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Hydraulic turbines, storage pumps and pump-turbines – Rehabilitation and performance improvement

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INTERNATIONAL
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

HYDRAULIC TURBINES, STORAGE PUMPS AND PUMP-TURBINES – REHABILITATION AND PERFORMANCE IMPROVEMENT

FOREWORD

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International Standard IEC 62256 has been prepared by IEC technical committee 4: Hydraulic turbines.

This second edition cancels and replaces the first edition published in 2008. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

– Tables 2 to 23 modified, completed and moved to Annex A;
– 7.3.2:
  • subclauses moved with text changes;
  • new subclauses on temperature, noise, galvanic corrosion, galling and replacement of components without assessment;
– 7.3.3: complete new subclause on residual life;
– Tables 29 to 32 moved to Annex C;

– new Annex B with assessment examples.

The text of this standard is based on the following documents:

FDIS	Report on voting
4/323/FDIS	4/326/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

Hydro plant owners make significant investments annually in rehabilitating plant equipment (turbines, generators, transformers, penstocks, gates etc.) and structures in order to improve the level of service to their customers and to optimize their revenue. In the absence of guidelines, owners may be spending needlessly, or may be taking unnecessary risks and thereby achieving results that are less than optimal. This document is intended to be a tool in the optimisation and decision process.

Edition 1 of this International Standard was based on the IEA document *Guidelines on Methodology for Hydroelectric Francis Turbine Upgrading by Runner Replacement*.

HYDRAULIC TURBINES, STORAGE PUMPS AND PUMP-TURBINES – REHABILITATION AND PERFORMANCE IMPROVEMENT

1 Scope

This document covers turbines, storage pumps and pump-turbines of all sizes and of the following types:

- Francis;
- Kaplan;
- propeller;
- Pelton (turbines only);
- bulb turbines.

This document also identifies without detailed discussion, other powerhouse equipment that could affect or be affected by a turbine, storage pump, or pump-turbine rehabilitation.

The object of this document is to assist in identifying, evaluating and executing rehabilitation and performance improvement projects for hydraulic turbines, storage pumps and pump-turbines. This document can be used by owners, consultants, and suppliers to define:

- needs and economics for rehabilitation and performance improvement;
- scope of work;
- specifications;
- evaluation of results.

This document is intended to be:

- an aid in the decision process;
- an extensive source of information on rehabilitation;
- an identification of the key milestones in the rehabilitation process;
- an identification of the points to be addressed in the decision processes.

This document is not intended to be a detailed engineering manual nor a maintenance document.

2 Normative references

There are no normative references in this document.

3 Terms, definitions and nomenclature

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

Wherever turbines or turbine components are referred to in the text of this document, they shall be interpreted also to mean the comparable units or components of storage pumps or pump-turbines as the case requires.

For the purpose of this document, the term "rehabilitation" is defined as some combination of:

- restoration of equipment capacity and/or equipment efficiency to near "as-new" levels;
- extension of equipment life by re-establishing mechanical integrity.

The term "performance improvement" means the increase of capacity and/or efficiency beyond those of the original machine and may be included as part of a rehabilitation.

Many other terms are in common use to define the work of "rehabilitation" and "performance improvement", however use of the above terms is suggested. Some of the terms considered and discarded for their lack of precision or completeness include:

- upgrade or upgrading – restoration of mechanical integrity and efficiency;
- uprating – increase of nameplate capacity (power) which may result in part from efficiency restoration or improvement;
- overhaul – restoration of mechanical integrity;
- modernization – could mean performance improvement and replacement of obsolete technologies;
- redevelopment – term frequently used to mean replacement of the powerplant and could involve changes to the hydraulics and hydrology of the site usually implying a change in mode of operation of the plant;
- refurbishment – restoration of mechanical integrity usually with restoration of performance (closely resembles "rehabilitation", the preferred term);
- replacement – usually refers to specific components but may involve the complete hydraulic machine in the case of small units.

The nomenclature in this document is in accordance with IEC TR 61364, which provides the "Nomenclature" in six languages to facilitate easy correlation with the terminology of this document.

Here is a list of the acronyms used throughout this document:

- AGC: automatic generation or direct frequency control
- B/C: benefit/cost ratio
- CFD: computational fluid dynamics
- ETA: event tree analysis
- FEA: finite element analysis
- FFT: fast Fourier transform
- FMA: failure mode analysis
- FMECA: failure modes effects and criticality analysis
- FTA: fault tree analysis
- HAZOP: hazard and operability study
- IRR: internal rate of return
- MT: magnetic particle inspection technique
- NDT: non-destructive testing
- NPV: net present value
- PCB: polychlorinated biphenyl

- PT: liquid penetrant inspection technique
- RSI: rotor-stator interactions
- SNL: speed no load
- UT: ultrasonic inspection technique
- VAR: Volt-Ampere Reactive

4 Reasons for rehabilitating

4.1 General

Hydroelectric generating facilities are among the most robust, reliable, durable structures and equipment ever produced. The robustness of the equipment permits owners to continue operating these facilities without major rehabilitation for relatively long periods. As shown in Table 1, the reliable life for a turbine prior to a major rehabilitation being necessary is typically between 30 and 50 years depending on type of unit, design, quality of manufacturing, severity of service, and other similar considerations. However, all generating equipment will inevitably suffer reduced performance, reliability and availability with time, which leads owners to the fundamental question of what to do with an aging plant. This crucial question cannot be answered easily since it involves many interrelated issues such as revenue, operating and maintenance cost, equipment performance, reliability, availability, safety and mission of generating facilities within the entire system. Ultimately, an owner will have to decide to rehabilitate the plant or eventually to close it. At some point in time, delaying a major rehabilitation ceases to be an option. This may come about as the result of a major component failure or as the result of an economic evaluation. Cessation of commercial operation does not necessarily relieve an owner of the responsibility for the maintenance of the civil structures, regulation of the flows and any other issues which have an impact on an owner's liability for the plant.

The governing reason for rehabilitation is usually to maximize return on investment and normally includes one or more of the following:

– reliability and availability increase;
– life extension and performance restoration;
– performance improvement:
  - efficiency;
  - power;
  - reduction of cavitation erosion;
  - enlargement of operating range;
– plant safety improvement;
– environmental, social or regulatory issues;
– maintenance and operating cost reduction;
– other considerations:
  - modified governmental regulations;
  - political criteria;
  - company image criteria;
  - modified hydrology conditions;
  - modified market conditions.

The opportune time for starting a rehabilitation is prior to the plant being beset with frequent and severe problems, such as generator winding failures, major runner cracking, cavitation or particle erosion damage, bearing failures and/or equipment alignment problems due to foundation or substructure movement or distortion. When a generating plant has reached such a stage, it is obvious that a technical and an economic assessment of the equipment should have been conducted years before. If the time frame of rehabilitation studies is too close to the end of the useful life of the plant and its equipment, the owner may lose the option of evaluating a range of alternatives. Catastrophic failures with potential major damage and loss of life are, at some stage of the plant life, real risks. If significant improvements can be made in the revenue generating capabilities of the plant by replacement of deteriorated equipment with state-of-the-art equipment or components, there may be justification for performing rehabilitation earlier than the date at which it would be required for purely reliability or life extension reasons.

Typically, the renewed life of a turbine following rehabilitation would be more than 25 years with normal maintenance. The residual life of the generating plant is dependent on the collective residual lives of each individual component group and therefore can be determined only by assessing all of the component groups including the civil structures.

Rehabilitation should result in a unit which is very close to its as-new condition.

Table 1 – Expected life of a hydropower plant and its subsystems before major work

Plant subsystems	Expected lifetime (years)	Considerations
Civil works		
Dams, canals, tunnels, caverns, reservoirs, surge chambers	60 to 80	Duration of water rights, quality of work, state of deterioration, safety, loss of water.
Powerhouse structures, water control structures, spillways, sand traps, penstocks, steel linings, roads, bridges	40 to 50	General condition, imposed stresses, quality of material, state-of-the-art, safety, quality of steel, corrosion, maintenance.
Mechanical installations		
Hydraulic machines		
Kaplan and Bulb turbines Francis, Pelton and Fixed-blade Propeller turbines Pump turbines (all types) Storage pumps (all types)	25 to 50 30 to 50 25 to 35 25 to 35	Safety of operation, loss of water, cavitation damage, erosion, corrosion, cracks, deterioration of efficiency, performance improvement.
Heavy mechanical equipment and auxiliaries		
Flat gates, radial gates, butterfly valves, spherical valves, cranes, auxiliary mechanical equipment	25 to 40	Quality of material, operating condition, safety considerations, quality of equipment, imposed stresses, performance improvement.
Electrical installations		
Generators, transformers	25 to 40	Winding and iron core condition, cleanliness, safety of operation, state-of-the-art, general condition, quality of equipment, maintenance.
High voltage switchgear, auxiliary electrical equipment, control equipment	20 to 25	
Batteries, DC equipment	10 to 20	
Energy transmission lines		
Steel towers Concrete towers Wooden poles Lines and cables	30 to 50 30 to 40 20 to 25 25 to 40	Right of way, corrosion, safety of operation, climatic conditions, quality of material, state-of-the-art, capacity vs. service conditions.

4.2 Reliability and availability increase

A thorough rehabilitation can significantly increase reliability and availability of the units. Following a thorough and well executed rehabilitation, an availability of approximately 98 % can be expected. This normally results in less lost revenue associated with having the units out of service for planned outages and fewer unplanned outages. By their nature, forced outages for unplanned repairs usually cost significantly more than would a similar planned repair, particularly when the consequential impacts are evaluated.

4.3 Life extension and performance restoration

The useful life of the turbine can be greatly extended by the rehabilitation or replacement of turbine components. The operating characteristics and the mechanical integrity of the machine can be restored to nearly “as-new” condition, guaranteeing safe and reliable operation for a long period.

Performance restoration is generally achieved by restoring the water passage and runner seals to the new condition although, for the water passage outside the distributor and the runner, this is not always economically justified, hence the term “nearly new” is often used.

The anticipated life extension of a rehabilitated turbine will depend greatly on the type of machine involved and on its operating conditions before and after rehabilitation. However, if major work is done, the owner would normally achieve life extension of 25 years and more.

4.4 Performance improvement

Advancement in turbine design tools, model testing, materials, manufacturing techniques, and inspection techniques have given rise to opportunities to substantially improve capacity, efficiency, and cavitation erosion performance. If there is no cavitation erosion problem with the existing equipment, the replacement equipment of modern design should also be erosion problem free, even with a significant increase in discharge. If there is a cavitation erosion problem with the existing equipment, the replacement equipment should reduce or solve the problem. The extent to which the performance parameters can be improved is, of course, site-dependent, but in most cases it is found to be economically justified to replace the runner and sometimes the guide vanes especially if the unit is being disassembled and re-assembled in any case, for life extension repairs or for reliability reasons.

In a few cases, energy production can also be increased by increasing the specific hydraulic energy (head) at the site if, of course, the modifications to the water retention structures and conduits or canals are cost effective. This usually requires that administrative authorization be obtained for modification of the water management parameters.

In some cases, a change of the speed of rotation of the unit may be justified.

4.5 Plant safety improvement

Without a pro-active maintenance and rehabilitation program, there will be a continual increase in the risk of a major failure that may involve both major economic and potential civil liabilities due to loss of life or contingent property damage.

An issue that should not be ignored is the ever-increasing risk of a major failure of one component that cascades to several other components. An example of such a scenario is a broken runner blade or guide vane failure due to serious erosion and/or cracking at the stems. A failed guide vane can interfere with the runner blades, which could result and has been known to result in a cascade failure of the adjacent components such as runner, discharge ring, bottom ring, headcover and stay ring. This may seem far-fetched but there are documented cases of such cascade type failures. Obviously, this type of failure is an extreme example, but it should serve as a reminder that turbines have a finite life, which can be extended by executing thorough and rigorous maintenance and ultimately, a rehabilitation program.

4.6 Environmental, social and regulatory issues

When a hydroelectric generating station is rehabilitated, environmental improvements may be addressed in some of the following areas without incurring any additional unit outage time:

- reduction of contaminants in water;
- minimum flow requirements;
- allowable rate of change of flows (ramping rates);
- fish and wildlife flows;
- reduction of hazardous materials in powerhouse;
- improvement of dissolved gas (oxygen) content of water;
- improvement of fish friendliness;
- provisions for recreational flows;
- provisions for domestic water/irrigation flows;
- reduction of fossil fuel emissions (any increase in hydro power production reduces the emissions produced by fossil fuel based energy production).

4.7 Maintenance and operating cost reduction

Rehabilitation of the unit can significantly reduce maintenance costs in the form of lower labour and material costs and often more importantly, can reduce lost revenues from lost energy production opportunities. Rehabilitation can also provide an opportunity to address limitations of the existing turbine design, or changes that have occurred since construction that cause ongoing maintenance problems such as vibration, cavitation erosion, or pressure pulsations. The rehabilitation of the turbines can also present an opportunity to automate the plant and reduce future operating costs.

4.8 Other considerations

There may be one or more other criteria such as those listed below which could have an impact on the decision to rehabilitate or its timing:

- governmental regulations and their development and modification over time can support or impose certain rehabilitation activities;
- political criteria are an external consideration which may have no direct relationship to the physical aspects of the electrical energy generating facility, but which can play an important part in rehabilitation decisions. Notable among those to be considered is water management;
- company image criteria may predominate in considering a rehabilitation project (maintenance or improvement of its image) and take precedence over other criteria;
- hydrology conditions may have changed over time;
- market conditions may have changed over time.

5 Phases of a rehabilitation project

5.1 General

Rehabilitation of a unit or a power station is a complex and iterative process which calls for the input of a large number of disciplines, extends over a relatively long period of time and takes place in several phases. These phases are shown in the form of a flow diagram in Figure 1 and are discussed in more detail in the following subclauses.

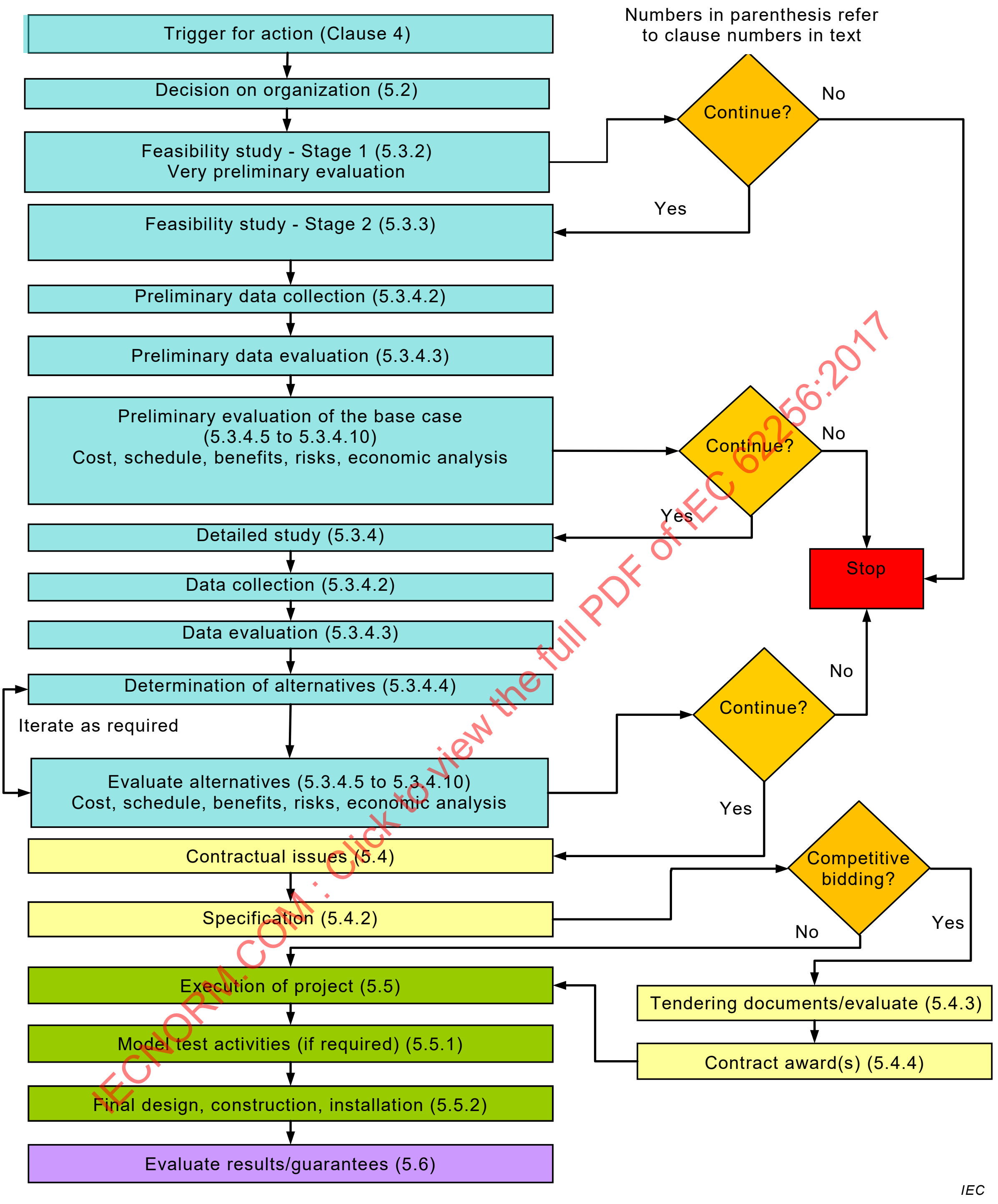

Figure 1 – Flow diagram depicting the logic of the rehabilitation process

5.2 Decision on organization

5.2.1 General

When it has been determined that the possibility of rehabilitation should be studied, the owner makes a decision on the strategy of execution of the project and puts in place the project team that will be responsible for executing the project, from feasibility study up to and including commissioning. The owner needs first to determine the in-house composition of the team. The depth to which the owner can or chooses to staff the in-house part of the team will have an impact on the composition of the external part of the team. Obviously, establishing a qualified and cohesive project team is essential to successful assessment, planning and execution. During the assessment and scope determination phases there is a multitude of options to be identified and evaluated in order to determine the most profitable strategy for the owner. During the planning and execution phases, a solid team effort will minimize "surprises" and thereby minimize the outage time, costs, and associated revenue loss.

5.2.2 Expertise required

When forming the team, the owner should consider that the rehabilitation process is an iterative process in all stages. In the feasibility stages, and in the final detailed planning stage, expertise from many different disciplines shall jointly focus on the best economic or other solution(s). The areas of expertise required include:

- Operation and income generation:
  - what are present and past operating problems?
  - how are units operated today?
  - how is owner paid today?
  - how will units be operated in the future?
  - how will owner be paid in the future?
- Hydraulic engineering:
  - what are current conditions and limitations?
  - what possible improvements could be made?
- Equipment assessment (condition, and power limits):
  - turbine and generator;
  - all other related mechanical and electrical equipment as well as civil issues;
- Cost estimating (all aspects);
- Scheduling;
- Licensing;
- Economic and financial analysis;
- Detailed engineering design;
- Model and field testing;
- Construction of new parts;
- Rehabilitation of existing parts;
- Transportation;
- Field installation;
- Commissioning.

5.2.3 Contract arrangement

There are two basic strategies with regard to contract arrangements for all or a part only of the project: competitive bidding or negotiated agreement with a pre-selected supplier. It is also possible to use a combination of these strategies:

– Some prefer the traditional approach of competitive bidding, evaluating bids and awarding contracts.
– Some prefer the negotiated agreement or partnership approach with a pre-selected supplier to form at least the equipment supply and repair external component of the team. Such an agreement can cover only the “equipment” phases of the process such as dismantling, design, manufacturing, transportation and installation (typical of large projects) or it can include all phases from feasibility study through commissioning (more typical of small hydro projects). These agreements can cover just a single component of hardware such as the turbine alone or one agreement can cover many types of related hardware including, for example, turbine inlet valve, turbine, governor, generator, excitation system and controls.

An independent consultant can be employed in either of the above approaches to whatever degree the owner’s situation requires. The degree of involvement is usually determined by a combination of the capabilities and availability of in-house staff, the nature and overall scope of the rehabilitation work involving both structures and equipment and the level of comfort and confidence the owner has in working directly with a supplier or with several suppliers.

Regardless of the composition of the team, the scope and goals shall be very clear. There is a strong need to be precise in either approach. Clarity in any agreement or contract is essential.

The choice of contract arrangement will influence the exact steps required. However, the basic steps are very similar regardless of contract arrangement. Therefore, the following subclauses cover the basic steps without distinction of the contract arrangement used. The owner shall determine how the selected contract arrangement will impact the achievement of equipment performance improvements, costs, schedule, environmental, social and regulatory issues, safety improvements, and future revenue generation.

5.3 Level of assessment and determination of scope

5.3.1 General

Subclauses 5.3.2 to 5.3.4 describe three levels of assessment and scope development: feasibility study – stage 1, feasibility study – stage 2, and detailed study. The main differences between these three levels are the degree of detail and the accuracy of results.

A thorough assessment of a plant will involve looking at alternatives for the turbine such as the following, some of which could have several sub-alternatives:

– do nothing major and continue to operate the plant until “failure of the units”;
– repair components which have known physical weaknesses, then operate with normal maintenance;
– restore the original water passage profiles to like-new condition (runner, guide vanes, stay vanes, draft tube) without dismantling the unit and continue to operate if the physical integrity is acceptable or re-established;
– replace the runner and possibly replace or modify guide vanes, runner seal rings, stationary seal rings, and stay vanes to benefit from the evolution in hydraulic profile design, with or without modifications to the stay ring and/or draft tube.

If the latter option is considered, the evaluation of the entire power train (turbine, generator, ancillaries, etc.) is necessary including compensation for wear and restoration of mechanical integrity.

It should be noted that grit blast or other cleaning of existing painted surfaces may involve the removal of lead-based coatings. This removal can be very costly when it is done respecting environmental regulations. This cost shall be factored into the overall project cost.

The determination of scope is an iterative process requiring the skills and expertise of the entire team. As the project moves forward, the process goes into more detail.

5.3.2 Feasibility study – Stage 1

This initial stage of feasibility is often accomplished by the owner's in-house staff. The staff should determine if there is enough indication that age, condition, performance, industry practice, etc. warrant a more detailed study. See Clause 4 for a list of indicators of a need for rehabilitation and performance improvement. If the results of this study indicate that there is the possibility of a need to rehabilitate, a more detailed feasibility study should be performed. If desired, a very preliminary economic analysis could be done at this stage.

5.3.3 Feasibility study – Stage 2

This feasibility study would go into more detail and look at a few alternatives. A possible "baseline" may be restoring to as-new condition. A possible first alternative may be assumed to consist of a new runner with other components being rehabilitated. It shall be noted that this particular alternative may not be the best solution. Therefore, if the results of this alternative do not look favourable, it may be necessary to look at few more alternatives. In order to determine if this project has the potential of achieving favourable economic returns, a rough estimate of performance, scope, cost, and schedule shall be made at this stage. If the initial result looks favourable, the project can move to the detailed study stage.

5.3.4 Detailed study

5.3.4.1 General

In this study, there shall be enough detail and sufficient accuracy to permit the decision to move on to the execution phase or to stop work.

During this study, all of the stakeholders should have input to the development of the scope as well as on the methods to be used to evaluate the various alternatives. Working with and getting the support of all of the stakeholders will greatly minimize any questions and related delays associated with scope, analysis methods, and management approval.

It is important to note that, while this document focuses only on the turbine, the scope, costs, benefits, schedule, etc. shall include all equipment, including generator, transformer, etc. and structures related to energy production and flow control in order for the economic analysis to be meaningful.

5.3.4.2 Data collection

The establishment of when a rehabilitation evaluation should be conducted requires that information regarding availability, operating and maintenance costs and energy production be assembled, evaluated and trended on a continual basis for each unit of the plant or at least for the whole plant. Although this document concentrates on a single plant and particularly on the turbines within the plant, one shall be aware that an overall parallel evaluation is also required on all structures and equipment and all plants in a system to allow development of a system strategy and prioritization. The system strategy is aimed at minimizing production losses and maximizing profitability.

Ten (10) or more years would provide a workable database, but if this is not reasonably obtainable, fewer years may be used with due regard for the possible impact of the reduced data set on the accuracy of the result. A minimum period of twenty-five (25) years is desirable for flow, head and energy production data. Flow data shall account for spillage. With the on going climate change, however, caution is recommended with historical records.

Collection of information regarding the following elements is recommended:

– energy production (GWh) and value of energy;
– ancillary service production and value;
– operation and maintenance costs;

– turbine reliability and availability status (outage data – forced and planned);
– hydraulic data in whatever form it exists in (hourly, weekly or monthly discharge, net head, head water level, and tail water level) for the longest available period of record;
– equipment assessment (mechanical integrity) and drawings for all major turbine components and related equipment and structures;
– performance assessment (original model test and/or original prototype performance test and recent prototype performance test or at least a recent power-gate test);
– data from original commissioning;
– operating and maintenance manual;
– history of modifications to original equipment;
– regulatory requirements, current and anticipated.

5.3.4.3 Data evaluation

5.3.4.3.1 General

Data evaluation is to establish:

– trend in total discharge (production and spillage) versus time;
– trend of energy production versus years;
– trend of annual operation and maintenance costs versus time;
– trend of revenue versus time;
– plant load factor versus time;
– determination of turbine mechanical integrity;
– determination of potential performance enhancements with current or revised hydraulic conditions.

5.3.4.3.2 Unit reliability, availability and restricted operation

A significant increase of the outage rate of a unit is a sign that it is time to think about the rehabilitation of the unit. But, before starting any rehabilitation study, it is important to get a complete history of the outages of the unit, their nature, their frequency and their duration for at least the last ten years in order to be able to identify trends.

When evaluating outages related to failure of the equipment, a distinction should be made between a forced outage and a planned maintenance outage because they do not have the same consequences and costs. Often, forced outages are "failure to start". Either type of outage can generate, in addition to direct maintenance costs, significant revenue losses due to a loss of production opportunity and to the cost of the energy replacement.

Restrictions on operation in certain power ranges can significantly reduce the operational flexibility of the plant and revenue generation. Elimination or reduction of these restrictions should be one of the performance improvement goals.

All of these factors shall be taken into account in the evaluation of the rehabilitation project.

5.3.4.3.3 Unit operation and maintenance cost

It is important to obtain all information regarding the turbine operation and maintenance records for the repairs which have been executed and the hours (or costs corrected for inflation) which have been incurred on the units over the last ten years or more. This information will be instrumental in assessing the degradation of the turbine, in highlighting troublesome components and in establishing the potential cost reductions resulting from a turbine rehabilitation project.

Potential maintenance cost reductions are usually secondary to other benefits, but they should be considered in the detailed economic analysis of alternatives.

It is also important to analyse the causes of the problems. For example, are they isolated failures or repeated failures of the same parts, problems related to a structural weakness such as runner cracking, to hydraulic design such as cavitation erosion, vibration, or hydraulic instability, or problems related to missing or faulty instrumentation.

5.3.4.4 Determination of alternatives

A sufficient number of alternatives shall be studied to reasonably assure that the best alternative has been identified. The number of different combinations of turbine design characteristics, extent of life extension work, length of outage, etc. can become very large. A logical screening method shall be established to limit the number of options to be studied and the amount of study time involved. The screening method is very site and owner dependent and therefore, cannot be defined in this document. The determination of the best alternative is an iterative process requiring the skills and expertise of the entire team. A new runner design can usually result in a significant increase in performance. However, if the new runner design increases the output to the point of requiring many of the mechanical and electrical power train components to be rehabilitated or replaced, it may not be the best solution; a smaller increase in power with concentration on improved efficiency may prove to be the better investment.

Each alternative shall be clearly identified as a separate consideration with its own associated benefits, costs, and economic analysis.

The following are examples of incremental modifications to water passage components that could lead to different alternatives:

- replace runner including new fixed and rotating wearing rings, if applicable;
- restore water passage surfaces;
- modify shape of stay vanes;
- modify or replace guide vanes;
- increase guide vane opening;
- modify draft tube shape;
- turbine inlet valve modification or replacement;
- modify headcover to accommodate more efficient seals.

If the output from the turbine is increased, it will be necessary to analyse all of the components (mechanical and electrical) in the power train. These include, but are not limited to:

- channels, power tunnels and penstocks;
- shafts;
- guide vane servomotor stroke and operating pressure;
- Kaplan runner servomotor stroke and pressure;
- thrust bearing;
- governors;
- generators;
- bus and cables;
- transformers;
- excitation systems;
- transmission lines;

– switchgear.

The electrical equipment is not covered in this document.

For evaluation purposes, the activities should be separated into those contributing to performance improvement, those required to reinstate an acceptable degree of reliability and those required for other reasons such as environmental, social, or regulatory.

For powerhouses with a large number of units and a low utilization factor, one should evaluate the benefits of not rehabilitating all of the units to the same level. A few units could be upgraded and operated on a continual basis while the balance of units, having lower performance, are used for infrequent high load demand periods or during short duration high discharge periods.

It is usually possible to identify, without turbine dismantling, the necessary major activities of a turbine rehabilitation. However, there are some types of problem, such as a crack in the water passage surface of the headcover that cannot be detected until the unit is dismantled. This type of problem can cause a significant extension of the outage. Appropriate contingencies shall be a part of any rehabilitation plan.

5.3.4.5 Determination of scope for alternatives

For each alternative, a detailed listing of planned modifications or replacements of equipment components shall be developed. It is important to identify which items can be obtained prior to the outage and which items shall be modified during the outage. In addition to the obvious impact on cost, this list may also significantly impact the schedule and transportation requirements.

While this document focuses only on the details for the turbine, the hardware modifications and procurement decisions shall include all equipment, including governor, generator, transformer, etc. to permit a meaningful economic analysis. Any required modifications to civil structures shall also be included.

5.3.4.6 Determination of cost for alternatives

The cost determination should consider all of the following elements:

- all costs related to the supply of new or replacement components;
- all engineering and project related costs by the owner, suppliers, and consultants;
- costs related to the modification of existing components;
- one-time costs such as model tests, field tests, patterns, etc.;
- costs of fieldwork: disassembly, re-assembly, machining, crane rehabilitation, etc.;
- lost opportunity costs during the outage (energy, capacity and other ancillary services);
- operation and maintenance cost changes;
- contingency for undetected problems in the planning phases;
- financing or interest charges;
- cost escalation;
- environmental/social/regulatory costs;
- influence of schedule on escalation and cash flow.

5.3.4.7 Determination of schedule for alternatives

It is very important to consider the schedule associated with each alternative. The time of year of the outage and length of outage can have a major impact on the cost of lost energy production during the outage. One outage per year on a given unit will allow for the outage to occur at the lowest energy production and value time of the year, but each outage will then incur a mobilization and de-mobilization cost. For a multiple unit plant with a low capacity factor, back-to-back outages will eliminate repeating mobilization and de-mobilization cost, result in less change of people in the work crew, and allow the owner to experience the benefits sooner. However, in many cases, back-to-back outages are not financially justified because they would extend into the high revenue periods or reduce the opportunities of satisfying peak demands. Changes in schedule will cause additional cost and will impact cash flow.

5.3.4.8 Determination of benefits for alternatives

The benefits for each alternative are determined by:

- obtaining the expected performance gains in efficiency and power from the hydrology and hydraulic engineering team members;
- determining the improvement in revenue by doing a computer simulation of plant operation with these performance gains, the anticipated operation scheme and the anticipated value of energy for the number of years in the financial analysis;
- evaluating the reduced operation and maintenance costs;
- evaluating the ancillary benefits.

5.3.4.9 Risk management for alternatives

Risks associated with the various alternatives being studied shall be considered and, where possible, evaluated. Areas of risk include the following:

- non-achievement of performance (power, efficiency, hydraulic instability and cavitation pitting);
- damage to or failure of a component that was not rehabilitated and establishment of related energy losses;
- damage to a component that was not intended to be rehabilitated, discovered after dismantling;
- escalation rates (sensitivity analysis is recommended);
- financing or interest rates (sensitivity analysis is recommended);
- currency exchange risk (if applicable);
- extended outage period and related energy losses;
- risks related to safety, environment, etc.;
- market changes;
- bonding (required extent and timing of coverage).

Note that the scope of the rehabilitation alternative will have an impact on the level of risk attributable to it.

5.3.4.10 Economic analysis for alternatives

An economic analysis is first performed for each alternative to ascertain the optimal solution. After an optimal solution has been selected, a financial analysis is performed to confirm the financing requirements and the overall viability of the project.

5.4 Contractual issues

5.4.1 General

The following subclauses can apply to either the bidding or the partnering approach of contract arrangement. The exact content of the documents could be different in the two approaches, but the goal is the same: precision and clarity.

5.4.2 Specification requirements

The scope of supply for each activity or component, the goals and the assignment of responsibility and project schedule shall be very clear and precise, as in any contract.

It is difficult when writing the specification for a rehabilitation project, to cover all work in detail and to define the sharing of the responsibilities between the contractors and the owner for unpredictable events and consequent changes in scope. Provisions should be made in the contract for changes in scope and extra work. Labour rates for the various trades should be called for in the tender to cover extra work involving field labour. For identifiable potential additional supply items, prices should be called for in the tender.

The schedule for all activities shall be very clearly defined. These activities could include assessment, determination of scope, preparation of specification, consulting services, supply of equipment, rehabilitation of equipment, disassembly, re-assembly, project management, etc.

The expected performance improvements should be clearly stated regarding power, efficiency, cavitation erosion and operating stability. Improvement of the turbine operating characteristics may be determined by a pre-outage “signature” test followed by a post-outage test; both performed on the same unit, using the same method and preferably using the same test instruments and test crew.

In the preparation of the specification, a decision is required on the method for performance guarantee validation: model testing (fully or semi-homologous) or relative or absolute prototype efficiency testing (in the plant), or both.

The manner in which the specifications are prepared and which team members are involved will depend on the selected strategy for the execution of the rehabilitation project.

5.4.3 Tendering documents and evaluation of tenders

The exact use of tendering documents will depend upon the contractual arrangement used. Tendering documents can be used to choose a partner or partners (near the beginning of the process), procure hardware and/or services, or a combination of these. The intent and use of tendering documents for a rehabilitation project is the same as for any other major contract.

Tendering documents shall be prepared in a manner that assures that those responding will submit information on a common basis and be judged on a common basis. To achieve this, the owner should make available to all tenderers, all necessary information pertaining to the design and performance of the existing unit and all available information on its condition. This should be done with due respect for current laws regarding disclosure of proprietary information. The tender documents should provide for a mandatory site visit early in the tender period, with access to the water passages of the unit to be rehabilitated, to fully inform all tenderers.

In the evaluation process, clarifications may be sought and adjustments made to the tendered information. Performance improvement claims shall be very carefully analysed during tender evaluation to develop confidence in the technical logic which has led the potential supplier to its conclusions, particularly in the case of turbine rehabilitation, where the other water passage components and the unit speed may not be ideal for a new modern runner of usual design.

The evaluation criteria shall be clear. The value of additional energy production (kWh) is most often represented by a value on increased weighted average efficiency and/or on increased power. The tender documents shall either specify in detail the evaluation criteria or specify the options which are to be priced and described in the tender along with their influence on guaranteed performance.

Another key criterion is the cost of the outage that can be represented as a cost per day for a given period of the year. The management of the outage period involves a balance between the costs of new parts to remove their rehabilitation from the critical path against the reduction of the outage period. The owner can offer a bonus for early completion and exact a penalty for late completion.

Strategies of performance evaluation should ensure that the tenderer is lead to quote a realistic level of guarantees. All of these strategies involve evaluation of performance guarantees at the time of tender evaluations then later with the chosen contractor, some involving bonuses and penalties at the conclusion of model or field testing.

5.4.4 Contract award(s)

The contract documents shall be consistent with all other documents used prior to contract award. These other documents include tender documents, all addenda to the tender documents, the selected supplier(s)'s tender, minutes of clarification and/or negotiation meetings and any other documents which may be pertinent to the execution of the contract. The contract documents shall identify all options and scope alternatives that are to be retained in the execution of the project.

5.5 Execution of project

5.5.1 Model test activities

The owner should monitor and review the following activities in progress or at conclusion to the extent required by its in-house policies:

- design, drawings and bills of materials;
- manufacturing with respect to homology tolerances and conformance to drawings and bills of materials;
- installation regarding conformance to drawings, tolerances and procedures;
- turbine model testing in manufacturer's laboratory or in an independent laboratory, if specified, including instrument calibrations.

