DESIGNING WITH FAILURE IN MIND

No design is perfect; all designs have a probability of failure and an associated risk. To prevent failure, or at least reduce it dramatically, there are varieties of techniques that may be employed during and after the design stage. Such methods are briefly described herein. Case studies and discussions will help you learn about the methods, and how to apply them to open-ended engineering problems and situations.

One major goal in design is to **reduce** failure, through:

1. identification of the modes and root causes of failure;
2. identifying and reducing the effects of failure;
3. identifying and reducing the frequency of occurrence;
4. identifying and reducing the degree of severity;
5. identifying and assessing (potentially increasing) the ability to detect failure;
6. identifying design, process, or human factor corrective actions;
7. assigning individual responsibilities for corrective action;
8. imposing completion dates;
9. identifying and implementation design validation tools;
10. identifying and implementing design monitoring and failure reporting;
11. verifying completion of design and other actions;
12. re-evaluation of risk after corrective actions have been taken.

Designing to avoid failure can be a proactive approach, or a reactive approach, or combination of the two.

Proactive: Mainly a brainstorming and spreadsheet calculation technique called "Failure Modes, Effects, and Criticality Analysis" (**FMECA**, aka **FMEA**). FMECA is a tool developed by NASA back in the mid-1960's as a result of APOLLO missions[1] (where there were a lot of failures…)–the original NASA report detailing the method can be found here. FMECA is meant to be used as a proactive tool to be used during the design process to **prevent** failure through design changes and monitoring, specifically through *minimization* of Risk Priority Numbers (**RPN**). FMEA can be applied to a variety of engineering products: 1) systems, 2) processes, and 3) designs. Non-destructive evaluation is another way to be proactive about failure.

Reactive: Failure analysis and prevention is the main approach of reacting to failures. Failure analysis aims to identify **all** root causes of failure (design, process, human, or otherwise) through brainstorming, creation of Fault Trees (**FT**), Failure Modes Assessment charts (**FMA**), and Technical Plan for Resolution charts (**TPR**). FT, FMA and TPR charts are linked and are

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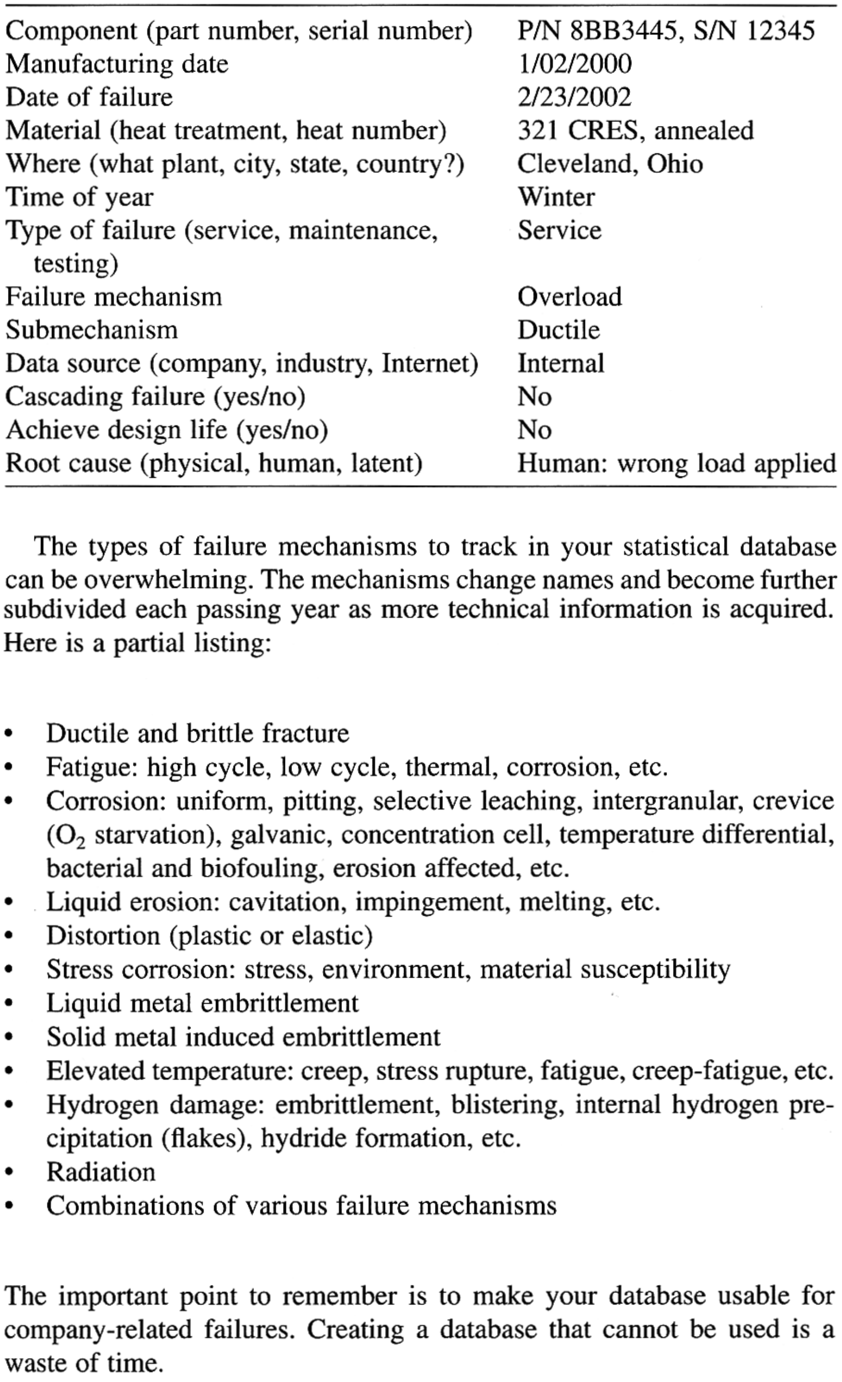
[1] Though there were serious issues with Apollo missions (Apollo 1: fire and tragedy in 1966; Apollo 13: explosion) the NASA FMECA method was published 8 months prior to the Apollo 1 incident, and was in its infancy for a while. Visit: https://ntrs.nasa.gov/citations/19700076494

living documents during an investigation which are used to find the ultimate root cause(s) and then plan for corrective actions for prevention.

Both of the above approaches benefit from creation, maintenance, and frequent review of failure **databases** created specifically for the institution of interest. **Statistics** are very important for dealing with failure from all angles (at all rungs of the Human-tech ladder as well).

