Process operability: Reliability

In this Lesson, we will learn

- The importance of reliability
- Key terms and definitions
  - Reliability, Failure Rate, Availability
- Process design to remove/replace equipment
  - Pump, valve, heat exchangers
- Process structures to increase reliability
  - Calculate system reliability
  - Pump, Boiler, Fuel system
- Inventory location for reliability
  - Tankage
Reliability

Stopping the production of a plant can be very costly*

- Lost sales
- Storage, disposal or reprocessing of material in plant
- Heating/cooling process
- Repair or replacement of equipment
- Shutdown of integrated units
- Possible damage to equipment

* Safety is addressed in a topic 4.
Reliability: The *probability* of a device successfully performing *its function* for a period of time under *specified conditions*.

- "*Its function*" clearly depends on the needs of the specific system.
- "*Specified conditions*" define what is occurring in the system and how the device is maintained.
- "*Probability*" can be determined; the outcome of one instance of the device’s action cannot be determined.

\[ R(t) = 1 - \frac{n_{\text{failed}}(t)}{n} \]

(Value between 0 and 1)

n = number of outcomes
Other terms that are useful in discussing reliability are:

- **Probability of failure, \( F(t) \):** \( F(t) + R(t) = 1 \)
- **Failure rate, \( \lambda(t) \):** The number of failures per unit of time at a specific lifetime divided by the number of items at that time.

\[
\lambda(t) = \frac{1}{n - n_f(t)} \frac{dn_f(t)}{dt}
\]

\[
\lambda(t) = -\frac{1}{R(t)} \frac{dR(t)}{dt}
\]

(Typical units: failures /10^6 h)
**Reliability**

**Failure rate**: The number of failures per unit time at a specific lifetime divided by the number of items at that time. A typical “bathtub curve” is shown below.

- **Break in**, **Infant mortality**
- **Chance failure period**, \( \lambda \) is constant.
- **Wear out**

**Terminology**

**Key Operability issues**

1. Operating window
2. Flexibility/controllability
3. Reliability
4. Safety & equipment protection
5. Efficiency & profitability
6. Operation during transitions
7. Dynamic Performance
8. Monitoring & diagnosis
Reliability

Data from Wells (1980) gives a good visual display of relative reliabilities of categories of process equipment.


Figure 3.2 Typical failure rates (mainly mean values) for a range of equipment

1 Not rechargeable batteries
2 Values are pipe lengths of 1 m; useful rule 10^-4/100 pipe diameters
3 Reciprocating prime movers, low values
4 Not HIPS (see Stewart, 1974)
5 Most measurements — not pressure gauge
6 Include off-specification readings
7 Does not include some items specially made with high reliability for nuclear use

Recommended sources: Farmer (1971); Green et al. (1965/66); USAEC (1975); Lees (1976)
### Terminology

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#### Table: Failure Rate (failures/10^6 h)

<table>
<thead>
<tr>
<th>Equipment Type</th>
<th>Failure Rate (failures/10^6 h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transistor equipments</td>
<td></td>
</tr>
<tr>
<td>Wiring</td>
<td></td>
</tr>
<tr>
<td>Microelectronic circuits</td>
<td></td>
</tr>
<tr>
<td>Discrete electronic parts (resistors...)</td>
<td></td>
</tr>
<tr>
<td>Electromechanical parts (relays...)</td>
<td></td>
</tr>
<tr>
<td>Diodes, triodes</td>
<td></td>
</tr>
<tr>
<td>Lamps</td>
<td></td>
</tr>
<tr>
<td>Batteries, fuses</td>
<td></td>
</tr>
<tr>
<td>Welded joints</td>
<td></td>
</tr>
<tr>
<td>Nuts/bolts/flanged joints</td>
<td></td>
</tr>
<tr>
<td>Pneumatic/hydraulic joints, seals, bellows</td>
<td></td>
</tr>
<tr>
<td>Filters, orifices</td>
<td></td>
</tr>
<tr>
<td>Hoses</td>
<td></td>
</tr>
<tr>
<td>Pipes ≤ 75 mm dia (leaks)^2</td>
<td></td>
</tr>
<tr>
<td>Pipes ≥ 75 mm dia (leaks)^2</td>
<td></td>
</tr>
<tr>
<td>Vessels (leaks)</td>
<td></td>
</tr>
<tr>
<td>Solenoid and control valves</td>
<td></td>
</tr>
<tr>
<td>Relief valves and discs (pinholes)</td>
<td></td>
</tr>
<tr>
<td>Hand valves</td>
<td></td>
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<tr>
<td>Exchangers, boilers</td>
<td></td>
</tr>
<tr>
<td>Turbines</td>
<td></td>
</tr>
<tr>
<td>Fans, boilers</td>
<td></td>
</tr>
<tr>
<td>Pumps, compressors</td>
<td></td>
</tr>
<tr>
<td>Automatic protective systems^3</td>
<td></td>
</tr>
<tr>
<td>Measuring systems^5</td>
<td></td>
</tr>
<tr>
<td>Analysers^6</td>
<td></td>
</tr>
<tr>
<td>Computers</td>
<td></td>
</tr>
<tr>
<td>Large electronic systems, redundancy</td>
<td></td>
</tr>
<tr>
<td>Large electronic systems, no redundancy</td>
<td></td>
</tr>
<tr>
<td>Transformers, circuit breakers</td>
<td></td>
</tr>
</tbody>
</table>
### Key Operability Issues

