Module 7: Plant integrity and safety

7.1. Objectives

On completion of this module, the student should be able to demonstrate an understanding of the issues underpinning plant integrity and safety, how these relate to costs, and how to maximise the benefit from money and effort spent on safety.

In particular, the student should understand:
- high availability is worth money to the plant owner
- the degradation modes affecting the life and safety of plant, including creep and fatigue
- the concept of risk and how it may be quantified
- how risk can be used to rationalise inspection activities
- how to get the maximum benefit in plant integrity from essential expenditure on safety
- the steps and processes involved in life assessment
- the benefits of timely life assessment, planning for this, and data requirements
- the benefits of life extension
- the benefits, costs and issues relating to plant re-rating.

7.2. Statutory and legal framework, standards

Historically, the safety of machinery was overseen by State Government authorities, with government inspectors being involved in the physical inspection, licensing and registration of plant. There has been a move away from this directive approach towards systems where more responsibility is placed on plant owners (Queensland Workplace Health and Safety Act 1995). This has made it clear that direct accountability for plant safety rests with plant owners.

The logical chain of legislation / regulations / standards for safety of plant in Queensland is:

*Workplace Health and Safety Act 1995*

*Workplace Health and Safety Regulation 1997*
- Schedule 3—Registrable Plant
- Boilers
- Pressure Vessels
- AS 4343 Hazard Levels A, B, C

*Registrable Plant Design*
- Pressure Equipment—Hazard Levels A, B, C, D

*Australian Standards*
- Hazard levels
- Inspection intervals
- In-service inspection
The trend is now for governments to adopt a ‘hands-off’ approach, and for the plant owners and managers to be in full and direct control of and accountable for the safety of machinery. Governments remain interested to the extent that no-one is injured and essential services are maintained. Government regulations compel registration of the design and installation of much equipment which, if it failed, could cause serious injury to workers or the public. *(Queensland Workplace Health and Safety Regulation 1997).* Registrable plant cannot legally be operated unless it is registered.

The onus is on plant owners to recognise safety issues and deal with them. In the event of safety problems arising, government departments have the power to intervene and shut plant down, impose heavy penalties or initiate legal action which could result in prison sentences. In power plants, pressure equipment comprises the major part of the high-risk machinery.

Some guidance is required for plant engineers to determine what levels of inspection are required. Australian Standards are collections of the best knowledge and experience of engineers throughout the world, with emphasis on the needs of Australian industry, and are a safe basis on which to judge the adequacy of plant. Most plant will have been constructed in accordance with Australian standards, while AS/NZS3788 *(Pressure Equipment—In-service Inspection)* is a leading document of its type. It is referenced by many overseas documents. Engineers basing their actions on these standards will be working from a strong philosophical, theoretical and practical foundation.

AS/NZS 3788 nominates maximum inspection intervals for different types of inspection and for different categories of pressure equipment. Under closely controlled conditions, these intervals may be increased if a risk based inspection (RBI) approach is taken. The implications of risk assessment are discussed later in this section.

The plant owner then has the option to:

1. perform inspections at intervals no greater than the maximum allowed under AS/NZS 3788
2. perform inspections at optimised intervals which are the result of a formalised risk based inspection process.

### 7.2.1. Aims of plant owner

A modern power plant would typically contain many items of high temperature equipment including boilers, high-pressure pipework, turbines, and other pressure vessels. The aims of the business are to provide a service (usually at minimum cost) and to make a profit for the owners—generally the greater the better.

Such plants are designed on an economic basis, where there is a trade-off of capital cost against running cost. In a well-designed plant high peak cycle temperatures translate into high efficiency with the benefits of reduced fuel cost, and reduced plant size for a given output. These same high peak temperatures mean either higher plant capital cost or higher maintenance costs, and often both. Conversely, low peak temperatures will result in low efficiency, higher fuel cost, and larger plant size for a given output. Materials suitable for high temperatures and stresses are more expensive than those suitable only for lower temperatures.
7.2.1.1. Continuity of supply, availability, reliability

Customers expect continuity of essential services from a supplier, otherwise they would have to find an alternative supplier of those essential services when required, or provide plant and equipment to provide the service themselves. This means that continuity of supply and the ability to supply on demand are services which are worth money, and for which customers are prepared to pay. For a power generation company this can mean bonuses for providing these services and penalties when unable to supply. Alternatively, if a power generation company is unable to achieve satisfactory levels of continuity of supply, its customers may demand payments to compensate for the loss of service, or be willing to pay only lower prices for the service.

Modern thermal power plants are capital intensive, where the cost of financing the operation forms a large part of the cost of operation. These financing costs are time-based, and do not stop when the plant is idle and not earning income. There is, therefore, an incentive to keep the plant operating at the highest possible reliability and availability (within economic constraints) to maximise the income potential for the plant. Limits will be reached, above which increased efforts and expenditure on maintenance and operation are not matched by corresponding increases in income. These are then the economic limits for these costs.

High and predictable availability also has the added benefit of allowing a particular demand to be met by a smaller total installed plant capacity than would be required for lower-availability plant.

Plant engineers need to know the factors which affect reliability and availability, and to exploit these factors to maximise the economic effectiveness of the plant. With sufficient information, reliability and availability models can be produced for a plant, allowing the influence of different capital, operating and maintenance expenditures to be studied. This allows long-term planning and costing for operation of the plant, capital expenditure, and maintenance.

7.2.2. The life of high temperature plant

7.2.2.1. Creep

Engineers are familiar with the use of factors of safety in the design of equipment. Such factors are intended to account for the uncertainty in knowledge of material properties, manufacturing processes and operating conditions. The aim of safety factors is to ensure that the probability of premature failure of the component in service is less than an acceptable number, often $10^{-5}$ over the planned lifetime.

At the time of design, the designer cannot know the exact properties of the actual materials to be used, because they probably haven’t even been manufactured yet. The as-supplied properties may be altered by manufacturing processes such as welding and heat treatment. Design codes, therefore, make use of known mean properties of the materials, and make assumptions about the spread of properties. Specifications for materials for use at high temperature require that the upper and lower bounds of the test data lie within +/-20 percent of the mean value. In the example in Figures 1, 2 & 3, for a material with mean properties, a stress of 50 MPa at 550 °C will cause failure in 291,000 hours.

The general message here is that for components subject to failure by creep, the risk of failure increases with time. Similar principles apply with fatigue, where the risk of failure increases with the number of applied fatigue cycles.
2.25Cr 1.0Mo Mean Properties, 550°C, Mean t.r = 291,000 hrs.
Probability Density Function

Figure 1: Probability density function for creep rupture strength of 2.25 Cr 1.0Mo steel
(Source: Author)

2.25Cr 1.0Mo, 550 °C
Mean t.r ~ 291,000 hrs.

Figure 2: Cumulative distribution function for creep rupture strength of 2.25Cr 1.0Mo steel
(Source: Author)

In this example, it can be seen that if the applied stress is less than 0.8 x (mean properties stress to rupture in 291,000 hrs.) the probability of failure before 291,000 hours will be very low. In fact the allowable design stress = mean stress to rupture / 1.3 to allow for material variations and the other factors mentioned above.
Figure 3: Cumulative distribution function for time to rupture for 2.25 Cr 1.0Mo steel. Applied stress = 50 MPa, temperature = 550 °C. It can be seen that the probability of failure increases with time. While a component is operating at less than ~ 185,000 hours under these conditions it is reasonably safe, while at < 150,000 hours the probability of failure is extremely low.
(Source: Author)

The inspection and life assessment processes, if carried out properly, will reduce the uncertainty in all the major variables affecting plant life, so that the spread of failure stresses and failure times shown above will be reduced. It is not uncommon for plant life to be increased by a factor of 1.5 after careful inspection and life assessment.