Failure Database Example [1]:



Component (part number, serial number)	P/N 8BB3445, S/N 12345
Manufacturing date	1/02/2000
Date of failure	2/23/2002
Material (heat treatment, heat number)	321 CRES, annealed
Where (what plant, city, state, country?)	Cleveland, Ohio
Time of year	Winter
Type of failure (service, maintenance, testing)	Service
Failure mechanism	Overload
Submechanism	Ductile
Data source (company, industry, Internet)	Internal
Cascading failure (yes/no)	No
Achieve design life (yes/no)	No
Root cause (physical, human, latent)	Human: wrong load applied

The types of failure mechanisms to track in your statistical database can be overwhelming. The mechanisms change names and become further subdivided each passing year as more technical information is acquired. Here is a partial listing:

- Ductile and brittle fracture
- Fatigue: high cycle, low cycle, thermal, corrosion, etc.
- Corrosion: uniform, pitting, selective leaching, intergranular, crevice (O_2 starvation), galvanic, concentration cell, temperature differential, bacterial and biofouling, erosion affected, etc.
- Liquid erosion: cavitation, impingement, melting, etc.
- Distortion (plastic or elastic)
- Stress corrosion: stress, environment, material susceptibility
- Liquid metal embrittlement
- Solid metal induced embrittlement
- Elevated temperature: creep, stress rupture, fatigue, creep-fatigue, etc.
- Hydrogen damage: embrittlement, blistering, internal hydrogen precipitation (flakes), hydride formation, etc.
- Radiation
- Combinations of various failure mechanisms

The important point to remember is to make your database usable for company-related failures. Creating a database that cannot be used is a waste of time.

A statistical treatment of data from database [1] in form of a Pareto chart to show cumulative probability of failure is shown below; fatigue accounts for about 45% of the failures whereas stress rupture occurs for about 3% of failures. However, such statistics can be misleading…what is missing is the cost of the failure types (e.g., monetary, human, environmental). As mentioned in [1], it could be that the failures from fatigue cost $5M/yr and those from stress rupture cost $20M/yr, so even though stress ruptures only occur 3% of the time significant effort is placed upon their prevention. The tables below [1] help to assess the importance of failures, which must be accounted over and above just the frequency.

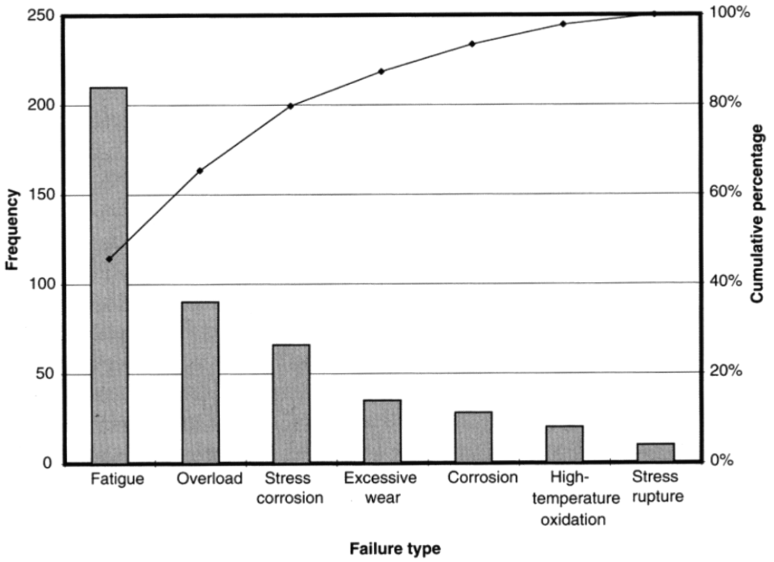


Fig. 1 A Pareto diagram is used to plot the relative importance of the differences between groups of data—in this case, the frequency of different types of failure at a company. The bars show the number of counts for each failure type, and the data points show the cumulative percentage (from left to right). In this example, the three most frequent failure types at the company account for 80% of total failures.

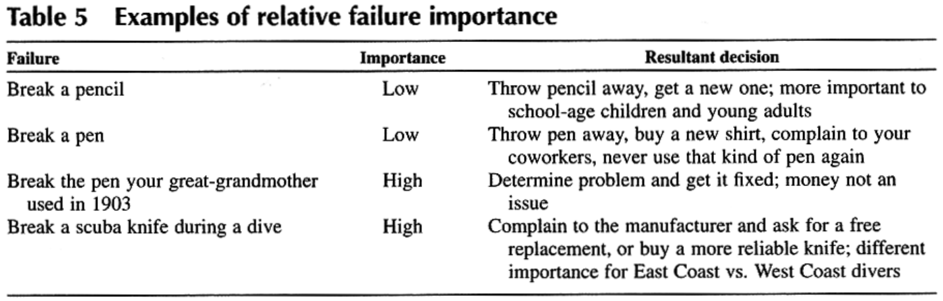


Table 5 Examples of relative failure importance

Failure	Importance	Resultant decision
Break a pencil	Low	Throw pencil away, get a new one; more important to school-age children and young adults
Break a pen	Low	Throw pen away, buy a new shirt, complain to your coworkers, never use that kind of pen again
Break the pen your great-grandmother used in 1903	High	Determine problem and get it fixed; money not an issue
Break a scuba knife during a dive	High	Complain to the manufacturer and ask for a free replacement, or buy a more reliable knife; different importance for East Coast vs. West Coast divers