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**Sample from CCPS Data Base**

**Guidelines for Process Equipment Reliability Data, CCPS (AIChE)**

#### DATA ON SELECTED PROCESS SYSTEMS AND EQUIPMENT

<table>
<thead>
<tr>
<th>Taxonomy No.</th>
<th>Equipment Description</th>
<th>ROTATING EQUIPMENT - COMPRESSORS</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Operating Mode</th>
<th>Process Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>UNKNOWN</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Population</th>
<th>Samples</th>
<th>Aggregated time in service (10^6 hrs)</th>
<th>No. of Demands</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Calendar time</td>
<td>Operating time</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lower</td>
<td>Mean</td>
</tr>
</tbody>
</table>

#### Failure mode

- CATASTROPHIC
  - a. Fails While Running
  - b. Rupture
  - c. Spurious Start/Command Fault
  - d. Fails to Start on Demand
  - e. Fails to Stop on Demand

- DEGRADED
  - a. External Leakage

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Equipment Boundary
Other terms that are useful in discussing reliability are:

- **Mean time to failure (MTTF):** The average time between a device being placed in operation and its first failure.

- **Mean time between failures (MTBF):** Can include repairable systems, with time to repair and wait included.

When the failure rate is constant,

\[
R(t) = \exp \left\{- \int_0^t \lambda(t') dt' \right\} = \exp(-\lambda t)
\]

\(R(t) = \) reliability

\(\lambda = \) failure rate

\[MTTF = \frac{1}{\lambda} \text{ (years/failure)}\]
Other terms that are useful in discussing reliability are:

- **Availability**: The ratio of the time a plant is producing product to the total time.

  \[
  \text{Availability} = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR} + \text{MTOW}}
  \]

  MTTF = mean time to failure
  MTTR = mean time to repair
  MTOW = mean time of waiting (for spare parts, etc.)
Reliability

Generally, we are interested in availability, but we also need to keep an eye on MTTF

Why? Is everything OK when Availability = 99.9%?

If MTTR (repair) and MTOW (waiting) are very low, we could have a very high Availability with many failures.

An example would be lots of computer failures with a fast reboot after each one. If the control computer keeps failing, that is not good!
Other terms that are useful in discussing reliability are:

- **Availability**: The ratio of the time a plant is producing product to the total time.

  \[
  \text{Availability} = \frac{\text{MTTF}}{\text{MTTF} + \text{MTTR} + \text{MTOW}}
  \]

For a continuous process, we aim for a very high availability, for example, operating 361 days and having a turnaround (maintenance) once per year.

With all of the individual elements that could fail, how can we achieve this?
Reliability

**AVAILABILITY:** We want 100%. We’ll never get it! What can we do to increase the reliability?

Some actions improve the reliability of each device.

- Match equipment to process conditions and requirements (slurries, clean-in-place, etc.)
- Operate after “break in” and before “worn out”
- Perform preventative maintenance
- Use high quality components (resistance to corrosion, compatible with process conditions, well manufactured, etc.)
- Repair quickly by highly trained personnel using spare parts stores

Besides the component reliabilities, what else affects plant reliability?
Reliability

How can we replace or remove equipment without stopping plant production?

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Remove/replace equipment

Only one pump needed; we want to switch between the two

The valve is leaking; therefore, we need to replace it

The heat exchanger is fouled; we need to take it out of service for mechanical cleaning
Reliability

How can we replace or remove equipment without stopping plant production?

Only one pump needed, want to switch between the two

Hint: add some of these

- Manual (hand) valve
- Check (one-way) valve

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How can we replace or remove equipment without stopping plant production?

The valve is leaking, we need to replace it

[diagram of a valve]

*Hint:* add some of these

- Manual (hand) valve
- Check (one-way) valve
Reliability

How can we replace or remove equipment without stopping plant production?

The heat exchanger is fouled, we need to take it out of service for mechanical cleaning

Hint: add some of these

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Reliability

Lesson Learned

Some equipment is not essential for acceptable plant operation, at least for a short time, and other equipment has a spare in a parallel configuration.

