



BSI Standards Publication

Hydraulic turbines, storage pumps and pump-turbines - Rehabilitation and performance improvement (IEC 62256:2017)

National foreword

This British Standard is the UK implementation of EN 62256:2017. It is identical to IEC 62256:2017. It supersedes BS EN 62256:2008, which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee MCE/15, Hydraulic turbines.

A list of organizations represented on this committee can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

© The British Standards Institution 2017
Published by BSI Standards Limited 2017

ISBN 978 0 580 90197 3

ICS 27.140

Compliance with a British Standard cannot confer immunity from legal obligations.

This British Standard was published under the authority of the Standards Policy and Strategy Committee on 30 September 2017.

Amendments/corrigenda issued since publication

Date	Text affected
------	---------------

English Version

Hydraulic turbines, storage pumps and pump-turbines -
Rehabilitation and performance improvement
(IEC 62256:2017)

Turbines hydrauliques, pompes d'accumulation et pompes
turbines - Réhabilitation et amélioration des performances
(IEC 62256:2017)

Wasserturbinen, Speicherpumpen und Pumpturbinen -
Modernisierung und Verbesserung der
Leistungseigenschaften
(IEC 62256:2017)

This European Standard was approved by CENELEC on 2017-07-04. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the CEN-CENELEC Management Centre or to any CENELEC member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CENELEC member into its own language and notified to the CEN-CENELEC Management Centre has the same status as the official versions.

CENELEC members are the national electrotechnical committees of Austria, Belgium, Bulgaria, Croatia, Cyprus, the Czech Republic, Denmark, Estonia, Finland, Former Yugoslav Republic of Macedonia, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.



European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
Europäisches Komitee für Elektrotechnische Normung

CEN-CENELEC Management Centre: Avenue Marnix 17, B-1000 Brussels

European foreword

The text of document 4/323/FDIS, future edition 2 of IEC 62256, prepared by IEC TC 4 "Hydraulic turbines" was submitted to the IEC-CENELEC parallel vote and approved by CENELEC as EN 62256:2017.

The following dates are fixed:

- latest date by which the document has to be implemented at national level by publication of an identical national standard or by endorsement (dop) 2018-04-04
- latest date by which the national standards conflicting with the document have to be withdrawn (dow) 2020-07-04

This document supersedes EN 62256:2008.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CENELEC shall not be held responsible for identifying any or all such patent rights.

Endorsement notice

The text of the International Standard IEC 62256:2017 was approved by CENELEC as a European Standard without any modification.

In the official version, for Bibliography, the following notes have to be added for the standards indicated:

IEC 60041	NOTE	Harmonized as EN 60041.
IEC 60193	NOTE	Harmonized as EN 60193.
IEC 60609 (Series)	NOTE	Harmonized as EN 60609 (Series).
IEC 60994	NOTE	Harmonized as EN 60994.
IEC 62097	NOTE	Harmonized as EN 62097.
IEC 62364	NOTE	Harmonized as EN 62364.

CONTENTS

FOREWORD.....	7
INTRODUCTION.....	9
1 Scope.....	10
2 Normative references	10
3 Terms, definitions and nomenclature	10
4 Reasons for rehabilitating.....	12
4.1 General.....	12
4.2 Reliability and availability increase.....	14
4.3 Life extension and performance restoration.....	14
4.4 Performance improvement	14
4.5 Plant safety improvement.....	14
4.6 Environmental, social and regulatory issues.....	15
4.7 Maintenance and operating cost reduction	15
4.8 Other considerations.....	15
5 Phases of a rehabilitation project.....	15
5.1 General.....	15
5.2 Decision on organization.....	17
5.2.1 General	17
5.2.2 Expertise required	17
5.2.3 Contract arrangement.....	17
5.3 Level of assessment and determination of scope	18
5.3.1 General	18
5.3.2 Feasibility study – Stage 1.....	19
5.3.3 Feasibility study – Stage 2.....	19
5.3.4 Detailed study.....	19
5.4 Contractual issues	23
5.4.1 General	23
5.4.2 Specification requirements.....	24
5.4.3 Tendering documents and evaluation of tenders	24
5.4.4 Contract award(s).....	25
5.5 Execution of project	25
5.5.1 Model test activities	25
5.5.2 Design, construction, installation and testing	25
5.6 Evaluation of results and compliance with guarantees.....	26
5.6.1 General	26
5.6.2 Turbine performance evaluation.....	26
5.6.3 Generator performance evaluation.....	27
5.6.4 Penalties and/or bonuses assessment.....	27
6 Scheduling, cost analysis and risk analysis	27
6.1 Scheduling.....	27
6.1.1 General	27
6.1.2 Scheduling – Assessment, feasibility and detailed study phases.....	28
6.1.3 Evaluating the scheduling component of alternatives	28
6.1.4 Scheduling specification and tendering phase	29
6.1.5 Scheduling project execution phases	29
6.2 Economic and financial analyses	29

