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LIFE-CYCLE OPTIMIZATION AND MANAGEMENT AT THE BASIC DESIGN PHASE: A RISK-BASED COST MODELLING APPROACH

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ABSTRACT

In order for a structure to satisfactorily fulfil its intended function(s) during the operational phase, life-cycle considerations must be integrated at all stages, notably in terms of life-cycle optimization (during Design and Construction) and management (during Operation). We will review some of the main concepts involved in life-cycle optimization during the basic design phase, illustrated by the application to the case of nuclear new build.

At the initial design stages of a project, major considerations (e.g.: basic concept, site, etc.) require fundamental decisions to be made which affect the entire life-cycle of the structure. Therefore it is critical to consider all the available information to make strategically informed decisions. Often short-term financial concerns may override long-term technical ones. In some cases, this may be a beneficial way to proceed, while in others it can be self-defeating. We will look at how to combine financial and technical considerations using a risk-based approach to provide the broadest possible perspective, leading to fully informed decision making and an optimized life-cycle.

NOMENCLATURE

CAPEX – Capital expenditure

D&B – Design and Build

O&M – Operation and Maintenance

OPEX – Operational expenditure

NPP – Nuclear Power Plant

NPV – Net Present Value

1. INTRODUCTION

This paper will present some of the key concepts involved in life-cycle optimisation at the basic design stage of major infrastructure projects, using a nuclear new build project as a hypothetical illustrative case.

It is important to employ risk-based methods at the basic design stage, as these provide the best means of informing decisions based on forecasts and of ensuring that risk is minimised at the earliest possible stage. The risk-based approach also allows one to consider the bigger picture, integrating technical and financial aspects for example, within one clear and consistent framework.

For the purposes of this paper, we will focus on one specific aspect of a hypothetical nuclear new build project, namely a decision between two technical design options for the piping of a safety-

classified primary cooling system. We will look at the decision factors involved, and how to analyse the available data to provide clear information to support the decision.

2. DECISION FACTORS

In order to make an informed choice about which option is best, it is necessary to define what is meant by “best”, and how to measure this. The overriding factor to consider in the case of a nuclear sector project is of course Nuclear Safety. The other key factor is cost. Both are interdependent in certain ways.

The Nuclear Safety factor is based upon the need to maintain the required supply of cooling water to the reactor via the piping. It is therefore a technical consideration – one design may be preferable to another in fulfilling this function.

The cost factor can be broadly broken down into CAPEX (Capital Expenditure) and OPEX (Operational Expenditure). The CAPEX for each design type is fixed, and is significantly higher in the case of the underground galleries. The OPEX for each design varies based on several time-dependant factors, the main one being O&M (Operation and Maintenance) costs to deal with ageing.

In this case, technical factors can be translated into cost factors. As the piping is Safety-Related, any cost of ensuring that the piping remains able to fulfil its Nuclear Safety function (leaktightness) must be borne. Therefore, any technical disadvantage in this respect will translate to increased costs. In addition, technical differences which result in different maintenance requirements can also be translated into costs.

As we are considering a case at the basic design phase of a new build project, it is legitimate to take a financial approach to the decision, as long as the technical aspects are properly considered and integrated into this approach.

3. OVERVIEW OF THE METHODOLOGY

By combining a financial model with a technical model of material ageing, and allowing for unforeseen events, the relative cost of each option can be calculated, giving firm indicators on which to base any decision.

To build the basic financial model, it is necessary to determine the CAPEX required for each option, and the OPEX associated with standard operation as well as for individual maintenance/repair actions. This is achieved on a real project using available project data. For a hypothetical study, this may be achieved by performing a review of costs for similar projects. For the purposes of this paper, we will not cover cost determination aspects, and simply assume that this information is known and used as input data for the financial model. The financial model must also consider financial parameters specific to each project such as the cost of capital, tax rates, etc. Likewise, we will assume that these are known beforehand.

To build the technical model, the failure modes which will lead to maintenance/repair works must be determined. Once this is done, the parameters which affect technical degradation/failure must be determined and calculated in order to model degradation/failure over the timescale considered. In the case of this study, we consider degradation due to material ageing and failure due to an external incident. The development of the

technical model is described in more detail in other sections of this paper.