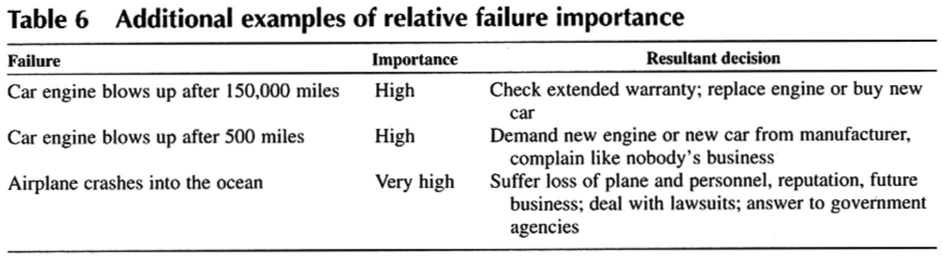
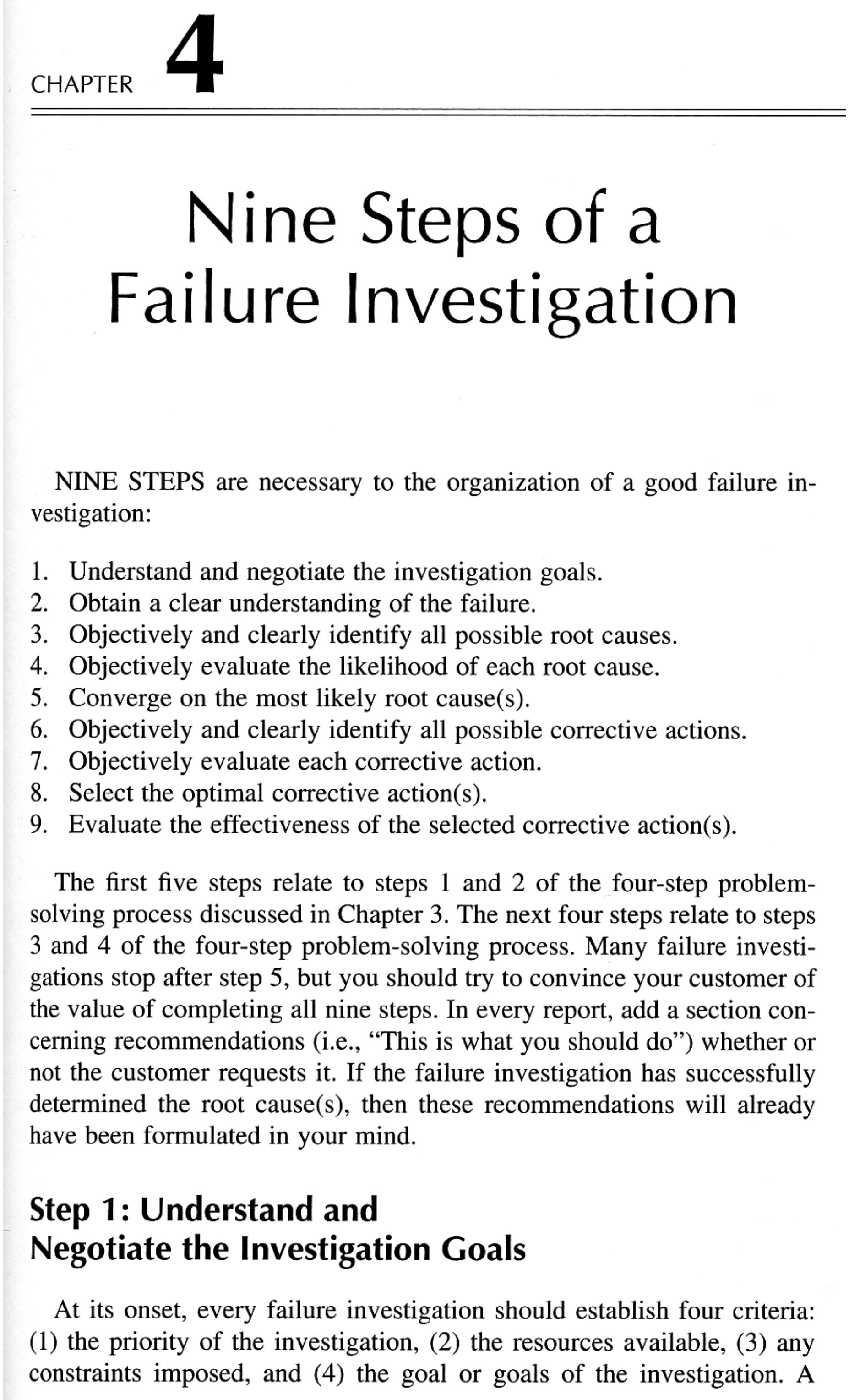


Table 6 Additional examples of relative failure importance

Failure	Importance	Resultant decision
Car engine blows up after 150,000 miles	High	Check extended warranty; replace engine or buy new car
Car engine blows up after 500 miles	High	Demand new engine or new car from manufacturer, complain like nobody's business
Airplane crashes into the ocean	Very high	Suffer loss of plane and personnel, reputation, future business; deal with lawsuits; answer to government agencies

Proactive tools (FMECA) are described later in this document.

The reactive tool of Failure Investigation



CHAPTER 4

Nine Steps of a Failure Investigation

NINE STEPS are necessary to the organization of a good failure investigation:

1. Understand and negotiate the investigation goals.
2. Obtain a clear understanding of the failure.
3. Objectively and clearly identify all possible root causes.
4. Objectively evaluate the likelihood of each root cause.
5. Converge on the most likely root cause(s).
6. Objectively and clearly identify all possible corrective actions.
7. Objectively evaluate each corrective action.
8. Select the optimal corrective action(s).
9. Evaluate the effectiveness of the selected corrective action(s).

The first five steps relate to steps 1 and 2 of the four-step problem-solving process discussed in Chapter 3. The next four steps relate to steps 3 and 4 of the four-step problem-solving process. Many failure investigations stop after step 5, but you should try to convince your customer of the value of completing all nine steps. In every report, add a section concerning recommendations (i.e., "This is what you should do") whether or not the customer requests it. If the failure investigation has successfully determined the root cause(s), then these recommendations will already have been formulated in your mind.

Step 1: Understand and Negotiate the Investigation Goals

At its onset, every failure investigation should establish four criteria: (1) the priority of the investigation, (2) the resources available, (3) any constraints imposed, and (4) the goal or goals of the investigation. A

From [1].