6.2.1	General	29
6.2.2	Benefit-cost analysis.....	30
6.2.3	Identification of anticipated benefits.....	31
6.2.4	Identification of anticipated costs and benefits	32
6.2.5	Sensitivity analysis	33
6.2.6	Conclusions.....	34
6.3	Risk analysis.....	34
6.3.1	General	34
6.3.2	Non-achievement of performance risk.....	34
6.3.3	Risk of continued operation without rehabilitation	35
6.3.4	Extension of outage risk	35
6.3.5	Financial risks	35
6.3.6	Project scope risk	36
6.3.7	Other risks.....	36
7	Assessment and determination of scope of the work.....	37
7.1	General.....	37
7.2	Assessment of the site	37
7.2.1	Hydrology	37
7.2.2	Actual energy production	38
7.2.3	Environmental, social and regulatory issues	38
7.3	The assessment of the turbine	39
7.3.1	General	39
7.3.2	Turbine integrity assessment.....	39
7.3.3	Residual life.....	52
7.3.4	Turbine performance assessment	61
7.4	The assessment of related equipment.....	83
7.4.1	General	83
7.4.2	Generator and thrust bearing	84
7.4.3	Turbine governor	84
7.4.4	Turbine inlet and outlet valves, pressure relief valve.....	85
7.4.5	Auxiliary equipment	85
7.4.6	Equipment for erection, dismantling and maintenance	86
7.4.7	Penstock and other water passages	86
7.4.8	Consequences of changes in plant specific hydraulic energy (head)	86
7.4.9	Grid integration.....	87
8	Hydraulic design and performance testing options	87
8.1	General.....	87
8.2	Computational hydraulic design	88
8.2.1	General	88
8.2.2	The role of CFD	88
8.2.3	The process of a CFD cycle.....	89
8.2.4	The accuracy of CFD results.....	89
8.2.5	How to use CFD for rehabilitation	90
8.2.6	CFD versus model tests.....	91
8.3	Model tests	91
8.3.1	General	91
8.3.2	Model test similitude	92
8.3.3	Model test content	93
8.3.4	Model test application.....	93

8.3.5	Model test location	95
8.4	Prototype performance test	96
8.4.1	General	96
8.4.2	Prototype performance test accuracy	97
8.4.3	Prototype performance test types	97
8.4.4	Evaluation of results	98
9	Specifications	99
9.1	General	99
9.2	Reference standards	99
9.3	Information to be included in the tender documents	100
9.4	Documents to be developed in the course of the project	101
Annex A (informative)	Check-list for evaluation of existing turbine	103
Annex B (informative)	Assessment examples	136
B.1	General	136
B.2	Runner (applicable to Francis, Kaplan, propeller and Pelton)	136
B.2.1	Documentation – available data	136
B.2.2	Design review	137
B.2.3	Inspection items	137
B.2.4	Assessment of inspection results	138
B.2.5	Current condition assessment	140
B.2.6	Scope of work	140
B.3	Stay ring	142
B.3.1	Documentation – available data	142
B.3.2	Design review	142
B.3.3	Inspection items	142
B.3.4	Assessment of inspection results	143
B.3.5	Current condition assessment	143
B.3.6	Scope of work (possible action to be taken)	144
B.4	Guide vanes	144
B.4.1	Documentation – Available data	144
B.4.2	Design review	145
B.4.3	Inspection items	145
B.4.4	Assessment of inspection results	146
B.4.5	Current condition assessment	147
B.4.6	Scope of work	147
B.5	Real life example: Pelton runner with severe crack	148
B.5.1	Data of the Pelton runner	148
B.5.2	Fatigue analysis	148
B.5.3	Fracture-mechanics analysis	150
B.5.4	Results for the Pelton runner	150
Annex C (informative)	Checklist for evaluation of related equipment	152
Bibliography		156
Figure 1	Flow diagram depicting the logic of the rehabilitation process	16
Figure 2	Critical zones for cracks “A” and “B” in Pelton runner buckets	51
Figure 3	Bathtub curve	53
Figure 4	Process of residual life estimation	54
Figure 5	Schematic behaviour for the different stages in the fatigue process	55

