Integrity Applications Incorporated

Fault Management for System Safety: Introduction to Fault Tree Analysis

Guest Lecture SYST 460/560:

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Overview

- What is Fault Tree Analysis?
- Relevant Definitions
- Role of FTA in Decision Making
- Probabilistic Risk Assessment
- Complete Analysis Considerations
- FTA Steps
- Ground Rules
- FTA Gate Symbols
- Simple Implementation Example
- Multi-engine Aircraft Example with Probabilistic Risk Assessment

What is Fault Tree Analysis (FTA)?

- FTA is a **powerful tool** for understanding component and subsystem **interactions** that can cause a **hazardous event**
- Top-down, qualitative **failure analysis methodology** that systematically deduces the **root causes** of an undesired, **hazardous event**
- **Logical** illustration of **events and relationships** that are necessary and sufficient to result in event
- **NOT** a model of **all possible system failures** or causes of system failure
- **NOT** a **quantitative model**, but can be used to support quantitative analysis (e.g., Probabilistic Risk Assessment)

Important Definitions

- **Fault** – unexpected response in which functionality is recoverable by fixing it, managing around it, or redundancy
- **Failure** – unexpected response in which functionality is NOT recoverable
- **Primary Failure** – component failure that cannot be further defined in a Fault Tree
  - Example: component on computer circuit board fails
- **Secondary Failure** – component failure that could be defined further but is not due to ground rules
  - Example: computer failure (not interested in details)
- **Command Fault** – inadvertent or untimely normal operation of a component
  - Example: draw bridge opens at wrong time due to operator entering command at improper time
  - **Common Cause Failure** – failures that are common to multiple parts due to poor material choice, manufacturing defects, etc.

Role of FTA for Decision Making

- Understand logic that leads to top event
- Prioritization of contributors that lead to top event
- Proactive tool to prevent top event
- Monitor system performance
- Optimize resources
- Assist in system design
- Identify and correct causes of top event

Probabilistic Risk Assessment

- **Probabilistic Risk Assessment (PRA)** assigns **probabilities** of each event, or combination of events, in the Fault Tree to determine the **likelihood of the top event**
- **Probability of failure** (success) calculated through PRA of a particular event is **only as good** as the **estimates** of component reliability
- PRA is **only effective** if the fault tree and associated probabilities is **regularly updated** to reflect system changes

Complete Considerations: Top-down and Bottom-up

- FTA uses top-down event analysis, which may not encompass all possible causes – Use of Bottom-up analyses allow evaluation of low-level failure consequences
  - **Parts Count**
    - Any single component failure leads to system failure
  - **Failure Mode and Effect Analysis (FMEA)**
    - ID and quantify component single failure modes
  - **Failure Mode Effect and Criticality Analysis (FMECA)**
    - Similar to FMEA, with criticality, assurances and controls to limit failures
  - **Preliminary Hazard Analysis (PHA)**
    - Hazards posed by the system
  - **Reliability Block Diagram (RBD)**
    - Elemental diagram of components based on system-success pathways

FTA Steps

- Identify objective
- Define top event
- Define scope
- Define resolution
- Define ground rules
- Construct fault tree
- Evaluate fault tree
- Interpret results