Creep life exhaustion is often expressed in terms of time fractions:

$\frac{\text{CreepLifeFraction}}{\sum_{T,\sigma} t_{T,\sigma}} \frac{t_{r,T,\sigma}}{t_{T,\sigma}}$

where

$t_{T,\sigma} = \text{time in service at temperature } T \text{ and stress } \sigma$

$t_{r,T,\sigma} = \text{time to rupture at temperature } T \text{ and stress } \sigma$

$\sum_{T,\sigma} = \text{sum over all combinations of temperature } T \text{ and stress } \sigma$

7.2.2.2. Fatigue

Fatigue life exhaustion is also expressed in terms of life fraction, but in this case in terms of numbers of cycles.

$\frac{\text{FatigueLifeFraction}}{\sum_{T,\sigma} n_{T,\sigma}} \frac{n_{f,T,\sigma}}{n_{T,\sigma}}$

where

$n_{T,\sigma} = \text{number of fatigue cycles applied at temperature } T \text{ and stress } \sigma$
\( n_{f,T,\sigma} \) = number of fatigue cycles to cause failure at temperature \( T \) and stress \( \sigma \)

\[ \sum_{T,\sigma} = \text{sum over all combinations of temperature } T \text{ and stress } \sigma \]

As the pressure equipment under consideration is usually static, high cycle fatigue should not be applied in service. High cycle fatigue is handled where possible by ensuring that the equipment is not subjected to such loading. Low cycle fatigue, and creep-fatigue are far more damaging on a per-cycle basis, and are the main considerations in design.

7.2.2.3. Failure criteria

For the purposes of design and life assessment computation, the useful life of a component is exhausted when the sum of the creep life fraction and fatigue life fraction equals unity.

\[ \text{RemainingLife} = 0 \quad \text{when} \quad \text{CreepLifeFraction} + \text{FatigueLifeFraction} = D \]

or,

\[ \sum_{T,\sigma} t_{T,\sigma} + \sum_{T,\sigma} n_{f,T,\sigma} = D \]

\( D \) takes values between 0.25 and 1.0 to account for the different behaviour of different materials.

The main point here is that the life of a component is reduced by both creep and fatigue. If a plant is designed for an assumed creep life and an assumed number of fatigue cycles, an alteration in the operating conditions affecting one factor will force a reduction or may allow an increase in the other.

An increase in fatigue life consumption must be compensated by a reduction in creep life consumption if component failure is to be avoided. That is, the allowable service hours of the component will be reduced.

7.2.3. Risk

The concept of risk is so pervasive in everyday life that it is accepted unknowingly and without question, apart from some examples which are brought to people’s attention. In a formal sense

\[ \text{Risk} = P \times C, \quad \text{where} \]

\( P \) = probability of an event occurring, with values between 0 and 1.0 means that the event cannot occur, whereas 1 means that it is certain. Some analyses include an additional multiplier for exposure. This is a modifier on probability, to account for the fact that some events are unlikely to affect people because they are not in the vicinity of the event when it occurs.

\( C \) = consequences of that event occurring. There are many ways of quantifying consequences, ranging from purely qualitative words such as ‘low’, ‘medium’ or ‘high’ to more useful measures such as physical or monetary values.
Example

A high temperature reheater header has a probability of catastrophic failure due to creep rupture in the next 5 years of 0.001. Some of the consequences are:

A major failure would put the unit out of service for at least 6 months. Assume unit capacity of 100 MW, average price paid for power generation $25.00/(MW.hr). Fuel cost of generation $16.00/(MW.hr). Average unit capacity factor 0.7.

Table 1
(Source: Author)

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Units</th>
<th>Values</th>
<th>Formulae</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability of event over time</td>
<td></td>
<td>0.001</td>
<td></td>
</tr>
<tr>
<td>Time frame for probability</td>
<td>years</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Unit capacity</td>
<td>MW</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Unit capacity factor</td>
<td></td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Length of outage</td>
<td>days</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>Cost of cleanup / investigation</td>
<td>$</td>
<td>200,000</td>
<td></td>
</tr>
<tr>
<td>Replacement header + installation</td>
<td></td>
<td>1,000,000</td>
<td></td>
</tr>
<tr>
<td>Power price</td>
<td>$/MW.hr</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>Fuel cost</td>
<td>$/MW.hr</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Capacity rate</td>
<td></td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Exposure of personnel</td>
<td></td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Disabling injuries</td>
<td></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Cost of disabling injury</td>
<td>$</td>
<td>600,000</td>
<td></td>
</tr>
<tr>
<td>Fines</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Company fine</td>
<td>$</td>
<td>200,000</td>
<td></td>
</tr>
<tr>
<td>Civil law actions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Costs</td>
<td>$</td>
<td>200,000</td>
<td></td>
</tr>
<tr>
<td>Settlements</td>
<td>$</td>
<td>400,000</td>
<td></td>
</tr>
<tr>
<td>Probability</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual probability events/yr.</td>
<td></td>
<td>0.0003333333</td>
<td>= p (event) / time for p(event)</td>
</tr>
<tr>
<td>MTBF</td>
<td>years</td>
<td>3000</td>
<td>= 1 / annual probability</td>
</tr>
<tr>
<td>Consequences</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generation loss</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generation foregone</td>
<td>MW.hrs</td>
<td>302,400</td>
<td>= Unit cap. × cap. factor × length of outage × 24</td>
</tr>
<tr>
<td>Generation income foregone</td>
<td>$</td>
<td>7,560,000</td>
<td>= Generation foregone × Power price</td>
</tr>
<tr>
<td>Fuel cost avoided</td>
<td>$</td>
<td>4,838,400</td>
<td>= Generation foregone × Fuel price</td>
</tr>
<tr>
<td>Generation profit foregone</td>
<td>$</td>
<td>2,721,600</td>
<td>= Generation income foregone + Fuel cost avoided</td>
</tr>
</tbody>
</table>
### Availability payments

<table>
<thead>
<tr>
<th>Description</th>
<th>Formula</th>
<th>Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit capacity rate</td>
<td>Capacity rate × Unit capacity</td>
<td>$150 = 150 × 1000</td>
</tr>
<tr>
<td>Capacity payments foregone</td>
<td>Unit capacity rate × Length of outage × 24</td>
<td>$648,000 = 150 × 64800 × 24</td>
</tr>
<tr>
<td>Total income foregone</td>
<td>Generation profit foregone + Capacity payments foregone</td>
<td>$3,369,600 = $648,000 + $2,721,600</td>
</tr>
<tr>
<td>Investigations &amp; Repairs</td>
<td>Cost of cleanup/investigation + Replacement header + installation</td>
<td>$1,200,000 = Cost of injuries × Cost of disabling injury</td>
</tr>
<tr>
<td>Safety cost</td>
<td>Cost of injuries × Cost of disabling injury</td>
<td>$1,200,000 = $1,200,000 × 1000</td>
</tr>
<tr>
<td>Total legal costs</td>
<td>Costs + Settlements</td>
<td>$600,000 = Costs + Settlements</td>
</tr>
<tr>
<td>Total safety cost</td>
<td>Cost of injuries + Company fine + Total legal costs</td>
<td>$2,000,000 = $1,200,000 + $800,000</td>
</tr>
<tr>
<td>Probable safety cost</td>
<td>Exposure × Total safety cost</td>
<td>$20,000 = Exposure × $2,000,000</td>
</tr>
<tr>
<td>Total cost of incident</td>
<td>Total income foregone + Probable safety cost</td>
<td>$4,589,600 = $3,369,600 + $1,220,000</td>
</tr>
<tr>
<td>Annual risk</td>
<td>Annual probability × Total cost of incident</td>
<td>$4,590 = Annual probability × $4,589,600</td>
</tr>
</tbody>
</table>

Every component can be treated with a risk assessment similar to the example above. Annual risks for all components can be ranked to show those with the highest and lowest risk. Judgement can then be used to determine a cutoff below which the risk is considered low enough to be acceptable. The higher risks will be treated by further investigation—usually beginning with inspections and possibly proceeding to replacement, upgrading, re-rating or retirement.

When the yearly risk figures for a component are plotted over time, changes in risk can be identified.