If the competitive bidding arrangement is chosen and if competitive model testing in manufacturers' laboratories and in an independent laboratory is chosen, then at least two turbine suppliers shall be selected for this testing. In the case of a competitive model test, manufacturers should be encouraged by specification to be inventive on the subject of how best to satisfy owner's interests regarding performance of the rehabilitated machine.

It is important to realize that fully homologous model tests will give a very reliable indication of the increased revenue that can be generated from the upgraded units provided that the surface condition of the entire water passage is properly taken into account. Therefore, it may be beneficial for project planning purposes, to perform the model tests by separate contract early in the detailed study stage.

If a project is relatively small, a model test may not be economically justifiable. In such cases, a hydraulic design can be finalized by the use of computational fluid dynamics (CFD) tools without the execution of a model test.

5.5.2 Design, construction, installation and testing

The owner will monitor and review the following activities in progress or at conclusion to the extent required by its in-house policies:

- component design, drawings and bills of materials;
- materials selection as compared to specified materials;
- quality assurance, and quality control (inspection) requirements;

- shop tests and inspections;
- dimensional control and homology verification (especially for the runner) in accordance with IEC 60193 and the contract specifications;
- site disassembly, reconditioning or modifications of components, re-assembly, and alignment;
- commissioning of the unit;
- prototype performance test (absolute efficiency), power-gate test or index (relative efficiency) test;
- load rejection test;
- runner testing to identify natural frequencies and vibration mode shapes;
- turbine component strain gauge tests;
- servomotor differential pressure test;
- mechanical heat run – measuring the bearing and oil temperatures;
- measurement of draft tube and spiral case pressure fluctuations, shaft system dynamic runouts and headcover deflections, the latter being usually limited to cases involving a new design and large machines.

5.6 Evaluation of results and compliance with guarantees

5.6.1 General

Guarantees can be established for:

- improvements in power and/or efficiency based on model tests and/or prototype (relative or absolute) tests;
- schedule performance;
- cavitation pitting limit;
- runaway speed withstand.

5.6.2 Turbine performance evaluation

Turbine performance evaluation is done normally by model tests in accordance with IEC 60193 and/or by prototype tests (absolute or relative) in accordance with IEC 60041, whichever is called for in the contract documents. IEC 60041 covers the arrangement for tests at the site to determine the extent to which the main contract guarantees are satisfied. This is the method best suited to the case where a model test is not performed in full homology or when the prototype components are not in full geometric similarity with the model. The cost of the measurement and the level of inaccuracy of measurement present the major drawbacks of this method to verify compliance of performance with guarantees. However, doing the before and after tests on the same unit using the same equipment and test team reduces the contractual significance of systematic inaccuracies.

Every effort should be made to establish the roughness of the existing prototype water passage surfaces before the bidding stage and therefore, before the guarantees are established. This is particularly important for the runner and the distributor (the stay ring, the guide vanes and the water passage surfaces of the headcover, bottom ring and discharge ring) whose friction losses are significant in the establishment of the overall turbine efficiency. Having this information in the tender document allows the tenderer to evaluate the potential benefits of various options regarding the improvement of water passage surfaces.

Following the specified guaranteed period of operation, an inspection for cavitation erosion should be performed. This inspection consists of recording and mapping any cavitation erosion damage on the runner and adjacent components. The damage is then compared against the guaranteed limits of the contract documents. For evaluation methods, see IEC 60609 (all parts).

5.6.3 Generator performance evaluation

If the contract is based on turbine efficiency as opposed to unit efficiency, generator performance tests should be carried out in accordance with applicable standards.

5.6.4 Penalties and/or bonuses assessment

At any point in the above processes, the owner may assess penalties and/or bonuses in accordance with the contract. Penalties and/or bonuses can be based on model and/or prototype performance, prototype cavitation pitting, conformance to the schedule, costs, safety, or any other aspect of quantifiable interest to the owner.

6 Scheduling, cost analysis and risk analysis

6.1 Scheduling

6.1.1 General

Consideration should be given to scheduling all phases of a rehabilitation project including assessment of the equipment, feasibility study, determining the scope of work, preparation of specifications, and execution of the project. Project organization will impact scheduling of the various project activities, but regardless of how the project is organized, all of the project activities need to be scheduled in a logical sequence.

Scheduling is a project management tool used to coordinate activities and ensure timely and cost-effective completion of the work processes. To determine the scope of work, a realistic work plan and schedule should be established and used to guide the work process. A realistic work plan and schedule will ensure that all of the activities required to determine the scope of work are completed in a timely manner, and that only activities required to determine the scope of work are performed.

The time that will be required to complete the activities and the associated costs are almost always significant factors in determining the feasibility of a project. Costs are closely related to the duration of the work. Costs may increase if the work shall be completed in an unusually brief time period and may also increase if the work is drawn out over an unnecessarily long period.

Whatever scheduling tool is used to organize the planning process, it should be sufficiently detailed to identify who does what and when. The more compressed the schedule, the more important detailed planning and scheduling becomes. The planning process should include a logical step-by-step identification of the work required to thoroughly perform the assessment activities. Whatever method of scheduling is employed, certain requirements are common to all methods:

- Definition – Identify work requirements and break them down into specific activities or tasks.
- Sequencing – Establish a logical order in which the work activities shall be done.
- Dependency – Identify inter dependency of activities or tasks. Does one activity need to be completed before another activity can start?
- Duration – Establish a reasonable duration for each activity. Identify the amount of effort (work) and length of time (duration) required to complete each activity.

A detailed work plan for all of the project phases needs to be developed and specific tasks identified. Once the work plan has been established (who does what and when) the sequencing or scheduling can be done.

6.1.2 Scheduling – Assessment, feasibility and detailed study phases

Collecting and evaluating historic river flow and plant operating data and conducting detailed equipment assessment can be very time consuming, but this information can profoundly affect the technical and economic aspects of the project. The organisational strategy of the project team has a significant impact on the schedule. Will a contractor or consultant be involved in this portion of the project? Is sufficient in-house staff available to work on multiple activities or will additional resources be needed? How long will it take for responses from government agencies or other sources of information or permits? Can equipment assessment activities be conducted during regularly scheduled maintenance outages at off-peak times?

6.1.3 Evaluating the scheduling component of alternatives

When considering the “baseline” scope of work and that for each alternative, the impact on the overall project schedule should be considered as well as the impact on the costs and benefits. Estimates of the time requirements of each alternative, if not within the capabilities of the owner, may be obtained from equipment manufacturers or from experienced consulting engineers. Alternative scheduling options should be evaluated to determine the most cost-effective option.

The cost of the construction phase of the project is a significant portion of the overall project costs and there is often opportunity to minimize some of the construction costs by properly scheduling the work. The advantages and benefits of the different schedule alternatives need to be weighed against the disadvantages and costs. Some of the aspects to consider are:

– Is there benefit to scheduling construction outages only during non-peak energy seasons (for minimum loss of revenue)? The time of the year and length of unit outage may have a big impact on cost of the outage. The foregone opportunity costs, (both for energy and capacity), should be evaluated when determining the construction schedule.
– Some of the disadvantages of split or discontinuous schedules can include project and contractor demobilization and remobilization costs, loss of team members and skilled craftsmen and having to repeat the learning curve with new crews.
– Can the contractor pre-assemble replacement components before the units are taken out of service, or between split outages to reduce the outage time?
– Scheduling rehabilitation of the units concurrently, overlapping unit outages, or even scheduling multiple unit outages can minimize the duration of the construction phase of the project. Are the resources available to support the schedule?
– Lay down space within the powerhouse, storage space outside the powerhouse, and floor-loading limits need to be evaluated. This is especially important if there is more than one unit apart at the same time or if extensive generator work is also planned at the same time or if increased capacity involves heavier components than the original components. Most powerhouses have different load carrying capacities in different areas to satisfy the original construction plan.
– For parts intended to be rehabilitated and reused, it shall be determined if this intent will affect the critical path of the project. Consideration may be given to making one new part for the first unit, and then rehabilitating the part removed from the first unit for the second unit, and so forth for additional units. This approach is applicable only to rehabilitation of multiple identical units.
– How will “surprises” which inevitably occur on rehabilitation projects, affect the schedule? Is the schedule flexible enough to accommodate unanticipated changes to planned activities or additional activities to “recover” lost time?
– Other constraints (such as fish migration periods for example) may influence the periods in which the units are available for rehabilitation.
– Schedule duration impacts cash flow, escalation and the cost of money.
– Transportation durations.
– Seasonal access constraints.

6.1.4 Scheduling specification and tendering phase

Sufficient time should be allowed for development and review of the tendering documents to assure completeness and accuracy. The tendering phase schedule will depend on the strategy for picking a contractor and on contractor participation, but in any case should allow sufficient time for:

– review of tenderer's qualifications;
– site visit by tenderers for inspection of a typical (or "problem") unit early in the tendering period if practicable (the importance of this activity cannot be over emphasized);
– responses to tenderer's questions;
– preparation of tenders;
– evaluation of tenders;
– negotiation of terms and internal approvals;
– award of contract(s) or notice(s) to proceed.

6.1.5 Scheduling project execution phases

The schedule for the execution phase of the project can have a significant impact on the overall profitability of the project. Delays in design, construction or installation can lead to project cost overruns. A sufficiently detailed schedule should be prepared by the tenderer then confirmed by the selected contractor to permit the owner to monitor progress. The schedule should be updated regularly and monitored by the project team. If the project begins to fall behind schedule, contingency plans should be implemented to get back on the contract schedule.

All events that can have an impact on the schedule should be evaluated. Some of the items to consider are:

– Outage duration (lost generation opportunities).
– Schedule rehabilitation of support equipment prior to rehabilitation. This includes such items as cranes, lifting devices, un-watering and drainage systems, headgates, turbine inlet valves, stoplogs, etc.
– Impact of hazardous or toxic product abatement such as lead, asbestos or PCBs.
– Impact of inspections following disassembly and refurbishment of equipment and components to be reused. Adequate durations shall be provided in the schedule for refurbishment of critical components or spare components shall be made available at the appropriate time.
– Impact of damaged equipment or components and problems not anticipated prior to disassembly. Does the schedule provide for contingencies?
– Aspects of the planned work shift schedules such as overtime costs, worker fatigue from excessive hours, shift-to-shift transfer of information, quality of supervision on all shifts, etc. need to be considered and planned around.
– Transportation modes available to access the powerhouse (and their limitations), availability of storage facilities on site, limitations of access and egress into the powerhouse and mobilization and staging areas all need to be evaluated.

6.2 Economic and financial analyses

6.2.1 General

Before starting any major rehabilitation or performance improvement program, it shall be recognized that major investment decisions should be evaluated over the life of the project. Most organizations will have their own well defined economic and financial analysis procedures which should be followed before capital can be committed and it is not intended that the following should in any way supersede those proprietary procedures. It is recommended that, where there is any doubt, professional help be obtained from a financial analyst who will ensure that proper procedures are followed. It is, however, up to the members of the project team to identify and quantify all of the factors which affect the cost(s) and benefit(s) of the project and the various alternatives to be considered.

For any rehabilitation or performance improvement project, there could be a number of different options and deciding the best way to proceed may not be straightforward. Some decisions might be easy such as the need to remove grease lubricated bearings to conform to revised environmental requirements. However, other choices are less clear-cut and require analysis of their financial impact before a decision can be made.

The benefit-cost analyses (economic analyses) of the various alternatives identified during the detailed study phase should be undertaken to rank the various alternatives and determine the most favourable course of action for the project. The benefit-cost analyses may be very simple or quite complex depending on the size of the project, number of units involved, number of alternatives studied, etc.

It is often useful for an engineer to complete a simplified economic analysis as a screening tool to identify those alternatives which provide the most favourable economic value and reduce the number of options that will subsequently be examined in more detail. As a base case, rehabilitation or performance improvement plans may be compared against the continued operation of the existing plant with no rehabilitation provided that the existing plant has no evident reliability or safety problems.

Whilst determining whether to proceed, the financial performance of the plant with a minimal intervention option should be compared against that of the plant having undergone the full rehabilitation and performance improvement.

6.2.2 Benefit-cost analysis

Although this document concentrates upon the framework and details of a rehabilitation or performance improvement of hydraulic turbines, these are only one component of a complete generating station and it would be unusual and indeed unwise to consider the rehabilitation of a turbine on its own without regard for the condition of the remainder of the plant. Consideration of benefits and costs should therefore include the full scope of the project including all equipment and structures essential to reliable energy generation.

Many different economic evaluation methods are used to evaluate the feasibility of capital expenditures. The common economic evaluation tools include:

– net present value (NPV);
– benefit/cost ratio (B/C);
– internal rate of return (IRR);
– pay-back period.

To balance the short term costs of rehabilitation against the long-term benefits, most utilities use some form of present worth or net present value to relate the benefit and cost streams which occur over time. The present value method is straightforward, can be used to compare incremental benefits and costs, and does not require detailed financial criteria.

The present value of all rehabilitation benefits achieved is compared to the present value of all costs attributable to the rehabilitation over a fixed period of time. Comparison may be made by subtracting the present value of the costs from the present value of the benefits or by dividing the present value of the benefits by the present value of the costs to obtain the B/C ratio. Theoretically, a rehabilitation investment is justified if the benefits exceed the costs or if the B/C ratio is greater than 1. Typically, organizations require the B/C ratio to be greater than 1 to allow for contingencies and a positive return on investment.

It shall be noted, for rehabilitation or performance improvement projects, that some costs will be incurred regardless of whether the project is rehabilitated or not. The benefits and costs of rehabilitation should be compared to the benefits and costs of a base case. Therefore it is essential that the benefits and costs of this base case be properly represented. Various approaches may be used to establish the base case, ranging from decommissioning of the units as they fail, to maintaining the plant in operating condition by repairing or replacing components as they fail. O&M costs would increase and generation would decrease over time. Another approach for consideration could be termed “life extension”, whereby the unit is disassembled and reassembled to inspect and repair the mechanical components to “like new” condition. For this approach, the cost of disassembly and reassembly are included in the costs along with outage and foregone income costs.

Care should be exercised when evaluating between alternatives to use only the incremental benefits and costs directly attributable to the specific alternatives being evaluated. Each utility’s costs and benefits are unique to that utility and as a result, the following can only be used as guidance. The utility’s own financial arrangements should therefore be used wherever available to determine the benefits and costs associated with any rehabilitation or performance improvement program.

6.2.3 Identification of anticipated benefits

6.2.3.1 General

The time interval used to evaluate the operating benefits is the period in which the organization wants to recover the costs of the rehabilitation or performance improvement program. The evaluation period may be the expected life of the rehabilitated plant, the financing period, or a shorter period should a more rapid recovery of investment costs be desired. The evaluation period should be established by each individual organization depending on its own unique circumstances.

6.2.3.2 Plant generation benefits

These include the following:

– Increased output – Alternatives that increase either or both the capacity or energy output of the plant need to be evaluated and ranked to determine which provide the best economic benefit/cost scenario.

– Increased efficiency – Efficiency gains from rehabilitation or performance improvement shall be considered as even small efficiency gains provide substantial economic benefits over the life of the project particularly if the units shall be rehabilitated for reasons of life extension in any event.

– Income from ancillary services – These include such items as spinning reserve, reactive power control (VAR), black start capability, automatic generation control (AGC), frequency control.

– Other benefits associated with the proposed (optimal) alternative.

6.2.3.3 Operation and maintenance (O&M) benefits

These include the following:

– Increased availability – Significant benefits can be realized by reducing the forced outage rate and increasing the unit availability thereby improving the plant’s reliability.

– Improvements to operation – Operation can be improved by incorporating modern control systems, and replacing or rehabilitating plant auxiliary equipment that has become or will become failure prone. Many manual devices can be replaced by automated data acquisition or supervisory control devices.

– Reduced operating and maintenance expenses – O&M costs of a rehabilitated plant often can be significantly lower than if the plant continued to operate with no rehabilitation.

– Evaluation of personnel requirements after rehabilitation can often provide substantial economic benefit. This is particularly evident where 24 h staffing requirements can be reduced to one shift staffing or remote control, for which positions may even be eliminated.
– Intervals between maintenance may also be increased after rehabilitation, and the extent of maintenance performed should be reduced considerably for many years as a result of rehabilitation.
– Insurance benefits – Quite often, insurance costs can be reduced when installing modern equipment with improved monitoring, control and protection systems.

6.2.3.4 Environmental benefits

Plant rehabilitation or performance improvement programs provide the opportunity to incorporate technological improvements that can provide environmental benefits as well as O&M benefits. Example would be replacing grease lubricated bearings with self-lubricating bearings or using of water filled Kaplan hubs.

Improved fish passage features may be incorporated into the turbine design if passage of fish is an issue at the particular project. Design producing minimum streamflow for downstream fisheries is another possibility as well as increased aeration of the discharge.

6.2.4 Identification of anticipated costs and benefits

6.2.4.1 General

As stated previously, care should be exercised when evaluating alternatives to use only the incremental costs and benefits directly attributable to the specific alternatives being evaluated. This is essential when examining the effect of increasing or decreasing the scope of the various rehabilitation options.

An example could be to examine the effect of increasing or decreasing the scope of the immediate rehabilitation. For instance, the remaining life of different equipment of the power station such as the turbine and generator can be different. It may be considered that the turbine could operate satisfactorily for a further five years before rehabilitation whereas the generator is in urgent need of repair. A reasonable question to ask would be whether the rehabilitation of the turbine should be delayed until repair became more urgent? There are therefore (at least) two options to be considered; firstly to rehabilitate the generator as soon as possible while delaying the rehabilitation of the turbine and secondly to rehabilitate both items of the plant at the same time. The main advantage of the former would be that it would minimize the immediate capital expenditure, whereas by rehabilitating both components at the same time, future unit availability would be maximized. The value of unit availability often predominates if the intervention options are in the near term.

6.2.4.2 Capital costs

The obvious capital costs include the following:

– Cost of equipment – Includes all direct costs for equipment, material, construction costs associated with disassembly, installation of new equipment, testing, and disposal of the old equipment.
– Cost of financing – Includes cost of financing the project such as interest, escalation, and other financing related costs.
– Contingency – Allowance for inaccuracies in other direct cost estimates as well as miscellaneous and unexpected costs. The magnitude of the contingency costs depends on the confidence level of the direct cost estimates.

6.2.4.3 Investment related factors

These include depreciation and salvage costs and other tax-related costs if applicable.

6.2.4.4 Outage costs

Income is only produced when the power station is generating or available to generate energy or to provide ancillary services. If the design of the power station and timing of the rehabilitation project is such that rehabilitation can be completed without spilling water, then there should be no reduction in the energy generated. However, unless the rehabilitation is being carried out following a plant failure that is preventing generation (forced outage), there will be a loss of generating capacity and/or ancillary services caused by the decision to rehabilitate (planned outage). If an adequate margin of installed capacity is available, then the loss of capacity during rehabilitation might not result in any appreciable loss of income to the utility. There may be seasonal periods where the value of capacity is low, or impact of capacity loss is low. The more interconnected the system being fed, the more likely there will be a "lost opportunity" cost associated with any rehabilitation project, even where spillage of water can be avoided.

Outage costs include:

– forgone revenue during rehabilitation outages (loss of energy income including potential spillage);
– lost market opportunity costs (peaking and ancillary services);
– potential loss of acquired rights (usually associated with re-licensing and not the rehabilitation *per se*);
– other costs associated with the proposed alternative (de-ratings, etc.).

6.2.4.5 Project staff costs

Office and staffing costs for planning, engineering, purchasing, environmental studies, factory and site QA and inspection, commissioning, field supervision, and on-site training costs should be considered when evaluating the project costs. While this list is not all inclusive, it identifies some of the project staffing costs associated with the project.

Temporary office facilities are required to house project personnel at the site for the duration of the project. Temporary facilities for project personnel include office space, support staff, rent, office equipment, utilities, temporary computer and communications infrastructure and all other costs necessary to support the project staff. At remote sites, this would also include living accommodation.

6.2.4.6 Schedule duration and effect of delay on the project

The scheduled duration of the project will affect many facets of the economic evaluation. Not only the total project duration and individual outage durations, but for multiple unit plants, the staging of successive unit outages can significantly impact both the benefits and the costs. Delays with respect to an established schedule affect both direct and indirect costs, their extent depending upon the cause. These can be very significant if the unit non-availability costs are high.

6.2.5 Sensitivity analysis

There are always uncertainties in any predictive analysis and it is good practice to determine the sensitivity of the economics of a project to changes in the base assumptions. The sensitivity analyses should include any parameters where a change would significantly affect the project performance. Typical parameters which merit sensitivity analyses would be changes in capital cost, changes in the duration of the rehabilitation project, the expected gain in efficiency and the value of energy and other revenue products.

Other sensitivities may be applicable for the particular project being considered and all identifiable significant risks should be evaluated. It is often useful to plot the results of the sensitivity analyses to more clearly indicate any trends.

6.2.6 Conclusions

The preceding subclauses give a brief introduction to a simple method of economic and financial analysis for rehabilitation projects. The procedure explained should be adequate for evaluation of options and should help plant engineers select from the economic and financial standpoints, the best rehabilitation option for their plant.

6.3 Risk analysis

6.3.1 General

Risk analysis is generally conducted in addition to the overall economic evaluation to justify proceeding with a rehabilitation project or to justify not proceeding with a project. Clause 7 discusses evaluation of the scope of the project, which is a prerequisite to being able to evaluate the risks associated with rehabilitating or not rehabilitating the plant. Risk is generally defined as the probability of an event occurring times its quantified consequences. Therefore, actions to decrease either the likelihood of the event occurring, or the cost of its consequences will reduce the (financial) risk. The equipment cost and other costs which may be incurred to reduce risk can be compared against the risk cost reduction when comparing alternatives.

A sensitivity analysis within the risk analysis can be conducted to determine the impact of certain assumption or factors on the alternatives. In addition to the significant influence of economic factors, the evaluation of alternatives involves estimating the probability of failure or when failure might occur.

Types of risks for analysis can be divided into the following categories, which will be described separately:

– non-achievement of performance risk;
– damage due to failure risk;
– extension of outage risk;
– financial risk;
– other risk.

Once the risk factors have been identified and assessed, contingency plans should be made to manage the risks.

– Can the project plan be changed to avoid, diminish or eliminate the risk?
– Can the probability or consequences of an adverse risk be mitigated or reduced?
– Are the risks acceptable, or can their impact be provided for by a contingency allowance of money, time, resources, etc.?

Like other aspects of the project, risks should be identified and monitored throughout the project to ensure effective control. Establishing and monitoring performance measures (such as project costs and schedules) will identify when contingency plans need to be implemented.

6.3.2 Non-achievement of performance risk

Rehabilitation work has many risks associated with the possibility that the contractor does not succeed in reaching its guaranteed performance values including for example power increase, efficiency increase, hydraulic instability limits and cavitation pitting limits. The cost impact of a failure to meet performance expectations is generally spread over the life of the equipment. The owner may attempt to recover such costs through warranty or liquidated damage provisions in the contracts signed with contractors.

The owner can choose some countermeasures for reducing these risks. Requiring and paying for a demonstration that the equipment design will result in the specified or guaranteed performance can reduce the probability of not achieving them. The use of CFD and model testing can provide increased confidence of meeting the performance expectations (at increased cost). The obligatory scheduling of prototype testing before and after the rehabilitation does not permit it to be used to reduce the owner's performance related risks. The potential uses of CFD and of various types of model or prototype testing are discussed elsewhere in this document.

6.3.3 Risk of continued operation without rehabilitation

One of the objectives of rehabilitating the turbine is to improve the reliability of the unit. It is important to include the "do not rehabilitate" option within the risk analysis. During the early assessment phase of the project, the risks associated with not rehabilitating the project such as a catastrophic failure of a component causing major project damage and an extended unplanned outage, should be determined. The evaluation of the type and magnitude of risks associated with the "do not rehabilitate" option should use the same approach as is used to evaluate risks of each of the rehabilitation options.

Risks associated with damage or failure can be of a minor nature, such as requiring installation of a new spare part, or can be of major proportions including catastrophic failure or danger to personnel. A condition, which is considered critical, potentially leading to a near term catastrophic failure or an identifiable high consequence failure or identifiable danger to personnel should be the basis for immediate rehabilitation.

The evaluation shall include the following costs associated with the alternative involving no rehabilitation:

– energy loss due to efficiency deterioration;
– lost revenue due to forced outages and unscheduled downtime;
– increasing O&M cost including additional inspection costs to maintain the plant;
– increased insurance premiums.

Failure to replace any component in seriously deteriorated condition will result in a high risk of failure and an associated high-risk cost. This can be quantified by estimating the number of years until the component encounters a major failure resulting in substantial loss of production and loss of life risk or both.

6.3.4 Extension of outage risk

Rehabilitation alternatives have a planned outage that is scheduled, plus the potential for the outage extending beyond what is planned. The likelihood of the extension of the planned outage for rehabilitation projects is higher than for new construction because of the potential for finding equipment that needs to be repaired or replaced as it is disassembled during the construction phase of the project.

The no rehabilitation option has the potential for equipment failure resulting in an extensive outage to cover design, procurement, fabrication and installation not only of the component which failed but possibly of many other components and of other equipment and even possibly, structures. Furthermore, the outage resulting from an equipment failure may come at the most critical time of the year when energy replacement costs are at their highest.

6.3.5 Financial risks

Examples of financial risks are:

– risk and impact of actual escalation not matching assumed escalation rate;
– risk and impact of the actual financing interest rate not matching the assumed rate;
– risk that rates for energy and capacity from which future revenue is evaluated, and from which the lost revenues during the rehabilitation work are evaluated, differ from the assumed values;

– financial risks including cost to purchase replacement energy during rehabilitation;
– currency exchange risk if applicable.

In addition to evaluating the financial risks based upon the best estimates of each component, it is generally prudent to also evaluate the sensitivity of the project economics to the assumptions made in the financial analysis. This being said, most owners have pre-established values for all financial parameters to be used in project evaluations.

6.3.6 Project scope risk

A good part of the financial and extension of outage risk is already built-in at the planning stage of the project.

Depending upon the importance of the unit being rehabilitated, any work on the critical path usually poses some risk related to its potential scope increase. Problems that are discovered after dismantling and inspection of the unit, can lead to extensive unplanned and unbudgeted work.

When defining the project scope, two different approaches can be taken:

– Under the terms of a contract which defines an anticipated scope, dismantle and inspect all components and execute required repairs according to engineering recommendations. This may and usually does give rise to scope changes.
– Plan in advance on replacing all doubtful existing components by new parts.

Those who try to minimize the initial budget and have, for reasons of plant hydrology, a comfortable planned downtime, usually retain the first approach. This normally creates the highest built-in risk of scope changes.

Those for whom downtime is critical usually lean toward the second approach, to minimize the risks related to an unplanned extension of the outage. In a multi-unit plant, this approach can be taken for the first unit and then a mix of the two approaches may be applied for subsequent units. The optimum project scope lies usually, somewhere between the two extremes.

When defining the scope of work in advance of the outage, there is the risk that the scope of the rehabilitation on a given part has been underestimated. Perhaps the larger risk is that of finding parts in an unforeseen deteriorated condition and having to do repairs on additional components. The solution to both of these problems is to do realistic planning which contains some “float” in the schedule and to provide contingencies which are greater than one would provide for new construction of comparable value. The level of contingencies will depend on how many components are planned to be replaced by new components, how good the plant records are concerning machine condition and how thorough an inspection was possible in advance of unit dismantling.

6.3.7 Other risks

Other risks such as risks for human safety and environmental risk should also be evaluated.

Human risks include the potential for injury or loss of life during the rehabilitation project, or the risk of corresponding losses from not rehabilitating the unit.

Environmental/fish damage risk from hydropower plants may be due to:

– planned or accidental flow changes caused by the outage for the rehabilitation or during operation following rehabilitation;
– planned or accidental reservoir level changes caused by the outage for the rehabilitation or during operation following rehabilitation;

– discharging contamination such as lubricating oil during the outage or during operation.

However, an extended outage may give an opportunity for conducting several positive environmental programs such as water quality, river flow improvement and bank protection work. Environmental improvements may also result from the rehabilitation project if, for instance, the runner is replaced using new design for improved fish passage.

The rehabilitated unit may have either a positive or negative influence on the environment depending upon the specific changes made. Generally, the environmentally least aggressive approach to increase power production is the one which does not change the discharge. The gain is then obtained from efficiency increase and the corresponding capacity increase from the existing units.

7 Assessment and determination of scope of the work

7.1 General

This clause presents the main elements which should be considered during assessment of the turbine and related equipment and which could influence or be influenced by the turbine rehabilitation and performance improvement work. A complete evaluation includes the following three items:

– assessment of the site;

– assessment of the turbine;

– assessment of the related equipment.

7.2 Assessment of the site

7.2.1 Hydrology

Optimal operation of a hydroelectric plant relies not only on the efficiency of the turbines but also on the best use of the available flow and head. The conditions prevailing at the time of construction of the facilities can change over the years. The hydraulic potential of the site and its operating mode should then be reviewed taking current conditions into account.

A sole turbine efficiency uprate should normally not have much effect on the operating pattern of the plant. However, a combination of power and efficiency uprate can result in a change to the operating mode of the power plant, reducing the usage factor and giving increased energy production with potential effects on the environment.

The main questions to be asked are:

– Is there any possibility to change the flow?

– Are there any new restrictions or opportunities on headwater or tailwater levels which would result in a change in the specific hydraulic energy on the turbines or to the plant Thoma number?

– Are there any new restrictions or opportunities on operating mode due to environmental or social considerations?

Good records for 25 years or more are required for reliable statistical analysis of potential future production. A summary of the site hydrology, that is the average hourly, daily, weekly or monthly heads and flows versus time, should be available for the longest possible period of operation.

If this information is unavailable directly via measurements, it can be deduced from energy production, headwater and tailwater elevation records, calculated or measured losses outside the turbine and measured or assumed efficiency of turbine and generator then taking into account any water releases at the spillways. Care shall be taken in using “assumed” efficiencies. They shall be based on original manufacturers data or earlier tests with due regard for deterioration resulting from machine condition. This information along with a correlation with adjacent hydraulic systems may be used to determine whether there has been a change in the hydrology of the site or in the hydraulic parameters of the power plant.

Changes in hydraulic parameters or in the intended mode of operation of the plant can change the turbine rated conditions and influence the selection of the best solution for the rehabilitation or improvement of the turbine.

7.2.2 Actual energy production

Existing data on annual energy production at the plant provides the owner with the baseline data from which he may establish the value of any potential improvement of the performance of the plant equipment. If independent sources of hydrologic data are available, the energy production data also provides the possibility of establishing a performance trend toward deterioration. If no such independent sources of hydrologic data are available, the past records of energy production, estimated records of spillage at the site and an approximate knowledge of the existing generating equipment characteristics allows one to construct a history of the hydrology at the plant with a potential inaccuracy of the order of plus or minus 5 %. This is at least as good as most available methods of establishing the hydrology at any undeveloped site.

For maximum usefulness, energy production records should be obtained for each unit under study for the longest possible period of record, more than twenty-five years but not less than ten years. When the period of records is that short, inaccuracies will be higher than 5 %.

The available information should be plotted over the period of record and any trends should be observed, questioned and explained.

Causes of changes may include equipment performance degradation, changes in hydrology, changes in the operating philosophy or water management and the impact of planned and forced outages which relate to equipment reliability. Care should be taken not to overweight short terms trends or events. If indeed equipment efficiency degradation is the root cause of a trend, it can be confirmed by a comparison between the present and the original efficiency curves wherever such data is available.

Often, significant gains in energy production can be achieved by improvements in reservoir management. Even if this aspect is not dealt with in this document, it should always be part of any serious rehabilitation study.

7.2.3 Environmental, social and regulatory issues

Environmental, social and regulatory rules set the conditions for the operation of the plant. These rules are intended to recognise multiple water use objectives by balancing environmental, social, and economic uses of the water. Some of the issues, which are reflected in these rules, are highlighted below:

– minimum flow requirements;
– limitations on headwater and tailwater elevation variations;
– allowable rate of change of flows (ramping rates);
– fish and wildlife flows;
– dissolved gas limits;
– recreational flows;
– domestic water/irrigation flows;
– electrical energy generation flows.

If the decision is to rehabilitate the plant for efficiency only, the flows would be the same before and after and hence the same regulatory rules may be applicable. However, any increase in output beyond that arising from the efficiency increase will involve the use of more water or changes in flow patterns during plant operation. These changes may trigger new rules that could be imposed even with no change in water use.

The possibility of new or revised rules regarding water management should be thoroughly reviewed at the start of any rehabilitation project to determine their impact, if any, on the operation and hence potential revenues of the rehabilitated plant.

7.3 The assessment of the turbine

7.3.1 General

The aim of the assessment process is to have in hand, upon conclusion, all of the information necessary to be able to determine if it is economically justified to proceed with rehabilitation of the turbine in order either to guarantee its reliability, to extend its life, to reduce maintenance costs and risk, or to improve its performance. Moreover, the assessment method can also be used by the owner to elaborate a preventive maintenance program and to predict the residual life of a given component.

There are two main aspects in the assessment of the existing turbine:

1) The **integrity** or mechanical condition of the turbine to be evaluated by a combination of:
   – deterministic approach: for each selected component, analysis of detailed visual inspection and/or measurements and/or NDT (non-destructive test);
   – statistical approach to take in account other considerations for non-detectable consequences of aging components.
2) The **performance** of the turbine which should be evaluated by a careful analysis of past operating records and conditions to assess the real performance improvement potential. This refers to:
   – efficiency;
   – power output;
   – mechanical vibration problems;
   – hydraulic stability;
   – cavitation/erosion problems;
   – operating conditions and restrictions.

The methods of measurement are described in IEC 60041. It is recommendable to repeat the assessment regularly, in order to capture any change or evolution of some phenomena that can be caused by aging process. In fact, the quality and precision of an assessment are directly linked to the assessments frequency and proximity. The owner shall therefore decide for himself which assessment method will best fit his needs. He has to define which components of the turbine he will assess and at what rate, trying to optimize the cost of assessment, the cost of operation and the risk he can sustain.

7.3.2 Turbine integrity assessment

7.3.2.1 General

The assessment of the turbine mechanical integrity is essentially done by detailed inspections ideally including those made at different times in the life of the machine. Such detailed inspection can be done only with the unit dewatered and safely isolated. It is imperative that the inspection of turbine components be performed by a qualified and experienced engineer who would implicitly know what areas are subject to high stresses and potential cracking, particularly since the turbine is not disassembled and components are not fully accessible. Even with the participation of an “expert”, it is essential to proceed with the aid of a structured checklist such as the one presented in Annex A for turbine components.

Detailed inspections as an assessment tool are therefore limited; the unknown integrity of the turbine components until the turbine is disassembled constitutes a major problem for defining the need and content of a rehabilitation project. The result is that the rehabilitation cost, the precise outage duration and the resulting potential lost revenue are difficult to determine with precision at the time of preparation of the scope of work.

This is why the assessment method shall involve other considerations for non-detectable consequences of aging. In order to keep it simple, some owners propose to take into account:

– the actual percentage of life expectancy which is based on the amortization period, and

– the maintenance ratio based on the actual hours used for maintenance compared to the usual or normal hours for the same component.

It becomes obvious that a rigorous maintenance program and reports, a journal of events and statistics on operation constitute the base of an analysis that allows to detect any abnormal increase of cost and unplanned shutdown.

The assessment can be divided into 3 categories of actions according to the order of priority:

1) easy to do inspections without dismantling and sometimes without dewatering;

2) more in depth investigation with NDT requiring dewatering and maybe dismantling;

3) repairs that can be considered temporary or permanent.

The first level of assessment is related to routine inspections and condition monitoring that should provide the basic information necessary to give an overview of the general condition of a power unit. It should also provide enough information to point out where additional investigations are required. The information collected should be recorded as part of the maintenance program and should serve the current condition assessment tool described in 7.3.3.4.

The typical routine inspection should include a mandatory visual inspection with observation report. Depending on the type of component, more typical parameters to monitor and typical routine inspections are given in Table 2.