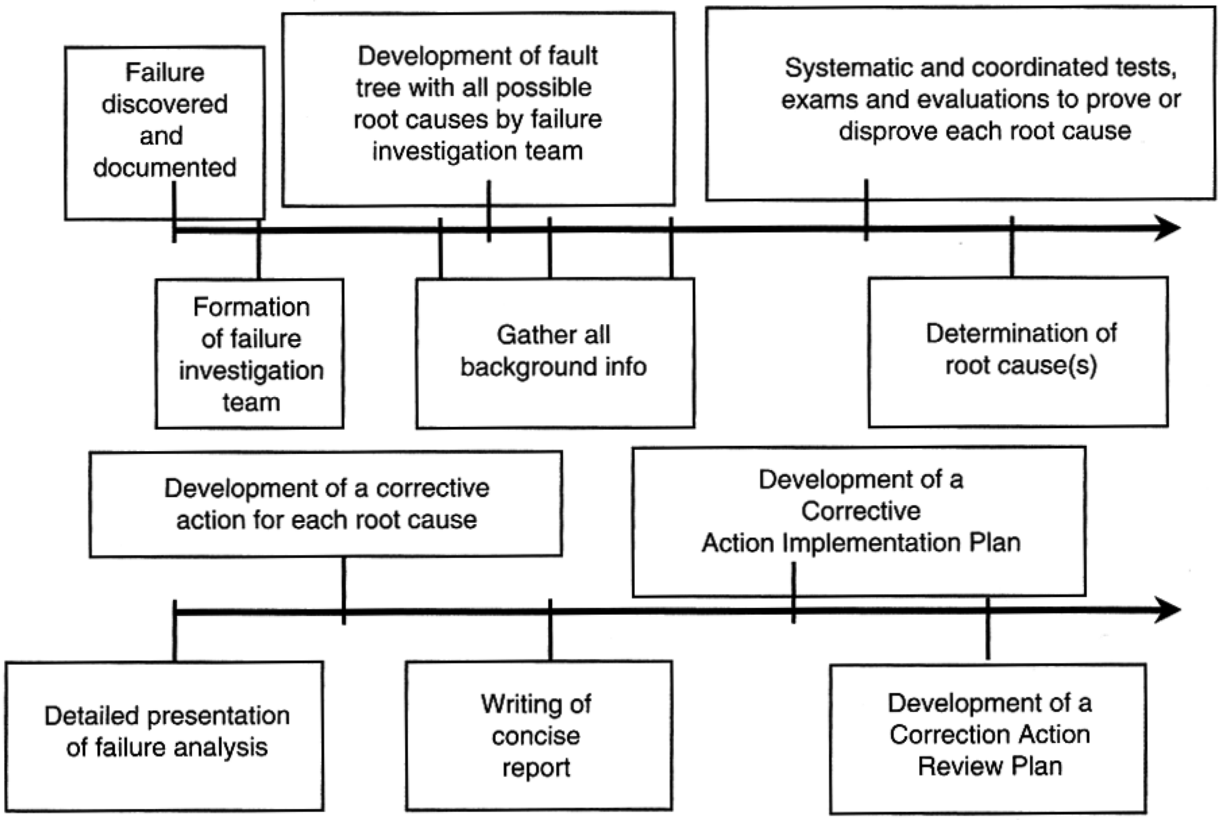
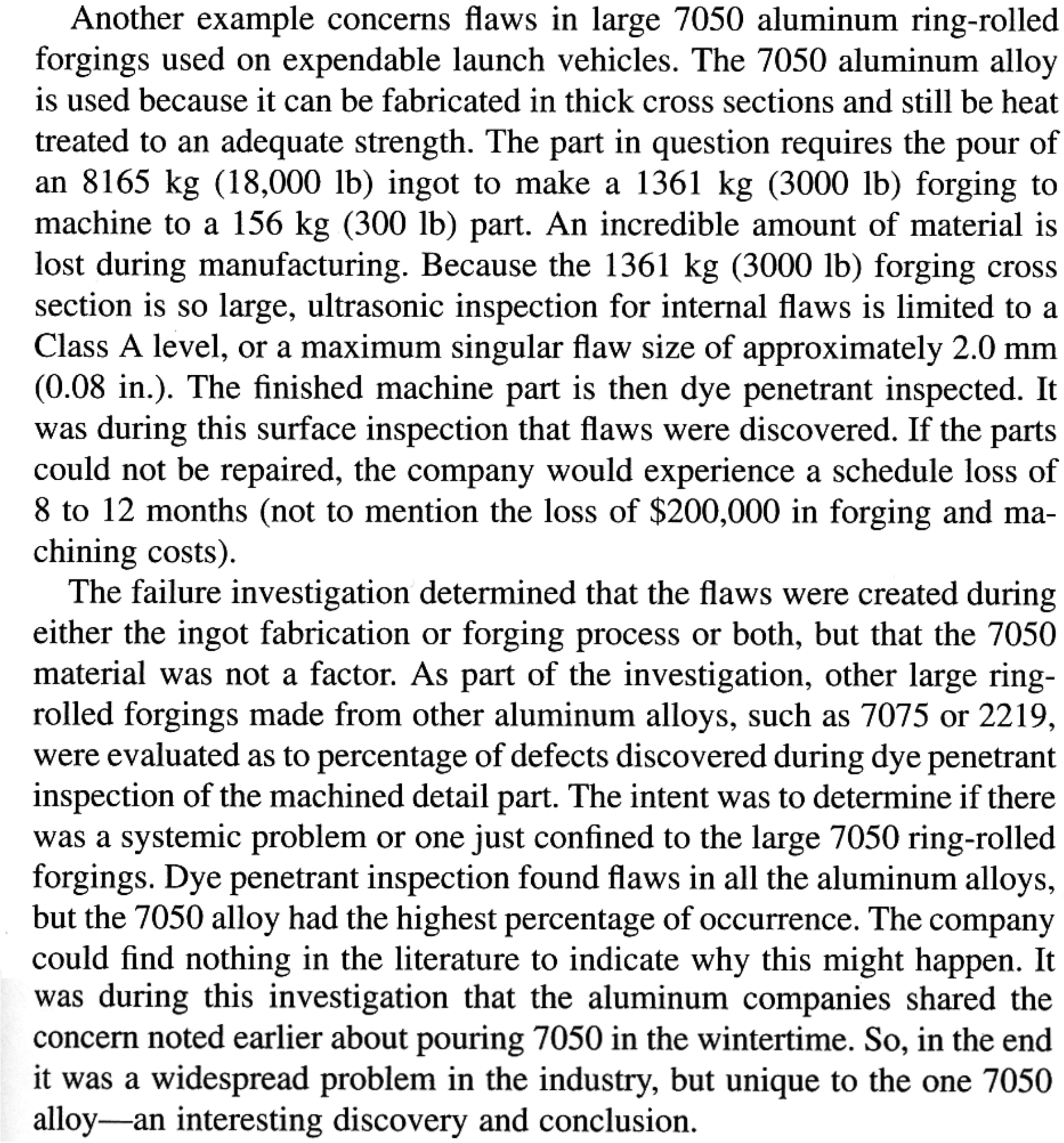


Fig. 8 Timeline of an *organized* failure investigation

The above figure shows the timeline for a well-planned organization [1]. Of important note: during the formation of the failure investigation team the purpose of the investigation should be decided.