A good starting point for plant engineers is to assume that all plant is unsafe unless proven otherwise. This approach is implied in AS/NZS 3788. Initial safety assurances to commence operation can be obtained by reviewing design calculations or design data, while more precise assessments can be made as actual material properties become known, component dimensions are determined, and operating conditions are analysed.

At initial assessment the risk attached to a component can be very high because of lack of knowledge about the component and its condition. The simple acts of inspection and assessment can allow a dramatic reduction in the assumed probability of failure and hence the risk.

### Example

A superheater inlet header is exposed to dust-laden flue gas. It has been in operation for 150,000 hours with no known problems due to external erosion. Past inspections have not concentrated on this mode of degradation. For the purposes of risk assessment it was assumed that the mean time between failures (for this mode only) was 200,000 hours. The likely cost of a single failure was estimated at $5.4 million. The annual risk was therefore $237,000 and highlighted the need for inspection at the earliest opportunity.
Inspections of the header revealed that there was negligible external erosion, and therefore the mean time between failures (for this mode only) was reset to 20,000,000 hours. This reduced the estimated annual risk from this cause to $2,400. This is the value of the risk from only one cause. The plant item has other potential failure modes which should be considered in a similar manner.

7.2.4. Alternative expressions for risk

There are many different methods of expressing risk. Some simpler methods employ a matrix with dimensions of probability and severity.

Example

Qualitative risk analysis matrix—level of risk

The following tables are re-drawn from Appendix B of AS/NZS 4360:1995

Table 2
(Source: Redrawn from Australian/New Zealand Standards 1995)

Table D1: Qualitative Measures of Likelihood

<table>
<thead>
<tr>
<th>Level</th>
<th>Descriptor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Almost certain</td>
<td>The event is expected to occur in most circumstances</td>
</tr>
<tr>
<td>B</td>
<td>Likely</td>
<td>The event will probably occur in most circumstances</td>
</tr>
<tr>
<td>C</td>
<td>Moderate</td>
<td>The event should occur at some time</td>
</tr>
<tr>
<td>D</td>
<td>Unlikely</td>
<td>The event could occur at some time</td>
</tr>
<tr>
<td>E</td>
<td>Rare</td>
<td>The event may occur only in exceptional circumstances</td>
</tr>
</tbody>
</table>

Table D2: Qualitative Measures of Consequence of Impact

<table>
<thead>
<tr>
<th>Level</th>
<th>Descriptor</th>
<th>Example detail description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Insignificant</td>
<td>No injuries, low financial loss</td>
</tr>
<tr>
<td>2</td>
<td>Minor</td>
<td>First aid treatment, on-site release immediately contained, medium financial loss</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
<td>Medical treatment required, on-site release contained with outside assistance, high financial loss.</td>
</tr>
<tr>
<td>4</td>
<td>Major</td>
<td>Extensive injuries, loss of production capability, off-site release with no detrimental effects, major financial loss.</td>
</tr>
<tr>
<td>5</td>
<td>Catastrophic</td>
<td>Death, toxic release off-site with detrimental effect, huge financial loss.</td>
</tr>
</tbody>
</table>

Table D3: Qualitative Risk Analysis Matrix—Level of Risk

<table>
<thead>
<tr>
<th>Likelihood</th>
<th>Insignificant</th>
<th>Minor</th>
<th>Moderate</th>
<th>Major</th>
<th>Catastrophic</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Almost certain</td>
<td>S</td>
<td>S</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>B</td>
<td>Likely</td>
<td>M</td>
<td>S</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>C</td>
<td>Moderate</td>
<td>L</td>
<td>M</td>
<td>S</td>
<td>H</td>
</tr>
<tr>
<td>D</td>
<td>Unlikely</td>
<td>L</td>
<td>L</td>
<td>M</td>
<td>S</td>
</tr>
<tr>
<td>E</td>
<td>Rare</td>
<td>L</td>
<td>L</td>
<td>M</td>
<td>S</td>
</tr>
</tbody>
</table>

Note: the number of categories should reflect the needs of the study.

Legend:
H = high risk; detailed research and management planning required at senior levels
S = significant risk; senior management attention needed
M = moderate risk; management responsibility must be specified
L = low risk; manage by routine procedures
Notes on qualitative descriptions:

- Qualitative descriptions can be quick to use and implement.
- Because they rely on the subtleties in interpretation of the English language—descriptions can mean different things to different people.
- The end result is again only a descriptive term.
- If decisions are made to treat a risk, monetary values will be implied in the decision making, even if they are not expressed explicitly.

The following example is an automatic calculation spreadsheet where the user dials in scores in accordance with guidelines provided by the spreadsheet for the user to overcome the uncertainty in interpretation of terms. The supporting tables precede the image of the spreadsheet below. Each organisation may have its own limits for assessing financial impacts.

### Probability

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Is the most likely and expected result if the hazard event takes place</td>
</tr>
<tr>
<td>5</td>
<td>Is quite possible, not unusual, has an even 50/50 chance</td>
</tr>
<tr>
<td>4</td>
<td>Would be an unusual sequence or coincidence</td>
</tr>
<tr>
<td>3</td>
<td>Would be a remotely possible coincidence</td>
</tr>
<tr>
<td>2</td>
<td>Has never happened after many years of exposure, but is conceivably possible</td>
</tr>
<tr>
<td>1</td>
<td>Practically impossible sequence (has never happened)</td>
</tr>
</tbody>
</table>

### Exposure

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Continuously (or many times daily)</td>
</tr>
<tr>
<td>5</td>
<td>Frequently (approximately once daily)</td>
</tr>
<tr>
<td>4</td>
<td>Occasionally (from once per week to once per month)</td>
</tr>
<tr>
<td>3</td>
<td>Unusually (from once per month to once per year)</td>
</tr>
<tr>
<td>2</td>
<td>Rarely (it has been known to occur)</td>
</tr>
<tr>
<td>1</td>
<td>Remotely possible (not known to have occurred)</td>
</tr>
</tbody>
</table>

### Consequences

<table>
<thead>
<tr>
<th>Score</th>
<th>Description</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>Catastrophe: numerous fatalities; damage over $4M; major disruption of activities</td>
<td>100</td>
<td>4,000,000</td>
</tr>
<tr>
<td>5</td>
<td>Multiple fatalities; damage $2M to $4M</td>
<td>50</td>
<td>2,000,000</td>
</tr>
<tr>
<td>4</td>
<td>Fatality; damage $400k to $2M</td>
<td>25</td>
<td>400,000</td>
</tr>
<tr>
<td>3</td>
<td>Extremely serious injury (amputation, permanent disability); damage $4k to $400k</td>
<td>15</td>
<td>4,000</td>
</tr>
<tr>
<td>2</td>
<td>Disabling injury; damage to $4k</td>
<td>5</td>
<td>400</td>
</tr>
<tr>
<td>1</td>
<td>Minor cuts, bruises, bumps; minor damage</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Damage Limits
In this case,

\[
\text{Risk Score} = \text{Probability Score} \times \text{Exposure Score} \times \text{Consequences Score}
\]

\[
\text{Cost Effectiveness Score} = \text{Cost Factor Score} \times \text{Degree of Correction Score}
\]

\[
\text{Justification Score} = \frac{\text{Risk Score}}{\text{Cost Effectiveness Score}}
\]

The output of this process, a justification score, may be useful for ranking of potential projects, but does not provide a direct measurement of risk, even though the necessary information would have been considered in the process.

The preceding examples are intended to show that more useful information is obtained by evaluating risk in consistent, commonly understood terms. The most common measure is monetary value.

### 7.2.5. A note on ethics

Many people will be uncomfortable with the concept of putting a cost on injuries, disability or death. Monetary values are already implied in the judgements made during a qualitative assessment, and should therefore be considered and documented openly where all the assumptions can be reviewed and justified. The insurance process makes detailed estimates of these costs, and they are always high. Consider that the loss of earnings alone for a disabled person could run into millions of dollars, while pain and suffering for those affected and those around them could also be shown to be very costly. As long as the costs attributed to injuries, disability, death, and environmental effects are considered honestly and diligently, the high resulting values will be reflected adequately in the risk.