Table 2 – Typical routine inspections

Type of component	Typical routine inspections
a) Embedded parts	– Inspection of manhole door, hinges and security features – Pressure measurements and/or monitoring (spiral case and draft tube) – Leak tests in piezometric end embedded piping – Voids in concrete (draft tube hammer survey) – Concrete to steel joints – NDT for crack detection (ex.: stay vanes)
b) Turbine non-embedded, non-rotating parts	– Leakage survey and/or tests (grease-water) (ex.: servomotors external oil leaks – water leak through head cover) – Gap measurements (ex.: guide vanes top, bottom, contact edges) – Friction test (operating mechanism) – Oil level and temperature measurements and/or monitoring for bearings – General wear condition (ex.: operating mechanism, bearing and journal, shaft seal and wear sleeve) – Visual inspection and hammer testing of critical component fasteners (such as headcover to stay ring fasteners)
c) Turbine rotating parts	– Blade to discharge ring gap – Runner seals to bottom ring and head cover gap measurements and/or monitoring – Cavitation (erosion) survey – Water intrusion or oil leakage for Kaplan runners – Vibration monitoring (dynamic bearing gap monitoring)
d) Auxiliaries	– Inspection and review of instrumentation set points and calibration – Pressure temperature and flow measurements and/or monitoring – Speed and load signals and guide vane position feedback systems – Leakage survey – Noise level survey

The assessment Tables A.1 to A.24, presented in Annex A, are designed to serve as checklists of the aspects that should be considered in the evaluation of each component of an existing turbine. Those aspects are presented under the headings “aspect of concern”, “possible causes or reasons” and “possible inspections/actions” and they cover inspection categories 2 and 3 described above.

The tables are arranged as follows:

a) Turbine embedded parts:
   - stay ring (Table A.1);
   - spiral or semi-spiral case (Table A.2);
   - discharge ring (Table A.3);
   - draft tube (Table A.4).

b) Turbine non-embedded, non-rotating parts:
   - headcover (Table A.5);
   - intermediate and inner headcover (Table A.6);
   - bottom ring (Table A.7);

- guide vanes (Table A.8);
- guide vane operating mechanism (Table A.9);
- operating ring (Table A.10);
- servomotors (Table A.11);
- guide bearings (Table A.12);
- turbine shaft seal (Table A.13);
- thrust bearing support (Table A.14);
- nozzles (Table A.15);
- deflectors and energy dissipation (Table A.16).

c) Turbine rotating parts:
- runner (Tables A.17, A.18 and A.19);
- turbine shaft (Table A.20);
- oil head and oil distribution pipes (Table A.21).

d) Turbine auxiliaries:
- speed and load regulation system (governor) (Table A.22);
- turbine aeration system (Table A.23);
- lubrication system (guide vane mechanism) (Table A.24).

Some of the tables apply to all types of turbines while others apply to specific types of turbine only, as indicated in the table headings. Some parts fall in more than one category but, for clarity, they are listed in only one. For example, some parts may be "embedded" or "non-embedded" depending upon the design.

A detailed discussion of the most relevant aspects of concern for the mechanical integrity assessment and for the performance improvement of the turbine is presented in the following paragraphs. It suggests more detailed recommendations for some components of the turbine or for specific behaviour. This will guide the owner to elaborate assessment method for all components he considers critical.

7.3.2.2 Recommendations on phenomena and behaviour

7.3.2.2.1 General

We can identify 3 aspects influencing turbine behaviour:

1) the quality of the original design and materials can affect the durability and the reparability of the turbine components and can limit the possibility of new or temporary extended operating conditions;
2) the quality of the unit's erection and maintenance; if issues originating from this aspect exist, they shall be properly identified in order to avoid their repetition with the rehabilitated components;
3) the hydraulic conditions and the setpoint under which the generating unit has been and will be operated can have an influence on its mechanical integrity.

The acquisition of information on these 3 aspects is fundamental for a good quality assessment.

With due regard to the original design, the information that can be collected are as-built drawings, modifications, bills of material and any other information available on the machine design and its operating limits. If one fails to find the appropriate technical documentation and information, it is necessary to proceed with a more in-depth survey of the existing machine and its components. If the material of a component is unknown and a repair or modification is contemplated, samples and analyses may be required to confirm the repair options available.

The owner is well advised to make use of qualified personnel and proven software systems for this work, be they in its own service or through manufacturers or consultants. Despite the fact that many modifications are often not documented, there may be some advantage in accessing to the original detailed drawings and bills of materials to facilitate the analyses, planning and scheduling of the work. In some instances, it may be possible for the owner to purchase the right to the use of the original drawings and documentation, if such right does not already reside with the plant owner.

When available, the original erection procedure and the operation and maintenance manual are very useful information. They can be used to assess the actual quality of assembly by comparing original tolerances with actual measurements. They may also show existing special tooling.

Even with all documentation available, one additional precaution is to capture the signature of the machine. It consists before any intervention of measurements of temperature, noise, vibration level and other parameters followed by observations of mechanical wear, inappropriate mechanical gap, misalignment of components and other dysfunctions.

The information related to the operation of the turbine is also essential to correctly evaluate the condition of the existing unit and to adequately design the new components. Bad condition of operation can damage some components by fatigue, wear or erosion.

7.3.2.2.2 Material defects

Cracks, pores and similar defects weaken a component. However, while they do not necessarily lead to the need for its replacement, they always require a thorough documentation, observation and analysis.

Basic aspects to be assessed are:

– the criticality of a potential failure of the component;
– the origin of the defect:
  - from original manufacturing (hot tears, porosity, lack of fusion, slag inclusions);
  - or a result of the applied loads from unit operation (fatigue cracks, permanent deformation);
– size of the defect and the limit at which it is expected to grow under the anticipated loading.

The criticality of a defect is high if a failure of the component can lead to an outage of the turbine or if human life is endangered. This is especially true for all components on the pressure side of the turbine.

In-built defects are often found in spiral casings, penstocks and other components built during the period of the early application of welding technology. There are other possible sources of in-built defects. They are as numerous as the methods and materials used in the construction of turbine components. If these defects have not grown during many years of operation, they might be considered to represent a minor and acceptable risk. Their size, orientation and location in relation to the stress pattern in the component should be analysed before a decision is made to excavate and repair the defect. Welding repairs in themselves, on components which cannot undergo a subsequent thermal stress relief, induce a change in the residual stress pattern in the component and represent a risk factor.

Cracks which develop in service are the consequence of dynamic loads usually in combination with high static and residual stresses or internal defects or both.

Internal defects which were not detected during original manufacturing or which were detected and considered, by their location, size and orientation, to be acceptable might reach the surface due to abrasion through particle or cavitation erosion. Some typical examples of exposed components and zones are the root or inner contour of a Pelton runner bucket, the contour of a guide vane body where it joins the driving (usually upper) trunnion and the junctions of the blades with the crown and band in a Francis runner.

Conditions which favour the initiation and growth of cracks are high residual and applied stresses/strains, local plastic strains, oscillating elastic stresses/strains and a corrosive medium. Typical areas where these factors are a consideration are the shaft of a Pelton turbine near the runner coupling, flanges in spiral casings or stay rings with improper sealing or the coupling zones of runners with the shaft particularly in horizontal shaft machines.

Essential for a good evaluation of the impact of such defects on the structural integrity is their documentation and the observation of their progress during operation. The documentation should comprise the description of the location, of the size and orientation verified by NDT and a prescription regarding how to deal with the defect if it reaches or exceeds defined limits.

The evaluation of the potential impact of defects may be done with conventional techniques involving analytical calculations or, if necessary, numerical analysis in conjunction with fracture mechanics like that described in British Standard BS 7910, *Guide to methods for assessing the acceptability of flaws in metallic structures*. In many cases, a comparative analysis using conventional methods is the most applicable where assumptions and references are taken from parts with similar geometry and strain under similar loading conditions and which have given satisfactory service. One shall avoid the trap of spending more on the analysis of the impact of leaving a defect than it would cost to repair it.

The repair of defects can be done by grinding them out and leaving the cavity or by rebuilding the original component geometry by welding and grinding.

In the case of removal by grinding only, care shall be taken to evaluate possible side effects, for example secondary flows due to a disturbance of the hydraulic profile or weakening of the component at the location of the defect.

In the case of repair by welding, the determination of the proper welding technology and process, based on metallurgy of both base and filler materials, is crucial as an improper repair or heat treatment can increase the damage.

Preparation of an appropriate repair procedure requires a complete understanding of the material properties, the original design and manufacturing processes and the details of any repair history.

The documents attesting to the quality of the turbine fabrication, inspection certificates and repairs, both in the shop and subsequently in the field, are an integral part of the turbine documentation to be delivered by the turbine supplier, the base material supplier and their respective inspectors or by the owner.

The filler metal shall be carefully selected. There are three possibilities:

- Homogeneous: Chemical composition of weld metal and base material is the same; also the microstructure is comparable.
- Similar: Chemical composition of weld metal and base material is similar; the microstructure is not identical.
- Dissimilar: Chemical composition of weld metal and base material and also the microstructure are not the same.

Precautions shall be applied in using dissimilar filler metals for repairs. For example, by the use of dissimilar (austenitic) filler metals in the repair of martensitic stainless steels, carbide precipitation leading to intergranular brittle cracking can occur during subsequent heat treatments.

In some cases, the replacement of a component can be more economical than the repair of cracks or other defects. This is especially true if the affected zones are accessible only after the dismantling of the component since the necessary repair time cannot be calculated accurately beforehand and the planned outage duration of the unit might be overstepped.

In evaluating the importance of defects which have not, to this point, resulted in failures and which one would propose to leave un-repaired, one shall be satisfied that, after rehabilitation, the loading conditions on the component concerned will not be aggravated.

7.3.2.2.3 Stress level

New stress analyses should be performed on existing components even if they have given good service without signs of deterioration to confirm their suitability for the planned life extension period. When changes are planned to the operating mode, power, head, discharge or speed of the unit, it is necessary to conduct more detailed analyses of which components will be affected by the proposed change and to what degree. Similarly, if a component has suffered cracking or extensive, unallowable deformation in service, the cause of this defective behaviour shall be determined. This may necessitate detailed stress and deflection analyses of some components and the application of more sophisticated calculation methods than were applied during the original design, for example the use of the finite element method.

The allowable stress levels in old turbines were established at a time when the best design tools available referred to empirical and analytical formulae destined to calculate “average” stresses in a given component or member. If no change is envisaged in the maximum loading conditions to be applied to the turbine whose rehabilitation is being considered, one can normally avoid detailed calculations of stress and deflection. If however, as is most often the case, an increase in maximum power is being considered, detailed calculations shall be done to assess the effects of the new conditions.

The use of finite element analysis techniques during the design phase allows the establishment of a much more accurate picture of stresses in the main components. A combination of quasi-static stress analyses and fatigue analyses should be done for the establishment of the useful life of the new component given the anticipated design conditions. Such analyses, though more difficult, should also be carried out for components to be reused. To the extent that the levels of dynamic stresses are determined from “experience”, there is a need to have occasional verifications of the assumed values. In the case of large units, the application of non-steady CFD calculations should be considered to evaluate the dynamic pressure loadings on the runner blades which can come from its interaction with the turbine distributor (often referred to as rotor-stator interactions RSI). If a change in the number of runner blades is foreseen for cavitation and efficiency reasons, the RSI excitation frequency will change. It then becomes even more important to perform rotor-stator interaction analysis and phase resonance checks inside the spiral case to evaluate the dynamic behaviour of the new runner inside the existing stator parts.

It is recommended, for large units with new runners or where power increases significantly without runner replacement, that the first runner of each design be subjected to strain gauge tests during commissioning to confirm that the dynamic loading assumed during the fatigue calculations has not been exceeded (see IEC 60944). If the manufacturer has similar data on fluctuating stresses and residual stresses on large units, it will be a significant benefit for the owners of smaller units.

7.3.2.2.4 Temperature

The temperature level and variation are symptoms of the behaviour of some equipment. For turbines, this equipment list includes, but may not be limited to, bearings, governor and the hydraulic power control unit.

It is a good practice to observe and report temperature at various locations for various operating points.

7.3.2.2.5 Noise

Noise heard in the machine vicinity contains information helpful for diagnostics. New noise or noise observed only in specific conditions or operating point can indicate a detrimental behaviour that needs to be investigated.

Generally, the noise level itself is limited by the technical specification. Measuring the noise level on the existing machine permits to appreciate the degree of improvement required on the rehabilitated machine.

More than the noise level, the acquisition of the noise for further analysis by FFT (fast Fourier transform) can help in the identification of the source of the noise and eventually to the correction of the problem. Runner blades or stay vanes excited by von Kármán vortices are examples of phenomena which can be identified by FFT analysis of sound recordings.

Therefore, even if only for comparison purposes, measuring the noise at various locations and at various operating points is recommended before dismantling the existing machine.

7.3.2.2.6 Stainless steel galvanic corrosion

Care shall be taken in assessing the condition of existing components. For example, in the case of a Kaplan or fixed blade propeller unit which has a discharge ring with stainless steel overlay or with stainless steel cladding, a corroded surface may not be an indication of an inadequate thickness of stainless coating, but rather, evidence of a carbon steel foreign object having been wedged between the runner blades and the discharge ring, leaving traces of carbon steel, which themselves have corroded.

The galvanic effect at the junction of the overlay of stainless steel on carbon steel runners or discharge rings can combine with local cavitation and accelerate erosion. This phenomenon is typical where cavitation erosion repairs have been done using stainless steel on carbon steel runners.

The use of contaminated grinding or polishing tools on stainless steel runners can initiate oxidation and corrosion and thus deteriorate the surface finish. The use of carbon steel tools on a stainless steel runner shall therefore be prohibited.

7.3.2.2.7 Galling

In order to minimize potential galling problems between adjacent moving parts, material selection is extremely important. Guide vane end surfaces, adjacent headcovers and bottom ring surfaces and runner seals are typical significant examples.

7.3.2.2.8 Mechanical vibrations

7.3.2.2.8.1 General

A problem that may occur frequently with hydraulic units is excessive vibration. The main sources of abnormal mechanical vibrations are:

– runner mechanical or hydraulic imbalance;

– guide bearing deficiency;

– runner seal clearance deficiency;

– generator mechanical or electromagnetic imbalance;

– generating unit misalignment;

– hydraulic instability.

See ISO 7919-5:2005 for allowable values of shaft vibration and ISO 10816-5:2000 for allowable values of non-rotating parts vibration. Both codes are currently under revision and a merged document ISO 20816-5 is expected in a near future. Performing vibration assessment of rotational and stationary components is recommended at various operating conditions to get a good signature of the unit. Displacements, velocity or acceleration measurements of the shaft and several stationary components should be carried out and analysed for subsequent comparisons with the refurbished unit. For units with monitoring systems, evolution of vibrations over time can provide valuable information about unit condition.

7.3.2.2.8.2 Runner mechanical or hydraulic imbalance

The runner mechanical imbalance will cause mechanical vibration (shaft runout) and will result in increased loading of the guide bearings and potential damage to supporting components. Balancing tolerances for modern runners (post 1970) are sufficiently tight to virtually eliminate this cause as a source of abnormal shaft run out (for example see ISO 1940-1 and Volumes I and V of the *Canadian Electricity Association Guide on Erection Tolerances and Shaft System Alignment*).

A hydraulic imbalance may result from runner non-uniformity of geometrical characteristics such as outflow openings, blade profile, inlet and outlet angles, etc. This type of imbalance is usually characterized by an increasing shaft runout with increasing load (discharge). IEC 60193 gives tolerances to be respected in this regard although many manufacturers and users impose even tighter tolerances. On the other hand, uneven flow distribution from distributor or draft tube can result in a non-rotating radial thrust.

7.3.2.2.8.3 Guide bearing deficiencies

Guide bearing stiffness in both the turbine and the generator shall be sufficient to withstand the most critical operating conditions without allowing contact in the runner seals or in the generator air-gap. The shaft system first critical speed shall have a sufficient margin above the turbine runaway speed to avoid resonance. This can be achieved only with appropriate attention to shaft system stiffness and guide bearing support stiffness. These factors are important in any unit rehabilitation if changes are proposed in either the rotating parts system or in the guide bearings or their support systems or if the turbine runner is being replaced with one having a higher runaway speed. The critical speed calculation shall be redone as well as a verification of the capability of the generator rotor to withstand the higher speed if a higher runaway speed by more than a few percent is involved.

Deficient tolerances on cold clearances at the guide bearings and changes in guide bearing clearances due to the thermal effects on both the rotating parts and on the bearing itself, from the cold condition to the operating condition, can lead to excessive vibrations or to mechanical damage on a generating unit. Excessive shaft runout usually results if the operating clearances are too large. Excessive bearing loads, overheating, and premature damage and failure usually occur if operating clearances are too small. If either problem has been experienced on an operating machine, the rehabilitation presents an opportunity to modify the design and correct the deficiency.

7.3.2.2.8.4 Runner seals clearance deficiency

The runner wearing rings or faces at the seals shall have adequate clearance to avoid contact with the fixed parts and shall be attached in such a manner as to avoid hydraulically induced vibrations or centrifugally induced separation of the rotating seal ring. A climate of high energy values can push the manufacturer and the owner to reduce runner seal clearances to obtain efficiency gains during rehabilitation. Prudence should be applied to avoid going below a safe minimum for the most critical steady state and transient operating conditions. Such gains may be achieved with a modified seal design without reduced seal clearance. Although momentary local contact in the runner seals at the runaway speed condition may not be catastrophic, full contact (on diameter) would be disastrous.

7.3.2.2.8.5 Generator imbalance

The generator related vibrations usually are of two types. The first is a mechanical imbalance resulting from the rotor fabrication (setting of rim and poles, guiding of the rim, etc.) or its original design or manufacture. The second is related to an unbalanced magnetic force that results from rotor concentricity or circularity errors with respect to the axis of rotation.

7.3.2.2.8.6 Generating unit misalignment

Runouts are indicative of some shaft misalignment. Excessive runouts of the shaft line system at the guide bearing locations can result in their premature failure. They can also indicate possible issues with runner clearance and generator gaps. Runouts can also originate from coupling offset, dogleg as well as lack of perpendicularity between the shaft line axis and the thrust bearing runner face. In any major rehabilitation, shaft line runouts should be measured before disassembly to determine any need for re-machining of the coupling or thrust runner face.

7.3.2.2.8.7 Hydraulic instability

Excessive vibration can be related also to a hydraulic instability which can result in an induced resonance and, from that, a component failure. The sources of hydraulic instabilities are covered in 7.3.4.

7.3.2.2.8.8 Erection and maintenance issues

Some of the problems found during assessment of a turbine or generating unit are in direct relation to the quality of the unit's erection and maintenance. A lack of maintenance can result in component failures such as burnt guide bearings or premature wear of the guide vane operating mechanism.

The evaluation of the distributor alignment with regard to the moving parts is an important aspect of the integrity assessment. The concentricity of the guide vane bushing bores in the bottom ring with respect to those of the headcover shall be verified. If the bores between the headcover and bottom ring are excessively eccentric, it would lead to pre-mature wear of the bushings due to an excessive edge loading and possibly binding of the guide vane mechanism. Line boring of the headcover and bottom ring may be required.

If these problems exist, they should be properly identified in order to avoid their repetition with the rehabilitated components.

7.3.2.3 Replacement of components without assessment

7.3.2.3.1 General

In a rehabilitation project, the replacement of some components can be considered to improve the performance, decrease the outage time and limit the risk for the schedule or the mechanical integrity. However, it is recommended, for some components, to proceed with the replacement without any other assessment or evaluation.

7.3.2.3.2 Fasteners and piping

It is good and justifiable practice during major overhauls, to replace all fasteners which are exposed to water passage or alternately humid and dry conditions. It is also good practice to replace fasteners subjected to loading on the high pressure side of the unit and those subjected to fatigue loading. The option of cleaning and careful inspection of fasteners can be as costly as the outright replacement. From the point of view of the schedule, replacement implies fewer risks. It is good and justifiable practice that all accessible bolts smaller than 63,5 mm in diameter be replaced during turbine rehabilitation or major overhaul.

Small piping in water service (50 mm and less), if it was originally supplied in non-corrosion resistant materials, should be replaced. Even original corrosion resistant materials should undergo hydro-static pressure tests, preferably during the project preliminary engineering phase such that a timely decision can be made on its need for replacement. Larger piping shall be cleaned, inspected and tested before a decision can be made.

It should be assumed that all seals and gaskets of parts that are to be disassembled and reassembled during the rehabilitation shall be replaced.

A major overhaul presents the opportunity to reassess the complete complement of instrumentation that was supplied and installed on the original unit. It is highly unlikely that the original instrumentation is still functional and, if it is not, that replacements of the same make and model can be found. The best approach is to do an assessment of the owner's needs in regard to unit indication, control and protection and to fulfil those needs with the most modern and most reliable equipment available at the time of the overhaul.

7.3.2.3.3 Use of self-lubricating materials

In old machines, all bushings in the distributor and its operating mechanism are grease-lubricated brass or bronze. Even if the system works properly and reliably, it should be seriously considered, for environmental reasons, to replace the wearing elements using self-lubricating materials.

The self-lubricating material should be selected with due consideration for its application and should have good abrasion resistance and be dimensionally stable when exposed to water. Care should be taken to prevent the intrusion of dirt between sliding surfaces by the use of adequate seals particularly on the bushings adjacent to the turbine water passage. From a maintenance perspective, the ease of inspection and replacement should be considered when selecting the material.

Many of the self-lubricating materials have thermal expansion coefficients much greater than the metals in which they are housed. This poses a concern of ensuring good interference fits under all operating temperatures, particularly in cold climates. Remaining interference fit at low temperature should be validated, as well as possible loosening and displacement during transportation.

All self-lubricating bushings and wearing plates require smooth non-corrosive mating surface materials such as stainless steel.

Some of the available materials and particularly the thin-film types require particular care to avoid damage during installation. When properly assembled however, they can give many years of reliable service.

The self-lubricating materials available on the market have a wide range of coefficients of friction. This necessitates a careful review of the capacity of the servomotors in the guide vane operating system.

The normal deflections of the guide vane bodies leads to a degree of edge loading particularly on the bushings on the guide vane stems adjacent to the water passage. The choice of guide vane bushing material should take into account the anticipated maximum degree of edge loading. The material shall accept to "wear in" without detrimental damage.

7.3.2.4 Recommendations for specific components

7.3.2.4.1 Foundations

The effect of the foundations on the condition of the turbine should not be overlooked.

Three phenomena affecting the foundations can perturb turbine operation:

- elastic deformation under pressure;
- swelling of the concrete, as a result of alkali-aggregate reactivity;
- creeping of the concrete under long term loads.

They lead to the creation of temporary or permanent and evolving displacements.

For example, swelling of the concrete is present in many old power plants. It leads to the displacement of the embedded turbine and generator components and usually results in the misalignment of the fixed and rotating parts of the generating unit. This misalignment can lead to inclination of the shaft and increased radial loading on the guide bearings, inclination of the distributor components and premature wear of the guide vanes, headcover and bottom ring and contact at the runner seals. It has also been known to cause stay vane cracking.

Rehabilitation is an opportunity to reset the alignment and incorporate adjusting mechanisms that will facilitate the work and reduce the outage time required to make future corrections.

7.3.2.4.2 Pelton runners

7.3.2.4.2.1 General

The most serious aspect that distinguishes Pelton turbines from all the other types of turbines is the manner in which the buckets of the Pelton runner are loaded. They are exposed to very high flow velocities of the medium, causing wear and abrasion, and the impacts of the jet result in a high number of load cycles (a speed of 500 revolutions/min, 6 nozzles, 1 500 h per year leads to $2,7 \times 10^8$ cycles per year).

Pelton turbines with their characteristic high head are often used in mountainous regions where, small but very hard and very abrasive particles are found in suspension in the water from glacier melt. These particles are difficult to remove in de-silting stilling basins because of their small size and low mass.

The areas in the bucket which shall be investigated thoroughly are shown at A and B in Figure 2. The first area A, in the bucket root, is subjected to high stresses, notably from steady state centrifugal stresses and from dynamic bending stresses, and therefore defects on the surface or slightly below it, will be the points of origin for cracks. The second area B, at the entrance edge on the splitter and in the cut-out, is also subject to high stresses because the wall thickness is small in addition to being subjected to erosion. In both areas, defects from the method of fabrication which are not always detected and removed in the workshop are possible.

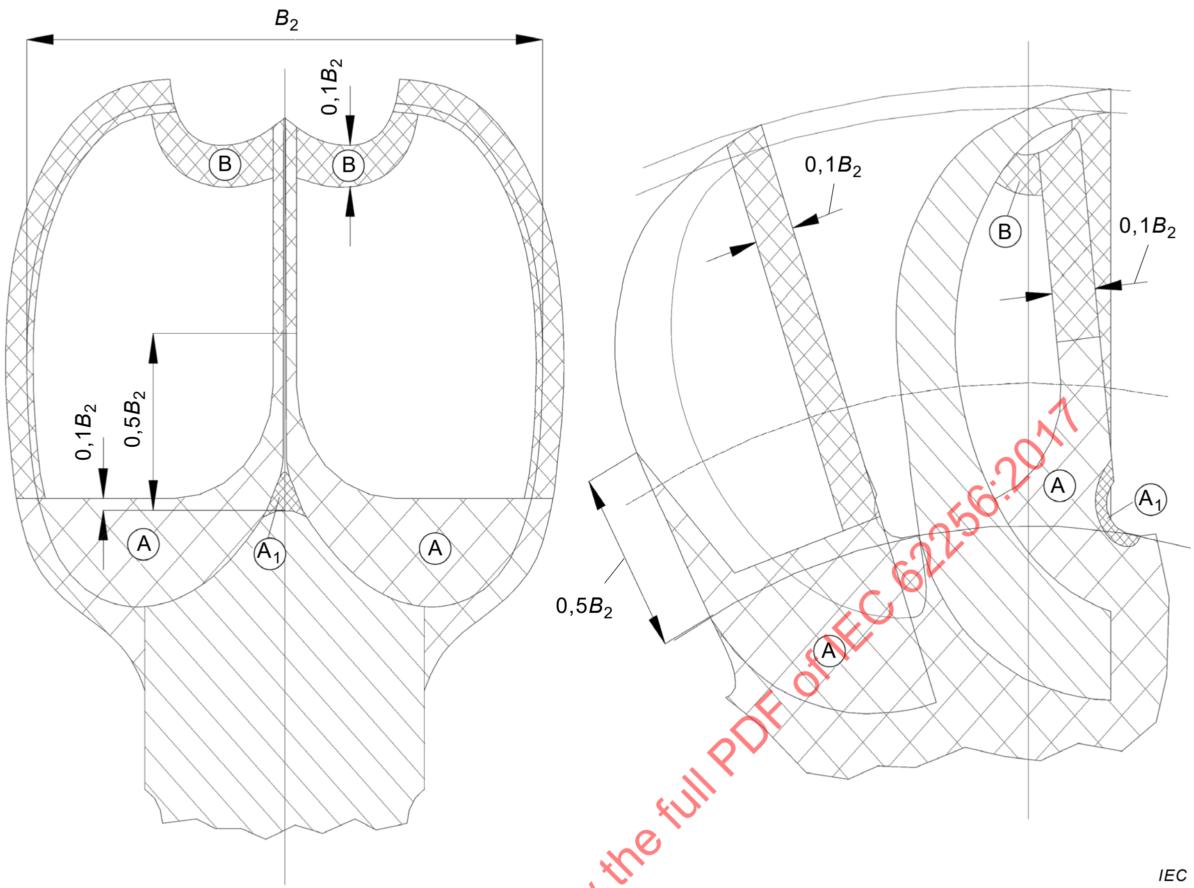

Figure 2 – Critical zones for cracks "A" and "B" in Pelton runner buckets

7.3.2.4.2.2 Determination of the condition of Pelton runners and consequent failure risk

Repair welds, even if they are small, have an influence on the structure of the component which may prove to be detrimental. For a successful repair, it is necessary to collect as much data as possible, starting with the manufacture of the turbine and including all previous repairs. The influence of the machining process (grinding, milling, etc.) is small and can be neglected.

The determination of extent of abrasion can be done with the aid of templates. Whenever possible, measurements of the buckets on a NC-machine are useful. A comparison between effective residual and designed contours shall be done and the remaining cross-sections determined to calculate and evaluate the consequent stresses.

For any weld repair which involves post weld heat treatment, the temperatures proposed shall be carefully chosen to avoid detrimental effects on the physical properties of the base material and to minimize distortions. Any heat treatment will involve distortions and the repair procedure shall provide for re-machining where necessary.

7.3.2.4.2.3 Other aspects of the Pelton turbine

There are problems on occasion with the tailwater channel if the tailwater level is too high or the aeration of the turbine housing and the outflow channel are inadequate. This will be true if the water level in the tailwater basin or river has increased, if the flow passages are blocked by sediments, if there are changes in the building structure or if the turbine maximum discharge has been increased without appropriate modifications to the capacity of the tailwater system.

An increase in the aeration of the turbine runner pit may be achieved by boring additional openings in the turbine housing, which then are connected by suitable piping to an atmospheric air source exempt from unwanted noise effects.

7.3.3 Residual life

7.3.3.1 General

The useful life of a component is influenced by many factors including the design, the materials used, the manufacturing methods, past and future operating conditions and effected maintenance.

Based on the importance of the component under consideration different maintenance strategies are used:

– corrective maintenance, or
– preventive maintenance.

The corrective maintenance was used in early years and it consists in replacing the components that failed. The life of the component is however 100 % used; this maintenance strategy could have a huge impact on the safety and availability of the generating unit if an important component fails. This is the reason why this maintenance strategy becomes less used and hence this subclause does not deal with it.

The availability of the generating unit, legal requirements on safety and other issues require preventive maintenance strategies, e.g. repair or replacement of a component should take place before it fails. Predetermined maintenance and condition-based maintenance are the two types of preventive maintenance strategies (EN 13306:2010). The estimation of residual life is the core requirement for their successful implementations.

Predetermined maintenance is carried out in accordance with established time intervals. Two widely used approaches are use-based maintenance when the time interval is determined by equipment use (e.g. operating time), or time-based maintenance when the time interval is determined based on calendar. The use-based strategy makes use of the bathtub curve (see Figure 3). The use-based maintenance relates to the safe life design strategy in the aviation and nuclear industries. The bathtub curve characterizes the typical deterioration process of a component or the whole unit. In the first phase, namely infant mortality phase, the failure rate decreases. The failure rate remains nearly constant in the second phase. The failure in this phase is random failure caused by sudden events such as overload, stability loss or resonance. The failure rate in the third phase increases rapidly and is related to wear-out failures caused by fatigue, wear, cavitation, erosion, or corrosion. The idea of use-based maintenance is to estimate the residual life of the component up to the beginning of the wear-out phase and then to replace the component.

The estimation of the residual life can be done by statistical methods resting upon assumption that the component life can be described by a probability distribution such as the Weibull distribution or log-normal distribution.

Condition-based maintenance and appropriate maintenance actions are trigged based on a combination of condition monitoring, inspections, tests and analyses of the equipment. Predictive maintenance is a type of condition-based maintenance carried out following a forecast of the remaining useful life. Fault prediction determines whether a fault is impending and estimates how soon and how likely a fault will occur. The predictive maintenance rests upon physical models of deterioration. Based on momentary deterioration, the residual life up to the maximum allowable deterioration is calculated. This maintenance strategy relates to damage tolerance design strategy. It is theoretically possible to calculate the residual life of a component with the fracture mechanics theory. However, the application of this method requires the evaluation of many parameters such as material properties, location, shape and dimensions of a defect, precise loading and local stresses in the component, and the characteristics of the loads applied including the amplitudes and number of cycles for dynamic conditions. Much of this data is difficult to establish with precision for most of the existing turbine components. In order to prevent unexpected damages caused by inaccurate calculations, this method may be completed by diagnostics and regular condition assessment.

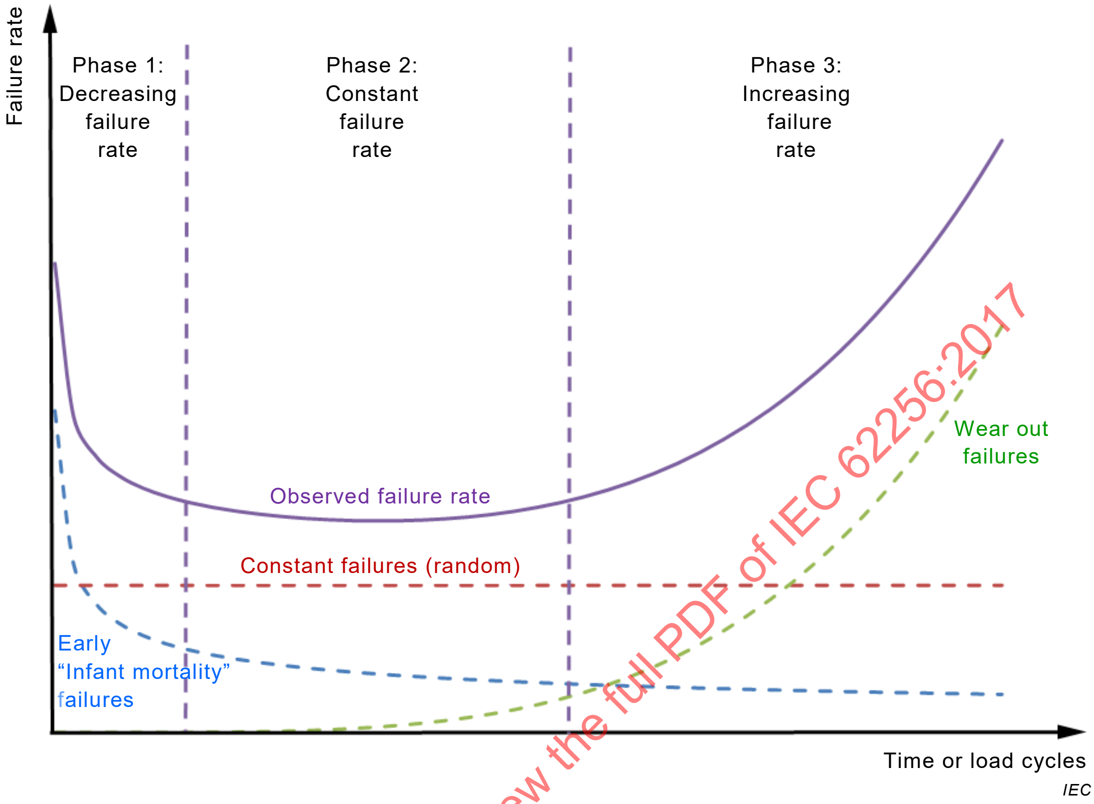

Figure 3 – Bathtub curve

If necessary data are not available, it is possible to evaluate the residual life of many components with a reasonable level of confidence solely by inspection, informed engineering judgment and comparison with components that were built with the same technology in terms of design and materials and which have been operated under similar conditions for many years. This statement applies as long as local significant manufacturing defects are not of concern. A significant disadvantage of this method is that one or more experienced persons carry out the estimation and the result relates more or less to the knowledge and experience of these persons. To prevent this disadvantage, the owners created systems for monitoring and judging the current condition of their equipment, for example *Hydro Life Extension and Modernisation Guides* by EPRI, or *Condition Rating Procedures/Condition Indicator for Hydropower Equipment,* from the Repair, Evaluation, Maintenance and Rehabilitation (REMR) Research Program of the US Army Corps of Engineers. Such systems for residual life estimation by engineering judgement shall ensure that a unique procedure reduces the influence of the human factor.

If we talk about residual life we have to point out that the life of a component, if it is affected by deterioration processes such as fatigue, abrasion, wear, erosion, cavitation and corrosion is a stochastic process and thus it is not possible to determine the life of the component exactly. In the case of residual life, the situation is more complicated as it is impossible to identify the state of deterioration precisely. The portion of the total life consumed can only be estimated based on relevant number of load cycles or operation hours to which the component has been subjected over time and based on the component's condition. This emphasizes the importance of gathering data on operational history and component condition. The diagram in Figure 4 shows graphically the requirements for residual life estimation (7.3.3.2); the residual life is dependent on load condition (7.3.3.5), component condition (7.3.3.4) and also on mathematical model of deterioration (7.3.3.2).

