Improved instructions to user</td>
<td>Improved run-in procedure</td>
</tr>
<tr>
<td>Changed dimensions</td>
<td>Applied surface treatment</td>
</tr>
<tr>
<td>Changed loading on part</td>
<td>Added sealant</td>
</tr>
<tr>
<td>Applied surface coating</td>
<td>Added or changed locking feature</td>
</tr>
<tr>
<td>Changed mechanism of operation</td>
<td>Adjusted part</td>
</tr>
<tr>
<td>Repositioned part</td>
<td>Provided drain</td>
</tr>
<tr>
<td>Repaired part</td>
<td>More easily replaceable part</td>
</tr>
<tr>
<td>Changed mode of attachment</td>
<td>Changed to correct part</td>
</tr>
<tr>
<td>Changed manufacturing procedure</td>
<td>Improved lubrication</td>
</tr>
<tr>
<td>Reinforced part</td>
<td>Made part interchangeable</td>
</tr>
<tr>
<td>Eliminated part</td>
<td>Relaxed replacement criteria</td>
</tr>
<tr>
<td>Strengthened part</td>
<td>Revised procurement specifications</td>
</tr>
<tr>
<td>Changed method or frequency of lubrication</td>
<td>Provided for proper inspection</td>
</tr>
<tr>
<td></td>
<td>Changed electrical characteristics</td>
</tr>
</tbody>
</table>

Ref: Engineering Design, Dieter
Goal of FMEA is Improved System Reliability

Reliability is the **probability of survival** or the likelihood of avoiding failure over a specified period of time under specific operating conditions (large numbers are good)

» Often quoted in time-based form as **Mean Time Between Failures (MTBF)**

Good reliability data for components and systems is hard to find (**need lots of operating experience**)  

In a systems reliability analysis, try to identify the systems that are “mission critical”.

» If all mission critical items do not have 100% reliability, design backup systems or redundant systems if necessary (based on the consequences of failure)
Guidelines for improved System Reliability

Avoid series reliability where the failure of any component causes system failure

\[ R_{\text{system}} = R_1 \times R_2 \times R_3 \times \ldots \]

\( R_1 = \) component 1 reliability (0-1), …

Example: \( R_1 = .9, R_2 = 0.9, R_3 = .9, R_{\text{system}} = .73 \)

Design redundant systems with parallel reliability. In a system with full active redundancy it is necessary for all components in the system to fail in order for the system to fail

\[ R_{\text{system}} = 1-(1-R_1)(1-R_2)(1-R_3)\ldots \]

Example: \( R_1=R_2=R_3=0.9, R_{\text{system}} = .999 \)
Guidelines for improved System Reliability

Implement a fail-safe approach
Make the system fail in a safe manner

Example: circuit breakers in electrical systems

Implement automated monitoring / preventative maintenance for weak link

Identify the “weak link” with respect to system reliability and initiate a monitoring / preventative maintenance / repair cycle to reduce risk of unexpected weak link failure
FMEA / System Reliability Recap

1. The most important thing is to look at your design in a new way, asking "what could go wrong?" rather than just hoping that everything will go right.

2. A design FMEA is not a one-time check but a working document that should be started as early in the design process as possible and continued through until the design is frozen. The process of putting together the initial FMEA Worksheet identifies areas where you need more information and highlights areas that need to be designed (or redesigned) to a high factor of safety.
FMEA / System Reliability Recap

3. FMEA worksheets and other tools of this type are primarily useful in helping organize your thought process and reducing the chance that you will overlook key items or spend too much time on relatively insignificant items.

4. Garbage in - Garbage out still applies here. The results of an FMEA will only be as good as your input, and it will be of no real benefit to your design if all you are doing is going through the motions and not seriously thinking about how this approach can improve your design.
5. It is useful to realize that you have three options for addressing FMEA generated concerns:

* **Severity** (add redundancy, make fail safe, etc)

* **Probability of occurrence** (improve design)

* **Probability of detection** (make it obvious)

Improving any of the items reduces the overall risk.