### Example

In the early 1970s the Ford Motor Company in the USA produced a ‘light compact’ car called the Pinto. Because of the rushed production schedule, the production tooling was ordered before design and testing were complete. This resulted in the car going on sale with a known propensity to spill fuel and catch fire after even a modest rear-end collision. At collision speeds greater than 40 m.p.h. the doors were likely to jam, trapping the occupants. Ford engineers knew this before the vehicle went into production, but the company management
was completely unreceptive to suggestions to modify the vehicle. Ford’s justification for not modifying the vehicle was based on the following risk assessment (MotherJones 1977).

$11 vs. a burn death

Table 3: Benefits and Costs Relating to Fuel Leakage Associated with the Static Rollover Test Portion of FMVSS208 (Source: From Ford Motor Company internal memorandum: ‘Fatalities Associated with Crash-Induced Fuel Leakage and Fires’)

<table>
<thead>
<tr>
<th></th>
<th><strong>BENEFITS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Savings</strong></td>
<td>180 burn deaths, 180 serious burn injuries, 2,100 burned vehicles.</td>
</tr>
<tr>
<td><strong>Unit Cost</strong></td>
<td>$200,000 per death, $67,000 per injury, $700 per vehicle.</td>
</tr>
<tr>
<td><strong>Total Benefit</strong></td>
<td>180 X ($200,000) + 180 X ($67,000) + $2,100 X ($700) = <strong>$49.5 million.</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th><strong>COSTS</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sales</strong></td>
<td>11 million cars, 1.5 million light trucks.</td>
</tr>
<tr>
<td><strong>Unit Cost</strong></td>
<td>$11 per car, $11 per truck.</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td>11,000,000 X ($11) + 1,500,000 X ($11) = <strong>$137 million.</strong></td>
</tr>
</tbody>
</table>

Juries took a different view, typically awarding damages of $millions per death. The assumption about the number of serious burns in relation to deaths was also wide of the mark. About 10 serious burns cases were sustained for each death.

Ford then began making out-of-court settlements to avoid jury trials. Ford was eventually forced to recall the vehicles.

A rupture-proof fuel tank could have been fitted for $5.08 per vehicle.

In this case it could be argued that a more rigorous risk assessment would have avoided many deaths, injuries and law suits, and saved a lot of money.

7.2.6. Summary of risk concept

The aim of all people involved in the operation of power plants should be to achieve high standards of safety, efficiency, reliability and availability. This will be achieved when systems are in place to ensure that the plant can meet its performance targets for the next planned running period with known very low probability of failure. Such a system requires knowledge of the characteristics of the plant, the current state of the plant, its failure modes, and the probability of failure over time. Provided that the plant is operated within expectations, this can be achieved by the combined processes of inspections, life assessment and maintenance.

Risk assessment should be undertaken only by people who are prepared to act honestly and fairly, who understand the situation, and are competent in the field of study.

7.2.7. Risk assessment in a power plant

Example

The following table shows an initial risk assessment on some superheater components. It can be seen that the methodology has produced relatively high probabilities of failure/year. This method is experience-based and not founded on life calculations. Life calculations could well form part of a revised risk assessment.

The number of effects considered in consequences is limited.

The safety rating translates to an order of magnitude of cost.
Assumptions:
In the event of a unit trip, thermal stresses will be applied to major plant items causing the consumption of some thermal fatigue life.

Table 4
(Source: Author)

<table>
<thead>
<tr>
<th>Description</th>
<th>Magnitude</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit Rating</td>
<td>100</td>
<td>MW</td>
</tr>
<tr>
<td>Capacity Factor</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Availability Value</td>
<td>10</td>
<td>$/MW.hr</td>
</tr>
<tr>
<td>Generation Profit</td>
<td>5</td>
<td>$/MW.hr</td>
</tr>
<tr>
<td>Unit Capacity loss for assumed trip</td>
<td>90</td>
<td>MW</td>
</tr>
<tr>
<td>Plant life cost of trip</td>
<td>7000</td>
<td>$</td>
</tr>
</tbody>
</table>

Table 5: Example of risk assessment of some boiler superheater components before inspection or risk mitigation
(Source: Author)

<table>
<thead>
<tr>
<th>Plant Group</th>
<th>Formulae</th>
<th>Boiler</th>
<th>Boiler</th>
<th>Boiler</th>
<th>Boiler</th>
<th>Boiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Item</td>
<td>Formulas</td>
<td>HT S/H Outlet Hdr.</td>
<td>HT S/H Outlet Hdr.</td>
<td>HT S/H outlet header - capping run on branch walls</td>
<td>HT S/H roof penetrations</td>
<td>HT S/H tubes</td>
</tr>
<tr>
<td>Cause</td>
<td></td>
<td>Creep</td>
<td>Fatigue</td>
<td>Creep</td>
<td>Overshielding</td>
<td>Creep</td>
</tr>
<tr>
<td>Type</td>
<td></td>
<td>Life exhaustion</td>
<td>Thermal stresses</td>
<td>Low specification materials</td>
<td>Tube movement</td>
<td>Life exhaustion</td>
</tr>
<tr>
<td>TBF/Item (hrs)</td>
<td>User input</td>
<td>150,000</td>
<td>100,000</td>
<td>100,000</td>
<td>10,000</td>
<td>20,000</td>
</tr>
<tr>
<td>Unit Failures/hr P(f)</td>
<td>= (Item Failures/hr) x (Items/Unit) x (TBF/Item)</td>
<td>5.64E-02</td>
<td>8.76E-02</td>
<td>8.76E-02</td>
<td>8.76E-02</td>
<td>8.76E-02</td>
</tr>
<tr>
<td>Loss of generation capacity (MW)</td>
<td>User input</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Time to restore (hrs)</td>
<td>User input</td>
<td>4,000</td>
<td>6,000</td>
<td>500</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Loss of availability (MW_hrs)</td>
<td>= Loss of generation capacity x Time to restore</td>
<td>400,000</td>
<td>500,000</td>
<td>50,000</td>
<td>20,000</td>
<td>20,000</td>
</tr>
<tr>
<td>LOA Cost ($)</td>
<td>= (Unit price of LOA) x LOA</td>
<td>4,900,000</td>
<td>9,400,000</td>
<td>900,000</td>
<td>200,000</td>
<td>200,000</td>
</tr>
<tr>
<td>Generation Profit Foregone ($)</td>
<td>= (Generation Profit Rate x Generation Profit) / (Unit rating x Capacity Factor)</td>
<td>2,000,000</td>
<td>2,100,000</td>
<td>175,000</td>
<td>70,000</td>
<td>70,000</td>
</tr>
<tr>
<td>Direct Repair ($)</td>
<td>User input</td>
<td>150,000</td>
<td>2,000,000</td>
<td>100,000</td>
<td>20,000</td>
<td>20,000</td>
</tr>
<tr>
<td>CONSEQUENTIAL Repair ($)</td>
<td>User input</td>
<td>500,000</td>
<td>500,000</td>
<td>20,000</td>
<td>20,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Plant Trip (Y/N)</td>
<td>= (Loss of gen. capacity x 500MW, then Y, else N)</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Life cost of trip ($)</td>
<td>= (Life of plant trip x 7000, then 0, else 0)</td>
<td>7000</td>
<td>7000</td>
<td>7000</td>
<td>7000</td>
<td>7000</td>
</tr>
<tr>
<td>Severity (0 to 5)</td>
<td>User input</td>
<td>8</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Conditional Probability of Safety Incident (0 to 1)</td>
<td>= (Severity) / (Severity + 2)</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Safety Cost ($)</td>
<td>= (100 x 10^4 x Conditional Probability)</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Likely Event Cost ($)</td>
<td>= Sum of Costs (LOA, Gen. Profit Foregone, Direct Repair, CONSEQUENTIAL Repair, Life cost of trip, Safety)</td>
<td>6,657,000</td>
<td>11,607,000</td>
<td>803,000</td>
<td>317,010</td>
<td>337,010</td>
</tr>
<tr>
<td>Annual Risk Cost ($)</td>
<td>= Likely Event Cost x Unit Failures/yr</td>
<td>388,769</td>
<td>1,016,773</td>
<td>70,343</td>
<td>185,134</td>
<td>14,761</td>
</tr>
<tr>
<td>NDT</td>
<td>Replication, MPI of stubs, butt welds &amp; support lugs; UT for ligament cracking</td>
<td>Visual (FO / remote video), UT</td>
<td>Replication, MPI</td>
<td>Visual</td>
<td>Replication; GD measurement</td>
<td></td>
</tr>
<tr>
<td>Comments</td>
<td>Obsolete construction technique. Illegal material use?</td>
<td>Good operation and control to eliminate rapid temperature changes, design for thin walls &amp; high conductivity</td>
<td>Reweld capping layers &amp; stress relieve</td>
<td>Check condition of grout</td>
<td>Check hottest tubes, hottest location</td>
<td></td>
</tr>
<tr>
<td>Prevention measures</td>
<td>Minimise operating temperatures where possible</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>On Line Monitoring</td>
<td>Monitor operating temperatures and pressures. On-line damage calculation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Record operating temperatures &amp; pressures</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 6: Revised risk profile for the same components after inspection and reassessment of probability of failure. If probability of failure was still high, consequences could be reduced by holding spares and planning other methods to reduce the length of the outage to repair a potential failure.