Once the basic financial model and the technical degradation/failure models are created, the two can be combined into a more sophisticated financial model tracking annual outgoings over time. Broadly speaking, this model combines capital costs, basic O&M costs, and variable O&M costs due to ageing/failure, all modelled at the specific time at which they occur during the lifetime of the plant. The variable O&M costs are based on the technical model by associating maintenance/repair costs with the modelled degradation/failure, allowing detailed tracking of O&M costs over time.

The model can be further improved by allowing for error, thus providing a more nuanced result. This is standard practice for such models, especially considering that in this case we are modelling over a timescale of 60 years (the design lifetime of a modern 3rd generation NPP (Nuclear Power Plant)). Two main methods can be used to achieve this: probabilistic analysis, or the use of scenarios. In this case, we will use various scenarios to provide a result. The scenarios will be calculated based on two factors: the rate of ageing (high, normal, low), and whether or not a severe incident is considered.

4. THE TWO DESIGN OPTIONS

The piping network considered has the following characteristics:

Total length of pipework: ~1 km
Pipe diameter: ~60 cm
Pipe wall thickness: 15 mm
Fluid carried: desalinated, treated water

The two design options considered for this study are briefly outlined below.

4.1 BURIED PIPES

The buried pipes design consists in burying piping in excavated trenches.

This design uses carbon steel piping, welded at joints, and covered by an epoxy anti-corrosion

coating. The pipes are further protected against corrosion by cathodic protection.

Buried connections are often favoured for piping as they are significantly cheaper to install.

4.2 UNDERGROUND GALLERIES

The underground galleries design consists of constructing rectangular concrete galleries to house the piping. The galleries have an interior width of about 2 m, allowing enough space to house the piping and additional electrical cabling, and for personnel to perform walk-down inspections.

This design also uses carbon steel piping welded at joints, but without epoxy coating or cathodic protection – instead the pipes are painted. These anti-corrosion measures are not necessary in this case due to the much less aggressive environment afforded by the galleries.

Underground galleries are sometimes favoured for Safety-Related piping as they allow for easier inspection and maintenance, and provide greater protection against ageing and failure.

5. MATERIAL AGEING FACTORS

As the cooling system will be carrying desalinated and treated water, internal corrosion of the piping will not be considered for this case. Only external corrosion is considered.

5.1 BURIED PIPES

By their nature, the buried pipes are clearly at a greater risk of corrosion, even considering their epoxy coating and cathodic protection, as they are in direct contact with the surrounding soil. Epoxy coating can be damaged or degrade over time, and cathodic protection may not always provide 100% protection at every location, for various reasons which will not be covered here.

5.2 UNDERGROUND GALLERIES

The piping in underground galleries is protected from the surrounding earth by the concrete walls of the galleries, and furthermore by a coat of paint. They therefore have a much reduced corrosion risk,

to the point where external corrosion is not considered for the underground galleries option.

6. FAILURE MECHANISMS

As the piping system considered is part of a primary coolant system, any failure is evidently highly detrimental to safety and plant availability, and is to be avoided at all costs.

In the case of the piping, the failure mode considered is a loss of leaktightness, which may lead to an inadequate supply of cooling water to the reactor. Therefore, failures considered are either perforations of the piping or catastrophic failures due to outside factors (e.g.: earthquake, excessive settlement, etc.).

The failure mechanism leading to pipe wall perforation is external corrosion. As the pipes housed in concrete galleries have such a low corrosion risk, it is considered that they will not become perforated over the lifetime of the installation. In the case of the buried pipes, the corrosion risk being non-negligible, the possibility of external corrosion leading to perforation of the pipe wall must be considered.

6.1 BURIED PIPES FAILURE SEQUENCE

As the buried pipes are protected against corrosion by an epoxy coating and by a cathodic protection system, the failure sequence is one which would lead to corrosion initiation, which in turn would lead in time to perforation. This failure sequence is detailed below:

- The first step in the failure sequence is the occurrence of a defect in the external epoxy coating. Broadly speaking, these defects are due to two causes: initial defects arising during application of the coating or during installation of the pipes, and general ageing of the coating (local disintegration, de-bonding, etc).
- If these defects are detected by indirect inspection methods, it is assumed that a direct inspection of the affected area will be undertaken, and the defect will be repaired. As the cooling system is Safety-Related, it is assumed that this will be done in the same year that the defect is detected.