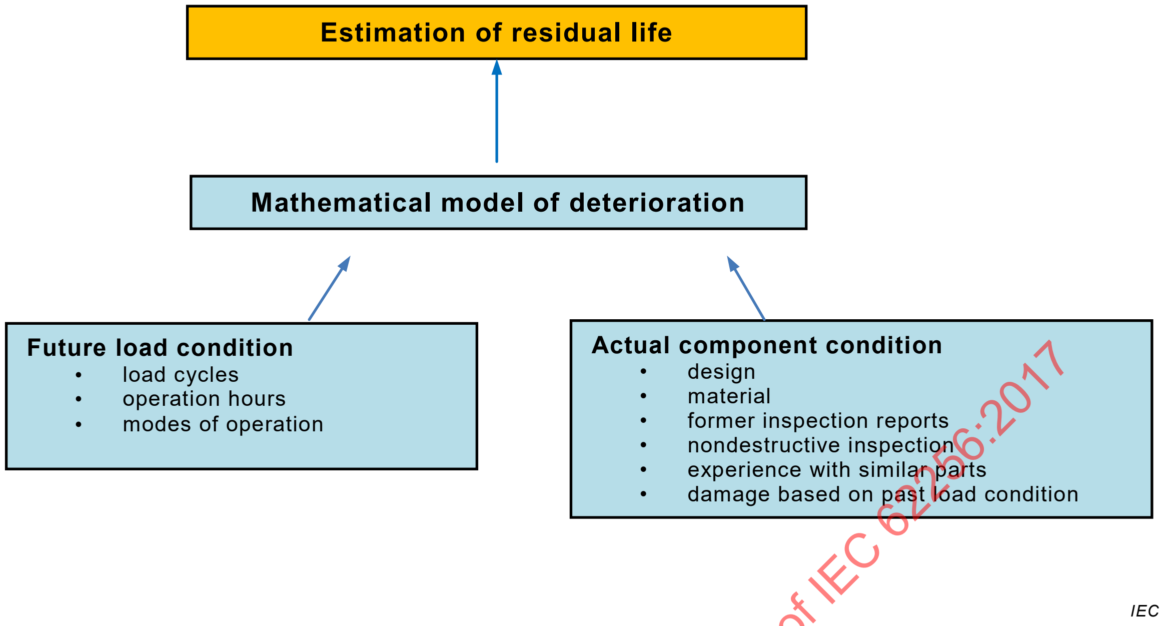

Figure 4 – Process of residual life estimation

As previously mentioned, the residual life of a component is a stochastic deterioration process and the residual life cannot be calculated exactly. It can only be estimated in combination with information on the probability of its estimated residual life. Thus, information such as "the residual life of this component is 20 years" cannot be given. Instead, the statement should be: "the component residual life of 20 years can be guaranteed with sufficient reliability". Of course, in relevant codes, such as ASME Section VIII Division 2 2013 and FKM 2012, there are design curves and it may look as if the life of a component could be calculated exactly. However, safety factors are imbedded in these design curves so that the estimated life of a component becomes very conservative.

One has to keep in mind that both unnecessarily high and unnecessarily low safety factors can have negative influence on cost-effectiveness and safety. Using safety factors that are too high will lead to underestimations of the residual life and hence to replacement of the component even if the risk of failure remains acceptable in the time period considered for life extension. On the other hand, using safety factors that are too low will lead to overestimations of the residual life and the consequence could be failure of safety-relevant components in the time period considered for life extension.

In a typical rehabilitation project, different types of restoration will be used depending on the condition of the respective components. This requires different residual life estimation procedures as mentioned above. Subclause 7.3.3.3 covers criteria for residual life assessment.

7.3.3.2 Residual life calculation (from current condition)

The lifetime of turbine parts is restricted by several mechanisms such as material fatigue, corrosion, cavitation, wear, and hydro-abrasive erosion due to hard particles in the water. Hydro-abrasive erosion applies particularly for hydro power plants in mountainous regions like the Alps, the Himalayas and the Andes. Calculation of hydro-abrasive erosion and remedial measures is covered in IEC 62364. The following schematic explanations focus on fatigue life calculation.

Fatigue damage can be interpreted as the initiation and growth of cracks that will eventually propagate to fracture under cyclic loading. Fatigue cracks occur most likely in zones of elevated local cyclic stresses, e.g. at small radii of notches and corners. If cyclic stress amplitudes exceed a certain threshold, microscopic cracks will begin to form. With an increasing number of load cycles, the crack grows until a technical crack size (i.e. a detectable crack length of about 1 mm) is reached. Up to this point we talk about crack initiation (see Figure 5). With an increasing number of cycles, the stage of crack propagation is entered. Within the stage of crack propagation, the crack may grow by each load cycle until a critical crack size is reached. This will cause a sudden fracture to a structural part of the entire structure. In general, the stage of crack initiation dominates the time period from virgin conditions until fracture. In technical literature, different statements about the proportion of crack initiations of the total fatigue life until fracture in terms of number of cycles (e.g. 60 % to 90 %) can be found depending on the existing conditions.

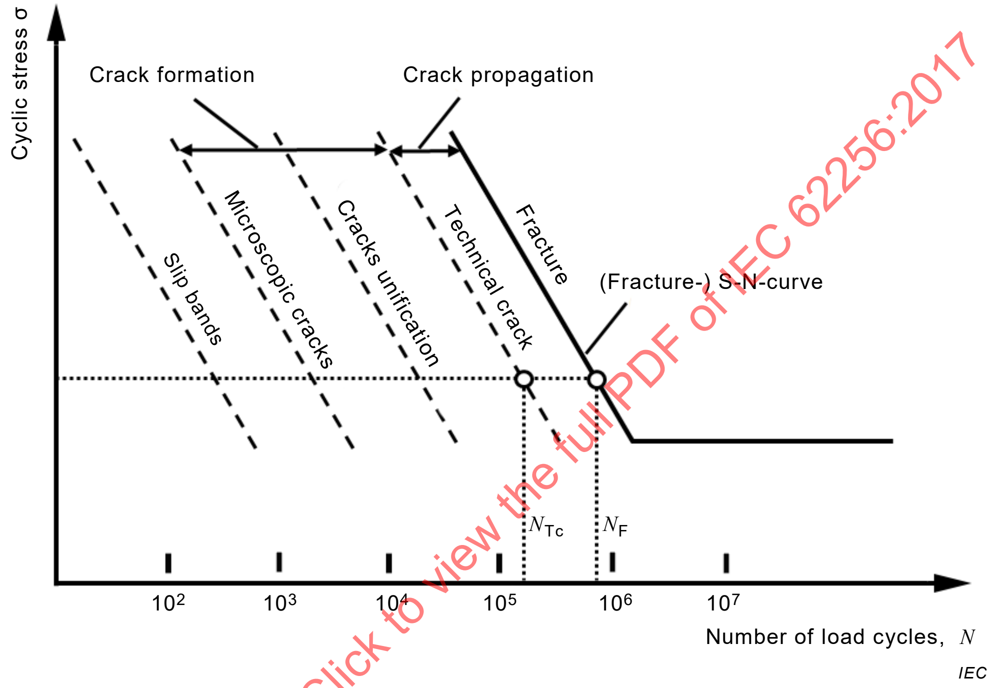

Figure 5 – Schematic behaviour for the different stages in the fatigue process

Different concepts which are described in relevant technical literature can be used for fatigue strength assessment. Nominal stress, structural stress, local stress and local strain approaches are based on a crack-free structure while the crack propagation analysis investigates the growth of an assumed or detected crack by means of fracture mechanics. Stress-life (S-N) approaches are widely recognized and often used for fatigue strength assessment in normative standards. Furthermore, S-N approaches can be used to determine the fatigue lifetime until critical values of either technical crack initiation or fracture are reached. The strain-life (ε-N) approach, which is (in its original version) applicable for assessing the technical crack initiation, takes into account the effect of local yielding and is more accurate at low-cycle fatigue.

The principle of fatigue strength assessment using S-N- or ε-N-approaches is to compare the acting cyclic stress/strain with their corresponding critical values, or alternatively to compare the number n of acting load cycles with the corresponding critical fatigue life values expressed in number N of cycles. In the case of a load spectrum (more than one cyclic stress/strain class), a procedure for the accumulation of partial damage sums of all cyclic stress/strain classes is necessary. In this connection, the partial damage D_i of a cyclic stress/strain class i is usually defined as $D_i = n_i/N_i$. The linear Palmgren-Miner approach is commonly used to accumulate the partial damage sums of cyclic stress/strain classes in order to get the total damage sum $D = \Sigma D_i$. Both acting cyclic stresses/strain values and their corresponding (critical) fatigue life values are scattered. Hence, scatter in loading and fatigue life should be taken into account in fatigue strength assessment. Thus, normative standards should be checked with respect to their scope in terms of limitation of applicability to distinct boundary conditions before applying them to a component of a hydro machine.

When assessing components of a hydro power plant after several years of operation, the components liable to fatigue should be checked in a fatigue strength assessment. The number of load cycles of all relevant operating modes and operating mode changes from commissioning to the end of the required service life or the next inspection has to be considered in the residual fatigue life calculation. Acting cyclic stresses/strains of hydro machine components are usually determined by either analytical methods or FEA (finite element analyses). Loads and boundary conditions have to be assumed realistically in order to get reliable results. If strain gauge measurements become available, load hypotheses for various operating conditions, and more specifically for transient and unstable ones, can be reevaluated. Furthermore, residual fatigue life assessment of hydro components can also be based on strain gauge measurements. In this case, the stress/strain spectrum is determined by Rainflow-Counting of measured time signals of strains (ASTM E1049). For fatigue strength assessment, usually standards such as FKM 2012, ASME Section VIII Division 2 2013, AWS 2010, IIW 2008, are applied. If test data for fatigue life of a (standard) material is available, this data can also be used for the fatigue life assessment. In selected cases, e.g. if no information about the material is available, laboratory testing on samples should be performed.

Generally, surface cracks should be removed. If necessary (e.g. if cracks have been detected with help of NDT), in regions with high local stresses, the shape of the structure can be improved by grinding, polishing or welding, etc. in order to fulfil the requirements regarding fatigue. If cracks can be removed completely in fatigue relevant regions, fatigue assessment may be performed using S-N- or ε-N-approaches. If cracks or inner flaws in areas liable to fatigue cannot be removed, a fracture mechanics analysis should be applied in order to estimate the residual fatigue life. Considering that the inner flaws behave like cracks, the fracture mechanics analysis gives an idea if and how fast the inner flaws will grow. In that case, refer to British Standard BS 7910. In this context, metallurgic studies can be helpful. Based on this analysis, the following process (e.g. the period until the next inspection) has to be defined.

Summarizing the above, it can be said that a residual life calculation is not easy to perform. Special technical know-how and experience is needed for this kind of calculation. Other difficulties consist in finding the past operating history of the unit (which is not always well documented) and in predicting the future operating history to define the load spectrum.

7.3.3.3 Residual life assessment criteria

As already mentioned before, the residual life is uncertain. Hence, the residual life cannot be determined exactly and remains an estimation, even if mathematical models for residual life calculation are used (see 7.3.3.2). This estimation can be sufficient in regard to the objectives of the power plant owner. However, the owner should define the criteria for the end-of-life of the component and the acceptable risk of not assessing this component's state precisely. One should be clear on these two important topics before a reasonable assessment of residual life can be done. Each owner has its own objectives. Among them are:

- extending plant life;
- limit risk of catastrophic failure;
- increase environmental friendliness;
- reduce unit downtime; and
- avoid obsolescence problems.

Above all, safety issues should be covered and in particular the risk of major catastrophic failure as the consequences can go further than just loss of revenue. Fatigue, erosion and cavitation are the main factors which can lead to major failures.

The availability of the turbine in relation to non-catastrophic failure should also be considered as it is directly linked to the owner's revenues. This can be failures on governor systems or auxiliary systems.

For these two points, a rating system may be helpful. Tools such as failure mode analyses (FMA) can be used to help in defining the risks or consequences of a failure and the probability that the failure happens (occurrence). Similar useful tools are, for example, fault tree analysis (FTA), failure modes effects and criticality analysis (FMECA), hazard and operability study (HAZOP) and event tree analysis (ETA).

In order to follow owner objectives, defining criteria for the residual life assessment is recommended; either one's own criteria can be created or existing criteria can be used for the assessment. Some existing criteria are listed below.

– The physical condition of the components is an important consideration for prediction of the remaining life (EPRI 2000, HydroAMP 2006). Special focus should be put on the parts and defects which could cause the failure modes mentioned above.
– The age of the component is an indicator of the remaining life. The number of component failures increases with age (EPRI 2000, HydroAMP 2006).
– Maintenance costs can be considered as a criterion on residual life (increasing costs means decreasing residual life for instance) (EPRI 2000, HydroAMP 2006).
– Another point to consider is performance reduction, such as decreasing efficiency owing to the wear of some components (i.e. cavitation on runner profile or abrasion on labyrinth seals of a Francis turbine) (EPRI 2000, HydroAMP 2006, IEA 2001).
– Operating conditions of the unit is also an important criterion. The more the unit was used or will be used apart from base load operation, the less residual life is available (see also 7.3.3.5) (EPRI 2000, HydroAMP 2006, EPRI 1989).
– Environmental issues can be a criterion with, for instance, the risk of oil leakage into the waterway (EPRI 2000, HydroAMP 2006). The quantity of oil that is used each year is a good measurement.
– Finally, the risk of obsolescence problems can be considered. The availability on the market of a given product or service is directly linked to the risk of obsolescence problems. Below a certain number of possible suppliers, we may consider that this given product is close to the end of its useful life (EPRI 2000).

Each owner may weight differently these criteria for its own purpose. All criteria could be used or just some of them. The idea is that they will be used for the rating of the components when carrying out the condition assessment.

7.3.3.4 Current condition assessment

7.3.3.4.1 Level of inspection

Determining the current condition of the turbine is an essential part in order to estimate the residual life. Several guidelines are available in the industry to assist owners in evaluating the current condition of their equipment, for example EPRI 2000, USACE 1993 or HydroAMP 2006.

It is necessary to begin with collecting available data which describes the equipment. This includes drawings, calculation reports and records from maintenance and operation. A review of existing information, particular records of previous problems and repair history, will give a first indication of the condition. The review will also give background for further investigation and inspections.

The most important data is gathered by field inspections and tests. For each component, the owner should develop a condition assessment guide where the types and frequency of inspection are specified together with rating criteria of the condition. Pre-defined checklists and inspection sheets should be used for the inspection to ensure uniform assessment. The tables in Annex A present the aspects that should be considered in the evaluation.

The inspections can be divided into two levels. The first level is related to routine inspections that are easy to do without dismantling and sometimes without dewatering. Examples of typical routine inspections are presented in 7.3.2.1. They are usually performed by on-site maintenance personnel over the course of time. These inspections are the foundation of the assessment process. Existing inspection reports should usually be relied upon at this level.

The second level involves more in-depth investigations which require dewatering and maybe dismantling. These inspections could be triggered by the routine inspections and often require specialized personnel. They include dimensional checks of non-accessible parts and non-destructive testing.

The quality of the assessment can be evaluated as an independent quality indicator. It should reflect the quality and level of the inspection in relation to when they were made. A more recent and thorough inspection can be considered more representative and thus have a better rating. This indicator should also be a sign of the quality of the documentation and information from the inspections. Documentation is important to support findings of the assessment.

7.3.3.4.2 Inspection results

The inspection results should be presented with an observation report including sketches and photos of the defects found and records from dimensional checks. Evaluation of inspection results is often subjective, based on the experience of experts. To provide a more objective assessment, a predetermined condition rating system with clearly defined rating criteria should be used. In this rating system, the results should be assigned numerical scores. The scoring criteria may refer to conditions such as excellent or poor condition. It could be represented by a percentage where 100 % is a perfect brand new component with no noticeable defects and 0 % is extensive wear or defects that impair the function. Other rating systems can also be used. Table 3 shows an example of a rating scale of condition with 5 levels. Many levels provide a greater differentiation but it also complicates the assessment because it becomes harder to distinguish each level.

The results should be compared with previous inspections and measurements to check for defects or progress wear.

Table 3 – Example of a rating system for the inspection results

Score	Condition	Condition description
80 to 100	Excellent	Perfect brand new component with no noticeable defects
60 to 79	Very good	Only minor deterioration or defects are evident
40 to 59	Good	Moderate deterioration but function is adequate
20 to 39	Poor	Serious deterioration and inadequate function but under control
0 to 19	Very poor	Extensive wear or defects that impair the function. Danger of failure is imminent.

7.3.3.4.3 Component rating based on relative importance

The different components should preferably be rated based on their relative importance as part of a power unit. Among the turbine parts, the runner is generally the most critical component, but the priority of components is at the owner's discretion. The weighting should be decided with great concern. It can be based on failure modes and effects analysis, and the costs to fix or replace the component. Individual component weights may be different as long as their sum equals 100 %. Once the weighting factors are determined, they should be fixed from unit to unit for the same type of turbines.

All components do not have to be included to determine the overall condition of the turbine. The list can be extensive or limited. Sometimes, it is limited to moving parts, like the runner, the guide vanes mechanism, the bearings and the shaft seal. But, it may also include the oil circuit and the governor and large components such as stay rings, stay vanes, the headcover, etc. An example of major turbine components that may be included is shown in Table 4. The different weight factors should be decided by the owner of the power plant.

Table 4 – Example of a typical list of turbine components for Francis and Kaplan with different weight factors X_1 to X_7 based on relative importance

Turbine components	Score	Weight	Weighted score
Runner		X_1 %	
Guide vanes		X_2 %	
Guide vane mechanism		X_3 %	
Guide bearing		X_4 %	
Shaft seal		X_5 %	
Hydraulic circuit		X_6 %	
Governor		X_7 %	
		100 %	Σ Score × Weight

7.3.3.4.4 Ranking of inspection findings

The weighted score of the inspection findings represents the mechanical or physical condition of the turbine. But other indications should also be involved in the assessment. The same criteria as described in 7.3.3.3 can be used for the assessment of current conditions, for example age and maintenance costs.

It is recognized that many damages cumulated with time, particularly fatigue damages, are not easy to detect. Therefore, the age of the component is an important factor to include. It can be represented as the ratio of the actual age to the time to amortize the cost or the expected lifetime of the component.

The maintenance costs are another indicator to consider, in particular the amount of corrective maintenance. It can be compared with the maintenance cost of the same component in other turbines. When the maintenance cost is not available per component, it can be referenced for the whole unit.

To rate the condition of the component, a score is given to each of the assessment criteria. The weighted sum of all determines the rating of the current condition of the component. An example is shown in Table 5. The weighting in this table is an example from a utility. It shows that physical condition usually is the most important indicator for the evaluation of the condition, but it is still less than 50 % of the weighting.

Table 5 – Example of rating of a single component assessment including three assessment criteria

Assessment criteria	Score	Weight	Weighted score
Physical condition	% of quality	47 %	
Age	% of time to amortize	20 %	
Maintenance cost	% of normal maintenance	33 %	
Rating of component			Σ Score × Weight

This method allows for a unit to be easily compared with another without the need to perform a complex grid and score analysis. The quality indicator described in 7.3.3.4.1 gives an idea of the precision of the assessment. This process for the assessment of the current condition can be used as a permanent tool to help the owner with the management of the fleet. It has to be organized and tuned to fit the owner's needs and goals according to the level of resources and risks they accept to sustain. Usually, this tool is part of the maintenance management software.

In addition to component assessment, some phenomena can be assessed, such as vibration, noise and temperature. The source of the phenomenon can be difficult to identify but its measurement can be easy. Referring to previous measurements of the same phenomenon can be a good way to follow the evolution of a unit's condition. The operating conditions have a significant impact on these phenomena and should be recorded. It could be useful for the owner to develop a guide on how to monitor and interpret these phenomena.

7.3.3.5 Effect of the operating conditions

As stated at the beginning of this document, hydraulic turbines are among the most robust and reliable structures ever built. It is not uncommon to find units still producing energy reliably after more than 50 years of operation. However, due to deregulation, new energy equipment (such as wind turbines) and new grid requirements, hydraulic turbines, which have been used mainly for base load generation, may now be required, due to their high operating flexibility, to operate on a much wider range. Moreover, the hydraulic conditions under which the generating unit is operated, as well as the load on the unit, can have an influence on its mechanical integrity.

Hydraulic turbines are nowadays very often used for power and frequency regulation. Operating as spinning reserve, synchronous condenser, peaking units with frequent start/stop cycles, and for extensive periods at low load operation are more and more common practices. Although these new operating schemes may be fully justified for grid or financial reasons, the operators have to realize the effects such decisions have on their equipment and be ready for the investments that will be required to maintain their availability.

Most existing machines have been hydraulically and mechanically designed to operate around peak efficiency with few start/stops. With such schemes, the machines usually run smoothly and reliably with minimum maintenance. Issues such as the ones originating from von Kármán vortices and rotor-stator interactions (RSI) are assumed to have been solved at the commissioning of the unit. The effects specifically related to new operating conditions may be the following:

- Frequent start/stops: one of the effects of stopping and restarting a unit is to remove the static loads required to produce the power, and then reapplying them, therefore creating a high stress range. At the same time, the machine has to go through the dynamic transient instabilities the change of state generates (see Figure 6).

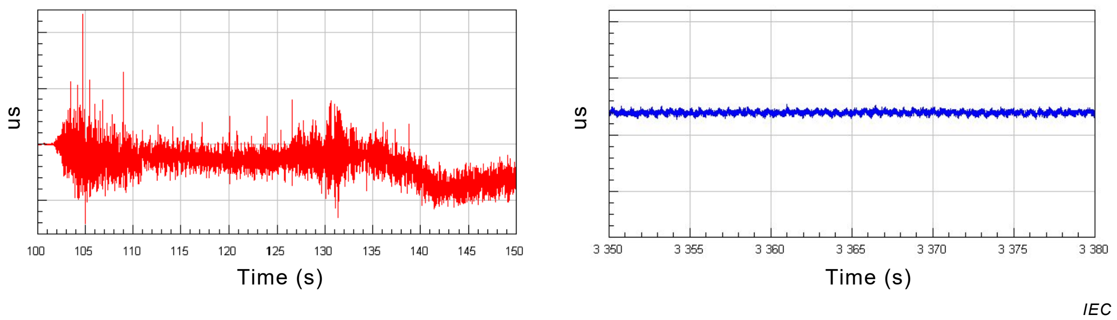

Figure 6 – Start-up and full load strain gauge signal on Francis blade

All these load cycles occurring at start-up create fatigue accumulation which can eventually lead to failure, which would not have happened so quickly had the number of start/stop cycles remained low. Studies indicate that increasing the number of start-ups can significantly decrease the life of the runner without cracks. Moreover, low cycle high loads, such as the cycles produced by start-ups, can influence high cycle low loads, such as the ones produced by RSI, by increasing the defects' stress intensities that can eventually exceed the material threshold, therefore leading to a rapid crack propagation. Low head Francis runners, as far as damage is concerned, are generally more sensitive to start-stop cycles than stiffer high head machines. However, some optimization of the start-up procedure may possibly be performed to decrease the damage caused.

- Synchronous condenser mode: since there is no water in the runner, the synchronous condenser mode may seem to be a smooth operating condition for an aging machine. But one has to keep in mind that the cycle from full power to synchronous condenser and back to full power consists of removing the pressure load on the blades and reapplying it. Therefore, in trying to relax the operation of a machine by using it in synchronous condenser mode a few times per day, the real effect is to accumulate more high load cycles, which may lead to quicker damage on components such as the runner and the covers.
- Regulation and control modes: operation of units in frequency and power control, with small or large variations of loads, may be very demanding on the machines. Regulating with Kaplan units, for instance, may lead to quicker than expected deterioration of the blade, lever bushings and seals.
- Operation at part load: the effect of the part load draft tube vortex on the draft tube, draft tube door and the surrounding foundations are well known, although the effect on the runner is not so clear. Some studies show that Francis runners are much more sensitive to Speed No Load (SNL) and very low load operations than to operation at part load under the rope. On other runners, however, the rope has been found to be quite damaging to the runner. However, if the unit is frequently operated at part load, it could suffer from increased loading on the guide bearings due to hydraulic instability.
- Operation at Speed No Load (SNL) and very low load: using the machine in spinning reserve at SNL and at very low load has been found to be quite damaging for the runner. The effect is not certain on other components.
- Overload operation: operation at overload increases the stress on components, including the runner, the shaft and the generator. Components should be checked before deciding on operating at overload. It can also push the operation in the region of high hydraulic instabilities and very low efficiency. If model test exists, such information may be available. If the tailrace level does not respect the design limits on the suction head, cavitation may also occur.
- Load rejection: overpressure and overspeed at load rejection may change if discharge increases owing to new a runner or modified guide vane openings. The effect of these changes on the unit should be assessed.

The information relating to the operation of the turbine is essential to correctly evaluate the condition of the existing unit and to adequately design the new components. The damage caused by new operating conditions is not the same for all the turbine components and they each have to be assessed individually. The required incremental costs of maintenance, however, have to be taken into account in calculating realistic benefits obtained in using the hydraulic turbines at these off-design steady-state and transient operating conditions.

7.3.4 Turbine performance assessment

7.3.4.1 General

The most important performance factors to be considered for a rehabilitation project are certainly a potential capacity (or power) increase, a potential efficiency increase, a reduction of cavitation erosion and an improvement in hydraulic stability. One should begin by evaluating, as accurately as possible, the potential performance gains one might expect from a new turbine with similar characteristics. The extent to which the performance of an existing (old) turbine can be improved is dependent on the type and the age of the unit. A rough assessment of potential gains is provided in the following subclauses. These data are based on a large number of turbine makes and sizes and should only be used for a first phase evaluation of gains in performance which one may expect to achieve by rehabilitating a given unit.

In specific cases, for example where a frequency change is being made on the generator, it is required to make a speed change on the turbine. This can be advantageous for the turbine performance if the runner is to be replaced. The technology is available at the time of publication of this document, to build into the rehabilitated machine a “variable speed” capability. Such a feature can be particularly advantageous for reversible pump-turbines, and for turbines and storage pumps operating under highly variable conditions of specific hydraulic energy (head). Changing the speed at a given site or using variable speed technology brings with it, the obligation to carefully study, the potential impact of the modified exciting frequencies of the hydraulic machine on a potential resonance with the overall conduit system.

Notwithstanding the aspect of improved performance which one might seek, the owner’s first priority will always be to have a generating station which has the highest possible reliability and availability. It will not benefit the owner to gain marginally in unit maximum output or in efficiency if the changes made to the unit result in a reduction of its reliability or availability. The following subclauses deal with the four main considerations in performance assessment.

7.3.4.2 Power increase

Based upon information collected from plant operating records over time, or determined by a carefully executed power-gate test or still better, by an index test corrected to rated hydraulic conditions, one may establish if there is evidence of serious power output degradation. For example, a decrease in excess of 4 % to 6 % in power output at full guide vane opening at rated hydraulic conditions should immediately lead to further investigation of the condition of the hydraulic surfaces of the turbine and of the related water passages. If time and conditions permit and the size of the unit justifies it, a professionally executed field test to determine the current performance of the turbine may be done. If the runner is more than 25 years old and it is evident for mechanical reasons that one has to intervene on a unit to maintain it in operating condition and that it has to be dismantled to be repaired, it is often economically justifiable to install a new turbine runner and possibly to modify other components to achieve improved performance.

What the economic solution is for a given plant in regard to maximum output depends on many factors including:

– the original design and condition of the mechanical components in the drive train;
– the maximum available discharge (this may have an environmental or other contractual consideration);
– the generator capacity (active power – MW);
– turbine setting with respect to tailwater level;
– type and characteristics of the draft tube;
– tail water level evolution vs. total discharge in tailrace channel;
– head losses in inlet conduits.

The mechanical design of the shafts, couplings, rotor spiders, stator soleplates, (the drive train) in older units are usually capable of accepting some increase in the maximum output of a unit with little or no modifications. In some cases, only minor modifications are required. The precise amount of any power increase can be determined only after verifying all the potential impacts and evaluating all cases where such action will give rise to higher stresses than were envisaged by the original designer.

Historically, power increases of between 10 % and 20 % are common since many old units already gave a full guide vane opening power which exceeded the nominal or “rated” value by 10 % to 15 % under the rated net head. This was typical in the days before computational fluid dynamics (CFD) and numerical control (NC) machining.

In addition, generators built before about 1965, had class B asphalt/mica type insulation systems on the stator windings which required a ground-wall insulation thickness much greater than the modern epoxy/mica based class F systems. This fact will allow a generator thermal capacity increase of between 20 % and 30 % by simply installing a new stator winding. The Hoover Dam Generating Station in the United States is an example of what can be achieved in the realm of rehabilitation and performance improvement when all conditions; hydraulic, electrical and mechanical and the market, are favourable.

The Hoover Dam Generating Station Units N1-4 underwent two rehabilitation projects in 1968 and 1986. The results presented by the owner are shown on Figure 7. But not all hydroelectric sites will provide the opportunities for increased power achieved at Hoover Dam (over 50 %). The interval between upgrades at that plant is also much shorter than is economically justifiable in most market circumstances.

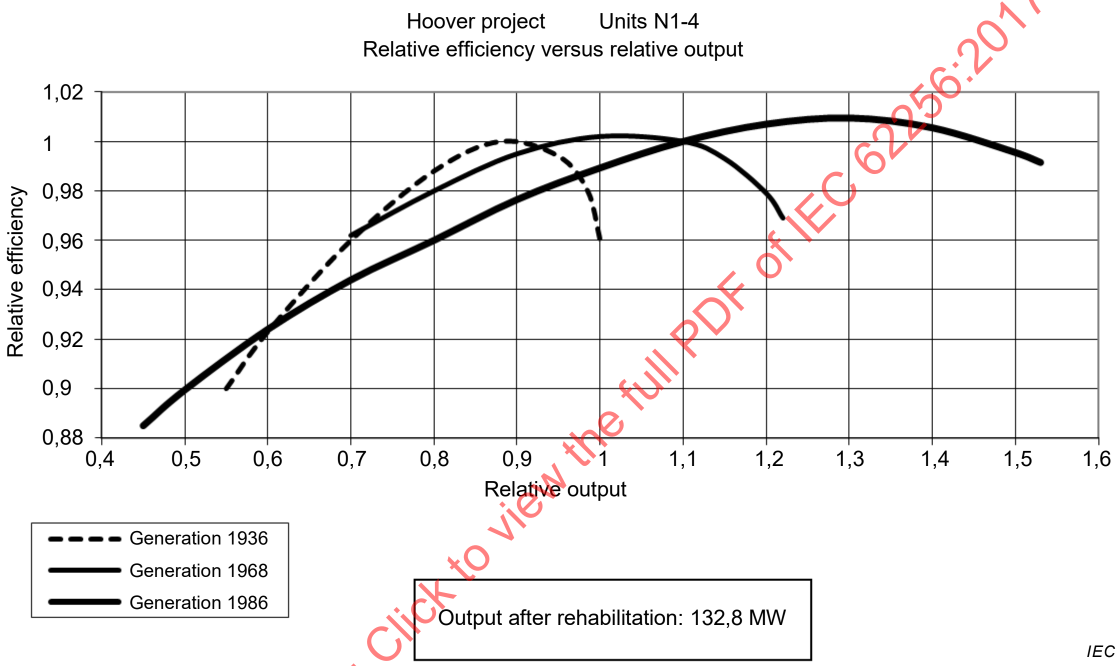

Figure 7 – Relative efficiency versus relative output – Original and new runners

Note that in the case of Hoover Dam, the peak efficiency increase was a relatively modest 1 % because a much higher discharge is being passed through the original water passages resulting in losses which partially offset the efficiency gained by new runner profiles.

In other cases, it is possible to increase the speed and power of the turbine by supplying a new generator and this can be justified economically if the increase in the maximum output of the units is large enough. The Outardes 3 turbine and generator rehabilitation project in Canada, Figure 8, is a good example of what can be achieved where the power increase of 44 % was accompanied by a more than 3 % increase in turbine peak efficiency. The original unit was commissioned in 1968 and the turbine rehabilitated and the generator replaced in 2003. The hydraulic losses in the power conduit outside the turbine will have increased for all conditions of operation above the original maximum power and these shall be evaluated in the calculation of the net benefits.

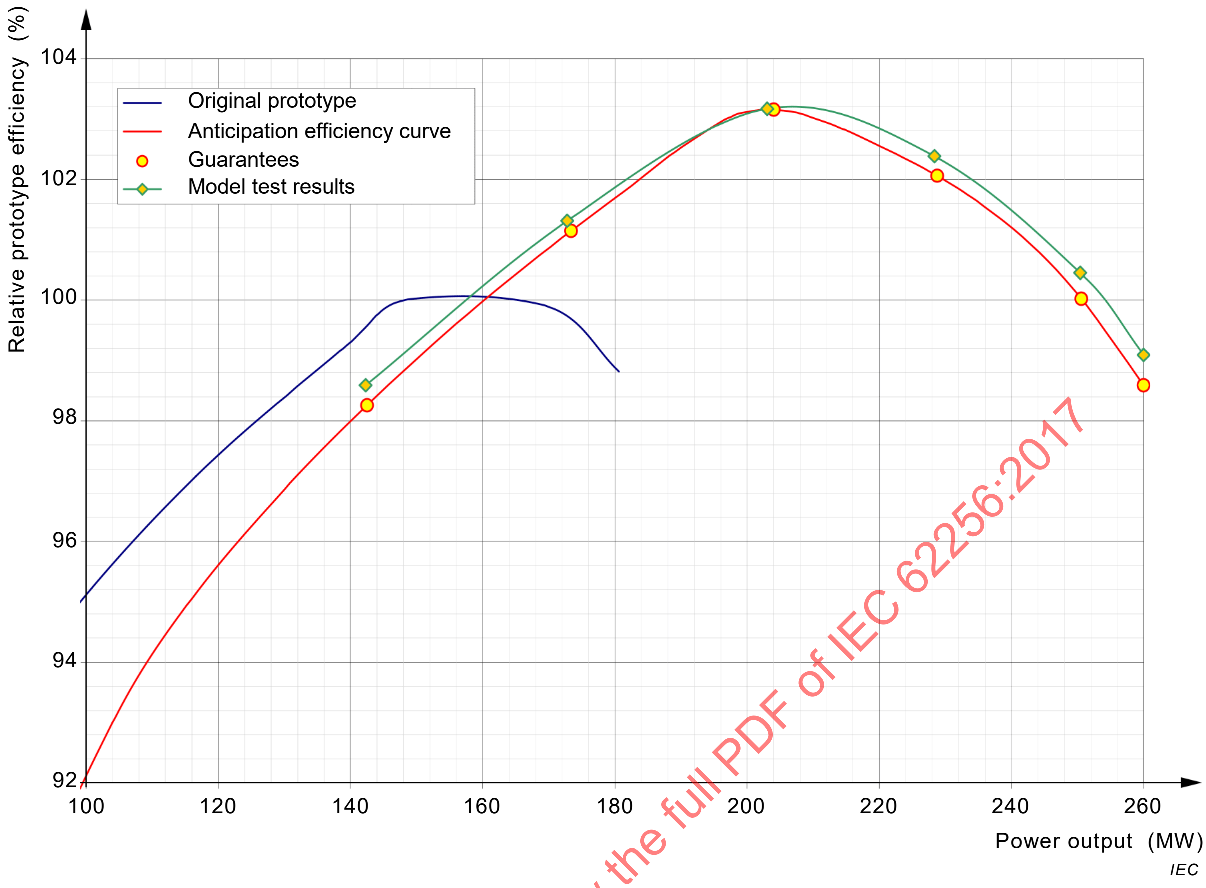

Figure 8 – Relative efficiency versus output – Original and new runners – Outardes 3 generating station

7.3.4.3 Efficiency improvements

7.3.4.3.1 Unit assessment

The first step in assessing potential efficiency improvement is to determine the performance of the turbine in its current state**.** The second is to see what the manufacturers can offer in the way of improved performance. These are essential to allow one to determine the performance improvement potential and from it, the potential benefits (annual revenue increase).

The turbine efficiency of the existing unit should be determined in accordance with IEC 60041.

Figure 9 is a plot of loss distribution at peak efficiency against specific speed $Nq = N\frac{\sqrt{Q}}{H^{\frac{3}{4}}}$

for a wide range of model Francis turbines in 2005. The left ordinate of the graph is the "per unit" peak hydraulic efficiency while the right ordinate is the "per unit" hydraulic losses. This plot gives a good idea of what one may expect in the way of performance for a totally new unit at that point in time. One shall keep in mind however that it is seldom practicable to rehabilitate an old turbine and to achieve the efficiency of a new turbine for the same hydraulic conditions and size. One can see from this plot that the turbine runner is the single most important component contributing to hydraulic losses. The distributor including the stay ring and guide vanes is the second most important part of the turbine, while for turbines of low specific hydraulic energy, the draft tube is also very significant.