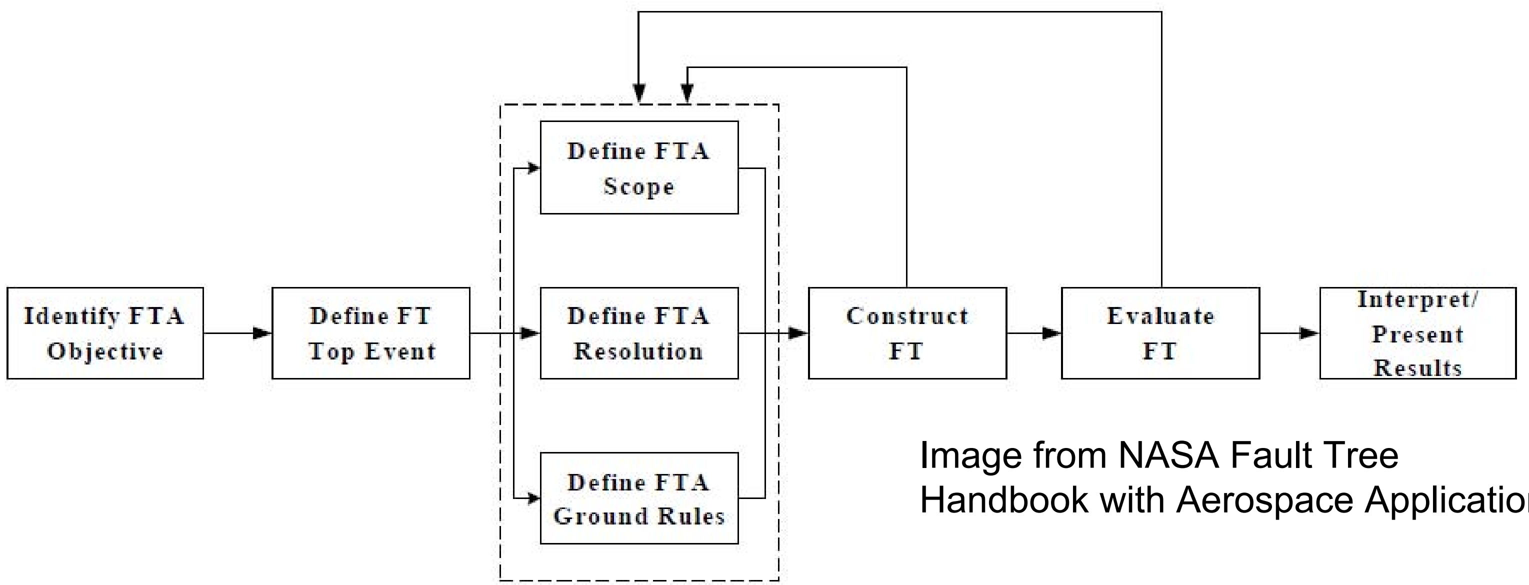


Image from NASA Fault Tree Handbook with Aerospace Applications

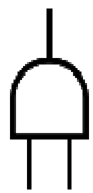
Basic Paradigm and Basic Rules

- Think small – Immediate causes of the event – small steps
- Clearly write the events as faults; state precisely what the fault is and the conditions under which it occurs. Do not mix successes with faults
- Event is classified as "state of component fault" if fault is a component failure, otherwise event is a "state of system fault"
- If the normal functioning of a component propagates a fault sequence, the component is assumed to function normally
- Each level of fault tree should be completed before moving to lower level
- Fault tree should be constructed to major component level
  - Individual circuit board, but not transistors