(Source: Author)

<table>
<thead>
<tr>
<th>Plant Group</th>
<th>Formulae</th>
<th>Boiler</th>
<th>Boiler</th>
<th>Boiler</th>
<th>Boiler</th>
<th>Boiler</th>
</tr>
</thead>
<tbody>
<tr>
<td>HT S/ H Outlet Hdr.</td>
<td>HT S/ H Outlet Hdr.</td>
<td>HT S/ H outlet header - capping area on branch welds</td>
<td>HT S/ H roof penetrations</td>
<td>HT S/ H tubes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cause</th>
<th>Creep</th>
<th>Fatigue</th>
<th>Creep</th>
<th>Creep</th>
<th>Creep</th>
<th>Creep</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Life exhaustion</td>
<td>Thermal stresses</td>
<td>Low specification materials</td>
<td>Tube movement</td>
<td>Life exhaustion</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TBF/Item (hrs)</th>
<th>User input</th>
<th>20,000,000</th>
<th>30,000,000</th>
<th>50,000,000</th>
<th>100,000</th>
<th>200,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item Failures/hr</td>
<td>P(fi)</td>
<td>5.000E-08</td>
<td>3.333E-08</td>
<td>2.000E-06</td>
<td>1.000E-05</td>
<td>5.000E-06</td>
</tr>
<tr>
<td>Loss of generation capacity (MW)</td>
<td>User input</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Time to restore (hrs)</td>
<td>User input</td>
<td>4,000</td>
<td>6,000</td>
<td>500</td>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>Loss of availability (MW/hrs)</td>
<td>= Loss of generation capacity x Time to restore</td>
<td>400,000</td>
<td>600,000</td>
<td>50,000</td>
<td>15,000</td>
<td>20,000</td>
</tr>
<tr>
<td>LOA Cost ($)</td>
<td>User input</td>
<td>4,000,000</td>
<td>6,000,000</td>
<td>500,000</td>
<td>150,000</td>
<td>200,000</td>
</tr>
<tr>
<td>Generation Profit Foregone ($)</td>
<td>User input</td>
<td>1,000,000</td>
<td>2,000,000</td>
<td>500,000</td>
<td>150,000</td>
<td>200,000</td>
</tr>
<tr>
<td>Direct Repair ($)</td>
<td>User input</td>
<td>100,000</td>
<td>200,000</td>
<td>20,000</td>
<td>20,000</td>
<td>20,000</td>
</tr>
<tr>
<td>CONSEQUENTIAL Repair ($)</td>
<td>User input</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Plant Trip (Y/N)</td>
<td>User input</td>
<td>1000</td>
<td>1000</td>
<td>7000</td>
<td>7000</td>
<td>7000</td>
</tr>
<tr>
<td>Life cost of trip ($)</td>
<td>User input</td>
<td>100</td>
<td>500</td>
<td>20,000</td>
<td>20,000</td>
<td>30,000</td>
</tr>
<tr>
<td>Severity (0 to 5)</td>
<td>User input</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Conditional Probability of Safety Incident (0 to 1)</td>
<td>User input</td>
<td>0</td>
<td>0.1</td>
<td>0.01</td>
<td>0.001</td>
<td>0.001</td>
</tr>
<tr>
<td>Safety Cost ($)</td>
<td>=100 x 19*(Severity) x Conditional Probability</td>
<td>1,000,000</td>
<td>1,000,000</td>
<td>1,000</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Likely Event Cost ($)</td>
<td>User input</td>
<td>6,607,000</td>
<td>11,607,000</td>
<td>803,000</td>
<td>248,510</td>
<td>337,510</td>
</tr>
<tr>
<td>Annual Risk Cost ($)</td>
<td>= Likely Event Cost x Unit Failures/hr</td>
<td>2,016</td>
<td>3,389</td>
<td>14,069</td>
<td>21,857</td>
<td>14,761</td>
</tr>
</tbody>
</table>

All the factors considered in the risk assessment have been documented and are available for review, challenge or audit.

There is almost no limit on the variations possible in this type of risk assessment. Comparison of risk between different events can only be made if the assessments are on a consistent basis. An organisation needs to settle on an acceptable method and use it consistently and exclusively.

At the conclusion of a comprehensive risk assessment, the total of all the risk components should be an indication of the insurance cover for the assessed plant.
7.3. Risk-based methodology

Risk-based methodology relies on the identification of components or assemblies which pose a high risk. (See definition of risk). It allows direction of limited resources to the areas of absolute necessity and those with a high return on the use of inspection and maintenance resources. This process is facilitated by employing a group of experienced people, preferably from a variety of backgrounds so that problems are seen from several viewpoints.

A logical sequence of actions is:

7.3.1.1. List all the significant plant components

7.3.1.2. For each component determine the possible failure modes

For each failure mode, determine a probability of failure. This could be the result of life calculations, or by employing knowledge of previous experience. Some sources of information on plant failure rates could be records of identical or similar equipment, insurers (some of which have very detailed information), or expert practitioners in that field.

Each failure mode on each component constitutes an event. The lack of failures in the past is not necessarily an indicator of future failure rates.

7.3.1.3. For each event determine the consequences of failure

All cost components should be included for each event. This process lends itself to automation, where the user is required only to respond to prompts, and an automatic system performs the necessary calculations.

7.3.1.4. For each event calculate or quantify the risk

\[ \text{Risk} = \text{Probability} \times \text{Consequences} \]

7.3.1.5. Rank the risks in order of magnitude

Determine a level of risk which is considered acceptable. Select the events above the cutoff risk for further treatment. (Remember the ethics issue.)

7.3.1.6. Determine a risk management strategy

Examine each event to determine the actions to be taken to reduce the risk. In pressure equipment, inspection is an essential step. This is where decisions can be made about continuing operation as usual, changing operating conditions, repair or replacement of the component or upgrading it.

7.3.1.7. Review the level of residual risk

Review each event to determine the level or risk remaining after the risk mitigation has been implemented. If it is too high, further assessment and management stages will be required.

7.3.1.8. Schedule inspections

Schedule inspections according to the level of risk known at the time.
7.3.1.9. Plan inspections

Specification of inspection scope, type, personnel qualifications and skills, access requirements, safety requirements, surface preparation required, timing, reporting, recording.

Optimise inspections in conjunction with other activities to minimise overall costs and outage times.