Figure 6 – Start-up and full load strain gauge signal on Francis blade.....	60
Figure 7 – Relative efficiency versus relative output – Original and new runners.....	63
Figure 8 – Relative efficiency versus output – Original and new runners – Outardes 3 generating station	64
Figure 9 – Efficiency and distribution of losses versus specific speed for Francis turbines (model) in 2005	65
Figure 10 – Relative efficiency gain following modification of the blades on the La Grande 3 runner, in Quebec, Canada.....	67
Figure 11 – Potential efficiency improvement for Francis turbine rehabilitation.....	71
Figure 12 – Potential efficiency improvement for Kaplan turbine rehabilitation	72
Figure 13 – Cavitation and corrosion-erosion in Francis runner.....	74
Figure 14 – Back side erosion of the entrance into a Pelton bucket.....	75
Figure 15 – Leading edge cavitation erosion on a Francis pump-turbine caused by extended periods of operation at very low loads.....	76
Figure 16 – Severe particle erosion damage in a Francis runner	78
Table 1 – Expected life of a hydropower plant and its subsystems before major work	13
Table 2 – Typical routine inspections	41
Table 3 – Example of a rating system for the inspection results	58
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.....	59
Table 5 – Example of rating of a single component assessment including three assessment criteria.....	59
Table 6 – Francis turbine potential efficiency improvement (%) for runner profile modifications only	66
Table 7 – Potential impact of design and condition of runner seals on Francis turbine efficiency with new replacement runner or rehabilitated runner (%).....	69
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.....	69
Table 9 – Potential additional efficiency improvement by rehabilitation/replacement of other water passage components on a Francis turbine (%)	70
Table A.1 – Assessment of turbine embedded parts – Stay ring	103
Table A.2 – Assessment of turbine embedded parts – Spiral or semi-spiral case	104
Table A.3 – Assessment of turbine embedded parts – Discharge ring	105
Table A.4 – Assessment of turbine embedded parts – Draft tube	107
Table A.5 – Assessment of turbine non-embedded, non-rotating parts – Headcover	109
Table A.6 – Assessment of turbine non-embedded, non-rotating parts – Intermediate and inner headcovers	112
Table A.7 – Assessment of turbine non embedded, non-rotating parts – Bottom ring	113
Table A.8 – Assessment of turbine non embedded, non-rotating parts – Guide vanes.....	115
Table A.9 – Assessment of turbine non embedded, non-rotating parts – Guide vane operating mechanism.....	117
Table A.10 – Assessment of turbine non embedded, non-rotating parts – Operating ring	118
Table A.11 – Assessment of turbine non embedded, non-rotating parts – Servomotors.....	119
Table A.12 – Assessment of turbine non embedded, non-rotating parts – Guide bearings.....	120

Table A.13 – Assessment of turbine non embedded, non-rotating parts – Turbine shaft seal (mechanical seal or packing box)	122
Table A.14 – Assessment of turbine non embedded, non-rotating parts – Thrust bearing support.....	122
Table A.15 – Assessment of turbine non embedded, non-rotating parts – Nozzles	123
Table A.16 – Assessment of turbine non embedded, non-rotating parts – Deflectors and energy dissipation	124
Table A.17 – Assessment of turbine rotating parts – Runner	125
Table A.18 – Assessment of turbine rotating parts – Runner	128
Table A.19 – Assessment of turbine rotating parts – Runner	130
Table A.20 – Assessment of turbine rotating parts – Turbine shaft.....	131
Table A.21 – Assessment of turbine rotating parts – Oil head and oil distribution pipes	132
Table A.22 – Assessment of turbine auxiliaries – Speed and load regulation system (governor).....	133
Table A.23 – Assessment of turbine auxiliaries – Turbine aeration system.....	134
Table A.24 – Assessment of turbine auxiliaries – Lubrication system (guide vane mechanism)	135
Table C.1 – Assessment of related equipment – Governor.....	152
Table C.2 – Assessment of related equipment – Generator and thrust bearing.....	153
Table C.3 – Assessment of related equipment – Penstock and turbine inlet valves	154
Table C.4 – Assessment of related equipment – Civil works.....	155
Table C.5 – Assessment of related equipment – Crane, erection equipment	155

INTERNATIONAL ELECTROTECHNICAL COMMISSION

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

FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as "IEC Publication(s)"). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
- 2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
- 3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
- 4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
- 5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
- 6) All users should ensure that they have the latest edition of this publication.
- 7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
- 8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
- 9) Attention is drawn to the possibility that some of the elements of this IEC Publication may be the subject of patent rights. IEC shall not be held responsible for identifying any or all such patent rights.