FTA Gate Symbols

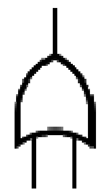
AND Gate

Input		Output
A	B	A and B
0	0	0
1	0	0
0	1	0
1	1	1



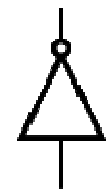
OR Gate

Input		Output
A	B	A or B
0	0	0
1	0	1
0	1	1
1	1	1



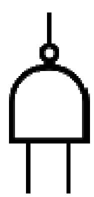
NOT Gate

Input	Output
A	NOT A
0	1
1	0



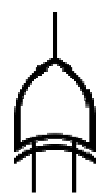
NAND Gate

Input		Output
A	B	A nand B
0	0	1
1	0	1
0	1	1
1	1	0



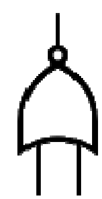
XOR Gate

Input		Output
A	B	A xor B
0	0	0
1	0	1
0	1	1
1	1	0



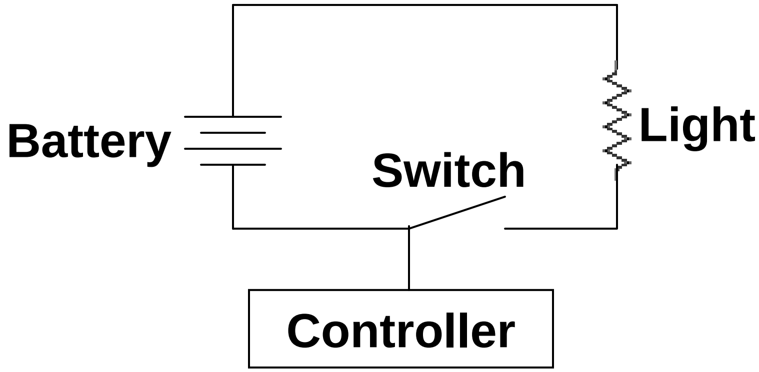
NOR Gate

Input		Output
A	B	A nor B
0	0	1
1	0	0
0	1	0
1	1	0

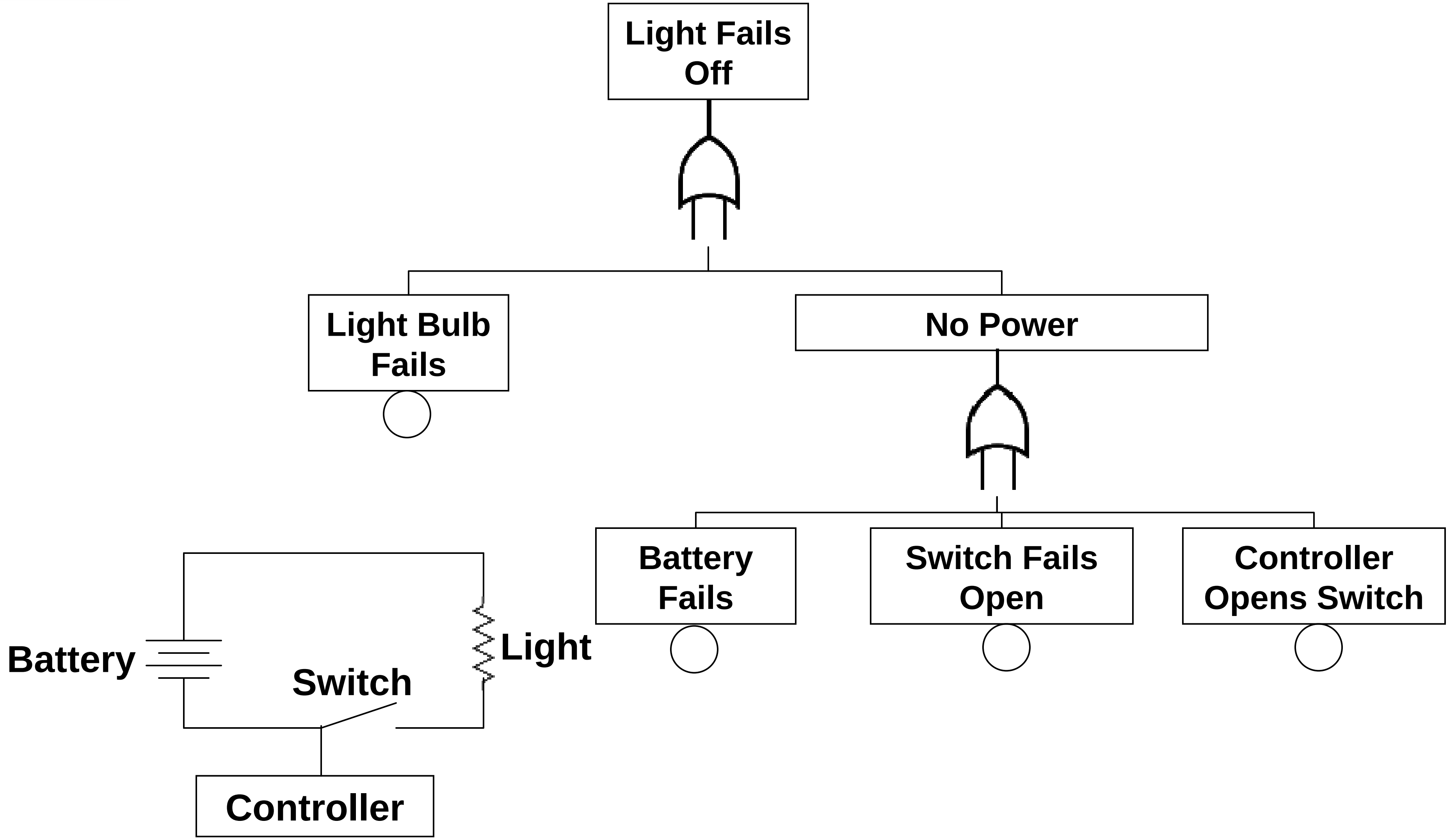


Simple Example FTA Implementation

- Step 1: Objective: Evaluate possible sources of failure of light system.
- Step 2: Top Event: Light fails off.
- Step 3: Scope: Will be limited to components internal to system.
- Step 4: Resolution: Focus on major system components.
- Step 5: Ground Rules:
  - Will not include human errors.
  - Will not consider common cause failures