7.3.1.10. Costing of inspections

Once the scope and timing of inspections are known, estimates of all the cost components for inspections can be made. This process also lends itself to automation. It is useful to segregate the various cost components, allowing review of different methods of achieving the same outcome.

7.3.1.11. Budgeting

As many organisations are tightly constrained by budgets, making sufficient financial provision for inspections well in advance of requirements is an important part of the annual and long-term budgetary process. A risk-based inspection system allows prediction of inspection requirements years in advance of the actual activity and expenditure.

7.3.1.12. Perform inspections

Manage inspections to ensure that all parts are completed according to specification. Ensure that all data is recorded. Identify and record any ‘surprises’ discovered during inspection.

7.3.1.13. Review inspection results

Analyse all inspection data to ensure that plant condition is determined accurately.

7.3.1.14. Report inspection results

Report the inspection results in a format which can be stored for later easy retrieval and use. Some inspection reports could remain useful for the following 30 years.

7.3.1.15. Review the whole process regularly

Knowledge of degradation processes continues to improve over time, as will the experience of people involved in inspection planning and performance. It is then worthwhile re-visiting previous risk assessments and inspection plans to determine whether improvements can be made. It is likely that advances in non-destructive testing will reduce the cost of inspections with the passage of time.

7.3.2. Cost of essential safety

7.3.2.1. Minimum position

A minimum position for a plant owner is that its plant must be safe. This then dictates certain actions such as setting safe operating limits, and ensuring that the plant remains in a safe physical condition. A plant owner ignorant of the nature of its plant and its degradation mechanisms can fall back on time-based inspections, maintenance and equipment replacement in accordance with the manufacturer’s unguided recommendations based on their most conservative assumptions. The result of this minimum position is that inspection and maintenance costs may be known in advance, but could be cripplingly high.
It should not be assumed that the manufacturer knows everything about a component, and therefore the views of independent experts can be valuable.

7.3.2.2. Selective inspection

Inspection of every component in a plant is seen to be unproductive, as in a major plant there will be a small number of components whose performance is critical or limiting, whereas most of the other components are not critical. Identification of the most critical components and their likely failure modes allows concentration of inspection and maintenance resources on those components where risk control is required. This then justifies risk-based inspection.

7.3.2.3. Grouping components for inspection

The total cost of inspection can be very high, particularly where access is difficult. Such cases might involve provision of scaffolding, gaining entry to pressure vessels, or large-scale removal of insulation. The cost of the actual inspection is small compared with the cost of the preparation and restoration. There will often be several components with lesser risk in the vicinity of the most critical components. Because the preparation costs will be incurred anyway, it often makes sense to perform inspections on the adjacent lower-priority components during the same access.

7.3.3. Precursors/alternatives to inspection

Traditionally components were subjected to physical inspection to determine their condition. This can be expensive and usually can only be done when the plant is shut down. It is often possible to infer the condition of these components by indirect measurements. Some examples are:

- if good records are available of the dimensions, material properties and operating history of a component, an estimate of its life consumption can be calculated. If on-line dimensional or strain measurements are available even better estimates can be made because the creep strain is a good indicator of component life.
- on-line performance calculations such as temperature pickup in a superheater or reheater can indicate the degree of internal and external scaling and the consequent effects on plant life.
- on-line monitoring of pressure drops through components can indicate blockages and erosion rates.

7.4. Life assessment

There are numerous reasons for undertaking life assessment, all of which can be justified on an economic basis:

- Safety
- Reliability and availability
- Prediction of future cash flows
- Life management—control of the rate of life expenditure
- Life extension
- Whole-of-life cost minimisation
- Planning, timing and financing of replacements and/or other options including new technology
- Public image.
Many owners concentrate on safety, reliability, availability, and short-term profit. In doing this they overlook the very large benefits, flexibility and economies in considering life management, life extension, and minimisation of whole-of-life costs.

Public perceptions can impose extra costs on the business or could shut it down. A plant with a reputation for good management in all of the above categories is likely to score highly in public perception. A good image can make it easier to recruit and retain staff. This is a very important economic effect where the cost of recruitment of a new staff member can be a substantial proportion of a year’s salary.

7.4.1. Timing

The earlier life assessment is started, the greater the benefits in whole-of-life cost minimisation. Ideally, life assessment should be envisaged at the design stage. This means that the project starts with a whole-of-life plan.

Plant designed to standards and codes often has no definite life. Plant designs should cover as a minimum the fields of:

- short-term strength (resistance to rupture under foreseeable loading)
- long-term creep strength (resistance to rupture under high temperature over an extended period).

For plant designed to recognised standards, the short-term strength will certainly be assessed and known. The design process does not always reveal a true creep rupture design life, because the allowable stresses may be based on a criterion other than creep rupture. Fatigue and creep-fatigue effects may also not be specifically evaluated.

Life calculations require knowledge of component operating stresses, temperatures, and material strength. All of this information should be available and would be considered during design, but can be difficult to assemble by anyone else. A design life for each component can be established by the designers at minimal cost. AS/NZS 3788-2006 implies that the first stage of life assessment should start when the plant is new, i.e., a design life must be known before decisions about further life assessment can be made.

Collection of critical dimensional data during manufacture and construction is highly cost-effective and can form part of the project quality assurance, rather than having to strip equipment down after operation to gain access and then to later reinstate it.

Knowledge of the rate of degradation of the plant allows early planning of refurbishment and upgrades.

The plant can be designed for easy inspection and life assessment by considering design details, inspection methods and access to critical parts. Baseline material (archival) samples and properties can be obtained during construction at virtually no cost, whereas representative baseline samples are almost impossible to obtain once the plant has been in operation for some time.

As a last resort, life assessment should be undertaken no later than stipulated in AS/NZS 3788–2006.
7.5. Example plant life management system

A high-effectiveness life management system in a mature operating organisation would have at least the following steps.

7.5.1. Project initiation
- Set up a life plan for the project
- Set up a financial model for the project
- Optimise the plant parameters to achieve an optimal financial model

7.5.2. Design
- Establish records system
- Record design decisions and calculations
- Record design drawings and other information useful in life assessment
- Calculate predicted life for each major component, and record
- Optimise component designs to meet owner’s requirements
- Design temperature, pressure and other monitoring systems to record all data required for later life assessment and monitoring

7.5.3. Manufacture and construction
- Record all dimensional data needed for life assessment
- Record materials used
- Record materials properties and test results
- Set up a materials archive with provision to store material samples without degradation for very long periods
- Take samples of new materials and place in safe storage. Link to records system
- Record details of manufacturing processes, particularly welding processes and heat treatment
- Record structural settings such as hanger loads and positions
- Record manufacturing defects and repairs where applicable
- Record critical dimensions, e.g., creep monitoring dimensions, turbine rotor diameters

7.5.4. Commissioning
- Record temperature profiles and temperature characteristics vs operating condition
- Record pressure characteristics vs operating condition
- Re-calculate life for each component and record results
- Compare predicted component life with design and record assessments
- Set up on-line performance monitoring programs
- Set up on-line plant life calculation programs
7.5.5. Operation and maintenance (up to and after plant life extension)

- Record significant operating data
- Record additional life monitoring and assessment data
- Calculate life expenditure at regular intervals
- Adjust operating modes to maximise value of plant life expenditure
- Optimise inspection intervals and scope
- Optimise maintenance scope
- Perform planned inspections
- Perform staged life assessments as required
- Update plant life plan, including provision for refurbishment, replacement, upgrading or re-rating
- Update financial models
- Report operating, maintenance and plant life costs

7.5.6. Plant life extension

- Partial repeat of Project Initiation, Design, Manufacture and Construction, Commissioning
- Archive retired material for future research
- Archive new material for future life assessment

7.6. Life assessment methodology

Life assessment is the determination of the current condition and future operational suitability of plant. Staged assessments, such as those documented in AS/NZS 3788–2006 are designed to be cost-effective, whereby the complexity, detail and cost necessary for an assessment stage is limited to the level of implied or assessed risk, i.e., increasingly rigorous (and increasingly expensive) assessment is required as the plant approaches its previously assessed life. As the plant approaches its assessed life the more rigorous assessments require physical assessment to support any theoretical results.