- If defects go undetected (and so unrepaired) corrosion may initiate locally at the surface of the exposed steel. However, the buried pipes are also equipped with cathodic protection, which will prevent corrosion initiation if it is applied at the correct level to the exposed area. For this reason, the ageing model must include a factor for the probability of corrosion initiation at a locally exposed area, which starts off fairly low, and rises gradually as time goes on. This means that, in the early years, only a fairly small amount of undetected defects are assumed to lead to local corrosion of the pipe wall, with this amount rising gradually over the 60 years considered.
- Once corrosion has initiated, the time required for perforation of the steel pipe wall depends on the rate of corrosion.
- If/when perforation occurs, it is assumed that the leak is detected in the year that it first occurs, and that the leaking pipe section will be completely replaced, also in the same year. This assumption is based on the fact that the system in question performs a Safety-Related function, and so leak detection and repair must be a priority for the operator. In reality leaks from buried pipes may take some time to be detected, especially as initially they may be small enough not to impact the function of the affected train.

7. TECHNICAL MODEL PARAMETERS

7.1 BURIED PIPE COATING DEFECTS

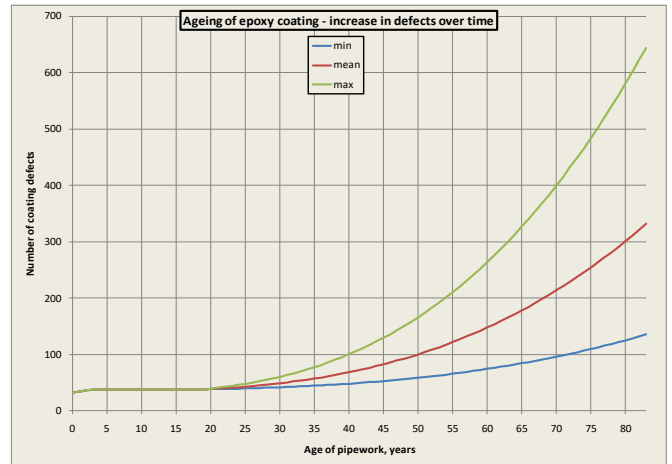
The failure sequence considered starts with a defect in the epoxy coating of the buried pipes. These are either due to initial defects arising during application of the coating or during installation of the pipes, and general ageing of the coating (local disintegration, de-bonding, etc).

A constant number of initial defects are modelled based on operating experience and the length of piping. In addition a very small number of defects are modelled as occurring over the first three years after installation to account for potential damage due to settlement.

No further defects are modelled as occurring over the first 20 years after pipe installation. After the initial 20 years, defects are modelled as occurring at an increasing rate (see Figure 1). This modelling

is based on multi-industry experience of using epoxy coatings for buried pipelines and scientific research [1] [2].

Figure 1: Min, max and mean coating defect models



7.2 DEFECT DETECTION PROBABILITY

The rates of detection of coating defects were based on operating experience. Various methods of indirect inspection are used, although to say that they all “detect” coating defects is somewhat misleading – more accurately speaking, they mostly identify areas where defects are likely. Feedback indicates that the reliability of these methods varies somewhat.

This rate of defect detection is set at an initial rate and modelled as decreasing very gradually over the 60-year service life, accounting for the ageing of the cathodic protection system, and the declining knowledge about the exact condition of the pipes. What this translates to in the model is the percentage of coating defects which go undetected will increase slightly over time.

It is assumed that perforation of the steel wall of the pipes will be detected in 100% of cases for both buried pipes and pipes in galleries. This is a fair assumption in both cases, however while detection will generally be very quick in galleries, it may take some time in the case of buried pipes, and so this is a simplification for practical reasons.

7.3 PROBABILITY OF CORROSION INITIATION

A probability governing the fraction of the total number of undetected defects at which the

exposed steel will begin to corrode is modelled. This is never 100%, as the pipes are equipped with cathodic protection, whose main purpose is to prevent corrosion initiation at exposed surfaces – a purpose for which it is generally effective.