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	25 to 50	Safety of operation, loss of water, cavitation damage, erosion, corrosion, cracks, deterioration of efficiency, performance improvement.
Francis, Pelton and Fixed-blade Propeller turbines	30 to 50	
Pump turbines (all types)	25 to 35	
Storage pumps (all types)	25 to 35	
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	30 to 50	Right of way, corrosion, safety of operation, climatic conditions, quality of material, state-of-the-art, capacity vs. service conditions.
Concrete towers	30 to 40	
Wooden poles	20 to 25	
Lines and cables	25 to 40	

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

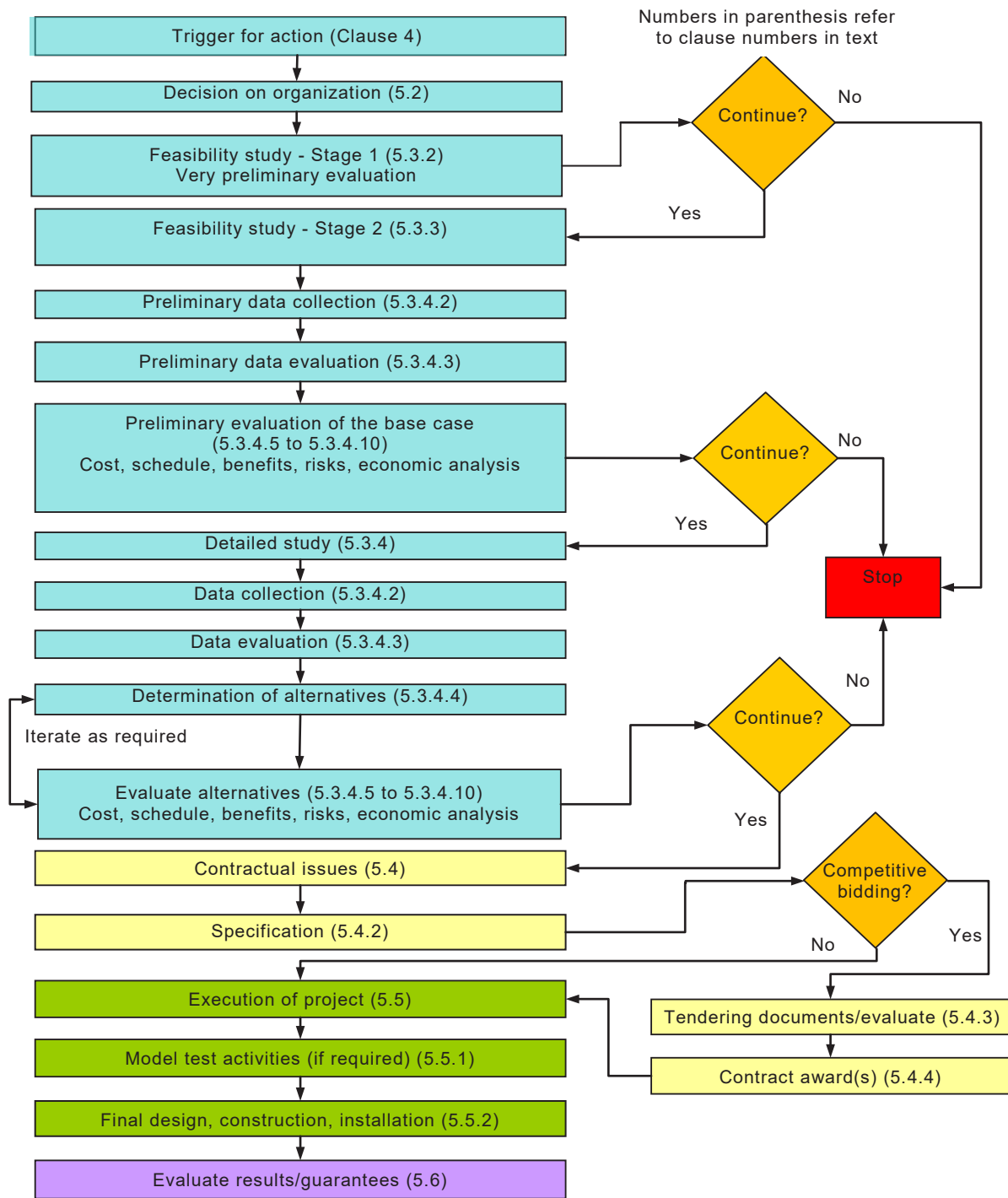
There may be one or more other criteria such as those listed below which could have an impact on the decision to rehabilitate or its timing:

- 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.



IEC

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 team

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.