The recommended stages of life assessment in AS/NZS 3788 (Appendix U) are:

**Stage 1**

This is basically a desktop study. It employs simple stress analysis as given in the design standards (e.g. circumferential stress calculations) and life calculated is on the basis of design operational parameters. The most conservative combination of dimensional tolerances should be used. In the absence of other information, minimum material properties are assumed.

If the original design was according to Australian / New Zealand standards and the plant is operated within the design parameters, this assessment should be quite conservative. This stage is a useful first pass in identifying equipment likely to require remaining life assessment. Experience and knowledge of the characteristics of plant are useful at this stage in identifying components for study.
Stage 2

Stage 2 is a more refined study relying on known plant data and supplemented by inspection data. Measurements of temperatures and pressures on the plant are required. The stress analysis employs actual plant dimensional data including deviations from the nominated geometry (e.g. wall thickness, and out of roundness) and accurate estimates of operating pressures. Estimates of operating temperatures are made to simplify life calculations.

Note—care is required in making these estimates, as creep life has an inverse exponential relationship to both absolute temperature and stress.

Some additional features of Stage 2 remaining life assessment are:
- non-destructive or visual examination
- review of operating history to allow assessment of secondary effects such as thermal stresses and external forces
- review of inspection, maintenance and replacement records
- surface micro-examination, usually by replication
- review of manufacturing records to ascertain actual material properties and chemical composition.

Stage 3

Stage 3 makes extensive use of more sophisticated inspection data such as replication and mechanical test data, and is supplemented by data gained from monitoring (e.g. thermocouple or strain gauging or vibration monitoring). It may require sophisticated stress analysis techniques such as finite element analysis (FEA), and it may be necessary to ascertain material properties by accelerated creep testing or fracture toughness testing. Strain gauging may be required to determine or confirm strain rates and accumulation. Accelerated corrosion or erosion testing may be required.

Stage 3 assessment is potentially expensive because of the high costs of FEA modelling, and sample extraction and testing. Creep testing by traditional means can be very expensive.

7.7. Data for life assessment—summary

Inputs required to cover the full range of life assessment are:
- dimensions—design, as-built, current, including departures from design (ovality, distortion, etc.)
- erosion, corrosion or wastage rates.
- materials properties—design, as-built, current
  - creep rupture data
  - creep strength data
  - hardness
- microstructure
- manufacturing and erection records, particularly weld imperfections, including significant ones at the fabrication stage. (These records can be overlooked or lost.)
- operating records—temperatures, pressures and load cycles
- degradation mechanisms
checks for departures from original installation
hanger loads
actual piping shape
actual operating stresses, temperatures
samples of original materials from archives
samples of service-exposed materials
representative materials properties.

Non-destructive testing results are important inputs to life assessment. Some NDT techniques are:

- hardness
- magnetic particle inspection
- penetrant inspection
- microstructure replication
- strain and strain rate measurement
- ultrasonic flaw detection, ultrasonic thickness measurement, oxide scale thickness measurement
- radiography
- acoustic emission damage assessment.

Actual material properties can be obtained by testing, e.g., accelerated creep rupture (ACR), fatigue, etc. These destructive testing techniques are inherently expensive, and often time-consuming. Indirect methods of inferring critical material properties are being investigated, with several being well-developed.

### 7.7.1. Life assessment—issues

#### 7.7.1.1. Timing

The earlier that life assessment is carried out, the greater the potential benefits. If the current state of life consumption is known, decisions can be made on its management. This might involve changing operating conditions or planning for replacement.

It is necessary to know plant condition well in advance of replacement because of issues with materials availability. Some materials and forms are difficult to obtain. There may be long lead times for others. New materials may offer many advantages if there is time to investigate their use and to plan for timely replacement.

A critical input to all stages of life assessment is materials properties. Early stages require only generic properties, whereas later and more rigorous stages require specific properties. Representative material properties can sometimes be difficult to obtain. Published creep-rupture data are often based on short-term tests and then extrapolated to longer failure times. Operating stresses are often below the published ranges. Methods of extrapolating published data reliably to these lower stress are currently under investigation.
7.7.1.2. Costs of life assessment

The most fundamental steps in life assessment can be carried out at almost zero cost. As described earlier an initial design life can be established at minimal cost, particularly at the design stage when all the necessary information is initially available.

Desktop/mathematical techniques can be used at moderate cost. When physical assessment is required, costs can be very high. Some cost components can be:

- shutdown and restart
- loss of revenue
- access and reinstatement.
- sampling
- NDT
- material property testing.

For these reasons, staged life assessment is seen to be cost-effective as the high cost activities are delayed until required.

7.7.1.3. Data

Accurate life assessment relies on good input data. The necessary data may be found in a variety of locations, ranging from site and company resources to national and global databases. Reliable storage and retrieval of such data can have a large influence on the cost of assessments.

The rapid changes in computer technology pose a particular challenge to long-term data storage. It is common for modes of data storage to be rendered obsolete within a few years. Proprietary storage systems and databases which originally seemed to be a good idea can end up being expensive dead-ends when there is no way to retrieve old data.

The progress of collection and storage of operating data has been:

- manual observation and written recording. Paper records.
- paper chart recorders. Stored paper charts.
- computer data collectors. Hard disc drive storage with multiple HDD backups.

Each of these steps has resulted in large cost reductions.

The cost of data storage has decreased continually over the lifetime of the computer industry, and is now extremely low. There is no longer any reason not to store most of the available on-line operating data. It must be stored in a form where it can be retrieved easily for further processing. As an older system is rendered obsolete, part of the project to implement a new system should be the conversion of all previous history to the new format. This then ensures that none of the old data is inadvertently lost due to obsolescence.
7.7.1.4. Materials

Materials samples representative of the actual plant are extremely valuable for life assessment, and should be obtained as part of the construction contracts. Systems are necessary for the safe preservation and storage of these samples for later retrieval and testing. Samples must be in perfect condition and identifiable up to 30 years after the samples were collected. If testing was carried out during construction, these results are also valuable for later life assessment.

7.7.1.5. Accuracy of operating data

Accurate records of operating data are necessary as creep life is very sensitive to small changes in stress and temperature. When estimates of operating conditions are necessary due to unavailability of real operating data, extreme care is required to ensure that the summary values give an accurate reflection of the life effects of the operating parameter being considered.

Example

Creep life is proportional to the negative exponential of absolute temperature. Simple averaging of temperatures will therefore result in underestimates in life consumption calculations.

The same effect applies with stress. (See below)

7.7.1.6. Temperatures

High temperature plant is likely to degrade by temperature-related phenomena such as creep, oxidation and corrosion. These are all phenomena governed by Arrhenius-type reaction rates, where a temperature increase of about 10–13 °C can double the rate of degradation (or halve the life). Accurate temperature measurement is therefore critical for life preservation and assessment. Thermocouples used for life assessment should therefore have high inherent accuracy, low drift in service, and be installed in locations and in such a manner that they reflect accurately the temperature of the components and their rate of change.

Thermocouples with adequate accuracy to 0.5 percent of measured range (Type N) are available at modest cost, and if ordered with new plant may not incur any extra expense.

7.7.1.7. Stresses

The following factors have a direct impact on stresses, and need to be considered in increasing detail as the rigour of the assessment is increased:

- Operating pressures in pressure equipment translate directly to operating stresses. Creep strain rate vs stress is closely approximated by an exponential relationship. Therefore, small changes in operating pressure can have a dramatic influence on plant life. Any small changes in operating pressure should be accounted for where possible.
- Stress concentration effects resulting from discontinuities such as penetrations, nozzles and branches and welds can similarly increase local rates of degradation and reduce the life of a component.
- Thermal stress effects, particularly in thick components, can be the life-limiting factor. Rapid temperature changes in heat transfer surfaces as the result of periodic shedding of ash and clinker by sootblowing or quenching during water blasting can initiate and propagate thermal cracks. Restraint of components can enhance this effect.
• High-cycle fatigue can result when components experience apparently small vibration at high frequency or over long periods, resulting in the application of a large number of cycles.