Example:

From [1]…



> Another example concerns flaws in large 7050 aluminum ring-rolled forgings used on expendable launch vehicles. The 7050 aluminum alloy is used because it can be fabricated in thick cross sections and still be heat treated to an adequate strength. The part in question requires the pour of an 8165 kg (18,000 lb) ingot to make a 1361 kg (3000 lb) forging to machine to a 156 kg (300 lb) part. An incredible amount of material is lost during manufacturing. Because the 1361 kg (3000 lb) forging cross section is so large, ultrasonic inspection for internal flaws is limited to a Class A level, or a maximum singular flaw size of approximately 2.0 mm (0.08 in.). The finished machine part is then dye penetrant inspected. It was during this surface inspection that flaws were discovered. If the parts could not be repaired, the company would experience a schedule loss of 8 to 12 months (not to mention the loss of $200,000 in forging and machining costs).
>
> The failure investigation determined that the flaws were created during either the ingot fabrication or forging process or both, but that the 7050 material was not a factor. As part of the investigation, other large ring-rolled forgings made from other aluminum alloys, such as 7075 or 2219, were evaluated as to percentage of defects discovered during dye penetrant inspection of the machined detail part. The intent was to determine if there was a systemic problem or one just confined to the large 7050 ring-rolled forgings. Dye penetrant inspection found flaws in all the aluminum alloys, but the 7050 alloy had the highest percentage of occurrence. The company could find nothing in the literature to indicate why this might happen. It was during this investigation that the aluminum companies shared the concern noted earlier about pouring 7050 in the wintertime. So, in the end it was a widespread problem in the industry, but unique to the one 7050 alloy—an interesting discovery and conclusion.

From this example, one can generate a fault tree with all conceivable root causes [1], as shown below:

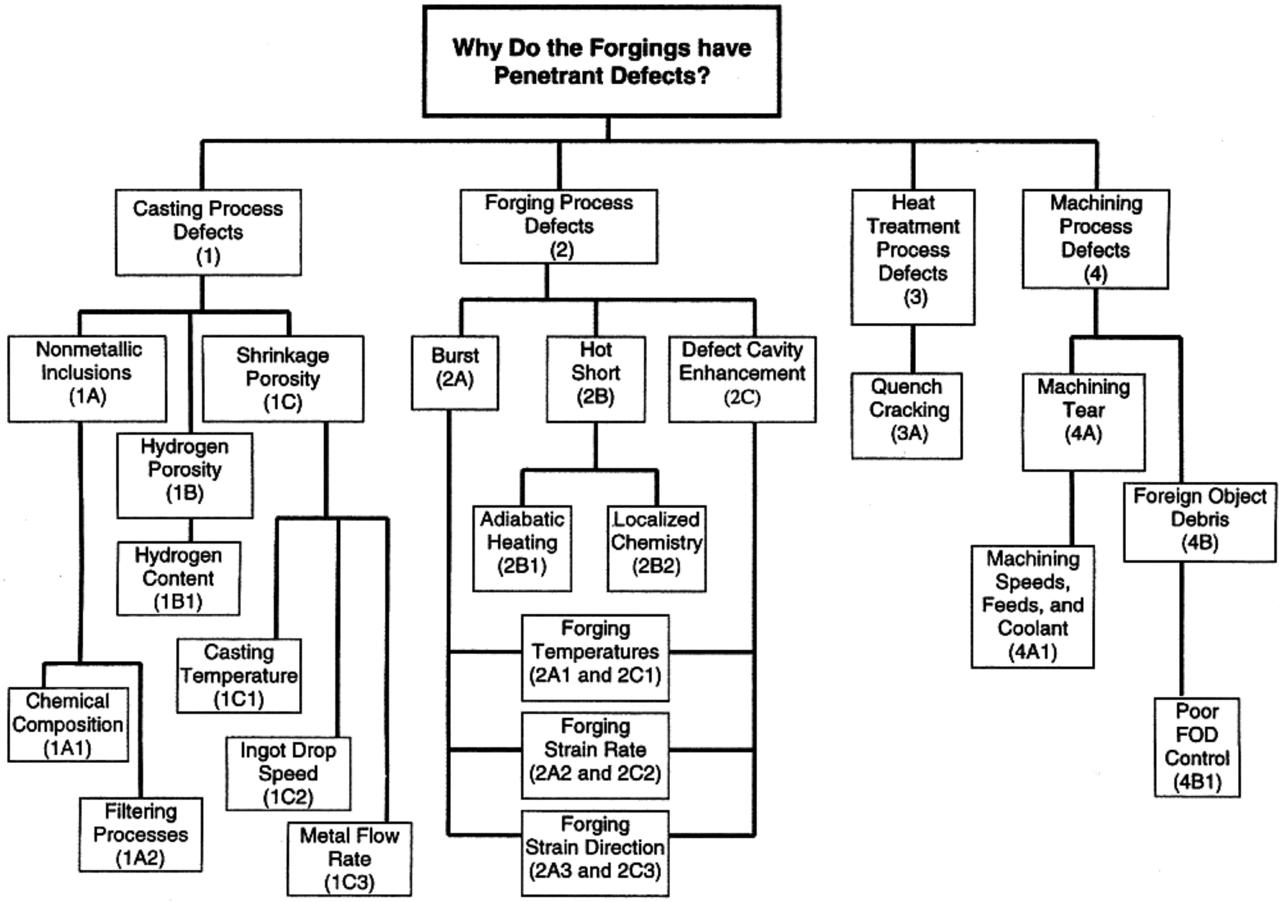


Fig. 3 Fault tree

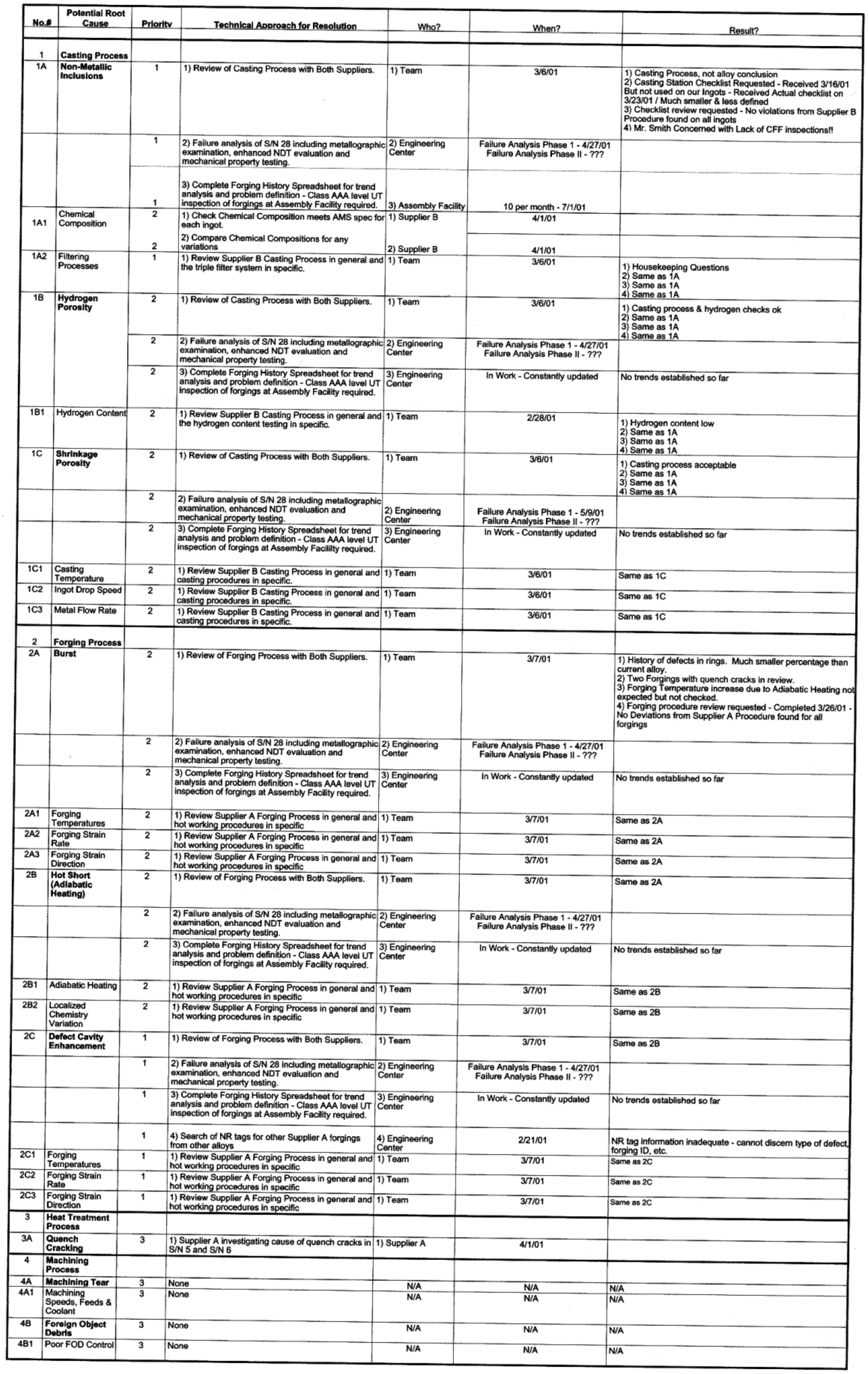
There are many ways to generate fault trees, with various logic methods (such as Boolean symbology)… the main goal is to generate root causes, and style will vary from industry to industry or company to company.

From fault trees, the numbered headings are used to generate a Failure Mode Assessment chart (FMA) [1]:

No.#	Potential Root Cause	Probability	Priority	Rationale	Technical Plan for Resolution
1	**Casting Process**				
1A	**Non-Metallic Inclusions**	Likely	1	I) Failure Analysis of S/N 1 discovered Al Oxide inclusion in Defect Cavity by Metallographic exam. Inclusion confirmed to be Al oxide with presence of Silicon by SEM & EDS Analysis. II) Grain flow around Defect Cavity discovered during failure analysis of S/N 1 & S/N 2 by Metallographic Exam.	1) Review of Casting Process with Both Suppliers. 2) Failure analysis of S/N 28 including metallographic examination, enhanced NDT evaluation and mechanical property testing. 3) Complete Forging History Spreadsheet for trend analysis and problem definition - Class AAA level UT inspection of forgings at Assembly Facility required.
1A1	Chemical Composition	Not likely	2	Chemical Compositions are within Spec	1) Check Chemical Composition meets AMS spec for each ingot. 2) Compare Chemical Compositions for any variations
1A2	Filtering Processes	Likely	1	Filtering Processes control non-metallic inclusion level in ingots	1) Review Supplier B Casting Process in general and the triple filter system in specific.
1B	**Hydrogen Porosity**	Not likely	2	I & II above. III) Hydrogen analysis of S/N 1&7 by Supplier A indicates low potential for hydrogen porosity. IV) This type of casting defect should heal during forging process.	1) Review of Casting Process with Both Suppliers. 2) Failure analysis of S/N 28 including metallographic examination, enhanced NDT evaluation and mechanical property testing. 3) Complete Forging History Spreadsheet for trend analysis and problem definition - Class AAA level UT inspection of forgings at Assembly Facility required.
1B1	Hydrogen Content	Not likely	2	I-IV above	1) Review Supplier B Casting Process in general and the hydrogen content testing in specific.
1C	**Shrinkage Porosity**	Not likely	2	I & II above. III) Pore count of S/N 1&7 by Supplier B indicates low potential for shrinkage porosity. IV) This type of casting defect should heal during forging process.	1) Review of Casting Process with Both Suppliers. 2) Failure analysis of S/N 28 including metallographic examination, enhanced NDT evaluation and mechanical property testing. 3) Complete Forging History Spreadsheet for trend analysis and problem definition - Class AAA level UT inspection of forgings at Assembly Facility required.
1C1	Casting Temperature	Not likely	2	I-III above	1) Review Supplier B Casting Process in general and casting procedures in specific.
1C2	Ingot Drop Speed	Not likely	2	I-III above	1) Review Supplier B Casting Process in general and casting procedures in specific.
1C3	Metal Flow Rate	Not likely	2	I-III above	1) Review Supplier B Casting Process in general and casting procedures in specific.
2	**Forging Process**				
2A	**Burst**	Not likely	2	I & II above. III) SEM analysis of S/N 1 & S/N 2 Defect Cavity surface not indicative of forging burst.	1) Review of Forging Process with Both Suppliers. 2) Failure analysis of S/N 28 including metallographic examination, enhanced NDT evaluation and mechanical property testing. 3) Complete Forging History Spreadsheet for trend analysis and problem definition - Class AAA level UT inspection of forgings at Assembly Facility required.
2A1	Forging Temperatures	Not likely	2	I-III above	1) Review Supplier A Forging Process in general and hot working procedures in specific
2A2	Forging Strain Rate	Not likely	2	I-III above	1) Review Supplier A Forging Process in general and hot working procedures in specific
2A3	Forging Strain Direction	Not likely	2	I-III above	1) Review Supplier A Forging Process in general and hot working procedures in specific
2B	**Hot Short (Adiabatic Heating)**	Not likely	2	I & II above. III) SEM analysis of 1 & S/N 2 Defect Cavity surface not indicative of hot tear.	1) Review of Forging Process with Both Suppliers. 2) Failure analysis of S/N 28 including metallographic examination, enhanced NDT evaluation and mechanical property testing. 3) Complete Forging History Spreadsheet for trend analysis and problem definition - Class AAA level UT inspection of forgings at Assembly Facility required.
2B1	Adiabatic Heating	Not likely	2	I-III above	1) Review Supplier A Forging Process in general and hot working procedures in specific
2B2	Localized Chemistry Variation	Not likely	2	I-III above	1) Review Supplier A Forging Process in general and hot working procedures in specific
2C	**Defect Cavity Enhancement**	Possible	1	I) S/N 1 Defect Cavity had no obvious inclusion and S/N 2 Defect Cavity was not filled with Al Oxide inclusion. II) Size of Defect Cavity unique.	1) Review of Forging Process with Both Suppliers. 2) Failure analysis of S/N 28 including metallographic examination, enhanced NDT evaluation and mechanical property testing. 3) Complete Forging History Spreadsheet for trend analysis and problem definition - Class AAA level UT inspection of forgings at Assembly Facility required.
2C1	Forging Temperatures	Possible	1	I-III above	1) Review Supplier A Forging Process in general and hot working procedures in specific
2C2	Forging Strain Rate	Possible	1	I-III above	1) Review Supplier A Forging Process in general and hot working procedures in specific
2C3	Forging Strain Direction	Possible	1	I-III above	1) Review Supplier A Forging Process in general and hot working procedures in specific
3	**Heat Treatment Process**				
3A	**Quench Cracking**	Not likely	3	Quench cracking does not normally produce small, multiple internal flaws.	Supplier A investigating cause of quench cracks in S/N 5 and S/N 6
4	**Machining Process**				
4A	**Machining Tear**	Not likely	3	No evidence of tearing, smearing, etc. on part surface or in Defect Cavity.	None
4A1	Machining Speeds, Feeds & Coolant	Not likely	3	No evidence of tearing, smearing, etc. on part surface or in Defect Cavity.	None
4B	**Foreign Object Debris**	Not likely	3	No FOD discovered on part surface or in Defect Cavity.	None
4B1	Poor FOD Control	Not likely	3	No FOD discovered on part surface or in Defect Cavity.	None