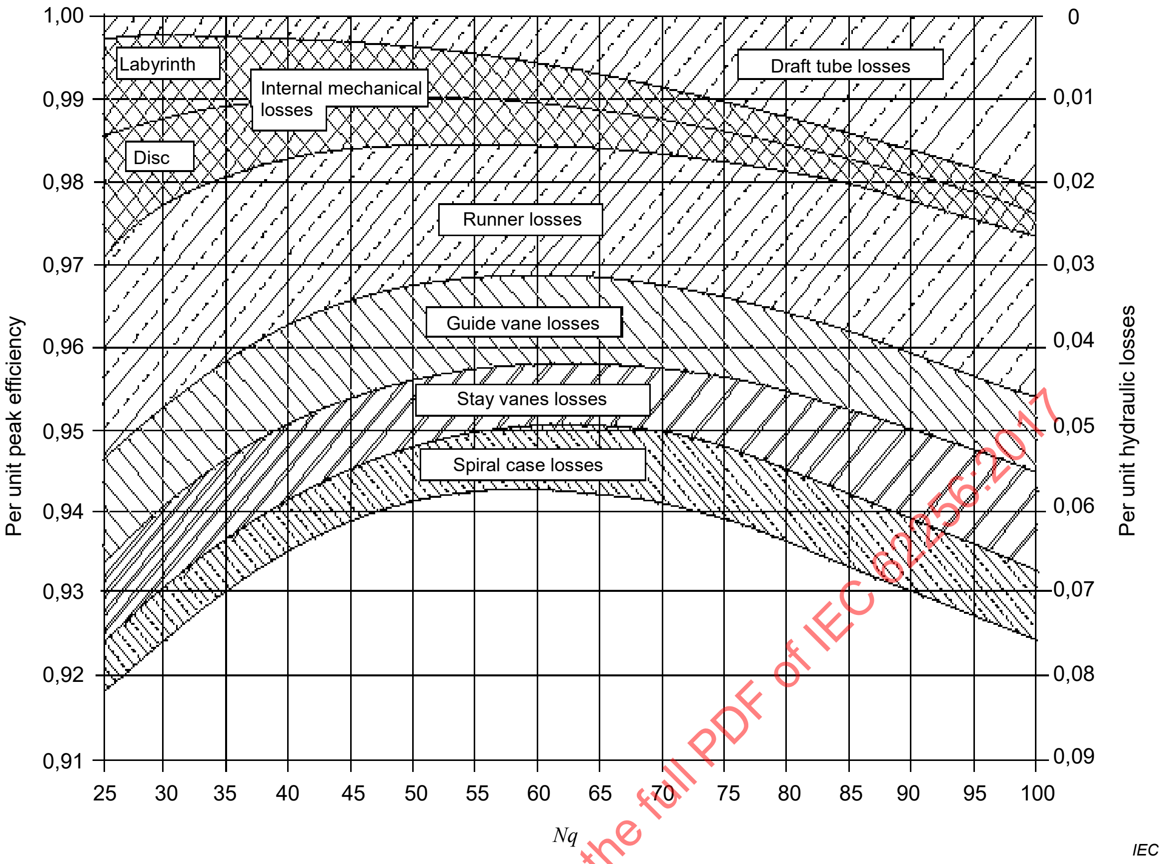

Figure 9 – Efficiency and distribution of losses versus specific speed for Francis turbines (model) in 2005

Significant performance degradation may be obvious from a carefully conducted recent power gate test, or index test, by comparing the results against reliable earlier tests.

For small units, this approach along with a careful unit inspection including measured runner seal clearances, wicket gate clearances and careful recording of all water passage damage, may be a sufficient basis for an evaluation by a qualified consultant or manufacturer, of the potential for efficiency improvement which may be achieved either by modification of the existing runner or by replacement of the runner with a new design. This exercise would assess all possible gains from improvements to the distributor, stay ring, spiral case and draft tube.

The comparison between recent test results and the original commissioning test results, as long as one has confidence in the earlier tests, always gives the best information to establish if degradation of turbine performance has taken place. The most recent test will serve as a benchmark for evaluating future performance improvements.

Because of the nature and cost of efficiency tests, the selection of the appropriate type of tests to be performed requires careful consideration based on the value of the project, the potential energy gains and the consequences of not meeting them completely. The options include the following:

– Field tests (a before and after test on the rehabilitated unit):
  - power/gate test under controlled hydraulic conditions;
  - index (relative efficiency) test under controlled hydraulic conditions;
  - absolute efficiency test (IEC 60041).
– Model tests (on a new model of the existing design and a new model of the new design).

– CFD analysis with or without verification by model testing. An economic analysis is required to determine the economic combination of studies and testing in this case.

These options are further elaborated upon in this document. Presented hereunder is a brief review showing typical efficiency gains (or loss reductions) attainable in old turbines.

Data is provided here below concerning the improvement in turbine efficiency which may be anticipated, depending upon the age of the unit and the date of the proposed changes. Note that the information provided concerning potential runner profile gains (Table 6) is for new machines in each era. A certain percentage of the apparent gain indicated is sometimes not achieved in rehabilitation because of the limited ability of the supplier to modify or totally rehabilitate economically, water passage components outside the runner itself. It shall be appreciated that the values given are averages for an era and, as has been indicated elsewhere in this document, all hydroelectric generating stations are particular cases which shall be ultimately studied on their own merits.

Any new runner shall be compatible with the other water passage components of the turbine, failing which the anticipated efficiency gains may not be achieved. In extreme cases, the new runner may have a lower efficiency than the old one.

7.3.4.3.2 Runner improvements

Table 6 is a compilation of the weighted and peak efficiency gains versus turbine vintage for runner profile modification only. These efficiency gains are determined by the difference of Francis turbine efficiency between new replacement runner and original runner only, with no other modification. The slightly better gains in weighted efficiency reflect the fact that the manufacturers have achieved not only an improvement in level of the efficiency curve but in its flatter shape (proportionately more improvement in the “off peak” regions than at the best efficiency point). Efficiency gains due to modifying other water passage components are dealt with separately. The efficiency gains are approximate values only, to be used in performing a preliminary feasibility study. For a detailed feasibility study, turbine manufacturers should be contacted to obtain specific values of potential efficiency improvement for the unit in question and for the proposed scope alternatives.

Table 6 – Francis turbine potential efficiency improvement (%) for runner profile modifications only

Francis turbine age (Years-period ending in 2000)					
60 years		**40 years**		**20 years**	
Peak	Weighted	Peak	Weighted	Peak	Weighted
2,2	2,7	1,0	1,3	0,5	0,7
NOTE This information was compiled by Rousseau Sauvé Warren Inc.(RSW) during its work on the IEA guide. The values in the above table come from its own experience and from the response to an RSW questionnaire by a major international turbine manufacturer during the IEA mandate.					

When a runner is being replaced, the manufacturers have the option to consider the potential benefits of changing the number of runner blades. All other things being equal, an increase in the number of runner blades affords the manufacturer the possibility of reducing the pressure differential across a given blade and improving the cavitation performance for a given maximum power. With an accompanying profile change, which is usual, one can expect to achieve an increase in maximum power. Any change in number of blades shall be done with due consideration for the dynamic interplay between the turbine distributor and the runner itself. Unsteady flow analyses may be justified, particularly in the case of plants with high specific hydraulic energy and close proximity between the trailing edges of the guide vanes and the leading edges of the runner blades.

Total runner blade area, which means blade length for a given distributor height, is another variable to consider when increased power is being sought. Overlapping of the runner band on the discharge ring or on the top of the draft tube liner and moving downstream the junction of the runner blades with the runner crown can be done only with due regard for the influence of this on the venting of the runner seal leakages to the draft tube since such changes affect the static pressures downstream of the upper and lower runner seals. Pressure changes can result in resonant vibrations.

Substantial gains can also be obtained in some cases through minor modifications to the blade profiles without replacing the runner. Figure 10 shows the increase in efficiency obtained on the La Grande-3 turbine runner, in Quebec, Canada, (commissioned in 1982) by slightly cutting back the blades at the outlet. This modification was carried out only after an extensive CFD analysis of the flow through the turbine.

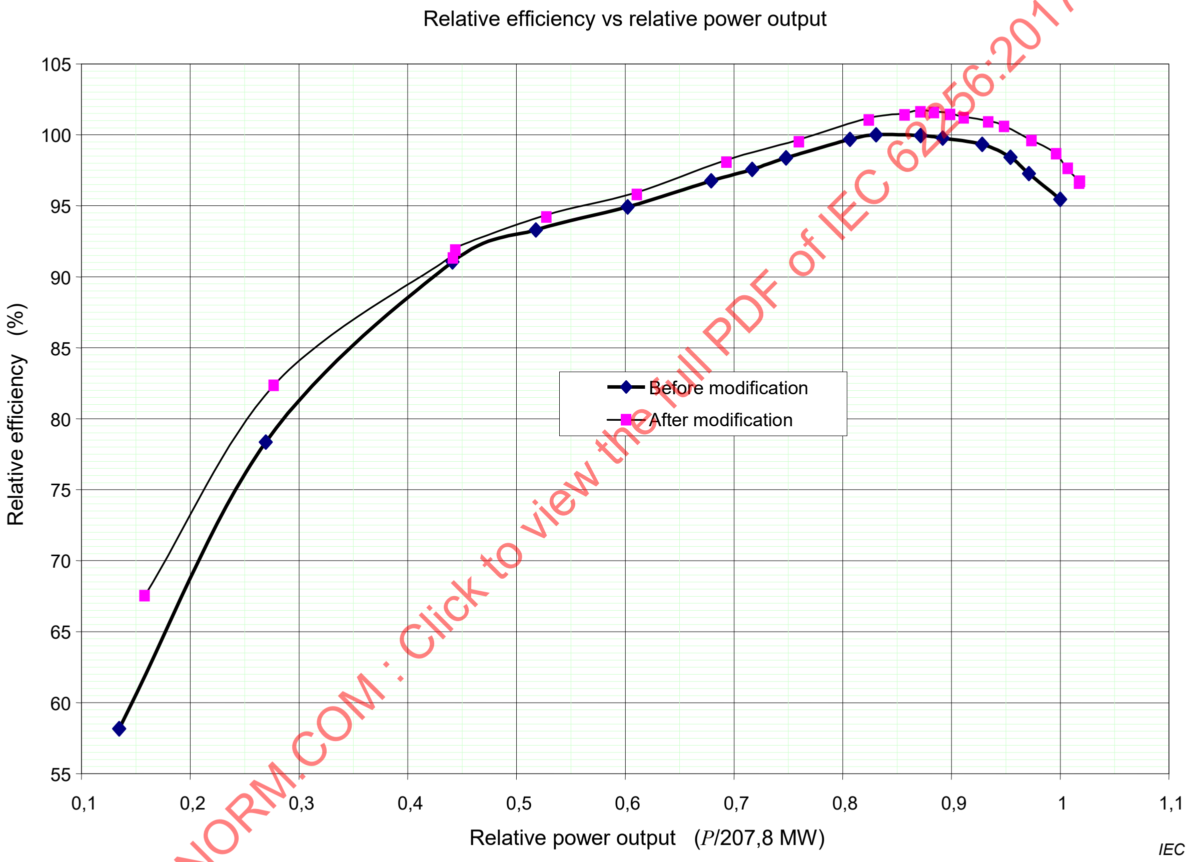

Figure 10 – Relative efficiency gain following modification of the blades on the La Grande 3 runner, in Quebec, Canada

In addition to the gains from a new hydraulic profile of the blades, some additional efficiency gains may be achieved through reduction of runner hydraulic friction losses both in the water passages and outside the band and crown (disk friction) and reduction of the runner seal gap loss (leakage discharge).

The magnitude of the potential gain in going from very rough to smooth surfaces in the water passages themselves and in the adjacent chambers could be anywhere between 0,2 % and 2 % depending on the current condition of the old runner.

Work is currently being done by IEC Technical Committee 4 leading to a more accurate prediction of the model to prototype efficiency step-up taking differential roughness into account. It might be possible to use an extension of this work in the future to estimate losses arising from gross roughness in old machines. As a first approximation, the maximum potential gain for improvement of surface condition may be assumed to be 2 % for 60 years, 1,5 % for 40 years and 1 % for 20 years since it may be assumed that most types of attack on the original surface condition of a runner are related to the duration of service. These gains would not be attainable if the original runner material was stainless steel and particle erosion is not a factor. During a Phase 1 Rehabilitation Study, one may assume gains from this source to be 1 % for 60 years, 0,50 % for 40 years and 0,25 % for 20 years. For any later phases of a rehabilitation study, it is recommended to seek expertise from manufacturers or qualified hydraulic laboratories to get a better assessment of the potential gains from improvement of surface condition in and around the runner.

The runner "disk friction" losses are influenced by the clearance with respect to the adjacent fixed components, the rotational speed and degree of surface roughness on both the rotating and fixed parts. If any of these parameters can be improved, a loss reduction may be achieved. Modifications may include a reduction of the clearance between the runner crown and headcover, the addition of an anti-circulation plate between the runner crown and headcover or a reduction of the surface roughness of the components involved (headcover, runner crown and band and discharge ring).

The runner seal gap losses increase with any increase of the seal clearances caused by erosion, cavitation and on occasion, wear due to contact. Re-establishing the original clearances or using a more effective seal design such as a multi-segment labyrinth in the place of a straight cylindrical seal, may contribute to loss reduction. The seal design may be re-analysed to determine the optimal theoretical clearance, but this shall be compared against a minimum safe clearance taking into account the following mechanical considerations:

– deflection of the headcover and bottom ring or discharge ring as a result of the pressure loads and the reaction loads from guide vanes;
– machining tolerances on the runner and on the adjacent fixed wearing rings;
– runout of shaft system within the bearing clearances which leads to runout of the runner in the seals;
– radial deflections of the runner components (mainly the band) during normal loading conditions and at runaway;
– turbine bearing support deflections including those resulting from occasional unequal loading from the servomotors when the forces acting on the operating ring are unbalanced.

The runner seal design and gaps impact leakage discharge and thereby the axial thrust on the turbine. An increase in axial thrust will result in higher losses in the thrust bearing, so it may be beneficial to consider the addition of an anti-circulation plate in the headcover to restrict the recirculation of leakage water from the outer crown seal thereby reducing the pressure load on the runner crown. Consideration should also be given to the ratio of balancing-hole area in the runner crown or balancing pipe area versus the upper seal clearance area. The balancing system transmits the upper runner seal leakage to the draft tube. A ratio of at least 5 to 1 is typical.

Table 7 provides an indication of potential efficiency improvement which may be expected solely from restoration or design modification of Francis runner seals and this is usually from restoration of the original runner seal clearances. The range of potential gains shown takes into account a wide range of cases of seal damage including serious particle erosion and serious wear. The table should be used with some foreknowledge of the particular case as indicated below and only for first approximations of a potential gain from the rehabilitation or design change of the seals themselves.

These efficiency improvements are determined as the difference between redesigned runner seals and the original worn runner seals only, in conjunction with a new replacement runner or a rehabilitated runner and no other modification. These efficiency improvements are approximate values only to be used in performing a preliminary feasibility study. The runner seal losses are not constant across the range of specific speeds (heads) as demonstrated in

Figure 9. For low specific speed turbines, losses in worn seals could be much greater than on high specific speed turbines due to the very different pressure gradients across the seals.

Table 7 – Potential impact of design and condition of runner seals on Francis turbine efficiency with new replacement runner or rehabilitated runner (%)

Runner seal component	Modification or replacement
Crown	0,2 to 2,0*
Band	0,2 to 2,0*
* Highly dependent on state of wear of existing seals and on specific speed of the turbine.	

If we set aside the particular cases of very bad runner seal wear due to particles transported in the flow, we can say that for a first approximation, the potential gain from repairing and improving the runner seals could be of the order of 0,5 % for each of the crown and band seals such that the potential gain for the runner replacement, again as a first approximation, could be taken as the values in Table 6 plus 1,0 % for a 60 year old turbine, 0,75 % for a forty year old turbine and 0,5 % for a 20 year old turbine.

Table 8 below shows the total gain which might be anticipated therefore for preliminary studies for a Francis runner replacement taking all aspects into account including profile improvements, rehabilitation of the seals and restoration of the surface finish on the blades crown and band of the water passages and on the runner external surfaces.

Table 8 – Potential total gain in efficiency from the replacement of a Francis turbine runner including the blade profile improvements, the restoration of surface condition and the reduction of seal losses

Francis turbine potential runner efficiency gains (Period ending in 2000)			
Age of unit	**60 years**	**40 years**	**20 years**
Profile improvements	2,2 %	1,0 %	0,5 %
Restoration of surface condition	1,0 %	0,5 %	0,25 %
Reduction of seal losses	1,0 %	0,75 %	0,5 %
Total approximate potential gain	4,2 %	2,25 %	1,25 %

The values of Table 8 are for the case involving Francis runner replacement. Efficiency gains can sometimes be made by modifying the existing runner blades as indicated in Figure 10 without replacing the runner. However, the total potential gains may be expected to be less than the values indicated in Table 8.

Additional potential gains in performance from modification of other turbine components are discussed in the following subclauses.

7.3.4.3.3 Improvements to other turbine components

Table 9 is a compilation of potential additional efficiency improvements by rehabilitation or replacement of other water passage components for a turbine vintage of (50 to 60) years. The potential efficiency improvements shown are from two possible sources; the improvement of the surface finish and modification or replacement of the component. The replacement or not of the turbine runner is not considered here in evaluating these potential gains. However, most studies involve runner replacement as a first option. Runner replacement has normally a high impact on turbine performance and the runner itself has usually a shorter useful life than the rest of the turbine. The potential efficiency improvements presented here are approximate values to be used in performing a preliminary feasibility study. For a detailed feasibility study, turbine manufacturers should be contacted to obtain specific values of potential additional efficiency improvement for the unit being studied.

Table 9 – Potential additional efficiency improvement by rehabilitation/replacement of other water passage components on a Francis turbine (%)

Water passage component	Surface finish improvements	Modification or replacement
Spiral case	0,3	
Stay ring	0,2	0,1 to 2,0
Guide vanes	0,2 to 1,0**	0,2 to 1,0**
Draft tube	0,3	0,3 to 1,0*

* Highly dependent on form of original draft tube and plant specific hydraulic energy (head). In extreme cases, could be as high as 2,0 %.

** In extreme cases, this improvement has been found to be as high as 2,0 %.

Since modifying the spiral case or its replacement for loss reduction is out of the question for all plants where it is embedded in concrete, the only remedial action is the improvement of the surface finish which shall be the subject of a benefit/cost analysis.

The stay ring cannot be replaced easily and this is seldom done, but its form can be more easily modified for loss reduction. The potential efficiency improvement from a stay ring modification can be determined by means of CFD analysis and confirmed by model testing, though an economic analysis is required to determine its feasibility. The turbine manufacturer can perform this CFD analysis. This analysis may demonstrate it to be feasible to modify the stay vanes to reduce losses. The stay ring is a very important structural component and therefore, careful structural analysis is required before any modifications are done. Modifications to the shrouds are sometimes considered to improve the flow from the spiral case to the stay ring by the addition of parallel shroud plates. For example a classic non-Piguet stay ring (with converging shroud plates) can be converted to the Piguet type stay ring having parallel shroud plates for a case where a significant increase in maximum discharge is contemplated. Modifications to the inflow edge profile and angle of the stay vanes may also be considered. The degradation of the surface finish will also have resulted in an increase of losses and the improvement of the surface condition of the stay vanes and shrouds may prove to be advantageous.

Apart from the turbine runner itself, the guide vanes are the next most likely component to present an economic possibility for performance improvement by replacement. Use of higher strength material for the guide vanes can permit reducing the thickness of the guide vane body and improving its hydraulic shape. Provided the new guide vanes use the same trunnion diameters, a change of guide vanes represents no significant modification to either the headcover or bottom ring. It should be noted however, that in addition to a change of the shape of the guide vane itself, additional maximum opening angle may be required to achieve an increase in maximum power and this will require a detailed review of guide vane hydraulic torque and the stroke and capacity of the servomotors.

The degradation of the surface finish of the guide vanes will also result in an increase of losses and, if they are to be retained, the improvement of their surface finish will contribute to loss reduction.

The contribution of the draft tube to total turbine losses is highly variable and site dependent and not always predominately related to “vintage” (see Figure 9). CFD analysis is essential to determine potential improvements and an economic analysis is required to determine the feasibility of any proposed changes. The degradation of the surface finish of the draft tube will also result in an increase of losses although this effect is usually secondary to poor draft tube design especially in very old machines.

Modifications for performance improvement may be limited to the areas involving the mechanical components alone but they may involve, if economically justified, substantial modifications to the concrete draft tube profiles. As indicated above, for best results, detailed drawings of the complete existing equipment including the draft tube and any existing flow improvement devices shall be made available to the contractors being considered to quote on any rehabilitation project.

Relatively minor concrete modifications are sometimes possible to improve the velocity profile of some of the earlier elbow draft tube designs allowing substantial performance gains at high discharge.

Figure 11 presents a plot of points showing gains attained for varying degrees of intervention on Francis type turbines. The points between 1908 and 1955 are from Japanese experience and are based mainly on before and after rehabilitation efficiency tests using a number of different methods. The points between 1978 and 1998 are from European and North American cases and are based on comparative model tests of Francis runners with the old and new hydraulic profiles but with conventional runner seals in comparable condition for the two designs hence represent the potential benefit of the blade number and profile changes only with no gain from surface condition nor from runner seal improvement. On these point plots, a curve is added based upon the assessments described above for runner replacement from the last line of Table 8.

The potential benefits of other component modifications shall also be considered but they are highly dependent on site specific conditions and are rarely considered in a Phase I feasibility study for turbine rehabilitation.

The reader should note from Figure 11 that there are many cases where the performance improvements which one might expect from the above data, were not attained and this underlines the importance of having the appropriate expertise devoted to the studies prior to commencement of the rehabilitation work in all cases.

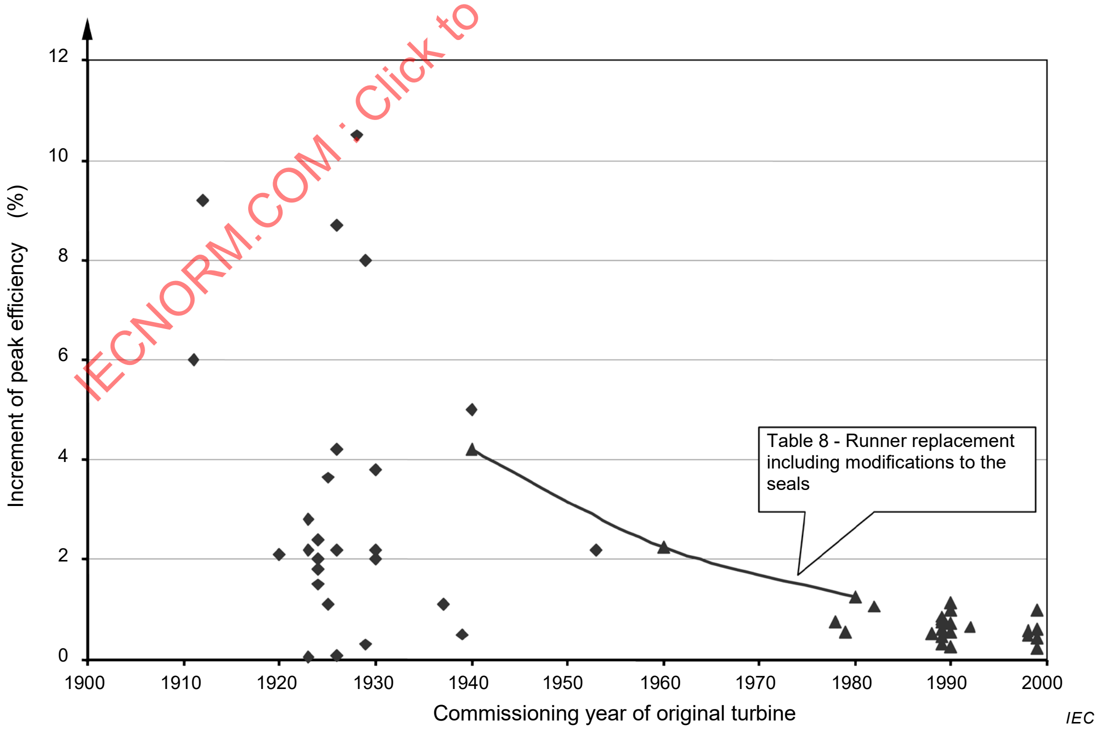

Figure 11 – Potential efficiency improvement for Francis turbine rehabilitation

Figure 12 is a plot based on Swedish experience of potential gains on Kaplan turbines arising from the replacement of the turbine runner and the discharge ring. Some of these rehabilitated machines now have discharge rings which are spherical throughout the zone swept by the runner blades, above and below the blade axis. Such interventions may not be economically justified in all cases where the discharge ring is embedded as it likely was in machines built before 1960. A number of efficiency gain evaluation methods were also involved and the reader shall be aware that each method carries its own inaccuracies.

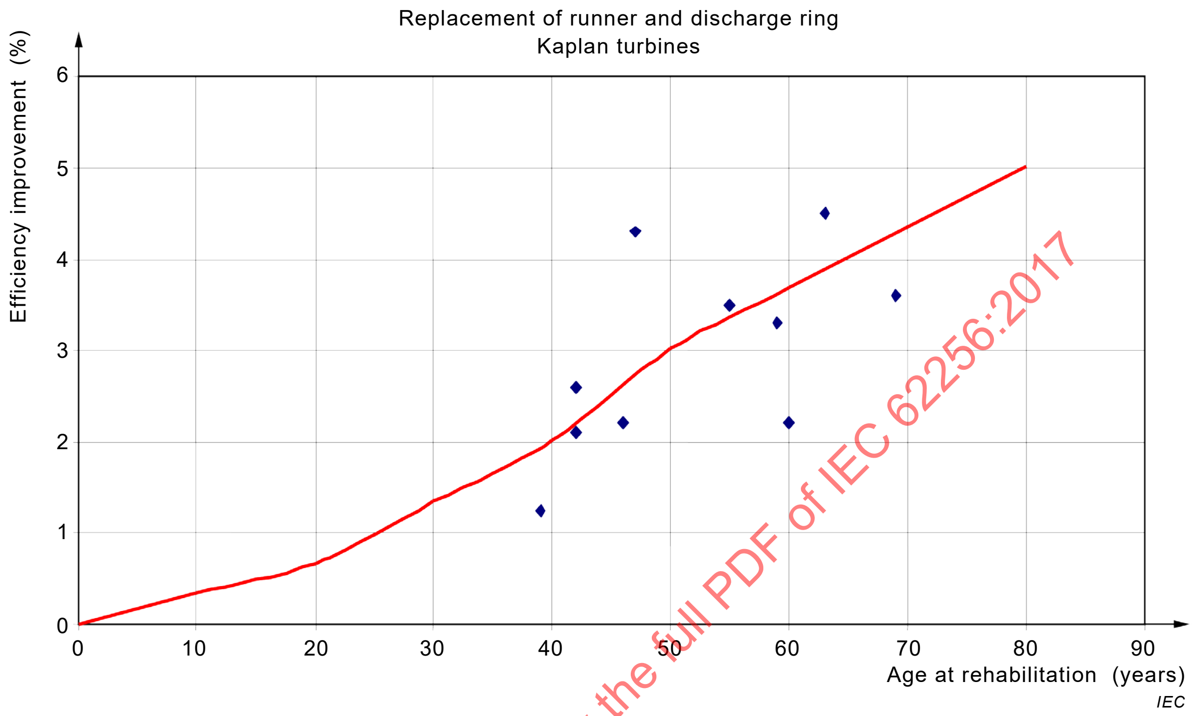

Figure 12 – Potential efficiency improvement for Kaplan turbine rehabilitation

As mentioned above, the deterioration of the surface finish of the components of a turbine can have a significant impact on its efficiency. In the order of potential importance, the components which have an influence are the runner, the guide vanes and the stay ring. Lesser but potentially significant effects result from deterioration of the water passage surfaces of the spiral case and draft tube. IEC 62097 provides a method of evaluating the impact of surface finish differences. Its limits of applicability are very strict however, since that publication was developed to permit evaluating the differences between the surface finishes of turbine models with respect to the corresponding prototypes, both in “new” condition (prediction of prototype performance from model tests). Further work is being done by both IEC Technical Committee 4 and International Association for Hydro-Environment Engineering (IAHR) to extend the range of evaluation of surface roughness effects. Rehabilitation of the surfaces of the runner and guide vanes or their replacement is almost always economically justifiable. Cleaning and painting of the stay ring, surfaces of the headcover and discharge ring exposed to the flow are also usually justified. The cleaning and painting or other resurfacing of the water passages of the spiral case and draft tube may be justified, sometimes for reduction of losses and sometimes to arrest material loss by corrosion/erosion.

7.3.4.4 Cavitation erosion

7.3.4.4.1 Cavitation in reaction turbines

Modern runner designs allow less submergence for cavitation erosion free performance at a given discharge coefficient than do older units. This is due to better pressure distributions, which the use of modern design and testing tools permit the manufacturer to attain (computational fluid dynamics (CFD) and model testing) particularly within the runner. The Thoma coefficient is fixed in an existing plant unless there are changes in hydraulic conditions or downstream channel improvements involved when the rehabilitation of the unit is done. The margin afforded by the new designs may be used by the turbine manufacturer to provide an increase in the maximum power at full guide vane opening (higher discharge coefficient). To the extent that additional discharge is involved and if no downstream channel improvements are done, an increase in the tailwater elevation for maximum discharge and increased plant sigma will result. In addition, the available specific hydraulic energy (net head) at the turbine will be reduced.

Several types of cavitation erosion are typical in Francis and axial flow reaction turbine runners. The first is “leading edge induced erosion” on either the pressure side or the suction side of the blades and can be caused either by design profile errors, poor flow distribution in the runner or by wide variations in the operating specific hydraulic energy or discharge. Manufacturers have learned to better accommodate these in post 1990 designs, although it can still occur. The second is near trailing edge erosion as shown in Figure 13 which may be caused by poor flow distribution giving high local velocities or local profile errors in a low pressure zone. The latter are related almost exclusively to high load operation with marginal downstream submergence (low Thoma coefficient). Figure 13 shows both cavitation erosion within the bounds of the stainless steel overlay and corrosion erosion upstream of the overlay. Axial flow fixed blade propeller and Kaplan turbines can also have cavitation erosion on the suction side of the blades at the periphery and on the adjacent discharge ring from cavitation occurring in the blade tip gap. This latter type is “design” related and is a function of pressure differential from the pressure side to the suction side of the blades all along the periphery, the blade thickness and the peripheral clearance between the blades and the discharge ring. Anti-cavitation lips are sometimes employed to eliminate this problem but, if poorly designed or manufactured, they may, themselves be the source of an erosion problem.

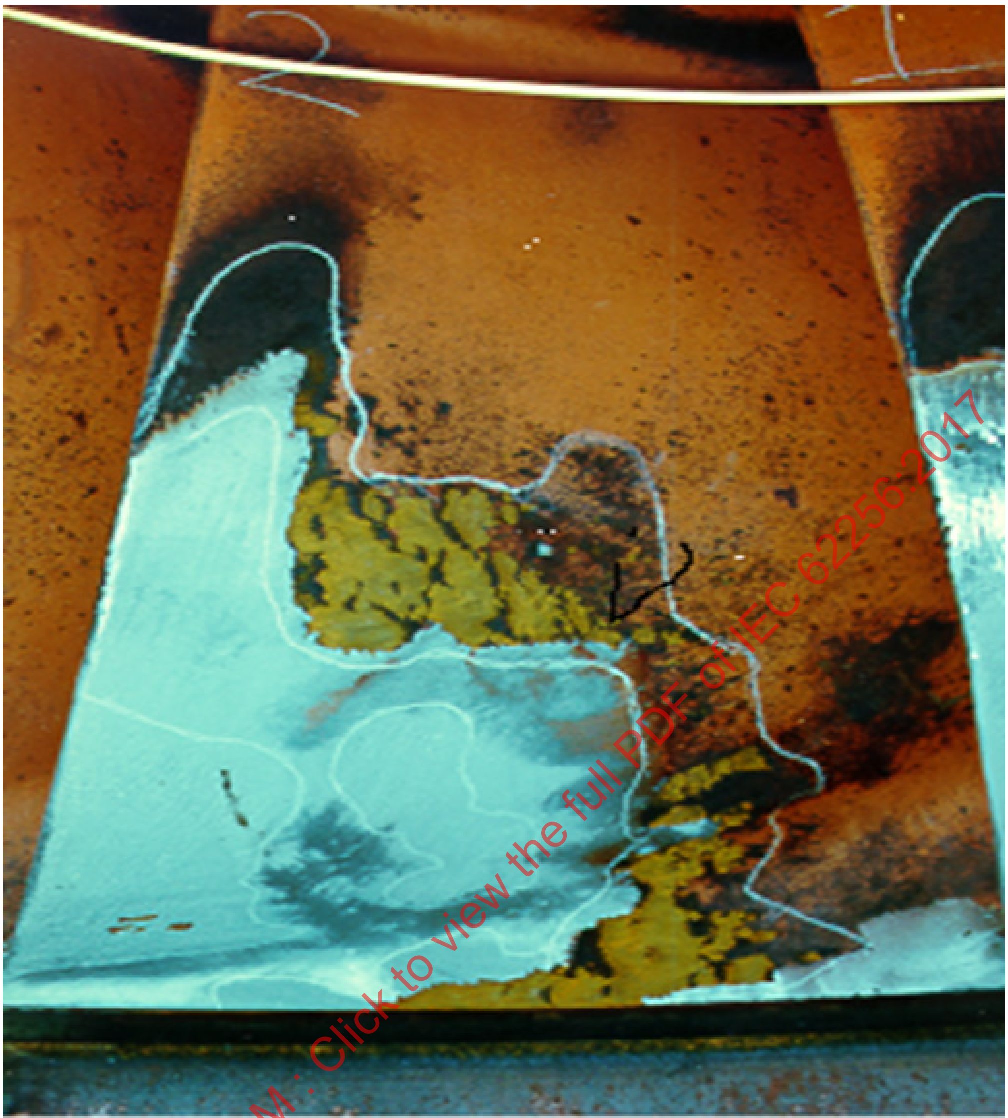

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Figure 13 – Cavitation and corrosion-erosion in Francis runner

7.3.4.4.2 Cavitation in Pelton turbines

The entrance edges of the buckets are often damaged by cavitation erosion or by droplet erosion. An example is shown in Figure 14.