However, due to the varying effectiveness of corrosion protection, as well as operating experience on the probability of corrosion of exposed steel, this probability is modelled as increasing slowly over time, using a mathematical progression based on industry experience and scientific research [1] [2]. This means that, in the early years, only a fairly small amount of undetected defects are assumed to lead to local corrosion of the pipe wall, with this amount rising gradually over the 60 years considered.

7.4 CORROSION RATE & TIME TO PERFORATION

The corrosiveness of the soil surrounding the buried connections is determined based on available information on soil chemical properties. In this case, we assume that the soil will be engineered backfill, chosen partly for its low corrosive properties. Corrosion rates for the buried pipes in these conditions are therefore modelled as being fairly low. However, it is expected that the low corrosiveness of the backfill will not remain constant over a period of 60 years, as various factors such as rainfall and the gradual leaching of chemical agents from surrounding soil will act to increase corrosiveness somewhat, although corrosion rates are still expected to remain relatively low.

The corrosion rate modelled is as shown in Figure 2 (the time to perforation is based on pipe wall thickness). A low “early” rate is modelled as constant for the first 15 years after pipe installation. This accounts for the inertia of the soil with regards to evolution of its chemical properties. After this period, the corrosion rate is considered to rise gradually and linearly over 30 years, to attain the higher “late” rate 45 years after pipe installation. This late rate is still fairly low, reflecting the low corrosiveness of the initial backfill.

This means that, in some cases, localized areas where the corrosion process initiates in early years

will take more time overall to perforate the pipe wall than zones where corrosion initiates later in the life of the installation.

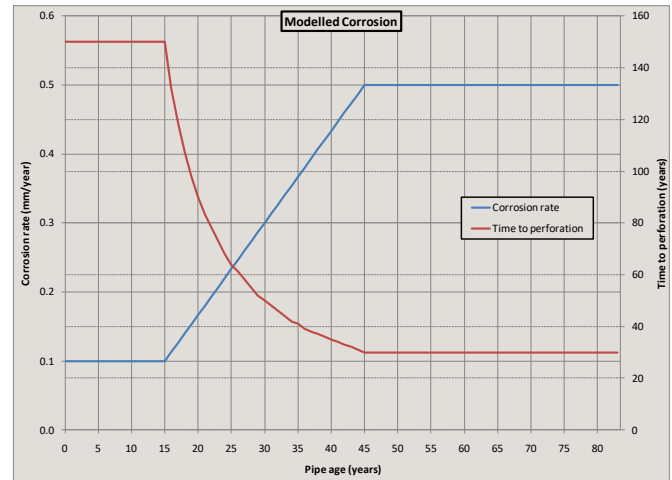


Figure 2: Modelled corrosion rate over time

7.5 SEVERE INCIDENT MODELLING

The severe incident taken into account is a situation in which greater than expected differential settlement causes damage to pipelines early on in the service life of the plant (modelled in the 5th year of operation). The impacts are different for each alternative design option.

As buried connections are directly in contact with surrounding soil, high differential settlement is more likely to cause damage to the pipes than in the case of galleries. For the purposes of this study, the settlement was assumed to create a major leak in one train, meaning that only the remaining trains are capable of fulfilling their safety function. In this case, where the incident is potentially generic to all trains, and as the primary coolant function is classified as Safety Related, it is assumed that the plant would be totally shut down until the apparently operable trains could be confirmed to be safe. The most effective method for determining this would be by internal inspection, and it was estimated that undertaking the (unplanned) inspections, interpreting the results, and finally deciding that the remaining trains were safe, would require 72 hours. It was assumed that the internal inspections did not find any serious damage. The costs incurred in this case are for repairs (damaged train; surrounding earthworks), emergency inspections, and lost production.

Pipework in galleries is protected to a certain extent from soil settlement impacts as the gallery acts as a sort of buffer zone. For the purposes of this study, it is assumed that the settlement causes only minor damage to the pipes, and so there is no leakage. The galleries are also assumed to have been slightly damaged in the affected area. No plant shutdown is necessary in this scenario, and the costs incurred are for repairs only (pipes; galleries; re-consolidation of earthworks). It is assumed that the extra inspections involved will not add to annual maintenance costs due to the ease by which pipes in galleries can be visually inspected along their entire length.