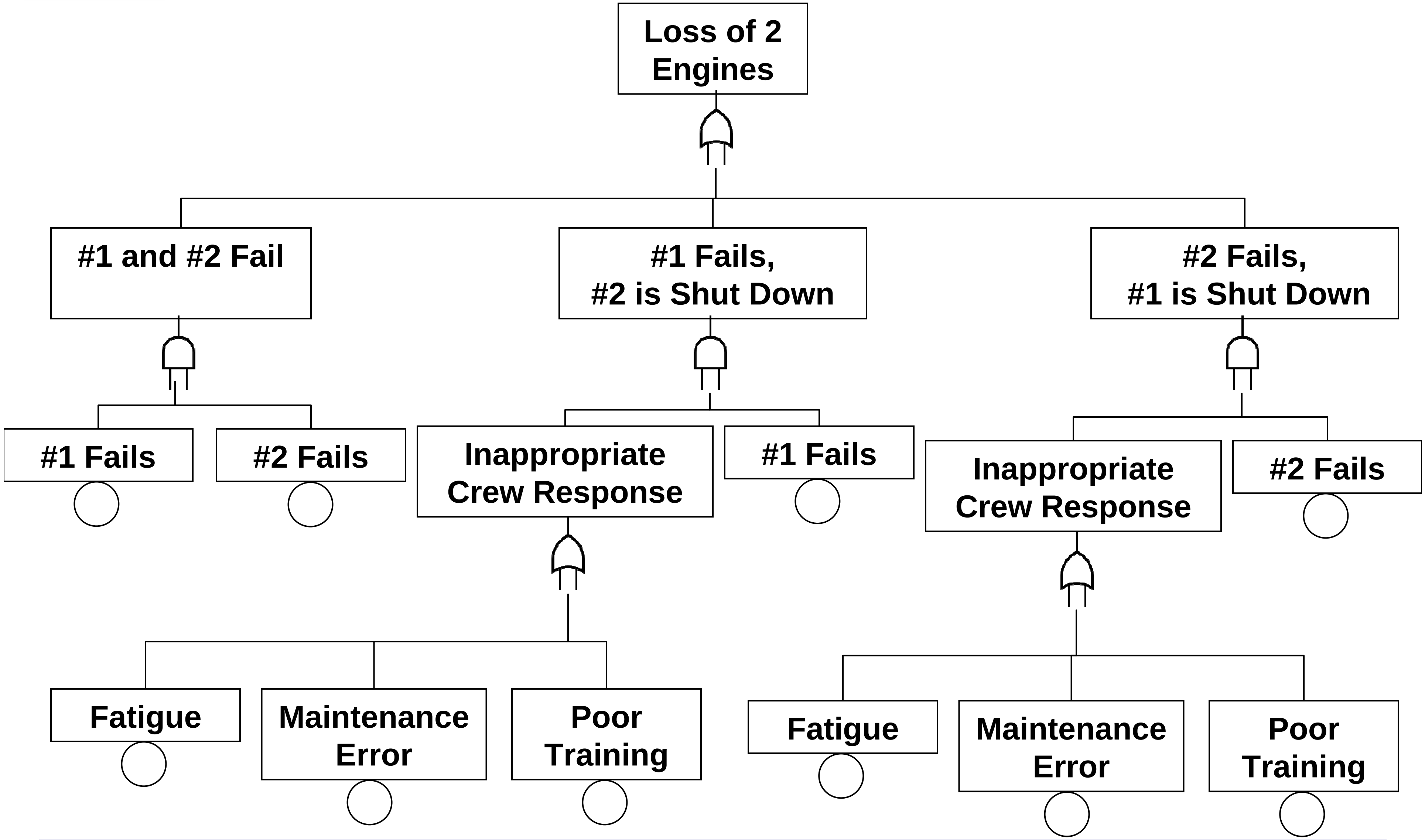
Fault Tree Construction



Multi-engine Aircraft Example

- Objective: Evaluate possible sources of failure of 2 engines.
- Top Event: Loss of 2 engines.
- Scope: Will be limited to components internal to system.
- Resolution: Focus on major system components.
- Ground Rules:
  - Multiple human errors will not be considered