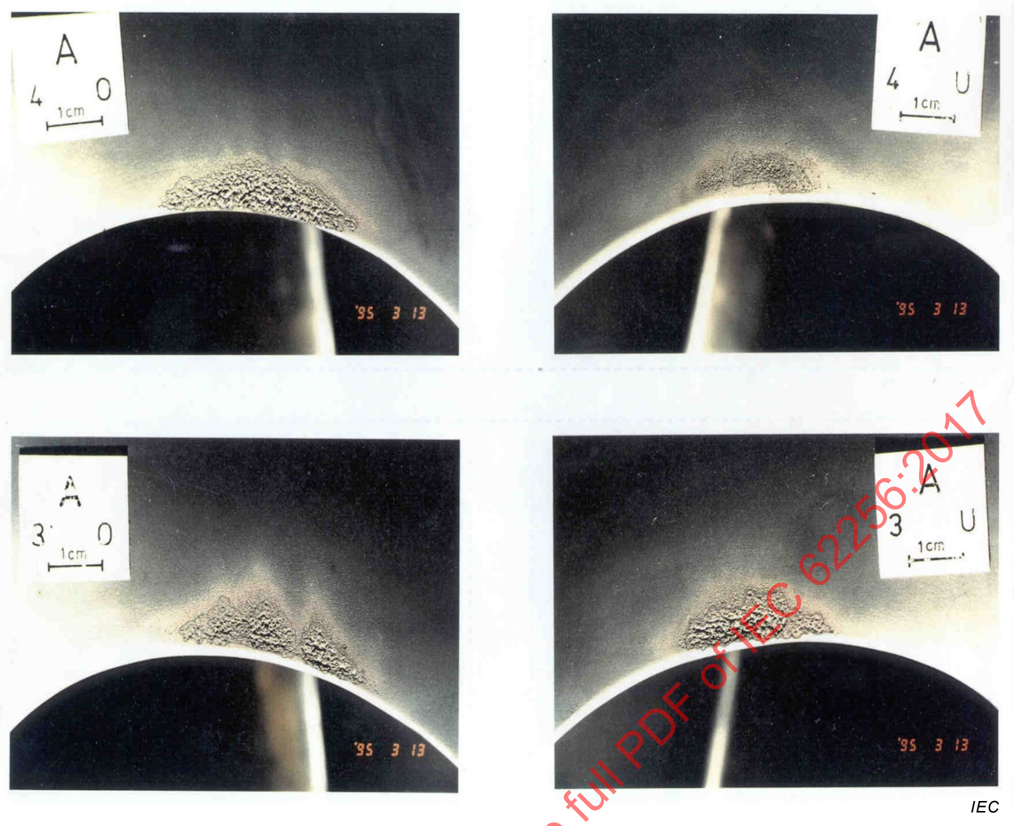

Figure 14 – Back side erosion of the entrance into a Pelton bucket

There are two reasons for this damage:

– low pressure on the backside of the bucket cutout if the profile is not correct;

– droplets with low velocity leave the bucket after the jet of the following injector enters with high velocity; these droplets are driven onto the runner material with sufficient force to erode it. This type of damage is often found in multi-jet turbines in which the time interval between two jets is too short for all the droplets to leave the bucket.

The repair requires welding and thorough re-profiling by grinding and polishing.

7.3.4.4.3 Cavitation in pump-turbines

The exposure of pump-turbines to cavitation erosion is very similar to that of the classic reaction turbines. However, because the profile of the vanes at the outlet and inlet of the impeller/runner is a compromise between that required by the pumping and turbining modes, there is a greater risk of cavitation erosion in the impeller/runner of the pump-turbine.

Typical cavitation erosion in the turbine mode is shown in Figure 15. This is particularly true for an installation which has a wide range of specific hydraulic energy and for which the demand in the turbine mode covers a wide range of load. Erosion on the pressure side, downstream of the blade inlet in the turbine mode is typical of units required to operate for long periods at speed-no-load or at very low loads. Erosion on the suction side, downstream of the blade inlet in the turbine mode is typical of units required to operate for long periods at very high loads. In the pumping mode, the risk of cavitation erosion on the suction side of the blade, near the entrance, increases as the downstream level diminishes.

Figure 15 – Leading edge cavitation erosion on a Francis pump-turbine caused by extended periods of operation at very low loads

7.3.4.4.4 Possibilities of reducing cavitation erosion in existing hydraulic machines

Modern runner designs are often based on higher strength stainless steel materials which also have higher cavitation erosion resistance than the original materials which were typically cast iron, bronze or mild steel. Modern runner designs are usually manufactured by assembly and welding of digitally-machined separate crown, blades and band while the original runners, prior to about 1975 in most cases, were manufactured using either one piece castings or hand finished castings assembled by welding. The modern approach permits better adherence to the homology between the theoretical design, the model and the prototype, which in turn, makes for more predictable cavitation erosion performance. Small runners, however, may be still manufactured using one piece castings. The homology between model and prototype of these runners will still be adequate so long as a qualified foundry is used. These foundries have developed techniques over the years which will ensure an acceptable level of precision for small units. Careful hand finishing is equally important in these cases.

Modern runner designs with all their attributes with respect to freedom from cavitation erosion by design and protection against cavitation erosion by the choice of more resistant materials should be nevertheless operated within the design range of specific hydraulic energy (head), power and submergence. Failure to comply with these contractual criteria could subject the new runner to cavitation erosion which may be avoidable and could void the manufacturer's guarantee. The keys to the longevity of the runner are strict operating rules and respect for them, regular inspections and timely, carefully controlled weld repair and surface grinding of any cavitation damage which does occur. Repairs of cavitation erosion damage should be made with erosion resistant electrodes using templates to re-establish or maintain the design blade profile.

As indicated in 5.6.2, the use of IEC 60609 (all parts) is recommended as a basis for the contract terms regarding cavitation erosion performance. The runner should not be the only component which is governed by the cavitation guarantees. Adjacent components such as the distributor, discharge rings and draft tube liners should be included in the guarantee coverage.

7.3.4.4.5 Experience with special overlay materials

Special overlay materials for enhanced cavitation erosion resistance should be considered when model testing observations indicate that an area of the runner will be subjected to cavitation within or even slightly beyond the design operating range and the manufacturer cannot eliminate this cavitation by further development efforts within the contract schedule. Another circumstance for the use of high cavitation resistant welding electrodes is when the new prototype runner has unexpected recurring cavitation erosion damage. Application of such materials necessitates the use of carefully controlled welding procedures.

7.3.4.5 Suspended particle erosion

7.3.4.5.1 Exposed components

The flow through turbines carrying suspended sediments can result in erosion on the water passage components exposed to high velocities. Severe erosion (see Figure 16) can result in substantial production losses due to the need for frequent repair welding or frequent component replacement. The key parameters governing the severity of erosion damage are sediment concentration, the density, hardness and shape of sediments and flow velocity. The flow velocity parameter divides the turbine into two areas which are subject to varying degrees of particle erosion: the components with low velocities such as spiral case and draft tube liner and those with high velocities or sudden flow directional changes such as the stay ring (particularly the stay vanes), guide vanes, headcover, bottom ring, discharge ring, runner and rotating wearing rings. Typically for Francis turbines, the worst erosion occurs in the runner, runner wearing rings, guide vane body extremities (surfaces adjacent to the headcover and bottom ring), headcover (particularly the stationary wearing ring), and bottom ring (particularly the stationary wearing ring).

Figure 16 – Severe particle erosion damage in a Francis runner

7.3.4.5.2 Causes and effects of suspended particle erosion

The causes of suspended particle erosion are as follows:

– Particle size increase will result in a corresponding increase in erosion rate up to a size threshold beyond which wear rate stabilizes. For velocities of 130 m/s and less, the particle size seems to have little or no impact. This covers all components of all reaction turbines and pump-turbines.

– The relative particle and base material hardness affect the erosion rate. A particle hardness equal to or greater than the base material hardness results in high erosion rates. Conversely when the base material hardness exceeds the particle hardness, the erosion rate is low.

– The particle shape has high impact on erosion rate with sharp-edged angular particles being the worst.

– The erosion rate will exponentially increase with impact velocity and the value of the exponent is a function of the base material elasticity. A high modulus material such as steel will have a higher exponent than a material with a lower modulus such as rubber.

– The impact angle will affect the type of erosion. A low impact angle and a sharp particle will literally cut away the base material; a high impact angle leads to fatigue failure of the base material whereby pieces are broken off by a hammering effect.

– Particle concentration and particle distribution have an important impact on the erosion rate.

The effects of the two erosion types (cutting and impact fatigue) can be observed in the components. For example, the erosion wear of the adjacent surfaces between the guide vane, headcover and bottom ring is the result of the cutting type of erosion due to the high velocity and low impact angle when the guide vanes are closed or at low openings. This will reduce the performance of the turbine and the increased clearances between these components will result in a higher torque being applied to the runner during a shutdown sequence. The impact fatigue type erosion occurs on the leading edge of runner blades, guide vanes or stay vanes. No matter what the type of erosion, it will reduce the structural integrity of the components by metal removal, alter the profile of the component and reduce the hydraulic machine performance. In the case of the runner, increased seal clearances will result in an increase in flow through the seals contributing also to a reduction in the performance of the turbine. Increased clearances at the seals may also result in higher hydraulic thrust loads. Erosion due to suspended particles and cavitation erosion will tend to accentuate one another. Damage due to cavitation erosion will lead to more vortices resulting in an increased erosion damage rate.

7.3.4.5.3 Experience with methods used to reduce suspended particle erosion

The first line of defence regarding suspended particle erosion is to reduce the concentration of the particles entering the turbine by causing their settlement in the storage reservoir or in siltation beds. Effective flushing of deposited materials is essential to the effectiveness of this method. Although, where the reservoir is used for sedimentation, its capacity will be eventually reduced. Some sites lend themselves to the installation of sediment traps with flushing provisions.

For minimal erosion rates, the operation of the turbines should be such that when the suspended particle load in the water is high, the turbine is operated at or near to its peak efficiency point. This will result in the most efficient flow for a corresponding power, thus exposing the components to lower secondary velocities and to optimal flow angles on the distributor components and on the runner blades, reducing particle impact angles. Turbine shutdowns without inlet valve closure or without penstock drainage should always be minimized thus minimizing the exposure of the closed distributor assembly to the high velocities at the adjacent surfaces of the guide vanes, headcover and bottom ring.

For components such as spiral cases and draft tube liners, which are subjected to low flow velocities, it is important to maintain the coating system. The use of tough elastic coatings such as epoxy and polyurethane-based plastics systems is recommended, since there is very little destructive energy released during the impact and the component surface is elastic enough to absorb slight deformation without damage.

As is suggested by the description of the mechanisms of suspended particle erosion, there are three basic approaches to reducing its effects on components exposed to very high flow velocities such as the distributor and the runner. They are:

a) design for reduced velocities in the critical regions of the hydraulic machine;
b) use of the hardest available materials for the critical components;
c) use of hard-facing materials in critical regions.

A combination of a) and b) is feasible in any new hydraulic machine and to a lesser degree in a major rehabilitation. Once the speed and geometry of the machine are fixed, modification of the design to minimize erosion has fewer possibilities. In the case of a runner replacement, the runner design should consider all the parameters governing suspended particle erosion: flow velocity; change in flow direction; elimination of local flow vortices; elimination of cavitation; runner material selection and design features. In this last category would fall, for example, turbine seals having segmented wearing rings on the headcover and bottom ring which are replaceable without the need for disassembling of the turbine.

If a turbine will be subjected to standstill conditions under pressure, the use of loaded (active) stainless steel end seals adjacent to the closed guide vanes may be considered. The guide vanes should be constructed with renewable stainless steel end surfaces. The heads of fasteners in the flow passages presenting discontinuities to the flow pattern should be avoided since they will produce vorticies and secondary flows, aggravating erosion rates.

Work is continually being done to assess and apply new materials in high risk erosion service. The best contribution an owner can make toward alleviating this problem is to ensure that the characteristics of the water and its suspended material are well defined in the specifications. In addition, the tender document should clearly indicate that the tenderer shall describe in its tender the means by which it will confront this problem.

Components such as the stay ring, headcover, bottom ring, guide vanes and runner which are subjected to high flow velocities may be lined with or constructed of a martensitic stainless steel such as ASTM A240 Type 405, 410 or 415 or ASTM A 743 Grade CA-6NM which have relatively good particle erosion resistance.

When the suspended particle content is very high, the use of applied coatings may be considered. This document does not recommend the use of any specific coating since many are experimental and have demonstrated varying degrees of success. The various applied coating options are ceramic, hard metal or polyurethane based. The additional expense of these coatings shall be carefully evaluated against the potential gains of production achieved by reduced downtime for repair. Even with special coatings, inevitably some turbine components will require frequent reconditioning or component replacement where the service conditions are severe.

Use of hard facing materials such as ceramics is fairly widespread in cases where the particles sizes are small and where it is clear that the selected coating is harder than the suspended particles. Erosion resistant coatings do not perform well under cavitation erosion attack, nor do they if there are very large particles such as "rocks" entrained in the flow (high impact loading). Modern cavitation free or near cavitation free designs are opening up new possibilities for the use of hard facing materials for particle erosion resistance.

The application of hard facing materials in the shop is relatively straight forward although relatively expensive. Successful application in field conditions is much more difficult and some would say, impossible. It is therefore wise to plan for a cycle of shop rebuilds whenever the use of hard facing materials is contemplated.

7.3.4.6 Hydraulic stability

7.3.4.6.1 General

These phenomena fall in three basic categories as follows:

– von Kármán vortex induced resonances;
– runner – distributor interactions;
– hydraulic pulsations with or without resonance and with or without power/frequency swings.

7.3.4.6.2 Von Kármán vortex induced resonances

The von Kármán vortex induced resonances have three usual sources: vortices shed by the stay vanes; vortices shed by the guide vanes and vortices shed by the runner blades. The frequency and intensity of such vortices are discharge (velocity) and component thickness and form dependent. So, if a rehabilitation project involves an increase in the maximum discharge, it could produce a resonant condition where one did not exist previously.

The first (from the stay vanes) are often at a low enough frequency to enter into resonance with one of the modes of vibration of the stay vanes themselves and as such can give rise, particularly in low head units, to cracking of the stay vane to stay ring shroud connections. The frequencies involved can be in the sub-audible to the low audible range (e.g. from a few Hz to 50 Hz). Modification of the shape of the stay vane trailing edge is the common solution to this potential problem.

The second (from the guide vanes) are much less common because, normally, the thickness of the trailing edge of the guide vanes relative to the flow velocities at that location makes them a less likely source. If they do occur, they too would be, for medium to large sized machines, in the low audible range (e.g. from 20 Hz to 100 Hz). The solution, if the problem does arise, is the same as for the stay vanes.

The third possible source of von Kármán vortices is the trailing edges of the turbine runner blades. At this location, the discharge velocities in a reaction turbine (axial flow or Francis type runner) are the highest flow velocities attained in the turbine and the frequencies generated can be in the range of the natural frequencies of the runner blades themselves in water. Turbine runners have a large number of vibratory modes and the frequencies vary greatly from what could be calculated by finite element method (FEM) or measured in air, to what would be measured in water. Accordingly, it is difficult with current design tools to predict whether or not a resonant condition will occur. The tools for assessing natural frequencies of runners in water are improving and it is recommended that the selected contractor be requested by specification to establish the potential forcing frequencies that can excite the runner and to estimate the natural frequencies in water of the proposed design. It should be required to avoid combinations of crown, blade and band thickness and form which expose the new design to potential resonance or forced response problems.

For new runners made from high strength materials, it should be stated that the blade thickness at the trailing edge tends to be less than the one of any design which they might be replacing. This tends to raise the forcing frequencies from vortex shedding. On the other hand, the fundamental natural frequency and all of the harmonics of a thinner blade are lower, increasing the possibility of resonant vibrations. In the runner, the induced frequencies are in the low to medium audible range (e.g. 50 Hz to 1 000 Hz). The one advantage with this type of “performance” problem is that its mechanisms are easily recognized and the knowledgeable manufacturers will be able to eliminate the problem by modification of the blade trailing edge shape at site. It is a problem which can be solved during commissioning and not one which should affect the long term performance of a rehabilitated unit.

7.3.4.6.3 Runner/distributor interaction

In regard to the forced response type of vibration problems, the solutions to runner/distributor problems are not at all so simple because they are a function of the number of guide vanes and runner blades and the juxtaposition of the two. This potential “problem” is most common in medium to high specific hydraulic energy (head) Francis machines for which there is close proximity between the trailing edges of the guide vanes and the leading edges of the runner blades. It is important that the manufacturer be required to demonstrate that the design which it proposes, has a solid basis in previous successful operation of geometrically similar machines or that any new feature has been analysed with the most sophisticated tools available and is shown to be safe and reliable. This type of problem has been known to necessitate making significant modifications to or even outright replacement of new runners. One should also consider that a new runner with different number of blades will change the forcing frequency on the stationary components.

7.3.4.6.4 Hydraulic pressure pulsations

Hydraulic pressure pulsations in the draft tube of a Francis turbine and, indeed, in the draft tube of any reaction turbine, are a normal feature of off-peak operation. Since the birth of the technology in the latter half of the 19 century, designers and manufacturers have been trying to minimize the secondary flows in and discharging from the runner to broaden the range of possible operation with respect to the peak efficiency zone. They have not yet in 2006, succeeded in eliminating the possibility that the pulsations generated by the runner, create resonance with the complete hydraulic system. This aspect of hydraulic design is further complicated by the fact that the possible resonances cannot be determined by model tests, even if the entire hydraulic system were to be modelled.

IEC TC 4 has been working on the establishment of criteria for judging the acceptability of hydraulic pressure pulsation for at least the last 50 years. To date, it has succeeded only in defining how pressure pulsations due to runner design should be measured (IEC 60994).

Analyses to determine the potential resonant frequencies shall take into account the entire water passage, “free surface to free surface” from the power intake structure through the power tunnel, the penstock, the surge tank, the manifold, the turbine, the draft tube and the tailrace conduit, whichever are applicable for each site. Forcing frequencies coming from the runner depend on the design and on the discharge and are usually in the range from 25 % to 100 % of the runner rotational frequency. Low load operation normally generates the lowest draft tube forcing frequencies while high loads generate the highest frequencies. In complex hydraulic systems, this large variation in potential forcing frequencies makes it difficult to preclude, by design, all possibilities of resonance. When rehabilitation involves increasing the maximum discharge passed through the unit, it is possible that the range of forcing frequencies will change and create a resonant condition where it did not exist previously.

The most common solution to a problem of hydraulic resonance is the modification of the natural frequency of the turbine draft tube by the admission or injection of air. The effects are obtained in two ways. Firstly, the form and frequency of precession of the draft tube vortex (the forcing frequency) changes when air is admitted to it and secondly, the resonant frequency of the complete draft tube changes due to the change in celerity of the modified two phase flow (water and air). Care shall be taken in applying this method of turbine stabilization because, in a complex hydraulic system, resonance can be created with air admission as easily as it can be eliminated. The other important factor is that when the quantity of air admitted (or injected) exceeds about 1 % to 1,5 % (standard temperature and pressure) of the turbine discharge, it can have a measurably detrimental effect on turbine efficiency, particularly in the region of the optimum efficiency of the turbine. It is therefore important not to admit or inject air in the normal range of guide vane opening, if it is not required for eliminating resonance. The admission or injection of air to the draft tube in the part load and overload ranges can be marginally beneficial for turbine efficiency.

It should be noted that for deeply set Francis turbines and particularly pump-turbines whose runner/impeller submergence is set by the requirements of the pumping mode, that if air is required, it will probably have to be injected from a compressed air source. The lowest static pressure point in the draft tube may be above atmospheric pressure.

Various types of draft tube flow straighteners have been tried with varying degrees of success but their big disadvantage is that they can be practically designed to be optimal for only a narrow range of discharge and are therefore a performance hindrance at all other operating conditions.

7.3.4.6.5 Power/frequency swings

Power or frequency swings can occur at the frequencies caused by draft tube pressure pulsations particularly if these are in resonance with the hydraulic conduit system. Repercussions caused by draft tube pulsations on the static pressure upstream of the turbine distributor (spiral case pressure pulsations) will result in discharge pulsations which have a direct influence on power. Such cases are more likely produced by the type of draft tube pulsations which occur at high loads and can usually be eliminated by minimizing the pressure pulsations as described above.

Power/frequency swings at lower frequencies can be related to improper governing parameters. At a plant where the intention is to increase the maximum discharge, the water starting time of the entire conduit system will increase. If no change is made to the inertia of the unit, the governing parameters shall be reviewed to confirm acceptable governing for any and all operating conditions of the powerplant (isolated operation or always on a grid). Transients shall also be verified (pressure rise and speed rise). An increase in maximum discharge usually means that the maximum rate of guide vane closure shall be slowed down to avoid exceeding the penstock and spiral case design pressures. This results in an increase in transient speed rise for a full load rejection, a factor which shall be confirmed to be within safe limits in relation to overspeed and runaway speed protection devices. It is usually acceptable for the rotating parts themselves which are normally designed for the full runaway condition, but this is an aspect which shall be evaluated and confirmed.

7.4 The assessment of related equipment

7.4.1 General

In the process of turbine rehabilitation, it is necessary to know the impact of the rehabilitation on all of the equipment and structures in the power plant.

We can consider three different categories of equipment involved:

a) related equipment, directly affected by the rehabilitation of the turbine: for example generator, governor, governor oil pressure system, pressure relief valve, turbine inlet valve, shut off valve, penstock, surge tank, power tunnel, surge chamber, tailrace tunnel;

b) equipment required for the maintenance and eventual overhaul of the unit and other equipment: for example cranes and their runway systems, disassembly and erection equipment and tools;

c) equipment required for connection or integration of the energy to the electric grid.

The impact of the turbine rehabilitation on the related equipment shall be determined by evaluating such aspects as:

a) mode of operation (e.g. increase in the number of start/stops per day could require improvements to the thrust bearing, and unit brake/jack equipment);

b) transients on load rejection particularly if an increased maximum unit output is being considered (speed rise and pressure rise);

c) governor adequacy.

d) increased axial thrust due to a new runner design (may necessitate changes to the thrust bearing cooling system);

e) runaway speed of the new runner (stresses in rotating parts and relationship with critical speeds);

f) risk of new adverse hydraulic pulsations due to new runner design, mainly for Francis turbines and pump-turbines (for test procedure, see IEC 60994);

g) change in tailwater elevation in relation to increased maximum flow of the turbine, which affects both specific hydraulic energy, and submergence of the turbine for cavitation considerations;

h) impact on specific hydraulic energy due to increased maximum flow of turbine (higher losses in the penstock, power tunnel and tailrace);

i) pressure–relief valve capacity required to limit pressure rise and speed rise during load rejection (if applicable);

j) turbine inlet valve and its control system adequacy.

It is highly probable that the related equipment will need rehabilitation to a degree similar to the turbine itself. The assessment of the related equipment will not be described in detail in this document; however a few aspects are mentioned concerning the direct influence of a new runner and possibly modified operating modes of the power plant.

The tables presented in Annex C give in a checklist format, for each component, the aspects that should be considered in the evaluation of the related equipment. These are presented under the headings “aspects of concern”, “possible cause or reason” and “possible action”. A detailed discussion of the most relevant aspects of concern for the assessment of the related equipment is presented in the following subclauses.

7.4.2 Generator and thrust bearing

The hydraulic thrust may change with the installation of a new turbine runner or with a new design of runner seals with smaller clearances. The design of the thrust bearing shall be verified for the new loading conditions. It may be useful to install a high-pressure oil injection pump to reduce the adverse effects of more frequent start/stops or to consider the use of thrust pads having a non-metallic coating. For sustained higher load operation, it may be necessary to modify the bearing or its oil cooling system.

A new turbine runner in a high head plant, if an increase in maximum discharge is planned, will often have an increased sustained runaway speed and an increased transient over-speed which may exceed the sustained runaway speed because of the transient overpressure. The latter may become the governing design maximum speed for the generator. In this context, the new sustained runaway speed and the new maximum transient over-speed shall be determined. This is especially important if there is a downstream surge chamber since the transient over-speed can be aggravated by the transient lower downstream pressure caused by the level drop in the surge chamber at the same time as the distributor is seeing a transient overpressure. These effects are sometimes overlooked.

If the number of runner blades or Pelton buckets is changed, then the relationship between the exciting frequency and the equipment natural frequencies shall be checked, particularly for the rotating parts.

The design of the coupling flange between generator shaft and the turbine runner or turbine shaft shall be reviewed. Very often, it is necessary to improve the alignment of the two components in order to decrease mechanical vibrations. It might be considered to replace fitted coupling bolts or keys with a modern friction coupling. To reduce the danger of stress corrosion cracking, the coupling, if exposed to the water passage, should be made watertight. This is particularly important for horizontal shaft Pelton units.

In the case of Pelton turbines (horizontal or vertical axis) with runners overhung on the generator shaft, the shaft surface is often exposed to water and needs, in that region, a thorough NDT examination. In many cases, a computation of the danger of stress corrosion cracking is merited.

An increase of turbine output might be limited by the maximum safe power output of the generator if it was not oversized in the original design. In many cases, the power output can be increased if the active parts of the generator are renewed and existing components like the stator frame or the shaft are verified and reused. It is normally unnecessary to make expensive changes to the civil works.

Generators built before about 1965, had class B asphalt/mica type insulation systems which required a ground-wall insulation thickness much greater than the modern epoxy/mica based class F systems. Therefore if the owner elects to install a new stator winding with class F insulation, the additional copper conductor area in the same stator core slots will allow a power increase of between 20 % and 30 % without doing much else to the generator and without having to exceed significantly, the Class B operating temperatures. Other modifications to be considered are a new design of the poles, the use of high permeability stator core laminations and non-magnetic material for the end region (winding support, keying of the poles, air-guides etc.)

An improvement of the generator-cooling system, especially the vanes mounted on the rotor and the channels which guide the cooling air, can allow higher capacity utilization within existing geometric dimensions with reduced ventilation losses.

7.4.3 Turbine governor

If the guide vanes or injector needles are modified or replaced or a new runner is supplied for the turbine resulting in a change to the maximum turbine discharge, then possible changes in the opening and closing parameters shall be considered. The dimensioning of the servomotors and particularly their stroke and the size of the oil-supply pumps and accumulator tank(s) shall be checked. The opening for speed-no-load and the speed rise following a load-rejection can change significantly with a new turbine runner in a reaction turbine.

An increase of maximum turbine discharge might lead to an increase of stroke for the guide vanes, injector needles or Kaplan runner blades which in turn also necessitates a review of the servomotor characteristics and the oil-supply system.

The minimum allowable sustained load on Francis turbines or pump-turbines and indeed on fixed blade propeller or Kaplan turbines due to low discharge swirl in the draft tube can change significantly with new runners, necessitating an adaptation of the control algorithm.

7.4.4 Turbine inlet and outlet valves, pressure relief valve

This equipment is usually of the same age as the turbine but normally is not as exposed to wear and abrasion because they serve a mainly transient and stand-by function. Nevertheless their mechanical integrity and their reliability of operation shall be investigated in the same manner as those aspects of the turbine.

An increase in the turbine specific hydraulic energy (rise in upstream level or lowering of downstream level) or in the turbine maximum discharge will necessitate a complete checking of the valve design and that of its operating system and of their ability to operate reliably and safely under an emergency shut-off.

An additional aspect which shall be dealt with is a potential increase over time of the friction in the bearings or bushings of the rotating disc plug or flap. If valves are kept open for long periods, then the friction coefficient in the bearings or bushings may increase owing to corrosion, to contamination by foreign particles or other deposits and will result in a decrease of their reliability to close under emergency discharge interruption conditions.

Furthermore, if the turbine foundation system has deteriorated, then the consequences on this ancillary equipment and their supports and anchor bolts shall imperatively have to be verified.

7.4.5 Auxiliary equipment

The pursuit of increased efficiency also includes the reduction of the power consumption of auxiliary equipment. To achieve this goal, pump motors, pump impellers and valves with high losses can be replaced.

Rehabilitation of the generator may necessitate revisions to the cooling water supply system for the generator surface air coolers. An energy balance calculation along with the assessment of costs, operating and maintenance considerations will dictate whether it is better to use tailrace water through a pumped system or to tap the supply off the upstream conduit trough a suitable pressure reduction device.

Another approach to improvement is the exchange of high viscosity lubricants with comparable products having lower viscosity where design conditions of the bearings permit. The use of bio-degradable lubricants and hydraulic fluids may also be considered. If the type of the lubricant or hydraulic fluid is changed within an existing hydraulic system, the system shall be cleaned thoroughly, as residual quantities of the old lubricant may not be compatible with the new product. The compatibility of any new product with rubber or polymer seals, system coatings or the material of impellers, valves, etc. shall be confirmed. With bio-degradable lubricants, it shall be assured that they will not be in contact with water since such contact may lead to decomposition and premature ageing.

Changes to the main shaft seal require verification of the adequacy of its clean cooling and lubricating water supply.

Changes in the hydraulic thrust require verification of the adequacy of the lubricating oil characteristics and the cooling system of the thrust bearing and possibly of its oil vapour scavenging system.

The supply of a new runner may necessitate modifications to the draft tube aeration system or indeed, may permit its elimination. In some instances, the quantity of air required for stabilisation of unit operation can be significant enough to unbalance the powerhouse heating and ventilating system, particularly in the case of an underground powerhouse.

7.4.6 Equipment for erection, dismantling and maintenance

The heaviest lift for which the powerhouse crane and crane runway are designed is usually, but not always, the assembled generator rotor. This equipment is needed for unit dismantling and this probably for the first time in decades. Before starting any major overhaul work, it is necessary to check and test the handling equipment and its support system under nominal load and to test the accuracy of load holding and positioning of the crane itself.

The cranes in the machine hall shall be able to handle any increase in design loads from new and perhaps heavier components. Special attention shall be paid to the design of the crane hook, lifting pins and lifting fixtures to ensure their compatibility with existing and new components.

7.4.7 Penstock and other water passages

The increase of maximum discharge or specific hydraulic energy (head) requires a thorough recalculation of the hydraulic transients. The maximum transient pressure rise will increase in proportion to the increase in the maximum discharge if the time gradient of the movement of the guide vanes or the injector needles is kept constant. This investigation should always be based upon actual recent measurements of pressure rise and speed rise to be sure that changes in design that have been made since the original commissioning are considered as well as changes to the friction coefficients of tunnels, penstocks and valves. This is especially true for plants with long tunnels, surge tanks and surge chambers or any combination of these features.

Pressure pulsations in the turbine draft tube or due to the interaction of the guide vanes and the runner vanes, whose number may be different in the new design, shall be carefully considered and evaluated.

The replacement of Kaplan turbine runners with increased maximum discharge also makes it necessary to investigate the hydraulic transients and their consequences on the civil structures.

The increase of maximum discharge may lead to higher losses or air-entraining vortices at the intake structure. This phenomena shall be evaluated and the vortex eliminated by redesign.

The draft tube is a critical component if the maximum discharge or the turbine efficiency at full load is to be increased. This is particularly true for low specific hydraulic energy plants. It can therefore be worthwhile sometimes to do CFD analyses which include the draft tube and the outlet channel with a view to introducing draft tube or channel form optimizations.

7.4.8 Consequences of changes in plant specific hydraulic energy (head)

In some cases these fundamental hydraulic characteristics have been changed over the years of operation; examples are:

– raising of the headwater level with the use of flash boards or other means;
– lowering of the tailwater level due to erosion of the riverbed or to the lowering or removal of flash boards at a downstream site.

The change of the elevation of the tailwater requires a verification of the submergence of the turbine runner (Thoma coefficient) to ensure adequate protection against cavitation erosion. It might also influence the frequency and magnitude of the swirl at the turbine runner outlet and the pressure pulsations in the draft tube itself which, in turn can be a source of hydraulic resonance. The lowering of the downstream level for a given discharge is particularly important in the case of pump turbines, since it may have an influence on the pump mode trash racks and will affect directly the net positive suction head (NPSH) available.

7.4.9 Grid integration

An important aspect of turbine rehabilitation is the connection or integration of the energy to the electric grid. The existing connection is specific to the original design of the machine. Any modification to these characteristics (energy, operating mode, power increase, etc.) may have an impact on the grid. These impacts should be studied and taken into consideration in the decision-making process because their related costs may be high and the amount of work required may influence the project schedule. The grid integration aspects may make a project less profitable, and therefore less of a priority, or even completely unprofitable.

8 Hydraulic design and performance testing options

8.1 General

When a decision has been made to rehabilitate a hydroelectric turbine-generator unit, it is worthwhile to consider all of the possible improvements that could be made in order to take advantage of technological progress which has occurred since the design of the existing machine.

This normally leads to the development of a new runner design and, sometimes of a new distributor and modified draft tube.

The new hydraulic design can be developed and verified by the means of more or less in-depth CFD calculations, laboratory model tests and more generally by a combination of both.

The model test still remains, today, the best available tool for confirmation of the accuracy of the design calculations. For large units, it is therefore recommended to perform model tests before prototype modifications are carried out. Hydraulic design changes to any pump-turbine should be always evaluated by model tests. For small units however, only reference to existing model test results for hydraulically similar machines is often used.

The final result can also be checked by prototype tests. However, at that stage, the possibility of making design modifications if a problem is detected, are necessarily much more limited than at the stage of a model test before prototype construction has begun. A prototype test is not a development tool, but rather a tool which allows determination of the degree of success of the design in relation to the contractual undertakings.

The extent of the investigations by hydraulic studies and model tests shall be determined by consideration of their relative cost and their relative necessity with regard to the technical difficulty of the project. For a huge project, for example, the relative cost of the hydraulic studies and the model tests in comparison with the total investment being very small or even negligible, it is easy to decide to use in depth hydraulic studies and model tests. At the other extreme, for a small machine with no specific hydraulic problems and good references from similar machines, minimal hydraulic studies without a model test are probably accurate enough. For most projects of intermediate size, the extent of the investigations shall be decided on a case by case basis.

In deciding how much one can afford to spend on development, one shall ask “what is the present value of the credible performance shortfall which may arise from the decision not to do a particular phase of the design studies and model tests?” A performance shortfall in power can often be offset by cutting back the trailing edges of the runner blades on the prototype. A performance shortfall of between 0,5 % and 1,5 % in weighted efficiency can be evaluated in the light of the anticipated plant operating conditions and compared against the cost of doing more design development studies (CFD) or model tests or both on a given project.

This process shall be initiated from the feasibility study stage and shall take into account the size, characteristics and features of each individual project. For any project with identified technical difficulties, the opinion of manufacturers on the feasibility of various options should be requested at the feasibility study stage, and hydraulic studies should be contemplated at the detailed studies stage.

In most cases the model test, if any, is carried out after award of the contract to the selected contractor. For very large projects, some owners have concluded that their interests are best served if the detailed design and model tests are done at the detailed studies stage under separate contract to two or more potential contractors and the results of their work are verified in an independent laboratory. In such cases it is advisable to have the potential contractors quote at the same time for both the design and model test stage and for the execution of the runner supply and the rehabilitation of the complete turbine. In this way, any real differences in tested performance can be evaluated against differences in the overall cost of the project.

To design new components for old machines, especially runners, adjacent parts of the existing flow path shall be included in the flow simulations. This is the typical case for rehabilitation and modernization of an existing turbine, where most of the old components remain unchanged. Reliable prediction of the performance of new components can be achieved only if the influence of the existing parts of the machine is properly taken into account. Therefore, the precise actual shape and condition of the old components used for the flow simulation and model testing, shall be available for use in building an accurate numerical model for these components.

8.2 Computational hydraulic design

8.2.1 General

To be economically justified, computational hydraulic design shall be conducted with consideration of the following aspects:

– Choice of the software.
  - The software (2D or 3D, viscous or non-viscous, stationary or unsteady flow) shall be selected with regard to the component to be calculated and to the overall value of the project.

– Extent of the calculations.
  - Calculation of the whole turbine or of critical components only?
  - Calculation of the existing turbine or of the rehabilitated turbine only or both?

The choice of the software as well as the extent of the calculations shall be decided on a case by case basis, with due regard for the size, operating conditions and other particular conditions of the turbine to be rehabilitated.

As of 2006, the most sophisticated CFD tools available allow one to limit the risks associated with rehabilitation to a very low level. However, to do so solely by CFD calculations is time consuming and the development costs can approach those typical of a limited model test programme.

8.2.2 The role of CFD

Numerical flow simulation or CFD (computational fluid dynamics) is a powerful tool when it is used correctly and when its restrictions and limitations are clearly understood. When applied to rehabilitation, it can be used for:

– design of new components for old (existing) machines;
– analysis of the fluid flow through existing machines to understand and solve operational problems related to the form of the water passage;
– the potential efficiency improvement linked to profile modifications can be determined by CFD analysis and confirmed by model testing, although an economic analysis is required to determine the feasibility of the physical changes involved.

In the design process to optimize new machines from inlet to outlet or to design for rehabilitated machines, CFD can be expected to reduce the number of modifications required on the physical model in the test rig to achieve the guaranteed performance. Cavitation can be reduced to a very low level to a degree quite impossible to achieve with the classical pre-CFD design methods and fine tuning during model tests. The reason for this is that with numerical simulation, the pressure distribution on critical parts of the runner blades and other surfaces of the machine can be verified and optimized resulting in better flow distribution and more equal sharing of the pressure loads.

In many cases, operational problems in the turbines of existing power stations can be solved using CFD. Flow analyses allow one to understand the flow phenomena. More importantly perhaps, CFD allows the evaluation of options when one is trying to solve a particular flow problem, by permitting one to change component shapes numerically and to study the corresponding change in the resulting flow pattern. Only if the CFD results of a given option are promising, would the new shape be integrated in the model or attempted in the prototype machine.