This equipment can be taken out of service for repair, if the design provides components for required reliability.

Result – many more valves and more parallel equipment than you might initially expect.
Reliability

Structure: A plant consists of many components connected in complex structures. These structures influence the reliability of the overall system.

Series

Parallel

If we know the reliability of each component, can we determine the reliability of the system?
Reliability

**Structure:** Simple *series* structure.

System functions only when all components function.

If each reliability is independent (e.g., no common failure causes), what is the reliability of a series structure which requires all to function?

$$R_{Series} = R_1 R_2 \cdots R_N = \prod_{i=1}^{N} R_i$$

What are “common-cause” failures?
Reliability

Structure: Simple \textit{series} structure.

\[
R_{\text{Series}} = R_1 R_2 \cdots R_N = \prod_{i=1}^{N} R_i
\]

Class Workshop: Give some examples of series equipment in process plants.
Reliability

Structure: Simple *series* structure.

What equipment has to function well for the process to be operable?
Reliability

Structure: Simple *series* structure.

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Process structures

- Digital controller
- Thermocouple temperature sensor, mV signal
- Analog signal transmission (4-20 mA)
- Analog to digital conversion
- Digital number
- Pneumatic signal transmission (3-15 psig)
- Digital controller
- Digital number
- Valve stem position (0-100%)
- Heating medium
- Analog signal transmission (4-20 mA)
- Digital to analog conversion

145 °C
7.734 mV
11.2 mA
11.56 psig
14.08 mA
63% open

D/A
A/D
i/p
Reliability

**Structure:** Simple *parallel* structure with no common cause faults.

System functions when either path (or both) function

**Two Parallel:** The system fails when both fail at the same time.

\[ R_{2\text{-parallel}} = 1 - (1 - R_1)(1 - R_2) \]

**N Parallel:** The system fails when *all fail* at the same time.

\[ R_{N\text{-parallel}} = 1 - \prod_{i=1}^{N} (1 - R_i) \]
Reliability

Give some examples of parallel equipment in process plants.
Reliability

Give some examples of parallel equipment in process plants.

Parallel pumps

Redundant sensors on same stream
Reliability

Determine the reliability of structures by condensing simple series or parallel sections.

Assume each device (box) has a reliability of 0.90.
Reliability

Which pump configuration has the highest reliability (longest mean time between failures) when only one is needed to perform the function?

Centrifugal pumps

Series

Parallel
When no steam is available, everything freezes in a Canadian winter. Which boiler system is more reliable?

**Design A: Several smaller boilers**

**Design B: One large boiler**

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When no steam is available, everything freezes in a Canadian winter. Which boiler system is more reliable?

By having many boilers in operation, we can replace one failure by increasing the steam from the remaining.

Also, we dramatically reduce the probability of having all boilers fail simultaneously.
Fuel gas is produced and consumed in many places in a plant. Discuss the good and poor aspects of this fuel gas distribution network.

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Process structures
Reliability

Distribution Network.

Networks have high reliability with shared redundancy. For example, a spare source can serve any consumer.

Networks are used for many “utilities”; steam, fuel, cooling water, hot oil, hydrogen, nitrogen oxygen, and so forth.
Reliability

Lesson Learned

When equipment is essential and component reliability is too low, redundancy can be provided in various plant structures to increase system reliability.

Results:

Low reliability equipment: Redundancy

Highly critical functions: Networks of suppliers and consumers
Reliability

How does a tank affect the reliability of a system? How would you determine the appropriate size of the tank?

Unit A can function without Unit B

Unit B can function without Unit A

If the failure probability for each plant is nearly the same, the tank should be maintained near half full.

Rough guideline: The tank holdup should equal 2 times the time to repair failed equipment.
Reliability

This is a big topic, and we have covered only a small slice! Many topics would require further study.

- We can determine reliability for typical structures and the advantages/disadvantages of these structures.
- We cannot determine reliability, MTBF or Availability for complex structures, with maintenance, etc.

No worries, I have mastered life-long learning!
Reliability

Industrial practice

- We design a highly reliable process structure (e.g., redundant equipment in a parallel) when
  - The consequence of a failure is high
  - The probability of a failure is too large

- We design to prevent a single cause from affecting several units or equipment.

- Prevent common cause failures

- Safety first! Then, economics (NPV, DCFRR, etc.).
Reliability

Industrial practice

- We automate the adjustment of redundant elements when the time to respond to an incident is short
- We provide by-passes around equipment that can be removed without requiring a process shutdown
- We isolate sections of a large plant with inventory to reduce the impact of a single failure
- We ensure that repair and replacement can be effected rapidly
PROCESS OPERABILITY: Reliability

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