Fig. 4 Failure Mode Assessment (FMA) chart. Forging with defects

Based on the FMA once can then generate a Technical Plan for Resolution TPR chart [1]:



No.#	Potential Root Cause	Priority	Technical Approach for Resolution	Who?	When?	Result?
1	**Casting Process**					
1A	**Non-Metallic Inclusions**	1	1) Review of Casting Process with Both Suppliers.	1) Team	3/6/01	1) Casting Process, not alloy conclusion 2) Casting Station Checklist Requested - Received 3/16/01 But not used on our Ingots - Received Actual checklist on 3/23/01 / Much smaller & less defined 3) Checklist review requested - No violations from Supplier B Procedure found on all ingots 4) Mr. Smith Concerned with Lack of CFF inspections!!
		1	2) Failure analysis of S/N 28 including metallographic examination, enhanced NDT evaluation and mechanical property testing.	2) Engineering Center	Failure Analysis Phase 1 - 4/27/01 Failure Analysis Phase II - ???	
		1	3) Complete Forging History Spreadsheet for trend analysis and problem definition - Class AAA level UT inspection of forgings at Assembly Facility required.	3) Assembly Facility	10 per month - 7/1/01	
1A1	Chemical Composition	2	1) Check Chemical Composition meets AMS spec for each ingot.	1) Supplier B	4/1/01	
		2	2) Compare Chemical Compositions for any variations	2) Supplier B	4/1/01	
1A2	Filtering Processes	1	1) Review Supplier B Casting Process in general and the triple filter system in specific.	1) Team	3/6/01	1) Housekeeping Questions 2) Same as 1A 3) Same as 1A 4) Same as 1A
1B	**Hydrogen Porosity**	2	1) Review of Casting Process with Both Suppliers.	1) Team	3/6/01	1) Casting process & hydrogen checks ok 2) Same as 1A 3) Same as 1A 4) Same as 1A
		2	2) Failure analysis of S/N 28 including metallographic examination, enhanced NDT evaluation and mechanical property testing.	2) Engineering Center	Failure Analysis Phase 1 - 4/27/01 Failure Analysis Phase II - ???	
		2	3) Complete Forging History Spreadsheet for trend analysis and problem definition - Class AAA level UT inspection of forgings at Assembly Facility required.	3) Engineering Center	In Work - Constantly updated	No trends established so far
1B1	Hydrogen Content	2	1) Review Supplier B Casting Process in general and the hydrogen content testing in specific.	1) Team	2/28/01	1) Hydrogen content low 2) Same as 1A 3) Same as 1A 4) Same as 1A
1C	**Shrinkage Porosity**	2	1) Review of Casting Process with Both Suppliers.	1) Team	3/6/01	1) Casting process acceptable 2) Same as 1A 3) Same as 1A 4) Same as 1A
		2	2) Failure analysis of S/N 28 including metallographic examination, enhanced NDT evaluation and mechanical property testing.	2) Engineering Center	Failure Analysis Phase 1 - 5/9/01 Failure Analysis Phase II - ???	
		2	3) Complete Forging History Spreadsheet for trend analysis and problem definition - Class AAA level UT inspection of forgings at Assembly Facility required.	3) Engineering Center	In Work - Constantly updated	No trends established so far
1C1	Casting Temperature	2	1) Review Supplier B Casting Process in general and casting procedures in specific.	1) Team	3/6/01	Same as 1C
1C2	Ingot Drop Speed	2	1) Review Supplier B Casting Process in general and casting procedures in specific.	1) Team	3/6/01	Same as 1C
1C3	Metal Flow Rate	2	1) Review Supplier B Casting Process in general and casting procedures in specific.	1) Team	3/6/01	Same as 1C
2	**Forging Process**					
2A	**Burst**	2	1) Review of Forging Process with Both Suppliers.	1) Team	3/7/01	1) History of defects in rings. Much smaller percentage than current alloy. 2) Two Forgings with quench cracks in review. 3) Forging Temperature increase due to Adiabatic Heating not expected but not checked. 4) Forging procedure review requested - Completed 3/26/01 - No Deviations from Supplier A Procedure found for all forgings
		2	2) Failure analysis of S/N 28 including metallographic examination, enhanced NDT evaluation and mechanical property testing.	2) Engineering Center	Failure Analysis Phase 1 - 4/27/01 Failure Analysis Phase II - ???	
		2	3) Complete Forging History Spreadsheet for trend analysis and problem definition - Class AAA level UT inspection of forgings at Assembly Facility required.	3) Engineering Center	In Work - Constantly updated	No trends established so far
2A1	Forging Temperatures	2	1) Review Supplier A Forging Process in general and hot working procedures in specific	1) Team	3/7/01	Same as 2A
2A2	Forging Strain Rate	2	1) Review Supplier A Forging Process in general and hot working procedures in specific	1) Team	3/7/01	Same as 2A
2A3	Forging Strain Direction	2	1) Review Supplier A Forging Process in general and hot working procedures in specific	1) Team	3/7/01	Same as 2A
2B	**Hot Short (Adiabatic Heating)**	2	1) Review of Forging Process with Both Suppliers.	1) Team	3/7/01	Same as 2A
		2	2) Failure analysis of S/N 28 including metallographic examination, enhanced NDT evaluation and mechanical property testing.	2) Engineering Center	Failure Analysis Phase 1 - 4/27/01 Failure Analysis Phase II - ???	
		2	3) Complete Forging History Spreadsheet for trend analysis and problem definition - Class AAA level UT inspection of forgings at Assembly Facility required.	3) Engineering Center	In Work - Constantly updated	No trends established so far
2B1	Adiabatic Heating	2	1) Review Supplier A Forging Process in general and hot working procedures in specific	1) Team	3/7/01	Same as 2B
2B2	Localized Chemistry Variation	2	1) Review Supplier A Forging Process in general and hot working procedures in specific	1) Team	3/7/01	Same as 2B
2C	**Defect Cavity Enhancement**	1	1) Review of Forging Process with Both Suppliers.	1) Team	3/7/01	Same as 2B
		1	2) Failure analysis of S/N 28 including metallographic examination, enhanced NDT evaluation and mechanical property testing.	2) Engineering Center	Failure Analysis Phase 1 - 4/27/01 Failure Analysis Phase II - ???	
		1	3) Complete Forging History Spreadsheet for trend analysis and problem definition - Class AAA level UT inspection of forgings at Assembly Facility required.	3) Engineering Center	In Work - Constantly updated	No trends established so far
		1	4) Search of NR tags for other Supplier A forgings from other alloys	4) Engineering Center	2/21/01	NR tag information inadequate - cannot discern type of defect, forging ID, etc.
2C1	Forging Temperatures	1	1) Review Supplier A Forging Process in general and hot working procedures in specific	1) Team	3/7/01	Same as 2C
2C2	Forging Strain Rate	1	1) Review Supplier A Forging Process in general and hot working procedures in specific	1) Team	3/7/01	Same as 2C
2C3	Forging Strain Direction	1	1) Review Supplier A Forging Process in general and hot working procedures in specific	1) Team	3/7/01	Same as 2C
3	**Heat Treatment Process**					
3A	**Quench Cracking**	3	1) Supplier A investigating cause of quench cracks in S/N 5 and S/N 6	1) Supplier A	4/1/01	
4	**Machining Process**					
4A	**Machining Tear**	3	None	N/A	N/A	N/A
4A1	Machining Speeds, Feeds & Coolant	3	None	N/A	N/A	N/A
4B	**Foreign Object Debris**	3	None	N/A	N/A	N/A
4B1	Poor FOD Control	3	None	N/A	N/A	N/A