8. FINANCIAL PARAMETERS

A wide range of financial aspects were included in the cost model, not all of which will be explained here. The most important aspect, in terms of influence on the final results, is the calculation of costs in terms of NPV (Net Present Value). These were calculated by discounting the real modelled cost cashflows using an NPV coefficient calculated using $(1+i)^t$, where i is the discount rate used and t is the time of the cash flow in relation to the NPV index year (taken as the year of first investment). Three pre-set discount rates were used in order to provide information for various possible scenarios.

This effectively means that as costs become more offset from the NPV index year, they become exponentially more discounted. Therefore, costs which are modelled as occurring after 60 years of operation are much more heavily discounted than initial investment costs. The length of time considered and the discount rates used means that end-of-life costs, although they may be significantly higher than initial costs in real terms, are much lower in NPV terms.

One other important financial parameter included in the model is inflation, which has the opposite effect to the NPV calculation, tending to increase the cost of offset cashflows.

9. MODELLING OF SCENARIOS

Six scenarios were modelled in order to cover a range of possible conditions and allow for uncertainties. Two key variables with a significant

influence on costs were taken into account, these being the ageing rate of the epoxy coating, and the consideration or not of a severe incident. The scenarios considered are summarised below:

Table 1: Scenarios modelled

| Scenario # | Incident | Ageing Rate |
|------------|----------|-------------|
| 1 | Yes | Max |
| 2 | Yes | Mean |
| 3 | Yes | Min |
| 4 | No | Max |
| 5 | No | Mean |
| 6 | No | Min |

In effect the scenarios represent a scale from #1 which is the worst case (severe incident modelled; maximum ageing rate), to #6 which is the best case (no severe incident; minimum ageing rate). For the purposes of this study, scenario #5 is taken as the “base case” (see Figure 3), representing the most probable scenario (no severe incident; mean ageing rate).

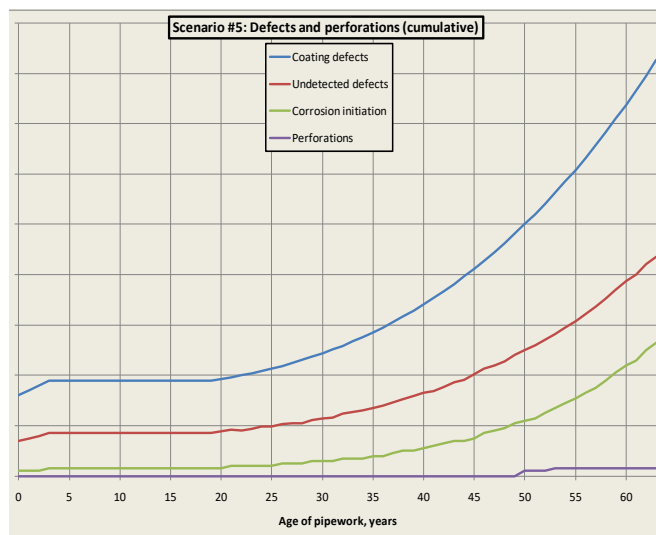


Figure 3: Modelled defects and perforations, scenario #5

The resulting ageing model for the base case scenario is summarised below.

The results of the ageing model show that the first perforation occurs 50 years after pipe installation (i.e.: after 45 years of plant operation). By the time the pipe is 60 years old, the ageing model predicts only 3 perforations. Based on operating experience and the design and conditions considered, this is in line with expectations.

10. RESULTS & INTERPRETATION

Full results and analysis of the results for the “base case” scenario (#5) are presented below, as well as a brief comparison with the results of the “best case” and “worst case” scenarios. Full results for each of the six scenarios are not presented in this paper.

10.1 BASE CASE RESULTS

To recall, scenario #5 was taken as the base case as it was deemed the most probable: the severe incident was not modelled, and a mean ageing rate was used.

Figures 4 and 5 show base annual and cumulative costs over the lifetime of the NPP (including the initial D&B (Design and Build) period before operation), without applying NPV calculations.

Note that the negative costs for the first 15 years of operation in the case of the underground galleries (see Figure 4) is due to the effects of tax depreciation on the initial investment which was included in the model. Likewise, the decreasing cumulative cost for the underground galleries in Figure 5 is due to the same effect.