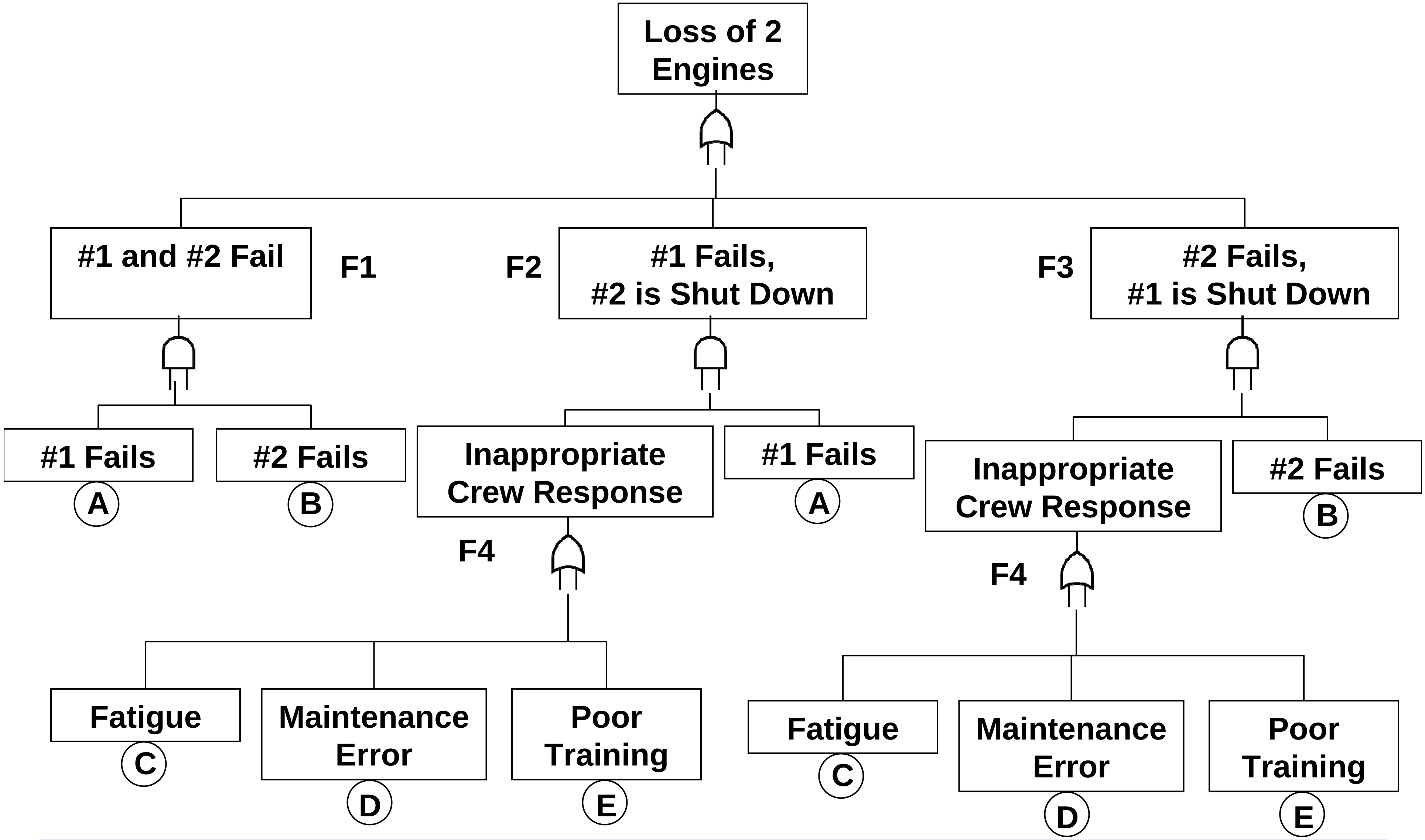
Aircraft Fault Tree Construction



Probabilistic Risk Assessment of 2 Engine Failures

- Determine Cut Sets – set of events that lead to top event
- Determine Minimum Cut Sets – minimum set of events that lead to top event (can be several combinations)
- Determine failure probabilities:
  - λ: component failure rate
  - t: relevant time interval
  - $P = 1 - e^{-\lambda t}$
- $P(top) = \Sigma P(M_i) = P(BE_1)P(BE_2)\ldots P(BE_k)$
  - OR gate: $P(A \text{ or } B) = P(A) + P(B) - P(A \cap B)$
    - Using rare event approximation: P(A OR B) = P(A) + P(B), generates conservative estimate
  - AND gate: P(A and B) = P(A)*P(B)

Determine Minimum Cut Sets



Determine Minimum Cut Sets (cont)

- Use top-down substitution:
  - T = F1 + F2 + F3, F1 = A*B, F2 = A*F4, F3 = B*F4, F4 = C + D + E
  - T = A*B + A*F4 + B*F4
  - T = A*B + A*(C + D + E) + B*(C + D + E)
  - T = A*B + A*C + A*D + A*E + B*C + B*D + B*E
- Results in 7 Cut Sets:
  - A: Engine 1 Fails, Engine 2 Fails
  - B: Engine 1 Fails, Crew Shuts Down Engine 2 Due to Fatigue
  - C: Engine 1 Fails, Crew Shuts Down Engine 2 Due to Maintenance Error
  - D: Engine 1 Fails, Crew Shuts Down Engine 2 Due to Poor Training
  - E: Engine 2 Fails, Crew Shuts Down Engine 1 Due to Fatigue
  - F: Engine 2 Fails, Crew Shuts Down Engine 1 Due to Maintenance Error
  - G: Engine 2 Fails, Crew Shuts Down Engine 1 Due to Poor Training

Multi-Engine Aircraft: Probabilistic Risk Assessment

- Single engine failure rate: 1 every 100 hours.
  - Probability in 5 hour flight = 0.0488
- Crew fatigue rate: 1 in 6 hours
  - Probability in 5 hour flight = 0.5654
- Maintenance error probability: $1.0*10^{-4}$
- Poor training probability: $1.0*10^{-6}$