Fig. 5 Technical Plan for Resolution (TPR) chart. Forging with defects

Once the FMA and TPR are "complete" (recall that they are living documents) a corrective action tree can be generated which helps connect back to the original fault tree [1]:

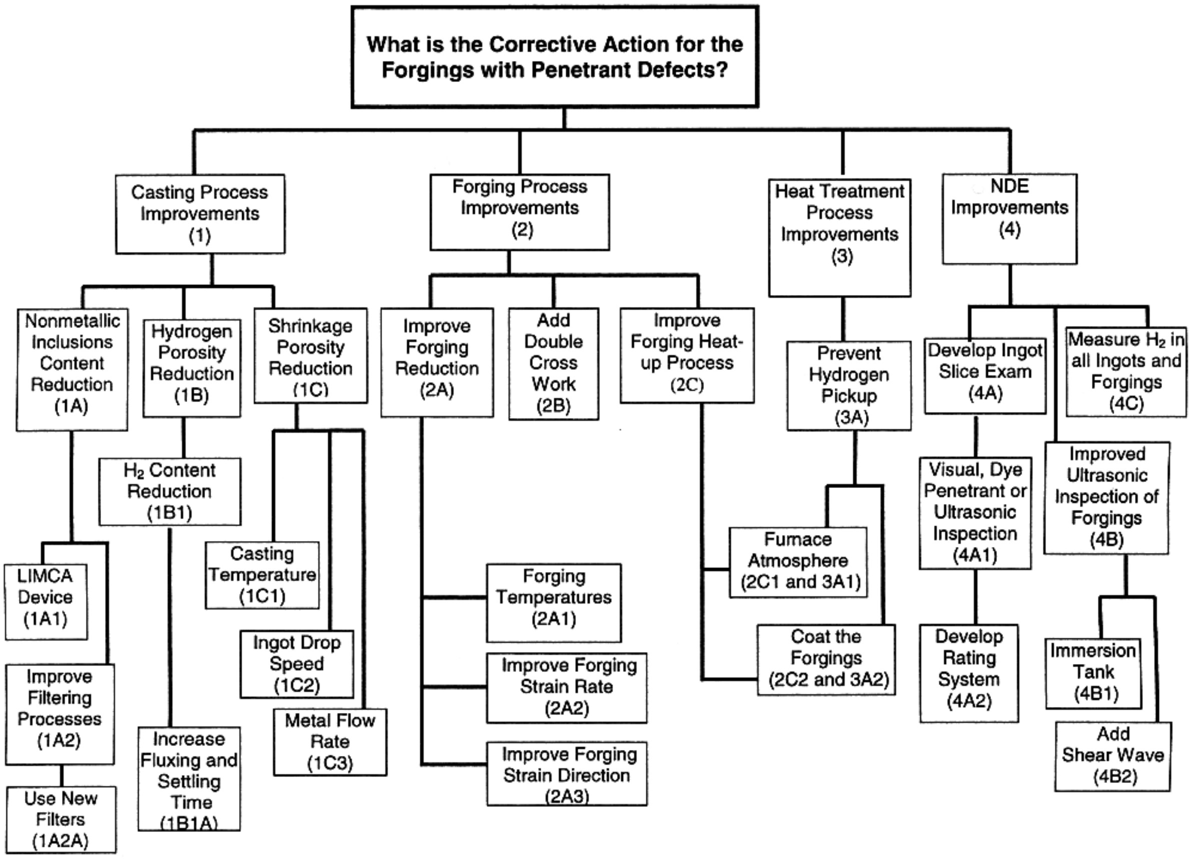


Fig. 6 Corrective action tree

The priority of each corrective action is listed in the TRP chart, and following up is aided by having individuals assigned with deadline completion dates. The corrective action tree does not necessarily emphasize the priorities, however the tree does show how each of the actions are interrelated and from analysis of the tree one can determine critical paths for corrective action.

Reference:

1. Daniel P. Dennies, "How to organize and run a failure investigation," 2005, ASM International