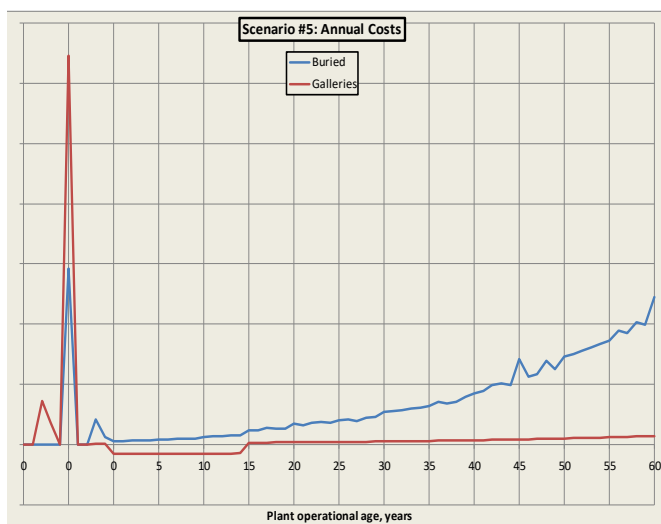


Figure 4: Annual costs for scenario #5 (base case)

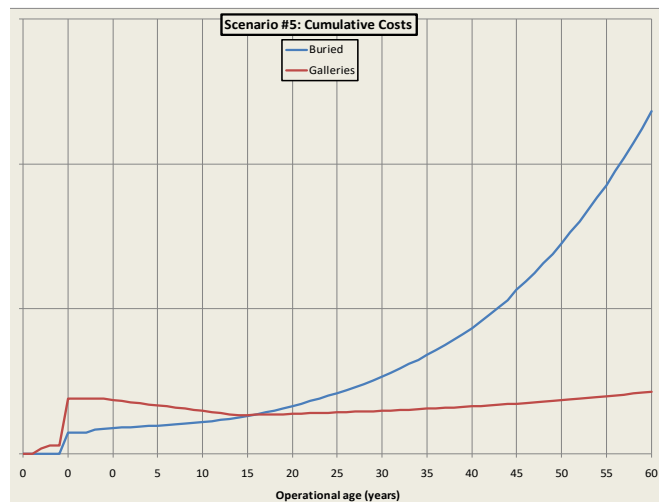


Figure 5: Cumulative costs for scenario #5 (base case)

What is immediately clear from these graphs is that the costs for the underground galleries are heavily front-loaded towards the initial investment, but significantly lower thereafter. The buried pipes present the inverse case, with initial CAPEX about half that required for the galleries, but with higher O&M costs over the 60 years of operation.

Figure 5 clearly shows that in cumulative terms, the buried pipes option is much more expensive – about 5.5 times more over the entire lifetime than the galleries in this case.

However, once the NPV calculations are applied to these results, the outlook is distinctly different.

Table 2: Base case results summary

| | Result |
|------------------------|----------------------------------|
| Cumulated costs | Buried pipes 5.5x more expensive |
| NPV @ 6% | Negligible cost differential |
| NPV @ 8% | Galleries 1.3x more expensive |
| NPV @ 10% | Galleries 1.6x more expensive |

Using a discount rate of 6%, both options cost roughly the same amount over the timescale considered, with a negligible difference in financial terms. Applying higher discount rates of 8% and 10% result in the galleries being respectively 1.3 and 1.6 times more expensive than the buried pipes.

The reason for this complete change of results when applying NPV calculations is simply that the costs for the gallery option are heavily front-loaded, requiring a much greater initial outlay. Although the buried option costs are much greater over time, they are distributed towards the end of the timescale considered. In NPV terms then, the buried pipes are more financially advantageous as they enable costs to be offset in time.

10.2 BEST & WORST CASE COMPARISON

The following tables summarise the results for the best and worst case scenarios. As a reminder, the best case considers a low ageing rate and no severe incident, while the worst case considers a high ageing rate and a severe incident after 5 years.