- Probabilities: Failure => Success
  - P(A) = 0.0488*0.0488 = 0.0024 => 0.9976
  - P(B) = 0.0488*0.5654 = 0.0276 => 0.9724
  - P(C) = 0.0488* $1.0*10^{-4}$ = 4.8800e-006 => 0.99999512
  - P(D) = 0.0488* $1.0*10^{-6}$ = 4.8800e-008 => 0.9999999512
  - P(E) = 0.0488*0.5654 = 0.0276 => 0.9724
  - P(F) = 0.0488* $1.0*10^{-4}$ = 4.8800e-006 => 0.99999512
  - P(G) = 0.0488* $1.0*10^{-6}$ = 4.8800e-008 => 0.9999999512
  - **P(Top) = 0.0576 => 0.9424**

FTA for Design Improvement

- Nearly 6% probability of top event
- Worst case scenario:
  - A failure of either engine and a pilot error due to fatigue
- How to improve design?
  - Pilot fatigue:
    - Decrease flight time
    - Decrease fatigue rate
  - Inappropriate Crew Response:
    - Automated systems (may introduce additional failures into fault tree)
    - Detailed procedures – possibly with audible alerts
  - Improve engine reliability:
    - Requires FMEA/FMECA analysis to understand most common failures
  - Introduce redundancy:
    - Additional engines
    - Reserve crew

Summary

- FTA is useful in evaluating the safety and reliability of complex systems
- Helpful to focus limited resources
- Identify critical components and combinations of critical events
- Methodical approach to evaluate system safety
- Supports Probabilistic Risk Assessment to understand event likelihood
- Must be updated with system changes, component modifications, and refined statistical analysis

References

- "Fault Tree Handbook with Aerospace Applications", NASA: Office of Safety and Mission Assurance; August, 2002.
- "Improving the Continued Airworthiness of Civil Aircraft: A Strategy for the FAA's Aircraft Certification Service", National Research Council; National Academy Press, Washington, DC, 1998.