8.2.3 The process of a CFD cycle

A CFD analysis involves the following major steps:

– the real coordinates and dimensions of the flow channels shall be determined (wetted surfaces);
– based on this data, the space within the flow channels shall be divided into discreet or finite elements or finite volumes;
– the boundary conditions as well as initial conditions for unsteady flow simulations shall be established for the actual operating points of interest of the turbine;
– the flow simulation is carried out;
– the results shall be post processed to provide the information that is necessary for an informed decision on the identified problem.

The validity and accuracy of the solution depend upon how each of the steps is performed and how the following questions are answered:

– are the basic coordinates of the machine components correct? More precisely, do they properly represent the current state of the machine?
– has the computational domain been correctly represented by the chosen discreet elements in order to minimize numerical errors?
– have the boundary conditions as well as the initial conditions been established correctly for the operating conditions of interest of the turbine in the power plant?
– what CFD-code has been used and have the specific parameters been set correctly (such as the turbulence model etc.)?
– can one be sure that all relevant information is given in the numerical results and that no important result is hidden or misrepresented?

8.2.4 The accuracy of CFD results

The accuracy of the results of CFD calculations depends on the CFD-code itself, the way it is used and on the professional experience of the user. It shall be emphasized that flow simulation cannot describe precisely the real flow in all its complexity. The simulation is based on a numerical model of the real flow, and therefore the key question is how close to reality the numerical flow simulation can come.

The governing equations used to describe the fluid flow through a turbine in a hydroelectric power plant are the Navier-Stokes (NS) equations. This set of equations is valid for laminar as well as turbulent flows. As a consequence, viscous as well as vortical flow phenomena are captured. However, the solution of the Navier-Stokes equations for flows through complex geometries such as hydraulic turbo-machines is not possible as of 2006. Thus, normally the Reynolds-Averaged-Navier-Stokes (RANS) equations are used for the simulation of turbulent flow. Here, a mean value and a fluctuation term are used for the local flow velocity and for the corresponding pressure instead of the true local values. This requires the introduction of a turbulence model which takes into account the effect of the "real" turbulence on the flow behaviour. Turbulence modelling is still under development. The turbulence model used for a precise computation of turbulent flow is of considerable influence on the accuracy of the analysis.

In addition, the RANS equations describe the flow as a continuum, but can only be solved for a finite (limited) number of points in space. As a consequence, the computational domain shall be divided (discretized) into a number of finite elements or finite volumes depending on the computational algorithm. This discretization can be of considerable influence on the numerical solution and therefore on the accuracy. There are some rules on how to generate a ”good” computational mesh, but even if the rules are known to the user of the CFD-code, in many cases it is not possible to completely avoid ”bad elements” owing to the geometric constraints given by the shape of the machine or the component to be analysed. The number of elements or the topology of the mesh for a given number of elements can have a considerable influence on the accuracy.

For all of these reasons, the accuracy of the simulation is limited. This is particularly true in the case of the draft tube and even more so for old forms of draft tubes.

8.2.5 How to use CFD for rehabilitation

There are two ways to use CFD to analyse the performance of a new turbine runner and/or other components and modifications in an existing hydraulic turbine:

– do the analysis on the new arrangement from scratch;

– analyse first the existing installation for reference calibrating with available test data, then the new or modified components to calculate the differences between the new and the existing installation.

The first approach relies solely on the accuracy of the numerical prediction. In this case, the predicted performance of the new components in the existing environment is based completely on the numerical means.

The second approach takes into account measurements from model tests, if available, or prototype tests or site data from operation of the power plant over the years. In this approach, the difference in the performance between the old and the new installation is analysed numerically. As a consequence, only this difference in the performance between the old and the new installation is affected by the accuracy of the numerical prediction. It is evident that the second approach is more reliable (more precise) in performance prediction using CFD. However, it is more time consuming than the first approach because both the existing as well as the new components shall be analysed. Furthermore, in order to perform a precise flow simulation for the existing turbine, the existing installation shall be well documented and consistent with the real water passages. Unfortunately, in many cases the documentation is poor and especially for runners, the documentation is often not available. In such cases, precise site dimensional measurements are necessary.

The second approach for performance prediction by the use of CFD for rehabilitation projects is more reliable than the first one. However, it is more expensive and more difficult because of the need to obtain accurate data on the existing component geometries.

8.2.6 CFD versus model tests

CFD is a good tool to compare alternatives, but not as a stand-alone tool for establishing the absolute efficiency level of a hydraulic machine. This is especially true for cases of machine rehabilitation. This characteristic of CFD is also true for the evaluation of cavitation performance.

The question of whether CFD calculations or model tests or both should be performed depends upon the size of the power plant and its average annual energy production after rehabilitation.

For a very small hydro power station for which a model test is often more expensive than the total costs for the rehabilitation measures, CFD is the only practical basis for the analysis of existing components or for the development of new ones.

For a medium-size power station, it can be feasible to perform semi-homologous model tests to test the new installations optimised with CFD (see 8.3.2). Semi-homologous model tests permit verification at a modest cost as to whether the numerical performance prediction is realistic. It gives confidence that the planned measures will be successful, and it provides the opportunity to improve the design further. However, one shall be aware of the fact that those machine components in the semi-homologous model which are not similar to the existing construction can have considerable influence on the measured performance. In many cases for semi-homologous model tests, only the new runner is homologous while the other parts of the model are dissimilar to some degree.

For a large power station with high energy production, fully homologous model tests are usually justified. If a 1 % deficit in efficiency or 1 % deficit in capacity over the years of operation is worth more than the costs for a model test, a homologous model test in a qualified laboratory should be considered. This approach will ensure with the best possible accuracy, the financial success of the rehabilitation of the generating units.

This leads to three categories of design approach for rehabilitation projects:

a) **Small hydro:** only CFD;
b) **Medium hydro:** CFD in combination with semi-homologous model tests;
c) **Large hydro:** CFD in combination with fully homologous model test.

The question as to whether any given rehabilitation corresponds to category a), b) or c) cannot be answered in general terms. The answer depends upon parameters which are specific to the power station under study such as:

– How much can the energy production be increased through upgrading?
– Is cavitation erosion a major problem and can it be reduced or avoided?
– Are there other operational problems to be improved upon such as hydraulic resonances?
– Are there unacceptable levels of draft tube pressure pulsations or vortices to be reduced or eliminated?

Many factors are changing with time including the accuracy of CFD analyses. The latter are continually being improved. The decision concerning which tools should be applied shall be made on a case by case basis. In all cases, a thorough cost-benefit calculation is needed.

8.3 Model tests

8.3.1 General

The development of hydraulic turbines, storage pumps and pump-turbines has been carried out historically, using a reduced scale model in a laboratory. This method, combined with empirical calculations based on previous designs, has shown itself to be a reliable development tool. Despite the improvement of hydraulic calculations with the advent of CFD techniques, model tests remain the only accurate way to assess the results of the calculations in a suitable and timely manner and predict the global performance of a prototype regarding all of the various and important aspects such as output and efficiency, cavitation erosion risk, runaway speed, pressure fluctuations, shaft torque fluctuations, guide vane torques, draft tube air admission benefits and hydraulic thrust. It shall be appreciated however that where instability phenomena and potential resonances are concerned, (pressure fluctuations, shaft torque fluctuations and draft tube air admission benefits) that the model test cannot be relied upon to identify potential resonance with the plant hydraulic conduits even if the latter were to be modelled.

Model tests allow one to establish the absolute efficiency of the hydraulic machine with a very low level of uncertainty (±0,2 % is common in well-equipped laboratories). Since efficiency is one of the most important performance parameters and since the model test is normally conducted early in the development stage of a project, it is particularly attractive as a potential benefit evaluation tool. Model test methods that are applicable to new hydraulic machines are also well suited to evaluate rehabilitated machines with various options for potential modifications (stay ring, distributor, runner and draft tube).

In cases where site tests are difficult or very expensive, or where they would have high uncertainties (large turbines having low specific hydraulic energy for example), model tests can be used also as contractual acceptance tests. This may be particularly applicable where model tests are conducted on a model which reproduces the existing profiles and then on one with the new profiles. The contract is sometimes based on demonstrated performance gains rather than on the absolute efficiency of the rehabilitated machine.

A similar technique is sometimes used with prototype testing (“before” and “after” tests) to reduce the systematic uncertainties.

A model test program with two runners (one old and one new), can cost from a few hundred thousand US Dollars to several million US Dollars depending upon whether or not some components of the model are already available and upon the scope of the test program. The latter would be fixed largely based on the value the anticipated efficiency gains and may, for large plants with tens of units, involve two or three manufacturers in competition with contractual tests in an independent laboratory.

8.3.2 Model test similitude

There are two categories of model tests:

– Fully homologous model tests

  The fully homologous model duplicates the hydraulic profiles of the existing turbine components as well as the hydraulic profiles of the new components. It requires having a complete and accurate geometric definition of the existing components through access to the original drawings and through site measurements. Note that even where the original as-built drawings are available, some site measurements may be advisable to confirm the existing profiles.

– Semi-homologous model tests

  In the semi-homologous model, components are very similar to but do not perfectly duplicate the hydraulic profiles of the existing or the modified improved turbine components.

  The advantage of fully homologous model tests is obvious since a semi-homologous model test requires the calculation of performance corrections in order to take into account the lack of homology of some components. Such performance corrections are subject to interpretation.

  However, when the degree of lack of homology is limited and the manufacturer has good experience in the region of the specific speed of the turbine involved, the risk in using semi-homologous model testing for a few relatively small units is limited. It is therefore, in some cases, of interest to do semi-homologous model test and to benefit from the reduced manufacturing and engineering design costs as well as from a reduced model test cycle time.

8.3.3 Model test content

A model test can cover the following aspects:

a) Essential investigations
   - efficiency hill chart covering the complete expected operating range of the hydraulic machine;
   - determination of inlet cavitation limits (suction side and pressure side);
   - outlet cavitation influence curves for power and efficiency (measurement of efficiency and power vs. the Thoma coefficient sigma with observations of the incipient cavitation conditions);
   - runaway speed at maximum guide vane opening and maximum specific hydraulic energy for normal and minimum plant Thoma coefficient;
   - pressure fluctuation measurements in the spiral case and the draft tube as a function of guide vane opening for the condition of normal plant Thoma coefficient and in some cases, for various Thoma coefficients in the range of the anticipated plant values;
   - shaft torque fluctuation measurements as a function of the guide vane opening and for various Thoma coefficients in the range of the anticipated plant values (influence of NPSH for a pump-turbine);
   - Kaplan blade torque tests;
   - hydraulic thrust;
   - representative checks of the principal dimensions of the model.
b) Additional data
   - guide vane torque measurements as a function of the guide vane opening and specific hydraulic energy including the influence of a desynchronised guide vane;
   - air admission influence on draft tube and spiral case pressure fluctuations and on shaft torque fluctuations;
   - axial and radial thrust measurements as functions of guide vane opening at maximum specific hydraulic energy;
   - influence of tailwater level on efficiency in a Pelton turbine for cases of increased maximum discharge;
   - needle force diagram if there is a significant change in the nozzle form;
   - deflector torque curve if there is a significant change to the manufacturer’s usual practice;
   - calibration of Winter Kennedy taps – pressure difference measurement at two or more points (on a spiral case section for example) for the limits of the ranges of plant specific hydraulic energy and unit discharge.

8.3.4 Model test application

8.3.4.1 General

A gain in performance can be established from the comparison of the results of a prototype efficiency test conducted before the rehabilitation compared against the results of a model test of the new design with appropriate step-up (“model to prototype prediction”) or by a direct “model to model” comparison by testing the old and new components in the same test set-up.

8.3.4.2 Model to prototype comparison

One way to proceed is to compare the existing prototype data obtained preferably from a recent prototype field test, with stepped-up model test results of the new machine.

This procedure yields relatively poor accuracy because:

– Field measurements involve a relatively large uncertainty (0,7 % to 2 % depending upon machine type, field conditions and test methods selected). In poor conditions, the uncertainties can be even greater.

– The limitations of the scale-up formulae to correctly represent the differences in real losses between a new model and the old prototype with a new runner and perhaps some other modifications. (IEC 60193 and IEC 62097 were developed for new models and new prototypes whose surface roughness does not cover the range often encountered in old prototype machines.)

In the worst case, the total inaccuracy of this procedure may exceed 2 %.

8.3.4.3 Model to model comparison

This method compares the existing and new machine characteristics directly by model tests of both old and new designs. Assuming that both designs are in the same surface finish condition, without cavitation erosion damage, corrosion or other surface deterioration and with the same runner seal clearances this method of comparison is very precise.

In the “model to prototype” prediction, the calculation of a step-up to be added to the model performance to estimate the prototype performances is necessary. When a model test is performed, the mechanism for predicting prototype performance is based on similarity between the model and the prototype. The prototype efficiency calculation relies on a precise knowledge of the geometry and actual roughness of the surfaces. The similarity requirements are described in IEC 60193. As of 2006, a working group of IEC TC 4 is involved in efforts to update the provisions of IEC 60193 which deal with scale effects and is in the process of elaborating a document which contains a calculation for accommodating the surface roughness effects of the various water passage components (IEC 62097). When the geometric similarity tolerances have been respected and the roughness of surfaces of the model and prototype are known, the prototype performance can be calculated. Caution shall be applied however when evaluating the roughness of the prototype machine when its age results in average roughness for important components such as the guide vanes and to a lesser extent, the stay vanes, which are well beyond those dealt with in the current document. The roughness should be measured on important components before the tender stage. The tenderer can then recommend the optimal upgrade on the various water passage components and the calculation of the scale effect can then be based on the condition of the rehabilitated components. If, for any reason, the surface roughness is not measured, an agreement shall be reached between the owner and the contractor concerning the evaluation of roughness effects.

In some rehabilitation projects, the contractor's scope does not include the entire turbine. The homologous model with the appropriate calculation of scale effects of components which are outside the responsibility of the contractor, permits managing the work in accordance with the defined contractual responsibilities.

In a “model to model” comparison, both runners (old and new design) and any other proposed modifications are tested in a model consisting of the same other turbine components. The efficiency difference observed between a new runner design and the old runner design can be defined with an accuracy that is better than that for a given stand-alone test. This approach requires the testing of two model runners in a common test set-up.

Model testing has the distinct advantage of being an effective development tool. Prototype testing, by comparison, provides only the means to evaluate the characteristics of the finished product or to make a comparison between the existing prototype and the rehabilitated machine.

The accuracy achievable in using a “model to model” comparison for any rehabilitation of a power plant relies on the accuracy with which one is able to construct a model fully homologous to the old machine. There are in most instances, significant differences in blade shape and position from blade to blade in the old runners. To accommodate this fact economically, it is usual to measure the profiles of at least three blades and to take an average of those profiles to construct the new model of the old prototype assuming the old runner has uniformly positioned blades. The fact is therefore that one cannot economically construct a new model which is perfectly homologous with the old prototype. These facts will therefore introduce an inaccuracy of undetermined magnitude in the "model to model" comparison.

The difference in efficiency between the old and new model runners and the old and new prototype runners will be similar provided that the homology of the old runner model is perfect. If we consider roughness differences only, the probabilities are that the difference between the old and new prototype efficiencies will be greater than the tested difference between the "old" and "new" models because of the deteriorated surface condition of the "old" prototype. However, this comparison will always have some unknowns because of the procedures described in the preceding paragraph.

This "model to model" approach implies:

– A higher degree of security for the owner, who will not be expecting unrealistic guaranteed efficiencies but rather, a measured efficiency increase which may be added with confidence to the prototype efficiency of the old turbine.
– A higher degree of security for the manufacturer, who will no longer be faced with having to guarantee an absolute efficiency value on a machine whose components outside the runner itself have deteriorated but rather, an efficiency increase with respect to the old turbine for one or more model tested modifications (e.g. runner and guide vanes). This prototype efficiency increase may be demonstrated in comparative field tests. It is to be assumed that all potential physical improvements to the condition of the other existing turbine components will be evaluated in cost/benefit assessments before the owner embarks on any one of them.

The "model to model" procedure also provides for a good evaluation of cavitation behaviour of the new runner, lowering the probability of disputes between the contractor and the owner of the hydraulic machines.

Where the "model to model" contractual comparison is used, an index test on the prototype, before and after the rehabilitation is sometimes used to confirm the gains predicted by the model results.

8.3.5 Model test location

The model test can be carried out either in the manufacturer's laboratory or in an independent laboratory.

a) Model test in the manufacturer's laboratory

   Practically all development model tests and most contractual model tests are carried out in the manufacturer's laboratory. However, some purchasers require that the contractual model tests be carried out in an independent laboratory. In such cases, the model is transported from the manufacturer's laboratory to the independent laboratory at the conclusion of the development tests.

b) Model tests in an independent laboratory

   1) Conventional contractual arrangement

      When a model test is required in an independent laboratory, it generally concerns the contractual model test of a fully homologous model. If convenient for the manufacturer, the development tests can be also carried out in the independent laboratory.

      The advantage of a contractual model test carried out in an independent laboratory is to provide for the verification of the performance guarantees by a third party. The drawback is the probable extension the total model test duration by up to a few months when the development tests are carried out in the manufacturer's laboratory and the contractual tests elsewhere.

If the owner opts for testing of the existing turbine and the new design, both tests shall be carried out in the same laboratory.

There is usually no problem for the adaptation of the physical model to the test loop of the independent laboratory. In the past, some laboratory test loops could not always accept models of the size elected by the contractor and the owner, and it was sometimes necessary to manufacture multiple models. As of 2006 all major manufacturers and independent laboratories use test loops of similar size and power.

2) Competitive model tests in an independent laboratory

For major rehabilitation projects (large capacity and/or large number of machines), it has been the practice of some owners to require a competitive model test in an independent laboratory. The various tenderers are invited, and often paid under separate contract, to demonstrate the performance of their model turbines before a rehabilitation contract is awarded for work on the prototype. This is clearly an expensive exercise when two or more contractors are required to perform the comparison. However, the cost could be reasonable and justified when, compared against the potential benefit, if manufacturers are invited to optimise their designs and test them in an independent laboratory. This may involve a set of modified components (not only the runner) developed using CFD analyses. In this case, the accuracy of the comparison is about ±0,15 % and can reliably permit the establishment of the long-term financial benefits of very small differences in efficiency.

8.4 Prototype performance test

8.4.1 General

Prototype test methods that are applicable to new hydraulic machines are also suited to rehabilitated machines.

In most instances, the main goal of prototype tests is to check the turbine efficiency against the manufacturer's guarantee. The advantage of the prototype test is that it gives the turbine efficiency directly within the uncertainties applicable to the selected method and site conditions. It is impossible during the period of the test, to verify other important parameters such as cavitation performance with any quantitative precision. Runaway speed tests are seldom carried out on the prototype because of the risks of damage to the unit and particularly the generator for an event which is highly improbable in the life of the machine. Some owners, with due regard for these risks, carry out a runaway speed test on one unit of each new design.

By way of comparison against new turbines, rehabilitated turbines offer the advantage of allowing comparative tests on the machine before and after rehabilitation. In such circumstances, the parameter of primary economic interest is the efficiency increase rather than the absolute efficiency. Provided the "before" and "after" tests are conducted by the same test crew with the same instruments, the inaccuracies in the efficiency increase are significantly less than those related to the absolute efficiency measured during either test.

In some cases (small units, for example), a minimum of field testing can be taken as sufficient. It can consist of checking of the guaranteed output of the unit as well as a general checking of the unit behaviour throughout the normal operating load range (smooth operation without levels of pressure fluctuations, vibration or noise which may be detrimental to the characteristics of the power delivered or to the long term reliability of the unit). Such basic checking requires no sophisticated test equipment. If this basic checking identifies a potential problem, specific measurements on the considered parameter can be carried out. The contract shall be clear as to the criteria for and the nature of expected testing and on the party which will support the costs of the additional measurements.

Most sites merit at least a prototype index test before and after the rehabilitation and some measure of model development testing. The methods and limitations of index tests are covered under IEC 60041.

8.4.2 Prototype performance test accuracy

A number of testing organisations have improved the technology for site testing of hydraulic turbines; however, the accuracy is still not as good as that of model tests.

The absolute level of uncertainty will depend upon the design of the machine. It will generally be easier to achieve high accuracy with a high head than a low head machine. The detailed design of the turbine and its conduit system is also important. It is easier, for instance, to achieve high accuracy where there is access to a substantial straight length of the unit penstock in which to install a flow meter than on a turbine fed by a conduit with many closely spaced bends. On higher specific hydraulic energy machines, the direct measurement of efficiency using the thermodynamic method is often a relatively low cost and accurate alternative.

The level of absolute uncertainty of the various IEC 60041 Primary test methods is between ±1,5 % to ±2 %. With the use of the most advanced methods and equipment, and a highly qualified test crew, this can be reduced to below ±1 % under the best conditions (for example with the thermodynamic method on a unit under a specific hydraulic energy of 2 900 $J.kg^{-1}$, a head over 300 m, or using the acoustic method with at least four crossed-paths, a total of eight paths, and ten diameters of straight conduit upstream of the measuring section). As for model tests, the inaccuracy of the prototype tests used to establish a difference in efficiency of the unit tested before and after the rehabilitation is better by about 20 % than the inaccuracies typical of the same method used for determining the absolute efficiency of the same unit (some of the systematic uncertainties are eliminated).

As a minimum, the selected procedure should be such as to confirm that the financial performance upon which the project has been justified is achieved.

If it is required to achieve a minimum gain in efficiency of 3 % for the project financial return to be achieved, and the guaranteed increase is 5 %, then a test that provided an uncertainty of ±2 % would be adequate.

Companies often have a minimum level of internal rate of return to justify an investment. If the level of uncertainty that can be achieved is, for instance, ±1 % then some companies would deduct 1 % from the guaranteed efficiency of all tenderers, before the rate of return is calculated. To do so or not is a matter of investment policy.

8.4.3 Prototype performance test types

The prototype performance tests are carried out to confirm compliance with contractual guarantees.

Absolute methods or relative methods can be used depending upon the contractual conditions. The descriptions and limitations of the various methods are given in the IEC 60041.

If absolute efficiencies have been guaranteed, they should be checked by absolute “primary” methods. The results can be used for assessment of penalty or bonus payments or any other contractual consequences concerning guarantees.

For rehabilitated machines, it is usual to justify at least part of the cost of rehabilitation by the improvement in efficiency that can be obtained. It is therefore judicious to measure the performance of the machine before and after the rehabilitation. For this reason, an absolute test is not obligatory and can be replaced by a relative test. The measurement of the absolute discharge through the turbine is therefore not necessary for these contractual considerations leading to a significant advantage and usually to cost savings. On the other hand, for projection of long-term earnings into the future, an absolute value of turbine efficiency shall be established. This can be either by relating past performance to the measured gain or by conducting an absolute efficiency test on the rehabilitated unit and sometimes by both methods.

With an index test (for example the Winter-Kennedy method), the generator power output is measured to the required level of accuracy. At the same time a pressure difference, generally between two points of a spiral case section, is measured. When the rehabilitation is completed, the power output of the rehabilitated machine is compared with the initial unit at the same discharge (same pressure difference in the spiral case for example). The change in power output at the same discharge is used to determine the improvement in performance. These measurements can be done over the full range of unit outputs.

Although index testing has many advantages and is probably the least costly solution, there are some difficulties with this technique:

– The scope of the rehabilitation has to be such that the "before" and "after" tests remain valid.
– The turbine shall be equipped with the means of measuring relative discharge. This would generally be by the use of Winter-Kennedy taps but these are not always installed nor always in usable condition. Other pressure differences occurring across different penstock diameters may also be used.
– The accuracy and level of the maximum efficiency of the "before test" shall be accepted by tenderers. This could be done through a test witnessed by the selected tenderer or by the employment of a qualified third party organisation for the execution of both the "before" and "after" tests.

8.4.4 Evaluation of results

The comparison of guaranteed efficiencies against measured efficiencies should be carried out in accordance with the applicable IEC publication taking into account the measurement uncertainties of the adopted method.

If the measured efficiencies, after application of the measurement uncertainties, are lower than the guaranteed values, the difference may come from the following factors:

a) If absolute guaranteed performance has been checked by a model test stepped-up:
   – Condition and dimensions of remaining existing components.
   – Physical differences between model and prototype, particularly on existing remaining components (existing drawings in poor condition or access difficulties resulting in measurement errors in the case of site dimensional measurements for example) could explain some performance differences from model to prototype.
   – Calculated scale effect higher than actual scale effect.
   – For a rehabilitation project, the actual condition (defects in form and roughness) of the existing remaining components can lead to a reduced real scale effect compared with the theoretical scale effect calculated in accordance with IEC 60193.
b) In the case where no model test has been carried out:
   – In addition to above explanations, the performance calculations may have been "too optimistic".

If relative performance (difference between "after" and "before" rehabilitation) has been guaranteed and checked by model tests, no problems related to the interpretation of the results need be expected.

9 Specifications

9.1 General

This clause should serve as guidance in the preparation of contract documents for the rehabilitation of hydraulic turbines. The rehabilitation of turbines is site specific requiring design criteria uniquely established for that particular site. The use of international standards is promoted insofar as they may be applicable. A list of items which should be covered in the detailed technical specifications is also presented in this clause.

There are two basic approaches that can be used in developing the specifications. One is to write detailed specifications in which the details of the equipment design, components, and the construction/installation procedures are defined. The second approach is to write a specification in which the performance results of the installed equipment are described, with freedom left to the contractor regarding how to design, fabricate, and install the equipment to meet those performance requirements. Most specifications are a combination of the above two approaches. The choice of one or the other usually depends upon the owner's normal practices and upon the size and importance of the equipment in its system.

9.2 Reference standards

The suggested basis for the tendering document is IEC TR 61366-1. This document covers all of the principal considerations in the preparation of tendering documents and presents under annexes:

– sample table of contents of tendering documents;
– comments on factors for evaluation of tenders;
– checklist for tender form;
– example technical data sheets;
– technical performance guarantee;
– example of cavitation pitting guarantee;
– checklist for model test specifications;
– sand erosion considerations.

Forming a part of this same series of documents and also recommended as a primary reference for the preparation of tendering documents are IEC TR 61366-2 to IEC TR 61366-7. These documents describe the technical requirements for the turbine under the following headings:

– tendering requirements;
– project, general, special information and conditions;
– general requirements, technical specifications/requirements;
– scope of work, limits of contract, supply by employer;
– design conditions, performance and other guarantees;
– mechanical design criteria;
– design documentation, materials and construction, shop inspection and testing;
– technical specifications for fixed/embedded, stationary/removable, rotating parts, guide vane regulating apparatus, bearings and seals, thrust bearings, miscellaneous components, auxiliary systems, instrumentation;
– spare parts;
– model tests;
– installation and commissioning;
– field acceptance test.

The above referenced IEC TR 61366-1 and IEC TR 61366-2 were prepared with a view to guiding a purchaser in the preparation of tender documents for new hydraulic machines. The general approach remains valid for documents governing the rehabilitation of existing machines. The objective of the above noted documents is to provide an overall checklist for the technical considerations in preparing tender documents and tender specifications. Subclauses 9.3 and 9.4 below provide a checklist of additional items that pertain to the development of the specifications for the rehabilitation of turbines, storage pumps and pump-turbines. It should also be noted that in rehabilitation projects, the specifications may need to be significantly more complex because of potential changes in the scope of the project necessitated by discovery of damaged components during the disassembly and subsequent inspections.

The bibliography provides a list of other international and national standards commonly referenced when preparing the specification for tendering documents covering a turbine rehabilitation. Most of the ISO and IEC documents are available in both French and English. IEC TR 61364 provides the hydraulic machine component nomenclature in six languages.

Certain national standards cited above and in the bibliography provide an indication of available references. Other equivalent national standards may be used when appropriate.

9.3 Information to be included in the tender documents

The following is a checklist of the data which should appear in the technical specifications or elsewhere in the tender document.

– Site conditions including:
  - range of plant “height” (gross head);
  - information regarding intake structure, gates, tunnels, penstock, valves and tailrace (to permit the determination of head losses, if they have not been measured);
  - information on current turbine water passage condition including surface roughness;
  - range of “specific hydraulic energy” (net head);
  - available discharge;
  - headwater and tailwater elevation ranges;
  - tailrace rating curve (elevation vs. discharge);
  - discharge data with corresponding headwater elevation, and tailwater elevation as a percentage of time;
  - water temperature range and water quality (physico-chemical and entrained solids such as sand, silt, etc.);
  - centreline elevation of turbine distributor and all other essential characteristic of the turbine;
  - powerhouse layout and unit rotational direction.
– Intended operational use such as base load, peaking service, run of river or any other constraints.
– Environmental constraints.
– Powerhouse and/or geometry constraints
– Customer requirements:
  - runner construction type;
  - unit axis (vertical or horizontal);
  - rotational synchronous speed (generator current design criterion);
  - current runaway design speed of generator (may be different from current steady-state runaway speed).

– Performance evaluation criteria and penalties (efficiency, power, cavitation and/or suspended particle erosion).
– Testing requirements for baseline and final model testing and/or field testing.
– Codes and standards for design, manufacturing, and testing of turbines.
– Mechanical design requirements.
– Sufficient penstock detail for transient analysis.
– Delivery schedules.
– Geometry and materials of existing turbine from “as-built” drawings (i.e. runner and runner clearances, shaft, guide bearing, shaft seal, spiral case, draft tube with complete water passage dimensions, draft tube liner, discharge or foundation ring, stay ring with stay vane profile details, headcover, bottom ring, guide vanes (including hydraulic and friction torque characteristics if known), guide vane operating mechanism, servomotors and stroke limitations).
– Current limiting capacities of the generator and/or transformer (lower of the two) including maximum capacity and, details of steps which the owner is prepared to consider modifying these (economic analyses are required).
– Current thrust bearing capacity.

9.4 Documents to be developed in the course of the project

The following is a list of documents to be obtained from the existing files or to be developed in the course of the work. The participant responsible for the preparation of each of these documents will depend upon what contractual arrangements are envisaged for each particular project:

a) before contract work begins:
   – pre-disassembly operational or ‘signature’ test procedure;
   – pre-disassembly operational or ‘signature’ test report;
   – disassembly and re-assembly procedure;
   – pre-disassembly alignment checks;
   – equipment assessment and inspection procedure;
   – re-assembly alignment check procedure;
   – re-assembly testing scope and procedures;
   – concrete substructure stability inspection report;
   – commissioning procedure.

b) Pre unit un-watering data:
   – Signature test consisting of following:
      • shaft runout vs. speed off-line and vs. load;
      • turbine stability (measurement of the draft tube and spiral case pressures and their fluctuations plotted against load for a known specific hydraulic energy);
      • vibration measurements (vertical and horizontal directions of guide bearing housing);
      • temperatures of bearings and shaft seal (observe the cooling water flow rate and temperatures in and out);
      • power gate test (generator output measured versus guide vane position for a known specific hydraulic energy);
      • load rejection test (measurement of speed and pressure rise during load rejection at 25 %, 50 %, 75 % and 100 % of full load);
      • servomotor differential pressure test (differential pressure of servomotor versus incremental servomotor stroke in both the guide vane opening and closing

directions, this is required when existing guide vane hydraulic torque is not available but desirable in all cases).

– Efficiency test:
  - index tests (measurement of the relative efficiency of the turbine) or
  - absolute efficiency tests.

c) Post unit un-watering:
  – guide vane contact clearances (verify the contact line clearances with and without servomotor squeeze);
  – guide vane upper and lower clearances (with and without squeeze);
  – guide vane opening versus servomotor stroke (angle of opening and open space between vanes);
  – guide vane opening and closing times, turbine in the dry with cushioning time.

d) Unit disassembly:
  – alignment and clearances verification and recording (shaft positions at all bearings, runner wearing rings, generator air gap);
  – verification of auxiliary system components for wear, damage or any other pertinent observations (greasing systems, oil, air and cooling water piping, instrumentation, walkways, etc.);
  – verification of generator components for wear, damage or any other pertinent observations;
  – verification of turbine components for wear, damage or any other pertinent observations, with particular attention to be given to the guide vane mechanism).

e) Unit reassembly:
  – dimensions, alignment, clearances and manual rotation runouts, verification and recording.

f) Commissioning:
  – dry test and calibration reports of all instruments;
  – dry test of the guide vane mechanism and servomotors including closing times and cushioning;
  – wet tests reports, to include the execution or the repetition of all signature tests described in b) here before and recommended at pre unit un-watering stage;
  – heat run report to testify the proper steady state operation of the unit at full load.

g) At design stage:
  – design calculations for turbine shaft;
  – design calculations for runner;
  – design justification for the runner wear ring clearances, material and design details;
  – design calculation for any modified component;
  – CFD analysis of water passage components (runner, guide vanes and stay vanes, spiral case or semi-spiral case, draft tube;
  – unit flow, output, efficiency and hydraulic thrust over the specified performance range;
  – transient calculations for new operating characteristics and impact on speed rise and pressure rise and resulting guide vane servomotor closing law with corresponding nominal and effective cushioning times;
  – drawings, engineering instructions, purchase specifications (raw material, or sub-contracted elements bought or fabricated), shop testing procedures.

Annex A
(informative)

Check-list for evaluation of existing turbine

The following tables give in a checklist format, for each component, the aspects that should be considered in the evaluation of an existing turbine. These are presented under the headings "aspect of concern", "possible cause or reason" and "possible inspections/actions". In the right-hand column of the tables, inspections, measurements and analysis are above the dotted lines. Maintenance and refurbishment actions are below the dotted lines.