Table 3: Best case results summary

| | Result |
|------------------------|----------------------------------|
| Cumulated costs | Buried pipes 5.1x more expensive |
| NPV @ 6% | Negligible cost differential |
| NPV @ 8% | Galleries 1.3x more expensive |
| NPV @ 10% | Galleries 1.6x more expensive |

Table 4: Worst case results summary

| | Result |
|------------------------|----------------------------------|
| Cumulated costs | Buried pipes 5.4x more expensive |
| NPV @ 6% | Buried pipes 1.1x more expensive |
| NPV @ 8% | Galleries 1.1x more expensive |
| NPV @ 10% | Galleries 1.4x more expensive |

In summary, when applying NPV calculations, the galleries are financially more attractive only in the worst case scenario and considering a discount rate of 6%. In all other cases, the buried pipes are less expensive or the cost differential is negligible.

11. OTHER CONSIDERATIONS

One aspect not included in the cost model developed for this study are the risks which arise when a leak from a buried pipe goes undetected

for a period greater than a couple of years. In this case, several complications can ensue, including:

- Weakening of the foundation soil, potentially leading to damage to the pipe sections in the immediate area due to soil movements, and, in the extreme case, having an impact on the settlement of nearby structures. Repair costs in this case are increased compared to a quickly detected leak due to extra earthworks repairs.
- Possible environmental concerns of leakage directly into the earth were not considered. The extreme case would be radiological contamination of the soil – this could potentially occur if the water in the coolant system becomes contaminated by a leak in the heat exchange system. This is a very low probability–severe consequence event.
- Potential impact on safety if the size of the perforation increases significantly enough to lead to bursting of the pipe, resulting in sudden loss of cooling function.

The cost simulations undertaken for this study considered a 60-year service life. However, this is the minimum design life of modern 3rd generation NPPs, and it is expected that most will operate beyond this period to at least an 80-year service life. Between 60 and 80 years of operation, ageing rates begin to result in O&M costs for the buried solution increasing to what may be deemed unacceptable levels. This means that a possible total replacement would need to be undertaken if the decision was made to extend the service life to 80 years. This would of course tend to increase the cost of the buried pipe option, although the cost would be so far in the future as to be nearly insignificant in NPV terms. However, this aspect, as well as the practical difficulties involved, may need to be taken into consideration even at this very early stage.

Finally, no potential effects to an operator’s image (to the general public, safety authorities, the nuclear industry, etc.) of incidents such as leaks and soil contamination were considered.

These aspects, although not directly integrated into the cost model developed for this study, and therefore with no impact on the quantitative results, should nonetheless be taken into account when

comparing the two options for the design of the piping of the coolant system.

12. CONCLUSIONS

We have seen how a risk-based approach can enable us to identify the potential hazards related to the design choices for infrastructure projects, and to determine their probability of occurrence and their consequences. Such an approach enables a holistic consideration of a wide range of factors which may not be considered in a simple purely financial or purely technical assessment. Combining these two types of assessment allows us to provide reliable indicators to support decisions at the basic design stage.

However, such an approach can only provide information to support decision-making – any decisions still need to be made while factoring in considerations which may not have been included in the model. In this case, several aspects should be considered in addition to the model results, as detailed in section 11 of this paper.

In the case considered, the buried pipes option appears to be the most financially attractive in nearly all cases modelled. However, the decision-makers will need to consider whether the financial advantage is enough to offset any disadvantages that the buried pipes option presents. In the base case scenario, the cost differential is negligible when applying a 6% discount rate for NPV calculations, and still fairly low at higher discount rates. Decision-makers may feel therefore that the extra costs (in NPV terms) may be worth bearing for the advantages conferred by the galleries option – namely lower O&M costs, better protection against ageing and severe incidents, and much greater ease of inspection and maintenance.

In conclusion then, a risk-based cost model combining both technical and purely financial factors can be a very valuable method to aid decision-making at the early stages of major infrastructure projects. However it should remain one of several inputs to the decision making process, and should be used alongside other considerations with full understanding of the inherent limitations, which depend on the sophistication and extensiveness of the model.

REFERENCES

NOTE: a large amount of the data used for the work described in this paper are from Oxand's confidential databases, as well as internal expertise and experience feedback, and as such will not be specifically referenced.

[1] Electric Power Research Institute (EPRI), 2005. 'Piping Failure Database Status Report'

[2] Institute of Nuclear Power Operators (INPO), 2010. 'Buried Piping Degradation Mitigation'

[3] Electric Power Research Institute (EPRI), 2005. 'Service Water Piping Guideline'