• Creep-fatigue can be particularly damaging, especially for cycling or fast-ramping plant, where large thermal stresses are applied during load changes and held for long periods, allowing accelerated creep to occur.

The complexity of evaluating the detailed effects discussed above requires the attention of specialists in this field.

7.7.1.8. Access to plant for inspection

The highest cost in performing inspections is usually the cost of obtaining access to the affected parts. It can, therefore, be economic to bring forward some future inspections, or to cluster the inspection of a group of components to avoid multiple incurrence of access costs to a component or group.

7.7.1.9. Need for low-cost NDT techniques

There are currently no low-cost NDT techniques for reliable life assessment. Some desirable attributes would be:

• direct assessment of component condition/remaining life (a big ask!)
• quick and accurate assessment.

Research is active in this field, with promising results for techniques such as measurement of elastic modulus, and instrumented indenter hardness testing.

Some techniques that are available tend to be very expensive. (High-temperature strain gauging, X-ray diffraction, neutron diffraction.)

7.8. Life prediction

Life prediction is simply an extension of life assessment, based on knowledge of future operating conditions, and the physical response of the plant to operating conditions and changes. Knowing the current state of the plant, future life expenditure can be calculated. Techniques are available to cost life expenditure, allowing trade-offs between plant life costs and other costs/benefits, and system optimisation. A whole-of-life plan can then be formulated with some confidence.

7.8.1. Desirable method

Life prediction follows the same methodology as life assessment, and requires the same inputs. There is the same requirement for easy availability of information:

• design information
• operating stresses, temperatures, materials, materials properties
• as-built dimensions and materials
• actual thickness if thickness loss is significant
• samples of new materials (archived) for creep testing
• relationships of operating stresses and temperatures with load
past operating profile of plant, including pressures, temperatures, number and type of load variations and shutdowns
• future operating profile of plant, including pressures, temperatures, number and type of load variations and shutdowns.

The same issues apply as for life assessment. Life prediction must also be based on reliable data. There will probably be requirements for extrapolation of materials creep properties. The interaction of creep and fatigue will require particular attention as it has been found that the common life-fraction addition rules are not always conservative.

7.9. Life extension

Life extension is a strong contender for preservation of and increasing plant capacity, as it can be very cost-effective.

- Refurbished or upgraded plants generally have far lower capital costs than new plant, because existing infrastructure can be re-used
- New sites are not always available
- New plant approvals can be difficult to obtain
- Environmental licenses are increasingly difficult to obtain

It would be extremely rare for all of the components in a power plant to reach the end of their lives at the same time. As individual components or assemblies reach the end of their lives, with knowledge of the remaining life of the remainder of the plant, decisions can be made about the viability of replacing the life-expired components.

This is an opportunity to take advantage of the best knowledge relating to design and materials. It is likely that new materials will have become available since the original installation.

Each decision to undertake life extension should be based on a new life plan for the plant, as it is pointless spending large amounts of time, effort and money on components which will last far longer than the planned life of the plant. It is also likely to be sub-optimal to install new components whose life falls just short of the planned life.

7.10. Plant re-rating

7.10.1. Reasons for re-rating

Plant is designed on certain assumptions which may become of less relevance with the passage of time.

- New design methods may become available
- Different allowable stresses may apply
  - e.g. EU Allowable Stress = (mean creep rupture stress) ÷ 1.25
  - whereas
  - AS Allowable Stress = (mean creep rupture stress) ÷ 1.3
- If the actual properties of the materials are known, it may be possible (or necessary) to take this into account.
- It may be possible to plan for reduced life—possibly due to imminent obsolescence of the whole plant.
• It may be possible to use higher settings on safety valves
• Refurbishment or upgrading of the plant may be involved
• There may be opportunities to trade off life costs against other costs

7.10.2. Trade-offs

Thermal power plant operating at higher peak cycle temperatures is capable of higher thermal efficiency, resulting in lower fuel consumption and lower operating costs.

Petrochemical plant operating at higher reaction temperatures is capable of higher reaction rates, giving higher productivity and higher income for the plant.

Higher operating temperatures will result in:
• higher creep rates, resulting in shorter plant life and higher plant life costs
• higher oxidation and corrosion rates leading to shorter plant life and higher plant life costs
• higher pressures will result in higher stresses, increased creep rates, shorter plant life and increased plant life costs
• reduced operating temperatures and/or pressures may prolong plant life, but at the expense of higher running costs (from energy inputs)
• operating temperatures and/or pressures may be increased for a short time to take advantage of very high product prices, but at the expense of plant life. It is important to account for this added expense.

7.10.3. Knowledgeable owners

Plant re-rating should be undertaken only by knowledgeable owners, in the full knowledge of all the effects. Such owners are able to use the full flexibility of codes and methods to optimise the long-term situation, and to make use of a wide range of alternatives for plant replacements, particularly when life expenditure is planned at the design stage.

7.10.4. Issues

Plant re-rating should be regarded as an integral part of asset management, where not only the benefits, but also the costs of changes and re-rating are accounted for. Provision can be made for the future consequences.

• Process knowledge can be used to predict the response of components to operating conditions and changes.
• Materials availability can often be a major restraint, where some materials may be difficult to obtain while there may be long lead times on others. New materials may offer many advantages.
• The same issues with material properties apply as for life assessment and life prediction.
• Risk management must be undertaken and documented sufficiently to justify actions and regulatory compliance.
• Re-rating design and implementation must be undertaken only by people who understand all the consequences of any changes.
7.11. Conclusion

- Life management is extremely important for highly stressed, highly expensive plant which degrades in service.
- Life management should commence at the design stage and continue throughout the life of the plant.
- Owners need to know all the costs they are dealing with, including those which are usually hidden.
- A holistic approach by a competent owner-finance-technology team should provide optimum solutions to provision of services at minimum cost.

Summary

When you finish this module you need to be able to describe the processes and issues that affect the safety and profitability of a power plant. You need to understand the concept of risk, and how it can be used to maximise the benefits from expenditure on safety. You should also be able to set up an inspection system.

The learning objectives at the start of this module provide a detailed breakdown of the task described above. Make sure that you can do each activity listed in the learning objectives.

If you feel that you cannot achieve the learning outcomes for this module, work through this Study Guide again and read the relevant sections from recommended books.

Remember that if you need assistance in your study, the lecturer and other University staff are there to assist you. We are only a phone call away.

Checklist

Use the following checklist to identify whether you achieved the essential elements of each of the enabling objectives and learning objectives in this module.

<table>
<thead>
<tr>
<th>Performance criteria ✓</th>
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<tbody>
<tr>
<td>Statutory Framework, Standards</td>
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<tr>
<td>☐ Describe the responsibilities of plant owners in relation to plant safety.</td>
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<tr>
<td>Life of High Temperature Plant</td>
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<tr>
<td>☐ Describe the processes which limit the life of high temperature plant.</td>
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<tr>
<td>Risk</td>
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<tr>
<td>☐ Describe the concept of risk, and be able to quantify it.</td>
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<tr>
<td>☐ Perform a risk assessment for a major component of plant.</td>
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<tr>
<td>Inspection</td>
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<tr>
<td>☐ Use the concept of risk to determine inspection requirements on a part of plant.</td>
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<tr>
<td>☐ Assemble an inspection plan for a part of plant.</td>
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<tr>
<td>Life Assessment</td>
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<tr>
<td>☐ Describe the optimum time to perform various stages of life assessment.</td>
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<td>☐ Determine the information required to perform the various stages of life assessment.</td>
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<td>☐ Describe the levels of precision required for input data for life assessment.</td>
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<td>Plant Re-rating</td>
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<td>☐ Describe the reasons for re-rating plant.</td>
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References