Table A.1 – Assessment of turbine embedded parts – Stay ring

Applicable to Francis, Kaplan and fixed blade propeller turbines

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Cracks in stay vanes	– Pressurization cycles/pressure surges/hydraulic resonance with von Kármán vortices (low, medium and high cycle fatigue) – Deformations due to alkali-aggregate reactivity in the concrete – Reduced structural integrity caused by erosion or corrosion – Weak structural capacity due to poor design or manufacturing defect – Material defect	– Inquiry on previous repairs (quantity and frequency) – Noise and vibration measurement aiming at noise frequency determination (FFT) – Complete visual inspection – NDT inspection at stay vane and shroud junctions – Material, flow and stress analysis – ------------------------------------ – Repairs by welding – Hydraulic profile modification
– Particle erosion	– Poor stay vane profile – Abrasive particles in water	– Complete visual inspection – Inquiry on previous repairs (quantity and frequency) – Comparative analysis with modern designs – Flow analysis – -- ---- – Surface rebuilding by welding – Hydraulic profile modification – Application of protective coating
– Corrosion	– Inappropriate coating or loss thereof – Aggressive water characteristics	– Complete visual inspection – -- ---- – Blast cleaning and appropriate coating
– Hydraulic losses	– Poor stay vane profile – Rough surface finish	– Flow analysis – Comparative analysis against modern designs – -- ---- – Blast cleaning/smoothing – Hydraulic profile modification – Painting
– Seepage through radial flanges	– Deteriorated condition of radial flanges due to concrete deformations – Fatigue cracking of seal welds if original flange bolting inadequate	– Visual inspection – -- ---- – Seal or structural repair welding

Table A.2 – Assessment of turbine embedded parts – Spiral or semi-spiral case

Applicable to Francis, Kaplan and fixed blade propeller turbines

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Cracks in region of stay ring; in plates or welded joints	– Deformation due to alkali-aggregate reactivity in concrete – Reduced structural capacity caused by abrasive erosion – Pressurization cycles/pressure surges/hydraulic resonance (low, medium and high cycle fatigue)	– Complete visual inspection; mapping of damage – NDT inspection at spiral case/stay ring junction and other suspect areas – Stress analysis – Inquiry on previous repairs (nature, extent and frequency) – ------------------------------------ – Adjustment of distributor closing time – Repair by welding
– Rivet deterioration	– Corrosion	– Complete visual inspection and NDT inspection (if possible) – ------------------------------------ – Repair by welding with careful investigation of material weldability and heat deformation – Replacement where accessible
– Surface finish deterioration	– Corrosion – Micro-organisms – Barnacles – Inappropriate coating or loss thereof	– Visual inspection – ------------------------------------ – Blast cleaning and appropriate coating
– Deteriorated concrete water passage surfaces	– Poor quality of concrete (general or local)	– Visual inspection – ------------------------------------ – Concrete repairs
– Wall thickness deterioration	– Abrasive particles in water – Combined effects of corrosion and erosion	– Plate thickness measurements – Stress analyses – ------------------------------------ – Application of protective coating – Application of corrosion resistant coating – Modifications to guide vane closure law or derating of the unit or both. – Reinforce spiral case
– Man hole leakage or door malfunction	– Corrosion – Door gasket and flange surface deterioration – Door adjustment – Deterioration of hinges – Bushing wear	– Complete visual inspection of sealing surfaces – ------------------------------------ – Gasket replacement – New seal design – Repair of sealing surfaces – Replacement or repair of hinge bushings and/or pins – Hinge design modification

Table A.3 – Assessment of turbine embedded parts – Discharge ring

Applicable to Francis, Kaplan and fixed blade propeller turbines

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Cracks	– Poor design – Manufacturing defect – Pressure fluctuations (Kaplan and fixed blade propeller turbines) Runner rubbing against discharge ring – Inappropriate weld repair	– Complete visual and NDT inspection – Stress analysis – Measurement of pressure fluctuations – -------------------------------- – Repairs by welding – Discharge ring reinforcement – Aeration (Francis) – Unit alignment and balancing
– Voids behind discharge ring	– Pressure fluctuations – Deformation due to alkali-aggregate reactivity in concrete – Poor initial concreting and/or anchor failures	– Hammer survey; mapping of voids – Measurement of pressure fluctuations – ----------------------------------- – Epoxy or cement grout injection – Supplementary anchors
– Water leaks	– Assembly defect – Poor design – Loose bolts	– Visual examination – Verification of bolting – --------------------------------- – Replacement of bolts – Repair or replacement of discharge ring
– Circularity defect	– Deformation of sub-structure concrete due to alkali-aggregate reactivity (AAR)	– Measure circularity and blade tip clearances – Check unit alignment – --------------------------------- – Intervention on sub-structure concrete – Reestablishment of blade tip clearances
– Discharge ring deformation, mis-alignment or inclination (Bottom ring support for Francis turbines)	– Assembly defect – Deformation of concrete due to alkali-aggregate reactivity	– Measure axial position of runner (Francis) with respect to discharge ring – --------------------------------- – Unit overhaul, reassembly and re-alignment
– Abnormal wear	– Runner rubbing against inner wall	– Visual examination – Verification of runner blade tip clearances – Unit alignment checks and corrections – --------------------------------- – Repair discharge ring
– Corrosion	– Aggressive water – Inappropriate coating	– Visual inspection – --------------------------------- – Blast cleaning and appropriate coating
– Particle erosion	– Suspended abrasive particles in water – Inappropriate material choice	– Visual inspection – ---------------------------------- – Abrasion resistant coating (metallization or welding) – Repair or replacement

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Cavitation erosion	– Operating conditions – Blade design – Blade tip clearances	– Inspection and mapping of cavitated areas – Verification of blade tip clearances – Review of operating conditions – ----------------------------------- – Repair of damaged surfaces – Application of cavitation resistant overlay (metallization or welding)
– Performance and environmental concerns	– Excessive blade tip clearances	– Verification of blade tip clearances – ----------------------------------- – Conversion to spherical discharge ring above and below blade axis

Table A.4 – Assessment of turbine embedded parts – Draft tube

Applicable to Francis, Kaplan and fixed blade propeller turbines

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Distortion/deformation	– Alkali-aggregate reactivity in concrete	– ---------------------------------- – Draft tube liner rebuilding
– Voids behind the draft tube liner or liner de-bonding from concrete	– Pressure fluctuations – Deformation due to alkali-aggregate reactivity in concrete – Poor initial concreting and/or anchor failures	– Hammer survey; mapping of voids – Measurement of pressure fluctuations – ------------------------------------ – Epoxy or cement grout injection – Supplementary anchors
– Cavitation erosion	– Inappropriate material or overlay – Extensive operation outside normal load or hydraulic conditions – Change in the plant operating mode – Flow disturbance from poor runner or distributor profile	– Complete visual inspection – Flow analysis – Comparative analysis against modern designs – Shell thickness measurements – ---------------------------------- – Restoration of the surface – Blast cleaning and painting – Use of cavitation erosion resistant overlay – Application of cavitation resistant overlay (metallization or welding)
– Cracks	– Detachment from anchors or external ribs – Pressure fluctuations due to core vortex at partial and high loads	– Complete visual inspection – Inquiry on previous repairs (quantity and frequency) – Shell thickness measurements – NDT inspection in region of man door and at junction with discharge ring – Measurement of pressure fluctuations – ------------------------------------ – Section replacement or surface rebuilding (welding, grinding and re-grouting)
– Corrosion and/or erosion damage	– Presence of corrosion catalytic micro-organisms in water – Number of immersion cycles – Aggressive water with or without electrolytic corrosion effect due to unfavourable material combination – Abrasive particle content in water	– Complete visual inspection – Shell thickness measurements – ---------------------------------- – Blast cleaning and application of corrosion and erosion resistant coating – Use of corrosion and erosion resistant overlay or liner in high velocity regions
– Efficiency or power shortfall with respect to nominal values	– Poor design – New operating conditions (load range or hydraulic conditions)	– Flow analysis – Comparative analysis against modern designs – ------------------------------------ – Steel/concrete profile modifications – Modification to discharge ring

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Draft tube surface and profile damage	– Missing pieces of water passage concrete due to poor concrete quality – Abrasive particle and/or cavitation erosion of concrete – Sustained high velocity erosion (secondary flows) – Aggression of cavitation downstream of the liner	– Complete visual inspection – Survey and mapping of damage – ------------------------------------- – Concrete rebuilding – Concrete grinding to achieve acceptable flow continuity – Correction of hydraulic profile

Table A.5 – Assessment of turbine non-embedded, non-rotating parts – Headcover

Applicable to Francis, Kaplan and fixed blade propeller turbines

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Cracks	– Repeated pressurizations, – Pressure fluctuations or pressure surges – Hydraulic resonance (low, medium or high cycle fatigue) – Deformation – Defective material or design – High mechanical stress by design	– Complete visual and NDT inspection – Stress analysis – Deflection and vibration measurements – ---------------------------------- – Repairs by welding – Headcover reinforcement – Headcover replacement
– Deterioration of wearing surface or facing plate	– Abrasive particles in water – Cavitation erosion – Combined effects of corrosion and erosion – Wire drawing (Wire drawing is a type of erosion produced by a high velocity clean water jet passing through a small gap) – Contact with guide vanes	– Complete visual and dimensional inspection – ---------------------------------- – Wearing surface repair and machining – Facing plate installation or replacement – Assembly realignment – Guide vane vertical adjustment
– Headcover – guide vane rubbing contact	– Headcover and/or bottom ring misalignment – Insufficient clearance between guide vanes and headcover – Headcover excessive deflection	– Evaluation of risk of guide vane malfunction by guide vane torque test – Complete visual inspection, searching for wear and/or galling at component interface – Complete dimensional inspection of guide vanes, headcover and bottom ring alignment – ---------------------------------- – Assembly realignment – Guide vane vertical adjustment – Headcover wearing surface rebuilding and re-machining – Wearing plate installation or replacement
– Upper runner seal (labyrinth) damage	– Headcover misalignment – Runner misalignment – Inappropriate clearances – Alkali-aggregate reactivity in concrete	– Complete visual inspection – Complete dimensional inspection of head cover and runner alignment – --------------------------------- – Clearance modification – Runner seal (labyrinth) machining or replacement – Head cover replacement – Runner replacement
– Level inaccuracy	– Assembly defect – Power station displacements – Alkali-aggregate reactivity in concrete	– Dimensional inspection of headcover seating surface. – ---------------------------------- – Machining of headcover seating surface (stay ring flange)

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Flatness of wearing surface or facing plate	– Assembly defect – Unequal wear	– Complete dimensional inspection of machined surfaces – ----------------------------------- – Machining of the headcover wearing surface or facing plate – Wearing plate installation or replacement – Headcover replacement – Unit reassembly
– Water leakage	– Wear of shaft seal or sealing surfaces – Guide vane seals wear	– Visual inspection – ----------------------------------- – Shaft seal replacement – Guide vane seals replacement – Reconditioning of sealing surfaces
– Lubrication including environmental concerns	– Broken grease conduit – Grease distribution system failure – Poor grease distribution grooving – Excessive loss of grease to the environment – Guide vane bushing wear	– Complete visual inspection of headcover and its bushing greasing system – ----------------------------------- – Guide vane bushing replacement – Installation of self-lubricating guide vane bushings – Greasing system modification, repair or reprogramming or elimination
– Loose or broken bolts	– Assembly defect – Deformation of headcover – Poor choice of material or lack of respect for the specified material – Quality control problems during manufacture and installation – Excessive design stresses – Abnormal pressure fluctuations – Hydraulic resonance (low, medium or high cycle fatigue loading) – Insufficient bolt pre-tension –	– Complete visual inspection of the flange and bolts and NDT – Measurement of vibrations and pressure fluctuations – Verification of theoretical bolt loads – ----------------------------------- – Bolt replacement – Modify headcover natural frequency – Improve turbine aeration – Modify number and/or size of bolts and/or their material and/or their preload
– Water retention (drainage problem)	– Blocked or insufficient drain holes – Insufficient drainage capacity – Fouling of drain piping – Main shaft seal and/or guide vane water leakage too high	– Complete visual inspection – Inquiry concerning past problems – Analyse pumping time for drainage system – Inspection of guide vaneseals, shaft seals and head cover flange seals – ---------------------------------- – Drain hole and piping cleaning – Drainage pump (ejector) repair or replacement – Drainage system design modification – Replacement of unit shaft seal or guide vane seals
– Access problem for maintenance consideration	– Poor design – New maintenance or security needs	– Comparative analysis against modern design – ----------------------------------- – Headcover design modification – Headcover replacement

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Problem with guide strips for gate-operating ring	– Guide strip segment wear – High friction	– Friction test – ---------------------------------- – Guide strip replacement or conversion to self-lubricating materials
– Guide vane bushing wear	– Bottom ring and headcover misalignment – Lubrication problem – Wear due to long or extreme service life	– Complete visual inspection – ----------------------------------- – Unit realignment – Bushing replacement or conversion to self-lubricating materials – Greasing system modification, repair or reprogramming or elimination

Table A.6 – Assessment of turbine non-embedded, non-rotating parts – Intermediate and inner headcovers

Applicable to Kaplan and fixed blade propeller turbines

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Cracks	– Design deficiency – Poor material or poor choice of material – Abnormal pressure fluctuations, pressure surges. – Frequent up-lift of the runner during transients – Intrusion of foreign objects in water passages	– Complete visual and NDT inspection – Stress analysis – Measurement of pressure fluctuations – ---------------------------------- – Repairs by welding – Reinforcement – Replacement – Check of clearance between runner and inner head cover
– Water leaks	– Assembly defect – Poor design – Loose bolts	– Visual inspection – Verification of bolting – ------------------------------- – Replacement of bolting – Joint seals replacement and/or sealing surfaces reconditioning
– Hydraulic surface erosion	– Abrasive particles in water – Discontinuity on hydraulic surface	– Visual examination and mapping of defects – ----------------------------------- – Weld overlay of damaged surfaces – Removal of hydraulic discontinuities
– Loose or broken bolts	– Assembly problem – Poor choice of material or defective material – Insufficient bolt pre-tension – Vibration loosening of bolts	– Visual examination for flange fit problems – Measurement of vibrations and pressure fluctuations – Verification of theoretical bolt loads, material and assembly torque – Verification of bolting – ------------------------------- – Replacement of bolting – modification of material and/or size of bolts – Machining of headcover seating and/or assembly surfaces
– Drainage problem	– Blocked or insufficient drain holes – Fouling of drain piping – Main shaft seal and/or guide vane water leakage too high – Insufficient drainage capacity	– Inspection of wicket gate seals, shaft seal and head cover flange seals – Analyse pumping time for drainage system – ---------------------------------- – Cleaning of drains and piping – Replacement or repair of drainage pump or ejector – Drainage system modification – Replacement of wicket gate seals, shaft seal and head cover flange seals
– Access problem	– Poor design – New maintenance or security requirements or regulations	– Comparison against modern designs – ---------------------------------- – Modifications – Replacement

Table A.7 – Assessment of turbine non embedded, non-rotating parts – Bottom ring

Applicable to Francis, Kaplan and fixed blade propeller turbines

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Facing plate deterioration	– Abrasive sediment in water – Cavitation erosion – Wire drawing – Contact with guide vanes	– Complete visual and dimensional inspection – ----------------------------------- – Surface repair and machining – Facing plate installation or replacement – Assembly realignment – Guide vane vertical position adjustment
– Interference with guide vane operation	– Headcover and/or bottom ring misalignment – Insufficient clearance between bottom ring and guide vanes	– Complete visual inspection – Complete dimensional inspection of guide vanes, bottom ring and head cover alignment – ----------------------------------- – Assembly realignment – Guide vane axial bearing replacement – Surface repair and machining – Facing plate installation or replacement
– Lower runner seal (labyrinth) damage (Francis turbines)	– Bottom ring misalignment – Runner misalignment – Inappropriate design clearances – Bottom ring deformation due to alkali-aggregate reactivity in concrete	– Complete visual inspection – Complete dimensional inspection of bottom ring and runner alignment – ----------------------------------- – Clearance modification – Runner seal (labyrinth) machining or replacement – Bottom ring replacement
– Level inaccuracy	– Assembly problem – Power station dimensional instability – Alkali-aggregate reactivity in concrete	– Complete dimensional inspection of bottom ring and its foundation – ------------------------------------ – Machining of bottom ring support surface
– Facing plate flatness	– Assembly problems – Wear – Distortion	– Complete dimensional inspection of machined surfaces – ----------------------------------- – Machining of the bottom ring – Bottom ring replacement – Unit reassembly – Facing plate installation or replacement
– Water leakage	– Seal damage or deterioration of sealing surfaces	– Visual inspection – ------------------------------- – Seal replacement – Sealing surfaces reconditioning

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Lubrication problems of lower guide vane bushing including environmental concerns	– Broken grease conduit – Poorly designed grease distribution grooves – Grease distribution system malfunction – Excessive grease loss to the environment – Guide vane bushing wear	– Complete visual inspection of bottom ring bushings and their lubrication system – ------------------------------------ – Guide vane bushing replacement – Installation of self-lubricating guide vane bushings – Lubrication system modification, repair or reprogramming
– Loose or broken bolts	– Assembly problem – Deformation of bottom ring – Poor choice of bolting material or poor material – Insufficient bolt pre-tension	– Complete visual inspection of bolting and sealing – Verification of theoretical bolt loads, material and assembly torque – -------------------------------- – Replacement of bolting – Modification of material and/or size of bolts – Machining of bottom ring seating and/or assembly surfaces
– Guide vane bushing wear	– Bottom ring and headcover misalignment – Lubrication problem – Extreme service or age – Alkali-aggregate reactivity in concrete	– Complete visual inspection – Complete dimensional inspection of bottom ring and headcover alignment – ------------------------------------ – Unit reassembly and realignment – Bushing replacement with similar or self-lubricating materials – Lubrication system modification, repair or reprogramming

Table A.8 – Assessment of turbine non embedded, non-rotating parts – Guide vanes

Applicable to Francis, Kaplan and fixed blade propeller turbines

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Cracking	– Vibration – Reduced structural integrity caused by particle or cavitation erosion – Defects in material, design or manufacture – Exceptional accidental loading – Improper control circuit (results in excessive number of load cycles)	– Inquiry on previous repairs (nature, extent and frequency) – Complete visual and NDT inspection – Vibration measurement aiming at vibration frequency determination (FFT) – Stress and material analyses – Measurement of dead band and insensitivity – ---------------------------------- – Repairs by welding – Re-machining – Profile modification – Replacement – Governor parameters adjustment
– Deformation	– Defects in material, design or manufacture – Exceptional accidental loading due to debris – Inadequate or malfunctioning of protective device	– Complete dimensional inspection – --------------------------------- – Replacement – Verification and correction or replacement of protective device – Repair or replacement of trash racks
– Cavitation erosion	– Guide vane profile – Operation under abnormal conditions – Significant changes in the plant operating or hydraulic conditions	– Complete visual inspection – Inquiry on previous repairs (quantity and frequency) – Material and flow analyses – Comparative analysis with modern designs – ---------------------------------- – Surface rebuilding by welding – Modification to hydraulic profile – Replacement
– Corrosion	– Inappropriate coating – Aggressive water with or without electrolytic corrosion effect due to unfavourable material combination – Contamination of stainless steel by carbon steel	– Complete visual inspection – ------------------------------- – Blast cleaning and application of corrosion and erosion resistant coating – Use of corrosion and erosion resistant overlay – Removal of contaminated area and rebuilding of profile – Passivation of guide vanes surfaces
– Abrasive erosion	– Abrasive sediments in water	– Complete visual inspection – Inquiry on previous repairs (quantity and frequency) – ------------------------------- – Surface rebuilding by welding – Deposit of abrasion resistant material (welding, metallization) – Replacement with more appropriate material

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Contact wear (rubbing, galling on headcover and/or bottom ring)	– Poor alignment at assembly – Poor choice of material combinations – Insufficient clearances – Initiation by foreign particles – Alkali-aggregate reaction in concrete	– Visual and dimensional inspection of guide vanes and distributor assembly – Investigate and eliminate if possible, sources of foreign particles – ------------------------------- – Surface rebuilding by welding – Use of anti-galling materials – Unit disassembly, adjustment and reassembly
– Hydraulic performance	– Poor hydraulic profile – Non uniform guide vane angular position – Inadequate maximum opening of guide vanes	– Flow analysis – Comparative analysis with modern designs – ---------------------------------- – Profile modification – Replacement – Verification and adjustment of guide vane operating mechanism
– Trunnion wear	– Greasing system malfunction – Abrasive sediments – Corrosion – Poor choice of material combination	– Visual and dimensional inspection – ---------------------------------- – New stainless steel sleeves on trunnion or stainless steel trunnion machining – Guide vane replacement – Replacement of grease lubricated bronze bushing system by self-lubricating bushings – Greasing system modification, repair or reprogramming
– Poor sealing at ends and on contact lines	– Wear/erosion on contact faces – Gap between guide vanes on vane to vane sealing line (poor adjustment) – Particle erosion or wire drawing at clearances between guide vanes and headcover and/or bottom ring (Wire drawing is erosion caused by a high velocity jet of clean water passing through a small clearance) – Insufficient contact pressure when closed – Poor original choice of materials	– Gap measurements – ---------------------------------- – Repair of contact faces – Repairs to headcover, bottom ring and ends of guide vanes – Adjustment of guide vane operating mechanism – Adjustment of servomotor preloading in closed position (squeeze) – Guide vane replacement with possible headcover/bottom ring repairs
– Vibration	– Loss of assembly tolerances – Deficient profile	– Complete dimensional and condition inspection of operating mechanism – Flow analysis – Vibration measurement aiming at vibration frequency determination (FFT) – ------------------------------- – Operating mechanism modification or repair – Modification of profile – Replacement

Table A.9 – Assessment of turbine non embedded, non-rotating parts – Guide vane operating mechanism

Applicable to Francis, Kaplan and fixed blade propeller turbines

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Cracks and deformation	– Exceptional loading due to debris or improper adjustments – Misalignment of components (servomotors to operating ring or operating ring to gate levers) – Failure of some shear pins or other load limiting devices or malfunction of friction drive system – Increase in servomotor operating pressure without due verification of the effects – Poor material or design	– Complete visual and dimensional inspection – NDT inspection – Operating mechanism friction test – Stress calculations and analysis – ---------------------------------- – Bushing replacement or conversion to self-lubricating bushings – Adjustments verification and correction – Component machining – Anti-gripping coating application
– Deterioration of surfaces	– Corrosion on guide vane links and levers	– Complete visual inspection – ------------------------------- – Blast cleaning and application of corrosion and erosion resistant coating – Use of corrosion and erosion resistant overlay
– Excessive play in linked components	– Bushing wear	– Visual and dimensional inspection – ------------------------------- – Bushing replacement or modification to self-lubricating bushings
– Adjustment difficulties	– Guide vane trunnion or bushing wear – Poor lever/link eccentric pin locking system – Access problem – Mechanism design	– Complete guide vane mechanism evaluation – Visual and dimensional inspection – ---------------------------------- – Modification to the eccentric link-pin locking system – Application of anti-galling coating – Access and tooling improvements
– Repetitive shear pin failures	– Guide vane and servomotor adjustment – Shear pin design – Guide vane restraint system design for broken shear pin – Problem with guide vane bushings – Contact with headcover and/or bottom ring	– Operating mechanism friction test – Inquiry regarding frequency, location and causes of failures – Stress analysis – ------------------------------- – Shear pin design modification – Modification of guide vane restraint system for broken shear pin – Guide vane, link, operating ring and servomotor adjustments – Rehabilitation of guide vane bushings or modification to self-lubricating bushings

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Lubrication including environmental issues	– Broken grease conduit – Grease distribution system malfunction – Bushing wear – Excessive grease entering the environment	– Complete visual inspection – --------------------------------- – Complete cleaning of the tube layout and distributors including centre holes in guide vane trunnions and any conduits within the guide vanes – Removal of existing system and modification to self-lubricating bushings – Lubrication system modification, repair or reprogramming
– Problem with shear pin failure detection system	– Electrical problem – Outdated detection system/poor design for humid conditions	– Detection system design review – --------------------------------- – Modernization or replacement of the shear pin failure detection system

Table A.10 – Assessment of turbine non embedded, non-rotating parts – Operating ring

Applicable to Francis, Kaplan and fixed blade propeller turbines

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Cracks and deformation	– Abnormal loading due to debris in guide vanes – Misalignment with respect to servomotors or guide vane levers – Poor material or design – Manufacturing defect	– Complete visual and dimensional inspection – NDT inspection – Stress analysis – --------------------------------------- – Re-alignment of servomotors – Replace wear strips supporting operating ring and realign operating system
– Abnormal wear	– Lack of grease – Defective link bushings or operating ring wear strips – Contamination of bearing surfaces by foreign material – Misalignment with respect to servomotors or guide vane levers	– Operating mechanism friction test – Complete visual inspection – ------------------------------ – Grease system verification – Replacement of link bushings or operating ring wear strips – Addition of barriers against contamination – Re-alignment of servomotors – Replacement of wear strips supporting operating ring and realignment of operating system

Table A.11 – Assessment of turbine non embedded, non-rotating parts – Servomotors

Applicable to Francis, Kaplan and fixed blade propeller turbines

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Oil leakage	– Broken or worn seals – Worn bushings – Piston rod wear or scoring due to oil contamination	– Complete visual inspection – Leakage test – ------------------------------------- – Seal replacement – Stem rebuild – Stem re-chroming – Stem replacement – Bushing replacement – Servomotor rebuild or replacement
– Alignment	– Inadequate servomotor bolting and dowelling – Soleplate surface flatness or alignment – Wear of operating ring support wear strips – Concrete instability affecting servomotor/operating ring alignment	– Servomotor alignment verification – ------------------------------------ – Servomotor/soleplate realignment – Wear strips supporting operating ring replacement and vertical position alignment
– Inadequate operating forces	– Piping problems – Governor/hydraulic system problem – Servomotor cylinder or piston ring wear (excessive leakage past piston) – Servomotor binding due to excessive bushing wear or misalignment	– Operating mechanism friction test – Piston ring leakage test – ------------------------------- – Piston ring replacement – Piston/piston rod rebuild – Cylinder honing and/or machining – Bushing replacement – Governor/hydraulic system rehabilitation – Operating system realignment
– Guide vane pre-stressing adjustment problems (closed position “squeeze”)	– Guide vane sealing line deterioration – Poor lever/link eccentric pin locking system design (loss of uniform simultaneous closure of all guide vanes) – Poor and/or maladjusted servomotor position indicator – Low oil pressure – Poor pre-stressing adjustment/stroke limit system design	– Visual inspection – Contact surfaces straightness and flatness – Contact edges gap measurements with and without pre-stress – ------------------------------- – Guide vane contact surface and sealing line rebuilding – Pre-stressing adjustment/stroke limit system and adjustment process modifications – Lever/link eccentric pin locking system modification – Servomotor rebuild – Servomotor replacement – Governor/hydraulic system rehabilitation

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Servomotor locking system problems and safety concerns	– Weak locking system design – Change in maximum opening of guide vanes – Wear or damage to parts	– Complete visual inspection – --------------------------------------- – Complete rehabilitation or replacement of locking system – Locking system design modification – Replacement of servomotors with new locking system

Table A.12 – Assessment of turbine non embedded, non-rotating parts – Guide bearings

Applicable to Francis, Kaplan, fixed blade propeller and Pelton turbines

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Oil loss	– Oil sump gasket/O-ring deterioration – Oil leakage over top of oil sump inner wall (at shaft journal location) caused by one or more of the following – Oil sump overfilling – Non-uniform spacing between sump inner wall and shaft journal skirt due to misalignment or inner wall distortion – Excessive disturbance and instability of oil flow in sump	– Complete visual inspection – --------------------------------------- – Gasket/O-ring replacement – Adjustment of oil level Inspection and correction of alignment of adjacent parts – Addition of oil retaining ring(s)/seal(s) at inner wall of oil sump – Guide bearing modification to stabilize oil flow – Inner oil sump repair (to restore inner wall circularity) or replacement
– Presence of water and/or solid particles in oil	– Cooling coil/water supply connection(s) leakage – Condensation – Contaminated oil – Inadequate or infrequent oil filtration – Paint coating deterioration – Babbitt deterioration	– Oil test for evidence of water and foreign particles – Babbitt inspection – ------------------------------- – Repair of water supply connection(s) – Cooling coil replacement – Oil filtration – Oil change (always use a filter during sump filling) – Re-babbitting – Surface cleaning and re-painting
– Babbitt in poor condition	– Excessive wear – Excessive shaft vibration – Loss of bond – Inappropriate oil quality or contaminated oil	– Complete inspection for evidence of babbitt deterioration: wear, melting, cracking and loss of bond – --------------------------------------- – Hand scraping or re-machining – Re-babbitting – Bearing pad or shell replacement

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Oil/bearing metal high temperature	– Malfunction of cooling water supply system or insufficient water supply – Too tight bearing/shaft journal clearance – Excessive shaft run-out at guide bearing (shaft vibration) – Shaft journal non-uniform wear – Loss of thermal detector calibration	– Complete visual inspection – Measurement of shaft journal circularity and concentricity – --------------------------------------- – Correct water supply fault – Water supply pipe cleaning – Readjustment of bearing/shaft journal clearance or remachine bearing – Correction of shaft run-out problem (unit mechanical or hydraulic balancing) – Re-machine shaft journal – Replace or recalibrate thermal detectors
– Excessive or non-uniform bearing/shaft journal clearance	– Babbitt wear – Shaft journal non-uniform wear – Poor adjustment of bearing shoes (shoe type bearings) – Misalignment or distortion of bearing shell (shell type bearings)	– Complete visual and dimensional inspection of bearing clearance – Complete inspection of babbitt condition and adherence – Inspection of the bearing shoes adjustment and blocking devices – -------------------------------- – Hand scraping or re-machining bearing – Re-babbitting – Readjustment of radial position of bearing shoes – Bearing shell realignment, or repair to restore circularity – Bearing pad replacement – Bearing shell replacement
– Cracks in bearing support	– Excessive vibration – High dynamic loads (stresses) – Abnormal operating conditions – Defective material or design – Loose or broken bolts	– Complete visual and NDT inspection – Analysis of operating conditions – Design review – --------------------------------------- – Bolt re-tightening or bolt replacement – Weld repairs with stress-relief and machining as required – Bearing support reinforcement – Bearing support replacement
– Instrumentation malfunction resulting in no alarm on abnormal temperature or oil level	– Unreliable or faulty devices – Loss of adjustment or calibration – Outdated technology	– Inspection and review of instrumentation set points and calibration – -------------------------------- – Instrumentation modernization, such as use of instruments with self-diagnostics – Adjustment and recalibration – Providing redundancy

Table A.13 – Assessment of turbine non embedded, non-rotating parts – Turbine shaft seal (mechanical seal or packing box)

Applicable to Francis, Kaplan and fixed blade propeller turbines

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Excessive water leakage or filtered water consumption	– Sealing element wear (segment or packing deterioration) – Corrosion damage on seal components – Shaft sleeve wear – Interruption or inadequacy of filtered water	– Complete visual inspection – ---------------------------------- – Ring replacement (sealing elements) – Shaft sleeve replacement – Shaft sleeve machining and/or stone polishing – Shaft seal packing and/or gland replacement
– Excessive wear rate of sealing elements	– Shaft sleeve wear – Corrosion damage	– Visual inspection of shaft sleeve – -------------------------------- – Shaft sleeve machining or hand polishing – Shaft sleeve replacement

Table A.14 – Assessment of turbine non embedded, non-rotating parts – Thrust bearing support

Applicable to Francis, Kaplan and fixed blade propeller turbines with separate bearing bracket or with thrust support on turbine headcover

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Cracks	– Poor material or design – High mechanical stress – Increased hydraulic thrust – Unit unbalanced – Abnormal dynamic loading (hydraulic or component resonance)	– Complete visual and NDT inspections – Inquiry regarding previous interventions – *In-situ* testing (loads, stresses, frequencies) – Stress and load analysis – ---------------------------------- – Weld repairs – Thrust-bearing support reinforcement – Identify and correct causes of abnormal static and dynamic loading – Verification and correction of runner upper seal water venting to draft tube – Unit alignment and balancing
– Level (or perpendicularity with axis of rotation)	– Assembly problem – Power station dimensional integrity	– Complete dimensional inspection of bearing support foundation – -------------------------------- – Machining or adjustment of bearing support foundations
– Access problem	– Poor design – New maintenance or safety requirements	– Comparative analysis with modern design – -------------------------------- – Thrust-bearing support design modification

Table A.15 – Assessment of turbine non embedded, non-rotating parts – Nozzles

Applicable to Pelton turbines

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Leakage and poor jet formation (poor jet formation can result in cavitation erosion on the cut-outs and splitter tips of the runner buckets)	– Wear of nozzle seat rings and needle tips – Foreign objects lodged between needle and nozzle seat ring, damaging the sealing edge	– Visual inspection – Leak testing – -------------------------------- – Design of replaceable nozzle seat ring – Rebuilding seat rings – Replace needle tips and nozzle seat rings
– Erosion on the needle and nozzle seat rings	– Abrasive sediment in water	– Visual inspection – Leak testing – -------------------------------- – Rebuild needle tips and nozzle seat rings – Replace needle tips and nozzle seat rings – Hard facing of the needle tips and nozzle seat rings
– Erosion on the nozzle bodies (nozzle hats)	– Abrasive sediment in water	– Visual inspection – -------------------------------- – Rebuild nozzle hats – Replace nozzle hats with or without change of materials
– Improper operation of needles	– Sediments in the bushings increasing the coefficient of friction – Lubrication system malfunction – Worn servomotors – Inadequate operating forces (deficient oil pressure or malfunction of mechanical compensating mechanism)	– Operating mechanism friction test – Look for time of similar event – -------------------------------- – Replacement of bushings (where practicable, design for self-lubricated bushings) – Overhaul lubrication system – Rehabilitate servomotors with replacement of piston rings – Overhaul governor and hydraulic system – Overhaul mechanical compensating mechanism
– Cracks or fracture	– Additional friction or stick-slip effect – Fracture of spring – Improper control circuit	– Visual inspection – Measurement of dead band and insensitivity – -------------------------- – See above: Improper operation of needles

Table A.16 – Assessment of turbine non embedded, non-rotating parts – Deflectors and energy dissipation

Applicable to Pelton turbines

Aspect of concern	Possible causes or reasons	Possible inspections/actions
– Improper operation	– Damaged bearings or bushings or operating mechanism – Worn servomotor – Eroded deflectors	– Visual inspection – Measurement of dead band and insensitivity – ------------------------- – See Table A.15: Improper operation of needles
– Damaged runner pit liner	– Frequent operation with jets deflected – Inadequate reinforcement of runner pit liner in zones of jet impingement – Loss of embedded anchors	– Visual inspection and appropriate NDT – -------------------------------------- – Weld repairs – Addition of anchors in affected zones – Reinforcement of runner pit liner in affected zones

Table A.17 – Assessment of turbine rotating parts – Runner

Applicable to Francis, Kaplan and fixed blade propeller turbines

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Cracks	– Exceptional operating conditions – Changes in the plant operating mode – Residual welding stresses – Load induced stresses – Metal loss caused by cavitation – Periodic stresses induced by contact in the runner seals – Thickness loss caused by surface erosion – Resonance with external exciting frequencies	– Inquiry into previous repairs (nature, scope and frequency) – Complete visual and NDT inspection – Measurements of model and/or prototype loading – Material, stress and flow analyses – Runner dynamic/modal analyses and testing – Fatigue analysis – Comparison analysis with modern designs – Evaluate effectiveness of post-weld stress relief heat treatment – Evaluate impact of weld repairs if done without thermal stress relief – --------------------------------------- – Weld repairs – Blade outlet edge profile modification (change Von Kármán vortex frequency and intensity) – Re-establishment of necessary runner seal or blade tip clearances – Runner modification – Runner replacement
– Water passage surface deterioration	– Poor material selection – Abrasive particle or cavitation erosion – Erosion of corrosion products – Barnacle type growths in low velocity runners	– Complete visual and NDT inspection – Inquiry into previous repairs (nature, scope and frequency) – Flow and material analysis – Model and/or prototype testing – -------------------------------------- – Repair welding with cavitation or particle erosion resistant materials – Hard-facing in zones subject to particle erosion – Blast cleaning and painting – Runner modification – Runner replacement with possible change of material

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Vibration	– Pressure fluctuations – Resonance – Mechanical unbalance – Hydraulic unbalance – Excessive or uneven main bearing clearance – Changes in the plant operating mode	– Complete visual and NDT inspection – Inquiry into past experience (causes, trends, operational or physical changes) – Prototype testing for vibration analysis – Verification of unit alignment – Flow analysis – Guide vane profile analysis – Draft tube analysis – Inspection of bearing and main shaft journal – ------------------------------- – Repair of bearings (with or without modification) – Inspection and repair of main shaft journals – Balancing of rotating parts – Runner modifications to improve hydraulic balance – Runner replacement
– Cavitation erosion	– Improper operation – Poor blade profile – Modification of profiles caused by inadequately controlled weld repairs – Change in the plant operating mode involving lack of respect for the power limits for cavitation free performance – Poor material selection	– Complete dimensional inspection – Complete visual and NDT inspection – Model and/or prototype testing – Inquiry into past operating and repair practices (scope and frequency) – Material and flow analyses – Comparative analyses against modern runner design – ------------------------------------- – Blade modifications – Runner replacement – Repair by overlay welding with cavitation resistant material and reestablishment of original or revised blade profiles
– Interference with headcover and bottom ring	– Assembly misalignment – Tight runner seal clearances by design – Bottom ring or headcover distortion due to unstable concrete foundations	– Complete visual, dimensional and ailgnment inspection – Inquiry into past experience (nature, dates and remedial actions) – ------------------------------------- – Unit realignment – Runner seal (labyrinth) machining or replacement – Bottom ring or headcover modifications – Re-machining of headcover and bottom ring support flanges (surfaces)

Aspects of concern	Possible causes or reasons	Possible inspections/actions
– Unusually limited range of stable operation	– Draft tube pressure fluctuations – Hydraulic resonance with the external water conduit system – Runner and/or draft tube hydraulic design – Hydraulic unbalance (unequal blade outflow openings) – Improper operation (e.g. long durations at very low loads) – Change in the plant operating mode – Ineffective draft tube aeration	– Complete dimensional inspection – Inquiry into operating practice changes and experience – Inquiry into changes in hydraulic conditions – Model and/or prototype testing – Flow analysis – Comparison with modern runner design – Evaluation/modification of draft tube aeration system(s) – -------------------------------------- – Runner modification – Runner replacement
– Efficiency or power shortfall with respect to nominal values	– New operating modes – Cavitation or particle erosion or other surface deterioration – Pressure fluctuations which limit load range – Excessive runner seal or blade tip clearances – Excessive air admission – Poor hydraulic design	– Complete dimensional inspection – Inquiry into changes in operating practices and experience – Model and/or prototype testing – Performance and flow analysis – Comparison with modern turbine design: spiral case, stay vanes, guide vanes, runner and draft tube hydraulic profile evaluation – ------------------------------- – Runner modification – Runner replacement – Replacement of guide vanes – Modifications to stay vanes and/or guide vanes and/or draft tube hydraulic profile